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Generation of Microsecond Ytterbium-Doped Fibre Laser Pulses using Bismuth Telluride Thin Film as Saturable Absorber

(Penjanaan Denyutan Laser Gentian Mikrosaat Iterbium-Terdop yang Menggunakan Filem Nipis Telurida Bismut sebagai Penyerap Boleh Tepu)

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ABSTRACT

Bismuth telluride (Bi_2Te_3), a type of topological insulators, is currently in hot pursuit due to its unique physical properties. Therefore, this paper describes a simple Q-switched Ytterbium-doped fiber laser (YDFL) by using Bi_2Te_3 thin-film as saturable absorber. The few layers Bi_2Te_3 film was fabricated using optical deposition technique and subsequently, was used in an all-fiber, YDFL setup. As a result, a self-starting Q-switching pulses were first occurred when the laser pumping power reached 88.6 mW. As the pump power level increased, the observed pulses repetition rates had increased steadily from 17 to 29.63 kHz. Hence, this work demonstrated that Bi_2Te_3 thin-film can be used to successfully generate Q-switching pulses at 1-micron region and is well suited for many photonic applications operated at this wavelength region.

Keywords: Bi_2Te_3; optical deposition; Q-switched; saturable absorber; ytterbium fiber laser

ABSTRAK

Telurida Bismut (Bi_2Te_3), sejenis penebat bertopologi adalah sejenis bahan yang menjadi tumpuan kajian pada masa ini kerana keunikan sifat bahannya. Justeru, kertas ini menerangkan tentang kaedah mudah untuk menghasilkan denyutan laser rangkaian-Q berasaskan gentian optik iterbium (YDFL) dengan menggunakan filem nipis Bi_2Te_3 sebagai penyerap boleh tepu. Beberapa lapisan filem nipis Bi_2Te_3 telah dihasilkan dengan menggunakan kaedah pemendapan optik dan seterusnya digunakan dalam satu persediaan penghasilan denyutan laser YDFL dengan hanya menggunakan komponen gentian optik sahaja. Hasilnya, denyutan laser rangkaian-Q yang mula kelihatan apabila kuasa pengepam mencapai 88.6 mW. Kadar pengulangan denyutan laser didapati meningkat dengan berterusan daripada 17 kepada 29.63 kHz apabila tahap kuasa pengepam dinaikkan sedikit demi sedikit. Sebagai kesimpulan, hasil kajian ini telah menunjukkan bahawa filem nipis Bi_2Te_3 dengan jayanya telah dapat menjana denyutan laser rangkaian-Q pada rantau 1-mikron dan keputusan ini telah membuka peluang dan sesuai digunakan dalam banyak aplikasi fotonik yang beroperasi pada panjang gelombang ini.

Kata kunci: Bi_2Te_3; laser gentian optik iterbium; pemendapan optik; penyerap boleh tepu; rangkaian-Q

INTRODUCTION

Passively Q-switching pulsed laser has attracted remarkable attention lately due to widespread and useful photonics applications in the area of material processing, optical imaging and high-speed communications. The generation of Q-switched pulsed laser by incorporating few layers of saturable absorber (SA) into a ring laser cavity is a well-known method due to its simple technique, low development cost, and flexibility (Ahmad et al. 2016). The saturable absorber or ‘Q-switcher’ (Bao et al. 2009; Keller et al. 1996) plays an important role to generate stable Q-switching optical pulses, including high power pulses generation (Razak et al. 2016). In recent years, carbon-based materials, for example carbon nanotube (CNT) and graphene thin films, have been widely used as SAs in order to generate optical pulses. In fact, CNT (Salim et al. 2018) and graphene (Bao et al. 2009) were found to give significantly improved results compared to the SA that is based on semiconductor saturable absorber mirror (SESAM) (Keller et al. 1996). SESAM has been the most widely used SA for few decades. However, SESAM is expensive, requires complex fabrication process, and prone to damage due to its Q-switching instabilities. The use of CNT, on the other hand, has been limited by a complex bandgap control, which prevent saturable absorption to occur at certain wavelength (Bao et al. 2009). Meanwhile, graphene has a relatively small optical absorption and low modulation depth (Bao et al. 2009). Therefore, extensive research work has been conducted to seek for new materials with efficient and effective performances as SA and possesses the following ideal characteristics: Low-cost fabrication process, wavelength-independent, large modulation depth, and high threshold damage.

