

# Soliton fiber laser mode locked with two types of film-based $\text{Bi}_2\text{Te}_3$ saturable absorbers

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Received December 8, 2014; revised February 2, 2015; accepted February 16, 2015;  
posted February 18, 2015 (Doc. ID 229140); published March 26, 2015

We propose a low-threshold soliton fiber laser passively mode locked with two different types of film-like saturable absorbers, one of which is fabricated by mixing  $\text{Bi}_2\text{Te}_3$  with de-ionized water, as well as polyvinyl alcohol (PVA), and then evaporating them in a Petri dish, and the other of which is prepared by directly dropping  $\text{Bi}_2\text{Te}_3$  solution on the PVA film. Both  $\text{Bi}_2\text{Te}_3$ -PVA films exhibit outstanding features of low loss, high flexibility, and easy synthesis. By incorporating  $\text{Bi}_2\text{Te}_3$ -PVA films into fiber lasers, stable single-soliton emissions are obtained at a low pump power of 13 mW. Our results suggest that the  $\text{Bi}_2\text{Te}_3$  can work as a promising mode locker for ultrafast lasers, while PVA is an excellent host for fabricating high-performance film-based saturable absorbers. © 2015 Chinese Laser Press

OCIS codes: (140.4050) Mode-locked lasers; (140.3510) Lasers, fiber; (160.4236) Nanomaterials; (190.7110)

Ultrafast nonlinear optics.

<http://dx.doi.org/10.1364/PRJ.3.000A43>

## 1. INTRODUCTION

Ultrafast fiber lasers have attracted a great deal of research interest due to their widespread applications in the fields of fiber telecommunications, material processing, frequency combs, nonlinear microscopy [1–4], etc. In recent decades, various techniques, including *Q*-switching and active and passive mode locking, were proposed to produce ultrashort pulsed lasers. In active mode locking, an optical modulator is utilized to modify the phase or amplitude of lasers, which is inconvenient and increases the cost for practical applications [5]. For passively mode-locked fiber lasers, a saturable absorber (SA) is indispensable in shaping the pulse in the temporal domain [6]. One kind of SA is based on nonlinear and/or birefringent effects, such as the Kerr lens [7], nonlinear polarization rotation technique [8,9], and nonlinear optical loop mirror [10,11]. These devices exhibit features of a large damage threshold and broad operating wavelength range, while they are less stable and tend to be affected by environmental perturbations. The other kind of SA arises from the nonlinear absorption of materials, such as the semiconductor saturable absorber mirror (SESAM) [12–14], carbon nanotube [15–17], graphene [18,19],  $\text{MoS}_2$  [20–22], and  $\text{WS}_2$  [23]. Among them, the SESAM and carbon nanotube have large modulation depths and are designed to operate at certain wavelengths. As a result of the unique zero bandgap, a graphene-based SA exhibits a broadband response and has been used in a mode-locked fiber laser operating at 1.06, 1.55, and 2  $\mu\text{m}$ , respectively [24].

Currently, motivated by graphene-like two-dimensional materials, topological insulators (TIs), a new state of quantum

matter with an insulating bulky gap and gapless edge or surface states, have been investigated in depth in condensed-matter physics and laser photonics [25–27]. A TI has a single Dirac cone on the surface around the  $\Gamma$  point and a small bandgap of 0.2–0.3 eV in the bulk. For a gap of 0.3 eV, a photon can excite an electron from the valence band to the conduction band when the light wavelength is shorter than 4.1  $\mu\text{m}$  [28]. As a result, TI may work as an ultrabroadband nonlinear element manipulating the light waves. Bernard *et al.* first demonstrated that  $\text{Bi}_2\text{Te}_3$  exhibited SA behavior at the telecommunication band [29]. Zhao *et al.* experimentally realized passive mode locking in a soliton fiber laser by dropping a  $\text{Bi}_2\text{Te}_3$  solution onto a quartz plate [30]. Recently, Luo *et al.* achieved a 2 GHz harmonic mode-locked fiber laser using a microfiber-based  $\text{Bi}_2\text{Te}_3$  SA [31]. Moreover, Lin *et al.* [32], Jung *et al.* [33], and Lee *et al.* [34] demonstrated that  $\text{Bi}_2\text{Te}_3$  coated on the end-face of fiber, mechanically exfoliated  $\text{Bi}_2\text{Te}_3$ , and bulk-structured  $\text{Bi}_2\text{Te}_3$  can act as effective SAs in fiber lasers. Sotor *et al.* [35] and Liu *et al.* [36] proposed a mode-locked erbium-doped fiber (EDF) laser using mechanically exfoliated  $\text{Sb}_2\text{Te}_3$  and polyvinyl alcohol (PVA)-based  $\text{Sb}_2\text{Te}_3$  SAs. These proposed SAs demonstrate an interesting step forward in the fields of TI-based ultrafast optics. However, compared with other methods, the film-based SA would be more favorable due to its superior attributes of low cost, flexibility, and controllability.

