Femtosecond pulse generation from a topological insulator mode-locked fiber laser

Hao Liu,[1] Xu-Wu Zheng,[1] Meng Liu,[1] Nian Zhao,[1] Ai-Ping Luo,[1] Zhi-Chao Luo,[1,*] Wen-Cheng Xu,[1,4] Han Zhang,[2] Chu-Jun Zhao,[3] and Shuang-Chun Wen[3]

[1]*Laboratory of Nanophotonic Functional Materials and Devices, School of Information and Optoelectronic Science and Engineering, South China Normal University, Guangzhou, Guangdong 510006, China*
[2]*Key Laboratory of Optoelectronic Devices and Systems of Ministry of Education and Guangdong Province, Shenzhen University, 518060, China*
[3]*Key Laboratory for Micro-/Nano-Optoelectronic Devices of Ministry of Education, College of Physics and Microelectronic Science, Hunan University, Changsha 410082, China*
[4]*xuwch@scnu.edu.cn*
[*]*zcluo@scnu.edu.cn*

Abstract: We reported on the generation of femtosecond pulse in a fiber ring laser by using a polyvinyl alcohol (PVA)-based topological insulator (TI), Bi_2Se_3 saturable absorber (SA). The PVA-TI composite has a low saturable optical intensity of 12 MW/cm^2 and a modulation depth of ~3.9%. By incorporating the fabricated PVA-TISA into a fiber laser, mode-locking operation could be achieved at a low pump threshold of 25 mW. After an optimization of the cavity parameters, optical pulse with ~660 fs centered at 1557.5 nm wavelength had been generated. The experimental results demonstrate that the PVA could be an excellent host material for fabricating high-performance TISA, and also indicate that the filmy PVA-TISA is indeed a good candidate for ultrafast saturable absorption device.

OCIS codes: (140.3510) Lasers, fiber; (140.4050) Mode-locked lasers; (250.5530) Pulse propagation and temporal solitons; (160.4330) Nonlinear optical materials.

References and links

1. L. E. Nelson, D. J. Jones, K. Tamura, H. A. Haus, and E. P. Ippen, "Ultrashort-pulse fiber ring lasers," Appl. Phys. B **65**(2), 277–294 (1997).
2. U. Keller, "Recent developments in compact ultrafast lasers," Nature **424**(6950), 831–838 (2003).
3. M. E. Fermann and I. Hartl, "Ultrafast fibre lasers," Nat. Photonics **7**(11), 868–874 (2013).
4. F. Ö. Ilday, J. R. Buckley, W. G. Clark, and F. W. Wise, "Self-similar evolution of parabolic pulses in a laser," Phys. Rev. Lett. **92**(21), 213902 (2004).
5. D. Y. Tang and L. M. Zhao, "Generation of 47-fs pulses directly from an erbium-doped fiber laser," Opt. Lett. **32**(1), 41–43 (2007).
6. D. A. Chestnut and J. R. Taylor, "Wavelength-versatile subpicosecond pulsed lasers using Raman gain in figure-of-eight fiber geometries," Opt. Lett. **30**(22), 2982–2984 (2005).
7. J. W. Nicholson and M. Andrejco, "A polarization maintaining, dispersion managed, femtosecond figure-eight fiber laser," Opt. Express **14**(18), 8160–8167 (2006).
8. Z. C. Luo, Q. Y. Ning, H. L. Mo, H. Cui, J. Liu, L. J. Wu, A. P. Luo, and W. C. Xu, "Vector dissipative soliton resonance in a fiber laser," Opt. Express **21**(8), 10199–10204 (2013).
9. O. Okhotnikov, A. Grudinin, and M. Pessa, "Ultra-fast fibre laser systems based on SESAM technology: new horizons and applications," New J. Phys. **6**, 177 (2004).
10. A. Chong, W. H. Renninger, and F. W. Wise, "Environmentally stable all-normal-dispersion femtosecond fiber laser," Opt. Lett. **33**(10), 1071–1073 (2008).
11. S. Yamashita, "A tutorial on nonlinear photonic applications of carbon nanotube and graphene," J. Lightwave Technol. **30**(4), 427–447 (2012).
12. Y. D. Cui and X. M. Liu, "Graphene and nanotube mode-locked fiber laser emitting dissipative and conventional solitons," Opt. Express **21**(16), 18969–18974 (2013).
13. H. Zhang, Q. L. Bao, D. Y. Tang, L. M. Zhao, and K. Loh, "Large energy soliton erbium-doped fiber laser with a graphene-polymer composite mode locker," Appl. Phys. Lett. **95**(14), 141103 (2009).
14. Q. L. Bao, H. Zhang, J. X. Yang, S. Wang, D. Y. Tang, R. Jose, S. Ramakrishna, C. T. Lim, and K. P. Loh, "Graphene-polymer nanofiber membrane for ultrafast photonics," Adv. Funct. Mater. **20**(5), 782–791 (2010).

