Lasing in thulium-doped polarizing photonic crystal fiber

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Received July 8, 2011; revised August 17, 2011; accepted September 7, 2011; posted September 9, 2011 (Doc. ID 150797); published September 27, 2011

We describe lasing of a thulium-doped polarizing photonic crystal fiber. A 4 m long fiber with 50 μm diameter core, 250 μm diameter cladding, and d/Λ ratio of 0.18 was pumped with a 793 nm diode and produced a polarized output with a polarization extinction ratio (PER) of 15 dB and an M^2 of <1.15. An intracavity polarizer and half-wave plate minimally increased the PER to 16 dB. The output power had 35% slope efficiency relative to the absorbed pump power. The maximum cw output power was limited to 4 W due to the quantum defect heating of the fiber. © 2011 Optical Society of America

OCIS codes: 140.3510, 060.5295.

High-power, diffraction-limited lasers with eye-safer wavelengths $>1.4\,\mu$m are desirable for applications requiring long-range atmospheric propagation, such as lidar [1] and directed energy [2]. Thulium-doped fiber lasers are of particular interest for such applications, because they offer the potential for compact and robust construction as well as high-power output in spectral ranges of high atmospheric transparency, which avoid absorption primarily from water vapor and CO_2 [3]. Thulium-doped fiber lasers also offer unique opportunities for medical applications due to the strong absorption of water at 1.94 μm [4], and for the pumping of mid-IR laser sources in the ~3–5 μm wavelength range [5,6].

The rapid development of thulium fiber laser sources has relied to date upon step-index fibers. Notable milestones include extremely broad laser tunability [7,8], high-power single-frequency output [9,10], high-peak-power generation [11–13], and 1 kW average power [14]. Many of these demonstrations have taken advantage of efficient 2∶1 cross-relaxation pumping [15], which enables >60% slope efficiency with 790 nm pump diodes.

Pulsed 2 μm fiber lasers with megawatt peak powers are required for applications such as lidar and optical parametric oscillator pumping; however, this level of performance has not yet been realized in thulium fiber lasers. As has been seen in the development of ytterbium fiber lasers, ultralarge mode fiber architectures are necessary to fundamentally surmount nonlinear effects [16]. In this Letter, for the first time, to the best of our knowledge, we demonstrate that the photonic crystal fiber (PCF) architecture can be successfully extended to operation at 2 μm laser wavelengths.

NKT Photonics A/S fabricated the PCF used in these experiments (Fig. 1). The core diameter is 50 μm with 0.04 NA, surrounded by a 250 μm diameter air cladding with >0.45 NA. The overall fiber diameter is 550 μm, coated by a single layer of high-temperature acrylate. The core glass composition is still being optimized, and is currently doped with 2.5 wt. % Tm and codoped with Al (1∶8 Tm/Al ratio) in order to prevent clustering. The pump absorption is ~6 dB/m for cladding pumping with 793 nm, whereas the core propagation loss is ~70 dB/km outside the absorption window.

The PCF has a hole size to pitch (d/Λ) ratio of 0.18 with a pitch of 12.8 μm. Preliminary results indicate that the mode-field diameter is ~36 μm at 1900 nm, corresponding to a mode-field area >1000 μm^2. The fiber is designed to provide single-mode propagation for bend diameter <80 cm, while fundamental mode bend losses have been observed for <35 cm bend diameters.

The hexagonal air hole lattice around the doped core includes boron-doped stress rods for polarizing operation. The polarizing behavior of this fiber is similar to that for PCFs with stress-applying parts designed for operation at 1 μm wavelength [17]. We estimate the birefringence to be $>1\times10^{-4}$ and that this fiber will exhibit polarized operation across a 200 nm spectral window centered at 2000 nm.

