FLAMN-19

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INTERNATIONAL SYMPOSIUM FUNDAMENTALS OF LASER ASSISTED MICRO- & NANOTECHNOLOGIES

JUNE 30 – JULY 4, 2019

Saint-Petersburg, Russia

ABSTRACTS

INTERNATIONAL SYMPOSIUM FLAMN-19

FUNDAMENTALS OF LASER ASSISTED MICRO- & NANOTECHNOLOGIES

DEDICATED TO THE 50TH ANNIVERSARY OF THE FIRST CONFERENCE

“NON-RESONANT LASER-MATTER INTERACTION”

Symposium Abstract Book

FLAMN-19

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JUNE 30 - JULY 4, 2019
ST. PETERSBURG, RUSSIA

INTERNATIONAL SYMPOSIUM

FUNDAMENTALS OF LASER ASSISTED MICRO– & NANOTECHNOLOGIES (FLAMN-19)

JUNE 30 - JULY 4, 2019
ST. PETERSBURG, RUSSIA

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E. Shahno, ITMO University, St. Petersburg, Russia.

Workshop “Industrial Application of Lasers"

S.Gorny, Laser Center LLC, St. Petersburg, Russia.

CONTENTS

PL-1 Laser printing of nanoparticles and living cells

B. Chichkov,

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Laser printing can be applied for printing very small and delicate objects like nanostructures, nanoparticles, living cells, and microorganisms. We will demonstrate several laser printing techniques allowing the generation and arrangement of spherical metal and dielectric nanoparticles in a very precise manner. We will discuss prospects of this technology for printing metalenses and realization of 3d nanostructures.

In a series of publications on laser printing of living cells we demonstrated that cells are not harmed by the printing process. Different cell types, including primary cells, stem cells, iPS cells, differentiated iPS cells, and microorganisms embedded in hydrogels as extra-cellular matrix, have been printed. I will report on our recent progress and ongoing research in this field.

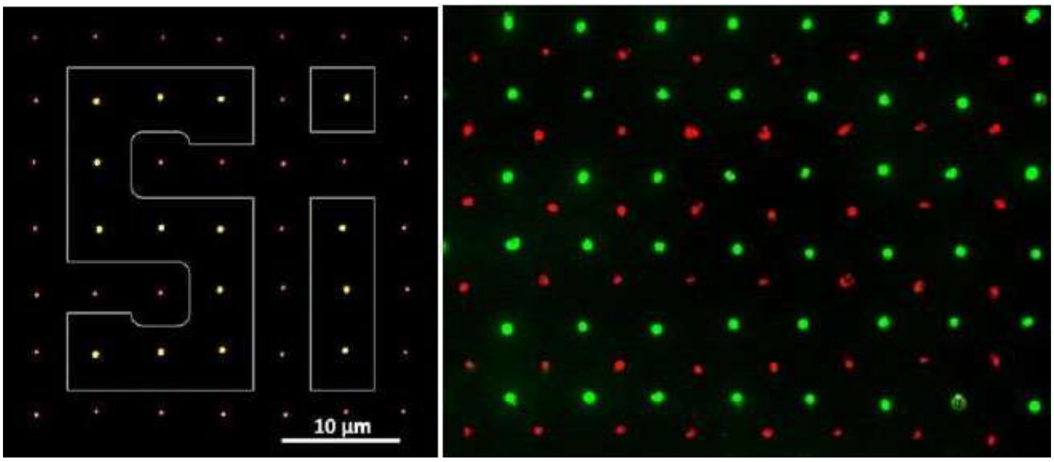

Fig. Examples of laser printed arrays of Si nanoparticles, and living (endothelial and stem) cells.

PL-2 Contribution of laser methods to the conservation and characterization -down to the nanoscale- of works of art

M. Menu[1,2], V. Detalle[1,2], T. Calligaro[1,2], X. Bai[1], M. Lopez[1], C. Koch-Dandolo[1],

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The C2RMF is a National laboratory in charge of the conservation and study of the artefacts kept inside the 1200 French museums. The laboratory inside gives service to the museums in terms of expertise and of assistance to conservation. It develops also research in these areas and more generally the research merging Natural Sciences and Art History on museum artefacts. To this goal the laboratory has an active research activity devoted to new developments and implementation of analytical methodologies taking into account the specificity of the works of art: preciousness, sensitivity,… For this purpose and with the support of National Research institutions (CNRS, CEA, universities,…) the C2RMF maintains and develops a unique Ion Beam accelerator 100% dedicated to the characterization of cultural heritage materials in a non-destructive way. On the other hand, during the 10 passing years, the laboratory was involved in the implementation of mobile instrumentations where lasers sources are an indispensable part. We shall present several applications of experiments achieved inside the laboratory such as OCT or UV Fluorescence imaging on Leonardo's paintings,… For conservation, we shall present some recent achievements on the varnish removal of paintings using short pulse lasers.

PL-3 PDT and High-Power Laser – from Experiments to Clinical application

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Biophotonics and laser medicine are very dynamic fields. Direct communication with medical doctors is necessary to identify specific requests and unmet needs. Information on innovative, new or renewed techniques is necessary to design medical devices for introduction into clinical application and finally to become established after positive clinical trials as well as medical approval.

Photodynamic therapy is a tumor treatment modality with high selectivity. Interstitial PDT is proposed to manage malignant gliomas which are devastating brain tumor diseases with very poor prognosis. Optical concepts for treatment as well as for on-line monitoring, which may be relevant with regard to treatment prognosis and strategy, will be presented.

The introduction of high power laser applications in clinical environments includes new laser wavelengths and laser parameters which showed innovative clinical potential in comparison to already used laser systems. With the aim of tissue reduction to achieve improvement while breathing, laser assisted coagulation of hyperplastic nasal turbinates could be performed. Laser assisted tissue ablation to remove of endobronchial stents becomes an innovative strategy in pulmonology. For minimizing side effects and handling optimisation, in urological stone management new laser parameters and equipment are under investigation.

Pre-requisit for all clinical applications is the intense and careful investigation of the envisioned clinical application in laboratory environment on which suitable laser parameter can be derived. Furthermore application devices can be developed and adopted for specific application purposes. Prior to clinical use the medical doctor in charge should be trained in the lab with regard to handling the laser system, to become aware of the in-situ laser-tissue interaction and finally in specific handling manoeuvres.

PL-4 Femtosecond laser 3D processing for fabrication of functional micro and nanosystems

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The extremely high peak intensity associated with ultrashort pulse width of femtosecond (fs) laser can induce nonlinear multiphoton absorption with materials that are transparent to the laser wavelength. More interestingly, focusing the fs laser beam inside the transparent materials confines the nonlinear interaction only within the focal volume, enabling three-dimensional (3D) micro and nanofabrication. This 3D capability offers three different schemes involving undeformative, subtractive, and additive processing. The undeformative processing preforms internal refractive index modification to construct 3D optical microcomponents inside transparent materials. Subtractive processing can realize the direct fabrication of 3D microfluidic structures in glass. Additive processing represented by two-photon polymerization (TPP) enables the fabrication of 3D micro- and nanostructures made of not only polymer but also protein. Hybrid approach of different schemes can further create much more complex 3D structures and thereby promises to enhance functionality of micro and nanosystems. For example, combination of subtractive 3D glass micromachining and additive TPP can create functional biochips. Specifically, the subtractive 3D glass micromachining is used to fabricate 3D microfluidic structures inside glass microchips with flexible gemometries. Successive TPP can then integrate complex shapes of polymer structures with a sub-micrometer feature size to create biomimetic structures inside the glass microfluidic structure. Thus, such advanced biochips can be utilized for many biological investigations including the mechanism study of cancer cell invasion and metastasis. Meanwhile, the subtractive 3D glass micromachining followed by femtosecond laser direct write ablation and successive electroless metal platig enables selective metalization of 3D glass microfluidic chips for electrical control of livng cell movement in 3D. This selective mtallization technique is also applied to fabricate 3D microfludic surface-enhanced Raman spectroscopy (SERS) sensers with an extremely high enhancement factor. This talk presents our recent achievements on fabrication of functional 3D micro and nanosystems including microfluidics, optofluidics, microsensors, and 3D

PL-5 Laser interaction below 15 fs duration on dielectrics and metals – applications to LIDT for Ti:Sa PW lasers

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In recent years, many very ambitious ultra-high intense (UHI) laser projects have emerged like ELI (Extreme Light Infrastructure), Apollon, etc. to explore new areas of physics using laser intensities > 10^{23} - 10^{24} W/cm^2 on target. In order to achieve such intensities one solution adopted by several facilities is to capitalize on the capability of Ti: Sa technology to amplify very broad spectrum laser pulses allowing after to compress them ultrashort pulse duration. Thereby multi –Petawatts Ti:Sa lasers are under construction to deliver a reasonable laser energy (< a few hundred Joules) and repetition rate (< 10 Hz) but with an ultra-short pulse duration (~ 15 fs). Nevertheless damage threshold of optical components remains a crucial issue when using such laser pulses especially in terms of reliability, compactness and running costs of PW class laser facilities. In this context, the results of fundamental laser induced damage threshold (LIDT) studies of dielectric (fused silica and sapphire) and metals will be shown and discussed for pulse duration from 100 fs down to 10 fs at 800 nm central wavelength. Finally, measurements of LIDT of optical components designed for PW laser class will be also presented.

PL-6 Material Functionalization with Femtosecond Lasers

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Femtosecond lasers are a powerful tool for high-precision material processing and functionalization. In this talk, I will discuss some of our recent advancements and activities in femtosecond laser micro- and nano-processing, including the resulting surface structures, their formation dynamics, and the drastically altered surface functionalities. I will also discuss the broader research activities in my lab, including extreme nonlinear optics, advanced material developments, nanophotonics, and ultrafast metrology.

LT-1 Novel method for precise and productive CVD diamond surface microstructuring based on ultra-short pulsed laser processing

V.I. Konov[1], T.V. Kononenko[1], D.N. Sovyk[1], V.S. Pavelyev[2], B.A. Knyazev[3], G.N. Kulipanov[3],

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`A new approach to fabricate microstructures on CVD diamond surface by means of intense ultra-short laser pulses combined with plasma treatment was proposed and experimentally realized. It allows avoidance of direct laser ablation of a diamond surface which, as it was found, leads to optical breakdown of diamond underlying layers and results in severe broadband radiation absorption and scattering.

A silicon substrate with laser microstructured surface is used to grow a CVD diamond plate in a microwave plasma reactor. After that the substrate is deleted by chemical etching and finally we obtain a diamond plate with one side having a desired profile of non-damaged material, being a negative to that of the laser produced on a silicon substrate – so called replica technique.

The object of this work was fabrication and testing of a cylindrical CVD diamond Fresnel lens as an example of a diffractive optical element (DOE) for high power THz radiation. Silicon substrate surface deep microstructuring with high precision and productivity was performed by ytterbium disk laser (λ_0=1030 nm) generating 1ps pulses at 200 kHz repetition rate.

The produced cylindrical diamond Fresnel lens for the THz beam of a free electron laser (mean power up to 100 W and wavelength λ_T=142 μm) had an aperture of 20 mm and thickness of 0.5 mm. Its structure depth was about 100 μm. The DOE elements surface roughness was determined by the quality of laser processing of the silicon substrate and did not exceed 0,7 μm, thus making THz beam scattering losses negligible. The focal length and energy distribution in the focal plane of the THz beam well matched with the calculated values, efficiency was close to 100 % (without reflection losses).

LT-2 Power limitations and some design ideas for high-power semiconductor lasers for laser material processing and LIDARs

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High-power semiconductor lasers emitting at wavelengths of 900-1500 nm are of crucial importance for a large number of applications. Many of these involve laser-matter interactions, from material processing/cutting (in which case they can be used either to pump solid-state lasers or in direct-diode systems), through biological and biochemical applications to LIDARs (in which case the interaction with matter is essentially reflection). The physics of the laser itself also involves nontrivial interactions of laser radiation with the semiconductor material, which determine the limitations to the laser power and efficiency – the major parameters for the applications in question.

The talk will overview these limitations, and present the analytical theory and numerical modelling developed by the speaker and co-authors to understand their nature. In general, the power limitations take the form of saturation of output power (pronounced sublinearity of light-current dependence) at high injection level. As high-power lasers typically operate very high above the threshold, it is most often the degradation in the efficiency of laser output (increase in internal parasitic losses), rather than the increase in the effective threshold of laser operation with current, that leads to the power saturation. The nature of the loss degradation varies depending on the laser design and the operating regime. In the case of true continuous wave operation (e.g. in lasers for material processing), the degradation is thermal in nature and consists in increased carrier escape from the active layer of the laser into the broad waveguide of the broadened separate confinement structure typical in high power lasers, increasing the parasitic free-carrier absorption. In combination with the increase in the effective threshold, which it partly facilitates, this effect can lead to power decrease and laser shutdown with increased current. In the case of quasi-continuous wave operation (pumping pulses long enough for the operation to be dynamically stationary but short enough to avoid heating, e.g. in biomedical applications and moderate resolution LIDARs), the main cause of loss increase with current is also absorption by free carriers in the waveguide, but with the carriers originating, not from thermal escape, but from the carrier transport across the waveguide layer and, in some structures, also from two-photon absorption. An analytical theory of these effects has been developed by our team, involving the Universities of York and Oulu and the Ioffe Institute.

The theory suggested a laser design – a strongly asymmetric heterostructure with a refractive index step at the waveguide/n-injector interface much smaller than at the waveguide/p-injector one – which can be used to substantially reduce the loss degradation and achieve high power and efficiency in both operating regime, particularly when the active layer is shifted towards the p-injector.

The same structure also allows for emission of high energy single optical pulses under gain-switching operation used for high-resolution LIDARs.

LT-3 Frontiers in micro- and nano-domain engineering of nonlinear-optical ferroelectrics

V.Ya. Shur, A.R. Akhmatkhanov, A.A. Esin, M.A. Chuvakova, E.A. Mingaliev, A.I. Lobov, M.S. Kosobokov,

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The lithium niobate $LiNbO_3$ (LN), lithium tantalate $LiTaO_3$ (LT) and titanyl phosphate $KTiOPO_4$ (KTP) crystals with tailored periodically poled domain structure (PPLN, PPLT, PPKTP) created with nanoscale period reproducibility are used for second harmonic generation (SHG) and optical parametric oscillation (OPO) based on quasi-phase-matched (QPM) nonlinear optical wavelength conversion [1]. The study of the conductivity relaxation of charged domain walls allowed optimization of the poling process [2]. The domain-domain electrostatic interaction has been investigated [3].

Multiply pulse laser irradiation has been used for switching under the action of the pyroelectric field without application of the external field [4]. Formation of the quasi-regular submicron stripe domain structures has been realized in LT by laser beam scanning. Switching at the elevated temperatures opens the way to complicated fractal and dendrite domain shapes. The unique snowflake domains can be created by domain growth at the elevated temperatures in the plates with artificial dielectric layer [5]. The information obtained from the first in situ study of the domain kinetics with high temporal resolution allowed to obtain original important information about domain wall motion mechanism and to characterize KTP as the most appropriate crystal for sub-micron periodical poling [6]. The poling process at room and elevated temperatures has been studied by in situ optical observation.

The obtained knowledge was applied for producing high-fidelity patterns: (1) PPLN:MgO for green and blue light SHG, (2) MgO doped stoichiometric LT for green and yellow light SHG with output power above 14 W for CW, (3) fan-out domain structures in 3 mm-thick MgO:LN for tunable OPO generation from 2,5 to 4,5 μm for 1053 nm pump. The uniformity of SHG efficiency and QPM temperature was demonstrated.

The equipment of the Ural Center for Shared Use “Modern nanotechnology” Ural Federal University was used. The research was made possible by Russian Science Foundation (Project 18-29-20077-mk). The work was supported by Government of the Russian Federation (Act 211, Agreement 02.A03.21.0006).

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LT-4 Dynamics of laser nanoprinting

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Laser-induced forward transfer (LIFT) is a high resolution digital printing technology which is used to transfer materials in solid or liquid phase. The typical dimension of the LIFT-printed structures is of few micrometers. By downscaling the donor film thickness together with the pulse duration and the spot size of the laser, sub-micrometers metal droplets have also been printed. Recently, we have proposed the double pulse LIFT process (DP-LIFT) which relies on the use of two laser beams to transfer metal droplets in liquid phase from a solid donor thin film. First, a quasi-continuous wave laser irradiates the thin metal donor film to locally form a liquid film, then, a second short pulse laser irradiates this area to induce the formation of a liquid jet and the printing of a small droplet on the receiver substrate.

We used time-resolved shadowgraphy to investigate the dynamics of high-velocity nanojets generated from solid copper films. These experiments show that this DP-LIFT approach induces the formation of very thin and stable liquid jets that expands over distances of few tens of micrometers for a large range of process conditions. We also demonstrated that the size of the melted metal pool plays an important role in the jet dynamics and allows controlling the size of the printed droplets. This process has been used to print 2D and 3D structures with micro and nano-meter sizes while avoiding the generation of any debris and these results demonstrates the high potential of DP-LIFT as a digital nano-printing process.

LT-5 Near-field laser ablation for surface nano-analysis: modeling and experiments

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Near-field laser ablation of different metal and semiconductor samples was studied with nanosecond (Nd:YAG, 4 ns, 532 nm and 266 nm) and femtosecond (Ti-Sapphire, 100 fs, 400 nm) lasers. The method is based on a near-field enhancement effect obtained by the interaction of laser radiation with a diamond coated silicon tip of the Atomic Force Microscope disposed at a few nanometers above the sample surface. Craters of the order of 100 nm in diameter and a few nanometers in depth were obtained by a careful adjustment of the interaction parameters. Laser ablation efficiency and accuracy were affected by both the sample properties (thermal diffusivity, absorption coefficient, etc.) and the near-field parameters (wavelength, laser pulse duration, tips nature and dimension, etc.).

Two theoretical approaches (the analytical one and the Boundary Element Method - BEM) were applied for modeling the near-field spatial distribution and the enhancement factor. Laser ablation may be regarded as a result of the local near-field heating of a sample surface. Multi-parametric theoretical studies with two-temperature thermal model were performed to understand the effect of the interaction parameters (laser fluence, tip dimensions, near-field spatial distribution, tip-to-sample distance, sample and tip optical features, etc.) on the efficiency of the near-field laser heating and ablation. The results of the near-field numerical simulations, as well as the localized heating and ablation of the gold sample surface will be presented along with the corresponding experimental results. The properties of nanometer scale craters were in a good correlation with the model predictions.

LT-6 Advanced laser technologies for photonics applications: 2D/3D photonics materials micro & nanostructuring

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At the present talk the main last results of the "Laser micro- & nanotechnologies" laboratory of the ITMO University will be considered.

1. Local laser oxidation of thin metal films to produce diffraction optical elements of new generation.

Laser oxidation of thin Cr-films is a well-known way to produce diffraction optical elements for different applications – from astronomy till medicine. The needs of new electromagnetic waves ranges (from terahertz to x-rays) applications as well as the tendencies in optics (metaoptics) dictate of its future development in the directions of higher resolution, multicontrast components fabrication and simplification of the processing. The ideas and its theoretical justification and experimental proofs on the ways which are most promising in the pointed directions: opto-thermo-chemo nonlinearities of the oxidation process, metal films with transparent oxides application etc. are discussed in the presentation.

2. Compressed laser-induced carbon μ-plasma (CLICμP) as an effective tool for transparent materials processing

The precise processing of transparent materials still a hard task for laser technology in spite of some limited results received by femto- and picosec lasers. At the same time there are a number of methods for such materials processing are known, beginning from diamond drilling [1] up to laser-induced plasma assisted methods where the glass plate contact (direct or indirect) with absorbing surface (LIPAA, LIBWE, LIBDE etc.) [2-4]. Most of these method based on action of microplasma induced at the interface of glass and absorbing target. The aim of reported work is a cardinal improvement of a laser-plasma action by taking into account different targets plasma properties, more detailed requirements to a laser source and to a geometry of a method (Fig. 1 "a-c"). Finally carbon target with small reflection, pulse fiber laser and confinement mode of geometry let us to achieve high abilities of such CLICμP method for fast and cost-effective microoptical components fabrication on glass surface (microlens array, multilevel phase plates or gratings, polarization-control plates on crystal materials such as Iceland Spar) (Fig. 1 "d, e") [5, 6].

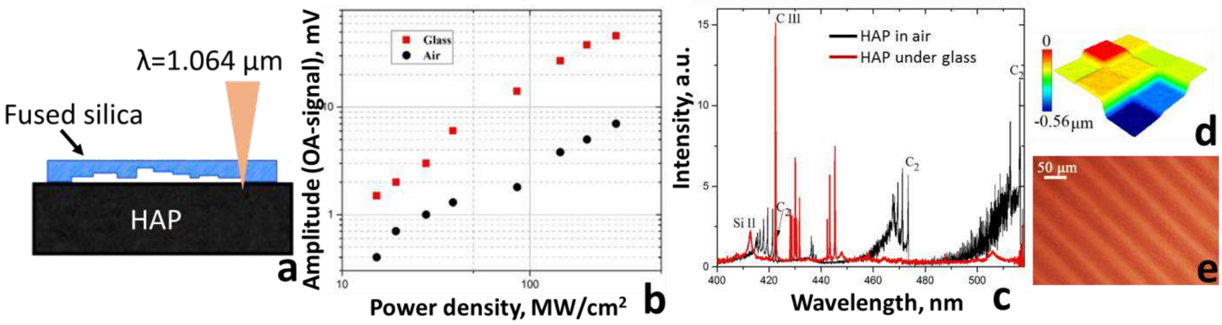

Figure 1. CLIMP method: schematic view of glass processing (a), the amplitude of acoustic signal at different power density (b), emission spectra of laser plasma (c); fabricated optical elements: multilevel phase plates (d) and phase grating (e).

3. Laser-induced porous glass densification – the way for integral sensors fabrication

Creation of an integrated matrix in the porous glass opens a new perspectives for different applications in a biomedicine (lab-on-chip), photonics, gas-analysis etc. The purpose of this part of a work is to demonstrate the laser-induced control of the porous glass (PG) density during formation of molecular barriers with full and selective permeability. The end-to-end densification of the PG was carried out in several stages: fabrication of extended densified regions inside the PG plates under the action of ultrashort laser pulses (λ = 515 nm, Ep = 1 - 2 μJ, τ = 200 fs, ν = 500 kHz) [7]. A set of similar regions along the thickness of the sample constitutes a molecular barrier inside of PG [8]. The permeability of the barrier is determined by the relative distance between the regions. The molecular barrier was densified from the surface by the action of CO_2 laser radiation. As a result of the strong absorption of CO_2 laser radiation, local densification along the barrier occurs, which ensures complete cell tightness. As a result, the set of molecular barriers was created inside of PG plate (Fig. 2 “a”). The impermeability of molecular barriers to rhodamine molecules was experimentally proved (Fig. 1 «b»). At the same time, the passage of water molecules by barriers was noticed.

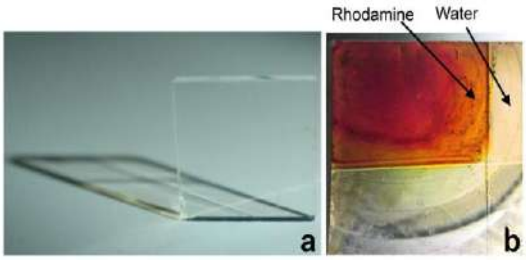

Figure 2 Molecular barriers inside of porous glass: general view (a) and barriers testing during its impregnation with water solution of rhodamine (b).

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LT-7 Laser exfoliation to improve the uptake of foliar-applied agrochemicals in orange plants

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One of the most widespread methods in modern agriculture to improve yields and crop health is the foliar application of agrochemicals. However, there are barriers that prevent the efficient entry of substances into plants and reduce the efficiency of the collection. The surface of leaves has a wax coating that fulfills the function of preventing the entry of pathogens and the loss of water, which in turn prevents the entry of external elements as agrochemicals. Although the movement of substances through the cuticle can be carried out preferentially through the stomata, they are located on the less exposed abaxial side, and their joint area is not significant, which explains the low percentages of penetration of agrochemicals applied by foliar route, and in turn, the high percentages of these agrochemicals are lost and generate an undesirable environmental impact. Anyway, the foliar application of agrochemicals both for fertilization and for combating agricultural diseases has been essential in increasing food production and remains one of the most widespread alternatives, so improving foliar penetration is of great importance.

In this work, we propose a new method to create openings in the wax cuticle of leaves, based on a mechanism of selective absorption of laser light by the water found in the epidermis, provoking partial separation of the cuticle and wax in an area of several square centimeters through the application of laser shots. We demonstrated that this method is very efficient and productive, and does not require focusing the laser, which will facilitate the future application in field conditions. As there is no damage to the epidermis, the cuticle regenerates in the short term, recovering its protective functions.

LT-8 The tendency and tasks of laser micro- and accuracy processing in Wuhan optics valley of China

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Introduced developing history of industry laser in Wuhan Optics valley. Basing on 3C (Computer, Communication, Consumer) market requirements, analyzed the developing tendency of micro- and accuracy laser processing. Tasks of laser micro- and accuracy processing in Wuhan Optics Valley clearly defined.

LT-9 Ultrafast dynamics at fs-laser-excited magnetic meta-surfaces

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Femtosecond laser interactions with magnetic materials result in an immense variety of physical phenomena from different area of physics: nonlinear optics, magnetism, ultrafast spintronics, acoustics, physics of shock waves and/or laser-induced phase transitions. From a metrological perspective different time scales associated with those phenomena can be measured with femtosecond temporal resolution in a variety of conventional linear and nonlinear-optical pump-probe experiments. However, in a typical pump-probe experiment, absorption of an ultrashort, femtosecond laser pulse by an opaque magnetic material simultaneously triggers a variety of coherent and incoherent dynamics of elementary excitations (electrons, phonons, magnons etc.). evolving on several, sometimes comparable time scales, rendering the identification of the underlying physical phenomena extremely challenging.

One of the ways to reduce the complexity of ultrafast optical measurements is to study the experimentally accessible monochromatic excitations and their interactions. To be more specific, here we are talking about the periodic oscillations of electromagnetic fields at the (fundamental, second harmonic, third harmonic etc.) optical frequencies, elastic deformations (surface acoustic waves) at MHz-THz frequencies and time-dependent perturbations of the magnetic order (ferromagnetic resonance, magneto-static or exchange-coupled magnon modes) oscillating at GHz-THz frequencies.

Apart from a trivial case of oscillating optical fields, the temporal periodicity of fs-laser-induced magnetic and acoustic dynamics is not granted. For example, the absorption of an ultrashort optical pulse in a magnetic material results in a famous but aperiodic phenomenon of ultrafast demagnetization [1]. However, under specific conditions dictated by the orientation of an external magnetic field ultrafast demagnetization can trigger ferromagnetic resonance (FMR) precession and oscillating spin-wave resonances at elevated frequencies in ferromagnetic thin films [2,3].

At the same time fs-laser excitation of opaque materials is signified by the thermo-elastic generation of single-cycle acoustic pulses with picosecond time duration [4], which may reach giant strain amplitudes up to 1%, strong enough to induce the nonlinear lattice dynamics at the nano-scale [5] or even switch magnetization in magnetostrictive thin films [6] and ferromagnetic nanostructures [7].

Monochromatic acoustic waves can be generated by fs-laser excitation of periodic gratings, either in the so-called transient grating geometry [8-9] or using permanent gratings [10]. The characteristic feature in these experiments is the possibility to excite monochromatic surface acoustic waves (SAWs) with frequencies tunable by the grating periodicity and going up to a few tens of GHz when using deeply sub-wavelength periodic structures with periods of the order of 100 nm. This sub-wavelength spatial periodicity for magneto-acoustic studies represents the link between ultrafast magneto-acoustics and (magneto-)optics of meta-surfaces. The intrinsic possibility to bring the FMR-frequency in resonance with acoustic waves, for example using a proper combination of grating periodicity and the magnitude of an external magnetic field, can result in the resonant enhancement of FMR precession [8-10], with the onset of parametric instabilities [9]. Whereas the experimental conditions to obtain large-amplitude FMR precession through the fs-laser mediated resonant magneto-elastic interactions have not yet been optimized, such possibility would open a new avenue to modulate the optical properties of magnetic meta-surfaces. Given the case that the static nonlinear magneto-optical and/or magneto-plasmonic effects are giant as compared to the linear ones [11-14], it makes sense to do beyond the time-resolved measurements based on linear magneto-optical effects and probe the dynamics of resonant magneto-acoustic interactions [8-10] with nonlinear magneto-optical detection schemas [11-14], hoping to develop real-life applications with magnetic meta-surfaces modulated on ultrafast time scales.

Whereas the discussed phenomena have been investigated on periodic nanostructures produced my lithographic techniques, their true potential can be explored while studying fs-laser produced periodic nanostructures on magnetic materials. Many physical properties (not accessible by conventional high-resolution imaging techniques) such as hidden periodicities of buried interfaces, sub-surface inhomogeneities of elastic properties and magnetic anisotropies, linear and nonlinear optical diffraction efficiencies etc. could be extracted from the reported magneto-optical and magneto-acoustic measurements.

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LT-10 Surface structuring with bursts of ps-delayed femtosecond laser pulses

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Since their first experimental observation, laser induced periodic surface structures (LIPSS) have attracted growing interest both from the scientific community to understand and possibly control the physical mechanisms underlying their formation, and from the industry since these microstructures can find application for the functionalization of surfaces and/or devices of different materials. Regardless of their generation mechanism, whether it is due to interference between the incident and the scattered electromagnetic waves on the surface or rather to microfluidic movements of the molten surface layer driven by temperature gradients, it is well recognized that the timescale of LIPSS formation is between tens and hundreds of picoseconds after irradiation of the first pulse. During this time frame, the surface material is in a transient state. In literature, most of the works have investigated LIPSS formation using trains of linearly polarized ultrashort pulses with time separations much longer that this timescale. Recently, in a few works, double-pulse irradiation was employed varying the time separation in the picosecond and nanosecond range and also the polarization state between the two pulses.

In this work, we utilize a robust and simple setup based on an array of birefringent crystals to generate bursts with variable number of femtosecond pulses and pulse-to-pulse delay in the range from 1.5 ps to

24 ps. Subsequently, these bursts are employed to produce homogeneous LIPSS over large areas of stainless steel samples. We show that the morphology of the LIPSS is greatly affected by the process parameters like the laser fluence, the number of pulses in the burst, the intra-burst delay, the total burst duration and the polarization state of the pulses within the burst. Finally, the static and dynamic wettability properties of selected surfaces characterized by quite different LIPSS morphologies has been analysed.

LT-12 Ultrafast all-optical switching due to photon-avalanche-like processes in heterostructures with deep quantum wells

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Novel features of nonlinear optical processes in heterostructures with deep quantum wells (QWs) under laser pulses will be considered. The following processes will be discussed:

a) type I (conventional) photon-avalanche (PA)-like effects and in systems of impure rare-earth (RE) ions and in deep QWs: for this type of effects the photon absorption and the energy transfer between electrons are involved in different elementary events;

b) type II: single- or many-photon absorption and the energy transfer are involved in one elementary event in intrinsic crystals with special types of the electron energy band structure, wide-gap crystals with high concentration of deep impurity centers, and deep QWs;

c) efficient up-conversion and light-with-light controlling involving both type I and type II PA processes in heterostructures with deep QWs [1, 2].

Quantum-mechanical calculations of the rates of elementary processes involved in above-mentioned phenomena were carried out within high-order perturbation theory. The results of these calculations were applied to analyze kinetics of non-equilibrium electron-hole pairs producing, optical transmission, and optical switching the media between states with essentially different optical and electrical properties.

It was shown that in all cases under consideration a rather narrow region of laser intensities j appears where both the populations of electron states and optical transmission dramatically change even at small change of j. A number of crystals and heterostructures, whose electron band structure and geometric parameters allow the above-described transient nonlinear processes of photoexcitation and optical switching, are considered in detail.

Typical times τ and densities of light energy Ξ for all-optical switching are estimated as $\tau\sim 0.1\div 10$ ns and $\Xi\sim 0.1\div 10$ pJ/cm^2 respectively.

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E.Yu. Perlin, A.A. Popov, and A.V. Ivanov, 2019, in press

LT-13 Chemical functionalization of graphene on patterned surfaces

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The role of ambient gases in material processing by high-peak-power laser pulses is still poorly understood due to a large variety and complexity of the involved processes. [1] Here we report on a discovery of accumulation effects upon propagation of focused fs laser pulses (800 nm, 120 fs) in air under multi-pulse irradiation conditions. The accumulation facilitates multiphoton ionization of air by subsequent laser pulses thus affecting the pulse energy transmitted through the focal region. The transmission measurements have been carried out in air at different pressures and in vacuum for comparison. We have also performed spectroscopic measurements in the air breakdown plasma which show that molecular nitrogen lines appear at fluences well below the breakdown threshold determined from the transmission measurements. The plasma absorption effects are found to be dependent on the pulse repetition rate and are stronger at 1 kHz than at 1-10 Hz. This suggests that metastable-state air molecules play an important role in initiation of air breakdown at high repetition rates. The spectroscopic data indicate that the ionization process involves the triplet (A) state of molecular nitrogen with a life time of about 10 ms. Modelling of laser-induced air ionization using the model [1] shows good agreement with the experimental data. The role of plasma absorption in material processing with high rep-rate and burst mode lasers will be discussed.

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LT-14 Deposition of Ag metal on glass with Laser-Induced Reverse Transfer techniques using a ps UV laser

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Silver coatings on glass have been fabricated using a Laser-Induced Reverse Transfer technique. One of the advantages of this technique is that coatings can be obtained in ambient air or in controlled atmospheres and avoids the use of liquids, solvents or similar. Laser induces the ablation of the metal and part of the ejected material is deposited on the surface of a glass. In this work, a subnanosecond UV laser has been used to generate the silver ablation. We have analysed the coating generation process studying how silver is deposited on the glass using burst-mode or isolated lines configurations. From these initial studies, the optimisation of the laser parameters for the generation of a uniform coating (frequency, laser scanning speed, scanning overlapping, laser power) has been performed. Two different processing configurations have been used, one based on beam scanning, the other one on laser line scanning. Microstructure of the coatings has been investigated using field emission scanning and transmission electron microscopy and XPS measurements with lateral resolution. Their quality has been evaluated from the value of the electrical resistance of the coating on the glass. It has been observed that, depending on the laser parameters applied, it is possible to modify the resistance of the coating by several orders of magnitude, reaching low values of several ohms. These deposits have been used to obtain Dielectric Barrier Discharge plasma elements by generating simple basic electrical circuits.

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LT-15 Laser and plasma assisted fabrication of immiscible nanocrystalline alloys

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In this work, we demonstrate that the combination of two non-equilibrium processes based on plasma and laser treatment of microparticles in liquid is efficient for the synthesis of alloyed NPs, including alloys of immiscible elements. Electrical discharge plasma treatment decreases the microparticles size while additional laser irradiation enables their further melting. Laser irradiation of colloidal nanoparticles mixture with the second harmonic of Nd3+: YAG laser (532 nm) could provide unique possibilities for the alloying with the control over their phase composition and size by varying the laser irradiation conditions. The method's efficiency was demonstrated on the Ag-Cu and Ge-Sn nanoalloys preparation that are promising for applications in medicine, sensors, microelectronics, catalysis, optoelectronics and photovoltaics.

The formation of alloyed nanocrystals was proved by the results of UV-Vis spectroscopy, EDX and HRTEM measurements. Measurements at macroscopic (solution absorption), microscopic (scattering of individual NPs) and nanoscopic (electron microscopy) scales confirm alloying of NPs and homogenization in size and composition. The average diameter of the alloyed AgCu NPs was found to be 15.5 nm, while that of Ge-Sn NCs - about 60 nm. The study of the phase composition revealed that the laser treated AgCu samples consist of two types of particles – bimetallic polycrystalline and monocrystalline alloyed of larger size. The prepared Ge-Sn NCs exhibited a shift of the Raman peak attributable to Ge to the lower wavenumbers that can indicate the incorporation of Sn into the lattice and alloy formation.

Thus, the combined process opens up a way to new design of nanoparticles with controlled properties. Laser induced rapid heating, subsequent co-melting, and re-solidification processes at high cooling rates have been considered to be experimentally achieved at the optimized laser processing parameters. With a synthesis rate of 360 mg/h, the proposed combined approach opens up interesting perspectives for non-equilibrium nanometallurgy of functional NPs.

LT-16 X-Ray source based on repetition rate femtosecond pulse interaction with structured magnetic tape

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Using structured targets leads to high energy coupling, enhancing energy of hot electrons and more efficient X-ray production.

One of the perspective material for x-ray source in repetition rate regime is commercially available magnetic tape. It consists of a thin layer of a magnetic pigment of iron oxides (in the form of nanocylinders) which orientation has a selected direction on average along the longitudinal axis of the film.

The goal of this work is to firstly investigate dependence of x-ray yield from plasma ignited on the surface of magnetic tape on orientation of polarization of incident laser radiation and to find regime when x-ray yield is maximal.

To investigate polarization dependence of x-ray yield we suggest the theoretical model in which in case of cylinders aggregation along longitudinal axis of the film we suggest the model of the structure as 1D grating. Period of the grating weakly differs from cylinders diameter. The profile height is defined by cylinders aggregation with depth. The surroundings permittivity is assumed as dielectric (air).

Due to this model we find that S polarization of laser pulses lead to more efficient energy absorption and higher X-ray yield

We obtained that X-ray yield from nanoplasma ignited by femtosecond laser radiation (1.24 μm, 200 fs, 10 Hz, f = 30 cm) with I~0.3 PW/cm^2 on the surface of a magnetic film located in the air has a maximal level at normal laser incident. The conversion efficiency achieve the value of $5*10^{-8}$. We find that at this intensities S polarization lead to more efficient energy absorption and higher X-ray yield as predicted theoretically.

In our presentation we also discuss the effects of laser pulses at an intensity of 1015 W/cm^2 at tightly focusing regime.

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LMI-1 Few-cycle laser damage on ZnSe surface

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With fast development of ultra-short high-intensity laser in recent years, laser-material interaction research has been deep into nucleus electrons dynamics. High power laser-induced periodic surface structures is commonly generated and deliberately modulated by controlling the incident laser pulse. The formation mechanism of ripples is still under investigation. In our work, the laser-induced damage experiment was conducted on ZnSe with 3-mJ, 2-cycle, and carrier-envelope-phase stable infrared laser source. The poly-crystalline grain boundaries affect the beginning of surface damages morphologies, and ripple evolved neatly as the laser shot accumulated. Electron dynamic calculations were employed according to Keldysh theory to demonstrate the electron density evolution in ZnSe surface. Our experiment demonstrated the very beginning of laser-induced ripples on the ZnSe surface by using the shortest infrared few-cycle laser pulse currently available. Grain boundaries in polycrystalline material regarded as the damage source in the very beginning of laser irradiation and eventually generate surface ripples.

LMI-2 Simulation of the structural response of nanostructures and proteins to femtosecond-laser- and microwave radiation

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We have used and developed different theoretical methods to describe the ultrafast nonthermal dynamics of nanostructures and proteins upon excitation by light pulses.

With the help of our in-house code CHIVES (Code for Highly excited Valence Electron Systems) we performed ab-initio molecular-dynamics (MD) simulations of the laser excitation of coherent phonons in BN nanotubes. We show that it is possible to fully control the three coherent optical phonons in BN-nanotubes by a pulse train. This control scheme also allows to produce shaped Terahertz emission [2].

Using CHIVES, we also investigated the ultrafast structural response of Graphene to femtosecond laser pulses. We explicitly included the electron-phonon interactions within the Eliashberg formalism. The approach is free of parameters. We found a biexponential decay of the intensity of the Bragg-peaks. The first fast decay is produced by the interaction of hot electrons with the SCOPS (strongly coupled optical phonons), whereas the slower decay comes from phonon-phonon collisions.

In order to investigate the contribution of ultrafast thermal and nonthermal effects to the melting and ablation of thin films we developed, with the help of a self-learning method, an electronic-temperature dependent analytical interatomic potential for antimony. The potential allows to explicitly include electron-phonon interactions and to perform MD-TTM (molecular-dynamics-two-temperature-model) simulations. We performed simulations on laser melting of Sb films seeking for a speed limit for this transition.

Finally, we present an extensive theoretical study of the influence of microwave radiation on proteins.

First, we performed MD simulations of the microwave-radiation induced dynamics of Amyloid β (1-40). Simulations explicitly included surrounding water molecules and included long runs (many runs up to $1\mu s$, a few runs up to 1ms). The resulting Big data were analyzed by means of a new developed nonequilibrium Markov-State-Modeling method [3]. We found that radiation favors conformations which lead to protein aggregation.

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LMI-3 Nanophysics in laser-induced cluster systems: topological quantum states in electrical conductivity and features of optical spectra. Theory and experiment for dimensional effects

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1. In theory and experiment the laser-induced nanocluster structures of various types (by topology and elemental compositions of noble metals/carbon, bimetals, semiconductors, etc.) were investigated taking into account correlations in an ensemble of nanoparticles with quantum-dimensional states. In our experiments, we obtained a dramatic enhancement (in several orders) of electro-conductivity due to the variation of topological peculiarities of a nanocluster thin film system. They may be presented as a grid ensemble of a single-electron system demonstrating a nonlinear quantum dynamic behavior around the forbidden gap. The process may be interpreted as a non-linear phase transition in topological structure induced by laser radiation.

2. In the experiments we used the multilayer film formation by dynamic nonlinear processes: first, induced nanoparticles in colloidal solution by ms/ns-laser pulses (10^6 – 10^7 W/cm^2) acting on target in liquid; and second, due to laser deposition of particles from colloid on solid surface under cw-radiation. The results are:

(1) in electroconductivity

- the tunneling delocalized effect depends on the size of nanoparticles, distance between them and shape of tunnel barriers, and also on variation of the thickness of the films resulting to local phase transitions from amorphous to crystalline structure;
- the thermally activated hopping regimes of the electronic transport between localized centers depending on local internal fields;
- the topology superconductor tendency in the cluster grid-system like in topological insulator;

(2) in optical characteristics

- the broadening of electronic levels occurs by the control way;
- optical metasurfaces characteristics can be measured for a specific structure;
- strong optical response may develop;
- density of e-state (on Fermi-surface) can modify in different aspects.

3. The noted features of the manifestation of fundamental effects in nanostructured thin-films suggest the formation of a new direction in topological photonics, applied to femtosecond nanoelectronics.

LMI-4 Nanoparticle research and the chemistry in laser-induced plasmas for space exploration and astrobiology

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Laser-induced breakdown spectroscopy is one the areas of analytical spectroscopy receiving a broadest interest. An increased understanding of the underlying phenomena occurring in the plasma and the use of new experimental strategies and improved instrumentation are current opening new fields of application of LIBS such as the analysis of nanoparticles or the use of molecular information in the plasma.

In the present talk, advanced in the use of LIBS for the characterization of single nanoparticles will be presented. The detection power of LIBS will be discussed for multielemental single nanoparticles analyzed in an optical trap. Also, some results on the chemistry in laser-induced plasmas will be presented with focus on the potential use of LIBS molecular fingerprints for space exploration.

LMI-5 Laser technologies: from physics of ablation to surface nanostructuring, synthesis of colloids, and 3D printing

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Laser technologies cover a wide range of modern industrial applications from automotive industry, ship building, and engineering to printing of metasurfaces for microelectronics, plasmonics, sensorics etc. In many cases these applications run ahead a physical theory which should support planning and optimization of production. Authors report here recently obtained results from the sources [1-7]. They reveal hierarchies of physical processes taking place during synthesis of colloidal solutions of nanoparticles via ablation of metals in liquid [1,2] and nanostructuring of metasurfaces via 3D laser printing [3-7]. Evolution from early to late stages of ablation in liquid is followed [1,2]. Influence of duration of a pulse is described [2]. Dissolution/evaporation of metal atoms through a surface barrier [1,2] into liquid and removal of this barrier at higher temperatures (surface tension decreases to zero) [2] and transfer from dissolution and diffusion to pure diffusion are considered. Condensation of dissolved metal atoms inside dense environment (thus outside existing theories of nucleation) is studied. Work was done for the government order (0033-2019-0007).

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LMI-6 Ultrafast laser-heating of solids: electron-lattice coupling effects

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The energy of ultrafast laser pulses is mainly absorbed by the electrons of a solid, bringing them to a highly nonequilibrium distribution. Electron-electron collisions thermalize the system to an elevated temperature within a few tens of femtoseconds [1]. Through electron-phonon collisions, energy is transferred from the hot electrons to the initially cold lattice. The energy balance can be readily described in the framework of the well-known two-temperature model [2].

In this contribution we show examples for metals [3] as well as for dielectrics [4] on how the electron-phonon coupling drives new nonequilibrium states of the electronic system. Moreover, we extract electron-phonon coupling parameters for different materials in different stages after ultrafast excitation.

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LMI-7 Laser dielectric interaction: new insight from double pulse experiments

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When an intense ultrashort light pulse – in the visible domain- interacts with a wide band gap dielectric, a plasma can be generated by non-linear photoexcitation of carrier from the valence band to the initially empty conduction band. These carriers can be further excited in the conduction band, leading to an increase of their energy distribution, and thus of the amount of energy transferred to the material. If this deposited energy exceeds some critical threshold, permanent modification, damage or ablation may take place. The two key parameters determining the energy deposition are the density and the temperature of the plasma. In this presentation, we wish to demonstrate that a sequence of double pulse can be used to better control these two parameters, and thus to optimize energy deposition and facilitate for instance ablation of insulators and semi-conductors in the VUV domain.

First, in the visible domain, using the second harmonic and the fundamental of a Ti-Sa laser, we show that time resolved double pump- and probe experiment allows to directly observe the sequence of events carrier excitation/ carrier heating, provided the parameters (energy, duration, delay) are appropriately chosen. Then, the ablation threshold (due to the first pulse) is dramatically reduced by the presence of the second pulse, while the characteristic of ablation are still determined by the first pulse [1]. Finally, new information regarding the excitation mechanisms, in particular impact ionization and avalanche are obtained [2].

In the second part, we show that this double pulse technique can be extended in the VUV domain.

Using high order harmonics of a Ti-Sa laser (harmonic 25, ie. wavelength of 32 nm), whose intensity of far too low to damage any material, we could observe direct ablation of a dielectric, namely quartz, a-SiO_2, when the VUV pulse if followed by an IR pulse with appropriate characteristics, paving the way to direct laser machining in the VUV domain.

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LMI-8 Electronic excitation-induced semiconductor-to-metal transition in monolayer $MoTe_2$

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Chalcogenide semiconductors are known to change their structure upon exposure to external stimuli such as light. The class known as chalcogenide vitreous semiconductors (e.g. As_2S_3), the structure of which contains lone-pair electrons, exhibits a wide range of photo-induced phenomena such as reversible photostructural changes, photo-induced anisotropy, photo-induced fluidity etc. Lone-pair electrons are crucial for these phenomena. For reviews see [1,2].

A different family of chalcogenides known as phase-change materials (typically, Ge-Sb-Te alloys) reversibly change their structure between the crystalline and amorphous phases, upon exposure to light (or current) pulses [2]. In the crystalline phase of these materials, lone-pair electrons are used for bonding and the mechanism of phase-change is usually attributed to heat effects of the light (current), although there is some evidence that electronic excitation of the system also plays a role [3].

In recent years transition-metal dichalcogenides such as MoS_2, $MoTe_2$ etc., and especially monolayers thereof, have attracted tremendous interest [4] and it was argued that their structure can be reversibly changed between the stable 2H and metastable 1T' phases by application of, for example, pressure [4].

In this work, we demonstrate through ab-initio density functional theory simulations that monolayer $MoTe_2$ changes its structure to 2H* phase upon electronic excitation [5]. Different from the 2H-to-1T' transition, the 2H* phase is unstable and decays to the 2H phase upon cessation of electronic excitation. We have also studied experimental response of $MoTe_2$ to femtosecond laser pulses, the results are discussed in conjunction with the 2H-to-2H* transition.

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LMI-9 Interaction of intense ultrashort terahertz pulses with narrow-gap semiconductors

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Interaction of intense terahertz (THz) pulse with matter has attracted considerable attention over the last decade. When a semiconductor is illuminated by intense THz radiation the average electron energy increases and the impact ionization process may be started. Development of intense few-cycle THz pulse sources has made possible studying carrier dynamics and impact ionization by purely optical methods [1]. A sevenfold increase in electron density above equilibrium was observed in n - type InSb when near single - cycle pulses with field strength up to 100 kV/cm and duration of 1 ps were used. Later, the intervalley scattering of electrons and impact ionization in InAs were investigated at 300K under the excitation of intense single-cycle THz 150 fs-long pulses [2].

We present the results of Monte Carlo simulation of electron dynamics and impact ionization in InSb and InAs induced by intense ultrashort terahertz pulses. It is established that E_{th} of n-InSb at 80 K is about 8 kV/cm for single cycle 1 ps-long pulses. The time of the repopulation of electrons between the Γ and L valleys in the strong electric field is evaluated to be of the order of 50 fs, which is in good agreement with experimentally measured the Γ- to -L intervalley scattering time of 44 fs. The threshold electric field of impact ionization of InAs at 300 K was estimated to be equal to 10 kV/cm for the case of 0.8 ps-long pulse. The calculations show that the threshold electric field E_{th} grows as the pulse gets shorter, and comes up to 80 kV/cm at τ = 150 fs. It was found that the THz radiation-heated electrons at first transfer from the □ to the L valley, and only then they are scattered from the L to the X valley. Characteristic time of repopulation of electrons between the □ and L valleys in strong electric field is found to be of the order of 100 fs, and that between the L and X valleys is about 120 fs.

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LMI-10 Kinetics of heterogeneous melting of a thin film near the threshold for complete melting: How slow can it get?

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Melting is one of the most common phase transformations in materials, and the mechanisms of melting have been thoroughly investigated theoretically, computationally, and experimentally over more than a century [1]. This well-studied phenomenon, however, reveals new and not yet fully understood facets under conditions of short pulse laser irradiation, when the crystal can be driven far from its thermal, mechanical, and electron-phonon equilibrium. In particular, recent ultrafast electron diffraction experiments [2] performed for 35-nm-thick Au films irradiated by 130 fs laser pulses were used to map the transition from slow (> 1 ns at the threshold for complete melting, Fmelt) heterogeneous melting proceeding through the propagation of melting fronts from the surfaces of the film to the fast homogeneous melting within just 17 ps after the laser pulse at a fluence of 5.3Fmelt. To facilitate the physical interpretation of the experimental results, we perform large-scale atomistic simulations of Au films under conditions similar to those used in the experiments. At energy densities close to the melting threshold the simulations are continued up to 3.5 ns, so that we could make conclusions about the system state. The comparison to experimental data is facilitated by the calculation of the time-resolved diffraction profiles, and the implications of the computational predictions on the electron temperature dependence of the strength of electron-phonon coupling is discussed.