#205686 - $15.00 USD Received 28 Jan 2014; revised 9 Mar 2014; accepted 9 Mar 2014; published 17 Mar 2014

15. Z. Sun, T. Hasan, F. Torrisi, D. Popa, G. Privitera, F. Wang, F. Bonaccorso, D. M. Basko, and A. C. Ferrari, "Graphene mode-locked ultrafast laser," ACS Nano **4**(2), 803–810 (2010).
16. Z. Q. Luo, Y. Z. Huang, J. Z. Wang, H. H. Cheng, Z. P. Cai, and C. C. Ye, "Multiwavelength dissipative-soliton generation in Yb-Fiber laser using graphene-deposited fiber-taper," IEEE Photonics Technol. Lett. **24**(17), 1539–1542 (2012).
17. F. Bernard, H. Zhang, S. P. Gorza, and P. Emplit, "Towards mode-locked fiber laser using topological insulators," in *Nonlinear Photonics*, OSA Technical Digest (online) (Optical Society of America, 2012), paper NTh1A.5.
18. C. J. Zhao, H. Zhang, X. Qi, Y. Chen, Z. T. Wang, S. C. Wen, and D. Y. Tang, "Ultra-short pulse generation by a topological insulator based saturable absorber," Appl. Phys. Lett. **101**(21), 211106 (2012).
19. C. J. Zhao, Y. H. Zou, Y. Chen, Z. T. Wang, S. B. Lu, H. Zhang, S. C. Wen, and D. Y. Tang, "Wavelength-tunable picosecond soliton fiber laser with Topological Insulator: Bi_2Se_3 as a mode locker," Opt. Express **20**(25), 27888–27895 (2012).
20. H. Yu, H. Zhang, T. Wang, C. J. Zhao, B. Wang, S. C. Wen, H. J. Zhang, and J. Wang, "Topological insulator as an optical modulator for pulsed solid-state lasers," Laser Photonics Rev. **7**(6), L77–L83 (2013).
21. Z. Q. Luo, Y. Z. Huang, J. Weng, H. H. Cheng, Z. Q. Lin, B. Xu, Z. P. Cai, and H. Y. Xu, "1.06μm Q-switched ytterbium-doped fiber laser using few-layer topological insulator Bi_2Se_3 as a saturable absorber," Opt. Express **21**(24), 29516–29522 (2013).
22. S. B. Lu, C. J. Zhao, Y. H. Zou, S. Q. Chen, Y. Chen, Y. Li, H. Zhang, S. C. Wen, and D. Y. Tang, "Third order nonlinear optical property of Bi_2Se_3," Opt. Express **21**(2), 2072–2082 (2013).
23. Z. C. Luo, M. Liu, H. Liu, X. W. Zheng, A. P. Luo, C. J. Zhao, H. Zhang, S. C. Wen, and W. C. Xu, "2 GHz passively harmonic mode-locked fiber laser by a microfiber-based Topological Insulator saturable absorber," Opt. Lett. **38**(24), 5212–5215 (2013).
24. J. Sotor, G. Sobon, W. Macherzynski, P. Paletko, K. Grodecki, and K. M. Abramski, "Mode-locking in Er-doped fiber laser based on mechanically exfoliated Sb_2Te_3 saturable absorber," Opt. Mater. Express **4**(1), 1–6 (2014).
25. Y. Chen, C. J. Zhao, H. H. Huang, S. Q. Chen, P. H. Tang, Z. T. Wang, S. B. Lu, H. Zhang, S. C. Wen, and D. Y. Tang, "Self-assembled topological insulator: Bi_2Se_3 membrane as a passive Q-switcher in an Erbium-doped fiber laser," J. Lightwave Technol. **31**(17), 2857–2863 (2013).
26. J. Zhang, Z. P. Peng, A. Soni, Y. Y. Zhao, Y. Xiong, B. Peng, J. B. Wang, M. S. Dresselhaus, and Q. H. Xiong, "Raman spectroscopy of few-quintuple layer topological insulator Bi_2Se_3 nanoplatelets," Nano Lett. **11**(6), 2407–2414 (2011).
27. K. M. F. Shahil, M. Z. Hossain, V. Goyal, and A. A. Balandin, "Micro-Raman spectroscopy of mechanically exfoliated few-quintuple layers of Bi_2Te_3, Bi_2Se_3, and Sb_2Te_3 materials," J. Appl. Phys. **111**(5), 054305 (2012).

