UNIVERSITI PUTRA MALAYSIA

PASSIVE Q-SWITCHED ERBIUM-DOPED FIBER LASER WITH TUNGSTEN DISULFIDE AS SATURABLE ABSORBER

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By

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ABSTRACT

PASSIVE Q-SWITCHED ERBIUM-DOPED FIBER LASER WITH TUNGSTEN DISULFIDE AS SATURABLE ABSORBER

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Faculty: Faculty of Science

In this research project, a passive Q-switched erbium-doped fiber laser with tungsten disulfide as saturable absorber in C-band wavelength region is demonstrated. Tungsten disulfide nanoparticles (WS_2) are partially soluble in water and acidic solutions. WS_2 is a semiconductor with a tuneable direct-indirect bandgap ranging from 1.3 to 2.1 eV.

Due to its semiconductor properties, tungsten disulfide (WS_2) has a unique band structure among TMDs, with broadband spectrum response, ultra-fast bleach recovery time, and outstanding saturable light absorption. In this studies, tungsten disulfide is deposited onto fiber ferrule with mechanical imprinting technique. The repetition rate is tuned within 8.404kHz to 15.53kHz when the pump power increase from 80.1mW to 126.7mW. The lowest pulse width is 11.7µs and the maximum single pulse energy of 80.7nJ is obtained at the pump power of 126.7mW.

ABSTRAK

PENYERAP BOLEH TEPU TUNGSTEN DISULFIDA UNTUK LASER GENTIAN BERDOP ERBIUM BERSUIS-Q SECARA PASIF

Oleh

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FEBRUARY 2022

Penyelia: Dr. Farah Diana binti Muhammad
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Dalam projek penyelidikan ini, laser gentian erbium-doped Q-suis pasif dengan tungsten disulfida sebagai penyerap boleh tepu dengan panjang gelombang C-band ditunjukkan. Tungsten disulfide nanopartikel (WS_2) sebahagiannya larut dalam air dan larutan berasid. WS_2 ialah semikonduktor dengan celah jalur langsung-tidak langsung yang boleh ditala antara 1.3 hingga 2.1 eV. Disebabkan sifat semikonduktornya, tungsten disulfida (WS_2) mempunyai struktur jalur unik di kalangan TMD_S, dengan tindak balas spektrum jalur lebar, masa pemulihan peluntur ultra pantas dan penyerapan cahaya tepu yang luar biasa. Dalam kajian ini, tungsten disulfida didepositkan pada ferrule gentian dengan teknik cetakan mekanikal. Kadar ulangan ditala dalam 8.404kHz hingga 15.53kHz apabila kuasa pam meningkat daripada 80.1mW kepada 126.7mW. Lebar nadi terendah ialah 11.7 µs dan tenaga nadi tunggal maksimum 80.7nJ diperolehi pada kuasa pam 126.7mW.

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LIST OF ABBREVIATIONS

AC	Alternating current
ASE	Amplified spontaneous emission
CNTs	Carbon nanotubes
CW	Continuous wave
dB	Decibel
DC	Direct current
EDF	Erbium-doped fibre
EDFA	Erbium-doped fiber amplifier
EDFL	Erbium-doped fibre laser
kHz	Kilohertz
LD	Laser diode
Mos_2	Molybdenum disulfite
$MoSe_2$	Molybdenum disulphide
MWCNTs	Multi-wall carbon nanotubes
Mw	Milliwatt
µs	micro second
nm	Nanometer
nJ	Nano joule
OSA	Optical spectrum analyser
QDs	Quantum dots
SA	Saturable absorber
SESAMs	Semiconductor saturable absorber mirrors
SWCNTs	Single wall carbon nanotubes
TMDs	Transition-metal dichalcogenides

WDM	Wavelength-division multiplexer
2D	Two dimensional

CHAPTER 1

INTRODUCTION

1.1 LASER

A laser is an acronym for Light Amplification by Stimulated Emission of Radiation. It is a device that produces extremely directional light by amplifying or increasing the intensity of light. Lasers amplify a narrow beam of light with highly comparable wavelengths for all of the light waves.The laser not only amplifies or raises the intensity of light, but it also produces it. Light is emitted by a laser by a process known as stimulated emission of radiation, which amplifies or enhances light intensity. Some lasers produce visible light, while others produce invisible ultraviolet or infrared rays. Laser beams are very narrow, highly brilliant, and can be focused into a very small spot due to the peaks of the laser's light waves are all lined up, or in phase, as they move together. Generally, when an electron jumps from a higher to a lower energy level, it generates light, also known as a photon. The energy difference between the energy levels equals the energy of the emitted photon. The atom as a whole is responsible for the loss of electron energy. As a result, it's possible to deduce that the atom is transitioning from a higher to a lower energy state.

1.2 PULSED WAVE LASER

Lasers can be divided into three main categories which are continuous wave (CW), pulsed, and ultrafast. Lasers that emit light in the form of optical pulses rather than in a continuous mode are known as pulsed lasers (light flashes). Pulsed lasers are often easier to operate, more versatile, have higher peak outputs, and cover a large part of the electromagnetic spectrum than continuous-wave (CW) lasers (Littman & Wang, 1997).The output power of a CW laser is constant and stable throughout time, whereas a pulsed wave laser allows the operator to control the duration and intensity of the beam. Pulse lasers are made up of a variety of different types of lasers. It depends on the pulse width, pulse repetition rate, pulse duration, pulse energy and wavelength required., Q-switched and mode-locked lasers are two of the most common types of pulse lasers. Q switched lasers, for example, create pulses that range from microseconds to nanoseconds, while mode-locked lasers produce pulses that range from picoseconds to femtoseconds.

1.2.1 Q-SWITCHING

Q-switching, also known as giant pulse creation or Q-spoiling, is a method for turning a laser into a pulsed output beam. Q-switched fiber lasers can produce reasonably brief light pulses with high energy and peak output. The technique enables the creation of light pulses with extremely high peak power (gigawatts), far greater than what a continuous wave (constant output) laser could create. Q-switching has substantially lowered pulse repetition rates, considerably greater pulse energies, and considerably longer pulse duration than Mode-locking, another approach for laser pulse creation. Repetition rates of less than 1 kHz are common for maximal pulse energy.

Pulse generation in Q-switched lasers is achieved by rapid changes in intracavity loss, causing the pumped cavity to suddenly go from below threshold to well above threshold, while below threshold energy is stored in the inverted gain medium, which is quickly dumped once the cavity goes above threshold (Town, 2003). During multiple cavity round trips, a short high-energy pulse is generated from spontaneous emission noise, quickly saturating the amplifier gain and forcing the inversion below threshold, after which the process can be repeated. There are two types of Q-switching which are active Q-switching and passive Q-switching in order to switch the cavity loss.

1.2.1a ACTIVE Q-SWITCHING

For active Q-switches, it depends on active loss modulation. It is basically acousto-optic modulators or electro-optic modulator that can found in the laser cavity. The pulse repetition rate of the active Q-switching laser is controlled with the modulator. While a voltage is provided to the Q-switch, the device prohibits a proper build-up of coherent laser energy with the cavity. A voltage is applied to the Q-switch and cause the large losses in to the first-order beam due to the diffraction. As the voltage source is turned off, the Q-switch becomes transparent to the laser beam, and the pulse is triggered. This will be able the Q switch to generate and leave the cavity.

1.2.1b PASSIVE Q-SWITCHING

For passive Q-switching, the losses are automatically modulated when the Q switch is replaced with a saturable absorber (SA). The saturable absorber initially causes a high optical loss. The absorber is saturated or its loss is reduced, once the gain reaches this loss level and the pulse begins to build up. This accelerates the pulse buildup even further. A passive Q-switched laser is more appealing and cost-effective since it does not require high voltage supplies. It is also more reliable and robust, with a lower chance of failure.

1.2.2 MODE LOCKING

Mode-locking is a laser technique for producing extremely short-duration pulses. The pulse duration of mode-locking is in the range of picoseconds or femtoseconds. One or possibly several pulses circulate in the laser resonator when the laser is mode locked. A single pulse is the most usual scenario. Because a portion of the energy from the pulse is emitted each time it strikes the output coupler mirror, the laser output is a regular pulse train. Each round trip, the gain medium replenishes the pulse energy. The pulse repetition rate is characterized by the resonator's round trip time and the number of pulses.

Basically, the mode-locking technique can be divided into active mode-locking and passive mode-locking. For active method, it is achieved with a modulator such as an electro-optic device that modulates the resonator losses in time with the resonator round trips. Passive mode-locking modulates resonator loss via a saturable absorber such as SESAM, resulting in shorter pulses than active mode-locking. Furthermore, compared to active mode-locking, passive mode-locking is easier to set up because the loss modulation synchronisation is established automatically.

1.3 ERBIUM DOPED FIBER LASER

Erbium doped fiber amplifier (EDFA) is an optical device that can amplify optical signals directly without the need to first convert it to an electrical signal. It boasts a high beam quality, a wide tunable wavelength range, a small size, and a reasonable cost. It can be viewed as erbium-doped fiber amplifier (EDFA) operating pattern in which amplified spontaneous emission is coherent oscillated. EDFA is used in dense wavelength division multiplexing, which is a method that multiplexes data signals from many sources and allows them to share a single optical fiber pair while maintaining complete data stream separation. Its Basically, there are two wavelengths that can be used to pump the EDFA which is either 980nm or 1480nm. The 980 nm pumps have a low noise and good gain, while the 1480 nm pumps are better for high output power. The erbium ion will absorb the pump energy and become stimulated to jump to an excited state if the EDFA is pump at 1480 nm. If enough pump power is applied, population inversion between the ground and excited states occurs. By stimulated emission, the excited ion decays back to its ground state and emits light with a wavelength of 1550nm. The pumping concept is the same with 980nm light, however 980nm light has a very limited lifespan before decaying, whereas 1480nm light is directly stimulated to a quasi-stable state.

1.4 SATURABLE ABSORBER

Saturable absorber is an optical component with a certain light absorbers with a lower degree of absorption at high optical intensities. Passive mode locking and Q switching are the main application of saturable absorber in order to generate short optical pulses. On the other hand, SA can be used for nonlinear filtering outside of laser resonators such as to clean up pulse forms, and in optical signal processing. In order to provide high pulse energy, a saturable absorber for a passive Q-switched laser must typically have a relatively high total non saturated absorption, low saturation fluency, and low nonsaturable losses.

