



**UNIVERSITI PUTRA MALAYSIA**

***GENERATION OF ULTRA-SHORT PULSED FIBER LASER BY  
EMPLOYING NON-LINEAR POLARIZATION ROTATION TECHNIQUE***

**NUR AISYAH BINTI MOHD**

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EMPLOYING NON-LINEAR POLARIZATION ROTATION  
TECHNIQUE**

By

**NUR AISYAH BINTI MOHD**

**198146**

**Thesis Submitted to the Department of Physics, Universiti Putra Malaysia, In Partial  
Fulfillment Of The Requirement For The Bachelor Of Science In Physics With  
Education (Honours)**

**2022**

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## DEDICATION

This dissertation is dedicated to:

- My supervisor, Dr Amirah bt Abd Latif, who have patienly guided and provided a lot of advices for me in accomplishing this project.
- My beloved parent, Mohd bin Semih and Soleha bt Muslimin who has raised and support me during my journey in Degree.
- My project coordinator Dr Shuhazly bin Mamat@Mat Nazir, who prepared seminar and workshop related to the preparation of thesis succesfully.
- Mrs. Nur Nazifah binti Radzi for helping me in understanding more about the project and help me in using equipment duiring the lab session.
- My friends who have given the support and help directly and indirectly during the preparation of this thesis.

Thank you so much.

## **ABSTRACT**

# **GENERATION OF ULTRA-SHORT PULSED FIBER LASER IN EMPLOYING A NONLINEAR POLARIZATION ROTATION TECHNIQUE**

**By**

**NUR AISYAH BINTI MOHD**

**198146**

**FEBRUARY 2022**

Supervisor: Dr Amirah Binti Abd Latif

Faculty: Faculty of Science

This thesis demonstrates a generation of ultrashort pulse fiber laser by employing a nonlinear polarization rotation technique. The technique chosen is due to the various advantages, such as being low-cost and compact compared to other techniques used in achieving an ultrashort pulse for fiber laser production. This kind of fiber laser is widely used in today's generation as it provides many advantages, such as in telecommunication and lasing surgery. A polarizer controller is needed by employing a nonlinear polarization rotation technique, and 4m Erbium-doped fiber is used in the cavity, which acts as a gain medium to produce wavelength ranging from 1530-1565nm or known as a C-band region. The oscilloscope, OSA, and OPM measure the output result, such as an optical spectrum, and the repetition rate resulting in the most stable pulsed obtained is at the 280 mW.

## **ABSTRAK**

### **PENJANAAN LASER GENTIAN BERDENYUT ULTRA PENDEK DENGAN MENGUNAKAN TEKNIK PUTARAN POLARISASI TIDAK SEJAJAR**

**Oleh**

**NUR AISYAH BINTI MOHD**

**198146**

**Februari 22**

Penyelia: Dr Amirah binti Abd Latif

Fakulti: Fakulti Sains

Tesis ini menunjukkan penjanaan laser gentian nadi ultrapendek dengan menggunakan teknik putaran polarisasi tak linear. Teknik yang dipilih adalah disebabkan oleh pelbagai kelebihan, seperti kos rendah dan padat berbanding teknik lain yang digunakan dalam mencapai nadi ultrashort untuk penghasilan laser gentian. Laser gentian jenis ini digunakan secara meluas dalam generasi hari ini kerana ia memberikan banyak kelebihan, seperti dalam telekomunikasi dan pembedahan lasing. Pengawal polarizer diperlukan dengan menggunakan teknik putaran polarisasi tidak sejajar, dan gentian dop Erbium 4m digunakan dalam rongga, yang bertindak sebagai medium perolehan untuk menghasilkan panjang gelombang antara 1530-1565nm atau dikenali sebagai rantau C-band. Osiloskop, OSA, dan OPM mengukur hasil dapatan, seperti spektrum optik, dan kadar pengulangan yang menghasilkan denyutan paling stabil yang diperoleh adalah pada 280 mW.

## ACKNOWLEDGEMENT

In the name of Allah, the Most Gracious and the Most Merciful. Alhamdulillah, all the praises to Allah for the strength that eases my journey in completing this thesis with His Blessing. Special appreciation goes to my beloved supervisor, Dr. Amirah binti Abd Latif, for her patient supervision and constant support. I will not be able to learn this new knowledge without her consent in taking me as her student for this subject. Her constructive comment and suggestion helped me a lot throughout the experimental and thesis that contributed to the success of this final year project.