1. Introduction

Ultrashort pulses have received much attention due to the great significance in a variety of applications, such as optical communications, spectroscopy, biomedicine, and material processing [1–3]. As a simple and economic ultrashort pulse source, passively mode-locked fiber lasers have been extensively investigated in the past decade. To date, several passively mode-locked techniques, such as nonlinear polarization rotation (NPR) [4,5], nonlinear amplifying loop mirror (NALM) [6–8], and real saturable absorber (SA) [9–16], were employed to achieve ultrashort pulses in fiber lasers. Among them, inserting a high performance material based SA into the laser cavity was allowing successful mode-locking to be achieved with free cavity designs compared with other two techniques. Therefore, several types of SAs had been demonstrated to achieve the passive mode-locking operation of fiber lasers. In recent years many researches had focused their attention on nanomaterial based SAs, which function as the rising candidates for ultrafast lasers due to their distinguished advantages in ultrafast recovery time, controllable modulation depth, and easy fabrication [11–16]. In particular, graphene, a type of Dirac nanomaterials, had been successfully demonstrated as a medium that allows for high performance ultrafast fiber lasers [13–16].

Recently, topological insulator (TI), another type of Dirac nanoscale materials, was also proposed to as SA device to obtain ultrashort pulses in fiber lasers. F. Bernard *et al*. have firstly presented the saturable absorption behavior of TIs around 1550 nm [17]. In the following, by inserting the TIs-based SA into the laser cavity, Zhao *et al*. further demonstrated the mode-locked picosecond pulses in fiber laser [18,19]. Very recently, it was also shown that the TIs possess the saturable absorption around 1060 nm wavelength range, indicating that the TI is a material with broadband saturable absorption [20,21]. In addition, taking advantage of the large nonlinear refractive index of TI [22], we had obtained high repetition rate pulse with a microfiber-based TISA, demonstrating that the TIs could operate as both the high nonlinear photonic device and the SA in the laser system [23]. However, all the mode-locked fiber lasers based on TISA delivered the pulse-trains with the durations of a few picoseconds while the femtosecond pulse have not yet been achieved. The limited pulse duration (picosecond regime) observed in previously reported TI mode-locked fiber lasers could be caused by the large anomalous cavity dispersion. Moreover, the TISAs reported before were fabricated by spraying TI on a quartz plate [18–20], and depositing it onto the fiber end facet [21,24] or microfiber [23]. In fact, for the purpose of flexibility, cost-effective and controllability, a filmy TISA composited by polyvinyl alcohol (PVA) or polymethyl methacrylate (PMMA) would be more favorable. As we know, the pulse characteristics, such as duration and stability, could be affected by the fabrication method of the nanomaterial-based SA and the cavity dispersion [13–16]. Therefore, a question would arise as to whether the femtosecond pulse could be achieved by inserting a filmy TISA into a fiber laser.

