High-Efficiency Ultrafast Tm-Doped Fiber Amplifier Based on Resonant Pumping

Xiaoxi Jin, Elizabeth Lee, Jiaqi Luo, Biao Sun, Vincent Ramalingam, Qi Jie Wang, Pu Zhou, and Xia Yu

***Abstract*—We demonstrated a high-efficiency ultrafast Tm-doped fiber amplifier based on resonant pumping technique. A continuous-wave fiber laser at 1940 nm was employed as the pump laser. The slope efficiency of the resonantly-pumped pulsed Tm-doped fiber amplifier reached 87% with respect to the launched pump power. The maximum average output power reached 40 W when the launched pump power was 53 W. The repetition rate and the pulse duration of the output pulses from fiber amplifier was 248 MHz and 129 ps, respectively. The corresponding peak power was 1.25 kW and the pulse energy was 161.3 nJ. As far as we know, this is the first demonstration of resonant pumping enabled high-power high-efficiency ultrafast fiber laser operates at 2 μm band.**

***Index Terms*—fiber lasers, resonant pumping, thulium-doped fiber amplifiers, ultrafast laser.**

I. INTRODUCTION

TM-DOPED fiber lasers operating at 2 μm are attractive fiber sources, attributed to the characteristics including eye-safety, broad gain spectrum and high brightness [1-3]. Therefore, pulsed Tm-doped fiber lasers have many applications for LIDAR [4], optical communication [5], material processing [6] and medicine [7]. They are also promising high-brightness pump lasers for mid-infrared supercontinuum generation based on nonlinear optical effects [8, 9]. Furthermore, they also have potential to be used in long-wavelength mid-infrared generation based on nonlinear frequency conversion [10]. The emergence of high power Tm-doped fiber lasers benefits from the rapid development of laser diodes (LDs) at 793 nm. With the cross-relaxation process, the quantum efficiency of Tm-doped fiber lasers pumped with 793 nm LDs can exceed 100% [11]. However, limited by the quantum defect, the slope efficiency of 793 nm LD-pumped continuous-wave (CW) high power Tm-doped fiber lasers were typically within 40%-65% [12-15]. For pulsed Tm-doped fiber lasers [16-21], the efficiency was even lower than that of CW counterparts, due to the small temporal overlap between the signal and pump. The moderate slope efficiency results in intense thermal load and abundant residual pump power in the gain fiber when operating at high power, which limits further power scaling.

Researchers have put forth effort to improve the slope efficiency of Tm-doped fiber laser operating at 2 μm. There are mainly two roadmaps: (i) optimizing the gain fiber, including doping concentration [11, 22] and fiber structure [23, 24]; (ii) optimizing pump laser, such as employing pulsed pumping to increase pump extraction ratio for pulse amplification [25], or using pump wavelength with lower quantum defect [26-34].

Among these methods, pumping with low quantum defect is a direct way to obtain high optical efficiency. S. D. Jackson *et al.* theoretically investigated the slope efficiencies of CW Tm-doped fiber lasers with different pump wavelengths, and the simulation results showed that $^3F_4$ pump band was the most efficient one [35]. For CW regime, research results on power scaling of Tm-doped fiber laser pumped in $^3F_4$ band have been reported in recent decade. Due to the immature of LD at $^3F_4$ pump band, the majority of employed high power pump sources were Er-doped fiber lasers and Tm-doped fiber lasers. In 2006, D. Y. Shen *et al.* reported a high-power Tm-doped fiber laser pumped with an Er-Yb co-doped fiber laser at 1.6 μm. The maximum output power was 19.2 W when cladding-pumped with the launched pump power of 38.2 W. The slope efficiency was 72% with respect to absorbed pump power [27]. In 2007, M. Meleshkevich *et al.* reported a 415 W single-mode CW all-fiber Tm-doped fiber laser cladding-pumped by Er-doped fiber lasers with the total power of 720 W. The slope efficiency of the Tm-doped fiber laser was 60% with respect to the absorbed pump power [28]. In 2014, D. Creeden *et al.* demonstrated a 123.1 W CW Tm-doped fiber amplifier with the slope efficiency of 91.6%, which was cladding-pumped by a 1908 nm Tm-doped fiber

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laser [31]. In 2015, Y. Wang *et al.* demonstrated an efficient high power Tm-doped fiber laser based on cascaded tandem pumping technique. The pump source was a high power double-cladding Tm-doped fiber laser at 1942 nm. The slope efficiency was 92% with respect to launched pump power, and the output power reached 35 W at 2020 nm [31]. With the progress of LD module at 1.6 μm, G. A. Newburgh *et al.* reported a 15 W quasi-continuous-wave resonantly diode-cladding-pumped Tm-doped fiber laser at 1930 nm recently. The slope efficiency was 67% with respect to the absorbed pump power at 1620 nm [33]. The efficiency improvement of Tm-doped fiber laser is remarkable and impressive based on resonant pumping technique. However, few high power pulsed resonantly-pumped Tm-doped fiber lasers were demonstrated, with high optical efficiency. In 2011, Y. Tang *et al.* reported a 1.94 μm gain-switched Tm-doped fiber laser with the slope efficiency of 80% with respect to absorbed pump power, resonantly pumped by a 1.914 μm Q-switched Tm:YLF laser. The pulse energy and peak power were 1.3 mJ and 21.3 kW, respectively [36]. Owing to the demands in various applications, high power ultrafast Tm-doped fiber lasers at 2 μm have widely attracted interests in recent years. However, resonant pumping enabled high power ultrafast Tm-doped fibers have not been reported as far as we know.