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LMI-12 Model of stimulated emission in aluminum laser-induced plasma produced by resonance pumping

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Stimulated emission observed experimentally in aluminum laser induced plasma is modeled via a kinetic approach. The simulated emission at several cascade transitions is created by a pump laser guided through the plasma at several microseconds after its creation and tuned in resonance with the strong transition at 266 nm. A two-dimensional space-time collisional radiative plasma model explains the creation of the population inversion and lasing at wavelengths 2.1 μm and 396.1 nm. The population inversion for lasing at 2.1 μm is created by depopulation of the ground state and population of the upper state via absorption of resonant radiation at 266 nm. The population inversion for lasing at 396.1 nm occurs during the laser pulse via the decay of the population of the pumped upper state to the lasing state via cascade transitions driven optically and by collisions. The model predicts that the population inversion and corresponding gain may reach high values even at moderate pump energies of several μJ per pulse. The efficiency of lasing at 2.1 μm and 396.1 nm is estimated to be on the order of a percent of laser pump energy. The polarization effect that the pump radiation at 266 nm imposes on the stimulated emission at 396.1 nm is discussed. The calculated results are favorably compared to experiment.

LMI-13 Thermal and dynamic effects of laser irradiation of thin metal films

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The problem of irradiation of a thin gold film deposited on a glass substrate by a narrowly focused single femtosecond laser pulse is considered. Different surface structures can emerge depending on amount of radiation energy absorbed by an irradiated surface.

The most important thermal driver for the formation of surface structures is the lateral electron heat flow in the film. This effect consists from three stages: (i) the distribution of the absorbed in the skin layer of laser energy from the frontal boundary of the film to the rear boundary to equalize the temperature; (ii) lateral transfer of energy along the film from the center to the edges; (iii) cooling and recrystallization of the heated region of the light spot. A model for the study of the effect is presented based on the two-temperature equations of S. I. Anisimov [1] and the semi-empirical wide-range equation of state of metal [2]. The model takes into account Gaussian pulse absorption, electron thermal conductivity and electron-ion relaxation in the metal.

If the invested energy is large enough, the shock-wave effect on the formation of holes in the film becomes possible. It includes following stages: (i) generation of a shock wave in the glass due to the transfer of energy from the metal; (ii) spherization of the formed shock wave, i.e. transition from one-dimensional to two-dimensional propagation mode; (iii) transverse propagation of the shock wave in the substrate along the boundary with the film; (iv) accumulation of positive pressure, layer by layer pushing the film substance away from the substrate with a sufficient amount of accumulated pressure, which leads to the formation of holes. Layers of backing material at the same time acting on film as the pistons. A hydrodynamic model for the study of holes formation based on the equations of hydrodynamics of the ideal Euler medium is presented.

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LMI-14 Interaction of doughnut-shaped laser pulses with transparent solids: effects of wavelength, focusing angle and pulse duration

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High-intensity femtosecond laser processing of transparent materials is an attractive, fast-developing technique for direct writing of multidimensional optical structures, such as waveguides, Bragg gratings, wave plates, and rewritable optical memories. The femtosecond laser writing process enables deposition of laser energy in a highly localized region whose dimensions can be comparable with, or even smaller than, the laser wavelength. The majority of direct laser writing techniques utilize laser beams of Gaussian spatial and temporal profiles. Recently it was shown [1,2] that doughnut-shaped femtosecond laser pulses (DLP) can be much more efficient for strongly localized energy deposition into the bulk of fused silica. The peak of absorbed laser energy density in the case of the DLP can be more than 10 times higher as compared with a Gaussian pulse of the same energy.

In this work, the results of comparative numerical simulations of laser energy coupling into the bulk fused silica will be reported for the cases of doughnut-shaped pulses for two different irradiation conditions typical for writing 3D structures: 800 nm wavelength with 45 fs pulse duration (Ti:sappire laser) and 1030 nm wavelength with 240 fs pulse duration (typical for Yb:KGW laser systems). The model is based on non-linear Maxwell's equations supplemented by the rate equation for electron excitation to the conduction band and the hydrodynamic-type equations for the generated free electrons. The roles of pulse duration, laser wavelength and focusing conditions will be discussed.

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C02-1 Studying the pathophysiological mechanisms of photodynamic effects on human tumor cells in cell cultures using digital holographic microscopy

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Nowadays, due to significant advances in photodynamic treatment, many types of photosensitizers are developed and investigated in both in vivo and in vitro studies. However investigation of their death mechanisms by means of fluorescence microscopy can be difficult in some cases because of high photosensitivity of the treated cells. This work is devoted to application of digital holographic microscopy technique for monitoring of cells optical and morphological parameters after intracellular photosensitized generation of singlet oxygen at various treatment modes. This technique is based on measurement of the object wave deformation and does not require cells staining or exposure to intensive illumination. At the same time it allows to quantitatively estimate cells volume, optical thickness, dry mass and several other parameters. It was found that dynamics of cells average phase shift variation can be used for identification of the cell death type and estimation of its typical duration. Apoptosis of the treated live cells can be observed at low doses of photodynamic treatment, and higher doses result in cells necrosis. Investigation of cell death dynamics has also shown that necrosis rate significantly depends on irradiation power density and cells type. We have also performed research on cell specimens prepared from neoplastic material taken from patients, transferred into a culture and subcultured for no less than 10 times. It was found that cells of the same type, taken from various patients may show significantly different response to photodynamic treatment with the same dose and mode. Our further research is aimed at comparative evaluation of the efficacy of various photosensitizers in photodynamic treatment of various cell lines.

C02-2 Advanced strategy for plasmonic photothermal therapy of tumors

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The analysis of recent studies on plasmonic photothermal therapy (PPT) after intravenous administration of gold nanorods (GNRs) has demonstrated that the effectiveness of nanoparticle-assisted laser hyperthermia depends on a correct dosage strategy of nanoparticles administration. Accumulation of GNRs in tumor tissue dramatically increases the local heating of the tumor without damage to healthy tissues. However, the optimal doses of GNR intravenous injections for effective accumulation in tumors, and optimal protocols of PPT are not designed yet. Our study was aimed for development of possible approaches to increase the PPT efficiency on the basis of preliminary assessment of tumor vascularity and multiple dosage strategy of GNR administration to ensure a

maximal gold nanoparticle accumulation in tumors while retaining minimal side effects.

For PPT experiments, the suspension of GNRs was used for multiple fractional intravenous administrations in outbred albino male rats with experimental model of rat liver cancer (cholangiocarcinoma line PC-1). Doppler ultrasonography was performed to characterize the vascularity of transplanted rat tumors before any treatment. Tumors were irradiated during 15 minutes by 808-nm NIR diode laser at a power density 2.3 W/cm^2.

The greater temperature increase at PPT was found after double- and triple-repeated nanoparticles injections, due to a maximal accumulation of gold in tumors. However, the multiple injections of GNRs caused significant gold accumulation in detoxication organs. The proposed PPT protocol provided significant damage to tumor tissue resulting in pronounced necrotic mass and retardation of the tumor growth. The efficiency of PPT depended on the presence of newly formed vasculature as revealed by the Doppler ultrasound investigation. Thereby, investigation of blood flow parameters of tumor feeding vessels and vascularization index assessment can be used to predict the efficacy of PPT. These results are encouraging us to propose application of sonographic techniques for mapping the tumor vascularity prior to GNP administration.

C02-3 A novel co-culture spheroid model for preclinical intercellular photosensitizer-mediated tumor study

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The preclinical drug screening of head and neck cancer treatments suffers from the absence of appropriate models capable to reproduce *in vitro* the heterogeneous tumor microenvironment. We describe in this paper the conception and the characterization of a novel 3D tumor model consisting of a double co-culture of head and neck cancer cells (FaDu) and macrophages (THP-1), which assembled to form a hetero-type multicellular tumor spheroid (MCTS). By histological analyses we have monitored the spatial distribution of each cell type and the evolution of the spheroid composition.

The study provides the uptake features of photosensitizer in the 3D cell cultures. Chlorine Ce6 such as promising photosensitizer was studied due to their specifics. The type of biocomponents, binding with the photosensitizer, affects the intensity, the lifetime and the spectral distribution of the fluorescence. The data obtained by the laser scanning microscopy demonstrates the Ce6 uptake inside the spheroid over the first hour by the increase of the fluorescence. In addition, it was found that the 3D co-culture cell model is heterogeneous by the analysis of the Ce6 fluorescence changes inside the spheroid.

Thus, the created model, which consists of 3D co-culture cell model and Ce6, allows estimating the metabolic cells' processes better than in 2D monolayer cell cultures. Also, this model allows estimating the photodynamic effect depending on the phenotypic features of different areas inside the heterogeneous 3D structure. The integration of the three cell types enabled to reproduce *in vitro* with fidelity the influence of the surrounding environment on the sensitivity of cancer cells to photodynamic therapy.

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C02-4 Photodynamic inactivation of *pseudomonas aeruginosa* bacterial biofilms using new polycationic photosensitizers

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Antibacterial photodynamic therapy (APDT) is a promising method of treating local infected foci, in particular, surgical and burn wounds, trophic and diabetic ulcers. Photodynamic inactivation is able to effectively destroy bacterial cells without developing resistance in response to treatment.

This work is dedicated to the study of photophysical and antibacterial properties of new photosensitizers (PS) based polycationic phthalocyanines and synthetic bacteriochlorins for photodynamic inactivation of *P. aeruginosa* bacteria and their biofilms.

PS were investigated for possible aggregation at different concentrations by means of absorption and fluorescence spectroscopy. The results of studies of the $ZnPcChol_8$, $(3\text{-}PyHp)_4BCBr_4$ and $(3\text{-}PyBrEt)_4BCBr_4$ in water and serum confirm the assumption of a low degree of their aggregation at high concentrations. Consequently their photodynamic efficiency is high in the studied concentration range enabling to use these PS at high concentrations to sensitize pathological foci for APDT.

It was shown that all the investigated photosensitizers have a high efficiency in photodynamic inactivation of Gram-negative bacteria *P. aeruginosa,* as well as their biofilms. Tetracationic hydrophilic near-infrared photosensitizer $(3\text{-}PyBrE)_4BCBr_4$ with reduced molecular size and molecular weight has significantly higher efficacy of photodynamic inactivation of *P. aeruginosa* biofilms compared with other studied photosensitizers.

C02-5 Chemosensitized blood photomodification in the treatment of cancer patients

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Introduction. For some patients, surgical intervention will undoubtedly bring benefits (these are patients of low risk of tumor progression), while in others the removal of the primary tumor will provoke a rapid growth of occult dormant micrometastases (high risk group), and the patient will die from rapid dissemination.

In the List of high-tech methods of treatment of various nosological forms of malignant tumors there are indications of the feasibility of using photodynamic therapy as a component of the combined treatment. But what happens to the blood circulating through the tumor during photodynamic exposure?

The impact on the circulating blood of a patient with light quanta is called blood photomodification. In recent years, expanding the indications for PDT in patients with common tumor processes, we became interested in the effectiveness of photomodification of chemosensitized blood among patients, receiving polychemotherapy for various malignant neoplasms.

Material and methods. All 10 patients received treatment for malignant neoplasms of stage IV. The group included patients with tumor spread of skin melanoma - 6 patients, melanoma metastases without a primary lesion - 1, uveal melanoma - 2, and soft tissue sarcoma - 1 patient. At the same time localization of distant metastases was different: metastases in the liver, in soft tissues, in the lungs, lymph nodes, in the adrenal glands, bones.

Results. Based on the data obtained, it can be assumed, that blood photomodification after a photosensitizer intravenous administration can in half of cases increase the effectiveness of chemoresistant nosological forms of disseminated malignant tumors treatment.

Conclusion.With the introduction of minimal doses of chlorine photosensitizers (Radachlorine), the systemic effects of blood photomodification are greatly enhanced compared with conventional laser irradiation of blood.

C02-6 Video system approbation with zoom on multicellular tumor spheroids model

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Head and neck squamous carcinoma is the most common tumor which located on a mucous head and neck due to a significant proportion of epithelial tissues. This type of cancer primarily arises from epithelial cells which consist of the mucous membrane. Incomplete removal of cancer cells promotes to the recurrence of the disease and the appearance of metastases. The video system with magnification which allows visualizing micrometers size samples was investigated. This approach allows to research processes of photosensitizer (PS) distribution in a small neoplasm and increase efficiency of photodynamic therapy. The video system approbation was tested on three-dimensional models of cancer cells. The size of tumor spheroids is approximately 500± 20 μm which consists of FaDu human pharyngeal squamous carcinoma cells. These experiments may allow predicting the features of the PS distribution processes during photodynamic therapy in vivo. Chlorine e6 (Ce6) was used as a photosensitizers for approbation of the new video system. Ce6 has properties to diffuse and penetrate into the depths of spheroids and accumulate in the necrotic area because of their various parts of spheroids have different rates of metabolism. The 3D models of FaDu spheroids were incubated with Ce6 for 3 and 24 hours. The accumulation of PS was accessed by fluorescence which was excited via laser source with 636 nm wavelength. The results obtained by the video system of Ce6 distribution in FaDu multicellular tumor spheroids were compared with results which were obtained by confocal microscopy previously. The main accumulation of Ce6 was observed in the central part of spheroids. Consequently, the system with magnification allows observing pathological cells in clinical practice. This work was supported by a Ministry of Science and High Education of the Russian Federation (agreement ID RFMEFI61618X0096 №14.616.21.0096 from 12.02.2018)

C02-7 Dynamic light scattering imaging with unsatisfying ergodicity conditions

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The Dynamic Light Scattering (DLS) technique is based on the statistical analysis of temporal intensity fluctuations of laser light scattered by moving particles. Nowadays, DLS-based modalities, such as laser Doppler flowmetry (LDF), Diffusing Wave Spectroscopy (DWS) and laser speckle contrast imaging (LSCI), are widely used for non-invasive diagnosis and imaging of blood flow in various medical and biomedical applications. In fact, the DLS-based approaches still suffering from several important drawbacks, which impede their transfer to the routine day-to-day clinical practice. The major one is that the non-ergodicity of the detected scattered light is not addressed in a proper way. Ergodicity is a key concept in probability theory that characterizes stochastic system, which tends in probability to a limiting form that is independent of the initial conditions. In respect to the DLS measurements, for ergodic scattering medium in the statistical sense the intensity of scattered laser light averaged in time must equal the intensity of light averaged across an ensemble average. As the majority of biological tissues are the highly heterogeneous media composing mixture of static and dynamic structural inclusions. The presence of static areas exhibit non-ergodic features providing systematic uncertainty in the quantitative interpretation of the measured DLS/LSCI signals. We examine the laser speckle contrast at the ergodic and ergodicity breaking conditions for the turbid tissue-like medium, containing mixture of dynamic and static centers of light scattering. Based on the simple phenomenological model we introduce a convenient approach for fast quantitative imaging of the blood vessels in vivo. The proposed approach improves the quality of LSCI, avoiding the discrepancies in oscillations of blood flow associated with the heart and respiratory activities.

C02-8 Benefits of tissue optical clearing for intensive laser actions

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A brief description of concept of controllable ‘tissue optical window’ and method of optical clearing (OC) based on reversible modification of tissue or cell optical properties by their impregnation with a biocompatible optical clearing agent (OCA) will be done [1-4]. Fundamentals and major mechanisms of OC allowing one to enhance efficiency of high power laser treatment of living tissues and cells under concurrent optical imaging will be presented. Water transport in tissues and temporal tissue properties modification under OCA action, including reversible dehydration and shrinkage, balance of free and bound water will be analyzed. The enhancement of probing/treatment depth and image contrast for different human and animal tissues, including skin, eye sclera, muscle, colorectal mucosa, gingiva, cerebral membrane (dura mater), cartilage, bone, blood vessels, and blood will be demonstrated using spectrophotometry, OCT, photoacoustic microscopy, linear and nonlinear fluorescence, SHG and Raman microscopy, polarization and speckle imaging. Experimental data on diffusion and permeation coefficients of glucose, glycerol, PEG, mixture of glycerol and propylene glycol (E-cigarette liquid vapor), albumin, x-ray contrast iohexol (Omnipaque^{TM}-300), and other OCAs for normal and pathological tissues (cancer and diabetes) will be presented. Perspectives and

benefits of immersion optical clearing technique aiming to enhance laser treatments, including femtosecond laser ablation of living tissues, will be discussed.

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C02-9 Clinical study and thermal effects in the area of operating tips during energetic cataract surgery

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Main aim of current study - compare the process of heating of the tips used in modern laser and ultrasound cataract surgery, and to determine the character of the heat propagation in a liquid and air environment. In clinical part of study, the comparison was carried out in two groups of patients. Group 1 (100 eyes) underwent the laser extraction using laser system “Rakot” (Nela Ltd, Russia) (Nd:YAG, $\lambda = 1.44$ µm). Group 2 included also 100 eyes operated by ultrasound phacoemulsifier “Millenium” (B&L Inc., USA). Nuclei had hardness grade 3-5. Posterior chamber IOLs with hard optics were implanted. In the thermophysical part of study, the generation and distribution of thermal energy during the operation when using ultrasonic phacoemulsifier and laser surgical complex under various operating conditions were studied. We studied two modes of the phacoemulsifier operation – continuous and pulsed (10 Hz) at maximum (100 %) and average installed power (40 %) of ultrasound. The operation of the tip of “Rakot” laser system was investigated in pulsed mode (30 Hz) at the maximum (300 mJ) and average installed (150 mJ) energy of the laser pulse. We investigated experimentally the thermal effect of tips operating in air, in liquid without irrigation and aspiration, in a closed tank with a liquid under conditions of effective irrigation and aspiration, and also on pig eyes.

A comparative analysis of two energetic methods of cataract destruction revealed following advantage of laser cataract extraction: nucleus of any hardness can be destroyed. During the laser operation it is not necessary to press on the nucleus, to help mechanically manually in breaking nucleus into pieces, it is cracked by energy action. The propagation characters of the generated heat at ultrasound and laser cataract surgery are different: during laser surgery, heat is localized near the impact area, and at ultrasound surgery the heat is distributed throughout the volume of liquid surrounding the tip, which can injure eye tissue during phacoemulsification of a cataract lens. The localization of heat reduces the flow of fluid through the eye and thus also decreases the traumatic effects. The revealed advantages of laser cataract extraction explain a rapid postoperative rehabilitation of the operated eye and a less endothelial cell loss.

C02-10 Optical-morphological justification of fractional laser treatment with a wavelength of 980 nm for human oral mucosa scars treatment

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Laser treatment is widely used for skin scarring treatment. Currently, the first attempts to implement fractional laser treatment for oral mucosa scars removal were made in dentistry.

Unfortunately, in modern times, the scar formation mechanisms on the oral mucosa are not fully studied. Scarring may cause a number of functional and aesthetic disorders for the patient. The lack effective and painless methods for oral mucosa scars removal causes the search for new methods such as including fractional laser treatment.

In the course of the present study, fractional laser treatment of the intact oral mucosa of rats (Wistar) and postoperative scars on the movable mucosa of the human oral cavity was carried out. For laser treatment stLase (DentalPhotonics, USA) with a wavelength of 980nm, average power 7W and pulse duration 120ms were used.

The intact mucosa was subjected to fractional laser treatment in the oral mucosa of rats. The complex of modern morphological methods was developed and applied to study the cellular mechanisms underlying the reparation of animal oral mucosa after fractional laser treatment. The human oral mucosa scar formations were treated by a fractional laser radiation. Before and after treatment the scars square were measured and the color was estimated in the CIELAB color model.

It has been found that fractional laser treatment with a length of 980nm may cause mast cell degranulation and remodeling of oral mucosa collagen fibers in animals. It can stimulate healing of a laser fractional wound without scarring. The clinical use of fractional laser treatment with a length of 980nm may cause a decrease of scar square and a change (reddening) in the color of the scar tissue, that indicates a partial healing of the scar.

C02-11 Pain and intense laser effects in dentistry

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Pain when performing dental operations are characterised by considerable intensity, which is explained by the anatomical and physiological features of the sensory organisation of soft and hard tissues of the maxillofacial area. The vast majority of such operations are performed using local anaesthesia. However, even the most modern locally anaesthetic methods and means are not always effective, that has a negative effect on the psycho-emotional state of patients and may be accompanied by somatic complications. In addition, the use of local anaesthesia increases swelling and postoperative pain, causing ischemia and tissue hypoxia.

The purpose of this study is to increase the efficiency and quality of dental operations by reducing the risk of psycho-emotional, somatic and postoperative complications based on the development and implementation of innovative laser and anaesthetic technologies in the dental practice.

Studies were conducted in 250 patients with dental implantation operations using local anaesthesia, sedation with preserved consciousness by prior 3-minute inhalation of xenon-oxygen mixture (30/70), and also transdermal electroneurostimulation (TENS).

The effect of each method of anaesthesia and their various combinations on the pain response of patients was studied using psychotesting methods, measuring pain thresholds, recording cortical somatosensory evoked potentials and indicators of peripheral and central hemodynamics. Surgical interventions were performed using both conventional surgical techniques and Er, Cr: YSGG laser (iPlus, 2780nm, Biolase, USA).

It was found that TENS had a pronounced analgesic effect, did not affect the psycho-emotional state and the regulation of hemodynamics, but increased the signals from non-pain mechanoreceptors. This led to an exacerbation of sensations during the interventions by conventional surgical methods, which was perceived by patients as insufficient anaesthesia. Inhalation of the xenon-oxygen mixture in sub-narcotic doses slightly reduced the pain sensitivity, but had a pronounced sedative and vegeto-stabilising effects.

The action of the laser, as a non-contact method of surgical invasion, activates only thermoreceptors associated with groups of sensory nerve fibers that are involved in the formation of pain. In this regard, the use of TENS when using a laser allowed to achieve good results of anaesthesia. The combination of TENS with inhalation of a xenon-oxygen mixture during dental implantation using a laser reduced the use of local anaesthesia by an average of 4-5 times. In some cases, the need for local anaesthesia has not arisen.

In the postoperative period, there was a significant decrease in edema and pain compared with the traditional intervention technique without the use of laser technology.

C02-12 Laser cutting of tissue: can old dogs be taught new tricks?

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Laser has been used as a surgery tool for several decades. Advantages and limitations of the existing laser cutting techniques are briefly reviewed. New possibilities created by recent advances in laser technology are analyzed. Special consideration is given to potential benefits of using ps laser pulses. Pre-clinical experimental data using 1030-1060 nm lasers with varying pulse energy (~0.07 to 0.7 mJ) and repetition rate (1 to 500 kHz) are presented. Results are discussed in the context of possible clinical applications. It is demonstrated that ps laser surgical systems can significantly expand capabilities of instrument armamentarium for several medical specialties.

C02-13 Optothermal fiber converter for laser surgery: theory and experiment

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To improve the efficiency of diode laser excision of soft tissue in the contact surgery on the distal end of the quartz optic fiber through which the laser radiation is delivered to the operation area the optothermal fiber converters can be placed. The properties of the converter depend on the light absorber material, which can be carbon, oxides of erbium, titanium, copper, etc. Carbon-doped converters are the most commonly used. The low resistance of these converters to mechanical influences and laser heating limits their lifetime and stimulates the development of new materials for converters.

At current report the results obtained by the authors in the process of development laser sintering method of converters creation will be presented. For the creation of converters, the impulse radiation of diode laser with wavelength 980nm and IR channel of detection of temperature of the converter was used. The results of the in vitro research of the soft tissue cutting with the help of carbon-, titanium- and erbium-doped converters are presented. It is shown that all three studied types of converters can be used for contact surgery of soft tissues. Er-doped and Ti-doped converters dissect soft tissue more effectively than C-doped. The results of comparative in vitro research of brain thermal destruction by 980nm diode laser radiation with and without Ti-doped converter are presented for the first time.

At present study the results of optical and thermo-physical modeling of laser heating of carbon- and titanium-doped converters are presented. The structural, optical and thermal models of each of these converters are discussed. Optical modeling was carried out according to the Monte Carlo method in the software package "TracePro®Expert-7.0.1 Release" ("Lambda Research Corporation"; USA). The thermal simulation was performed in the software package "COMSOL Multiphysics®" (COMSOL Inc., USA; version number 5.4). The results of optical and thermo-physical modelling of soft tissue cutting with Ti-doped converter in contact mode also are presented. The theoretical dependencies are compared with the results of the experiment. It is shown that the temperature of the Ti-doped converter resulting from the calculations generally corresponds to the temperature measured experimentally.

C02-14 Interaction of terahertz radiation with bio-like objects: theoretical and numerical modelling, real objects and phantom experiments

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Introduction

New biomedical devices require test objects to check their performance and periodic calibration to monitor the system efficiency over the time. A phantom is a bio-like object mimicking the intrinsic real-tissue properties that serves as a test object. A variety of phantoms are commercially available.

Phantoms are already used in spectroscopy within various spectral range. However, currently, the THz frequency range suffers from a lack of investigations in this direction. Only the first steps have been performed [1]. In the present work, we investigate interaction of submillimeter radiation with the breast-mimicking and skin-mimicking phantoms. Results for breast-mimicking phantom were compared with numerical models based on a double-Debye model of the dielectric permittivity for different content of fat, fibrous and cancerous tissue. The wave front propagation using the angular spectrum representation was used to simulate the theoretical response of skin-mimicking phantoms.

Model of wavefront propagation

Electromagnetic fields can be represented in various ways. The angular spectrum representation is a numerical technique describing optical fields in a homogeneous media [2]. Optical fields are described as a superposition of plane waves and evanescent waves. A useful approach to describe optical field diffraction is to conduct the Fourier analysis at a given plane so that the different Fourier components of the field distribution are identified as plane waves propagating away from that plane in different directions. Thus taking less computation time for numerical reconstruction. This technique is preferable for the analysis of light diffraction by histological slides [3]. Angular spectrum representation consists of the following stages: (i) the representation of the field through the angular spectrum of 2D waves (Eq.1); (ii) multiplication by the transfer function that contains a complex refractive index of the object (Eq.2); (iii) the back transition from plane waves to the wave field in the calculated z-plane (Eq.3).

$$C\left(f_x, f_y, v\right) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} G\left(\tilde{x}, \tilde{y}, v\right)_{z=0} \exp\left(-2\pi i\left(\tilde{x} f_x + \tilde{y} f_y\right)\right) d\tilde{x} d\tilde{y} \quad (1)$$

$$g_{x,y}\left(f_x, f_y, v\right) = C\left(f_x, f_y, v\right) \exp\left(-i\frac{2\pi v n(v)}{c}\sqrt{1-\left(\frac{f_x c}{v n(v)}\right)^2 - \left(\frac{f_y c}{v n(v)}\right)^2}\, z\right) \quad (2)$$

$$C\left(x, y, v, z\right) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} g_{x,y,z}\left(f_x, f_y, v, z\right) \exp\left(2\pi i\left(x f_x + y f_y\right)\right) df_x df_y \quad (3)$$

where $n\left(\tilde{x}, \tilde{y}, v\right) = n_{re}\left(\tilde{x}, \tilde{y}, v\right) + i n_{im}\left(\tilde{x}, \tilde{y}, v\right)$ is the spatial and frequency distribution of the complex index of refraction.

Materials and methods

a. Sample preparation

We have used three-component phantoms made of fat, protein and water of different content. Vegetable oil (10 – 75%), soya (13 – 75%) and water (0 – 70%) were homogenized to generate an emulsion. Then, the phantoms were deposited into vacuum packages.

b. THz-Spectrometer

The commercially available TPS 4000 (Teraview Ltd, UK) spectrometer working in reflection mode was used. The spectral range of the system is from 0.06 to 4.50 THz. The entire system was under an air-dried dome to limit the interaction of water molecules with generated pulses. Samples were mounted on a sapphire substrate during measurement. The sapphire cut was chosen not to exhibit a birefringence that would disrupt results of measurements [4]. Each sample was measured 5 times, independently, i.e. the sample was removed and replaced again into system.

c. Numerical modelling

A double-Debye model of the dielectric permittivity was used to compare optical properties of the three-component phantoms and some biological tissue (adipose, fibrous and cancerous) taken from our previous paper [5].

Results and discussion

The propagation dynamics of the pulsed THz radiation through a skin sample was numerically simulated in the temporal and spectral domains. The index of refraction, nre, absorption coefficient, α, as well as real, εre, and imaginary, εim, part of dielectric permittivity was calculated from the experimentally obtained data. Figure 1a depicts the time-domain spatial evolution of the THz pulse. Agreement between measured and simulated THz waveforms is confirmed by the comparison shown in Figure 1b.

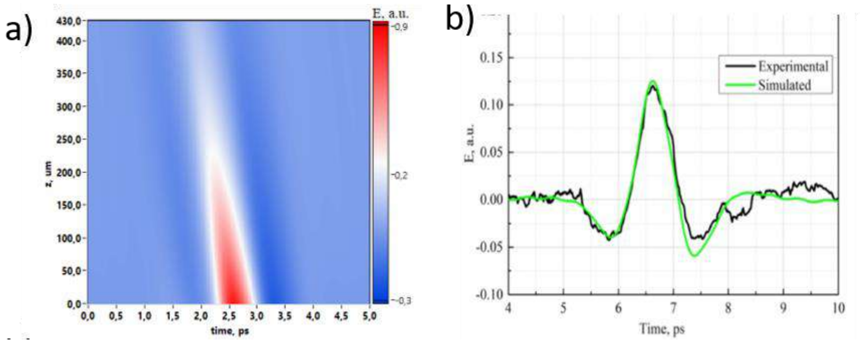

Fig. 1. Experimental and numerically simulated THz pulses propagated through a skin-mimicking sample. (a) THz spatial distribution. (b) THz waveforms.

In Figure 2 the spectral dependences of the absorption coefficient of the three-component phantoms consisting of fat, protein and water are depicted. It is shown that within the spectral window, the absorption coefficient of phantoms containing water exceeds the absorption coefficient of phantoms free of water. This is due to the fact, that water molecules, which strongly absorb THz radiations, are replaced by low absorbing components (fat and protein). Our results were compared with simulated signals of adipose, fibrous and cancerous tissues taken from our previous paper [5].

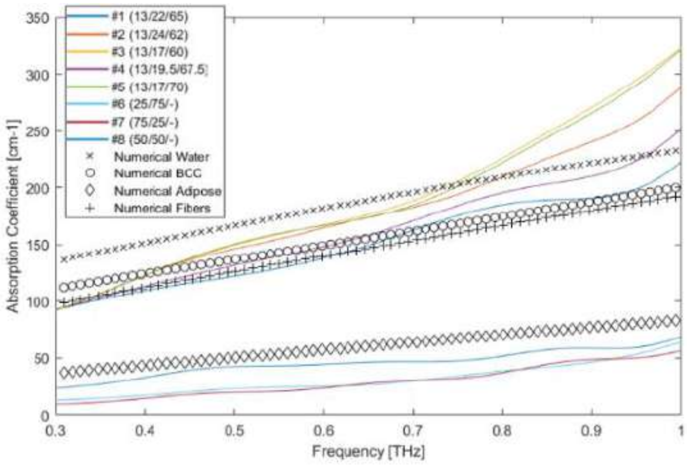

Fig. 2. Spectral dependences of the absorption coefficient of the three-component phantoms consisting of fat, protein and water in the THz frequency range (solid-colored lines) versus simulated signal of water and purely adipose, fibrous and cancerous tissue types

Conclusion

To overcome the lack of knowledge on tissue-mimicking phantoms within the submillimeter spectral range, we conducted preliminary studies on skin- and breast tissue-mimicking samples. Simulations performed for skin-mimicking phantoms have match the experimental spectral data.

Thus demonstrating advantages of the technique used in this study. The spectral dependences of absorption coefficient extracted from measurements for breast-mimicking phantom are clearly differentiated into two distinct groups. One for phantoms containing water and those being water-free. Such a discrimination is also shown via the double-Debye model of the dielectric permittivity. Thus, finding of a proper composition of tissue phantom is possible by an appropriate matching of model and experimental data, in particular for prediction of impact on THz radiation probing depth of tissue reversible dehydration using hyperosmotic optical clearing agents [3]. Deeper investigations are however still required to fulfill a set of phantoms that could be used to perform tissue measurement within the THz-range. Such a set would be profitable to design new medical THz-devices without human biopsy.

Acknowledgments

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C02-15 Recent advances in tissue biomechanics using Dynamic Optical Coherence Elastography

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The biomechanical properties of tissues can be dramatically altered by various diseases, such as keratoconus for the cornea of the eye and systemic sclerosis for the skin. Therefore, the ability to measure tissue biomechanical properties could provide critical information for assessing its health and detecting disease etiology as well as monitoring disease progression. Here, we present results on development of noncontact dynamic optical coherence elastography (OCE) technique to evaluate the biomechanical properties of the cornea and skin of healthy subjects and those affected by diseases. For example, we demonstrate that OCT and OCE can clearly differentiate the healthy and Systemic Sclerosis patients and show strong correlations with the standard clinical evaluation techniques. Also, the first pilot studies on measuring elastic wave propagation in human subjects will be demonstrated.

C02-16 Laser ablated nanoparticles in nuclear medicine and radiotherapy

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There has been a great deal of interest in developing nuclear nanomedicine which utilizes nanoparticles (NPs) as carriers of radionuclides. When functionalized by biopolymers such as polyethylene glycol (PEG), NPs promise safe and controllable transport of radionuclides in the blood stream, as well as a passive vectoring mechanism for targeting tumors based on their selective size accumulation (enhanced permeability and retention (EPR) effect). In addition, NPs can be more heavily loaded with radionuclides to ensure an enhanced therapeutic outcome in the tumor region. We propose silicon (Si) NPs (Si*NPs) synthesized by promising laser-based approaches - pulsed laser ablation in liquids - as a nearly ideal carrier of radionuclides for nuclear nanomedicine.

One can use these methods to make stable colloidal dispersions of silicon nanoparticles in both organic and aqueous media, which are suitable for a multitude of applications across the important fields of health care. Size tailoring allows production of Si*NPs with efficient photoluminescence that can be tuned across a broad spectral range from the visible to near-IR by varying particle size and surface functionalization. These applications encompass several types of bioimaging and various therapies, including photodynamic therapy (PDT), RF thermal therapy, and radiotherapy.

The uniqueness of such Si*NPs is based on their biodegradability, which makes possible rapid elimination of these structures from the organism within several days even if their initial size is large (30-80 nm) under absence of any toxic effects, which was earlier confirmed in a mice model. In addition, in contrast to Si nanostructures prepared by conventional chemical or electrochemical routes, laser-synthesized Si*NPs have ideal round shape, controllable size with low size dispersion, and are free of any toxic impurities, which promises a better transport in vivo and the absence of side effects.

Synthesized nanoparticles were tested as carries for promising radionuclides (Re-188, Ga-68, Y-90) in nuclear medicine, as well as sensitizers in radiation therapy. We demonstrate the possibility for fast PEGylization and conjugation of laser-synthesized Si*NPs with Rhenium-188 (188Re) radionuclide, which is one of most promising generator-type therapeutic beta-emitters with the energy of positron emission of 1.96 MeV (16.7%) and 2.18 MeV (80%) and half-decay time of 17 hours1. We show that such conjugates can efficiently deliver the radionuclide through the blood stream and retain it in the tumor region. We also show that Si NPs ensure excellent retention of 188Re in tumor, not possible with the salt, which enables one to maximize therapeutic effect, as well as a complete time-delayed conjugate bioelimination. Finally, our tests on rat survival demonstrate excellent therapeutic effect (72% survival compared to 0% of the control group). Combined with a series of imaging and therapeutic functionalities based on unique intrinsic properties of Si*NPs, the proposed biodegradable complex promises a major advancement of nuclear nanomedicine

C02-19 Multifunctional nanoparticles in bio-medical research and applications

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Recently development of different kinds of nanostructures opens new possibilities at using in bio-medical investigations and in theranostics. New and promising approach is using of multifunctionality of nanostructures. Thus, nanoparticles (NP) properties allow integration of several functionalities together; they can include bio-imaging, bio-sensing, drug delivery control and monitoring, and number of treatments. In this presentation the properties of nanosystems based on diamond nanoparticles (nanodiamond, ND) and methods of the properties modification for multifunctional use are discussed. Nanodiamonds exist in very high variety of sizes, structures, and correspondingly, surface, photonics and other physical-chemical properties. ND is considered like promising material due to its biocompatibility demonstrated on different levels of the bio-system organization. ND's surface allows conjugation with molecules of interest, combining multiple components, controllable release and affecting these molecules functional properties. Optical-spectroscopic properties are applicable for bio-imaging, bio-sensing, development of highly localized treatments which are based on mechanisms of the NP-light interaction. First of all, the fluorescence properties of ND, which are determined by structural defects of diamond lattice – various fluorescent color centers. Type of the color centers, their distribution, interaction with ND surface and with shell in core-shell particles (for example, plasmonic metal shell) affect the ND fluorescence parameters and allow development of methods of bio-imaging and bio-sensing. The fluorescence of different kinds of ND and ND-based hybrid NP at one- and two-photon excitation, ways to changes the fluorescence properties of nanostructured carbons, modification of some other physical and structural characteristics are discussed in the presentation from point of view of applications for bio-imaging and bio-sensing with spectroscopic detection.

C02-20 Laser-ablated nanoparticles from crystalline and porous silicon and their applications in optical bioimaging and therapy

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Silicon nanoparticles (SiNPs) are actively used in biophotonics owing to their low level of toxicity, high biocompatibility and biodegradability. Usually, the SiNPs produced by mechanical grinding of porous silicon are effectively applied as photoluminescent markers and photosensitizers [1 – 3]. However, the milling technique has limitations to fabricate the particles with a size smaller than 100 nm, which is necessary for more efficient employment in biomedical applications. We suggest employing the pulsed laser ablation in liquids (PLAL) technique to form the small and chemically pure SiNPs to achieve the required characteristics.

The pico- and femtosecond laser radiation was used to form the SiNPs via PLAL from crystalline and porous silicon targets. In our experiments the SiNPs fabricated in ethanol and liquid nitrogen demonstrate efficient photoluminescence (PL) with emission maxima in the range of 700 – 800 nm and typical sizes from 2 to 60 nm, which is appropriate for biomedical in vivo applications. The spectrophotometry measurements of suspensions of the ablated SiNPs in water and ethanol revealed effective light scattering. Optical coherence tomography (OCT) imaging of the suspensions drops administered on agar gel surfaces indicated high efficiency of the SiNPs as contrast agents providing the contrast up to 30 dB. The penetration of the SiNPs into a rabbit ear skin followed by light irradiation revealed a pronounced tissue reaction confirming potential of the particles as photosensitizers.

Thus, the perspectives of the SiNPs formed via PLAL in optical imaging and photodynamic therapy are demonstrated.

Spectrophotometry and OCT studies are supported by the Ministry of Science and Higher Education of Russian Federation (IAP RAS governmental project #0035-2019-0014).

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C02-21 Research of tumors tissue heating kinetics by radiation of the near IR spectral range at the introduction of gold nanoparticles in the tissue

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The growth of a number of oncological diseases stimulates extensive development of both early tumor diagnostics and therapy methods. However, the hyperthermia is restricted by low selectivity, which leads to significant damage of healthy tissues adjacent to the tumor. The laser hyperthermia is a promising method of tumors treatment that provides more heating locality than the traditional hyperthermia, which allows damage reduction in surrounding healthy tissues. In this work the heating kinetics of model cancerous tumors with intravenous injection of suspensions of gold nanorods (volume of each injection of 1 ml) with concentrations 0.4 and 0.8 mg/ml and laser irradiation at the wavelength of 808 nm during 15 minutes was studied. The objects of the study were 40 outbred rats with xenografted tumors of the cholangiocarcinoma of the PC-1 line. The obtained results made it possible to compare the protocols of introducing gold nanorods (GNR) in tumor tissue with a high and low vascularization to provide an effective tumor heating using laser radiation. It was shown that the greatest increase in tumor temperature is associated with the maximal accumulation of gold nanorods in the tumor. It is observed after triple intravenous injection of suspension with concentration 0.4 mg/mL (the total dose 1.2 mg) 72, 48, and 24 hours before irradiation. It is provided that the vascular system of the tumor is sufficiently developed, since the accumulation of nanorods in the tumor tissue depends on its vascularization degree. With double and triple increase of the GNR doze, the temperature necessary for damaging the cancer cells is achieved. However, when using a triple GNR injection, one can observe a damage of the surrounding tissues. Thus, to our opinion, the double injection of suspension with concentration 0.4 mg/ml (the total dose 0.8 mg) 48 and 24 hours before the irradiation is more preferable, if the vascular system of the tumor is sufficiently developed.

C02-22 Application of laser technologies for micromanipulation and diagnostics of preimplantation mammalian embryos

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In this presentation we review progress and achievements of laser embryology. This field of knowledge develops the methods of use of lasers for micromanipulation and microsurgery of preimplantation mammalian embryos (PME) and the laser methods to characterize the quality and condition of the early embryos. These expanded applications of lasers in embryology open possibilities to develop effective non-invasive methods of control, analysis and diagnostics of PME.

The novel methods have been developed using pico- and femtosecond lasers for embryo microsurgery manipulations, and demonstrated for embryo enucleation and fusion of somatic cell with embryo. In the presented work the examples of laser fusion and enucleation are demonstrated, highest specificity of laser methods for microsurgery in PME is discussed in comparison with today routinely used methods.

Different optical-spectral methods, as Raman spectroscopy, 2-photon fluorescence lifetime imaging microscopy (FLIM) are used for diagnostics and control of PME conditions. Their applicability is discussed. The Raman spectra of mice living oocytes and embryos on different stages of development were measured with varied excitation wavelength (488, 532 and 785 nm), laser power in focal spot and total exposition. The developmental rate of embryos after the Raman measurements was characterized via estimation of the embryo ability to reach morphologically normal blastocyst stage and counting the cell number in the embryo.

For all treatment and investigation methods the main criterion of applicability is the ability to determine properly parameters under which the embryo development proceeded as close as possible to the control samples, when the interaction with light doesn't give destructive effects.

We summarize research applications, encompassing embryos studies.

Future trends of femtosecond laser systems and some possible applications for PME are discussed.

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C02-23 Application of laser technologies for micromanipulation and diagnostics of preimplantation mammalian embryos

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In this presentation we review progress and achievements of laser embryology. This field of knowledge develops the methods of use of lasers for micromanipulation and microsurgery of preimplantation mammalian embryos (PME) and the laser methods to characterize the quality and condition of the early embryos. These expanded applications of lasers in embryology open possibilities to develop effective non-invasive methods of control, analysis and diagnostics of PME.

The patent ductus arteriosus (PDA) is a common heart problem in premature infants, which is associated with phototherapy that leads to dilation of the ductus arteriosus. Currently the treatment options for PDA consist of the use of inflammatory drugs and/or surgical ligation. Both treatment options have serious side effects and may cause death of an infant. Therefore, alternative methods to prevent PDA are urgently required.

One such alternative method, is to target the relationship between phototherapy and vasodilation of the PDA. The photorelaxation of blood vessels with light of 420 – 460 nm wavelength has been verified in many clinical studies in premature infants. It has been suggested that phototherapy induced dilation of the PDA may be primarily seen in premature infants due to increased translucency of their premature skin. In addition, the new phototherapy units provide high irradiances, which are beneficial for the jaundice treatment but are more likely to induce vasodilation and tissue damage due to heating. Shielding infants' chest during phototherapy is a preventive approach to phototherapy induced dilation of the PDA. In this contribution, we will discuss the unique requirements to chest shield material properties. We will also describe the development, characterization and testing of a chest shield design.

Our chest shield is the first targeted approach to prevent PDA rather than focusing on treating its complications. The implementation of our prototype could lead to early enteral nutrition, decreased incidence of the PDA, and decreased hospital stay and cost. These benefits will further extend to the future development of these children since it has been shown that children who develop symptomatic PDA are at increased risk for neurodevelopmental delay due to complications from the PDA itself or its treatment.

W03,04-1 Optical characterization of antirelaxation coatings for photonics applications

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Antirelaxation (AR) coatings are organic films, usually with nano-thickness, used in optical vapour cells, which reduce the depolarization of alkali atoms after collisions with the cell walls. The long lived ground state polarization is a basis for development of atomic clocks, magnetometers, quantum memory, slow light experiments, and precise measurement of fundamental symmetries.

Light Induced Atomic Desorption (LIAD) is a non-thermal process in which atoms are desorbed from the AR coated walls under illumination. It is applied mostly for realization of optical atomic dispensers in cases when high atomic densities at low temperature or fast modulation are needed – for example for loading atomic devices and their miniaturization. However as desorption depends on the atom–surface interaction, it can be applied for optical characterization of the coatings, too.

In this work optical characterization of antirelaxation coatings from point of view to their applications in coherent spectroscopy is presented. The measurements were performed in two AR coated cells with PDMS coatings prepared with two different solutions in ether (PDMS 2% and PDMS 5%). The efficiency and dynamics of LIAD, as well as the AR properties in the two cells are compared. The dependence of the relaxation rate (number of collisions without relaxation) on LIAD /atomic density/ and homogeneity of illumination is investigated. The influence of the stem is analyzed.

The results for temperature and/or light control of atomic density are summarized and compared with the results from literature. Application of LIAD for all-optical control and miniaturization of sensors for photonics is commented.

This work was supported by the National Science Fund of Bulgaria according to contracts: (i) Bilateral project Bulgaria – Russia ("Nonlinear spectroscopy of spatially restricted alkali vapor: methodology and applications"): DNTS/Russia 01/5 from 23.06.2017 + RFBR grant No17-52-18037, the Government of Russian Federation (Grant 074-U01) and goszadanie #3.4903.2017/6.7 and (ii) DO08-19/2016, "New coherent and cooperative effects in hot alkali vapour".

W03,04-2 High resolution laser spectroscopy of spatially restricted hot alkali atom and dimer vapor

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The fields of photonics have undergone immense advancement in the past decade related to optical sensors miniaturization. An important task is to integrate the narrow band diode laser light interaction with hot spatially restricted alkali vapor [1].

We discuss a new use of a micrometric thick optical cell filled with Cs vapor that intrinsically contains extremely small concentration of Rb atoms. When heated up to temperatures around 350 °C such mixture consists of Cs_2 dimers, Cs atoms and a small number of Rb atoms that allow building a high density but optically thin alkali vapor layer producing diatomic molecules together with atoms for the purpose of the linear/nonlinear spectroscopy of the complex assemble. We study the selective reflection profiles of Rb atoms in the presence of high-density Cs atoms considered as a buffer gas for Rb atoms and Cs dimers. The Rb hyperfine spectrum is used as a precise absolute frequency reference for measurement of the spectral profile widths and the frequency positions of experimentally observed spectral lines of Cs_2 molecules in the spectral region around the 87Rb D_2 resonance line with wavelength λ=780 nm [2].

This work was supported by the National Science Fund of Bulgaria according to contracts: Bilateral project Bulgaria – Russia ("Nonlinear spectroscopy of spatially restricted alkali vapor: methodology and applications"): DNTS/Russia 01/5 from 23.06.2017; RFBR according to the research project № 17-52-18037, Government of Russian Federation, Grant 08-08, the Ministry of Science and Higher Education of Russian Federation (Project 3.4903.2017/6.7) and DO08-19/2016 "New coherent and cooperative effects in hot alkali vapour".

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W03,04-3 Resonant reflection of the light from a thin layer of a gaseous medium

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Spectral line profile of selective reflection of the light from a gas-dielectric interface depends strongly on the density of atomic vapor. In the limit of sufficiently low vapor densities, the location of Doppler-free peak in the reflection spectra matches the atomic transition frequency. The self-consistent way of solving field and polarization density equations can help attain more precise the structure of the field within the gaseous medium.

The study deals with the reflection of the plane monochromatic electromagnetic wave (at normal incidence) from a thin gas layer located between two dielectric media. The aim of this work is to determine the effect produced by the density of atomic vapor and layer thickness on the shift, broadening, and deformation of the spectral profile of the reflection coefficient. The theoretical study is based on the approximation of specular boundary conditions, according to which atoms are reflected from the boundaries of the layer without changing their polarization. The chosen boundary conditions allow to represent the field as the sum of a Fourier series and use the self-consistent approach to solve the system of equations for the density matrix and the field in the medium with respect to the surface admittance.

This study features the first calculation of the spectral contours of the reflection coefficient of the resonance radiation from a thin layer of a gaseous medium outside the approximation of highly rarefied gas. The gas layer thickness has proven to be the factor that influences the reflection coefficient resonance portion significantly. At thicknesses that are multiples of the incident wavelength, the sub-Doppler structure is absent in the reflection spectrum, while at layer thicknesses equal to the half-integer number of wavelengths, it manifests itself most clearly as an approximately even contour, whose center shifts towards the shortwave part of the spectrum with increasing concentration.

W03,04-4 Resonant interactions of alkali-metal atoms with gold plasmonic nanoparticles

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Properties of plasmonic resonance in metallic nanoparticles depend on the external environment. Because of that, many researchers explore interactions between plasmons and atoms, molecules, quantum dots, and other plasmons. In this work, interaction between spheroidal plasmonic nanoparticles and atomic vapor of alkaline metal is investigated.

Small size of the particle compared with the wavelength of light allows us to use in calculations quasi-static approximation, which assumes the homogeneous field inside a particle. We approximate that relatively thin layer of surrounding atoms interacts with nanoparticles because of the fast attenuation of the near-field of plasmon. It allows us to consider the model of spheroidal nanoparticle in the shell, which is consisted of atomic vapor of alkaline metal. The advantage of the quasi-static model is the opportunity of consideration of the shape of nanoparticles and their interaction with atoms surrounding them via simple analytic formulas.

In the study, theoretical absorption spectra of gold spheroidal nanoparticles surrounded by atomic vapor of sodium were calculated in cases of the Lorentz and Voigt profile of dielectric constant of gas. Absorption spectra were calculated for different temperatures of atomic vapor. The frequency of plasmonic resonance in the spheroidal particle depends on the eccentricity of the spheroid. We use this fact to combine plasmonic resonance with the atomic resonance. The calculation results show that when resonances coincide, a dip in the plasmonic peak near the absorption peak of alkali-metal atoms is observed. The dependency between the depth of the dip and the concentration of atomic vapor is obtained.

The calculation of absorption spectra of gold spheroidal nanoparticles in atomic sodium vapor leads us to conclude that there is strong interaction between resonant transitions in alkali-metal atoms and plasmons localized in metal nanoparticles.

W03,04-5 Adsorption of potassium and rubidium atoms on sapphire and glass surfaces studied by laser induced desorption

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The current trend for devices miniaturization requires thorough knowledge of interaction between atoms and solid surfaces because in the nanoscale devices atoms frequently collide with surfaces. Such collisions lead to atoms adsorption and depolarization that negatively affect the technical characteristics of devices. Studies of atom-surface interactions are necessary also in developing of efficient quantum memory devices that have been offered recently by several scientific groups. On the other hand, the theory of interaction between atoms and dielectric surfaces is still in its infancy. Hence, experimental studies of alkali atoms interaction with wide-band dielectric surfaces acquire great importance.

Alkali atoms adsorption and desorption from sapphire and glass surfaces have been studied using the time-of-flight technique. Rubidium and potassium atoms have been desorbed by laser pulses of 10 ns duration (λ = 532 nm). Registration of the flux of desorbed atoms has been carried out by measuring the changes in the absorption of radiation of a continuous narrow-band semiconductor laser tuned to the D2-line of rubidium atom or D1-line of potassium atom.

Two mechanisms of desorption have been observed. The thermal desorption arises when the laser power density is large enough for substantial heating of the substrate surface. In this case desorption is induced by the temperature rise achieved in the course of laser irradiation. An alternative mechanism of desorption that proceeds without appreciable heating of the substrate surface is called photodesorption. The threshold power density that separates these desorption mechanisms has been found for rubidium and potassium atoms on different substrates. We also determined the sticking probability of the atoms colliding with the substrate surface and the adsorption energies of rubidium and potassium atoms on transparent dielectric substrates. The obtained values have been compared with the previously measured values for sodium atoms.

