ISSN 1674-1056
http://cpb.iphy.ac.cn
http://iopscience.iop.org/cpb
中国物理 B
Chinese Physics
中国物理
Chinese Physics B

Femtosecond Tm-Ho co-doped fiber laser using a bulk-structured Bi_2Se_3 topological insulator

Jinho Lee(李珍昊), Ju Han Lee(李周翰)

Citation: Chin. Phys. B . 2018, 27(9): 094219. **doi:** 10.1088/1674-1056/27/9/094219

Journal homepage: http://cpb.iphy.ac.cn; http://iopscience.iop.org/cpb

What follows is a list of articles you may be interested in

Two-dimensional materials for ultrafast lasers

Fengqiu Wang(王枫秋)

Chin. Phys. B . 2017, 26(3): 034202. **doi:** 10.1088/1674-1056/26/3/034202

Yb-doped passively mode-locked fiber laser with Bi_2Te_3-deposited

Li Lu, Yan Pei-Guang, Wang Yong-Gang, Duan Li-Na, Sun Hang, Si Jin-Hai

Chin. Phys. B . 2015, 24(12): 124204. **doi:** 10.1088/1674-1056/24/12/124204

Compact, temperature-stable multi-gigahertz passively modelocked semiconductor disk laser

Song Yan-Rong, Guoyu He-Yang, Zhang Peng, Tian Jin-Rong

Chin. Phys. B . 2015, 24(8): 084208. **doi:** 10.1088/1674-1056/24/8/084208

Influences of cavity dispersion distribution on the output pulse properties of an all-normal-dispersion fiber laser

Li Pan, Shi Lei, Sun Qing, Feng Su-Juan, Mao Qing-He

Chin. Phys. B . 2015, 24(7): 074207. **doi:** 10.1088/1674-1056/24/7/074207

1.12-W Q-switched Yb:KGW laser based on transmission-type Bi_2Se_3 saturable absorber

Liu Jing-Hui, Tian Jin-Rong, Hu Meng-Ting, Xu Run-Qin, Dou Zhi-Yuan, Yu Zhen-Hua, Song Yan-Rong

Chin. Phys. B . 2015, 24(2): 024215. **doi:** 10.1088/1674-1056/24/2/024215

SPECIAL TOPIC — Nanophotonics

Femtosecond Tm–Ho co-doped fiber laser using a bulk-structured Bi_2Se_3 topological insulator*

Jinho Lee(李珍昊) and Ju Han Lee(李周翰)†

School of Electrical and Computer Engineering, University of Seoul, Seoul 02504, Republic of Korea

(Received 24 May 2018; revised manuscript received 30 July 2018; published online 28 August 2018)

We experimentally demonstrate a femtosecond mode-locked thulium–holmium (Tm–Ho) co-doped fiber laser incorporating a saturable absorber (SA) based on a bulk-structured bismuth selenide (Bi_2Se_3) topological insulator (TI). The SA was prepared by depositing a mechanically exfoliated Bi_2Se_3 TI layer onto a side-polished optical fiber platform. Unlike high-quality nano-structured Bi_2Se_3 TI-based SA, bulk-structured Bi_2Se_3 with non-negligible oxidation was used as a saturable absorption material for this experimental demonstration due to its easy fabrication process. The saturation power and modulation depth of the prepared SA were measured to be ~ 28.6 W and ~ 13.4%, respectively. By incorporating the prepared SA into a Tm–Ho co-doped fiber ring cavity, stable soliton pulses with a temporal width of ~ 853 fs could be generated at 1912.12 nm. The 3-dB bandwidth of the mode-locked pulse was measured to be ~ 4.87 nm. This experimental demonstration reaffirms that Bi_2Se_3 is a superb base material for mid-infrared passive mode-locking even under oxidation.

Keywords: topological insulator, mode-locked lasers, femtosecond pulse, fiber lasers

PACS: 42.55.Wd, 42.60.Fc, 42.65.–k, 42.70.Mp **DOI:** 10.1088/1674-1056/27/9/094219

1. Introduction

Pulsed lasers operating at mid-infrared (IR) are promising light sources because they can be used in many practical applications, such as eye-safe light detection and ranging (LIDAR),[1] gas sensing,[2] free-space optical communication,[3] and laser surgery.[4] Recently, the use of optical fiber laser technique in the mid-IR spectral region exhibits several advantages over solid-state counterparts in terms of beam quality, reliability, and environmental stability.[5,6] To obtain sub-picosecond ultra-short pulses, mode-locking technique is commonly used. Mode-locking accomplished by locking relative phases of multiple longitudinal modes within the cavity is realized through two schemes: active and passive. To achieve passive mode-locking in a fiber laser, the key element is a saturable absorber (SA). Until now, commonly-used saturable absorbers have been based on III–V compound semiconductors because of their proven practical performance.[7] However, due to their limited operating bandwidth and the need for expensive fabricating facilities, many investigations have been searching for an alternative. In the past decade, carbon-based materials such as carbon nanotubes (CNTs),[8–15] graphene,[16–25] graphene oxide (GO),[26–31] and graphite[32–34] have been intensively investigated as alternatives. Recently, topological insulators (TIs),[35–52] transition metal dichalcogenides (TMDCs),[53–74] gold nanoparticles,[75–80] black phosphorus (BP),[81–84] filled skutterudites,[85] and MXene[86] have also been identified as efficient saturable absorption materials.

Among these saturable absorption materials, TIs have attracted a great amount of technical attention in the field of condense matters because they possess extraordinary charge and spin properties on the edge or surface.[87] TIs feature gapless metallic states on the surface due to band conversion by combination of strong spin–orbit coupling and time-reversal symmetry even if the bulk interior of the material exhibits insulating energy gaps. Two-dimensional (2D) topological insulator was theoretically predicted by Bernevig *et al.*[88] Mercury telluride (HgTe) quantum well structures were experimentally identified as a 2D topological insulator by König *et al.* in 2007.[89] After that, bulk crystal of $Bi_{1-x}Sb_x$, bismuth selenide (Bi_2Se_3), bismuth telluride (Bi_2Te_3), and antimony telluride (Sb_2Te_3) were subsequently confirmed to be three-dimensional (3D) topological insulators.