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## LIST OF ABBREVIATIONS AND KEYWORDS

NPR	Nonlinear Polarization Rotation
nm	Nanometer
SESAM	Semiconductor Saturable Absorber Mirror
EDF	Erbium Doped Fiber
EDFA	Erbium Doped Fiber Amplifier
LD	Laser Diode
WDM	Wavelegnth Division Multiplexer
OC	Output Coupler
OPM	Optical Power Meter
OSA	Optical Spectrum Analyzer
OSC	Oscilloscope
PC	Polarization Controller
FWHM	Full Width at Half Maximum
ASE	Amplified Spontaneous Emmision
C-Band	Conventional Band

# **CHAPTER 1: INTRODUCTION**

## **1.1 Background of Study**

Optical fiber is widely used in today's life and industry. Optical fiber which is also known as fiber optic is used to transmit information such as pulses of light through a medium of fiber made of glass. Fiber optic is a thin strand with a diameter of human hair but capable of transmitting data over longer distances and faster than other mediums.

The structure for the bare fiber optic basically contains the core, cladding and coating. The core is made up from a high-purity glass that can transmit optical signal from an attached light source to a receiving device. As for the cladding, it is used to act as a boundary, thus light can travel only in the core through the fiber. Next, coating is a plastic that coated the cladding and the core. It helps in absorbing shocks and providing extra protection against the cable bends.

This structure of the fiber optic led to application of the total internal reflection theory. All the data transmitted by fiber optic is applying the total internal reflection phenomenon. The total internal reflection involves the light that trave from denser medium to a less dense and it only occurs with angle of incidence that is larger than the critical angle. This is the same as in the fiber optic when the light travels through the core, it will bounce back and forth when it hits the boundary or cladding. Thus, the data that enter the fiber with an angle greater than the critical angle can travel down the fiber without leaking out.

Fiber optic is a gain medium used in a fiber laser that has been doped with a rare-earth element such as Er, and Yb. As for the Er-doped fiber, the corresponding operation wavelength range is from 1.53 -1.56  $\mu\text{m}$ , which can be used for optical fiber communication systems. Meanwhile, the quantum efficiency for the Yb-doped is as high as ~80%, thus the highest power of the fiber laser is achieved by using the Yb-doped fiber (Nishizawa1, 2014). Both of the rare-earth doped fiber is also used in obtaining the 1.55 $\mu\text{m}$  as the high gain wavelength region.



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## 1.2 Objectives

The objectives of this project are:

- i. To achieve the passively Mode-Locked Fiber Laser by employing the Non-Linear Polarization Rotation technique.
- ii. To analyze the performance of the high-power Mode Locked Fiber Laser by employing the Non-Linear Polarization Rotation technique.

## 1.3 Problem Statement

A passively mode locked fiber laser can be achieved using a Saturable Absorber (SA). There are two types of SA which are physical and artificial SA. Semiconductor saturable absorber mirror (SESAM) is one of the SA that can be used in order to achieve passively mode locking in fiber lasers. Other than SESAM, the carbon nanotubes (CNT) are also one of the physical saturable absorbers used to initiate pulses with higher intensity, thus the mode lock could be achieved. However, SESAM has recovery time that is longer than 1 ps and the operating bandwidth is limited. As for the CNT, the bandwidth can be determined by the CNT diameter distribution. For graphene, it is wavelength- independent but it could not stand for high energy operation (Luo et al., 2014). The Non-linear Polarization Rotation (NPR) technique is an artificial saturable absorber that can be used to achieve the ultrashort pulses in fiber lasers. By using NPR, a narrower pulse width and larger pulse energy can be obtained although the environment for NPR is sensitive. Compared to the SESAM, the recovery time for NPR is sub-picosecond and it is not wavelength dependent. Therefore, by using the NPR technique, it is promising to exploit in obtaining the ultrashort pulsed fiber laser.