In this paper, we demonstrated a high-efficiency ultrafast Tm-doped fiber amplifier based on resonant pumping technique. A home-made fiber laser with a repetition rate of 248 MHz and the central wavelength of 1970 nm was employed as the seed laser. A high power CW fiber laser at 1940 nm was used as pump laser to achieve resonant pumping in ultrafast Tm-doped fiber amplifier. The slope efficiency of resonantly-pumped Tm-doped fiber amplifier was 87% with respect to the launched pump power, and the maximum average output power reached 40 W. No additive cooling techniques were used to cool down the gain fiber at the maximum output power, which indicates the dramatic efficiency improvement when using resonant pumping technique in pulse amplification at 2 μm. The power evolution process in the main-amplifier was simulated based on rate equations. The influences of pump laser filling factor on output power and slope efficiency were also discussed.

II. EXPERIMENTAL SETUP AND RESULTS

A. *Experimental Setup*

The resonantly-pumped Tm-doped fiber amplifier consists of an ultrafast seed laser, a pulse stretcher, an all-fiber pre-amplifier, and a main-amplifier. The resonant pumping technique was achieved in the main-amplifier stage.

The setup of ultrafast fiber oscillator, pulse stretcher and the pre-amplifier were schematically depicted in Fig. 1(a). The ultrafast seed laser was a home-made fiber-based oscillator with a repetition rate of 248 MHz and the pulse width of sub-400 femtosecond (fs) [37, 38]. The central wavelength of seed laser was 1970 nm. The output pulses from seed laser were stretched to improve the threshold of nonlinear effects. The stretcher was comprised of a fiber-pigtailed circulator at 2 μm and a chirped fiber Bragg grating (CFBG). The stretching ratio of CFBG was +8.3 ps/nm. The operating spectral range of CFBG was from 1950 nm to 1990 nm and the reflectivity is higher than 99%. The short wavelength end of CFBG was directly fusion spliced with the second port of circulator to provide wavelength-dependent time delays. And the long wavelength end of CFBG was angle-cleaved and then was coated with high-refractive index gel to decrease the Fresnel reflection from fiber facet. The stretched pulses of signal laser and pump laser were launched into the core and inner cladding of single-mode double-cladding thulium-doped fiber (TDF) via matched signal-pump combiner, respectively. A 793 nm laser diode (LD) with the power up to 12 W was used as the pump laser of pre-amplifier. The core diameter of TDF was 10 μm, and the inner cladding diameter was 130 μm. The cladding absorption coefficient at 793 nm was 3 dB/m, and the length of the TDF was 6.4 m. An isolator was spliced with the TDF directly.

The setup of main-amplifier based on resonant pumping was shown in Fig. 1(b). The pump laser was a CW fiber laser operating at 1940 nm. The pulsed signal laser from pre-amplifier and the CW pump laser were combined via free-space optics, including lenses and dichroic mirror (L1, L2 and DM1 in Fig. 1(b)). The position of dichroic mirror was adjusted to get high reflectivity at pump wavelength and high transmissivity at signal wavelength. A piece of 7 m large-mode-area (LMA) TDF was employed as the gain medium of amplifier to provide sufficient pump absorption. The core/pedestal/inner cladding diameter of LMA TDF was 25/50/250 μm. The signal laser was coupled into the core of LMA TDF, and the pump laser was slightly defocused from the core to be coupled into the pedestal [31], which avoided the polymer absorption of outer cladding and coating at 2 μm. The pump absorption coefficient was measured to be 2.4 dB/m. And the fiber was coiled on a copper drum with the diameter of 10 cm. No other additive cooling techniques were used in the main-amplifier. The fiber ends of LMA TDF were angle-cleaved to prevent facet feedbacks. After amplification, the output laser was collimated by another lens L3 and the residual pump laser was filtered by dichroic mirror DM2.

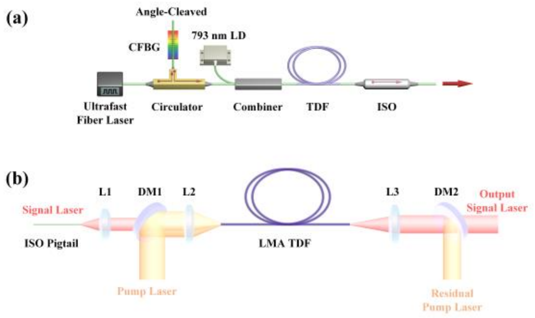

Fig. 1. Schematic setup of the Tm-doped fiber amplifier based on resonant pumping. The ultrafast seed laser, pulse stretcher and pre-amplifier are shown in (a). And the free-space main-amplifier is shown in (b). CFBG: chirped fiber Bragg grating; LD: laser diode; TDF: thulium-doped fiber; ISO: isolator; L1, L2, L3: lenses; DM1, DM2: dichroic mirror; LMA TDF: large-mode-area thulium-doped fiber.

