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Tandem-pumped, tunable thulium-doped fiber laser in 2.1 μm wavelength region

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Abstract: We present a continuously tunable thulium(Tm)-doped fiber laser operating in the important 2.1 μm region, which is tandem-pumped by another Tm-doped fiber laser at 1908 nm. The advantages of pumping a Tm-doped fiber laser at the long-wavelength absorption tail (>1900 nm) of the fiber include a reduced quantum-defect, and efficient suppression of the amplified spontaneous noise (and potential parasitic lasing) at the short-wavelength region. This facilitates attainment of stable lasing operation in the long-wave emission tail of the Tm fiber at ~2.1 μm. By rotating a diffraction grating inside the Tm fiber laser cavity, we experimentally achieved a wavelength-tuning range of 2000-2172 nm. At central wavelengths of 2050 nm, 2150 nm, and 2172 nm, the slope efficiencies were 23%, 16%, and 9.9%, respectively. To the best of our knowledge, this is the first demonstration of long-wavelength operation of a Tm fiber laser system tandem-pumped at >1900 nm.

1. Introduction

Laser sources operating in the 2.1 μm region will benefit many applications, including environment monitoring, remote sensing and medical surgery [1–3], since the 2.1 μm waveband contains broad windows of high atmospheric transparency, and strong, narrow-band molecular vibration absorption resonances of atmospheric constituents, such as water vapor and CO_2 [4]. Lasers at over 2.1 μm are also desirable sources for pumping optical parametric devices based on $ZnGeP_2$ or orientation-patterned-GaAs crystal, with reduced two-photon-absorption induced loss [5–7], thus offering an efficient scheme for generating long-wave mid-infrared emission at over 6 μm. Moreover, the 2.1 μm waveband also offers a potential technical route to extend the transmission capacity of fiber-based optical telecomm system [8,9].

The 2.1 μm waveband could be addressed by a holmium (Ho)-doped fiber laser system [4,10,11]. For instance, Simakov *et al.* reported a Ho-doped fiber laser with a wavelength-tuning range of 2043-2171 nm [10]. Thulium (Tm) -doped silica fibers, with an emission spectrum over a wide wavelength region spanning 1.65-2.2 μm relevant to the $^3H_4 \rightarrow ^3H_6$ transition [4,12], can also be utilized as a gain medium for generating light emission in the 2.1 μm waveband. A notable feature of a Tm fiber gain medium is that it could support a wider gain bandwidth, thus potentially enabling a broader wavelength-tuning range. However, due to the diminishing emission cross-section at the edge of emission tail of the Tm: fiber and thus the gain competition from the center of the emission spectrum, operation of a Tm-doped fiber laser (TDFL) in the long-wave tail at the 2.1-2.2 μm region will induce the generation of significant amplified spontaneous emission (ASE) at shorter wavelengths, resulting in a degraded signal-to-noise-ratio (SNR) of the output and increased sensitivity to parasitic

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lasing. Highly wavelength-selective elements, e.g. fiber Bragg gratings (FBGs), are required to be placed inside the laser cavity for eliminating the parasitic lasing and producing a stable output at the 2.1-2.2 μm region from a Tm-doped fiber laser [13]. In most demonstrations of widely-tunable Tm fiber laser systems, in which FBGs were not used, the wavelength-tuning at the long-wave region were rather limited [8,14,15]. In [16], a wavelength tuning range over 1920-2140 nm was obtained from a Tm-doped fiber laser, but the output spectrum and stability of such a system were not reported. With the exception of this result, the long-wave tuning limits of all other widely-tunable Tm fiber laser systems have been < 2100 nm [8,14,15].