A schematic of the counterpropagating laser configuration is shown in Fig. 2. The pumped end of the fiber was fixed in a water-cooled heat sink, at 14 °C. The remaining length of the fiber is air cooled. To protect the air holes from contamination, both ends of the fiber were fused to collapse the air holes then cleaved to an angle below 1°. The light from a 793 nm, 35 W diode was directed to the fiber facet using a 1∶1 free-space telescope and a dichroic mirror (DM), which reflected the pump but transmitted the signal beam. The pump coupling efficiency was 86%. The signal output from the opposite fiber facet

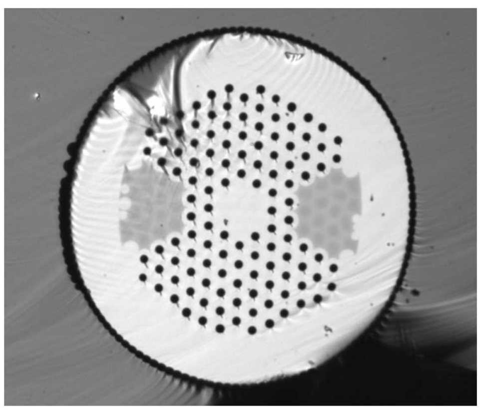

Fig. 1. Image of the fiber facet, showing the 50 μm core, 250 μm diameter cladding, and the stress-applying parts.

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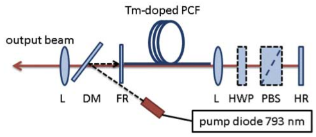

Fig. 2. (Color online) Schematic of the counterpropagating cavity: L, collimating lens; DM, dichroic mirror; FR, 4% Fresnel reflection; HWP, half-wave plate; PBS, polarizing beam splitter; HR, high-reflective mirror.

was collimated using a 26 mm focal length triplet and feedback using a high-reflectivity (HR) mirror. The cavity was formed between the mirror and the 4% Fresnel reflection from the flat-cleaved fiber facet on the pump end. After transmission through the DM, the output beam was collimated using another 26 mm focal length triplet. For some experiments, a half-wave plate (HWP) and a polarizing beam splitter (PBS) were inserted into the cavity. In the results reported here, the 4 m long fiber was coiled to a 40 cm bend diameter; however, we did not observe any significant influence of bend diameter on slope efficiency, beam quality, or polarization for bend diameters from 40 to 70 cm.

The output power with respect to the absorbed power is shown in Fig. 3. The slope efficiency of the system is approximately 36.6% with a maximal output power of 4 W. The maximum pump power was limited to ~23 W, as the temperature of the polymer coating reached 40–50 °C at this level. At this temperature, the fiber coating softens, resulting in misalignment of the free-space pump coupling. The elevated fiber temperature also reduced slope efficiency. Although the improvement was minimal, a measurable 2% increase in the slope efficiency was achieved by circulating air around the fiber with fans.

The beam quality was measured using a pyroelectric array camera. The M^2 was 1.25 along the X and Y axes; however, if an aperture was used to remove the signal light propagating in the cladding, M^2 was reduced to 1.13 and 1.15 along X and Y, respectively. Figure 4 shows the beam at an output power of 4 W in the near and far fields, and the M^2 data. The fiber exhibited purely single-mode operation with no degradation of beam quality observed by misaligning the laser cavity or perturbing the fiber.

The ~100 nm wide (FWHM) amplified spontaneous emission (ASE) of the fiber was maximal at ~1910 nm. The attenuation of the ASE signal for wavelengths from ~1800 to 1950 nm was the result of absorption from atmospheric water vapor. The lasing spectrum contains

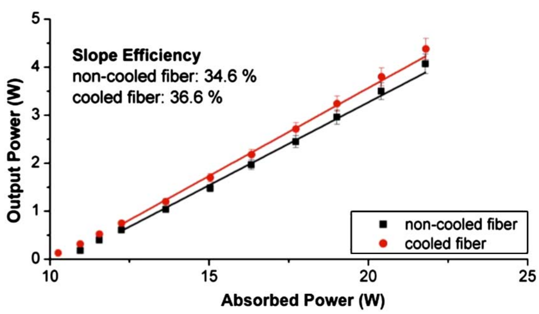

Fig. 3. (Color online) Laser performance.

