High-Efficiency 2.09 μm Single-Oscillator Monolithic Thulium-Doped Fiber Laser

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***Abstract*— A single-oscillator monolithic thulium-doped fiber laser in which the 793 nm core absorption of 8.42 dB/m allows emitting 193 W (46 % of slope efficiency) at 2.09 μm is presented. An 8°-cleaved angle of the fiber facet suppresses the parasitic cavity that formerly limited the power scaling. The characteristics of the thulium laser operating at the uncommon 2.09-μm long wavelength is compared to the power performances of a similar thulium-holmium codoped fiber laser.**

***Index Terms*— High power fiber lasers, infrared lasers, optical fibers, thulium.**

I. Introduction

THE 2-μm laser wavelength is very useful for both civil and military applications as it can be generated at high powers by solid-state or fiber lasers. Fiber sources can offer more compact and alignment-free systems which make them the better suitable architecture for military applications such as laser weapons or directed infrared countermeasures. These specific applications require also very high power and good beam quality in order to use the laser emission for long distances. The 2-μm spectral band presents the benefit of a good atmospheric transmission in an "eye-safe" region. Nevertheless, the precise choice of the wavelength around 2 μm is essential since multiple absorption rays as water absorption lines are present in the atmosphere.

Different strategies have been adopted in the literature to cover all the spectral bands around 2 μm by fiber lasers. Thulium ions pumped around 790 nm are able to emit high laser powers exceeding 180 W at 1.94 μm [1], [2], [3], 1.97 μm [4], [5], 1.98 μm [6], [7], 2.0 μm [8], [9], 2.04 μm [10], [11], and 2.05 μm [12], [13]. For longer wavelengths, the thulium is used to pump holmium ions (emission at 2.11 μm [14] or 2.12 μm [15]). More recently, Tm-Ho co-doped fibers have been used for intermediate wavelengths: 2.05 μm [16] and 2.09 μm [17].

Rare-earth ions doping into silica glass capitalizes on the inhomogeneous broadening of the energy levels through phonon-assisted processes to exhibit both broad absorption and emission. These features are particularly involved for tunable laser sources to emit above 2.05 μm. Li et al. demonstrated in 2014 a 2198.4-nm laser emission from a thulium fiber with both a low slope efficiency and a low output power (17.8 %, 0.4 W) [18]. Indeed, the tunability of thulium lasers towards longer wavelengths is range-limited by the emission cross sections of standard thulium-doped fibers. For example, a power drop larger than 15 % was observed by Clarkson et al. in 2002 [19] and Li et al. in 2013 [20] between the maximum emission power at 1.94 μm and the output power at an imposed wavelength of 2.09 μm. In particular, a lower out-coupling transmission of the cavity is required in order to access longer emission wavelengths in thulium-doped fiber lasers. Normally, the gain required to achieve lasing is reduced. However, due to the spectral properties of the gain medium, the laser efficiency is also reduced. Finally, the output spectral quality is also degraded by the higher sensitivity of the cavity to parasitic lasing and amplified spontaneous emission (ASE). Therefore, the emission of thulium-doped fibers is limited to 2.05 μm for high power and holmium is privileged to emit above this limit.

In this letter, we study a 2.09-μm monolithic single-oscillator thulium-doped fiber laser. First, we highlight the presence of a parasitic cavity that degraded the laser performances. Then, we propose an 8°-cleaved angle of the fiber facet to suppress this cavity and to improve the results. Finally, the 193-W output power achieved by this thulium-doped fiber laser source is compared to the power measured at the output of a thulium-holmium co-doped fiber laser source based on the same architecture.

II. Experimental Setup

The experimental setup of the laser is shown in Fig. 1. Four high-power 793-nm fiber-coupled pump diodes are

Manuscript received 23 January 2023; revised 2 March 2023; accepted 21 March 2023. Date of publication 4 April 2023; date of current version 7 April 2023. This work was supported in part by the French Direction Générale de l'Armement (DGA) and in part by the German Bundesamt für Ausrüstung, Informationstechnik und Nutzung der Bundeswehr (BAAINBw). *(Christophe Louot and Arnaud Motard are co-first authors.) (Corresponding author: Christophe Louot.)*

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Color versions of one or more figures in this letter are available at https://doi.org/10.1109/LPT.2023.3262296.