Conventionally, Tm-doped fiber lasers were pumped at 792 nm ($^3H_6 \rightarrow {}^3F_4$ transition), allowing for direct diode pumping and offering high conversion efficiencies due to the 2-for-1 cross-relaxation process of the Tm ions [14,17,18]. Alternatively, Tm-doped fiber lasers were also pumped at around 1565 nm ($^3H_6 \rightarrow {}^3H_4$ transition) by Er-doped fiber lasers with a diffraction-limited beam [15,19–21], with the advantages of high Stocks efficiency and hence low quantum-defect-induced heat generation. A Tm-doped fiber laser could also be tandem-pumped by another Tm: fiber laser at > 1900 nm, since the absorption band of a Tm-doped silica fiber related to the $^3H_6 \rightarrow {}^3H_4$ transition extends up to > 1900 nm [12], thus allowing for higher Stocks efficiency and further reduction of quantum-defect-induced heat generation [22–25]. Indeed, tandem-pumping scheme was widely employed in kW-level Yb-doped fiber lasers to minimize the quantum-defect-induced heat generation, thus enabling high-power operation of fiber lasers [26,27]. Recently, Creeden *et al.* used a 1908-nm source to in-band-pump a Tm-doped fiber laser operating at 2005 nm, demonstrating >90% slope efficiency and a potential of power-scaling to 2 kW [22,23]. Similarly, Jin *et al.* used a 1940-nm source to resonantly-pump an ultra-fast Tm-doped fiber amplifier at 1970 nm, with an inherent Stokes efficiency up to 98.5%, achieving a slope efficiency of 87% [25].

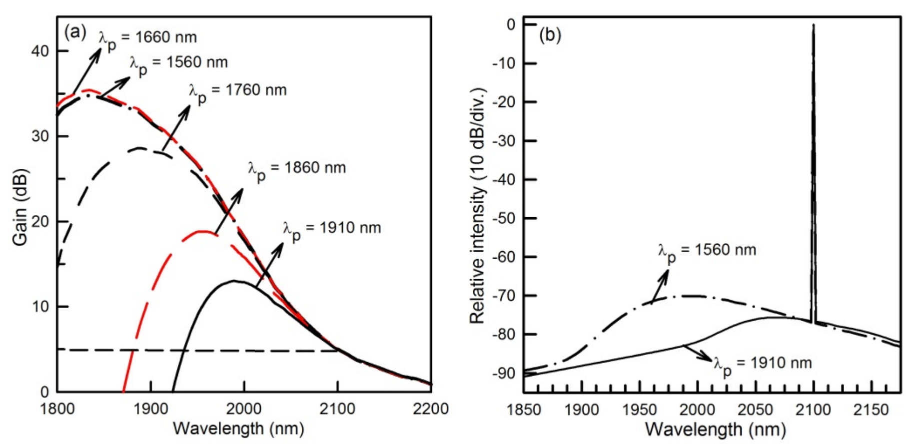

Fig. 1. (a) Calculated gain spectrum of a Tm-doped fiber pumped at different pumping wavelengths. Simulation parameters: pump power, 1W; small-signal absorption of the Tm: fiber at 1560 nm, 300 dB/m; the lengths of the Tm: fibers were selected to obtain a gain of 5 dB at 2100 nm; the absorption and emission cross-section data of the Tm fiber were taken from [4]. (b) Simulated output spectra of Tm-doped fiber lasers lasing at 2100 nm and pumped at 1560 nm and 1910 nm.

Remarkably, pumping a Tm-doped fiber laser at >1900 nm also has an advantage of producing much less parasitic gain at shorter wavelengths, and thus also represents a preferred pumping approach for generating laser emission at 2.1-2.2 μm. To illustrate this, Fig. 1 shows the calculated gain spectra of a Tm-doped fiber at different pump-wavelengths over 1560-1910 nm, based on a gain model reported by Pask *et al.* [28]. As shown in Fig. 1(a), at a pump-wavelength of 1560 nm, the gain at 1830 nm is 30 dB higher than that at 2100

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nm, implying that a wavelength-selective element with a side-mode suppression ratio of more than 30 dB is required to suppress the parasitic lasing in a laser oscillator operating at 2100nm. In comparison, at a pump-wavelength of 1910 nm, the gain difference between the peak wavelength and 2100 nm was only 8 dB, clearly illustrating the reduced parasitic gain in a Tm fiber by using of a longer pump wavelength.

Another advantage of using 1910 nm pump source is the potential of achieving improved SNR of the laser output. We simulated the operation of a 2100 nm TDFL at pump-wavelengths of 1910 nm and 1560 nm respectively by using a model reported in [29]. The simulation parameters for the 1910 nm-pumped laser were similar to our experimental configuration (see Section 2), while that for the 1560 nm-pumping scheme, the length of the Tm-doped fiber was selected to obtain the same gain at the lasing wavelength (0.68 m). As shown in Fig. 1(b), the calculated SNRs of the output spectra from the laser were 37 dB and 48 dB respectively when the pump-wavelengths were 1560 nm and 1910 nm. Here, in the calculation of SNRs, the noise power was obtained by summarizing all the power over the wave region away from the central oscillating wavelength of the laser. This clearly illustrates the benefit of using a 1910 nm pump source in improving the SNR of the laser output.