The potential use of TIs in the field of photonic applications as a saturable absorber was discovered by Bernard *et al.* in 2012.[35] Soon after that, intensive investigations on the use of TIs as saturable absorbers for *Q*-switching or mode-locking have been conducted.[35–52] TIs have small bandgap bulk and gapless surface. Therefore, ultrabroad saturable absorption could happen under the help of Pauli-blocking phenomenon. Intensive experimental investigations on the use of Bi_2Te_3 with a small energy bandgap (~ 0.15 eV) as an SA for *Q*-switching and mode-locking have been performed.[35–43] Re-

*Project supported by the National Research Foundation of Korea (NRF) Grant Funded by the Korea Government (MSIT), Republic of Korea (Grant No. NRF-2018R1A2B6001641), Ministry of Science and ICT (MSIT) under the Information Technology Research Center (ITRC) Support Program (Grant No. IITP-2018-2015-0-00385), and supervised by the Institute for Information and Communications Technology Promotion (IITP).

†Corresponding author. E-mail: j.h.lee@ieee.org

© 2018 Chinese Physical Society and IOP Publishing Ltd

cently, our group has conducted a series of studies on the use of bulk-structured Bi_2Te_3 TI as an efficient SA for a simplified fabrication process.[38–40] Bi_2Se_3 with an energy bandgap of $\sim$ 0.3 eV[90] also has a saturable absorption wavelength range from visible to mid-infrared (4.1 μm). As a result, many studies on saturable absorption of Bi_2Se_3 in the wavelength regions of 1 μm to 1.5 μm have been reported.[46–51] In 2014, Luo *et al.* demonstrated the use of a Bi_2Se_3 TI-based SA to *Q*-switched fiber laser in the wavelength region of 2 μm.[52] However, to the best of our knowledge, there has been no report on the use of a Bi_2Se_3-based SA for mode-locked fiber laser in 2 μm wavelength region. In 2018, our group performed a theoretical investigation about electronic band structures and optical properties of Bi_2Te_3 and Bi_2Se_3 using density functional theory (DFT) calculations[91] and confirmed that Bi_2Se_3 had an excellent potential as a saturable absorption material for mid-infrared laser mode-locking.[91]

In this paper, we experimentally demonstrate the use of an SA based on a bulk-structured Bi_2Se_3 TI for the generation of mode-locked femtosecond pulses from an all-fiberized cavity in 2 μm wavelength region as an ongoing study. Our SA was prepared by depositing mechanically exfoliated Bi_2Se_3 TI layer on top of the flat side of a side-polished fiber. Using the prepared SA within a thulium–holmium (Tm–Ho) co-doped fiber ring cavity, stable mode-locked pulses with a temporal width of $\sim$ 865 fs could readily be generated through evanescent field interaction between oscillated beam and bulk-structured Bi_2Se_3 TI layer at a wavelength of 1912 nm. To the best of our knowledge, this is the first study that demonstrates the use of an SA based on a bulk-structured Bi_2Se_3 TI layer for femtosecond mode-locking of a 2 μm fiber laser.

2. Fabrication and characterization of Bi_2Se_3-based saturable absorber

The starting material, Bi_2Se_3 bulk crystal (99.999%, Alfa Aesar), was commercially available. To prepare the Bi_2Se_3 TI layer, we used mechanical exfoliation method.[92] Using an adhesive tape, a thin layer Bi_2Se_3 was repeatedly stripped off from bulk crystal to obtain a micrometer-thick layer. Since our targeted thickness of the Bi_2Se_3 TI layer was at micrometer level, no special care was taken during the exfoliation process. The thickness of the Bi_2Se_3 TI film was measured to be $\sim$ 15 μm. It was measured using an alpha-step profiler. It is believed that the impact of the film thickness on the saturable absorption performance of our prepared bulk-structured Bi_2Se_3 TI-deposited side-polished fiber is negligible.[93] Figure 1(a) shows the scanning electron microscope (SEM) image of the Bi_2Se_3 TI film. We observed a clean surface without distinctive layered structures, indicating that our prepared Bi_2Se_3 TI film was bulk-structured rather than nanostructured. It should be noticed that the measured SEM image of the bulk-structured Bi_2Se_3 TI surface exhibits no distinctive layered structures unlike few-layered, nano-structured ones, as reported in Ref. [94] . Figure 1(b) shows measured Raman spectrum of the Bi_2Se_3 TI film. We observed three Raman optical phonon peaks: A^1_{1g} at $\sim$ 72 cm^{-1}, E^2_g at $\sim$ 130 cm^{-1}, and A^2_{1g} at $\sim$ 173 cm^{-1}. These three peaks are typical in bulk crystalline Bi_2Se_3.[51,94] It is well-known that A^1_{1g} peak redshifts in the nanosheets by $\sim$ 3 cm^{-1},[94] however, the sort of redshift was not observed in our prepared Bi_2Se_3 TI film. This confirms that our prepared Bi_2Se_3 layer is in a bulk crystalline state.

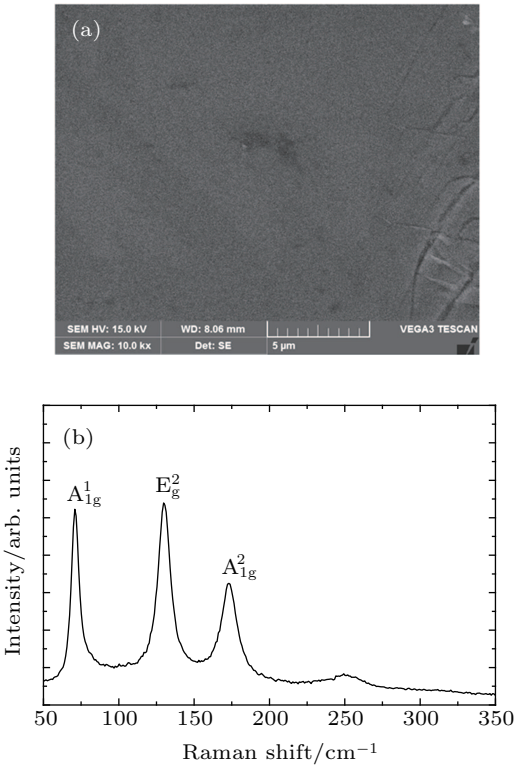


Fig. 1. Measured (a) SEM image and (b) Raman spectrum of Bi_2Se_3 film surface.

