Preparation of Bi_2Te_3 Based on Saturable Absorption System and Its Application in Fiber Lasers

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Fiber laser is a fundamental component of laser systems and is of great significance for development of laser technology. Its pulse output can be divided into *Q*-switched and mode-locked. Achieving ultrashort pulse with narrower pulse duration and higher power is the focus of current research on mode-locked lasers. As an important component of fiber laser systems, saturable absorber (SA) can modulate losses in the optical cavity and generate pulses, enabling the laser system to achieve pulse output under long-term normal operating conditions better. Therefore, expanding the selection range of materials with better saturable absorption properties to improve the quality of pulse output is an important topic in current research. Here, the second generation topological insulator Bi_2Te_3 single crystal is prepared, and a ring fiber laser system is built with the Bi_2Te_3 SA. The mode-locked pulse with a pulse duration of 288 fs and a signal-to-noise ratio of 80.202 dB is realized. This result verifies that Bi_2Te_3, as a member of topological insulator, has good saturable absorption characteristics, and has broad prospects for the application research in lasers.

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Fiber lasers have the advantages of good beam quality, high reliability, and low cost, and are widely used in fields such as optical sensing,[1] laser processing,[2] laser medicine,[3] and materials science.[4] In recent years, ultrashort pulse lasers have attracted a great deal of attentions from scholars in the field of ultrafast optics due to their unique advantages such as narrow output pulse duration.[5–19] The realization of ultrashort pulse lasers can be divided into active mode-locking and passive mode-locking.[20–29] The former periodically modulates the phase or amplitude of the optical field by adding a modulator in the resonant cavity. When increasing the complexity of the resonant cavity and pulse broadening, it is difficult to generate stable ultrashort pulse. However, passive mode-locking technologies, such as nonlinear fiber ring mirror, nonlinear polarization rotation, low-dimensional nanomaterial saturable absorber, can generate ultrashort pulse by using the characteristics of gain material or saturable absorber, which has the advantages of high stability and low cost, and is most widely used in ultrashort pulse lasers.[30–42]

Saturable absorber (SA), as a passive mode-locking technology with some advantages, has been studied widely in recent years. How to achieve mode-locking is that the saturation absorption effect causes low intensity laser to be absorbed, while high intensity laser is continuously amplified, resulting in a series of pulses. With the further increase in laser demand towards higher power and shorter pulse duration, the demand for SA materials is also increasing.[9] The unique crystal structure of graphene endows it with properties of ultra-high carrier mobility, ultrafast broadband optical response, high flexibility, etc., making it an effective SA.[10] However, its low absorption rate limits its further application in lasers.[11] Topological insulators (TI) are a kind of nanoscale materials with Dirac cone structure. Their surface states are gapless metal states, so they have a higher modulation depth.[13] In addition, TIs inverse the strong coupling effect between the time symmetric spin orbit interaction and the protected surface state, which makes them have unique optical and photoelectric properties,[14] so they are considered to be the most likely alternative to graphene.

Bi_2Te_3 belongs to the second generation of TI, which has a hexahedral layered structure, and its thermoelectric properties show obvious anisotropy. Different layers of Bi_2Te_3 are connected by Te–Bi covalent bond with high bond energy, which ensures the stability of the sheet structure of the material. The different Fermi velocities of the crystals in different directions give Bi_2Te_3 unique advantages.[15] In 2009, Chen *et al.* investigated the Bi_2Te_3, and reported its characteristics. The test results show that the material has obvious characteristics of topological insulator. In addition, Bi_2Te_3 is very easy to produce and use in practical applications, not only can it be manufactured through existing mature semiconductor technology, but also its performance can be easily tuned. In 2016, Feng *et al.* conducted a study on the nonlinear optical properties of Bi_2Te_3. The Bi_2Te_3 crystal was excited by an 800 nm femtosecond pulse laser, and the nonlinear refractive index of the material reached the order of $10^{-14}\,m^2/W$ through theoretical calculations and experimental data fitting. This indicates that Bi_2Te_3 has excellent nonlinear optical properties and has broad prospects for applications in nonlinear optical devices.

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Bi_2Te_3 has been widely studied and applied in the field of thermoelectric materials, but research in the fields of nonlinear optics is still rare. Based on the above analysis, in this work, we prepare the Bi_2Te_3 single crystal and build a fiber laser based on the Bi_2Te_3 SA to achieve pulse output. We analyze the experimental data and compare it with the experimental data of other similar materials to explore the application value of the Bi_2Te_3 SA.

