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Sub-200 fs, 344 MHz mode-locked Tm-doped fiber laser

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We demonstrate a compact, self-starting mode-locked thulium-doped fiber laser based on nonlinear polarization evolution (NPE), with a fundamental repetition rate of ~344 MHz and a pulse duration of ~160 fs. The generated pulses centered at ~1975 nm have a maximum output power of ~560 mW, corresponding to a pulse energy of ~1.63 nJ. To the best of our knowledge, the achieved repetition rate represents the highest value of fundamentally NPE mode-locked fiber lasers at ~2 μ m, while the average output power is also higher than the previously-reported 2 μ m ultrafast fiber oscillators based on single mode fiber. The timing jitter in the integrated range [5 kHz, 10 MHz] and the integrated relative intensity noise in the range [10 Hz, 10 MHz] reach ~35 fs and ~0.009%, respectively. Our high-performance laser is an ideal candidate for various applications, including mid-IR frequency metrology and high-speed optical sampling. © 2020 Optical Society of America

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High performance passively mode-locked ultrafast lasers with repetition frequency in the range of several hundred MHz to GHz have been extensively studied and developed over the past few decades. They have a relatively large mode spacing which enables the access to and manipulation of each individual mode. This feature is of particular importance for numerous applications, such as high speed optical sampling [1], frequency metrology [2, 3], and optical arbitrary waveform generation [4]. Among them, fiber-based laser sources draw more attention due to their significant advantages of compact size and inherently high beam quality [5-11]. On the other hand, ultrafast fiber lasers operating at ~2 μ m have recently been demonstrated as an efficient platform to access the mid/far-infrared (IR) spectral region via nonlinear frequency conversion [12, 13]. This spectral region features

major absorption bands of numerous gas molecules [14]. It is, therefore, envisaged that the development of high repetition rate fiber lasers at 2 μ m is highly sought after for frequency metrology and molecular spectroscopy applications.

A common approach toward high repetition rate is to employ harmonically mode-locked technique [15-17]. However, it suffers from the drawback of the increase of pulse noises (e.g., pulse-to-pulse timing jitter and amplitude fluctuations), and even worse, it is susceptible to the environmental disturbances, possibly leading to the change of repetition rate. In contrast, fundamentally mode-locked fiber lasers operating at a high repetition rate are much preferable, because the emitted pulses have a period strictly equal to the round-trip time resulting in much lower noise level. While the fundamental repetition frequency rate is inversely proportional to the cavity length, a linearly fiber laser cavity with a short piece of thulium (Tm)-doped or thulium/holmium (Tm/Ho) co-doped gain fiber mode-locked by a semiconductor saturable absorber mirror (SESAM) was primarily chosen to generate high repetition rate (e.g., >200 MHz) pulses at 2 μ m [18-20]. For example, a 37 cm Tm/Ho fiber served as gain medium in a compact SESAM mode-locked linear cavity can produce femtosecond pulses with a high repetition rate of ~253 MHz [21]. The repetition rate was later scaled up to 1.25 GHz by using a shorter highly-doped Tm fiber of 7 cm [22]. With a total cavity length of < 5 cm, the repetition rate could reach as high as ~2.8 GHz at 2 μ m [23]. However, these cavities utilized a saturable absorber (SA) which normally has a picoseconds recovery time and a limited damage threshold, typically restricting the achievable pulse output power (< 50 mW) and pulse duration (> 300 fs) [18-23]. An impressive result of 58 fs, ~1 nJ pulses generated from a SESAM mode-locked 508 MHz Tm fiber soliton laser has been demonstrated [24], however, with the requirement of careful intra-cavity power manipulation and nonlinear pulse shaping which makes the laser system complex. Another potential drawback of the use of SAs is their tendency to degrade over time which may hinder their long-term operation.

An effective way to overcome the above-mentioned drawbacks is to utilize the nonlinear polarization evolution (NPE) mode-locked technique which is based on the nonlinear Kerr effect, inherently

enjoying fast response time (a few femtoseconds) and high damage threshold. The NPE technique has successfully mode-locked an Yb fiber laser with a fundamental repetition rate up to 1 GHz [25], while the output average power and pulse duration reached impressive 600 mW and 64 fs, respectively. Thus far, the highest fundamental repetition rate reported in an NPE mode-locked fiber laser at 2 μ m is 248 MHz [26]. However, the benefits of the NPE have not yet been fully exploited in the laser, because the output power is limited to 36.3 mW and the pulse duration is >300 fs. Hence, in 2 μ m fiber lasers, the NPE technique deserves further research.

