GENERATION OF Q-SWITCHING PULSE TRAIN WITH TOPOLOGY INSULATORS

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ABSTRACT

This report presents two Q-switched Erbium-doped fiber lasers (EDFLs) utilizing topology insulators (TI) as saturable absorber (SA). The SA was fabricated by embedding Bismuth (III) Selenide (Bi_2Se_3) or Bismuth (III) Telluride (Bi_2Te_3) into a polyvinyl alcohol (PVA) film. The first Q-switched EDFL was obtained by incorporating a Bi_2Se_3 film inside the laser cavity. The laser generates stable pulse train by changing the pump power from 86.1 mW to 116.6 mW with repetition rate that can be tuned from 84.08 kHz to 87.03 kHz. It operated at 1559.8 nm wavelength with an excellent stability. The RF spectrum showed the signal noise to ratio of about 60 dB. The maximum pulse energy of 36.9 nJ and the lowest pulse width of 5.11 μs were obtained at pump power of 116.6 mW. The second Q-switched EDFL was demonstrated using TI Bi_2Te_3 material. The laser operates at 1558.5 nm with a lower threshold pump power of 25.0 mW. The repetition rate of the laser varies from 38.76 kHz to 77.88 kHz as the 980-nm pump power increased from 25.0 mW to 106.4 mW. The Q-switching operating has the shortest pulse width of 6.56 μs, the maximum pulse energy up to 127 nJ and the peak-to-pedestal ratio of 65 dB for the RF spectrum. These results shows that Bi_2Te_3 film performed better than Bi_2Se_3 one in terms of pulse energy and wider tuning range for repetition rate and pulse width. The experimental results also verify that both TI films possess the potential advantage for stable Q-switched pulse generation at 1.5 μm.

ABSTRAK

Laporan ini menunjukkan dua suis-Q laser gentian terdop erbium (EDFLs) mengunakan penebat topologi (TI) sebagai penyerap tertepu (SA). Penyerap tertepu telah dihasilkan dengan menerapkan Bismut (III) selenide (Bi_2Se_3) atau bismut (III) Telluride (Bi_2Te_3) ke dalam polyvinyl alkohol (PVA). Suis–Q EDFL yang pertama telah diperolehi dengan menggabungkan Bi_2Se_3 ke dalam litar laser. Laser menghasilkan gelombang pulsa dengan mengubah kuasa pam dari 86.1mW sehingga 116.6 mW dengan kadar pengulangan boleh dilaraskan dari 84.08 kHz sehingga 87.03 kHz. Ia telah beroperasi pada 1559.8 nm panjang gelombang dengan kestabilan yang sangat baik. Spektrum RF menunjukkan isyarat bunyi kepada nisbah kira-kira 60 dB. Maksimum pulsa tenaga pada 36.9 nJ dan lebar pulsa yang paling rendah pada5.11 µs telah diperolehi pada kuasa pam 116.6 mW. Suis-Q EDFL yang kedua telah ditunjukkan dengan menggunakan bahan TI iaitu Bi_2Te_3. Laser beroperasi pada 1558.5 nm dengan kuasa pam ambang yang lebih rendah pada 25.0 mW. Kadar pengulangan laser berbeza-beza dari 38.76 kHz sehingga 77.88 kHz kerana kuasa pam meningkat dari 25.0 mW sehingga 106.4 mW. Operasi suis-Q mempunyai lebar pulsa terpendek iaitu 6.56 µs. Maksium tenaga pulsa meningkat sehingga 127 nJ dan nisbah puncak-ke-bawah 65 dB untuk spectrum RF. Keputusan ini menunjukkan filem Bi_2Te_3 lebih baik daripada Bi_2Se_3 dari segi tenaga pulsa dan lebar larasan jarak untuk kadar pengulangan dan lebar pulsa. Keputusan eksperimen juga mengesahkkan kedua-dua filem TI mempunyai kelebihan potensi untuk pulsa suis-Q dihidupkan pada 1.5 µm.

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LIST OF SYMBOLS AND ABBREVIATIONS

Bi_2Se_3	:	Bismuth (III) Selenide
Bi_2Te_3	:	Bismuth (III) Telurride
BP	:	Black Phosphorus
CNT	:	Carbon Nanotubes
CW	:	Continuous-Wave
EDF	:	Erbium-Doped Fiber
EDFA	:	Erbium-Doped Fiber Amplifier
EDFL	:	Erbium-Doped Fiber Laser
Er^{3+}	:	Erbium
FESEM	:	Field Emission Scanning Electron Microscopy
FSF	:	Frequency Shifting Feedback
FWHM	:	Full Width Half Maximum
HO^{3+}	:	Holmium ion
ISO	:	Isolator
MOPA	:	Master Oscillator Power Amplifier
MoS_2	:	Molybdenum Disulfide
$MoSe_2$	:	Molybdenum Diselenide
Nd^{3+}	:	Neodymium
OSA	:	Optical Spectrum Analyzer
Pr^{3+}	:	Praseodymium
PLD	:	Pulsed Laser Deposition
PVA	:	Polyvinyl Alcohol

RF	:	Radio Frequency
SA	:	Saturable Absorber
SBS	:	Stimulated Brillouin Scattering
SESAM	:	Semiconductor Saturable Absorber Mirrors
SHB	:	Spatial Hole Burning
SNR	:	Signal to Noise Ratio
TiO_2	:	Titanium Dioxide
TI	:	Topology Insulators
Tm^{3+}	:	Thulium
TMDS	:	Transition-Metal Dichalcogenides
WDM	:	Wavelength Division Multiplexing
WS_2	:	Tungsten Disulfide
Yb^{3+}	:	Ytterbium

CHAPTER 1:
INTRODUCTION

1.1 Motivation

Topological insulator (TI) is a material with non-trivial topological order that behaves as an insulator in its interior but whose surface contains conducting states, meaning that electrons can only move along the surface of the material. It is expected to show unique photonics properties owing to its broadband spectral response ranging from terahertz to infrared as a result of the intrinsic gapless surface band, in analogy to graphene (Zhang et al., 2010) and strong spin-orbital coupling effect that may lead to novel opto-spintronic devices (Mclver et al., 2012). Bismuth (III) Selenide (Bi_2Se_3) and Bismuth (III) Telluride (Bi_2Te_3) are typical examples of TI materials. Despite that their electromagnetic properties had been extensively investigated (Abanin et al., 2012; Hossain et al., 2011), their equally interesting optical properties were under very limited studies. In the meanwhile, they possess different physical and chemical properties, such as band gap, band structure, Fermi energy level and carrier density (Zhang et al., 2011; Cho et al., 2011), leading to new insights on photonics, which deserves further exploration by the optics community.

Passively Q-switched fiber lasers had attracted much attention because of their potentials as compact, simple, flexible, stable sources in medicine, laser processing, telecommunications, and remote sensing. They had been investigated intensively using different kinds of saturable absorbers (SAs), such as metal-doped crystals (Flippov et al., 2001), Sm-doped fiber (Luo et al., 1999), semiconductor quantum well structures (Lecourt et al., 2006), and carbon nanotubes (Zhou et al., 2010). However, due to some intrinsic drawbacks of those SAs, such as free space alignments, complex fabrication process required, limited operation bandwidth, their applications are limited. Recently, graphene, a single two-dimensional atomic layer Dirac materials of carbon atom arranged in a hexagonal lattice as the next-generation passive Q-switcher emerges, with the advantage of ultrafast recovery time and broadband saturable absorption (Wang et al., 2012; Martinez et al., 2012; Martinez et al., 2010). The advancement in graphene SA renders us to raise a fundamental but interesting question, whether other type of Dirac material topological insulator could also exhibit saturable absorption?

In this report, two different passively Q-switched Erbium-doped fiber laser (EDFL) are demonstrated using a few-layers Bi_2Se_3 and Bi_2Te_3 based SAs to exploit the wideband saturable-absorption characteristic of the TIs. For this purpose, we prepare free-standing Bi_2Se_3 and Bi_2Te_3 polymer composite SA films by implanting the powder of these materials into a polyvinyl alcohol (PVA) host. These films are used in a fully fiber-integrated laser cavity for generating Q-switching pulses train.

1.2 Objectives

The research work aims to explore the use of TI materials as a saturable absorber (SA) for Q-switching pulse generation. This research embarks on the following objectives:

- To demonstrate a Q-switched EDFL using a Bi_2Se_3 based SA
- To demonstrate a Q-switched EDFL using a Bi_2Te_3 based SA

1.3 Outline of this report

This report describes an experimental work on Q-switched EDFLs a few-layers Bi_2Se_3 and Bi_2Te_3 based SAs. The content is arranged in 5 chapters, including this introductory chapter and conclusion chapter. Chapter 1 explained the motivation and objectives of this research work. The literature reviews on fiber lasers and Q-switching are described in Chapter 2. Chapter 3 describes on the preparation of Bi_2Se_3 based SA and the Q-switching results. The Bi_2Se_3 SA film was obtained by embedding the powder of this material into a PVA polymer. Chapter 4 describes the Q-switched EDFL using the Bi_2Te_3 based SA. Finally, Chapter 5 concludes the finding of this research.

CHAPTER 2:
LITERATURE REVIEW

2.1 Introduction

The working mechanism of EDFL and Q-switch fiber laser are described in this chapter. The characteristic of saturable absorber was also discussed. This research work is focused on the development of Q-switched erbium-doped fiber laser using topological insulators (TIs) based saturable absorber. Bi_2Se_3 and Bi_2Te_3 are proposed as SAs.

2.2 Background of fiber lasers

The fiber laser technology has grown massively over the last 10 years. For the pasts few years, the most developed fiber laser is based on Erbium-doped fiber (EDF) as the gain medium (Bellemare et al., 2001). Besides that, the technology of fiber laser has opened various new applications such as laser based on measurement and communication systems. By using a fiber laser, the usage and design of the laser is much more flexible. The higher the surface of the volume ratio of fiber allows high efficiency heat dissipation. In addition, Erbium-doped fiber (EDF) is used as gain medium in this work since its can efficiently amply light in the 1550 nm wavelength region, where telecom fibers have their loss minimum (Mears et al., 1987).

The EDF has large gain bandwidth which centered at 1550 nm and it is typically used as an amplifier device in the modern optical communication system. The EDF is also capable to amplify data channels with the highest data rates simultaneously in dense wavelength division multiplexing (DWDM) with a low noise (Desurvire et al., 1987). On the other hand, EDF laser (EDFLs) gained interest of many researchers due to its capability in the optical communication and fiber sensor applications (Kang et al., 2016).

So, to enhance the utilization of the data transmission in optical fibers and to satisfy the bandwidth demand of future networks, multiplexing techniques that contain of merging several communications channels have been exploited (Vasseur J., 2006). The methods of wavelength multiplexing (WDM) has increased the performances of the broadband optical access network and opened the available fiber limit. The new low-cost laser sources creation is one of the necessary components (Bracket et al., 2005).

Fiber laser is a technology in which active gain medium is an optical fiber doped with rare-earth elements such as aserbium, ytterbium, neodymium, dysprosium, praseodymium, thulium and holmium. Those rare-earth elements are related to doped fiber amplifiers which provide light amplification without lasing. Besides that, the laser can be determined into two types which are linear cavity or ring cavity. The first rare-earth element doped fiber lasers have produces a few miliwatts (mW) at a wavelength of around 1 μm (Maiman, 1960). The demand for more efficient and cost effective Q-switched is growing day by day due to endless applications in various fields. For instance, pulsed laser are used in laser surgical, tattoo removal and skin treatment in medical field (Haris et al., 2016). Due to over helming request of ultra-short pulse laser in manufacturing, medication as well as in communication applications as it can provide a high resolution micro-processing due to high repetition rate. The Q-switched method is a common method which is used to produce a pulse laser output. On the other hand, Q-switch is originally obtained by modulating the quality factor of laser cavity which can be realized by inserting a saturable absorber (SA). Figure 2.1 describes the growth of fiber laser technology in the last 25 years.

