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Abstract: Yb:YAG single crystal fiber (SCF) amplifiers have recently drawn much attention in the field of amplification of ultra-short pulses. In this paper, we report on the use of SCF amplifiers for the amplification of cylindrically polarized laser beams, as such beams offer promising properties for numerous applications. While the amplification of cylindrically polarized beams is challenging with other amplifier designs due to thermally induced depolarization, we demonstrate the amplification of 32 W cylindrically polarized beams to an output power of 100 W. A measured degree of radial polarization after the SCF of about 95% indicates an excellent conservation of polarization.

OCIS codes: (140.0140) Lasers and laser optics; (140.3280) Laser amplifiers; (260.5430) Polarization.

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1. Introduction

Laser beams with cylindrical polarization states, namely radial and azimuthal polarization, have gained remarkable attention in the last decade, as the axially symmetric polarization of such beams enhances many laser-based applications in different fields. Particularly in laser material processing, the cylindrical polarization enables new processing strategies. The constant polarization along the circumference of the laser beam can be utilized in order to increase speed in cutting, enable higher aspect ratios in drilling, as well as to reduce spattering in welding [1]. Furthermore, the donut-like intensity distribution of cylindrically polarized beams features steeper flanks than Gaussian beams, which leads to a significant reduction of the heat-affected zone for some processes.

Cylindrically polarized laser beams can be efficiently generated within a laser cavity, or converted from linearly polarized beams using an extra-cavity polarization converter. During the last 30 years different methods for the generation of radially and azimuthally polarized beams have been developed and reported by several scientific groups [2–8]. Recently, it has been demonstrated that both intra-cavity and extra-cavity methods have matured to an industrial level, enabling high-power, high-brightness laser systems with radially or azimuthally polarized beams [9–12].

In order to combine the benefits of cylindrical polarization with those of ultrafast lasers, a suitable amplifier concept is needed. Typically, when it comes to the generation of ultra-short pulses in the femtosecond regime, master-oscillator-power-amplifier (MOPA) schemes are predominantly used, where the ultra-short pulses of a low power seed laser are amplified in order to achieve high pulse energies and peak powers at the same short pulse duration. Diode-pumped solid-state laser concepts featuring high surface-to-volume ratios like the thin-disk laser and the fiber laser are commonly used as amplifiers, each exhibiting its specific benefits and drawbacks. In order to achieve a simple and robust setup for the amplification of ultra-short pulses, the concept of single crystal fibers (SCFs) has proven to be a promising concept, filling the gap between fiber and “bulk”-technology [13–17]. SCFs are long and thin crystalline rods, with diameters typically below 1 mm and a length of several centimeters. Provided a sufficient thermal contact between fiber and heat sink, the small cross section of the crystals along with the short distance of the heat source from the heat sink leads to an efficient extraction of the heat generated in the fiber, making this concept suitable for high-power pumping and amplification. As the pump radiation is guided in the SCF, the requirements to the brightness of the pump diodes can be drastically reduced. The relatively large mode diameter of the unguided signal beam prevents the onset of nonlinear effects, while at the same time the rather long interaction length leads to a high gain.

Recently, it has been demonstrated that Yb:YAG SCF-based amplifiers are suitable for the amplification of ultra-short pulses, with the successful generation of 330 fs pulses at an average power of 12 W [15], as well as 380 fs pulses with an energy of 1 mJ [16]. Furthermore, SCFs have been successfully used as highly efficient cw-oscillators at up to 250 W of output power [17], illustrating the potential of SCF amplifiers in terms of power scaling.

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However, being a „bulk“-crystal concept, thermally induced effects, e.g. thermal lensing and stress induced birefringence are to be expected with this concept at high power levels. It is well known [18] that in the case of axially symmetric gain media, stress-induced birefringence [19, 20] leads to bi-focusing, meaning that the azimuthal and the radial polarization components of a beam traveling through the gain medium experience different focal lengths. Therefore, linearly polarized input beams will be depolarized to a certain extent when amplified in such a gain medium. Cylindrically polarized input beams, however, will not suffer from this effect, so that the initial polarization state should be conserved even when amplified by such gain media. Based on these foundations, the use of a SCF as amplifier for cylindrically polarized laser beams seems very promising in terms of both power handling and conservation of polarization. In order to evaluate the suitability of the SCF concept for the amplification of high-power cylindrically polarized laser beams, we investigate the amplification of linearly, radially and azimuthally polarized cw seed laser beams.