In this Letter, we demonstrate a NPE mode-locked Tm-doped fiber oscillator that generates $\sim$ 160-fs pulses with a fundamental repetition rate of $\sim$ 344 MHz at 2 μ m. This repetition rate represents the highest value of fundamentally NPE mode-locked fiber lasers in 2 μ m region. Moreover, the maximum average output power of our laser reaches $\sim$ 560 mW, which is also higher than that of previously reported Tm or Ho ultrafast fiber oscillators based on single mode fiber.

The fiber laser setup is illustrated in Fig. 1(a). A $\sim$ 30 cm length of commercial highly-doped Tm fiber (Nufern, SM-TSF-5/125) serves as the gain medium, with its fiber ends spliced to two short standard single mode fibers (Corning SMF-28e, a total length of $\sim$ 16 cm) for the ease of light coupling and thermal management. The pump light offered by a commercial 2.5 W, 1560 nm fiber laser is coupled into the cavity through a dichroic mirror, having a measured pump light coupling efficiency of $\sim$ 76%. Three waveplates in combination with a polarization beam splitter (PBS) implement NPE based mode-locking, while the rejection port of the PBS is used as the laser output port. An isolator is also inserted into the cavity to ensure unidirectional light operation. The total cavity loss caused by the free space coupling and the absorption/reflection of the optical elements is $\sim$ 40%. The free-space length in the cavity is $\sim$ 19 cm and the total cavity length is $\sim$ 0.65 m. Note that it's difficult to further reduce the total fiber length in the cavity due to the strong fiber bending loss at 2 μ m. Due to the high absorption coefficient of the gain fiber ($\sim$ 340 dB/m) at 1560 nm, the thermal effect is strong if the launching pump power is high, resulting in low pump-to-signal conversion efficiency. Thus, a short piece of gain fiber close to the pump side is placed on an actively cooling metal plate for thermal management, which also provides a stable ambient temperature for mode-locking operation.

Fig. 1. Schematic setup of the compact Tm-doped fiber oscillator. TDF, Tm-doped fiber; QWP, quarter-wave plate; HWP, half-wave plate; ISO, isolator; PBS, polarization beam splitter; DM, dichroic mirror; PC, polarization controller.

By properly arranging the waveplate orientations, stable mode-locked laser operation at a repetition rate of $\sim$ 344 MHz could be easily achieved if the pump power was higher than 2.3 W. Once the mode-

locking was established, no pulse breaking or continuous wave (CW) spikes happened when the pump power was continuously tuned between $\sim$ 2.15 W and 2.5 W. The average output power varied from $\sim$ 470 mW to 560 mW, corresponding to the pulse energy ranging from $\sim$ 1.37 nJ to 1.63 nJ. The achievable maximum output power is only limited by our available pump power ($\leq$ 2.5 W), rather than the laser cavity configuration. One potential drawback of the NPE technique is that it is sensitive to environmental changes, such as vibrations and temperature drift, leading to poor self-starting capability. If the mode-locking disappears, readjustment of the waveplates is required to initiate it, which may not be able to recover the previous pulse properties. In our experiment, the laser exhibited reliably self-starting mode-locking in fixed waveplate orientations, and the pulse performance kept almost unchanged in a couple of weeks, indicating a stable long-term mode-locked operation. This benefits from the well thermal management, as well as the use of a short fiber cavity which significantly reduces the NPE sensitivity to environmental disturbances.

