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Wavelength-tunable picosecond soliton fiber laser with Topological Insulator: Bi_2Se_3 as a mode locker

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Abstract: Based on the open-aperture *Z*-scan measurement, we firstly uncovered the saturable absorption property of the topological insulator (TI): Bi_2Se_3. A high absolute modulation depth up to 98% and a saturation intensity of 0.49 $GWcm^{-2}$ were identified. By incorporating this novel saturable absorber material into an erbium-doped fiber laser, wavelength tunable soliton operation was experimentally demonstrated. Our result indicates that like the atomic layer graphene, the topological insulator Bi_2Se_3 could also operate as an effective saturable absorber for the passive mode locking of lasers at the telecommunication band.

OCIS codes: (060.4370) Nonlinear optics, fibers; (060.5530) Pulse propagation and temporal solitons; (140.4050) Mode-locked lasers; (160.4236) Nanomaterials.

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1. Introduction

Ultrafast fiber lasers have widespread applications ranging from industrial material processing, medical treatment, to basic researches [1]. In comparison with other types of lasers, fiber lasers are highly efficient, compact, and robust, and always deliver high quality

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laser beams. To achieve the ultra-short pulses emission of a fiber laser, normally a saturable absorber (SA) whose light absorbance decreases with the increase of the light intensity is incorporated in the cavity [1–3]. Among the various types of SAs, the semiconductor saturable absorber mirrors (SESAMs) [2, 3], single wall carbon nanotubes (SWNTs) [4–8] and graphene [9–21] SAs were extensively investigated. They are all found to be effective laser mode lockers. However, SESAMs require complicated fabrication and packaging technique, and have limited operation bandwidth; SWNTs and graphene SAs demand less stringent fabrication method, have advantages of fast recovery time, low saturation intensity and low cost. Moreover, because graphene has a Dirac-like electronic band structure, it could respond to a wide spectrum of photons, making it applicable as a broadband SA [22, 23] and standing out other types of SA [9, 14]. Very recently, another type of Dirac material, topological insulators (TI), has been widely studied in the condensed-matter physics [24, 25]. Like graphene, TI has also a band structure with Dirac-like linear dispersion in its surface state [26–30]. Several materials, such as Bi_2Te_3, Bi_2Se_3 and Sb_2Te_3, have been experimentally confirmed as the three-dimensional TI with a single Dirac cone in its surface state. Among these TI materials, Bi_2Se_3 has a relatively larger bulk band gap (0.3 eV), and it is considered as a promising optical material for the room-temperature applications [28]. Despite that many findings on the electronic property of the TI materials had been reported, their optical property, which is equally important as their electronics counterpart, are however less addressed. Very recently, researchers had studied the nonlinear optical property of TI: Bi_2Te_3, and found that its absorbance could become transparent under strong illumination [31]. Triggered by their finding, we have experimentally investigated the nonlinear absorption of TI: Bi_2Se_3 by using the open aperture Z-scan technique. We found that, like graphene, TI: Bi_2Se_3 exhibits saturable absorption, for the first time. By inserting the TI: Bi_2Se_3 saturable absorber in an erbium-doped fiber laser cavity, we further experimentally demonstrated the passive mode locking of the laser. Stable mode locked solitons with 1.57 ps pulse width at the 1565 nm wavelength were directly generated. Wavelength tuning of the solitons was also achieved by using the intrinsic cavity birefringent filter effect of the fiber ring lasers.

2. Preparation of the Bi_2Se_3 nanoplatelets

High quality TI films can be produced by MBE growth [32], vapor-liquid-solid growth [33], and mechanical exfoliation of thin sheets from bulk crystals [34]. Here, the Bi_2Se_3 nano-platelets (NPs) used were synthesized via a polyol method reported by Ref [35]. All reagents are of analytic purity and used without further purification. The synthesis was conducted as follows: 0.20 g $Bi(NO_3)_3 \cdot 5H_2O$, 0.1g sodium selenite, 0.44 g polyvinyl pyrrolidone, and 20 mL ethylene glycol were added into a 50.0 mL two-neck flask containing a Teflon-coated magnetic stirring bar. The flask was connected with a reflux condenser and placed on a heating mantle. The temperature of the solution was increased to 190 °C under constant stirring. After 2 hours, the flask was then removed from the heating mantle. The product was cooled, centrifuged, washed with isopropyl alcohol (IPA) several times. We took out some dispersion and the others were dried at 60 °C. Figure 1(a) shows the representative SEM images of the chemically grown NPs.