We then measured x-ray photoelectron spectroscopy (XPS) spectrum of Bi_2Se_3 layer. Figure 2(a) shows Bi 4f spectrum and figure 2(b) shows Se 3d spectrum. Two peaks at 157.8 eV and 163.2 eV in the Bi 4f region are consistent with reported values of binding energies of Bi $4f_{7/2}$ and Bi $4f_{5/2}$ while two small peaks at 53.3 eV and 54.1 eV in the Se 3d region are consistent with those of Se $3d_{5/2}$ and Se $3d_{3/2}$.[95,96] The existence of those additional peaks can be attributed to the oxidation of Bi and Se atoms on the surface.[95] Our group has recently demonstrated that the excellent potential of Bi_2Se_3 as a saturable absorption material for mid-infrared laser mode-locking cannot be negated by oxidation.[91]

For implementation of an all-fiberized SA, a side-polished fiber platform was used in this experiment. Side-polished fiber was prepared by polishing on side of SM2000 single mode fiber while the fiber was fixed onto a V-grooved

slide glass. The distance between the flat side and the fiber core was measured to be ∼ 7 μm as shown in Fig. 3(a). Beam propagation loss and polarization dependent loss (PDL) of the prepared side-polished fiber were measured to be ∼ 1 dB and ∼ 0.05 dB, respectively. The prepared Bi_2Se_3 layer was transferred together with scotch tape and placed onto the top flat surface of a side-polished fiber. We used a small amount of index matching oil onto the fiber flat surface to induce proper light coupling between the prepared Bi_2Se_3 film and the fiber core. The beam interaction length of the Bi_2Se_3 TI-deposited side-polished fiber was ∼ 2 mm. The insertion loss and polarization dependent loss of the Bi_2Se_3 TI-deposited side-polished fiber were significantly increased to ∼ 3.7 dB and ∼ 5.9 dB, respectively.

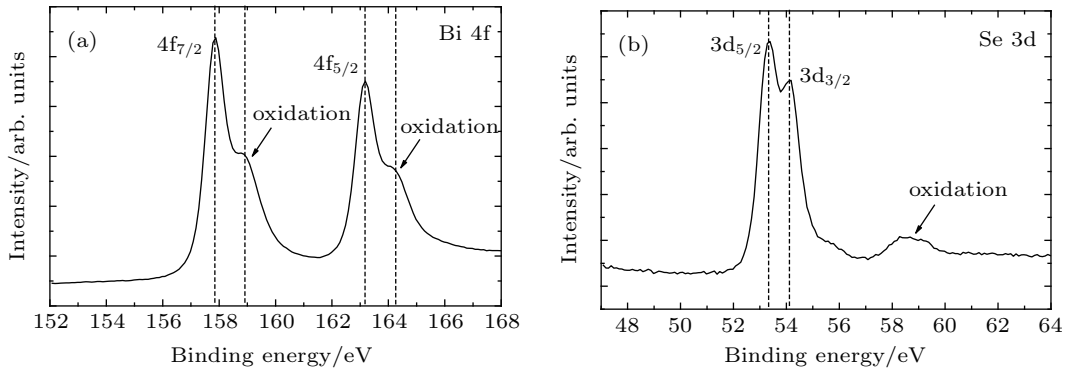


Fig. 2. Measured XPS spectra of (a) Bi 4f region and (b) Se 3d region.

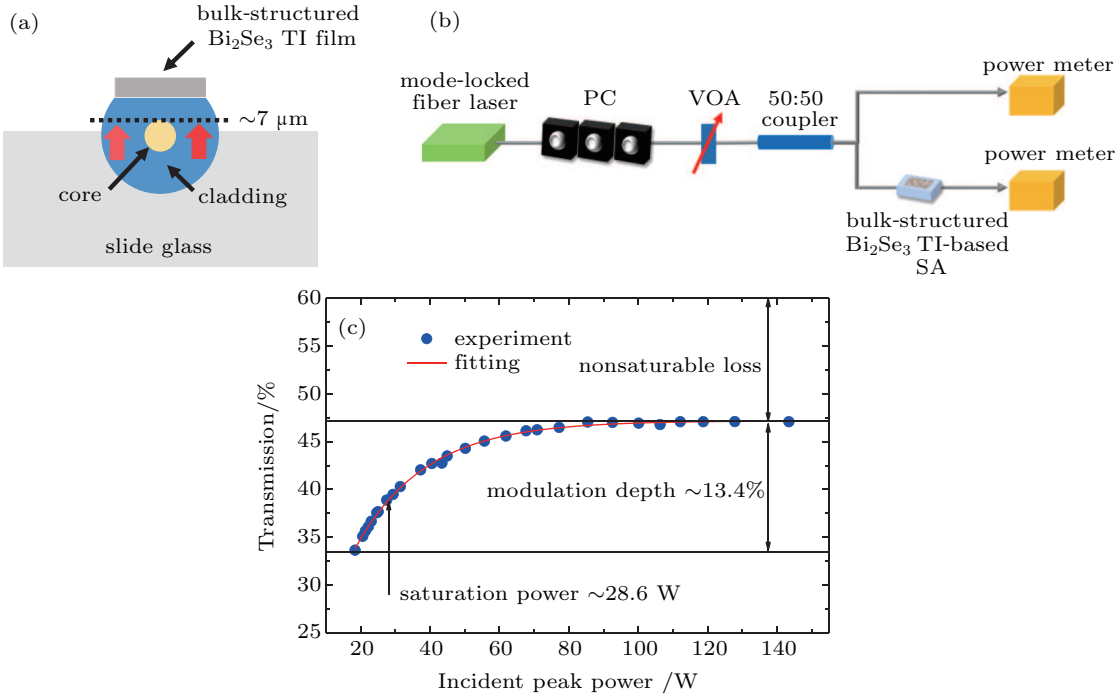


Fig. 3. (color online) (a) Schematic of the prepared Bi_2Se_3 TI-deposited side-polished fiber. (b) Measurement setup for nonlinear transmission curves of the bulk-structured Bi_2Se_3 TI-based SA. (c) Measured nonlinear transmission curve for TE-mode beam.