Figures 2(a-d) shows the typical pulse features at the pump power of 2.17 W. The pulse spectrum was measured by an optical spectrum analyzer (Yokogawa, AQ6375B) with a resolution bandwidth (RBW) of 0.1 nm, as shown in Fig. 2(a). The central wavelength is $\sim$ 1975 nm and the FWHM bandwidth of the central part is $\sim$ 21.3 nm. Clear Kelly sidebands are observable over the spectrum, implying that the laser operates at soliton mode-locking state. According to the positions of the Kelly sidebands, the net cavity dispersion is calculated to be $\sim$ 0.029 ps² [27]. We note that slight spectral modulation with a period of $\sim$ 1.8 nm appears on the spectrum. This could be due to the birefringent filtering effect caused by the PBS which is based on a YVO₄ birefringent crystal. The corresponding free spectral range is determined by $\Delta\lambda = \lambda^2 / \Delta n \cdot L$ [28], where λ is the center wavelength, Δn is the difference in refractive indices for extraordinary ray and ordinary ray, and L is the crystal length. According to the parameters offered by the manufacture, the calculated $\Delta\lambda$ is $\sim$ 1.86 nm, close to the experimental value. Using the same bulk optics, we also observed similar modulation period in our previously mode-locked long cavity Tm fiber lasers [27]. More output performance details in spectral and time domain were characterized by a second harmonic generation (SHG) frequency-resolved optical gating (FROG). The FROG measurement error is $<0.7\%$ for all measurements. Strong agreement between the measured and retrieved optical spectra (see Fig. 2(a)) indicates highly reliable FROG measurement. We also notice a tiny spike appeared on the first Kelly sideband on the right side of the spectrum, which is possibly caused by the spectral modulation. Tortuous spectral phase in Fig. 2(a) implies that the pulse is nonlinearly chirped. Figure 2(b) shows both the retrieved and transformed-limited pulse profiles. The retrieved pulse FWHM duration is $\sim$ 165 fs, larger than the transform-limited value of $\sim$ 120 fs. Strong pulse pedestal spanning a >3 -ps range is attributed to the Kelly sidebands. By integrating the whole temporal profile, the peak power is estimated as $\sim$ 5.8 kW and $\sim$ 71.8% pulse energy is located at the main pulse. An autocorrelator (APE PulseCheck) was also used to measure the autocorrelation (AC) trace of the pulse, which exhibited a good agreement with the retrieved AC trace from FROG (see the inset of Fig. 2(b)), further confirming the reliability of the retrieved pulse profile. The microwave radio frequency (RF) spectral trace recorded with an RBW of 100 Hz is shown in Fig. 2(c), giving a fundamental repetition rate of $\sim$ 344.07 MHz, which coincides with the overall cavity length. The signal to noise ratio is as high as $\sim$ 85 dB, indicating good pulse stability. Single-pulse CW mode-locking operation is confirmed by the measured wideband RF spectrum (up to 5 GHz) without any visible modulation or any indication of multi-pulsing effects (see Fig. 2(d)). Apart from the above pulse characteristics, the measured pulse

duration and calculated peak power as a function of the pump power are also provided in Fig. 2(e). The highest peak power of ~ 6.18 kW and the shortest pulse duration of ~ 160 fs can be achieved at the maximum pump power of 2.5 W.

Fig. 2. Laser pulse performance. (a) The independently measured spectra in linear and logarithmic scales from an optical spectrum analyzer, and the retrieved spectrum and corresponding spectral phase from FROG. (b) Retrieved and calculated transform-limited profiles in the time domain. Inset, the measured AC trace from APE autocorrelator (black line) and the retrieved AC trace from FROG (red line). (c) RF spectrum of the fundamental repetition rate centered at ~ 344.07 MHz. (d) Wide span RF spectrum (up to 5 GHz). (e) The calculated peak power and the measured pulse duration under different pump powers. The lines are to guide the eye.

To evaluate noise characteristics of our fiber laser, a 12.5 GHz photodetector (Newport, 818-BB-51F) connected with a phase noise analyzer (Rohde & Schwarz, FSWP) is used to measure the laser pulse train. The single sideband (SSB) phase noise of the first RF harmonic of the laser is illustrated in Fig. 3(a). The root-mean-squared (RMS) timing jitter integrated from 10 MHz down to 1 kHz is also presented as a red line. The integrated RMS jitter is ~ 35 fs in the range [5 kHz, 10 MHz], which is comparable to that of previously reported low-noise free-running high repetition rate fiber lasers [21, 29–31]. Noticeable increase of the RMS jitter below 5 kHz is mainly attributed to the technical noises (such as pump intensity noise and acoustic noise) and the influence of environmental fluctuations (such as the temperature drift and mechanical vibrations) on the effective cavity length [32]. Such jitter could be suppressed by locking the repetition rate via a phase-locked loop which typically has a response bandwidth of up to 10 kHz [30]. Figure 3(b) shows the relative intensity noise (RIN) of the laser. Over the entire frequency interval [1 Hz, 10 MHz], the integrated RIN is $\sim 0.048\%$, while the RIN drops to $\sim 0.009\%$ in the integrated range [10 Hz, 10 MHz]. The increase of the RIN below 10 Hz might be a result of the pump power fluctuation because $\sim 1\%$ fluctuation with a