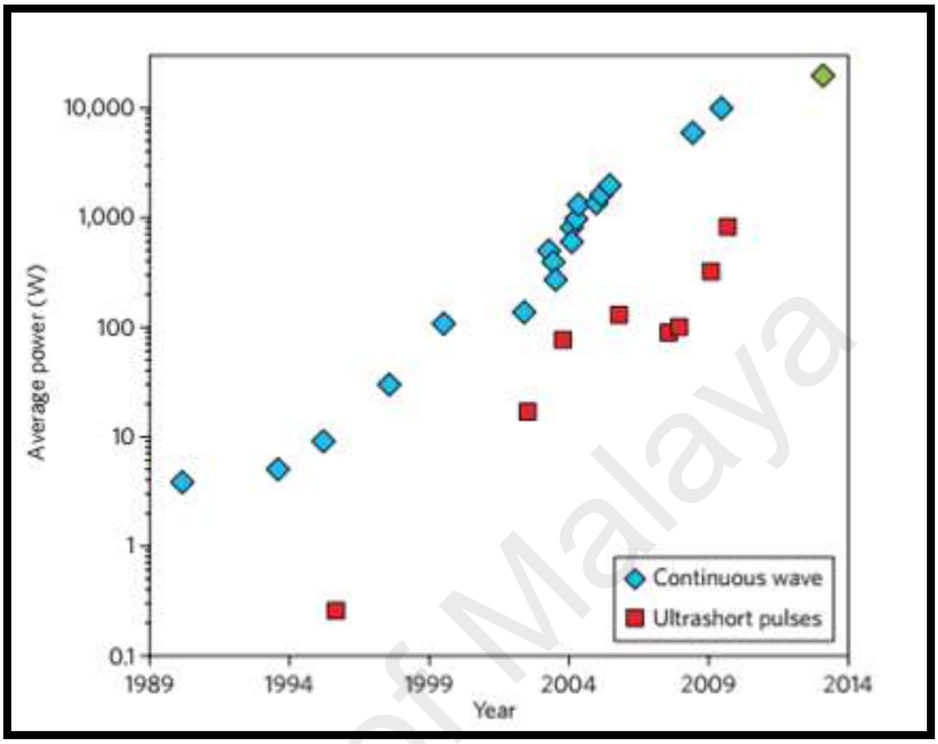

Figure 2.1: The growth of fiber laser over the past 25 years (Jauregui, Limpert & Tunnermann, 2013)

Passively Q-switched fiber lasers can find a mass application on the areas of medicine, communications, material processing and manufacturing as well as basic research and so forth due to their simple design which allows for the development of compact and cost- effective pulsed laser sources (Fermann et al., 2013). To date, various passive saturable absorbers (SA) has been proposed and demonstrated for pulse generation. Semiconductor SA mirror (SESAM) is one of the most popular SA in solid state lasers (Keller U et al,. 1996). However, SESAM requires complex and costly fabrication process. So that, many researchers have shifted their interest to carbon materials such as single walled carbon nanotubes (CNTs) and graphene as new SAs for pulsed generation (Harun S W et al., 2013).

Recently, there are several new SAs that are extensively being investigated and one of them is transistion- metal dischalcogenides (TMDs). The example of TMDs such as molybdenum disulfite (MOS_2), Molybdenum diselenide ($MoSe_2$) and tungsten disulphide (WS_2). The arising material such as black phosphorus (BP) which is basic structure is similar to bulk graphite at the intense focus of researchers as it has direct energy bandgap structure regardless of thickness (Haris et al., 2016). Another interesting candidate of new SA for pulsed laser generation is Dirac material which also called as topology insulators (TI). This report explores the application of TI materials for Q-switching pulses laser generation.

2.3 Working Principle of Erbium-Doped Fiber Laser (EDFL)

The rare-earth ions Er^{3+} can provide gain in a wide wavelength range around 1.5μm which is more remarkable for optical communication applications. Thus, erbium-doped fiber (EDF) was studied through the 20th century. The first EDF was fabricated and reported in 1985 (Poole et al., 1985). These rare-earth elements are optically active and they can absorb light at one wavelength and emit light at another (Mendez et al., 2011). The strong nonlinear optical property of graphene is also used for the first time to suppress the mode competition of EDF for realizing the dual wavelength Q-switched output (Zhengqian et al., 2010). In addition, Er^{3+} ion is usually used as an active element since the ion can operate at low loss region of 1550 nm which is suitable for communication applications. The amplifier which is Erbium-doped fiber amplifier

(EDFA) and erbium-doped fiber laser (EDFL) are used EDF to operate based on similar mechanism. EDFA can be transformed to EDFL device by incorporating a fed back system in configuration. For ultra-short pulses generation, the EDF is usually used as a gain medium due to its fiber gain spectrum which is wide ranging and the fiber dispersion at 1.55 μm is anomalous (Haris et al., 2014). This unusual dispersion works with the nonlinearity in the fiber promising a good self-stable pulses generation that can be used in different type of practical application, especially in telecommunication window for WDM network (Tanabe et al., 2002). Figure 2.2 shows the loss characteristic of silica fiber and emission bands of same rare-earth ions.

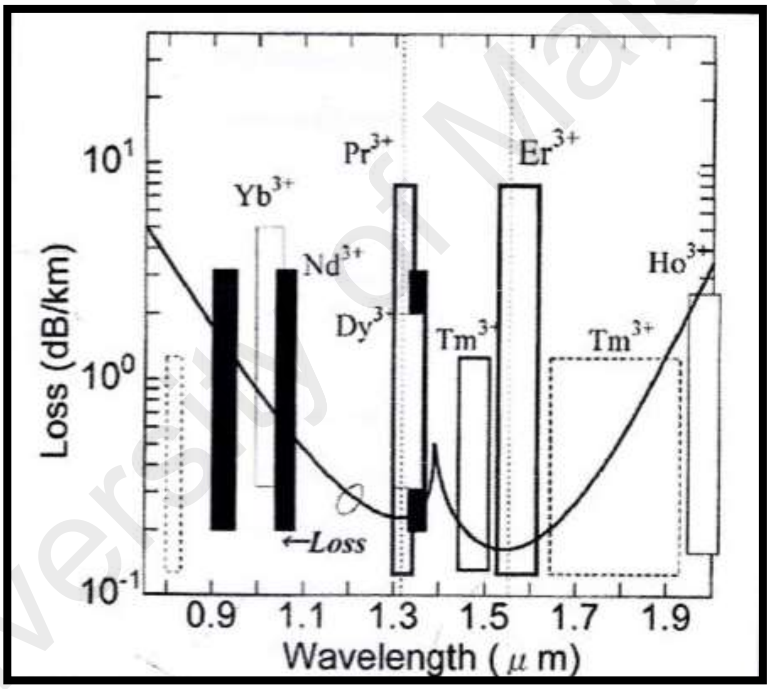

Figure 2.2: Loss characteristic of silica fiber and emission bands of some rare-earth ions (Zhu et al., 2015).

Besides that, EDF has emerged as strong candidate for employment as a gain medium in a fiber ring laser with particular desirable properties such as large gain bandwidth of typically tens of nanometers due to lack sharpness in its energy level

(Zhang et al., 2009). The main absorption band of Er^{3+} ions is at 980n nm and at 1480 nm which accessible with the commercial semiconductor laser diodes. In lasers, the Er^{3+} ion carries on as semi three-level framework (Okhotnikov et al., 1994). Table 2.1 shows the rare-earth elements, its host glasses and emission wavelength ranges. There are a few examples of rare-earth ions that usually used in fiber-doped gain medium such as Er^{3+}, Nd^{3+}, Ho^{3+}, Yb^{3+}, Tm^{3+}, and Pr^{3+} ions.

Table 2.1: Rare-earth ions with common host glasses and emission wavelength ranges.

Ion	Er^{3+}	Nd^{3+}	Ho^{3+}	Yb^{3+}	Tm^{3+}	Pr^{3+}
Common Host Glasses	Silicate, Phosphate and Fluoride glasses	Silicate and fluoride glasses	Silicate and phosphate glasses	Silicate, germinate and fluoride glasses	Silicate glass	Silicate and fluorozirconate glasses
Emission Wavelength Ranges (µm)	1.5-1.6, 2.7, 0.55	1.3, 0.635, 0.6, 0.52, 0.49	1.03-1.1, 0.9-0.95, 1.32-1.35	1.7-2.1, 1.45-1.53, 0.48, 0.8	1.0-1.1	2.1, 2.9

In the previous research of EDFLs, it operates in 3rd communication window in the range from 1.5 to 1.62 µm. The EDFLs can generate CW and pulses sources with broadband and narrowband on the $^4I_{13/2}$ or $^4I_{15/2}$ transition of erbium. Figure 2.3 shows the illustration of energy level of Er^{3+} ion in silica fiber.When the photon is pump, it will absorbed and Er^{3+} ion is excited to a level $^4I_{11/2}$ or $^4I_{13/2}$ which is depending on the pump wavelength used. In this research, Er^{3+} ion is excited by photons at 980 nm wavelength and it has non-radiative decay to a state $^4I_{13/2}$ where it can stay excited since the laser diode pump is provided from 980 nm wavelength. Besides, Er^{3+} ion can be excited at 1480 nm laser diode pumping. If it relaxes too quickly, more photons are need to keep it excites and its means more input power is needed to make the amplifier work (Giles et al., 1991).

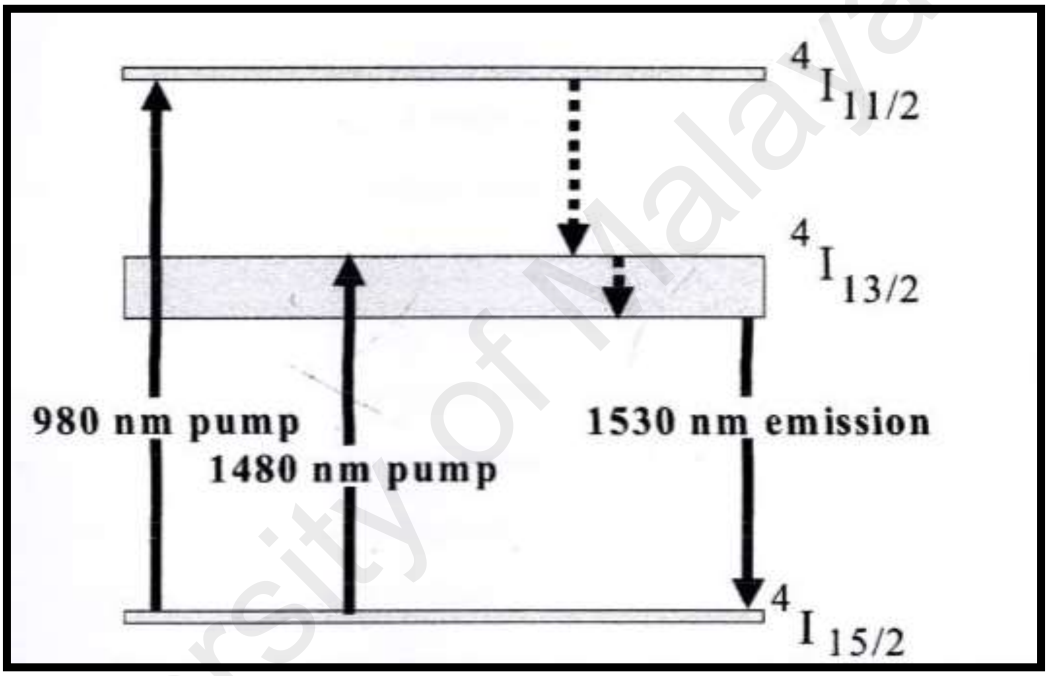

Figure 2.3: Illustration of energy level diagram of Er^{3+} ions in silica fibers (Zhu et al., 2015).

2.4 Q-switching

Q-switching is a well-known traditional technology to generate pulse. Q-switching will produce high pulse energy, wider pulse durations and low repetition rate compared to mode-locking technique. In the Q switching method, we are able to achieve single solid and short pulse trains of a laser radiation (Subhash et al., 2012). Q-switching technique produces a short pulse fiber laser where typical pulse width ranges from microsecond to nanosecond and the repetition rate is in kiloHertz (kHz) regime (Yu et al., 2006).

Usually, the pulse repetition is in the hertz (Hz) and a few megahertz (MHz) regimes which always much lower than cavity round trip time (Stumpf et al., 2010). Moreover, the Q-switching technique is a way of obtaining short and powerful pulses of laser and the Q means the quality factor of laser resonator. When the quality factor of laser resonator is high, the losses become low while when the quality factor is low, the losses become high. Actually, the term of Q-switching is refers to an abrupt switching of cavity Q from low to high values. Furthermore, the method of Q-switching consists of two which are active and passive Q-switching. Compare to active Q-switched fiber lasers, passively Q-switched fiber lasers possess the attractive advantages of compactness, simplicity and flexibility in design (Zhengqian et al., 2010). The active Q-switching requires expensive and complex externally driven of electro-optical or acoustic-optic (AO) modulators inserted into cavity (Kalisky et al., 2004). On top of that, the advantages of passive Q-switched are it is simple in design, low cost, provide stable and consistent output power compared to active Q-switch. Figure 2.4 shows the basic structure of passive Q-switch laser cavity.

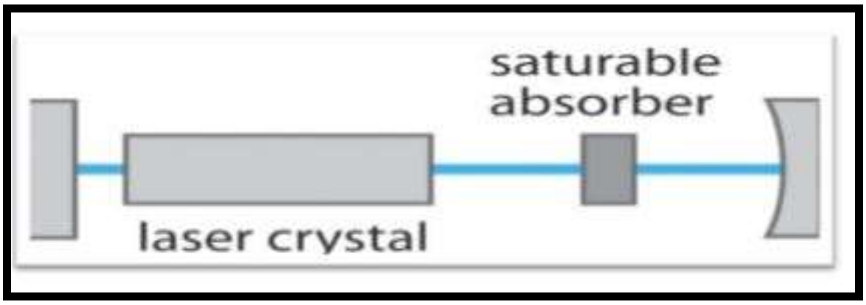

Figure 2.4: Basic structure of passive Q-switch laser cavity (Paschotta, 2008).