2. Experimental setup

For our experiments, a Taranis-SCF-module provided by Fibercryst was used in single-pass configuration. Consisting of a 40 mm long Yb:YAG SCF with a diameter of 1 mm doped at 0.5%, the SCF is integrated in an actively water cooled copper block, permitting an efficient heat removal. The end facets of the SCF are anti-reflection coated for both the pump and seed wavelength. This SCF is pumped at up to 515 W at a wavelength of 940 nm provided by a fiber-coupled diode laser. The end of the pump fiber (a 600 µm core diameter fiber with a NA of 0.22) is imaged onto the SCF using two aspheres with a focal length of 100 mm each at a unity magnification factor. A fundamental-mode cw thin-disk laser (M^2<1.1 throughout the usable power range) was used as seed laser, providing a linearly polarized laser beam at about 40 W of power incident on the SCF module. The seed beam is focused a few centimeters in front of the entrance facet of the SCF using an lens with a focal length of f = 250 mm, so that the seed beam is injected into the SCF slightly divergently in order to compensate for thermal lensing. The beam diameter on the entrance facet of the SCF was measured to be about 500 µm. The complete setup is shown in Fig. 1.

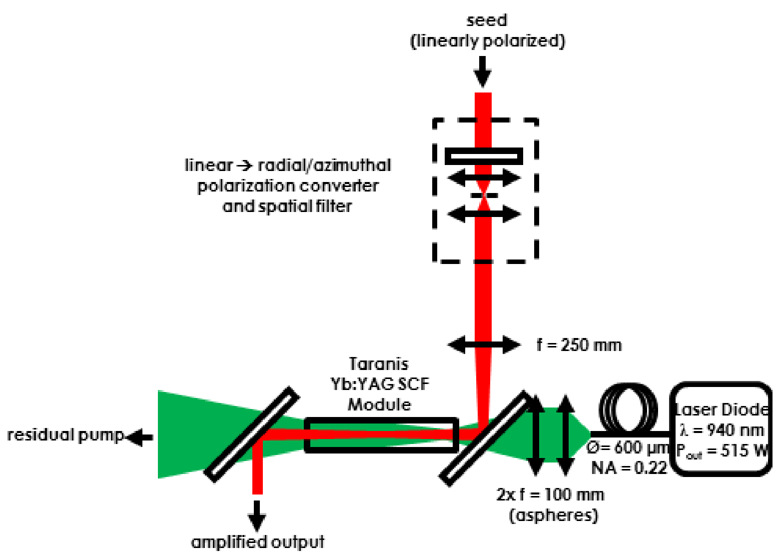

Fig. 1. Experimental setup.

3. Linear polarization

At first, the output power of the linearly polarized seed was set to 1.1 W. With this a single-pass amplification to a power of 18.8 W was measured at the maximum pump power of 515

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W, indicating a 17-fold amplification. As the seed power was increased to a maximum of 40 W, the output power reached 127 W (see Fig. 2), resulting in an amplification factor of about 3. This decrease of amplification is caused by saturation of the gain provided by the pumped SCF. The beam quality of the amplified signal beam, measured with a Coherent Modemaster, remained better than $M^2 = 1.35$ at all pump/seed power levels. This excellent conservation of beam quality indicates very low aspherical wavefront distortions induced by the SCF.

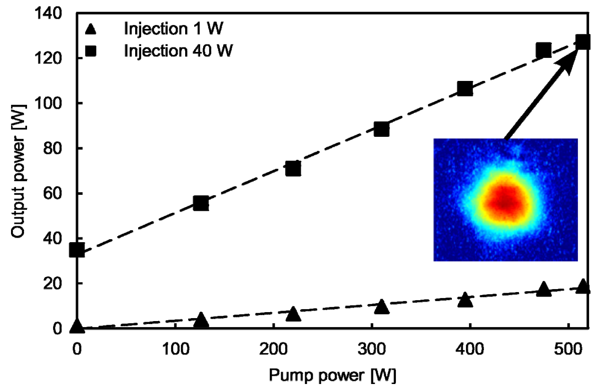

Fig. 2. Output power of the amplified beam for the case of linear polarization. The inset shows the far-field intensity distribution of the output beam measured at maximum pump and maximum seed power.