frequency of several Hz could be easily observed when we monitored the pump power. However, the achievable RMS RIN is still better than that of SESAM mode-locked high repetition rate fiber lasers at 2 μ m [20–22]. Although both phase noise and RIN of our laser are already at a relatively low noise level in the free-running mode-locked fiber laser family, they represent an upper limit as the measurement is already limited by the system noise above 200 kHz (see Fig. 3).

Fig. 3. Noise characteristics of the 344 MHz Tm fiber laser. (a) The single sideband (SSB) phase noise (black line) and the integrated RMS timing jitter (red line). (b) The relative intensity noise (RIN) (black line) and the integrated RMS RIN (red line).

Fig. 4. (a) The energy of the central part of the pulse spectrum (blue square) and the remaining pulse energy (black triangle) as a function of pump power. The solid lines are to guide eye. Inset, the schematic diagram of the grating-based spectral filter. (b) The pulse spectrum after sidebands filtering, and the fittings with Gaussian and sech² shapes. (c) The Fourier transform-limited pulse.

Since the Kelly sidebands are quite strong, it is stringent to know how exactly they affect pulse performance. A grating-based spectral filter (see the inset of Fig. 4(a)) was used to measure the energy distribution of the different parts of the spectrum under different pump powers, as shown in Fig. 4(a). The energy of the central part of the pulse spectrum remains at ~ 0.85 nJ, while the remaining pulse energy, mainly originating from Kelly sidebands increases linearly with the increase of the pump power. It implies that the energy of the soliton part in the pulse is almost saturated and the extra pulse energy sheds into the copropagating dispersive waves, resulting in strong Kelly sidebands. Figure 4(b) shows the central spectrum after the sideband filtering, well-fitting by a Gaussian shape profile, rather than a sech² shape, as both the leading and trailing edges of the soliton

spectrum are filtered out. The corresponding Fourier transform limited pulse with a pulse duration of ~ 291 fs is given in Fig. 4(c). Its peak power is calculated to be ~ 2.7 kW. A potential drawback of the presence of the Kelly sidebands is that they result in a poor pulse quality. However, compared with the filtered pulses, the original pulses with sidebands have ~ 1.8 times shorter pulse duration and >2 times higher peak power (see Fig. 2(e)). Therefore, a soliton mode-locking fiber laser with strong Kelly sidebands might be a good choice for the laser applications requiring short duration and high peak power.

In conclusion, we have developed a compact, self-starting NPE mode-locked Tm-doped fiber. The laser directly produces ~ 160 -fs pulses at ~ 344 MHz fundamental repetition rate, with a maximum output power of ~ 560 mW (corresponding to a maximum pulse energy of ~ 1.63 nJ) which is not an upper limit as the available pump power is limited. A relatively low noise level is confirmed by the noise characterization, where the integrated RMS timing jitter is ~ 35 fs in the range [5 kHz, 10 MHz] and the integrated RIN is $\sim 0.009\%$ in the frequency range [10 Hz, 10 MHz]. This low-noise, large mode spacing femtosecond Tm laser is a potential source for mid-IR frequency comb and high-speed optical sampling applications.

