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RESEARCH ARTICLE

HIGH BRIGHTNESS 1908nm TM-DOPED FIBER LASER WITH POWER SCALING TO >75W

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ABSTRACT

In this paper, we have studied monolithic diode-pumped Tm-doped fiber laser to be used as a pump source for Ho-YAG systems. The cavity is designed to achieve high optical-to-optical efficiency and robustness against amplified spontaneous emission (ASE) induced parasitic oscillations via optimizing the doped fiber length and cavity parameters. Experimentally, we have demonstrated 1907.7 nm fiber laser with an output power of 79 W from 10/130 μm Tm-doped double clad fiber, enabling high brightness and radiance density as well. The laser cavity has a slope efficiency of ~55%, ASE suppression of > 40 dB and a near-diffraction-limited beam quality of M^2~1.07.

Keywords: Thulium doped fiber lasers, Mid-IR lasers, Parasitic oscillations

1. INTRODUCTION

Fiber lasers, compared to bulk crystal alternatives, offer unique compact, more reliable, robust, highly efficient, power scalable and high-brightness sources [1–4]. Thulium-doped fiber lasers (TDFL), having broad gain spectrum emitting at 1.8-2.1 μm regime facilitates many applications in emerging fields ranging from industry, remote sensing and medical to defense. In particular, 2 μm laser sources possessing lesser atmospheric scattering-distortion, and reduced thermal blooming compared to 1 μm alternatives facilitates long range LIDAR, free-space optical communication and directed energy systems [5]. Additionally, in material processing (cutting, welding, drilling) industry, while 1 μm lasers are frequently used in metal processing, 2 μm lasers with having significantly higher absorption peaks enables more efficient processing of non-metals such as plastics and glass materials [6]. Similarly, strong water absorption peaks around IR and mid-IR regime makes it possible to use 1.9-2.1 μm laser sources in medical applications especially in precise tissue surgery and lithotripsy [7-8]. On the other hand, high brightness Tm-doped fiber lasers (TDFL) around 1.9 μm constitutes an excellent pump source for solid-state laser systems (e.g. Ho-YAG) allowing for high quantum efficiency, are useful for in-band and core pumping of TDFLs and facilitates parametric frequency conversion to mid-IR and THz regime [9-11].

Thanks to the advances in commercially available semiconductor laser diodes (LD) emitting at ~790 nm, multi-clad fiber technology and high quantum efficiency due to cross-relaxation; a numerous amount of high power Tm-doped fiber lasers and amplifiers emitting ~2 μm have been successfully demonstrated [12]. In this approach, MOPA systems using large mode area (LMA) fibers with core diameter up to 25 μm are designed to achieve more than 1kW of output power at ~2.05 μm [13]. Yet, compared to multi-stage amplifier systems, high-power oscillators minimize cost and complexity providing more stability, robustness and precise control. Direct diode-pumped TDF oscillators operating below 2 μm have been reported at incremental power levels and different wavelengths as 170 W and 300W at 2050 nm [14-15], 278W at 1967 nm [16] and 185 W at 1950 nm [17].

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To achieve emission at the far end of spectrum (> 2.05 µm), Ho-doped systems such as Tm-Ho co-doped fibers (more expensive and not fully established especially for high powers) and Ho: YAG (cost efficient and mature technology) are mostly favored. Hence, TDFLs emitting at 1908 nm plays a crucial role to pump such Ho: YAG systems. However, due to the severe gain competition (emission vs re-absorption) within the ASE spectrum which tends to lase at 1.95-1.98 µm, it is more challenging to design robust and stable TDFLs operating at 1908nm [18-19]. To develop such high power 1908 nm lasers, double-clad fibers (DCF) with core diameters > 15 µm are commonly used [18-22], which, however, degrades the beam quality, brightness $B\sim\left(\frac{Power}{(\lambda M^2)^2}\right)$, and radiance density $RD\sim\left(\frac{Intensity}{(\lambda M^2)^2}\right)$. Such single-mode fiber lasers with core diameters ≤ 10 µm and having high radiance density, on the other hand, facilitates power scalability by efficient beam combining, resonant in-band pumping of TDFLs and enhances gain medium excitation in solid-state lasers.

In this paper, we have demonstrated 1908 nm narrow linewidth single-mode fiber laser employing 10/130 µm Tm-doped fiber. As a design criteria, the doped fiber length and cavity parameters are optimized to achieve high output power and high ASE noise suppression for stable operation. Experimentally, we achieved 79 W near-diffraction-limited laser beam at 1907.7 nm with ~55% slope efficiency, > 40 dB ASE suppression and a M^2 of ~1.07.