In this work, we report the first, to our knowledge, experimental investigation of long-wavelength operation of a Tm-doped fiber laser in-band-pumped at >1900 nm. The use of a pump source at 1908 nm, with its advantage in suppressing the gain at short-wavelengths, allows us to build a widely-wavelength-tunable source for accessing the long-wave emission tail of the thulium fiber gain medium at the important 2.1 μm region. A wavelength tuning range over 2.0-2.17 μm was obtained by simply rotating an intra-cavity diffraction grating inside the laser cavity.

2. Experimental setup and results

2.1 Experimental setup

A 1908 nm laser was used as a pump source for the wavelength-tunable Tm-doped fiber laser. The layout of the full system is shown in Fig. 2. The 1908 nm pump source (shown in the dashed frame of Fig. 2) was a Tm-doped fiber laser, cladding-pumped by a 793 nm laser diode, with a pair of narrow-band fiber Bragg gratings as the reflection mirrors and a pump/signal combiner for coupling the light from the 793 nm multi-mode diodes into the cladding of the Tm fiber. The pump source generated diffraction-limited output centered at 1908 nm, defined by the central wavelength of the FBGs, with a maximum output power of 4W.

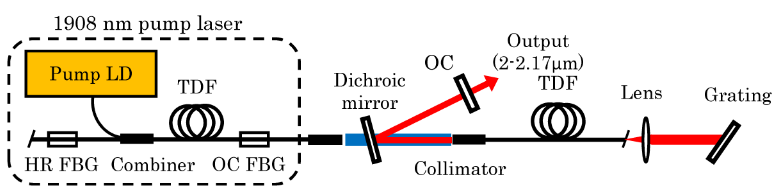

Fig. 2. The layout of the 2.1 μm Tm-doped fiber laser, which was pumped by another Tm-doped fiber laser at 1908 nm laser. LD, laser diode; TDF, Tm-doped fiber; FBG, fibre Bragg grating; HR, high reflector; OC, output coupler.

The wavelength-tunable Tm-doped fiber laser was core-pumped by the 1908 nm pump source. The Tm-doped fiber (Nufern, PM-TDF-10P/130HE) had a 10 μm core with a numerical aperture (NA) of 0.15. The small-signal absorption in the core of the Tm-doped fiber was estimated to be ~39 dB/m at 1908 nm. We used 5.5 meters of Tm fiber in order to enhance re-absorption and achieve lasing at longer wavelengths. The 1908-nm pump laser was collimated by a fiber collimator (uncoated) and then coupled into the core of the Tm-doped fiber via. another collimator, with a measured coupling efficiency of 80%. A dichroic mirror, with high-transmission (>99%) at 1908 nm and high-reflection (>99%) in the range of 2050-2400 nm, was inserted between the two fiber collimators to split the 1908-nm pump source and the generated long-wavelength light from the Tm-doped fiber. The wavelength-tunable Tm-doped fiber laser cavity, comprised an un-coated aspheric lens of 6 mm focal length and a diffraction grating with 450 grooves/mm in a Littrow configuration providing wavelength-selective feedback and hence a means for tuning the lasing wavelength. The grating, with a design wavelength of 3.1 μm, could support an optimum wavelength range over 2-4 μm. As the laser polarization was not controlled, the diffraction efficiency of the grating was estimated to be ~75% at around 2.1 μm. The fiber end near the grating was angle cleaved to avoid parasitic lasing that may compromise the wavelength-tuning range. A partial-reflection mirror, with reflection of 60% at 2000-2700 nm, was placed on the other end of the laser cavity as the output coupler (OC) of the laser.