During the experiment, the output pulse trains and pulse duration were measured by a digital oscilloscope (6 GHz bandwidth) and an InGaAs photodetector (12.5 GHz bandwidth). The output spectra were measured by an optical spectrum analyzer (OSA).

B. Experimental Results

We firstly measured the spectrum of ultrafast seed laser and the transmissivity of stretcher and dichroic mirror, which were shown in Fig. 2. The central wavelength of seed laser was 1970 nm and the 3 dB bandwidth was 18 nm. A home-made broadband fiber-based superfluorescent source was employed to measure the spectral response of CFBG, along with the insertion loss of circulator. Due to the limited bandwidth of CFBG and the insertion losses of circulator, the laser power launched into circulator port 1 was 23 mW, and the output power from circulator port 3 was 7.5 mW. The stretched pulsed duration was 150 ps, matching with the bandwidth of seed laser and the stretching ratio of CFBG. Then the stretched pulses were pre-amplified to 3.2 W when the launched 793 nm pump power was 10.6 W. The slope efficiency of pre-amplifier was 47% with respect to the launched pump power. The insertion loss of ISO was 1.5 dB, and the output power from ISO was 2.3 W.

In the main-amplifier stage, signal laser and pump laser were combined via dichroic mirror DM1. Since the transmissivity of dichroic mirror is sensitive to the incident angle, we finely adjusted the incident angles of signal laser and pump laser to DM1, to get both transmitted signal power and reflected pump power maximum simultaneously. The transmissivity of dichroic mirror at the fixed position in our setup was also shown in Fig. 2. The transmissivity of DM1 at 1970 nm was higher than 90%, and the reflectivity at 1940 nm was 90%. The combined signal power was measured to be 2 W, which matches with the characterized transmissivity of DM1 in our setup.

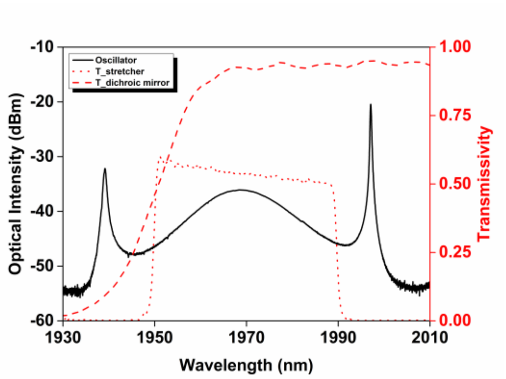

Fig. 2. Optical spectrum of ultrafast seed laser (black solid line) and the measured transmissivity of stretcher (red dotted line) and dichroic mirror (red dashed line).

Then we studied the power scaling of resonantly-pumped main-amplifier. The output signal power and residual pump power were shown in Fig. 3(a). The maximum output power reached 40 W when the launched pump power was 53 W. The slope efficiency of resonantly-pumped Tm-doped fiber amplifier was 87% with respect to the launched pump power. The residual pump power was 2 W when the main-amplifier reached maximum output power. During the amplification, we also monitored the temperature of TDF which was just exposed in the ambient temperature. The highest surface temperature of TDF was 35 degrees centigrade, which also indicates the high efficiency of the main-amplifier. The optical spectrum of main-amplifier at the output power of 40 W were shown in Fig. 3(b). A piece of multimode fiber was employed in the experiment to couple the output laser into OSA. Due to the reabsorption of shorter wavelengths in 7 m long TDF, the central wavelength of main-amplifier red-shifted to 1977 nm, and the 3 dB bandwidth narrowed down to 7 nm. The residual pump at 1940 nm and long-wavelength Kelly-sideband centered at 1997 nm can also be observed. We also measured the temporal characteristics of the output laser. The repetition rate of the pulse train was 248 MHz, which was shown in Fig. 3(c). The pulse shape was depicted in Fig. 3(d). The pulse duration was 129 ps, narrower than that of the stretched pulse output from circulator. The temporal narrowing could be attributed to the spectral narrowing effect mentioned above. The peak power and pulse energy was calculated to be 1.25 kW and 161.3 nJ, respectively. Moreover, the output pulses could be recompressed via dispersion components such as chirped volume Bragg grating. According to the output spectrum of main-amplifier, the transform-limited pulse duration was calculated to be 1.19 ps if Gaussian-shaped pulse profile assumed.

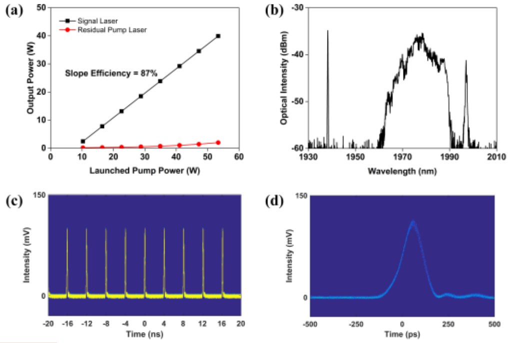

Fig. 3. Characteristics of resonantly-pumped Tm-doped fiber amplifier. (a) Output signal power and residual pump power with respect to the launched pump power; (b) Optical spectrum at maximum output power; (c) Pulse trains with repetition rate of 248 MHz; (d) Pulse profile with the pulse duration of 129 ps.