Preparation of Materials. In this experiment, the Bridgman crystal growth method and mechanical peeling method were used to prepare Bi_2Te_3 thin films,[16] and the preparation process is shown in Fig. 1. Firstly, the initial reactants were mixed with high-purity Bi (99.999%, Alfa Aesar) and Te (99.999%, Alfa Aesar) according to the ratio and placed evenly in an ampoule. The ampoule was then heated at 850 ℃ for 48 h, and the material inside the ampoule was melted at high temperature. Then, slowly cool the ampoule, and the material begins to crystallize at the bottom of the ampoule as the temperature decreases. By controlling the cooling rate, high-purity Bi_2Te_3 single crystals can be obtained.

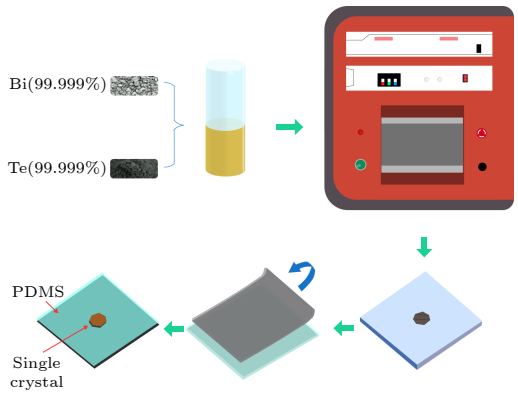

Fig. 1. Bi_2Te_3 thin film preparation process flow.

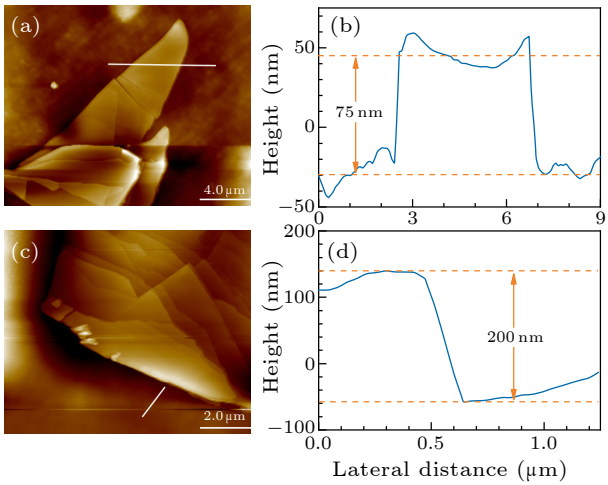

Fig. 2. Characterization of Bi_2Te_3 SA: [(a), (b)] AFM image and film thickness of 75 nm Bi_2Te_3 SA. [(c), (d)] AFM image and film thickness of 200 nm Bi_2Te_3 SA.

After obtaining Bi_2Te_3 single crystal, a polydimethylsiloxane (PDMS) film was applied to cover the Bi_2Te_3 single crystal, and then the PDMS film was quickly peeled off. Due to the excellent electrostatic adsorption ability and adhesion effect of PDMS, Bi_2Te_3 thin films can be obtained by quickly peeling off the PDMS film. The morphology and thickness of Bi_2Te_3 thin films can be observed with atomic force microscopy (AFM) shown in Fig. 2. As shown in Fig. 2(b), the randomly selected line from Fig. 2(a) suggests that the thickness is 75 nm. As displayed in Fig. 2(d), the cross-section height profile along the line in Fig. 2(c) indicates the thickness of 200 nm. Then, we made sandwich type saturable absorption devices from the dense and flat Bi_2Te_3 thin films for use in laser systems.

Experimental Setup. We build an erbium-doped fiber laser system with Bi_2Te_3 SA, and the device diagram is shown in Fig. 3. The laser system contains a pump operating at 980 nm, a wavelength division multiplexer (WDM), an erbium doped fiber (EDF), an optical coupler (OC), Bi_2Te_3 SA, an isolator (ISO), and a polarization controller (PC), with a ring cavity length of 530.7 cm. The light generated by the pump enters the laser cavity through a 980/1550 nm WDM and is amplified by EDF. We determined its length to be 36 cm based on the pump power. There is 20% of the light that is separated by the OC for observation of the working status and measurement of data. ISO is used to ensure unidirectional transmission of light, prevent reverse transmission of light from damaging optical components in laser systems, and has a certain degree of polarization adjustment ability. PC is used to further regulate the polarization state of light, making the state of the laser more stable. Bi_2Te_3 SA can modulate the loss in the optical cavity, which is conducive to achieving narrower pulse duration and higher power pulse output. Finally, using the following equipment, we completed the detailed exploration and characterization of laser: The waveform was observed and recorded by an oscilloscope (Tektronix DPO 3054). The pulse duration was observed and recorded by an autocorrelator (APE Pulse check). The optical spectrum was observed and recorded by a spectrum analyzer (Yoko-gawa AQ 6370 C). The spectrum of the pulse was observed and recorded by a radio frequency (RF) spectrum analyzer (Rohde & Schwarz FSW26).

