GENERATION OF Q-SWITCHED AND SOLITON MODE-LOCKED PULSES WITH BISMUTH TELLURITE SATURABLE ABSORBER

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We demonstrated Q-switched and soliton mode-locked pulses operating at 1569.51 nm and 1564.45 nm, respectively by using a newly developed Bismuth Telluride Polyvinyl Alcohol (Bi_2Te_3 PVA) film as saturable absorber (SA). By incorporating the SA into an Erbium-doped fiber laser (EDFL) cavity, Q-switched pulses were obtained within a pump power range from 101.90 to 175.82 mW. At the maximum pump power, the laser operated at repetition rate of 92.76 kHz and pulse width of 4.76 µs while producing the highest single pulse energy of 39.4 nJ. By incorporating an additional 200 m long single-mode fiber into the laser cavity, stable soliton mode-locked pulses were generated. It operated at repetition rate of 0.97 MHz with a pulse width of 2.97 ps and a signal-to-noise ratio (SNR) of 50.89 dB.

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1. Introduction

Q-switched and mode-locked fiber lasers have attracted tremendous research interest since the last decade due to their important roles in numerous applications including optical fiber communication, optical metrology, material processing and so on. They can be produced in various fiber laser cavities using either active or passive techniques [1,2]. Compared to active technique, passive technique based on saturable absorption of the material was simpler and preferable. Up to date, various materials such as carbon nanotubes [3], graphene [4], black phosphorus [5], metal oxides [6], transition metal dichalcogenides [7,8] and topological insulators (TIs) [9], have been intensively investigated as saturable absorber (SA). Among these materials, TIs have drawn more research interest since they exhibit a relatively large modulation depth, which can make saturable absorption becomes more efficient [10]. Furthermore, they have unique electrical and optical properties such as high nonlinearity, good thermal management, and fast relaxation time.

Bismuth Selenide (Bi_2Se_3) and Bismuth Telluride (Bi_2Te_3) are the most investigated TI materials especially on their electromagnetic properties [11,12]. Their optical properties are also equally interesting, but they were under very limited studies. Previously, Haris et al. demonstrated passively Q-switched and mode-locked fiber lasers using TI Bismuth Selenide (Bi_2Se_3) as SA operating at 1.55 µm region [13]. The Q-switched pulses operated at repetition rate and pulse width ranging from 23.5-68.2 kHz and 2.4-8.6 µs while the mode-locked laser produced pulses with repetition rate of 23.3 MHz and pulse width of 0.63 ps. In this paper, passively Q-switched and mode-locked Erbium-doped fiber lasers (EDFLs) are demonstrated using Bi_2Te_3 based SA to

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exploit its saturable-absorption characteristic. For this purpose, free-standing Bi_2Te_3 film was prepared by embedding the powder of this material into a polyvinyl alcohol (PVA) host. The film was integrated into an all-fiber EDFL cavity for generating Q-switched and mode-locked pulse trains

2. Preparation and optical characterization of SAs

In this work, a new film-based SA was developed based on Bi_2Te_3 material as the absorber material to integrate into an EDFL cavity for Q-switched and mode-locked pulse generations. The commercial few-layer Bi_2Te_3 powder (Sigma Aldrich) with molecular weight of about 800 g/mol was employed as the SA material. 1 g of the PVA powder was dispersed into de-ionized (DI) water (120 ml) with the assistance of a magnetic stirrer. 5 ml of the solution was then used a host polymer.

25 mg of Bi_2Te_3 powder was mixed into the PVA solution and stirred for about 3 hours. The mixture was then sonicated inside an ultrasonic bath for about an hour until the Bi_2Te_3 molecules are fully bond to the PVA. A thin film was formed by pouring the thoroughly mixed Bi_2Te_3 PVA solution onto a petri dish and left to dry.