W03,04-6 Optical manipulation with a Meta-Lens

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The ability to manipulate small objects with focused laser beams opens a broad spectrum of opportunities in fundamental and applied studies, for which precise control over mechanical path and stability is required. Although conventional optical tweezers are based on refractive optics, the development of compact trapping devices that could be integrated within fluid cells is in high demand. The integration of auxiliary micro and nano structures within fluidic devices provides numerous opportunities for flexible optomechanical manipulation including transport, trapping and sorting, which are highly demanded in lab-on-a-chip applications and many others.

In particular, plasmonic polarization-sensitive metasurface-based lens, embedded within a fluid cell, is demonstrated which provides several stable spatially separated optical traps along the optical axis with on-demand switching capability. The position of a particle in this architecture is controlled with the polarization of the incident light, interacting with plasmonic nanoscale patch antennas, organized within overlapping Fresnel zones of the lens. While standard diffractive optical elements face challenges to trap objects in lateral direction outside the depth of focus, bi-focal Fresnel meta-lens demonstrates the capability to immobilize a bead along 10 micrometers line and allows to control the position of the bead over time.

W03,04-7 Nano fingerprint: how to study and discriminate nanoparticles with laser light

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Metallic nanoparticles synthesized by laser ablation [1-3] or gas-phase deposition [4-6] are emerging as useful materials in a variety of fields ranging from pathogens control and sensing to energy storage.

I will present a review of the thermo-mechanical properties of streptavidin conjugated gold nanospheres adhered to a surface, investigated by two-color infrared asynchronous optical sampling pump-probe spectroscopy. The nanospheres have been deposited on a sapphire substrate in high and low densities. Applying data mining techniques to spectroscopic traces [7] we identify the thermo-mechanical response variation which discriminates the nanospheres according to their density. This analysis is important in view of the widespread application of conjugated gold nanospheres in medicine and biology.

Functionalized gold nanoparticles are extensively used in many technological areas spanning from novel optical biosensors, distribution of drugs to diseased organs, photothermal cancer treatment. As a consequence, it is becoming an increasing key technological issue to understand the heat transfer, thermal transport and the mechanical properties of such nano-objects. Here we address the influence of the bonding and the surrounding chemical environment of functionalized nanoparticle on their thermo-mechanical properties. Despite their success, conventional optical spectroscopies suffer some major drawbacks, such as the lack of specific surface sensitivity and time-resolved capabilities, i.e. the potential to follow transient molecular excitations initiated by an external trigger. In order to overcome some of the above-mentioned shortcomings we de- veloped a molecular discrimination technique, based on time-resolved optical microscopy and data mining techniques. The experiment is based on the optical excitation of a variable number of nanoparticles, depending on their surface density, and to discriminate their response based only on their optical response.

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W03,04-8 Numerical research of the interaction gas-powder jets formed by coaxial nozzles for laser cladding

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One of the objectives of direct laser deposition of materials is the transportation and focusing of the powder in the cladding area. With using coaxial nozzles the gas-powder jets actively interact in the crossing zone, resulting the flow structure is change, especially noticeable with increasing of the powder consumption. The purpose of this work was study this interaction with variation of the gas and powder feeding rates, aimed at optimizing the distribution of the powder flux density in the focus area. The range of parameters are determined, for which it is required to take into account the reverse effect of the particles on the gas and collisions between the particles.

The outflow processes of gas-powder jets from coaxial nozzles were simulated in the focusing area, as well as particles colliding with each other. The mathematical model is based on the Navier–Stokes equations solved together with the SST $k-\omega$ turbulence model. The powder particle trajectories in a gas are determined using the Lagrangian method with simultaneous calculation of all particles in the considered volume. The calculation program was based on modified open source OpenFOAM code.

Calculated data about changes of the flow structure in the jet interaction region are presented depending on the gas and powder feeding rates. The reverse effect of particles on gas is demonstrated: the gas velocity significantly reduced in the high particle concentration region and the effect of the gas flow bypassed this region is occurred. Special attention is paid to the question of particle collisions between themselves and their effect on the distribution of the powder flux density. Particle collisions are simulated by the method of inelastic collisions of sphere. The gas and powder feeding rates have been determined, when it's necessary to take into account the pair particle collisions. Intersecting jets of particles pass through each other at low powder feeding rate. As the feeding rate increases their interaction begins to appear due to the numerous collisions of particles from the opposite jets. As the result, after the focus, the dusty vertical “tail” appears downstream with a uniform distribution of powder flux density along the transverse radius of the jet.

The calculation results were verified by comparing with experimentally determined powder spots sizes in the focusing region and downstream depending on the powder feeding rate.

W03,04-9 Plasmonic planar optics: from basic elements to quantum generator

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The key advantage of plasmonics is in pushing our control of light down to the nanoscale. It is possible to envision lithographically fabricated plasmonic devices for future quantum information processing or cryptography at the nanoscale in two dimensions.

Here we demonstrate the development of the basic elements of planar plasmonic nanooptics: plasmonic optics media, focusing and reflecting plasmonic elements, plasmonic interferometer, plasmonic autocorrelator and planar plasmonic quantum generator.

W03,04-10 Dipole model of Purcell effect in metal-enhanced fluorescence and surface-enhanced Raman scattering

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In a conventional scheme of metal-enhanced fluorescence (MEF), the fluorescent molecules attached by Van-der-Waals forces to a plasmonic nanoparticle (PNP) form an array in which each molecule interacts coherently with the PNP but there is no coherent interaction between the molecules. Therefore, one can consider a dimer where the active dipole and a passive dipole couple with one another by near fields. The same situation holds in the conventional scheme of surface enhanced Raman scattering (SERS) where the molecule excited at two Raman frequencies by the incident wave induces the dipole moment in a PNP on which it is located. In both cases (MEF and SERS), the radiation of a PNP coherent with the emission of a molecule dominates over the last one. In MEF, one needs that the frequency of the optical transition coincides with that of localized surface plasmon (LSP) in PNP, in SERS one needs that both incident wave frequency and at least one of Raman frequencies lie within the band of LSP. In both MEF and SERS, the molecule transfers more power to the PNP than to free space. This phenomenon, called the Purcell effect, plays the crucial role for both MEF and SERS. Usually, one refers the Purcell effect as a phenomenon of the so-called weak interaction and even identifies with the effect of MEF. However, it is not so. There is also the non-radiative Purcell effect, when the power transferred from the quantum emitter to the PNP dissipates. One usually considers it as an undesirable parasitic feature of the radiative Purcell effect. In this report, I show that this is so only for SERS and this is why we do not observe the distortion of the Raman spectrum and quenching of the Raman radiation – only the presence or absence of the Raman enhancement. In the case of the fluorescence, the non-radiative Purcell effect holds drastically beyond the regime of the weak coupling and may dominate over the radiative Purcell effect. This regime accompanied by the Rabi splitting of the fluorescence spectrum may even cause the generation of a growing LSP.

W03,04-11 Metal-dielectric optical resonance in metasurfaces and SERS effect

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Anomalous optical response of metasurfaces, fabricated from regular silicon resonators is investigated. The resonators are manufactured in form of two-dimensional bars or regular cylinders and covered by the semicontinuous silver film. The calculations as well as real experiments demonstrate Wood anomalies in visible and near IR spectral ranges. We associated resonances with excitation of surface waves in the metafilm by means of the diffraction of the incident light on the metal-dielectric bars or cylinders. The multiple metal-dielectric resonances result in much enhanced local electromagnetic fields on the surface of the resonators. For example, the silicon cylinder resonator exhibits various em modes including dipolar modes and hybrid whispering gallery modes. The axial symmetry of the metal-dielectric cylinders results in the angular momentum quantization and excitation of the modes with axial, azimuthal, and radial quantum numbers. The highest quality factor Q corresponds to the modes with the largest possible azimuthal number. It opens new venue in R&D of the substrates for the surface enhanced Raman scattering (SERS) including design sensors for detecting specific substances.

We observe the anomalous optical response from the metasurface by measuring the reflectance for various angles of the light incidence. The meta-surface is formed on silicone substrate by using high-resolution e-beam lithography and subsequent reactive ion etching. The top metallization comprising of 30 nm thick silver layer, which is deposited by e-beam evaporation. To investigate the SERS effect the film is covered by molecules of phenylboronic acid that form covalent bonds with the silver layer. We obtained in situ the 10^4-10^5 enhancement of the Raman scattering, by direct matching Raman signals from the metasurface and the flat silver surface. We propose that designed metasurfaces can be used to detect glycated proteins of the humane blood.

W03,04-12 Non-steady resonant light scattering by an obstacle

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A survey of the recent results of the author in the unsteady high-Q resonant scattering of ultrashort laser pulses by nanoparticles is presented. It is shown that the unsteadiness of the scattering process may result in qualitative changes of the phenomenon both in the near field and in far field wave zones. The most attention is paid to the dynamics of the nonradiating anapole modes and dynamical Fano resonances, which are discussed in detail. Simple, analytically tractable models are proposed to describe the transient processes. Their comparison with the results of the direct numerical integration of the complete set of the Maxwell equations shows that the models exhibit high accuracy in the quantitative description of the phenomenon.

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W03,04-13 Localized surface plasmon resonance as a partner in the exciton-plasmon interactions

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In this contribution I am going to discuss the exciton-plasmon interaction in a model system: metal core and a shell that possesses more or less narrow absorption band. Metal core implies that the real part of the core material dielectric function is negative, while the value if its imaginary part may vary. To keep the theory as simple as possible both the core and the shell are taken to be concentric spheres with the radii much smaller than the wavelength of the incident radiation. That leads to the possibility of using quasi-static approximation in its simplest dipole form.

Literature keeps numerous records of this model employments for interpretation of different experimental data. The most popular arguments are based on the well known fact of the near field enhancement when the incident field is in resonance with the localized plasmon resonance in the metal core. This argument was first put forward in connection with SERS and work very well in that domain because the shell is supposed to be transparent at the incident radiation wavelengths.

When it comes to the enhanced absorption, the things become much more complicated. It was argued theoretically and proved experimentally that at the exact resonance, extinction cross section of the core-shell structure is reduced rather than enhanced as is may be expected from the simple arguments based on the near field enhancement. This phenomenon was termed as a strong coupling regime. Anomalous dispersion that always accompanies the absorption bands also contributes to the plasmon resonance spectral shift. An attempt will be made to separate different contributions to the resultant extinction cross section and to find if this analysis may lead to novel application of plasmon nanoparticles in spectroscopy and sensing applications.

W03,04-14 Ellipsiodal model of light scattering by small particales of non-ellipsoidal shapes

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Light scattering by small particles is an important research subject in many scientific and engineering fields, including nano-optics. Natural scatterers are usually non-spherical and often inhomogeneous, which complicates modeling their optical effect.

In this paper we consider such scatterers in the Rayleigh approximation, i.e. under condition $|m|\,a \ll \lambda$, where m and a are the complex refractive index and size of a particle, respectively, λ is the wavelength of the incident radiation. The Rayleigh approximation was developed for homogeneous spheres, infinitely long cylinders, and ellipsoids, and has been extended to layered ellipsoids with confocal layer boundaries.

We present an extension of the Rayleigh approximation to small scatterers of non-ellipsoidal shape by applying an analog of the T-matrix method. We show that the particle polarizability is proportional to the T11 element of the matrix

$$T = -(m^2-1)\, L^{11}\, [I + (m^2-1)\, L^{31}]^{-1}, \quad (1)$$

where L^{11} and L^{31} are the integrals depending just on the particle shape, I is a unit matrix.

We suggest and discuss an ellipsoidal model of non-spherical scatterers. Our numerical calculations demonstrate that the model provides the cross-sections for parallelepipeds, cones, finite cylinders, Chebyshev and various other particles with relative errors of a few percent in a wide range of the particle sizes.

We have rigidly solved the electrostatic problem for core-mantle particles with the non-confocal spheroidal layer boundaries and constructed the Rayleigh approximation. We also suggest an approximate way to calculate the polarizability (the element T11) for layered spheroids, when all the fields are represented just by a single term (i.e. all the matrices in Eq. (1) are just numbers). Our numerical computations indicate that such approximation has the accuracy of about 1%.

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W03,04-15 Si-based Integrated Microwave Photonics

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Hybrid plasmonic waveguides with an embedded layer of conductive oxide can be used to create fast and compact electro-optical modulating devices. Due to limitations connected with plasmonic modes polarization such devices are incompatible with grating couplers, which are utilized to input light into waveguides. It is shown that designed structure of a modulating sandwich allows to construct a compact polarization converter, which allows to overcome the problem of the polarization adjustment [1]. A novel type of plasmonic structure to achieve strong light-matter interaction for effcient electro-optical modulation will be discussed. A hybrid waveguide concept enables coupling plasmonic modes with a waveguide mode. Fast modulation at small distances is achieved due to epsilon near zero effect in indium tin oxide. Instead of confined surface plasmon-polaritons, which are often used in this context, edge plasmon structure is proposed. Such plasmons may interact with horizontally polarized waveguide modes needed for applications. It allows the resulting modulator to work directly with effcient vertical input/output grating couplers and avoid using bulky polarization converters. The suggested device geometry is asymmetric and requires full 3D numerical computations based on Maxwell and drift-diffusion equations. Effective modes, stationary charge and field distributions, an extinction coeffcient, optical losses and charge transport properties are analyzed.

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W03,04-16 Laser-assisted ultraprecise fabrication of nanoscale resonant structures at the surface of an optical fiber

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Surface Nanoscale Axial Photonics (SNAP) is a novel platform for fabrication of photonic circuits at the optical fiber surface and their characterization with unprecedented sub-angstrom precision. Their fabrication usually consists of exposures to a CO2 laser beam, which locally anneals the optical fiber and releases tension frozen into the fiber during manufacture. Other methods include fabrication with a femtosecond laser inscription, local heating, and bending. All these methods result in fabrication of microresonators with an effective radius variation on the order of nanometers. In this presentation we overview the ideas and applications of SNAP technology and concentrate on our recent findings obtained in 2017-2019. In particular, we will describe our theoretical and experimental results on SNAP at the capillary fiber for applications in microfluidics, frequency comb generation in SNAP bottle resonators, and optomechanics of SNAP bottle resonators.

W03,04-17 Permanent and reconfigurable WGM microresonators at optical fibres: mechanical and laser-assisted tuning

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Microresonators are often considered as the key elements of photonic integrated circuits with applications in telecommunications, classical and quantum optical signal processing, and ultraprecise sensing. In particular, microresonators are the necessary components of miniature slow light devices, namely, miniature optical delay lines and buffers. In the past decade, many approaches for fabrication of these devices were implemented, e.g. those based on coupled ring resonators and photonic crystals [1]. However, the remarkable fabrication precision of a few nanometres achieved in silicon photonics is still way insufficient for the fabrication of realistic miniature low-loss delay lines. In addition to high insertion losses and insufficient fabrication precision slow light devices fabricated to date experience additional physical limitations having significant signal dispersion and narrow bandwidth.

In the first part of the report, we fabricate two coupled high Q-factor SNAP microresonators at the fibre surface with resonances that are matched with a better than 0.16 GHz precision corresponding to a better than 0.17 Å precision in the effective radius variation (ERV) of the fibre [2]. The achieved precision is only limited by the measurement resolution of our spectrum analyser. In the second part of the report, we show that a SNAP microresonator can be introduced temporarily by local heating of the fibre and maintain its shape with subangstrom precision for the predetermined period of time and be completely annihilated under request [3]. In the third part of the report, we demonstrate SNAP microresonators formed by mechanical bending of an optical fibre [4]. We suggest that the developed method pave the way for the fabrication of ultralow loss, tunable, and reconfigurable microresonator-based photonic integrated circuits.

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W03,04-18 Electron-Vibrational Interactions in Molecular Aggregates: from Exciton Absorption and Luminescence to Exciton-Polaritons in Nanofibers and Switching Waves

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We have developed a model to account for electron-vibrational effects on absorption, luminescence of molecular aggregates and exciton-polaritons in nanofibers [1]. The model generalizes the mean-field electron-vibrational theory developed by us earlier [2] to the systems with spatial symmetry, exciton luminescence and the exciton-polaritons with spatial dispersion. The correspondence between manifestation of electron-vibrational interaction in monomers, molecular aggregates and exciton-polariton dispersion in nanofibers is obtained by introducing the aggregate line-shape functions in terms of the monomer line-shape functions. With the same description of material parameters we have calculated both the absorption and luminescence of molecular aggregates and the exciton-polariton dispersion in nanofibers. We apply the theory to experiment on fraction of a millimeter propagation of Frenkel exciton polaritons in photoexcited organic nanofibers made of thiacyanine dye.

In the second part of the paper the bistability response of the electron-vibrational model of organic materials in the condensed phase has been demonstrated. Intermolecular interactions give rise to the excitation transfer along organic thin films. If the film transverse size exceeds the characteristic diffusion length, transverse phenomena such as switching waves (SW), known in optical bistability, should take place. We present the alternating-sign dependence of the SW velocity on pump intensity and the conditions for the spatial hysteresis realization [3]. As a matter of fact, in the case under consideration SW represents the wave of dramatic change of the dielectric permittivity of organic dye films that may have many applications. In particular, the SWs enable us to observe the bistability of surface polaritons.

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W03,04-19 Regular optical patterns formation by a single Gaussian beam passed through a photorefractive $LiNbO_3$:Fe crystal

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We report for the first time the regular optical patterns formation in a laser beam propagating though a photorefractive Fe doped lithium niobate (LN:Fe) crystal.

The experiments were performed with the use of single mode laser radiation at 632.8nm wavelength with beam powers of 0.5 ÷ 10mW. The LN:Fe sample with 0.03wt% concentration of Fe and 10mm length along beam propagation was used in the experiments. The C-axis of the crystal was oriented along its surface. The laser beam was focused to the size of 72μm at the input face of the LN:Fe crystal. The forward traveling laser beam at the output face of the crystal was projected by lens to the entrance of CCD camera, which provides the measurements of beam transverse profile time evolution.

The evolution of the regular patterns depending on both the time and optical beam power has been studied. The time evolution of the beam intensity distribution shows the splitting of a Gaussian beam into two beams and then formation of regular patterns of focal spots. The low milliwatt level power of the optical beam provides a slow evolution of nonlinear processes in the crystal (~500 s) and allows the observation of all details of evolution of the intensity distribution in the beam.

The observed phenomenon of optical patterns formation is explained with the light induced complex refractive index formation in the crystal with a central minimum (negative lens) and side maxima (positive lenses) along optical C-axis due to photovoltaic effect. Light-induced complex lens produces beam defocusing from the beam center and focusing on the periphery. Mutual interference of the beams with different phases leads to the regular light patterns formation. The formed regular optical patterns inside the photorefractive crystal, in turn, create micrometric scale refractive lattice structures which are promising for numerous photonic applications.

W03,04-20 Control of photoprocesses in colloidal silver sulfide quantum dots

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The results of studies of the photostability of the optical properties of colloidal Ag2S quantum dots (QDs), passivated by thioglycolic acid (TGA) and possessing luminescence in the NIR region, are presented. The studies were performed by transmission electron microscopy, absorption and luminescence spectroscopy, photoluminescence decay study (time correlated single photon counting). An increasing of the average QDs size from 1.8 nm to 5.5 nm, and also a shift of the luminescence band from 620 nm to 950 nm, were found at using of TGA molecules and sodium sulfide as a sulfur precursor. A decreasing in the photoluminescence intensity of open colloidal Ag_2S QDs was established under irradiation with laser radiation at a wavelength of 445 nm, starting with the values of the effective power of 10 mW. The observed effect is interpreted as a photochemical reaction of formation of new channels of nonradiative recombination in Ag_2S QDs under the action of the excitation radiation. To increase the photostability of the Ag_2S QDs, a method of surface passivation due to the formation of the core/shell structures Ag_2S/ZnS and Ag_2S/CdS has been developed. The growth of semiconductor shell leads to an increasing of the intensity of luminescence up to 5 times compared with the intensity of open Ag_2S QDs with a constant maximum position of the band and an increasing of the photostability of photoluminescent properties at time up to 3000 s. Using the time-correlated photon counting, we found an increase in the average luminescence lifetime from 2.6 ns to 15 ns of Ag_2S QDs as a result of shell expansion. The observed increasing in photostability is associated with the healing of nonradiative recombination channels as a result of the overgrowth of the interface states when the shell of more wide-gap semiconductor (ZnS, CdS) is enlarged.

W03,04-21 Laser fabrication of nanoemitters and nanolasers from halide perovskites

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Halide-perovskite nanolasers have demonstrated fascinating performance owing to their efficient light emission and low-threshold lasing at room temperature as well as low-cost fabrication. However, being synthesized chemically, controllable fabrication of such nanolasers remains challenging, and it requires template-assisted growth or complicated nanolithography. Here, we review recent achievements for the fabrication of light-emitting nanoparticles and nanolasers by laser ablation of a thin films on glass with femtosecond laser beams. The fabricated nanoparticles and nanolasers are made of MAPbBrxIy perovskite, which is a popular material in optoelectronics and photovoltaics. High-speed fabrication and reproducibility of nanostructures parameters, as well as a precise control of their location on a surface, make it possible to fabricate centimeter-sized arrays of the nanolasers. Our finding is important for direct writing or printing of fully integrated coherent light sources for advanced photonic and optoelectronic circuitry.

W03,04-22 Photoinduced nanocomposites: experimental results and theoretical modeling

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In photoinduced nanocomposites, the laser/UV irradiation leads to the formation of inorganic nanoparticles within the initially homogeneous transparent polymer materials. Specially designed precursor molecules play a significant role here. We present experimental evidences of plasmon photoinduced nanocomposites with metallic nanoparticles, exciton photoinduced nanocomposites with semiconductor CdS nanoparticles, and exciton-plasmon nanocomposites with the nanoparticles of both kinds simultaneously. With photoinduced nanocomposites, it is possible to obtain samples with spatially modulated absorption, luminescence and optical nonlinearity. Different laser sources are used in these experiments including harmonics of a Nd:YAG laser. The possible application of pico- and femtosecond lasers is discussed. The important role of UV LED operating at 365 nm wavelength for the investigation of the features of particle growth kinetics is shown. The opportunity to employ recently designed broad-spectrum white LEDs for in situ monitoring of the nanoparticle growth process is demonstrated. The role of ambient temperature is analyzed. We present the theoretical consideration of some aspects of the processes involved including the problem of spatial localization of laser induced nanoparticles formation and explanation of the experimentally observed exposure-dependent kinetics in UV LED irradiated materials. We discuss the restrictions imposed by the requirement of the model self-consistency on the important parameters such as diffusion coefficient of the elementary species. The role of matrix inhomogeneity is also considered.

We discuss the possibility of fixing the structures recorded by a focused laser beam by posterior unfocused UV LED irradiation.

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W03,04-23 Applications of ultrafast lasers in materials engineering and diagnostics

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This presentation will focus on the application of advanced ultrafast photonic approaches for novel materials synthesis, as well as for the development of advanced photonic techniques to probe at the nanoscale, which are issues of great interest in current materials science and engineering research [Adv. Mat., 29, 1700335 (2017)].

In particular, Nature inspires us in tailoring unique surface properties based on synergetic effects of chemical composition and multiscale surface morphology. We show that highly controllable, biomimetic structures, exhibiting multifunctional water repellent, anti-reflection, friction reduction and photoresponsive properties can be directly written on metallic and dielectric surfaces upon processing with femtosecond laser beams of tailored polarization [Adv. Mat., 20, 4049 (2008) ; Biomicrofluidics, 5, 013411 (2011)]. It is shown that biomimetic laser structuring is a versatile method to tune neuronal cell adhesion, proliferation and orientation and can be promising for biomaterial scaffolds for neural tissue regeneration [Biomaterials 67, 115-128 (2015)].

The second part of the presentation will focus on the application of advanced ultrafast laser based techniques for the synthesis and diagnostics of materials and components in photovoltaic, light emitting, chemical sensing and energy storage systems. In particular, the pulsed laser assisted fabrication of transparent graphene electrodes and interlayers for flexible photovoltaic devices, is demonstrated [Adv. Func.l Materials, 25, 2213 (2015)]. Furthermore, we present a fast, non-destructive and roll-to-roll compatible photochemical method for the doping of graphene [Nanoscale, 6, 6925-6931(2014)] and transition metal dichalcogenide (TMD) crystals [2D Materials 6, 015003 (2018)]. In parallel, our recent advances in the synthesis [Nanoscale, 9, 18202 (2017)] and femtosecond laser spectroscopic diagnostics of perovskite and TMD nanocrystals. The applications of the as-synthesized materials in sensors and energy storage systems [Nanoscale, 2018, DOI: 10.1039/C8NR10009H] are demonstrated and discussed.

Finally, we present all-optical, non-invasive ultrafast laser-scanning optical microscopy methods to resolve, with unprecedented resolution, the crystallographic imperfections of atomically thin graphene, TMD and perovskite nanocrystals, via experimentally probing and theoretically interpreting their nonlinear optical properties [Light: Science & Applications 7 (5), 18005 (2018)].

W03,04-24 Laser-induced periodic surface nanostructures

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This presentation reviews the current state in the field of Laser-induced Periodic Surface Structures (LIPSS). These surface nanostructures are a universal phenomenon and can be generated on almost any material by irradiation with intense linearly polarized radiation [1]. LIPSS are formed in a "self-ordered" way and are often accompanying material processing applications. They can be produced in a single-step process and enable surface functionalization through the adaption of optical, mechanical and chemical surface properties. Their structural sizes typically range from several micrometers down to less than 100 nanometers and show a clear correlation with the polarization direction of the laser radiation. Various types of surface structures are classified, relevant control parameters are identified, and their material specific formation mechanisms are analyzed for different types of inorganic solids, i.e., metals, semiconductors, and dielectrics, through time-resolved optical experiments [2,3,4] and theoretical simulations [4,5]. Finally, technological applications featuring surface functionalization in the fields of optics, fluidics, medicine, and tribology are discussed [6].

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W03,04-25 Atmospheric pressure pulsed laser deposition of plasmonic nanoparticle silver films for surface-enhanced Raman spectroscopy

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Silver nanoparticle (NP) films on glass and paper were fabricated using pulsed laser deposition (PLD) in vacuum and in argon (Ar) at atmospheric pressure. In atmospheric pulsed laser deposition (APLD) the ablated material forms a NP aerosol near the target and is transported to the substrate by flowing the Ar gas. The ablation was done using a high repetition rate 640 ns, 1060.5 nm fibre laser operating at 33 kHz. In APLD the Ar gas was flowed across the ablation spot at ~30 m s^{-1}, and the substrate was positioned 10 mm from the ablation spot. Films were also prepared using supersonic gas jet to drive the aerosol to the substrate. Various substrates used, including glass, quartz and filter paper.

The NP films were characterized using scanning electron microscopy (SEM) and UV-visible optical extinction measurements. The vacuum PLD sample showed closely-packed irregularly-shaped NPs indicative of metal films in the growth regime where coagulation is occurring on the substrate. Nanoparticle clusters up to ~200 nm are observed in the APLD sample. Clustering is also observed in the supersonic APLD sample, but on a smaller scale than the APLD sample. For the samples made on filter paper the NPs are well separated with little evidence of coagulation. The mass thickness of the various films was 4 - 7 nm, as estimated from the optical extinction at 300 nm.

The surface enhanced Raman spectroscopy (SERS) performance of the various films was measured using a 10^{-4} M aqueous solution of Rhodamine 6G. For the films made by supersonic APLD the apparent enhancement factor (AEF) was 15000, compared to the value of 100 measured for commercial paper-based Ag SERS substrate. This study clearly demonstrates the utility of APLD for the fabrication of noble metal NP films for SERS applications.

W03,04-26 Shape control of PbO nanoparticles produced by laser ablation in liquid

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The formation of PbO micro- and nanoparticles and structuring of the target surface by laser ablation in liquid (water and isopropyl alcohol) have been studied. PbO micro- and nanoparticles of various shapes (hexagonal and round plates, rods, and octahedra) were revealed. The influence of unavoidable hot water treatment during laser ablation as an additional mechanism leading to formation of the non-spherical nanoparticles has been demonstrated.

The lead target (99.99% purity) was used for laser ablation in deionized water and in isopropyl alcohol (IPA, puriss.). The target has been covered by oxide layer which phase has been controlled by oxidation procedure. Natural oxidation resulted in β-PbO (orthorhombic), however, the treatment by oxygen plasma resulted in α-PbO (tetragonal).

Stable spherical Pb nanoparticles with diameter below 30 nm have been produced by laser ablation in IPA. Contrarily, the similar Pb nanoparticles produced in water were unstable. The shape of PbO nanoparticles were dependent on its phase. The hexagonal plates consisted of β-PbO and all other shapes – of α-PbO.

The unavoidable hot water treatment during laser ablation in water have a significant role in the formation of non-spherical micro- and nanoparticles. It was found that the octahedra and rods at the target surfaces appeared even without laser ablation after water treatment at 75 ºC during about two minutes (comparable to ablation time).

The obtained formation of non-spherical particles was explained in terms of metal oxidation and oriented growth processes. The PbO nanoparticles produced by laser ablation played the role of nuclei which phase depends on the target preparation procedure. The elevated water temperature during laser ablation accelerated the growth of nanocrystals.

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W03,04-27 The laser synthesis of new carbon allotropes - elongated linear carbon chains

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A regular flat array of ultimate one-dimensional (1D) carbon nanostructures – carbynes (also known as linear acetylenic or polyyne carbons) – allows fully analytical treatment within the nearest-neighbor tight-binding model. A Peierls-type double-period distortion in the direction normal to carbyne chains results in a significant reduction of the band gap of the resulting 2D crystal and even in the band gap collapse for very closely-packed collapse. This effect is opposite to the Peierls distortion band gap opening in the purely 1D case. This system also allows analytic treatment of interband dipole transitions predicting a strong polarization and frequency dependence of the transition matrix elements.

We synthesize elongated linear carbon chains (carbynes) in a colloidal solution. The method based on the formation of carbon threads by laser ablation in a colloid accompanied by the stabilization of resulting linear carbon chains by gold nanoparticles. We deposit the synthesized carbyne threads and study free standing carbyne films with the transmission electron microscopy (TEM). TEM images of the carbon threads with gold nanoparticles attached to their ends demonstrate the straight monoatomic carbon chains with linear parts about 10-24 atoms. We observe the signatures of the polyyne allotrope of carbyne in the photoluminescence and Raman spectra of the solutions. We offer the tight-binding model for calculation the HOMO-LUMO optical transition in finite-length carbon chain. The results of our experiments and theoretical description pave the way to fabrication molecular system on base with controlled and tuned optical properties.

W03,04-28 Carbon nanostructures for solid-state laser mode-locking in the 2-μm spectral range

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Single-walled carbon nanotubes (SWCNTs) and graphene represent 2D and 1D carbon nanostructures, respectively, featuring unique nonlinear optical characteristics. Both exhibit saturable absorption properties which can be exploited not only for passive Q-switching but also for mode-locking of solid-state lasers to generate ultrashort pulses at high repetition rates (~100 MHz).

The absorption band of SWCNTs spans from 0.8 to 2.1 μm. While the saturable absorption (SA) of SWCNTs vanishes towards 2.1 μm, graphene shows a broad absorption extending into the mid-IR. A graphene monolayer is characterized by "universal" small-signal absorption equal to 2.3%. For multi-layers of graphene, the small-signal absorption scales with the number of layers almost linearly which permits to increase the modulation depth of graphene-SAs. While the linear absorption of graphene is almost constant the saturable part shows pronounced wavelength dependence with decreasing saturation intensity at longer wavelengths. The relevant properties of the carbon nanostructures are similar to those of semiconductor SA mirrors (SESAMs), with somewhat lower modulation depth and faster relaxation times. Their main advantages are related to the simple and inexpensive fabrication methods, especially when compared to the complex technology of SESAMs for the 2-μm spectral range, e.g., GaSb-SESAMs with short relaxation times. Moreover, such sophisticated SESAMs exhibit a limited spectral range of operation while carbon nanostructures are expected to be applicable near 2 μm independent of the specific laser material, typically Tm- or Ho-based, and ultimately yield the shortest pulses. In the presentation, the nonlinear properties of the different SA's will be compared and recent results obtained with bulk Tm- and Ho-lasers passively mode-locked by SWCNT- and graphene-SAs will be presented.

W03,04-29 Ultra-fast optically induced structural dynamics in phase-change materials probing by time-resolved x-ray diffraction using a free-electron laser

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Chalcogenide materials are widely used for optical data storage media, such as CDs, DVDs, and Blu-ray discs. Very recently, $Ge_2Sb_2Te_5$ (GST) has been demonstrated to be a compound well suited for non-volatile memory applications, owing to the fast phase-change process between amorphous and crystalline phases. In contrast to the conventional phase-change model, dominated by lattice thermal effects, it has been proposed that non-thermal pathways may be present when ultrafast laser pulses give rise to strong electronic excitation from bonding to anti-bonding states in GST. However, dynamics of non-thermal pathways remain largely unknown, despite recent growing efforts on laser spectroscopic studies.

In this work we show and quantify the solid-solid switching dynamics induced via strong electronic excitation to have a two-step temporal evolution (non-thermal and thermal) by virtue of state-of-the-art x-ray diffraction techniques based on the x-ray free electron laser and epitaxial GST samples, providing a precise structural dynamics as opposed to polycrystalline films. We find that the x-ray diffraction intensity decrease is associated with the appearance of a metastable state with softened interatomic interaction, caused by the transient weakening of resonant bonding. This conclusion is supported by results of an independent time-resolved x-ray absorption fine structure study, providing evidence for the existence of metastable excited state. The extremely long lifetime of the disrupted crystalline state of GST was confirmed, and the possibility of its use for further development of memory devices by application of energy-efficient electronic stimuli, avoiding the undesired heating of the memory cells, and ultimately multi-level principle implementation and other applications with characteristics well above the current limits was proposed.

W03,04-30 Laser assisted functionalisation's of micro- and nanosystems with coatings

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Micro- and Nanosystems are widely used in different fields of applications. Micro-machining technology using femtosecond lasers has only been possible to produce tailored three-dimensional structures in the micro and nanometer range for about ten years.State of the art is to use these systems uncoated.

An important aspect for applications of this technology in microoptics, micromechanics, microelectronics and microchemistry are the possibilities to modify their inner surfaces. For many applications, such modifications often require the introduction of metals or metal components into such micro- or nanosystems.

In this invited talk, different selected coating technologies like Chemical Vapour Deposition (CVD) in order to coat even complex Micro- and Nanosystem[1, 2] are introduced. The chemical vapour deposition of organometallic compounds (OMCVD) allows the deposition of metals from the gas phase, without damaging these often-very temperature-sensitive micro- or nanostructured substrates.

The main objective is to obtain in a first step – e.g. with the help of micro-machining technology with femtosecond lasers - novel complex micro- and nanostructures.

In a subsequent step, they will be functionalised with interesting metals by means of the OMCVD, so that novel applications in the fields of micro (nano) optics, micro (nano) mechanics, micro (nano) electronics and micro (nano) chemistry can be made possible.

This functionalisation will be presented and discussed intensively in this talk.[3]

[1] J. Wochnowski et al., Modified multichannel structures and their production and use

Patents: WO 2008135542 (DE 102007020800 (A1), EP2152928 (A1).

[2] J. Wochnowski et al., Hollow waveguide used in medicine and in structural analysis comprises a channel structure having an inner coating with a specified thickness Patents: DE 102007049929 (B4)

[3] J. Wochnowski et al., Surface-modified structures, useful e.g. in optical or catalytic

applications, comprise substrate, e.g. of glass, silicate primary coating and secondary

coating, e.g. of metal Patents: DE 102007049930 (B4).

W03,04-31 Nanotechnology in optics

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Some advantage of the nanotechnology features applied to optics will be considered. The comparative study of the spectral parameters, wetting phenomena, as well as of the micro hardness improvement for the large groups of the model optical materials such as: NaCl, KCl, KBr, LiF, MgF_2, BaF_2, CaF_2, Si, Ge, ZnS, ZnSe, Sc, Cu, Al, etc. will be shown via surface structuration. The carbon nanotubes with the refractive index close to 1,1 are chosen as the specific and the effective nano-objects, which permit to modify the materials physical-chemical characteristics with good advantage. The laser oriented deposition (LOD) technique with an additional procedure to use the surface electromagnetic waves (SEWs) will be discussed. The CO_2-laser at the wavelength of 10,6 microns and with the power of 30 W is used in this case. Some special accent will be given to postulate the nanostructurization process advantage to modify the ITO conducting coatings and the PVA thin-film polarizers. The resistivity and refractivity change of the ITO coatings will be presented; the improvement of the transmittance of the parallel component of the electromagnetic wave for the PVA polarizers will be shown and explained. Analytical and quantum-chemical simulations will support the experimental results. Furthermore, an additional data are received and will be discussed for the nanostructured organic conjugated materials (polymers, monomers and the liquid crystal ones) via change of their refractive parameters. The fullerenes, shungites, graphene oxides, etc. nano-sensitizers are used for this aim. Nd-pulsed laser operated under the Raman-Nath diffraction conditions is applied in this case. The area of the structured materials application can be extended via comparative analysis between the peculiarities of the nano- and bio-structuration. Partially, some data are shown in the recently published papers: N.V. Kamanina, etc., OPTICS EXPRESS, 2016, Vol. 24(2), 6 pages; N.V.Kamanina, etc., Sensors 2018, 18(9), doi: 10.3390/s18093013.

W03,04-32 Nanoparticle formation in nanoporous structures and applications

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Diffusion and transport play a key role in a wide range of physical, chemical and biological phenomena. Their details are determined by the surface interaction between the diffusing object and the substrate. In this context, adsorption and desorption can change the nano-scale dynamics. The way to control these two mechanisms represents a key tool to investigate the interactions at the nanoscale, where the atomic mobility is strongly affected by the substrate. Many efforts, both experimental and theoretical, have been dedicated to investigate how particles are transported in porous and fractal mediums: in such porous materials, transport is governed by the adsorption/desorption events at pores surface, where atomic clusters are grown due to atomic surface diffusion and to nucleation processes. Moreover, the formation of metallic or semiconductor nanostructures can be influenced by the light. Our paper will summarize the experiments in Siena, describing the interaction of alkali atoms and porous glasses ass mediated by light, and the recent, preliminary results on porous alumina.

W03,04-33 Optical properties of nanowires synthesized in regular nanochannels of porous matrices

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One possible method of obtaining bundles of parallel nanowires is based on their synthesis in templates with parallel channels. The class of such materials includes, e.g., MCM-41, chrysotile, porous silicon, etc. These materials, once their pores are infilled with appropriate materials, comprise a parallel array of nanowires made of these fillers. An interesting object in this respect is offered by the natural mineral chrysotile (white asbestos), since this matrix can reach macroscopic dimensions. Chrysotile consists essentially of nanotubes with an inner diameter of about 5 nm and an outer diameter of about 30 nm. These nanotubes can be about 1 cm long and ordered in a nearly hexagonal packing. Previously, chrysotile has already been successfully used to form semiconductor, ferroelectric, and metal nanowires, the structure and electrical, ferroelectric, magnetic, thermal, and other properties of which have been studied.

This message is intended to briefly describe the possibility of filling chrysotile nanochannels with fusible and refractory materials. And also about the experimental observation of linear and nonlinear optical properties of nanostructures obtained in chrysotile. Namely, about the features of the generation of the second optical harmonic when filling macroscopically ordered regular channels with fusible ferroelectrics, absorption of anisotropic materials, about the possibility of observing plasmon optical phenomena from gold and silver nanowires, and the generation of Raman scattering in nanowires of various metals and indium antimonide semiconductor located in the chrysotile channels.

The possibility of isolating one filled chrysotile fiber allows us to hope for its use in a more complex linear or nonlinear optical scheme.

W03,04-34 Au coated nanoporous silicate matrices in biomedical application of Surface Enhanced Raman Scattering

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Raman signals from molecules and analytes can be increased by several orders of magnitude if used on the SERS substrates [1]. Surface Enhanced Raman Scattering (SERS) is a techniques for detection of ultra-trace molecules in low solutes concentrations [2]. Signals from various cell components can be detected, and dynamic biochemical processes can be monitored [3]. Typical SERS substrates have nanorough surfaces, mainly coated with gold, or with suspension of gold nanoparticles, that often have low reproducibility of nanostructures and high cost [4].

Experimental testing of the gold coated nanoporous silica matrices (NPSM) as SERS substrates was the goal of the current study [5]. A significant enhancement of the SERS signal was achieved. Depending on the type of gold coated NPSM, at 1 ppm concentrations of an analyte, a signal greater than 40 and 160 times of magnitude, relative to a NPSM without gold coating, was obtained.

It was demonstrated that that NPSM can be a promising substrate for SERS experiments. It was discussed that unique characteristics of NPSM such as high biocompatibility and large surface of pores have significant advantages in biochemical and molecular experiments, especially due to the fact that fluorescence intensity of a regular glass is largely decreased in a porous structure. The technology of production of nanoporous matrix allows for control of optical properties and size of the pores. The substrates of this type great potential for use in pharmacology and biomedicine.

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W03,04-35 Photo-, thermo- and electromagnetic effects in laser-assisted fabrication of random and periodic nanocomposite materials

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Nanoporous matrices doped with metallic salts are laser-irradiated to fabricate nanocomposite materials. Because of their unique properties, both metal-semiconductor and metal-dielectric nanocoposites have found many applications in optics, photonics, optoelectronics, security and medicine. To better understand and to optimize nanoparticle formation processes, experimental results are analyzed by using a combined self-consistent multi-physical modeling. It is demonstrated that a set of photo-, thermo- and electromagnetic effects are involved in nanoparticle formation under laser irradiation. The roles of these processes are analyzed to design and optimize laser nano-structuring for several promising combinations of matrix-nanoparticle materials. Among these processes, laser light propagation and local enhancement, energy absorption, material ionization, reduction, photo-oxidation, heating, electron-phonon coupling, heat diffusion, diffusion-controlled growth, reaction controlled growth, ion and cluster migration, etc. The key issue is the choice of the essential physical processes to be included into the model for several experiments. In this talk, several combinations of metal nanoparticle and matrix materials (for example, AgNPs/ AgNPs in TiO_2/SiO_2), are considered for several laser-irradiation conditions, ranging from CW to fs laser. The corresponding modeling results allow a better control over nanoparticle growth, and, hence, over the resulting properties of nanocomposite materials.

Acknowledgements

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W03,04-36 Perspectives of laser local oxidation nanolithography for fabrication of subwavelength and high-na diffractive optical elements

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In this paper, we consider the prospects for the use of the laser local oxidation nanolithography on metal films for manufacturing of metalenses, sub-wavelength diffractive elements, and high-aperture focusing diffractive elements. The application of local oxidation of thin metal films by focused laser radiation or by current of conductive AFM tip has been actively studied recently for nanofabrication. Local heating with a laser beam makes it possible to form a pattern much faster and in a larger area than the AFM, but usually with considerably lower resolution. Thermochemical effects of laser radiation on films of various metals have been studied for a long time for writing of micropatterns. Laser-induced oxidation of thin chromium films followed by selective liquid etching is applied for fabrication of computer-generated holograms and general-purpose photomasks. The spatial resolution of thermochemical writing on metal films can be significantly enhanced by through oxidation, which dramatically increases the effect of feedback on the beam energy absorption. Our study of laser writing on films of metals from a titanium sub-group (titanium, zirconium, and hafnium) showed their prospects for high-resolution fabrication of the diffractive structures. The paper discusses the experimental results, the advantages and disadvantages of using these recording media for laser nanolithography by local oxidation with sharply focused continuous laser beam and for formation of laser-induced periodic light-transmitting gratings by various types of interference of pulsed laser radiation including multi-beam interference of picosecond laser radiation and formation of highly-ordered thermochemical LIPSS by single focused femtosecond laser beam.

W03,04-37 Femtosecond laser micromaching of a polymeric Lab-on-a Chip for particle sorting

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Lab-on-chips (LoCs) are microsystems capable of transport, mix, separate, react and analyze very small volumes (micro- to nanoliters) of biological samples in microfluidic channels. They have a huge application potential, from basic science to point-of-care medical analysis. A challenging task for microfluidic devices is the sorting of rare cells, including the isolation from blood of rare target cell populations (i.e. circulating tumor cells and circulating fetal cells).

Usually, microfluidic devices for cell sorting are made of PDMS and fabricated by soft lithography. However, this technology presents some drawbacks: (i) it allows to pattern structures on just one side of the chip thus limiting the achievable geometries to enhance the throughput of target particles; (ii) due to PDMS softness, at high-pressure flows the microfluidic behavior may change because of channel deformations along the devices, leading to ambiguous results.

This work proposes the use of femtosecond laser micromachining (FLM) for the developing of a LoC for high throughput size-based inertial particles sorting, using poly(methyl methacrylate) (PMMA) as substrate material. PMMA is, indeed, stiffer than PDMS, biocompatible and transparent. The flexibility of FLM allows microfabrication of a complex network of channels and chambers on both sides of the chip, which aim to parallelize the sorting process. FLM allows the material removal with negligible thermal damage to the surrounding substrate, thus creating milled features with micrometer resolution almost completely free from thermally induced defects. Several layouts, based on the results of computation fluid dynamic simulations, are investigated and tested with beads of dimensions comparable to those of blood and circulating tumor cells, respectively, aiming to maximize the trapping efficiency and the throughput of the microfluidic device.

W03,04-38 Laser-induced tuning of optical properties in hybrid nanostructures

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The new concept of metal-dielectric nanophotonics combines plasmonic and dielectric nanoparticles in a single resonant nanostructure and reveals a number of interesting optical effects, such as broadband unidirectional scattering, efficient second-harmonic generation, etc.

The report will represent brief overview of our recent results on fabrication and research of hybrid metal-dielectric nanostructures, as well as demonstrate the potential of their use in creating optical information recording devices, ultrafast optical switches, and optical sensors.

In particular we will demonstrate novel approach for fabrication of asymmetrical hybrid nanostructures [1], tuning of far-field [2] and near-field [3] optical properties in oligomers made of these nanosystems. The new results demonstrating nonlinear properties (second harmonic generation, ultrafast tuning, white light generation) in such nanostructures well be also discussed, as well as application of hybrid nanocavity for real-time tracing of molecular events [4].

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W03,04-39 Direct laser printing of functional surfaces and microdevices with structured beams

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Laser patterning of various materials using short- and ultrashort laser pulses has become a matured technology allowing rapid prototyping of various nanotextured morphologies, surface and devices. Currently, pulse repetition rate of the commercially available laser systems used in the nanotexturing experiments enters sub-GHz range ensuring extremely fast and rather precise material patterning at the speed reaching several cm^2 per second allowing fast cost-effictive fabrication of functional surfaces and devices. Also, material processing with structured laser radiation, representing specially designed laser beams with a complex intensity profile and polarization states, which provide very specific conditions for laser energy deposition into the irradiated material, becomes a hot topic in the area of laser nanofabrication. Here, we present our recent results related to direct nanofabrication of various micro- and nanoscale structures as well as functional surfaces and devices using short and ultrashort laser pulses shaped into the specific beams with complex intensity pattern. First, we present the results on formation of chiral surface nanorelief under direct ablation of the noble-metal films and silicon substrates with “perfect” vortex beams having variable topological charge and fixed donut-shaped intensity distributions as well as specially designed zero-angular-momentum spiral beams [1]. Both types of the laser beam were generated using specially designed diffractive optical elements (DOEs). We emphasised the underlying formation mechanisms of helical plasmonic nanoneedles with structured light beams as well as point out the ability to tune the chirality of the structures via shaping the laser beam intensity. Then, we discuss results related to ultra-fast direct laser fabrication of patterned plasmonic metasurfaces exhibiting high-quality tunable resonances in near- and mid-IR spectral range [2]. Using a specially designed DOE, we applied the laser beam multiplexing technique to achieve 10 million per second printing rate of high-quality IR plasmonic metasurfaces [3]. The reported high-speed metasurface printing technology with a robust output and well-controlled IR resonances pose great opportunities for design of sensors and wave-shaping structures. Finally, we discussed an approach for fabrication of microlasers by direct laser ablation of a halide perovskite thin film on glass substrate using vortex laser beams. The fabricated microlasers represent CH3NH3PbBrxIy microdisks with diameters ranging from 2 to 9 μm being controlled by a topological charge of the vortex beam. As a result, this method allows for the fabrication of single-mode perovskite microlasers operating at room temperatures in a broad spectral range (550-800~nm) with the Q-factors up to 5500. High speed of the fabrication and reproductivity of microdisks parameters as well as precise control of their location on a surface make it possible to fabricate cm-scale arrays of such microlasers [4].

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W05,06-1 How spatiotemporal coupling in ultrashort laser beams can induce 3D writing anisotropy: insight from inside

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Numerous experimental studies in recent years have revealed intriguing symmetry breakings during nonlinear interaction of ultrashort laser pulses with materials. Dependence of the modification structures on the direction of laser scanning and polarization, an effect known as non-reciprocal writing is one of the most commonly observed asymmetries. These observations are generally attributed to spatio-temporal coupling (primarily pulse-front tilt) in the laser pulses. Even though such coupling indeed break the spatial symmetry of the light-matter interactions, a detailed understanding of ongoing phenomena in the microscopic level is still lacking. In this work, we present our theoretical results, which to best of our knowledge, constitute the first demonstration of the physical mechanisms behind non-reciprocal writing in transparent media. Our model is based on nonlinear Maxwell's equations supplemented by the hydrodynamic equations for free electron plasma [1]. Description of the spatio-temporal distortion of Gaussian pulses has been introduced into the model according to the theory developed in [2]. Numerical simulations have enabled to gain a qualitative insight into the features of propagation of ultrashort laser pulses with tilted pulse fronts, in the regimes of volumetric laser modification of transparent materials. In particular, we observed that asymmetric distribution of self-trapped exitons and color centers cause the observed dependence of structural modifications on laser scanning direction.

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W05,06-2 Generation of deterministic nanostructures with ultrashort UV pulses under predefined interface boundary conditions

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A direct comparison of simulation and experimental results of UV ultrafast laser induced surface nanostructuring of gold is presented. Theoretical simulations and experiments are performed on an identical spatial scale. The experimental results have been obtained by using a mask projection setup to generate a spatially periodic intensity profile on a gold surface with a sinusoidal shape and a period of about 500 nm. The formation of structures on the surface upon single pulse irradiation is analyzed by scanning electron microscopy (SEM) and atomic force microscopy (AFM). Depending on the laser fluence, an elevation of the surface within the irradiated lines, or the formation of grooves with elevated, narrow ridges on both sides are observed. The observed structure strongly depends on the

interface boundary conditions. E.g., a thin confinement film of SiO_2 deposited on top of the gold film changes the final structure significantly.

For the simulations, a hybrid atomistic-continuum model capable of capturing the essential mechanisms responsible for the nanostructuring process was used to model the interaction of the laser pulse with the gold target. In this model, the kinetics of the induced phase transition processes is addressed at an atomic level with molecular dynamics (MD) simulation. At the same time, the processes of laser-light absorption by conduction-band electrons, fast electron heat conduction, and the generated strong electron-phonon nonequilibrium are described in the continuum with the help of the two temperature model (TTM).

The good agreement between the modelling results and the experimental data justifies the proposed approach as a powerful tool revealing the physics behind the nanostructuring process on metal surfaces and providing a microscopic insight into the dynamics of the structuring processes of metals in general.

