# CW-lasing and amplification in $Tm^{3+}$-doped photonic crystal fiber rod

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We report lasing and amplification in a rod type thulium-doped photonic crystal fiber with 80 μm core diameter. The rod is pumped with a 793 nm laser diode and produces more than 20 W output power at a beam quality $M^2 < 1.3$. The laser/amplifier has a slope efficiency of 27.8%/20.1% relative to absorbed pump power with a lasing threshold at 28.6 W. The output wavelength in the lasing configuration can be tuned over 180 nm from 1810–1990 nm. © 2012 Optical Society of America

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Fiber laser development in the last decade has seen a rapid rise in output power [1]. Today, ytterbium doped fiber laser systems deliver multi-kW powers in CW and high peak powers in pulsed operation. These achievements particularly result from double clad designs that allow efficient coupling and guiding of the pump light in the fiber, and by overcoming nonlinear effects using ultra-large mode area fiber designs.

However, single mode operation cannot be guaranteed for very large mode area step index fibers. Several alternative concepts have been developed to preserve single mode operation for large mode areas, in particular photonic crystal fibers (PCFs) and PCF rods [2]. Although the PCF approach is well established for 1 μm wavelengths, PCFs have only recently been utilized at 2 μm wavelength.

In the "eye-safe" (>1.3 μm) wavelength regime, 2 μm fiber laser systems are useful for applications requiring long range propagation, such as light detection and ranging (LIDAR) and differential absorption LIDAR. The longer wavelength also leads to a higher stimulated Brillouin scattering threshold, enabling power scaling of narrow linewidth/single frequency fiber laser sources relative to ytterbium based systems [3].

Noteworthy developments at 2 μm wavelength comprise broad laser tunability [4], high power single frequency output [5], and high peak-power generation [6]. The 2∶1 cross relaxation pumping has been utilized to increase the slope efficiency with 790 nm pump diodes >60% [7], partially compensating for the disadvantage of a high quantum defect.

We have recently reported CW lasing of a new class of 2 μm thulium-doped flexible PCFs with >1000 $\mu m^2$ mode field area, single-mode beam quality ($M^2 < 1.15$), and polarized output [8]. Actively *Q*-switching this PCF-based oscillator with an acousto-optic modulator provided polarized, diffraction-limited output with 435 μJ energy and ~49 ns pulse duration [9]. Here we demonstrate, for the first time, CW lasing of a PCF rod with similar chemical composition as in [8] and larger mode area.

The PCF rod tested was fabricated by NKT Photonics A/S (Fig. 1). The fiber rod is 1.36 m in length and has an all-glass triple clad design with an outer diameter of 1520 μm and an inner air cladding diameter of 220 μm with >0.4 NA at 790 nm. The 80 μm diameter silica glass core is doped with 2.5% Tm and codoped with Al (1∶8 Tm/Al ratio) to circumvent clustering and has an estimated mode field area of >2800 $\mu m^2$ with 0.02 NA. The pump absorption at 790 nm is ~17 dB/m. The PCF rod inner cladding has a hole size to pitch ratio ($d/\Lambda$) of 0.191 with a pitch of 13.7 μm.

Figure 2, in configuration A, illustrates the CW-lasing setup in counterpropagating pump configuration. A 1.36 m long metal V-groove was made to serve as the fiber mount. Six metal water-cooled cuboids (13°C) were used to control the temperature of the rod. To prevent contamination, the fiber ends were fused to collapse the air holes. To prevent parasitic lasing, the fiber facets were angled to ~4°. The rod was pumped with a 790 nm, 100 W laser diode with 200 μm diameter delivery fiber. The pump beam was coupled into the rod by a 1∶1 telescope ($f_3$, $f_4$) and a dichroic mirror (Mp) reflecting 790 nm and transmitting light at 2 μm wavelength. The signal emitting from the opposite fiber facet was collimated using a 26 mm focal length triplet ($f_1$) with antireflection coating at 2 μm wavelength and fed back using a high-reflectivity mirror (M) at 2 μm wavelength. The signal light was collimated after the dichroic pump mirror with an uncoated 50 mm doublet lens ($f_2$). The Fresnel reflection from the uncoated surface of a 3° wedge (~4% reflectivity) was utilized as the output coupler and completed the laser cavity. For the investigation of tunability, M was replaced by a diffraction grating.