2. EXPERIMENTAL SETUP

The proposed 1908 nm monolithic fiber laser is illustrated in Figure 1. The cavity is composed of a fused pump combiner (Nx1), a pair of fiber Bragg grating (FBGs) mirrors, Tm-doped DCF, cladding power stripper (CPS) and fiber pigtailed collimator. Laser diodes (LDs) emitting at 790nm [30W, 105/125 µm] are employed to couple ~150 W pump power into the cavity via using 7x1 multi-mode pump combiner with < 0.05 dB insertion loss. A pair of matched FBG mirrors, including high reflector (HR: λ_c=1908.07 nm, R=99.98%, and $\Delta\lambda$=2.81 nm) and output coupler (OC: λ_c=1908.03 nm, R=10.23%, and $\Delta\lambda$=1.08 nm) is used to form a resonating cavity. As the gain medium, 10/130 µm single-mode Tm-doped DCF with high clad absorption (α=8.37 dB/m at 789nm) and 0.15/0.46 numerical aperture (NA) is used. The doped-fiber length is optimized based on numerical analysis concerning the gain competition, namely the cavity is forced to lase at the wavelength with the lowest inversion (average excitation, n_2). To design such robust cavity against parasitic lasing with high ASE suppression, high conversion efficiency and adequate pump absorption, ~2 m TDF is employed as a gain medium. Even though it is less prominent for a-few-mode area fibers (≤10 µm), to attain a high beam quality (single-mode beam), namely to suppress higher order modes (HOMs) especially due to LP_{11} mode, and to achieve effective cooling, the gain fiber is wrapped spirally into a U-grooved channel (R_{min}= 75 mm) on a water-cooled Al heat sink.

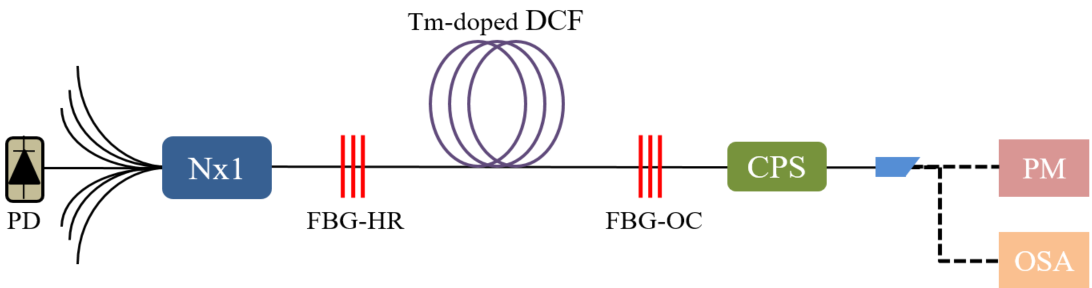

Figure 1. Experimental setup for 1908 nm monolithic CW fiber laser. PD: pump diode; PM: power meter; OSA: optical spectrum analyzer.

At the end of the cavity, a polymer-free CPS fabricated on a passive (Ge-doped) 10/130 µm DCF is used to strip unwanted cladding light stemmed from high NA residual pump light and low NA light escaped from core such as HOMs due to bending loss, lossy splices and ASE in gain medium. The coating of the DCF is window stripped and cladding surface is chemically etched (L=50 mm, ET=20 min) to create roughness on the glass clad. The performance of the etched fiber is tested in terms of the power handling capability, the stripping efficiency (Eff_{strip}), and the thermal load at the hot spot. Fabricated CPS packed in an Aluminum heat sink for mechanical protection and beam dump, can handle up to 100 W cladding power with ~17 dB attenuation and ~0.08 (°C/W) low thermal slope (TS), Figure 2.

