Full length article

Passively Q-switched Erbium-doped and Ytterbium-doped fibre lasers with topological insulator bismuth selenide (Bi$_2$Se$_3$) as saturable absorber

H. Haris$^a$, S.W. Harun$^{ab}$, A.R. Muhammad$^a$, C.L. Anyi$^b$, S.J. Tan$^c$, F. Ahmad$^d$, R.M. Nor$^e$, N.R. Zulkepely$^f$, H. Arofa$^a$

$^a$ Department of Electrical Engineering, University of Malaya, 50603 Kuala Lumpur, Malaysia
$^b$ Department of Physics and Astronomy, University of Canterbury, Christchurch 8140, New Zealand
$^c$ KDU University College, Sekyen U1, 40150 Shah Alam, Selangor, Malaysia
$^d$ Department of Electronic Systems Engineering, Malaysia-Japan International Institute of Technology (MJIT), University of Technology Malaysia, 54100 Kuala Lumpur, Malaysia
$^e$ Department of Physics, University of Malaya, 50603 Kuala Lumpur, Malaysia

A R T I C L E   I N F O

Keywords:
Q-switched
Topological insulator
Saturable absorber
Erbium doped fibre
Ytterbium doped fibre
Bismuth selenide

A B S T R A C T

This paper portrays a simple Q-switched Erbium-doped fibre (EDF) and Ytterbium doped fibre (YDF) lasers by using topological insulator (TI) Bismuth Selenide (Bi$_2$Se$_3$) as saturable absorber. The modulation depth of the fabricated Bi$_2$Se$_3$ is about 39.8% while its saturating intensity is about 90.2 MW/cm$^2$. By depositing the TI Bi$_2$Se$_3$ SA onto fibre ferrules and incorporate it inside the proposed cavity, a stable Q-switching operation was achieved at 1 $\mu$m and 1.5 $\mu$m. The fabricated Bismuth Selenide (Bi$_2$Se$_3$) as saturable absorber (SA) is a broadband SA where it offers a compact and low cost fabrication which is beneficial in various photonic applications.

1. Introduction

The demand for more efficient and cost effective Q-switched laser is growing day by day due to their endless applications in various field. For instance, pulsed lasers are used in laser surgical, tattoo removal and skin treatment in the medical field [1,2]. High peak power pulsed lasers are also used in metal cutting and drilling in the processing industry [2,3]. Other applications that utilized Q-switched lasers are remote sensing [4], optical data storage [5], optical communication [6] and the list goes on. Passively Q-switched lasers are more preferable than their active counterpart due to their advantages of compactness, simplicity and versatility [7]. Q-switching in laser can be achieved when an intensity modulator is incorporated into the laser cavity [8].

The most popular intensity modulator is the semiconductor saturable mirrors (SESAM) [9,10]. Although SESAMs are available in the market nowadays and can be purchased easily, but the major setback is that they are expensive due to their complicated fabrication [11]. There are also other types of saturable absorbers (SAs) such as metal-doped crystals [12], semiconductor quantum well structures [13] and erbium (Er) ions [14]. However, they often offer various drawbacks such as complex fabrication process, free space alignments and limited operation bandwidth.

In the past few years, novel SAs such as carbon nanotubes (CNTs) and graphenes were discovered where they exhibit advantages which were mentioned above such as ease of fabrication and low cost alternatives [15–18]. Nevertheless, CNTs based SA are limited by their limited wavelength dependent operation [19] while graphene based SA offers relatively low modulation depth [20]. Therefore, the search for new type of SAs is still an important research as we owe to discover SAs with properties such as wavelength-independent operation, large modulation depth, high damage threshold and most importantly, low cost.

Recently, there are several new SAs that are extensively being investigated. One of them are the transition-metal dichalcogenides (TMDs) such as molybdenum disulphite (MoS$_2$) [21], molybdenum diselenide (MoSe$_2$) [22] and tungsten disulphide (WS$_2$) [23]. This group of materials possess layer dependent properties and are excellent for optoelectronics and photonics applications. Another arising material, black phosphorus (BP) [24] whose basic structure is similar to bulk graphite is at the intense focus of researchers as it has direct energy bandgap structure regardless of thickness.