## 1.4 Application of Fiber Laser

Fiber lasers are the most practical high-power lasers and are currently used as laser sources in a wide range of laser applications. Owing to its advantages such as the output beam can be focused on a small spot stably, the laser processing is the most popular laser application because it is irradiated stably from the small circular core. Besides, fiber lasers exhibit excellent environmental stability and function as maintenance-free lasers since there is practically no bulk component, so it has been widely used in laser processing. Other than that, fiber lasers can be found in “imaging” field where ultrashort pulsed fiber laser is used in investigating ultrahigh resolution (UHR) optical coherence tomography. Using ultrashort pulses fiber laser, the practical, fiber-based, high power and wideband source of the OCT can be demonstrated. Next, the ultrashort pulse fiber laser is also useful as a practical optical frequency comb system. This optical frequency comb works as the optical frequency standard that enables to demonstrate a precise spectroscopy and highly accurate distance measurement (Nishizawa1, 2014). Other than that, the ultrashort pulsed fiber laser can also be used as the pulse source for the THz generation and detection.

## 1.5 Thesis arrangement

For this thesis, Chapter 1 is about the background of study for this project which contain the general information about the material used which is the optical fiber as the basic component for this project. Next, the objective and the problem also stated in this chapter as the guidance to the reader in order to understand this project better. Besides, the application of the optical fiber is clearly written in this chapter to give a better understanding.

In Chapter 2, the literature review of this topic and other component related to this topic is collected. It is a collection of review from the other researchers in order to understand about the working principle, method involved and the material used in this topic.

For Chapter 3, the methodology and the optical devices used for this project is explained and showed. The chronology in preparing the fiber optic linkage, the characterization of LD pump, ASE of Erbium Doped Fiber, the preparation of the cavity for the mode locked fiber laser and the extraction of the result from the OSA, OSC and OPM is clearly stated in this chapter.

In chapter 4, the result obtained for the characterization of the laser diode, ASE and output spectrum and frequency will be discussed precisely.

As for the last chapter which is Chapter 5, the conclusion for the finding of this project will be explained and the recommendation on how to enhance the performance of the Non-Linear Polarization Rotation technique for the future research.

## **CHAPTER 2: LITERATURE REVIEW**

### **2.1 Ultra Short Fiber Laser**

An ultrashort pulse fiber laser is a laser that emits light, not in a continuous mode but in a pulse form. In order to achieve a pulsed laser, the net gain is not constant. However, it is temporarily varied by pulse pumping in the gain medium, or it can be generated by modulating the cavity loss. The simplest approaches to obtaining the ultrashort pulses fiber laser are q-switching and mode-locking laser using a saturable absorber or a nonlinear polarization rotation technique.

The ultrashort pulsed fiber laser application is widely used in the welding and sealing field in the industry. It also has been used as a promising tool in biomedical application and microfabrication due to their unique nonthermal reaction mechanisms with the material (Huang & Guo, 2009). Furthermore, ultrashort pulsed fiber can also be used in inducing a local modification inside the bulk of transparent material because of the nonlinear absorption and being utilized for fabrication of waveguide and active integrated optical devices (Huang et al., 2012).

In 2011, (Nishizawa et al., 2011) proposed that the configuration of an Er-doped ultrashort pulsed fiber laser using a single wall nanotube (SWNT) dispersed in a polyimide film. The fibre laser cavity can be easily inserted as the carbon nanotubes polyimide film can work as a transmission type saturable absorber. Using this scheme, all the polarization maintaining-type fiber laser that shows high environmental stability can be easily demonstrated. Furthermore, a passively mode-locked Er-doped fiber laser has been experimentally demonstrated using a CuO nano powder embedded in a PVA film and SA in 2018 by (Sadeq et al., 2018). The stable mode-locked pulses were generated with a 1.7 ps pulse

width and 983 kHz repetition rate. Thus, the result obtained indicates that CuO can be considered as a promising material in order to generate stable mode-locked pulses.

## 2.2 Mode Locked Fiber Laser

A mode-locked fiber laser can be achieved by inducing all the oscillating multiple longitudinal modes to lock in phase with each other at a specified mode spacing. It is a technique applied to create a very short duration pulse, particularly within the picosecond and femtosecond regimes. Furthermore, a mode-locked fiber laser can be obtained due to the constructive interference between the multiple modes then take place and facilitate the formation of a stationary waveform in time and space; thus, a pulses train can be observed from the oscilloscope. Mode locking has a broad 3 dB bandwidth or linewidth of the output spectrum. The pulse repetition rate for mode-locking is higher than a Q-switched pulse, which is in an MHz-GHz range, and the pulse energy is in the range of pJ. A mode-locking operation can be achieved by using either the active or passive technique.