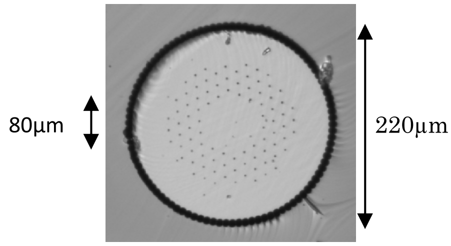


Fig. 1. Image of the fiber facet, showing the 80 μm diameter core and the 220 μm diameter inner cladding.

 

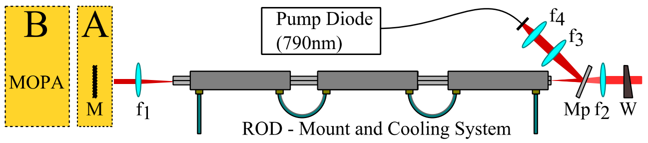


Fig. 2. (Color online) Schematic of the counterpropagating cavity. $f_1$, $f_2$: collimating lenses, $f_3$, $f_4$: 1∶1 pump telescope, Mp: high reflective mirror at 790 nm, W: wedge with 4% reflectivity at 2 μm. **Configuration A:** M: high reflective mirror at 2 μm. **Configuration B:** MOPA as seed.

Figure 2, in configuration B, shows the utilization of the PCF rod as an amplifier by removing M and seeding the PCF rod with a master oscillator power amplifier (MOPA) recently presented in [10]. The MOPA was configured to provide 4 W CW output power at 1961 nm.

Figure 3 shows the dependence of output power on estimated absorbed pump power for the CW-lasing and amplification configuration with corresponding slope efficiencies of 27.8 ± 0.2% and 20.1 ± 0.2%, respectively. In [8], we achieved a slope efficiency >36% in a flexible PCF with identical chemical composition. In the lasing configuration the low slope efficiency is partially the result of the non-antireflection coated cemented doublet lens $f_2$ with only 80% transmission leading to a relatively high lasing threshold of 28.6 W launched pump power. The peak output power of 22 W was limited by the available pump power. The comparatively small amplifier slope efficiency is primarily the result of the lower gain at 1961 nm. As part of these tests, we found that the PCF rod preserved the polarization for pump powers up to 100 W.

Figure 4 shows the spectra for the lasing configuration producing 15 W output power and when amplifying at 1961 nm. Also shown is the spectrum of amplified spontaneous emission (ASE) at 17 W pump power, which had a maximum at ~1900 nm and an FWHM of ~200 nm. This ASE is broader and extends to a much lower wavelength than was observed in a flexible PCF with similar core composition [8]. This data suggest that there is much less self-absorption from the three-level energy structure of thulium in the rod than in the flexible PCF. This is related to the difference in length, but it has not yet been possible to measure the ASE as a function of length in these thulium-doped PCF structures. Likewise, it has not yet been possible to accurately measure the propagation loss at the signal wavelength or to determine the number of guided transverse modes.

When lasing, the spectrum consisted of multiple narrow linewidth peaks spanning from ~1900 nm to 1950 nm (Fig. 4). Lasing was slightly shifted to longer wavelengths compared to the ASE maximum, which may be the result of absorption from atmospheric water vapor in the free-space portions of the laser cavity.

An $M^2$ measurement was performed at 5 W output power to investigate the beam quality of the lasing output. The collimated laser beam was focused with a 500 mm singlet lens. The beam width was measured with a pyroelectric array camera. The $M^2$ measurement was carried out with and without the pinhole, reaching the same result in both cases. Measurements indicated <5% of the total output power is trapped in the cladding. The $M^2$ in the $x$- and $y$-direction is $1.15 \pm 0.04$ and $1.05 \pm 0.02$, respectively. The higher $M^2$ value for the horizontal ($x$) orientation is the result of astigmatism caused by the path of the laser beam through the pump mirror. The same configuration was used to characterize the amplification. In Fig. 5 the beam radii are plotted for different $z$ positions. High power $M^2$ measurements showed no significant degradation in beam quality. However, the coupling into the core is very sensitive and leads to results ranging between $M^2 = 1.01$ and $M^2 = 1.35$. This increase in $M^2$ was associated with subtle changes in optimal seed alignment relative to seed power. There was no dependence of $M^2$ on pump power. Without pumping the rod, the mode field diameter (MFD) was found to be $(50 \pm 5)$ μm and slightly smaller than expected. Using this and the $M^2$ at 20 W output power the NA is $0.031 \pm 0.004$, confirming the theoretical estimation.

