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# 195-W Continuous Wave Laser Emission at 2.09 $\mu\text{m}$ from a $\text{Tm}^{3+}$ , $\text{Ho}^{3+}$ -Codoped Single-Oscillator Monolithic Fiber Laser

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**Abstract:** We report on a high efficiency (45%) single-oscillator monolithic  $\text{Tm}^{3+}$ ,  $\text{Ho}^{3+}$ -codoped fiber laser emitting 195 W at 2.09  $\mu\text{m}$  in CW mode of operation, with a beam quality near the diffraction limit ( $M^2 = 1.08$ ). © 2020 The Author(s)

## 1. Introduction

Laser sources emitting around 2  $\mu\text{m}$  have a particular interest because they match with the infrared atmospheric window, and then allow to achieve different applications such as surgery, material processing, or optical countermeasures. Thanks to their high robustness and compactness, monolithic fiber lasers constitute one of the most promising sources for these applications. Thulium-doped ( $\text{Tm}^{3+}$ ) active media pumped at 793 nm, for efficient laser emission at 1.95  $\mu\text{m}$  wavelength, and holmium-doped ( $\text{Ho}^{3+}$ ) media pumped at 1.95  $\mu\text{m}$ , to generate efficient radiations beyond 2  $\mu\text{m}$ , have been predominantly used for conceiving infrared monolithic fiber lasers [1]. For both active media, monolithic fiber laser architectures delivering high powers around 2  $\mu\text{m}$  have been largely demonstrated with MOPA (Master Oscillator Power Amplifier) systems [2]. Nevertheless, limitations due to MOPA laser physics (ASE filtering, nonlinear effects) and the high number of amplification stages with optical isolation needed to get a high average output power, lead to relatively high complexity and volume for such laser sources. Single-oscillator architectures have been studied, using  $\text{Tm}^{3+}$ -doped all-fiber laser sources principally [3]. In most of cases, a cladding light stripper (CLS) is placed extracavity to improve the output beam quality [4]. Single-oscillator architectures based on  $\text{Tm}^{3+}$ ,  $\text{Ho}^{3+}$  co-doped fiber have also been achieved using free-space pumping schemes [5,6]. In this contribution, we present for the first time a 793-nm diode-pumped high power monolithic  $\text{Tm}^{3+}$ ,  $\text{Ho}^{3+}$  co-doped fiber laser emitting at 2.09  $\mu\text{m}$  in continuous waves (CW) regime, based on a simple and compact all-fibered single-oscillator architecture.

## 2. Experimental setup

The laser setup is shown in Fig. 1. It consists of a 10 m-long silica double-clad PM fiber (iXblue Photonics) with a  $\text{Tm}^{3+}$ ,  $\text{Ho}^{3+}$ -codoped core of 20  $\mu\text{m}$  diameter, surrounded by a low index Ge-doped pedestal, and a round-shaped cladding of 300  $\mu\text{m}$  diameter (“Thulium-Holmium Doped Fiber”, THDF). Four high-power 793-nm fiber-coupled diodes are used to symmetrically pump the THDF. The diodes are fusion spliced to two 2+1×1 fiber pump combiners (PCs) which directly inject the total pump power of 540 W into the active fiber. The laser cavity is composed on one side of a high reflectivity (HR) Fiber Bragg Grating (FBG) reflecting intracavity light at 2.09  $\mu\text{m}$ . The other side of the cavity is an output coupler (OC) made with the PC output passive fiber cleaved at 0° (4 % Fresnel reflection). All the fibered components are fusion-spliced by a CO<sub>2</sub> splicer. The fiber is cooled by deionized water at 18 °C.

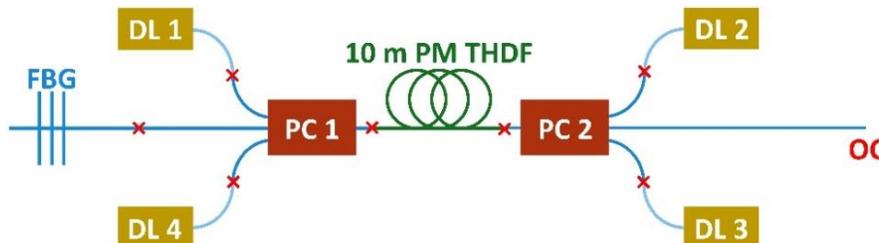


Fig. 1. Schematic of the setup. Passive and active fibers are represented in blue and green lines, respectively. DL: 793-nm fiber-coupled Laser Diode; PC: 2+1×1 Pump combiner; FBG: 2.09- $\mu\text{m}$  Fiber Bragg Grating; OC: Output Coupler (0° fiber cleaved angle). Fiber fusion splices are represented by red crosses.