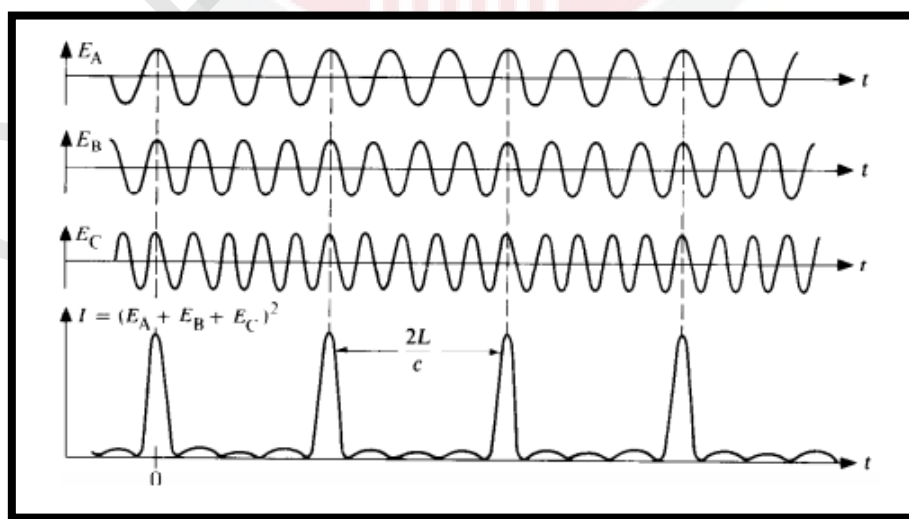


Figure 1: Mode-Locked Pulse

### 2.2.1 Active Mode Locking

An active mode-locking can be achieved with the aid of a modulator such as an electro-optic type that will modulate the resonator losses in exact synchronism with the resonator round trips. The circulating pulse goes through the modulator when the losses are smallest; the slightly higher losses in the pulse wings slightly shorten the pulses. After thousands of round trips, a steady-state reached where the shortening effect is balanced by the pulse broadening effect. An example of the pulse broadening effect is the limited gain bandwidth or chromatic dispersion. The pulse duration is only 1-100 ps of range, which will add complexity to the system that is limited to the electronic speed of the external modulator.

The first inverse pulse width that has been achieved using an active mode locking has been invented by the Kuizenga and Siegman. In 1996, there are a research conducted by the (Jones et al., 1996) for a study of the stability regime of an actively mode locked polarization-maintaining fiber ring laser.

(Yao et al., 2001) conducted an experiment where the active mode locking is used in tunable multi wavelength fiber ring laser. The experiment is carried out using a unidirectional ring cavity that has been combined with an amplitude modulator and a single sampled fiber Bragg grating (SFBG). As the result, the advantages in using the active mode locking are stated as the cavity is simple and the equal-step wavelength is equal. Besides, the laser also can emit the cw output even with the amplitude modulator has been removed.

### 2.2.2 Passive Mode-Locking

A passively mode locked fiber laser is a bit different from the active mode locking because it is based on the saturable absorber such as carbon nanotubes (CNT) and cadmium sulfide (CdS) where it is used in order to obtain a self- amplitude modulation (SAM) of the light inside the laser cavity. The benefit for the passive technique is much more simple, fast response, easiness to implement and superior performance compared to actively mode-locking technique.

In 2006, (Takayanagi et al., 2006) experimented with generating a pedestal-free 22 fs ultrashort pulse in all-fiber systems. The 260-fs ultrashort pulse from a passively mode-locked Er-doped fiber laser with a repetition rate of 48 MHz was introduced into the chirped-pulse fiber amplifier system, and a high-power Raman shifted soliton pulsed generated.

Next, the experiment is proposed by (Luo et al., 2011) to demonstrate a highly flexible fiber laser that capable of generating a stable multiwavelength picosecond and a single wavelength femtosecond pulses emission in a passively mode-locked fiber laser by using a semiconductor saturable absorber mirror and a contrast ratio tunable comb filter. The result gained by employing a contrast ration tunable comb filter and a SESAM in the laser cavity was 11 wavelength passively mode-locked pulsed in 3dB bandwidth with a channel spacing of 0.8 nm and a single wavelength with 576 fs soliton pulse.