Passive technique of Q-switching fiber laser can be achieved using many types of SAs such as SESAM, CNT and graphene. SESAMs with wide range of laser parameters usually allow for reliable self- starting pulse and very high output power allows to be operated in appropriate regime (Keller et al., 1996). The previous studied show the major drawbacks of SESAMs are costly, complex to fabricate, it operates in narrowband, have low threshold damage and long recovery time (Ahmed et al., 2014). The demonstration of passively Q-switched EDFL operating at 1536.6 nm wavelengths by utilizing a graphene based saturable absorber and the repetition rate is increase from 10.3 kHz to 32.4 kHz while the pulse width is varied from 10.7 μs to 31.0 μs as the pump power increases (Saleh et al., 2014).

In passive Q-switching, the operation of generating pulse is different from the process that running in active Q-switching laser which in the early process of passive Q-switched the losses is introduced by Q-switched are too high for laser process to start. In spite of that, the action of lasing begins at low power level and start to arise at low rate once the laser gain becomes a little larger than the total loss. Figure 2.5 shows the evolution of gain and losses in a passive Q-switching laser.

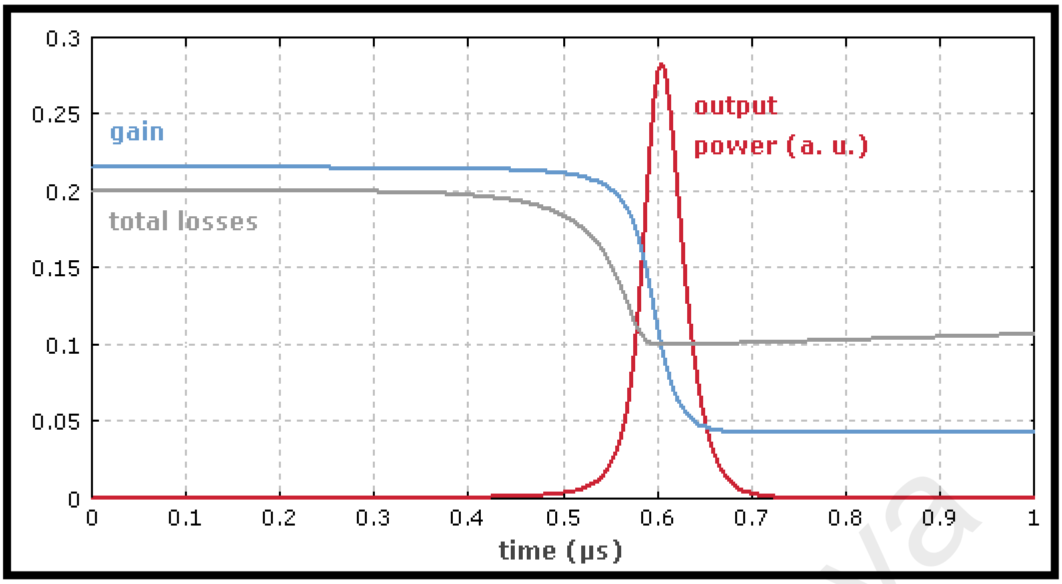

Figure 2.5: The evolution of gain and losses in passive Q-switching technique.

2.5 Topology Insulator (TI)

Saturable absorber (SA) is an optical material that has a lower loss at high optical intensity of light. The properties of SA are broadband absorption, low saturation intensity, ultrafast recovery time (~ps) and high modulation depth that make them useful for different lasers such as solid-state, fiber and semiconductor laser which operating at different wavelengths range from 500 nm to 2500 nm (Sobon, 2016). A saturable absorber (SA) absorbs light with different degrees that depends on the optical intensity of incident light with a high degree of absorbance for low intensity light and eventual saturated absorption causing a low degree of absorbance for high light intensity (Hercher, 2004). SAs is consists of a material that absorbs laser wavelength and has small amount of saturation intensity. On top of that, the characteristic of SAs as stated below:

- Maximum pulse energy, the modulation depth (maximum loss reduction) must approximate to one and half of initial gain and the losses of non-saturable absorber should be as lower as possible.
- For minimum pulse energy and higher repetition rate (R_r), small depth is suitable.
- The saturation energy should be lower than the saturation energy of the gain medium to ensure that the fast saturation of absorber can be kept and loss of pulse energy can be kept to minimum level
- The recovery time of the saturable absorber should be longer than the pulse duration but the time is enough to ensure that the loss is recovered before the gain after the emission of the pulse.

TI was discovered to possess a large bandgap and single Dirac cone that is similar to graphene SA (Yang.K et al., 2012). The SAs based on TI has lower saturation intensity and broad effective bandwidth compared to graphene (Haris et al., 2016). TIs can be classified as materials that have insulting gap in the bulk while being gapless on the edge (surface) (Zhang et al., 2011). The examples of TIs are Mercury/Cadmium Telluride (HgTe/CdTe) quantum wells, Bi-Sb-alloys, Bi_2Se_3 and half-Heusler compounds (Zhao et al., 2012).

In this research, TIs such as bismuth selenide (Bi_2Se_3) and bismuth telluride (Bi_2Te_3) are used as saturable absorber to generate Q-switching pulse train. Bismuth or Bi is in the nitrogen group which is in group 15 in periodic table. The characteristic of bismuth as stated below:

- Hard
- Brittle
- Lustrous

Bi_2Se_3 is a compound of bismuth and selenium. The characteristic of Bi_2Se_3 compound is low saturation intensity and can be beneficial advantage to develop low-threshold pulsed lasers (Luo et al., 2014). The topological Insulator (TI), Bi_2Te_3 exhibit an optical transmittance increase as result of saturable absorption. Based on an open-aperture Z-scan measurement at 1550 nm, it show that the Bi_2Te_3 is indeed a very high modulation depth which is up to 95% saturable absorber (Zhao et al., 2012).

2.6 Pulsed Laser Parameter

In this research, different equipment has been used to measure the important parameters of fiber laser. The parameters are peak power, repetition rate, pulse width and pulse energy that are used to characterize and evaluates of pulsed laser. The equipment that has been involved in getting the measurement is an oscilloscope with photo-detector (OSI), an optical spectrum analyzer (OSA), power meter and autocorrelator. An oscilloscope with photo-detector is used to measure the repetition rate and pulse width while power meter is used to measure input and output power. Besides that, autocorrelator is used to measure full width at half maximum (FWHM) and optical spectrum analyzer is used to analyzed the wavelength spectrum. Figure 2.6 shows the important pulsed laser parameters.

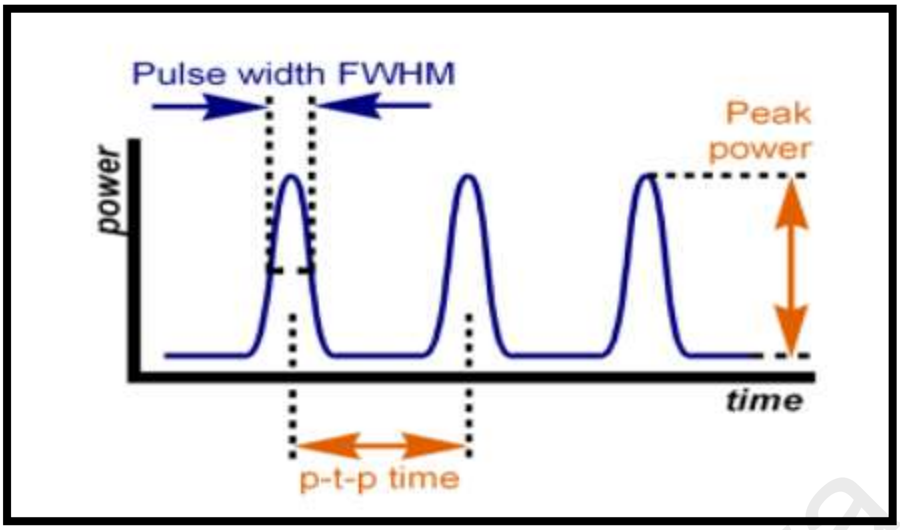

Figure 2.6: The important pulsed laser parameters

2.6.1 Peak Power (*Pp*)

Peak power (*Pp*) is the highest optical power level in pulses. In spite of short pulse duration, it can generate high peak power even for moderately energetic pulse. From the pulse width and the pulse energy, the value of peak power can be calculated by using the formula below:

$$Pp \approx f_s \frac{PE}{\Delta t} \qquad (2.1)$$

where f_s is the numerical factor and it depends on the shape of pulse while P_E is pulse energy. For the soliton pulse with a sech^2 fitting, the peak power is

$$Pp \approx 0.94 \frac{PE}{\Delta t} \qquad (2.2)$$

2.6.2 Pulse Width or Pulse Duration (Δt)

The pulse width is defined as the width of pulse which the power is at the half peak power or also known as full width at half maximum (FWHM). Sech^2 function or

Gaussian function fitting is used in the autocorrelation of pulse to describe pulse shape. For the Q-switching technique, the pulse width is in between nanoseconds regime (Choudhary et al., 2015).

2.6.3 Repetition rate (R_r)

Repetition rate (R_r) is determined as a number of emitted pulses per second or inverse temporal pulse shaping. The repetition rate is inversely proportional to pulse width. In Q-switching method, the repetition rate is varied with changes of pump power.

2.6.4 Pulse Energy (P_E)

Pulse Energy (P_E) is describes as the total optical energy content of pulse. For Q-switching method, pulse energy is at range micro joules to mill joules. The pulse energy is calculated by dividing the average of output power, P_o and the repetition rate (R_r).

$$P_E = \frac{Po}{Rr} \tag{2.3}$$

CHAPTER 3:

Bi_2Se_3 MATERIAL AS SATURABLE ABSORBER IN PASSIVELY Q-SWITCHED FIBER LASER

3.1 Introduction

The demand for more efficient and cost effective Q-switched laser is growing day by day due to their various applications in medical field such as tattoo removal, skin treatment and laser surgery (Galecki et al., 2010; Kurkov et al., 2010). High peak power Q-switched lasers are also used for cutting and drilling in the metal processing industry (Kurkov et al., 2010; Tonouchi., 2007). Other applications that utilized Q-switched lasers are remote sensing (Barnes et al., 2009), optical data storage (Watanabe et al., 1998), and optical communication (Mahony et al, 2001). Passively Q-switched lasers are more preferable than their active counterpart due to their advantages of compactness, simplicity and versatility (Xio et al., 1997). They can be realized by incorporating a saturable absorber (SA) into the laser cavity, which functions to induce intensity modulation (Degnan., 1995). The use of passive SAs such as semiconductor SA mirrors (SESAMs) (Keller et al., 1996; Spühler et al., 1999), carbon nanotubes (CNTs) (Ahmed et al., 2015; Jung et al., 2012), graphene (Al-Masoodi et al., 2015; Zhao et al., 2014) has attracted much attention due to their considerable saturable absorption rate, ultrafast timing recovery, and a good compatibility with other components in the setup. SESAMs are well known for their stability and flexibility. However, fabricating a SESAM is complex and it requires expensive facilities. Furthermore, the operating range of a SESAM or its optical response is usually limited. Thus, CNTs and graphene based SAs are preferable since they are cheaper and easier to fabricate (Harun et al., 2012; Popa et al., 2011). However, CNTs based SA is limited by their limited wavelength dependent operation while graphene based SA offers relatively low modulation depth. 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 is the Dirac materials called topological insulators (TIs). TI was discovered to possess a large band gap and a single Dirac cone that is similar to the graphene SA (Yang et al., 2012; Xu et al., 2013). Henceforth it may serve as another possible and ultimate SAs for generating Q-switched and mode-locked lasers. Furthermore, TIs have a large modulation depth with an efficient saturable absorption property. Thus, SAs based on TI has lower saturation intensity and broad effective bandwidth compared to graphene. For instance, Bismuth Selenide (Bi_2Se_3) has relatively low saturation intensity (Xu et al., 2013) and this unique characteristic can be a beneficial advantage to develop low-threshold pulsed lasers (Luo et al., 2013; Luo et al., 2014; Chen et al., 2013). Bi_2Se_3 as a Q-switcher was demonstrated (Chen et al., 2013; Luo et al., 2013; Chen et al., 2014). (Chen et al., 2013) demonstrated Q-switched EDFL with pulse repetition rate from 4.5 kHz to 12.9 kHz, pulse width of 13.4 μs to 36 μs and pulse energy from 11.8 μJ to 13 μJ. (Luo et al., 2013) 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., 2014) 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.

In this chapter, we demonstrate a simple, stable and widely tunable pulse repetition rate Q-switched Erbium doped fibre laser (EDFL) utilizing Bi_2Se_3 as SA. At first, free-standing Bi_2Se_3- polymer composite SA film is fabricated by implanting the powder of this material into a polyvinyl alcohol (PVA) host. This film is used in a fully fiber-integrated EDFL cavity for generating Q-switching pulses train.