The prepared thin film was characterized utilizing a Field-Emission Scanning Electron Microscope (FESEM). Fig. 1(a) shows the FESEM image showing high density of micro-rods and micro-grains, which were distributed randomly on the film surface. These micro-rods and micro-grains have irregular shapes with average diameter in a range of 0.5-1.9 µm. Fig. 1 (b) shows the real image of the fabricated film, which was placed onto a fiber ferrule. To confirm their optical saturable absorption property, the nonlinear optical response for the Bi2Te3 film was also investigated based on dual optical power meter techniques. The experimental setup is shown in Fig. 1(c). A homemade mode-locked laser operating at repetition rate of 17 MHz and pulse width of 900 fs was used as input light source. The output power of the laser is approximately 5 mW. The transmission curve was plotted as shown in Fig. 1(d). Based of this figure, the modulation depth, saturation intensity and non-saturable absorption were calculated to be 30%, 40 MW/cm^2 and 50%, respectively.

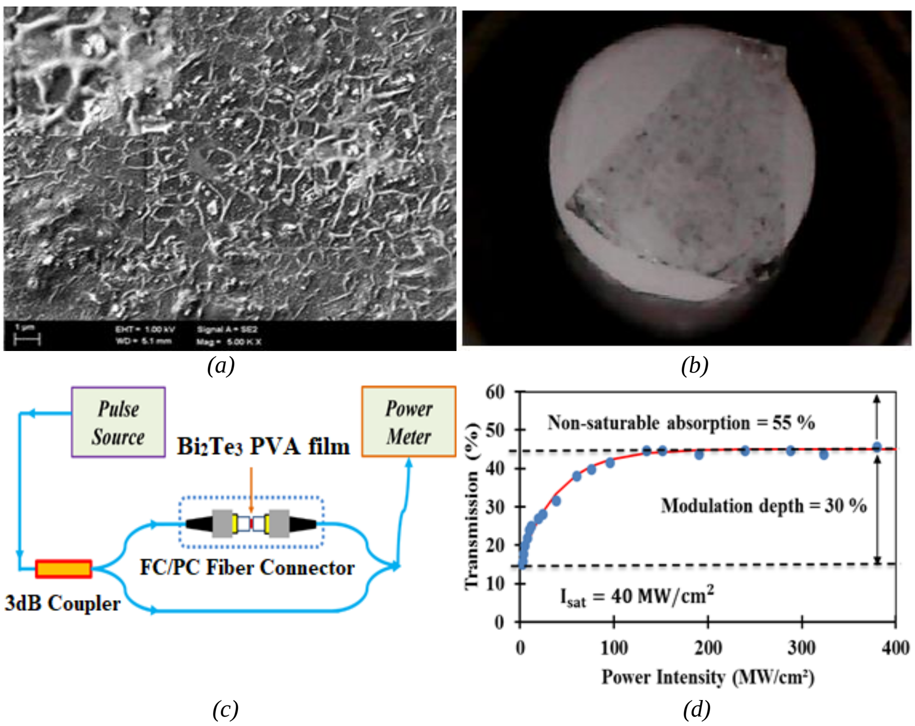

Fig. 1. Bi_2Te_3 characteristics (a) image of the SA film onto the fiber ferrule (b) FESEM image (c) the balance twin-detector measurement set up (d) nonlinear transmission curve.

3. Experimental setup

For laser test, all-fiber ring cavity was built as shown in Fig. 2. It consists of a 2.8 m long Erbium-doped fiber (EDF) as gain medium, an optical isolator, a SA device, a 10 dB output coupler and a 980/1550 nm wavelength division multiplexer (WDM) fiber. The EDF has a pump absorption rate of 23 dB/m at 980 nm with a core diameter of 4 µm and a numerical aperture of 0.16. It was forward pumped by a 980 nm pump laser through the WDM. The isolator was used to force the light propagation inside the cavity in forward direction and thus preventing any detrimental effects. The SA device was constructed by cutting the prepared Bi_2Te_3-PVA film, place it onto the fiber ferrule as shown in the inset figure and close the connection with another clean ferrule. The output coupler was used to couple out the output pulse from the ring resonator via 10% port of the coupler. The remaining 90% of oscillating laser was forced to turn back into the cavity for further oscillation. The laser cavity produced the Q-switched pulses, which the output power and spectrum were monitored with a power meter and an optical spectrum analyzer (OSA), respectively. A digital oscilloscope and RF spectrum analyzer were used in conjunction with a high-speed photodetector to monitor an output pulse train and electrical spectral characteristic, respectively. A 200 m long standard single-mode fiber (SMF) was added in the cavity to change the operation mode of the laser from Q-switching to mode-locking. The mode-locked pulses were realized due to the dispersion and nonlinearity characteristics inside the cavity, which was tailored by the inclusive of additional SMF. It is worthy to note that no pulses are obtained as the Bi_2Te_3-PVA film was removed from the laser cavity.