1.5 TUNGSTEN DISULFIDE NANOPARTICLE

Tungsten disulfide nanoparticles (WS_2) are partially soluble in water and acidic solutions. Tungstenite, a mineral, is where it can be found in nature. These nanoparticles are the most important component of hydrodenitrification catalysts. WS_2 nanoparticles have excellent performance in new solid lubricant materials, which can be utilised not only for general lubrication but also in high-temperature, high-pressure, high-vacuum, high-load applications with radiation and corrosive fluids. For bulk form and monolayer, WS_2 is a semiconductor with a tuneable direct-indirect bandgap ranging from 1.3 to 2.1 eV. Moreover, tungsten disulfide (WS_2) has a unique band structure among TMDs, with broadband spectrum response, ultra-fast bleach recovery time, and outstanding saturable light absorption (Ding et al., 2021). Other than that, one of the most common materials used as industrial lubricants is tungsten disulfide (WS_2). The product has been employed in a wide range of industries, including aerospace, automotive, military, and even medicine. The marine and automotive industries have reaped significant benefits from the use of the lubricant.

1.6 MOTIVATION AND PROBLEM STATEMENT

In this work, tungsten disulfide is used as saturable absorber in order to demonstrate a passive Q-switched erbium-doped fiber laser. Although SESAMs and CNTs have been widely used in obtaining passive Q-switched laser, but they still have their weakness. SESAMs requires complex fabrication and needs to be prepared using an expensive packaging. For CNTs, although it was simple, low cost and has high damage threshold, but it has a limited wavelength range of saturable absorption and also poor stability. Tungsten disulfide have a tuneable direct band gap, making them ideal for a variety of optical applications. It overcomes the weakness of CNTs, which has a narrow wavelength range of saturable absorption, due to its superior optical and electrical properties such as wide absorption band and high binding energy. The fabrication of tungsten disulfide also very convenient, rapid and efficient. Thus, tungsten disulfide (WS_2) is used as saturable absorber to demonstrate the fiber laser in this project.

Passive Q-switched is preferred over active Q-switched because the former is more reliable and resilient, with a lower risk of failure and a lower cost. A modulator or a high voltage supply are not required for passive Q-switched. As a result, despite its lower power, passive Q-switched is preferable for providing a simpler and more cost-effective system as long as the output pulse produced is similar to that produced by active Q-switched applications.

1.7 RESEARCH OBJECTIVES

These objectives of the research are:

I. To fabricate tungsten disulfide onto the fiber ferrule with mechanical imprinting technique

II. To investigate the functionality of the tungsten disulfide as saturable absorber for Q-switched fiber laser generation.

III. To analyse the output performance of the passive Q-switched fiber laser by using tungsten disulfide as saturable absorber.

CHAPTER 2
LITERATURE REVIEW

2.1 LASER OPERATING MODE

Generally, there are several modes of laser operation such as continuous-wave , quasi-continuous, gain-switched, Q-switched, mode lock and Q-switched mode-locked operation that can be used. Q-switched and mode-locking with the operation based on saturable absorber in order to produce emission of laser pulse are the most common technique used due to the low cost and easy to setup characteristics (Chen et al., 2015).

2.1.1 Q-SWITCHED LASER

Q-switched laser sources have gotten a lot of interest in recent decades because of their wide range of applications in business and scientific research, including laser materials processing, remote sensing, range finding, medicine, telecommunications, and nonlinear optics (Fu et al., 2020). Fiber lasers have a number of advantages over other types of lasers, including reduced heat accumulation, environmental stability, alignment-free operation, and compactness (Lee & Lee, 2021). If the loss of an optical resonator is rapidly switched from a high to a low value, a laser could emit short pulses. Q-switching allows the creation of laser pulses with short duration is from nanosecond to picosecond range and high peak power by adjusting the Q-factor of a laser resonator. The Q-factor is given by:

$$Q = \frac{2\pi f_0 \, \varepsilon}{P}$$

where f is the resonant frequency, ε is stored energy in the cavity and $P = -\frac{dE}{dt}$ is the power dissipated. If a laser's cavity's Q-factor is rapidly changed from a low to a high value, the laser will release a significantly more powerful pulse of light than the laser's continuous output. Q-switched can be divided into two types which are active Q-switched and passive Q-switched. Active Q-switching uses modulation devices that adjust the losses in response to an external control signal. There are three types which are mechanical, electro-optical, and acousto-aoptics. During the pump cycle, they stop the laser from working. The laser in passive Q-switching is made up of a gain medium and a saturable absorber. The saturable absorber absorbs low-intensity light and transmits high-intensity light. As the gain medium is pumped, it accumulates stored energy and emits photons. The photon flux begins to observe gain, fixed loss, and saturable loss in the absorber after numerous round-trips. The photon flux may rise if the gain medium saturates before the saturable absorber, but the laser will not create a short and intense pulse. On the other hand, if the photon flux reaches a level that saturates the absorber before the gain medium saturates, the intracavity loss and laser Q-switches in the laser resonator will rapidly decrease, resulting in a short and powerful pulse of light (Ismail et al., 2016).

2.2 SATURABLE ABSORBER

Saturable absorbers of various types were employed to demonstrate the research, which focused on either passive Q-switching or passive mode-locking. Different types of lasers require saturable absorbers with various properties, and various devices were used. Normally, semiconductors saturable absorber mirrors (SESAMs) are used for passive Q-switching and passive mode-locking. This was due to SESAM which was more noticeable at lower pulse energies. Nevertheless, SESAMs had their weakness and others material had been demanded to act as a saturable absorber (SA). For example, carbon nanotubes (CNTs), quantum dots (QDs), and others. Thus, the benefits and drawbacks of various types of saturable absorbers as well as the output performance of lasers based on saturable absorbers were reviewed in this section.

2.2.1 TYPE OF SATURABLE ABSORBER

According to Zayhowski, (2013), SESAMs have been employed with a variety of gain media working across a wide range of wavelengths to generate Q-switched pulses with durations less than 100 ps. SESAMs can be designed with a number of parameters to fit self-starting and reliable mode-locking of a wide range of laser systems. They also offer both advantages and limitations when compared to bulk saturable absorbers. SESAMs are fascinating where appropriate combinations of gain medium and bulk saturable absorber have not been identified, because they can be constructed to operate at a wide range of wavelengths. However, SESAMs is known for its inefficient and time-consuming fabrication process (Kuo & Hong, 2014). Therefore, a variety of innovative saturable absorber materials with simple manufacture and cheap cost alternatives were chosen to replace SESAMs. Kurkov, (2011) also states that one of main disadvantages of SESAMs is the high risk of optical damage to a semiconductor mirror which restricts the energy of the generated pulse.

Due to the high cost fabrication issue, the different options were studied until the carbon nanotubes (CNTs) and graphenes were discovered. The CNT SAs and graphenes have been widely implemented for Q-switching and mode-locking at different operating wavelengths (Yuzaile et al., 2018). CNTs had disadvantages like CNTs were SA that had limited wavelength while graphene had a low modulation depth. CNTs can be divided into two main groups which are single wall carbon nanotubes (SWCNTs) and multi-wall carbon nanotubes (MWCNTs).

Long before graphene, single-walled carbon nanotubes (SWCNTs) were used as a saturable absorber (SA) for mode-locking fibre lasers (Ismail et al., 2016). Based on Zhou et al.,(2010), single-wall carbon nanotubes (SWCNTs) can be employed as a saturable absorber due to its compatibility with optical fibres. They also offer low saturation intensity, subpicosecond recovery time, a broad operational bandwidth, and mechanical and environmental robustness. However, Multi-wall carbon nanotubes (MWCNTs) have been developed to overcome the weaknesses of SWCNTs. According to Lin et al., (2013), the MWCNTs material does not require complicated procedures or unique growing conditions to grow rather than SWCNTs. Thus, MWCNTs was cheaper than SWCNTs since they did not use any special method to generate. Furthermore, due to the increased mass density of the multi-walls, MWCNTs have stronger mechanical strength, better thermal stability, and can absorb more photons per nanotube than SWCNTs (Ahmed et al., 2015). But, Yusoff et al., (2019) has reported that the wavelength tunability of CNTs is dependent on their shapes and size which adds to the complexity of pulse creation. For example, in order to change the band gap of CNTs, structural, morphological and alignment control have to be established. Hence, graphene is introduced due to excellent electronic and optical characteristics.

Based on Dong et al., (2012), graphene as a saturable absorber has numerous advantages over SESAMs or CNTs, including rapid saturation recovery time, low saturation threshold, huge saturable-absorption modulation depth, and a wavelength-independent saturable-absorption range. Anyway, there is a critical component of a practical graphene's material structure that is required for its realization. To fabricate the crystalline structured and few layered graphene, complex and sophisticated fabrication method has been used (Yuzaile et al., 2018).

2.2.2 OUTPUT PERFORMANCE OF LASERS BASED ON SATURABLE ABSORBER

Wang, Chen, Huang, and Chen (2014) demonstrated a passively Q-switched Er-doped fibre laser employing SESAMs in their research. With respect to pump power, they observed output power produced at a slope efficiency of 29.4%.The continuous wave (CW) lasing and Q-switching thresholds were both operated at 19mW and 28mW pump power, respectively. They achieved a maximum average output of 8.37mW and the pulse repetition frequency increased from 1.72kHz to 7.95kHz. The maximum pulse energy obtained was 17.2nJ at pump power of 46.75mW while pulse duration obtained was 30μs.

Since SESAMs has the high fabrication issue as mentioned in the previous section, carbon nanotubes (CNTs) and graphenes were discovered as they display advantages of ease in fabrication and low cost need when compared to SESAMs. Based on research Ahmed et al., (2015), they have previously demonstrated Q-switched erbium doped fiber lasers based on single and multiple walled carbon nanotubes embedded in polyethylene oxide film as a saturable absorber. With SWCNTSs, The laser produced repetition rate increases from 9.52kHz to 33.33kHz while repetition rate decreases from 16.8μs to 8.0μs when the pump power increases from 48.5mW to 100.4mW. Besides, repetition rate increases from 6.12kHz to 33.62kHz as the pulse duration decreases from 9.52μs to 4.2μs when the pump power increases from 37.9mW to 120.6mW for MWCNTs. From this research, it can be seen that $MWCNT_s$ produces substantially shorter pulse widths and has a higher repetition rate than SWCNT. This is due to the thickness of the carbon nanotubes layer in MWCNTs being thicker than SWCNTs.

According to Zhang et al., (2011), SWCNTs require special methods to produce which cause they become expensive. This can be proven from research Harun et al., (2012) where they had demonstrated research on Q-switched erbium-doped fiber lasers with single wall carbon nanotubes (SWCNTs) as a saturable absorber. They observed it with different methods of deposition. They used optically driven deposition and normal deposition. . They tend to get the results of optical deposition obtained at a lower threshold which is at 70mW. Maximum pulse energy obtained was 90.3nJ and pulse width of 11.6µs at pump power of 120mW. Therefore, it can be concluded that MWCNTs do not require any specific procedures to produce it and need lower cost than SWCNTs.

