Q-switched Thulium-doped fibre laser using Bismuth (III) Telluride-based saturable absorber

M F M Rusdi¹, X S Cheng², A A Latiff³, A H A Rosol¹, M T Ahmad¹, M F A Rahman¹, SW Harun¹

¹Photonics Engineering Laboratory, Department of Electrical Engineering, Faculty of Engineering, University of Malaya, 50603 Kuala Lumpur, Malaysia
²School of Engineering, KDU University College, Shah Alam, Selangor Darul Ehsan, Malaysia
³Faculty of Electronic and Computer Engineering, Universiti Teknikal Malaysia Melaka, 76100 Hang Tuah Jaya, Melaka, Malaysia
⁴Fakulti Teknologi Kejuruteraan Elektrik & Elektronik, Universiti Teknikal Malaysia Melaka, 76100 Hang Tuah Jaya, Melaka, Malaysia.

xs.cheng@kdu.edu.my

Abstract. We demonstrate a passive Q-switched thulium-doped fibre laser (TDFL) pulse generation using bismuth (III) telluride (Bi₂Te₃) thin film as saturable absorber. The Bi₂Te₃ was fabricated by a simple processing technique; simply by embedding the Bi₂Te₃ into the polyvinyl alcohol (PVA) film. By sandwiching 1 mm x 1 mm Bi₂Te₃ thin film between two fibre ferrules in a TDFL ring cavity, a stable Q-switching pulses train was generated. The repetition rate and pulse width were tuneable from 10.72 kHz to 39.9 kHz and 13.08 µs to 5.98 µs, respectively, as the pump power increased from 309 mW to 454 mW. The slope efficiency was 4.51%, while the maximum pulse energy was calculated as 0.17 µJ.

1. Introduction

Passively Q-switched pulsed fibre laser operating at 2-micron wavelength region have attracted growing attention in recent years as it can be used in various applications such as military, spectroscopy, medical surgery, and light detection and ranging (LIDAR) [1, 2]. Compared to an active Q-switched laser, the passive technique is more popular in the recent years, because of its dimension which is small in nature, cheap and easy in fabrication process, as well as can provide considerably high laser efficiency [3]. The passively Q-switched pulses can be generated by using a saturable absorber (SA), which modulates a continuous wave (CW) into a repeated pulses train. Up to date, many passive SAs have been demonstrated including semiconductor saturable absorber mirrors (SESAMs), single-wall carbon nanotube (SWCNT), carbon nanotubes (CNT), and two dimensional (2D) materials such as graphene, transition metal dichalcogenides (TMD), topological insulator (TI) and black phosphorus (BP) as well as other types of SA [4-12]. Among these materials, graphene has attracted much research interest due to its small band gap, sufficient modulation depth and efficiency saturable properties [13, 14].

Previously, passively Q-switched fibre lasers were demonstrated by using Bismuth (III) Selenide (Bi₂Se₃) and Bismuth (III) Telluride (Bi₂Te₃) SAs at 1.55 µm region [15-19]. In this paper, we demonstrated a passively Q-switched Thulium-doped fibre laser (TDFL) by incorporating Bi₂Te₃ thin film SA. The Bi₂Te₃ film SA was prepared by dissolving Bi₂Te₃ powder into PVA host solution. The formed thin film was then integrated into a ring cavity fibre laser for generating a self-pushed Q-switching pulses train.
2. Preparation and Characterization of Bi$_2$Te$_3$ SA
The Bi$_2$Te$_3$-SA was formed by a simple method process; where, 14 mg of Bi$_2$Te$_3$ powder with a molecular weight of 800.76 g/mol was dissolved in 5 ml of the polyvinyl alcohol (PVA) (Sigma Aldrich) solution using a magnetic stirrer for three hours. Then, the Bi$_2$Te$_3$-PVA solution was placed in the ultrasonic bath for about 10 minutes to ensure all the Bi$_2$Te$_3$ powder fully dissolved within the PVA. This process was repeated for a few times until the Bi$_2$Te$_3$-PVA solution fully dissolved. The prepared solution was then poured onto the petri dish. It was left to dry at a room temperature for 48 hours to form a Bi$_2$Te$_3$-PVA composite film. The Bi$_2$Te$_3$-PVA thin film was then cut into 1 mm x 1 mm dimension and sandwiched between two FC/PC fibre ferrules. The nonlinear optical profile of the Bi$_2$Te$_3$ film was investigated via a twin-balance detector measurement technique. A stable self-mode-locked fibre laser with a repetition rate of 1 MHz was used as an input laser source. A reference power for normalization was recorded as a function of incident intensity by varying the input power. Figure 1 shows the data obtained for the nonlinear absorption curve of Bi$_2$Te$_3$, where these data were fitted based on a simple two-level SA model; \[ T(I) = 1 - \alpha_0 \cdot \exp(-I/I_{sat}) - \alpha_{ns}, \] where \( T(I) \), \( \alpha_0 \), \( I \), \( I_{sat} \) and \( \alpha_{ns} \) stand for the transmission, modulation depth, input intensity, saturation intensity and non-saturable absorption, respectively [20]. The modulation depth and non-saturable absorption were measured to be 30% and 55%, respectively.