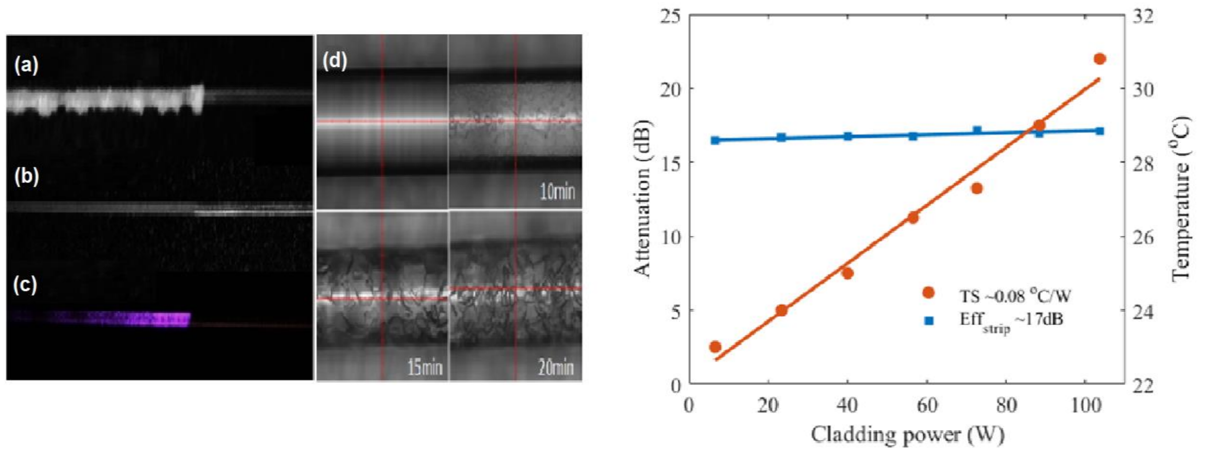

Figure 2. 10/130µm DCF after coating strip and etching process (a). The etched fiber (b) is examined under the white light (c). Microscope images (214µm x 265µm) of unetched and etched (for 10, 15 and 20mins) 10/130µm DCF for characterization (d). The stripping performance of fabricated CPS is studied in terms of stripping efficiency (Eff_{strip}) and thermal slope (TS) (e).

To test the laser performance, fiber coupled collimator with internal isolator (6.5 mm, <1 mrad divergence, >50 dB return loss) is spliced to the end of CPS to prevent any back reflections and hence the parasitic lasing. The power ratings, such as the output power and the slope efficiency, of the 1908 nm contınuous-wave (CW) fiber laser is measured with an air-cooled thermopile (Thorlabs S322C, 200 W) as illustrated in Figure 3. Thanks to the cross-relaxation in Thulium, the cavity produces up to 79 W single-mode laser beam with high slope efficiency of ~55%. As the performance of laser diodes strongly depends on the temperature, the emission shifts to the longer wavelengths (~1 nm/A) and gets locked to 790-793 nm (> 95% power in band) only at higher currents. At low currents, however, the pump light cannot be absorbed adequately due to the narrow absorption peak of the Tm at 790 nm and this, in turn, results in a reduction of the lasing efficiency and increase in thermal load on the CPS. Thus, unlike those driven in series, the pump diodes (x7) are operated one by one, making the slope efficiency stay almost constant as the pump power increases.

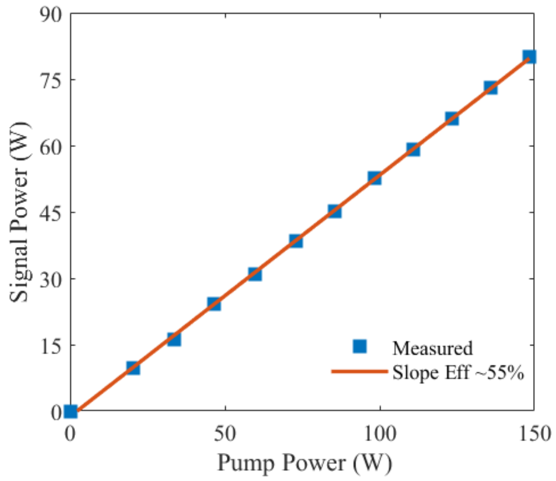

Figure 3. The output signal power versus pump power ratings. The cavity produces up to 79 W output power with approximately 55% slope efficiency.

The spectral content of the laser is simultaneously monitored by optical spectrum analyzer (OSA, Thorlabs 205C, 1.0-5.6 μm) to observe any ASE induced parasitic lasing. ASE mainly builds up in the spectral range of 1940–2000 nm and the parasitic oscillations in the vicinity of 1980 nm (peak emission for unforced cavity) is triggered as the signal power increases due to the high inversion. As shown in Figure 4, the laser emits at 1907.7 nm with a 0.13 nm spectral bandwidth and > 40 dB ASE noise suppression at full power of 79 W.