In order to quantify the depolarization losses induced by thermal stress in the SCF, the amplified signal beam was split into two linear polarization components perpendicular and parallel to the polarization of the seed laser using a high-power thin-film polarizer. Without pumping the SCF, the power content of the beam component which is polarized perpendicularly to the polarization of the seed, i.e. the amount of depolarization, was measured to be about 1% at all seed power levels. With full pump power (515 W), the depolarization losses increased to about 1.5% at a seed power of 1 W. This indicates that only a small fraction of the injected seed is depolarized in the pumped SCF. When the seed power was increased to 40 W, the depolarization losses increased to about 6.2% at the same pump power. This increase in depolarization losses is attributed to an increase of pump absorption with seed power, leading to a higher thermal load and hence higher thermally induced stress in the SCF. However, it is worth pointing out that, owing to the SCF geometry, even at full pump power (515 W) and full signal power (40 W), the depolarization losses remain at a very low level.

4. Cylindrical polarization

For the amplification of radially and azimuthally polarized seed beams, an external converter element [11] is used, converting the linear polarization of the seed laser beam to radial or azimuthal polarization, depending on the orientation of the converter element relative to the axis of the incoming linear polarization, as shown in Fig. 3. As the polarization converter consists of segmented waveplates, the intensity distribution of the converted beam is slightly distorted at the intersections of the waveplates and has to be filtered in order to achieve a good donut-shaped intensity distribution. This filtering was performed by focusing the beam onto a 120 µm pinhole and collimating the beam afterwards, using two f = 75 mm lenses. After this spatial filter, the available seed power was limited to about 32 W. As the fundamental donut beam is the Laguerre-Gaussian LG_{01*} mode the beam propagation factor of the cylindrically polarized seed beam should be $M^2 \approx 2$. Hence, the position of the focusing lens (f = 250 mm) at the entrance of the SCF was adjusted to keep the focusing in front of the SCF. With this, the diameter of the seed beam on the entrance facet of the SCF was increased to about 600 µm - 650 µm for both radially and azimuthally polarized input.

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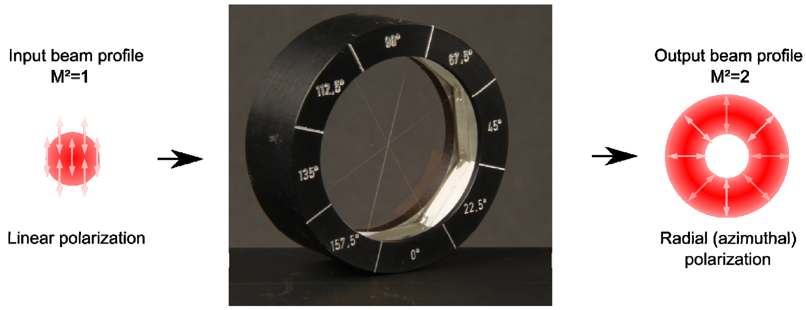

Fig. 3. Linear to radial / azimuthal polarization converter based on segmented waveplates. The lowest transversal order mode with cylindrical polarization is the LG_{01*} -mode with a donut-shaped intensity distribution.

As shown in Fig. 4, the output power of the amplified signal beam reached about 100 W at the maximum input power of 32 W and maximum pump power for both radially and azimuthally polarized seed. This corresponds to a single-pass gain of 3, which is comparable to the single pass gain achieved for the linearly polarized seed laser. Figures 5 (a) and 5(e) show the far-field intensity distributions of the radially and azimuthally polarized output beams, respectively, recorded at maximum pump and maximum seed power. This donut-shaped beam profile of the output beam was observed throughout all combinations of pump and seed power, with slight deviations arising from interference effects in the optics used to image the intensity distributions onto the camera and by the segmentation of the polarization converter and imperfect spatial filtering. These issues can be solved by using radial/azimuthal grating mirrors as intra-cavity polarizing devices since they generate a polarization purity higher than 99% and an ideal donut-like mode [10,12].

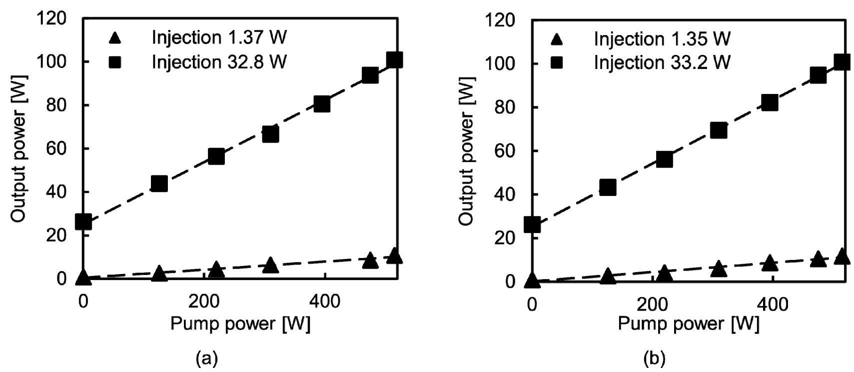

Fig. 4. Output power of the amplified beam for (a) radial and (b) azimuthally polarized input.