3.2 Preparation and optical characterization of Bi_2Se_3 based SA

The commercially available few-layer Bi_2Se_3 powder with molecular weight of 654.84 g/mol was used to prepare the SA in this experiment. To prepare the host polymer, 1 g of polyvinyl Alcohol (PVA) (Sigma Aldrich) is dissolved in 120 ml de-ionized (DI) water with the aid of a magnetic stirrer at room temperature. Next, 14 mg of Bi_2Se_3 powder was mixed with 3 ml of the PVA solution before they are thoroughly mixed using a magnetic stirrer for three hours. Then the Bi_2Se_3-PVA solution was placed in ultrasonic bath for 10 minutes to make sure the Bi_2Se_3 material fully binds with the PVA. After that, the Bi_2Se_3 suspension was carefully poured onto petri dishes to avoid trapping any air bubble and is left to dry at room temperature for 48 hours to form Bi_2Se_3-PVA composite film. Figure 3.1 shows the field emission scanning electron microscopy (FESEM) image of the fabricated Bi_2Se_3 film. As shown in the figure, the Bi_2Se_3 film has a high dense of micro-rods and micro-grains, which can be clearly viewed on the substrate surface and distributed randomly on the substrate surface. These micro-rods and micro-grains are in irregular shapes with an average size of 0.3 to 1.66 µm.

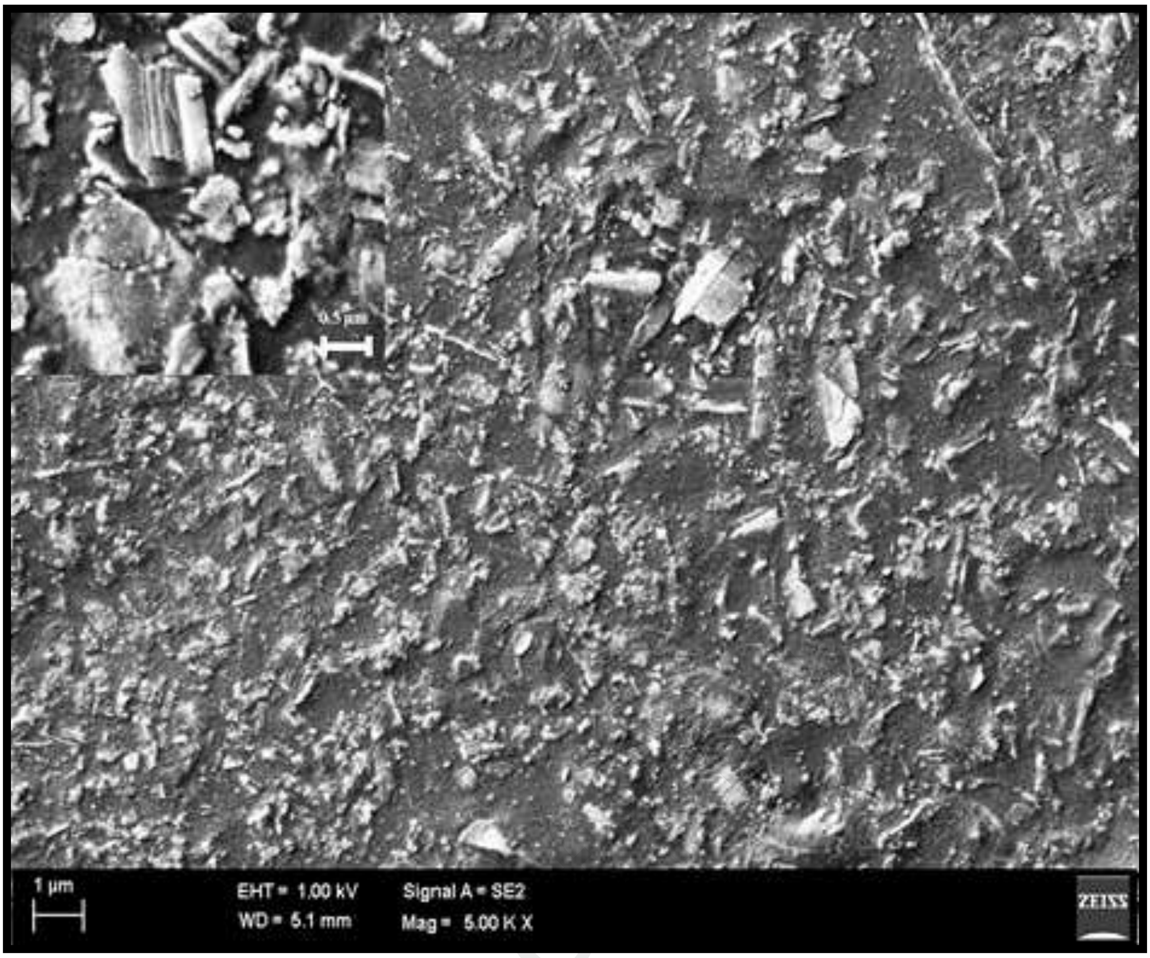

Figure 3.1: FESEM image of the Bi_2Se_3 composite film. Insert shows the image with higher magnification.

Figure 3.2 illustrates the absorbance spectrum of the prepared Bi_2Se_3-PVA film in the range of 200 nm to 1100nm. The figure attests a constant absorbance for the Bi_2Se_3-PVA film which indicates that it possesses a broadband resonance wavelength like graphene. Figure 3.3 shows the Raman spectrum of the fabricated Bi_2Se_3-PVA film. The spectrum indicates three distinct peaks at ~67 cm^{-1}, ~126 cm^{-1}, and ~170 cm^{-1}, which can be assigned to the A^1_{1g}, E^2_g and A^2_{2g} vibrational modes, respectively.

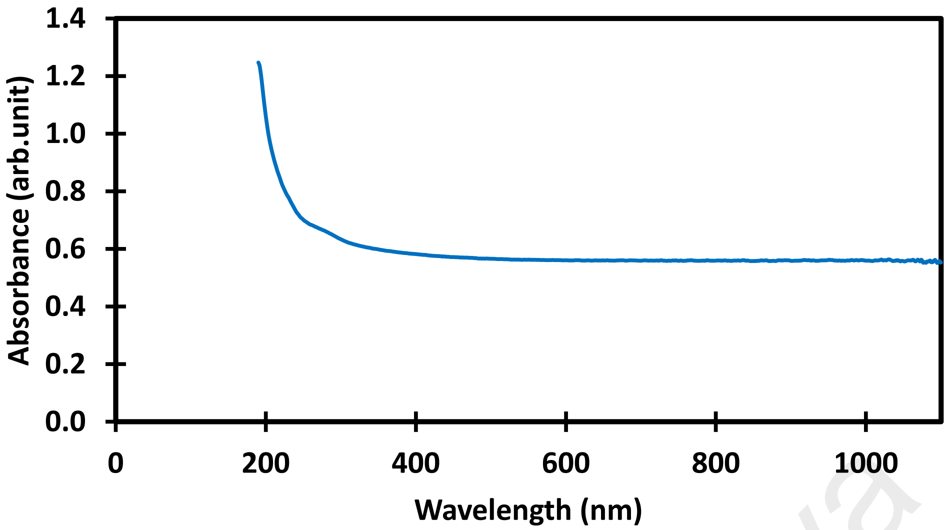

Figure 3.2: Linear transmission of the free standing Bi_2Se_3-PVA film.

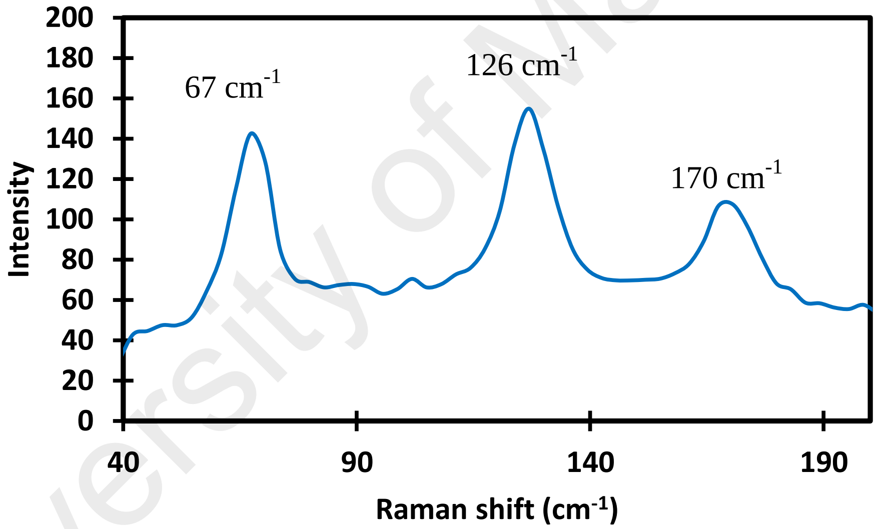

Figure 3.3: Raman spectrum for the free standing Bi_2Se_3-PVA film.

The nonlinear optical response property for the Bi_2Se_3 film was aslo investigated to confirm its saturable absorption characteristic by applying dual optical power meter techniques. The pulse input source used a mode-locked fiber laser, which has femtosecond output pulse with a 17 MHz repetition rate and a 900 fs pulse duration, which the output power is approximately 5 mW. Figure 3.4 shows the transmission characteristic of the Bi_2Se_3 SA, which was fitted using the following simple saturable absorption model equation;

$$T(I) = 1 - \alpha_0 \exp\left(-I/_{I_{sat}}\right) - \alpha_{ns} \qquad (3.1)$$

where $T(I)$, α_0, I, I_{sat} and α_{ns} stand for the transmission, modulation depth, input intensity, saturation intensity, and non-saturable absorption, respectively. The modulation depth, non-saturable absorption and saturation intensity were measured to be approximately 15.9 %, 77 % and 50 MW/cm^2, respectively as shown in Figure 3.4.

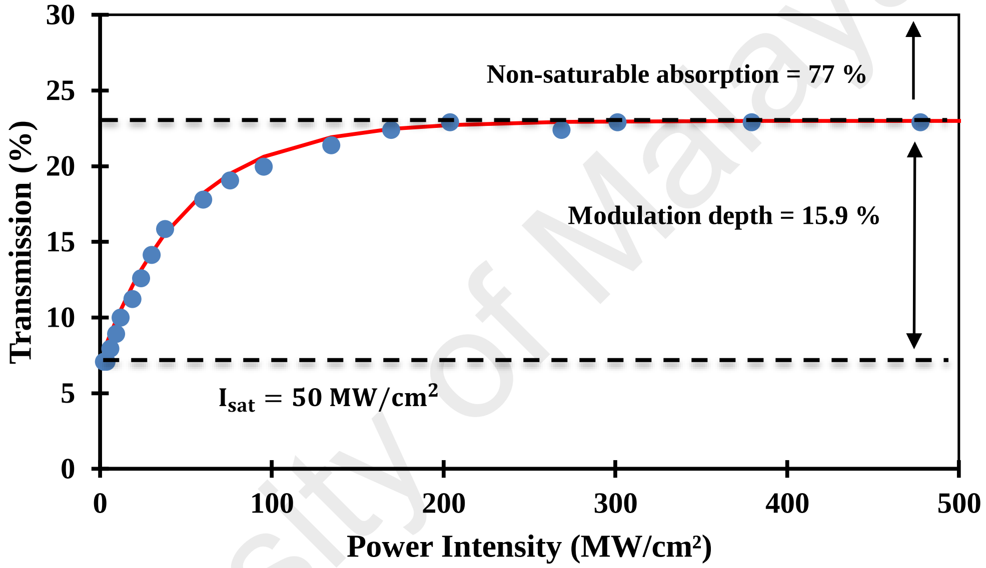

Figure 3.4: Nonlinear absorption characteristic for the Bi_2Se_3-PVA film.

3.3 Configuration of the Q-switched laser with Bi_2Se_3 based SA

The schematic experimental setup of the proposed Q-switched EDFL with Bi_2Se_3 based SA is depicted in Figure 3.5. The ring laser consists of a 2.4 m long EDF as the active medium, a 980/1550 nm wavelength division multiplexer (WDM), an optical isolator, a Bi_2Se_3 SA device and an 80/20 output coupler. The EDF used has a numerical aperture (NA) of 0.16 and erbium ion absorption of 23 dB/m at 980 nm with core and cladding diameters of 4 µm and 125 µm, respectively. It is pumped by a 980 nm laser diode through the WDM. The other end of the EDF is spliced to an optical isolator, which ensures unidirectional propagation of the oscillating laser in the ring laser cavity. The SA device was fabricated by sandwiching a ~ 1 mm×1 mm piece of the Bi_2Se_3 composite film between two fiber ferrules using a fiber adaptor. Index matching gel is applied at the connection to minimize parasitic reflections. The laser signal was coupled out using 80:20 output coupler while keeping 80% of the light oscillating in the ring cavity for both spectral and temporal diagnostics. The output laser was tapped from a 20% port of the coupler. The spectral characteristic was measured using an optical spectrum analyzer (OSA) with a spectral resolution of 0.02 nm while the temporal characteristics were measured using a 500 MHz oscilloscope and a 7.8 GHz radio-frequency (RF) spectrum analyzer via a 1.2 GHz photodetector. The total cavity length of the ring laser is about 6 m.