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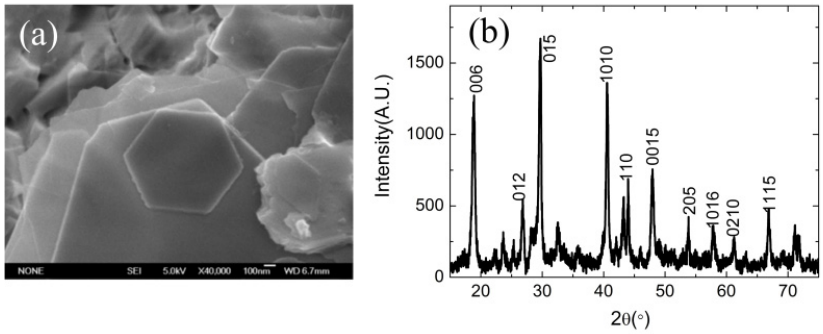

Fig. 1. (a) SEM images, and (b) XRD diffraction pattern of as-grown Bi_2Se_3 nano-platelets.

It can be seen that most high quality NPs exhibit hexagonal morphologies with planar dimensions that could extend up to several micrometers. The XRD pattern shown in Fig. 1(b) indicates that the product shown in Fig. 1(a) has the rhombohedral phase (JCPDS card No. 33-0214) with good crystalline.

3. Experimental results and discussions

In order to conveniently investigate the linear and nonlinear optical properties of the as-prepared TI: Bi_2Se_3 and to insert the TI sample into the fiber laser cavity, we firstly dropped the TI dispersion solution onto a 1 mm thick quartz plate. After that, the plate was placed inside a drying oven for evaporation for 8 hours.

The linear absorption spectrum of the sample was measured with a spectrophotometer (Lambda 950) and the result is shown in Fig. 2(a). It clearly shows that the TI has a smooth transmission curve in the near-infrared wavelength band, suggesting that, like graphene, the TI is a promising broadband optical material. We then experimentally investigated the saturable absorption property of the TI: Bi_2Se_3 using the open aperture Z-scan technique. The experimental setup used was reported previously [36]. A picosecond pulse laser (pulse duration: 3.8 ps, pulse repetition rate: 100 MHz) was used to excite the nonlinear absorption. The pico-second pulses were generated with a mode locked fiber laser. 5% of the laser beam was split as the reference beam that was monitored with a photo-detector; the residual laser beam was focused by an objective lens (20 times) perpendicularly to the TI sample surface. The TI sample was mounted on a linear translation stage. The relative distance between the objective lens and the TI sample can be continuously varied by the motorized linear translation stage. A second detector was used to measure the entire laser beam intensity passing through the TI sample. By dividing the output power by the reference power, a normalized *Z*-scan curve was obtained as shown in Fig. 2(b). It clearly shows a very high on-off extinction ratio, i.e. the ratio of the maximum to the minimum optical transmittance, of up to 39. Based on the relation between the laser beam spot size and the normalized transmittance, a nonlinear saturable absorption curve is calculated as shown in Fig. 2(c). By fitting the curve with the following formula

$$T = A\exp\left(\frac{-\Delta T}{1+\frac{I}{I_{sat}}}\right)$$

where T is the transmission, A is a normalization constant, ΔT is the absolute modulation depth, I is the intensity and I_{sat} is the saturation intensity, we have obtained the saturation intensity I_{sat} = 0.49 GWcm^{-2} and the absolute modulation depth ΔT = 98%. The experiment

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clearly demonstrates that the TI: Bi_2Se_3 possesses high-modulation-depth (up to 98%) saturable absorption. Researchers experimentally found that a high modulation depth saturable absorber could suppress the wave-breaking effect, which is an intrinsic nonlinear phenomena and can limit the maximum per-pulse energy [37]. Here, the TI: Bi_2Se_3 with high modulation depth may have promising applications for high power pulse formation.