III. DISCUSSION

We numerically simulated the output power and slope efficiency of the main-amplifier based on rate equations. According to the theory in [39], the model can be simplified by assuming population inversion reaching steady state, due to high repetition rate. The time derivatives in rate equations could be neglected if the repetition rate is much higher than the recovery rate of upper energy level populations. The parameters used for simulation were depicted in Table I, which were consistent with the experimental setup. And the data on cross sections of Tm-doped fiber were from [40]. We firstly simulated the power evolution along Tm-doped fiber, and the filling factor of pump laser was set to be 0.93 as an example. The results was show in Fig. 4(a). When the pump power was 53 W, the output signal power and residual pump power was 46.3 W and 2.4 W, respectively. And the slope efficiency was 89.2%. Pump power was absorbed sufficiently in the main-amplifier, although the cross section at the chosen pump wavelength is much smaller than that at 793 nm.

TABLE I
PARAMETERS FOR SIMULATION

Parameter	Symbol	Value	Unit
pump wavelength	λ_p	1940	nm
signal wavelength	λ_s	1970	nm
cross sections	$\sigma_a(\lambda_p)$	1.1818×10^{-26}	m^2
	$\sigma_e(\lambda_p)$	4.3000×10^{-25}	m^2
	$\sigma_a(\lambda_s)$	6.7173×10^{-27}	m^2
	$\sigma_e(\lambda_s)$	3.5946×10^{-25}	m^2
upper level lifetime	τ	334.7	µs
Tm ions concentration	N	2.85×10^{26}	m^{-3}
filling factor of signal laser	Γ_s	0.93	
pump power	P_p	53	W
signal power	P_s	2	W
fiber length	L	7	m

We also investigated how the output power and the slope efficiency varied with the filling factor of the pump laser. Since we manually defocused the pump laser from the core of LMA TDF in the experiment, the filling factor of pump laser could range from 0.25 to 0.93. The simulation results was shown in Fig. 4(b). Compared to the size of inner cladding of commercial double-cladding fiber, the size of pedestal is much smaller, which means the filling factor of pump laser in our setup is high. However, it was still obvious that the absorbed pump power decreased with the drop of filling factor. When the filling factor of pump laser decreased from 0.93 to 0.25, the pump absorption dropped from 95.5% to 62.9%. Insufficient pump absorption resulted in the drop of slope efficiency with respect to the launched pump power. When the filling factor of pump laser was 0.93, the slope efficiency was calculated to be as high as 89.2%. The slope efficiency dropped to 56.0% when the filling factor of pump laser decreased to 0.25. Therefore, high filling factor of pump laser is the key to achieve efficient power amplification in the resonantly-pumped fiber amplifier, due to the small absorption cross section at 1.9 µm. This conclusion is also consistent with the experiment demonstrated in [31]. To improve pump absorption, long and highly concentrated Tm-doped fiber has been adopted in the experiment, which may risk further power scaling by nonlinear effects such as stimulated Raman scattering. The simulation results indicate the importance of design and fabrication Tm-doped fiber for being specially pumped at 1.9 µm, which will help to achieve efficient resonantly-pumped Tm-doped fiber laser in all-fiber format. Also, optimizing the pump and signal wavelengths based on the cross sections of Tm-doped fiber was another way to improve output power and slope efficiency.

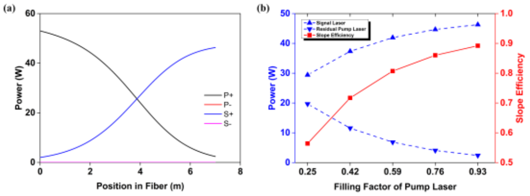

Fig. 4. Simulation results of high repetition rate Tm-doped fiber amplifier based on rate equations. (a) Power evolution along Tm-doped fiber when filling factor of pump laser was 0.93; (b) Output signal power, residual pump power and slope efficiency varies with different filling factor of pump laser.

IV. CONCLUSION

In conclusion, we demonstrated a 40 W high-efficiency ultrafast Tm-doped fiber amplifier at 1970 nm based on resonant pumping. The slope efficiency was as high as 87% with respect to the launched pump power. As far as we know, this is the first demonstration of resonant pumping enabled high-power high-efficiency ultrafast fiber laser operates at 2 µm band. Based on this technique, further power scaling of ultrafast Tm-doped fiber laser could be reached if more pump power is available. Resonant pumping technique provides an alternative route for Tm-doped fiber lasers to improve the

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moderate optical efficiency, not only for CW ones, but also for pulsed ones. The output power and optical efficiency could be further improved if the Tm-doped fiber length, signal and pump wavelengths are optimized based on the cross sections of Tm-doped fiber. Moreover, this investigation also indicates the significance of design and fabrication special Tm-doped fiber pumped at 1.9 μm, which will make the all-fiber resonantly-pumped Tm-doped fiber laser achievable.

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REFERENCES

[1] S. D. Jackson, A. Sabella and D. G. Lancaster, "Application and Development of High-Power and Highly Efficient Silica-Based Fiber Lasers Operating at 2 μm," *IEEE Journal of Selected Topics in Quantum Electronics*, vol. 13, no. 3, pp. 567-572, 2007.

[2] S. D. Jackson, "Towards high-power mid-infrared emission from a fibre laser," *Nature Photonics*, vol. 6, no. 7, pp. 423-431, 2012.