Apart from all the new SAs mentioned above, Dirac materials called topological insulator (TI) is also an interesting candidate for pulsed laser generation. TI was discovered to possess a large bandgap structure regardless of thickness. From all the new SAs mentioned above, Dirac materials called topological insulator (TI) is also an interesting candidate for pulsed laser generation. TI was discovered to possess a large bandgap structure regardless of thickness.

http://dx.doi.org/10.1016/j.optlastec.2016.09.015
Received 3 December 2015; Received in revised form 1 July 2016; Accepted 13 September 2016
0030-3992/ © 2016 Published by Elsevier Ltd.
lasers. SAs based on TI has lower saturation intensity and broad effective bandwidth compared to graphene. TIs are characterized as materials that have an insulating gap in the bulk while being gapless on the edge (surface) [27]. Examples of TIs are Mercury/Cadmium Telluride (HgTe/CdTe) quantum wells, Bi-Sb-alloys, Bi$_2$Se$_3$, and half-Heusler compounds [28]. Even though their unique electronic properties had been intensively explored, its nonlinear optics property is relatively fewer studied. The combination of the small bandgap bulk and the gapless surface allows TIs to possess broad bandwidth of saturable absorption operation. Bismuth Selenide (Bi$_2$Se$_3$) has relatively low saturation intensity [29] and this unique characteristic of Bi$_2$Se$_3$ can be a beneficial advantage to develop low-threshold pulsed lasers [30–32].

Bi$_2$Se$_3$ as a Q-switcher was demonstrated in [33–36]. Chen et al. [33] demonstrated Q-switched EDFL with pulse repetition rate from

---

**Fig. 1.** Preparation of TI Bi$_2$Se$_3$ SA (a) Bi$_2$Se$_3$ composite solution before ultrasonic bath (b) stable Bi$_2$Se$_3$ composite solution (c) Fibre ferrule in the TI suspension during optical deposition; (d) TI nanosheet were successfully deposited on the fibre core.

**Fig. 2.** (a) FESEM image of layered Bi$_2$Se$_3$; (b) Raman spectrum of layered Bi$_2$Se$_3$; (c) the bright island; (d) EDX spectrums for deposited Bi$_2$Se$_3$.

**Fig. 3.** Nearly flat linear absorption in the near-infrared wavelength band.
4.5 kHz to 12.9 kHz, pulse width of 13.4 μs to 36 μs and pulse energy from 11.8 nJ to 13 μJ. Luo et al. [34] presented that 1 μm Q-switched fibre in a linear cavity with repetition rate of 7–29 kHz, pulse width of 2–8 μs and pulse energy from 5 nJ to 16 nJ. On the other hand, Luo et al. [32] demonstrated the 2 μm Q-switched Ytterbium doped fibre with repetition rate from 8.4 kHz to 26.8 kHz, pulse width from 4 μs to 18 μs and pulse energy 0.1 μJ to 0.3 μJ. Chen et al. [33] demonstrated tunable wavelength Q-switched EDFL from 1510.9 nm to 1589.1 nm with repetition rate from 2 kHz to 12 kHz, pulse width from 14 μs to 49 μs and pulse energy from 0.9 μJ to 1.5 μJ.

In this paper, we demonstrate a simple, stable and widely tunable pulse repetition rate Q-switched Erbium doped fibre laser (EDFL) and Ytterbium doped fibre laser (YDFL) utilizing Bi2Se3 as SA at 1.0 and 1.5 μm regions. In the 1.5 μm region, the achieved pulse repetition rate can be tuned from 14.9 kHz to 62.5 kHz. The demonstrated repetition rate in this experiment is wider than the above mentioned works in [33–36]. Meanwhile in the 1.0 μm region, the obtained repetition rate and pulse width can be varied from 23 kHz to 47 kHz and 5 μs to 13 μs, respectively. This shows that our fabricated Bi2Se3 is a broadband SA, by producing stable Q-switched laser at both 1.0 and 1.5 μm regions. We first demonstrate the fabrication of Bi2Se3 as SA via optical deposition followed by a brief demonstration on the characterization of our Bi2Se3 SA. Finally, we demonstrate the achievement of Q-switching by incorporating Bi2Se3 as SA into the constructed cavities.