2.2 Experimental results

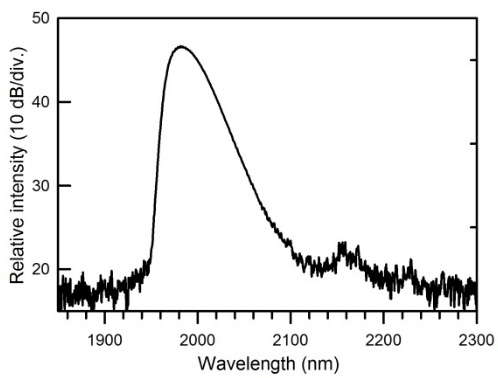

Fig. 3. Measured backward ASE spectrum at a pump power of 2.7W.

In order to characterize the ASE spectrum from the Tm fiber, the OC and the grating were removed from the TDFL system (Fig. 2). The generated ASE was collimated and reflected by silver-mirrors into the input-port of an optical spectrum analyzer (OSA) (APE waveScan USB IR extended). Figure 3 shows the backward ASE spectrum (measured at a launched pump power of 2.7 W), which extended over 1940- 2200 nm, indicating that laser operation at this region is possible.

Figure 4(a) presents the output spectra of the tunable laser measured with a spectral resolution of 0.5 nm at a maximum launched pump power of 3W, exhibiting a wavelength-tuning range spanning over 2000-2172 nm. The full-width at half-modulation (FWHM) bandwidth of the laser spectrum was measured to be ~1 nm, very close to the spectral resolution of 0.5 nm of the OSA. Lasing operating at the wavelength shorter than 2000 nm was inhibited by the reflection band of the dichroic mirror (with high-reflection in the range of 2050-2400 nm). Stable operation at longer wavelength (>2172 nm) was limited by the reduced emission cross-section and the relatively-high loss of the laser cavity.

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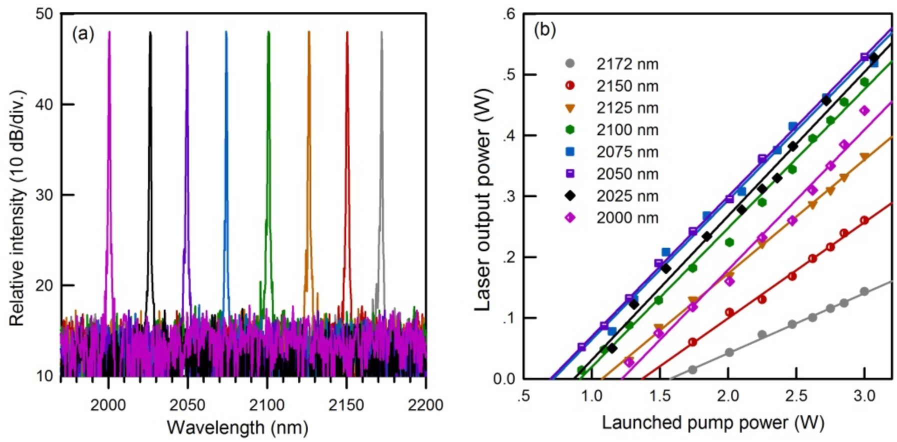

Fig. 4. (a) Measured output spectra from the wavelength-tunable Tm-doped fiber laser, and (b) Measured output laser power versus launched pump power at different oscillation wavelengths.

The output power was measured after the output coupler (with an out coupling ratio of 40%). Figure 4 (b) shows the output power versus the launched pump power at different emission wavelengths. At a lasing wavelength of 2050 nm, the oscillation threshold was 0.7 W, and the slope efficiency was 23%. More than 95% of the pump power was absorbed by the Tm-doped fiber. Considering the extra loss inside the laser cavity, including 40% loss from the two free-space-to-fiber coupling processes, 8% single-pass loss from the un-coated aspheric lens, 25% diffraction loss from the grating, we estimate that the generated power was significantly higher than that measured after the output coupler. For a laser operating at ~2100 nm and pumped by a 1908 nm source, the calculated quantum defect is only ~10%. Indeed, Creeden *et al.* demonstrated an 81% optical efficiency and 90% slope efficiency from a 1908-nm-pumped Tm-doped fiber laser operating at 2005 nm [22]. The maximum output power of 0.53 W was measured at a launched pump power of 3 W.