In this work, we reported on the generation of femtosecond pulse from an anomalous-dispersion fiber ring laser by using a filmy TISA composited by the PVA. The measured Raman spectrum of the PVA-TISA shows that the TI: Bi_2Se_3 nano-sheets could maintain their structure when embedding into the PVA. The modulation depth and the saturable intensity are 3.9% and 12 MW/cm^2, respectively. By inserting the PVA-TISA into a fiber laser, ~660 fs output pulse centered at 1557.5 nm wavelength could be obtained. These results suggest that the TISA could be indeed a good candidate of ultrafast saturable absorption device, and also demonstrate that the PVA could be the excellent host for fabricating high-performance TISA.

2. Fabrication and characteristics of the PVA-TISA

The TI: Bi_2Se_3 nanosheets could be synthesized by various methods such as chemical vapor transport, mechanical exfoliations by Scotch tape or peeling by an atomic force microscope tip, molecular beam epitaxial growth *etc* . Here, the polyol method was utilized to synthesize Bi_2Se_3 nanosheets [25,26]. The TI nanosheets for the SA fabrication are the same as those reported in Ref [22]. The dispersion enriched TI solution is prepared by ultra-sonicating Bi_2Se_3 nanosheets for 1 hour in acetone solution, as shown in Fig. 1(a). The concentration of TI/acetone solution is ~0.1 mg/ml. Then 1 mL TI/acetone solution is mixed with 5 mL aqueous solution of polyvinyl alcohol (PVA) and ultrasonicated for 30 minutes. The mixture is then evaporated at room temperature on a slide glass, resulting in the formation of a filmy PVA-TI composite, as presented in Fig. 1(b). Finally the prepared PVA-TI composite is placed between two fiber connectors to form a fiber-compatible SA, as shown in Fig. 1(c).

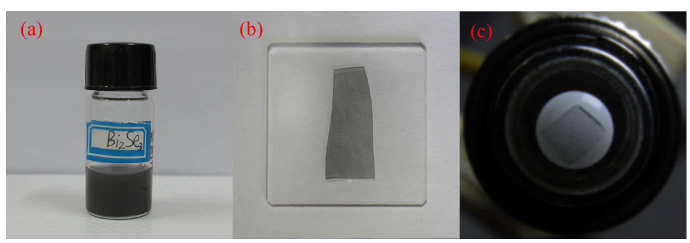

Fig. 1. (a) Image of Bi_2Se_3 acetone solution; (b) Image of TI-PVA film; (c) Image of the fabricated fiber-compatible PVA-TISA.

In order to check that whether the TI Bi_2Se_3 nano-sheets could maintain their structures or not after it has been embedded into PVA, we performed the Raman spectrum analysis on the samples. Figure 2(a) compares the Raman spectra of the filmy PVA-TISA (blue curve) and pure PVA film (black curve) in the range of 0-1250 cm^{-1} using the 514 nm excitation line at room temperature by a Renishaw inVia micro-Raman system (Renishaw Inc., New Mills, UK). The spectrum of the TI-PVA composite, which shows the Raman peaks of both TI Bi_2Se_3 and PVA, can be seen as a superposition of PVA (black curve) and TI (red curve).