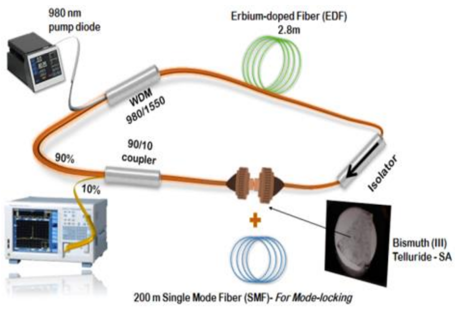

Fig. 2. The proposed Q-switched EDFL cavity with Bi_2Te_3 PVA film as a SA. The mode-locked pulses were generated with the addition of 200 m long SMF.

4. Results and discussion

The Q-switching performance was firstly investigated. The threshold pump power of the Q-switched laser was 101.9 mW, which is higher than the CW laser due to the insertion loss of the Bi_2Te_3 PVA film SA. The output spectrum of the Q-switched laser is shown in Fig. 3(a), which indicates the laser wavelength centered at 1569.51 nm. The repetition rate and pulse width were recorded by an oscilloscope as shown in Fig. 4(b). When the pump power increased from 101.90 to 175.82 mW, the pulse repetition rate increased from 67.11 to 92.76 kHz and the pulse width decreased from 6.34 to 4.76 µs. This is a typical phenomenon of Q-switched lasers. The typical oscilloscope trace is shown in Fig. 3(c) at 175.82 mW pump power, which indicates a repetition rate of 92.76 kHz. The stability of the Q-switched pulses was also investigated by measuring the RF spectrum as illustrated Fig. 3(d). We observed the fundamental frequency at 92.76 kHz, which is inline with the oscilloscope trace of Fig. 3(c) and other harmonic frequencies. The fundamental frequency has a signal to noise ratio of 51.25 dB, which indicates that the generated laser pulsing is very stable. The average output powers and single pulse energies versus pump power are given in Fig. 4. As the pump power was increased from the threshold of 101.90 mW to a maximum of 175.82 mW, the output power linearly increased from 2.41 to 3.66 mW, delivering a slope efficiency of 16.8 %. Under the pump power of 175.82 mW, the maximum achieved single pulse energy is up to 39.46 nJ.

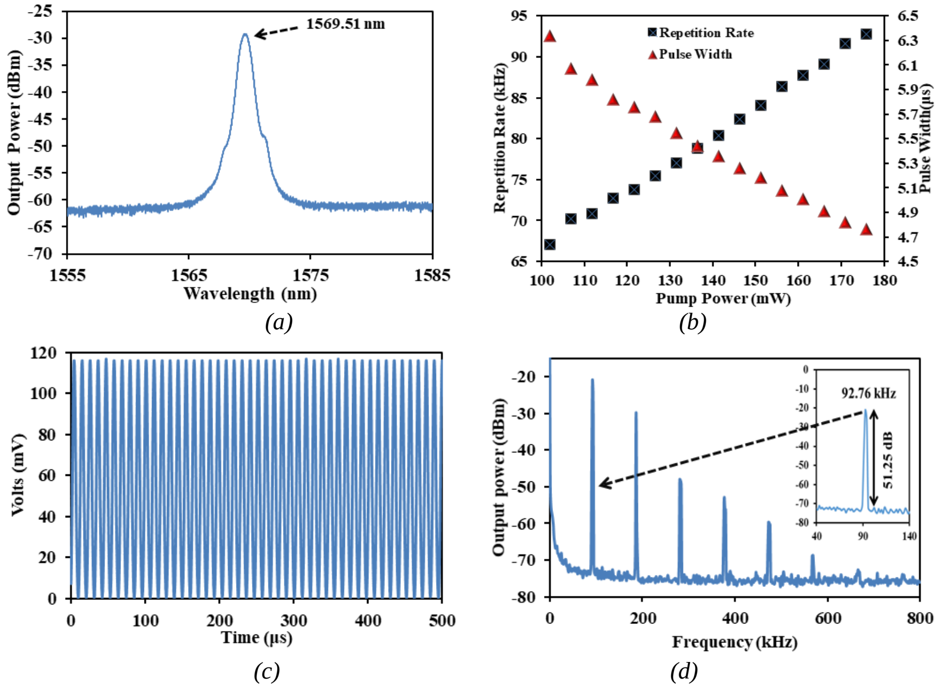

Fig. 3. Q-switching results (a) Output spectrum (b) repetition rates and pulse widths versus pump power (c) typical pulse train (d) RF spectrum