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References

1. A. Bartels, R. Cerna, C. Kistner, A. Thoma, F. Hudert, C. Janke, and T. Dekorsy, *Rev Sci Instrum* **78**, 035107 (2007).
2. T. Udem, R. Holzwarth, and T. W. Hansch, *Nature* **416**, 233 (2002).
3. S. A. Diddams, *J. Opt. Soc. Am. B* **27**, B51 (2010).
4. S. T. Cundiff and A. M. Weiner, *Nat. Photonics* **4**, 760 (2010).
5. M. E. Fermann and I. Hartl, *Nat. Photonics* **7**, 868 (2013).
6. K. Wu, X. Zhang, J. Wang, and J. Chen, *Opt Lett* **40**, 1374 (2015).
7. J. Zhang, Z. Kong, Y. Liu, A. Wang, and Z. Zhang, *Photon. Res.* **4**, 27 (2016).
8. K. Wu, X. Zhang, J. Wang, X. Li, W. Zou, and J. Chen, *Opt Mater Express* **9**, 4688 (2019).
9. B. Guo, Q.-l. Xiao, S.-h. Wang, and H. Zhang, *Laser Photonics Rev* **13**, 1800327 (2019).
10. G. Hu, L. Yang, Z. Yang, Y. Wang, X. Jin, J. Dai, Q. Wu, S. Liu, X. Zhu, X. Wang, T.-C. Wu, R. C. T. Howe, T. Albrow-Owen, L. W. T. Ng, Q. Yang, L. G. Occhipinti, R. I. Woodward, E. J. R. Kelleher, Z. Sun, X. Huang, M. Zhang, C. D. Bain, and T. Hasan, *Science Advances* **6**, eaba5029 (2020).
11. J. Xinxin, H. Guohua, Z. Meng, A.-O. Tom, Z. Zheng, and H. Tawfique, *Nanophotonics* **9**, 2445 (2020).
12. V. O. Smolski, H. Yang, S. D. Gorelov, P. G. Schunemann, and K. L. Vodopyanov, *Opt. Lett.* **41**, 1388 (2016).
13. J. Zhang, K. Fai Mak, N. Nagl, M. Seidel, D. Bauer, D. Sutter, V. Pervak, F. Krausz, and O. Pronin, *Light-Sci. Appl.* **7**, 17180 (2018).
14. A. Schliesser, N. Picque, and T. W. Hansch, *Nat. Photonics* **6**, 440 (2012).
15. M. Pang, W. He, and P. St.J. Russell, *Opt. Lett.* **41**, 4601 (2016).
16. Y. Wang, J. Li, K. Mo, Y. Wang, F. Liu, and Y. Liu, *Scientific Reports* **7**, 7779 (2017).
17. F. Wang, T. Wang, W. Ma, Q. Jia, D. Zhao, R. Liu, and C. Wang, *Optical Fiber Technology* **49**, 71 (2019).
18. Q. Wang, J. Geng, T. Luo, and S. Jiang, *2 μ m mode-locked fiber lasers*, SPIE LASE (SPIE, 2012), Vol. 8237.
19. P. Kuan, K. Li, L. Zhang, X. Li, C. Yu, G. Feng, and L. Hu, *IEEE Photonics Technology Letters* **28**, 1525 (2016).
20. H. Cheng, W. Lin, Z. Luo, and Z. Yang, *IEEE J. Sel. Top. Quantum Electron.* **24**, 1 (2018).
21. A. E. Akosman and M. Y. Sander, *IEEE Photon. Tech. Lett.* **28**, 1878 (2016).
22. J. Zeng, A. E. Akosman, and M. Y. Sander, *Opt. Express* **26**, 24687 (2018).
23. T. Qiao, H. Cheng, X. Wen, W. Wang, W. Lin, Y. Zhou, Y. Guo, Y. Liu, and Z. Yang, *Opt. Lett.* **44**, 6001 (2019).
24. J. Jiang, C. Mohr, J. Bethge, A. Milk, W. Mefford, I. Harti, M. E. Fermann, C. C. Lee, S. Suzuki, T. R. Schibli, N. Leindecker, K. L. Vodopyanov, and P. G. Schunemann, in *Conference on Lasers and Electro-Optics*, 2012), CTh5D.7.
25. C. Li, Y. Ma, X. Gao, F. Niu, T. Jiang, A. Wang, and Z. Zhang, *Appl. Opt.* **54**, 8350 (2015).
26. B. Sun, J. Luo, B. P. Ng, and X. Yu, *Opt. Lett.* **41**, 4052 (2016).
27. Z. Zhu, H. Zhang, M. Wang, R. Wei, Z. Zheng, P. Yan, S. Ruan, J. Wang, T. Hasan, and Z. Sun, *IEEE Photon. Tech. Lett.* **32**, 117 (2020).
28. S. Zhu, *Appl. Opt.* **29**, 410 (1990).
29. H. Byun, D. Pudo, J. Chen, E. P. Ippen, and F. X. Kartner, *Opt. Lett.* **33**, 2221 (2008).
30. J. J. McFerran, L. Nenadović, W. C. Swann, J. B. Schlager, and N. R. Newbury, *Opt. Express* **15**, 13155 (2007).
31. G. Liu, X. Jiang, A. Wang, G. Chang, F. Kaertner, and Z. Zhang, *Opt. Express* **26**, 26003 (2018).
32. J. Kim and Y. Song, *Adv. Opt. Photon.* **8**, 465 (2016).

