Bismuth (III) Telluride (Bi_2Te_3) embedded in PVA as a passive saturable absorber in a 2 micron region

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Received November 14, 2016; accepted December 21, 2016; published December 31, 2016

Abstract—We demonstrate passive Q-switching in a 2μm region by integrating Bismuth (III) Telluride (Bi_2Te_3) embedded in Polyvinyl Alcohol (PVA). Bi_2Te_3 was embedded in PVA by a solution casting approach to develop a Bi_2Te_3-PVA film and integrated in the laser cavity with a ring configuration to generate a pulse laser. The experimental works show that the proposed passive saturable absorber operates at input pump power ranges from 637mW to 784mW with a central wavelength of 1957.6nm. We observed a tunable repetition rate from 12.6kHz to 26.1kHz with the shortest pulse width of 2.22μs. The laser produces maximum instantaneous output peak power and pulse energy of 0.42W and 0.94μJ, respectively.

The first demonstration of Bi_2Te_3 as a passive saturable absorber (SA) for ultrafast laser generation was demonstrated by Zhao *et al*. [1] by using Bismuth (III) Telluride (Bi_2Te_3) dispersed in isopropyl alcohol and drop cast on a quartz plate. Since then, Bi_2Te_3 in acetone and bulk Bi_2Te_3 interaction with an evanescent wave has been reported for pulse laser generation in a mode-locked regime in a 1.5μm region [2-4]. Apart from that, Lin *et al*. [5] demonstrated mechanical exfoliation of bulk Bi_2Te_3 attached on a fiber connector for soliton compression in the same region [5]. The reported works on passive Q-switching employing Bi_2Te_3 as passive SA showed a wider operating wavelength at 1μm, 1.5μm, 2μm and 3μm [6-10] displaying the broadband operation of a topological insulator (TI). The integration of Bi_2Te_3 in the laser cavity is approached either by evanescent wave interaction [6-9], sandwiching [7-8] or free space coupling [10]. The TI based passive SA application in a 2μm region has only been reported by Lee *et al*. [9] using Bi_2Te_3 and Luo *et al*. [11] using Bismuth (III) Selenide (Bi_2Se_3). Luo *et al*. prepared a few layers of Bi_2Se_3 by liquid-phase exfoliation (LPE) and then mixed with a Chitosan acetic (CS-HAc) solution. The Bi_2Se_3 based SA was attached to the end of fiber ferrule using an optical deposition method with an input pump power of 20mW at 974nm for 30 minutes. The central wavelength of 1.98μm, with a maximum pulse energy of 313nJ, range of repetition rate from 8.4kHz to 26.8kHz and the shortest pulse width of 4.18μs is reported. Lee *et al*. [9] attached a bulk structured Bi_2Te_3 on the polished side of the fiber to generate a Q-switched pulse at a 1.89μm region using a Thulium (Tm)-Holmium (Ho) co-doped gain medium in the the fiber ring cavity. The generated pulse recorded maximum pulse energy of 11.54nJ, range of repetition rate from 35kHz to 60kHz and the shortest pulse width of 1.71μs. Both reported TI based SA at a 2μm region did not mention the signal-to-noise ratio (SNR) measurement to be compared with other previously reported SA of the same region. The use of bulk structured Bi_2Te_3 as passive SA is not efficient for scalable production of SA, the process is time consuming and the thickness is uncontrollable. In contrast, this work proposes a simpler approach in developing a Bi_2Te_3-PVA film as passive SA at 2μm using nano-engineered Tm-doped fiber [12]. The generated Q-switched pulse operated at a central wavelength of 1957.6nm, tunable repetition rate from 12.6kHz to 26.1kHz with the shortest pulse width of 2.22μs. The laser produces maximum instantaneous output peak power and pulse energy of 0.42W and 0.94μJ, respectively.