Digital Object Identifier 10.1109/LPT.2023.3262296

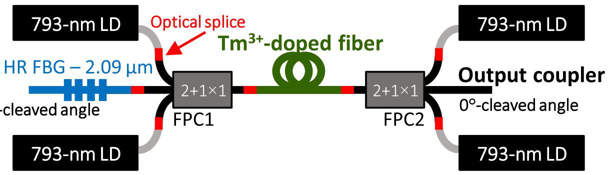

Fig. 1. Schematic of the experimental setup of the thulium-doped fiber laser source.

fusion-spliced to two 2+1×1 fiber pump combiners (FPCs) to pump symmetrically a piece of thulium-doped fiber (TDF) with a total injected pump power of 450 W. The active fiber is a 5-m silica double-clad TDF from *exail* (formerly *iXblue Photonics*). Its thulium-doped core has a diameter of 20 μm (numerical aperture N.A. = 0.09) in order to maintain a quasi-singlemode propagation of the 2-μm signal [17]. It is surrounded by a Ge-doped pedestal (diameter 60 μm) and by an octagonal-shaped cladding (diameter: 250 μm, N.A. = 0.46). The core of the fiber is highly doped in order to provide a cladding absorption of 8.42 dB/m at around 789 nm. FPCs were made on a piece of passive fiber matching with the TDF. It exhibits a 20-μm core (N.A. = 0.08) and a circular 250-μm cladding (N.A. = 0.46). The slight difference of N.A. between the TDF and the passive fiber can be responsible for some coupling between the core of the TDF and the cladding of the passive fiber when splicing.

The cavity is formed by a High-Reflectivity (HR) Fiber Bragg Grating (FBG) centered at 2090.0 nm (Full Width at Half Maximum, FWHM = 1.26 nm) and a 0° cleave of the FPC passive fiber (4 % Fresnel reflection). The FBG was carefully manufactured in order to limit its temperature increase. It was estimated by the constructor to be lower than 1 °C/W for a non-cooled component (suspended in the air). During the experiment, both the FBG and the FPCs are put on a cooled plate to further limit the temperature increase. This thermal management allows for reducing the potential shifting and broadening that could be observed in similar setups with non-optimized FBGs [5], [17]. The thulium-doped fiber was immersed in a bath of 17 °C deionized water to maintain a safe operation without excessive heat load.

III. Study of the Thulium-Doped Fiber Laser Source

A. Power Evolution

The evolution of the 2-μm signal measured at the output coupler (OC) and at the output of the FBG fiber is depicted in Fig. 2. A maximum OC power of 164 W was recorded, corresponding to a slope efficiency of 40 %. However, one can note a perturbed and not strictly linear evolution of the power. On the other side of the fiber, the FBG transmitted a power of 60 W at the maximum pump power. This is higher than we expect from the nominal reflectivity of the FBG at 2.09 μm (99 %, estimated by the constructor).

B. Spectral Measurements

The spectrum at the output of the laser source is measured by the means of an optical spectrum analyzer (*Yokogawa*, AQ6376). Fig. 3 displays the spectrum spanning from 1980 nm to 2100 nm. We detect a main emission at 2090 nm (composed of two peaks, as shown in the inset of Fig. 3) and a large secondary emission of multi-peaks between 2000 nm and 2020 nm. Thanks to the proper heat dissipation, the main peak imposed by the FBG at 2090 nm was stable: during the power scaling, the peak shifted by 0.1 nm towards the longer wavelengths and was not broadened. The secondary band corresponds to the free-emission of the laser source (without any FBG imposing the wavelength). Obviously, these secondary peaks are the signature of a parasitic cavity that coexists with the main cavity (FBG-OC).