#205686 - $15.00 USD Received 28 Jan 2014; revised 9 Mar 2014; accepted 9 Mar 2014; published 17 Mar 2014

Three typical Raman peaks of Bi_2Se_3 (Inset: Zoom-in view of the Raman peaks of Bi_2Se_3) centered at ~70 cm^{-1},~130 cm^{-1} and ~173 cm^{-1}, were found in the Raman spectra of TI-PVA, which are correlated with the out-plane vibrational mode A_{1g}^1, in-plane vibrational mode E_g^2 and the out-plane vibrational mode A_{1g}^2 of Se-Bi-Se-Bi-Se lattice vibration, respectively [26,27]. Therefore, one can conclude that Bi_2Se_3 nanosheets could still keep their structures even though they are embedded into PVA matrix, also indicating that the optical property of TI does not encounter significant change.

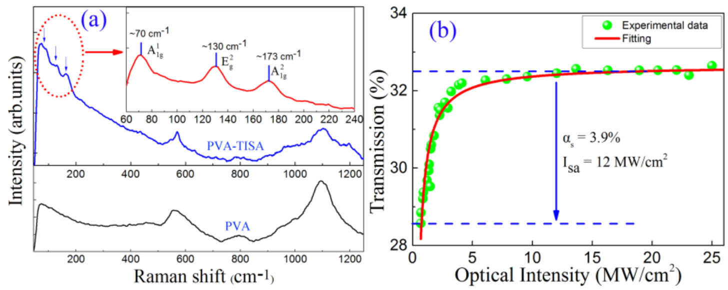

Fig. 2. (a) Raman spectra of TI-PVA, inset: zoom-in view of the Raman peaks of Bi_2Se_3; (b) Measured nonlinear saturable absorption curve and corresponding fitting curve.

For further investigating nonlinear optical characteristics of the fabricated PVA-TISA, the nonlinear absorption of TISA was measured by the power-dependent transmission technique. The experimental setup is the same as that in Ref [23]. In the setup of saturable absorption measurement, it should be noted that the pulse duration of the pump source broadens slightly from 502 fs to 513 fs after amplification. Figure 2(b) provides the saturable absorption data of PVA-TISA and the corresponding fitting curve as a function of peak intensity. As can be seen here, the modulation depth is ~3.9% and the non-saturable loss is ~67.5%. Note that the non-saturable loss is a bit large in this experiment. However, it was expected that the non-saturable loss could be improved by further optimizing the quality of the PVA-TISA film such as the thickness of film and the uniformity of TI within the composites. It should be also noted that the saturable intensity of the fabricated PVA-TISA is about two orders of magnitude less than the reported one (0.49 GW/cm^2) by depositing the TI onto a onto a thick quartz plate [19] and also smaller than the one (53 MW/cm^2) deposited onto fiber end facet [21]. With such a low saturable intensity, it would be predicted that the threshold of mode-locking using the as-prepared PVA-TISA can be significantly reduced.

3. Laser performance

To check the laser performance by using the prepared PVA-TISA, the PVA-TISA was inserted into a fiber ring laser cavity. Figure 3 shows the schematic of the proposed fiber laser. A 4 m EDF was used as the gain medium fiber. The group velocity dispersion (GVD) parameter of the EDF, which was calculated through the Kelly sidebands, was ~-15 ps/nm/km. The 976 nm pump light was coupled into the gain fiber by a wavelength division multiplexer (WDM). The polarization state of circulating light in the laser cavity could be controlled by adjusting a pair of polarization controllers (PCs). A polarization insensitive isolator (PI-ISO) was used to force the unidirectional operation of the laser cavity and a 10/90 coupler was used to output the laser emission. An optical spectrum analyzer (Anritsu MS9710C) and an oscilloscope (LeCroy Wave Runner 104MXi, 1 GHz) with a photodetector (New Focus P818-BB-35F, 12.5GHz) were used to study the laser spectrum and output pulse train, respectively. In addition, the pulse duration was measured with a commercial autocorrelator (FR-103XL).

