Mode locked Erbium doped fiber lasers using 45° tilted fiber grating

Tianxing Wang, Zhijun Yan, Qianqian Huang, Chuanhang Zou, Chengbo Mou*, Kaiming Zhou, and Lin Zhang

***Abstract*—We have systematically studied the 45° tilted fiber grating (45TFG) as a functional device for Erbium doped fiber laser (EDFL) mode locking. A number of 45TFGs with different polarization dependent loss (PDL) have been fabricated. Mode locked Erbium doped fiber laser using these devices have been characterized in terms of threshold, pulse duration, signal to noise ratio (SNR), and spectral width. Our results show that a 45TFG with higher PDL could achieve better laser results. By using a 45TFG with 24dB PDL, the mode locked laser has 8.1% conversion efficiency and a threshold of 200mW.**

***Index Terms*—fiber gratings, fiber lasers, laser mode locking**

I. Introduction

ULTRAFAST fiber lasers emitting ultrashort pulses have attracted a lot of attention in the past decade due to their compact size, high beam quality, low cost, maintenance free and alignment free. They have been found wide applications in the areas of ultra-precision, metrology, micro machining, medical imaging, telecommunication and fundamental scientific research [1]-[5]. To obtain ultrashort pulses, the laser generally require a saturable absorber to achieve the mode locking mechanism. Various approaches have been developed since the early days of ultrafast lasers including physical light intensity absorbers such as semiconductor saturable absorption mirrors (SESAMs) [6], [7], carbon nanotubes [8], [9], graphene [10], [11], topological insulators [12], [13], black phosphorous [14], [15], and most recently transition-metal dichalcogenides (TMDs) [16], [17]. However, these physical absorbers either have bandwidth limitation or stability issues. Furthermore, the production of these materials are not very much low cost. Moreover, the implementation of these absorber materials always break the all-fiber structure of the laser system. On the other hand, artificial saturable absorbers based on Kerr nonlinearity of the optical fiber generally use low cost telecom fiber components and are inherently fiber compatible i.e. nonlinear optical loop mirror (NOLM), nonlinear amplifying loop mirror (NALM) and nonlinear polarization rotation (NPR). Among these, NPR is still the driving horse of the artificial mode locker which currently outputs the shortest light pulse duration from the oscillator at 1.5 µm region [18].

Fiber gratings, firstly demonstrated in 1970s [19], have been extensively investigated from the fundamental theory to applications in optical communication [20], nonlinear signal processing [21], various types of sensors and lasers [22], [23]. With its inherent fiber format, the fiber grating devices have been intensively applied as reflection mirrors of fiber laser cavity [24]. Standard fiber grating devices have a typical periodic structure of refractive index modified planes perpendicular to the light propagation direction or fiber axis. This one dimensional photonic crystal structure allows coupling of the forward propagating core mode into either backward propagating core mode [25] or forward propagating cladding modes depends on the grating structure [26].

Furthermore, another type of fiber grating with tilted grating planes have attracted a lot of attention in the last decade. By breaking the symmetry of the fiber cylinder structure, these titled fiber grating devices always possess polarization properties. One specific TFG is the 45TFG that the grating planes tilt at 45° with respect to the fiber axis. Based on the Brewster angle principle, such device shows strong polarization dependent loss (PDL) across a wide range of wavelength. Various applications have been implemented using the 45TFGs such as PDL equalizer [27], in-fiber polarimeter [28], in-fiber polarizer [29], spectrometer [30], interference filter [31] and fiber lasers [32]. We have previously demonstrated that 45TFG can effectively mode lock an Erbium fiber laser in a soliton regime. In this paper, we systematically study how the properties of a 45TFG affect the fiber laser mode locking performance.

The paper has been organized as following. In section II, we will briefly describe the principle, fabrication of 45TFG. A

Manuscript received XXXXXX. This work was supported by the National Natural Science Foundation of China (No. 61605107, No. 61505244),Young Eastern Scholar program (QD2015027) at Shanghai Institutions of Higher Learning, and the "Young 1000 Talent Plan" program of China.

T. Wang, Q. Huang, C. Zou and C. Mou are with The Key Lab of Specialty Fiber Optics and Optical Access Network, Joint International Research Laboratory of Specialty Fiber Optics and Advanced Communication, Shanghai Institute for Advanced Communication and Data Science, Shanghai University, Shanghai, 200072 P. R. China (e-mail: wtx11100@i.shu.edu.cn; cecilin@i.shu.edu.cn; chuanhangzou@i.shu.edu.cn; corresponding author mouc1@shu.edu.cn;).