Next, we measured the nonlinear transmission curve of the Bi_2Se_3 TI-deposited side-polished fiber as a function of the incident optical pulse peak power to determine the nonlinear absorption performance. For the modulation depth measurements, we used a mode-locked, 1.9-μm fiber laser with a temporal width of ∼ 660 fs at a repetition rate of ∼ 36.9 MHz and the measurement setup is shown in Fig. 3(b). Since the prepared SA had a large polarization dependent loss of ∼ 5.9 dB, a polarization controller (PC) was incorporated into the setup to change the polarization status of the mode-locked optical pulses. A variable optical attenuator (VOA) was used to adjust the optical power of the mode-locked optical pulses. A 50:50 optical coupler was used to split the optical pulses into two ports. One of the two ports was connected to the prepared SA while the other was directly connected to a power meter to monitor the input optical power into the prepared SA.

Another power meter was used to monitor the output power from the SA for its comparison with the input power. Modulation depth measurements were performed for both transverse electric (TE) mode beam and transverse magnetic (TM) mode beams. Due to high PDL, no saturable absorption was observed for the TM mode. Figure 3(c) shows the measured nonlinear transmission curve for TE mode together with a fitting curve.[37] The saturation power and modulation depth of the prepared SA were estimated to be ~ 28.6 W and ~ 13.4%, respectively.

3. Laser configuration and mode-locking performance measurement

Figure 4 shows the experimental schematic of our constructed passively mode-locked fiber laser using the prepared SA. The gain medium was a 1-m-long Tm–Ho co-doped fiber (CorActive, TH512) with absorption of 13 dB/m at a wavelength of 1550 nm. The laser cavity consisted of a 1550/2000 nm wavelength division multiplexing (WDM) coupler, an optical isolator, a 90:10 coupler, a polarization controller, and a Bi_2Se_3-deposited side-polished fiber. A 1550-nm laser diode with a maximum pump power of ~ 297 mW was used as a pump source that entered the gain fiber via the 1550/2000 nm WDM coupler. The mode-locked laser output beam was extracted from the ring cavity using a 10% output port of a 90:10 coupler.

We monitored the laser output with a combination of a 16-GHz real-time oscilloscope and a 15-GHz photodetector while the pump power was enlarged. Stable mode-locked pulses were readily obtained at a pump power of 200 mW. The PC was properly adjusted to obtain stable mode-locked pulses. Since our prepared Bi_2Se_3 TI-deposited SA has a high polarization dependent loss, it is believed that both saturable absorption and nonlinear polarization rotation (NPR) contributed to the mode-locking of this laser.[97] The pump power range for the fundamental mode-locking was found to be between 200 mW and 297 mW. It is well known that stable mode-locking at a fundamental resonance frequency is broken by increasing the pump power due to multiple-soliton generation and soliton energy quantization effect.[98–100] It is also known that harmonically mode-locked pulses can be produced from a cavity since pulse splitting occurs when large photon energies exist within the cavity.[101] During our experiment, no harmonic mode-locking phenomenon was observed.

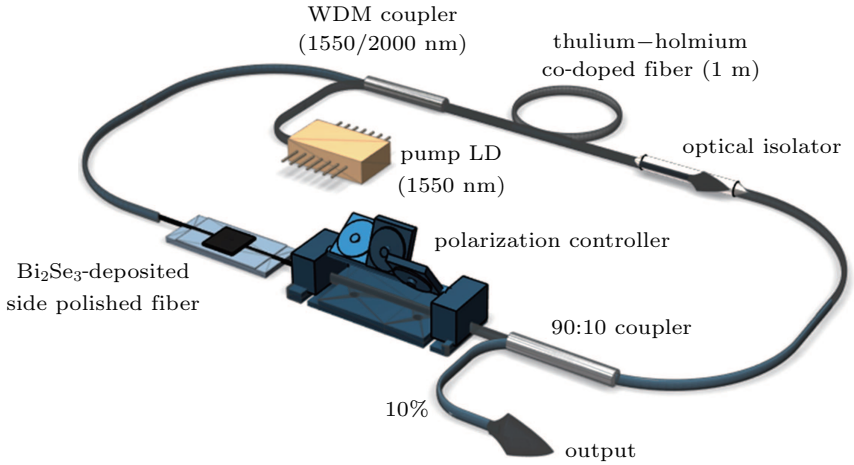


Fig. 4. (color online) Experimental configuration of our mode-locked fiber laser.