#205686 - $15.00 USD Received 28 Jan 2014; revised 9 Mar 2014; accepted 9 Mar 2014; published 17 Mar 2014

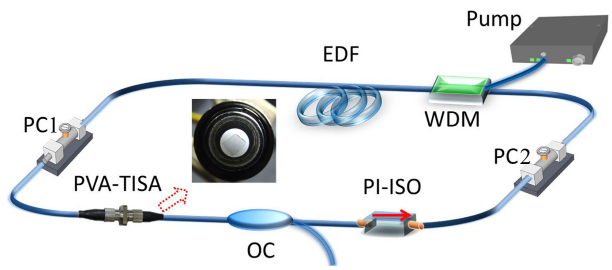

Fig. 3. Schematic of mode-locked fiber laser with a PVA-TISA.

Continuous wave operation started at a pump power of about 10 mW and the self-started mode-locking occurred at about 25 mW. For better performance of the fiber laser, the pump power was further increased to 90 mW. Figure 4(a) shows the typical spectrum of the mode-locked pulses at 90 mW. Here, the central wavelength and the 3 dB spectral bandwidth are 1557.5 nm and 4.3 nm, respectively. The evident Kelly sidebands on the spectrum indicate that the mode locked laser is operating in the soliton regime. Here, a cw peak centered at 1554.4 nm was shown on the mode-locked spectrum. It should be noted that the passive mode-locking state of the fiber laser could be also observed when the positions of the TISA placed onto fiber ferrule was moved. The corresponding pulse-train is presented in Fig. 4(b). The repetition rate is 12.5 MHz, which was determined by the 16.4 m cavity length. In this case, the average output power is 1.8 mW. Therefore, the pulse energy is 0.144 nJ. Then a commercial autocorrelator was employed to measure the pulse width. The measured result in Fig. 4(c) indicates that the fiber laser delivers a pulse-train with duration of 660 fs if the Sech^2 intensity profile was assumed. Thus, the time-bandwidth product is about 0.351, which was slightly higher than 0.315, indicating that the mode-locked pulses are slightly chirped. Moreover, as can be seen in Fig. 4(c), there is small pedestal shown on the autocorrelation trace. It could be attributed to the imperfect alignments of the autocorrelator.

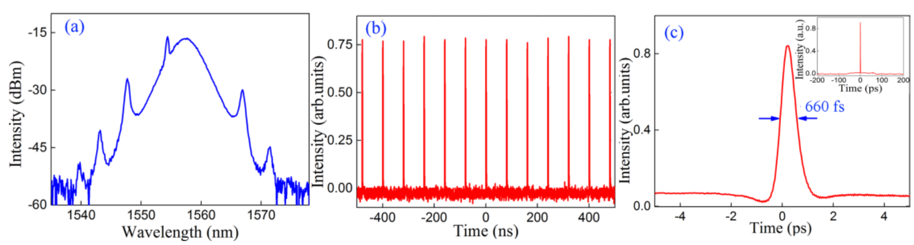

Fig. 4. Mode-locked operation. (a) Mode locked spectrum; (b) Corresponding pulse-train; (c) Corresponding autocorrelation trace; Inset: autocorrelation trace with full range scan.

To verify whether the mode locking operation was stable, the RF spectrum (Advantest R3131A) of the mode-locked pulse was measured, as presented in Fig. 5(a). The fundamental peak locates at the fundamental repetition rate of 12.5 MHz with a signal-to-noise ratio of over 55 dB, indicating that the stable pulse operation was obtained in this case. The RF spectrum up to 2 GHz was shown in Fig. 5(b). The wideband RF spectrum is free of spectral modulation, suggesting that the fiber laser operates well in the cw mode-locking state. To further investigate the stability, we recorded the optical spectra of the mode-locked laser every 2-hour, as shown in Fig. 5(c). It should be noted that the central spectral peak locations, spectral bandwidth, spectral strength remained reasonably stable over the time period.