Z. Yan is with School of Optical and Electronic Information, National Engineering Laboratory for Next Generation Internet Access System, Huazhong University of Science and Technology, Wuhan, 430074 P. R. China (e-mail: yanzhijun@hust.edu.cn).

K. Zhou and L. Zhang are with Aston Institute of Photonic Technologies (AIPT), Aston University, Birmingham, B4 7ET United Kingdom (e-mail: k.zhou@aston.ac.uk; L.zhang@aston.ac.uk).

series of 45TFG with various PDL has been fabricated. In section III, the experimental detail of the soliton fiber laser will be given. In section IV, experimental results of soliton laser with different 45TFG will be compared in terms of pulse duration, bandwidth, time bandwidth product (TBP), SNR, output power, calculated timing jitter *etc*. Finally, the discussion and conclusion will be given in section V.

II. Fabrication & Characterization of 45TFG

The 45TFG has been UV inscribed in hydrogenated SMF28 fiber using typical phase mask scanning technique. In [31], C. B. Mou *et al* describe the detailed fabrication of 45TFG. Four 45TFGs have been fabricated under the same UV exposure fluence and scanning length with various scanning speed. In our experiment, all the gratings have a fixed scan length of ~25mm that is defined by the physical length of the effective area of phase mask. To characterize the 45TFGs, a commercial optical component analyzer (LUNA vector analyzer) incorporated an external high precision tunable laser (Agilent 8164, 1pm resolution) was utilized. The measured PDLs of the four 45TFGs have been shown in Figure. 1(a). The PDL values of 45TFGs are 5.4 dB, 9 dB, 14 dB, and 24 dB under the wavelength of ~1555 nm, respectively. It is found experimentally that a lower scanning speed would lead to 45TFG with strong PDL. This corresponds well with our theoretical prediction that under the same UV fluence and scanning length, the slow speed indicates a large index modification hence a stronger grating i.e. strong PDL [30]. The measured insertion losses (ILs) of these fabricated elements are depicted in Fig. 1(b). We can see from Fig. 1(b) that, all the ILs are controlled around 4 dB. The reason why IL looks so large is owing to the fact that this IL contains both *s*-light and *p*-light. Actually, *p*-light shows low IL when the light transmit through the 45TFG. In both measured PDL and IL spectra, the curves looks slightly noisy and rippled, this is mainly due to the application of high resolution tunable laser and refractive index mismatch of air/cladding [32]. Nevertheless, one could notice that the spectra of the 45TFG are rather flat without obvious spectral features. This also proves the excellent property of a broadband polarizer. The measurement in our experiment is limited by the wavelength tuning range of the tunable laser. As one may be aware that the strong PDL and low IL could further extend to wavelength region less than 1530 nm. This is indeed expected based on the previous theoretical study [33]. In this paper, we will focus on the polarization properties of 45TFG around 1550nm region.

III. Fiber Laser Configuration

The schematic of the passively mode locked Erbium doped fiber laser based on a 45TFG is shown in Fig. 2. The laser consists of ~62.5 cm of commercial Erbium doped fiber (EDF, Liekki ER 80-8/125) as the gain medium with a peak absorption of 80 dB/m. The dispersion of the EDF is estimated to be -20 ps^2/km. 2.2 m corning flexcor optical fiber corresponds to pigtails of wavelength division multiplexor (WDM) with anomalous dispersion of -5.8 ps^2/km. The remainder is composed of SMF-28 with anomalous dispersion β_2 = -22.8 ps^2/km. Therefore, the whole laser cavity is ~17 m, fitting well with the measured fundamental repetition rate of ~12 MHz. A 980nm laser module is employed to pump the laser cavity through a WDM. The maximum power of the pump LD is 660mW. 20% of the laser light has been extracted out of the cavity through a fused 20:80 fiber coupler. A polarization independent isolator (PI-ISO) is used to ensure single direction operation of the fiber laser cavity. The 45TFG is spliced into the cavity to maintain the all fiber format configuration. Two in-line polarization controllers (PCs) have been mounted at each end of the 45TFG to perform NPR mode locking. To maintain the comparison consistent, the 45TFGs spliced into the laser cavity have been carefully controlled with similar length (~50mm).