2. Fabrication and characterization of the TI Bi2Se3 SA

To prepare the exfoliated Bi2Se3, 5 mg of nano-sheet Bi2Se3 is dissolve in 50 ml isopropyl alcohol by using hot plate stirrer with the aid of magnetic stirrer for 24 h. The mixer is dispersed well with isopropyl alcohol and being ultra-sonicated for 6 h. Then, this mixture Fig. 1(a) is put into ultra-sonic bath (Branson 2510, 40 kHz) for about one hour to produce a stable Bi2Se3 composite solution as shown in Fig. 1(b). In this work, when 1480 nm laser diode at 50 mW was injected into the fibre, the fibre ferrule in the TI suspension started the optical deposition for about 20 min as shown in Fig. 1(c). Then it was moved out from the suspension to evaporate for 15 min. This process was repeated for three times to enhance Bi2Se3 adhesion. Ti nanosheet were successfully deposited on the fibre core as clearly seen from the Fig. 1(d).

In order to conveniently characterize the exfoliated Bi2Se3, we dropped the Bi2Se3 composite onto a cuprum plate by the spin-coating method, and then evaporating to dryness in an oven. Then, the field emission scanning electron microscopy (FESEM) measurement, Raman spectroscopy, and EDX analysis were performed on the sample and the results are presented in Fig. 2. As shown in Fig. 2(a), the FESEM image of exfoliated Bi2Se3 synthesized from Bi2Se nano-sheet which produce layers-like complex flakes. The thickness of the few-layer Bi2Se was measured to be around 3–4 nm. Fig. 2(b) shows the Raman spectrum from the Bi2Se3, which clearly indicates three peaks assigned with different vibrational modes based on Raman selection rules reported in [32]; A1g mode at 72 cm−1, E2g mode at 132 cm−1, and A1u mode at 173 cm−1. All these three peaks recorded within the scanned frequency range and agreed well with the previously reported experimental and calculated phonon vibration modes of Bi2Se3 [37–39]. The compositions of the deposit were analysed with EDX and shown in Fig. 2(c) and (d). Fig. 2(c) shows the enlarge image of the surface like an island and Fig. 2(d) shows the EDX spectrum of Bi2Se3. A linear and nonlinear absorption measurements were then carried out on the exfoliated Bi2Se3 sample. The nearly flat linear absorption in the near-infrared wavelength band in Fig. 3 clearly shows that the Bi2Se3 sample has a broadband optical response at the telecommunciation band. The nonlinear optical response property for the Bi2Se3 was investigated to confirm its saturable absorption by applying dual optical power meter technique. A self-constructed mode-locked fibre laser (1558.2 nm wavelength, 1.25 ps pulse width, 21.8 MHz repetition rate) is used as the input pulse source. Output power of mode-locked laser source was made adjustable by amplified it using our homemade EDFA through a variable optical attenuation (VOA). Fig. 4 shows the
nonlinear transmission curve. The curve was fitted with the following equation:

\[ T(I) = 1 - \left( \frac{\alpha_s}{1 + I/I_{sat}} \right) + \alpha_{ns} \]

where \( T(I) \) is the transmission, \( \alpha_s \) is the modulation depth, \( I \) is the input intensity, \( I_{sat} \) is the saturation intensity, and \( \alpha_{ns} \) is the non-saturable absorption. Upon fitting the measured experimental data by the above equation, we can conclude that the saturating intensity \( I_{sat} \) is about 90.2 MW/cm² and the modulation depth is about 39.8%. A laser of 0.1 W was injected into the Bi₂Se₃ that is deposited on the fibre ferrule. No optical damage is observed and this shows that the produced SA has high optical damage.