### 2.3 Erbium-doped Fiber Amplifier

An Erbium-doped fiber amplifier is a fiber amplifier that has been doped with a rare-earth-doped element as a core. It can efficiently amplify light in the 1.5  $\mu\text{m}$  wavelength region, where telecommunication fiber have their loss minimum. By using a rare-earth-doped element, a laser amplification can be provided by stimulating emission when it is optically pumped with other light was injected into the fiber.

When Erbium is irradiated with light energy at an appropriate wavelength such as 980 nm or 1480 nm, this will lead to a long-lifetime intermediate state, which ultimately decays to the ground state by producing light in the 1525-1565 nm band. Erbium may be pumped with either 980 nm or 1480 nm light, in which case it goes through an unstable short lifespan state before quickly fading to a quasi-stable state, or it may be directly stimulated to the quasi-stable state. It decays to the ground state by producing light in the 1525-1565 nm band after it has reached the quasi-stable state. Pre-existing light may drive this decay process, resulting in amplification.

From the findings that has been conducted by a few researcher, it stated that the EDFA contains a lot of advantages such as low noise figure, have high saturation output power and polarization independent gain (Desurvire et al., 1989).

## 2.4 Nonlinear Polarization Rotation (NPR)

A nonlinear polarization rotation is a technique that applies the phenomenon of the changes in the polarization direction of light in a fiber by depending on the optical intensity. The optical devices used to run an experiment by employing the technique is by using a polarization controller. When an intense optical pulse propagates in a not polarization-maintaining optical fiber, there will be a nonlinear change in the polarization state. The changes affect the rotation of a linear polarization direction, but it will affect the change to some elliptical polarization state. This effect will relate to self-phase modulation and cross-phase modulation and some birefringence of the fibre. When the pulses pass a polarizer, the power throughput will effectively be depending on the optical power. By using NPR, there are many advantages such as wavelength independence, high modulation depth, high thermal damage threshold, fast response time, low cost and compactness (Ling et al., 2019)

In 2006, an experiment was carried out by (Feng et al., 2006) based on the nonlinear polarization rotation (NPR) effect to gain stable multiwavelength oscillations in an erbium-doped fiber laser. In the experiment, two polarization controllers have been used, a commercial erbium-doped fiber amplifier (EDFA), a single-mode fiber (SMF), and a Fabry-Perot (F-P) thin film filter. As a result of the research stated that by applying the NPR technique, the multiwavelength operation with the number of wavelengths could be varied from 2 to 28 by adjusting the PCs. Besides, a stable multiwavelength oscillation in an erbium-doped fiber ring laser can be generated, and the multiwavelength-intensity-dependent loss can be induced using a nonlinear polarization rotation effect.

Recently, research was conducted to observe the function of a wave plate in the dynamics of an all-normal-dispersion fiber laser. The experiment is carried out in 2020 by Zhang et al., resulting in that the transition between the different regimes may be obtained by just rotating the wave plates, and this offer an alternative to the use of a bandwidth tunable filter to obtain the transition between the dissipative soliton and amplifier similarity. As a conclusion from the finding, it stated that the rotation of waveplates is an effective way to change the relative contribution of spectral filter and NPR (Zhang et al., 2020).

(Tiu et al., 2014) has demonstrated an experiment based on the nonlinear polarization rotating technique to propose a simple mode-locked erbium doped fiber laser (EDFL) with a three switchable operation state. As a result, it has been successfully carried out by employing a 6.9 km -long DSF in the ring cavity. (Zhang et al., 2020). (Shang et al., 2019)

