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Narrow-linewidth all-solid large-mode-area photonic crystal fiber amplifier

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ABSTRACT

Large-mode-area (LMA) photonic crystal fiber (PCF) amplifiers are attractive for high-power amplification of single-mode (SM) narrow-linewidth light. Traditionally, LMA PCF designs include air holes but splicing and interfacing of fibers with air holes is complicated. Recently, this was addressed with the development of a LMA PCF amplifier fiber without air holes but with SM operation maintained. This all-solid fiber can be spliced with standard splicers and thus enables integration of PCFs into all-fiber monolithic laser systems.

The new fiber, named DC-250/30-PM-Yb-FUD, is demonstrated in a free-space configuration for high-power amplification of 1064 nm light with a narrow linewidth of less than 20 kHz. A seed power of 380 mW is amplified to 40 W, corresponding to a single-stage gain of 20 dB, with an optical to optical efficiency of 69%. No indication of stimulated Brillouin scattering is observed, and the output is stable during frequency modulation of the seed laser.

Keywords: Photonic crystal fiber, fiber amplifier, narrow-linewidth, large-mode-area, all-solid fiber, high-power

1. INTRODUCTION

High-power narrow-linewidth fiber laser systems with diffraction-limited beam quality are applied in many areas of science and industry, including gravitational wave detection,[1–3] trapping and cooling of atoms,[4,5] and lidar technology.[6] In many of these applications modulation of the seed laser frequency is required e.g. in order to lock it to an external reference. Typically, the systems are configured as a master oscillator power amplifier (MOPA), which consists of a low-power narrow-linewidth seed laser followed by several amplifier stages that scale the power.[7]

The main challenge to power scaling of narrow-linewidth is stimulated Brillouin scattering (SBS). This can be mitigated by applying external thermal gradients to the power scaling fiber amplifier or by tailoring its acoustic properties.[8] However, the simplest way to mitigate SBS is to use short LMA fiber amplifiers. This makes PCFs amplifiers very attractive candidates for high-power narrow-linewidth amplification, since they can be designed with LMA cores that are SM at the operating wavelength.

Traditionally, LMA PCF designs include air holes whose diameters are adjusted to ensure a low effective index contrast between core and cladding, and thereby SM performance. However, splicing and interfacing of fibers with air holes is complicated. Recently, this was addressed by Papior et al. who reported the development of a LMA PCF amplifier without air holes and demonstrated SM high-power amplification of pulsed light.[9] A similar PCF amplifier is considered in this work, but for narrow-linewidth amplification. The all-solid DC-250/30-PM-Yb-FUD fiber fabricated by NKT Photonics A/S enables splicing with standard fusion splicers and thus integration of PCFs into all-fiber monolithic systems.[10] These are more compact, robust against environmental perturbations, and reliable than systems based on free-space components.

In Sec. 2 a short description of the fiber and its passive properties is presented. In Sec. 3 the experimental demonstration of narrow-linewidth amplification with the fiber is reported.

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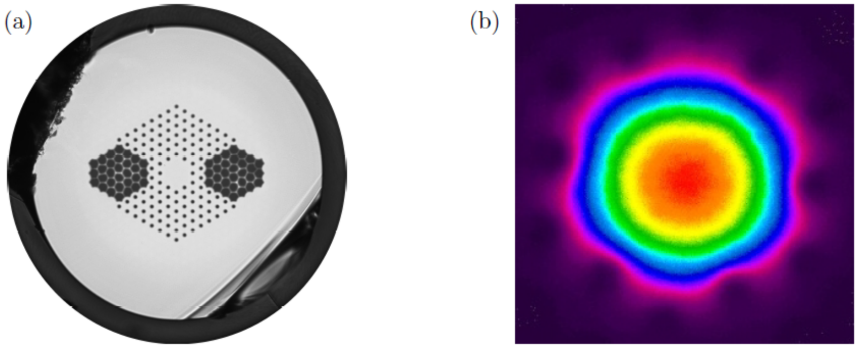

Figure 1. (a) Cross-sectional microscope image of the all-solid PCF. (b) Near-field image of the fiber mode for a coil diameter of 22 cm.

2. ALL-SOLID PHOTONIC CRYSTAL FIBER

A cross-sectional microscope image of the DC-250/30-PM-Yb-FUD fiber is shown in Fig. 1(a). It has a 30 µm diameter ytterbium-doped core surrounded by a periodic array of solid low-index inclusions that enable index-guiding of the core light. The fiber has a double-clad structure with an inner cladding diameter of 250 µm and NA $>$ 0.46. The pump light is confined to the inner cladding by a low-index polymer coating, which is itself surrounded by a protective coating (not shown in the figure). Two stress-applying elements induce birefringence that makes the fiber polarization-maintaining.