2.3 TUNGSTEN DISULFIDE AS SATURABLE ABSORBER

Tungsten disulfide (WS_2) and molybdenum disulfide (Mo_{s2}) are two semiconducting TMDs that stand out for their graphene-like two-dimensional (2D) layered structure, unique thickness-dependent bandgap, and stronger light–matter interaction than graphene (Razak et al., 2017). Li et al., (2018) also reported that TMDs are of great relevance for research because of their diversity and unique complementarities to graphene. Thus, many studies demonstrate pulse laser operatiom with WS_2 as a saturable absorber, either via Q-switching or mode-locking techniques. According to woodward et al.,WS_2, a TMD_s material similar to Mo_{s2}, has a bulk indirect bandgap of 1.3 eV that grows to a direct bandgap of 2.1 eV in single-layer form.

Razak et al., (2017) have reported that they created a SA device by placing a WS_2 thin film layer at the end of an optical fibre ferrule. The SA is used to generate a Q-switching pulse train at 1559.8 nm using an Erbium-doped fibre laser (EDFL) cavity.

When the input pump power is 142.1mW at a wavelength of 980nm, stable passively Q-switched EDFL pulses with a maximum output pulse energy of 123.2nJ, repetition rate of 104.1kHz, and pulse width of 9.61µs are produced.

Li et al., (2018) had demonstrated a stable Q-switched Er-doped fiber (EDF) laser with WS_2-based saturable absorber (SA). By employing WS_2/PVA film into EDF laser cavity, stable Q-switched operation with a central wavelength of 1560 nm is accomplished. With increasing pump power from 30 to 320 mW, the repetition rate can be adjusted from 16.15 to 60.88 kHz and the single pulse energy increases from 82 to 195 nJ and then drops to 156 nJ. At a pump power of 220 mW, the shortest pulse duration is 2.396µs, and the maximum single pulse energy is 195 nJ.

Chen et al., (2016) also reported that they demonstrate high damage resistant tungsten disulfide saturable absorber mirror (WS_2-SAM) fabricated by magnetron sputtering technique. The stable Q-switching operation is realised using the WS_2-SAM in an Erbium-doped fibre laser (EDFL) with linear cavity at a central wavelength of 1560 nm, with repetition rates ranging from 29.5 kHz to 367.8 kHz and pulse durations ranging from 1.269µs to 154.9ns. The WS_2 works reliably with an output power of 25.2 mW, a pulse energy of 68.5 nJ, and a signal-to-noise ratio of 42 dB when the maximum pump power is 600 mW.

Rosol et al., (2019) had demonstrated Q switched fiber laser by using tungsten disulfide (WS_2) two dimensional nanomaterials. The use of tungsten disulfide (WS_2) twodimensional nanomaterials as a passive saturable absorber (SA) to adjust the loss inside the laser cavity. The SA was made by repeatedly dropping and drying WS_2 solution over microfiber to generate a layer of nanosheets. To create Q-switching pulses at 1568 nm, the WS_2 coated microfiber is placed into the ring laser cavity, which is constructed with a 2.4 m long Erbium-doped fibre (EDF) as the gain medium. The repetition rate of the pulse train produced by the Q-switched laser can be adjusted from 62.0 kHz to 78.0 kHz by increasing the pump power from 151 to 193 mW. At 193 mW pump power, the lowest pulse width was 4.72 μs and the maximum pulse energy was 20.5 nJ. The generated Q-switching pulses are steady, making it suited for a variety of applications.

CHAPTER 3
METHODOLOGY

3.1 FLOWCHART

A flow chart shows how an experiment is carried out and the major steps involved. The flow chart in Figure 3.1 depicts the flow of methodology used in this project experiment. The experiment started with the setup of the laser cavity such as the EDF, WDM, isolator and so on. Using the mechanical imprinting process, the saturable absorber was then prepared and fabricated onto the core of the fibre ferrule. The cavity of a Q-switched EDFL was filled with well-fabricated tungsten disulfide. For the analysis of the result, the output performance of Q-switching was examined in terms of repetition rate, pulse width, pump threshold, and pulse energy and were recorded using a variety of output performance analyzers, including an optical spectrum analyzer and an oscilloscope.

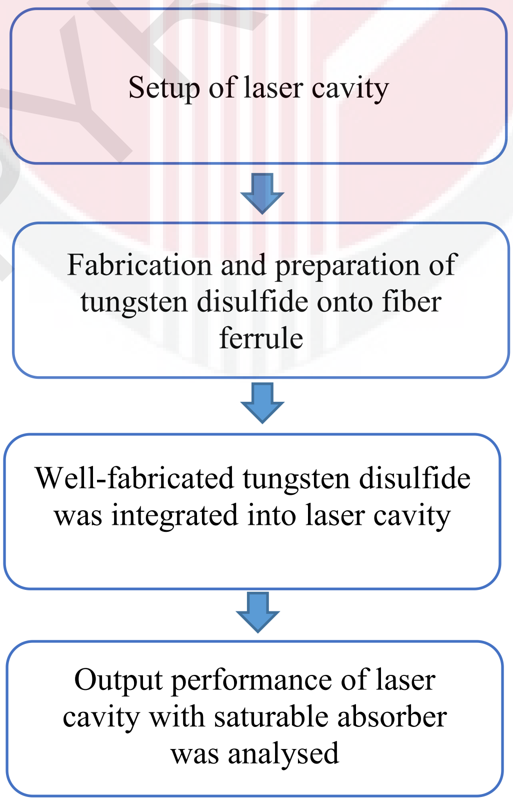

Figure 3.1 Flowchart of methodology

3.2 EXPERIMENTAL SETUP EQUIPMENT

All of the components must be linked to produce a full laser cavity in order to perform Q-switching. The important components including fiber fusion splicer, fiber cleaver, laser diode, Erbium-doped fiber, optical isolator, polarization controller and wavelength division multiplexing. However, presence of different output devices such as optical power meter, oscilloscope and optical spectrum analyse are important in result analysis.

3.2.1 FIBER FUSION SPLICER

The fusion splicer is used for splicing two optical fibers end-to-end into a single fiber which it allows two optical fibers to be permanently connected.The spliced fiber must have a flat end to provide minimal loss when spliced to another fiber. It fuses the two fibers together so that light passing through the fibers is not scattered and reflected back by the splice. Thus, the splice and the surrounding region are practically as strong as the virgin fiber itself. A fiber fusion splicer is shown in Figure 3.2 .

Figure 3.2 Optic Splicer

3.2.2 FIBER CLEAVER

The deliberate, controlled breaking of a fiber to produce a flat end face for coupling or fusion splicing is known as fiber cleaver (Figure 3.3). Before the fiber is cleaved, it needs to be stripped of its outer covering and cleaned by alcohol. If the fiber end is not flat enough for splicing, transmission loss will occur within the fibre when it is spliced with another fibre.

Figure 3.3 Fiber Cleaver (FC-6S)

3.2.3 LASER DIODE

A laser diode (Figure 3.4) is a semiconductor that produces coherent radiation with the same frequency and phase in the visible or infrared spectrum using a p-n junction. The laser diode generates this coherent light using a technique known as "Light Amplification by Stimulated Emission of Radiation," or LASER for short. Laser diodes can also be used to modulate the current driving the light source, resulting in light intensity modulation. It injects power into the laser cavity to pump the gain medium.The gain medium absorbs energy and produces excited states in the atom. For driving single-mode and distributed feedback lasers, a laser diode driver is required. The EM 595 benchtop controller was used in this project. It is a laser diode driver that works with both single-mode and distributed feedback (DFB) lasers.

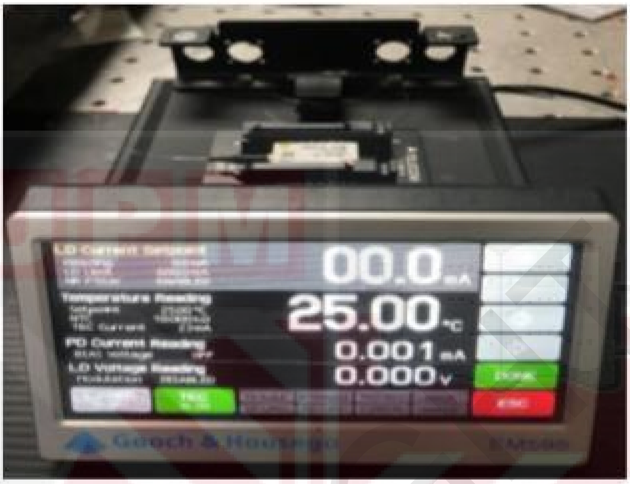

Figure 3.4 EM 595 Benchtop Laser Controller

3.2.4 POLARIZATION CONTROLLER

A polarization controller (Figure 3.5) is an optical device that allows the polarization of light within fibers to be controlled. Polarization controllers can be controlled manually or using electrical impulses from a generator, or they can be controlled automatically. Various fiber-optic devices, such as interferometers, require a polarization state of light in a fiber that may be adjusted. Different types of fier polarization controllers have been developed for this purpose.

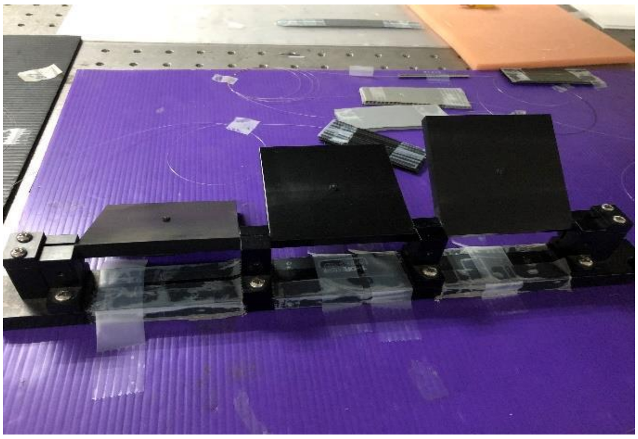

Figure 3.5 Polarization Controller

3.2.5 ERBIUM-DOPED FIBER LASER

Erbium-doped fiber (EDF) as shown in Figure 3.6 is an optical fiber with rare-earth elements such as erbium, ytterbium, neodymium, dysprosium, praseodymium, thulium, and holmium serves as the active gain medium in a fiber laser. Erbium-doped fiber is used as a gain medium to increase the signal and is commonly pumped using a laser at 980nm or 1480nm wavelength. When 980nm light is used to pump EDF, it goes through an unstable short lifetime state before rapidly decaying to a quasi-stable state, then decaying to ground state and emits light in the 1525-1565nm band. When 1480nm light is pumped into EDF, it is directly stimulated to a quasi-stable state and subsequently decays down to ground state, emitting light in the 1525-1565nm range. With a silica host, EDF will create wavelengths in the C-band, which is around 1550nm, and the L-band, which is around 1590nm.

