

Single-frequency master-oscillator photonic crystal fiber amplifier with 148 W output power

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Abstract: We report on a high-power ytterbium doped photonic crystal fiber amplifier using a single-frequency Nd:YAG non-planar ring oscillator seed source. With a large-mode-area photonic crystal fiber, operation below the threshold of stimulated Brillouin scattering is demonstrated with up to 148 W of continuous-wave output power and a slope efficiency of 75%. At maximum output power the amplified spontaneous emission was suppressed by more than 40 dB and the polarization extinction ratio was better than 22 dB. In order to investigate the overlap of the photonic crystal fiber transverse-mode with a Gaussian fundamental mode, sensitive beam quality measurements with a Fabry-Perot ring-cavity are presented.

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1. Introduction

Photonic crystal fibers (PCF) have been intensely investigated in the last few years for applications as passive waveguides and active laser media. Remarkable properties of these fibers have been reported like endlessly single-mode light guiding [1], super-continuum generation [2] and reduced nonlinear effects in large-mode-area (LMA) PCF for high-energy pulsed amplifiers [3]. In the continuous-wave (cw) laser regime, single transverse-mode operation with up to 320 W was demonstrated using a rod-type fiber [4]. The ability to extend the active fiber core diameters and still maintain single transverse-mode operation makes PCF very promising candidates to overcome limitations arising from nonlinear optical effects in high-power fiber laser systems. A major limiting factor when power scaling single-frequency continuous-wave laser sources with fiber amplifiers is for instance the onset of stimulated Brillouin scattering (SBS) [5,6].

High-power single-frequency laser using nonplanar ring-oscillator (NPRO) [7] seed sources have found application in fundamental research for gravitational wave detection where injection-locked oscillator rod-laser systems are currently developed with up to 195 W of output power [8]. The scaling of single-frequency laser sources to even higher output power levels by fiber amplification is of special interest in the field of coherent beam combining [9]. Using step-index ytterbium doped fibers with large core diameters a NPRO was amplified to 108 W of output power in Ref. [10]. A narrow-linewidth distributed feedback laser source was even amplified to 264 W without a sign of SBS owing to a specific thermal fiber management [11]. In this paper we investigate for the first time to our knowledge the potential of ytterbium doped PCF for power scaling of single-frequency laser sources.

2. Experimental setup

For the presented fiber amplifier experiments a setup with counter-propagating seed and pump laser beams was employed. The active fiber was seeded by a single-frequency NPRO with up to 1.4 W of continuous-wave output power at 1064 nm. An integrated Faraday isolator protected the NPRO against light coming from the fiber. Approximately 65% of the seed power could be coupled into the core of the PCF (DC-225-22-Yb from Crystal Fibre A/S) which had a nominal mode field diameter of $22 \pm 3 \mu\text{m}$ at 1060 nm and a numerical aperture of 0.04. The photonic bandgap fiber structure is formed by air-holes having a diameter of $0.22 \mu\text{m}$ and a pitch Λ of $11 \mu\text{m}$ between them. Three central air-holes are missing and form the triangular ytterbium doped fiber core. The pump cladding surrounding this structure is specified with a diameter of $225 \pm 10 \mu\text{m}$ and a numerical aperture of approximately 0.6. Pump light absorption at 976 nm is specified to be about 3.5 dB/m. The amplifier fiber was pumped by a fiber coupled high-power laser diode module (LDM 200-200 from Laserline GmbH, 300 μm fiber diameter, NA 0.22) emitting at 976 nm with 2.5 nm (FWHM) spectral bandwidth and a maximum power of 218 W measured after all focussing optics. With 4.2 m active fiber length the pump absorption was in the range of 95%, measured in amplified operation. In order to avoid fiber damage through uncoupled pump light, the fiber was clamped between water-cooled copper plates. Furthermore the fiber was coiled on a metal

spool with a diameter of 25 cm. The coiling was applied to enable single transverse-mode operation of the PCF through macro-bending losses [12].