### 3. Experimental setup

Fig. 5(a) shows the experiment setup for our proposed Q-switched EDFL. The cavity is pumped by a 1480 nm laser diode and connected to a 1480/1550 nm wavelength division multiplexer (WDM) and output of the WDM is connected to a gain medium of 1 m Erbium doped fibre (EDF). The EDF we used in this experiment has a core and cladding diameters of 4 µm and 125 µm respectively, a numerical aperture of 0.16 and Erbium ion absorption of 23 dB/m at 1480 nm, Erbium concentration of 2000 ppm and a dispersion parameter of -21.64 ps/nm km at \( \lambda \) = 1550 nm. Our TI Bi₂Se₃ saturable absorber (TI Bi₂Se₃ – SA) that was deposited on the fibre ferrule is connected to another fibre ferrule and fusion spliced to one end of the gain medium and a polarizer controller (PC) respectively. Insertion loss of the Bi₂Se₃ – SA is measured to be 1.5 dB at 1550 nm. The PC was incorporated to adjust the polarization of the oscillating laser. The other end of the PC was connected to a 95/5 coupler where its 95% port is connected to an isolator while its 5% port is connected to another 50/50 coupler. Therefore, 95% of the light is retained inside the laser cavity and 5% of the light is tapped out from the output for measurement. The isolator is inserted inside our cavity to ensure unidirectional of the oscillating laser. The output is connected to a 50/50 coupler in order to measure the amplified spectrum emission (ASE) via an optical spectrum analyser (OSA) (Yokogawa AQ6370B) with a spectral resolution of 0.02 nm and monitor the Q-switched pulses via an oscilloscope (Tektronix TDS3052C) through a 1.2 GHz bandwidth photo-detector (Thorlab DET01CFC) simultaneously. Total cavity length is approximately 5.5 m.

The experiment was repeated by replacing the EDF with YDF. The experimental setup for Q-switched YDF is as shown in Fig. 5(b). The YDF used is of 1 m long, it has core and cladding diameters of 4 µm and 125 µm respectively, a numerical aperture of 0.16 and Ytterbium ions absorption of 23 dB/m at 1020 nm. The YDF was pumped by a 980 nm laser diode via a 980/1020 nm wavelength division multiplexer (WDM). TI Bi₂Se₃ saturable absorber (TI Bi₂Se₃ – SA) that was deposited on the fibre ferrule. The insertion loss of the SA was recorded as 1.4 dB at 1100 nm.
4. Result and discussion

Q-switching operation was observed from our proposed Q-switch EDFL at a pump power of 56 mW. Fig. 6 shows the output spectrum of our proposed Q-switched EDFL, with and without TI Bi$_2$Se$_3$ – SA, at the pump power of 56 mW. We observed the Q-switched emission spectrum (blue line) is operating at a broader spectrum with approximately 10 dBm higher intensity than the continuous wave (CW) of the laser emission (red line). The emission of EDFL with TI Bi$_2$Se$_3$ – SA is broader due to Q-switching operation which commences at this pump power. The observed lasing wavelength is shifted around 0.25 nm from 1560.58 nm to 1560.33 nm. The wavelength shift and higher intensity suffered by our proposed EDFL is due to the addition of TI Bi$_2$Se$_3$ – SA integration inside the cavity. Since the losses at shorter wavelength is fixed, the broadening of the lasing spectrum via self-phase modulation (SPM) and cross phase modulation (XPM) will force the center
wavelength to shift in order to aid in broadening the laser spectrum for Q-switching pulses to operate. The Q-switching operation is observed to be stable throughout the whole experiment as the pump power is raised to the maximum limit at 117.3 mW.