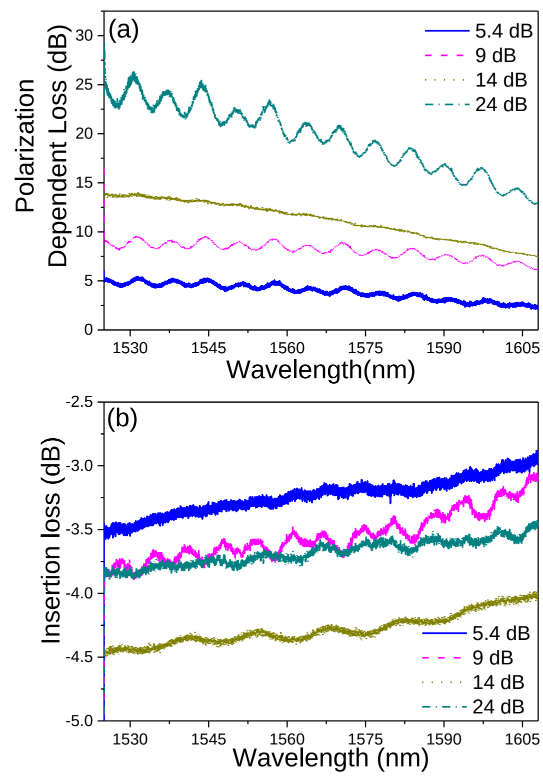

Fig. 1. (a) PDL profiles, and (b) IL spectra of 45TFGs from 1525 nm to 1608 nm.

An optical spectrum analyzer (OSA, Yokogawa AQ6370C), a commercial autocorrelator (AC, Femtochrome FR-103HS), a high speed photodiode (PD, Newport 818-BB-51F), a RF spectrum analyzer (RFSA, Siglent SSA3032X) and an oscilloscope (OSC, Tektronix MSO4104) are used to characterize the laser performance. A commercial optical power meter (OPM, Thorlabs PM 100D) is employed to collect the data of average output power.

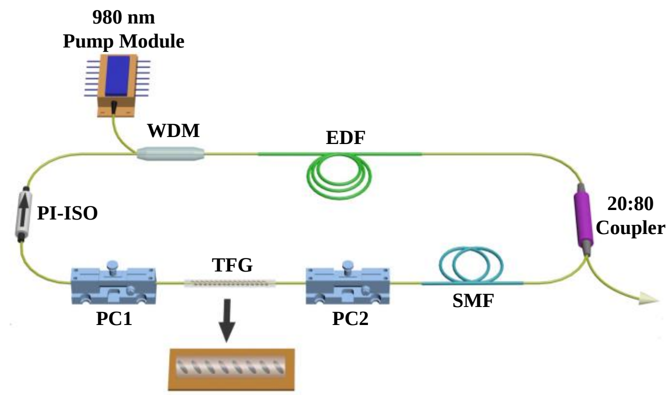

Fig. 2. Schematic of mode locked Erbium doped fiber laser based on a 45TFG.

IV. Experimental Results

At first, we build a mode locked fiber laser based on a 45TFG with the PDL value of 5.4 dB. By carefully adjusting the intra cavity PCs, we can achieve a typical soliton-like spectrum centered at 1559.1 nm with a bandwidth of 2.5 nm under the pump power of 160 mW as shown in Fig. 3(a). The typical Kelly side bands structure indicates strong soliton pulse shaping within the laser cavity. The pulse duration is measured to be 1.5 ps through the corresponding autocorrelation (AC) trace that fits well with Sech^2. Then, we replace the 45TFG with different PDL including 9 dB, 14 dB and 24 dB while keeps the total length of the cavity almost constant. This was confirmed by the measured similar repetition rate of each laser. As described in Fig. 3(b)-(d), the pulse width is measured to be 1.3 ps, 860 fs, and 830 fs with the optical spectral bandwidth of 2.8 nm, 4.1 nm and 4.4 nm. All the optical spectra features soliton type Kelly side bands and all the AC traces match well with Sech^2 fitting. The reason why we choose the 160 mW as the reference is due to the fact that continuous wave (CW) component will occur from time to time when the mode-locked threshold is reached based on the low PDL 45TFG. Owing to the mode locking hysteresis [34] and the reduction of the intra-cavity nonlinearity, the optical spectra were recorded in the state without CW component when the pulse trains are stable. However, stable mode locking without CW component were easily observed while we use a 45TFG whose PDL value is larger than 10 dB. Therefore, we usually employ those 45TFGs with large PDL value to carry out ultrafast laser experiments [35]. It can be seen from Fig. 3(a)-(d) that the central wavelength of mode locked laser has a slightly shift when the 45TFG changed. Since the state of PC is different under each individual mode locking state, the intra-cavity nonlinearity will change to cause spectra shift [36].