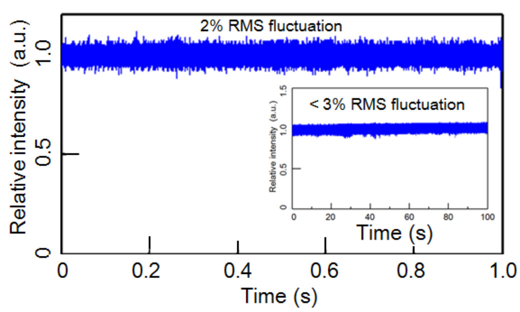

Fig. 5. The power stability of the Tm-doped fiber laser, measured at an emission wavelength of 2150 nm under the maximum pump power over 1 second (Inset: the power stability measured over 100 seconds).

The power stability of the laser was characterized at the maximum pump power by monitoring its output power with an extended InGaAs detector (with a response bandwidth of 10 MHz). Over the full wavelength-tuning range, the laser was very stable. A typical result, measured at an emission wavelength of 2150 nm, is shown in Fig. 6, exhibiting a root-mean-square (RMS) fluctuation of less than 2% over a measurement time of 1 second. The RMS fluctuation was less than 3% over a measurement time of 100 seconds (inset in Fig. 5).

3. Discussions

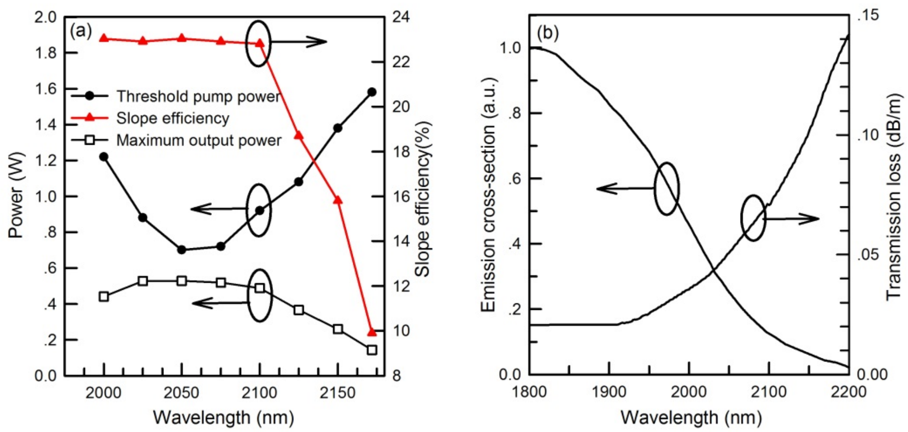

Fig. 6. (a) The oscillation threshold power, maximum output power and slope efficiency versus oscillation wavelength, (b) The emission cross-section of Tm fibers [4] and the transmission loss of a typical silica fiber (obtained from the specification of Thorlabs SM2000 fiber).

The oscillation threshold powers, maximum output powers and slope efficiencies at different lasing wavelengths are summarized and shown in Fig. 6(a). It can be seen that at the 2000-2100 nm wavelength range, the slope efficiencies were constant, indicating that the background loss in the fiber was relatively low. Beyond 2100 nm, the slope efficiency drops with the increase of the oscillation wavelength. This could be explained by the increasing background loss in the silica fiber beyond 2100 nm. Figure 6(b) shows the transmission loss of a typical silica fiber. The slope efficiencies at 2101 nm, 2126 nm, 2150 nm, and 2172 nm were 23%, 19%, 16%, and 9.9% respectively. At an emission wavelength of 2172 nm, the maximum output power was 0.14 W. The oscillation thresholds were ~0.7 W at the oscillation wavelength of 2050-2076nm. The increased threshold at the shorter-wavelength was due to the lower reflectivity of the dichroic mirror in this region, while the increased threshold beyond 2100 nm can be explained by the increasing background loss in the silica fiber and the diminishing emission cross-section of Tm fibers [see Fig. 6(b)].

In our preliminary experiment, we demonstrated a wavelength-tuning range over 2000-2172 nm. Extending to shorter wavelengths can be achieved by using a suitable dichroic mirror and to longer wavelengths by reducing the intra-cavity loss (e.g., by using an anti-reflection-coated collimation lens or an output coupler with higher reflectivity). The measured ASE spectra (Fig. 3) indicated a potential wavelength tuning range over 1940-2200 nm. In addition, the tandem-pumped Tm fiber systems could also be employed to build broadband light amplifiers at ~2.1 μm, with potential applications in fiber communication systems [8,9] and amplification of ultra-short optical pulses [25], which could facilitate the generation of long-wave mid-infrared emission through nonlinear frequency conversion [5–7].