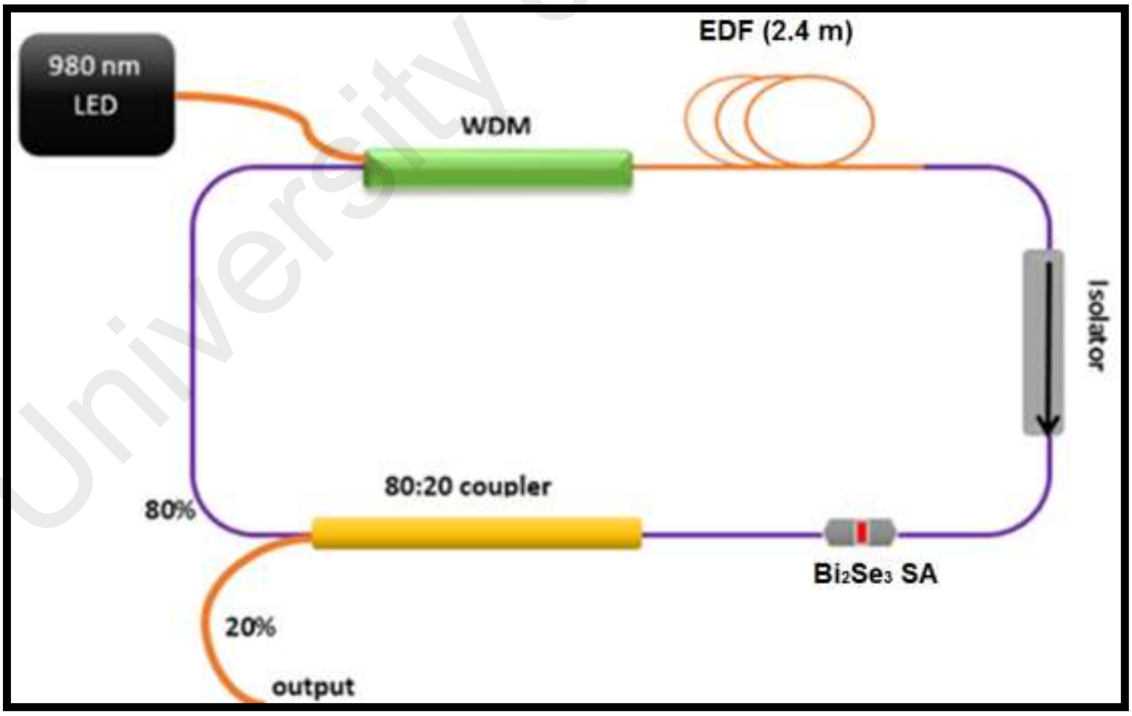

Figure 3.5: Configuration of the Bi_2Se_3 PVA film based Q-switched EDFL

3.4 Q-switching performance

Q-switching pulses train was firstly observed from the proposed Q-switched EDFL at a threshold pump power of 86.1 mW. As the pump power is further increased, the Q-switching operation was maintained up to 116.6 mW. Figure 3.6 shows the output spectrum of the proposed Q- switched EDFL, with and without Bi_2Se_3 based SA, at the pump power of 116.6 mW. It is observed that the Q-switched emission spectrum (solid line) is operating at a broader spectrum with approximately 3.7 dB higher intensity than the continuous wave (CW) of the laser emission (dotted line). The spectral broadening is due to the Q-switching operation which commences at this pump power. The peak spectrum of the laser is also shifted by 1.2 nm for 1561.0 nm to a shorter wavelength of 1559.8 nm. The wavelength shift and higher intensity obtained by the proposed Q-switched EDFL is due to the integration of Bi_2Se_3 based SA device 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 116.6 mW.

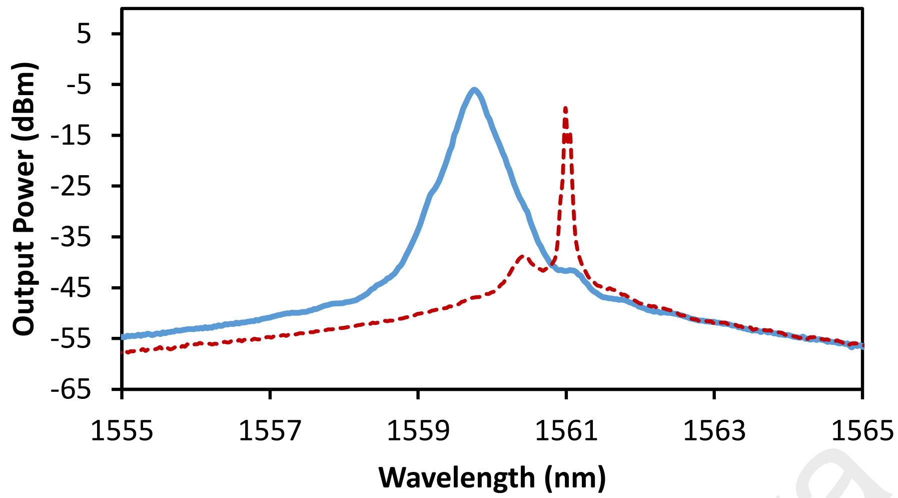

Figure 3.6: Output spectrum of the EDFL configured with and without Bi_2Se_3 based SA at pump power of 116.6 mW.

A stable pulse train with an increasing repetition rate was observed within the pump power from 86.1 to 116.6 mW, which is a typical characteristic for the Q-switched laser (Popa et al., 2011). Figure 3.7 shows the typical oscilloscope trace of the Q-switched pulse train at the pump power of 116.6 mW. It shows the peak-to-peak duration of 11.49 µs, which is equal to the repetition rate of 87.03 kHz. It is also observed that the Q-switched pulse output is stable and no amplitude modulations in the pulse train can be observed, which indicates that there is no self-mode locking effect during the Q-switching operation. Figure 3.8 shows a single envelop of the Q-switching pulse at pump power of 116.6 mW. The pulse is observed to have an almost symmetric shape with a pulse width of approximately 5.11 µs. To verify that the passive Q-switching was attributed to the Bi_2Se_3 SA, the film was removed from the ring cavity. In this case, no Q-switched pulses were observed on the oscilloscope even when the pump power was adjusted over a wide range. This finding confirms that the Bi_2Se_3 SA was responsible for the passively Q-switched operation of the laser.

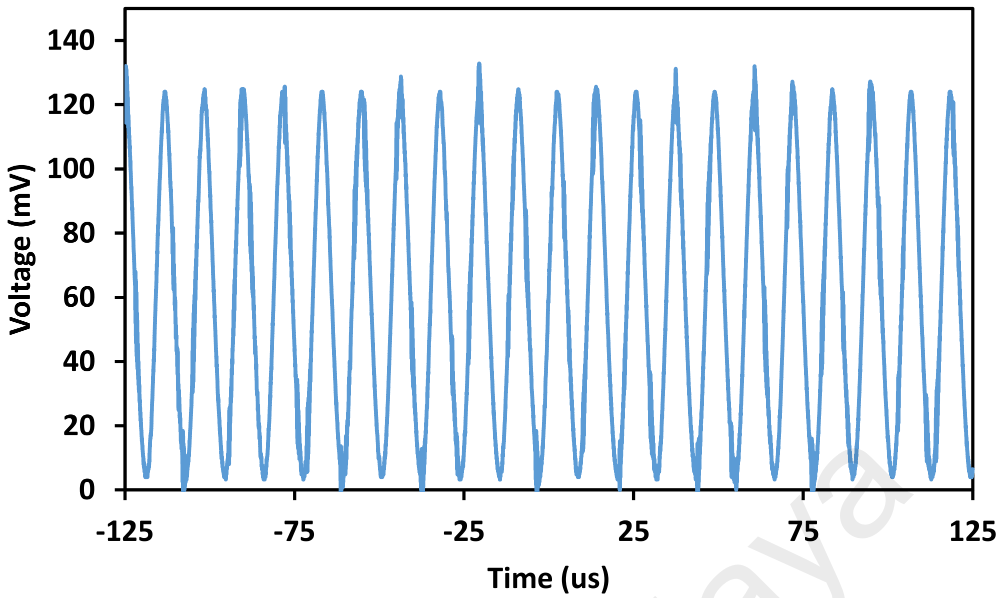

Figure 3.7: Oscilloscope trace for the EDFL with Bi_2Se_3 SA at 116.6 mW pump power showing a repetition rate of 87.03 kHz.

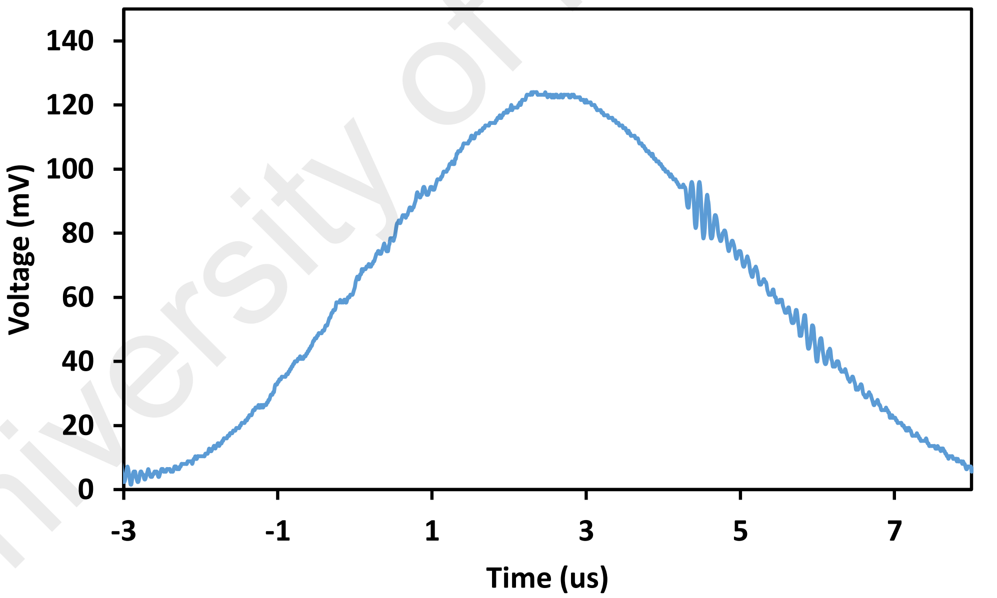

Figure 3.8: A single pulse envelop for the EDFL with Bi_2Se_3 SA at 116.6 mW pump power showing a pulse width of 5.11 μs.

Figure 3.9 shows the relationship between the repetition rate and the pulse width against the pump power. The repetition rate of the proposed Q-switched EDFL can be tuned from 84.08 to 87.03 kHz as the pump power is raised from 86.1 to 116.6 mW. In the meantime, the pulse width reduces from 5.41 μs to 5.11 μs as the pump power is increased within the same range. Figure 3.10 illustrates the relationship between the pulse energy and the peak power as the function of the pump power. The peak power is showing a steady increasing pattern from 2.52 mW to 3.21 mW as the pump power is increased from 86.1 mW to 116.6 mW. The highest pulse energy obtained was 36.9 nJ at the pump power of 116.6 mW.

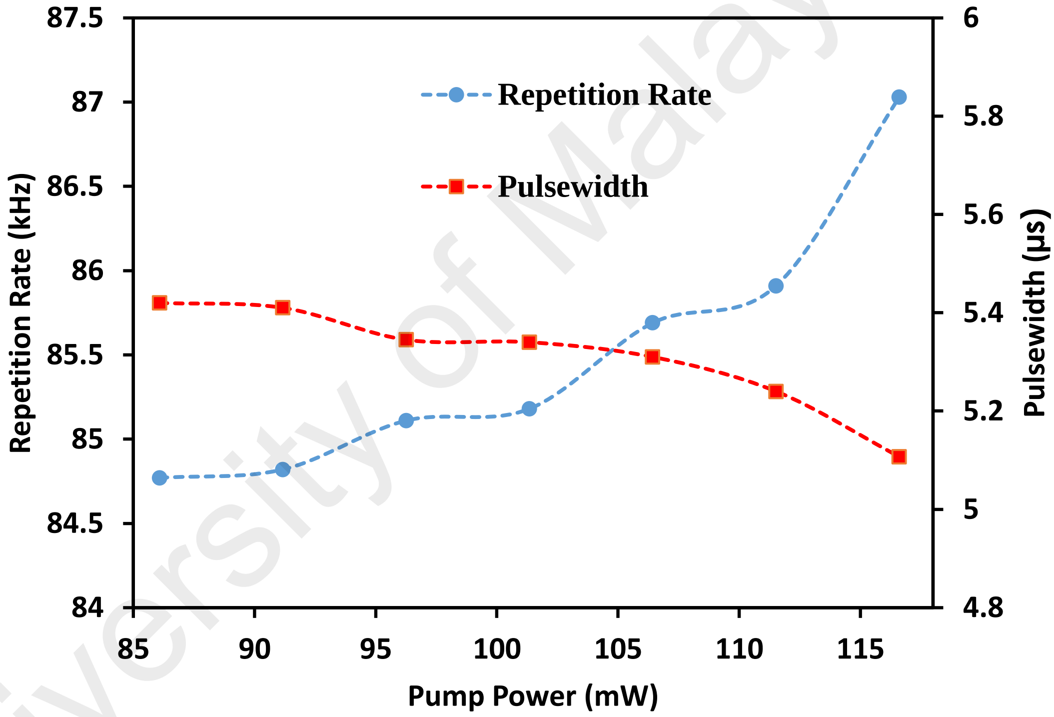

Figure 3.9: Pulse Width and Repetition Rate as a function of pump power.