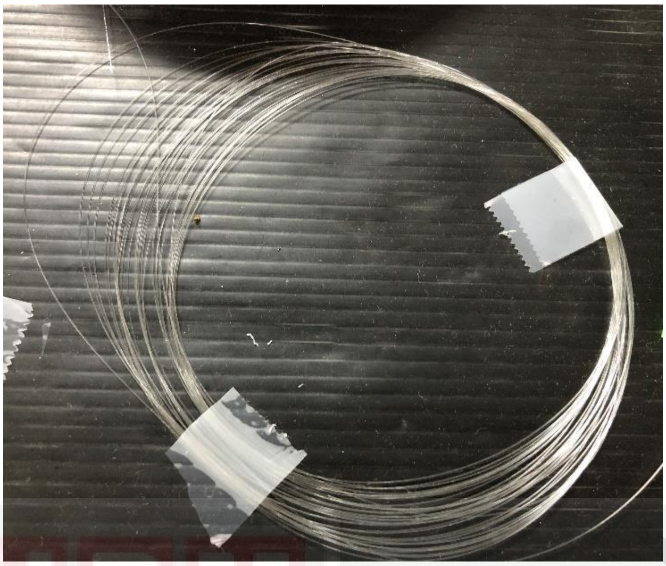

Figure 3.6 Erbium-doped fiber

3.2.6 WAVELENGTH DIVISION MULTIPLEXER

WDM (wavelength-division multiplexing) is a fiber-optic communications method that multiplexes a number of optical carrier signals onto a single optical cable by employing different wavelengths. WDM enables for capacity expansion or bidirectional communication over a single cable. WDM refers to an optical carrier that is normally characterised by its wavelength, whereas frequency-division multiplexing refers to a radio carrier that is typically described by its frequency. A wavelength division multiplexer is shown in Figure 3.7.

Figure 3.7 Wavelength-division multiplexer

3.2.7 OPTICAL ISOLATOR

An optical isolator (Figure 3.8) is a device that allows solely unidirectional optical signal transmission. It is frequently used in optical systems to eliminate undesired optical reflections. A single-frequency semiconductor laser, for example, is extremely sensitive to external optical feedback. Even a very tiny quantity of optical reflection from an external optical circuit, on the order of –50 dB, is enough to enhance laser phase noise, intensity noise, and wavelength instability significantly. Thus, In applications requiring low optical noise and stable optical frequency, an optical isolator is frequently required at the output of each laser diode.

Figure 3.8 Optical isolator

3.2.8 OPTICAL COUPLER

An optical coupler (Figure 3.9) is a semiconductor device that uses light waves to transfer electrical signals between circuits or systems, providing coupling with electrical isolation. It can combine two or more inputs into a single output, or can separate a single input into multiple outputs. It also permits light waves to travel in numerous path. A 90:10 coupler is used in this experiment to split the signal so that 90% of it can continue to travel inside the cavity while 10% is connected to an oscilloscope or OSA for signal analysis. There are also various types of fiber optic coupler like X couplers, stars couplers and trees couplers.

Figure 3.9 Optical coupler

3.2.9 OPTICAL POWER METER

Figure 3.10 shows an optical power meter. An optical power meter (OPM) is an instrument for determining the power of an optical signal.The average power of a fiber optic system is normally measured with an optical power meter. An optical power meter is made up of a calibrated sensor, an amplifier, and a display. An optical power meter's measurement range is typically from 0 dBm (one milliwatt) to -50 dBm (ten nanowatts).

Figure 3.10 Optical power meter

3.2.10 OSCILLOSCOPE

An oscilloscope (Figure 3.11) is a device that displays and analyses the waveform of a signal's voltage with respect to time. The x-axis and y-axis are exits in an oscilloscope's graph display. It shows the change in electrical signal over time on the x-axis and the change in electrical signal over voltage on the y-axis. It can be display either in alternating current (AC) or direct current (DC) with frequency range of 1Hz to several megahertz (MHz). In this project, the oscilloscope is used to measure the pulse repetition rate and pulse length of Q-switched EDFL.

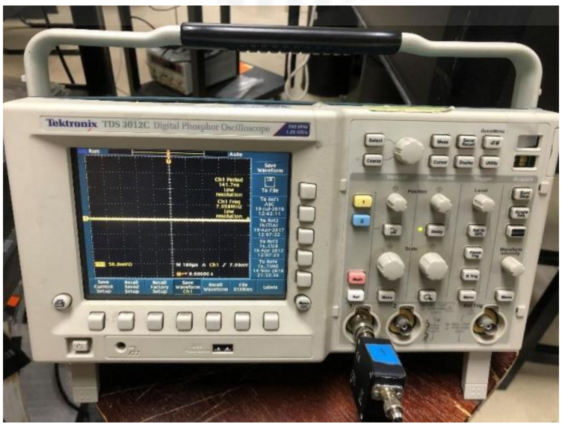

Figure 3.11 Oscilloscope

3.2.11 OPTICAL SPECTRUM ANALYZER

Figure 3.12 shows how an optical spectrum analyzer (OSA) is used to measure and display the power distribution of an optical source over a particular wavelength span. It has the ability to measure at a fast rate while maintaining high resolution, sensitivity, and frequency, as well as having full analysis capabilities. Due to its high sensitivity, OSA can detect optical power from about +20dBm to -70dBm. It also has a high resolution and a wide dynamic range, allowing it to distinguish between closely allocated signals and noise.

Figure 3.12 Optical Spectrum Analyzer (Yokogawa AQ6370C)

3.3 PREPARATION AND FABRICATION OF TUNGSTEN DISULFIDE ONTO THE CORE OF FIBER FERRULE

There are a few steps of WS_2 preparation before integrating into the ring cavity of Q-switched EDF. Firstly, a small amount of SA powder is poured onto a piece of clean filter paper as shown in Figure 3.13(a).The SA powder is then dipped into an FC SMF-28 fiber ferrule, which allows the SA powder to stick to the fiber ferrule core. As seen in Figure 3.13(c), the SA powder attached to the core is thick and irregular. Because the SA powder that attached to the core is thick and uneven, a clean scotch tape is used to distribute the deposited SA powder multiple times (Figure 3.13(d)). Lastly, the cerium oxide powder deposited fiber ferrule is attached to another fiber ferrule to fabricate the SA in the cavity (Figure 3.13(e)).

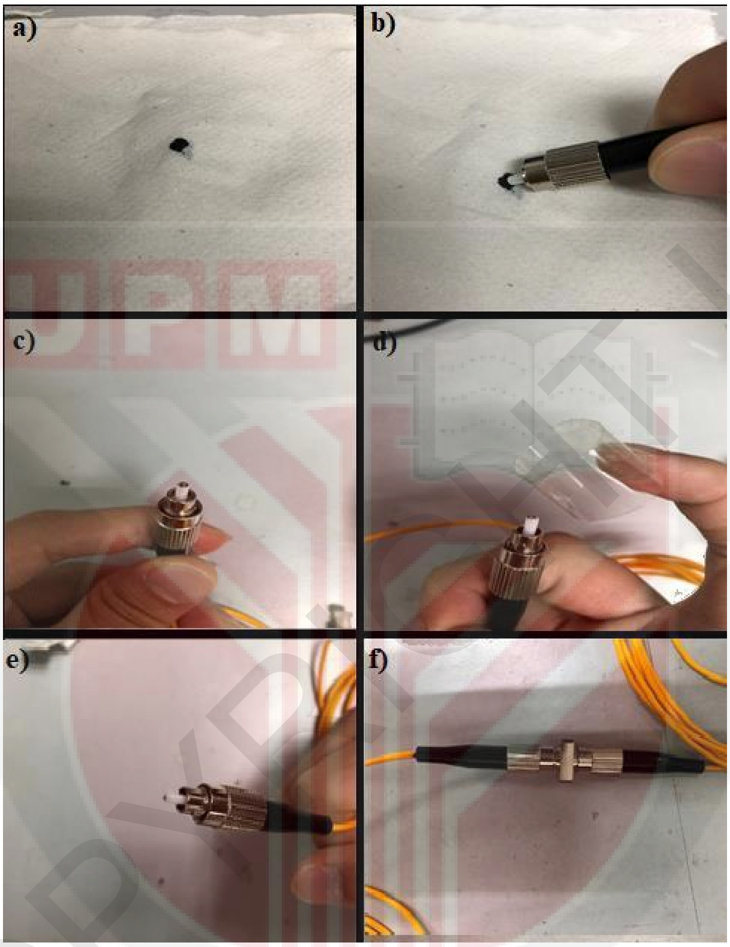

Figure 3.13 Fabrication procedures of saturable absorber

3.4 EXPERIMENTAL SETUP OF Q-SWITCHED EDFL

Figure 3.14 shows a schematic diagram of the experimental setup. In this experiment, a 980 nm laser diode, EDF, WDM, optical isolator, optical coupler, polarization controller, and saturable absorber were used. The EDF is pumped by the laser diode via 980/1550 nm WDM. The other end of the EDF is connected to the isolator followed by polarization controller. The position of SA was between polarization and coupler. In this experiment, a 90:10 output coupler was attached to the PC output, so that 90% of the signal was returned to SA and channelled back to WDM. The 90% output was connected back to the ring cavity which was toward another end of WDM and 10% was connected to OSA or oscilloscope in order to obtain the output spectrum and output pulse train of the Q-switching respectively. The analysis of EDFL begins with calibrating the pump laser used. Table 3.1 shows the calibration of the output power of laser diode pump and output power of EDFL as a function of current of laser diode 980nm for ring configuration. The input current given are from 0mA to maximum 350mA, however in this paper only the readings which there is lasing action are tabulated.