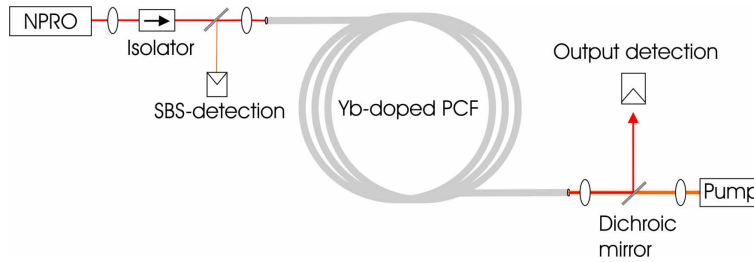


Fig. 1. Experimental setup of the single-frequency PCF amplifier.

Both fiber ends were sealed by thermally collapsing the air-holes and then polished to an angle of 8° to avoid parasitic oscillations. A dichroic mirror was used to separate the pump and amplified radiation. To monitor possible SBS, a small fraction of the backwards propagating light from the fiber was separated from the NPRO seed radiation by using a glass substrate.

3. Results

The output power characteristics of the presented single-frequency PCF amplifier system are shown in Fig. 2. With a maximum launched pump power of ~ 195 W an amplifier power of 148 W was obtained. The slope efficiency with respect to the launched pump power was about 75%. In order to verify operation below the threshold of SBS the power of backward propagating light from the PCF was monitored at all amplifier output powers (Fig. 2). The constant slope of this graph indicates SBS free operation [13]. Additionally, the intensity noise spectrum of the amplifier output was measured at maximum output power and showed no excess noise at frequencies above the resonant relaxation oscillation of the NPRO caused by SBS like reported in Ref. [13].

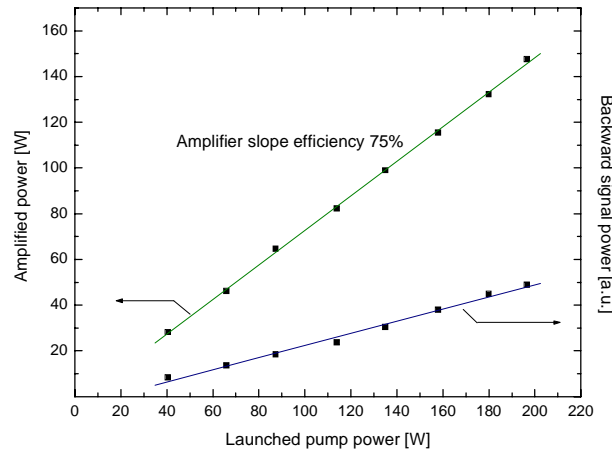


Fig. 2. Output power characteristic of the single-frequency PCF amplifier. Power of the backward propagating light versus launched pump power.

At maximum output power the optical spectrum was measured to investigate the contribution of amplified spontaneous emission (ASE) to the total output power (Fig. 3). By integration over the measured optical spectrum, taking into account the resolution bandwidth of 0.5 nm, the suppression of the ASE was estimated to be better than 40 dB corresponding to a ratio of ASE to amplified radiation of $\sim 8 \cdot 10^{-5}$.

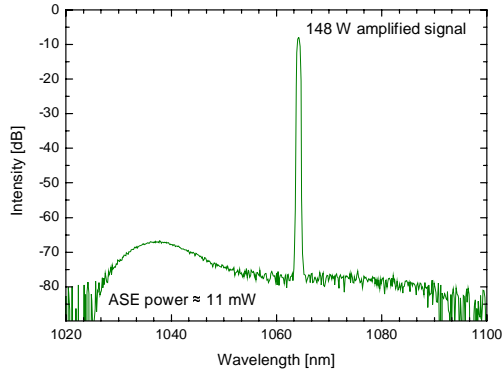


Fig. 3. Optical spectrum of the single-frequency fiber amplifier taken at 148 W of output power.