W05,06-03 Ultrashort laser-induced damage thresholds of metals and semiconductors in air and water

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Pulsed laser ablation in liquids (PLAL) is an efficient and flexible technique for nanoparticle production and surface nanostructuring. Although PLAL is simple in realization, the process itself is very complicated and still poorly understood. The complexity of the PLAL process can be illustrated by the example of the laser-induced damage threshold (DT), a well-defined parameter which can be unequivocally measured and serve as a reference for understanding and modelling of the PLAL process. However, available data on DTs in liquids are rather contradictory, provide threshold fluences higher, equal to, and lower than the corresponding values in air, and various mechanisms are invoked to explain the difference. Thus, a recent work with nanosecond laser pulses showed [1] that the DTs of metals in water are considerably higher than the air values due to scattering of the incident laser light by the vapor-liquid interface due to a vapor bubble formation in the subnanosecond timescale. However, these scattering processes obviously do not play any role for picosecond and femtosecond laser pulses since the pulses end before the liquid starts to be heated and vaporized.

In this work, we measured the DTs in water for crystalline silicon, gold and a gold-silver alloy. The targets were irradiated by 260-fs and 7-ps laser pulses at 1030 nm wavelength in single-shot and multi-shot regimes. The results are compared with data obtained under identical irradiation conditions in air. The influences of the pulse duration, surface reflectivity, focusing conditions, accumulation effects and non-linear effects during laser pulse propagation in water are discussed.

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W05,06-4 Low collision rate model of inter- and intra-band electron excitation by ultrashort laser pulses in wide-band-gap crystals

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Laser-induced electron excitations via nonlinear absorption is a major mechanism of ultrafast energy transfer from femtosecond laser pulses to electrons of a wide-band-gap solid transparent to low-intensity visible-through-mid-infrared radiation. Modeling of the electron excitations is a major part of various simulations of ultrafast high-intensity laser-solid interactions.

Traditional models of the ultrafast electron excitations consider cycle-averaged uncoupled inter-band and intra-band transitions. The inter-band excitation is attributed to electron promotion from a totally filled valence band to an empty conduction band by direct action of laser-pulse electric field (photoionization) or by energy transfer via electron-particle collisions (impact ionization). The intra-band processes consider collision-driven electron dynamics and associated free-carrier absorption in the conduction band. The photoionization is dominantly simulated by the Keldysh photoionization-rate formula that assumes the electrons perform collision-free laser-driven oscillations in the momentum space. The collision-driven intra-band dynamics, impact ionization, and transient optical response are simulated with either the Drude model or collision integrals combined with the Keldysh formula in a kinetic or a rate equation for conduction-band electrons. Those models deliver the collision rate at the level of 1015 1/s and contain a contradiction between the zero-collision approximation of the Keldysh formula and the high-collision-rate models of the impact ionization and intra-band electron dynamics.

Since the traditional models substantially overestimate the electron-particle collision rate, we propose a low-collision-rate approximation for both intra-band and inter-band laser-driven electron dynamics. This approach assumes that all laser-driven electron excitations happen between oscillating states. The model consists of an energy-resolved rate equation for the conduction-band electron density coupled to the Vinogradov equation for average absorption rate by the conduction-band electrons. The impact ionization is neglected in a natural way. Laser-driven modifications of energy bands are incorporated. Uncoupled contributions from several valence bands and non-monochromatic corrections to the Keldysh formula are included. We discuss the physical effects predicted by this approach and compare it to the usual models. This material is based upon work supported by the Air Force Office of Scientific Research under award number FA9550-15-1-0254.

W05,06-5 Formation of fine LIPSS on metals irradiated by double pulse beam of femtosecond laser

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To achieve laser nano-fabrication in which size much smaller than that of diffraction limit, the knowledge of the laser-matter interaction is important, especially for producing the LIPSS on solid surface. The periodicity of LIPSS has been down to $\lambda/13$- $\lambda/25$ dependeing on the wavelength λ of excitation laser pulses. LIPSS can be produced on materials surface irradiated by femtosecond laser pulses slightly higher in fluence than the ablation threshold. Therefore the ablation threshhold might be one of the key issues to discuss physics of the laser-matter interaction. Firstly, the ablation threshold has been measured precisely and compiled all data publised for metals. We found that the nonlinear absorption on metal surface irradiated by femtoseocnd laser pulses is important role for determined the ablation thershold.

With using the femtosecond double-pulse laser beam in which laser fluence close to the ablation threshold, several interesting features such as the ablation suppression, the dotted coloring, the fine LIPSS with high regularity have been seen. In this talk, the results of the two-color femtosecond double-pulse laser irradiation to produce the LIPSS with high regularity on titanium (Ti) surface are presented. The double pulse beam consists of 800 nm with 150 fs pulse and 400 nm with > 150 fs pulse. The fundamental-pulse fluence F_{800} is kept below ablation threshold ($F_{800\ th}$ = 0.108 J/cm^2) while the second harmonic pulse fluence F_{400} are kept above the ablation threshold ($F_{400\ th}$ = 0.090 J/cm^2). At the delay time Δt= 0, the the LIPSS with high regularity is produced.

W05,06-6 Hydrodynamic modeling of surface nano- and microstructuring by femtosecond laser

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Multipulse femtosecond laser irradiation of surfaces represents a non-trivial interplay between photo-thermal mechanisms of energy absorption and heat confinement and hydrodynamic processes leading to phase transitions, melt flow, and material removal. On one side, ultrashort laser modifies surface relief producing significant roughness, sub-surface cavities, nanoparticles, nanobumps and nanopillars, as well as self-assembled periodic and aperiodic structures, including ripples, spikes, and grooves [1-2]. As a result, laser-structured surfaces acquire unique antireflective, plasmonic, chemical, antibacterial, mechanical and wettability properties due to nano- and microscopic dimensions. On the other side, light couples to the laser-induced nanostructures via constructive and destructive interference, contributing to the nanostructure growth or erasure after irradiation by multiple pulses [3-4].

We propose a coupled electromagnetic-hydrodynamic approach to follow accurately surface relief formation, amplification, and regulation upon multipulse ultrashort laser ablation. The model allows us to describe the processes of nanostructure self-organization and pulse-by-pulse evolution, paving the way towards better understanding and control over the nanofabrication processes. For instance, the surface topography is shown to impose the dominant contributions to surface sub-wavelength patterns by selecting the appropriate wave character from plasmonic to evanescent cylindrical waves [4].

Our multiphysical model serves also as a useful tool to predict the regimes, in which the significant roughness, undesirable for industrial applications and reducing the processing quality of laser drilling, can be avoided. For this, the evolution of laser-induced surface reliefs is investigated as a function of laser fluence and number of applied pulses, revealing different phenomena, including sub-surface cavitation and spallation, volcano-like crater formation, and self-organization of ripples.

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W05,06-7 Large-scale atomistic simulations of nanoparticle generation and surface modification by short laser pulses in vacuum and liquid environment

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The ability of short pulse laser ablation in liquids to produce clean colloidal nanoparticles and unusual surface morphology and microstructure has been employed in a broad range of practical applications. In this presentation, we report the results of large-scale molecular dynamics simulations aimed at revealing the key processes that control the structure of laser-modified surfaces and nanoparticle size distributions generated by pulsed laser ablation in liquids [1-4]. The simulations of Ag and Cr targets irradiated in water are performed with an advanced computational model combining a coarse-grained representation of liquid environment and an atomistic description of laser interaction with metal targets. The simulations reveal that at relatively low laser fluences, in the regime of melting and resolidification, the presence of a liquid environment suppresses nucleation of sub-surface voids, provides an additional pathway for cooling of the metal surface, and facilitates the formation of nanocrystalline structure of the resolidified region of the metal target [1]. One of the most interesting predictions of simulations performed at sufficiently high laser fluences, in the regime of phase explosion, is the emergence of Rayleigh–Taylor and Richtmyer–Meshkov hydrodynamic instabilities at the interface between ablation plume and superheated water, leading to the formation of nanojets and emission of large droplets into the water environment [2-4]. The droplets are rapidly quenched and solidified into nanoparticles featuring complex microstructure and metastable phases. Rapid nucleation and growth of small nanoparticles in the expanding metal–water mixing region and the breakup of the hot metal layer into larger droplets due to the hydrodynamic instabilities represent two distinct mechanisms of the nanoparticle formation that yield nanoparticles of two different size ranges as early as several nanoseconds after the laser irradiation. This computational prediction provides a plausible explanation for experimental observations of bimodal nanoparticle size distributions in short pulse laser ablation experiments [4].

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W05,06-8 Expansion and fragmentation of droplets after short-pulse irradiation

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Fragmentation mechanisms of micrometer-sized liquid droplets irradiated by short light pulses are studied using the consistent atomistic and hydrodynamics simulation methods. Our experiments demonstrate either symmetric or asymmetric expansion of the droplet depending on laser pulse intensity. To reveal the underline processes we perform simulations complying with the experimental conditions. We found that the fast energy deposition generates a strong shock wave followed by a tensile wave, which propagates from the frontal side to the rear side of droplet. Convergence of such waves inside the droplet leads to cavitation nearby the center, which causes the droplet to expand symmetrically. But the later shock reflection from the rear side of droplet may lead to spallation of a thin rear-side layer, which results in the asymmetrical droplet expansion. The calculated energy threshold for the rear-side spallation is higher than a threshold required for the central cavitation. Those thresholds and corresponding expansion velocities agree well with the experimental results in both regimes of droplet expansion.

W05,06-9 Modeling of ultrafast electron dynamics near silicon/vacuum interface and related phenomena induced by the action of ultrashort laser pulse

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The processes of electron emission during ultrafast excitation of solids attracted the attention of researchers for many years. It has been hypothesized that strong electron emission caused by the action femtosecond laser pulse can lead the destruction of surface layers of solids ("coulomb explosion") [1,2]. Also some researchers believe that electron emission can be responsible for creation of some types of microstructures on silicon surface under the action of femtosecond laser pulses via creation of dynamic waveguide structure in surface layers of semiconductor [3,4]. The existing physical and mathematical models of ultrafast electron emission processes play an important role in the interpretation of experimental results. However most of them [2 - 4] do not take into account the influence of generated during emission charge separation electric field on emission process (space charge effect).

In this work we present an improved model of electron emission processes caused by the action of femtosecond pulse on silicon which take into account space charge effect. In the framework of proposed model we have analyzed the possibility of "coulomb explosion" and formation of dynamic waveguide structure in silicon irradiated by intense ultrashort pulse. Also we show that the charge separation caused by emission should lead to the generation of the terahertz radiation. The investigation of the properties of such terahertz pulses can serve as a research tool for studying of the processes of ultrafast electron emission induced by the action of femtosecond laser pulses on solids.

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W05,06-10 MD-based modeling of nanoparticles generation due to laser ablation of metals in liquids

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In this work we investigate the mechanism of nanoparticles generation due to laser ablation of metals in liquid media with numerical atomistic-continuum model. The mode is capable of addressing the mechanisms of non-equilibrium laser-induced phase transition processes at atomic level with Molecular Dynamics (MD) approach, whereas the effect of free electrons, playing a determinant role during short laser pulse ablation, is described in continuum with Two Temperature Model (TTM). Such the combined MD-TTM model [1] was utilized in a super large scale modeling of the process of nanoparticles generation in water. The obtained nanoparticles are then characterized from the point of their size distribution and morphology. This characteristics was then studied as functions of the laser parameters (pulse duration and fluence), the ablated materials (Al and Au), and surrounding media (air and water) [2]. The performed simulations enable the direct comparison of the modeling results and the experimental data [3] and allow for drawing a possibility of the manipulation with the laser parameters and surrounding media for generation of the nanoparticles with predesigned properties. The results have a strong impact on the IT-and Bio-technologies.

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W05,06-11 Numerical study of thermal dynamics and stress build-up in Laser-Induced Periodic Surface Structures formation on metals and dielectrics

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Laser-induced periodic surface structures (LIPSS) are believed to originate from a periodic deposition of the laser energy, result of the interference between electromagnetic surface waves and the laser pulse itself [1]. From this periodic absorption of the laser light to the final morphology of LIPSS, different pathways of material relocation are conceivable [2]. In this study, we wish to shed light on possible routes leading to LIPSS formation.

We investigate numerically the dynamics of temperature upon irradiation of different materials by an ultrashort laser pulse and estimate stress build-up. To this aim a 2D numerical code based on the two-temperature model is developed. A modulation is introduced in the laser pulse spatial profile to reproduce the inhomogeneous deposition of energy [3] and the amplitude of the subsequent temperature modulation is followed at the surface of gold and fused silica. Change in optical properties during the laser pulse action are considered via the Drude model in gold and by monitoring carriers excitation dynamics in fused silica.

It is found that perturbations of the temperature profile can remain substantial for several hundreds of ps in the molten phase of gold in spite of its relatively high thermal conductivity. Change in optical properties also shows significant effect in the regimes of fluence considered, above the material modification threshold. Additional investigations are presented which relate to the thermal stress developing at the surface of the target materials in our particular irradiation configuration.

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W05,06-12 Ultrafast diagnostics of microplasma induced by tightly focused infrared femtosecond laser pulse in bulk silicon

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By combination of fluence technique and shadow photography, we investigate the process of energy deposition from the infrared femtosecond laser pulse into the bulk silicon under different focusing conditions and different peak-to-critical power ratios (from several up to 10^4). The shadow photography gives information about the plasma density distribution and the fluence technique allows retrieving the 3D profile of laser energy deposited into the volume of silicon and gives opportunity to investigate the dynamics of laser-matter interaction. In contrast to dielectrics a high linear refractive index and a high density of the free electrons to be appeared under laser excitation leads to the delocalization of the femtosecond laser pulse energy even at the case of high numerical apertures. Under focusing of the infrared femtosecond laser beam λ=1240 nm) the filament is fired inside the silicon. The length of the filament exceeds several millimeters. It is worth mentioning that at similar experimental conditions the superfilamentation regime is implemented in dielectrics. The increase of the lens numerical apertures leads to the growth of the efficiency of energy deposition into the medium with simultaneous decrease of interaction area. However, the value of the deposited energy density does not overcome the threshold of the micromodification formation. Nevertheless, using of hyperfocusing (using solid immersion) and two-color excitation can help to overcome this limit.

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W05,06-13 Femtosecond laser-induced periodic surface structure transform on the amorphous silicon surface: experiment and theory

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Femtosecond laser modification allows formation of laser-induced periodic surface structures (LIPSS) on the amorphous hydrogenated silicon (a-Si:H) films due to plasmon-polariton excitation [1]. Such anisotropically modified a-Si:H films are of interest as a material for polarization-sensitive optoelectronic devices, since they possess dichroism [2]. To better understand the possibility to control experimentally observed LIPSS-related anisotropy of the modified a-Si:H surface, it is necessary to provide both experimental and theoretical description of various LIPSS types formation at different laser pulse exposure.

In this work two main types of LIPSS were revealed on the a-Si:H surface after femtosecond laser pulse treatment (1250 nm, 125 fs, 0.15 J/cm^2, 10 Hz) in the scanning mode with different speeds. The mentioned LIPSS have orientation orthogonal or parallel to the laser polarization, and the same period of 1.20 ± 0.02 μm.

Such structure formation is caused by nonequilibrium carriers photoexcitation and subsequent surface plasmon-polaritons generation [3]. The LIPSS orientation is turning from perpendicular to parallel relatively to laser polarization when the laser beam scanning speed decreases (the exposure time of the same area increases) due to the feedback emerging between irradiated film optical properties and excitation of certain plasmon-polariton modes at the sample surface [1].

The LIPSS formation was theoretically described using the model proposed by John E. Sipe et al. [4]. According to this model, the LIPSS orientation is turning when the dielectric permittivity real part, achieved on the a-Si:H surface during femtosecond laser pulse action, varies from $\mathrm{Re}\varepsilon < -1$ to $\mathrm{Re}\varepsilon > 1$, which is in accordance with data of [3] also. The Reε depends on the photoexcited carrier concentration N, and corresponding threshold value of N required for LIPSS orientation turning was estimated as $8.2 \cdot 1021$ cm^{-3}.

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W05,06-14 Beam shaping in macro- and micro- scale for laser processing

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In laser processing, micro- and micro- structures of the beam profile are the key parameters. In this paper, control of the unit structure of interference pattern by using phase and amplitude variation between the beams is explained[1–3]. Then, beam shaping technique by using active phase grating overlaid by a SLM (Spatial-light modulator) with a 4fsystem is explained[4]. In addition, fabrication of nanowhiskers [5,6], chiral structures[7] in lattice, and nanoparticles[8] by interference laser processing are introduced.

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W05,06-15 Nonlinear Kerr lensing array for surface laser parallel processing

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Femtosecond laser pulses interacting with material surfaces generate micro- or nano-structures and modify material surface properties such as reflectance, hydrophilicity. Thus femtosecond laser is promising for material surface processing and manufacturing of functional surface devices. However, conventional femtosecond laser surface processing relies on time-consuming motion of the laser head or workpieces, limiting its efficiency and broad application.

Here we propose an all-optical technique for parallel laser surface processing. In this technique, three or four collimated femtosecond laser beams overlap in a transparent nonlinear Kerr medium, generating a laser beamlet array due to interference. By controlling the incident laser intensity, each laser beamlet experiences nonlinear self-focusing in the nonlinear Kerr bulk material. Thus each beamlet forms a converging wavefront at the exit and keeps focusing to an intensity hotspot in the air. The workpiece can be placed at the nonlinear focal plane or its conjugate plane of a relay imaging system. Thus a wide area can be processed by the focused intense beamlet array.

Simulation results showed that the peak fluence at the work piece is up to ~1J/cm^2, which is a typical range for black silicon laser processing. The scaling length of the parallel processing area is 3mm, improving the efficiency by three orders of magnitude. In addition, the focal spot positions of the beamlet array can be conveniently controlled by the relative phase between interfering laser beams.

W05,06-16 Ultrashort-pulsed laser micro structuring of large cylindrical embossing tools for surface functionalization in industrial applications

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The scaling up of precise and optimized ultrashort pulse laser ablation processes for the generation of large area surface microstructures under high throughput conditions requires high power ultrafast laser sources as well as efficient beam delivery strategies. Despite of today's availability of high power USP lasers up to several hundred Watt it is still a challenge to generate microstructures with a resolution of some microns on large surface areas of several square meters within an acceptable processing time for industrial production. The results of two different approaches for the high throughput engraving of large print- and embossing rollers of Cu and Steel will been presented: One of these methods is the parallel treatment of a cylinder by a multi beam array (up to 16 beams in parallel, each of them individually modulated at a repetition rate of 1 MHz). A 500 W, 10 ps- laser beam at 1064 nm was split into 16 sub-beams, which were coupled into a compact optical multichannel system comprising two 8-channel-modulators (arranged closely together, but independent from each other) with modulation rates up to 1 MHz per channel. At an image resolution of 2000 Lines/cm on the cylinder this allows for a summarized effective pulse rate of 16 MHz and an easy performable cylinder surface rotation speed of only 5 m/s without additional scanner. In the second approach, a fast beam scanning method has been evaluated up to 100 m/s using a polygon scanner combined with a high pulse repetition rate of the laser (6 MHz for one channel). In order to achieve highest ablation volume per irradiated laser energy and to avoid heat accumulation and unwanted energy loss, in both approaches the laser power and fluence should be set as close as possible to the theoretical optimum $F_{peak} = e^2 \cdot F_{threshold}$ of the fluence. In case of linear absorption, the optimized ablation process is characterized by the condition, that the ablation depth of a single pulse is just as deep as the penetration depth of the energy of the optical irradiance. However, in practice there are some limitations given by the laser, scanner and modulation parameters.

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W05,06-17 Synthesis of high-quality graphene and graphene-based structures by laser processing of carbides

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After almost fifteen years of intense fundamental graphene research it is generally accepted that graphene's superior physical properties are currently well understood. Major experimental challenges are now related to the large-scale production of high-quality graphene, which is the prerequisite to evolve fundamental graphene science into technological applications. The full potential of laser-assisted methods in graphene production has not yet been unlocked, despite that these methods offer a number of advantages as they are fast, low-cost, environmentally friendly and adaptable to current technological platforms. Few investigations have appeared so far aimed at producing graphene using laser beams, while much more systematic approaches have been undertaken for processing of graphene oxide (GO) towards obtaining reduced graphene oxide (rGO). Laser wavelengths ranging from ultraviolet to infrared have been used both in the cw and pulsed modes. In their vast majority, studies of laser-assisted methods result in graphene of dubious quality. We will review the current status of the role of lasers in graphene production and processing and discuss recent advances in our laboratory concerning the laser-assisted growth of graphene and graphene-based structures. In particular, we will present activities related to: (i) the growth of epitaxial graphene on SiC(0001) [1] using a continuous wave infrared CO_2 laser (10.6 μm); (ii) preparation of graphene-coated SiC particles and their anti-ballistic applications [2]; and (iii) the reduction of GO to rGO of ultralow sheet resistance using pulsed lasers [3].

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W05,06-18 Metal surface nanostructures developed with sub-ns UV laser line scanning under different atmospheres

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Surface structuring of metal surfaces has become a hot topic in the recent literature, particularly in the case of conforming Laser induced Periodic Surface Structures or LIPSS [1], which have been recently obtained at large scale using a pulsed fs laser fitted with galvo scanner technology [2]. This opens the way to develop large area surfaces for industrial applications, which may be quite varied and based on superhydrophobic, biocidal, self-cleaning and icephobic properties, among others.

Recent work on metal surface structuring in our laboratory has centered on the use of sub-ns pulsed nIR (1064 nm) and UV (355 nm), air-cooled lasers, directly in air, or under controlled atmosphere chambers. In addition, the use of beam scan and line scan modes has yielded surprising results, as the scanning sequence does affect the outcome of the laser structuring process herewith described.

A description of the most representative results, along with the properties associated with a diversity of nanostructures attained will be discussed in terms of the relationship between laser irradiation parameters, surface micro and nanostructure generation and functionlization of the irradiated surface.

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W05,06-19 Modification of surface and near-surface layers of metal materials for medical application by pulsed laser irradiation

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The report presents an overview and results of original studies of the structure and properties of titanium alloys for medical purposes, made by low-cost and high-performance technological schemes, including a combination of cross-screw and longitudinal rolling with traditional methods of mechanical and thermal treatment. On the example of technically pure titanium grade VT1-0 it is shown that the use of these schemes allows to form a submicrocrystalline structure that provides a significant improvement of the complex mechanical properties of the considered alloys (under static and cyclic loading), corresponding to the level of widely used in medicine high-strength doped alloys based on titanium.

Special attention is paid to the unique possibilities of surface treatment of titanium alloys, including alloys with coatings, by pulsed (femto-and nanosecond) laser irradiation. The main advantage of this treatment is the ability to modify the surface and surface layers of materials without significant heating of their volume. The latter is especially important for the nanostructured and submicrocrystalline metals and alloys with reduced thermal stability of structure and mechanical properties due to the increased internal energy associated with the developed system of internal interfaces, the main of which are the grain boundaries and dislocation sub-boundaries.

As a result of pulsed laser treatment, a developed multiscale relief is formed on the surface in the form of clearly expressed grooves with nano- and microroughness. Moreover, carrying out such treatment allows you to purposefully change the characteristics of the wettability of the surface and achieve extreme wettability characteristics with the possibility of demonstration of superhydrophilic or superhydrophobic properties of the surface. The use of such capabilities allows you to purposefully change the parameters of biocompatibility of materials.

The work was prepared with the support of the state task of the Ministry of science and higher education of the Russian Federation to universities № 3.3144.2017/4.6 and the Thematic Map of Basic Scientific Research of the Institute of Problems of Chemical Physics of RAS.

W05,06-20 Optical properties for femtosecond laser ablation of pre-irradiated titanium

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Ablation rate of titanium irradiated by a double-pulse beam is experimentally investigated with the time delay of 0.3-30000 ps. The double-pulse beam consists of two 800-nm femtosecond laser pulses. The fluence of the first pulse F_1 is kept lower than the ablation threshold fluence F_{th} (~100 mJ/cm^2), while that of the second pulse F_2 is higher than Fth. Suppression of the ablation rate of the titanium is observed with the time delay around 100 ps when the fluence $F_1 > 0.6\ F_{th}$. The ablation rate becomes smaller as the fluence F_1 increases. The ablation rate with the time delay 100 ps at the fluences $F_1 = 1.0\ F_{th}$ and any $F_2 > F_{th}$ is half of the ablation rate for single-pulse irradiation at the fluences F_2. This indicates that the first pulse does not cause visible damage on the titanium surface, but would cause an invisible temporary change of the optical properties of the surface. It is well-known that the optical penetration length and the ablation threshold are important properties to control the femtosecond laser ablation. In double-pulse experiment, these properties would be changed by the first-pulse irradiation. We have evaluated the temporal change of the optical penetration length and the ablation threshold after the first-pulse irradiation by measuring the detailed dependences of the double-pulse ablation rate on the fluences F_1 and F_2. Both the optical penetration length and the ablation threshold change as the time delay or the fluences F_1 changes. Therefore, the change of the optical properties by laser pre-irradiation is of much importance to discuss the suppression mechanism of the ablation rate for double-pulse laser irradiation.

W05,06-21 Laser functionalization of titanium implants surface: from idea to manufacturing application

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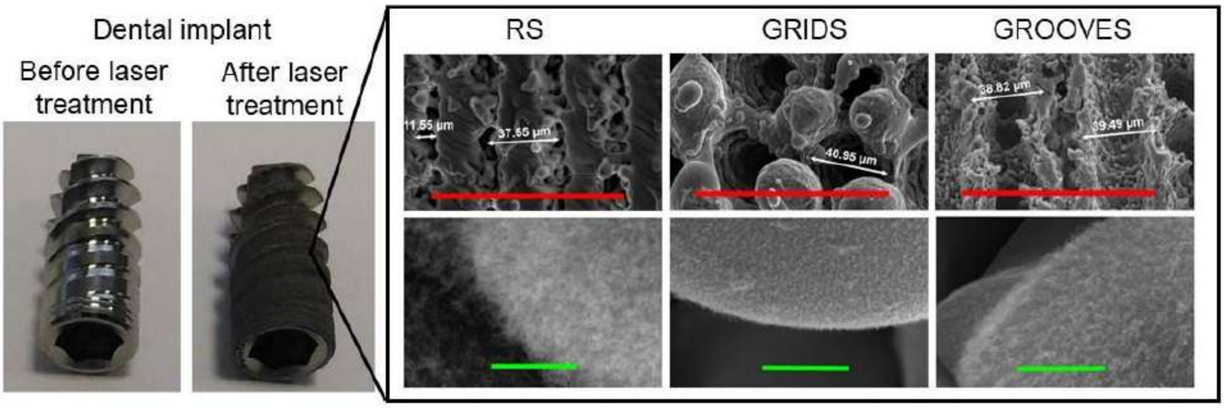
It is known that surface geometry, chemical composition, anti-bacterial, and other surface characteristics were shown to be crucial for implant biocompatibility and survival. Nowadays, it is generally accepted that micro- and nanostructured implants have a better mechanical interlocking of the bone-implant interfaces than smooth surfaces and proteins typically respond to surface nanostructures. Laser treatment, furthermore, does not require any consumables, such as sand-blasting and plasma spraying need powders or chemical solutions for acid etching. Despite numerous previous studies, it is still unclear which topography and, particularly, sizes of surface microstructures are preferable for implant osseointegration in the living body as well? To answer this question, we realize several surface topographies (grids, random structures (RS) and grooves) that mimic natural cell-specific dimensions trying to minimize stresses acting on cells. The obtained in vitro and in vivo results demonstrate that the optimum surface microrelief corresponds to the average biomimetic cell size.



Images of dental implant before and after laser treatment. SEM images of titanium surface after laser treatment. The scale bars are 100 μm (red) and 1 μm (green).

In conclusion, we developed non-toxic, robust and single-step laser technology for the formation of biocompatible surface in cooperation with Lenmiriot Dental Implant Prosthetics Manufacture.

W05,06-22 Laser induced fabrication of cobalt-doped zinc oxide nanostructured films

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Among the different doped ZnO structures, the Co-doped ZnO films have attracted much attention because of their potential applications in magneto-electrical and magneto-optical devices, spintronics, and as laser passive Q-switchers. In this work, we present the pulsed laser assisted fabrication of Co-doped ZnO nanocrystalline layers on a glass substrate. The purpose is to achieve the substitutional incorporation of Co^{2+} ions on the Zn site inside ZnO nanoclusters through the fast laser induced heating, subsequent melting, and re-solidification processes at extremely high cooling rates.

The first technique was based on the Co NPs deposition by spin-coating method over the preliminarily formed 100 nm ZnO layer deposited on the glass substrate by magnetron sputtering technique. The Co NPs were prepared by laser ablation in acetone. As an annealing laser source, the Nd:YAG laser with a pulse duration of 10 ns was used. For the determination of optimal conditions, the dependence of Co incorporation on the laser wavelength (second and fourth harmonic) and pulse energy was studied. After adjusting the laser energy density to provide several hundreds nanometer penetration depth for the incident laser radiation it is possible to deliver very rapid melt/solidification cycles. For comparison, another technique based on sequential laser ablation of Zn and Co targets in distilled water was applied for doped ZnO nanocrystals formation. In this case, the formed nanocrystals were also deposited on the glass substrate using spin-coating technique.

The morphology, structure and optical characteristics of the synthesized films depending on the experimental conditions were analyzed. To quantify the Co content in the sample after laser treatment, LIBS analysis of the synthesized samples composition was performed. The results showed the formation of films constituted of nanocrystallites having rather homogenous distribution of cobalt ions inside the ZnO matrix. The incorporation of Co atoms into the ZnO structure could be also elucidated from the Raman spectra analysis.

W05,06-23 Femtosecond laser micro-texturing to reduce friction of soft matter surfaces

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In this work, an experimental investigation on laser surface micro-texturing of fluoroelastomer samples with a 200 fs laser source at a wavelength of 1030 nm is presented for friction reduction applications. In order to reduce heat accumulation and assure high accuracy and precision of the micro-structures, the laser has been operated at 1 kHz and low fluence. Two different textured patterns have been machined, one having large and deep dimples and the other with smaller and shallower holes. Moreover, two different configurations have been tested on a pin-on-disk tribometer, i.e. non-conformal and conformal contact, for measuring the tribological performances.

In the first case, no improvements were found with both the experimented textures. This is ascribed to the low number of dimples involved in the contact region that prevents any beneficial mechanism for reducing friction such as cavitation or trapping of wear debris inside the dimples.

In case of conformal contact, a higher number of dimples falls within the contact area thanks to the larger size of the spherical cap of the tribometer. In case of large and deep dimples, in mixed and elastohydrodynamic lubrication regime turbulence effects prevail on cavitation at the bottom of the dimples, thus generating eddies and causing the friction coefficient to increase. For smaller and shallower dimples, a reduction of the 60% of the friction coefficient has been found in mixed lubrication, where the formation of fluid eddies is less likely and the dimple rather act as micro-reservoir for lubricant. At slower sliding speeds, both the textures showed an improvement of the friction performances thanks to the oil entrapment and release between the tribopair.

W05,06-24 High-resolution observations of crystal grains beneath ultrafast laser-induced periodic surface structures on yttria-stabilized zirconia

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Three-mol% yttria-stabilized tetragonal zirconia polycrystal (3-mol% Y_2O_3-doped ZrO_2, 3Y-TZP) is a fine ceramic with high fracture resistance and flexural strength utilized for mechanical components and medical implants. We have investigated the formation of laser-induced periodic surface structures (LIPSS) by ultrashort pulse lasers on 3Y-TZP. The observed LIPSS lines were parallel to the linearly polarized light and the periods Λ were comparable to or larger than the laser wavelength ($1< \Lambda/\lambda<1.5$) for the investigated laser wavelengths from 343 nm to 1030 nm. The period also depended on the pulsewidth. Cross-polarized and counter-rotating circularly polarized double pulse irradiations were carried out and found out that the first arrived pulse determined the morphology of the LIPSS even when the first pulse was weaker than the latter pulse. For smaller delay where the two pulses overlapped in time, the relative phase played an important role on the LIPSS morphology, which was explained with the evolution of the polarization state of the combined pulses.

In this study, to understand the LIPSS formation dynamics including melting and re-solidification, detailed observation and analysis of the crystal grains beneath the LIPSS were carried out by the transmission electron microscope (TEM). The 3Y-TZP plates were made from a fine powder (TZ-3YB-E, Tosoh) at a sintering temperature of 1350ºC. The surface was wet-polished to mirror quality. A Ti:sapphire laser (810 nm, ~100-fs FWHM), and a Yb:KGW laser (1030 nm, ~200 fs) and its harmonics (515 nm, 343 nm) were employed for LIPSS formation. Fourty pulses were irradiated onto samples in ambient air with appropriate peak fluences. The specimens for TEM (FEI corp, Tecnai Osiris) observation were made by the focused ion beam (FIB) etching and additional Ar ion milling. energy-dispersive X-ray spectroscopy (EDX) , high-resolution (HR) TEM, and selected area electron diffraction (SAED) analysis were carried out.

W05,06-25 Laser micromachining of Silicon with bursts of fs- and ps-pulses in the NIR

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In this work we report on our experiments concerning the specific removal rate (removed volume per energy) and surface quality for silicon by machining squares with pulse bursts, on the one hand with 10 ps pulses (12 ns intra burst time separation, 1064 nm) and on the other hand with 350 fs pulses (25 ns intra burst time separation, 1030 nm).

Due to cavity formation the surface roughness first increases to about 1.7 µm for single pulses and both pulse durations when the peak fluence is raised from the threshold to 1.1 J/cm^2. But in contrast to fs pulses, with continuously increasing roughness values, it drops down, due to melting effects, to values below 400 nm for 10 ps pulses and for all investigated peak fluences up to 6.5 J/cm^2.

For both pulse durations the obtained specific removal rate increases with the number of pulses if 3 or more pulses per burst are applied. For a 4 pulse burst e.g. the maximum specific removal rate amounts about 3.2 µm^3/µJ and 4.2 µm^3/µJ for 10 ps and 350 fs pulses, respectively. For the 10 ps pulses the number of pulses per burst is further increased and a maximum rate of 8 µm^3/µJ is obtained for a 14 pulse burst. This value is near the recently reported 11 µm^3/µJ by Kerse et al. for GHz bursts of 800 fs pulses, especially when the higher wavelength and pulse duration is considered. Calorimetric measurements show that changes of the surface roughness and absorptance cannot explain this observed high gain. But, transmission measurements for a wafer of thin silicon clearly indicates that the non-linear absorption could be responsible for this high specific removal rate even for the GHZ burst situation.

Kerse et al., ”Ablation-cooled material removal with ultrafast bursts of pulses”, Nature, 2016 537 (7618):84-884

W05,06-26 Surface plasmon polaritons and nanostructuring of materials

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Self-organized surface structures on metals could be produced by ultrashort laser pulses. This technology has a lot of applications including wetting, medical applications, tribology and others. Thus, it is important to understand the basic governing mechanisms of energy deposition to the irradiated material.

Surface plasmon polaritons [1,2], i.e. surface plasmons coupled to a laser-electromagnetic wave, can be excited on a rough material surface. The interference of the plasmons wave and the incoming pulse leads to a periodic modulation of the deposited laser energy along the surface of a sample. The spatial and temporal evolution of the periodically modulated absorbed laser energy is studied after irradiation of gold in the framework of the two-temperature model (TTM) [3]. We present a new source term in the TTM, which takes into account the excited plasmon subsystem and therefore spatial periodicity. We also investigate conditions of the SPP excitation and influence of the angle of incidence and wavelength of the laser field on the resulting structured heating. Implementation of the SPP waves into the combined atomistic-continuum molecular dynamic-TTM model [4] will be a focus of our future work. The developed approach can also be used to study the morphological effects and nanostructuring for many upcoming technological applications.

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W05,06-27 Large-scale atomistic modeling of short-pulse laser-induced generation of crystal defects in Ni-based single-phase binary solid-solution alloys

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Single-phase concentrated solid-solution alloys exhibit enhanced mechanical characteristics and radiation damage resistance, making them promising candidate materials for applications involving an exposure to rapid localized energy deposition. Large-scale atomistic modeling is used in this work to investigate the mechanisms of the generation of vacancies, dislocations, stacking faults, and twin boundaries in Ni, $Ni_{50}Fe_{50}$, $Ni_{80}Fe_{20}$, and $Ni_{80}Cr_{20}$ targets irradiated by short laser pulses in the regime of melting and resolidification [1]. The decrease in the thermal conductivity and strengthening of the electron−phonon coupling due to the intrinsic chemical disorder in the solid-solution alloys are found to have important implications on localization of the energy deposition and generation of thermoelastic stresses. The interaction of the laser-induced stress waves with the melting front is found to play a key role in roughening of the crystal−liquid interface and generation of dislocations upon the solidification. A common feature revealed in the structural analysis of all irradiated targets is the presence of high vacancy concentrations exceeding the equilibrium values at the melting temperature by about an order of magnitude. On the basis of the results of molecular dynamics simulations of solidification occurring at fixed levels of undercooling, the generation of vacancies is correlated with the velocity of the solidification front, and the processes responsible for creating the strong vacancy supersaturation are revealed. The suppression of the vacancy generation in the solid−solution alloys is also revealed and related to combined effect of enhanced vacancy mobility and higher energy of the vacancy formation in the alloy systems. The analysis of the first atomic shells surrounding the vacancy sites in Ni-Fe alloys uncovers the preference for the vacancy sites to be surrounded by Fe atoms and suggests that atomic-scale chemical heterogeneities may play an important role in defining the behavior and properties of the single-phase concentrated solid-solution alloys.

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W05,06-28 Nonthermal phase transitions in solids: large-scale simulations with ab-initio accuracy

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We present a self-learning method for constructing Te-dependent analytical interatomic potentials able to describe, on experimental length- and time scales, laser induced nonthermal phenomena with Density-Functional-Theory accuracy. The method can describe any type of bonding and always finds the global minimum in the parameter space. We applied this method to silicon and antimony and derived analytical T_e-dependent interatomic potentials, Φ_{Si} and Φ_{Sb}, which can describe the relevant interactions and reproduce all thermal and nonthermal effects described by ab-initio simulations. The potentialsare designed to reproduce ab-initio molecular dynamics simulations (performed using our code CHIVES) by requiring force- and energy matching at each time step.The potentials allow to include electron-phonon interactions and can be used in TTM-MD (two-temperature-model-MD) schemes.

We use Φ_{Si} to simulate laser-excited Si nanoparticles and find critical damping of their breathing modes due to nonthermal melting [1]. Moreover, we analyze ultrafast effects during nonthermal melting of a Si film.

We demonstrate that our derived potential is the optimal one among all existing potential forms [2]. The analytic potential for antimony Φ_{Sb} allowed us to simulate a laser induced inverse Peierls transition in thin films and to compare with experimental results.

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W05,06-29 Laser surface structuring: large and small irradiation spots, short and long pulses

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Laser action is widely used to modify surface morphology [1-5]. Laser treatment transforms ordinary surface into metasurface which has desirable artificial properties: optical changes, enhancement of catalytic ability, and variation of an effective surface tension coefficient are possible. Results of a single laser action depend on spatial dimension and structure (Gaussian versus vortex beams) of an irradiated spot and duration of a pulse. Dimension may varies from a tiny scale defined by diffraction limit (thus of the order of micron for optical lasers) to few or many tens of microns. Dimension becomes significant because in our range of absorbed energies a material transits into liquid state thus capillary force influences dynamics [1-5]. Duration of a pulse defines how pronounced are thermomechanical forces: shorter durations – then stronger these forces are. We vary durations from 0.1 to 500 ps covering four orders of magnitudes [6]. Even at duration equal to 50 ps we see nucleation of the cavitation bubbles and formation of foam in a bulk target [6]. But at 500 ps the foam disappears [6]. Foam rupture and crystallization are important as they define random surface structures remaining at a surface in the case with a large spot [7]. The report was prepared under the government order (0033-2019-0007).

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W05,06-30 Ultrafast electronic and structural non-equilibrium in laser surface structuring

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The time needed for a metal to structurally respond to electronic excitation is key in defining material behaviors under extreme conditions. In current views it is usually set by electron-phonon coupling and defines the limitations in the achievement of non-thermal rapid structural phases. Employing time-resolved optical techniques we show that ultrashort laser excitation of metallic tungsten determines unexpectedly fast optical and structural transformations, almost on the timescale of the laser pulse. Driven by Fermi redistribution of carriers around a d-band pseudogap in the vicinity of the damage threshold, quasi-resonant optical excursions occur upon pumping with near-infrared photons, initiating a transient plasmonic state for the initial non-plasmonic metal. We discuss the potential impact of this transition in the generation of laser-induced periodic structures. Beyond this range, sub-ps ablation occurs, challenging current thermally-driven scenarios relying on vibrational coupling and phase transformations. We indicate a correlated action towards structure destabilization involving charge depletion, ultrafast screening, and electronic pressure. If, at low excitation, primarily localized states are populated due to Fermi smearing, screening the electron-ion potential, the transfer reverses between low-lying bands to delocalized states with increasing electronic temperature, and a strong charge deficit appears on bonding orbitals. In the presence of pressure gradients, this is prone to rapidly destabilize the structure even in a metallic environment. Using time-resolved ellipsometry, first principle molecular dynamics and hydrodynamic calculations we demonstrate that various mechanisms concur in a correlated way. They include mutual effects of charge-induced bond-softening, swift mechanical pressure drives, or thermodynamic supercritical trajectories. An ultrafast competition between non-classical charge distortions, electron-driven mechanical stress, and classical electron-phonon dynamics appears, with coexistence of thermal and non-thermal effects on scales believed prohibitive for the former.

W05,06-31 Origin of two-dimensional nanostructures formation under circular polarized femtosecond laser radiation interaction with condensed media

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It is well known that the appearance of ordered micro-and nano-structures on surface and in bulk of condensed media under the action of ultraviolet laser pulses is explained in framework of universal polariton model (UPM) [1]. But the majority of experiments have been conducted with linear polarized laser radiation. Published experimental data causing the ordered structure formation on metals, semiconductors and dielectrics under circular polarized laser pulses action were not elucidated [2 – 6]. According to theoretical model verified by experiments under the interaction of circular polarized nanosecond laser radiation with semiconductors and metals the arrays of resonant gratings were produced having different orientations for left and right circular polarizations (the Fourier images of structures are asymmetric relative to the center of image) [7].

Under the action circular polarized ultrashort laser radiation interaction with semiconductors and dielectrics the isotropic spatially ordered structures were formed in the shape of spherical nanoparticles of typical size $s \leq \lambda/\eta$ [2-4]. Under the interaction of ultrashort laser pulses with metals more complicated two-dimensional anisotropic nanostructures were produced having $s \leq \lambda/\eta$ and symmetry axis along surface normal [5, 6]. Here η is the real part of surface plasmon polaritons (SPP) refractive index for air-excited media boundary. To explain the origin of nanostructures and their peculiarities in framework of UPM the approach is suggested based on the interference of SPP (having all possible propagation directions) with incidence wave followed by array of nanospheres formation with well defined spatial scale $s \approx \lambda/\eta$ and on the mutual interference between SPPs and their spatial harmonics and nanosphere production with $s \approx \lambda/2\eta k$, where k=1, 2, 4, … . This result is confirms by known experiments for dielectric and semiconductors [2 – 4]. As for metals, one of the peculiarities of the nanostructures formation mechanism is the surface layer oxidation. This mechanism prevents from dynamic restructuration of created nanostructures. That is why the array of ordered square cells with $s \approx \lambda/\eta$ were produced on titanium film surface [5] and for selectively oxidized magnetic stainless steel the array of hexagonally symmetric nanostructures, $s \approx \lambda/\eta$ [6]. Our finding may be used for controllable production of surfaces possessed chiral properties.

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W05,06-32 The low-dimensional carbon nanostructure synthesis under fs-laser radiation on bulk graphite units in liquid nitrogen: nonlinear dynamic theory and experiment

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1. Development of non-stationary technique for the laser-induced functional elements synthesis based on micro- and nanostructures in graphite samples studied. Carbon nanostructures such as graphene, nanotubes and nanodiamonds have been obtained in our experiments. The formation mechanisms of nanostructures and microcrystals under femtosecond laser radiation for graphite in liquid nitrogen are analysed. Femtosecond laser pulses with high power allows to achieve the local transient conditions for the material processing resulting in ablation, sufficient modification of the structure and/or changing of the phase composition of the materials. Liquid nitrogen as a cryogenic and/or reaction liquid contributes to additional fast cooling and stabilization of the fabricated micro- and nanostructures.

2. At the processing of carbon samples (HOPG-1,7-10x10x1-1 and glassy carbon SU-2000) in liquid nitrogen by Ytterbium laser (λ=1030 nm, f=10 kHz, τ=280 fs, Epmax=150 μJ) the graphene structures (graphene tapes and plates, crumpled graphene) were obtained. It is shown that graphene units are multilayer with thickness up to 14 nm. The developed method is not inferior to traditional methods of micromechanical or liquid-phase separation, and is much superior to them in the speed and purity of obtaining graphene. The mechanisms of graphene exfoliation under the action of femtosecond laser radiation on graphite samples in liquid nitrogen were established: (1) breaking of weak interplanar π-bonds due to heating of intercalated nitrogen in graphite lattice; (2) separation the surface layers of the target due to the formation of a high pressure region in the walls of the laser cavity. In addition, at exposed by another femtosecond pulses laser radiation (λ=800 nm, τ=50 fs, f=1 kHz, E_{pmax}=1mJ) on graphite samples in liquid nitrogen the carbon microcrystals of sizes 1÷10 μm were obtained.

3. The problems being under our study have both fundamental and practical possible applications in topological photonics for creation of different functional elements.

W05,06-33 Silicon nanocrystals and micron-sized periodic structures created at the surface of the crystal and amorphous silica by resonant CO_2 laser irradiation

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The creation of nanoclasters and micrometer sized periodical structures at the surface of silica (crystal quartz and fused quartz) by action of pulsed CO_2 laser radiation (pulse energy of 1 J, pulse time of 70 ns) have been investigated.

The laser action on the surface of samples lead to appearance of two kind of structures – periodical micron-sized structures with the period length close to half wave length of CO_2 laser irradiation and more small – nanometer - sized clusters with two range of sizes: first - from 2 to 10 nm and second – from 40 to 100 nm. That has been confirmed be means of atomic force microscopic investigations of irradiated samples. The luminescense spectra of irradiated samples give the possible to conclude that nano-sized clusters are represent the silicon nanocrystals with two range sizes : from 2 to 10 nm and from 40 to 100 nm - for amorphous silica and that ones with only size of 40 – 100 nm - for crystall silica [1,2].

The periodical structures and the silicon nanocrystalls appearance connects with the intensive ablation of matter at the maxima of standing waves, which are results of the interference of falling, and surfaces waves. This connects with the resonant absorption of infrared laser radiation by silicate minerals [3].

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W05,06-34 Picosecond laser processing of photosensitive glasses for lab-on-a-chip applications

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Photosensitive glass is an attractive material over photoresists for the fabrication of 3D microstructures, in particular for biochips based on microfluidics. Specifically, it is biocompatible and exhibits good transparency for optical interrogation, superior strength for easy handling and chemical resistance. NIR femtosecond lasers are usually used so far for processing transparent photosensitive glass to create 3D complex shapes. We propose herein an approach for the fabrication of true 3D structures in the photosensitive glass by high repetition picosecond laser. In particular, the influence of the critical irradiation dose and etching ratios are discussed together with a comparison of different wavelengths, i.e, 355 nm and 532 nm, in processing. Different shapes composed of embedded micro-channels and open reservoirs, for a variety of biochip designs, are achieved in volume of the glass by picosecond laser irradiation followed by thermal treatment and wet chemical etching. We further address the possibility to perform precise 3D micro-fabrication of photosensitive glass for biomimetic applications. The biomimetic processing refers to the flow aspects, 3D characteristics and possibility of producing shape-structure function. We have designed and fabricated a large area configuration consisting of a microfluidic splitter with three channel arms with different sizes for the controlled release of a protein, such as fibroblast growth factor (FGF2). In silico simulations and tests demonstrated that the release of very small quantities of FGF2 delivered with a controlled perfusion flow over a week enhanced the in vitro osteogenic differentiation of mesenchymal stem cells. This experiment is relevant for proposing ultimately personalized drug therapies for people suffering from bone deficiencies, such as osteopenia or osteoporosis.

W05,06-35 3D structuring of bulk optical materials down to the nanoscale

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Ultrafast pulse lasers contribute essentially to the development of micro/nanotechnologies, being able to structure materials in two and tree dimensions with utmost precision. Present advances in photonics include the development of optical devices based on laser-induced volume refractive index engineering in optical materials. Ultrafast laser photoinscription can confine energy in micro-domains of arbitrary geometries, modifying the material refractive index and laying down the concept of 3D design for efficient optical functions embedded in the bulk. Here nanoscale precision can deliver high levels of performance. Therefore bypassing the diffraction limit is key for a new range of applications in optics requiring optical access at the nanoscale. We discuss the capability of Gauss and Bessel-Gauss pulses with engineered dispersion to localize light on subwavelength scales. We show how sculpting beams in space and time can bring advantages for controlling the interaction between light and matter and for achieving extreme confinement of energy. We discuss physical mechanisms of photoinscription in fused silica by following the dynamics of excitation over the entire evolution cycle, serving as guidelines for control. We explore the influence of pulse temporal and spatial design in achieving index structures on 100 nm scales, either in direct focusing or in self-organization schemes in silica glass. Non-diffractive beam excitation takes advantage of this localization and achieve unprecedented high-aspect-ratio structuring. We indicate how nanoscale can be achieved following a cavitation scenario under strong gradients. Subsequently we present photonic systems where hybrid micro/nanoscale features can develop advanced optical functionalities. We will show their capability to transport, manipulate and access electrical fields, either for Bragg sensing or for reconstruction spectral information in embedded laser-written in silica and chalcogenide glasses. Finally we indicate a range of applications, from telecom to astrophotonics.

W05,06-36 Material modification at Megabar pressures with ultrashort laser pulses

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Ultrafast laser pulses create microexplosions under extreme focusing in transparent materials. The pressure created by few nano to micro joules of light is enough to generate new materials phases in the compressed zone around a laser-created void in sapphire or silicon [1-3]. Reaching extreme pressures is of fundamental interest not only for the formation of new material phases, but also for the study of the Warm Dense Matter, reproducing the state of the cores of planets in table-top laboratory experiments.

Swift excitation of transparent dielectrics by ultrashort and highly intense laser pulse leads to ultra-fast re-structuring of the electronic landscape and generates many transient material states, which are continuously reshape in accord with the changing pulse intensity [4]. The excited material is transparent and conductive at the same time. The real part of permittivity of the excited material changes from positive to negative values with the increase of excitation, which affects strongly the interaction process during the laser pulse. When the incident field has a component along the permittivity gradient the amplitude of the field increases resonantly near the point of zero permittivity, which dramatically changes the interaction mode and increases absorption in a way that similar to the resonant absorption in plasma.

The resonant absorption might be especially significant for the Bessel beams interactions with transparent dielectrics [4] due to large length of the focus, the essentially oblique incidence of the beam and high intensity in the axial spike. Moreover, the electric field has a component along the zero permittivity surface. The ionised plasma state has maximum electron density, and thus – minimum absorption depth and maximum energy concentration, at the area where the real part of dielectric function has the most negative value, which is not necessarily is at the axis of the beam.

The new interaction provided by the Bessel beam is a novel approach to reach extreme conditions on macroscopic volumes. We believe this will open novel routes for applications and fundamental physics based on laser-matter interaction.