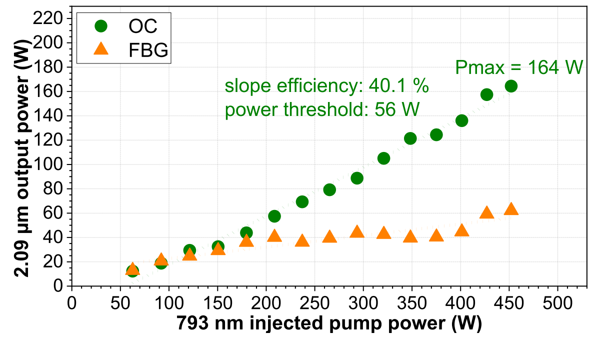

Fig. 2. Output powers measured on the OC side (green dots) and on the FBG side (orange triangles) versus 793-nm incident pump power (FBG fiber cleaved at 0°). Residual pump power at the maximum pump power: 3.4 W.

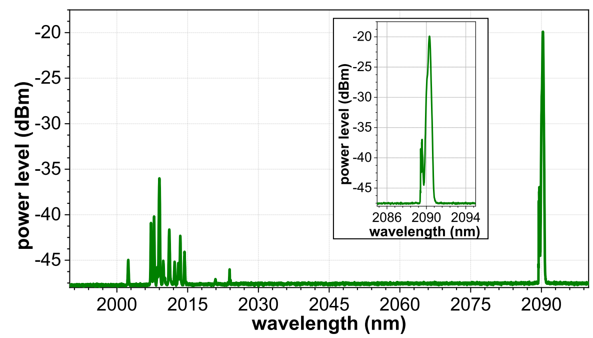

Fig. 3. Normalized output spectrum at the maximum output power when the wavelength is imposed by a 2.09-μm FBG (0°-cleaved angle of the fiber facet). Inset: zoom on the main peak at 2090 nm.

The presence of a parasitic cavity is linked to the 0°-cleaved angle of the FBG fiber. Indeed, this fiber facet also provided the 4 % Fresnel reflection and acted as a second output coupler for the light transmitted by the FBG. Moreover, the signal between 2000 nm and 2020 nm is transmitted by the FBG. This explains the larger amount of power collected from the FBG side of the source, measured up to 60 W (orange triangles in Fig. 2).

IV. Suppression of the Parasitic Cavity

A. Power Evolution and Slope Efficiency

In order to suppress the parasitic cavity, an 8° cleave of the FBG fiber is realized (Fig. 4, inset). The 8°-cleaved angle is known as a solution to avoid back reflections on fiber end facets. The Fresnel reflection provided by the air/silica interface is not guided in the fiber core allowing to suppress the

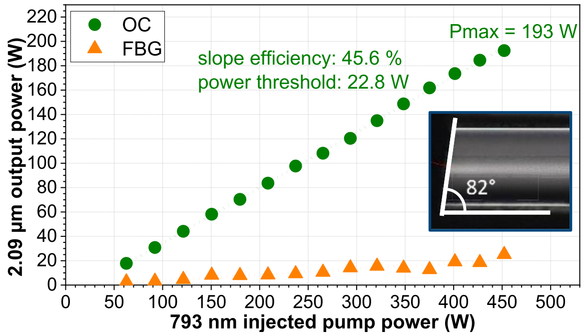

Fig. 4. Output powers measured on the OC side (green dots) and on the FBG side (orange triangles) versus 793-nm incident pump power. Inset: microscope picture of the 2.09-μm FBG fiber cleaved at 8°. Residual pump power at the maximum injected pump power: 2.6 W.

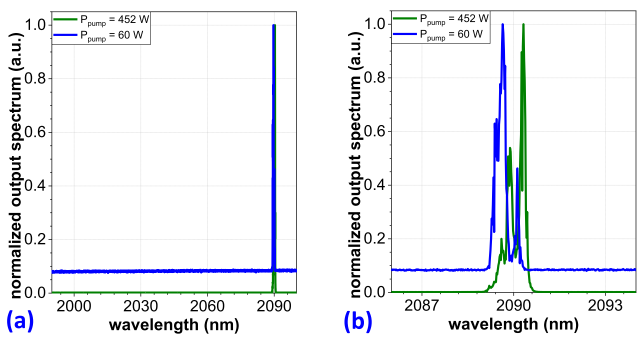

Fig. 5. Normalized output spectra at 60 W (blue) and 452 W (green) of injected pump power when the wavelength is imposed by a 2.09-μm FBG (8°-cleaved angle of the fiber facet) on a 110-nm large span (a) and on a 7-nm short span (b).