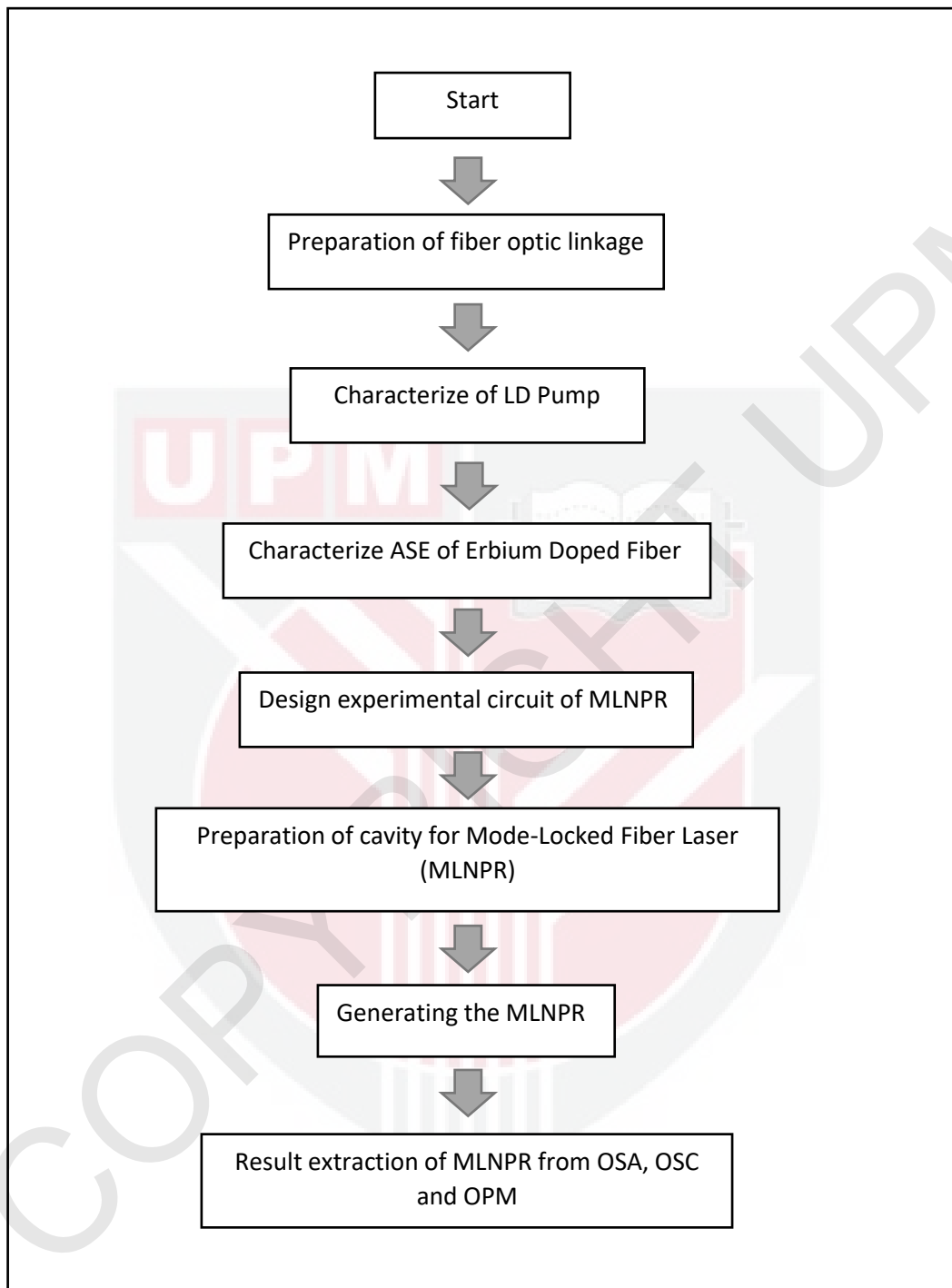
## **CHAPTER 3: METHODOLOGY**

### **3.1 Introduction**

In this chapter, the process and the optical devices used in this project will be explained further. The processes in obtaining the mode-locked pulsed fiber laser using the Non-Linear Polarization Rotation (NPR) technique will be discussed to give a deeper understanding about the mode-locked technology. The process includes the preparation of the fiber optic linkage, the characteristics of the laser diode pump, designing the circuit in generating the Mode-Locked Non-Linear Polarization Rotation. Last section of this chapter will include the method use in the experiment on result extraction from the Optical spectrum analyzers (OSA), Optical Power Meter (OPM) and Oscilloscope (OSC).