Recently, topological insulators (TIs) (Bernard et al. 2012) have emerged as new alternatives SAs. TI SA such as bismuth selenide (Bi_2Se_3) (Ahmad et al. 2015; Zhao et al. 2012) and bismuth telluride (Bi_2Te_3) (Pinghua et al. 2013), have been extensively investigated for their performance in generating mode-locked and Q-switched pulses. Bismuth telluride is a new type of quantum electronic material, which behaves as a metal at the outer surface but in contrast, behaves as insulator at the inner layer (Chen et al. 2009; Zhang et al. 2009). The Bi_2Se_3 with 0.2-0.3eV non-trivial energy gap, indicates a saturable absorption effect at shorter wavelength than 4.1 µm (0.3eV) (Zhang et al. 2009). These materials obey Pauli's blocking principle (Zitter 1969), which stated that two or more identical fermions cannot occupy the same quantum state. The improvements of TIs have been demonstrated successfully through various publications in recent years. TIs have recorded as much as 98% of modulation depth, as reported by Zhao et al. (2012), which makes them practical and reliable SAs. Moreover, Luo et al. (2013) reported that TIs does have broadband absorption. Furthermore, TIs have added advantages in terms of simple fabrication process, low development cost, low saturation intensity, and broad effective bandwidth. Recently, researchers discovered that the nonlinear absorption property of Bi_2Te_3 could become transparent under strong illumination effect (Bernard et al. 2012). The operation of the Bi_2Te_3 based SAs have been extensively proposed in erbium doped fiber lasers (EDFL) for Q-switching operation (Chen at al. 2014; Harun et al. 2017; Li et al 2014; Luo et al. 2013). However, there are only few reports available for Q-switching operation at 1 micron region utilizing the Bi_2Te_3 based SA (Lee et al. 2014). Therefore, due to this limitation, this work is focused in bridging this research gap. The optical deposition technique that was used to fabricate SAs has been demonstrated through various work such as by using graphene oxide (Ahmad et al. 2012), single wall CNT (Mohamed et al. 2017), graphene (Luo et al. 2012) and Bi_2Te_3 (Chen et al. 2014). However, those work focus at wavelength of 1550 nm, using erbium fiber laser, which are different from the 1-µm region. Passive Q-switched ytterbium fiber lasers using Bi_2Te_3 have also been reported, such as in our previous work (Salim et al. 2017). It generated dual-wavelength Q-switched laser pulses by using photonics crystal fiber (PCF). Other works in this aspect used mechanical exfoliation method (Lee at al. 2014) and facile solvothermal method (Sun et al. 2015). Recently, there have been research work that uses Bi_2Te_3 thin flim to generate Q-switching pulses. However, in these work, high pump power (over 1W) was used and mainly suits for high power application.

In this report, we demonstrate optical deposition technique to fabricate Bi_2Te_3 SA for a single wavelength Qswitched Ytterbium-doped fiber laser. The SA was sandwiched between two fiber ferrules, consequently, realizing an all-optical fiber setup. The resultant optical spectrums, pulse durations, repetition rates as well as pulse energies were recorded as pump power were increased.

EXPERIMENTAL SETUP

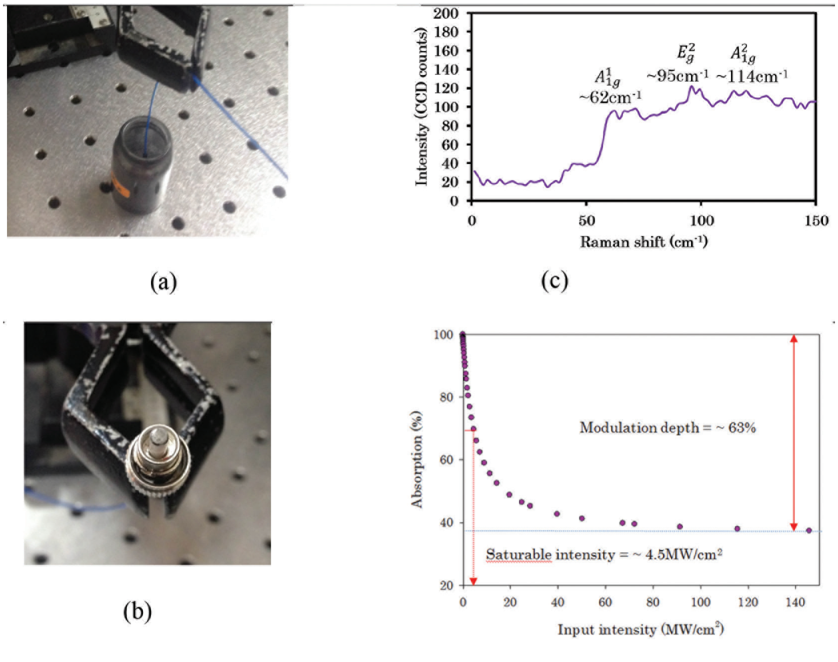
The optical deposition method (Kashiwagi et al. 2009; Martinez et al. 2010) was employed to create few-layer Bi_2Te_3 SA by inserting the suspended fiber ferrule inside the Bi_2Te_3 solution, as given in Figure 1(a). A laser diode with center wavelength of 974 nm was emitted at the other side of the fiber ferrule with an output power of 108.1 mW. The fiber ferrule was immersed in a Bi_2Te_3 solution for 30 min. The ferrule was then, dried in an oven for 3 h at 90°C to remove all the excess moisture. The image in Figure 1(b) shows that few layers of Bi_2Te_3 was successfully formed on the surface of the fiber-ferrule facet after drying. Subsequently, the fabricated saturable absorber was incorporated in the laser ring cavity setup. The presence of Bi_2Te_3 in the thin-film was proved by Raman spectrum result, as illustrated in Figure 1(c). This result is similar with the findings and analysis of Bi_2Te_3 thin-film that was discussed in detailed by Russo et al. (2008).