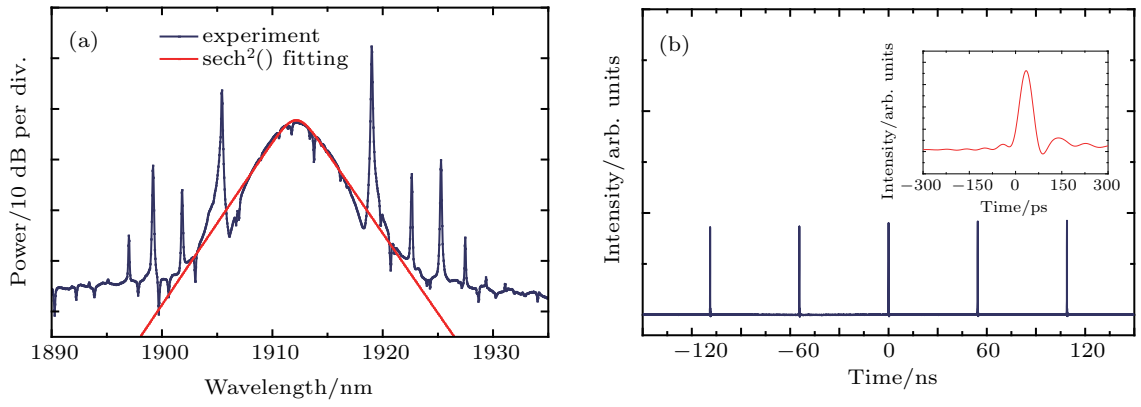


Fig. 5. (color online) Measured (a) optical spectrum and (b) oscilloscope trace of output pulses. Inset: oscilloscope trace for a narrow span.

Figure 5(a) shows the measured optical spectrum of the mode-locked pulses with its sech^2() fitting curve. The center wavelength and 3-dB bandwidth were measured to be ∼ 1912.12 nm and ∼ 4.87 nm, respectively. Figure 5(b) shows the measured oscilloscope trace of output pulses while the inset of Fig. 5(b) shows a magnified view of a single output pulse. The period of the output pulses was measured to be ∼ 54.5 ns, corresponding to a repetition rate of ∼ 18.37 MHz. This measured repetition rate coincided with the fundamental cavity resonance frequency.

Next, we performed the autocorrelation measurement using a second harmonic generation (SHG)-based autocorrelator. Figure 6(a) shows the measured autocorrelation trace of the mode-locked pulses with a sech^2() fitting curve. The pulse width was measured to be ∼ 835 fs. Considering the 3-dB bandwidth of ∼ 4.87 nm, the estimated time-bandwidth product was ∼ 0.337, which was slightly higher than the 0.315 of transform-limited sech^2() pulses, indicating that the output pulses were slightly chirped. Finally, the electrical spectrum was measured to check the phase noise of mode-locked pulses as shown in Fig. 6(b). A strong signal peak with an electrical signal-to-background ratio of ∼ 65 dB was clearly observed at a fundamental repetition rate of ∼ 18.37 MHz. The inset in Fig. 6(b) shows the electrical spectrum with a wide span for 1 GHz and the observed clean harmonic frequencies, confirming that the output pulses are stable mode-locked pulses. We have checked the long-term stability of the mode-locked fiber laser by measuring the output laser for several hours, but did not find any problem.

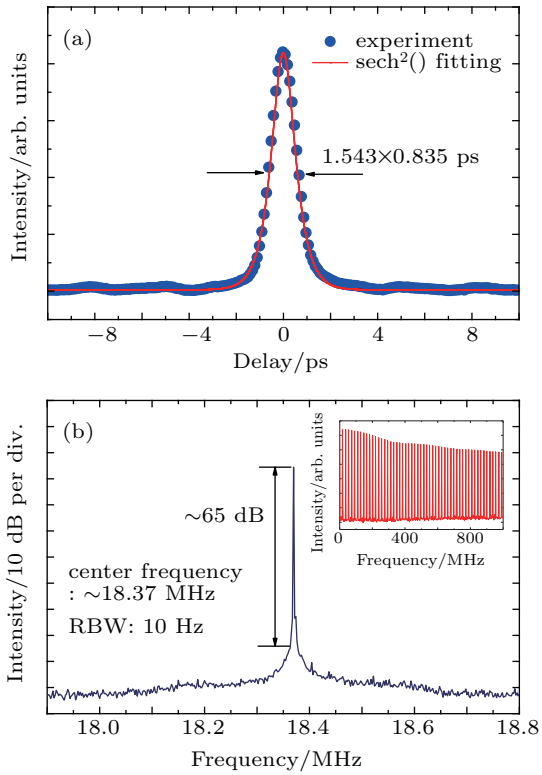


Fig. 6. (color online) Measured (a) autocorrelation trace and (b) electrical spectrum of output pulses. Inset: electrical spectrum for a span of 1 GHz.

Table 1. Output performance comparison between the present work and previous mode-locked fiber lasers using other saturable absorption materials at 2 μm wavelength region.

Saturable absorption materials	Fiber platform	Operating wavelength /nm	Modulation depth /%	Saturation level	Pulse width /ps	Ref.
CNTs	fiber ferrule	1930	NA[a]	NA[a]	2.05	[13]
CNTs	tapered fiber	1885	NA[a]	NA[a]	0.75	[14]
CNTs	fiber ferrule	1870	NA[a]	NA[a]	0.45	[15]
graphene	fiber ferrule	1940	NA[a]	NA[a]	3.6	[22]
graphene	fiber ferrule	1884	NA[a]	NA[a]	1.2	[23]
graphene	fiber ferrule	1935	4	NA[a]	2.1	[24]
graphene	fiber ferrule	1876	3.7	110 μJ/cm^2 [b]	0.603	[25]
GO	side-polished fiber	1910	NA[a]	NA[a]	NA[a]	[28]
GO	side-polished fiber	1950	7.1	∼ 14.83 W[c]	0.59	[29]
Bi_2Te_3	side-polished fiber	1935	20.6	∼ 29 W[c]	0.795	[39]
Bi_2Te_3	tapered fiber	1909.5	9.8	NA[a]	1.26	[41]
Sb_2Te_3	side-polished fiber	1945	NA[a]	NA[a]	0.89	[45]
MoS_2	HR gold mirror	1905	13.6	23.1 MW/cm^2 [d]	843	[58]
WS_2	side-polished fiber	1941	10.9	∼ 1.9 W[c]	1.3	[60]
$MoSe_2$	side-polished fiber	1912.6	4.4	∼ 25.7 W[c]	0.92	[68]
WSe_2	microfiber	1863.96	1.83	3.7 MW/cm^2 [d]	1.16	[71]
WTe_2	microfiber	1915.5	31	7.6 MW/cm^2 [d]	1.2	[74]
gold nanorod	fiber ferrule	1982	4.1	35.5 MW/cm^2 [d]	4.02	[78]
BP	fiber ferrule	1910	4.1	NA[a]	0.739	[83]
Bi_2Se_3	side-polished fiber	1912.12	13.4	∼ 28.6 W[c]	0.835	this work

[a]Not available, [b]saturation fluence, [c]saturation power, and [d]saturation intensity.