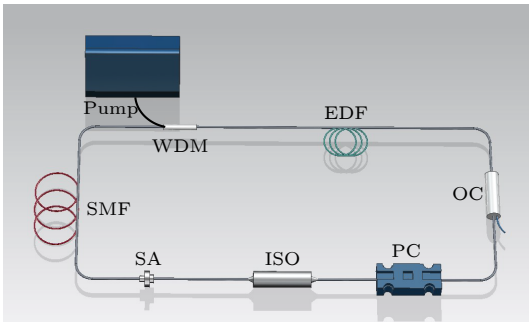

Fig. 3. Device diagram of mode-locked fiber laser.

Experimental Data Analysis. In this experiment, we tested the Bi_2Te_3 SA with a thickness of 200 nm. After multiple tests by turning on the pump, it was found that a mode-locked waveform can be obtained when the pump power is 173 mA, with a relatively low threshold. This indicates that the ring fiber laser can easily achieve stable mode-locked pulses, and we can measure its mode-locked pulse waveform through an oscilloscope (Fig. 4). We measured the pulse duration of the laser and fitted the sech^2

curve to obtain a pulse duration of 288 fs [Fig. 4(a)]. This data result is better compared to other experimental results of Bi_2Te_3 SA. Using an RF spectrometer, we obtained that the pulse is concentrated at a repetition frequency of 37.78 MHz, with a signal-to-noise ratio (SNR) of 80.202 dB [Fig. 4(b)]. To further verify the stability of the pulse, we measured the spectrum of the output pulse using a spectral analyzer [Fig. 4(c)]. The central wavelength of the spectrum is stable at 1566.60 nm, with a bandwidth of 25.20 nm. In addition, we recorded the optical spectrum every over 5 h. Especially, the spectral shape, spectral intensity, spectrum bandwidth remained unchanged over this time period, suggesting that the long-term stability is good. We calculated the time bandwidth product (TBP) using the following formula:

$$\mathrm{TBP} = c\frac{\Delta\tau\Delta\lambda}{\lambda^2}.$$

The TBP is 0.8872, which fully verifies the reliability of the mode-locked pulse output. Based on the above results, we found that the pulse output properties of Bi_2Te_3 SA mode-locked fiber laser are good. In order to further verify the value of further research and application prospects of Bi_2Te_3 as an SA material, we compare the experimental results in this work with other TI materials or other experimental results of the same material (Table 1).

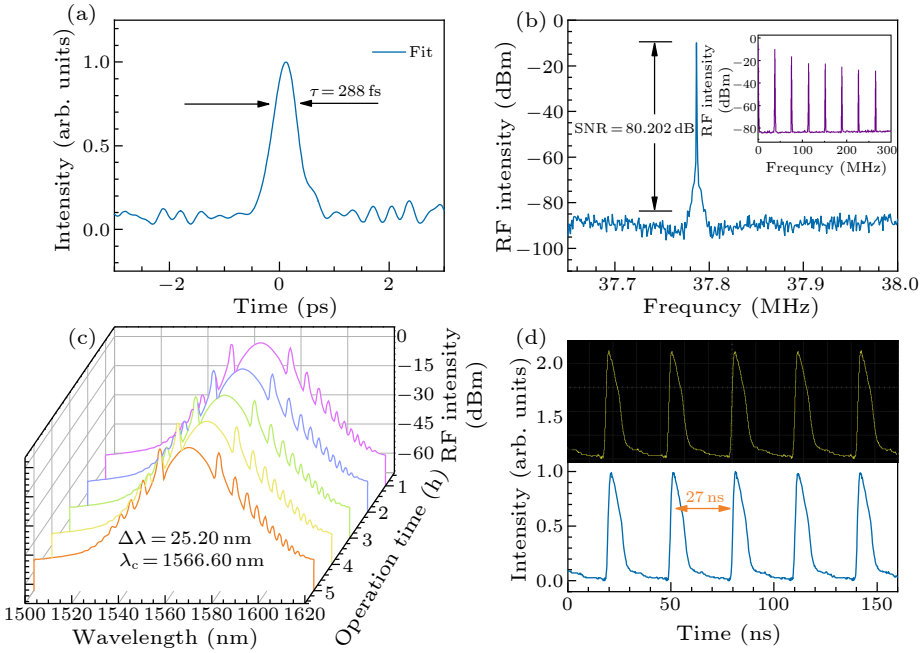

Fig. 4. Output characterization of a 200 nm Bi_2Te_3 SA mode-locked fiber laser: (a) pulse duration, (b) peak distribution in the RF spectrum, (c) femtosecond pulse output spectrum, (d) mode-locked pulse sequence.