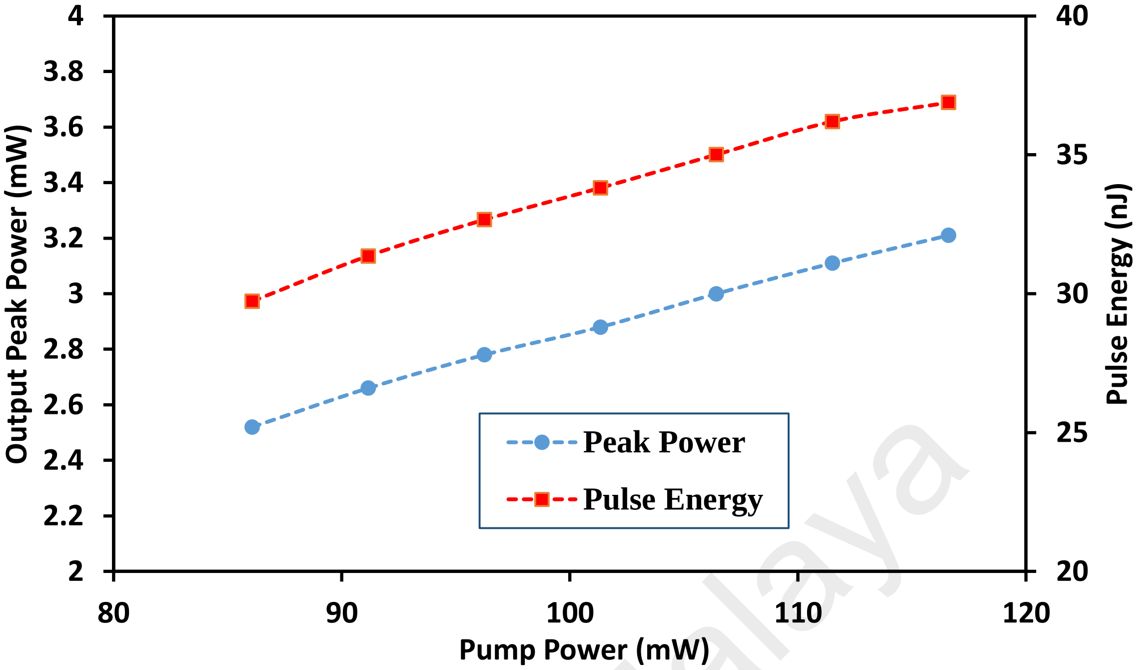

Figure 3.10: Pulse energy and peak output power as a function of pump power.

Figure 3.11 shows the RF spectrum of the Q-switched laser output which was measured by the radio frequency (RF) spectrum analyser at pump power of 116.6mW. It shows a stable repetition rate of 87.03 kHz and peak-to-background ratio of about 60 dB. This indicates the produced pulses are stable.

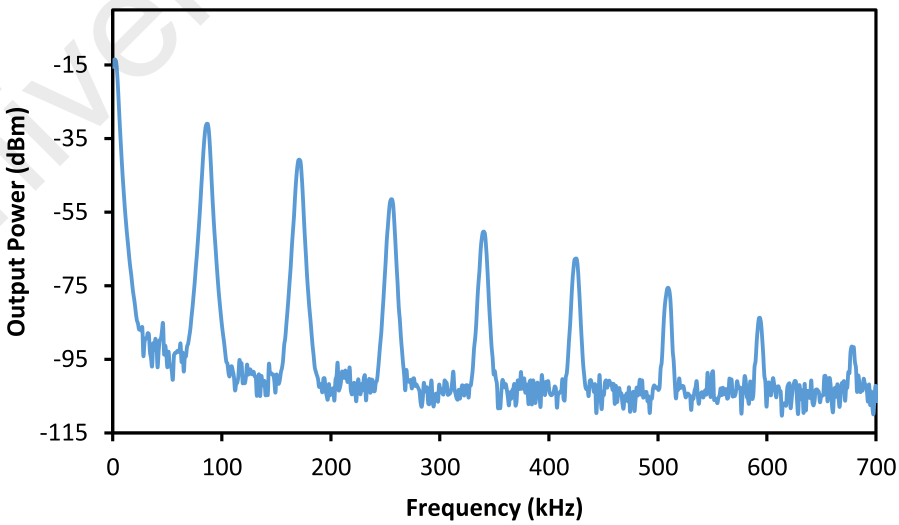

Figure 3.11: RF spectrum for the EDFL with Bi_2Se_3 SA at 116.6 mW pump power.

CHAPTER 4:

Q-SWITCHED EDFL WITH BI_2TE_3 MATERIAL AS SATURABLE ABSORBER

4.1 Introduction

In the previous chapter, passive saturable absorber (SA) made of topological insulator (TI) Bismuth (III) Selenide (Bi_2Se_3) material have been shown to be capable of generating stable Q-switched laser. In general, TIs have a large modulation depth with an efficient saturable absorption property, they are suitable for making SAs. For instance, Bismuth (III) Telluride (Bi_2Te_3) has the modulation depth and saturation intensity of about 22% and 57 MW/cm^2 respectively (Chen et al., 2014). Therefore, Q-switched fiber laser was demonstrated in recent years based on Ytterbium-doped fiber using Bi_2Te_3 SA (Luo et al., 2013). In this chapter, a passively Q-switched Erbium-doped fiber laser (EDFL) is demonstrated using a few-layers Bi_2Te_3 based SA to exploit the wideband saturable-absorption characteristic of the TIs. For this purpose, we prepare free-standing Bi_2Te_3-polymer composite SA film by implanting the powder of this material into a polyvinyl alcohol (PVA) host. The fabricated film is then integrated into an EDFL cavity for generating Q-switching pulses train.

4.2 Preparation and optical characterization of Bi_2Te_3 based SAs

The commercially available few-layer TI powder of Bi_2Te_3 with molecular weight of 800.76 g/mol was used to prepare the SA based on the similar method as described in the previous chapter. At first, 1 g of PVA is dissolved in 120 ml de-ionized (DI) water to prepare the host polymer. Then, 14 mg of Bi_2Te_3 powder was thoroughly mixed with 3 ml of the PVA solution using a magnetic stirrer. The mixture solution was placed in ultrasonic bath for 10 minutes before the suspension was poured onto petri dishes and dried at room temperature to form a Bi_2Te_3 PVA composite film. The field emission scanning electron microscopy (FESEM) image of the Bi_2Te_3 film is shown in Figure 4.1. Similar to the previous Bi_2Se_3 film, Bi_2Te_3 film has also a high dense of acicular grains formation like micro-networks, which are in irregular shapes in a size between 0.5 to 1.9 μm.

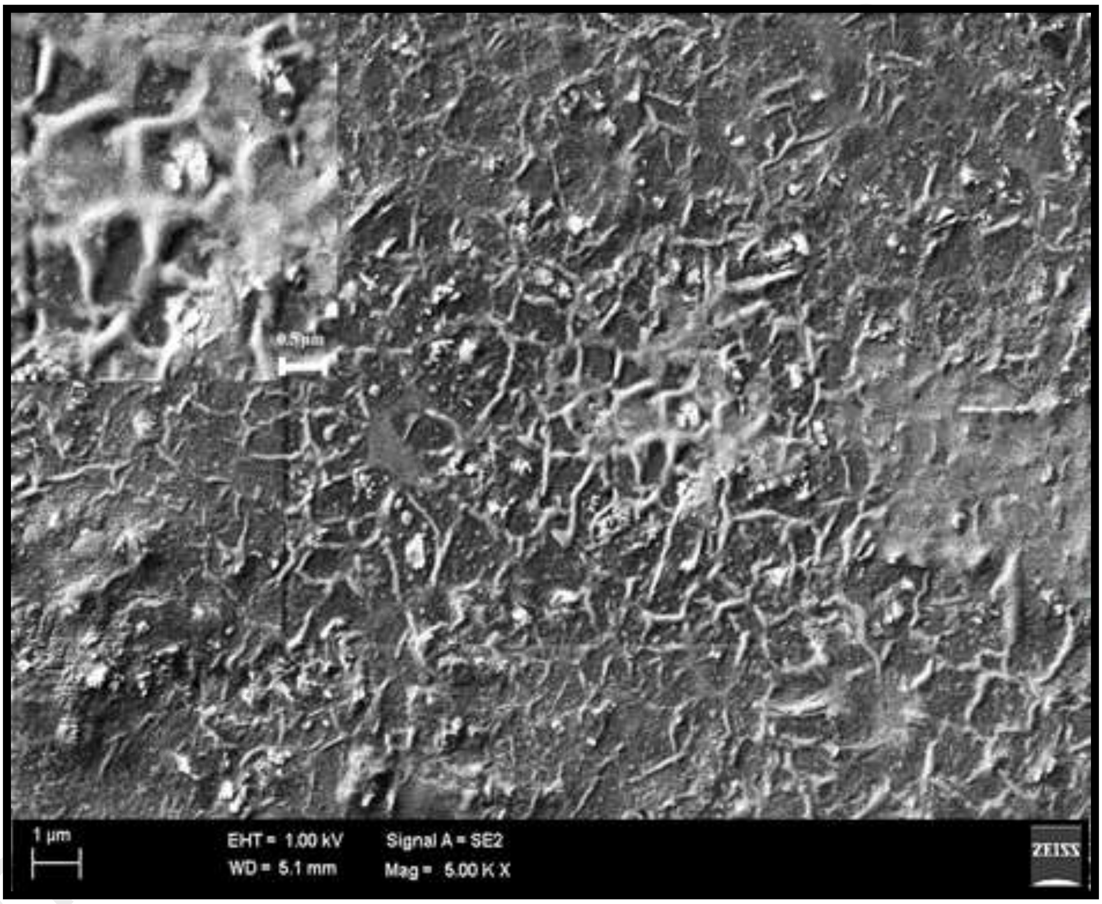

Figure 4.1: FESEM image of Bi_2Te_3 composite film. Insert shows a high magnification of the image.

Figure 4.2 illustrates the absorbance spectrum of the prepared Bi_2Te_3-PVA film which indicates that it has a broadband resonance wavelength like graphene. At around 1100 nm, the Bi_2Te_3 film suffers an almost identical absorption loss with Bi_2Se_3. Figure

4.3 shows the Raman spectrum of the fabricated Bi_2Te_3 film. Unfortunately, only two peaks are spotted at ~62 cm^{-1} and ~99 cm^{-1} which belong to A^1_{1g} and E^2_g vibrational modes and this may be due to the low dispersion of the Bi_2Te_3 nano powder in PVA. This could be improved by lengthening the stirring and sonification times. Figure 4.4 shows the nonlinear absorption profile of the Bi_2Te_3 film, which was obtained using the similar technique as described in the previous chapter. As shown in the figure, the modulation depth, non-saturable absorption and saturation intensity were approximately 30 %, 55 % and 40 MW/cm^2, respectively. In this case, the modulation depth of Bi_2Te_3 sample is higher, however the saturation intensity is smaller than in the Bi_2Se_3 sample.

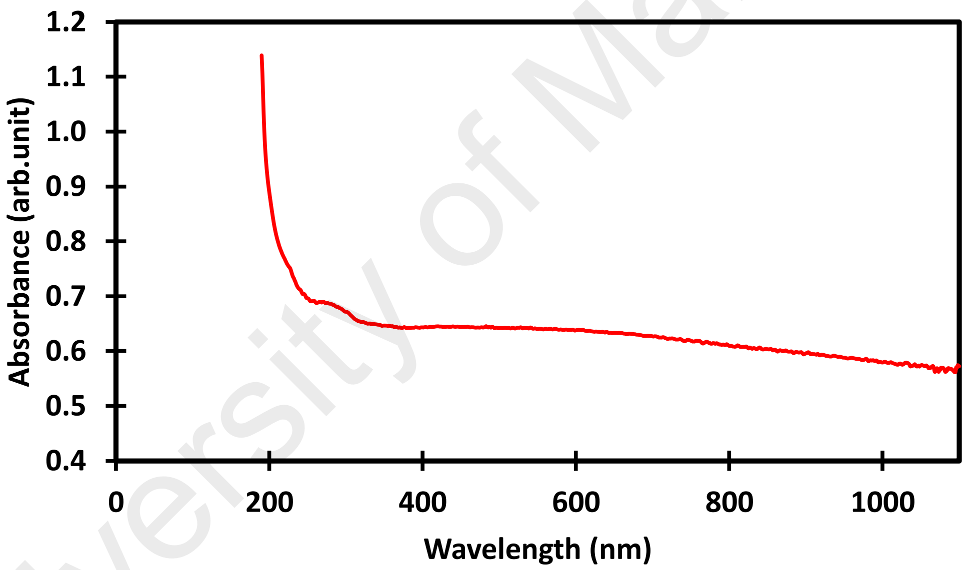

Figure 4.2: Linear transmission of the free standing Bi_2Te_3-PVA film.