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W05,06-37 Femtosecond laser-driven shock compression of solids and its engineering applications

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Understanding the physics under shock compression has been an important subject over the past century. Many experimental results have revealed that the shock-compressed material initially behaves as a purely elastic medium, and finally results in plastic deformation. However, the details of the transition between these two states has not been fully understood. We directly observed transient structural dynamics of iron induced by shock wave using brilliant X-ray Free Electron Laser (XFEL) pulses with a duration less than 10 femtoseconds. We found that the shock at an early stage produces an elastic strain corresponding to a stress of 22 GPa. We suggest that the giant elasticity induces generation of dislocations causing a high density of lattice defects inside the material, and that the plastic deformation without dislocations occurs, which was theoretically predicted but has not been observed. Our findings elucidate mechanisms of ultrafast phenomena under extreme conditions driven by shock compression, and promote to emerge novel characteristics in matters.

W05,06-38 Effect of femtosecond laser pulse parameters on nanograting inscription in sodium-germanate glasses

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Femtosecond laser pulses are the powerful tool for precision three-dimensional mirco- and sub-micromodification of transparent dielectrics. One of the most interesting types of femtosecond laser-induced modification in glass is a self-assembled nanoperiodical stucture possessing uniaxial birefringence (so-called nanograting). The slow axis of birefringence in nanogratings is always perpendicular to the polarization of the writing laser beam whereas the provided retardance can be controlled by laser pulse parameters. Applications of nanogratings were suggested for many fields from optical data storage to photonic components and microfluidics. Most of studies of nanogratings were performed in fused silica and some silicate glasses. Recently, inscription of nanogratings in sodium germanate glasses was reported but only up to 5 mol.% of Na_2O [1]. In the present study we show that tuning laser enables formation of nanogratings in sodium germanate glasses in a much wider Na_2O content range up to more than 20 mol.%. Unlike in fused silica or vitreous GeO_2, the presence of a sharp pulse duration threshold below which nanogratings can’t be inscribed has been shown for sodium germanate glass. A minimal number of laser pulses inducing noticeable birefringence is demonstrated to increase exponentially with growth of Na_2O content in glass. Influence of pulse duration and energy is investigated for a set of sodium germanate glass with different Na_2O/GeO_2 ratio. Formation of nanogratings in germanate glasses with high content of sodium oxide can be accompanied by precipitation of nanocrystals inside and around the nanograting.

This work was financially supported by Mendeleev University of Chemical Technology of Russia (project 034-2018).

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W05,06-39 Efficient laser writing in glasses with a sub-nanosecond burst of ultra-short pulses

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Femtosecond laser direct writing (FLDW) of waveguides in dielectric glasses and crystals is well-recognized technique for manufacturing of compact laser sources, optical sensors, labs-on-a-chip and optical chips for quantum computing [1]. However a compaction of optical circuits and an increase in the number of elements on an optical chip are prevented by constraints on the refractive index contrast Δn between the core and the cladding of a waveguide. One of the main reasons for this is a restriction of the deposited energy density in a process of laser writing.

Recently we found that simultaneous actions of rarefaction and electronic excitation lead to enhanced negative refractive index change in the laser modified spots in silica glass and sapphire [4], wherein the required conditions were produced by a sub-nanosecond burst of femtosecond laser pulses. Here we report on FLDW of tracks and waveguides in $70TeO_2$-$22WO_3$-$8Bi_2O_3$ and the sodium-borosilicate (K8) glasses with a sub-nanosecond burst of femtosecond pulses with exponentially decaying amplitudes in each burst, and the separation interval between pulses in range of 100 - 250 ps. We found that the sub-nanosecond bursts produce tracks in tellurite glass with decreased track height (size in the direction of the writing beam) and increased refractive index change as opposite to a train of ordinary pulses. We consider that the reduced track height and the enhanced index change are due to better localization of the absorbed burst energy.

Only the first pulse peak intensity in our burst exceeds the ionization threshold, and absorption of the burst tail is due to transient electronic excitations initiated by the first pulse and developed in the time domain of the burst tail. This way the destructive Kerr self-focusing and the intensity clamping effect due to plasma reflection are suppressed. We found that effects dealing with burst writing are much more pronounced for tellurite glass than for sodium-borosilicate glass that we explain by different thermo-mechanical properties of these glasses.

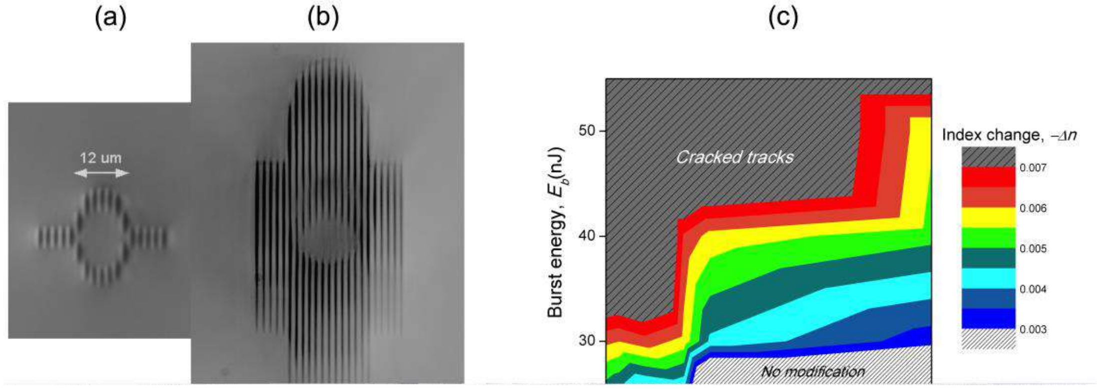

Fig. End views of the depressed cladding waveguides in $70TeO_2$-$22WO_3$-$8Bi_2O_3$ glass, inscribed with the bursts, Δn =-0.006 (a) and ordinary pulses, Δn =-0.002 (b). Mapping of Δn in tracks inscribed by the bursts with objective lens of NA=0.85 (c).

We consider that the new technique of FLDW paves the way for writing compact optical circuits consisted of depressed cladding waveguides.

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W05,06-40 Laser processing of glassy composite with plasmonic nanoparticles

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The development of methods for the synthesis of nanoparticles with required plasmon properties, as well as their organization into structures in glass materials, have become increasingly important during last decade. Such methods are in a grate demand for the fabrication of new optical surfaces, microanalytical integrated components [1], photovoltaics and optoelectronics [2], as well as for quantum computing systems [3]. However, most methods of laser synthesis of nanoparticles in composite materials do not provide any control possibilities over the optical properties of the composite in the localized space during the laser exposure. To enable such a control, here we propose to use laser irradiation of impregnated porous glass inducing nanoparticle growth and their self-organization [4].

In particular, we have investigated two mechanisms of plasmonic structures formation in composite nanopous materials with concentration of metal phase equal to 30-150 mol/cm^3. The process of photochemical reaction induced by CW laser was studied first in Ag-Cu doped sol-gel film. Another photothermally-activated process was studied in the bulk of photochromic porous glass. An anomalous transparency changes and metal cluster migration has been found after laser irradiation. The nanoparticle sizes have been found to be in the range of 3-100 nm.

To analyze experimental results, we used Bruggeman effective medium model in Bergman approximation together with Fresnel equations. The model takes into account optical properties of an ensemble of nanoparticles with size correction in the dielectric matrix with a finite thickness. The simulation is based on adapted effective medium theory and model of diffusion-controlled growth of plasmonic nanoparticles. This model reveals the photochemical and photothermal mechanisms of nanoparticles laser synthesis, describing their plasmon properties, changeable during the laser action. Such simulation allowed the development of a novel scientific basis for predicting and correcting of optical properties of composite materials with nanoparticles and nanostructures in the process of their laser synthesis.

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W07-2 Coupling laser spectroscopies: how LIBS-LIF-Raman can improve cultural heritage characterization

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The IPERION-CH European Framework support the creation of new mobile instrumentations and the C2RMF is involved in the development of Laser-Induced Breakdown Spectroscopy-Laser-Induced Fluorescence-Raman Spectroscopy (LIBS-LIF-Raman) portable instrumentation. As a nondestructive analysis method, LIF and Raman are generally implemented in continuous mode. But the pulsed laser is also recommended in order to improve the Raman signal to fluorescence background ratio and to give the possibility to work in ambient light.

This three laser-based spectroscopic techniques are combining in order to provide a complementary elemental and molecular analytical information from the same analysis point at one time. As a result, laser sources, appropriate optics and detection modules have to be integrated on a mobile platform capable of supporting conservation campaigns when extensive measurements and on-site decision-making are needed. LIBS diagnostic is a time resolved spectroscopy, fit to qualitative and quantitative analysis for all elements from the periodic table. Therefore, it provides the possibility to use only one laser source to carry out the analysis of these three spectroscopic techniques.

We will present the results obtain with different wavelength and the incidence that induce in the result on different material.

W07-3 Laser-induced breakdown spectroscopy in cultural heritage: depth-resolved analysis of layered painting samples

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Including scientific analytical techniques in the investigation of the objects of the cultural heritage helps provide key information, e. g. on the material composition, the process of their production or their stratigraphy. That can lead to a better authentication of the artworks and to the determination or estimation of their age and provenance. Considering the historical value of the works of art, the least destructive approach possible is always searched for. Laser-Induced Breakdown Spectroscopy (LIBS) enables the analysis of solid samples without the need of previous sample preparation or extensive sampling. Moreover, a good spatial resolution of the technique enables a depth-resolved analysis of layered materials. Here we present the outcomes on the study of the possibility of distinguishing individual paint layers of a model painting samples on a wooden support, based on the behaviour of the characteristic elements for each layer in the depth profiles acquired by LIBS. The detailed examination of the depth and the shape of the ablation craters is also shown. To obtain the depth profiles, 30 pulses were applied into one point of the sample surface, using a modified New Wave UP-

266 MACRO ablation system equipped with the TRIAX 320 Czerny-Turner monochromator and the PI max 3 iCCD detector. The non-invasive X-ray fluorescence spectrometry (XRF), frequently used in the analysis of paintings, was also involved in the determination of the chemical composition as a complementary technique to LIBS, using a handheld Delta Premium spectrometer.

W07-4 Laser cleaning of golden embroidery of the Peter the Great small throne hall at the State Hermitage Museum

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The Peter the Great (or Small Throne) Hall was created in the late Classicism style by the architect Auguste de Montferrand in 1833. This Hall is dedicated to the memory of Peter the Great.

It is the extra luxurious decoration of the Peter the Great Hall that attracts particular attention. All across the Hall, on the walls covered with red Lyons velvet, on the gilded moulding, and in the vaults painting, we can see Russian Empire emblems, crowns, and wreaths of glory. By the start of restoration works, the velvet, the woven eagles and the sewing works were covered with a thick layer of organic pollution, furnace black, and silver sulfides. The embroidery had traces of numerous restorations. Most of the velvet fabric was found without pile. The silk velvet base was very fragile with a lot of cuttings; metal threads of sewing and eagles strongly oxidized and turned black. The sewing works had many damages, the threads and the sequins wore out. The recent restoration of the Peter the Great Hall started in 2012 and was carried out by the Department of Scientific Restoration and Conservation of the State Hermitage. The laboratory for the scientific restoration of precious metals developed a technique for laser cleaning of gold-embroidery decor, lace, cords, laces, beads, and finish nails. Using the laser plant, tin and copper iron oxides were removed without damage. The organic layers that were impossible to clean with the traditional chemical reagents were evaporated. The laser plant allowed to cleaning the pollution without damaging the metal and the fabric base. All panels were dismantled from the walls; the eagles and the gold embroidery parts were removed from the old velvet and cleaned. After removing the dirt and old restoration glues, the gilded decor was transferred to a new velvet.

The silver decorative items of the Hall such as wall lamps, floor lamps, candelabra, and tables were restored. The experts of the laboratory for scientific restoration of precious metals made 6 lost gilded curtain holders.

When the restoration was completed, the opening ceremony of Peter the Great Hall of the Winter Palace was held on December 9, 2015, during the Hermitage Days.

W07-5 Laser cleaning of typographical anilox shafts from pigments: from idea to serial production

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The Lazer company is engaged in laser cleaning of printing cylinders from the remains of printing ink. The company was founded in 2010 as a result of the development of a graduation project of the University of Printing on the basis of the Department of Laser Technologies at ITMO University. The idea, the ability to turn it into metal, and the capabilities of the LT department made it possible to make a really working prototype of the equipment, and after that serial laser machines for cleaning the LaserEcoClean series.

s. on the shaft, and as a result, allow the shaft to be cleaned as often as necessary to ensure high print quality. High accuracy and performance of the equipment pays for the initial costs of its acquisition. The global market for equipment for laser cleaning of anilox rolls is 200-300 units, at the moment the

Company has sold 20 units of such equipment.

The created equipment and the developed cleaning process are notable for the detailed study of all process parameters: laser power, beam scanning speed and shaft rotation speed, gas blowing and suction directions, etc., which allowed toincrease a spray transfer up to 40% without mechanical and thermal effects on the shaft , and as a result, it allows for shaft cleaning as often as necessary to ensure high print quality. High accuracy and performance of the equipment pays for the initial costs of its acquisition. The global market for equipment for laser cleaning of anilox rolls is 200-300 units, at the moment the Company has sold 20 units of such equipment.

W07-7 Laser cleaning of archaeologically corroded iron

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A lot of museums around the world have in their storage number of items containing inlays with precious metals. Such objects are often of archaeological origin. Restoration of archaeological objects from metals is a complex and multistep work, including the object’s analysis, strengthening its surface and internal structure, stabilization of corrosion processes, conservation, reconstruction of fragments, and replenishment of losses. Cleaning from corrosive layers plays a significant role due to its possibility to remove pollutions, to reveal the shape of the object being restored and its technological and decorative features. Currently, there are many methods of cleaning metal objects, among which are mechanical, chemical, electrochemical ones and so on.

Mechanical cleaning methods are based on the use of brushes, scalpels, scrapers, hand-piece drills, and other tools. The mechanism of used chemicals is based on the principle of chemical conversion and dissolution of corrosion products for their subsequent removal. Electro-chemical cleaning is a rather gentle technology that allows cleaning the object from corrosive layers, however, it can take a long time, and cannot be used for items containing inlays.

Our paper presents the results of several years of research on the possibility of using a laser for the controlled layer-by-layer removal of iron corrosion from gilded silver. Lasers generating radiation at wavelengths of 355, 532, 1064 nm, 2.97, 10.6 μm were tested. A comparison of pulse durations of 100 μs, 100, 8, 6 ns, 75 px, 100 fs was made. Rust samples were irradiated in air, in an argon atmosphere, in water, in ethanol, in engine oil, in glycerine. The performed analysis allow us recommending the parameters of laser radiation, which can provide the process of layer-by-layer ablation of archaeological rust without structural modification of the underlying layers and their darkening.

W07-8 Characterization of CH surfaces by different laser techniques

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Nowadays scientific study of Cultural Heritage accompanies most of the time historical artistic evaluation and an assessment of the conservation state by humanistic experts and restorers. The need to characterize archaeological and artistic surfaces by chemical and physical methods is not more questioned. Several laboratory methods with high sensitivity are well established (ICP-MS, FTIR,…), and many methods for in situ rough characterization of large surface are widely diffused (thermovision, UV photography,…), in addition to instrumentation for punctual analysis to be applied also in field (XRF, colorimetry, …). However, the request for systems that can provide rapid detailed characterization on large surface in any storage conditions is still a hot topic. This is combined with the ever-increasing demand for digital material for documentation, fruition and study. Laser-based systems, and in particular LIF (Laser Induced Fluorescence), LIBS (Laser Induced Breakdown Spectroscopy) and Raman spectroscopy, due to the characteristics of these sources and the detectors to which they can be coupled, respond well to these needs. The TECFIS-DIM (Diagnostic and Metrology) Laboratory of the ENEA center of Frascati (Rome, Italy) in the last decade has put an effort to develop more and more compact and efficient laser systems for in situ material characterization on cultural heritage surfaces. Results from measurement campaigns carried out with LIF, LIBS and Raman applied alone or in combination among them in the past three years will be here presented. In fact, during the regional projects COBRA (Conservation of Cultural Heritage through Radiation and Enabling Technologies) and ADAMO (Technologies for analysis, diagnostics and monitoring for the preservation and restoration of cultural heritage) such instruments have been applied to the study of several completely different classes of artworks, and then materials, such as marbles, painted wood, mural painting.

W07-9 Multi-analytical investigation of the encapsulated XIIIth century French Legendarium F-403 from the Library of Russian Academy of Science

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The multi-analytical study of the XIII - XIV century French medieval Legendarium manuscript is presented. In the beginning of the XX century in Petrograd-Leningrad the manuscript was seriously damaged. The parchment has become moldy and rotten because it was soaked in water for unknown reasons, and then kept in a closed safe. The sheets of parchment after drying stuck together in integral block. In the 1960-s, despite the depressing state of the parchment “brick”, it was decided to start a restoration work on the separation of glued sheets. Now the manuscript consists of 214 sheets encapsulated in polyethylene terephthalate (PET) conservation envelopes. The damaged manuscript sheets are in different states, some illustrations and text parts are in rather bad condition. At the same time, the blurred traces of pigments and inks, which were used to write letters and make illustrations, were preserved on the parchment. Works carried out with this unique monument, include research using the optical microscopy (OM), micro-Raman spectroscopy, shifted- excitation Raman difference spectroscopy (SERDS) technique and Scanning Electron Microscopy (SEM) with EDX analysis. Moreover, the research focused on micro-particles, which were found inside the envelopes and were collected by restorers. The conducted study allow to judge about the composition of the ink and pigments which were used to create the manuscript. Non-destructive research opens up perspectives for developing the new ways for the possible reconstruction of the lost text elements and codex images.

W07-10 Comparative Study of two Frescoes from Campana Collection of the State Hermitage Museum

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The collection of Giampietro Campana, Marchese di Cavelli are of the utmost importance to the Hermitage. Among the items purchased for a collection of the museum there were eight frescoes, which were created for the villa on the Palatine Hill in circa 1520.

The aim of this study was to compare the execution technique and states of preservation of four Palatine frescoes before their restoration. “Venus Tying a Sandal” and “Venus and Amur” were investigated among them.

Non-destructive and non-invasive techniques were applied: X-ray radiography, UV luminescence, IR reflectography, and XRF analysis. Multi-analytical study also included OM, FTIR, Raman spectroscopy, SEM-EDX and XRD methods.

The frescoes are characterized by numerous losses of painting layers and restoration interventions. The state of preservation of the painting surface was very heterogeneous. The obtained data allows us to distinguish between original and conservation materials. Unsurprisingly, various organic materials, including proteins, polysaccharides, lipids (wax, oil), and acrylic polymers were found in the protective layers. A number of conservation materials containing calcite mixed with gypsum, as well as kaolin, zinc white, barium sulfate, lead white, and Prussian blue were also identified. The artist's materials included calcite, gypsum, smalt, azurite, ochre (celadonite), malachite, cinnabar, and Naples yellow.

FTIR analysis revealed the presence of calcium oxalates with the characteristic absorbance bands at around 1622, 1320 and 779 cm^{-1}. In addition, atacamite was identified in the paint green-bluish layers.

The information about the painting stratigraphy, chemical composition, and stylistic background along with state of preservation, demonstrated the necessity of a diagnostic investigation before a restoration work.

W08-1 Some approaches for a transition instability suppression in pulsed fiber lasers

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Material processing is most popular application for modern lasers. Some applications for material processing requires high speed and quality which means a high speed response and accuracy for laser to applied modulation. There are some physical limitations in standard laser modulation using direct pump modulation. A great flexibility in fiber laser configurations provides a few realistic approaches to create pulsed source with suppressed transition instabilities. Some of these configurations will be described in terms of (dis)advantages for practical usage in modern pulsed fiber lasers.

W08-6 Interaction of pulsed radiation with non-ferrous metals during laser shock treatment

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The article describes the method of impact laser processing to reduce tensile residual stresses in welded joints of aluminum alloys. The method consists in the action of powerful short pulses of laser radiation on the surface of the material. The paper uses a solid-state laser "Solar LQ 829" with a wavelength of 532 nm. To transfer the pulse to the material, an absorbing coating is applied to the surface to be treated, which is necessary to increase the efficiency of ablation and to protect the surface from melting. The choice of coating material depends on the substrate material, density and sound velocity, which can create an acoustic impedance effect. A transparent medium with a high value of acoustic impedance, necessary for the re-direction of the shock wave energy, must be above the absorbing coating. The conditions under which laser ablation occurs lead to a high degree of directivity of the action, which is the main cause of a greater depth of the rivet

The analysis and experiments on the choice of absorbing materials and the restraining medium are carried out. It was found that the best results, based on the measurement of micro-hardness, are achieved when used as an absorbing material of aluminum foil glued to the treated surface with a flexible adhesive tape, and water as a deterrent. Selected equipment and cutting-we processing. The impact laser treatment of welded joints of aluminum alloy AMg6, which allowed to change the tensile stresses arising after welding, compressive with a value of 3-4 times greater than before processing, which favorably affects the mechanical properties.

W08-7 Laser-filament glass cutting

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The article describes the method of impact laser processing to reduce tensile residual stresses in welded joints of aluminum alloys. The method consists in the action of powerful short pulses of laser radiation on the surface of the material. The paper uses a solid-state laser "Solar LQ 829" with a wavelength of 532 nm. To transfer the pulse to the material, an absorbing coating is applied to the surface to be treated, which is necessary to increase the efficiency of ablation and to protect the surface from melting. The choice of coating material depends on the substrate material, density and sound velocity, which can create an acoustic impedance effect. A transparent medium with a high value of acoustic impedance, necessary for the re-direction of the shock wave energy, must be above the absorbing coating. The conditions under which laser ablation occurs lead to a high degree of directivity of the action, which is the main cause of a greater depth of the rivet

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W08-10 Technology of CFRP and GFRP precision cutting by a ytterbium fiber laser

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One of the modern industries development directions is the widespread introduction to the products design carbon and glass fiber reinforced plastics (CFRP and GFRP). In such materials, carbon and glass fibers are used as reinforcing fillers, and thermosetting and thermoplastic polymers are used as the bonding matrix. At the final stage of the CFRP and GFRP parts manufacture becomes necessary dimensional processing to form therein technological windows, narrow grooves, holes for different purposes and other items [1]. Traditional machining methods: mechanical and water-jet cutting ensure acceptable quality and speed of processing, but have significant drawbacks: rapid wear of an expensive cutting tool, high cost of consumables, material delamination due to vibration and shock loads, restrictions on the cutting contour. Laser cutting is an alternative to traditional methods of processing and is characterized by a number of significant advantages: no tool wear, high accuracy and productivity and reproducibility of processing without restrictions on the complexity of the contour, the shape and size of the part. At the same time, the main drawback that limits the use of laser technology in industry is the formation of a heat-affected zone with irreversible thermal destruction of the polymer matrix [2].

Experimental setups based on pulsed nanosecond and cw ytterbium fiber lasers with an emission wavelength 1,06 μm and 2D scanner with focusing F-Theta lens were developed for experimental evaluation of laser cutting of CFRP and GFRP with a thickness from 1 to 8 mm. The main criteria for evaluating the parts quality are: structure of internal defects (heat-affected zone, delamination), defects of the kerf geometry (taper and surface roughness) and processing cycle time. Studies have shown that when the recommended technological parameters and the processing algorithm are established, the heat-affected zone does not exceed 50 microns, the taper of the cut channel wall is less than 100 microns. Mechanical tests for strength of samples in accordance with the GOST 33375-2015 "Polymer composites. The test method for tensile strength of specimens with an open hole" and GOST 33344-2015 "Pultrusion structural profiles of polymer composites" showed that laser machining provides a result comparable to cutting with diamond tools and is higher than with water-jet cutting. The obtained results indicate the prospects of use multi-kilowatt range (in pulsed or continuous mode) ytterbium fiber lasers for efficient CFRP and GFRP cutting.

[1] Mihailin U.A. Fiber polymer composite materials in the technique. SPb., Scientific basis and technology, 2015, 720 p.

[2] Jamal Y. Sheikh-Ahmad Machining of Polymer Composites. Berlin, Springer, 2009, 315 p.

PS1-LT-1 Femtosecond laser annealing of layered structures based on germanium and silicon

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Today detection of optical infrared radiation and its transformation to electricity relate to application of thin-film structures based on amorphous germanium (a-Ge) and polymorphous germanium/silicon structures. One of the approaches to modify their properties is the pulsed laser annealing [1]. As a result, nanocrystalline areas are formed in the thin films and effective light absorbance and charge transport are revealed themselves. The use of femtosecond laser pulses is more effective in comparison with nano- and picosecond duration due to better dissipation of the absorbed laser radiation by semiconductor surfaces during treatment.

In our work an a-Ge thin film with thickness 200 nm and multi-layered film comprising 40 alternating amorphous germanium / amorphous silicon (a-Ge/a-Si) layers with thicknesses of layers 10 and 5 nm, respectively, were studied. Pulsed laser annealing was carried by a $Cr:Mg_2SiO_4$ laser (1250 nm, 0.5 mJ, 125 fs, 10 Hz). Structural properties were investigated by methods of scanning electron microscopy (SEM) and Raman spectroscopy at the excitation wavelength 1064 nm.

SEM-image analysis revealed that islet films are formed as a result of the a-Ge thin films laser-induced melting. On the other hand, in the case of the multi-layered sample a-Ge/a-Si ripples formation on the irradiated areas were observed. Such of ripples are formed due to surface plasmon-polariton generation and consequent interference with incident radiation [2].

The Raman spectroscopy of the initial samples showed amorphous structure of the germanium layers (line 280 cm^{-1}). The appearance of the line 300 cm^{-1}in the spectra demonstrates crystallization of the a-Ge after laser irradiation. Additionally, in case of multi-layered structure study the Ge-Si bond (line 380 cm^{-1}) was observed. It can be explained by diffusion of germanium atoms to silicon layer.

Thus, the structures for effective application in optoelectronics based on a-Ge with crystalline inclusions can be fabricated using the pulsed laser annealing technique.

O. Salihoglu, U. Kürüm, H. Yaglioglu et al. // J. Appl. Phys. 2011 V. 109, № 12, P. 123108-1 – 123108-9.

D.V. Shuleiko, F.V. Potemkin, I.A. Romanov et al. // Laser Phys. Lett. 2018 V. 15, P. 056001-1 - 056001-8.

PS1-LT-2 Study of changes in properties of submicrocrystalline titanium as a result of femtosecond laser treatment

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The report presents an overview of the results of the author's original research with colleagues on the effect of femtosecond laser irradiation on the wettability characteristics of the surface and mechanical properties of thin plates (0.2 and 0.5 mm thick) of submicrocrystalline technically pure titanium VT1-0 in tensile and cyclic loading tests.

The structure of the surface and near-surface layers of the material was investigated by scanning electron microscopy. It is shown that as a result of laser treatment a micro - and nanoscale quasi-periodic structure is formed on the surface. Due to ablative processes, grooves with a width of about 300 nm and an average distance between them of 100 nm parallel to the scanning direction are formed.

Established that associated with the laser modification changes the surface and subsurface layers practically does not effect on the ultimate strength and yield strength of the studied material in tests under conditions of active quasi-static stretching, however, the treatment leads to some increase in the strain values to failure. Thus, the material is characterized by increased plasticity. In addition, the samples after femtosecond laser treatment, on average, withstand a greater number of cycles to failure than in the initial state without treatment, which is reflected in an increase in the value of the conditional limit of endurance (based on tests 10^6 cycles). Carrying out these tests allows to predict the behavior and reliability of finished products made of this material during operation.

The effect of femtosecond laser treatment on the wettability characteristics of the surface depending on the degree of its purification is analyzed. It is shown that as a result of plasma cleaning of the surface, the superhydrophilic state observed immediately after the treatment is restored.

The advantages of surface treatment of titanium alloys for medical application by femtosecond laser in comparison with other methods, in particular with the formation of bioactive and bioinert coatings by microarc oxidation, are discussed.

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PS1-LT-3 Particle characterization using forward elastic light scattering

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This work shows the design of an instrument to measure the forward extinction and light scattering for a particle monolayer by using a beam stop, which acts as spatial filter. Its importance in the science field is because, it can be used as a non-invasive optical tool for biological samples characterization, which includes cancer detection, changes in the red blood cells morphology or lysis process, characterize morphological parameters in yeast cells. The larger the particle's size parameter, the scattering pattern direction is nearer to the forward direction. Thus, this presents a challenge because of the difficulty to distinguish between the scattering and the extinction light due to the sample and the un-scattered incident light beam. An optical instrument this describes, which applies a technique to measure the near forward light scattered by biological cells. By taking advantage of the Fourier properties of a lens and the spatial filtering in the Fourier plane, and image-based cells sizing on the scattered light.

Our device, consist of a collimated green LED illuminating the sample. The forward scattering light and the un-scattered light portion of the incident beam is collected by lens the first lens, which is placed at the focal distance. The lens collects the far-field pattern over an angular range in the polar θ and azimuthal φ angles, respectively. The first beam splitter divides the light signal, where the un-scattered portion of the incident beam is focused in the back focal plane on an opaque black spot, with a 0.4 mm diameter. This spot acts as a spatial filter in the Fourier plane, the un-scattered beam is absorbed by this filter, in the forward direction the collimated scattering light is transmitted. While the second splitted signal is filtered by an adjustable iris diaphragm, this iris diaphragm lets the extinction light being transmitted.

PS1-LT-4 Second harmonic generation in magneto-plasmonic metasurfaces

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Nowadays, hyperbolic plasmonics attracts researchers' attention by its exciting optical properties [1-6]. Hyperbolic metasurfaces (HMSs) support highly localized low-loss surface plasmon-polaritons (SPPs), providing drastic increase of the light-matter interactions near the surface. Moreover, HMSs allow the very effective manipulation by SPPs varying from routing them towards specific directions within the sheet, dispersion-free propagation (canalization), and to the negative refraction.

Usually HMSs are realized by deeply subwavelength grating of plasmonic (metallic) surface [1-6]. For non-linear magneto-plasmonics, metal-ferromagnet multilayer structures have a great potential [7]. Hyperbolic magneto-plasmonic metasurface may be constructed by combination of these two ideas, i.e. by subwavelength grating of magneto-plasmonic multilayers. Here, depending on the position of ferromagnet and grating depth three variants are possible (see Figure 1 for details): noble metal covered by ferromagnetic metasurface (similar structure has been investigated recently [8], but for non-hyperbolic regime), hybrid metal-ferromagnet structure covered by noble metal based metasurface, and noble metal covered by hybrid metal-ferromagnet metasurface (similar structures have been investigated in [9], but not for hyperbolic regime as well).

In order to investigate SHG in hyperbolic magneto-plasmonic MSs, theoretical model based on effective medium approximation has been performed. In contrast to hybrid metal-ferromagnet plasmonic structure, hyperbolic magneto-plasmonic MSs will have a highly anisotropic dielectric permittivity tensor. This leads to significantly anisotropic SHG signal (with respect to SPPs propagation direction).

In directions where SPPs cannot propagate, SHG signal will have the similar behavior as for the system without the metasurface, while in directions where canalization of SPPs observed SHG signal significantly increase.

In contrast to usual hybrid metal-ferromagnet multilayers, proposed structure will have an additional surfaces for SHG signal caused by grating. For hybrid metal-ferromagnet multilayers non-magnetic SHG is caused by z-component of non-linear polarization Pz at all the interfaces (z-axis is perpendicular to the interfaces, x- and y- axis lies in-plane), while magnetic SHG is caused by Px. For noble metal covered by ferromagnetic metasurface and for noble metal covered by hybrid metal-ferromagnet metasurface an additional z-component of non-linear polarization will be induced by interfaces between magnetic metal and air in grating. In turn, for hybrid metal-ferromagnet structure covered by noble metal based metasurface, and for noble metal covered by hybrid metal-ferromagnet metasurface an additional x-component of non-linear polarization will be induced by interfaces between non-magnetic metal and air in grating.

The work was financially supported in part by RFBR (16-37-00023, 16-07-00751, 16-29-14045, 17-57-150001), Act 211 Government of the Russian Federation (contract № 02.A03.21.0011).

PS1-LT-5 The development of picosecond terawatts CO_2 laser and its applications in particle acceleration

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Picosecond terawatts CO_2 laser is an important potential source for the development of ultra-short continuous x-ray source, high-energy particle accelerator, high-energy laser weapons, inertial confinement fusion, and the field of ultra-short Pulse Laser industrial application and laser medical chemotherapy, for it can produce low divergence, high quality and high speed proton bunch in the interaction with plasma. The current picosecond terawatt CO_2 laser system has technical problems of expensive isotope, high pressure, and large volume, making its manufacture difficult. In order to increase the CO_2 laser output power to 100TW and above, the architecture of the picosecond CO_2 MOPA system must be considered. The key issue is how to use amplification technology in the first stage of amplification to amplify nJ-level 10um pulses to 1-10mJ. Solid-state seed light will not only greatly reduce the size of the front end of the CO_2 MOPA system, but more importantly it eliminates the pulse broadening when seed light is first amplified. This is the key to increasing the seed light intensity level and entering the final level of amplification, and is expected to produce very high peak power at the end. Another key to the development of picosecond terawatt CO_2 lasers is how to solve the problem of gain spectrum discontinuity in CO_2 lasers. This article focus on researching the method to acquire a smooth, continuous gain spectrum in ultra-short CO_2 laser, meanwhile proposes a method to solve the temporal splitting of amplified pulse and improve its contrast, that will be meaningful for the development of Ps Tw CO_2 laser system, and has board application prospects in strong-field physics, laser-plasma accelerator for electrons/protons, X-FEL, IFEL and other fields.

PS1-LT-6 Packaging and adjustment of fiber coupled laser diode module

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Laser diode modules (LDM) are widely used in a variety of industries and scientific research. The most important task is increasing the devices output power by individual laser diodes combining radiation from several units to several tens.

The results of fiber coupled laser diode module packaging are presented. The optical system includes two cylindrical lenses for collimation of each laser beams, high reflecting mirrors and aspherical lens for fiber coupling. A mounting base and a drop housing are made of copper to provide better heat dissipation. The optical system allow entering the radiation from three laser diodes into the multimode optical fiber with core diameter 400 microns and numerical aperture 0.22 (Fig. 1a). Three steps of laser diode beam shaping as collimation, spatial combining and focusing are realized.

The report describes equipment and stand configuration for LDM packaging and the optical components adjustment sequence. The experimental stand developed design serves for the optical micro-components gripping, their precise alignment and mounted with a UV-curable adhesive. The laser beams divergence control, as well as their optical axes parallelism is carried out using a beam profile meter. The paper presents a losses estimate in the optical system after each laser beam conversion stage and the overall efficiency of the system.

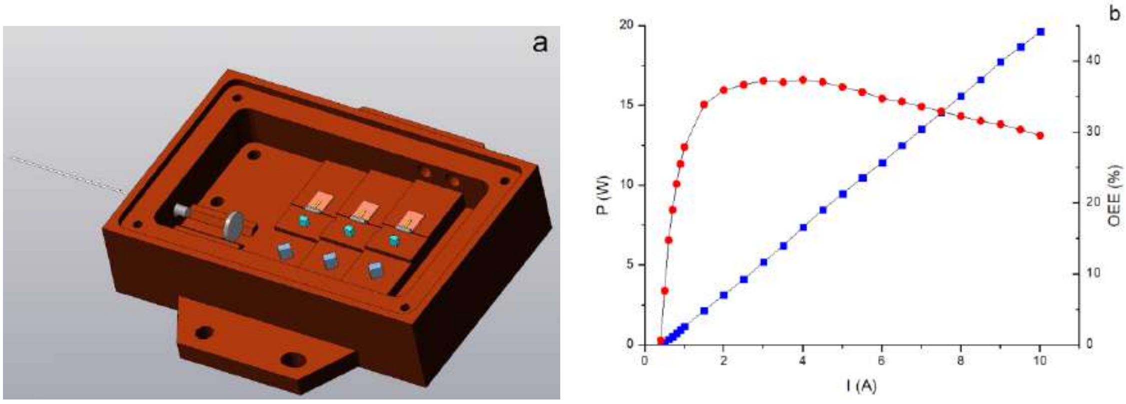

Figure 1 – a) LDM computer model, b – LDM prototype PI characteristic and efficiency factor for liquid cooled single laser diodes package

The maximum output optical power is 19.65 W at the optical fiber output, which corresponds around 30% of LDM optical to electricity efficiency - OEE (Fig. 1b). The radiation input efficiency into the optical fiber is more than 80% compared to the individual laser diodes output optical power at the same current values.

PS1-LMI-1 The change in fluorescence of ZnO films doped with detonation nanodiamonds under DNA action

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In the recent years, research related to the interaction of detonation nanodiamonds (DND) with biological structures has gained a great importance, since detonation ND of all carbon nanoparticles have the lowest toxicity and are used, for example, for the treatment of tumors and create biocompatible implants.

In the present work, ZnO films modified with DNA were obtained for the first time using the hydrothermal method. Their optical properties were investigated. Interesting was the study of these films interaction with extremely important for medicine, organic molecules such as DNA.

Therefore, the purpose of this work was to study the interaction of DNA with ZnO films doped with DND.

20 μl of DNA at a concentration of 10–10M by spincoating method were deposited to ZnO:DND plates (80%: 20%). The dopant concentrations were varied from 10% to 40% relative to ZnO.

Fluorescence spectra of samples were measured on a spectrofluorimeter (Shimadzu RF 5001). The obtained fluorescence spectra with and without DNA are shown in Figure 1.

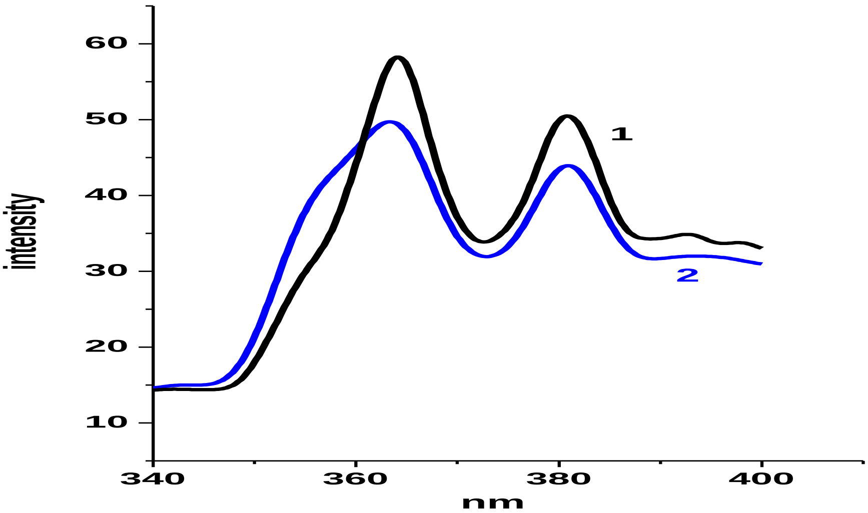

Fig.1. Fluorescence spectra: 1 - ZnO, doped DND in the ratio of 80%: 20% and 2 - ZnO, doped DND (80%: 20%) in the presence of DNA.

The presence of DNA on the surface of the film leads to the quenching of fluorescence by 25% and formation of a shoulder in the region of 355 nm. Fluorescence of DNA in the region of 355 nm apparently refers to the fluorescence of nucleotides, in particular, to guanine.

Thus, it was revealed that the presence DNA (in the amount of $0.2 * 10^{-11}$ mg) on the surface of ZnO films doped with detonation ND affects the optical properties of the material.

PS1-LMI-2 Conical beams in selective laser cladding

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Laser cladding process with powder or wire should be an outstanding performer in additive manufacturing Recently, conical laser beams began to be introduced into the laser wire cladding technology. However, the developed devices use a single conical beam, which does not provide optimal heating of the wire and surface and energy-consuming. In addition, the proposed optical systems are inefficient when using a powder.

For separated heating of the deposited material and surface new approach in selective laser cladding using conical laser beams has been elaborated. Initial round laser beam is divided into 2 circular beams with regulated distribution of the laser power throughout the circular beams. Circular beams are transformed to conical beams , which are focused separately on the surface and on the deposited material for heating. The laser energy delivery to powder stream is very efficient because a total uniform absorption of laser energy in the dense powder stream (10^4-10^5 1/cm^3).Optimal regimes of powder cladding under multipass scheme were determined. Under wire deposition the required power density for melt contact formation is significantly reduced , while increasing accuracy.

Coaxial laser wire cladding with conical beams has a lower dilution rate compared to other cladding processes with high travel speed and minimal heat input, maximizing the temperature of the wire, which is quickly melted off in the puddle.

The result is that the process can be operated at higher speeds resulting in thinner layers, with less heat input, and therefore, less impact dimensionally or metallurgically to a part. The optimal regimes of laser cladding can be achieved using new approach.

PS1-LMI-3 Selective laser melting of multi-material parts

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The use of multi-materials may be viewed as a technically challenging and economically favorable manufacturing method . There are machines for laser cladding, which can produce a 3D multi-material product, but the precision does not exceed 100 microns and the product requires significant improvement, such as milling.

The selective laser melting (SLM) process is well- suited to the incorporation of multiple powdered materials which makes it possible to obtain accuracy up to 10 microns

So far, at the present time there are no technical solutions to be implemented in the framework of the industrial production process of manufacturing multi-material objects by SLM.

New method and SLM machine project for 3D multi-material (MM) parts production has been elaborated , where standard recoating systems with roller or blade can be used.The main idea consists in using a narrow fraction of powders of various materials with different medium particle size and special algorithm of powder layer recoating. This not only makes possible three dimensional MM parts , but method enables to separate the overflow powders of a various materials for re-use. The main mechanisms of SLM machine have been elabotated and physically modelled. Removal of the unsintered powder at the process of the multi-material 3D-object production has been the object of much attention. The estimation shows that height of powder bead during the process of machanical removing a powder layers with thickness 20-100 μm at a distance 500 μm range up to 4-10 mm. Because of this a original combination of mechanical and vacuum cleaning has been elaborated. The cross-contamination effect has been studied experimentally. Not more then 0.1% cross-contamination are fixed.

The influence of main physical processes in melted powder layer , dissolution in liquid pool and shrinkage, on accuracy of the position of a contact surface between various material have been given adequate consideration.

PS1-LMI-4 Strain gauge based on Bragg fiber grating

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In this work, we tested a method for creating strain gauge sensors, the sensitive element of which is a fiber Bragg grating. The results of the obtained data are presented and the main dependences of the shift of the central wavelength of the fiber grating on the magnitude of the elongation are constructed. The possibility of using as a strain gauge of the Bragg fiber grating itself, as well as various designs of sensitive elements based on the Bragg structures, is demonstrated.

Current trends are leading to an increase in interest in the development of fiber-optic sensors (FOS) using fiber Bragg gratings (FBG) as a sensitive element in measuring physical quantities, such as pressure, temperature, deformation, etc.

A change in external influences on a material (temperature, mechanical stresses, pressure, etc.) leads to a change in its geometrical parameters, which is also true for an optical fiber. In addition, a change in the geometric characteristics of the optical fiber leads to a change in its refractive index, as well as a change in the parameters recorded in it by the FBG, in particular their period. Analyzing these changes, one can judge the nature of external influences on the FBG.

To calculate the strain and mechanical stress arising in the test prototype of the strain gauge, a simulation was performed, which resulted in a graph of the dependence of its relative elongation versus the applied load. Experimental results obtained when testing the tensiometric sensor layout showed that the parasitic effect of hysteresis present in the resulting signal. In accordance with this, methods have been proposed to eliminate this influence.

To improve the characteristics of the resulting signal, changes were made to the method of connecting the sensitive element and the test layout, and it was also proposed to test the FBG with other lengths of these structures.

The paper presents the results of testing the FBG, glued directly to the beam of uniform strength, as well as the test of the sensitive element based on the FBG, mounted on the beam of uniform strength by means of bolted and welded connections. The obtained data showed the possibility of using as a strain gauge of the Bragg fiber grating itself, as well as various designs of FBG-based sensing elements.

PS1-LMI-5 Inscription and investigation of the spectral characteristics of tilted fiber Bragg gratings

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This paper is devoted to the study of the process of creating tilted fiber Bragg gratings. The presented method allows the selection of parameters of the recorded structures (the angle of inclination of the strokes, the period, the reflection coefficient, etc.) in a wide range of values. In addition, the paper presents an inscription method of superimposed tilted fiber Bragg gratings, which allows to increase their reflective efficiency.

Tilted fiber Bragg grating (TFBG) is a structure whose strokes have an angle of inclination relative to the cross section of the optical fiber other than 0 °. This feature leads to partial coupling of radiation with resonant wavelengths by such elements from the core of the fiber to its cladding [1]. In the reflection spectrum of such structures (Figure 1a), as in the case of standard gratings, there is one maximum. In the transmission spectrum (Fig. 1b), a number of additional minima are observed in the short-wave region, which are caused by coupling of radiation into the cladding.

PS1-LMI-6 Picosecond Nd:YAG lasers in laser-induced μ-plasma (LIμP) applications

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Nowadays a lot of methods of laser glass micromachining (direct and indirect) are widely developed. The combined technologies based on strong absorption of laser radiation with different solution or metals contacting with the back side of the glass plate obtain an extensive use for microstructure formation on glass surface [1].

In our method plasma plume is limited in size and energy density by focused laser beam. Plasma extension is limited by close contact between glass plate and highly absorbing target, so it's in a confinement mode. High efficiency of laser energy conversion (~95 %) to microplasma is achieved by utilization of "blackbody" target, which contains the carbon compounds and obtains low reflectivity and small thermal losses [2].

The method of laser-induced microplasma (LIμP) described here is effective tool for high precision processing of surface of transparent material. It allows to fabricate phase gratings , microlens arrays and random phase plates with the relief depth up to 5 μm in case of usage ns-pulse duration laser source [3, 4].

In this work a new laser source is applied for LIμP method. It helps to minimize plasma plume volume and achieve high precision and quality of fabricated microrelief on glass surface. Thus, high stable and robust Nd:YAG laser with pulse duration ~ 30 - 100 ps and repetition rate up to 1 kHz was used [5]. In order to use the picosecond pulses in the LIμP method, on the one hand, enough energy is needed to remove a certain layer of material and form a surface relief, and on the other hand, strong non-linear absorption in the glass plate should be avoided.

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PS1-LMI-7 Air flow motion rate measuring method, based on fiber Bragg gratings

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In this paper, the possibilities of fiber-optic anemometry based on the "hot wire" technique were studied. Various methods for laser light coupling from an optical fiber core to its cladding with the purpose of the silver layer spot heating were presented and the efficiencies of the studied methods were compared. The analysis of the effect of air flows with different speeds on the spectral characteristics of fiber diffraction structures was carried out.

To date, fiber Bragg gratings (FBGs) are used in various industries, and one of the most important of these areas are fiber-optic sensor devices. The principle of operation of such equipment is the use of diffraction structures as sensitive elements, the spectral characteristics of which depend on many factors; these structures can be adapted to measure the necessary physical quantities (temperature, pressure, humidity, deformation, etc.).

One of the possible applications of Bragg gratings is to measure the flow speed (of various liquids and gases), which is necessary in such areas as the chemical and aerospace industries, energy, meteorology, and so on. Previously, a heated metal wire was used as a sensing element, which was cooled by air flow, as a result of which the temperature of the wire and its final resistance changed. The disadvantage of this method was the oxidation of metals, which can be avoided by replacing the sensitive element with optical fiber. In addition, the all-fiber version, which does not require additional power supply, allows the use of fiber-optic sensors on Bragg gratings in extreme conditions, eliminating the interference of electromagnetic and radiation effects.

Fiber optic anemometer includes the area of the laser light coupling from the fiber core into its cladding, covered with a substance with a high thermal conductivity, in order to heat this fiber section. In the same region, FBG1 is formed, whose heating leads to a red-shift of the Bragg resonance wavelength. When an air flow is created, the heated region is cooled, as a result of which the Bragg wavelength shifts to the blue part of the spectrum, while its shift is directly proportional to the flow speed. At a certain distance from FBG1, FBG2 is formed, which has a different Bragg wavelength and registers only the flow temperature. Measurement of the Bragg wavelength difference between the first and second FBGs and the subsequent processing of the data obtained will make it possible to determine the speed of the air flow and its temperature.

In this paper, the existing methods for the implementation of sensitive elements of fiber-optic anemometers were investigated. The results of the study of various methods of laser light coupling from an optical fiber core to its cladding with the purpose of the silver layer spot heating: changing the geometry of the fiber (offset, increase/decrease its diameter), tilted FBG inscription, the use of Bragg gratings of type II were shown. The reflection spectra of FBGs were presented for various values of the flow motion rates.

The dependence of the wavelength shift of the Bragg resonance caused by the air flow motion on its speed demonstrates the possibility of using this structure as a sensitive element of a fiber-optic anemometer.

PS1-LMI-8 Photoinduced nonradiative relaxation due to the vibronic coupling in two-level dissipative systems

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Interaction of matter with an intense laser field is characterized by the appearance of the Rabi oscillations of the electron density. In the case of the condense matter systems, the oscillations of the electron density give rise to the rearrangement of the electron and vibrational energy spectra. For instance, the Rabi oscillations lead to the periodic displacement of equilibrium positions of reservoir oscillators, which means the appearance of an additional mode in the vibrational spectrum. If the conditions for the dynamical Stark effect are satisfied, electron levels of the system become split with the energy gaps, which are comparable with the energies of vibrational modes. Therefore, the electron and vibrational motions in a dissipative system are mixed, and the nonadiabaticity of the coupling must be taken into account. It is should be stressed that such coupling is occurred in an electron-photon-phonon system and allows to control the energy transference between subsystems by changing the parameters of a laser field. Thus, the system may be heated or cooled by the use of the appropriate frequency and intensity of the laser pulse. A key role in these processes plays the nonradiative relaxation between the Stark split sublevels of the electron subsystem, which provides the absorption of the vibrational energy. In the present work, the quantum mechanical calculations are performed for nonradiative relaxation due to the vibronic interaction in the two-level dissipative system. The rates of the nonradiative relaxation are comparable with the acoustic phonon frequencies, while the density of states involved in the process is comparable with the density of states of optical phonon modes. The results of the calculations may be useful for different quantum dot applications.

PS1-LMI-9 Electrostatic instability of dielectrics lattice under intensive laser action

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In a previous paper [1] it was noted that the intrinsic optical breakdown of transparent dielectrics, which was studied under conditions that exclude self-focusing of radiation [2,3], is characterized by a number of unusual features that cannot be explained within the framework of traditional models - avalanche [4] or multiphoton [5].

The most surprising peculiarity is independence of the breakdown threshold on the laser pulse duration in the interval ($\tau \sim 10^{-8} \div 10^{-13}$ sec) and the width of the forbidden gap of the material.

Earlier [1] we proposed a breakdown mechanism based on the assumption of the breaking of chemical bonds of a solid lattice under the direct action of an electric field of a light wave on bound electrons.

In current presentation we continue to discuss the processes in a lattice that lead to irreversible disturbance of charge equilibrium in it under an external electric field action. Due to this disturbance, it becomes possible the motion of charged lattice sites and, finally, the lattice damage as a result of critical stresses arising.

A simple interpretation of the causes of irreversible breaking the bonds in crystalline lattice due to to charge motion inside the dielectric is given, the ways and conditions for the occurrence of electrostatic instability of the lattice under the action of intense laser pulses are discussed.