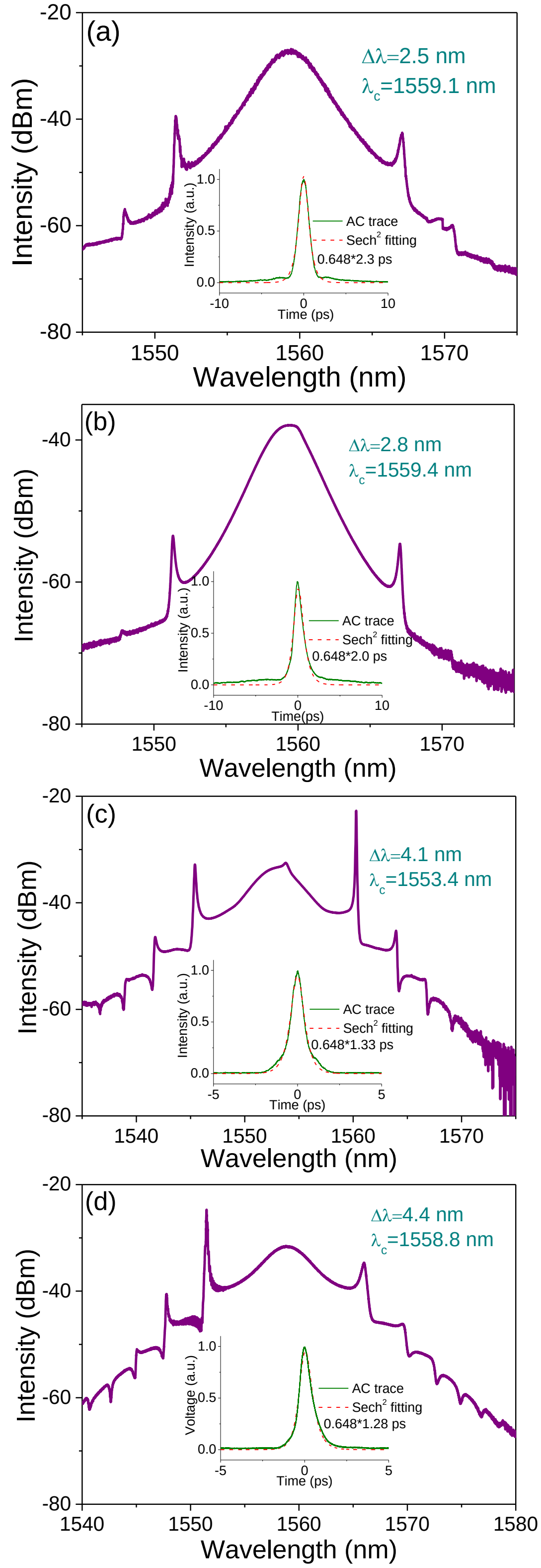

Fig. 3. Optical spectra and AC traces (inset) of passively mode locked Erbium doped fiber laser based on 45TFGs with PDL of (a) 5dB, (b) 9dB,(c) 14 dB, (d)24dB under the pump power of 160 mW.