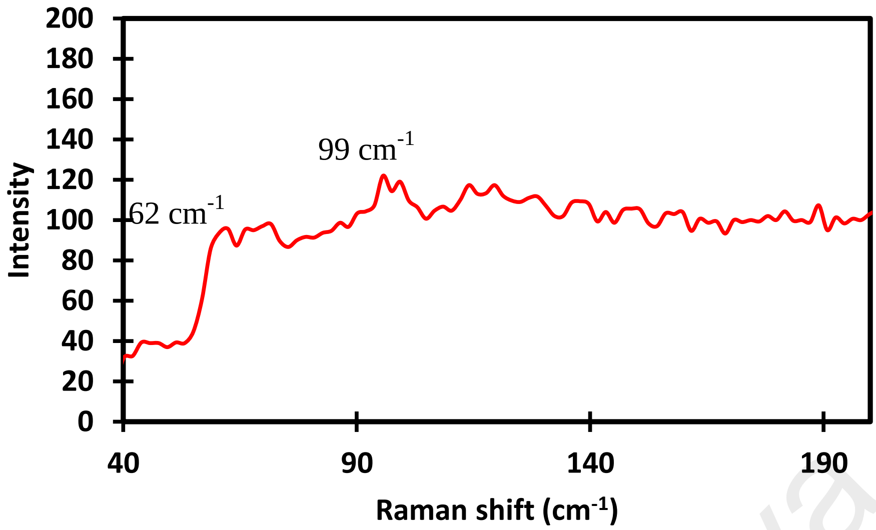

Figure 4.3: Raman spectrum of the free standing Bi_2Te_3-PVA film.

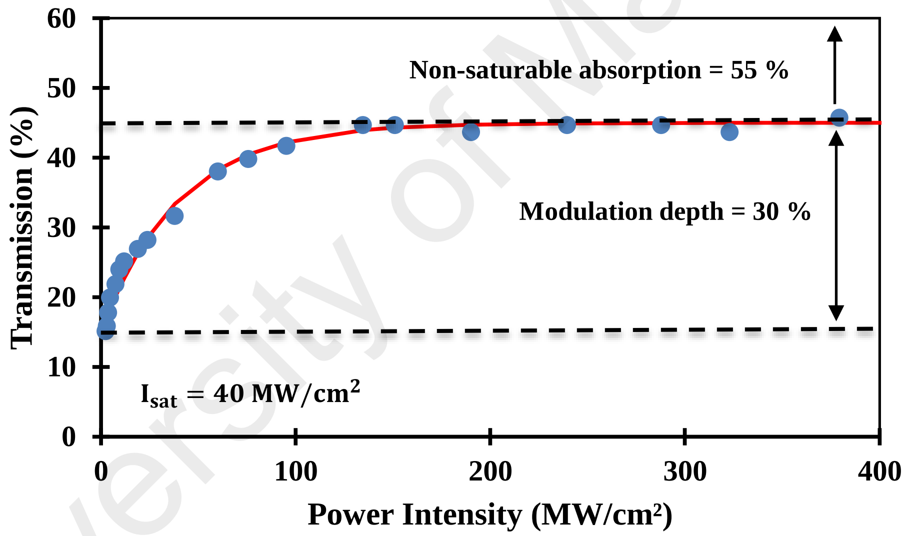

Figure 4.4: Nonlinear absorption profile for the Bi_2Te_3 PVA film.

4.3 Experimental setup

Figure 4.5 shows the experiment setup for the proposed Q-switched EDFL based on Bi_2Te_3 PVA film. The cavity is pumped by a 980 nm laser diode and connected to a 980/1550 nm wavelength division multiplexer (WDM) and output of the WDM is connected to a gain medium of 2.4 m Erbium doped fiber (EDF). The EDF we used in this experiment is similar with the previous setup in Chapter 3. The Bi_2Se_3 PVA film was sandwiched between two fiber ferrules integrated into the ring cavity as a Q-switcher. An isolator is placed between the EDF and SA device to ensure unidirectional operation of the laser. The other end of the SA device was connected to an 80/20 coupler where its 80% port is connected to the WDM to complete the ring resonator. Therefore, 80% of the light is retained inside the laser cavity and the remaining 20% is tapped out from the cavity for measurement.

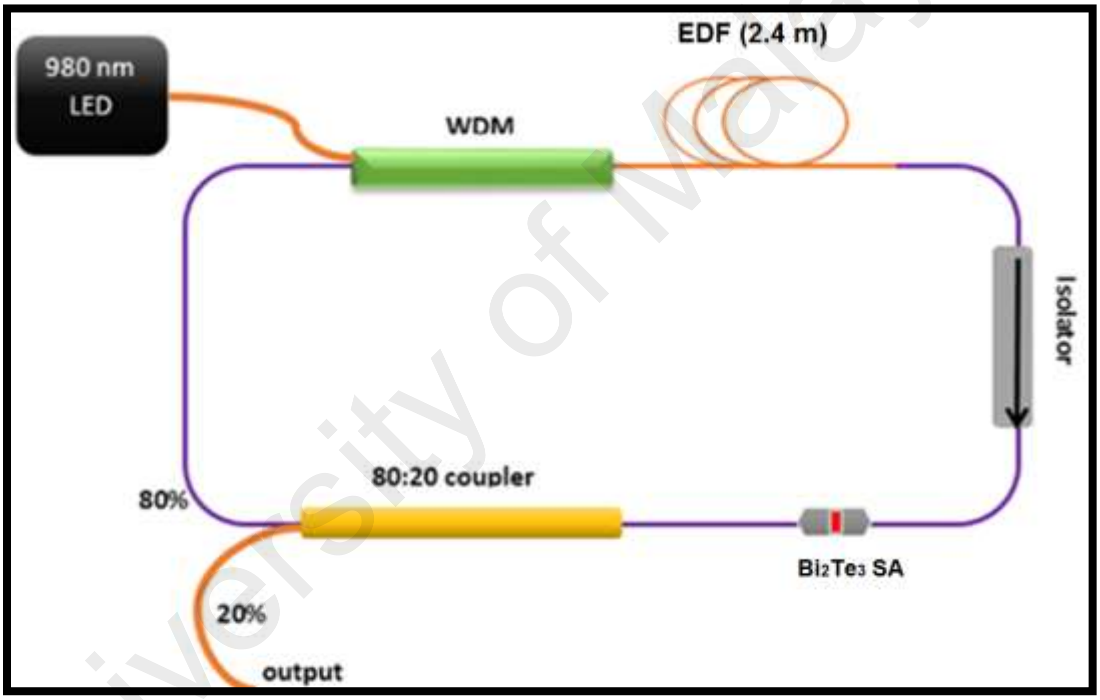

Figure 4.5: Configuration of the Q-switched EDFL with Bi_2Te_3 PVA film.

4.4 Q-switched laser performance

The performance of the proposed Bi_2Te_3 based Q-switched EDFL cavity was investigated by varying the power of the 980 nm pump. A self-starting and stable Q-switched operation was obtained when the pump power reached the threshold of 25.0 mW and its operation was maintained with the increase of pump power up to 106.4 mW. Figure 4.6 illustrates the output optical spectrum of the Q-switched EDFL at 106.4 mW pump power. As shown, the spectrum centers at wavelength of 1558.5 nm with 3dB bandwidth of 0.2 nm. Compared to the previous Bi_2Se_3 based laser, this laser operates at a slightly shorter wavelength and smaller 3 dB bandwidth. The operating wavelength shifts to a shorter wavelength due to the higher insertion loss inside the cavity. The Q-switched lasers operate at a shorter wavelength, which has a higher gain to compensate for the loss. This result indicates that the Bi_2Te_3 film has a slightly higher loss than Bi_2Se_3. Slight spectral broadening is also observed in the Q-switched laser due to self-phase modulation (SPM) effect in the ring cavity.

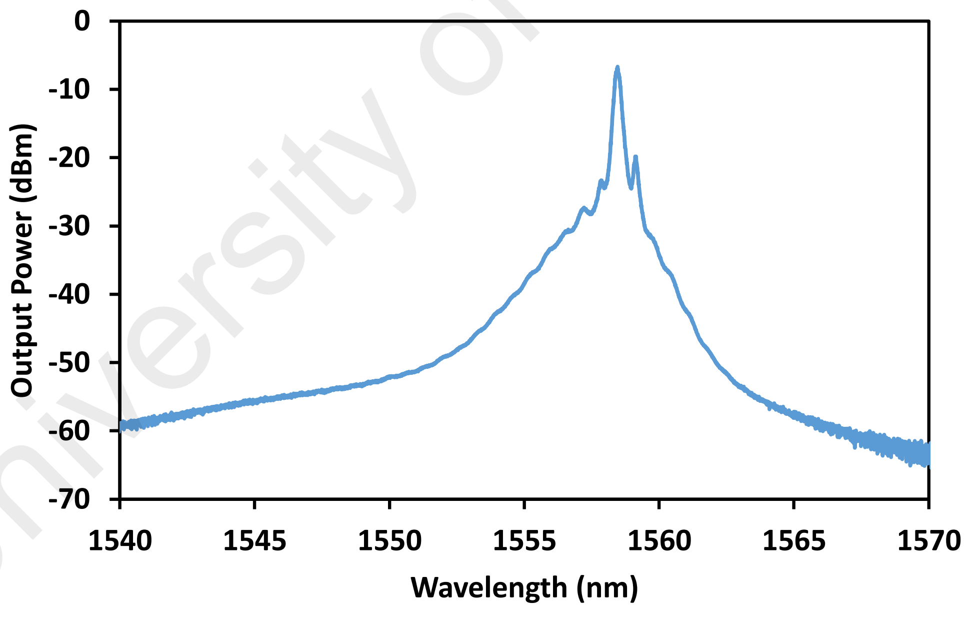

Figure 4.6: Emission spectrum of the EDFL with Bi_2Te_3 film-based SA at 106.4 mW pump power.

Figure 4.7 shows the oscilloscope trace of our proposed Q-switched EDFL at the pump power of 106.4 mW. The measured peak to peak spacing is 12.84 μs and this translates to a repetition rate of 77.88 kHz. A zoom in view at the oscillation trace (Figure 4.8) shows that the pulse duration is measured at approximately at 6.56 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. To investigate the stability of Q-switching operation, we measure the signal to noise ratio of electrical signal transformed by photodiode and analyze the electrical spectrum with the help of electrical spectrum analyser (ESA). Figure 4.9 shows the electrical or RF spectrum at pump power of 106.4 mW. As illustrated in the figure, the fundamental repetition rate of the laser is obtained at 77.88 kHz with a signal-to-noise ratio of more than 65 dB. This indicates that the produced pulses are more stable than that of the previous Bi_2Se_3 based laser. Agree to Fourier transform, the peak of fundamental repetition rate gradually decrease until the 7th harmonic. Throughout the experiment, we can confirm that no mode-beating frequency presence.

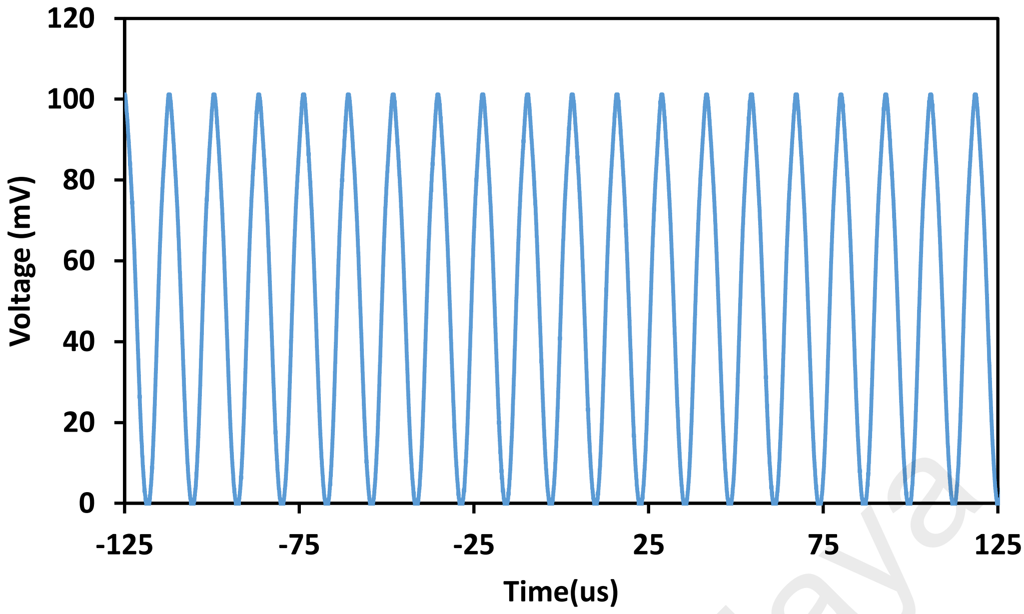

Figure 4.7: Typical pulses train for the EDFL with Bi_2Te_3 film-based SA at 106.4 mW pump power.