parasitic cavity. The cleave angle on the other side is still 0° to act as the output coupler of the cavity. The characterization of the source is shown in Fig. 4. A maximum output power of 193 W and a slope efficiency of 45.6 % are achieved. To the best of our knowledge, this is the first monolithic thulium-doped fiber laser source emitting at 2.09 μm. We can notice that the efficiency at 2.09 μm is particularly high. The laser operates with a slope efficiency exceeding the Stokes efficiency defined as the $\lambda_{pump}/\lambda_{signal}$ ratio (37.9 % at 2.09 μm). It demonstrates a very efficient two-for-one cross relaxation process in the fiber. On the other side, the power measured at 2 μm decreased from 60 W to 20 W. This result underlines that there is less power emitted out of the FBG reflection band. In particular, the suppression of the parasitic emission makes the power evolution on the OC side more linear.

B. Spectral Behavior

The normalized output spectrum at low power, shown in blue in Fig. 5, exhibited a main peak at 2089.64 nm (FWHM = 0.3 nm) and a second peak, 54 % lower, centered at 2090.12 nm (FWHM = 0.1 nm).

At maximum output power, we can notice an inversion of the main peak from the left to the right peak. The right peak was centered at 2090.32 nm (FWHM = 0.18 nm) and the 46-% lower left peak was centered at 2089.88 nm (FWHM = 0.22 nm). Both peaks are shifted by 0.2 nm and broadened by less than 0.1 nm due to the heating of the

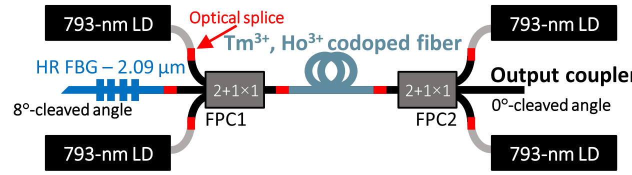

Fig. 6. Schematic of the experimental setup of the thulium-doped fiber laser source.

FBG. We assume this two-peak shape is due to the FBG inscribed on a polarization-maintaining (PM) passive fiber. Indeed, due to the birefringence induced by the presence of the two boron stress rods in the PM fiber, the maximum reflectivity wavelength of the FBG is different for the modes propagating on the slow and fast axes of the fiber, respectively.

V. Comparison With a Thulium-Holmium-Codoped Fiber Laser

All the previous results indicate that the 2.09 μm wavelength is achievable with single thulium doping (only). Here, we compare them with the results obtained with a monolithic single-oscillator thulium-holmium co-doped fiber (THDF) laser. The setup shown in Fig. 5 was similar to the setup in Fig. 1 and is presented in details in Ref. [17]. The active 20/300 PM double-clad THDF fiber is 10-m long, exhibiting an absorption at 793 nm of 3.79 dB/m. The FBG is exactly the same as those used in the previous experiment and its fiber is cleaved at 8° to avoid parasitic cavities. Two FPCs adapted to the new active fiber (PM, cladding of the signal fiber: 300 μm) simplify the splice process between fibers. All the fibers in this setup are PM (6). Their boron stress rods were all manually aligned in the splicer before splicing the fibers together. Due to the PM nature of the fibers, the output beam may be naturally polarized, even without any polarizing element in the laser cavity.

This laser achieved 181 W for 489 W of pump power and a slope efficiency of 39.9 % (Fig. 7a). As expected, the power evolution is perfectly linear, due to the absence of competition between the main cavity and a second parasitic cavity. The results are very similar both with thulium-doped and thulium-holmium co-doped fibers (Fig. 7a). Furthermore, losses can be exacerbated in the thulium-doped laser due to the geometry mismatch between the FBG fiber (20(0.10)/300) and the signal fiber of the first combiner (20(0.08)/250). Both the numerical aperture mismatch and the difference of cladding (in which the signal is also propagating) diameter can create more losses when splicing the two fibers together. Thus, in a setup with perfectly adapted components and fibers, we expect to achieve an even higher efficiency with the thulium-doped fiber. An explanation of the higher power obtained with the 5-m long TDF than with the 10-m long THDF might be the difference of pump absorption of the two fibers and their difference of core/cladding diameter ratio: 3.79 dB/m for the 20/300 codoped fiber and 8.42 dB/m for the 20/250 thulium doped fiber.