Table 1. Comparison of pulse output data of TIs SA mode-locked fiber laser.

Materials	Pulse width (fs)	Pulse energy (nJ)	Energy conversion rate(%)	SNR (dB)	Repetition frequency (MHz)	Mode-locked threshold (mW)	References
Sb_2Te_3	1.32×10^3	283.84×10^3	0.51	61.21	10.88	307.6	20
Sb_2Te_3	380	32×10^{-3}	0.13	67	17.07	320	21
Sb_2Te_3	128	44.8×10^{-3}	0.3	65	22.32	80	22
Sb_2Se_3	890	4.19	9.36	57	22.36	390	23
Bi_2Se_3	210×10^3	0.83	5.5	49	32.68	125	24
Bi_2Se_3	579	0.112	1.1	54	14.25	60	25
Bi_2Se_3	398×10^6				0.527	105	26
Bi_2Te_3	1.63×10^3	0.259	1.98	80.1	13.5	44.9	27
Bi_2Te_3	230×10^3	0.599	0.43	77	1.44	200	28
Bi_2Te_3	317×10^3	2.8			19.8	230	29
Bi_2Te_3	505			67.7	13.14	63.7	30
Bi_2Te_3	288		3.6	80.20	37.78	173	This work

We find from analysis that the pulse duration of the Bi_2Te_3 SA mode-locked pulse in this work is narrower, and the SNR, mode-locked threshold and other data also perform well. Compared to Ref. [27], the pulse duration was shortened by one order of magnitude when the SNR was close.[27] Compared to Ref. [30] the SNR was also improved by 18.5% when the pulse duration was shortened by 43%. Overall, although the mode-locked threshold based on the Bi_2Te_3 SA fiber laser is slightly higher than that of the Bi_2Se_3 SA, it is still at a relatively low level,[20–30] which can be reduced to < 50 mW.[27] Then we conducted a theoretical analysis on the principle of good output per-

formance of the Bi_2Te_3 SA fiber laser. Due to the high nonlinear refractive index of Bi_2Te_3, strong self-interaction will occur when the laser passes through the Bi_2Te_3 SA, leading to strong nonlinear optical effects in the process of light transmission, such as self-focusing and self-phase modulation. Those nonlinear effects can cause the focusing and bunching of laser beams, thereby increasing the intensity of the light field in a small region, making it easier to achieve laser amplification and photon emission. Therefore, the high nonlinear refractive index of Bi_2Te_3 SA results in a shorter transmission distance of light, requiring less laser power or current to reach the mode-locked threshold. The experimental results, combined with Bi_2Te_3, have good bandgap (0.15 eV) and carrier concentration (1.2×10^{-19} cm^{-3}), which indicates that Bi_2Te_3, as a relatively new TI-like SA material, has good saturable absorption characteristics in the near-infrared band, which is conducive to achieving better pulse output.

In summary, we have introduced a mode-locked fiber laser based on the Bi_2Te_3 SA. Firstly, Bi_2Te_3 thin films have been prepared using the Bridgman crystal growth method and mechanical peeling method. Then, an erbium-doped fiber laser has been constructed based on the Bi_2Te_3 SA and successfully achieved mode-locked pulse. The pulse duration of this mode-locked pulse can reach 288 fs, with a repetition frequency of 37.79 MHz and an SNR of 80.202 dB. Compared with the experimental results of Bi_2Te_3 SA or other TI material SA fiber lasers, the present result has achieved certain optimization and improvement in pulse duration, SNR, mode locking threshold, etc. This work not only measured the nonlinear optical properties of the Bi_2Te_3 by combining the TI-material Bi_2Te_3 with fiber laser, but also theoretically analyzed the principle of Bi_2Te_3-SA mode-locked fiber laser system to achieve good pulse output. From the perspective of nonlinear refractive index, Bi_2Te_3 can be used as a good SA material for research and application in fiber lasers. Due to its excellent nonlinear optical properties, combined with its advantages of easy production, preparation, and tuning, Bi_2Te_3 can be further studied and developed in combination with fiber lasers, and has good application prospects in the field of nonlinear optics.

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