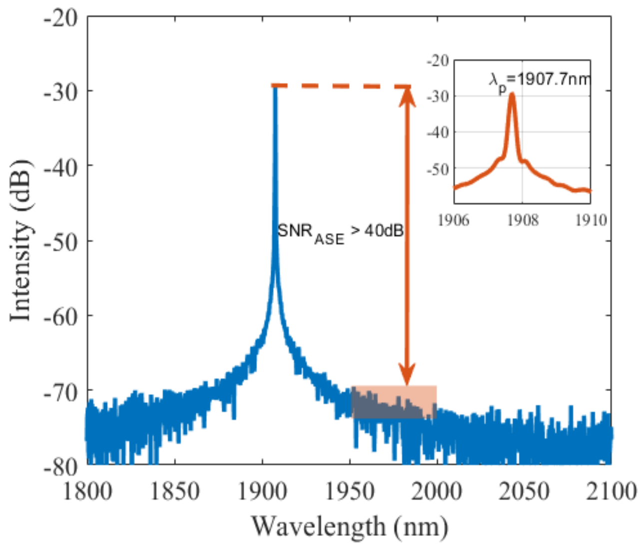

Figure 4. The spectral content of the laser cavity. The cavity lases at 1907.7nm with >40 dB ASE suppression within 1.95-2.0 μm spectral window.

Meanwhile, the beam quality, namely the spatial mode content, of the laser beam is characterized, and the M^2 factor is directly quantified by Ophir beam monitor (NanoModeScan) based on the second-moment method (99% at 4-sigma), as shown in Figure 5. The laser produces a near-diffraction-limited beam with ~120 mrad half-angle divergence and M^2 factor of 1.07 (M^2_x=1.06 and M^2_y =1.09), which indicates single-mode laser, in which the HOMs are suppressed, with high brightness and radiance density (scales quadratically with NA and core diameter). Such lasers with small beam-parameter product (BPP) and high radiance density enables power scalability by efficient beam combining and enhances the gain medium excitation in solid-state lasers (i.e. Ho: YAG) with high overlap factor.

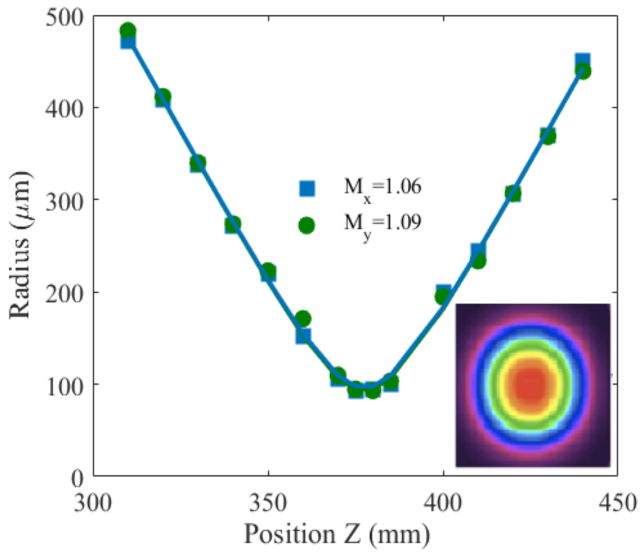

Figure 5. The far-field beam profile of the output laser at 79 W full-power. A diffraction-limited beam with M^2~1.07 is achieved. Beam profile at the waist (inset).

3. CONCLUSION

In conclusion, 1908 nm high brightness single-mode fiber laser employing10/130 µm double-clad Tm-doped fiber is demonstrated. The cavity parameters and doped-fiber length are optimized to achieve high robustness against parasitic lasing, high optical efficiency and adequate pump absorption. Experimentally, we have achieved 79 W output power with ~55% slope efficiency, peak emission at 1907.7 nm with > 40 dB ASE noise suppression and a diffraction-limited beam with an M^2 factor of 1.07. With the help of such a 1.9 µm high-brightness lasers, power scalability via efficient beam combining, in-band pumping of Ho-doped fiber laser/amplifier which reduces quantum defect and increases O-O efficiency, core-pumping in Ho-doped fiber laser/amplifiers and efficient excitation of gain medium in Ho-YAG solid-state lasers for medical and mid-IR frequency conversion application are facilitated.

CONFLICT OF INTEREST

The author stated that there are no conflicts of interest regarding the publication of this article.

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