[3] J. Geng, Q. Wang, Y. Lee, and S. Jiang, "Development of eye-safe fiber lasers near 2 μm," *IEEE Journal of Selected Topics in Quantum Electronics*, vol. 20, no. 5, pp. 150-160, 2014.

[4] G. J. Koch, J. Y. Beyon, B. W. Barnes, M. Petros, J. Yu, F. Amzajerdian, and M. J. K. A. Singh, "High-energy 2 μ m Doppler lidar for wind measurements," *Optical Engineering*, vol. 46, no. 11, p. 116201, 2007.

[5] R. Soref, "Group IV photonics: Enabling 2 μm communications," *Nature Photonics*, vol. 9, no. 6, pp. 358-359, 2015.

[6] H. Kalaycıoğlu, P. Elahi, Ö. Akçaalan, and F. Ö. Ilday, "High-Repetition-Rate Ultrafast Fiber Lasers for Material Processing," *IEEE Journal of Selected Topics in Quantum Electronics*, vol. 24, no. 3, pp. 1-12, 2018-01-01 2018.

[7] N. M. Fried, "Thulium fiber laser lithotripsy: an in vitro analysis of stone fragmentation using a modulated 110-watt Thulium fiber laser at 1.94 microm," *Lasers in Surgery and Medicine*, vol. 37, no. 1, pp. 53-58, 2005.

[8] K. Liu, J. Liu, H. Shi, F. Tan, and P. Wang, "24.3 W Mid-infrared Supercontinuum Generation from a Single-mode ZBLAN Fiber Pumped by Thulium-doped Fiber Amplifier," in *Advanced Solid State Lasers*, 2014, pp. AM3A. 6.

[9] I. Kubat, C. R. Petersen, U. V. Møller, A. Seddon, T. Benson, L. Brilland, D. M. Echin, P. M. Moselund, and O. Bang, "Thulium pumped mid-infrared 0.9-9μm supercontinuum generation in concatenated fluoride and chalcogenide glass fibers," *Optics Express*, vol. 22, no. 4, pp. 3959-3967, 2014.

[10] D. Creeden, P. A. Ketteridge, P. A. Budni, S. D. Setzler, Y. E. Young, J. C. McCarthy, K. Zawilski, P. G. Schunemann, T. M. Pollak, and E. P. Chicklis, "Mid-infrared ZnGeP2 parametric oscillator directly pumped by a pulsed 2 μm Tm-doped fiber laser," *Optics Letters*, vol. 33, no. 4, pp. 315-317, 2008.

[11] S. D. Jackson and S. Mossman, "Efficiency dependence on the Tm 3+ and Al 3+ concentrations for Tm 3+-doped silica double-clad fiber lasers," *Applied Optics*, vol. 42, no. 15, pp. 2702-2707, 2003.

[12] G. D. Goodno, L. D. Book and J. E. Rothenberg, "Low-phase-noise, single-frequency, single-mode 608 W thulium fiber amplifier," *Optics Letters*, vol. 34, no. 8, pp. 1204-1206, 2009.

[13] T. Ehrenreich, R. Leveille, I. Majid, K. Tankala, G. Rines, and P. Moulton, "1-kW, all-glass Tm: fiber laser," in *Proc. SPIE*, 2010, p. 758016.

[14] X. Wang, X. Jin, W. Wu, P. Zhou, X. Wang, H. Xiao, and Z. Liu, "310-W Single Frequency Tm-Doped All-Fiber MOPA," *IEEE Photonics Technology Letters*, vol. 27, no. 6, pp. 677-680, 2015.

[15] T. Walbaum, M. Heinzig, T. Schreiber, R. Eberhardt, and A. Tünnermann, "Monolithic thulium fiber laser with 567 W output power at 1970 nm," *Optics Letters*, vol. 41, no. 11, pp. 2632-2635, 2016.

[16] Q. Fang, W. Shi, E. Petersen, K. Kieu, A. Chavez-Pirson, and N. Peyghambarian, "Half-mJ All-Fiber-Based Single-Frequency Nanosecond Pulsed Fiber Laser at 2-μm," *IEEE Photonics Technology Letters*, vol. 24, no. 5, pp. 353-355, 2012.

[17] P. Wan, L. Yang and J. Liu, "High power 2 μm femtosecond fiber laser," *Optics Express*, vol. 21, no. 18, pp. 21374-21379, 2013.

[18] Y. Tang, L. Xu, Y. Yang, and J. Xu, "High-power gain-switched Tm 3+-doped fiber laser," *Optics Express*, vol. 18, no. 22, pp. 22964-22972, 2010.

[19] A. M. Heidt, Z. Li, J. Sahu, P. C. Shardlow, M. Becker, M. Rothhardt, M. Ibsen, R. Phelan, B. Kelly, and S. U. Alam, "100 kW peak power picosecond thulium-doped fiber amplifier system seeded by a gain-switched diode laser at 2 μm," *Optics Letters*, vol. 38, no. 10, pp. 1615-1617, 2013.

[20] G. Imeshev and M. E. Fermann, "230-kW peak power femtosecond pulses from a high power tunable source based on amplification in Tm-doped fiber," *Optics Express*, vol. 13, no. 19, pp. 7424-7431, 2005.