A detailed passive characterization of the fiber is given in Ref. 10. The fiber can be coiled with diameters down to the bend loss edge of approximately 19 cm of the fundamental mode in the slow axis polarization (parallel to the stress-applying elements). The bend loss edge of the fundamental mode in the fast axis polarization (perpendicular to the slow axis) is approximately a coil diameter of 25 cm. Fig. 1(b) shows a near-field image for a coil diameter of 22 cm and a wavelength of 1064 nm. A mode-field diameter of approximately 24 µm is measured in this configuration where the fiber is single-mode. The fiber can be spliced to itself with a standard splice program with a loss of less than 0.2 dB for all wavelengths in the range 1005-1200 nm.[10]

3. ALL-SOLID PHOTONIC CRYSTAL FIBER FOR NARROW-LINEWIDTH AMPLIFICATION

The all-solid LMA PCF amplifier is demonstrated for high-power amplification of 1064 nm light with a narrow linewidth of less than 20 kHz in a counter-pumped free-space configuration shown schematically in Fig. 2. The

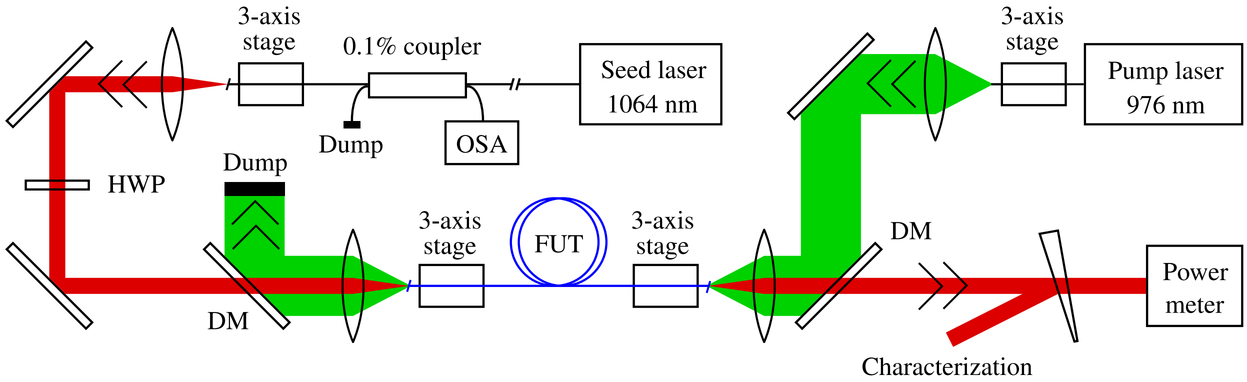

Figure 2. Schematic illustration of the free-space setup. OSA stands for optical spectrum analyzer, HWP for half-wave plate, DM for dichroic mirror, FUT for fiber under test (the DC-250/30-PM-Yb-FUD fiber), M for mirror, L for lens, and W is a silica wedge. Signal (1064 nm) light is indicated with red (black) and pump (976 nm) light with green (grey).

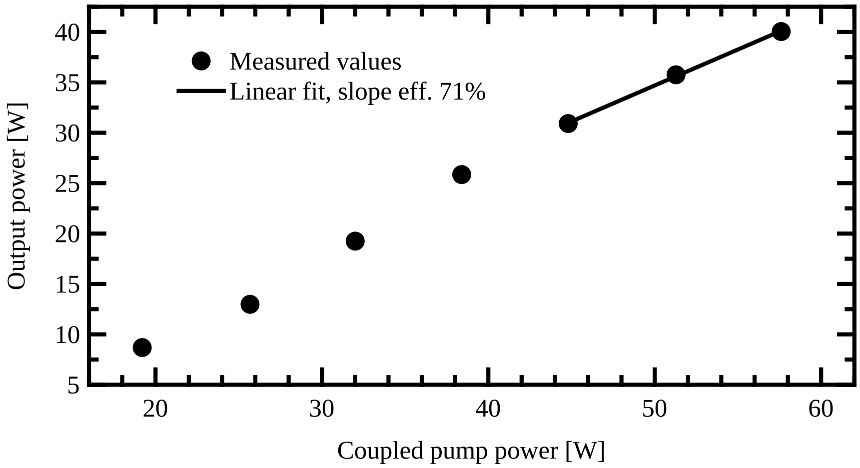

Figure 3. Output power as a function of coupled pump power for the 30 µm core all-solid photonic crystal fiber amplifier of length 3.6 m. A slope efficiency of 71 % is achieved above coupled pump powers of 45 W (the three last measurements) where all the pump light has a wavelength of 976 nm.

