The use of nanoparticles of the Rayleigh light scattering mechanism in the metrology of optical currents and fields

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Abstract
Theoretical and experimental approaches for diagnosing of internal optical flows and corresponding optical forces caused by these flows are offered. These approaches are based on the investigation of the motion of tested particles in the formed optical field. The possibility of using the kinematic values defining the motion dynamics of particles of the Rayleigh light scattering mechanism for making a quantitative assessment of the degree of coherence of mutually orthogonal linearly polarized in the incidence plane waves is demonstrated.

Keywords: Rayleigh particles, degree of coherence, optical flows

1. Introduction
Alternative ways for creating the optical manipulators and optically controlled systems are proposed in the given paper. Optical flows are attractive for use to diagnose spatially inhomogeneous in energy optical fields where classical methods cannot be applied. The paper proposes to use the Rayleigh light scattering mechanism for studying and diagnosing optical fields. The aim of this paper is to study the influence of optical fields and optical flows on particles of the nanometer range for manifold investigations of the optical field structure.

2. The mechanism of spin flow action
The results of the modulation of spin flows are experimentally confirmed in the scheme (Fig. 1), where the interaction of two circular-polarized beams determines the interference distribution around the focus [1]. An inhomogeneous intensity distribution is formed. A circulation of energy takes place within each maximum and it determines the rise of spin flows.

![Fig. 1. Schematic of the experimental setup: 1, 2 - input beams (b = 0.7 mm)
of semiconductor lasers (λ = 0.67 μm), 3 - objective lens (f = 10 mm), 4 - cell with tested particles suspended in water, a = 1.3 mm, θ = 7.4°, NA = 0.16.](image-url)
A strict focusing of the circular-polarized beam causes the transformation of the spin flow into the orbital one. In this case the mechanical effect of the generated flow on the particles doesn’t allow separating the effects of the spin and orbital momentums. That is why to avoid this ambiguity, the focusing strength should not be high (in accordance with the known data, the spin-orbital conversion is negligible and does not exceed 1% at $NA \approx 0.2$, the focusing angle $\theta \approx 11^\circ$). Of course, this leads to a certain loss in the energy concentration. However, one can avoid essential reduction of the focal-region of the spin momentum density if the decrease of intensity is compensated by the increase of the beam inhomogeneity. It is obvious that the circulatory flow of spin nature exists within each lobe, while the orbital momentum density is completely radial, attributed to the beam divergence. This radial field momentum can be used for probing particle confinement at a desirable off-center position, allowing one to observe the spin-induced orbital motion [2, 3].

Within an inhomogeneous optical field any tested particle is subjected to the gradient force [4, 5] that pulls the particle towards the intensity maximum. The radial orbital momentum of a divergent beam pushes the particle away from the axis. As a result, both forces can compensate each other at certain off-axial points within the central lobe of the interference pattern. The spin momentum in the two-beam interference pattern is approximately 2.5 times higher than in a single Gaussian beam focused with the same NA objective. The interference technique of the focal pattern formation facilitates the avoidance of this undesired spin to orbital conversion and promotes the observation of the mechanical action of the ‘pure’ spin flow without any contamination influence of the orbital one.

To define the “pure” effect of spin flows in the experiment a cell contained an ensemble of latex microparticles (refractive index 1.48) suspended in water was used. The particles were chosen so that their shape was close to ellipsoidal with approximate size $1.5 \times 1 \mu m$, which allowed observing the individual particles within a single lobe of the interference pattern formed in the focal region.

The asymmetric particle spins around its own centre of mass, which is explained by partial absorption of the incident circularly polarized light and its inherent angular momentum. A new observation is that simultaneously the particle’s centre of mass performs an orbital motion, which can only be associated with the azimuthal light pressure originating from the spin momentum circulation. This attribution is confirmed by the reverse rotational direction when the sign of the circular polarization is changed. When both beams are linearly polarized, the particle stops.