[21] J. Liu, J. Xu, K. Liu, F. Tan, and P. Wang, "High average power picosecond pulse and supercontinuum generation from a thulium-doped, all-fiber amplifier," *Optics Letters*, vol. 38, no. 20, pp. 4150-4153, 2013.

[22] P. C. Shardlow, D. Jain, R. Parker, J. Sahu, and W. A. Clarkson, "Optimising Tm-Doped Silica Fibres for High Lasing Efficiency," in *The European Conference on Lasers and Electro-Optics*, 2015, pp. CJ_14_3.

[23] C. Jollivet, K. Farley, M. Conroy, H. Dabhi, J. Edgecumbe, A. Carter, and K. Tankala, "Design optimization of Tm-doped large-mode area fibers for power scaling of 2 μm lasers and amplifiers," in *Fiber Lasers XIV: Technology and Systems*, 2017, p. 100830I.

[24] C. Jollivet, B. Samson, L. Leick, L. Shah, M. Richardson, and A. Schülzgen, "Comparative study of light propagation and single-mode operation in large-mode area fibers designed for 2-μm laser applications," *Optical Engineering*, vol. 54, no. 1, p. 011006-011006, 2015.

[25] A. Malinowski, J. H. Price and M. N. Zervas, "Overlapped pulsed pumping of tandem pumped fiber amplifiers to increase achievable pulse energy," *IEEE Journal of Quantum Electronics*, vol. 53, no. 2, pp. 1-8, 2017.

[26] T. Yamamoto, Y. Miyajima and T. Komukai, "1.9 μm Tm-doped silica fibre laser pumped at 1.57 μm," *Electronics Letters*, vol. 30, no. 3, pp. 220-221, 1994.

[27] 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," *Optics Express*, vol. 14, no. 13, pp. 6084-6090, 2006.

[28] 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 *2007 European Conference on Lasers and Electro-Optics and the International Quantum Electronics Conference*, 2007, p. 1-1.

[29] X. Wang, P. Zhou, H. Zhang, X. Wang, H. Xiao, and Z. Liu, "100 W-level Tm-doped fiber laser pumped by 1173 nm Raman fiber lasers," *Optics Letters*, vol. 39, no. 15, pp. 4329-4332, 2014.

[30] D. Creeden, B. R. Johnson, S. D. Setzler, and E. P. Chicklis, "Resonantly pumped Tm-doped fiber laser with> 90% slope efficiency," *Optics Letters*, vol. 39, no. 3, pp. 470-473, 2014.

[31] 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," *Optics Express*, vol. 22, no. 23, pp. 29067-29080, 2014.

[32] Y. Wang, J. Yang, C. Huang, Y. Luo, S. Wang, Y. Tang, and J. Xu, "High power tandem-pumped thulium-doped fiber laser," *Optics Express*, vol. 23, no. 3, pp. 2991-2998, 2015.

[33] G. A. Newburgh, J. Zhang and M. Dubinskii, "Tm-doped fiber laser resonantly diode-cladding-pumped at 1620 nm," *Laser Physics Letters*, vol. 14, no. 12, p. 125101, 2017.

[34] X. Jin, X. Du, X. Wang, P. Zhou, H. Zhang, X. Wang, and Z. Liu, "High-power ultralong-wavelength Tm-doped silica fiber laser cladding-pumped with a random distributed feedback fiber laser," *Scientific Reports*, vol. 6, no. p. 30052, 2016.

[35] S. D. Jackson and T. A. King, "Theoretical modeling of Tm-doped silica fiber lasers," *Journal of Lightwave Technology*, vol. 17, no. 5, pp. 948-956, 1999.

[36] Y. Tang, F. Li and J. Xu, "High peak-power gain-switched Tm3+-doped fiber laser," *IEEE Photonics Technology Letters*, vol. 23, no. 13, pp. 893-895, 2011.

[37] B. Sun, J. Luo, B. P. Ng, and X. Yu, "Dispersion-compensation-free femtosecond Tm-doped all-fiber laser with a 248 MHz repetition rate," *Optics Letters*, vol. 41, no. 17, pp. 4052-4055, 2016.

[38] B. Sun, J. Luo, Z. Yan, K. Liu, J. Ji, Y. Zhang, Q. J. Wang, and X. Yu, "1867-2010 nm tunable femtosecond thulium-doped all-fiber laser," *Optics Express*, vol. 25, no. 8, pp. 8997-9002, 2017.

[39] R. Lindberg, P. Zeil, M. Malmström, F. Laurell, and V. Pasiskevicius, "Accurate modeling of high-repetition rate ultrashort pulse amplification in optical fibers," *Scientific Reports*, vol. 6, no. p. 34742, 2016.

[40] P. F. Moulton, "High power Tm:silica fiber lasers: current status, prospects and challenges," in *Lasers and Electro-Optics Europe (CLEO EUROPE/EQEC), 2011 Conference on and 12th European Quantum Electronics Conference*, 2011, p. 1-1.

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References:

[1] S. D. Jackson, A. Sabella and D. G. Lancaster, "Application and Development of High-Power and Highly Efficient Silica-Based Fiber Lasers Operating at 2 μ m," *IEEE Journal Of Selected Topics In Quantum Electronics,* vol. 13, no. 3, pp. 567-572, 2007.