4. Summary

In summary, we have demonstrated a core-pumped Tm fiber laser continuously-tunable over 2000-2172 nm. Implementation of a 1908 nm tandem-pumping scheme plays a key role in suppressing potential parasitic lasing in the short-wavelength region and enabling stable lasing operation at the long-wave emission tail of Tm fiber gain media. This is, as far as we know, the first demonstration of long-wavelength operation of a Tm-doped fiber laser in-band-pumped at >1900 nm. Over the full wavelength-tuning range, an optical SNR of more than 30 dB was measured. The maximum output power was 0.53 W at a central wavelength of 2050 nm with a launched pump power of 3 W, and the maximum slope efficiency was

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~23%. At the emission wavelength of 2172 nm, the maximum output power was 0.14 W, and the slope efficiency was 9.9%. Widely-tunable laser sources operating at 2.1 μm region are ideally suitable for many applications, including environment monitoring, remote sensing, and hyper-spectral imaging [1–4]. The capability of providing broadband light amplification at 2.1 μm would also benefit applications in optical fiber communication and nonlinear frequency conversion.

5. Funding

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References

1. J. P. Cariou, B. Augere, and M. Valla, "Laser source requirements for coherent lidars based on fiber technology," Compt. Rend. Phys. **7**(2), 213–223 (2006).
2. K. Scholle, S. Lamrini, P. Koopmann, and P. Fuhrberg, *2 μm laser sources and their possible applications*, in Frontiers in Guided Wave Optics and Optoelectronics, (InTech, 2010).
3. D. E. Johnson, "Use of the holmium:YAG (Ho:YAG) laser for treatment of superficial bladder carcinoma," Lasers Surg. Med. **14**(3), 213–218 (1994).
4. A. Hemming, N. Simakov, J. Haub, and A. Carter, "A review of recent progress in holmium-doped silica fibre sources," Opt. Fiber Technol. **20**(6), 621–630 (2014).
5. N. Leindecker, A. Marandi, R. L. Byer, K. L. Vodopyanov, J. Jiang, I. Hartl, M. Fermann, and P. G. Schunemann, "Octave-spanning ultrafast OPO with 2.6-6.1 μm instantaneous bandwidth pumped by femtosecond Tm-fiber laser," Opt. Express **20**(7), 7046–7053 (2012).
6. E. Sorokin, A. Marandi, P. G. Schunemann, M. M. Fejer, R. L. Byer, and I. T. Sorokina, "Efficient half-harmonic generation of three-optical-cycle mid-IR frequency comb around 4 μm using OP-GaP," Opt. Express **26**(8), 9963–9971 (2018).
7. M. Schellhorn, G. Spindler, and M. Eichhorn, "Mid-infrared ZGP OPO with divergence compensation and high beam quality," Opt. Express **26**(2), 1402–1410 (2018).
8. 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. **38**(22), 4739–4742 (2013).
9. Z. Li, A. M. Heidt, J. M. O. Daniel, Y. Jung, S. U. Alam, and D. J. Richardson, "Thulium-doped fiber amplifier for optical communications at 2 μm," Opt. Express **21**(8), 9289–9297 (2013).
10. N. Simakov, A. Hemming, W. A. Clarkson, J. Haub, and A. Carter, "A cladding-pumped, tunable holmium doped fiber laser," Opt. Express **21**(23), 28415–28422 (2013).
11. N. Simakov, Z. Li, Y. Jung, J. M. O. Daniel, P. Barua, P. C. Shardlow, S. Liang, J. K. Sahu, A. Hemming, W. A. Clarkson, S.-U. Alam, and D. J. Richardson, "High gain holmium-doped fibre amplifiers," Opt. Express **24**(13), 13946–13956 (2016).
12. S. D. Jackson and T. A. King, "Theoretical modeling of Tm-doped silica fiber lasers," J. Lightwave Technol. **17**(5), 948–956 (1999).
13. J. Li, Z. Sun, H. Luo, Z. Yan, K. Zhou, Y. Liu, and L. Zhang, "Wide wavelength selectable all-fiber thulium doped fiber laser between 1925 nm and 2200 nm," Opt. Express **22**(5), 5387–5399 (2014).
14. 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. **27**(22), 1989–1991 (2002).
15. D. Y. Shen, J. K. Sahu, and W. A. Clarkson, "High-power widely tunable Tm:fibre lasers pumped by an Er,Yb co-doped fibre laser at 1.6 μm," Opt. Express **14**(13), 6084–6090 (2006).
16. Z. S. Sacks, Z. Schiffer, and D. David, "Long wavelength operation of double-clad Tm: silica fiber lasers," Proc. SPIE **6453**, 645320 (2007).
17. Z. Hu, P. Yan, Q. Xiao, Q. Liu, and M. Gong, "227-W output all-fiberized Tm-doped fiber laser at 1908 nm," Chin. Phys. B **23**(10), 104206 (2014).
18. B. Ibarra-Escamilla, M. Durán-Sánchez, R. I. Álvarez-Tamayo, B. Posada-Ramírez, P. Prieto-Cortés, E. A. Kuzin, J. L. Cruz, and M. V. Andrés, "Tunable dual-wavelength operation of an all-fiber thulium-doped fiber laser based on tunable fiber Bragg gratings," J. Opt. **20**(8), 085702 (2018).
19. Z. Zhang, D. Y. Shen, A. J. Boyland, J. K. Sahu, W. A. Clarkson, and M. Ibsen, "High-power Tm-doped fiber distributed-feedback laser at 1943 nm," Opt. Lett. **33**(18), 2059–2061 (2008).
20. B. Posada-Ramírez, M. Durán-Sánchez, R. I. Álvarez-Tamayo, B. Ibarra-Escamilla, E. Bravo-Huerta, and E. A. Kuzin, "Study of a Hi-Bi FOLM for tunable and dual-wavelength operation of a thulium-doped fiber laser," Opt. Express **25**(3), 2560–2568 (2017).
21. M. Durán-Sánchez, R. I. Álvarez-Tamayo, B. Posada-Ramírez, B. Ibarra-Escamilla, E. A. Kuzin, J. L. Cruz, and M. V. Andrés, "Tunable dual-wavelength thulium-doped fiber laser based on FBGs and a Hi-Bi FOLM," IEEE Photonics Technol. Lett. **29**(21), 1820–1823 (2017).
22. D. Creeden, B. R. Johnson, S. D. Setzler, and E. P. Chicklis, "Resonantly pumped Tm-doped fiber laser with >90% slope efficiency," Opt. Lett. **39**(3), 470–473 (2014).