Bi_2Te_3 powder (Sigma Aldrich) characterized with −325 mesh and 99.99% trace metals basis with a molecular weight of 800.76g/mol was used as per received. To prepare the host polymer, 1g of PVA (Sigma Aldrich) was dissolved in 120ml de-ionized (DI) water with the aid of a magnetic stirrer at room temperature. TI based passive SA film was prepared by mixing 25mg of Bi_2Te_3 with 5ml of PVA suspension and thoroughly mixed with the aid of a magnetic stirrer for three hours. Then the Bi_2Te_3-PVA was placed in an ultrasonic bath for one hour to make sure the Bi_2Te_3 powder was fully binded with the binder (PVA). After that, the suspension was carefully poured onto a petri dish to avoid any air bubble formation and was left at room temperature for 48 hours to develop a Bi_2Te_3-PVA composite film. The developed film was

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characterized using a Field-Emission Scanning Electron Microscope (FESEM) as shown in Fig. 1, where it is clearly shown that the Bi_2Te_3 powder was thoroughly mixed with a PVA host polymer. The transmission characteristics of the developed film were further measured using a UV-VIS-NIR spectrophotometer (Perkin Elmer, Lambda 750) with a pure PVA film as reference. Figure 2 shows the transmission spectrum of the fabricated Bi_2Te_3-PVA film, demonstrating the transmittance of 20% in a 2µm region. The film can be also investigated in a 1µm and 1.5µm region showing the broadband properties of the TI of Bi_2Te_3 based passive SA as the structure of the TI is not affected by any host polymer [13].

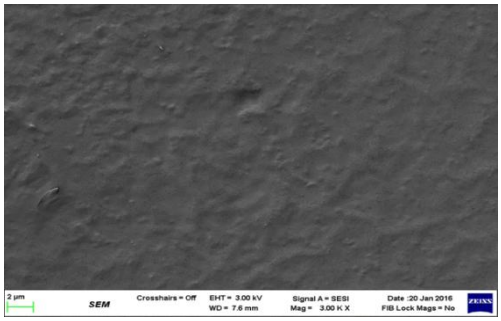

Fig. 1. FESEM image of Bi_2Te_3-PVA film.

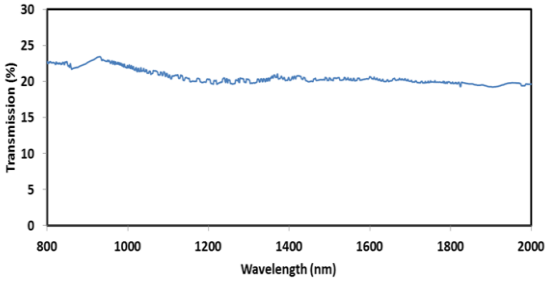

Fig. 2. Transmission spectrum of Bi_2Te_3-PVA film.

For fiber cavity integration, a small portion of the developed Bi_2Te_3-PVA is attached to the end of a fiber ferrule with the aid of index matching gel. This approach has been widely used in fiber cavity integration of other SA materials such as carbon nanotubes and graphene [14]. The experimental set-up to investigate the performance of the developed Bi_2Te_3-PVA film as passive SA in a 2µm region with nano-engineered Thulium-doped fiber (TDF) as a gain medium is illustrated in Fig. 3. The TDF of 7m length which operates at a 1.85÷2.0µm wavelength was pumped by a 1552nm pump via a 1550/2000nm wavelength division multiplexer (WDM). The parameters of TDF used in this work has a diameter core/cladding of 13.43/125µm with 0.21 NA, and absorption loss of 165dB/m at 793nm. To avoid any back reflection in the laser cavity, an isolator was placed after the gain medium and the use of an isolator could confirm that the generated pulse was due to a passive saturable absorber and not due to mode beating. The spectral and temporal performance of the generated pulse was tapped by a 90%/10% output coupler. While 90% of the light is propagated back into the laser cavity and the remaining 10% was characterized. The tapped output was connected to a 3dB coupler for simultaneous observation of the optical spectrum analyzer (OSA) /oscilloscope (OSC) and optical power meter (OPM)/Radio frequency spectrum analyzer (RFSA). A 7GHz photodetector was used to convert the light into electrical signals to be processed by a 500MHz oscilloscope (OSC) for pulse characterization. A small portion of the Bi_2Te_3-PVA film was placed in between the 90% coupler and the wavelength-division multiplexing (WDM). No pulse was observed when the Bi_2Te_3-PVA film was detached from the laser cavity.