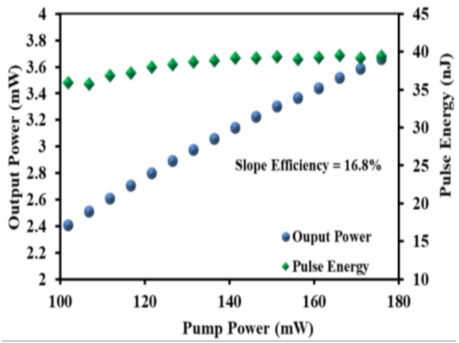

Fig. 4. Output power and pulse energy at various pump powers.

As 200 m long SMF was inserted into the laser cavity to modify the dispersion and nonlinearity characteristics, we obtained mode-locked pulses instead of Q-switched laser. Stable mode-locked pulses were self-started at the threshold pump power of 151.18 mW. Unlike the previous laser, the longitudinal modes inside the cavity are successfully locked in a fixed relationship via a mode-locking process. Thus it produces pulses with narrower width as compared to the Q-switched laser. The mode-locking operation was maintained up to pump power of 200.46 mW. At this pump power, average output power and pulse energy for the generated pulse is 5.77 mW and 5.97 nJ, respectively. Fig. 5(a) shows the output spectrum of the mode-locked pulses, which operates at 1564.45 nm. Kelly sidebands were also observed in the spectrum, which indicates the soliton pulses were generated. Soliton pulses were realized since the insertion of additional SMF has balanced the anomalous dispersion and self-phase modulation inside the laser cavity. The sidebands were formed due to the phase matching between the soliton pulses and the dispersive waves in the cavity. Fig. 5(b) shows the typical pulse train of the mode-locked pulses. The laser operated at repetition rate of 0.97 MHz, which corresponds to the total length of the cavity. Fig. 5(c) shows the typical autocorrelator trace of the soliton pulses, which was obtained to measure the actual pulse width. As seen, the experimental data follows the $sech^2$ fitting at the autocorrelator. The pulse width was approximately 2.97 ps while the time-bandwidth product (TBP) was calculated to be about 0.44. This value is larger than the theoretical value of 0.315 for the $sech^2$ profile of pulses. This indicates that the soliton pulses produced is slightly chirped. Fig. 5(d) illustrates the typical RF spectrum of the mode-locked laser. The signal-to-ratio value is more than 50 dB at the fundamental frequency of 0.97 MHz.