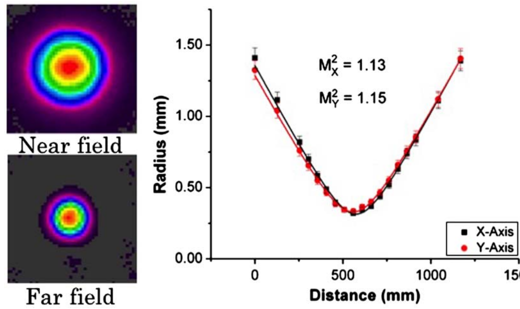

Fig. 4. (Color online) Left: beam in the near and far fields. Right: M^2 measured at 4 W output power.

several narrow linewidth emission peaks with wavelengths from ~1975 nm (Fig. 5). Although the specific laser emission changed versus time and pump power, we always observed many emission peaks.

The redshift of the laser output relative to the ASE peak results primarily from the three-level laser nature of thulium and, to a lesser degree, from the loss associated with water vapor absorption during free-space propagation in the cavity.

The polarization extinction ratio (PER) was measured with and without an intracavity HWP and PBS (Fig. 6). An additional measurement of the PER was made after an aperture to remove cladding light. The PCF produced a polarized output with a PER of 15 dB without any intracavity polarization optics. The addition of the HWP and PBS marginally increased the output PER to 16 dB, confirming that the fiber itself is sufficient for effective polarization control. The output PER increased to 19 dB if the cladding light was removed with an aperture. Light trapped in the cladding corresponded to ~8% of the total output.

We have demonstrated, to the best of our knowledge for the first time, lasing of thulium-doped PCF. The single-mode, single-polarization output of this ultralarge mode area fiber is extremely attractive for the generation and amplification of high-energy and high-peak-power pulses. Relative to bendable PCFs used at 1 μm wavelengths, this fiber demonstrates a significant increase in mode-field area without sacrificing bend diameter. This indicates that there is room to further scale the PCF architecture to maximize mode-field area for operation at 2 μm in both bendable and fiber-rod-type configurations.

Improved fiber cooling is necessary to further scale the output power and to improve slope efficiency.

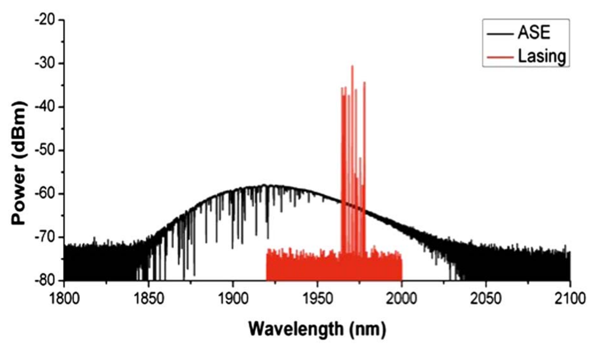

Fig. 5. (Color online) Spectrum of ASE and lasing at the same pump power (corresponding to 4 W lasing output power).

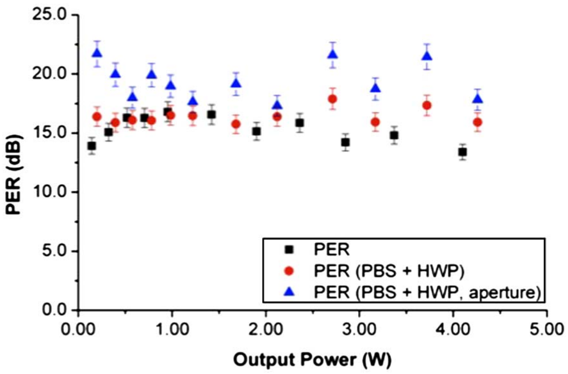

Fig. 6. (Color online) Polarization extinction ratio of the PCF.

Furthermore, increasing the Tm concentration beyond 2.5% should also increase the slope efficiency above the Stokes limit of 40% [15]. We are currently investigating the performance of Tm:PCF in pulsed formats as this PCF technology may offer a new path in the development of fiber lasers producing few-megawatt peak powers in the 2 μm wavelength regime.

The authors acknowledge the support of the Joint Technology Office (JTO) through a Multidisciplinary Research Initiative (MRI) program (contract #W911NF-05-1-0517), the State of Florida, and the European Commission through project IMPROV (Grant Agreement 257894).

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