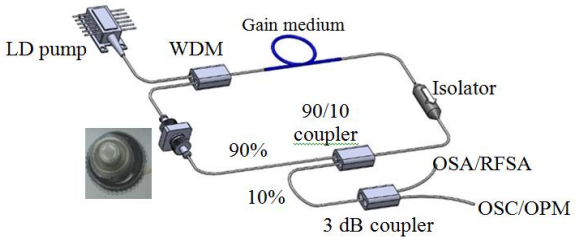

Fig. 3. Schematic of Q-switched TDFL.

The Q-switched regime occurred at a threshold incident pump power of about 638mW to the maximum input pump power of 785mW. The calculated pulse energy is in the range of µJ which is better than in the previously reported work [15] which is in nJ. Beyond the maximum power, the pulse laser is not observed, and upon inspection, we found that the film was dislocated from the original position on the fiber ferrule. When the film is attached back into the laser cavity, we could generate a pulse using the same film, which indicates that the film is not damaged. Figure 4 shows the optical spectrum of a Q-switched pulse at a maximum pump power of 785mW with a central wavelength of 1957.6nm and a 3dB spectral bandwidth of 0.3nm.

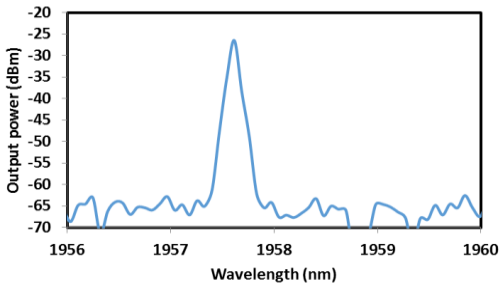

Fig. 4. OSA trace.

The measured oscilloscope traces for a maximum input incident pump power of 785mW is shown in Fig. 5 with fluctuation in peak intensity. To further analyze the evolution of a pulse circulated in the laser cavity with the changing pump power, the relation of the repetition rate and pulse width as a function of pump power is illustrated in Fig. 6. The graph shows that the repetition rate is proportional to the input pump power where the repetition rate increases from 13.51kHz to 27.7kHz with increasing pump power. As observed, the pulse width is inversely proportional to the input pump power where the pulse width is decreased from 4.52µs to 2.22µs. From the measured pulse repetition rate, pulse width and average output power, we calculated the pulse energy and peak power, the data being tabulated in Fig. 7. As shown, the calculated pulse energy increased proportionally with the input pump power from 0.74µJ to 0.94µJ. These values are considered higher compared to the previously reported works [9, 11, 16]. The calculated peak power also recorded the same trend from 0.16W to 0.42W when the input pump power was tuned from the threshold pump power to the maximum pump power. In order to verify the stability of the generated Q-switched pulse generation, the radio frequency was measured as plotted in Fig. 8. At the fundamental repetition rate of 25kHz with a signal-to-noise (SNR) ratio of 41dB, promisingly, the obtained SNR in this work is slightly better than the reported Q-switching in 2µm using graphene oxide based SA [16].

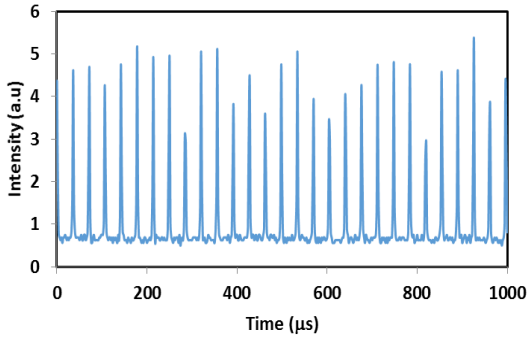

Fig. 5. Pulse train at 785 mW.

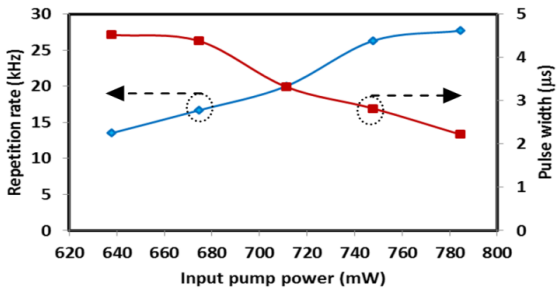

Fig. 6. Repetition rate and pulse width as a function of pump power.