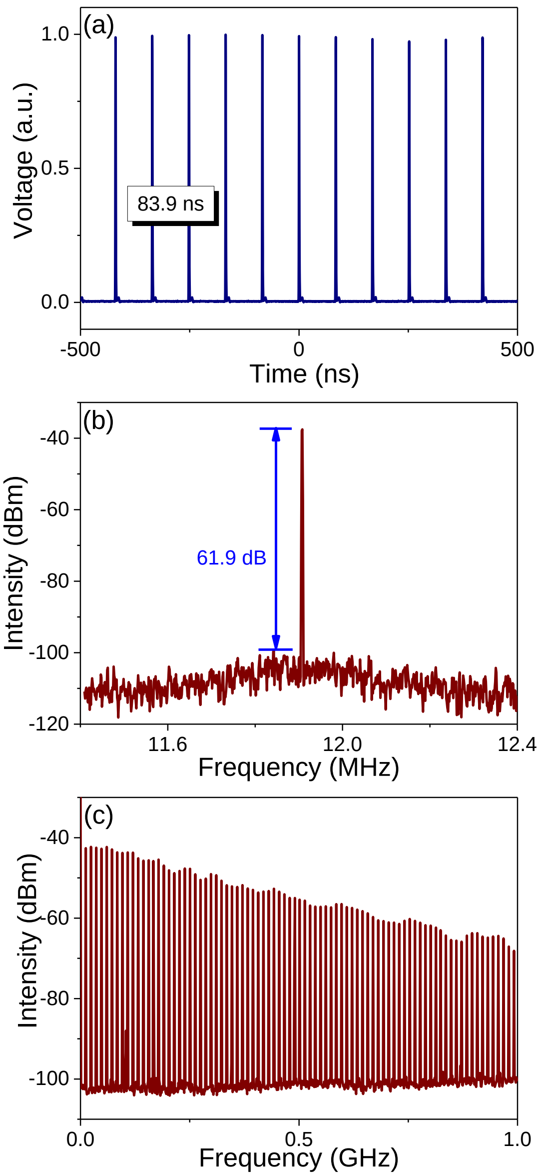

Fig. 4. (a)Mode locked pulse trains showing in the oscilloscope, (b) Typical RF spectrum of fundamental repetition rate with the span of 1 MHz and resolution bandwidth (RBW) of 1 kHz, (c) RF spectrum with the span of 1GHz and RBW of 10 kHz.

Figure. 4(a) depicts the typical measured mode locked pulse trains with a period of 83.9 ns according well with the length of cavity by employing both of OSC and PD. The RF spectrum is brought to characterize the stability of output laser. It can be seen clearly from Fig. 4(b), the signal of fundamental repetition rate centers at ~11.9 MHz with a SNR of 61.9 dB which shows highly stable pulse generation. 1 GHz RF spectrum with RBW of 10 kHz in wide frequency range indicates a desired mode locking operation described in Fig. 4(c).

In order to have a better understanding about the influence on laser output performance by changing the PDL of 45TFG, we have carried out four sets of similar experiments. By increasing the pump power monotonically, we effortlessly get the mode locking thresholds and conversion efficiencies of four EDFLs. As shown in Fig. 5(a), an intuitive diagram about the relationship between pump power and output power can be achieved. Along with the enhanced PDL value from 5.4 dB to 24 dB, the threshold decreases from 310 mW to 220 mw when the conversion efficiency of EDFL increases from 3.9 % to 8.1 % monotonically as depicted in Fig. 5(b). Under the pump power of 160 mW, we investigate whether the value of PDL has an impact on TBP, SNR, time jitter and energy fluctuation based on the same laser cavity. In this case, TBP and SNR basically maintain a stable state with the increase of PDL. Thus, we also can infer from Fig. 5(c) that 0.015 and 1.6 dB variation of TBP and SNR are achieved, respectively. According to the methods depicted in [37], we can estimate $\Delta t/T \approx 7.7 \times 10^{-5}$, corresponding to the time jitter $\Delta t \approx 6.5$ ps. In addition, we also can apply the before-mentioned approach to calculate the pulse energy fluctuation $\Delta E/E \approx 0.08$ %. By comparing the lasers with 45TFG under different PDL values, it is noticed that the changes in the calculated time jitter and energy fluctuation are so small shown in Fig. 5(d). This is useful because slight change (a few dBs) in PDL could be easily obtained during the fabrication, the output performance of the mode-locked EDFL will not be significantly affected. Therefore, 45TFG is an ideal in-fiber polarizing element in mode locking fiber lasers.