[2] S. D. Jackson, "Towards high-power mid-infrared emission from a fibre laser," *Nature Photonics,* vol. 6, no. 7, pp. 423-431, 2012.

[3] J. Geng, Q. Wang, Y. Lee, and S. Jiang, "Development of eye-safe fiber lasers near 2 μ m," *IEEE Journal Of Selected Topics In Quantum Electronics,* vol. 20, no. 5, pp. 150-160, 2014.

[4] G. J. Koch, J. Y. Beyon, B. W. Barnes, M. Petros, J. Yu, F. Amzajerdian, and M. J. K. A. Singh, "High-energy 2 μ m Doppler lidar for wind measurements," *Optical Engineering,* vol. 46, no. 11, p. 116201, 2007.

[5] R. Soref, "Group IV photonics: Enabling 2 [mu] m communications," *Nature Photonics,* vol. 9, no. 6, pp. 358-359, 2015.

[6] H. Kalaycıoğlu, P. Elahi, Ö. Akçaalan, and F. Ö. Ilday, "High-Repetition-Rate Ultrafast Fiber Lasers for Material Processing," *IEEE Journal of Selected Topics in Quantum Electronics,* vol. 24, no. 3, pp. 1-12, 2018-01-01 2018.

[7] N. M. Fried, "Thulium fiber laser lithotripsy: an in vitro analysis of stone fragmentation using a modulated 110-watt Thulium fiber laser at 1.94 microm," *Lasers in Surgery and Medicine,* vol. 37, no. 1, pp. 53-58, 2005.

[8] K. Liu, J. Liu, H. Shi, F. Tan, and P. Wang, "24.3 W Mid-infrared Supercontinuum Generation from a Single-mode ZBLAN Fiber Pumped by Thulium-doped Fiber Amplifier," in *Advanced Solid State Lasers*, 2014, pp. AM3A. 6.

[9] I. Kubat, C. R. Petersen, U. V. Møller, A. Seddon, T. Benson, L. Brilland, D. M. Echin, P. M. Moselund, and O. Bang, "Thulium pumped mid-infrared 0.9-9 μ m supercontinuum generation in concatenated fluoride and chalcogenide glass fibers," *Optics Express,* vol. 22, no. 4, pp. 3959-3967, 2014.

[10] D. Creeden, P. A. Ketteridge, P. A. Budni, S. D. Setzler, Y. E. Young, J. C. McCarthy, K. Zawilski, P. G. Schunemann, T. M. Pollak, and E. P. Chicklis, "Mid-infrared ZnGeP2 parametric oscillator directly pumped by a pulsed 2 μ m Tm-doped fiber laser," *Optics Letters,* vol. 33, no. 4, pp. 315-317, 2008.

[11] S. D. Jackson and S. Mossman, "Efficiency dependence on the Tm 3+ and Al 3+ concentrations for Tm 3+-doped silica double-clad fiber lasers," *Applied Optics,* vol. 42, no. 15, pp. 2702-2707, 2003.

[12] G. D. Goodno, L. D. Book and J. E. Rothenberg, "Low-phase-noise, single-frequency, single-mode 608 W thulium fiber amplifier," *Optics Letters,* vol. 34, no. 8, pp. 1204-1206, 2009.

[13] T. Ehrenreich, R. Leveille, I. Majid, K. Tankala, G. Rines, and P. Moulton, "1-kW, all-glass Tm: fiber laser," in *Proc. SPIE*, 2010, p. 758016.

[14] X. Wang, X. Jin, W. Wu, P. Zhou, X. Wang, H. Xiao, and Z. Liu, "310-W Single Frequency Tm-Doped All-Fiber MOPA," *IEEE Photonics Technology Letters,* vol. 27, no. 6, pp. 677-680, 2015.

[15] T. Walbaum, M. Heinzig, T. Schreiber, R. Eberhardt, and A. Tünnermann, "Monolithic thulium fiber laser with 567 W output power at 1970 nm," *Optics Letters,* vol. 41, no. 11, pp. 2632-2635, 2016.

[16] Q. Fang, W. Shi, E. Petersen, K. Kieu, A. Chavez-Pirson, and N. Peyghambarian, "Half-mJ All-Fiber-Based Single-Frequency Nanosecond Pulsed Fiber Laser at 2- μ m," *IEEE Photonics Technology Letters,* vol. 24, no. 5, pp. 353-355, 2012.

[17] P. Wan, L. Yang and J. Liu, "High power 2 μm femtosecond fiber laser," *Optics Express,* vol. 21, no. 18, pp. 21374-21379, 2013.

[18] Y. Tang, L. Xu, Y. Yang, and J. Xu, "High-power gain-switched Tm 3+-doped fiber laser," *Optics Express,* vol. 18, no. 22, pp. 22964-22972, 2010.

[19] A. M. Heidt, Z. Li, J. Sahu, P. C. Shardlow, M. Becker, M. Rothhardt, M. Ibsen, R. Phelan, B. Kelly, and S. U. Alam, "100 kW peak power picosecond thulium-doped fiber amplifier system seeded by a gain-switched diode laser at 2 μ m," *Optics Letters,* vol. 38, no. 10, pp. 1615-1617, 2013.