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PS1-LMI-10 Quality analysis of optical crystals by means of high-resolution THz spectroscopy

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Present methods of quality control for optical crystals used in modern laser facilities allow measuring impurities concentration, type of impurity, structural features, anisotropy, inclusions, defects etc. The dielectric crystal is usually either placed between capacitor plates for potential difference registration during laser scanning through the volume of the crystal [1], or probed by polarized laser beam for measuring depolarization in different points at the output [2]. Additional verification method of quality control based on high resolution THz spectroscopy is proposed, which proved to be very efficient [3] in nondestructive examination of laser optical materials. This method will be helpful when the crystals should work with beams having different wavelengths, so there must be several probing lasers for quality control.

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PS1-LMI-11 Modeling the influence of laser-induced plasma on the target heating under nanosecond pulses in an ambient gas

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The absorption of laser radiation by metals, especially in the infrared wavelength range, such as the CO2 laser, isn't very significant. Therefore, applicability such lasers as the source for heating the targets and further coating of cladding materials doesn't have the high energy efficiency, although it also has the number of advantages. In this paper, we propose to consider the effect of laser-induced near-surface plasma on the efficiency of energy transfer from the beam to the target using nanosecond CO2 laser pulses.

In the pulsed impact process of the high-power laser radiation occurs intense heating and active evaporation of the target material. The vapor layer appears near it surface, pushing the ambient gas. Evaporation has a complex nonequilibrium character, as the result of which at distance of the several mean free paths temperature, density, and pressure vary significantly. The Knudsen layer approximation was used to simulate this — the nonlinear system of equations was solved, consisting approximate solutions of kinetic equations in the Knudsen layer, supplemented by conservation laws. As the result the parameters of the expiring vapor in the considered volume were determined.

The concentration of free electrons avalanche-like grows and the plasma appears in the target material vapor with a high intensity of radiation. The shock wave forms due to the rapid heating in the gas phase as well as the ionization zone arise, wherein the incident laser power active adsorption occurs. In this zone the temperature can reach several electron-volts and re-emitted photons have great importance in heat transfer. For simulation such processes the equation of radiative transfer is solved in the multi-group diffusion approximation in conjunction with the Navier-Stokes equations.

The calculations of the thermal state of the target were carried out, the gas-dynamic flows structures, the formation and propagation of plasma were investigated under the influence of repeating laser pulses in the one-dimensional approximation. With the first pulses the target material is heated and melted, then intensely evaporated, therefore the thickness of the vapor layer increases, pushing back the surrounding gas. There is observed sharp increase in the temperature of the vapor as well as an increase in the degree of its ionization and the shock wave formation. During the time between pulses, depending on their periodicity, the existed plasma can disappear. However with the beginning of the next pulse, it reappears with the new formation of the shock wave.

PS1-LMI-12 Numerical modeling of energy relaxation in molybdenum thin films on glass substrates upon irradiation by femtosecond and picosecond laser pulses

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Pulsed laser irradiation of thin films has enabled a number of applications in industry (photovoltaics, electronics component manufacturing) and is a cornerstone of widely employed techniques such as laser-induced forward transfer, or for testing the laser-induced damage threshold of optical components in intense laser chains. In contrast to bulk materials, subtle effects such as thickness-dependent electron-phonon collision rates or stress generation have been observed and require thorough theoretical investigations. Their theoretical description requires further studies in view of achieving better control in thin film processing by ultrashort laser pulses.

In this work, a numerical code based on two-temperature model (TTM) in 1 dimension was developed for the case of a thin molybdenum film deposited on fused silica (resp. soda-lime glass) substrates irradiated by short laser pulses of 200 fs (resp. 10 ps). The validation of the numerical scheme was performed by comparison with analytical solution of simplified cases and by the demonstration of energy conservation. Melting threshold fluences were calculated for different thicknesses of films and compared with experimental data on femtosecond and picosecond irradiation from [1] and [2], respectively.

Several temperature-dependencies of molybdenum properties (e.g. thermal conductivity or heat capacity) and different sets of optical properties were considered to analyze their repercussions on the evolution of the damage threshold fluence with the layer thickness.

The possible fracturing of the film is discussed, based on estimation of maximal thermal-induced stress. Then the influence of melting and fracturing on the damage threshold of the molybdenum thin films will be touched.

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PS1-LMI-13 Nonlinear scattering in photorefractive $LiNbO_3$ crystals

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Characterization of nonlinear optical materials is a key step in order to choose the most adequate material for a given nonlinear optical process. The values nonlinear refraction (NLR) n_2 and nonlinear absorption (NLA) β coefficients are interesting for high-intensity applications. The Z-scan technique is a well-established sensitive method to determine these nonlinearities of optical materials. However, there are the limitations of the Z-scan method for the determination of the NLR and NLA in photorefractive media. These limitations are essentially caused by the presence of nonlinear scattering (NLS) that masks the third-order nonlinear response. Therefore, a modified open-aperture Z-scan setup is used to evaluate partial contributions of NLS in the observed transmission attenuation. Our study was undertaken with a cw-excitation at 514.5 nm in nominally pure, Mg- and Zr-doped LiNbO3 crystals. It has been established that the wide-angle photoinduced light scattering represents a dominating contribution to NLS in photorefractive $LiNbO_3$ crystals and gives the significant transmission modulation within the open-aperture Z-scan trace. NLS has a significant magnitude in the undoped, strongly Zr-doped ($[Zr] \geq 2$ mol%) and Mg-doped $LiNbO_3$ at the moderate and high light intensities, and in the moderately Zr-doped ($0.625 \leq [Zr] \leq 1.5$ mol%) LiNbO3 crystals even at low intensities. The relation between the NLS coefficient αnls, gain factor Γ (coupling efficiency between the pump and scattered waves) and seed scattering ratio m0 is derived by us. The actual values of these parameters depend on dopant type, concentration and light intensity. They reach extremely high values (αnls = 46.1 cm^{-1}, and m0 = 0.0068) in the moderately Zr-doped $LiNbO_3$ crystals.

PS1-LMI-14 Frequency down-conversion of femtosecond pulses in nanocomposites

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It is well known that nonlinear properties of nanocomposites depends on not only features of nanoparticles embedded into a matrix but also on parameters of the matrix itself. In this work we study femtosecond light pulse interaction with nanocomposites consisted of semiconductor metal-oxide quantum dots (QD) incorporated into a dielectric non-centrosymmetric matrix, accounting for large permanent dipole moment (PDM) of QDs and quadratic nonlinearity of matrix. Our investigations are aimed to elaboration of efficient scheme generation of terahertz (THz) radiation. Below we present the results of our theoretical analysis of the frequency down-conversion processes in such nanocomposites via resonant and nonresonant optical rectification mechanism.

We suppose that phase-matching conditions are fulfilled due to the Zakharov-Benney resonance between THz harmonic and the pump pulse. THz generation by a femtosecond laser pulse being in resonance with the QDs and out of resonance with dielectric matrix is investigated. The resonant mechanism of THz generation is shown to be more effective than non-resonant one. One- and two-photon resonances as well as local field effects are accounted for. THz generation efficiency is estimated in coherent and incoherent light-matter interaction regimes allowing possible phase modulation of the pump pulse and phase capture of THz harmonic. As is shown when the PDM influence is weak and one-photon transitions predominate the dependence of the THz field on the pump pulse is quadratic. In this case the THz generation efficiency does not exceed 10^{-3}. When two-photon transitions prevail the frequency down-conversion process becomes more efficient providing the THz generation efficiency 16-17% and higher under phase capture conditions of THz harmonic. Figure demonstrates THz generation process in nanocomposite material with large PDM at input pump pulse area $\Theta 1=5\pi$. Even if matrix absorbs the THz radiation, the nanocomposite demonstrates high enough its generation efficiency.

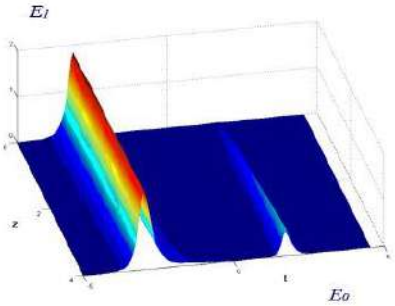

Figure THz generation process in nanocomposite material with large PDM at $\Theta 1=5\pi$:

E1 (t,z) - propagating pump pulse, E0 (t,z) - generated THz wave

Phase modulation of the pump pulse also increases the THz generations efficiency.

PS1-LMI-15 Comparative analysis of light bullet scenarios for powerful femtosecond vortex and Gaussian pulses in Kerr media

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Spatio-temporal localization problems of femtosecond pulses are topical due to fundamental and applied aspects as remote sensing of atmosphere, lightning strikes, high precision micromachining, precise ophthalmic femtosecond surgery et al. Optical vortex beams are of large potential for information processing, cryptography, manipulation by particles and cells, micromotors, soliton algebra, astronomy. Stability of vortices is an important issue under linear and nonlinear propagation regimes.

The light bullets formation in a Kerr medium with anomalous group velocity dispersion (GVD) is revealed. The spatio-temporal localization conditions of high-power femtosecond singular pulses in Kerr medium depending on topological charge m and the ratio α of input pulse power to critical one are studied on the base on generalized non-linear Schrödinger equation for the complex envelope of the electric field and the rate equation for free-electron plasma density. The underlying physical mechanism for the stable propagation of the femtosecond vortex is the dynamic competition between the Kerr self-focusing, photoinduced plasma and GVD. Semi-analytical two-scale variational analysis and numerical simulations are performed.

The motion equations for both temporal T(z) and spatial R(z) vortex radii, deduced in the frame of variational approach, allow to obtain their stability regions in fused silica for m=1, 2 at λ range within 1500 - 2000 nm and α =12÷400. It should note that the stability region originated from plasma impact is very narrow. Stationary values T0 and R0 were found, for which the Gaussian light bullets (GLB) and vortex light bullet (VLB) are stable and robust under propagation. It was established that increase of m leads to decrease of T0 and non-monotonous behavior for R0, while the more α, the more the values T0 and R0. If the initial radius and duration of the Gaussian as well as vortex pulsed beam are detuned from their stationary values, then such a pulse oscillates during propagation. At this, the pulse duration and its radius may oscillate in phase or in antiphase.

In difference to the light bullets formed with Gaussian beams, VLB are shown to obey threshold condition on the topological charge: α > 2m/0.093. Only pulsed beams obeying this condition may propagate in light bullet regime.

Numerical calculations confirm in general the results of variational analysis, whilst demonstrate more soft conditions for GLB and VLB formation. Oscillating dynamics of the vortex pulsed beam for m=1-3, α=30-900, T0 =10 -30 fs, R0 =10-30 μm at the propagation distance of several diffraction lengths was studied. The obtained values of transverse and temporal radii of the input pulse may be quite attainable in experiment.

PS1-LMI-16 Algorithms of result processing automatization for light induced damage threshold measurements

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Light induced damage threshold (LIDT) measurement methods (fig. 1a) that allows to produce standard 1-on-1 and S-on-1 LIDT tests [1, 2] are require considerably big amount of time to process acquired images of treated sample and plot the diagram of LID probability vs laser pulse energy. Present study is focused on comparing of several algorithms for automatic analysis of tested sample image, which allows to speed up result processing.

Experimental setup for LIDT measurement is shown on fig. 1b. It consists of Nd:YVO4 Q-switched laser with second harmonic generation, galvanometer scanning system with f-theta lens and motorized z-axis. Laser output parameters are up to 300 uJ pulse energy with 5 ns pulse duration, repetition rate up to 2 kHz, wavelength – 532 nm. This setup allows both 1-on-1 and S-on-1 LIDT measurements [3].

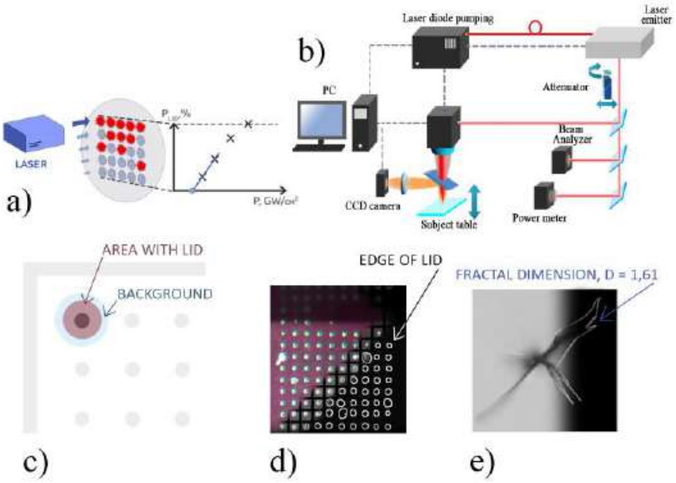

Figure. LID image processing algorithms: a – illustration of LIDT measurement methods; b – experimental setup for LIDT measurement; c – comparison of intensity in treated area with background; d – Canny edge detector-based algorithm; e – calculation of fractal dimension of treated area.

First algorithm for automatization of result processing (fig. c) is based on comparing of intensity in the area of laser treatment with averaged background intensity. Weakness of this algorithm is high sensitivity to lighting conditions of the image. Second one (fig. d) based on Canny edge detector and include several steps: image preparation (blurring, binarization), which allows to distinguish LID marks from noise, and actual contours detecting. Length of calculated contours defines the presence of LID marks. Third algorithm (fig. 1c) complements the second one. It based on calculation of fractal dimensions in the area of LID mark, which is defined by Canny edge detector algorithm. This algorithm increases LID detection reliability and gives additional information on LID morphology.

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PS1-LMI-17 Reflectivity of niobium in ablation with nanosecond laser pulses at 1.06 and 0.69 μm

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This paper contains the results and discussion of a study conducted to measure the total hemispherical reflectivity, of a mechanically polished niobium sample, when influenced by a laser beam of two different wavelengths (1,06 y 0,69 μm). The laser used for the ablation of the sample was a Q-switched Nd;YAG laser that generates 50-ns pulses at a wavelength of 1064 nm. An ellipsoidal light reflecting technique was used to measure the hemispherical reflectivity.

The fluence of the laser varies from 0.1 to 100 J/cm^2. Experimentation shows that effect of the wavelength of the laser over the sample's reflectivity is significant for low fluence values, whereas for the higher values, past the fluence threshold point, the effect of the wavelength becomes insignificant. The disappearance of the wavelength effect might be due to the increase in the absorption of laser light caused by plasma formation.

Another reason for the drop in the reflectivity is due to the dependency of Drude's temperature with the optic constants of a metal heated by laser pulses and the absorption of the laser light by the plasma, formed over the irradiated spot of the sample.

Fusion temperatures and fluence threshold points were calculated and defined for each of the wavelengths. It is observed that the calculated fluence threshold points do not match with the experimental ones, instead, the formation of plasma for the experimental case happens at a lower surface temperature than what expected from the calculated case, this shows the importance of the nanostructural defects in a metal surface.

PS1-LMI-18 Generation of controrable supercontinuum accompanying femtosecond filamentation in high density gases and supercritical fluids: enhancement of the SC generation under cluster formation

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We demonstrate that the clustering of dense gases and supercritical fluids plays a crucial role in the process of the supercontinuum generation under filamentation of femtosecond laser pulse (λ=1240nm). The high-density gases and supercritical fluids have anomalously high nonlinear refractive index due to the clustering. Besides the nonlinear properties of fluids can be tuned by the change in pressure or temperature. The clustering leads to the formation of two regions, where the supercontinuum generation is the most efficient: the region of the subcritical pressures and the vicinity of the Widom line that divides the supercritical region into liquid-like and gas-like supercritical fluids. These regions are distinguished by the best balance between the highest nonlinear refractive index and the lowest density fluctuations. In these regions, on the one hand, the nonlinear properties are maximal. However, on the other hand, the clustering leads to the increase of density fluctuations. To increase the efficiency of the supercontinuum generation medium with a synthesized nonlinearity can be applied. The binary mixtures represents such type of media, by combining noble gas with high nonlinear refractive index and molecular gas with high molecular part of nonlinear refractive index it is possible to increase the width of the spectrum (about 1.5 times). Besides the clustering is more efficient in mixtures that can additionally increase the efficiency of the supercontinuum generation. We demonstrate that the efficiency of the SC generation in the IR wing in mixture CO_2+Xe is twice as high then in the case of the supercontinuum generation in a single component.

This work was supported by the Russian Found for Basic Research (RFBR 18-29-20074); Ministry of Science and Higher Education within the State assignment FSRC «Crystallography and Photonics» RAS in part of «development of the hardware base laser and supercritical technologies»; E.I Mareev is the scholar of Foundation for the Advancement of Theoretical Physics “BASIS”.

PS1-W03-1 Optical properties of ZnO nanoparticles and thin films relevant for gas-sensor applications

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Zinc oxide possesses very promising optical properties. As a wide direct band gap semiconductor (Eg ~ 3.37 eV) ZnO is transparent in the visible range of spectrum. Besides that, the binding energy of the exciton in ZnO (60 meV) largely exceeds the thermal energy at room temperature (26 meV) making the observation of the excitonic transition rather easy. Finally, inherent nonstoichiometry of this substance leads to rather large conductivity as well as visible luminescence. Both of these properties are sensitive to the environment. Because of that ZnO is widely used in sensing applications. It is expected that the ZnO nanostructures may be especially useful as transducer materials in gas sensors.

Several techniques have been used to produce ZnO nanoparticles and thin films: chemical synthesis, laser ablation and magnetron sputtering. For chemical synthesis zinc acetate, isopropanol and water were mixed, and the obtained solution was stirred at 60 C for two hours. After that the solution was deposited on the quartz substrate using spin-coating technique. Then, ZnO thin film was annealed at 450 C. The obtained zinc oxide thin film demonstrates a pronounced absorption band at 360 nm and a broad luminescence band centered at 490 nm. Intensity of this green luminescence is known to be sensitive to the amount of oxygen in the atmosphere.

In another approach, ZnO films on sapphire substrates were obtained in the course of laser ablation of a zinc oxide tablet in air. The second harmonic of Nd:YAG laser pulses of 10 ns duration was focused on the tablet surface at the angle of incidence of 60 degrees. After irradiation at 10 Hz repetition rate for 30 second a thin film of zinc oxide with the extinction maximum at 350 nm was obtained.

PS1-W03-2 Spaser emission of a monolayer of silver nanoparticles coated with coumarin 481 dye

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Since the theoretical proposal of the spaser in 2003 there were a number of its experimental realizations based on metal nanoparticle colloids and laser dyes. However, the disaffection with these realizations grows as conditions of the performed experiments were too close to that of the random-lasing phenomena. In this work we tried to reduce an unintended feedback due to the multiple scattering events by creating a monolayer of metal nanoparticles on the solid surface and cover them with a thin layer of dye molecules.

A monolayer of plasmonic nanoparticles was prepared in an ultra-high vacuum chamber by evaporation of pure silver on a quartz substrate. The equivalent thickness of the layer was 10 nm. After thermal annealing, dewetting led to the formation of discontinuous film consisting of isolated nanoparticles. The monolayer of Ag nanoparticles was covered with well-dissolved polymethylmethacrylate in toluene and was dried up at ambient conditions. The obtained spacer layer played a role of buffer which minimizes uncontrollable de-excitation of molecules due to metallic quenching of fluorescence and electron harvesting. As a gain medium Coumarin 481 was used because its absorption and fluorescence spectra overlap the plasmon band of silver nanoparticles. Thus, one of the key requirements for spaser realization was fulfilled.

The dye molecules fluorescence was excited by laser light at the wavelength of 355 nm and 436 nm. In both cases the definitive features of stimulated emission were observed, i.e. nonlinear dependence of the fluorescence intensity on the pumping energy and spectral narrowing at pump energies above a threshold. The thresholds were 0.5 mJ at the wavelength of 436 nm and 3 mJ at the wavelength of 355 nm. In addition, in the presence of nanoparticles the radiation pattern and polarization of the stimulated emission differ substantially from that in the case of a pure dye lasing.

PS1-W03-3 Laser deposition of Fe- and Ni-based micro-powder coatings

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This paper presents the results of experimental research concerning the laser deposition of Fe-Cr-Mo-V and Ni-Cr-B-Si micro-powder coatings. The experiments were carried out at the technological installation created at the Institute. The installation includes:

1) CO_2-laser generator-amplifier system on the basis of a LOK-3 laser operating in continuous mode with an average power up to 2 kW or in pulse-periodic mode with a repetition rate of 20-120 kHz and a pulsed power up to hundreds kW;

2) coordinate table with movable optics;

3) a two-mirror scanner and a focusing head with a slotted nozzle mounted on a movable carriage of a coordinate table. The scanner provides a scanning frequency in the range of 50-300 Hz with amplitude of 3-10 mm;

4) two-channel powder feeder manufactured by MC Thermal Spray Equipment model PFC-3500T;

5) a system for monitoring the parameters of laser radiation and the technological process.

The formation of a gas-powder jet with an optimal distribution of powder particles has a significant impact on the shape and quality of the deposited coating. We used two variants for feeding powder through self-made nozzles: a coaxial nozzle and a lateral nozzle. The lateral nozzle was used in conjunction with scanning the laser radiation in the direction perpendicular to the movement of the nozzle. Cylindrical and flat samples made of structural steel were used as substrates.

It was shown that the coating thickness is dependent on the processing mode and varies between 10-150 mkm for coaxial nozzle and 100-500 mkm for lateral nozzle with scanning. Microhardness of the obtained coatings reaches values of 5-8 GPa. Using optical microscopy and SEM the structure and elemental composition of the coatings was investigated. Optimal modes for the obtaining of micropowder coatings by adjusting the main deposition parameters were defined. The effect of the fractional composition of the powder and the heating mode of the powder particles and substrate on the process efficiency was studied.

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PS1-W03-4 Topological electroconductivity in nanocluster metallic thin films: a shape depended nonlinear model for the electroconductivity physics enhancement

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1. The physical properties of nanocluster systems are very sensitive to the form, size and distance/spatial distribution between their components. The fact is well known for any material in general, but to change these parameters and to carry out the stable conditions for the ordinary solid state objects we need to put the objects under extremal conditions. In contrast, nanocluster structures can be easily modified in necessary way in the femto- nanophotonics laser experiments. In superconductor problem the question is how to fabricate the coupling states for charged particles being responsible for electroconductivity. For a cluster system we discuss some alternative mechanisms of electronic coupling (in equilibrium states), and not via a standard Cooper phonon coupling only).

2. In our study such tendency to superconductivity is based on several principal effects discussed below.

First, the electrophysics is strongly depending on the topology of the nanostructured films on solid surface. Such electrical transport properties are due to the quantum correlated states resulting in tunnel and hopping electrical conductivity.

Second, the modeling of both thin films thickness (layer by layer) and optical spectra for their carried out by us. The original shape of the nanoobjects was considered spherical but being transformed by the key parameters: values and numbers of the azimuthal distortion coefficient (in terms of «latitude») and the zenithal distortion coefficient («longitude»). The fact results in some new physical states of the system, particularly, in electrophysics and optical response

3. The principal problem is, how to determine the specific numerical values of the control parameters of the nanocluster system from these general relations to achieve the desired final result in experiment. Nevertheless, observed phenomena give us an opportunity to establish the basis of new physical principles to create the functional elements for topological photonics in hybrid set-up (optics + electrophysics).

PS1-W03-5 Laser assisted fragmentation of metal nanoparticles

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The effect of high-power resonant laser radiation on the morphology and optical properties of gold and silver films supporting quadrupole plasmon oscillations was experimentally investigated. Metal films were obtained by physical vapor deposition in vacuum chamber. Mass thickness of the samples was 10, 15 and 30 nm for silver films and 30 nm for gold films. On the top of gold film the 5 nm Al_2O_3 film was deposited by e-beam deposition. After deposition the thermal annealing of samples was produced. Temperature of annealing was 200 °C for silver films and 1000 °C for gold film. Two peaks corresponded to dipole and quadrupole resonances of metal nanoparticles are clearly distinguishable in the spectrum of optical density.

All samples were irradiated by pulsed Nd:YAG laser. Second harmonic (512 nm) was used for gold films and third harmonic (355 nm) for silver films which are close to the maximum of quadrupole resonance position. The pulse duration was 10 ns and the energy density were varied from 50 to 500 mJ/cm^2. After irradiation the intensity of quadrupole mode was decreased. But the main changes of the optical density spectrum were observed in the region of the dipole plasmon resonance. The dipole resonance maximum shifted to the short wavelength region and a large long-wave shoulder arose. SEM and AFM images showed that the large metal nanoparticles were fragmented and form closely spaced smaller particles. Particles larger than 300 nm were not completely fragmented. In this case two peaks of dipole plasmon resonance of large and small nanoparticles were observed in spectrum.

Surface enhanced Raman scattering of a thin layer of 3,3’-diethyl-tiamonocarbocyanin iodide deposited by spin-coating above the granular metal film surface was also observed. The Raman signal enhancement on the laser irradiated film was 5 time stronger than that on the thermally annealed film.

PS1-W03-6 Study of optical and photoelectric properties of nanocomposite material based on titanium dioxide and graphene oxide

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Nanostructured material based on graphene oxide and TiO_2 with a ratio of 1:100, 1:20 and 1:10 was synthesized. For hydrothermal synthesis single-layer graphene oxide (GO, Cheaptubes) and TiO_2 (d<21 nm, Sigma-Aldrich) were used. The formation of nanocomposite was confirmed by FTIR analysis. It was shown that GO partially reduces during synthesis. The appearance of a broad band below 1000 cm^{-1} indicates the formation of bonds between TiO_2 and GO. The Raman spectra of the nanocomposite contain peaks characteristic for both TiO_2 and GO.

Absorption spectrum of pure TiO_2 and GO was recorded in the UV region. Nanocomposite TiO_2-GO also actively absorbs light in the UV spectral region. But the edge of the absorption band shift towards the red wavelengths, which is associated with a change in the band gap of the semiconductor.

Measurements of the electrophysical characteristics of the nanocomposite material have shown that it possesses with improved electron transport characteristics as compared to pure TiO_2. For sample of pure TiO_2, the resistance to electron transport was 2200 Ohms, while for a nanocomposite material – 780, 760 and 680 Ohms was registered for the 1:100, 1:20 and 1: 10 TiO_2-GO, respectively.

When studying the photocatalytic activity of the samples by photodegradation of the Methylene blue, it was found that after 180 minutes of irradiation only 38% and 15% of the dye molecules for pure TiO_2 and TiO_2-GO remained in the solution, respectively. When measuring the photocurrent obtained by irradiating of nanocomposite films with Xe lamp light, Igen was increased by 2.7, 5.6 and 4 times for TiO_2-GO ratio of 1:100, 1:20 and 1:10, respectively.

Thus, it can be argued, that addition GO to the semiconductor leads to enhancement of its photocatalytic activity due to an increase in the adsorption capacity and electron transport properties of TiO_2.

PS1-W03-7 Photoinduced electron transfer in multilayered hybrid structures based on CdSe quantum dots and TiO_2 nanoparticles

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The hybrid structures based on colloidal quantum dots (QDs) and titanium dioxide nanoparticles (TiO_2NPs) are a prime example of systems that have enormous potential for the application in the bacterial infection therapy. Such structures will demonstrate antibacterial activity in wide spectral range due to effective electron transfer from QD to TiO_2 nanoparticle. The functionality of TiO_2/QDs hybrid structures is directly related to theelectron transfer efficiency. Identifying patterns of electron transfer in hybrid structures is a necessary step in the creation of new class of antibacterial systems.

The key parameters determining the electron transfer efficiency are their HOMO and LUMO positions and a donor-acceptor distance. We use here CdSe QDs with the smallest diameter (2.5 nm) as the best CdSe electron donor for titanium dioxide nanoparticles and form our multilayered hybrid structures using Langmiur-Blodgett technology that provides the minimum donor-acceptor distance. Our estimation of electron transfer rate (ket~$3\cdot10^8$ s^{-1}) using QDs luminescence decay analysis and study of the reactive oxygen species (ROS) generation by our hybrid structures under visible light confirm the efficient electron transfer (54%) in the TiO_2/QDs structures.

The results of our work demonstrate that TiO_2/QDs multilayered hybrid structures are prospective systems for antibacterial therapy.

PS1-W03-8 Optical properties of molecular layer of cyanine dye coated on Ag or Au island film

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Over the last decades, the optical properties of metallic nanoparticles have been exploited for light manipulation, ultrasensitive spectroscopy and sensorics. Many of these applications are underpinned by the fact that the optical absorption of organic molecules on the surface of nanoparticles is enhanced. However, in such studies the dye concentration is often large to maximize interactions. So dye–dye interactions cannot therefore be neglected and are expected to induce resonance shifts of the dye layer independently of any effects of nanoparticles. In fact, many studies specifically work with J-aggregates rather than isolated monomers.

The overlapping of plasmon resonances of nanoparticles and the absorption band of a molecular layer of the cyanine homologues was studied for thin film. The nanoparticles in form of the island film of gold or silver were obtained by thermal vacuum deposition. The homologous series of cyanine dyes differing in the length of the conjugation chain (pseudo-, mono- and dicarbocyanines) and the absorption maximum was chosen as organic molecules. Hybrid films consisting of monomers and aggregates were obtained by spin-coating of dye solution on island films.

The absorption of dicarbocyanine dye in the presence of nanoparticles for both metals was increased by several times. However, enhanced absorption of a shorter wavelength dyes (monocarbo- and pseudoisocyanine) is observed only for the Ag island films. This is explained by the longer-wave position of the plasmon resonance of gold nanoparticles with respect to the dye absorption, which leads to the decrease of plasmon near fields. The dip in the absorption spectrum of the hybrid film at a wavelength corresponding to the maximum of the J-aggregate band is observed for pseudoisocyanine coated on nanoparticles of both metals. The presence of the transparency is explained by the strong coupling of the exciton transition in the J-aggregate with the plasmon resonance of nanoparticles.

PS1-W03-9 Photoinduced chirality of semiconductor quantum dots

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Chirality has a crucial role in a number of areas, such as chemistry, pharmacy, biology, and medicine. In particular chiral nanocrystals have better biocompatibility compared to their achiral analogues and can be embedded in biosystems using well-known molecular biological mechanism of molecular recognition.

Here we report an appearance of optical activity after the photochemical reaction in the sample by illumination with circularly polarized light. In our laboratory, a concept has been suggested and developed, according to which any nanocrystal potentially can be chiral due to its low symmetry, arising from the presence of chiral defects both on the surface and in the volume of nanocrystal. The total sample is optically inactive because the presence in a mixture of an equal numbers amounts of laevorotatory and dextrorotatory enantiomers in nanocrystals ensemble.

In our work, a colloidal solution of quantum dots was irradiated with circularly polarized light with right or left polarization. It was expected that, due to the intrinsic chirality of the nanocrystals, L and D nanocrystal enantiomers present in a nanocrystal ensemble would absorb circularly polarized light with different efficiency and, consequently, undergo some kind of a photochemical transformation to a different extent. Such enantioselective photochemical reaction should give a rise to optical activity of the irradiated sample. The dissymmetry factor (DL-DR)/D for samples of quantum dots with photochemically induced circular dichroism in long wavelength absorption band according to our results is comparable in magnitude to the dissymmetry factor of intrinsically chiral quantum dots obtained by enantioselective phase transfer.

PS1-W03-10 Optical properties of molecular layer of pyrylium compaunds

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Aromatic heterocyclic compounds have a variety of applications, in various biological processes in particular. Moreover, some aromatic heterocycles have conductive properties and others are dyes. Within these colored substances there is a well-known family called pyrylium salts, whose structures have a pyrylium cation. Because of the fluorescence properties, pyrylium salts are used as labeling, phototherapeutic, and anticarcinogenic agents, and as chemosensors. Pyrylium compounds are widely used in photographic materials and photosemiconductors as sensitizers. Also, they are applied in lasers, as active media, Q switches, and mode lockers. Despite the comparatively small transition cross-sections, the lasing efficiency of pyrylium solutions is comparable to that of Rhodamine 6G and their tunability range is twice broader. Such unique lasing properties are mainly due to the fact that the Stokes shift of the fluorescence spectrum of pyrylium solutions is considerably higher than of other laser media.

The first spectral studies of a large series of pyrylium salts were published in 1960. However, the comprehensive study of the optical properties of pyrylium compounds on solid surface has not been carried out to date.

We study the absorption and dichroic spectra of molecular layers of some pyrylium compounds and their luminescence excitation and emission spectra. We found that the absorption and excitation spectra of the layers do not always coincide, depending on the structure of a molecule. We shown that the pyrylium layers studied are highly stable against a nanosecond laser irradiation.

PS1-W03-11 Morphological and optical properties of isolated zinc nanoparticles obtained by magnetron sputtering on quartz substrates

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Ensembles of isolated Zn nanoparticles supported on transparent substrates have potential applications as a plasmonic material as well as a precursor for zinc oxide nanoparticles formation. In this study zinc nanoparticles were formed by magnetron sputtering on fused silica substrates with the use of Q150TS/E/ES (Quorum Technologies, Lewes, UK). The feature of the used equipment is its ability to control the target sputter current and the deposition rate.

Surface morphology of the obtained zinc nanostructures was studied by scanning electron microscopy. SEM images reveal that the films morphology is characteristic for an islands growth mechanism. The nanoparticle surface occupancy of the substrate varies depending on the amount of the deposited material in the range of ~20 – 60%, and the distance between the particles varies in the range of ~20 – 200 nm, with an average size of individual particles varying in the range of ~10 – 30 nm. At the same time, Zn nanoparticles of rounded shapes are clearly visible in SEM images. An increase of deposited zinc mass leads to an increase of the number of nanoparticles per unit area, while the nanoparticles sizes increase as well.

Optical characteristics of zinc nanoparticle films were studied with a Shimadzu UV-3600 spectrophotometer in the spectral range of 200 – 800 nm. Three characteristic resonances with maxima near the values of 240 nm, 285–290 nm, and 360–365 nm were found in the extinction spectra. The first two maxima correlate well with the plasmon resonances of Zn nanoparticles in SiO_2 matrix and colloidal solutions known from the literature. The 3rd maximum is close to the absorption band of ZnO nanoparticles.

It is established that the optical properties of zinc films substantially depend on the technological parameters of the deposition process, thus providing for an opportunity of controlling the morphology and optical properties of the Zn nanoparticles ensembles. Further oxidation of the obtained zinc nanoparticles may lead to the formation of the ZnO nanoparticles with the controlled size distribution or core-shell nanoparticles with metal core and oxide shell that keep promise from the point of view of gas sensing applications.

PS1-W03-12 Self-assembled formation of nanodomain structures by multiple IR laser pulse irradiation of lithium niobate crystals

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Uniaxial ferroelectric lithium niobate $LiNbO_3$ (LN) obtaining high nonlinear-optical and piezoelectric coefficients in wide temperature range is an attractive material for a number of applications. It is known that the useful properties of LN can be improved by tailored periodical micro- and nanodomain patterning [1]. Therefore, LN is the most popular material for domain engineering [2]. Moreover, the high crystal quality and simple domain structure allowed to consider LN as a model material for studying the domain structure evolution by various modern microscopic methods with high spatial resolution.

We will show the experimental and theoretical study of the domain structure evolution in LN crystals of congruent composition as a result of multiple pulse irradiations by infra-red CO_2 laser. The qualitative change of the domain wall shape from straight to wavy and irregular has been revealed with increasing the pulse number. The formation of the isolated nanodomains representing the domain wall traces after each laser pulse irradiation was discovered in the samples with polar surface covered by indium tin oxide (ITO) thin layer. This effect was applied for extracting the detail information about the evolution of the domain wall shape after each pulse. The switching leading to increase of the domain width and wall length has been caused by pyroelectric field appeared during heating and cooling in the temperature range below 200^{o}C. [3]

The mechanism of self-assembled wall shape evolution caused by the local wall accelerations and decelerations existence of the shape fluctuations (bumps and valleys) as a result of was proposed. It was shown by computer simulation that the fluctuations randomly distributed along the domain wall led to formation of the quasi-regular comb-like structures similar to experimentally observed ones. The discovered effect can be applied for formation of the stable quasi-regular domain structures thus opening the way for development of the domain engineering methods.

The equipment of the Ural Center for Shared Use “Modern nanotechnology” UrFU was used. The research was made possible by Russian Science Foundation (Project 18-29-20077-mk). The work was supported by Government of the Russian Federation (Act 211, Agreement 02.A03.21.0006).

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PS1-W03-13 Application of metal nanoparticles for intracellular uptake monitoring

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Surface plasmon-polaritons propagating along thin metal films and localized plasmon resonances in metal nanoparticles are highly sensitive of the dielectric surrounding of the metal nanostructures. This sensitivity underlies a new generation of label-free biosensors. In spite of the fact that the first devices appeared on the market almost thirty years ago, a number of possibilities for their improvements and developments remain. In particular, metal nanoparticles supporting localized plasmon excitations may be employed in the study of intracellular processes, for example, endocytosis.

In this contribution, we explore the possibility of using silver nanoparticles obtained in the form of colloidal solution in distilled water by laser ablation of a metallic target. Free from stabilizing agents silver nanoparticles with dimensions of 20 to 50 nm that are stable for a month or even more were obtained in this way. Due to rather a broad shape and size distributions of the obtained nanoparticles the width of the plasmon band is larger than it may be expected from the calculation pertinent to the monodisperse solutions. Despite that, the shift of the plasmon band maximum due to the refractive index change is measurable. To simulate the nanoparticle transition from subcutaneous water to cellular membrane we measured the shift of the plasmon band maximum when the nanoparticles were transferred from water with a refractive index of 1.33 to a sucrose solution with a refractive index of 1.4. In this case, the shift as large as 3 nm was observed.

We went further with numerical simulations of the plasmon position shifts in different situations relevant to the endocytosis: transition through the plain boundary between two media with different refractive indices, transition through the thin film of a higher refractive index material representing the cell membrane, core-shell structures representing the nanoparticle in a vesicle inside a cell and so on. The results of simulations substantiate the feasibility of the proposed approach for endocytosis diagnostics by means of the far field spectroscopy with noble metal nanoparticles.

PS1-W04-1 Synthesis and optical characteristics of core-shell nanostructures of Ag-SiO_2

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The nanostructures (NS's) «plasmon core of Ag and semiconductor shell of SiO_2» are of interest for various scientific fields related to the creation of new functional materials. The aim of the work was to obtain an Ag–SiO_2 NS's with a small thickness of SiO_2 shells and measure their optical characteristics.

Tetraethyl orthosilicate (TEOS), ammonium hydroxide (NH_4OH), ethanol and water were used for the synthesis of the SiO_2 shell. Depending on the desired final size of the nanoparticles (NP's), chemical conditions, as well as the required reaction time frame were determined during the synthesis of the SiO_2 NP's. It possible to obtain smaller sizes of SiO_2 nanoshells with a shorter time of synthesis and a smaller amount of TEOS. The synthesis was carried out at room temperature for 1-3 minutes with constant stirring. Sizes of synthesizes of SiO_2 NPs decreased from 220 nm to 25 nm with decreasing concentration of TEOS in solution and with decreasing time of synthesis.

As known SiO_2 absorbs light intensively in the ultraviolet region of the spectrum (λ_{REG} = 200 nm-250 nm). Optical density of the solution didn't change significantly in this region spectrum with changing time of synthesis and concentration of TEOS in solution.

Solution of silver NPs with 5.3 nm diameter was used for the synthesis of Ag–SiO_2 NS's. Sizes of the obtained NPs were determined by particle size analyzer Zetasizer Nano ZS (Malvern). They were obtained NS's with 7 and 9 nm of diameter for selected synthesis conditions. An increase in the optical density of the solution in the ultraviolet region of the spectrum (λ_{REG} = 200 nm) also indicates the formation of SiO_2 in the solution.

PS1-W04-2 FBGs inscription in multicore fibers with an ordinary and an astigmatic Gaussian beam

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Refractive index change with femtosecond laser pulses is a versatile technique for 3D structures writing inside transparent materials. The inscription of various optical devices has been demonstrated with this technique by this time: waveguides in different materials, couplers, polarizing optical elements, periodic structures in optical fibers. The advantages of femtosecond refractive index change are most pronounced in case of fiber Bragg grating (FBG) inscription, because it allows one to inscribe FBG in non-photosensitive fiber with desirable period and profile of grating. Moreover by focusing femtosecond pulses into the volume of the fiber and by controlling the transverse spatial position of the pulse absorption region it is possible to selectively modify the individual fiber cores of the multicore fibers and at the same time specify geometry of the each grating.

In this work we present the results on point-by-point fiber Bragg gratings inscription with femtosecond laser pulses in a Fibercore 7-core single-mode optical fiber with a tightly focusing of an ordinary and an astigmatic Gaussian beam. We show that different longitudinal profiles of coupling coefficient can be realized for the FBG, including uniform, chirped and apodized ones. The optical characteristics of FBG inscribed with different type of Gaussian beam are compared.

The results of the work can be interesting in a number of studies and application areas in which multicore fibers are used, including lasers, microwave photonic devices, communication lines and next-generation optical sensors, where the FBG wavelengths shifts for different cores can be used to calculate the bend radius and direction. This allows one to develop vector bending sensors for applications in structural-health monitoring, robotics and minimally invasive surgery, where the 3D shape estimation of manipulator is required for accurate and reliable control of the manipulator movement inside the patient's body.

PS1-W04-3 Optical fiber 3D shape sensor based on fiber Bragg gratings chirped array

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The research and development of a measurement system for remote determination and monitoring of the location and bends of extended objects in 3D space are actual at the moment. In these work fiber optic measurement system based on fiber Bragg gratings chirped array were presented.

Fiber optic measurement systems are widely used in various industries: avionics, metallurgy, thermal engineering and power engineering, medicine. Fiber Bragg gratings (FBGs) are currently one of the most important sensitive element in such fiber optics devices and measurement systems of various physical quantities. The research and development of a measurement system for remote determination and monitoring of the location and bends of extended objects in 3D space are actual at the moment. This system, which allows determining the shape of an object, including long flexible bodies, is used in medicine (monitoring the position of minimally invasive surgical devices and instruments inserted into the human body), in the aerospace industry (monitoring of deployable structures during flight), in energy (measuring the blade shape on wind turbines to control them in real time) and etc.

In this work the development of a sensitive part of fiber optic measurement system based on chirped FBGs array inscribed in an optical fiber is proposed. The method essence lies independence determination of the grating period change in each core on the bending radius of the fiber, that gives the possibility to reconstruct remotely optical fiber 3D shape.

The work presents experiment results with an optical fiber with an array of chirped FBGs. The experimental optical scheme and the reflection spectra before and after the optical fiber bending are shown. The geometry and computer model of multi-core fiber section with a given radius bend are described.

The obtained experimental results showed that the fiber is sensitive to bends and a pattern is observed in the change in wavelengths in the spectra from FBGs. A further processing of the results will allow us to determine optical fiber 3D shape without using the methods of optical frequency domain reflectometry, which determine the location of the Bragg gratings along the optical fiber length.

PS1-W04-4 Fast fabrication of phase diffraction elements on silicon by laser-induced microplasma action

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Laser-indused microplasma processing (LIMP) is using for glass and glass-like material structuring [1], because of their high transparency for the emission of most technological lasers, and as a result, the limited possibilities of direct laser processing. LIMP allows the micro- and nanorelief formation of the glass surface and it is using to fabricate, for example, diffractive optical elements (DOEs), such as phase gratings (PG) [1], or micro-analytical systems, such as lab-on-chip, electro- and opto-fluidic systems [2].

There is an interest to extend the LIMP to other materials, which are not transparent in such a wide range of wavelengths, and to evaluate the effectiveness of this method. In particular, crystalline silicon can be chosen as such material, which can also be used in the field of diffraction optics [3].

The aim of this work is to fabricate a phase grating on the surface of silicon using a CO_2 laser and a fused silica target.

In this work by the LIMP method, several phase gratings were fabricated. Size of each PG was 5x5 mm^2. The gratings relief depth was h=0.5 – 3 μm and the gratings period was p=70 – 90 μm. Fabrication time was about 15 minutes. The use of a fused silica target reduced the processing time, due to the absence of a sample cleaning operation from the target material, in contrast to [1], and also facilitated the search for the focal plane in which the treatment was performed. The gratings were tested for beam-splitting of CO_2 laser radiation. It was possible to split the laser beam on 0 and ± 1 orders of diffraction, with different distances L between the orders and different diffraction efficiencies η of the orders, with different gratings relief parameters. In the end, with the help of the PG, we were produced two-beam interference processing. The values of the interference period $\boldsymbol{\Lambda}$, as well as the values of L and η, satisfactorily correlated with the calculated values.

Acknowledgments

The reported study was financially supported by the Ministry of Education and Science of the Russian Federation, research agreement № 14.587.21.0037 (RFMEFI58717X0037).

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PS1-W04-5 Formation of thin films of ZnO doped with REI by laser annealing

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The creation of ZnO thin films doped with REI is necessary for the creation of optoelectronic emitting devices with high quantum yield, operating on the basis of the effect of radiation from intracenter 4f-transitions [1,2].

The purpose of this work was to form, using the method of laser-stimulated doping, ZnO thin films doped with Yb and Er ions. Such films have a high photoluminescence yield in the range corresponding to the transparency window of fiber optics with a quartz core.

We used a pulse-periodic YAG: Nd laser operating at a wavelength of 1.064 μm for laser-stimulated doping of thin semiconductor films in our experiments. A thick film of erbium oxide or ytterbium oxide was deposited on the surface of ZnO, which is a solid-state source of doping agent. The process of pounding and distillation of dopant REI from a solid-state source was carried out using non-equilibrium laser-stimulated doping. The presence of REI inside a ZnO thin film was confirmed by photoluminescence spectra in the IR spectral band 1.0 - 1.8 μm.

It was found that zinc oxide films containing erbium and ytterbium ions exhibit intensive photoluminescence at room temperature at wavelengths corresponding to intracenter 4f-transitions in erbium. The study of generation-recombination processes and the transfer process of the charges injected into the studied structure made it possible to estimate the main parameters of the deep traps in the system of ZnO:(Er: Yb).

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PS1-W04-6 Influence of nanoporous silicate matrices surface nanoroughness on the SERS signal

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Nanoporous silicate matrices (NPSM) open a wide range of possibilities for studying substances in molecular dispersed states in a confined volume [1]. Characteristics of nanoporous silicate matrices that determine their internal structure are known [2]. In cases of using NPSM as a surface-enhanced Raman scattering (SERS) substrate, the parameters of the SERS signal are determined by the surface structure of NPSM [3].

In this research, the surface structure of the NPSM samples according to data obtained using an atomic force microscope was considered. Mathematical processing of NPSM surface roughness data using the Matlab software package was carried out. Enhancement of SERS signal on samples of different types of NPSM with different regimes of gold deposition was researched. Correlation between the change in the enhancement of SERS signal and the roughness parameters was shown.

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PS1-W04-7 Formation of nanoparticles from thin silver films under a liquid layer by single-shot nanosecond laser action

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The formation of monodisperse noble metal nanoparticles (NP) is of considerable interest for some applications, such as SERS, catalysis, the development of various sensors, and photovoltaic power engineering. Metallic thin films deposited on dielectric substrates are, as a rule, thermodynamically unstable at elevated temperatures and can disintegrate into separate NPs due to minimization of the free energy of the system associated with the film interfaces [1,2]. When the substrate-film system is in a liquid medium, the formation of NPs occurs not only due to the thermodynamic instability of the film but also under the influence of the Rayleigh-Taylor (R-T) instability, which occurs between two contacting continuous media of different density [3].

Here, we experimentally investigated the laser-induced dewetting of thin (10 nm) silver films on a dielectric substrate, caused by R-T nanoscale instability, which occurs due to the vapor pressure of the liquid on the molten film, and the effect of liquid viscosity on the dimensional characteristics of the resulting nanoparticles is considered.

Laser irradiation was performed at normal incidence by Nd:YAG laser (λ=532 nm, 6-9 ns pulse duration) in a single-shot mode with an unfocused laser beam. The sample was placed in an under a layer of liquid (water, glycerol, polypropylene glycol, ethylene glycol, aceton) or in the air (for reference).

The structures obtained were studied by optical spectroscopy and scanning electron microscopy (SEM). It is demonstrated that NPs obtained by laser exposure in liquids with a high viscosity have a rather narrow size distribution and larger mean size as compared to NPs produced by irradiation in air.

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PS1-W04-8 Cylindrical and flat surface electromagnetic waves in laser technology of silicon surface texturing with a double femtosecond pulse

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Special attention is paid to microstructures arising on the silicon surface under the influence of ultrashort laser pulses. The unique properties of micro-structured silicon: high absorption and anti-reflectivity, controlled wettability, enhanced tribological properties make it possible to create multifunctional surfaces for a wide range of technological applications. In this regard, the requirements for process productivity and the possibility of laser processing at high pulse repetition rates, increase. The accumulation of heat and structural changes that occurs on the surface between pulses [1-2] becomes an important factor. Method of double femtosecond laser pulses with time delays in the nanosecond range makes it possible to investigate irradiation regimes with frequencies of the order and more than 100 MHz [3].

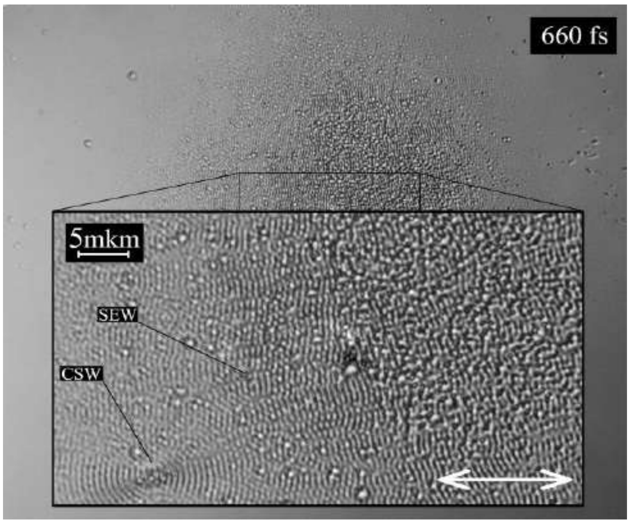

Fig. Optical image of a silicon surface irradiated with one double femtosecond laser pulse with energy density of 0.2 J/cm^2; Δt = 660 fs. The arrow indicates the direction of polarization of the laser radiation.

The paper presents the experimental results of laser modification of monocrystalline silicon surface near the ablation threshold under the action of double femtosecond pulses with varying delays in the femtosecond and picosecond ranges, and also presents the results of numerical simulation (based on the physico-mathematical model [4]) of the semiconductor photoexcitation process in the dielectric permittivity approximation.

Irradiation with one double femtosecond pulse with short delay times allowed to investigate the role of accumulative phenomena occurring in the electronic subsystem of semiconductor. Interpretation of the obtained experimental and theoretical results based on the theory of polaritons has shown that the excitation of cylindrical surface waves (CSW) not only precedes the excitation of flat surface electromagnetic waves (SEW) (Fig.), but is also a determining factor in the accumulation of changes in the dielectric constant of the medium and for creation conditions for SEW excitation.

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PS1-W04-9 Laser direct writing of microstructures on thin titanium films by cw laser radiation

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Laser direct writing (LDW) became one of the most powerful techniques for developing optical devices such as diffractive optical elements (DOEs) or Fresnel lens in recent years because of its simplicity, high performance and low cost. LDW method can be applied to thin titanium films, (forming transparent oxide layer TiO_2) for performing an etching-less, mask-less, and perspective one-step thermochemical writing technology for micro/nanofabrication. Titanium dioxide TiO_2 is well-known by its properties such as high refractive index, biocompatibility, chemical stability and of course transparency in the visible region. Due to these advantages, it is extremely suitable for the fabrication of micro/nano-optical devices.