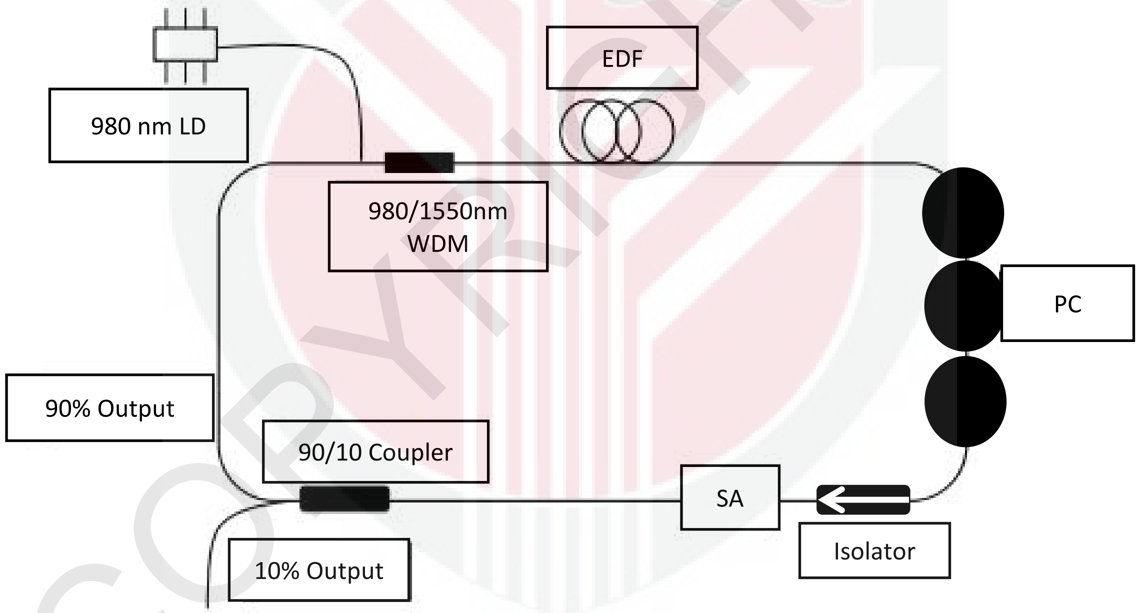

Figure 3.14 Schematic of experimental setup

Table 3.1 The output power of laser diode pump and output power of EDFL as a function of current of laser diode 980 nm for ring configuration.

Input current from laser diode 980 nm (mA)	Output power of laser diode 980 nm (mW)	Output power of Erbium doped fiber laser (mW)
170	80.1	0.12
175	83.5	0.18
180	86.7	0.29
185	89.6	0.36
190	92.4	0.37
195	95.7	0.40
200	98.9	0.46
205	102	0.53
210	105.2	0.56
215	108.1	0.58
220	111	0.61
225	114.1	0.66
230	117.5	0.81
235	120.5	0.91
240	123.6	1.03
245	126.7	1.25

CHAPTER 4
RESULTS AND DISCUSSION

4.1 CHARACTERIZATION OF THE EDFA

Figure 4.1 shows the amplified spontaneous emission (ASE) spectrum of erbiumdoped fiber amplifier (EDFA). The ASE spectrum begins to appear at 77mW pump power, and the image is as illustrated in Figure 4.1. The ASE spectrum, as shown in the diagram, remains within the wavelength range of 1520nm to 1570nm. At a wavelength of 1531nm, the ASE spectrum exhibits the maximum power of -26 dB.

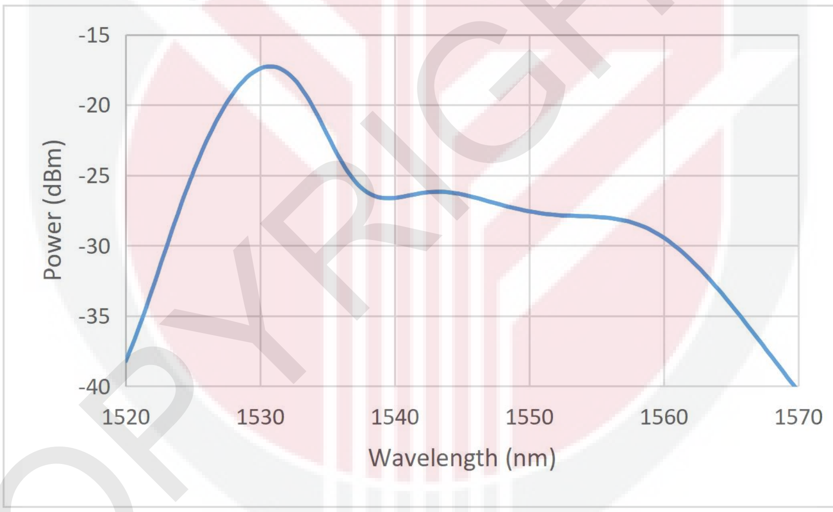

Figure 4.1 ASE spectrum of EDFA

4.2 OUTPUT PERFORMANCE OF THE EDFL WITHOUT TUNGSTEN DISULFIDE

Figure 4.2, Figure 4.3, and Figure 4.4 show the optical spectra of the EDFL's output without WS_2. The output spectra from the OSA were obtained at three different pump powers, which are 80.1mW, 114.1mW, and 126.7mW. When the pump power is increased, there are more peaks with higher power. The maximum peak at 80.1mW pump power is around -41.49dBm. For pump power 114.1mW, the maximum peak reach around -40.55 dBm, whereas the highest peak for a pump power of 126.7mW is around -38.72dBm.

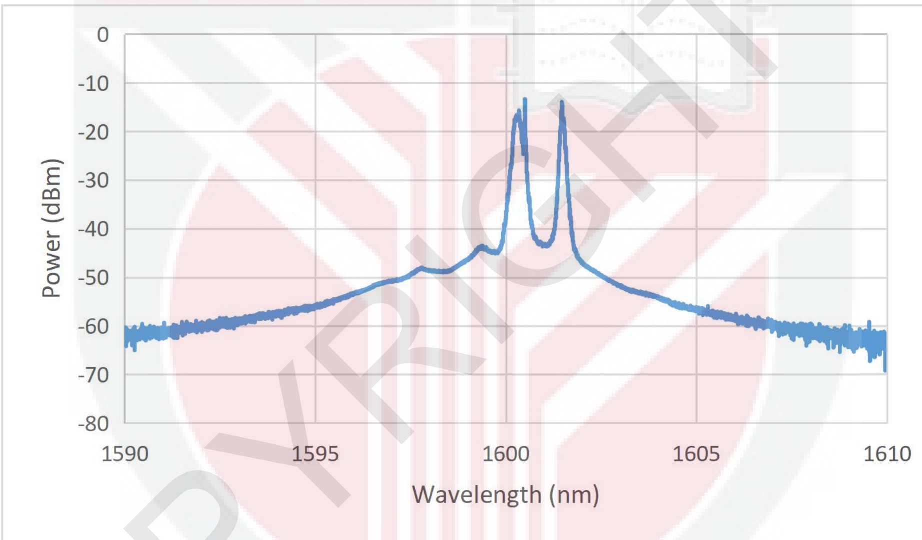

Figure 4.2 Output laser performance of EDFL at pump power of 80.1mW

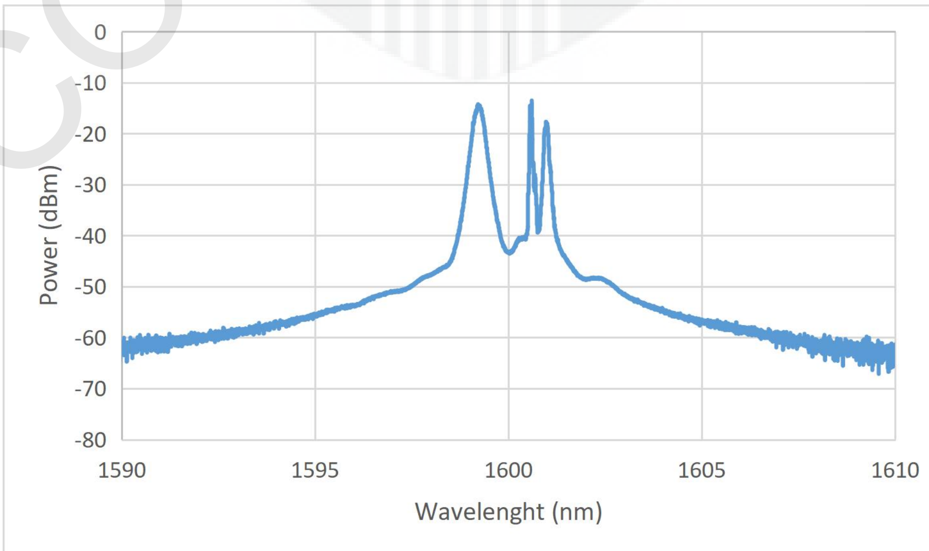

Figure 4.3 Output laser performance of EDFL at pump power of 114.1mW

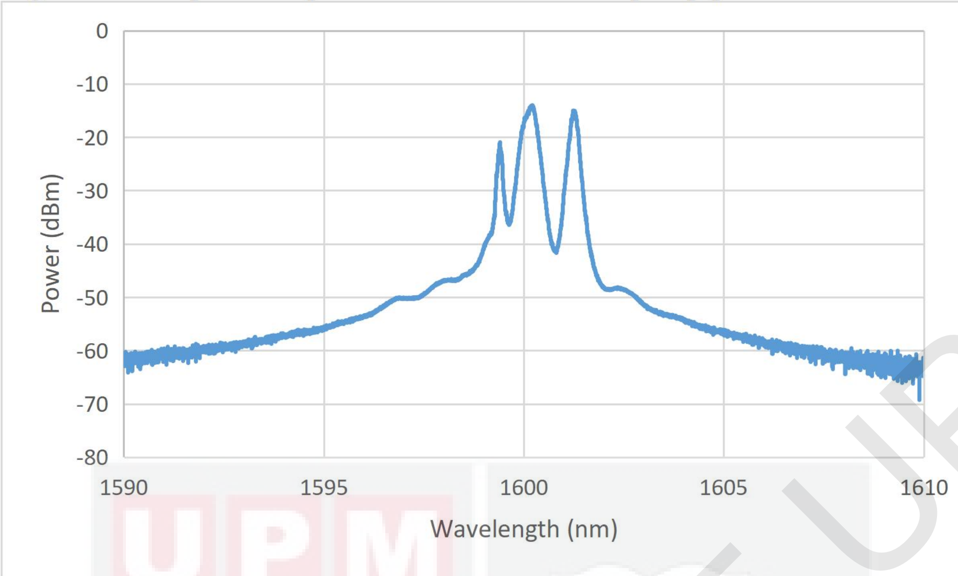

Figure 4.4 Output laser performance of EDFL at pump power of 126.5mW

Figure 4.5 shows the graph of average output power versus pump power without deposition of WS_2 into cavity. The average output power is increase as the pump power increase. The setup generates a continuous wave laser at 57.1 mW pump power which is known as the lasing threshold . After the lasing threshold is reached, the average output power increases by around 0.03 mW for every increase in pump power. The slope efficiency over the threshold value is 0.16%, as indicated by the graph's slope.

