applied sciences

MDPI

Editorial

Foreword to the Special Issue on Thulium-Doped Fiber Lasers

Maria Michalska

Institute of Optoelectronics, Military University of Technology, 2 Sylwestra Kaliskiego Street, 00-908 Warsaw, Poland; maria.michalska@wat.edu.pl

Fiber laser sources operating in the 2 μm wavelength region have gained extensive attention due to their wide range of applications, including in medicine, remote sensing, spectroscopy, plastic material processing, and mid-infrared generation [1–5]. Silica thulium-doped fibers (TDFs) are probably the most technologically mature active fibers and offer a broad output spectral range of about 1.7–2.1 μm [6,7]. Their wide gain bandwidth makes them an excellent choice for the generation of ultrashort laser pulses in the mid-infrared spectral region. Numerous demonstrations of mode-locked thulium-doped fiber lasers (TDFLs) have been reported in the literature [8,9], but there is still a relatively small number of reports on self-starting and environmentally stable ultrafast lasers developed using all-PM-fiber technology that emit linearly polarized pulses.

Another type of TDFL that has experienced intense, tremendous progress over the last decade is high-power TDFLs. High-power 2 μm fiber laser systems are attractive for applications in long-range atmospheric transmission, remote sensing, medicine, and directed energy. Additionally, the wavelength of 2 μm belongs to the so called "eye-safe" spectral region, which promotes the application of TDFLs in many fields of industry to replace the currently commonly used ytterbium-doped fiber lasers and amplifiers. The most desired are narrow-linewidth, high-power fiber laser systems, which enable coherent beam combining to further scale up the output power of laser radiation [10]. Efficient generation at 2 μm can be obtained via the in-band pumping of Tm^{3+}-doped fibers by a TDFL emitting at a shorter wavelength or by pumping at 790 nm using commercially available high brightness, fiber-coupled laser diodes [11]. Pumping at 790 nm could yield high efficiency due to the cross-relaxation process, in which two excited-state ions are created from one pump photon [12]. The cross-relaxation efficiency in TDF is closely correlated with the dopant concentration of the active fiber and must be carefully optimized. However, the generation of over 20 W of laser radiation at 2 μm with a high slope efficiency exceeding 70% has been presented in TDFL diode pumped at 790 nm [13]. This appears very promising for further improvements in high-power TDFLs and amplifiers.

The papers contained in this Special Issue aim to present the most recent advancements in TDFLs and their applications, including new concepts for active fibers, detailed studies of phenomena responsible for different generation regimes, and novel fiber laser system designs. Studies on nonlinear effects, which usually limit the enhancement of the output parameters, are also highly welcome. Finally, I would like to encourage discussions not only on the advantages of TDFLs but also on their limitations and weaknesses.

Funding: This research received no external funding.

Conflicts of Interest: The author declares no conflict of interest.

Citation: Michalska, M. Foreword to the Special Issue on Thulium-Doped Fiber Lasers. *Appl. Sci.* **2022**, *12*, 11267. https://doi.org/10.3390/app122111267

Received: 2 November 2022
Accepted: 4 November 2022
Published: 7 November 2022

References

1. Scholle, K.; Lamrini, S.; Koopmann, P.; Fuhrberg, P. 2 μm Laser Sources and Their Possible Applications. In *Frontiers in Guided Wave Optics and Optoelectronics*; Pal, B., Ed.; InTech: Rijeka, Croatia, 2010; pp. 471–500.
2. Traxer, O.; Sierra, A.; Corrales, M. Which Is the Best Laser for Lithotripsy? Thulium Fiber Laser. *Eur. Urol. Open Sci.* **2022**, *44*, 15–17. [CrossRef] [PubMed]
3. Huang, Y.; Jivraj, J.; Zhou, J.; Ramjist, J.; Wong, R.; Gu, X. Pulsed and CW adjustable 1942 nm single-mode all-fiber Tm-doped fiber laser system for surgical laser soft tissue ablation applications. *Opt. Express* **2016**, *24*, 16674. [CrossRef] [PubMed]
4. Mingareev, I.; Weirauch, F.; Olowinsky, A.; Shah, L.; Kadwani, P.; Richardson, M. Welding of polymers using a 2 μm thulium fiber laser. *Opt. Laser Technol.* **2012**, *44*, 2095–2099. [CrossRef]
5. Kneis, C.; Donelan, B.; Manek-Hönninger, I.; Robin, T.; Cadier, B.; Eichhorn, M.; Kieleck, C. High-peak-power single-oscillator actively Q-switched mode-locked Tm^{3+}-doped fiber laser and its application for high-average output power mid-IR supercontinuum generation in a ZBLAN fiber. *Opt. Lett.* **2016**, *41*, 2545–2548. [CrossRef] [PubMed]
6. Zhang, L.; Zhang, J.; Sheng, Q.; Fu, S.; Shi, W.; Yao, J. High-efficiency Thulium-doped fiber laser at 1.7 μm. *Opt. Laser Technol.* **2022**, *152*, 108180. [CrossRef]
7. Clarkson, W.A.; Barnes, N.P.; Turner, P.W.; Nilsson, J.; Hanna, D.C. High-power cladding-pumped Tm-doped silica fiber laser with wavelength tuning from 1860 to 2090 nm. *Opt. Lett.* **2002**, *27*, 1989–1991. [CrossRef] [PubMed]
8. Rudy, C.W.; Digonnet, M.J.; Byer, R.L. Advances in 2-μm Tm-doped mode-locked fiber lasers. *Opt. Fiber Technol.* **2014**, *20*, 642–649. [CrossRef]
9. Kirsch, D.C.; Chen, S.; Sidharthan, R.; Chen, Y.; Yoo, S.; Chernysheva, M. Short-wave IR ultrafast fiber laser systems: Current challenges and prospective applications. *J. Appl. Phys.* **2020**, *128*, 180906. [CrossRef]
10. Wang, X.; Zhou, P.; Wang, X.; Ma, Y.; Rongtao, S.; Xiao, H.; Si, L.; Liu, Z. 108 W coherent beam combining of two single-frequency Tm-doped fiber MOPAs. *Laser Phys. Lett.* **2014**, *11*, 105101. [CrossRef]
11. Sincore, A.; Bradford, J.D.; Cook, J.; Shah, L.; Richardson, M.C. High Average Power Thulium-Doped Silica Fiber Lasers: Review of Systems and Concepts. *IEEE J. Sel. Top. Quantum Electron.* **2018**, *24*, 1–8. [CrossRef]
12. Jackson, S.D. Cross relaxation and energy transfer upconversion process relevant to the functioning of 2 μm, Tm^{3+}-doped silica fibre laser. *Opt. Commun.* **2004**, *230*, 197–203. [CrossRef]
13. Ramírez-Martínez, N.J.; Núñez-Velázquez, M.; Umnikov, A.; Sahu, J.K. Highly efficient thulium-doped high-power laser fibers fabricated by MCVD. *Opt. Express* **2019**, *27*, 196–201. [CrossRef] [PubMed]