In this paper, we propose two methods to fabricate film-based SAs by combining  $\text{Bi}_2\text{Te}_3$  and PVA. One type of film is formed by homogeneously mixing  $\text{Bi}_2\text{Te}_3$  with de-ionized water, as well as PVA, and then evaporating them in a Petri

dish. The other type of film is prepared by directly dropping the  $\text{Bi}_2\text{Te}_3$  solution on the PVA film. By using two types of SAs, conventional solitons operating at the telecommunication band are achieved separately in the fiber laser at a low pump power of 13 mW. The experimental results show that both  $\text{Bi}_2\text{Te}_3$ -PVA films can work as flexible, broadband, and cost-effective mode lockers that can find important applications in ultrafast optics.

## 2. PREPARATION AND CHARACTERIZATION OF A $\text{Bi}_2\text{Te}_3$ -PVA-BASED SA

The  $\text{Bi}_2\text{Te}_3$  nanosheets were synthesized by the hydrothermal intercalation/exfoliation approach [30]. Based on previous reports [37], the recovery time of interband scattering from the bulk conduction band is about 0.5 ps, while the relaxation time for the Dirac cone nonequilibrium electrons to recover a Fermi-Dirac distribution of the surface states is over 10 ps. Figure 1(a) shows the scanning electron microscopy image of  $\text{Bi}_2\text{Te}_3$  nanosheets deposited on a quartz plate, in which well-exfoliated hexagonal nanosheets with a size of 0.5–1  $\mu\text{m}$  can be seen clearly. The as-prepared  $\text{Bi}_2\text{Te}_3$  nanosheets were dispersed in isopropyl alcohol with a concentration of  $\sim 0.1$  mg/mL, as shown in Fig. 1(b). In our experiment, two different methods were used to fabricate the film-based SAs. The first method is as follows. The obtained  $\text{Bi}_2\text{Te}_3$  solutions were diluted in de-ionized water at a volume ratio of 1:4 and ultrasonicated for 1 h using an ultrasonic cleaner. Then, 5 wt. % aqueous PVA solution and the  $\text{Bi}_2\text{Te}_3$  solution were mixed at a volume ratio of 1:2 by a magnetic stirrer for 5 h. The final mixture was dropped on a Petri dish. Slow evaporation under ambient temperature and pressure resulted in a thin  $\text{Bi}_2\text{Te}_3$ -PVA composite film, as shown in the top of Fig. 1(c). Here, the concentration of  $\text{Bi}_2\text{Te}_3$  can be precisely controlled and excessive agglomeration of  $\text{Bi}_2\text{Te}_3$  can be eliminated to avoid unwanted insertion loss. The second method is much simpler and is different from that in previous reports [36]. The amounts of the PVA and  $\text{Bi}_2\text{Te}_3$  solutions are the same as in the first method. The PVA film was fabricated by dropping the PVA solution on a Petri dish. After evaporation, the  $\text{Bi}_2\text{Te}_3$  nanosheets in isopropyl alcohol were directly dropped on both sides of the PVA film and were evaporated for tens of minutes, as shown in the bottom of Fig. 1(c). Because the SA is formed by directly dropping the solution on film, the fabrication procedure, time, and cost are significantly reduced. However, the concentration and agglomeration of the second SA cannot be precisely controlled, which will further affect the mode-locking performance. This fabrication