The spectrum measured at the output of the THDF laser (Fig. 7b) is centered at 2090.0 nm and exhibits also two peaks: a main peak at 2089.6 nm (FWHM = 0.28 nm)

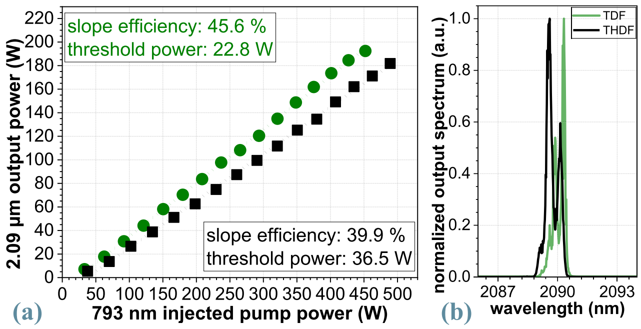

Fig. 7. (a) Output powers versus 793-nm incident pump power of the TDF (green dots) and THDF (black squares) laser sources with a 2.09-μm FBG. Residual pump power at the maximum injected pump power: 7.5 W; (b) Normalized output spectrum at the maximum output powers (wavelength imposed by a 2.09-μm FBG).

and a second peak, 40 % lower centered at 2090.14 nm (FWHM = 0.26 nm). These peaks correspond to the wavelength at which the FBG has the maximum reflectivity on the two polarized modes in the PM fiber. This fact is confirmed experimentally by the observation that it is possible to suppress one of the two peak by means of an extra-cavity polarizer. Despite the two peaks, the spectrum remains narrow enough for most of the possible applications (FWHM < 1 nm).

VI. Conclusion

In this letter, we studied the laser efficiencies that can be achieved by a thulium-doped fiber that exhibits a high 793-nm absorption of 8.42 dB/m. The high absorption could be responsible for the emission at a higher wavelength, commonly obtained by holmium doping. The stability of the source was improved by the suppression of a parasitic cavity allowed by the 0°-cleaved angle of the FBG fiber. The new cleave at 8° of this facet improved the evolution of the signal power and decreased the losses due to the FBG transmitted light. With the 8°-cleaved angle, the source reached 193 W of 2.0-μm output power and 45.6 % of slope efficiency. These results are equivalent to results obtained within a same laser architecture based on a thulium-holmium co-doped fiber. To the best of our knowledge, these are the highest output power and the best slope efficiency achieved at 2.09 μm from a thulium doped fiber laser. Up to now, thulium fiber lasers emitted until 2.05 μm only according to the literature, we show new opportunities to emit up to 2.09 μm by highly-doped thulium fibers. Power scaling was only limited by the available pump power. Limits of thulium ions emitting at long wavelengths are not yet achieved. Future experimentations will be devoted to both power scaling and change of the FBG to longer wavelengths.

References

[1] M. Meleshkevich, N. Platonov, D. Gapontsev, A. Drozhzhin, V. Sergeev, and V. Gapontsev, “415W single-mode CW thulium fiber laser in all-fiber format,” in *Proc. Eur. Conf. Lasers Electro-Opt. Int. Quantum Electron. Conf.*, Jun. 2007, p. 1.

[2] K. Yin, R. Zhu, B. Zhang, G. Liu, P. Zhou, and J. Hou, “300 W-level, wavelength-widely-tunable, all-fiber integrated thulium-doped fiber laser,” *Opt. Exp.*, vol. 24, no. 10, p. 11085, 2016.

[3] W. Yao et al., “790 W incoherent beam combination of a Tm-doped fiber laser at 1941 nm using a 3 × 1 signal combiner,” *Appl. Opt.*, vol. 57, no. 20, p. 5574, 2018.

[4] X. Wang, X. Jin, P. Zhou, X. Wang, H. Xiao, and Z. Liu, “High power, widely tunable, narrowband superfluorescent source at 2 μm based on a monolithic Tm-doped fiber amplifier,” *Opt. Exp.*, vol. 23, no. 3, p. 3382, 2015.