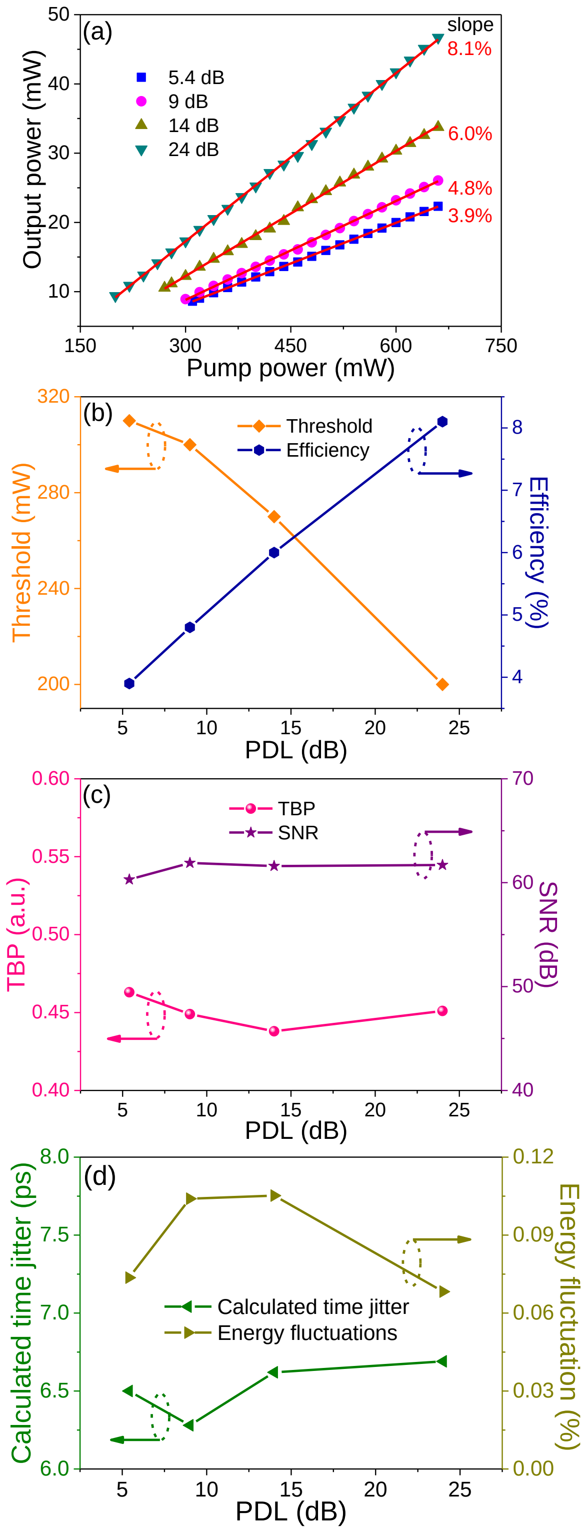

Fig. 5. (a)Average output power variations with the increasing pump power (red line is the linear fitting of the relationship between output power and pump power), (b) Threshold and conversion efficiency variations of the enhancing PDL value, (c) TBP and SNR changes with different PDL value under the pump power of 160 mW, (d) Calculated time jitter and energy fluctuation along with elevating PDL value under the pump power of 160 mW.

V. Discussion & Conclusion

In summary, we have done a systematic experiment about performance of laser output by using the same all-fiber Erbium doped laser cavity based on 45TFGs which own different PDL. In particular, this EDFL based on a 45TFG with a PDL value of 24dB owns a repetition rate of 11.9 MHz, a bandwidth of 4.4 nm, a SNR of 61.9 dB, a pulse duration of 830 fs and an average output power of 6.6 mW. With the PDL value enhanced from 5.4 dB to 24 dB, threshold variation from 310 mW to 220 mW has been obtained under the conversion efficiency variation from 3.9 % to 8.1 %. In addition, the TBP, SNR, calculated time jitter and energy fluctuations keep a small floating state under the same pump power of 160 mW. It can be seen from the results that a 45TFG with high PDL would generate shorter pulse duration with lower threshold. A higher conversion efficiency could also be achieved under the soliton pulse regime. For future work, we would like to explore fabrication of 45TFG with much higher PDL i.e. >40dB to achieve better laser results. The ultimate goal is to fabricate 45TFG with polarization properties comparable to existing bulk polarizers. On the other hand, we are developing 45TFGs in short length i.e. <1mm with high PDL. This would be useful for building lasers with high repetition rate. Moreover, the timing jitter of the demonstrated laser is not of practically low. We would also like to carry out further studies on reducing the phase noise of mode locked fiber laser based on 45TFGs.

The systematic investigation of 45TFGs as functional in-fiber polarizers indicates that all-fiber mode locked lasers based on a 45TFG could have wide range of practical applications as an efficient seed in ultra-wide spectrum generation, nonlinear optics, spectroscopy, and micromachining, *etc*. Demonstrations of applications of 45TFG in ultrashort pulse generation in other wavelengths have also been successful [33], [38]. We believe the 45TFG could be an effective all-fiber polarizing device for more versatile mode locked fiber laser systems across a broad wavelength range.