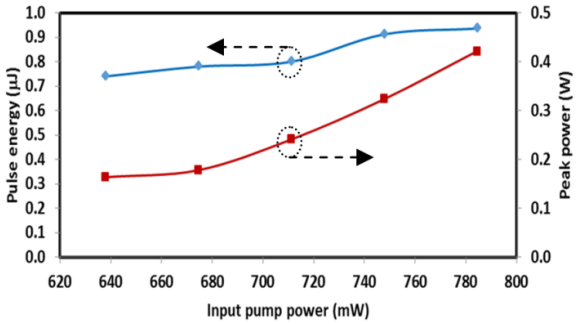

Fig. 7. Peak power and pulse energy as a function of pump power.

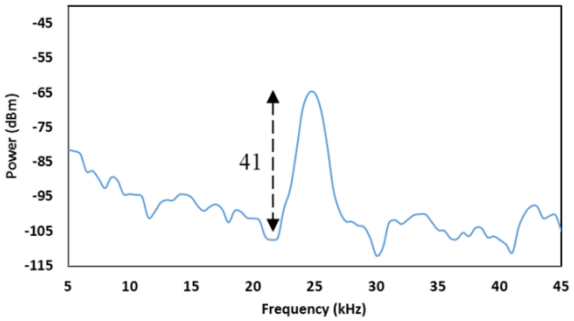

Fig. 8. RFSA measurement of first beat note at a repetition rate of 25 kHz .

A simple solution casting approach in fabricating Bi2Te3-PVA as passive saturable absorber at 2 micron region has been successfully demonstrated in this work.

References

[1] C. Zhao, H. Zhang, X. Qi, Y. Chen, Z. Wang, S. Wen, D. Tang, Appl. Phys. Lett. **101**, 211106 (2012).
[2] Z.C. Luo, M. Liu, H. Liu, X.-W. Zheng, A.-P. Luo, C.-J. Zhao, H. Zhang, S.C. Wen, W.-C. Xu, Opt. Lett. **38**, 5212 (2013).
[3] J. Lee, J. Koo, Y.M. Jhon, J.H. Lee, Opt. Expr. **22**, 6165 (2014).
[4] M. Jung, J. Lee, J. Koo, J. Park, Y.W. Song, K. Lee, S. Lee, J.H. Lee, Opt. Expr. **22**, 7865 (2014).
[5] Y.H. Lin, C.Y. Yang, S.-F. Lin, W.H. Tseng, Q. Bao, C.I. Wu, G.R. Lin, Laser Phys. Lett. **11**, 055107 (2014).
[6] J. Lee *et al.*, J. Optics **16**, 085203 (2014).
[7] Y. Chen *et al.*, IEEE J. Select. Topics in Quantum Electr. **20**, 315 (2014).
[8] M. Wu *et al.*, IEEE J. Quantum Electr. **50**, 393 (2014).
[9] J. Lee *et al.*, IEEE J. of Select. Topics in Quantum Electr. **21**, 31 (2015).
[10] J. Li *et al.*, Opt. Lett. **40**, 3659 (2015).
[11] Z. Luo *et al.*, IEEE J. Select. Topics Quantum Electr. **20**, 0902708 (2014).
[12] M.C. Paul, A. Dhar, S. Das, A.A. Latiff, M.T. Ahmad, S.W. Harun, IEEE Photonics J. **7**, 7100408 (2015).
[13] H. Liu *et al.*, Optics Expr. **22**, 6868 (2014).
[14] Z. Sun, T. Hasan, A.C. Ferrari, Physica E **44**, 1082 (2012).
[15] J. Lee, M. Jung, J. Koo, C. Chi, J. Lee, IEEE J. Select. Topics in Quantum Electr. **21**, 0900206 (2015).
[16] H. Ahmad, A.Z. Zulkifli, K. Thambiratnam, S.W. Harun, IEEE Photonics J. **5**, 1501108 (2013).