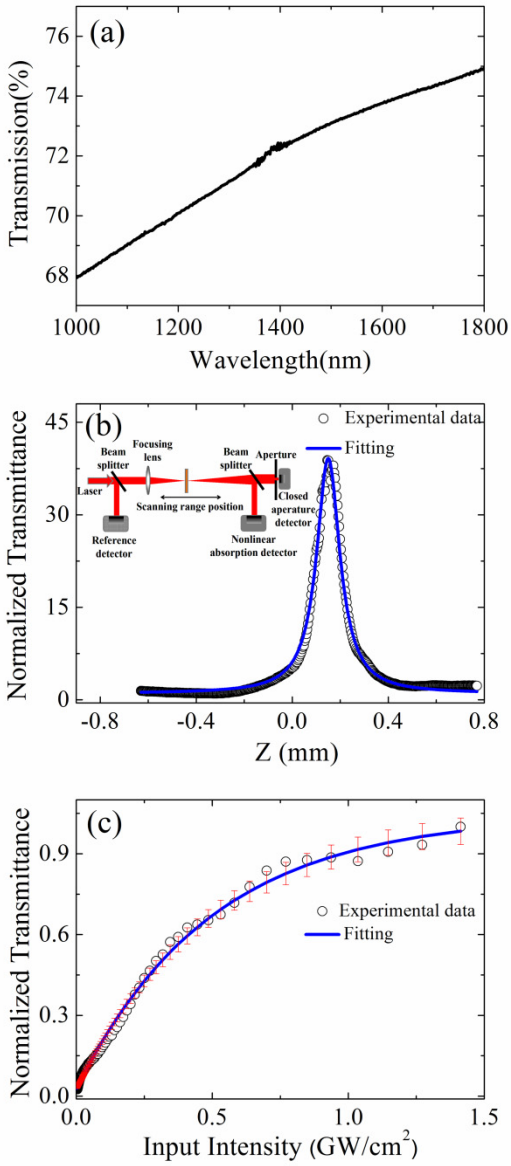

Fig. 2. (a) The near infrared linear absorption spectra of TI. (b) A typical Z-scan peak curve of TI: Bi_2Se_3 at 1550 nm. Insert: Z-scan experimental setup. (c) The corresponding nonlinear saturable absorption curve.

Taking advantage of the saturable absorption property of the Bi_2Se_3, we further designed a passively mode locked erbium-doped fiber laser with the Bi_2Se_3 as a mode locker. The fibre laser setup is schematically shown in Fig. 3. The laser cavity is made of a piece of 1.1 m

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heavily doped Erbium-doped fiber (LIEKKI Er80-8/125) with group velocity dispersion (GVD) of ~–20 ps^2/km, and 167 m single mode fiber (SMF) with GVD of –23 ps^2/km. The net cavity dispersion is estimated as –3.86 ps^2. A polarization independent isolator was used to force the unidirectional operation of the ring, and an intracavity polarization controller (PC) was used to adjust the cavity birefringence. A 980/1550 wavelength-division-multiplexer is used to couple the pump light into the cavity, and a 10% fiber coupler is used to output the laser emission. To incorporate the TI saturable absorber into the cavity, a fiber pigtailed bench is inserted in the cavity with a Bi_2Se_3 coated quartz plate mounted in it. The laser operation is simultaneously monitored with an oscilloscope (Tektronix TDS3054B) and a commercial autocorrelator (FR-103MN). The optical spectrum is measured with an optical spectrum analyzer (Ando AQ-6317B).

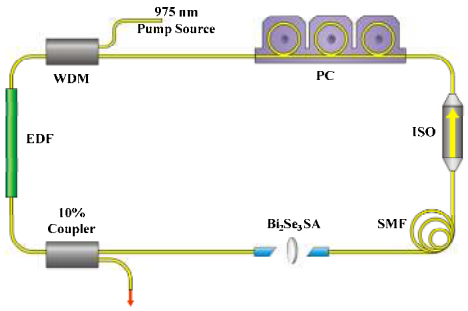

Fig. 3. Schematic of the fiber laser. PC: polarization controller. WDM: wavelength division multiplexer. EDF: erbium doped fiber. SMF: single mode fiber.

Self-started mode locking of the laser occurred at an incident pump power of about 65 mW. The mode locking state could be maintained to the maximum available pump power of ~500 mW. Figure 4(a) shows the optical spectrum of the mode locked pulses at a pump power of 130 mW. The output spectrum is centered at 1564.6 nm with a 3 dB bandwidth of 1.79 nm. The Kelly sidebands are clearly visible on the optical spectrum, indicating that the mode-locked operation is in the soliton regime [38]. Figure 4(b) shows a measured autocorrelation trace of the mode locked pulses. It has a FWHW width of 2.42 ps. If a $Sech^2$ pulse profile is assumed, the soliton pulse duration is 1.57 ps. The time-bandwidth product of the pulses is ~0.35, indicating that they are slightly chirped. Figure 4(c) shows the measured oscilloscopes trace in the nanosecond time scale. A pulse is circulating in the cavity at the fundamental cavity repetition rate of 1.21 MHz. Under strong pumping, multiple soliton pulse operation was also observed. In order to evaluate the mode-locking stability, we recorded the optical spectra of the laser every 4-hour over 2-days, as shown in Fig. 4(d). We note that the central spectral peak locations, spectral bandwidth, spectral strength remained reasonably stable over the time period.

It is well-known that large residual cavity birefringence could induce artificial narrow band pass filter effect in a fiber ring laser [39]. Together with the limited bandwidth of the laser gain, this artificial cavity birefringence filter effect could be used to control the central operation wavelength of a laser and achieve tunable mode locked pulses. Making use of the effect of the fiber ring laser we have further designed a wavelength tunable passively mode locked fiber laser with the TI: Bi_2Se_3 as a saturable absorber. Figure 5 shows the optical spectrum evolution of the solitons as the orientation of an intracavity PC is varied. The wavelength of the solitons could be shifted from 1557 to 1565 nm continuously. To verify whether the mode locking operation is purely contributed by the saturable absorption of the Bi_2Se_3 nano-platelets, the TI SA was purposely removed out of the laser cavity. In this case no mode locking was observed, despite that the pump power was increased from zero to the maximum available power and the polarization controller was rotated in a full range.

