Dissertation title:

Generation and amplification of ultrashort pulsed high-power cylindrical vector beams

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Due to their unique properties, the cylindrical vector beams (CVB) with their axially symmetric polarization state, and in particular the LG01 mode with its doughnut-shaped intensity distribution, have shown their potential in various applications such as e.g. particle trapping and the excitation of plasmons in rotationally symmetric structures [1] or the acceleration of electrons [2].
Particularly in several applications in the field of laser material processing the performance could be improved by using a CVB instead of a linearly or circularly polarized Gaussian beam. For example, depending on the process and processed material, the cutting speed and quality can be improved for laser cutting with a CO2 laser [3, 4]. For laser drilling applications with pulsed laser sources e.g. increased drilling speeds of 1.5 - 4 times could be demonstrated [5].
As a consequence of the disparity of the promising results and the small number of existing data on this matter, the European Union supported the project RAZIPOL, which started in 2013. To further investigate surface structuring of large areas and the drilling of wholes with a large aspect ratio, a system delivering several 100 W of average output power with an either radially or azimuthally polarized output beam was built. To obtain such a performance, a system composed of a seed laser, several single-crystal fiber (SCF) stages, and a subsequent thin-disk multipass (TDMP) amplifier was set up. The radial or azimuthal polarization of the output beam was realized by means of a polarization converter within the preamplifier stage. Even though the results achieved within RAZIPOL were impressive, it turned out that the high level of complexity of the seed system can cause problems in terms of long-term stability and the quality of the CVB.
Therefore, the aim of the present work was to develop an alternative seed system. Especially a reduced complexity, compared to the RAZIPOL system, and a good beam quality of the CVB, in terms of the homogeneity of the intensity and the radial polarization distribution, were the target. The latter is necessary as it strongly affects the final quality of the CVB after the amplification in the TDMP. The minimum targeted output power was 50 W and determined by the requirements of the TDMP amplifier.

To realize the desired results, a combination of a mode-locked thin-disk oscillator and a subsequent SCF amplifier was chosen. The thin-disk technology was used due to the power scalability of the concept. Mode-locked operation was achieved by means of a semiconductor saturable absorber mirror (SESAM). To obtain the radial polarization of the output beam of the system a grating waveguide mirror was used. This device is a grating mirror which additionally employs a waveguiding effect in its dielectric layers to achieve the desired polarization dependent reflectivity. The spectral behavior is modelled by varying the parameters of the grating and the layers.

Until the beginning of this work, at the IFSW these devices were only used as highly-reflective mirrors at one end of the cavity in conjunction with a standard output coupler at the other end. As this time the SESAM already had to be positioned at one end of the cavity to obtain stable single-pulse operation, the grating waveguide mirrors' parameters had to be adapted, such that it could additionally act as an output coupler with the desired reflectivity. Due to the grating waveguide nature of the device and its use as an output coupler, the device is called "Grating Waveguide Output Coupler" (GWOC). As already mentioned before, one SCF amplifier stage was used to boost the output of the oscillator to the power level required by the TDMP. Compared to the SCF stages in RAZIPOL, a crystal with a lower doping concentration was chosen. This was done to diminish the thermal load in the crystal and thus, to reduce detrimental thermal effects which can negatively affect the CVB quality.

With this approach, the first mode-locked thin-disk oscillator with a radial output polarization could be demonstrated. A maximum output power of 13.3 W was achieved at a pump power of 61 W. The maximum average output power was limited by the onset of instabilities in the mode-locking process and the intensity distribution of the beam. The pulse repetition rate of the oscillator was 42.1 MHz, which resulted in a pulse energy of 316 nJ. Under the assumption of a sech2-shape of the pulses, a pulse duration of 907 fs was measured. This results in a pulse peak power of 0.31 MW. In terms of average output power, peak power and pulse duration these values were records for pulsed oscillators generating CVBs. The pulse energy was formerly only exceeded by Q-switched CVB systems. At the same time, the obtained homogeneity of the doughnut-shaped intensity distribution as well as the high degree of radial polarization (DORP) of 97±1 % were unprecedented for such a pulsed oscillator system. With measured values of the M2 below 2.1 this parameter was also close to the theoretical case.

As mentioned before, the oscillator output was boosted in a subsequent SCF amplifier. For this amplifier stage, two different pump diodes with nominal wavelengths of 940 nm and 969 nm were tested. Surprisingly, the diode with an emission wavelength of 940 nm lead to a better performance in terms of output power. With this particular diode an average output power of the amplifier of 69.7 W was obtained at a pump power of 482 W.

In comparison, with the second diode an average output power of 66.3 W was achieved for a pump power of 519 W. The pulse durations after the amplification were 1030 fs and 909 fs, respectively. The different values were a result of a variation of the pulse duration of the seed source, which was 938 fs in the experiment with the 940 nm diode and 800 fs in the experiment with the 969 nm diode. This resulted in pulse energies of 1.68mm (940 nm) and 1.63mm (969 nm) and corresponding pulse peak powers of 1.48 MW and 1.58 MW, respectively. While the gain of 5.2 was larger in the first experiment (compared to 5.0), the long-term stability was better when pumping at 969 nm. The values of the M2 slightly increased to 2.1-2.4 in both experiments with the SCF booster. Additionally, the beams became slightly distorted and developed a minor astigmatism. As a result of a linear phase shift inside the

SCF crystal and a subsequent optical component, the transmitted beams were polarized in the so-called "hybrid1" (H1) polarization. The degrees of H1 polarization were 96.4_1 % and 96.1_1 % for the case of pumping at 940 nm and 969 nm, respectively. To show that such a phase shift can easily be compensated, a half-wave plate was introduced in front SCF in the setup with the 969 nm diode. This resulted in a degree of radial polarization of the amplified beam of 94.1_1 %, while the other parameters stayed unaffected by the compensation. Despite the minor degeneration of the quality of the beam and the polarization state, the results are still very promising. Thus, an alternative seed system with a reduced complexity and a good beam quality was successfully realized.