The most challenging problem we're facing nowadays is development micro/nanodevices with resolution higher than 1 μm-1, but it's difficult for researchers to have such an objective or develop a complicated optical system to achieve such a small focal spot. So, in this work we have proposed a novel study of submicron modification the thin titanium films by using similarities with micro scales. The similarities that have been studied by measuring optical contrast, transmittance, FWHM of the recoded structures, and dynamics of surface temperature during the recording process.

In this work cw-Yb-fiber laser has been coupled with a scanning system with rotating mirrors allowing to scan the film surface with various speeds. In addition, we used Gentec-EO Solo2 power meter to control the laser power, thermal camera FLIR Titanium 520M to evaluate temperature distribution on the surface of sample, and optical microscope Carl Zeiss Axio Imager A1.m to examine recorded microstructures. Presented results are significant for developing the one-step laser thermochemical writing technology with high-resolution.

This work was supported by the grant #17-19-01721 from the Russian Scientific Foundation.

PS1-W04-10 Structural and optoelectronic properties of multimodal nanocomposites formed by laser-assisted modification of silicon-based nanoparticles

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Laser-assisted fabrication is one of the foremost and versatile techniques for manufacturing of contamination-free multifunctional nanostructures. In particular, pulsed laser ablation provokes fast and facile formation of different nanoparticles (NPs) such as silicon, silicon carbide, germanium, gold, silver, palladium etc. that can be employed for a wide range of applications [1,2]. In addition, it also allows synthesis of core-shell and alloy bimetallic nanoparticles with variable chemical content (e.g., AuAg, AuPd, AuFe etc.). Such nanocomposites attract great research interest due to combination of the unique modalities of several elements leading to remarkable improvement of NP functionalities compared to single component nanomaterials.

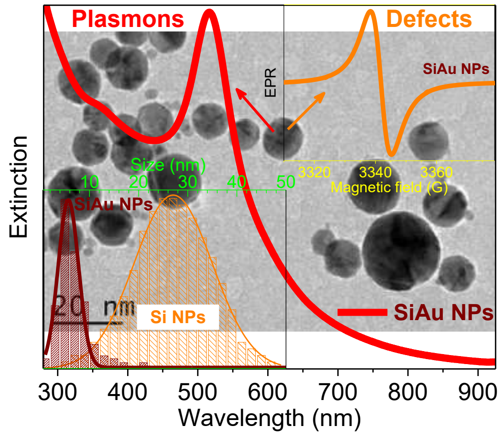

Figure. Multimodal properties of SiAu NPs.

Lately, possibility of laser-assisted interaction between both semiconductor and metal species (e.g., Si-Au) leading to formation of composite NPs is just reported in few papers [3]. These single elements show huge perspectives in the field of nanomedicine and their combination in form of one nanoparticle can provoke significant extension of their employment for bio-related applications.

In this work, composite Si-based nanoparticles with multiple modalities are synthesized using different approaches of pulsed laser ablation in liquids. Their structural and optoelectronic properties as well as chemical composition are investigated for the first time by such methods as high-resolution transmission electron microscopy, energy-dispersive X-ray spectroscopy, X-ray diffraction, electron paramagnetic resonance, photoluminescent and Raman spectroscopies. Influence of experimental conditions on properties of Si-based nanocomposites is established too and formation mechanisms are proposed. In addition, their ability to molecule detection using surface-enhanced Raman scattering is shown.

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PS1-W04-11 Photocatalytic properties of TiO_2 and TiO_2-Ag nanoparticles synthesized by pulsed laser ablation in liquid

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Titanium dioxide (TiO_2) nanoparticles (NPs) are efficient and cheap photocatalysts, so TiO_2 NPs are widely used for the decomposition of organic substances. Today, an important task is to increase the photocatalytic efficiency of TiO_2, which can be achieved by controlling the phase composition of TiO_2 NPs. Another direction is the transition from UV range light sources in photocatalytic processes to sources of the visible spectrum; this problem can be solved by creating nanocomplexes based on TiO_2 and plasmonic NPs (Ag, Au, Cu), which have a resonant absorption in the visible part of the spectrum. This study is devoted to solving these problems using the pulsed laser ablation in liquid (PLAL) method.

In the present work, a pulsed fiber laser (IPG-Phototnics, 1064 nm, 20W, 1.6-1000kHz) was used to synthesize TiO_2 and TiO_2-Ag NPs, the radiation was focused on a mechanically polished titanium plate (Ti - 99.5%) into the spot of 55 microns. Distilled water and an aqueous solution of $AgNO_3$ were used as liquids. The properties of the nanocolloidal solutions were studied using the means of optical spectroscopy, Raman spectroscopy, the morphology of the obtained NPs was studied with the scanning and transmission microscopy. Experiments were conducted on the photodegradation of methylene blue dye using the obtained nanocolloidal solutions, for which various light sources were used both in the self-absorption region of TiO2 NPs (UV-lamp, 254 nm) and the visible range (halogen lamp, 400 – 900 nm).

As a result of our research, laser irradiation regimes were obtained, which make it possible to effectively control the phase composition of TiO_2 NPs and obtain different phase ratios (anatase, brookite, rutile). It was experimentally shown that the presence of the rutile phase greatly reduces the photocatalytic efficiency of TiO_2, the highest photodegradation rates were achieved using ultrafine (<5 nm) TiO_2 NPs in the anatase and brookite phases. Based on the obtained pure TiO_2 NPs, hybrid TiO_2-Ag NPs were synthesized, which showed a high photocatalytic ability upon irradiation with a broadband light source in the visible range. This indicates the effective visible light conversion of Ag NPs for photocatalytic reactions. Thus, it is shown that PLAL is an effective, adaptive and environmentally safe method for the synthesis of NPs with high photocatalytic ability.

PS1-W04-12 Fast fabrication of spiral varying retarder on $CaCO_3$ plate by laser-induced microplasma for generating radially polarized light

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Recently, sufficient attention is given to the creation of a radially polarized annular beams. Such beams find application in manipulation of metal and dielecric particles, super-resolution microscopy, cooling of atoms, also in precision laser microprocessing of materials [1-3]. One of the successful technical solutions for generating radially polarized beams from linearly polarized Gaussian beams is the use of a spiral varying retarder (SVR) made on the plate of birefringent material (fig. 1(a)) [2, 3]. Two technologies have been used for SVRs' fabrication: laser-induced backside wet etching on crystalline quartz [2] and multistage dry etching process with inductively coupled argon gas plasma using silicone masks on α-BBO crystal [3]. The first one is characterized by a low SVR quality and the other is a long and complicated process.

We propose to use laser-induced microplasma (LIMP) processing for fast, reliable and effective fabrication of SVR on the $CaCO_3$ plate. The laser irradiation regimes were experimentally determined, enabling to vary the etching depth of $CaCO_3$ in the range of up to 14 μm without cracks in the processing area. The LIMP allows to create SVR with diameter of 10 mm consisting of 20 sectors with a roughness of 50 nm (fig. (b)) in less than 7 minutes. When SVR fabricated by the LIMP technology placing between two quarter wave plates with orthogonal slow axis into experimental setup with He-Ne laser the registration of typical images of intensity distribution in the far field without analyzer (fig. 1 (c)) and for its four positions (0º, 45º, 90º, 135º) (fig. 1 (d)) confirmed the SVR's ability to generate radially polarized light of high purity.

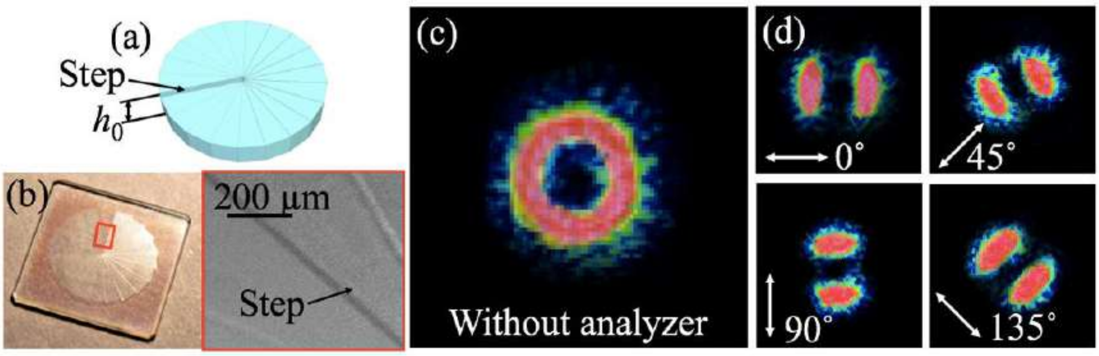

Fig. Concept of SVR (a); photos of fabricated SVR; the annular intensity distribution in the far field (c); the far field intensity distribution upon analyzer rotation (d)

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PS1-W04-13 Direct writing of micropatterns using selective laser sintering technique and their application as non-enzimatic sensors

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At present, flexible and wearable electronics is a promising and rapidly developing technology, which in recent decades attracts a great attention both for industrial and academic applications. However, one of the significant obstacles on the way to the implementation of such systems for the aforementioned purposes is the lack of high-performance flexible electrodes and other functional elements of dielectric and semiconductor nature.

In this work, the composite electrodes on the surface of different dielectrics (PEN, PI, glass, glass-ceramics) is fabricated using reactive selective laser sintering (SLS). The main objective of the current project is to study the effect of laser processing conditions and the solution composition on the properties of the deposited structures in order to develop controlled methods of laser-induced synthesis of functional electrode materials for enzyme-free sensors. A metal oxide NP solution including metal oxide NPs, a reducing agent, and poly(vinyl pyrrolidone) (PVP), is irradiated by CW and femtosecond lasers and 2D Cu electrodes are successfully formed by laser-induced reduction, agglomeration, and sintering of oxide NPs. Metal- and oxide-rich micropatterns (electrodes) have been selectively fabricated by controlling the laser scanning speed, pulse energy and power density. The fabricated materials were characterized by SEM, EDX, XRD techniques.

The sensor properties of microelectrode were examined by recording CVs in solutions containing different concentration of D-glucose and other biomarkers. In addition, the amperometric technique was also used to evaluate electrocatalitical activity towards detection of aforementioned analytes. Moreover, microelectrodes showed high selectivity towards glucose in the presence of interfering compounds such as uric acid (UA), ascorbic acid (AA), and 4-acetamidophenol (AP), which usually coexist with glucose and hydrogen peroxide in human blood.

PS1-W04-14 Usage of laser-induced microplasma for fabrication of birefringent phase plate to generate ring beam from linearly-polarized Gaussian beam

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It is known to date that the use of beams with null intensity on axis because of their unique properties finds wide application in such areas as photonics, super resolution microscopy, manipulation of metal and dielectric particles in strong laser fields, biomedical microanalysis. It is also aware that the most effective for majority of laser microproceeding technologies is the use of such beams[1].

One of relatively simple optical element for conversion of a linearly polarized Gaussian beam into an annular beam is a phase plate (PP) of various geometry. The operation principle of the PP on an amorphous material lays in the creation a phase difference of π radians in different parts of the incident beam[2]. As a result, destructive interference occurs between parts of focused beam.

In the present paper will be proposed the use of a birefringent uniaxial crystal whose crystal axis is oriented parallel to the plate surface (Y-cut) for the fabrication of PP. The principle of work of the PP is based on the creating phase shift in π between two parts of passed beam. The outer ring bounding the PP, coaxial with the central circle, will be etched to the same depth (Fig.).

The minimum etching depth, implemented at m = 0, will be:

$$h = \frac{\lambda}{2(n_0 - n_e)} , \qquad (1)$$

The PP testing will be performed on the transformation of a linearly polarized Gaussian beam into an annular one in two schemes, the first of which is the imaging scheme and the second is the focusing scheme.

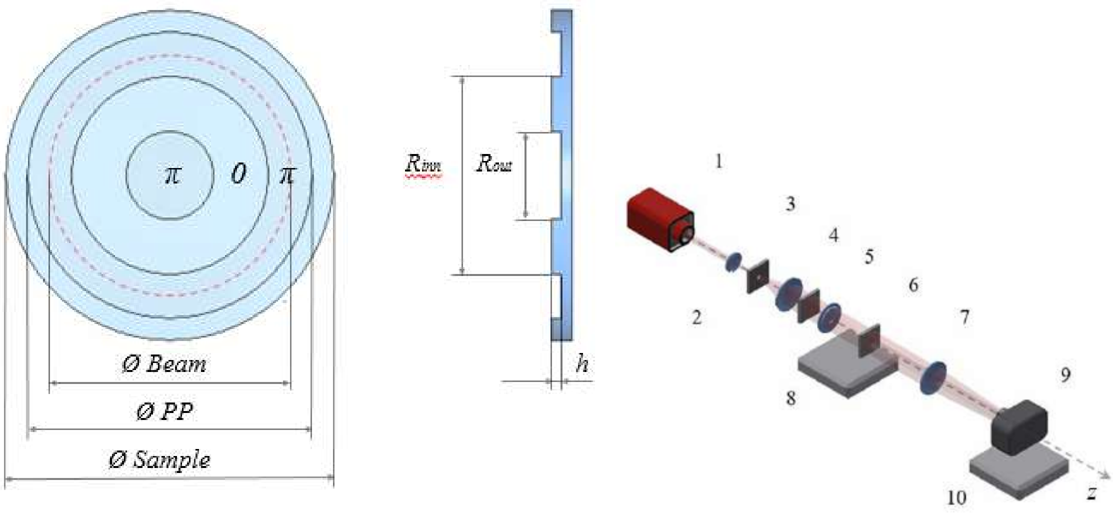

Fig. Concept of PP (a); The setup for testing of PP (b)

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PS1-W04-15 The effect of the size of gold nanoparticles on the effect of fluorescence intensity enhancing of a polymethine dye

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The effect of gold nanoparticles of various sizes on the plasmon-enhanced fluorescence of a polymethine dye in ethanol solutions was studied. For the study, a dye solution in ethanol with a constant concentration of 10^{-5} mol/L was used. The concentration of Au nanoparticles (NPs) was varied in the range of $10^{-10} - 10^{-13}$ mol/L. Au NPs were obtained by the laser ablation, average sizes of the NPs were equal to 20, 40 and 60 nm.

The spectral-luminescent properties of a polymethine dye in the presence of plasmon NPs were investigated. Measurements have shown that the addition of Au NPs with d = 20 nm leads to an increase in the fluorescence intensity of almost 4,5 times at a concentration of nanoparticles of $2 \cdot 10^{-10}$ mol/l.

When 40 nm NPs were added to the dye solution, the two-fold growth of the fluorescence intensity was registered at the NPs concentration of 10^{-11} mol/l.

For solutions with d= 60 nm NPs the maximum increase the fluorescence intensity (almost in 1,7 times) was registered at Au concentration of $2*10^{-12}$ mol/l.

In all three cases, a further increase in the NPs concentration in the dye solution leads to a decrease in the fluorescence intensity. The lifetime of the fluorescence of the dye at the same time was decreased by only 5%.

Thus, it was shown that the greatest effects of enhancement of the fluorescence intensity of the dye can be obtained in the case of using smaller gold NPs.

It is likely that the observed increase in the fluorescence intensity is due to the growth of the excitation rate of dye near the silver nanoparticles, increase in the rate of radiative decay of the studied dye does not occur.

The experimental results obtained are important for application in optoelectronic devices and laser media.

PS1-W04-16 Kinetic of micro-relief formation on fused silica by laser-induced microplasma action

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Laser-induced methods are a promising tool in the field of optical materials structuring, possessing high resolution and easy application. One of these methods is microplasma processing (LIMP) developed by our team. In short description, laser radiation passes through the optically transparent sample and acts with highly absorbing target. As a result, plasma plume arise and interact with glass material forming micro/nano relief [1]. It was found out that proposed method allows to fabricate a relief in depth (0.1 – 5 μm) having a roughness of 50 nm. In this way, we have successfully fabricated a wide class of microoptical, phase elements, even multilevel elements on glass surface [2].

It is obvious that LIMP resolution (like in LIPAA, LIBDE etc.) depends not only on focusing condition, but also on the gap between the target and the glass [3, 4]. The size of the gap effects on the volume of cellular graphite appeared during laser processing. In addition, graphite particles decrease the radiation intensity passing in the processing region. All this points have to be determined and investigated.

The aim of the work is to determine the effect of graphite particles on the maximum relief depth and the resolution of proposed method.

The array of 100 craters was registered on fused silica by LIMP method. The number of impulses N+1 corresponded to each subsequent crater (fig. 1, a). That allowed analyzing the effect of graphite particles on the depth of the recorded crater. Optical profilometer was used to investigate geometrical and morphological properties of fabricated craters (fig. 1, b-d).

An experiment with a change in the gap between the target and the sample with the help of a motorized slide confirmed the widening of a plasma plume, the scattering angle of which was 6.7°.

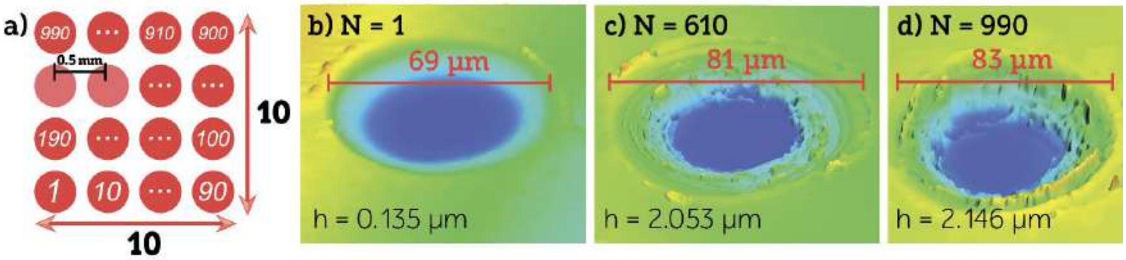

Figure 1 – a) Array layout; b-d) Surface profiles: red is higher, blue – deeper

In particular, the wide of craters grows weakly with an increase in the number of pulses and shows a linear relationship. The depth has the same way in the beginning – a rapid linear growth, but then a deceleration portion follows, and finally the value begins to oscillate around a certain value (deviation of laser pulse-to-pulse value).

The reported study was financially supported by the Ministry of Education and Science of the Russian Federation, research agreement № 14.587.21.0037 (RFMEFI58717X0037).

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PS1-W04-17 Atomistic simulation of laser ablation of silicon by ultrashort laser pulses

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Laser fabricated resonant silicon nanoparticles have been employed for a broad range of applications. It can be assumed that the mechanism of nanoparticle formation in this work is similar to the laser ablation mechanism. So, the laser ablation process in the various conditions is studied using two-temperature atomistic model. This model describes ionic subsystem by means of molecular dynamics while the electron subsystem is considered in the continuum approach.

The surface modification after laser irradiation can be caused by ablation and melting. For low energy laser pulses, the nanoscale ripples may be induced on a surface by melting without laser ablation. Laser ablation occurs at a higher pulse energy when a crater is formed on the surface. The ablation thresholds of surface ablation by ultrashort laser pulse of variable width at various temperatures of silicon are calculated. Absorbed threshold fluence decreases by 20 mJ/cm^2 when the initial temperature of Si increases from 300 K to 900 K. Whereas increase in laser pulse width from 0.1 – 4 ps in atomistic simulations results in threshold fluence increase. In experiments square-root rise of ablation threshold with increasing pulse width for silicon is associated with two-photon IR excitation. Also, the dependence of the modification depth (ablation or melting) on absorbed fluence is obtained. The results of simulations are compared with the available experimental data for silicon.

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PS1-W04-18 Laser-induced growth and degradation of gold nanoparticles in titanium dioxide porous film

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Nanocomposite materials containing resonant metallic nanoparticles have wide perspectives due to their unique optical properties. For ages people have been using different glasses containing gold nanoparticles for decoration of different artworks and architectural monuments. Nowadays, laser sources provide possibilities of a highly localized control over optical properties of glass-like composite materials. Thus, numerous new applications appear in such fields as advanced nanophotonics and optoelectronics, nonlinear optics and security.

In this work we investigate the processes occurring in a TiO_2 mesoporous thin film containing small (d<5nm) Au nanoparticles under femtosecond laser irradiation. The experiments were performed using the 180 fs laser source with the wavelength of 532 nm and repetition rate of 610 kHz. Interestingly, the laser treatment initiates both the growth of nanoparticles and their decomposition. It was found that at a low scanning speed V_{sc}=0.16 mm/s it is characteristic the growth of nanoparticles due to coalescence of initial ones. After laser treatment the nanoparticles of about 40 nm appear. The porous film in this case modified and cavities around large NPs occur at the top of the film. Such phenomenon is related to the temperature increase on nanoparticles which are large enough to initiate the resonant absorption, thus, the local temperature rapidly increases. Due to the high temperature gradients, the nearby material experiences stresses and is solidified in the form of a tiny cavity surrounding the nanoparticles. Such modification was represented for average power range of 160 – 220 mW.

On the other hand, for the higher scanning speed V_{sc}=1.6 mm/s the number of small nanoparticles is even lower than in the initial film within the same power range. Upon laser energy absorption, small nanoparticles move from the top of the film and the temperature rise is not enough to initiate their coalescence growth. In this case, the film mostly stays unmodified.

The results of this work allow deeper understanding of the processes taking place in the nanocomposite films under fs laser irradiation.

PS1-W04-19 Modeling the optical properties of composite materials based on metal nanoparticles of elliptical shape

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Recently, technologies for creating and processing miniature and multifunctional materials and systems have been actively developing [1-3]. In photonics, special interest is given to the creation and processing of composite materials that are capable of combining various properties. Examples of such materials with nonlinear optical properties are dielectric or semiconductor matrices containing nanoparticles of noble metals: Au, Ag, Cu. The optical characteristics of these materials are significantly affected by the plasmon resonance of nanoparticles, which manifests itself as a peak in the visible spectral range. The shape and position of the plasmon resonance peak depend on the shape of the nanoparticles, size, concentration, and other parameters [4-6]. In particular, composite materials containing elliptical nanoparticles exhibit more pronounced nonlinear optical properties in comparison with composites based on spherical nanoparticles [7]. The materials created on the basis of such nanoparticles are used for the manufacture of superlens [8], elements for solar cells [9], and light filters or digital sensors [10].

In order to model the optical properties of functional materials, methods based on the effective medium theory are widely used. One of the methods for calculating a two-phase system is the Burgemann approximation in the Bergman solution, according to which the effective dielectric constant of the medium is expressed through the spectral density function [11, 12]. A significant amount of work is devoted to determining the spectral characteristics of composite materials based on spherical nanoparticles using the Bergman solution; however, this model does not allow to model the spectral characteristics for samples containing nanoparticles of other shapes.

This work is devoted to the ascertainment of the spectral characteristics of composites containing nanoparticles of noble metals of elliptical shape. For this purpose, the conditions for correcting the Bergaman method for the case of elliptic particles were determined, and spectral characteristics were obtained using the corrected model. The obtained results are compared with the Maxwell-Garnett model for the case of elliptic particles.

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PS2-W07-1 The removal of candle soot and coating varnish from the surface of oil painting by hydrogen fluoride laser

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The report presents the results of research aimed at studying the possibility of using electric-discharge non-chain chemical HF-lasers for removing candle soot and removing varnish that has lost transparency from the surface of oil painting. The first task seems to be the most actual for our country. The second task is one of the fundamental in the restoration practice of the whole world.

As objects for laser action fragments of an amateurish painting (made with oil paints more than 60 years before the experiments) were used. Fragments were covered with soot from a “typical” church candle (with a high content of paraffin).

The laser used by us (EMG 101) generated in a non-selective mode on a group of vibrational-rotational transitions of HF molecules in spectral range 2.6–3 μm.

The value of the energy exposure of the irradiated images varied within 0.2–2 J/cm^2; the duration of the generation pulse (at a level of 0.5) was ~ 0.1 μs. The effects of exposure were assessed using a microscope, visually and in the colorimetric space of CIE L*a*b.

In our work the possibility of removing candle soot from the surface of oil painting with the HF-laser without damaging the paint layer was demonstrated, and the possibility of top coat lacquer removing was also shown. Both tasks can be solved without the use of solvents. The values of the energy exposure, providing a safe mode of action for the paint layer were estimated.

In our opinion, the main mechanism for the removal of soot is the evaporation of paraffin. Linseed oil based coating varnish was removed due to multiphoton (multi-stage) absorption of IR-radiation. Nonlinear absorption of IR-radiation in a top coat lacquer leads to a decrease of the ablation threshold and increases its speed, reduces the irradiance of the underlying pigment layer.

PS2-W07-2 Optimization of cleaning of various contaminated surfaces using YAG: Nd^{3+} laser

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Various modes of cleaning contaminated opaque surfaces (copper, iron, aluminum, wood), as well as the cleaning of transparent substrates from the applied coatings were investigated.

It was found that the most technologically advanced laser source (i.e., the optimal device in terms of price, performance, and quality of cleaning) is Q-switched YAG: Nd^{3+} - laser with a 1-10 ns pulse duration. At longer pulse durations (20 ns-100 μs), the process of melting the metal base of the samples begins to predominate. With shorter pulse durations up to femtsecond ones, the quality of purification improves, but such sources are much more expensive and, therefore, non-technological.

The specified laser source effectively removes layers of corrosion and some types of paint up to 150 microns thick in a single pass with a pulse energy of 6-8 mJ and a focus spot diameter of 1-2 mm. The mechanism of radiation effect on the surface in this case, presumably, is ablative.

An introduction of laser radiation into a multimode fiber with a core diameter of 600 microns has been made. Input efficiency was about 70%. At the exit of the fiber, a lens was installed, which allows focusing the spot at a distance of 3-5 cm from the exit. Using this device, laser radiation can be supplied to any surface to be cleaned. At the same time, it was found that the quality of cleaning of contaminated surfaces is significantly improved due to the fact that the radiation emerging from the fiber propagates under a large range of angles.

The cleaning of thick layers of rust (≥ 1 mm) on an iron plate was investigated. Direct exposure to laser radiation in air does not have any noticeable effect on the contaminating layer, even at an energy density close to the air breakdown threshold. It was found that when such samples are immersed in an auxiliary medium, the nature of interaction with laser radiation changes significantly. Laser pulses of the same energy quickly remove thick layers of rust (up to 1-3 mm per pulse at a pulse energy of 50-70 mJ, the spot diameter is 2-3 mm). Upon reaching a clean metal surface, the interaction ceases. The mechanism of such interaction is subject to additional research.

During laser cleaning of transparent films with coatings (magnetic tape, film), it was found that the cleaning efficiency (removal rate of the coating) increases by more than an order of magnitude when the laser irradiates the non-working side of the film. The resulting plasma torch significantly enhances the removal of the coating substance in the direction of radiation. As a result, a complete cleaning occurs in 1–2 pulses (6–8 mJ pulse energy, 2 mm diameter). When exposed to the working layer, the coating with each pulse is slightly removed and subsequently, laser irradiation leads to heating and melting of the film.

Our investigations allowed as to improve the technology of laser cleaning of contaminated surfaces and apply it in various practical applications.

PS2-W07-3 Investigation of 19th century glass beads degraded areas by Raman spectroscopy and luminescence spectroscopy

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Objects from the historical art glass are the important part of the cultural heritage and could give a lot of information about glass-making technology development.

It was noticed that one of the particular feature for some historical glass beads of 19th century is a tendency to more intense destruction than others. A number of internal (e.g., the glass composition) and external factors, such as temperature, humidity and other storage conditions are responsible for chemical and physical processes on the glass surface and inside.

In this work to estimate a preservation state of the art glass items and to understand the mechanism of the blue seed beads degradation the micro-Raman spectroscopy and fluorescence were used. The Ar^+ laser mode 488 nm was chosen to excite both Raman scattering and fluorescence recording stokes part from 489 to 950 nm. The investigated areas of beads were selected visually by strong change in it’s colour from blue one to yellow one. In the yellowish area it was found formation of copper (I) oxide which structure was almost perfect in the centre of degraded area and becomes more defective at the boundaries. Also formation of KSS crystals in volume of glass in beads it was found, that is in agreement with results of XRD investigation. The transition from non-destructive glass area towards yellow one is discussed in the framework of this study. The attention is paid to non-contact and sensitive detection of yellowish area formation via fluorescence bands of formed crystals inside the glass.

PS2-W07-4 Laser cleaning of lead and zinc exterior sculpture. The role of the pulse duration

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Lead is one of the first metals that became known to a human (along with gold, copper and iron). One of the widely known applications of lead is the ancient system of pipelines in Pompei. The zinc extraction from ore was mastered much later, only in the 19th century; both small objects and exterior sculptures were made of zinc. Production of zinc sculptures even replaced bronze products for a while due to the low cost of zinc manufacturing and its low melting temperature. Over the past decades, the state of the atmosphere has deteriorated significantly, and rate of exterior monuments' destruction has increased, especially in industrial cities like Saint Petersburg. Mechanical and chemical cleaning methods are used to restore the exposition species of monuments; however, chemical reagents (formic, sulfamic, sulfuric acids; Trilon B) can harm the restorer's health. Electrochemical cleaning methods require complete immersion of the object in the solution, which is practically not applicable for monumental exterior sculpture. Lead is also a fairly soft metal, and abrasive or hard manual cleaning can produce marks on the lead surface. Thus, there is an urgent task to find new, alternative methods for cleaning zinc and lead sculptures. Our poster reports experimental results of applying laser as a tool for cleaning the surface of exterior sculptures from corrosion layers.

Comparison of lasers with different durations was made, pcs laser shown the best results in cleaning both of zinc and lead. The measuring of reflectance of corrosion layers indicates minimum in UV part of spectrum, however there were no positive cleaning results using 355nm 25 ns laser. The pulse duration is much more important parameter in preservation of surface during laser cleaning, as shown. Also, the surface state plays significant role – the technology of producing of object and its history of exposition.

PS2-W07-5 Layer-by-layer analysis of archaeological coins by means of laser-induced breakdown spectroscopy

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In the research of archaeological artifacts, the task of analyzing their chemical composition is very popular. But in the process of natural degradation, chemical changes occur mostly near the surface of the object. The composition of the alloy changes and layers of mineral patina form on the surface. Often the surface may be covered with soil contamination. Therefore, measurements taken directly from the surface can give controversial results. One of the ways to solve this problem may be the layer-by-layer removal of the material with the analysis of its chemical composition.

The only micro-destructive method of layer-by-layer analysis is LIBS, which allows to determine the qualitative and quantitative composition of objects with sufficient accuracy of depth distribution and the possibility of express analysis.

In our work, a layer-by-layer analysis of coins of archaeological origin from different alloys and different time periods has been carried out. Attention was directed towards the study of the qualitative composition of the patina layer, the surface layer of coins, and the composition of the main alloy. The composition of the alloy of coins was also investigated before and after the restoration cleaning from layers of contamination performed by the traditional method of using liquid cleaning compositions. LIBS results were compared with the data obtained using XRF and the data on the coinage alloy published by the mint. The purpose of the study was to identify the qualitative composition of different layers of the coin: the patina layer and the base material - for determining the content of impurities in these layers, which could ultimately provide important information in the historical aspect. In the experiments, a solid-state Nd:YAG laser (Lotis TII, 532 nm, 10 ns, 10 mJ) was used to excite the plasma, the radiation of which was focused into a spot 50 μm in diameter on the target surface, the plasma spectrum was recorded using a three-channel fiber spectrometer (Avantes, ULS2048, 210-710 nm, resolution 0.12 nm).

Layer-by-layer analysis of the copper coins showed non-monotonic dynamics of the luminescence intensity of Cu I, Cu II spectral lines: up to 20 pulses, an almost exponential increase in their intensity was observed, after 20 pulses a linear decrease in their luminescence occurred, the intensity of the impurities (Na, Ca, Fe), on the other hand, dropped towards the 20th pulse. The analysis of the crater profile showed that in 20 pulses the patina layer is completely removed. This fact explains the disappearance of the lines of impurities (Na, Ca, Fe) contained in the patina layer.

Thus, a layer-by-layer analysis of a series of coins made from an alloy of copper and silver was carried out, and the luminous intensity of the spectral lines was correlated with the thickness of the patina layer. Impurities elements contained in the mineral layer can be used as markers for the border of the metal layer of the patina and the metal layer of the coin, and can be implemented in the laser ablation systems with LIBS control.

PS2-W07-6 Laser cleaning of easel painting with near infrared fiber laser radiation

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Today one of the unsolved problems of cultural heritage preservation and restoration is the problem of easel painting cleaning process. Traditional chemical and mechanical cleaning methods are not able to fully solve a number of issues, such as: removing soot and smut from the surface of paintings and removing aged varnish coatings. Such contaminants, as well as some varnishes, do not dissolve well even with the most powerful solvents, and presence of craquelure on varnish or pigment layer makes the process of traditional cleaning quite complicated, as they contribute to the penetration of the solvent into the inner layers of painting, which can lead to irreversible reactions and destruction of the composition.

This research topic is of particular interest for Russian Federation, as for a country with a rich cultural heritage of easel painting, namely icons. The above problems of painting preservation and restoration are most critical for works of Russian iconography. For example, due to unfavorable storage conditions, a large number of icons are in a form, which is unsuitable for a museum exhibit, and the darkened varnish coatings, used in the past centuries by Russian craftsmen, are practically not subjected to chemical cleaning. Therefore, alternative cleaning methods are being actively investigated today, including laser cleaning methods.

In this work, laser cleaning of samples, which simulate the real easel painting layers, was investigated using a scanning laser system operating in the near IR- range. The effect of radiation with a wavelength of 1.06 μm and 2 μm on surface varnish layers and coloring pigment layers of organic and inorganic composition was explored. In addition, layers that simulate contamination were applied to the samples. That allowed creating conditions, which are as close as possible to the process of real easel product cleaning. Results showed the potential use of the presented laser equipment for cleaning paintings from surface contamination and varnish coatings.

PS3-C02-1 Determination of level of tissue denaturation at upconversion particles

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The actual question of laser thermolysis is the determination of the minimum amount of energy necessary for the thermal termination of the vital activity of the cell. In recent years, a new class of nanoscale luminophores is studying such as upconversion luminescent nanoparticles. Rare earth doped upconversion nanoparticles, which can convert long wavelength near infrared radiation into short wavelength visible radiation via a non-linear optical process, are emerging as a new class of fluorescent biolables. The unique photoluminescence properties of upconversion nanoparticles induced by NIR benefit bioimaging via enhanced image contrast, due to absence of tissue autofluorescence, and enhanced photostability, which enables prolonged imaging even on the single nanoparticle level. In this way, it therefore allows for deep tissue penetration, making them attractive as promising contrast agents for biological sensing, biomedical imaging, and disease theranostics. Hep-2 (HeLa derivative) cell line human was used. We applied the in-house synthesized upconversion nanoparticles $NaYF^4$: Yb^{3+}, Er^{3+}. Upconversion nanoparticles (ca. 220 nm in size) incubated with the cells was found to be endocytosed by cells. In the samples with nanoparticles and after irradiation zones with a pronounced cytotoxic (necrotic) effect were observed. It was obtained several types of cell damage (denaturation) after laser heating of cell culture with upconversion nanoparticles. It depended of concentration nanoparticles in cell and amount of absorbed laser irradiation.

PS3-C02-2 Effects of scattering and birefringence on phase retardation of polarized light propagated in biological tissues

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The use of polarized light in various biomedical applications has been growing explosively over the past decades. In the widely used Mueller-matrix decomposition approach, the phase shift between electric field components occurring due to birefringence can not be distinguished from the phase shift due to scattering, whereas the variation in these processes may be an evidence of different morphological alterations in biotissue. In this study, we present the approach to separate contributions of scattering and birefringence in the phase retardation of polarized light after interaction with biotissue using Stokes vector and Poincaré sphere approach.

In the current study, we examined a set of biotissue-mimicking phantoms with different optical properties and chicken skin tissue with means of circularly polarized light sensing, Stokes vector and Poincaré sphere approaches. With the help of biotissue-mimicking phantoms, alterations of scattering and birefringence were imitated independently and their influence on the incident circularly polarized light was traced on the Poincaré sphere. Based on the model experiments, the samples of chicken skin with alterations of scattering and birefringence were examined. The scattering in skin tissue was reduced by optical clearing, whereas birefringence was induced by mechanical stretch of the sample. The inducement of birefringence via mechanical stretch in chicken skin was validated by second-harmonic generation imaging.

The results have shown different patterns of the state of polarization of light mapped on the Poincaré sphere for scattering and birefringence alterations, which makes it possible to identify these two mechanisms of phase retardation. Thus, the magnitude of the form birefringence in tissue samples was estimated separately from scattering.

PS3-C02-3 Complex spectral assessment of organic composition of the bone bioimplants in their manufacture

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At the moment, the pressing challenge of implantology is to assess the quality of treatment of biomatrix, which are produced for the restoration of bone defects and reparative osteogenesis.

The study of bone proteins and their modifications has become an urgent task for a better understanding and detection of bone diseases. However, because bone is mineralized, the analysis of protein content in bone is more difficult than the analysis of proteins in other non-mineralized tissues [1].

Engraftment of bioimplants depends on the removal of cellular proteins and nucleids – the main factor of antigenicity, as well as on their quality and production technology aimed at preserving the necessary biological substances involved in the regenerative process, such as hydroxyapatite, collagen, glycosaminoglycans, osteopontin, osteomodulin, osteoglycin and others [2]. Therefore, it is necessary to constantly quality control of implants with assessment of the organic component.

Objects of the research were 36 demineralized spongy bone bio-implants in the form of a cube 5*5*5 mm, made using the "Lioplast"® technology (ТУ-9398-001-01963143-2004).

Estimation of qualitative composition and relative concentration of bone bioimplants components were carried out using the experimental stand, which consists of an optical Raman module PBL 785 in combination with a diode laser module LML-785.0RB-04 (power until 500 mW, wavelength 784,7 ± 0,05 nm) and a high-resolution digital spectrometer Shamrock sr-303i with a built-in cooled camera DV420A-OE , providing a resolution of 0,15 nm.

Basic spectral bands of the organic component of demineralised implants are correspond to the components of organic matrix : amide II, lipids and fatty acids, DNA, phospholipids, Proline, glycogen and phenylalanine.

Using extended spectral analysis of Raman spectra and proteomic mass spectrometry of implants made on the basis of bone tissue, the main differences between cadaveric and intraoperative materials and presence of extracellular matrix components affecting their quality and providing the possibility of a good clinical effect: glycosaminoglycans, collagen, proline, hydroxyproline and phenylalanine and proteins are shown.

Thus, the optical method for the assessment of bone bioimplantation by spectral relations Ki can be used further for optimization of the production process and the selection of the donor material at the time of bioimplants manufacture.

The results were compared with proteomic mass spectrometry.

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PS3-C02-4 Detailed analysis of Raman spectra for rapid assessment of the bioimplants quality for dentistry

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Bioimplants of human tissues are widely used for reconstruction and restoration of supporting and connective tissues of a recipient. At nowadays, the problem of development and treatment of a gingival recession is relevant, which is primarily due to the high prevalence of pathology. It is 45.5 – 99.3 % according to various data [1]. In this disease, patients are usually concerned about aesthetics, increased sensitivity of exposed teeth roots, discomfort in process of cleaning and caries [2]. Lack of treatment can lead not only to deformation of the teeth, but also to their loss. Therefore, the elimination of a gingival recession is an important and necessary measure.

At the moment, one of the most optimal technology for the production of bioimplants with subsequent use in dentistry is the technology "Lioplast" (Russia, Samara) [3]. During processing, biomaterials are exposed to lyophilization.

The objects of the study were samples of bioimplants of hard palate, made by "Lioplast" technology. The samples were divided into two groups. The first group consisted of lyophilized samples, the second group – samples without treatment.

Raman spectroscopy method was chosen as the main research method. It was implemented by the experimental stand equipped with a digital spectrometer Andor Shamrock sr-303i with a built-in cooled camera DV420A-OE, providing a resolution of 0,15 nm and an optical Raman module PBL 785 in combination with a diode laser module LML-785.0RB-04 (power until 500 mW, wavelength 784,7 ± 0,05 nm). The obtained spectra were processed in Wolfram Mathematica software.

A comparative spectral assessment of component composition of hard palate implants surfaces, which made by "Lioplast" technology with and without lyophilization was carried out.

It was found that the main differences between the groups appear on the wavenumbers 1446, 1738 (phospholipids), 1660 cm^{-1} (amide I), 852 and 938 cm^{-1} (Proline), 1062 cm^{-1} (GAG's), 1204 cm^{-1} (tyrosine), 1555 cm^{-1} (amide II).

It was found, using the extended component analysis of the studied samples by the method of spectrum deconvolution, that the relative component composition of the outer and inner sides of bioimplants is similar. Insignificant differences appear only on the line 1738 cm^{-1} (phospholipids), which indicates the high-quality technology of processing bioimplants in their manufacture.

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PS3-C02-5 Fraunhofer diffraction and waveguide light propagation in tooth enamel

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The increased interest in the study of the optical characteristics of hard tooth tissues in modern dentistry is due to the use of methods of direct aesthetic restorations of teeth with light-cured materials as well as the use of optical methods for diagnosing of teeth lesions. Due to presence of ordered structures enamel and dentin are anisotropic optical media in which the ratio of transmission and scattering of light depends on orientation of the incident light flux with respect to these structures. Due to anisotropy the study of optical effects in the hard tooth tissues allows to clarify the morphological features of the hard tooth tissues which are important for the work of clinicians.

A study of the propagation of light in tooth enamel was carried out on longitudinal meridional thin sections of extracted teeth.

It is shown that the propagation of light in enamel depends on the angle of incidence of the light beam relative to the direction of enamel prisms. When a laser beam is incident on the enamel perpendicular to the plane of the thin section Fraunhofer diffraction can be observed. When a laser beam is incident on the tooth surface in the thin section plane the pattern of propagation of laser radiation in the enamel can be explained by waveguide propagation of light along enamel prisms. On the basis of the waveguide model conditions for the manifestation of a known optical effect in the form of Hunter-Schreger bands in reflected and transmitted light are explained. It is established that the presence or absence of a diffraction pattern depends on the age of the tooth and thickness of the thin section. The obtained data allow us to recognize the nature of the age mineralization of enamel in the process of its maturation which leads to an increase in the transparency of enamel and a decrease in the degree of its optical anisotropy.

PS3-C02-6 The optical analysis of surfaces of regenerates after performing different methods of chondroplasty

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The problem of restoration of full-layer defects of the articular surface is relevant in modern traumatology and orthopedics. The preservation of the joint cartilage defect leads to the progression of destructive processes in the joint, the development of the most common diseases – osteoarthritis. It is based on a violation of the metabolism and structure of the articular cartilage and subchondral bone, which leads to their destruction. As a result of these processes, cartilage becomes thinner, rough, turbid, less elastic, erosion appear in places of maximum load [1]. Lack of blood supply to cartilage and low metabolism due to the small number of cells per unit volume of tissue lead to the fact that its full reparative regeneration is possible only with small area and depth of damage [2,3]. In recent years, platelet-enriched autoplasma (PEA) is used widely in different branches of surgery. At the same time, studies of chondroprotective and structurally modifying influence on joint cartilage are non-innumerable and contradictory. One of the ways to fill joint defects is their plastic with the use of different materials. Evaluation of the effectiveness of chondroplasty using PEA can be performed by applying Raman spectroscopy to analyze the surface of macropreparations.

The aim of the study is to apply the method of Raman spectroscopy to assess the quality of restoration of the joint defects after different types of chondroplasty in experiments on rabbits.

As study materials were used samples of distal epiphysis of the «Chinchilla» rabbits femur. The animals had a plasty after creating of two full-layer bone-cartilage defects of articular surface in the femoral condyle. It was made in two ways – enrichment by platelet plasma and combination with demineralized bone tissue. Raman spectra of the newly formed regenerates were studied after two weeks and one, two, three months from the date of surgery.

The spectral measurements of the bones were carried out using the experimental stand, which consists of a diode laser module LML-785.0RB-04, an optical Raman module PBL 785, a spectrometer Shamrock sr-303i, a built-in cooled camera DV420A-OE and a computer. The use of the spectrometer provides a resolution of 0.15 nm (~ 1 cm^{-1}) and low noise. The camera cooled till -60 ° C for reducing noise. The obtained spectra were processed in Wolfram Mathematica [4] software. For separation of overlapped peaks we used MagicPlotPro 2.5.1 software [5].

As a result of the research component analysis was extended using deconvolution. In particular, scanning of the surface of the newly formed regenerates after PEA defect plasty, after 2 weeks and 1 month, showed that the ratio of PO3-4 phosphate and Amide I at the wave numbers 956 and 1660 cm-1, respectively, decreases during the transition from the intact cartilage to the boundary zone and the plastic zone. This may indirectly confirm non-organic composition of the newly formed regenerate.

It was found that the spectral composition of the regenerate surface changes depending on the time elapsed since the chondroplasty.

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PS3-C02-7 Theoretical study of iron oxide nanoparticles for laser photothermal therapy

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Photothermal therapy is a kind of therapy based on increasing the temperature of tumor cells up to and above 42°C. This therapy used laser beam which illuminates through cells and generates temperature helping to destroy the tumor cells. This type of therapy is safer than chemotherapy because the side effects from phototherapy are much less due to strongly localized action on the tumor and no effect on the health tissue. In recent years photothermal therapy is considered as an emerging technique for cancer treatment. Photothermal therapy is enhanced considerably at application of exogenous photothermal agents that can be effectively delivered into tumor. In this model, nanoparticles are often used, especially those formed by iron oxides. These magnetic nanoparticles can be injected directly into the tumor before exposure to laser beam. In addition, magnetic energy in the nanoparticles can be converted into heat allowing for a more rapid rise of temperature in the tumor to the desired level. Iron oxide magnetic nanoparticles were considered for this study as they are non toxic and biocompatible. In this theory, we used magnetic nanoparticles which were directed magnetically to the site of the tumor. Using laser radiation which helps to release heat in tissue via selective absorption by inserted magnetic nanoparticles and generate temperature cells up to and above 42°C that damage the tumor cells. This technique can shrink tumor cells with minimal side effects. The objective of this work is to evaluate the temperature distribution of an ordinary tumor over the different sizes and concentration of magnetic nanoparticles. The specific absorption rates (SARs) were obtained through simulation. Various characteristics of the nanoparticles such as diameter, magnetic susceptibility and concentration are considered. The equation of motion describing the problem was solved by numerical simulation.

PS3-C02-8 Automatic classification of fluorescence and diffuse reflectance spectra of biological tissues with significantly different optical properties

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During intraoperative fluorescent navigation when removing various neoplasms, as well as when conducting pharmacodynamic studies of photosensitizers on laboratory animals, in many cases the ratio of photosensitizer accumulation in the tumor and normal tissue can reach tenfold or more, which inevitably changes their optical properties. At the same time, the tumor process induces a number of metabolic and structural changes at the cellular and tissue levels, which also lead to variations in optical properties.

A method and a spectral system for recording fluorescence and diffuse reflectance spectra with an extended dynamic range were developed and they were validated on the optical phantoms with different concentrations of photosensitizers, absorbers and scatterers. Using the developed system with an extended dynamic range, an array of specific features of fluorescence and diffuse reflection spectra was obtained for various organs and tissues of laboratory animals with prior administration of photosensitizers. The resulting array was divided into training and test samples, which were used to train and validate the automatic classification algorithm designed to determine the type of tissue.

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PS3-C02-9 Kinetics of optical properties on selected laser lines of human periodontal gingiva when exposed to glycerol-propylene glycol mixture

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The work is devoted to the determination of changes in optical properties of a highly scattering mucous membrane of a human gum in vitro under the action of such hyperosmotic substances as glycerol-propylene glycol mixture. The gums are the mucous membrane that covers the parts of both jaws around the teeth. It lies close to the jaw bones, goes into the soft tissue of the oral palate and mandibular pterygoid folds. The gum contains stratified epithelium and connective tissue, including collagen, elastic fibers. The epithelium (basal layer) due to the contained glycosaminoglycans (heparin, hyaluronic, chondroitin sulfuric acid) is keratinized, that is why it is resistant to mechanical, thermal, and chemical stimuli. For intensive laser light treatments, it is important to estimate amount of the absorbed light of a certain wavelength by the mucosa of the periodontal that may have photothermal or photochemical effects on certain structures of biological tissue, which leads to various physiological changes. In the work, the diffuse reflectance and diffuse transmittance of sections of the mucous membrane with periodontal lesions before and after impregnation by a mixture of glycerol-propylene glycol were measured. A Shimadzu UV-2550 (PC) two-beam spectrophotometer (Japan) with an integrating sphere in the mode of diffuse reflection and transmission in the spectral range of 200–800 nm was used. All experiments were carried out at room temperature (25 °C). The kinetics of diffuse reflectance and transmittance on particular laser lines of the periodontal mucosa at action of glycerol-propylene glycol mixture was studied. It was found that the reflection decreases and transmission increases with time for all wavelengths selected. As a result, laser beams can be delivered to greater depths of a sample without strong beam distortion, which makes it possible to obtain more valuable information about its structure, pathological changes at the cellular and subcellular levels, as well as provides more precise laser action on tissue. Determination of the optical properties of periodontal gingival tissue in a wide range of wavelengths is an urgent task at present. Determining the quantitative dependences of optical properties is of fundamental importance for creating correct methods for working with quite dangerous and traumatic laser devices in clinical conditions, for conducting photodynamic and photothermal destruction of cells and tissues, as well as for developing new approaches in photodynamic therapy, optical tomography, optical biopsy and etc.

PS3-C02-10 LED devices for the extremely limited high-intensive PDT of onychomycosis and phototherapy of COPD

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Currently, phototherapy and photodynamic therapy (PDT) are being expanded at the expense of new applications. In clinical medicine the most demanded applications of photo- and photodynamic therapy are oncology and dermatology but in last time these therapies come into use in neurology, dentistry, endocrinology and pulmonology. Irradiation of the biotissue with light parameters, the excess of which leads to hyperthermia of the skin can be called extremely limited high-intensive photo- and PDT.

In the current study the results of pilot application of LED devices with wavelength 660nm and 850nm and original mirror focusing system for extremely limited high-intensive PDT of onychomycosis and phototherapy of chronic obstructive pulmonary disease (COPD) were presented.

A matrix of LED sources with a wavelength of 660±10nm and a light power up to 10W «LEDForester660» (Nela LLC, Russia) and photosensitizer «Revixan» (Areal LLC, Russia) with absorption coefficient of about 5cm-1 at a wavelength of 652±2nm was used for extremely limited high-intensive PDT of onychomycosis of foots or wrists.

A matrix of LED sources with a wavelength of 850±10nm and a light power up to 10W «LEDForester850» (Nela LLC, Russia) was used for extremely limited high-intensive phototherapy of COPD.

Both devices were equipped with an original mirror focusing system which allows to create in a rectangular spot 6x16cm on the treated surface (in this case, the surface of the fingers, toes or thorax) uniform light distribution with an intensity of up to 180±20 mW/cm^2.

Onychomycosis treatment showed that one month after therapy by new method average increase in area of healthy part of nail for all patients amounted 6% and COPD treatment showed improvement of state of health of patients, which indicates a good prospect of extremely limited high-intensive photo- and PDT.

PS3-C02-11 Laser ablation of porous silicon for biomedical imaging

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Chemically pure silicon nanoparticles (Si-NPs) have high potential for optical theranostics due to their high biocompatibility, biodegradability and low level of toxicity [1, 2].