### 3. Results

The output power of the laser is depicted in Fig. 2a. A maximum continuous wave output power of 195 W was obtained at 2.09  $\mu\text{m}$  with 472 W of maximum injected pump power (12 % pump insertion losses in PCs). The laser setup was only pump power limited in this experiment. The emission power threshold is about 39 W and the laser slope efficiency is 44.8 %. These results are, to the best of our knowledge, both the highest output power and slope efficiency reported from a monolithic single oscillator laser source based on a  $\text{Tm}^{3+}$ ,  $\text{Ho}^{3+}$ -codoped silica fiber. The Fig. 2a inset shows the spectral power density of the output beam measured at 195 W. The FWHM of the output spectrum is 3 nm.

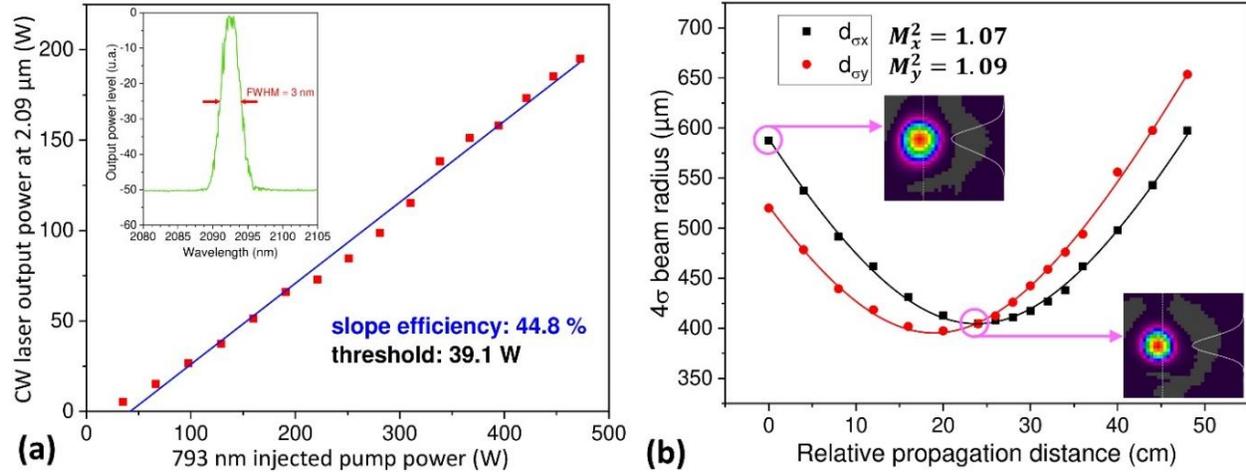


Fig. 2 (a) 2.09- $\mu\text{m}$  continuous wave output power versus 793-nm injected pump power. The inset shows the emitted spectrum measured at 195 W output power; (b) Measured caustic of the focused laser output beam and derived  $M^2$  beam quality factors at maximum output power (195 W).

The  $M^2$  beam quality factors of the collimated output beam have been measured at different output power levels using a 250-mm focal-length lens to focus the output beam. The beam profile and radius have been recorded for the  $x$  and  $y$  transverse directions using a Pyrocam III HR camera at different distances from the lens, according to the D4 $\sigma$  formalism. The beam radius depicted in Fig. 2b has been measured at maximum output power (195 W), and allows to calculate an average  $M^2$  value of 1.08, indicating that the output laser beam operates near the diffraction limit, which seems to be better than previously demonstrated monolithic single-oscillator  $\text{Tm}^{3+}$ -doped fiber laser sources without CLS ( $M^2 = 2.6$  at 567 W output power) [4]. The resulting  $M^2$  value is near to the  $M^2$  factor from monolithic single-oscillator systems using an output CLS ( $M^2 = 1.03$  at 170 W output power) [5].

### 4. Conclusion

In conclusion, we report on a  $\text{Tm}^{3+}$ ,  $\text{Ho}^{3+}$ -codoped fiber laser source based on a simple monolithic all-fiber single-oscillator architecture delivering 195 W of optical power at 2.09  $\mu\text{m}$ . A laser slope efficiency of 45 % has been obtained for a laser setup only pump power limited in this experiment. The output beam quality corresponds to an average  $M^2$  beam quality factor of 1.08 at maximum output power, i.e. close to the diffraction limit.

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