[5] T. Walbaum, M. Heinzig, T. Schreiber, R. Eberhardt, and A. Tünnermann, “Monolithic thulium fiber laser with 567 W output power at 1970 nm,” *Opt. Lett.*, vol. 41, no. 11, pp. 2632–2635, 2016.

[6] Y. Liu et al., “406 W narrow-linewidth all-fiber amplifier with Tm-doped fiber fabricated by MCVD,” *IEEE Photon. Technol. Lett.*, vol. 31, no. 22, pp. 1779–1782, Nov. 15, 2019.

[7] Y.-Z. Liu et al., “530 W all-fiber continuous-wave Tm-doped fiber laser,” *Acta Phys. Sinica*, vol. 69, no. 18, 2020, Art. no. 184209.

[8] A. Hemming, S. Bennetts, A. Davidson, N. Carmody, and D. G. Lancaster, “A 226 W high power Tm fibre laser,” in *Proc. OECC/ACOFT Joint Conf. Opto-Electron. Commun. Conf. Austral. Conf. Opt. Fibre Technol.*, Sydney, NSW, Australia, Jul. 2008, pp. 1–2.

[9] J. Liu, H. Shi, K. Liu, Y. Hou, and P. Wang, “210 W single-frequency, single-polarization, thulium-doped all-fiber MOPA,” *Opt. Exp.*, vol. 22, no. 11, pp. 13572–13578, 2014.

[10] G. D. Goodno, L. D. Book, and J. E. Rothenberg, “Low-phase-noise, single-frequency, single-mode 608 W thulium fiber amplifier,” *Opt. Lett.*, vol. 34, no. 8, p. 1204, Apr. 2009.

[11] T. Ehrenreich, R. Leveille, I. Majid, and K. Tankala, “1-kW, all-glass Tm fiber laser,” *Proc. SPIE*, vol. 7580, Jan. 2010, Art. no. 758016.

[12] P. F. Moulton et al., “Tm-doped fiber lasers: Fundamentals and power scaling,” *IEEE J. Sel. Top. Quantum Electron.*, vol. 15, no. 1, pp. 85–92, Jan. 2009.

[13] J. S. Shin et al., “200-W continuous-wave thulium-doped all-fiber laser at 2050 nm,” *Curr. Opt. Photon.*, vol. 5, no. 3, pp. 306–310, Jun. 2021.

[14] A. Hemming et al., “Development of high-power holmium-doped fibre amplifiers,” *Proc. SPIE*, vol. 8961, Mar. 2014, Art. no. 89611A.

[15] A. Hemming et al., “A monolithic cladding pumped holmium-doped fibre laser,” in *Proc. Conf. Lasers Electro-Opics*, San Jose, CA, USA, Jun. 2013, pp. 1–2.

[16] P. Forster, C. Romano, C. Kieleck, and M. Eichhorn, “Advances in two-micron lasers for nonlinear conversion into the mid-IR,” *Proc. SPIE*, vol. 11355, Apr. 2020, Art. no. 1135509.

[17] A. Motard et al., “Diffraction limited 195-w continuous wave laser emission at 2.09 μm from a Tm^{3+}, Ho^{3+}-codoped single-oscillator monolithic fiber laser,” *Opt. Exp.*, vol. 29, no. 5, pp. 6599–6607, 2021.

[18] J. Li et al., “Wide wavelength selectable all-fiber thulium doped fiber laser between 1925 nm and 2200 nm,” *Opt. Exp.*, vol. 22, no. 5, pp. 5387–5399, Feb. 2014.

[19] W. A. Clarkson, N. P. Barnes, P. W. Turner, J. Nilsson, and D. C. Hanna, “High-power cladding-pumped Tm-doped silica fiber laser with wavelength tuning from 1860 to 2090 nm,” *Opt. Lett.*, vol. 27, no. 22, pp. 1989–1991, 2002.

[20] Z. Li, S. U. Alam, Y. Jung, A. M. Heidt, and D. J. Richardson, “All-fiber, ultra-wideband tunable laser at 2 μm,” *Opt. Lett.*, vol. 38, no. 22, pp. 4739–4742, 2013.

[21] N. Simakov et al., “Design and experimental demonstration of a large pedestal thulium-doped fibre,” *Opt. Exp.*, vol. 23, no. 3, pp. 3126–3133, 2015.