Fig. 7(a) shows the oscilloscope trace of our proposed Q-switched EDFL at the pump power of 117.3 mW. The measured peak to peak spacing \( t_{\text{ptp}} \) is 16 μs and this translates to a repetition rate of 62.5 kHz. A zoom in view at the oscillation trace (Fig. 7(b)) shows that the pulse duration is measured at approximately 2.1 μs. Moreover, the peak amplitude of the pulse is observed to be constant throughout the projection and this shows that the Q-switched pulse is stable at laboratory environment. The peak output power is 1.15 mW and the equivalent pulse energy is 2.104 nJ. Fig. 7(c) shows the RF spectrum of the Q-switched laser output which was measured by the radio frequency (RF) spectrum analyser. It shows a stable repetition rate of 62.5 kHz and peak-to-peak background ratio of about 40 dBm. This indicates the produced pulses are stable.

Fig. 8 illustrates the relationship between (a) repetition rate and (b) the pulse width against the pump power. The repetition rate of our proposed Q-switched EDFL can be tuned from 14.96 kHz to 62.5 kHz as the pump power is raised from 56 mW to 117.3 mW. In the meantime, the pulse duration varies between 2.1 μs to 7.56 μs within this range of pump power.

The relationship between the pulse energy and the peak power as the function of the pump power is depicted in Fig. 9(a) and (b). The peak power is showing a steady increasing pattern from 0.81 mW to 1.15 mW as the pump power is increased from 56 mW to 117.3 mW. The highest pulse energy obtained was 6.1 nJ at the pump power of 56 mW.

In a YDFL cavity, we start to observe stable Q-switching operation when the pump power is increased above 75 mW. Fig. 10 shows the comparison between output spectrum of the Q-switched YDFL with and without TI Bi\(_2\)Se\(_3\) SA when the pump power is fixed at 116.65 mW. Without the SA, the YDFL operates at a center wavelength of 1069.4 nm. However, the center wavelength of the laser is shifted to 1050.4 nm when we incorporate the TI Bi\(_2\)Se\(_3\) SA inside the cavity. This is attributed to the cavity loss of the ring cavity which increases with the incorporation of TI Bi\(_2\)Se\(_3\) – SA. In order to compensate for the loss, the laser operates at a shorter wavelength, approaching the peak absorption wavelength of the YDF. The laser was operating in continuous wave (CW) mode without the SA.

Fig. 11(a) shows the oscilloscope trace of our proposed Q-switched YDFL at the pump power of 116.15 mW. The measured repetition rate is 47.04 kHz and the constant peak to peak spacing is 21.3 μs. A zoom in view at the oscilloscope trace reveals that the pulse width is 5.89 μs. The output from the 50:50 coupler is also fed into the RF spectrum analyser to check the stability of pulse. The measured signal to noise ratio is 33 dBm at 47.04 kHz. Fig. 12(a) depicts the relationship between pulse width and repetition rate with pump power. As the pump power increases from 76 mW to 117 mW, the pulse width shows a decreasing trend, with 13.4 μs at 76 mW and 5.44 μs at 117 mW. On the other hand for repetition rate, the repetition rate increases from 23 kHz to 46 kHz. Fig. 12(b) shows the relationship of pulse energy and peak power with respect to pump power. Both pulse energy and peak power increase with pump power. The pulse energy increases from 63 nJ to 89 nJ while the peak power increases from 4.7 mW to 16.3 mW for the increment of pump power from 76 mW to 117 mW. The pulse energy for EDFL and YDFL showed different trending as the pulse energy depends on the rate of change of average power and repetition rate. Higher pulse energy can be obtained with YDFL.

5. Conclusion

A simple and stable erbium-doped and ytterbium-doped Q-switched fibre laser with Ti Bi\(_2\)Se\(_3\) – SA is achieved. The Ti Bi\(_2\)Se\(_3\) – SA has saturating intensity, \( I_{\text{sat}} \) about 90.2 MW/cm\(^2\) and the modula-
Acknowledgement

Authors acknowledge University Malaya and funding by Malaysian Ministry of Education for high impact research grant (Grant No: D000009-16001).

References