The nonlinear absorption characteristic of Bi_2Te_3 SA was determined using dual-detector measurement system as in Kashiwagi et al. (2009). The pulse seed is a 'homemade' passively mode-locked pulses with repetition rate of 27.6 MHz and pulse width of 0.51 ps. The output power from the laser can reach up to 20 mW. Later, the relation between intensities and optical absorption are associated by the following equation:

$$\alpha = \frac{\Delta\alpha}{(1+\frac{I}{I_{sat}})} + \alpha_{linear}$$

where $\Delta\alpha$, α_{linear} and I_{sat}, correspond to the modulation depth, non-saturation loss and saturable optical intensity, respectively. When plotted, the result of Bi_2Te_3 nonlinear absorption is shown as in Figure 1(d), with saturable intensity and modulation depth values of ~4.5 MW/cm^2 and 63%, respectively.

The fiber laser setup to generate Q-switched pulses using bismuth telluride YDFL is depicted in Figure 2(a). This setup comprised of a laser diode model LC96A74P-20R (Oclaro) with the central wavelength of 974 nm. The laser diode was connected to the input port of a 980/1060 nm wavelength division multiplexer (WDM). The common port of the WDM was connected to a 70 cm ytterbium doped fiber (YDF) (DF1100 Fibercore). Then the YDF was attached to the polarization insensitive isolator to ensure unidirectional propagation of light and to prevent back scattering reflection. The output of the isolator was then attached to a polarization controller (PC) that manage the polarization state of light by tuning the PC's waveplates. Then, the other end of the PC is connected to the fabricated Bi_2Te_3 SA, which was placed between two fiber ferrules. Then the other end of the ferrule was then linked to an input of 90/10 optical coupler (OC), referred as OC1. The 90% output port of OC1 is connected to the reflection port of the WDM to complete the loop. Meanwhile, the 10% output port of the optical coupler was connected to the 3dB optical fiber coupler, which is referred as OC2. The OC2 was used



(a) (c)

(b) (d)

FIGURE 1. (a) The optical deposition of Bi_2Te_3, (b) a few-layer of Bi_2Te_3, and (c) nonlinear saturable absorber characteristics of Bi_2Te_3 SA

to measure two results simultaneously using two different types of instruments; YOKOGAWA optical spectrum analyzer (OSA) – model AQ6373 – with a 0.02 nm resolution, and Thorlabs's photodetector – model D400FC – connected to a YOKOGAWA oscilloscope (model DLM2054). In addition, a radio frequency spectrum analyzer and an optical power meter were also used in this experiment to monitor the results.

RESULTS AND DISCUSSION

The Q-switched first appeared at the pumping power level of 88.6 mW. The signal was optimized by finely tuning the PC waveplates. The pulses were monitored by using a digital oscilloscope. Like other typical Q-switching pulses, the pulse width and the repetition rate are dependent on the pump power. The repetition rate has increased as the pump power levels increased while in contrast, the pulse duration has decreased during this increment in pumping power levels. Moreover, by increasing the pumping power to 95.2, 102.0, and 108.1 mW, respectively, stable pulses with various repetition rates were recorded, as depict in Figure 2(b), 2(c) and 2(d). These show that the outputs performed according to the behavior of a Qswitched laser.