#205686 - $15.00 USD Received 28 Jan 2014; revised 9 Mar 2014; accepted 9 Mar 2014; published 17 Mar 2014

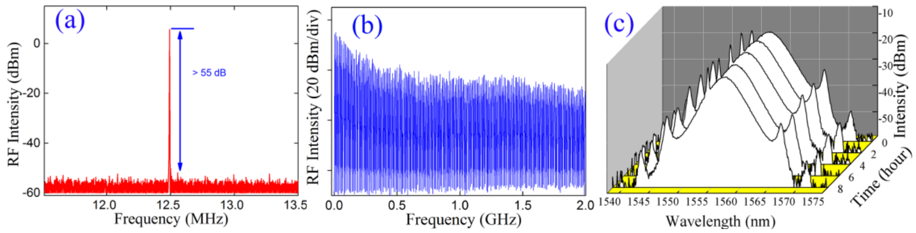

Fig. 5. Stability of femtosecond pulses. (a) RF spectrum; (b) RF spectrum in 2 GHz span; (c) Long term optical spectra measured at a 2-h interval.

In the experiment, ~660 fs pulse could be obtained by employing the prepared PVA-TISA. It should be noted that, apart from the quality of the SA, the pulse duration could be also affected by the cavity dispersion. To investigate the influence of cavity dispersion on the pulse duration, a segment of 9.9 m long SMF was inserted into the laser cavity to increase the cavity dispersion to ~-0.4 ps^2. The fiber laser was still mode locked with the same piece of PVA-TISA. In this case, only the picosecond pulse could be achieved despite of the variation of PC settings and pump power level. The results are shown in Fig. 6. Here, the 3 dB bandwidth of mode-locked spectrum is 2 nm, as shown in Fig. 6(a). The pulse train is presented in Fig. 6(b), whose repetition rate is 7.78 MHz. The measured autocorrelation trace in Fig. 6(c) shows that the pulse duration is 1.45 ps. The comparative experiments demonstrated that the femtosecond pulse generation from our fiber laser could be attributed to the combination effect of PVA-TISA and cavity dispersion.

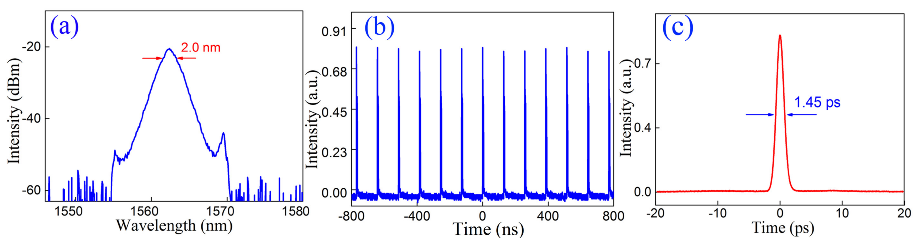

Fig. 6. Mode-locked operation when the cavity dispersion is increased to be ~-0.4 ps^2. (a) Mode-locked spectrum; (b) Corresponding pulse-train; (c) Autocorrelation trace.

4. Conclusion

In summary, we have demonstrated a femtosecond pulse fiber laser mode-locked by a filmy TISA. The filmy TISA, which is composited by the PVA, shows a modulation depth of ~3.9% and a low saturable optical intensity of 12 MW/cm^2. With the prepared PVA-TISA, the fiber laser delivers stable pulse-train with ~660 fs duration at the fundamental repetition rate of 12.5 MHz. Based on the experimental observations, it was expected that the PVA could be an excellent host material for fabricating high-performance TISA. The obtained results suggest that the PVA-TISA could be employed as a simple, low-cost ultrafast saturable absorption device for the applications such as mode-locked fiber lasers.

Acknowledgments

We would like to thank Yong-Fang Dong (South China Normal University) for help in measuring the Raman spectra. This work was supported in part by the National Natural Science Foundation of China (Grant No. 11074078, 61378036, 61307058, 11304101), and the PhD Start-up Fund of Natural Science Foundation of Guangdong Province, China (Grant No. S2013040016320).