seed laser is based on a Koheras BASIK Y10 laser, which delivers 1064 nm light with a linewidth of less than 20 kHz.[11] The seed light is coupled into the core of the DC-250/30-PM-Yb-FUD fiber with two three-axis stages, two mirrors and a half-wave plate such that the polarization is aligned with the stress elements of the fiber. Similarly the (unpolarized) pump is coupled into the inner cladding from the other end of the fiber with two three-axis stages and two mirrors, one of which is a dichroic mirror that reflects pump (976 nm) light and transmits the output signal (1064 nm) light. Any residual pump light, which is not absorbed but exits the fiber at the input end, is dumped by a dichroic mirror that reflects pump light and transmits signal light. A silica wedge in the output beam extracts a proportion of the light for characterization. The signal power at the fiber output end is calculated from the power measured by the power meter corrected for loss due to components between the fiber output end and the power meter.

The performance for 3.6 m of fiber is shown in Fig. 3. The pump wavelength is stabilized at 976 nm for coupled pump powers above approximately 45 W. A coupled seed power of 380 mW is used, and an optical to optical efficiency of 69 % is achieved for the maximum output power of 40 W. A gain of 20 dB is thus achieved with a single amplification stage. A slope efficiency of 71 % is obtained for coupled pump powers above 45 W where the pump wavelength is stabilized at 976 nm.

Fig. 4 shows the output spectrum with a resolution of 1 nm. The signal peak is approximately 45 dB above the amplified spontaneous emission (ASE), and the ratio of signal power to integrated ASE is 29 dB.

The backward-reflected light was monitored with a 0.1 % coupler connected to an optical spectrum analyzer, and no indication of SBS was observed. Furthermore, the output power is stable during frequency modulation (FM) of the seed laser. The FM stability was monitored by a fast detector in the characterization, both for a large modulation depth of 10 GHz with a modulation frequency of 10 Hz, a high modulation frequency of 5 kHz with a modulation depth of 0.2 GHz, and modulation settings in between.

The results reported above were obtained in a free-space configuration but the DC-250/30-PM-Yb-FUD fiber is not restricted to free-space operation. It has been demonstrated by Christensen et al. in a monolithic forward-pumped setup for amplification of pulsed 1032 nm light up to 43 W.[10] The combination of this monolithic demonstration and the results reported in this work thus indicates that the DC-250/30-PM-Yb-FUD fiber enables few-stage monolithic MOPAs with narrow-linewidth output powers of several tens of watts.

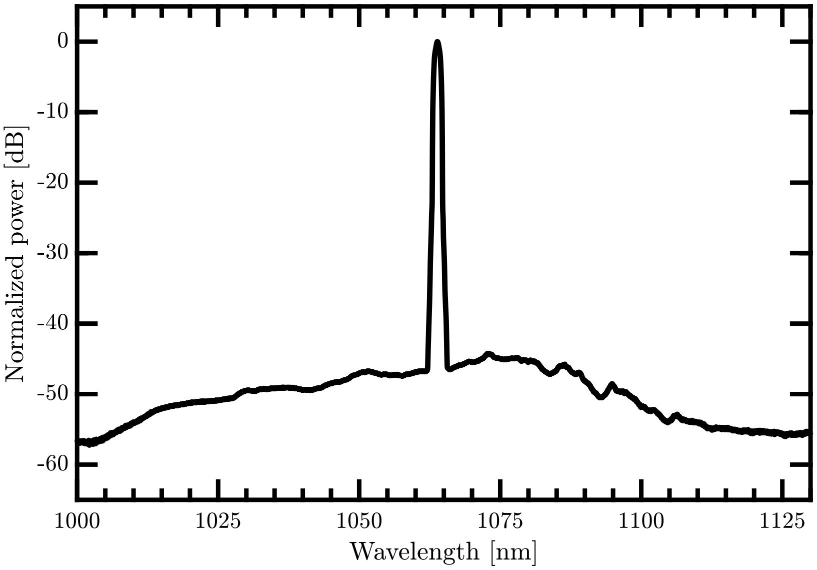

Figure 4. Output spectrum at 40 W output power with a resolution of 1 nm.

4. CONCLUSION

In summary, an all-solid PCF with diffraction-limited beam quality is presented for high-power amplification of narrow-linewidth light. It is demonstrated in a free-space configuration as an amplifier with 40 W output power, a slope efficiency of 71 %, no detectable SBS, and a 29 dB ratio of signal power to integrated ASE.

The output is stable during frequency modulation of the seed laser. Moreover, the output corresponds to a high single-stage gain of 20 dB, and the fiber is monolithic-compatible. It thus enables few-stage monolithic MOPAs with narrow-linewidth output powers of several tens of watts.

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