### 3.2 Flowchart

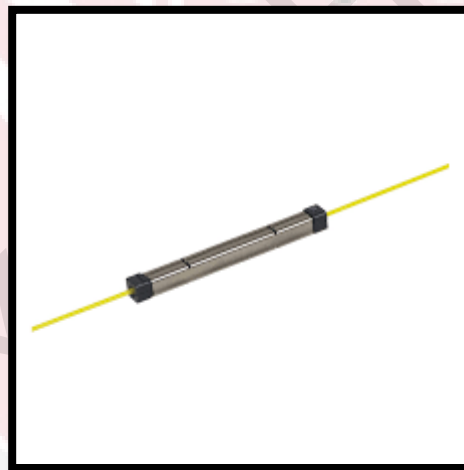
Figure 3.1 shows the flowchart of generating an ultrashort pulse from a fiber laser until the extracting result is a final step. Firstly, the preparation of fiber optic linkage is essential as a first step because the cavity needs to be fully prepared to produce ultra-short pulses. Fusion splicing is used to splice two different fibers together during the preparation. Next, the laser diode characterization was conducted to obtain the minimum current needed to supply and to know the laser diode performance. After that, the characterization of amplified spontaneous emission of erbium-doped fiber was completed to acknowledge the emission produced by the ASE. The next step will be designing the experimental circuit for mode-locked nonlinear polarization rotation to create a useable circuit in obtaining the ultra-short pulses. After designing, the cavity preparation for the MLNPR was done by locating the polarization controller, WDM, isolator optical polarizer, and EDF. Last but not least, generating the MLNPR was conducted by using the cavity prepared before. Lastly, the result from the experiment was extracted for analysis by using the optical spectrum analyzer, oscilloscope, and optical power meter.



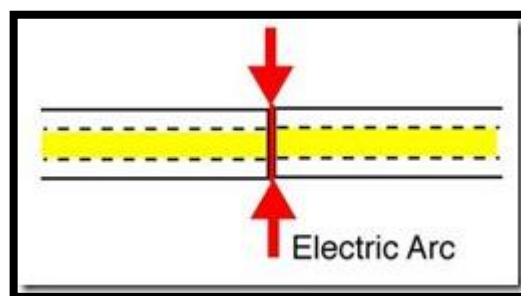
**Figure 3.1** The flow chart in generating the ultrashort-pulses from a fiber laser by employing the Non-Linear Polarization Rotation technique.

### 3.3 Preparation for the Optical Fiber Linkage

There are two types of fiber splicing process available currently, which are mechanical and fusion splicing. Mechanical splicing is combining technique that does not involving fusing the two optical fiber ends together, but the two fibers are held end to end inside a sleeve using a mechanical combining mechanism. Thus, there are some losses would happen in at the splicing point, which are by insertion losses and back reflection loss. The second splicing technique is through fusion splicing technique. By using this technique, the two fibers are welded or fused by an electric arc. It is widely used as it provides the lowest insertion loss and virtually no back reflection. Besides, it provides the most reliable joint between the two fibers, so the fiber will not disjoint or break easily.



**Figure 3.2** Example of Mechanical Splicing used to hold two different optical fiber together



**Figure 3.3** Fusion Splicing of two different optical fibers by an electric arc for a permanent combination

### 3.3.1 Stripping the optical fiber

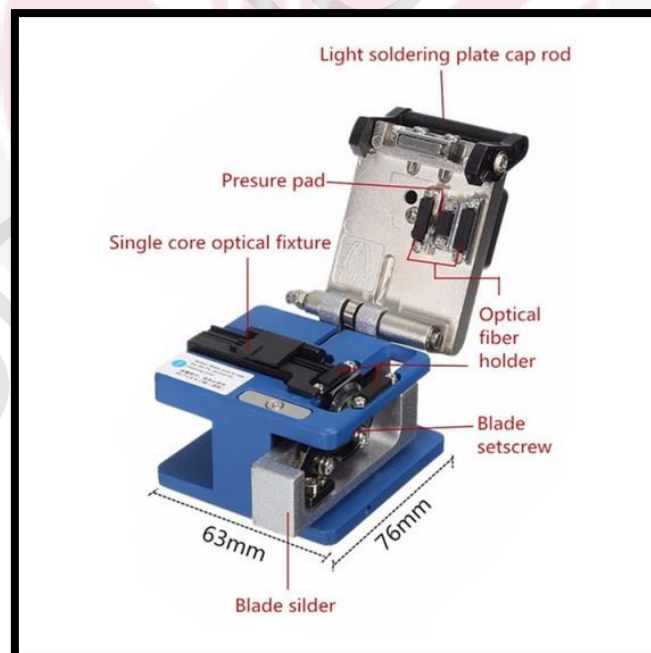
Before the fusion splicing process is being done, the first involve is optical stripping. Optical stripping is the process of removing the protective layer (or known as the coating) of the fiber optic. The stripping process can only be done by removing the coating of both ends of the fiber optic which to be spliced together. For this process, using a stripper can easily remove the coating layer that is often in 250  $\mu\text{m}$  diameter only. By measuring enough length of the fiber optic to be stripped, placed the fiber on the exact hole based on their diameter and then strip the fiber carefully to avoid fracture. Next, the fiber needs to be cleaned with the dampened-alcohol Kimwipes tissues. Reduce the pressure while stripping to avoid the fiber from being accidentally cut off at the unwanted location.