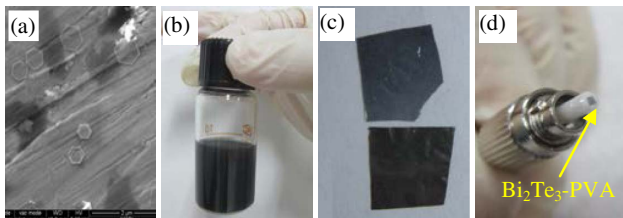


Fig. 1. (a) Scanning electron microscopy image of  $\text{Bi}_2\text{Te}_3$  nanosheets, (b)  $\text{Bi}_2\text{Te}_3$  isopropyl alcohol solutions, (c)  $\text{Bi}_2\text{Te}_3$ -PVA film, where the top and bottom films are prepared by the first and second methods, respectively, and (d)  $\text{Bi}_2\text{Te}_3$ -PVA film attached to the facet of a fiber connector.

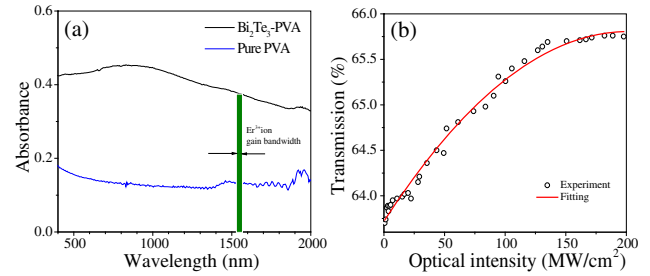


Fig. 2. (a) Absorption spectra of  $\text{Bi}_2\text{Te}_3$ -PVA and pure PVA films, where the vertical olive line illustrates the spectral gain region of the EDF, (b) nonlinear absorption characterization of the  $\text{Bi}_2\text{Te}_3$ -PVA SA. The solid curve is fitted from the experimental data (circle symbols).

method may also apply to graphene, nanotube, and  $\text{MoS}_2$  solutions. Figure 1(d) shows a photograph of  $\text{Bi}_2\text{Te}_3$ -PVA film that is coated on the facet of the fiber connector.

Figure 2(a) shows the linear absorption spectrum of the  $\text{Bi}_2\text{Te}_3$ -PVA film in comparison with pure PVA, which is measured by a spectrometer (Hitachi UV4100). It is demonstrated that the  $\text{Bi}_2\text{Te}_3$  exhibits a relatively broad transmission from the visible to near-IR wave band, indicating that  $\text{Bi}_2\text{Te}_3$  could be another broadband optical material manipulating light waves. The nonlinear absorption of the  $\text{Bi}_2\text{Te}_3$  SA was experimentally measured by a power-dependent transmission technique based on a balanced twin-detector measurement system, which was elaborated in Ref. [31]. The illumination pulse was delivered by a homemade passively mode-locked fiber laser (repetition rate: 20 MHz, pulse duration: 1.8 ps, central wavelength: 1560 nm). As shown in Fig. 2(b), the modulation depth is about 2% and the nonsaturable loss is about 34% after fitting the measured data. The saturable optical intensity and saturation fluence of the SA at 1560 nm are about 180  $\text{MW}/\text{cm}^2$  and 3.3 mW, respectively. In addition, we measured the nonlinear properties of the same SA several times and found that the saturable absorption parameters were almost identical, indicating that the device was beyond the damage threshold during the test procedures.