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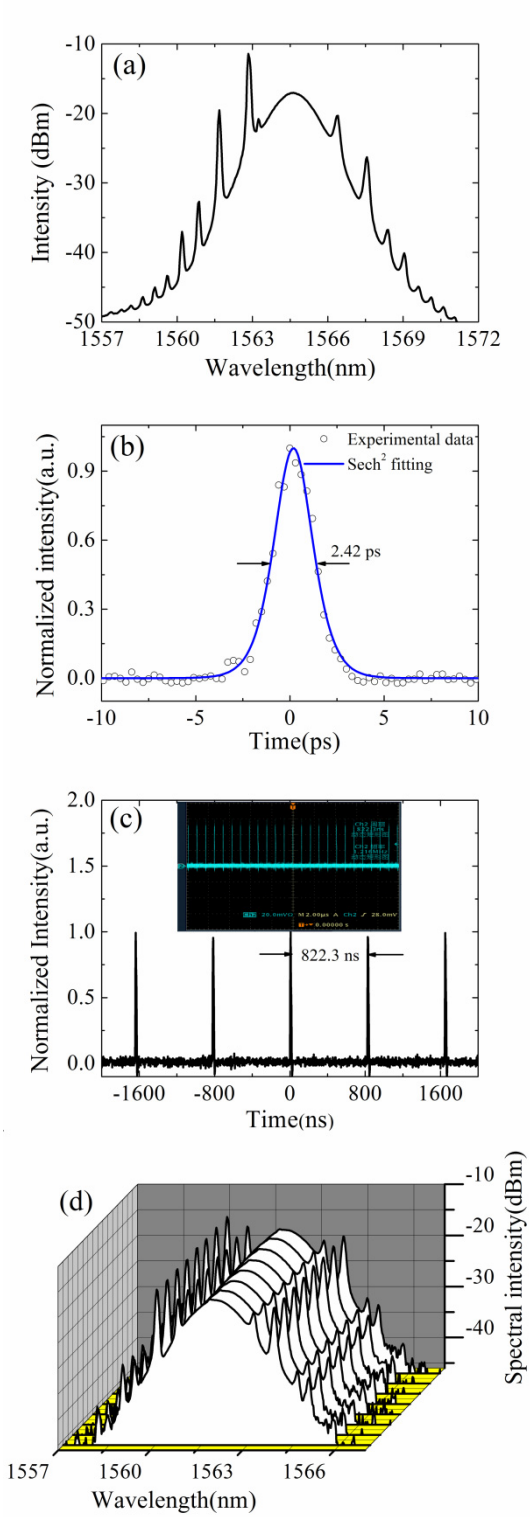

Fig. 4. (a) The mode locked soliton spectrum. Its corresponding autocorrelation trace (b) and oscilloscope trace (c). (d) Long term optical spectra measured at a 4-hour interval over 2-days.

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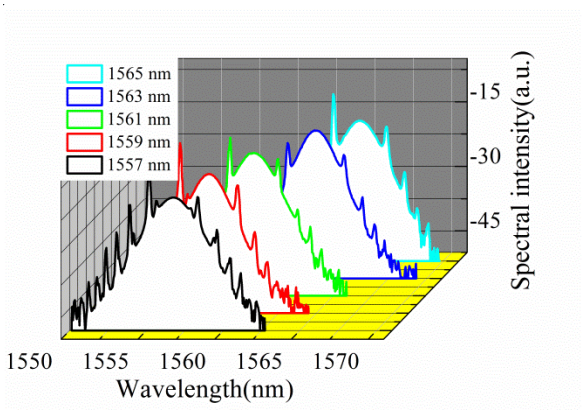

Fig. 5. Soliton spectra obtained from the TI SA mode-locked tunable fiber laser.

4. Conclusion

In conclusion, we have experimentally studied the saturable absorption property of TI: Bi_2Se_3 at the telecommunication band using the *Z*-scan technique. Our result shows that TI: Bi_2Se_3 has strong saturable absorption with a large absolute modulation depth. Taking advantage of the saturable absorption, we firstly demonstrated the passive mode locking of an erbium-doped fiber laser with the TI: Bi_2Se_3 as a passive mode locker. Stable soliton pulses with 1.57 ps pulse width at 1564.6 nm were obtained. Continuous wavelength tuning from 1557 to 1565 nm was also achieved in a Bi_2Se_3 mode locked fiber laser by taking advantage of the intrinsic cavity birefringence filter effect. Our experimental results demonstrated that TI: Bi_2Se_3 could be a cost-effective saturable absorber for fiber laser mode locking.

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