Acknowledgment

This work is supported by the National Natural Science Foundation of China (NSFC) (61605107, 61505244).C. B. Mou acknowledges Young Eastern Scholar Program from Shanghai Institutions of Higher Learning (QD2015027) and “Young 1000 Talent Plan” Program of China.

References

[1] M. E. Fermann, and I. Hartl, “Ultrafast fiber laser technology,” *IEEE J. Sel. Top. Quantum Electron*., vol. 15, no. 1, pp. 191-206, 2009.

[2] U. Keller, “Recent development in compact ultrafast lasers,” *Nature*, vol. 424, no. 6950, pp. 831-838, 2003.

[3] S. Y. Set *et al*., “Ultrafast fiber pulsed laser incorporating carbon nanotubes,” *IEEE J. Sel. Top. Quantum Electron*., vol. 10, no. 1, pp. 137-146, 2004.

[4] Z. Sun *et al*., “A stable, wideband tunable, near transform-limited, graphene-mode-locked, ultrafast laser,” *Nano Res*., vol. 3, no. 9, pp. 653-660, 2010.

[5] Q. Bao *et al*., "Atomic - layer graphene as a saturable absorber for ultrafast pulsed lasers," *Adv. Funct. Matert*., vol. 19, no. 19, pp. 3077-3083, 2009.
[6] U. Keller *et al*., "Semiconductor saturable absorber mirrors (SESAM's) for femtosecond to nanosecond pulse generation in solid-state laser," *IEEE J. Sel. Top. Quantum Electron*., vol. 2, no. 3, pp. 435-453, 1996.
[7] Y. Y. Luo *et al*., "Dynamics of dissipative solitons in a high repetition rate normal-dispersion erbium-doped fiber laser," *IEEE Photonics J.*, vol. 8, no. 4, pp. 7101507, 2016.
[8] Z. Sun *et al*., "A compact, high power, ultrafast laser mode-locked by carbon nanotubes," *Appl. Phys. Lett*., vol. 95, no. 25, pp. 253102, 2009.
[9] Z. Sun *et al*., "L-band ultrafast laser mode-locked by carbon nanotubes," *Appl. Phys. Lett*., vol. 93, no. 6, pp. 061114, 2008.
[10] H. Zhang *et al*., "Large energy mode locking of an erbium-doped fiber laser with atomic layer graphene," *Opt. Express*, vol. 17, no. 20, pp. 17630-17635, 2009.
[11] C. Li *et al*., "A Fiber Laser Using Graphene-Integrated 3-D Microfiber Coil," *IEEE Photonics J*., vol. 8, no. 1, pp. 1500307, 2016.
[12] Z. C. Luo *et al*., "2 GHz passively harmonic mode-locked fiber laser by a microfiber-based topological insulator saturable absorber," *Opt. Lett*., vol. 38, no. 24, pp. 5212-5215, 2013.
[13] M. Zhang *et al*., "Solution processed MoS_2-PVA composite for sub-bandgap mode-locking of a wideband tunable ultrafast Er:fiber laser," *Nano Res.*, vol. 8, no. 5, pp. 1522-1534, 2015.
[14] S. B. Lu *et al*., "Broadband nonlinear optical response in multi-layer black phosphorus: an emerging infrared and mid-infrared optical material," *Opt. Express*, vol. 23, no. 9, pp. 11183-11194, 2015.
[15] Y. Chen *et al*., "Mechanically exfoliated black phosphorus as a new saturable absorber for both Q-switching and Mode-locking laser operation," *Opt. Express*, vol. 23, no. 10, pp. 12823-12833, 2015.
[16] P. G. Yan *et al*., "Microfiber-based WS_2-film saturable absorber for ultra-fast photonics," *Opt. Mater. Express*, vol. 5, no. 3, pp. 479-489, 2015.
[17] H. Chen *et al*., "Transition-metal dichalcogenides heterostructure saturable absorbers for ultrafast photonics," *Opt. Lett*., vol. 42, no. 21, pp. 4279-4282, 2017.
[18] X. Li *et al*., "41.9 fs hybridly mode-locked Er-doped fiber laser at 212 MHz repetition rate," *Opt. Lett*., vol. 39, no. 6, pp. 1553-1556, 2014.
[19] K. O. Hill *et al*., "Photosensitivity in optical fiber waveguides: Application to reflection filter fabrication," *Appl. Phys. Lett*., vol. 32, no. 10, pp. 647-649, 1978.