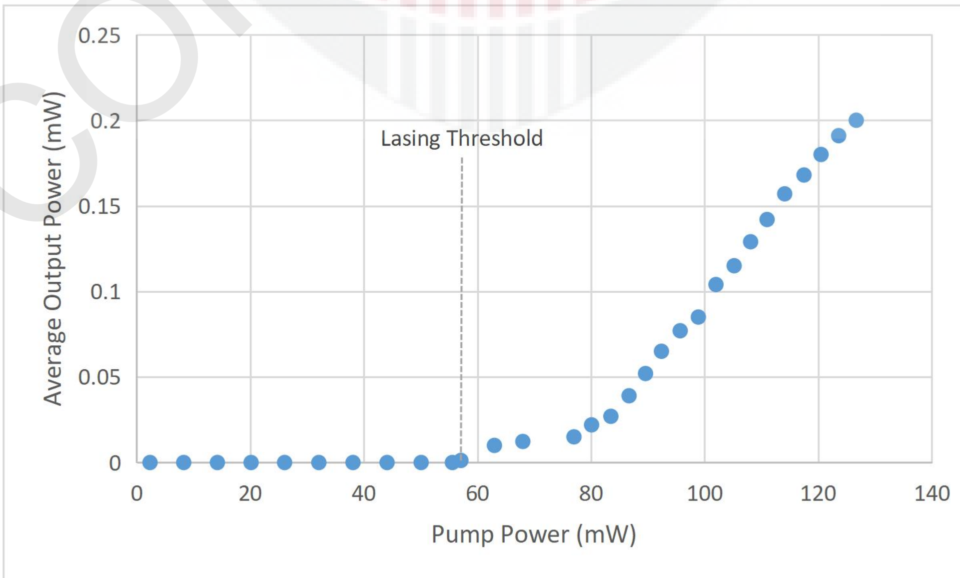

Figure 4.5 Average output power against pump power without WS_2

4.3 Q-SWITCHED FIBER LASER PERFORMANCE

Figure 4.6 shows the graph of average output power against pump power when the WS_2 is fabricated into the cavity.When the pump power reaches roughly 50.1 mW, the system begins to emit a continuous wave laser. When the pump power increases, the average output power increases from 0.0201mW to 1.25mW. The slope efficiency above the threshold value is 0.8%.

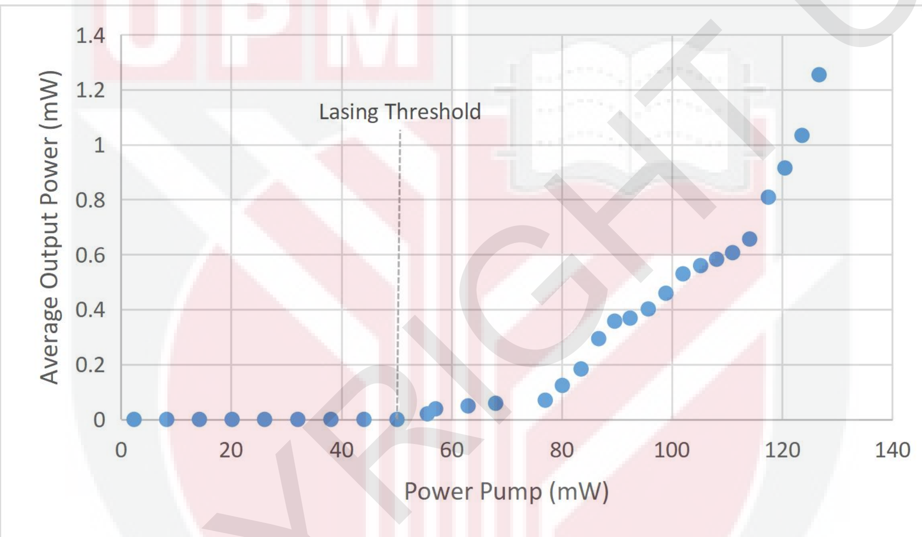

Figure 4.6 Average output power against pump power with WS_2

4.3.1 Comparison of output laser performance at different pump power

Figure 4.7 compares the average output power of EDFL with and without tungsten disulfide to the pump power. The average output power against pump power without tungsten disulfide exhibits a linear graph, whereas the graph SA shows a rising output power as pump power increases. The laser threshold of the one without WS_2 is 57.1mW while the one with WS_2 is 50.1mW respectively. As a result, the cavity without WS_2 requires more pump power to reach the laser threshold than the cavity with WS_2. At a pump power of 126.7mW, the average output power of the EDFL with

WS_2 is almost 3 times higher than that of the EDFL without WS_2, 1.25mW and 0.2mW, respectively. Average output power of EDFL with WS_2 shows higher value because the WS_2 act as saturable absorber and strongly saturated, this resulting in more gain. The peak of pulse is formed due to the gain is exceeding the remaining loss in cavity. The gain continues to be saturated after the bursting laser round trip and the operation is repeated in the laser cavity.

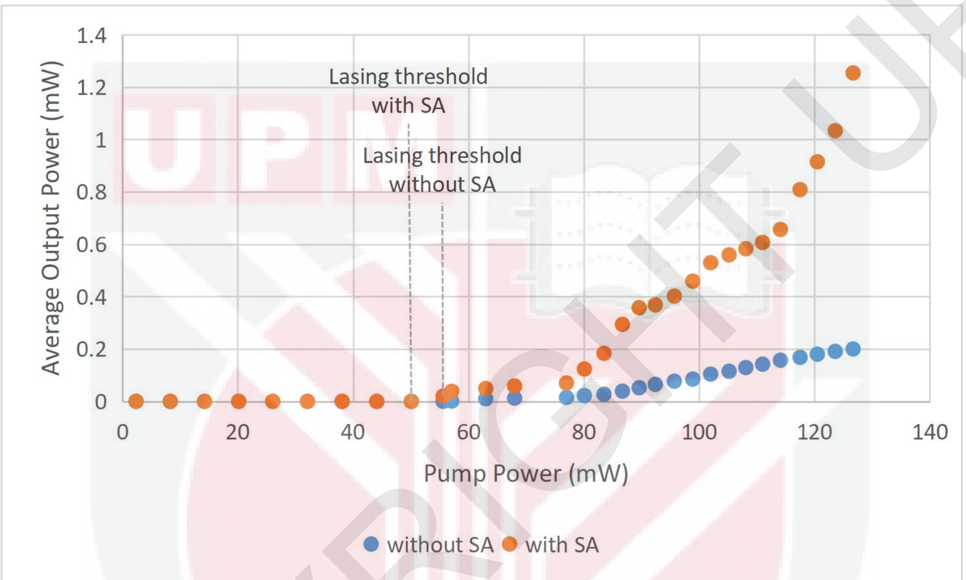

Figure 4.7 Comparison of average output power between with and without SA at different pump power

The effect of pump power on pulse duration and pulse repetition rate are shown in Figure 4.8 and Figure 4.9. When the pump power of 980 nm LD is increased, the pulse width of the cavity drops, but the repetition rate increases. Pump power of 80.1mW is the Q-switching threshold the EDFL cavity in our experiment power. After reaching the Q-switching threshold, the pulse width is 30.8µs with 80.1 mW pump power and it decreases to 11.7µs when the pump power is 126.7 mW. For the repetition rate, a reading is increases from 8.404kHz to 15.53kHz as the pump power increases from 80.1mW to 126.7mW. As pump power increases, more gain is delivered to saturate the SA, resulting in a higher repetition rate.

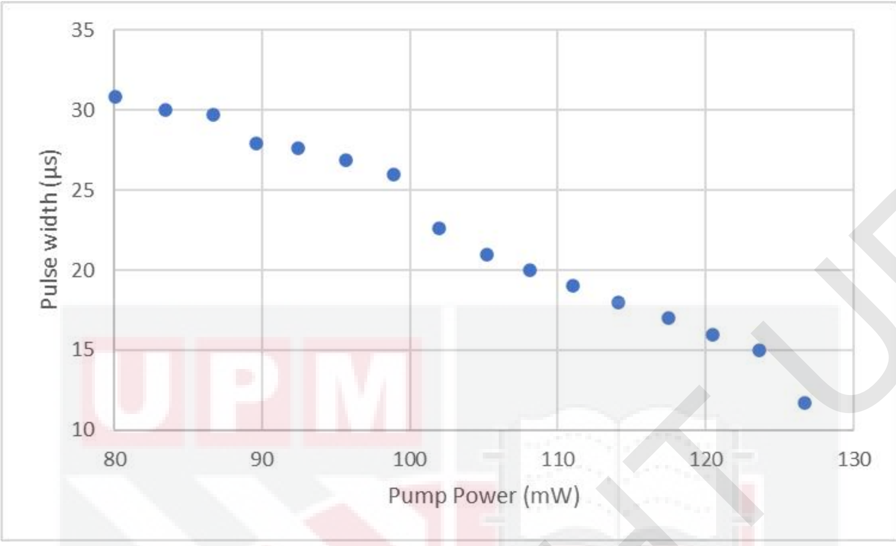

Figure 4.8 Pulse width against pump power

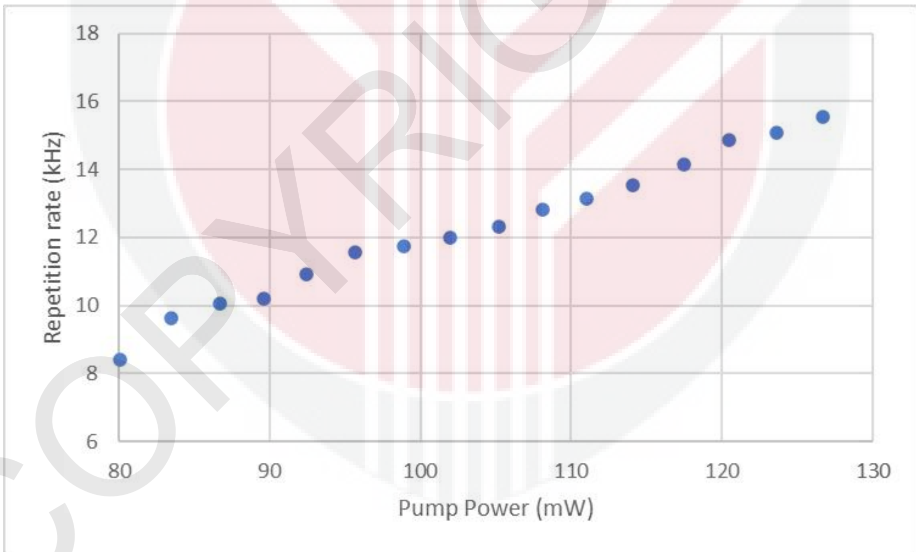

Figure 4.9 Repetition rate against pump power

4.3.2 Pulse train trace of Q-switching at pump power of 102mW

An oscilloscope is used to observe the pulsing operation. Figure 4.10 shows the pulse train trace of Q-switching at pump power of 102mW. The repetition rate is 11.99kHz. The intensity obtained is at 0.0068 a.u..Figure 4.11 shows the zoom in view of pulse train trace of Q-switching at 102mW. The duration for each pulse is around 22.6μs.

This duration increases with a lower pump power because repetition rate decreases with pump power.