Finally, the output performance of our mode-locked fiber laser was compared to that of mode-locked fiber lasers using other saturable absorption materials at 2 μm wavelength region. Results are summarized in Table 1. The modulation depth of our Bi_2Se_3-based SA is almost comparable to the modulation depth (ca. 13.6%) of the MoS_2-based SA,[68] exhibiting a smaller modulation depth than Bi_2Te_3-based SA.[39] In terms of the pulse width, our laser exhibits a reasonable level of the output pulse width (835 fs) for femtosecond applications.

4. Summary and conclusion

In summary, we have experimentally demonstrated the use of a bulk-structured Bi_2Se_3 TI-based saturable absorber for the generation of femtosecond mode-locked pulses in the 2 μm wavelength region. The SA was constructed on a side-polished fiber platform by depositing a bulk-structured Bi_2Se_3 TI layer onto the flat side of the platform. Using the prepared SA within a Tm–Ho co-doped fiber ring cavity, stable optical pulses with a temporal width of $\sim$ 853 fs could readily be generated at $\sim$ 1912 nm.

Compared to nanostructured TI films that demand complicated high precision fabrication facilities, the fabrication process of bulk-structured TI films with non-negligible oxidation is practical and straightforward. This is a huge advantage of a bulk-structured TI-based SA. As a further study after our group's theoretical prediction in Ref. [91], this experimental demonstration reaffirms that a Bi_2Se_3 is a superb base material for mid-infrared passive mode-locking even under oxidation.

We believe that bulk-structured TI films should be able to provide a low-cost material platform for the implementation of practical saturable absorber, which are essential for industrial ultrafast lasers.