The behavior of Q-switching at 111.3 mW pump power was recorded as depict in Figure 3. The repetition rate of 29.63 kHz and the pulse duration of 31.20 µs were obtained from the oscilloscope traces, as illustrated in Figure 3(a). In addition, Figure 3(b) shows the full width at half maximum (FWHM) of pulse width was measured as 14.54 µs. The result of the repetition rate obtained from the oscilloscope was verified by comparing the output spectrum recorded by the radio frequency analyzer (RFSA) with the fundamental frequency of 29.63 kHz, as shown in Figure 3(c). The inset in Figure 3(c) shows the peak-to-pedestal ratio of 42 dB. In Figure 3(d), an optical spectrum with lasing at 1070.08 nm and with output power of 10.42 dBm, was observed by using OSA.

The behavior of the pulse width and the repetition rate with different pump power levels were plotted in Figure 4(a). Due to the gain compression of the Qswitched fiber laser (Herda et al. 2008), the pulse width reduces with the increment of the pumping power. Shorter pulse width can also be obtain using shorter cavity length and by optimizing cavity loss (Herda et al. 2008; Zayhowski et al. 1991). The difference in pulse width indicates linear correlation with pump power and the curve was at the same as graphene trajectory reported by Liu et al. (2011) and Zhang et al. (2012). The minimum pulse width was measured as 14.54 µs when pump power was at 111.3mW. The pulse repetition rate was observed from 17 to 29.63 kHz. Meanwhile, Figure 4(b) shows the impact of varying the pump power on the performance of the average output power and the pulse energy. In this experiment, the highest pulse energy of 3.37 nJ was recorded at the pump power of 111.30 mW. As reported by Martinez et al. (2010), by incorporating a high gain fiber such as double-cladded fiber, maximum pulse energy could be facilitated. Furthermore, to optimize the pulse generation significantly, an improved cavity design in terms of connection –minimizing the connection insertion losses - and an optimized cavity length, as well as higher pump power could also be considered.

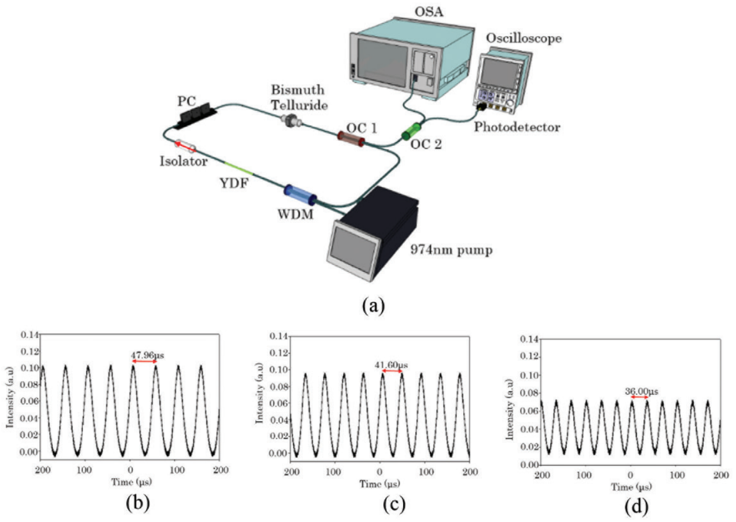


FIGURE 2. (a) The Q-switched ytterbium fiber laser setup, with pulse train corresponding to (b) 95.2 mW, (c) 102.0 mW and (d) 108.1 mW pump power with repetition rate of 19.84, 23.24 and 27.85 kHz, respectively