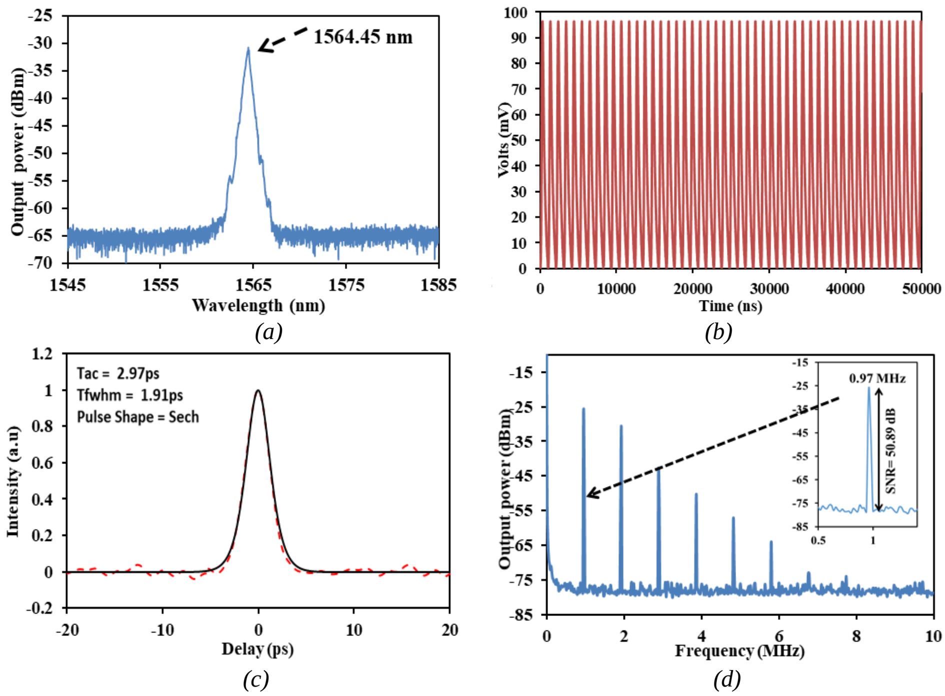

Fig. 5. Mode-locking performances (a) output spectrum with Kelly sidebands (b) typical pulse train (c) autocorrelator trace (d) RF spectrum

5. Conclusions

Stable Q-switched and mode-locked fiber lasers were successfully established using Bi_2Te_3 PVA film with 30% modulation depth as SA. Q-switched pulses operating at 1569.51 nm was demonstrated by incorporating the SA device inside an EDFL cavity. The repetition rate of the Q-switched pulses monotonically increased from 67.11 to 92.76 kHz while the pulse width reduced from 6.34 to 4.76 μs as the pump power increased from 101.90 to 175.82 mW. The pulse energy of 39.4 nJ was obtained at the maximum pump power. By adding 200 m long SMF into the current cavity, the laser operation was changed to mode-locking regime. The mode-locked laser generates soliton pulses with repetition rate of 0.97 MHz with a pulse width of 2.97 ps and a SNR of 50.89 dB.

Acknowledgements

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References

[1] A. F. El-Sherif, T. A. King, Optics communications **218**, 337 (2003).
[2] R. Woodward, R. Howe, G. Hu, F. Torrisi, M. Zhang, T. Hasan, E. J. R. Kelleher, Photonics Research **3**, A30 (2015).
[3] N. Kasim, A. H. H. Al-Masoodi, F. Ahmad, Y. Munajat, H. Ahmad, S. W. Harun, Chinese Optics Letters **12**, 031403 (2014)
[4] Q. Bao, H. Zhang, Y. Wang, Z. Ni, Y. Yan, Z. X. Shen et al., K. P. Loh, D. Y. Tang, Advanced Functional Materials **19**, 3077 (2009).
[5] A. A. Latiff, M. F. M. Rusdi, Z. Jusoh, M. Yasin, H. Ahmad, S. W. Harun, Optoelectron. Adv. Mat. **10**, 801 (2016).
[6] A. Nady, M. Baharom, A. Latiff, S. Harun, Chinese Phys. Lett. **35**, 044204 (2018).
[7] Z. Jiang, H. Chen, J. Li, J. Yin, J. Wang, P. Yan, Applied Physics Express **10**, 122702 (2017).
[8] H. Xia, H. Li, C. Lan, C. Li, X. Zhang, S. Zhang, Y. Liu, Optics Express **22**, 17341 (2014).
[9] C. Zhao, H. Zhang, X. Qi, Y. Chen, Z. Wang, S. Wen, D. Tang, Applied Physics Letters **101**, 211106 (2012).
[10] J. Sotor, G. Sobon, W. Macherzynski, K. M. Abramski, Laser Physics Letters **11**, 055102 (2014).
[11] L. Sun, Z. Lin, J. Peng, J. Weng, Y. Huang, Z. Luo, Scientific reports **4**, 1 (2014).
[12] R. Z. R. R. Rosdin, M. C. Paul, A. Dhar, S. Das, S. W. Harun, N. F. Razak, M. Yasin, Chalcogenide Letters **16**, 471 (2019)
[13] H. Haris, S. W. Harun, A. R. Muhammad, C. L. Anyi, S. J. Tan, F. Ahmad, R. M. Nor, N. R. Zulkepely, H. Arof, Optics & Laser Technology **88**, 121 (2017).