References

[1] Henderson S W, Suni P J M, Hale C P, Hannon S M, Magee J R, Bruns D L and Yuen E H 1993 *IEEE Trans. Geosci. Remote Sens.* **31** 4
[2] McAleavey F J, O'Gorman J, Donegan J F, MacCraith B D, Hegarty J and Mazé G 1997 *IEEE J. Sel. Top. Quantum Electron.* **3** 1103
[3] Ebrabim-Zadeh M and Sorokina I T 2008 *Mid-Infrared Coherent Sources and Applications* (Netherlands: Springer)
[4] Polder K D and Bruce S 2012 *Dermatol. Surg.* **38** 199
[5] Richardson D J, Nilsson J and Clarkson W A 2010 *J. Opt. Soc. Am. B* **27** B63
[6] Fermann M E and Hartl I 2013 *Nat. Photon.* **7** 868
[7] Keller U, Weingarten K J, Kärtner F X, Kopf D, Braun B, Jung I D, Fluck R, Hönninger C, Matuschek N and Aus der Au J 1996 *IEEE J. Sel. Top. Quantum Electron.* **2** 435
[8] Set S Y, Yaguchi H, Tanaka Y and Jablonski M 2004 *J. Lightwave Technol.* **22** 51
[9] Yamashita S, Inoue Y, Maruyama S, Murakami Y, Yaguchi H, Jablonski M and Set S Y 2004 *Opt. Lett.* **29** 1581
[10] Song Y W, Yamashita S, Goh C S and Set S Y 2007 *Opt. Lett.* **32** 148
[11] Kivistö S, Hakulinen T, Kaskela A, Aitchison B, Brown D P, Nasibulin A G, Kauppinen E I, Härkönen A and Okhotnikov O G 2009 *Opt. Express* **17** 2358
[12] Jung M, Koo J, Chang Y M, Debnath P, Song Y W and Lee J H 2012 *Laser Phys. Lett.* **9** 669
[13] Solodyankin M A, Obraztsova E D, Lobach A S, Chernov A I, Tausenev A V, Konov V I and Dianov E M 2008 *Opt. Lett.* **33** 1336
[14] Kieu K and Wise F W 2009 *IEEE Photon. Technol. Lett.* **21** 128
[15] Chernysheva M A, Krylov A A, Kryukov P G, Arutyunyan N R, Pozharov A S, Obraztsova E D and Dianov E M 2012 *Opt. Express* **20** B124
[16] Bao Q, Zhang H, Wang Y, Ni Z, Yang Y, Shen Z X, Loh K P and Tang D Y 2009 *Adv. Funct. Mater.* **19** 3077
[17] Sun Z, Hasan T, Torrisi F, Popa D, Privitera G, Wang F, Bonaccorso F, Basko D M and Ferrari A C 2010 *ACS Nano* **4** 803
[18] Song Y W , Jang S Y , Han W S and Bae M K 2010 *Appl. Phys. Lett.* **96** 051122
[19] Zhang H, Tang D, Knize R J, Zhao L, Bao Q and Loh K P 2010 *Appl. Phys. Lett.* **96** 111112
[20] Liu J, Wu S, Yang Q H and Wang P 2011 *Opt. Lett.* **36** 4008
[21] Ma J, Xie G Q, Lv P, Gao W L, Yuan P, Qian L J, Yu H H, Zhang H J, Wang J Y and Tang D Y 2012 *Opt. Lett.* **37** 2085
[22] Zhang M, Kelleher E J R, Torrisi F, Sun Z, Hasan T, Popa D, Wang F, Ferrari A C, Popov S V and Taylor J R 2012 *Opt. Express* **20** 25077
[23] Sobon G, Sotor J, Pasternak I, Krajewska A, Strupinski W and Abramski K M 2013 *Opt. Express* **21** 12797
[24] Wang Q, Chen T, Zhang B, Li M, Lu Y and Chen K P 2013 *Appl. Phys. Lett.* **102** 131117
[25] Sobon G, Sotor J, Pasternak I, Krajewska A, Strupinski W and Abramski K M 2015 *Opt. Express* **23** 9339
[26] Loh K P, Bao Q, Eda G and Chhowalla M 2010 *Nat. Chem.* **2** 1015
[27] Xu J, Liu J, Wu S, Yang Q H and Wang P 2012 *Opt. Express* **20** 15474
[28] Jung M, Koo J, Debnath P, Song Y W and Lee J H 2012 *Appl. Phys. Express* **5** 112702
[29] Jung M, Koo J, Park J, Song Y W, Jhon Y M, Lee K, Lee S and Lee J H 2013 *Opt. Express* **21** 20062
[30] Lee J, Koo J, Debnath P, Song Y W and Lee J H 2013 *Laser Phys. Lett.* **10** 035103
[31] Ko S, Lee J, Koo J, Joo B S, Gu M and Lee J H 2016 *J. Lightwave Technol.* **34** 3776
[32] Lin G R and Lin Y C 2011 *Laser Phys. Lett.* **8** 880
[33] Lin Y H and Lin G R 2012 *Laser Phys. Lett.* **9** 398
[34] Lee J, Lee J, Koo J and Lee J H 2016 *Appl. Opt.* **55** 308
[35] Bernard F, Zhang H, Gorza S P and Emplit P 2012 *Proc. Advanced Photon. Congress* June 17–21 2012 Colorado, United States, p. NTh1A.5
[36] Zhao C, Zhang H, Qi X, Chen Y, Wang Z, Wen S and Tang D 2012 *Appl. Phys. Lett.* **101** 211106
[37] Chen Y, Zhao C, Chen S, Du J, Tang P, Jiang G, Zhang H, Wen S and Tang D 2014 *IEEE J. Sel. Top. Quantum Electron.* **20** 0900508
[38] Lee J, Koo J, Jhon Y M and Lee J H 2014 *Opt. Express* **22** 6165
[39] Jung M, Lee J, Koo J, Park J, Song Y W, Lee K, Lee S and Lee J H 2014 *Opt. Express* **22** 7865
[40] Lee J, Jung M, Koo J, Chi C and Lee J H 2015 *IEEE J. Sel. Top. Quantum Electron.* **21** 0900206
[41] Yin K, Zhang B, Li L, Jiang T, Zhou X and Hou J 2015 *Photon. Res.* **3** 72
[42] Lee J, Koo J and Lee J H 2016 *Opt. Eng.* **55** 081309
[43] Lee J, Lee J, Koo J, Chung H and Lee J H 2016 *Opt. Eng.* **55** 076109
[44] Sotor J, Sobon G, Macherzynski W, Paletko P, Grodecki and Abramski K M 2014 *Opt. Mater. Express* **4** 1
[45] Tarka J, Boguslawski J, Zybala R, Kowalczyk M, Sobon G and Sotor J 2016 *Proc. SPIE 9728 Fiber Lasers XIII: Technology, Systems, and Applications* February 13–18 2016 California, United States, p. 972820
[46] Chen Y, Zhao C, Huang H, Chen S, Tang P, Wang Z, Lu S, Zhang H, Wen S and Tang D 2013 *J. Lightwave Technol.* **31** 2857
[47] Luo Z, Huang Y, Weng J, Cheng H, Lin Z, Xu B, Cai Z and Xu H 2013 *Opt. Express* **21** 29516
[48] Liu H, Zheng X W, Liu M, Zhao N, Luo A P, Luo Z C, Xu W C, Zhang H, Zhao C J and Wen S C 2014 *Opt. Express* **22** 6868
[49] Ahmad H, Salim M A M, Azzuhri S R, Soltanian M R K and Harun S W 2015 *Laser Phys.* **25** 065102
[50] Haris H, Harun S W, Muhammad A R, Anyi C L, Tan S J, Ahmad F, Nor R M, Zulkepely N R and Arof H 2017 *Opt. Laser Technol.* **88** 121
[51] Xu B, Wang Y, Peng J, Luo Z, Xu H, Cai Z and Weng J 2015 *Opt. Express* **23** 7674
[52] Luo Z, Liu C, Huang Y, Wu D, Wu J, Xu H, Cai Z, Lin Z, Sun L and Weng J 2014 *IEEE J. Sel. Top. Quantum Electron.* **20** 0902708

[53] Zhang H, Lu S B, Zheng J, Du J, Wen S C, Tang D Y and Loh K P 2014 *Opt. Express* **22** 7249

[54] Wang S, Yu H, Zhang H, Wang A, Zhao M, Chen Y, Mei L and Wang J 2014 *Adv. Mater.* **26** 3538

[55] Luo Z, Huang Y, Zhong M, Li Y, Wu J, Xu B, Xu H, Cai Z, Peng J and Weng J 2014 *J. Lightwave Technol.* **32** 4679

[56] Woodward R I, Kelleher E J R, Howe R C T, Hu G, Torrisi F, Hasan T, Popov S V and Taylor J R 2014 *Opt. Express* **22** 31113

[57] Wu K, Zhang X, Wang J and Chen J 2015 *Opt. Lett.* **40** 1374

[58] Tian Z, Wu K, Kong L, Yang N, Wang Y, Chen R, Hu W, Xu J and Tang Y 2015 *Laser Phys. Lett.* **12** 065104

[59] Mao D, Wang Y, Ma C, Han L, Jiang B, Gan X, Hua S, Zhang W, Mei T and Zhao J 2015 *Sci. Rep.* **5** 7965

[60] Jung M, Lee J, Park J, Koo J, Jhon Y M and Lee J H 2015 *Opt. Express* **23** 19996

[61] Khazaeinezhad R, Kassani S H, Jeong H, Park K J, Kim B Y, Yeom D I and Oh K 2015 *IEEE Photon. Technol. Lett.* **27** 1581