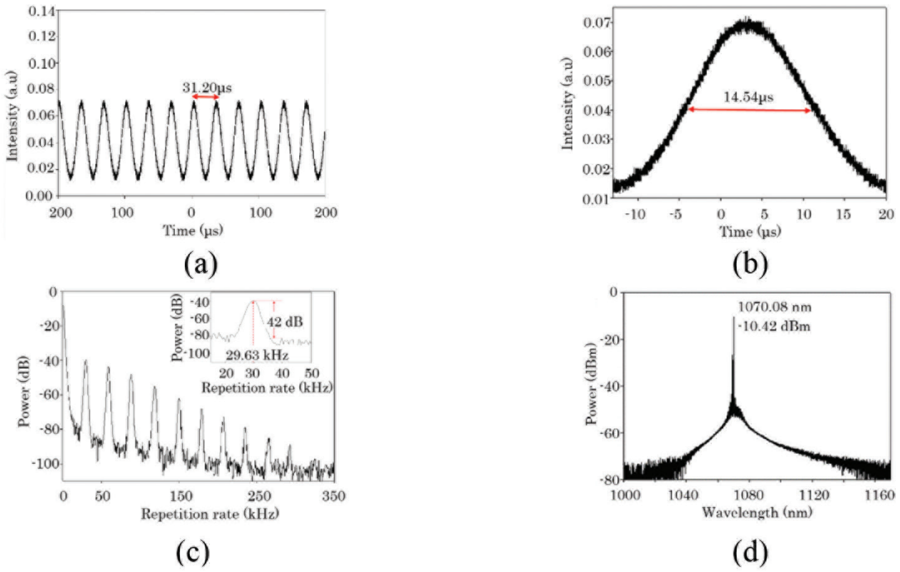


FIGURE 3. (a) The pulse train Q-switched with (b) pulse width of 14.54μs, (c) frequency spectrum and (d) centered optical wavelength at 111.3 mW pump power and 29.63 kHz repetition rate

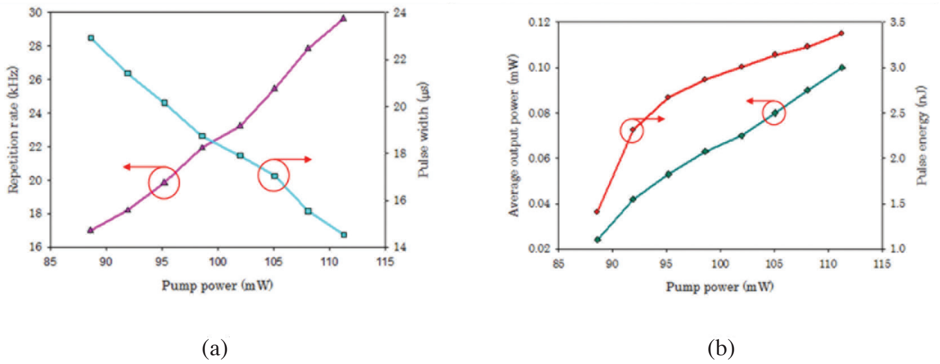


FIGURE 4. The relationship between (a) repetition rate and pulse width, and (b) pulse energy and average output power corresponding to pump power

TABLE 1. Comparison of Q-switching results of Bi_2Te_3 SA fiber laser pulses

Reference	Wavelength (μm)	Type of SA	Laser Pump Power (mW)	Pulse Repetition Rates (Max.)
Luo et al. (2013)	1	thin film, liquid-phase exfoliation method	106.2	29.1 kHz
Lee et al. (2014)	1	Bulk-structured, mechanical exfoliation method	204	77 kHz
Li et al. (2014)	1	Bi2Te3 saturable absorber mirror, hydrothermal / exfoliation method	5270	151.5 kHz
Sun et al. (2015)	1	Thin film, Facile solvothermal method	5400	114 kHz
Salim et al. (2017)	1	Thin film, cryogenic grinding method	154	15.63 kHz
Gao et al. (2018)	2	Thin film, liquid phase synthesis method	2220	57.7 kHz
Lin et al. (2018)	1	Deposit on quartz substrate, mechanically exfoliated first and then processed by hydrothermal exfoliation	3500	80 kHz
Yang et al. (2018)	1	Thin film, commercial	12200	630 kHz
This work	1	Thin film, optical deposition method	111	30 kHz

As a comparison, the results of previous wok and this work is tabulated in Table I. Although repetition rate over 50 kHz were achieved (Gao et al. 2018; Lee et al. 2014; Li et al. 2014; Lin et al. 2018; Sun et al. 2015; Yang et al. 2018), these work require higher pumping power. This work also produces better results than our previous work (Salim et al. 2017) that uses more complex process of implementing the SA. While the work by Luo et al. (2013) shows nearly similar result, the optical deposition method that was used in this work is simple and very low cost.

CONCLUSION

This work has successfully demonstrated the use of few-layer bismuth telluride (Bi_2Te_3) saturable absorber in an all-fiber laser ring cavity. As a result, Q-switched pulses in 1-μm wavelength region using ytterbium-doped gain medium were generated. The optical deposition technique was used to fabricate bismuth telluride-based saturable absorber on a fiber ferrule. Using the fabricated SA, Q-switched pulses were generated with repetition rates ranging from 17 to 29.63 kHz at the variation of pump power levels between 88.6 mW to 111.3 mW. The minimum pulse duration and the maximum pulse energy were measured as 14.54 μs and 3.37 nJ, respectively. With an SNR of 42 dB, the results demonstrated that the proposed setup performs stable operation at room temperature. The pulsed laser used simple fiber configuration and is a low cost setup. We believe the results presented in this paper will pave the way and encourage further progress in one micron laser development for near future photonics applications.

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