3. The diagnostics of correlation properties of mutually orthogonal linearly polarized optical fields

Some technological difficulties derived from the necessity to register the polarization information on corresponding materials dictate the search for other methods, based on measuring kinematic values, such as the value of the motion velocity of the tested nanoparticles. In this case it is possible to avoid the difficulties connected with the registration of polarization information, because the measurements are based not on the spatial modulation of polarization itself, but on the energy inhomogeneity of the field, caused by the spatial modulation of polarization. Depending on the properties of the particles and the field intensity value the influence of the field on the tested particles will be different.

We use the Rayleigh particles with the mass $M$ and the radius $r$ for testing the optical field and its coherence properties.

To obtain a direct linkage between the averaged velocity of the tested particles and the degree of coherence of the superposing fields we choose as an example particles characterized by the following set of properties: the Rayleigh mechanism of light scattering is peculiar to
them, the values of the scattering and absorbing components of the optical force affecting these particles are much smaller than the value of the gradient component of the optical force.

In this case the value of the averaged motion velocity of nanoparticles in the optical field, or more precisely, the velocity of trapping the given particles by the field is determined by the degree of mutual coherence of superposing fields and is written down as

$$
\bar{v}(t) = \frac{1}{M} \left( e^{-\frac{6\pi r}{M}} - 1 \right) \frac{2\pi n}{c} \eta^{(1,2)} \sum_m \left\{ \frac{1}{\Delta x_m^2} + \frac{1}{\Delta y_m^2} \right\}.
$$

If we normalize the change of the averaged velocity with time to the maximum of the trapping velocity for each corresponding moment of time obtained in the absolutely coherent field, we get $\bar{v}_{rel}(t) = \eta^{(1,2)}$.

Thus, the relatively averaged motion velocity of nanometer range particles in the energy inhomogeneous optical field, created by the interaction of partially coherent optical fields converging at the angle of 90°, enables us to estimate the degree of mutual coherence of these fields. The field gradient is able to move the Rayleigh particles of about $\lambda/100$ nm in size into the maximum region, where the trapping takes place.

The motion velocity of nanoparticles depends on the distribution of the energy volume density in the observation plane, and, accordingly, on the degree of coherence of superposing waves. The change of the degree of coherence causes the change of the normalized value of the averaged velocity of particle redistribution. Their trapping in the optical field under the effect of optical forces takes place (Fig. 2).

**Fig. 2.** The change of the normalized value of the averaged motion velocity of Rayleigh particles (the particles of about $\lambda/100$) with time and with the change of the degree of coherence of interacting waves ($\eta^{(1,2)}$): the legend shows different degrees of coherence that correspond to different curves.

As it is shown by the results of the computer simulation, the particles are practically immediately "trapped" into the region of the maximum gradient value of the Poynting’s vector. The maximum normalized value of the averaged motion velocity is realized at the initial moments of time.

The first estimation of the size and order of this force presets the temperature boundary at which the Brownian force does not change the general force distribution and, consequently, does not influence the averaged value of the normalized particle motion velocity [8].
temperatures higher than 350-400 K the uniqueness of the particle motion velocity and the degree of coherence of the optical field are lost. In this case the Brownian motion disguises the information about the coherence and polarization properties preset in the optical field under investigation. Moreover, nonlinear effects arise at these temperatures. The inclusion of these effects distorts the general force distribution, masking the information about the optical field properties.

4. Conclusion
The essential dependence of the force, determined by the spin and orbital flows on the size and properties of the particles, makes possible to separate, analyze and investigate the mechanical effect not only of orbital flows, but of spin flows as well. The analysis done in this work can be useful in making an experimental estimation and investigation of spin and orbital parts of the internal energy flow in the optical field. Corresponding peculiarities of the formation of optical force components set the prerequisites for using particles of the Rayleigh light scattering mechanism for diagnosing optical flows and defining the correlation features of interacting mutually orthogonal linearly-polarized in the incidence plane fields. The investigation of the motion dynamics of the tested particles permits to diagnose optical fields as well.

References