[20] T. Erdogan *et al*., "Fiber grating spectra," *J. Lightw. Technol.,* vol. 15, no. 8, pp. 1277-1294, 1997.
[21] A. D. Kersey *et al*., "Fiber-optic Bragg grating strain sensor with drift-compensated high-resolution interferometric wavelength-shift detection," *Opt. Lett*., vol. 18, no. 1, pp. 72-74, 1993.
[22] A. D. Kersey *et al*., "Fiber grating sensors," *J. Lightw. Technol.,* vol. 15, no. 8, pp. 1442-1463, 1997.
[23] C. B. Mou *et al*., "All-fiber passively mode-locked femtosecond laser using a 45°-tilted fiber grating polarization element," *Opt. Express*, vol. 18, no. 18, pp. 18906-18911, 2010.
[24] L. Y. Shao *et al*., "High-Resolution Strain and Temperature Sensor Based on Distributed Bragg Reflector Fiber Laser," *IEEE Photonics Technol. Lett*., vol. 19, no. 20, pp. 1598-1600, 2007.
[25] O. Xu *et al*., "Analysis of spectral characteristics for reflective tilted fiber gratings of uniform periods," *Opt. Commun*., vol. 281, no. 15, pp. 3990-3995, 2008.
[26] S. Lu *et al*., "Analysis of radiation-mode coupling in reflective and transmissive tilted fiber Bragg gratings," *J. Opt. Soc. Am. A*, vol. 26, no. 1, pp. 91-98, 2009.
[27] S. J. Mihailov *et al*., "Fabrication of tilted fibre-grating polarization dependent loss equaliser," *Electron. Lett*., vol. 37, no. 5, pp. 284-286, 2001.
[28] P. S. Westbrook *et al*., "In-line polarimeter using blazed fiber gratings," *IEEE Photon. Technol. Lett*., vol. 12, no. 10, pp. 1352-1354, 2000.
[29] K. M. Zhou *et al*., "High extinction ratio in-fiber polarizers based on 45° tilted fiber Bragg gratings," *Opt. Lett*., vol. 30, no. 11, pp. 1285-1287, 2005.
[30] G. Q. Wang *et al*., "Highly efficient spectrally encoded imaging using a 45° tilted fiber grating," *Opt. Lett*., vol. 41, no. 11, pp. 2398-2401, 2016.
[31] Z. J. Yan *et al*., "All-fiber polarization interference filters based on 45°-tilted fiber gratings," *Opt. Lett*., vol. 37, no. 3, pp. 353-355, 2012.
[32] Z. J. Yan *et al*., "UV-Inscription, Polarization-Dependent Loss Characteristics and Applications of 45° Tilted Fiber Gratings," *J. Lightw. Technol.,* vol. 29, no. 18, pp. 2715-2724, 2011.
[33] X. L. Liu *et al*., "All-fiber normal-dispersion single-polarization passively mode-locked laser based on a 45°-tilted fiber grating," *Opt. Express*, vol. 20, no. 17, pp. 19000-19005, 2012.
[34] K. Tamura *et al*., "77-fs pulse generation from a stretched-pulse mode-locked all-fiber ring laser," *Opt. Lett*., vol. 18, no. 13, pp. 1080-1082, 1993.
[35] Z. X. Zhang *et al*., "Sub-100 fs mode-locked erbium-doped fiber laser using a 45°-tilted fiber grating," *Opt. Express*, vol. 21, no. 23, pp. 28297-28303, 2013.
[36] V. Deepa *et al*., "Effect of pump power on the tuning range of a filterless erbium-doped ring laser," *Appl. Phys. B*, vol. 89, no. 2-3, pp. 329-332, 2007.
[37] D. Von der Linde *et al*., "Characterization of the noise in continuously operating mode-locked lasers," *Appl. Phys. B*, vol. 39, no. 4, pp. 201-217, 1986.
[38] J. F. Li *et al*., "Thulium-doped all-fiber mode-locked laser based on NPR and 45-tilted fiber grating," *Opt. Express*, vol. 22, no. 25, pp. 31020-31028, 2014.

ALL BIOS ARE REQUIRED IF PAPER IS ACCEPTED

Tianxing Wang was born on July 17, 1992 in Jiangsu, China. And he is currently working towards the M. S. degree at the Key Lab of Specialty Fiber Optics and Optical Access Network, Shanghai University, Shanghai, in 2015. His research interests include mode-locked fiber lasers and nonlinear fiber optics.