## 3. EXPERIMENTAL SETUP AND RESULTS

Figure 3 shows the experimental setup of the fiber laser. The mode locker is assembled by sandwiching the  $\text{Bi}_2\text{Te}_3$ -PVA film between two fiber ferrules, as shown in the inset. The laser resonator consists of 3 m EDF, a polarization-insensitive

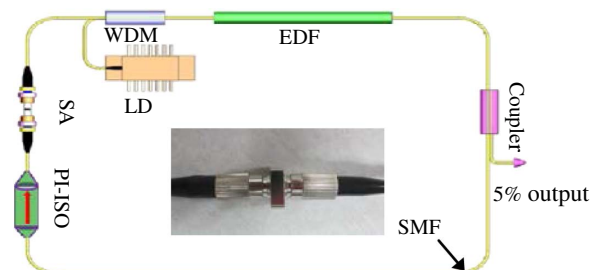


Fig. 3. Experimental setup of the fiber laser with  $\text{Bi}_2\text{Te}_3$  as a mode locker. LD, laser diode; WDM, wavelength division multiplexer; PI-ISO, polarization insensitive isolator. The SA is achieved by sandwiching the  $\text{Bi}_2\text{Te}_3$ -PVA film between two fiber ferrules, as demonstrated in the inset.

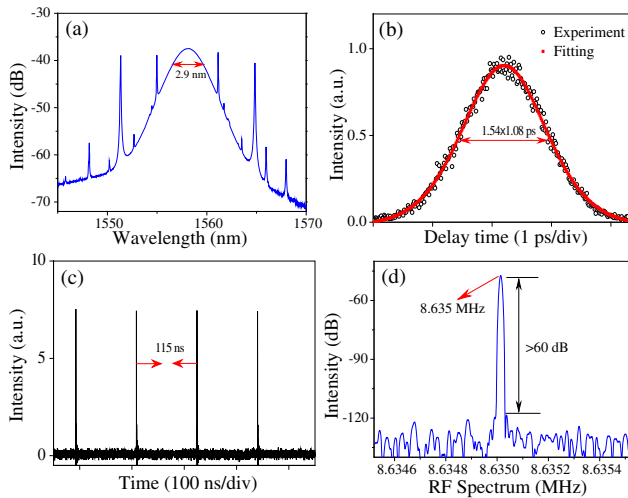


Fig. 4. (a) Spectrum, (b) autocorrelation trace, (c) oscilloscope trace, and (d) RF spectrum of the pulse. The SA is fabricated by dispersing the  $\text{Bi}_2\text{Te}_3$  into PVA (first method).

isolator, and a SA. The fiber laser is pumped by a 975 nm laser diode through a wavelength division multiplexer coupler. The 5% port of an optical coupler provides the laser output. All of the other fibers are standard single-mode fiber (SMF) with a total length of 20.8 m. The dispersion parameters  $D$  at 1550 nm for EDF and SMF are  $-16$  and  $17$  ps/(nm · km), respectively. The net cavity dispersion  $\beta^2$  is calculated as  $-0.39$  ps<sup>2</sup>.

Continuous wave emission was achieved at an incident pump power of 6 mW using  $\text{Bi}_2\text{Te}_3$ -PVA film fabricated by the first method ( $\text{Bi}_2\text{Te}_3$  mixed with PVA). Self-starting soliton mode locking was observed at a pump power of 30 mW. In this case, the fiber laser operated at the multisoliton state and the output power was about 0.4 mW. Decreasing the pump power to 13 mW, stable single-soliton mode locking was realized in the fiber laser with an output power about 0.14 mW. At a pump power of 19 mW, a single pulse was split into dual pulses with an output power of 0.25 mW. Figure 4(a) shows the output spectrum, which exhibits symmetrically distributed Kelly sidebands on both sides. The small spectral sidebands may arise from the inherent four-wave mixing of the vector soliton [38], confirming that the as-fabricated passive mode locker is polarization insensitive. The central wavelength and 3 dB spectral bandwidth are measured to be 1557 and 2.9 nm, respectively. We also found that the laser wavelength was shifted toward longer wavelengths by increasing the pump power, which may be attributed to the joint contribution from the Raman effect and pump-dependent gain effect [39,40].