[20] G. Imeshev and M. E. Fermann, "230-kW peak power femtosecond pulses from a high power tunable source based on amplification in Tm-doped fiber," *Optics Express,* vol. 13, no. 19, pp. 7424-7431, 2005.

[21] J. Liu, J. Xu, K. Liu, F. Tan, and P. Wang, "High average power picosecond pulse and supercontinuum generation from a thulium-doped, all-fiber amplifier," *Optics Letters,* vol. 38, no. 20, pp. 4150-4153, 2013.

[22] P. C. Shardlow, D. Jain, R. Parker, J. Sahu, and W. A. Clarkson, "Optimising Tm-Doped Silica Fibres for High Lasing Efficiency," in *The European Conference on Lasers and Electro-Optics*, 2015, pp. CJ_14_3.

[23] C. Jollivet, K. Farley, M. Conroy, H. Dabhi, J. Edgecumbe, A. Carter, and K. Tankala, "Design optimization of Tm-doped large-mode area fibers for power scaling of 2 μ m lasers and amplifiers," in *Fiber Lasers XIV: Technology and Systems*, 2017, p. 100830I.

[24] C. Jollivet, B. Samson, L. Leick, L. Shah, M. Richardson, and A. Schülzgen, "Comparative study of light propagation and single-mode operation in large-mode area fibers designed for 2- μ m laser applications," *Optical Engineering,* vol. 54, no. 1, p. 011006-011006, 2015.

[25] A. Malinowski, J. H. Price and M. N. Zervas, "Overlapped pulsed pumping of tandem pumped fiber amplifiers to increase achievable pulse energy," *IEEE Journal of Quantum Electronics,* vol. 53, no. 2, pp. 1-8, 2017.

[26] T. Yamamoto, Y. Miyajima and T. Komukai, "1.9 mu m

Tm-doped silica fibre laser pumped at 1.57 mu m," *Electronics Letters*, vol. 30, no. 3, pp. 220-221, 1994.

[27] 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," *Optics Express*, vol. 14, no. 13, pp. 6084-6090, 2006.

[28] 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 *Lasers and Electro-Optics, 2007 and the International Quantum Electronics Conference. CLEOE-IQEC 2007. European Conference on*, 2007, p. 1-1.

[29] X. Wang, P. Zhou, H. Zhang, X. Wang, H. Xiao, and Z. Liu, "100 W-level Tm-doped fiber laser pumped by 1173 nm Raman fiber lasers," *Optics Letters*, vol. 39, no. 15, pp. 4329-4332, 2014.

[30] D. Creeden, B. R. Johnson, S. D. Setzler, and E. P. Chicklis, "Resonantly pumped Tm-doped fiber laser with> 90% slope efficiency," *Optics Letters*, vol. 39, no. 3, pp. 470-473, 2014.

[31] 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," *Optics Express*, vol. 22, no. 23, pp. 29067-29080, 2014.

[32] Y. Wang, J. Yang, C. Huang, Y. Luo, S. Wang, Y. Tang, and J. Xu, "High power tandem-pumped thulium-doped fiber laser," *Optics Express*, vol. 23, no. 3, pp. 2991-2998, 2015.

[33] G. A. Newburgh, J. Zhang and M. Dubinskii, "Tm-doped fiber laser resonantly diode-cladding-pumped at 1620 nm," *Laser Physics Letters*, vol. 14, no. 12, p. 125101, 2017.

[34] X. Jin, X. Du, X. Wang, P. Zhou, H. Zhang, X. Wang, and Z. Liu, "High-power ultralong-wavelength Tm-doped silica fiber laser cladding-pumped with a random distributed feedback fiber laser," *Scientific Reports*, vol. 6, no. p. 30052, 2016.

[35] S. D. Jackson and T. A. King, "Theoretical modeling of Tm-doped silica fiber lasers," *Journal of Lightwave Technology*, vol. 17, no. 5, pp. 948-956, 1999.

[36] Y. Tang, F. Li and J. Xu, "High peak-power gain-switched Tm3+-doped fiber laser," *IEEE Photonics Technology Letters*, vol. 23, no. 13, pp. 893-895, 2011.

[37] B. Sun, J. Luo, B. P. Ng, and X. Yu, "Dispersion-compensation-free femtosecond Tm-doped all-fiber laser with a 248 MHz repetition rate," *Optics Letters*, vol. 41, no. 17, pp. 4052-4055, 2016.

[38] B. Sun, J. Luo, Z. Yan, K. Liu, J. Ji, Y. Zhang, Q. J. Wang, and X. Yu, "1867-2010 nm tunable femtosecond thulium-doped all-fiber laser," *Optics Express*, vol. 25, no. 8, pp. 8997-9002, 2017.

[39] R. Lindberg, P. Zeil, M. Malmström, F. Laurell, and V. Pasiskevicius, "Accurate modeling of high-repetition rate ultrashort pulse amplification in optical fibers," *Scientific Reports*, vol. 6, no. p. 34742, 2016.

[40] P. F. Moulton, "High power Tm: silica fiber lasers: current status, prospects and challenges," in *Lasers and Electro-Optics Europe (CLEO EUROPE/EQEC), 2011 Conference on and 12th European Quantum Electronics Conference*, 2011, p. 1-1.