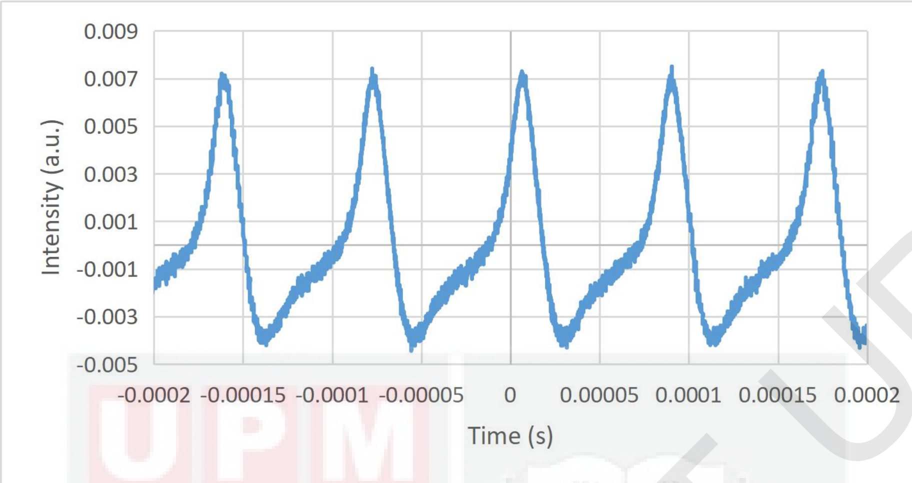

Figure 4.10 Pulse train trace of Q-switching at 102mW

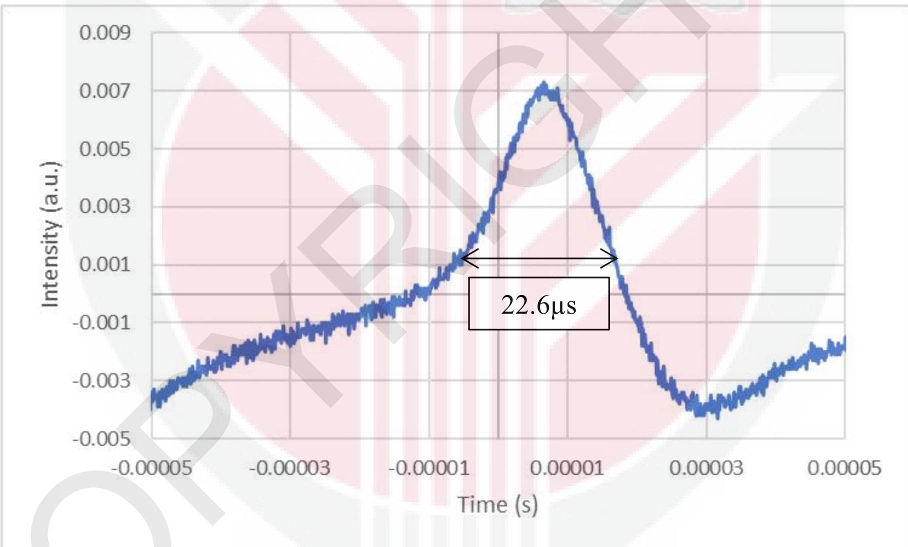

Figure 4.11 Pulse train trace of Q-switching at pump power of 102mW

Figure 4.12 shows the pulse train trace of Q-switching at 114.1mW. The repetition rate obtained is 13.52kHz. The intensity obtained is approximately 0.0079 a.u.. Figure 4.13 shows the zoom in view of pulse train trace of Q-switching at 114.1mW. The duration for each pulse is around 18μs. This duration is shorter compared to the duration of the pump power of 102mW because the duration is decreased with the increase of pump power.

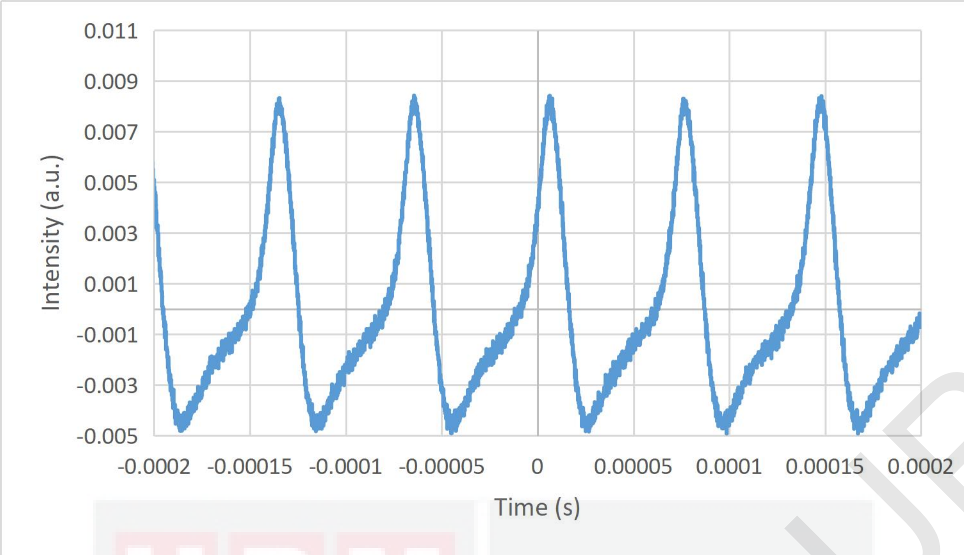

Figure 4.12 Pulse train trace of Q-switching at 114.1mW

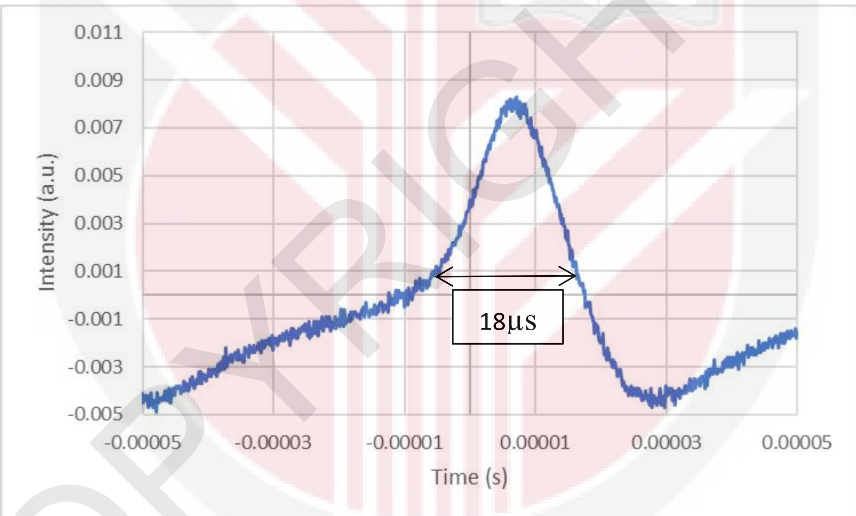

Figure 4.13 Zoom in view of pulse train trace of Q-switching at 114.1mW

4.3.3 Pulse train trace of Q-switching at pump power of 126.7mW

Figure 4.14 shows the pulse train trace of Q-switching at pump power of 126.7mW. The repetition rate obtained is 15.53kHz and pulse width of 11.7μs. The intensity is approximately 0.0093 a.u..Figure 4.15 shows the zoom in view of pulse train trace of Q-switching at 126.7mW. The duration for each pulse is around 11.7μs. This duration is the shortest among the three pump power and this shows that the duration is decreased with the increase of pump power.It shows unstable pulse train when the pump power exceeds 150mW.

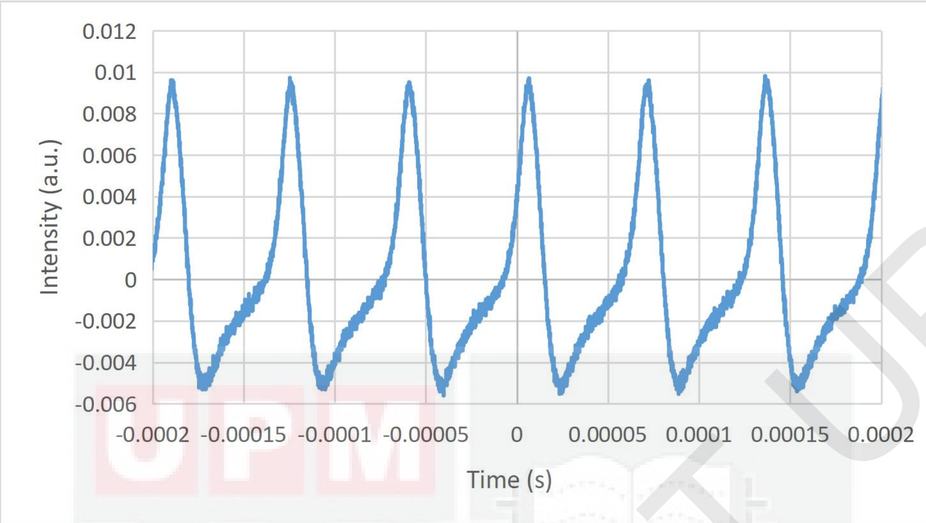

Figure 4.14 Pulse train trace of Q-switching at 126.7mW

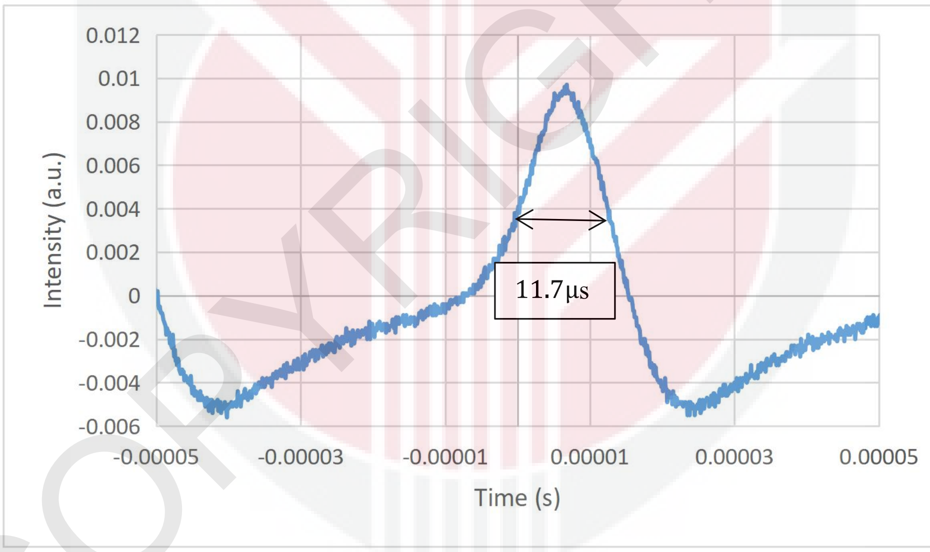

Figure 4.15 Zoom in view of pulse train trace of Q-switching at 126.7mW

4.3.4 Comparison on pulse train trace at pump power of 102mW, 114.1mW and 126.7mW

As shown in Figure 4.10, 4.12 and 4.15, the pulse width decreases as the pump power increases. For a standard Q-switched to operate, the pulse width will decrease as the repetition rate is increased. Figure 4.11 shows zoom in view of pulse train trace of Q-switching at 114.1mW. The duration for each pulse is around 18 μs.When the repetition rate is increased from 11.99kHz to 13.52kHz, the pulse width is shorter compare to the duration with pump power of 102 mW which is around 22.6μs. Figure 4.14 shows the pulse train trace of Q-switching at 126.7mW. The repetition rate at pump power 126.7 mW is the highest among the three pump power. When the repetition rate is increased from 13.52kHz to 15.53kHz, the duration is reduced from 22.6μs to 11.7μs and the duration is the shortest among the three pump power. This shows that the duration is decreased with the increased of pump power. The intensity also increase as the pump power increase.A typical fiber laser goes through three stages, the first of which is the CW laser generate, followed by unstable Q-switching, and ultimately stable Q-switching. As the pump power continues to rise, a stable Q-switching is formed.