23. D. Creeden, B. R. Johnson, G. A. Rines, and S. D. Setzler, “High power resonant pumping of Tm-doped fiber amplifiers in core- and cladding-pumped configurations,” Opt. Express **22**(23), 29067–29080 (2014).
24. Y. Wang, J. Yang, C. Huang, Y. Luo, S. Wang, Y. Tang, and J. Xu, “High power tandem-pumped thulium-doped fiber laser,” Opt. Express **23**(3), 2991–2998 (2015).
25. X. Jin, E. Lee, J. Luo, B. Sun, V. Ramalingam, Q. Wang, Y. Zhang, P. Zhou, and X. Yu, “High-efficiency ultrafast Tm-doped fiber amplifier based on resonant pumping,” Opt. Lett. **43**(7), 1431–1434 (2018).
26. V. Gapontsev, V. Fomin, A. Ferin, and M. Abramov, “Diffraction limited ultra-high-power fiber lasers,” in Lasers, Sources and Related Photonic Devices (Optical Society of America, 2010), paper AWA1.
27. P. Zhou, H. Xiao, J. Leng, J. Xu, Z. Chen, H. Zhang, and Z. Liu, “High-power fiber lasers based on tandem pumping,” J. Opt. Soc. Am. B **34**(3), A29 (2017).
28. H. M. Pask, R. J. Carman, D. C. Hanna, A. C. Tropper, C. J. Mackechnie, P. R. Barber, and J. M. Dawes, “Ytterbium-doped silica fiber lasers: versatile sources for the 1-1.2 µm region,” IEEE J. Sel. Top. Quantum **1**(1), 2–13 (1995).
29. Y. Wang and H. Po, “Dynamic characteristics of double-clad fiber amplifiers for high-power pulse amplification,” J. Lightwave Technol. **21**(10), 2262–2270 (2003).