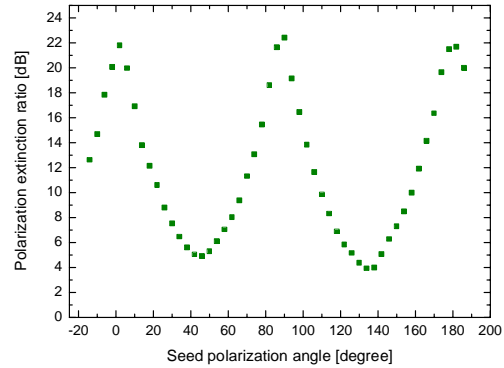


Fig. 4. Polarization extinction ratio versus seed polarization angle at 148 W of output power.

The polarization extinction ratio (PER) of the PCF amplifier output was measured with a half-wave plate and a polarizing beam splitter. Turning the polarization angle of the seed beam with a half-wave plate, strong changes of the PER were observed. In Fig. 4 the PER is plotted over a 180° turn of the seed polarization angle at 148 W output power. Although the PCF is not intentionally designed as a polarization maintaining fiber, a high PER of about 22 dB was achieved. We attribute this birefringence to imperfections in the PCF air hole structure as reported in Ref. [14]. Bending-induced coupling between polarization states is still relatively low for the fiber coiling diameter of 25 cm.

Measuring the caustic of the focused amplified beam with a CCD-camera, M^2 values in the range of 1.12 to 1.17 were determined, depending on the measuring axis and output power. A plot of an M^2 measurement at maximum output power is shown in Fig. 5 with the measuring planes X and Y set to the triangular output beam geometry like illustrated. The beam waist was defined by the second moment diameter [15]. At lower output powers of 28 W the beam propagation factor only slightly improved with M^2 of 1.12 ± 0.05 and 1.14 ± 0.05 in the X and Y plane, respectively. Theoretical considerations on M^2 factors of different PCF reported in Ref. [16] predict values in the range of 1.22 for fundamental transverse-mode operation of this type of fiber.

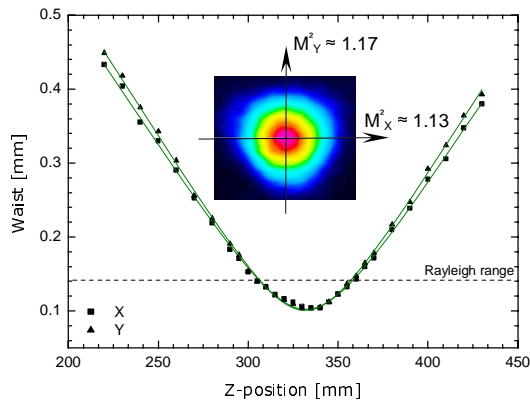


Fig. 5. M^2 measurement at 148 W output power. Inset: CCD-camera far-field beam profile.

In order to investigate the real overlap of the PCF transverse-mode with a Gaussian fundamental mode, sensitive beam quality measurements were carried out with a Fabry-Perot ring-cavity premode cleaner. A detailed description of the measuring setup can be found in

Ref. [17]. By scanning the length of the ring-cavity over a free spectral range (FSR), the relative power of higher order transverse-modes with respect to the Gaussian TEM₀₀ mode are obtained. Premode cleaner scans of the fiber amplifier are plotted with normalized intensity and frequency axis for 28 W and 148 W of output power in Figs. 6 and 7, respectively. In both cases, the analyzed beam was attenuated to about 200 mW to avoid damage of the ring-cavity.

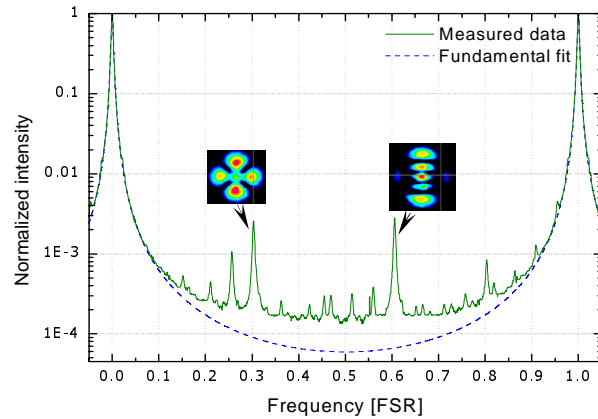


Fig. 6. Normalized transmitted intensity through a premode cleaner as a function of the ring-cavity length in units of a free spectral range (FSR) at 28 W of amplifier power. Insets: CCD-camera profile of two higher-order modes.