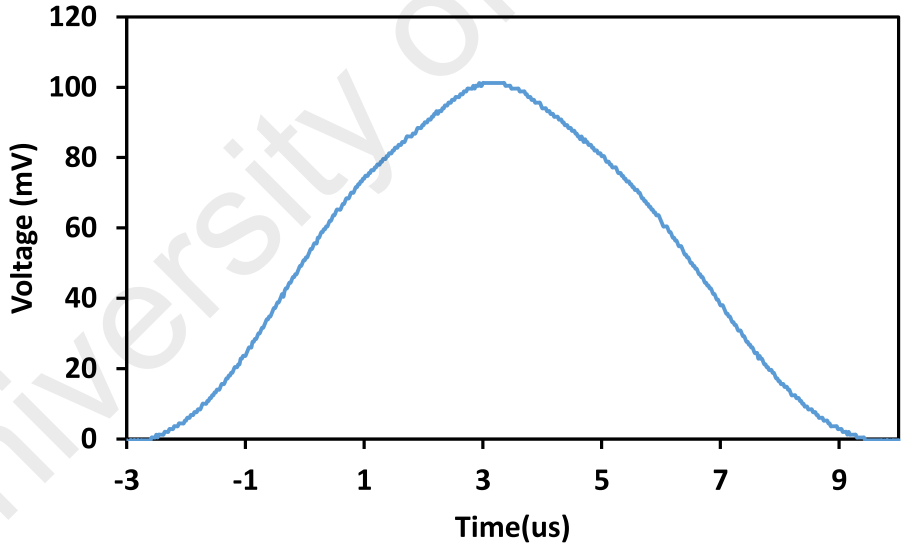

Figure 4.8: A single envelop of the pulse for the EDFL with Bi_2Te_3 film-based SA at 106.4 mW pump power.

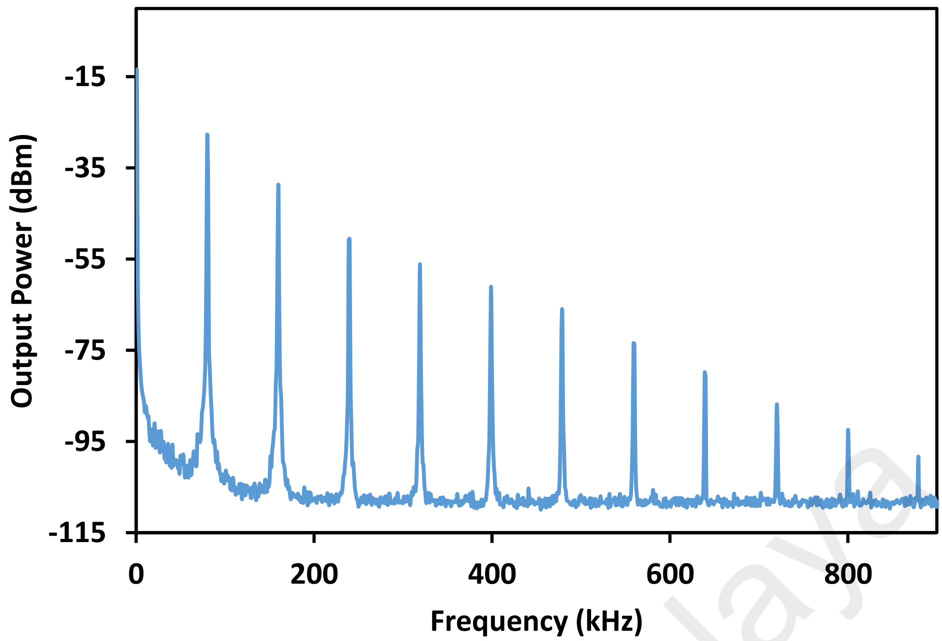

Figure 4.9: RF spectrum for the EDFL with Bi_2Te_3 film-based SA at 106.4 mW pump power.

The pulse repetition rate and pulse width of the Bi_2Te_3 film-based Q-switched EDFL are investigated as functions of pump power. The results are plotted in Figure 4.10, which indicates that the repetition rate of the Q-switching pulses can be increased from 38.76 kHz to 77.88 kHz as the power of the pump is varied from 25.05 mW to 106.4 mW. Concurrently, the pulse width decreased from 12.96 µs to 6.56 µs. The pulse width could be decreased further by either shortening the laser cavity length. In addition, the peak output power and the corresponding single-pulse energy of the laser are also investigated at various pump powers. The results are plotted in Figure 4.11. It shows that both peak output power and pulse energy increase with the increase of input pump power. The maximum peak output power of the Q-switched laser is 9.89 mW. The maximum pulse energy of 126 nJ is obtained at the maximum pump power of 106.4

mW. This Q-switching performance could be further improved by optimizing the cavity design and the SA parameters such as modulation depth and insertion loss.

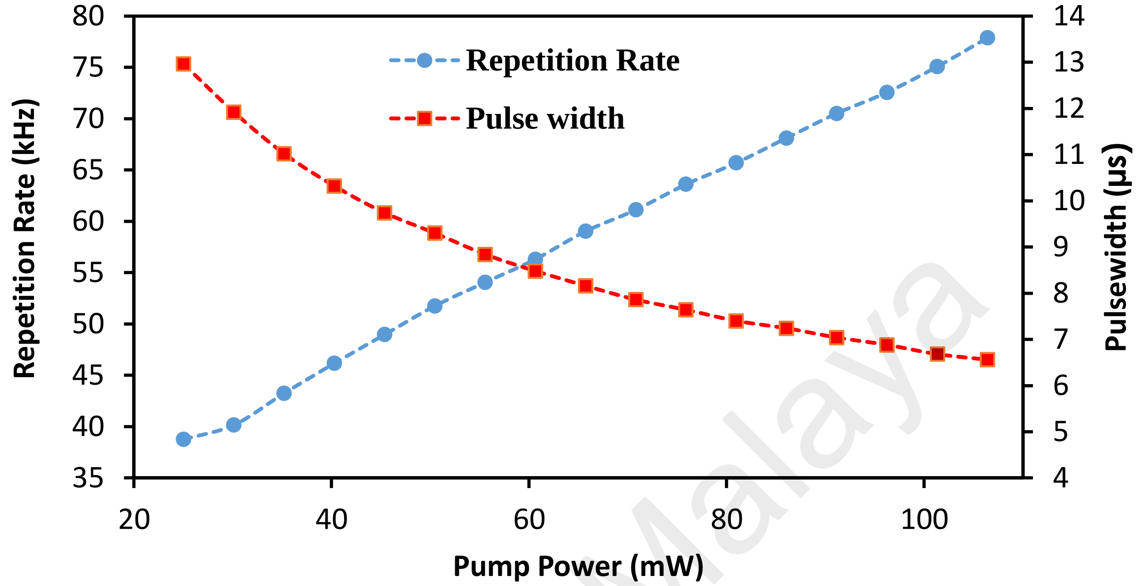

Figure 4.10: The pulse repetition rate and pulse width against pump power.

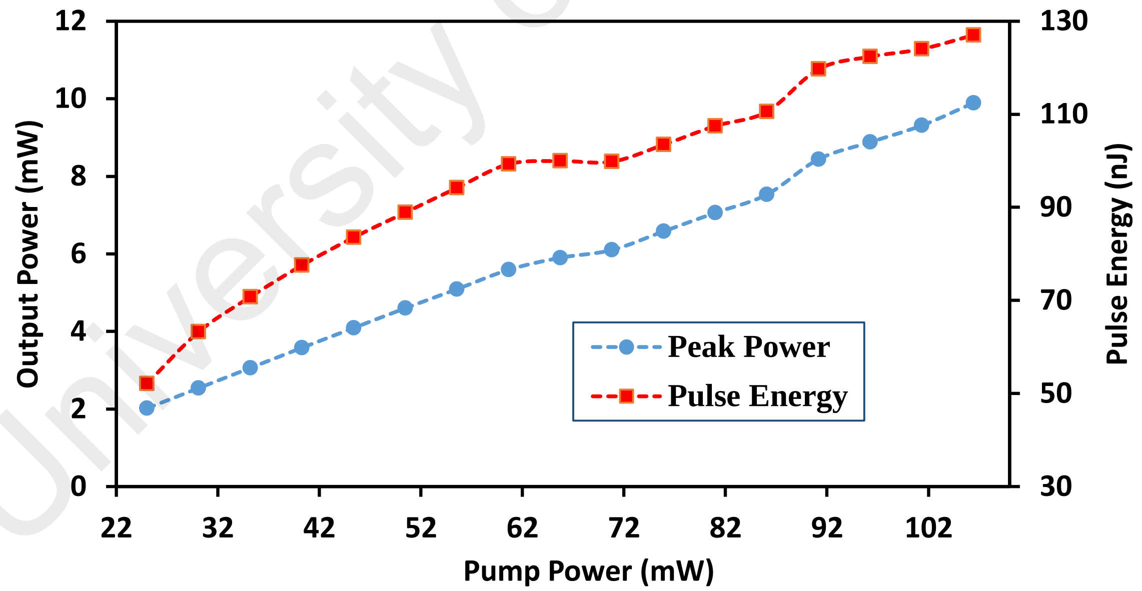

Figure 4.11: The average output power and the corresponding single-pulse energy against pump power.

CHAPTER 5:
CONCLUSION

The research work aimed to demonstrate Q-switched Erbium-doped fiber lasers (EDFLs) utilizing topology insulators (TI) as saturable absorber (SA). Two types of TIs were explored in this study; Bismuth (III) Selenide (Bi_2Se_3) and Bismuth (III) Telluride (Bi_2Te_3), to exploit the wideband saturable-absorption characteristic of the TIs. For this purpose, we prepare free-standing Bi_2Se_3-and Bi_2Te_3-polymer composite SA films by implanting the powder of these materials into a polyvinyl alcohol (PVA) host. A small piece of the film was sandwiched in between two fiber ferrule via a fiber connector and incorporated into the Erbium-doped fiber laser (EDFL) cavity for Q-switching pulse generation experiments.

At first, the Q-switched EDFL was demonstrated in using a Bi_2Se_3 film as SA. The lasers was self-started and generate stable pulse train by changing the pump power from 86.1 mW to 116.6 mW with repetition rate that can be tuned from 84.08 to 87.03 kHz. It operated at 1559.8 nm wavelength, which was slightly red-shifted from the CW laser without the SA due to insertion loss of the SA device. The spectral broadening was also observed due to self-phase modulation effect inside the laser cavity. The RF spectrum showed the signal noise to ratio of about 60 dB, which indicates Q-switched operates with an excellent stability. The output power increases from 2.52 to 3.21 mW as the pump power increased from 86.1 mW to 116.6 mW. The maximum pulse energy of 36.9 nJ was obtained at pump power of 116.6 mW. The lowest pulse width of 5.11 μs was also obtained at pump power of 116.6 mW.

In another experiment, passively Q-switched EDFL was also demonstrated using TI Bi_2Te_3 material, which was embedded into PVA film as a SA. By inserting the SA into an EDFL ring cavity, stable Q-switching pulse operating at 1558.5 nm was obtained at threshold pump power of 25.0 mW, smaller than the previous Bi_2Se_3 based EDFL. The repetition rate of the laser varies from 38.76 kHz to 77.88 kHz as the 980-nm pump power increased from 25.0 to 106.4 mW. The Q-switching operating has the shortest pulse width of 6.56 μs, and the maximum pulse energy up to 126 nJ. The Q-switching pulse shows no spectral modulation with a peak-to-pedestal ratio of 65 dB indicating the stability of the laser.

Based on these results, it is found that Bi_2Te_3 film performed better than Bi_2Se_3 one in terms of pulse energy and wider tuning range for repetition rate and pulse width. The experimental results also verify that both TI films possess the potential advantage for stable Q-switched pulse generation at 1.5 μm.

There are several aspects that need to be considerate for further improvements. First, the cavity length can be further optimized to obtain a better repetition rate and pulse width. Future studies should be focusing on exploring more on the optical properties of both Bi_2Se_3 and Bi_2Te_3 SAs for ultrafast laser generation. The optical characterization should also be carried out for both materials.

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