To investigate oscillator wavelength tunability (configuration A), the HR mirror M was replaced by a

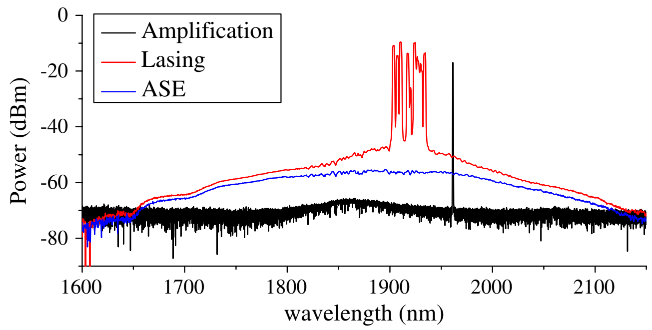


Fig. 4. (Color online) Spectra of ASE at 17 W pump power. Lasing and amplification at 70 W pump power.

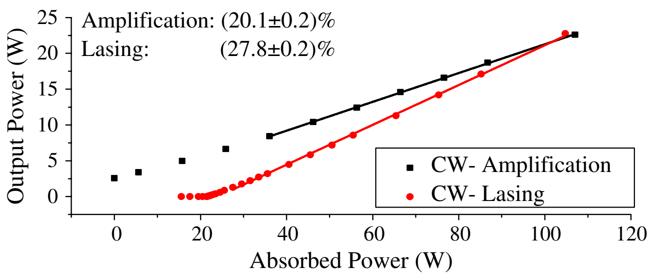


Fig. 3. (Color online) Slope efficiencies for CW-lasing and amplification at 1961 nm with respect to absorbed power.

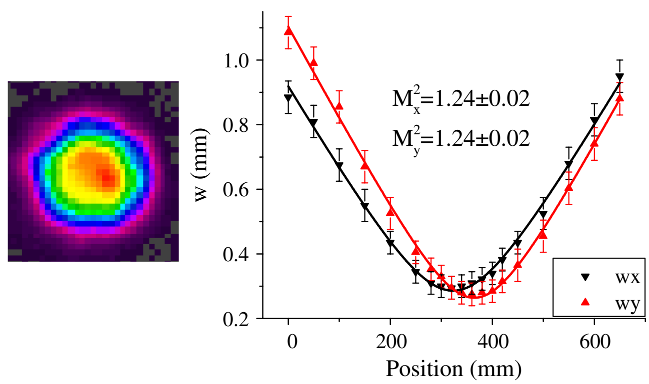


Fig. 5. (Color online) Right: $M^2$ of amplified signal measured at 20 W output power. Left: beam in the far field.

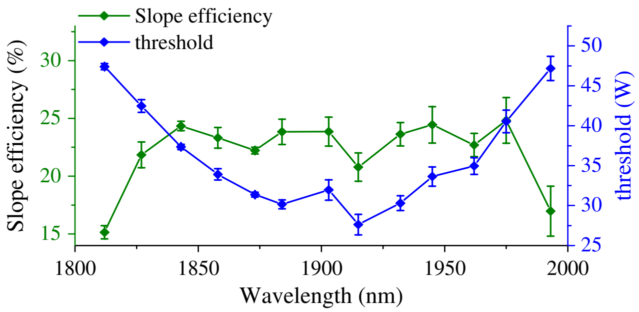


Fig. 6. (Color online) Slope efficiencies and thresholds for selected wavelengths.

600 line/mm gold-coated reflection grating. Lasing was achieved from ~1810 nm to ~1990 nm (Fig. 6), and the tuning range follows the ASE spectrum. However, lasing seems to favor longer wavelengths most likely as a result of water vapor in the atmosphere. The slope efficiency of the oscillator at 1961 nm is in agreement with the efficiency of the amplifier at the same wavelength.

We have validated, to the best of our knowledge for the first time, CW-lasing and amplification in a thulium doped PCF rod. The ultra-large mode area and the excellent beam quality make this fiber design very interesting for the generation and amplification of high-energy and high-peak power pulses. The broad tunability from 1810 to 1990 nm is also interesting and the ASE spectrum indicates that wider tuning may be possible.

Although the lasing slope efficiency is relatively low, this can be partially improved by eliminating the astigmatism induced in the current cavity configuration, reducing cavity losses and optimizing the output coupler. Low efficiency has also been observed in flexible PCF [8], and improvements are needed to achieve efficient cross-relaxation. Further work is necessary to determine the limits of mode area scaling with this design, but these initial results are extremely promising.

We are currently investigating the performance of this PCF rod as an amplifier stage for nanosecond pulses, to scale energy and peak power into the mJ and MW range.

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