At an amplifier output power of 28 W the overlap with the fundamental Gaussian transverse-mode (dashed line) was measured to be 98%. These results coincide with premode cleaner beam quality measurements carried out with single-frequency amplifiers using different ytterbium doped standard step-index LMA fibers in Ref. [18]. Insets of Fig. 6 show two transmitted higher-order modes that contribute both around 0.25% to the higher-order mode power. These beam profiles were taken with a CCD-camera in transmission to the premode cleaner while slowly scanning over the FSR of the ring-cavity.

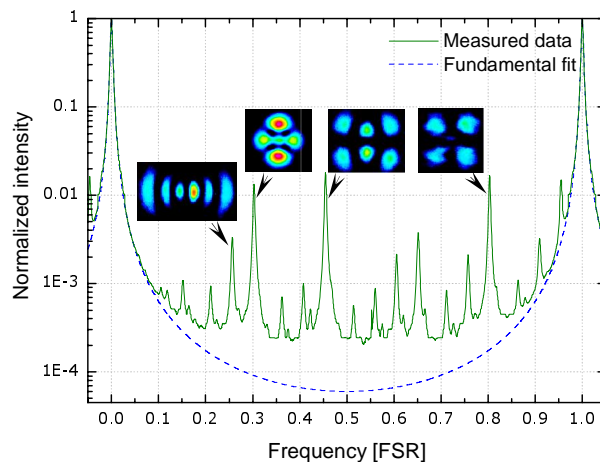


Fig. 7. Normalized transmitted intensity through a premode cleaner as a function of the ring-cavity length in units of a free spectral range (FSR) at 148 W of amplifier power. Insets: CCD-camera

As the fiber coiling diameter of 25 cm and therefore the propagation losses for higher-order modes were not changed during these experiments, the higher-order mode power of the amplifier output beam is expected to rise when increasing the pump power. Additionally, the increased thermal load inside the PCF gives rise to transversal mode profile changes [19]. This can be seen in Fig. 7, showing a premode cleaner scan at 148 W of amplified output power. Besides the higher-order modes at the normalized length of 0.3 FSR and 0.6 FSR, already observed at lower output powers (insets of Fig. 6), several more pronounced modes arise at higher output powers illustrated by the insets of Fig. 7. These modes individually carry up to 1.8% of the total output power. However, the overlap with the fundamental Gaussian transverse-mode is still 92.6%. Like has been reported from a different type of PCF in Ref. [20], despite the angular fiber geometry most of the light intensity is guided in the central part of the fiber core having a nearly Gaussian distribution and even the inhomogeneous ytterbium doping does not seem to alter the beam profile.

4. Conclusion

In conclusion, a single-frequency master-oscillator fiber amplifier using an ytterbium doped photonic crystal fiber and a Nd:YAG non-planar ring oscillator seed source was demonstrated. With a maximum continuous-wave output power of 148 W and a slope efficiency of 75% the photonic crystal fiber proved to be a promising candidate for high-power single-frequency amplification. No sign of stimulated Brillouin scattering was observed. The amplified beam showed a suppression of the amplified spontaneous emission of more than 40 dB and the polarization extinction ratio was better than 22 dB. The beam propagation factor M^2 was better than 1.2. By using a Fabry-Perot ring-cavity the beam quality was investigated in more detail. An overlap of the PCF amplifier output with the fundamental Gaussian transverse-mode of 92.6% was measured at maximum output power and even 98% at lower output powers of 28 W.