When a polarization analyzer is placed in the output beam, two lobes of the intensity distribution can be observed, changing azimuthal position when rotating the analyzer axis (see Figs. 5(b)-5(d) and Figs. 5(f)-5(h)). This qualitatively confirms the radial and azimuthal polarization state, respectively. Additionally, in order to get a more quantitative assessment of polarization conservation, the local polarization of the radially polarized output beam was measured at full power (see Fig. 6) using a custom-made camera based Stokes-polarimeter as described in [21]. The results indicate a high degree of radial polarization of above 95% +/– 2-3%, which is close to that of the seed beam after the polarization converter and therefore confirms the suitability of the SCF concept for the amplification of radially or azimuthally polarized lasers.

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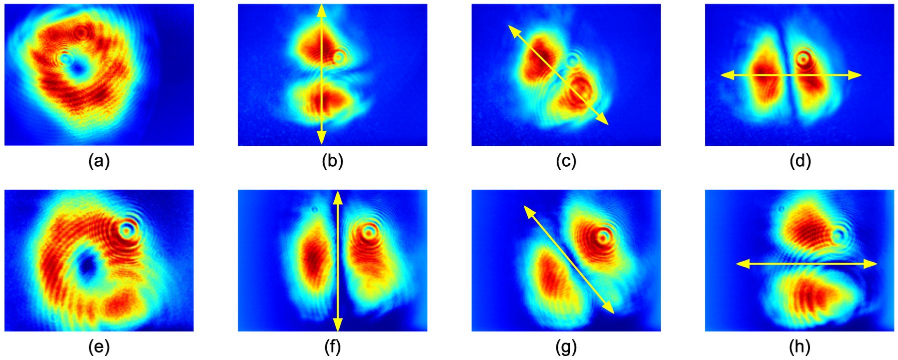

Fig. 5. Far-field intensity distribution of the amplified beam at maximum pump and maximum seed power for radial polarization (a) and azimuthal polarization (e). (b-d) Intensity distribution with rotation of the analyzer axis (the arrow indicates the transmission axis of the analyzer). (f-h) Intensity distributions with rotation of the analyzer axis.

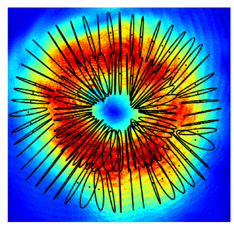

Fig. 6. Measured local polarization ellipses overlaid with the measured intensity distribution. The individual ellipses depict the local polarization state measured at the pixel in the center of each ellipse.

5. Summary and conclusions

In conclusion we have investigated the amplification of cw laser beams with different polarizations using a Yb:YAG single-crystal fiber amplifier in single-pass configuration. We have demonstrated that the polarization of a linearly polarized seed beam is well maintained with very low depolarization losses even at high power levels. Furthermore, we measured only a slight degradation of the beam quality of the amplified beam when pumping the amplifier at up to 515 W at 940 nm. Both the radially and the azimuthally polarized seed lasers with 32 W of power were amplified by a factor of 3 to an output power of 100 W, which is comparable to the gain achieved for the linearly polarized seed laser but with less depolarization.

The high single-pass gain in combination with the excellent conservation of both beam quality and state of polarization demonstrated in our experiments leads to the conclusion that the concept of an SCF-based amplifier, which has recently shown its significant potential for the amplification of ultra-short pulses, is most suitable for the amplification of cylindrically polarized ultra-short pulses as well. The simple, compact and robust amplifier setups that can be realized by using SCFs in single- or double-pass configuration seem to meet the requirements of industry-level ultrafast laser systems. As the devices used for the generation of cylindrically polarized laser beams have recently evolved to an industrial level as well, this amplifier concept will ultimately enable the investigation and exploitation of the benefits of radial and azimuthal polarization at ultra-short pulse durations for a wide range of industrial and scientific applications in the near future.

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