[62] Yan P, Liu A, Chen Y, Chen H, Ruan S, Guo C, Chen S, Li I L, Yang H, Hu J and Cao G 2015 *Opt. Mater. Express* **5** 479

[63] Lee J, Park J, Koo J, Jhon Y M and Lee J H 2016 *J. Opt.* **18** 035502

[64] Chen B, Zhang X, Wu K, Wang H, Wang J and Chen J 2015 *Opt. Express* **23** 26723

[65] Woodward R I, Howe R C T, Runcorn T H, Hu G, Torrisi F, Kelleher E J R and Hasan T 2015 *Opt. Express* **23** 20051

[66] Luo Z, Li Y, Zhong M, Huang Y, Wan X, Peng J and Weng J 2015 *Photon. Res.* **3** A79

[67] Koo J, Park J, Lee J, Jhon Y M and Lee J H 2016 *Opt. Express* **24** 10575

[68] Lee J, Koo J, Lee J, Jhon Y M and Lee J H 2017 *Opt. Mater. Express* **7** 2968

[69] Mao D, She X, Du B, Yang D, Zhang W, Song K, Cui X, Jiang B, Peng T and Zhao J 2016 *Sci. Rep.* **6** 23584

[70] Guo C, Chen B, Wang H, Zhang X, Wang J, Wu K and Chen J 2016 *IEEE Photon. J.* **8** 1503612

[71] Wang J, Lu W, Li J, Chen H, Jiang Z, Zhang W, Zhang M, Li I L, Xu Z, Liu W and Yan P 2018 *IEEE J. Sel. Top. Quantum Electron.* **24** 1100706

[72] Mao D, Du B, Yang D, Zhang S, Wang Y, Zhang W, She X, Cheng H, Zeng H and Zhao J 2016 *Small* **12** 1489

[73] Koo J, Jhon Y I, Park J, Lee J, Jhon Y M and Lee J H 2016 *Adv. Funct. Mater.* **26** 7454

[74] Wang J, Jiang Z, Chen H, Li J, Yin J, Wang J, He T, Yan P and Ruan S 2017 *Opt. Lett.* **42** 5010

[75] Jiang T, Xu Y, Tian Q, Liu L, Kang Z, Yang R, Qin G and Qin W 2012 *Appl. Phys. Lett.* **101** 151122

[76] Kang Z, Li Q, Gao X J, Zhang L, Jia Z X, Feng Y, Qin G S and Qin W P 2014 *Laser Phys. Lett.* **11** 035102

[77] Koo J, Lee J, Shin W and Lee J H 2015 *Opt. Mater. Express* **5** 1859

[78] Kang Z, Liu M Y, Gao X J, Li N, Yin S Y, Qin G S and Qin W P 2015 *Laser Phys. Lett.* **12** 045105

[79] Lee J, Koo J, Lee J and Lee J H 2017 *J. Lightwave Technol.* **34** 5250

[80] Lee J, Koo J and Lee J H 2017 *Laser Phys. Lett.* **14** 090001

[81] Chen Y, Jiang G, Chen S, Guo Z, Yu X, Zhao C, Zhang H, Bao Q, Wen S, Tang D and Fan D 2015 *Opt. Express* **23** 12823

[82] Park K, Lee J, Lee Y T, Choi W K, Lee J H and Song Y W 2015 *Ann. Phys.* **527** 770

[83] Sotor J, Sobon G, Kowalczyk M, Macherzynski W, Paletko P and Abramski K M 2015 *Opt. Lett.* **40** 3885

[84] Lu S B, Miao L L, Guo Z N, Qi X, Zhao C J, Zhang H, Wen S C, Tang D Y and Fan D Y 2015 *Opt. Express* **23** 11183

[85] Lee J, Yu B K, Jhon Y I, Koo J, Kim S J, Jhon Y M and Lee J H 2017 *Adv. Opt. Mater.* **5** 1700096

[86] Jhon Y I, Koo J, Anasori B, Seo M, Lee J H, Gogotsi Y and Jhon Y M 2017 *Adv. Mater.* **29** 1702496

[87] Hasan M Z and Kane C L 2010 *Rev. Mod. Phys.* **82** 3045

[88] Bernevig B A, Hughes T L and Zhang S C 2006 *Science* **314** 1757

[89] König M, Wiedmann S, Brüne C, Roth A, Buhmann H, Molenkamp L W, Qi X L and Zhang S C 2007 *Science* **318** 766

[90] Zhang H, Liu C X, Qi X L, Dai X, Fang Z and Zhang S C 2009 *Nat. Phys.* **5** 438

[91] Jhon Y I, Lee J, Jhon Y M and Lee J H 2018 *IEEE J. Sel. Top. Quantum Electron.* **24** 1102208

[92] Novoselov K S, Geim A K, Morozov S V, Jiang D, Zhang Y, Dubonos S V, Grigorieva I V and Firsov A A 2004 *Science* **306** 666

[93] Vinogradov E A 1996 *Laser Phys.* **6** 336

[94] Zang C, Qi X, Ren L, Hao G, Liu Y, Li J and Zhong J 2014 *Appl. Surf. Sci.* **316** 341

[95] Yan Y, Liao Z M, Yu F, Wu H C, Jing G, Yang Z C, Zhao Q and Yu D 2012 *Nanotechnology* **23** 305704

[96] Mao F, Guo J, Zhang S, Yang F, Sun Q, Ma J and Li Z 2016 *RSC Adv.* **6** 38228

[97] Bogusławski J, Soboń G, Zybała R, Mars K, Mikuła A, Abramski K M and Sotor J 2015 *Opt. Express* **23** 29014

[98] Renninger W H, Chong A and Wise F W 2010 *J. Opt. Soc. Am. B* **27** 1978

[99] Grudinin A B, Richardson D J and Payne D N 1992 *Electron. Lett.* **28** 67

[100] Tang D Y, Zhao L M, Zhao B and Liu A Q 2005 *Phys. Rev. A* **72** 013816

[101] Grudinin A B, Richardson D J and Payne D N 1993 *Electron. Lett.* **29** 1860