![Non-saturable absorption = 55](image)

**Figure 1.** Nonlinear absorption curve of the Bi$_2$Te$_3$ thin film SA.

3. Q-switched TDFL Experimental setup
The TDFL experimental setup is shown in Figure 2. The laser cavity consists of 1552 nm erbium ytterbium co-doped fibre laser (EYDFL) pump power, 1550/2000 nm wavelength division multiplexer (WDM), 5 m TDF as a gain medium and the optical coupler of 90/10. TDF used (Nuferm SM-TSF-9/125) has a core and cladding diameter of 9 µm and 125 µm respectively. The total cavity length of TDFL ring cavity is about 13.1 m and composed of single mode fibre (SMF) with the group velocity dispersion (GVD) of 80 ps$^2$/km at 1990 nm. To minimize the insertion loss in the cavity, all connections of fibre are directly spliced except for a joint, where to put the SA. The Bi$_2$Te$_3$ film SA was cut into 1 mm and 1 mm and then sandwiched between two FC/PC fibre ferrules. The 90/10 optical coupler splits the output laser into two, where 90% is circulated back into the ring cavity, while, 10% is used as the measurement output. The measurement devices used in this experiment consists of an optical spectrum analyzer (Yokogawa AQ6370B); to measure the optical spectra of the laser output, while, the pulses train and radio frequency (RF) spectra were measured via an oscilloscope (LeCroy Wavejet 352A) and RF spectrum analyzer (Anritsu MS2683A), respectively.
Figure 2. The proposed TDFL ring cavity experimental setup.

4. Result and discussion

Figure 3 shows the performance of Q-switched TDFL using the Bi$_2$Te$_3$ thin film as SA. A self-generated Q-switched TDFL appears as the pump power increase from the threshold of 309 mW to the maximum pump power of 454 mW. Figure 3(a) shows the optical spectrum of Q-switched TDFL at the threshold pump power. As illustrated, the blue color of the spectrum is a continuous-wave (CW) spectrum, while, the red color is a Q-switched TDFL spectrum, with each of them has a central wavelength of 1940.33 nm and 1968.99 nm, respectively. After the SA integrated into the TDFL ring cavity, the spectrum shifted to the left and this phenomenon is called as a blue shifted. Figure 3(b) shows the characteristic of the output power, that increases from 0.3 mW to 6.6 mW, when the pump power is increased. As shown, the pulse energy also increases from 0.03 µJ to 0.17 µJ. The slope efficiency obtained from the output power profile is measured as 4.51%. Figure 3(c) shows the pulse train of the Q-switched TDFL at the maximum pump power of 454 mW. The repetition rate is observed as 39.5 kHz. The insert of Figure 3(c) shows the enlargement image of the pulse train, where it can be seen, that the measured peak-to-peak is 26 µs. The fundamental frequency of the Q-switched TDFL with several harmonics is shown in Figure 3(d). At the maximum pump power of 454 mW, the signal-to-noise ratio (SNR) is measured as 38.73 dB. The fundamental frequency is obtained as 39.9 kHz, which confirms the validity of the obtained pulses train in the time domain (Figure 3(c)).
Figure 3. Performance of the Q-switched TDFL by using Bi$_2$Te$_3$ thin film SA. (a) Optical spectrum. (b) Output power and pulse energy (c) Pulse train in the time domain (d) RF spectrum.

5. Conclusion
We have demonstrated a passively Q-switched TDFL using Bi$_2$Te$_3$ thin film SA, which was obtained via a simple processing technique; by embedding Bi$_2$Te$_3$ elements into the PVA. The Q-switched TDFL self-generated at a threshold pump power of 309 mW and was centred at 1940.33 nm wavelength. The repetition rate was tuneable within a range of 10.72 - 39.9 kHz, as the pump power varied from 309 mW to 454 mW. This allowed the formation of a pulse width within a range of 13.08 - 5.98 µs. The maximum pulse energy was calculated as 0.17 µJ, while, the corresponding slope efficiency was obtained as 4.51%.

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