FULL REFERENCES

- [1]. A. Bartels, R. Cerna, C. Kistner, A. Thoma, F. Hudert, C. Janke, and T. Dekorsy, "Ultrafast time-domain spectroscopy based on high-speed asynchronous optical sampling," *Rev Sci Instrum* **78**, 035107 (2007).
- [2]. T. Udem, R. Holzwarth, and T. W. Hansch, "Optical frequency metrology," *Nature* **416**, 233-237 (2002).
- [3]. S. A. Diddams, "The evolving optical frequency comb [Invited]," *J. Opt. Soc. Am. B* **27**, B51-B62 (2010).
- [4]. S. T. Cundiff and A. M. Weiner, "Optical arbitrary waveform generation," *Nat. Photonics* **4**, 760-766 (2010).
- [5]. M. E. Fermann and I. Hartl, "Ultrafast fibre lasers," *Nat. Photonics* **7**, 868-874 (2013).
- [6]. K. Wu, X. Zhang, J. Wang, and J. Chen, "463-MHz fundamental mode-locked fiber laser based on few-layer MoS₂ saturable absorber," *Opt Lett* **40**, 1374-1377 (2015).
- [7]. J. Zhang, Z. Kong, Y. Liu, A. Wang, and Z. Zhang, "Compact 517 MHz soliton mode-locked Er-doped fiber ring laser," *Photon. Res.* **4**, 27-29 (2016).
- [8]. K. Wu, X. Zhang, J. Wang, X. Li, W. Zou, and J. Chen, "WS₂ based 523 MHz mode-locked erbium-doped fiber laser for microwave photonic application," *Opt Mater Express* **9**, 4688-4699 (2019).
- [9]. B. Guo, Q.-l. Xiao, S.-h. Wang, and H. Zhang, "2D Layered Materials: Synthesis, Nonlinear Optical Properties, and Device Applications," *Laser Photonics Rev* **13**, 1800327 (2019).
- [10]. G. Hu, L. Yang, Z. Yang, Y. Wang, X. Jin, J. Dai, Q. Wu, S. Liu, X. Zhu, X. Wang, T.-C. Wu, R. C. T. Howe, T. Albrow-Owen, L. W. T. Ng, Q. Yang, L. G. Occhipinti, R. I. Woodward, E. J. R. Kelleher, Z. Sun, X. Huang, M. Zhang, C. D. Bain, and T. Hasan, "A general ink formulation of 2D crystals for wafer-scale inkjet printing," *Science Advances* **6**, eaba5029 (2020).
- [11]. J. Xinxin, H. Guohua, Z. Meng, A.-O. Tom, Z. Zheng, and H. Tawfique, "Environmentally stable black phosphorus saturable absorber for ultrafast laser," *Nanophotonics* **9**, 2445-2449 (2020).
- [12]. V. O. Smolski, H. Yang, S. D. Gorelov, P. G. Schunemann, and K. L. Vodopyanov, "Coherence properties of a 2.6–7.5 μm frequency comb produced as a subharmonic of a Tm-fiber laser," *Opt. Lett.* **41**, 1388-1391 (2016).
- [13]. J. Zhang, K. Fai Mak, N. Nagl, M. Seidel, D. Bauer, D. Sutter, V. Pervak, F. Krausz, and O. Pronin, "Multi-mW, few-cycle mid-infrared continuum spanning from 500 to 2250 cm^{-1} ," *Light-Sci. Appl.* **7**, 17180-17180 (2018).
- [14]. A. Schliesser, N. Picque, and T. W. Hansch, "Mid-infrared frequency combs," *Nat. Photonics* **6**, 440-449 (2012).
- [15]. M. Pang, W. He, and P. St.J. Russell, "Gigahertz-repetition-rate Tm-doped fiber laser passively mode-locked by optoacoustic effects in nanobore photonic crystal fiber," *Opt. Lett.* **41**, 4601-4604 (2016).
- [16]. Y. Wang, J. Li, K. Mo, Y. Wang, F. Liu, and Y. Liu, "14.5 GHz passive harmonic mode-locking in a dispersion compensated Tm-doped fiber laser," *Scientific Reports* **7**, 7779 (2017).
