Progress in pulse fiber lasers of UV range

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Abstract—We will report on the recent progress of the nanosecond laser development in the ultraviolet spectral range at IPG Photonics. The development of high-energy single-mode Yb:fiber lasers with 1-2 nanosecond pulse duration and excellent polarization and spectral characteristics recently enabled highly efficient non-linear optical frequency conversion to third and fourth harmonics at 355nm and 266nm, respectively. Up to 50% conversion efficiency was achieved at 355nm and 30% at 266nm. A comparative study of fourth harmonic generation using BBO and LBO crystals will be presented.

Keywords—fiber laser; ultraviolet; UV; DUV; LBO; BBO;

I. INTRODUCTION (HEADING 1)

A wide variety of industrial micromachining applications require high-power single-mode nanosecond ultraviolet (UV) and deep ultraviolet (DUV) lasers [1]. In general, the micromachining quality and precision is significantly improving with decrease of the laser wavelength. In addition as shorter wavelengths most of the materials begin to absorb light very efficiently and therefore the pulse energies required are not as high as in the visible or infrared spectral regions [1]. However, for the same reason, the reliability of the ultraviolet lasers is far lower thus leveraging the ultraviolet laser market to a much smaller size than its real potential. The combination of those factors and the constantly demanded high repetition rates and average powers for high production throughput makes harmonic fiber lasers (see Fig. 1) ideal candidate for most micromachining suitable UV and DUV lasers.

IPG Photonics is currently committed to develop and provide on the market in the next few years much more reliable UV and DUV lasers than the current state of the art.

For simplicity we will refer to UV lasers as the lasers with wavelength between 300nm and 400nm, as e.g. 355nm, and to DUV lasers as the lasers with wavelength below 300nm, e.g. 266nm.

II. PUMP FIBER LASER

Recent advances in proprietary fiber growth and high-power Yb:fiber laser technology allowed developing a reliable high-energy linearly polarized Yb:fiber based MOPA at 1064nm. With M²<1.2, clean narrow-band spectrum with <0.1nm at FWHM (see Fig. 2), and pulse duration of 1-2ns this laser was ideally suitable for efficient and reliable harmonic generation. Its high average power of up to 50W at high repetition rates of up to 600kHz makes it very suitable for high-throughput micromachining applications. Pulse energies of up to 230uJ at 100kHz repetition rate were used in the harmonic experiments presented below.

III. SINGLE-PASS HARMONIC GENERATION

The high peak power available from the fiber pump laser allows using quasi-collimated beams while still achieving very high conversion efficiencies up to saturation. The beam from the pump laser is collimated by a Keplerian lens telescope placed right in front of the harmonic generation setup (see Fig. 1). We use LBO nonlinear crystals for second harmonic generation (SHG) and third harmonic generation (THG). For fourth harmonic generation (FHG) we used either LBO or BBO [2]. No lenses are used in-between the nonlinear crystals. Various crystal lengths and techniques for harmonic separation were used without altering notably the presented results.
Non-critical SHG phase-matching is implemented with conversion efficiency of >80% \[2\]. No crystal degradation has been noticed so far for several years of operation.

THG was performed by sum-frequency generation (SFG) in a second LBO. Type II phase matching was used for the THG LBO. More than 50% conversion efficiency was obtained (see Fig. 3) that is the highest THG conversion efficiency reported from sub-MW peak power lasers to our knowledge. A life-time of excess of thousand hours was obtained per a crystal spot limited by surface damage.

FHG was attempted in several ways. For a direct comparison we present here the two extreme cases of using SFG of the third harmonic and fundamental beams in LBO and SHG of the green beam in BBO. When using BBO, no THG was implemented resulting in a simpler setup of only two nonlinear crystals. A record high conversion efficiency of >30% was achieved with the possibility of a further increase if a higher peak power would have been available from the pump laser.

However, we have verified a major obstacle for scaling of FHG in BBO at higher repetition rates and average powers. Due to nonlinear absorption effects, a considerable heat is deposited inside the BBO crystal leading to various thermal effects including detuning of the effective phase-matching temperature. This effect was observed by optimizing the phase-matching temperature at each pump power setting (see Fig. 4). A change of ~10K was recorded when varying the pump average power from 1 to 23W at 100kHz repetition rate. This change is outside the ~4.5K temperature bandwidth of the FHG phase-matching in BBO leading to quite complicated operational conditions of the otherwise simple FHG setup.

In a direct comparison the FHG in LBO yielded to only ~0.8K change in phase-matching temperature (see Fig. 4) which is the best result among all other nonlinear crystals we have tested. This change is well within the ~3.5K temperature bandwidth of the FHG phase-matching. In addition to that no beam profile variation was observed when varying the pump power. Therefore we conclude counterintuitively that using an all-LBO triple-crystal FHG concept is the most reliable and power scalable approach. The maximum FHG conversion efficiency of only >20% in this case is lower due to the higher number of nonlinear frequency conversion steps. We believe that by increasing the peak power of the fiber pump laser the maximum FHG conversion efficiency will rapidly increase and will become closer but not exceeding the alternative FHG approaches.

The life-time of the FHG crystals is nearly identical and considerably shorter than the SHG or THG LBO crystals.

IV. CONCLUSION

A review of the recent progress of nanosecond pulsed fiber lasers in the ultraviolet spectra range within IPG Photonics Corporation was presented. A specifically dedicated fiber pump laser was developed at 1064nm with 1-2ns pulse duration yielding record high saturation limited nonlinear frequency conversion efficiencies of 80%, 50%, and 30% at the second, third, and fourth harmonics, respectively. We believe the reported system will prove most suitable for UV laser micromachining applications in the near future.

Two alternative approaches for fourth harmonic generation were presented in a direct comparison using BBO and LBO crystals. The LBO crystal approach was identified as the favorable one due to an order of magnitude less nonlinear absorption effects.

REFERENCES