Figure 4(b) shows the autocorrelation trace of the output soliton measured with a high-sensitivity autocorrelator. The FWHM of the autocorrelation trace is about 1.59 ps, and the pulse duration is found to be 1.08 ps by using the sech<sup>2</sup> fitting. The corresponding time bandwidth product (TBP) is calculated as 0.39, indicating that the soliton has little chirp, which may arise from the nonlinear phase shift accumulated during amplification. As shown in Fig. 4(c), the separation between adjacent pulses is about 115 ns, which is equal to the cavity round-trip time. Figure 4(d) shows the RF spectrum at a span of 1 kHz and resolution of 9.1 Hz. The fundamental repetition rate is given as 8.635 MHz, which coincides

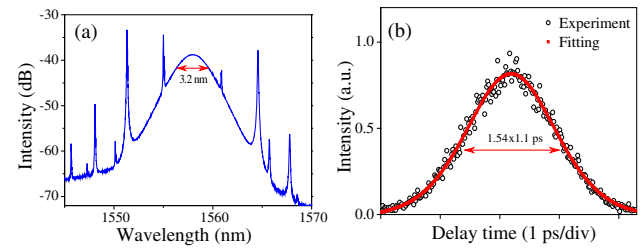


Fig. 5. (a) Spectrum and (b) autocorrelation trace of the pulse. Herein, the SA is formed by directly dropping the  $\text{Bi}_2\text{Te}_3$  solution on the PVA film (second method).

with the temporal separation of 115 ps. The signal-to-noise ratio is higher than 60 dB, indicating its good mode-locking stability.

Utilizing the  $\text{Bi}_2\text{Te}_3$ -PVA film fabricated by the second method ( $\text{Bi}_2\text{Te}_3$  solution dropped on PVA film), stable soliton mode locking can be also achieved in the same fiber laser. The oscilloscope trace and RF spectrum are similar to Figs. 4(c) and 4(d) and are omitted for conciseness. Figures 5(a) and 5(b) show the spectrum and autocorrelation trace of the pulse at the same pump power of 13 mW, respectively. The output power is measured as 0.11 mW, slightly less than in the first case, which may be attributed to a larger insertion loss of the second SA. Here, the 3 dB spectral width and pulse duration are given as 3.2 and 1.1 ps, which gives a TBP of 0.44. The TBP difference of the two operations may be attributed to the change of SA or external conditions, such as fiber bends and loss.

The experimental results show that the damage thresholds for the first and second SAs are about 240 and 180 mW, respectively. Fiber lasers mode locked with  $\text{Bi}_2\text{Te}_3$ -PVA SAs can stably operate at the same state for tens of hours as long as the pump power is kept unchanged, and they can withstand slight mechanical perturbation and temperature variations. To verify whether the soliton formation is caused by only the saturable absorption of the  $\text{Bi}_2\text{Te}_3$ , we have purposely removed or replaced the  $\text{Bi}_2\text{Te}_3$ -PVA film with pure PVA film from a laser cavity. No mode locking was observed in either case, despite the fact that the pump power was changed from zero to the maximum and the fiber was bent and twisted over a large range. Based on the aforementioned results, we conclude that  $\text{Bi}_2\text{Te}_3$  plays a key role in realizing passive mode locking in the fiber laser.

#### 4. CONCLUSIONS

We have proposed two different methods of fabricating a film-based SA by combining  $\text{Bi}_2\text{Te}_3$  and PVA. One of the films is formed by homogeneously mixing  $\text{Bi}_2\text{Te}_3$ , de-ionized water, and PVA, and then evaporating them in a Petri dish. The other film is prepared by directly dropping the  $\text{Bi}_2\text{Te}_3$  solution on the PVA film. The two types of SAs exhibit the features of broadband transmission, low cost, and ease of fabrication. By inserting the  $\text{Bi}_2\text{Te}_3$ -PVA films inside the laser cavity, a single soliton can be obtained at a pump power of 13 mW, which is quite low in mode-locked fiber lasers. Our results suggest that the PVA is an excellent host for fabricating a high-performance SA, and the  $\text{Bi}_2\text{Te}_3$  can be further developed as a useful passive mode-locking element.



## ACKNOWLEDGMENTS

This work was supported by the Fundamental Research Funds for the Central Universities (Grant Nos. 3102014JCQ01101, 3102014JCQ01099, and 3102014JCQ01085), the 973 Program (Grant No. 2012CB921900), and the National Natural Science Foundation of China (Grant Nos. 61405161, 11404263, and 61377035).

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