Figure 4.16 shows the average output power and pulse energy of the Q-switched pulsed laser against the pump power. The Q-switched threshold occurs at pump power of 80.1mW. The pulse energy is calculated by dividing the average output power by repetition rate. From Figure 4.16, it clearly shows that the pulse energy is increases as the pump power increases. The pulse energy rises from 14 nJ at 80.1mW pump power to 35nJ at 89.6mW pump power, followed by a drop to 31.29nJ at 95.7mW pump power. The pulse energy continues to increase until 90.47 nJ at maximum pump power of 126.7mW. There is a possibility that the system is going exceed its optimal operating point for the decreases in pulse energy for a few points. Other than that, nonlinear effects may take place and resulting in affect the performance of the system (Ahmad et al., 2012).

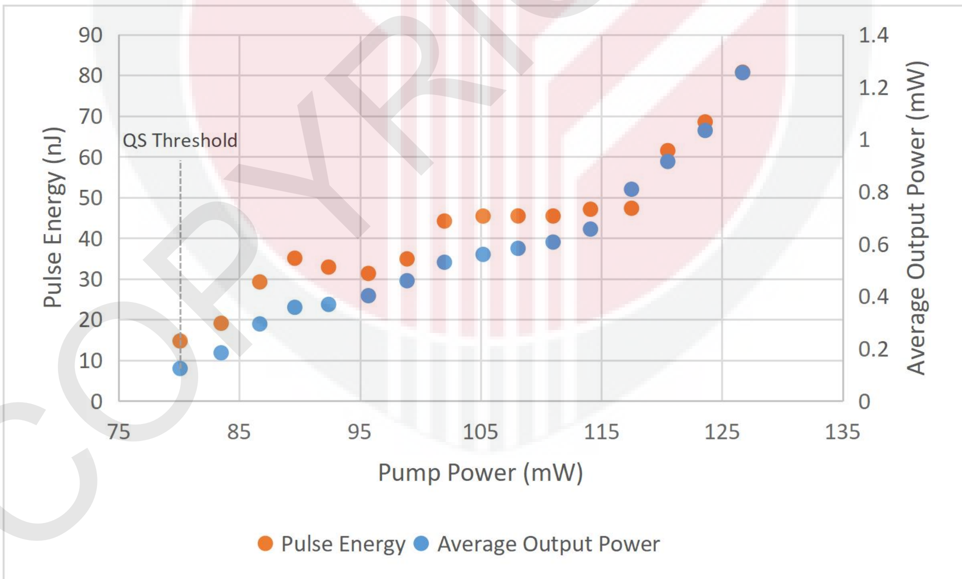

Figure 4.16 Average output power and pulse energy at different pump power

The peak power and pulse energy at various pump powers are shown in Figure 4.17. By dividing the pulse energy by the pulse width, the peak power value may be computed. The peak power obtained at 80.1mW pump power is 0.48mW. When the pumping power is at its highest, the maximum peak power of 6.9mW is attained at 126.7mW. Both the peak power and the pump power is proportional to the pulse energy. At peak power of 0.48mW, the pulse energy obtained 14.7nJ which is produced under the Q-switched threshold. The pulse energy is 80.7nJ at maximum peak power of 6.9mW.

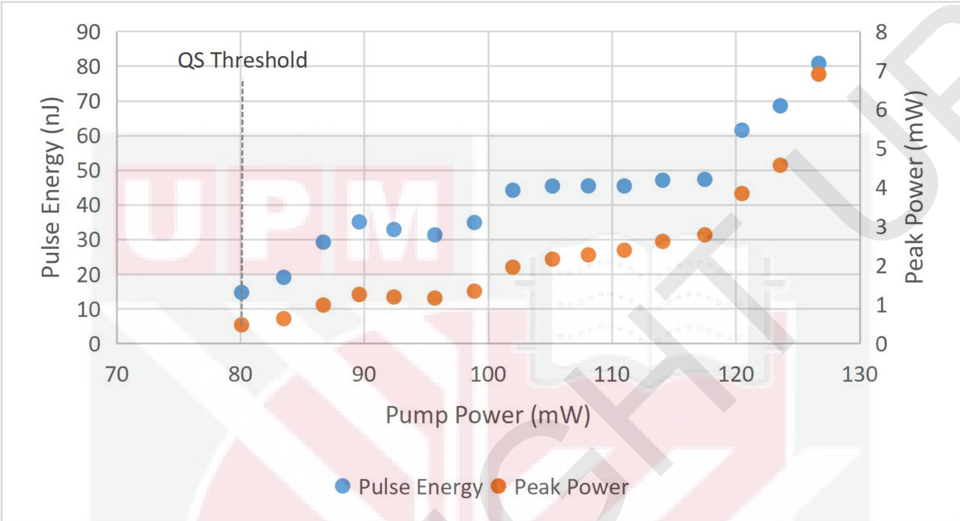

Figure 4.17 Peak power and pulse energy at different pump power

Figure 4.12 shows the output laser spectrum of Q-switched EDFL at different pump power as observed by OSA. Pump power of 102mW, 114.1mW and 126.7mW are taken as results to show the different of output laser performance produced at different pump power. It shows that the laser spectrum is covering the wavelength range approximately from 1587nm to 1593nm. Stable Q-switched laser is obtained. At the same time, there is central wavelength shift happened when the SA is inserted. This is due to the losses incurred when WS_2 is inserted into the cavity and made the system to compensate by moving to a higher gain of region. It demonstrates that when pump power increases, the output laser spectrums of Q-switched devices become wider and the peak power increases. This shows that as the further increase of the pump power, the Q-switching is getting more stable. Although the output power amplitude varies with the pump power, but the power spectral density is not affected by the pump power (Ahmad et al., 2012).

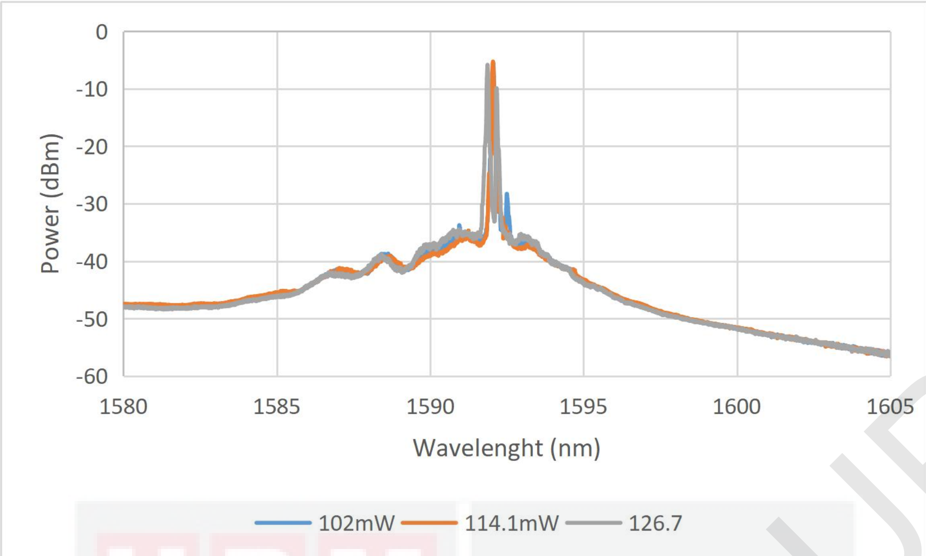

Figure 4.18 Output laser spectrum of Q-switched EDFL at different pump power

CHAPTER 5

CONCLUSION

5.1 CONCLUSIONS

In conclusion, this experiment uses a more cost-effective passive Q-switched fibre laser method with tungsten disulfide as the saturable absorber. The mechanical imprinting approach was used to deposit the tungsten disulfide into the cavity, which is a simple but compact way to deposit a material. This mechanical imprinting process uses only alcohol to clean the tip end of the fiber ferrule and does not require any solution to dissolve the tungsten disulfide powder for deposition. This may help to mitigate the impact of other solutions on tungsten disulfide's overall performance in the EDFL cavity.

Besides, the output performance of the passive Q-switched fiber laser based on tungsten disulfide as saturable absorber is analysed. The maximum average output power is 1.25mW at pump power of 126.7mW. The slope efficiency of average output power against pump power with WS_2 is 0.8%. It shows that the slope efficiency of graph with WS_2 is higher than slope efficiency without WS_2. The tungsten disulfide-coated fibre ferrule is employed inside the EDFL cavity to operate as a saturable absorber for the passive Q-switched to work. There are ultrashort pulses created. The oscilloscope produces a stable Q-switched pulse when the pump power is increased to 102mW. According to the results, the repetition rate is tuned within 8.404kHz to 15.53kHz when the pump power increase from 80.1mW to 126.7mW. On the other hand, the pulse duration drops from 30.8μs to 11.7μs when the pump power increase. The lowest pulse width was 11.7μs and the maximum single pulse energy of 80.7nJ are obtained at the pump power of 126.7mW. These results show that tungsten disulfide can be used as a saturable absorber in a passive Q-switched erbium-doped fibre laser. Thus, the objective of this experiment has been achieved.

5.2 FUTURE WORKS

As laser technology has become a widespread and well-known issue among scientific and medical fields, this study might be maintained for more and better output performance for many purposes. In future study, the thickness of tungsten disulfide when deposited into the end of a fibre ferrule can be improved. The thickness of the tungsten disulfide in EDFL might impact its output performance. Other than that, a variety of methods for depositing tungsten disulfide (WS_2) into fibre ferrules can be investigated further. Different outcomes will be obtained depending on the type of deposition used. It is possible to see a better deposition method for depositing WS_2 into the fibre ferrule and a better strategy to make a better Q-switching laser.

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