We report on silicon nanoparticles fabrication approach consisting in sequential application of electrochemical etching and pico- and femtosecond laser ablation of silicon in liquids (water, ethanol, and liquid nitrogen). As a result, suspensions of Si-NPs with the size of less than 50 nm were formed with a shape close to a spherical one. Si-NPs exhibit effective photoluminescence (PL) with an emission peak within the biotissues transparency window (at 720 nm for laser ablation in ethanol and at 740 nm for liquid nitrogen). Due to the relatively small size, these nanoparticles are promising as PL markers for optical bioimaging.

Optical properties of silicon nanoparticle suspensions produced by ablation in water and ethanol were reconstructed from spectrophotometry measurements employing inverse Monte Carlo technique. All the studied samples revealed a monotonous decrease of the absorption coefficient with the wavelength increase in the range of 400 – 1100 nm. Scattering coefficient of the Si-NPs suspensions was demonstrated to exceed absorption coefficient in the entire considered range. The study of the efficacy of the produced suspensions as contrasting agents for bioimaging was performed by optical coherence tomography (OCT) imaging of agar phantoms upon suspensions topical administration. The Si-NPs were demonstrated to sufficient increase the OCT signal level in comparison with the pure agar phantom, and were proved to serve as contrasting agents for biological tissues and tissue-like media during optical imaging.

Si-NPs fabrication and PL studies are supported by the Russian Foundation for Basic Research (Grant # 18-32-00884 mol_a). Spectrophotometry and OCT studies are supported by the Ministry of Science and Higher Education of Russian Federation (IAP RAS governmental project #0035-2019-0014).

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PS3-C02-12 Active drug delivery of Zn-containing nanomaterials using radiation of Er:Ylf laser

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One of the common pathologies of the nail is onychomycosis – a fungal infection. Photodynamic therapy (PDT) is a promising method of onychomycosis treatment. Zn-containing nanomaterials, such as ZnO and $Zn(NO_3)_2$, are used for PDT of fungal diseases, since they have a high redox potential. In the presence of nanoparticles of zinc oxide, substances with active oxygen (for example, singlet oxygen [1, 2]) are formed, which inhibit the growth of microbes. During the treatment of nail onychomycosis, aqueous solutions, including those with nanoparticles, do not penetrate to the nail bed due to the low permeability of the nail plate. To increase the efficiency of drug delivery to the nail bed, laser microperforation of the nail plate can be used [3].

The rate of penetration of drugs into biological tissue can be increased by the action of laser radiation [4]. It is very important to create a laser whose radiation would not impact on the nanoparticles themselves, but on the medium in which these particles are located (matrix) in order to avoid transformation of their properties under the action of laser radiation. Note that it is extremely difficult to use and store nanomaterials in suspensions (liquids) because of their high fluidity and limited lifetime. Therefore, placing Zn-containing nanoparticles in a solid or gel-like matrix is a very actual task along with creating a method for their efficient laser delivery.

The aim of the work is to create ZnO and $Zn(NO_3)_2$ nanoparticles and to study the behavior of these nanoparticles initially placed in water or polyvinylpyrrolidone gel before and after active laser drug delivery, as well as to determine the activity of these nanomaterials on the fungus T.rumbrum.

The report will describe the dependences of active laser delivery rate of different drugs on the parameters of laser radiation. The results of fungal cell viability assessment after laser drug delivery with PDT will be presented.

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PS3-C02-13 Modeling of the heating process of biological tissues during multipulse ultrashort laser irradiation

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The actual problem of modern laser medicine is the development of methods for precise treatment of various biological tissues with minimal collateral damage. The most promising direction in this area is the use of laser systems with ultrashort pulses. Ultra-short pulsed lasers are mainly used in ophthalmology and show promising potential for dermatology and surgery of hard tissues. In order to achieve high rate of laser treatment, the regimes of multipulse irradiation are used. In this case, laser irradiation can lead to the residual heating. The contribution of residual heat to the process of biological tissue treatment can increase with increasing pulse repetition rate, causing irreversible damage to surrounding tissues. In this connection, it is important to analyse the features of thermal impact of trains of ultrashort laser pulses on biological tissues.

In the report an analytical model is proposed to describe the cooling of a biotissue surface after irradiation by a series of ultrashort laser pulses. A dehydrated bone tissue, a pig skin sample with the black tattoo ink deposited on its rear side and a cotton fabric coloured with the same ink are used as model objects, which are considered as the quasi-homogeneous mediums with averaged values of thermophysical and optical characteristics. The obtained spatial distributions of heat accumulated by the surfaces of model objects in dependence of the pulse repetition rate, number of pulses and laser fluence are compared with the data of experimental irradiation of model objects carried out by the authors [1, 2], as well as the experimental data presented in [3, 4]. In the report is shown, that the model is applicable for nano-, pico- and femtosecond laser pulses.

The application of the model to biological tissues can essentially simplify the search for optimal parameters of lasers that would provide safety and high precision of operations.

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PS3-C02-14 Spectral analysis of bone tissue after ovariectomy and the effectiveness of its treatment with allogeneic hydroxyapatite

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Osteoporosis is a chronic and progressive skeletal disease [1]. It is characterized by systemic bone tissue loss and microstructural damages, which lead to increase of bone fragility and fracture risk due to osteoporosis. Osteoporosis after ovariectomy belongs to the secondary class of osteoporosis and is accompanied by a level recession of microcirculation in the periosteum and bone tissue [2]. Almost every woman in a state of surgical or medical menopause has a low bone mass of the femoral neck, spine or distal forearm [3].

The purpose of the study is analysis of bone tissue using Raman spectroscopy and evaluation of the conducted treatment using allogenic hydroxyapatite (HAP) in different concentrations.

The mature female rats with a mass of 180-290 grams were used as the samples in the research. The modeling of osteoporosis in animals was carried out by bilateral ovariectomy. On the day of the ovariectomy part of the animals had a suspension of allogenic HAP in isotonic sodium chloride solution introduced into the femoral muscle via a disposable syringe in a dose of 10, 20 and 30 mg/kg. The last group rats had the HAP suspension introduced twice – on the day of surgery and one month later. For comparison animals without ovariectomy were chosen. They had single injection of the HAP suspension introduced in doses 10 and 20 mg/kg. Animals that had injections of isotonic sodium chloride solution were as a control group. The study period in the all groups was 2.5 months.

The spectral measurements of the bones were carried out using the experimental stand, which consists of a diode laser module LML-785.0RB-04, an optical Raman module PBL 785, a spectrometer Shamrock sr-303i, a built-in cooled camera DV420A-OE and a computer. The use of the spectrometer provides a resolution of 0.15 nm (~ 1 cm^{-1}) and low noise. The camera cooled till -60° C for reducing noise [4]. Biochemical and histological methods were used as additional research methods, which included comparative analysis of serum hydroxyproline fractions and biometric studies for all groups of the samples.

As a result of the research, spectral changes were revealed at wavenumbers 850 cm^{-1}, 877 cm^{-1}, 957 cm^{-1}, 1038 cm^{-1}, 1243 cm^{-1}, 1069 cm^{-1} for the all samples. The introduced coefficients allow estimating the treatment of the osteoporosis model after ovariectomy using hydroxyapatite (HAP) of different concentration (10, 20, 30 mg/kg). Treatment with HAP showed that for the spongy bone, the consequences of ovariectomy can be partially compensated, and for the cortical bone almost completely compensated for the coefficients «I1069/I1739», «I850/I1739», «I1243/I1739».

Analysis of biochemical, histological parameters and femoral biometrics data showed that double and single introducing of hydroxyapatite to ovarioectomized rats effectively reduces the development of resorption processes.

PS3-W05-1 The fluctuation of the absorbed energy during femtosecond laser writing as a factor for the on-line control of waveguide quality

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One of the most promising trends in photonics and integrated optics development is creation of waveguide structures with low optical losses. Sources of femtosecond laser pulses are widely used for this purpose. Due to high peak intensity it becomes possible to modify any materials due to non-linear absorption of ultra-short pulses. Quality of waveguides of all types plays crucial role for decreasing of optical losses and is determined by parameters of laser writing: energy, duration of pulses, scan rate. Main way to check quality of waveguide is to measure its waveguide properties directly. And there are still no methods, that could reflect quality of future waveguide during the process of its writing.

In present paper we suggest a method of quality evaluating based on measurement of energy fluctuation passed through sample during laser writing process at laser repetition rate of 1-10 kHz. Series of track were written inside YAG:Nd crystal with various pulse energy and scan rate. Parameters responsible for track quality were fluctuation of energy and track asperity. Fluctuation of energy were measured via collecting energy passed through sample using objective with numerical aperture higher than numerical aperture of writing objective and the precision meter measured energy of each pulse. Track asperity was evaluated based on two-dimensional Fourier spatial spectra of track images obtained using quantitative phase microscopy. It was revealed that energy fluctuations grow up with pulse energy with saturation tendency. In the same time dependence of energy fluctuations upon scan rate has different behavior for different material. Analysis of dependence of track asperity on scan rate showed good correlation with dependence observed for energy fluctuation.

PS3-W05-2 Structural modifications of $LiNbO_3$ crystal at femtosecond-laser writing of waveguides

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Direct laser writing (DLW) has emerged as a unique and flexible method for the fabrication of integrated optical (IO) devices in glasses and crystals. The DLW technique has outstanding advantages as a single-step and facile process for generating IO devices in processing times of the order of only seconds to minutes depending on the device complexity. The technique was initially demonstrated in glasses, and later extended to crystals, where extensive laser-writing studies of $LiNbO_3$ have followed. Despite widespread interest, little is known about the mechanisms responsible for the formation of this laser-induced optical waveguide, and the micro-structural lattice modifications underlying the refractive index changes in $LiNbO_3$, having a complex crystal structure into which the extreme interactions of fs-pulses can drive defects, significant strains and localized amorphization.

Raman characterization was systematically applied by us to the channel $LiNbO_3$ optical waveguides fabricated by DLW in the regime of high-repetition rate ultrafast processing (a repetition rate of 0.1 MHz, τ =360 fs, at 1.04 μm). A scanning confocal Raman microscope was used to map the A_1(TO) phonon modes in a transverse plane to the laser-formed waveguide. Raman data on the frequency shift and linewidth of each A_1(TO) phonon mode have provided information on the spatial distribution of defects, residual strain field and local disorder. The stress range corresponding to this strain field was between -64 and + 525 MPa. We also report a Raman study of crystal defects that match the optical morphology of previously observed amorphization found into the fs-laser focal volume.

PS3-W05-3 Femtosecond laser-induced tailoring of crystalline tracks in glass by beam shaping and partial amorphization

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Laser-induced crystallization of glass has been drawing much attention during the last two decades as it gives an opportunity of space-selective growth of functional crystal architectures in glass with the micro-scale resolution. A cutting-edge application of this effect is femtosecond laser writing of oriented single-crystal tracks inside glass which are applicable as channel waveguides with functional properties (i.e. the second-order optical nonlinearity). One of the key problems limiting the performance of the crystal-in-glass channel waveguides and enhancing the propagation losses in them is a strongly elongated, cross-section of the femtosecond laser-written crystalline tracks, often even the horseshoe-shaped one due to bilateral growth of the track on both sides of the writing beam [1].

Here, we describe two ways to improve the cross-section shape of those tracks by an example of stillwellite-like $LaBGeO_5$ tracks in lanthanum borogermanate glass. Application of the Laguerre-Gaussian beam (LG_{01} mode) providing different temperature profile and smaller temperature gradients in glass as compared to the conventional Gaussian beam is shown to avoid the effect of the bilateral growth and to form an oblong cross-section of the track with the improved aspect ratio. Recently, we have suggested a method of femtosecond laser-induced amorphization of the laser-written $LaBGeO_5$ crystalline track in lanthanum borogermanate glass [2]. Now, we report a technique for partial laser-induced amorphization of $LaBGeO_5$ tracks which transforms an elongated cross-section of the track into a smaller, nearly circular one. The effect of the helical and sinusoidal trajectories of the amorphizing beam is compared.

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PS3-W05-4 Anomalously oriented nanograting formation under ultrashort polarized laser radiation interaction with condensed media

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In physics of ultrashort laser-matter interaction the hot topic is the elucidation the mechanism of nanograting **G** production of anomalous orientation, $\mathbf{G} \perp \mathbf{E}$, where E is the electric field strength of laser radiation. One of the causes of such interest is the anomalously small periods **D** of such gratings. We present the review of the experimental publications causing anomalous nanogratings production on condensed media with sufficiently different physical properties and related mechanisms of their formation. The formation of anomalous gratings is not the peculiarity of ultrashort laser radiation action. Their formation was observed in nanosecond laser-matter interaction regimes. The variety of proposed mechanisms of anomalous nanograting formation were analyzed: capillary waves generation, spallation of material, interference with surface plasmon polaritons (SPPs) participation, mutual interference of localized SPPs and others.

The model of mutual interference of localized (channel and wedge) SPPs (including their spatial harmonics) was analyzed in more details. The usual irradiation geometry and nonstandard one (for instance, the two-beam interference) for nanograting formation were considered. Special attention was devoted to periods of G which overcome the optical diffraction limit value and reach the values of the order of **D**≤λ/40. The pure physical limitation on the smallest period value formation arises from the thermal grating smoothing due to thermal conductivity which do not permit the experimental realization more smaller values from the set of Feigenbaum's universality λ/2kζ of higher k values, where ζ is the real part of the refractive index of nonequilibrium solid state plasma –air boundary for local SPPs, k=1, 2, 4, … The experimentally realized values of the period D frequently overcome the Abbe criterion as a result of the nonlinear process of their production.

We show that the universal polariton model takes place for ultrashort terahertz radiation interaction with matter. For such large wavelengths the process of thermal grating smoothing is less sufficient. That is why for terahertz radiation the smallest periods **D**≤λ/25 (λ~100 μm) for monocrystalline silicon and ≤λ/100 for aluminum films were observed.

In summary, the phenomenon of anomalously oriented nanograting formation has universal character. It was shown, that known experimental results causing anomalously oriented gratings production are well explained in the model of mutual interference of local (channel and wedge) surface plasmon polaritons.

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PS3-W05-5 Influence of band filling effect on photo-excitation of semiconductors by short and ultrashort laser pulses at wavelength near the edge of interband absorption

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The irradiation of semiconductors by pico- and femtosecond laser pulses leads to generation of free carriers with concentration about 10^{21} cm^{-3} or even higher [1,2]. In such conditions one cannot consider the valence band as totally full and the conduction band as totally free. Thus band filling effect should be taken into account while analyzing the optical properties of highly excited by the action of ultrashort pulses semiconductor especially at wavelength near the edge of interband absorption.

In this work we analyzed the influence of band filling effect on photoexcitation and heating of silicon by short and ultrashort laser pulses at wavelength 1.06 μm. We show that this effect strongly influence the photo-excitation process of silicon for picosecond laser pulses. The calculations that take into account band filling effect allow to achieve a satisfactory agreement with experimental dependence of melting thresholds on pulse duration.

In addition we studied the transient optical properties of thin silicon plate at wavelength 1.06 μm after intense photo-excitation by femtosecond pulse. The results of calculations show that cooling of electron subsystem via electron-phonon interaction lead to a formation of population inversion state for one-photon transitions between the levels with corresponding energy differences slightly larger than E_g (E_g – band gap). So the fast increase of transmittance of thin silicon plate at wavelength 1.06 μm occurs. We suggest that this effect can be observed in pupm-probe experiments and can serve as a tool for investigation of electro-phonon relaxation processes in semiconductors.

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PS3-W05-6 Dislocation-related luminescence in Si and Si/SiO_2 structure after laser irradiation

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The appearance of four luminescence lines D1 – D4 in near IR range of spectra in silicon samples with high dislocation density usually called dislocation-related luminescence. The most intense line D1 corresponds to the transparency window of fiber optics (~ 1.55 μm), «survive» at room temperatures and is of interest for creation of light-emitting diodes for silicon optoelectronics [1,2]. In this regard, the studies of new methods of controlled formation of extended defects in silicon that are compatible with traditional semiconductor technology are extremely important. One of such methods is laser irradiation. However its capabilities are practically not studied.

In this report we present the new results on the influence of laser irradiation on structural and luminescent properties of silicon in near IR range. We studied the influence of laser processing mode on luminescent and structural properties for different samples (Si and Si/SiO_2 structure). The spectral properties of observed luminescence lines were studied as well as temperatures dependence of its intensities. The types of introduced by laser action defects were revealed by TEM methods.

Our studies shown that laser irradiation at different processing modes lead to appearance of so called dislocation-related luminescence and can be considered as a technological tool for the controlled introduction of optically active extended defects into silicon for further creation of light emitting diodes.

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PS3-W05-7 Modeling of interference thermochemical recording on thin metal films by ultrashort laser pulses

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Laser thermochemical recording (LTR) on thin metal films currently plays an important role in the formation of high-resolution topology of planar structures. Film structures are widely used in various fields, one of which is the fabrication of diffractive optical elements (DOEs). In recent years, new ideas have arisen about one-step laser thermochemical processing without the following etching operation when using thin films of titanium, forming transparent oxide layers. Thus, direct, one-step laser recording become possible, i.e. one can get planar structures immediately after exposure. Using the laser writing by focused laser beam onto the film surface is a low process, and high-resolution of obtained thermochemical images at a large scale may not be achieved. Therefore, by applying the periodicity of an interference field of multi-beams one can completely solve both the size problem and the processing speed. On the other hand, the use of ultrashort (picosecond) laser pulses due to low thermal scattering is well suited for recording interference structures with high resolution. However, using them for the formation of transparent oxide structures such as titanium or zinc films requires exposure with a large number of pulses at a low repetition rate to eliminate heat accumulation in the film and its thermal damage.

In this work, we presented a theoretical investigation of the LTR on thin metal films in the interference field of two beams. The strong nonlinear dependence of the oxide formation rate on the surface temperature and the negative feedback between the optical properties and the oxide thickness were considered. For successful planning and determining LTR potentials in the interference field, the aim of this work is to achieve optimal numbers of pulses that are necessary to gain high optical contrast and minimum FWHM. Therefore, the dependences of the optimal number of laser pulses for various film thicknesses, wavelengths and metals are shown. Obtained results are highly important for developing ultra-resolution optical devices with one-step LTR technology based on interference model.

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PS3-W05-8 Photoacoustic and spectroscopic study of double-pulse femtosecond laser ablation of silicon and transparent dielectrics

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The interaction of femtosecond laser pulses with semiconductors and transparent dielectrics remains a fundamental question for laser physics, and the solution for it is quintessential for effective nano- and microprocessing of these materials.

In our experiments, we used Avesta-Project laser system (λ = 800 nm, τ = 100 fs, E = 1 mJ) and plates of silicon and transparent dielectrics (SiO_2, CaF_2). Laser irradiation was focused by a quartz lens with a focal length of 45 mm onto a sample that was moved using a coordinate table (Standa). Double-pulse regime was realized using Michelson interferometer, which provided a delay range from 300 fs to 1 ns. A photoacoustic signal that forms during an interaction between the laser pulses and the target was registered with a PVDF detector (band pass 5 MHz), the detector was placed 20 mm from the target. In order to register ablation plume spectra, a three-channel fiber spectrometer (Avantes, ULS2048, 210-710 nm, resolution 0.12 nm) was used. Ablation craters were studied using white light interferometry and scanning electron microscopy.

A correlation between the amplitude of the photoacoustic signal, spectral lines intensity and the depth of ablation craters was noticed after researching silicon ablation with double femtosecond laser pulses. For all the targets, both acoustic and optical emission increased for the delays of 10–50 ps, the dependency saturated for the delays of 50–300 ps and then both acoustic and optical emission decreased monotonously after 300 ps. For the delays between 100 and 1000 ps, a significant self-reversal of Si I lines was detected, which indicates the formation of optically dense non-homogeneous plasma. At the same time, the largest mass yield was achieved at the same delays and was half an order of magnitude bigger than the yield of a single pulse with the same fluence. Therefore, the regimes of double-pulse femtosecond laser irradiation were determined for the largest energy input into silicon and several transparent dielectrics.

The authors would like to thank A.V. Redkov for conducting experiments of ablation craters on the white light interferometer. This study was performed using the equipment of the Unique scientific facility (USF) “Physics, chemistry, and mechanics of crystals and thin films” of the Institute of Problems of Mechanical Engineering, Russian Academy of Sciences (St. Petersburg).

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PS3-W05-9 Femtosecond supercontinuum generation in dissipative medium: photoacoustic and spectroscopic investigations

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Supercontinuum (SC) generation is a phenomenon that occurs during filamentation of high-power laser radiation in a medium with Kerr nonlinearity. Filamentation is a complex physical phenomenon that also includes self-focusing of laser radiation and plasma generation. Filamentation is used for remote sensing, remote spectroscopy, and ultrafast absorption spectroscopy, as one of the directions of the development of the "pump-probe" method. Nowadays method of ultrafast absorption spectroscopy isn't well studied. It allows investigating the dynamics of excited molecules in real time.

In this work, we investigate the ability nonlinear broadband spectroscopy of nanoparticle colloids. Supercontinuum generation has been researched during pulse filamentation femtosecond laser radiation extremely high power in dissipative medium (nanoparticle colloids, saline solution). Filamentation has been obtained by focusing of Ti-sapphire laser's radiation (800 nm wavelength, frequency 10 Hz, pulse duration 100 fs, pulse energy 1.2 mJ, pick power 12 GW) in a cuvette with nanoparticle colloids and water. The measurements were carried out by methods of optical emission spectroscopy and photoacoustic method.

As a result of this work, we observe the effects of saturating two-photon interband absorption of nanoparticles in the spectral region of supercontinuum generation and enhancement of the SC yield in the region of plasmon resonance of nanoparticles. That allows us to assume that SC generation is enhanced by near fields of nanoparticles. The possibility of two-photon transitions is confirmed by photoacoustic measurements. The photoacoustic response in water is described by cubic dependence, while it in nanoparticle colloid is described by quadratic dependence. It's explained by the intrinsic nonlinear three-photon absorption of water and impurity two-photon absorption of nanoparticles respectively.

PS3-W05-10 Ultrafast nonlinear magnetization dynamics and magnetization switching in magnetostrictive nanomagnets

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Here we report on a design and theoretical investigation of ultrafast elastic magnetization switching in Ni-based nanostructures excited by femtosecond laser pulses.We consider a structure consisting of 2 ingredients: a thin-film thermoelastic transducer and a bistable switchable nanomagnet (a single nanoscale magnetic bit). Such complex-shape ferromagnetic nanostructures can be fabricated by electron lithoghraphy from polycrystalline ferromagnetic thin films deposited on a dielectric or semiconducting substrates, as demonstrated in recent applications in magneto-photonics [1].

Absorption of a short femtosecond laser pulse with steep spatial intensity gradients (under tight focusing conditions or using the transient grating geometry) in a piece of ferromagnetic thin film result in the ultrafast generation of the transient thermoelastic stress that excites ultrashort pulses of surface acoustic waves propagating along the surface [2,3]. After having propagated away from fs-laser excited spot an ultrashort, picosecond acoustic wave packet interacts with a single elliptical nanomagnet by magneto-striction [4]. Understanding the elastically induced magnetization dynamics in a single polycrystalline Ni nanoparticle in a shape of an ellipsoidal disc is in focus of our investigation [5]. The elliptical nanomagnet sticking to the nonmagnetic dielectric substrate is placed in a variable magnetic field H pointing along the x axis, which enables tuning the height of the potential energy barrier between the two meta-stable states with well-defined magnetization directions.

The action of an ultrafast acoustic pulse dynamically perturbs the landscape of the magneto-elastic energy density and triggers the complex precessional magnetization dynamics. In the case or acoustic strain amplitudes exceeding the threshold value of about 10-4 the phenomenon of magnetization switching occurs. This switching threshold between two metastable single-domain magnetization states depends on the amplitude and duration of acoustic pulses, the magneto-elastic coupling efficiency and the height of the potential barrier between these states. Ultimate speed limits of magneto-acoustic switching are investigated solving LLG equations driven by dynamic acoustic waves strains. The 10-4 switching threshold for elliptical Ni nanomagnets appears to be significantly lower as compared to highly magnetostrictive thin films of Terfenol-D switchable by ultrashort longitudinal acoustic pulses with amplitudes 10-2 propagating in the direction perpendicular to the surface [4].

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PS3-W05-11 Magneto-acoustics in ferromagnetic nanostructures with zero magneto-striction

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Discovery of ultrafast demagnetization induced by femtosecond laser pulses in 1996 [1] opened a new fast-growing field of ultrafast laser manipulation and control of magnetization dynamics [2, 3] and became the key mechanism for further development in ultrafast spintronic technology.

Recently, optically induced acoustic pulses have been shown to trigger the magnetization dynamics in ferromagnetic materials via magneto-strictive switching mechanism [4, 5]. We have extended these studies by demonstrating the possibility to switch magnetization in elliptical nanomagnets of polycrystalline Ni by ultrashort pulses of surface acoustic waves [6].

An open question is whether elastic waves can be used to manipulate magnetization in ferromagnetic materials with negligibly small magneto-striction such as permalloy (Py). One of the mechanisms proposed by Chudnovsk and Jaafar [7] is based on the mechanical rotation of a nanomagnet in an oscillating field of a surface acoustic wave.

Here we propose a new mechanism based on strain-induced modulation of demagnetizing fields of a ferromagnetic nanoparticle. In our simulations, Py nanoparticle is modelled as an ellipsoidal disc deposited on a dielectric substrate. Elastic compressing and stretching of the Py nanoparticle slightly changes its dimensions thereby altering the components of the so-called demagnetization tensor. To evaluate the magnetization dynamics , we solve the Landau-Lifschitz-Gilbert (LLG) equation assuming that the free energy density consists only of the (static) Zeeman energy and the (time-dependent) energy of the demagnetizing field. The magnetization switching diagram is obtained for different shapes of Py nanomagnets, different amplitudes and durations of the acoustic pulse. The switching diagram contains multiple switching zones which depend on the applied magnetic field and the Gilbert damping parameter.

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PS3-W05-12 Inscription of waveguides in porous glass by femtosecond laser-induced densification

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In this work, direct writing of waveguides in porous glass based on laser-induced densification was demonstrated for the first time. By changing pulse energy and translation speed, waveguides were fabricated, with core diameter of ~5 um and FWHM divergence half-angle of ~6.3 mrad of out-coupled beam. In principle, the refractive index contrast between modified region and un-irradiated region can reach ~0.1, which, to the best of our knowledge, is the highest possible value of laser direct writing waveguide in high silica glass. Because of low-bending loss and easily impregnation, porous glass is assumed to be a promising material for fabrication of compact and multifunctional photonic and biophotonic chips.

A 0.5-mm thick porous glass plates (mass fraction, %: 0.30 Na_2O, 3.14 B_2O_3, 96.45 SiO_2, 0.11 Al_2O_3, pore radius 4 nm and porosity of 26%) were used [1]. Experimental setup for laser writing is given in detail in references [2-3], where a Yb-doped fiber laser beam with wavelength λ = 515 nm, pulse width τ=200 fs and repetition rate ν=500 kHz was focused by an objective (10X, 0.25) with focal spot of $2\omega0$ ~2.8 μm.

For waveguides testing (Fig.(A)), a He-Ne laser with wavelength λ=633 nm was coupled into a waveguide by an objective (60X, 0.85 NA). Out-coupled beam was captured by a beam-profiling camera (Gentec-EO, Inc. BEAMAGE-3.0).

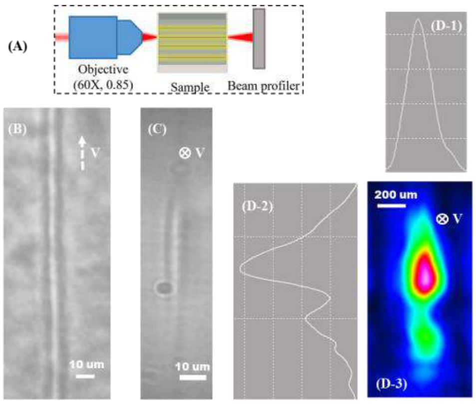

Fig. Illustration of the experimental setup (A). Image of a waveguide by optical transmission microscopy in top-view (B) and in cross sectional view (C). Far field distribution of out-coupled beam (D-1, D-2, and D-3). Scanning direction V is implied.

In the written plane (FIG.(B)), the waveguide has a uniform axial symmetrical shape with a brighter central part in contrast with initial material. That indicates a positive refractive index change. The cross section of waveguide has a shape of ellipse with lengths of ~5 um and ~50um, and the elongation of this waveguide was attributed to self-focusing and filament propagation. Compared with waveguides in fused silica [4], in cross sectional view of our waveguide (FIG.(C)), there is a dark region surrounding the core which may accounts for very strong ability to guide light of the waveguide. More importantly, there is not apparent heat affected region nearby the both darker sides (FIG.(B) and (C)), which indicates rapid release of heat-induced stress.

The out coupled beam diameters were measured by beam-profiling camera at difference places and the far-field divergence angle was calculated by its linear fitting. The field distribution in FIG. (D-1), which shows an approximate single Guassian mode with FWHM divergence half-angle of ~6.3 mrad. The field distribution in FIG. (D-2), shows a multiple mode, which can be explained by the waveguide elongation.

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PS3-W06-1 Laser-induced synthesis of carbon-based nanostructures on the substrate of polyimide

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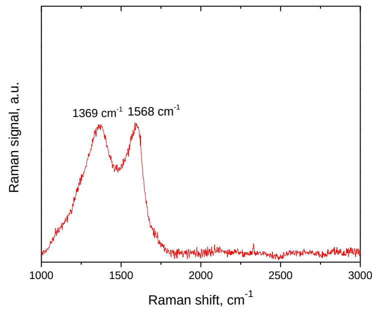
The growing interest in biosensors with high electrochemical activity has led to many research in the past few years. The significant part of this research is based on using a variety of laser-induced methods of synthesis of metal-based micro- and nanostructures on ceramic or glass-like composite materials with high-developed surface.

However, synthesis of aforementioned structures on stretchable polymers is becoming more and more actual nowadays. These polymers with sensitive microelectrodes on it have the potential to be used as parts of non-invasive stretchable devices for medicine, e.g. glucometers.

The main difficulty in forming microelectrodes on the surface of stretchable polymer is that focused laser irradiation of the polymer may destroy the substrate by melting or oxidizing it. Hopefully, these negative effects may be diminished and even avoided by selecting the suitable conditions at which the synthesis is provided.

In this work we report the synthesis of carbon-based nanostructures on the substrate of polyimide by the method of 2D direct laser writing. Continuous wave 532 nm diode-pumped solid-state Nd:YAG laser was used in this experiment.



Picture 1. The Raman spectra of one of the obtained microstructures. 1568 sm^{-1} and 1369sm^{-1} peaks relate to the vibration of sp^2 carbon atoms and defects in monolayer graphene, respectively.

The topology and crystallization phase of these structures were observed by means of scanning electron microscopy and X-ray diffraction, respectively. The electrochemical properties of synthesized materials were investigated by cyclic voltammetry and amperometry. The electrochemical sensivity of obtained structures dependance on the speed of laser beam scanning and the power of laser beam was also investigated.

Possible photochemical reactions induced by laser radiation and the mechanism of the formation of carbon nanostructures on polyimide are also considered in this work.

PS3-W06-2 Thermochemical LIPSS formation on Si films with an astigmatic Gaussian beam

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Relatively recently, thermochemical laser-induced periodic surface structures (TLIPSS) have become the subject of active research. These structures are formed due to the oxidation of the material surface illuminated with ultrashort laser pulses and are characterized by the elevation of the relief, forming parallel oxide protrusions. In contrast to the more studied ablative LIPSS, they are oriented parallel to the polarization of incident radiation and highly uniform over the period and height. So far, there were studies of TLIPPS formation by fs laser pulses on the surface of metal films such as titanium, chromium, nickel and their alloys. Here, for the first time, to our knowledge, we are reporting on TLIPSS formation on the surface of silicon films of various thicknesses. The dependence of TLIPSS quality on the radiation power (270 – 360 mW) and scanning speed (100 – 500 μm/s) was investigated. The fabrication was performed using an astigmatic Gaussian beam with the axes ratio of 1:10 and the length of the long axis of 155 μm, which allowed to enhance the uniformity of the obtained structures and to increase fabrication performance. For the case of a thin silicon film (40 nm) weakly ordered structures with a period of ~1 μm are formed, while at scanning rates higher than 100 μm/s for all energies, the periodicity is lost and individual chaotic oxide centers begin to dominate. In the case of a thick film (600 nm), well ordered TLIPSS with a period of ~1 μm are observed at scanning speeds from 100 to 150 μm/s for energies of 270 and 285 mW and from 150 to 200 μm/s for energies of 300 mW and higher. Also, in addition to the main structure, in the central region of the writing track, ablative substructures with a period of ~150 nm, oriented perpendicular to the main one, are formed in the gaps between the oxide protrusions. The obtained results may be useful in studies of the surface structuring of semiconductors.

PS3-W06-3 Formation of oxide films with given thickness during laser oxidation of metals

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The use of laser heating makes it possible to form an oxide metal film of various thickness in a locally defined area with non-contact action to the material. It is known that by changing the thickness of the oxide film of iron, titanium and other metals, it is possible to change the spectral characteristics of the metal surface in the visible range due to the phenomenon of light interference in the oxide film, and with increase of temperature of the metal surface during laser heating the thickness of the oxide films rises as well. This effect formed the basis of the technology of color laser marking of metals, which has already found its application in modern art (knife coloration, etc.), medicine (coloration of dental abutments and trauma implants), etc.

Here a mechanism of local control of the thickness of the oxide film of titanium in an atmosphere under pulsed laser exposure is proposed. Experimental and theoretical studies have shown that due to repeated exposure of an area already irradiated, it is possible to control the thickness of the oxide layer on the surface of the titanium.

In conclusion, the technology of altering spectral and colorimetric properties on titanium surface during multiple exposures in the air is demonstrated.

PS3-W06-4 Investigation of the spectral characteristics of Ag –Ag_2O nanoparticles produced by laser ablation in air

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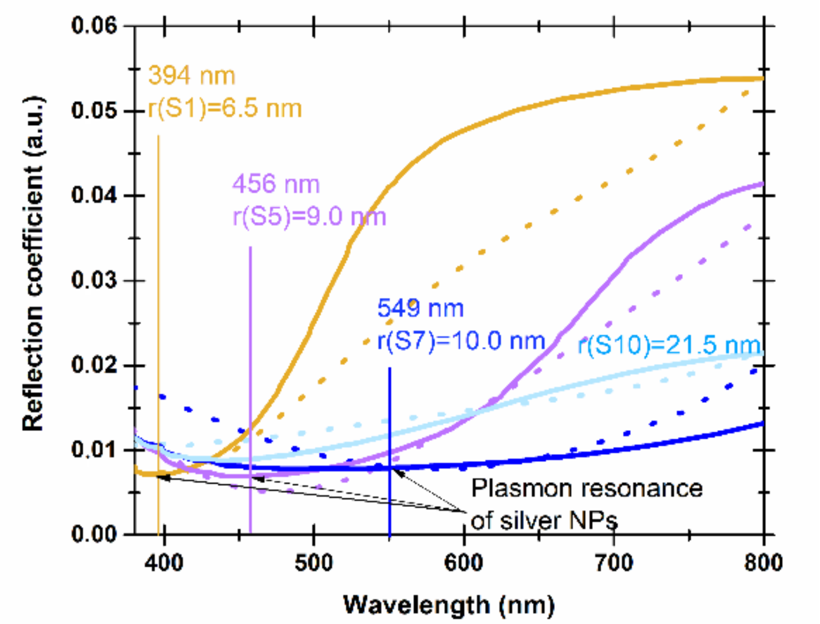
Nowadays, laser methods of coloring metal surfaces draw keen interest. Here we propose a method for coloring the surface of precious metals using a thermochemical synthesis of nanoparticles due to the evaporation-condensation process. This method allows the formation of Ag-AgO_x nanoparticles with corresponding plasmonic properties on a silver substrate due to laser exposure in air. In this case, the reflection spectra of silver with nanoparticles is modified.

The color of the surface depends mainly on nanoparticles size and size distribution. A series of experiments showed that with an increase of nanoparticles size, the minima of the reflection spectra shift to the infrared region. This fact was confirmed by simulation of the reflection spectra of the silver surface with Ag-Ag_2O nanoparticles formed from the vapor-gas phase as a result of laser ablation, considering the experimental data obtained on the size, concentration, and distribution of nanoparticles.



Reflectance spectra of the silver substrate covered by NPs of radiuses r(S1)=6.5 nm, r(S5)=9 nm, r(S7)=10 nm, r(S10)=21.5 nm: dashed – experimental, solid – simulated results; vertical lines show SPR peak positions.

The model showed that the width of the minimum of the reflection spectrum is governed by the size of the nanoparticles. In this case, the hypothesis was confirmed that an increase in the radius of nanoparticles leads to a shift of the reflection spectrum minimum to the infrared region. This simulation allows one to anticipate the chemical composition of the resulting nanoparticles, the final size, as well as their spectral characteristics. Besides, the model allows determining the interaction of parameters, such as the size of nanoparticles, their concentration and chemical composition, and their influence on the reflection and transmission spectrum of the film and makes it possible to predict the experimental results.

PS3-W06-5 Formation of biomimetic materials for structural coloration under the action of nanosecond laser pulses

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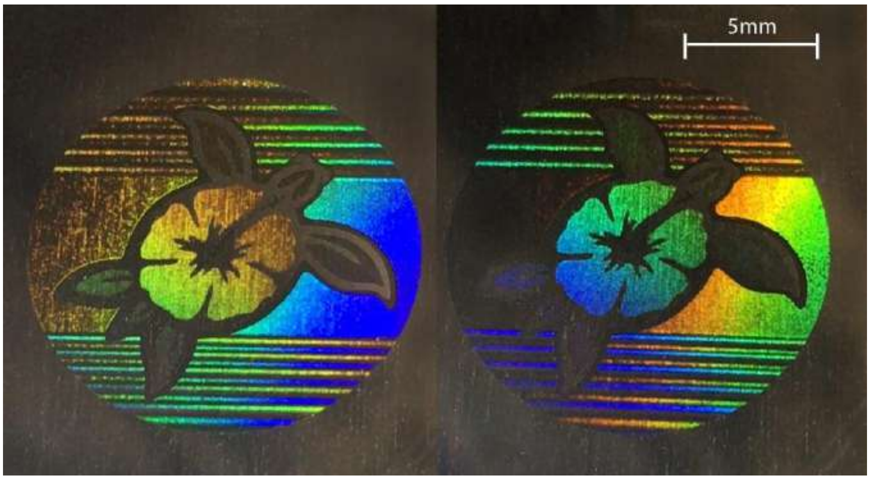
In this work, we created a structural color based on imitation of unique morphologies found in nature. Structural colors are the result of selective reflection of light that occurs due to interference, diffraction, scattering, and surface plasmon resonance. This paper shows a single-step process of creating morphologies on AISI 304 steel due to oxidation and surface structuring with nanosecond (ns) laser exposure at a wavelength of 1.06 μm. The formation of structures was carried out by line scanning with overlapping along the axes; a two-scale relief was formed: the large-scale relief corresponds to the laser pulses overlapping ($\Lambda 1 > 10$ μm), the small-scale relief corresponds to the laser radiation wavelength ($\Lambda 2 = \lambda$). In this case, it is possible to control the period of the formed laser-induced periodic surface structures by changing the angle of incidence of the laser radiation. The orientation of the microstructures depends on the polarization of the laser radiation. The transition of LIPSS to pseudo-ordered structures is also observed, associated with the overlapping of interference fields. Thus a controlled structuring is possible, depending on the parameters of laser exposure. As a result, because of the diffraction of light on LIPSS and interference in oxide layers, bright color elements were obtained, which can smoothly change the color spectrum with a change of observation angle.

This technology has great potential for numerous industrial applications. In particular, it can be used for identification markings and optical data storage. With careful adjusting of structural elements, bright and contrast colors can be achieved, which allows combining structural elements and creating security markings with hidden information. It also demonstrates the ability to create moving effects with the usage of dynamically changing orientation of the LIPPS.



Laser-induced images obtained on the surface of the steel due to LIPSS formation.

PS3-W06-6 Laser-induced formation of hydrophobic and hydrophilic biomimetic structures on metal surface

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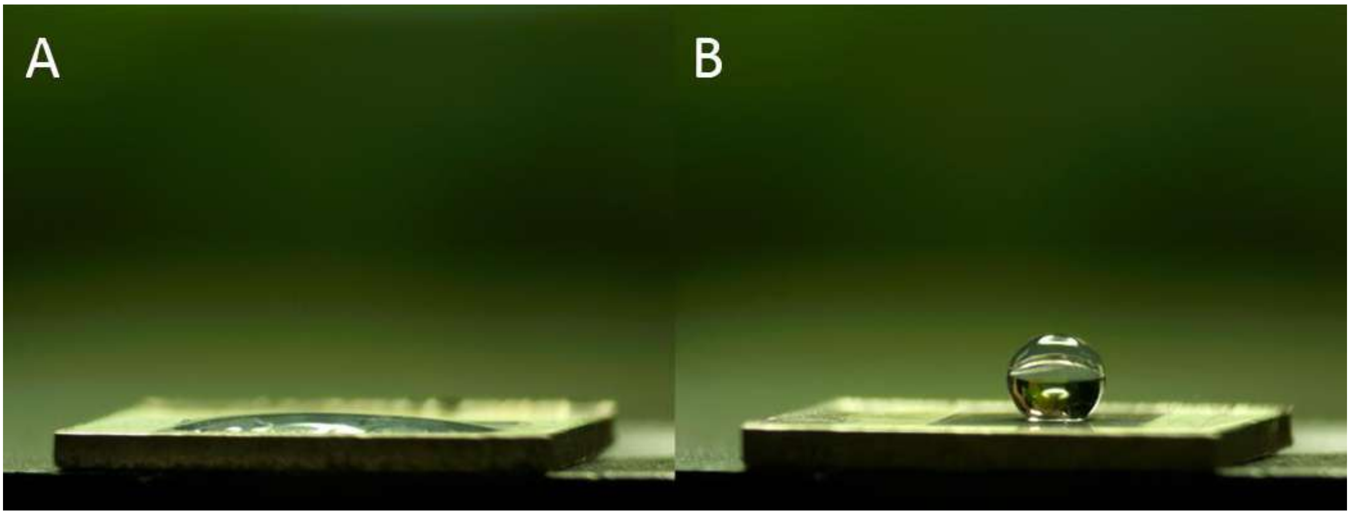
Hydrophobic and hydrophilic surfaces are used in various areas, such as corrosion protection, microfluidic systems, oil-water separation, reduction of friction and self-cleaning.

Here we demonstrate the formation of hydrophilic and hydrophobic surfaces on stainless steel AISI 304 and technological titanium Grade 2 by creation a laser-induced relief. Structuring was performed using a nanosecond fiber laser with a wavelength of 1.06 μm. In this work, laser radiation affects the steel and titanium surfaces and thereby changes their wettability properties by forming micro and nanostructures to create hydrophilic and hydrophobic structures that retain their properties over time. The analysis of the influence of surface relief parameters on the values of the wetting angle has been carried out.

Both hydrophilic and hydrophobic surfaces were produced on steel and titanium. The dependences of the wetting angles on laser pulses overlapping and intensity was obtained. With an increase of intensity and overlapping, the treated surface acquires super-hydrophilic properties. Aging surfaces in the air (the change in wettability properties over time) was observed. An experiment was conducted on aging the structured surface by low-temperature annealing, which was carried out with a different soaking time (2, 4 and 6 hours) and heating temperature (from 100 to 300°C). The experiment revealed good thermal stability of structures with overlapping of 90%. The analysis of changes in wettability in the air over time has been carried out, and laser irradiation modes that ensure longer preservation of the surface wettability properties have been found.



Laser structured titanium surface with superhydrophilic properties (A),
with superhydrophobic properties (B).

PS3-W06-7 Laser-induced formation of microcones on germanium in oxidizing atmosphere and vacuum. Dynamics of relief

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The mechanisms of the laser-induced formation of micro- and nanostructures of residual relief on surfaces of materials are of fundamental interest. A strong influence of composition of gas atmosphere on the laser-induced relief structures was marked in a number of works but a reasonable explanation was lacking. The significant role of the degree of wetting by melt of its solid phase in the mechanism of the laser-induced formation of the cone-shaped peaks (microcones) on metals was proposed in [1]. Formation of the microcones on the (111) surface of germanium in vacuum, air and oxygen at the atmospheric pressure as a result of local laser irradiation with the energy density Q lower than the ablation threshold was studied in this work. The height of the microcone was growing with Q. The microcone and adjacent melted area in oxidizing atmosphere were covered by a GeO oxide. To study dynamics of the relief in air a rapid-speed video filming has been carried out. The value of wetting angle θ between the meniscus and tangent to the solid state – gas boundary $\theta=(35\pm3)^o$ in air measured in the video images was about three times more than $\theta=(13\pm1)^o$ in vacuum measured in [2]. This result correlates with the about three times growth of the microcone height in air as compared with vacuum.

The growth mechanism for microcones caused by the melt redistribution under the action of surface tension force in conditions of partial wetting and density changing at the phase transition and mathematical model for the microcone formation were proposed.

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PS3-W06-8 Laser-induced breakdown spectroscopy for micromapping of coating formed by laser cladding

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A key factor for the development of laser cladding technology is the control of uniformity and the absence of defects in the layer formed by this method. Based on the analysis of the distribution of chemical elements over the cross-section of the coating, it can be concluded that the selected laser cladding regime is optimal, such an analysis should be implemented at the microscale. Currently, the mapping of such objects with micron accuracy is possible using the method of spectroscopy of laser-induced plasma.

In our work, the capabilities of the LIBS method for mapping the cross-section of a coating obtained by laser cladding of a powder consisting of microparticles of chromium, nickel, and iron are shown. In the experiments, a picosecond solid-state Nd:YAG laser (Ekspla PL2143, 25 ps, 1064 nm, 30 mJ) and nanosecond solid-state Nd:YAG (Lotis TII, 10 ns, 532 nm, 30 mJ) were used to excite the plasma, the radiation of which was focused into a spot 30 μm in diameter on the target surface, the plasma spectrum was recorded using a three-channel fiber spectrometer (Avantes, ULS2048, 210-710 nm, resolution 0.08 nm). The qualitative difference of the plasma spectra induced by various laser sources is shown.

The results demonstrate the advantages of using a picosecond laser for micromapping using the LIBS method. With the use of picosecond laser pulses, the spatial resolution of the mapping is increased threefold; another advantage is the reduction of the self-absorption effect of the spectral lines compared to the nanosecond laser action. This is due to the mechanisms of ablation and plasma formation when exposed to nanosecond and picosecond pulses. Further work will be aimed at creating an automated system for the rapid analysis of surface coating using the LIBS method.

PS3-W06-9 Reactive laser-induced microplasma: physical properties and technological capabilities for micromachinnig of transparent dielectrics

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The creation of new and cost-effective methods of micro-processing transparent dielectrics determines the development of photonics and microfluidics. Today, direct ablation methods for transparent dielectrics using femtosecond lasers are being developed, but the development of “indirect” laser micromachining is also continuing. In "indirect" methods, laser plasma is often used, with which surface etching occurs. In this work, it is proposed to use a chemically active laser-induced plasma containing fluorine radicals for microprocessing of various dielectrics.

To create chemically active laser plasma, we used a pulsed fiber laser (IPG-Photonics, 1.6–1000 kHz, 4–200 ns, 1064 nm, 20 W), the radiation of which was focused onto the surface of a fluoroplast through a plate of transparent dielectric (fused silica, calcium fluoride), which was tightly pressed to the surface of the fluoroplastic. We investigated the emission spectra of a laser-induced plasma, its lifetime, determined the temperature and the density of the particles, investigated single craters in transparent dielectrics as well as the parameters of microtracks formed by laser plasma depending on the laser irradiation regime.

It is shown that as a result of the use of chemically active laser plasma, the etching volume of fused quartz per a single laser pulse increases by half the order of magnitude in comparison with the etching volume achieved, for example, using femtosecond laser irradiation. This is due to the presence of two sources of material removal: carbon radicals, which initiate the local thermal decomposition of the surface of a transparent dielectric and fluorine radicals, which initiate a chemical reaction with the formation of volatile compounds. Thus, a new efficient method of micro-processing of transparent dielectrics with the help of a conventional pulsed fiber laser has been developed.

PS3-W06-10 Effect of auxiliary substances on the surface structure of titanium after laser treatment

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Underwater laser treatment is considered as one of the most perspective techniques designed to minimize the undesirable effects of laser processing of a dry sample, such as surface roughness, high degree of re-deposition of ablated material, and thermo-mechanical damage of a massive sample. In this paper, we study the effect of radiation from a commercially available laser system Minimarker-2 on the surface of titanium in the modes of simple (dry ground and polished titanium) and assisted processing (polished titanium under a layer of liquid, etc.). The dependences of the parameters of the formed microstructures (depth, diameter and roughness of craters) were measured depending on the parameters of laser exposure (power density, pulse duration, processing mode). The laser impact thresholds for titanium ablation and operating regimes for the most efficient processing have been determined. Alternative settings of the experiments were considered, such as laser treatment under the laminar water flow or in the absorbing water solution. Also the treatment under auxiliary high-volatile film was considered, and operating regimes were evaluated, thus the zinc film thickness of 20±5 μm has been proposed as a suitable material for the auxiliary layer. Comparison of zinc with other volatile metals by overall thickness and expected accuracy of film deposition showed that zinc film is more preferable for assisted structuring of titanium than, for example, bismuth and antimony films, for which the acceptable ranges are about 90±3 μm and 100±3 μm respectively.

PS3-W06-11 Laser marking of polymer composites

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We review the technology of laser marking of various polymer composites. The superiority over analogues in time and resource consumption makes this marking method interesting for industrial production. Nowadays laser marking is carried out with the laser printers and laser coders by «Macsa» and «Trotec» companies. [1-2] The disadvantages of these analogues are: low quality; technology based on the removal of the upper coloring layer; lack of ability to work with volumetric objects; the resulting image is more vulnerable to external mechanical impacts. Originality of the proposed technology is about the use of polymer composites saturated with laser-sensitive substances (nanoparticles). [3]

The main purpose of our work is to obtain a contrast image on a polymer matrix. During the study, such laser sources as the Yb:fiber laser, thulium laser and semiconductor lasers with 405 and 445 nm wavelengths were used. The optical properties of samples before and after laser treatment, such as transmission/reflection spectra were investigated to determine the contrast. Based on experimental results the optimal regime of laser treatment for formation of image with high contrast were defined. As a result, the necessary price/productivity/quality ratio for use of different laser sources were estimated. Processing modes approval based on experimentally obtained data thresholds of phase transformations of polymer composites. To increase productivity, different methods of laser writing of contrast images were investigated, as well as was varied the size of the spot of the laser beam.

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2. Laser marking and engraving of plastics // Trotec Laser 2019. URL: https://www.troteclaser.com/ru/oblasti-primeneniya/plastik

3. Optical characteristics of composites obtained by ion implantation of silver ions in polyethyleneterephthalate, Yu.A.Bumai, V.S.Volobuev, V.F. Valeev, N.I. Dolgikh, M.G. Lukashevich, R.I. Khaibullin, V.I.Nuzhdin,c and V.B.Odzhaevb [2012]

LASER ECO CLEAN

"Laser Ltd" is founded on 2010 at the base of the
Laser Photonics and Optoelectronics Faculty ITMO University.
The company specializes on the laser cleaning of
typographical anilox shafts from pigments.
The company started its small-scale production of equipment in 2016.
A representative office of the "Laser Ltd" in Germany is opened in 2015.

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