- [17]. F. Wang, T. Wang, W. Ma, Q. Jia, D. Zhao, R. Liu, and C. Wang, "High repetition-rate passively mode-locking Tm-doped fiber laser based on narrow bandwidth filtering," *Optical Fiber Technology* **49**, 71-75 (2019).
- [18]. Q. Wang, J. Geng, T. Luo, and S. Jiang, *2 μm mode-locked fiber lasers*, SPIE LASE (SPIE, 2012), Vol. 8237.
- [19]. P. Kuan, K. Li, L. Zhang, X. Li, C. Yu, G. Feng, and L. Hu, "0.5-GHz Repetition Rate Fundamentally Tm-Doped Mode-Locked Fiber Laser," *IEEE Photonics Technology Letters* **28**, 1525-1528 (2016).
- [20]. H. Cheng, W. Lin, Z. Luo, and Z. Yang, "Passively Mode-Locked Tm³⁺-Doped Fiber Laser With Gigahertz Fundamental Repetition Rate," *IEEE J. Sel. Top. Quantum Electron.* **24**, 1-6 (2018).
- [21]. A. E. Akosman and M. Y. Sander, "Low Noise, Mode-Locked 253 MHz Tm/Ho Fiber Laser With Core Pumping at 790 nm," *IEEE Photon. Tech. Lett.* **28**, 1878-1881 (2016).
- [22]. J. Zeng, A. E. Akosman, and M. Y. Sander, "Scaling the repetition rate of thulium-doped ultrafast soliton fiber lasers to the GHz regime," *Opt. Express* **26**, 24687-24694 (2018).
- [23]. T. Qiao, H. Cheng, X. Wen, W. Wang, W. Lin, Y. Zhou, Y. Guo, Y. Liu, and Z. Yang, "High-power 2 GHz fs pulsed all-fiber amplified laser system at 2.0 μm ," *Opt. Lett.* **44**, 6001-6004 (2019).
- [24]. J. Jiang, C. Mohr, J. Bethge, A. Milk, W. Mefford, I. Harti, M. E. Fermann, C. C. Lee, S. Suzuki, T. R. Schibli, N. Leindecker, K. L. Vodopyanov, and P. G. Schunemann, "500 MHz, 58fs highly coherent Tm fiber soliton laser," in *Conference on Lasers and Electro-Optics*, 2012), CTh5D.7.
- [25]. C. Li, Y. Ma, X. Gao, F. Niu, T. Jiang, A. Wang, and Z. Zhang, "1 GHz repetition rate femtosecond Yb:fiber laser for direct generation of carrier-envelope offset frequency," *Appl. Opt.* **54**, 8350-8353 (2015).
- [26]. 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," *Opt. Lett.* **41**, 4052-4055 (2016).
- [27]. Z. Zhu, H. Zhang, M. Wang, R. Wei, Z. Zheng, P. Yan, S. Ruan, J. Wang, T. Hasan, and Z. Sun, "Soliton Mode-Locked Large-Mode-Area Tm-Doped Fiber Oscillator," *IEEE Photon. Tech. Lett.* **32**, 117-120 (2020).
- [28]. S. Zhu, "Birefringent filter: theory and design," *Appl. Opt.* **29**, 410-415 (1990).
- [29]. H. Byun, D. Pudo, J. Chen, E. P. Ippen, and F. X. Kartner, "High-repetition-rate, 491 MHz, femtosecond fiber laser with low timing jitter," *Opt. Lett.* **33**, 2221-2223 (2008).
- [30]. J. J. McFerran, L. Nenadović, W. C. Swann, J. B. Schlager, and N. R. Newbury, "A passively mode-locked fiber laser at 1.54 μm with a fundamental repetition frequency reaching 2GHz," *Opt. Express* **15**, 13155-13166 (2007).
- [31]. G. Liu, X. Jiang, A. Wang, G. Chang, F. Kaertner, and Z. Zhang, "Robust 700 MHz mode-locked Yb:fiber laser with a biased nonlinear amplifying loop mirror," *Opt. Express* **26**, 26003-26008 (2018).
- [32]. J. Kim and Y. Song, "Ultralow-noise mode-locked fiber lasers and frequency combs: principles, status, and applications," *Adv. Opt. Photon.* **8**, 465-540 (2016).