**Figure 3.4** Optical Stripper Use in Stripping the Coating of The Fiber Optic.

### 3.3.2 Cleaving optical fiber

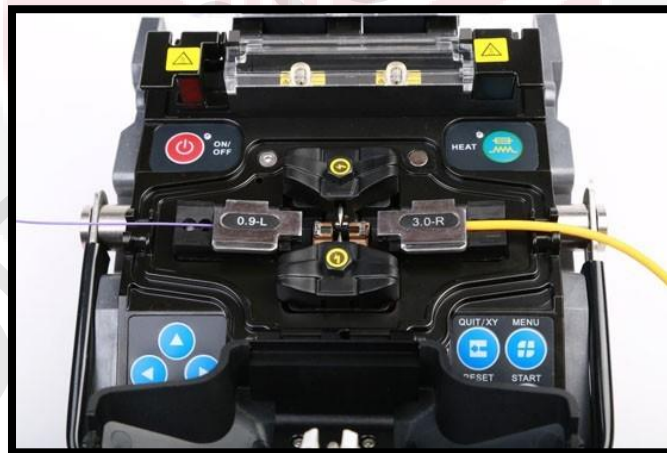
After the stripping process is completed, the next step is cleaving to obtain a straight cut at the fiber end to achieve a good splicing point without significant splicing loss. Cleaving is a process when the optical fiber is cut or being broken precisely for termination process (Hayes et al., 2021). The fiber is cut by scratching the surface and applying enough pressure until the glass breaks in a smooth line by using a diamond blade. If the process is being done correctly, the fiber will be cleaved straight, with a smooth surface perpendicular to the length of the fiber, with no extending glass on either end of the fiber (called a lip). A cleaver is used to get a smooth end of the fiber as it is a tool designed to hold the fiber under low tension, locate the fiber at the proper location, and a great tension will be applied until the fiber breaks.



**Figure 3.5** Cleaver use to cleave the fiber optic to gain a clean-cut optical fiber

### 3.3.3 Splicing process of optical fiber

After the cleaving process is done, the fiber optic is ready for fusion splicing, which is both of the fiber optics' end will be placed in alignment fixtures in the fusion splicer. Fusion splicer is a machine used to fuse or weld two optical fibers together. It is a high-precision machine that will identify any error that occurred before the splicing process begins. Once the fiber optic on both sides is fixed perfectly, the process will begin by heating with the electrode, and then both of the end fibers are fused together. Then the process of splicing is already completed. As a precaution note, while splicing, prepare the "stage" where the spliced fiber will be placed to avoid being broken. A good fiber optic splicing point will be achieved, which less than 0.01 dB of insertion loss, if, splicing process being conducted properly and carefully.



**Figure 3.6** Fusion Splicing Machine Use in Splicing Two Fiber Optic Together.

### 3.4 Optical Devices Used in the Experiment

Every optical device used in this experiment has its own function to ensure the generation of mode-locked optical fiber laser at the same time, the device also helps to ensure that the experiment conducted will be running smoothly throughout the course of the project. Therefore, all the items and devices used in this project, will be explained for a further and clearer view to the readers.

#### 3.4.1 Laser Diode

A laser diode is a semiconductor device that is similar to a light-emitting diode (LED). It was pumped to the cavity of initiate the energy to it. The gain is generated by an electrical current flow through a p-n junction of the laser diode. Using the p-n junction will emit a coherent light in which all the waves are at the same phase and frequency. Thus, a narrow beam of laser light is produced. This laser is provided with the Peltier cooler, referred to as a thermoelectric cooler (TEC), which will maintain the laser diode temperature to a certain degree of temperature to avoid it from over heat and damage. This feature's main advantages are, such as central wavelength control, increased the power amplitude stability and decreased the relative intensity noise.



**Figure 3.7** Laser Pump as a Pump Source in Generating an Ultra-Short Pulse.

### 3.4.2 Polarization Controller (PC)

A polarization controller is a device that allows one to control the state of polarization of light within fibers (Paschotta, 2021). Each loop rotation will cause the principal axes of the birefringent fiber sections to spin concerning the input polarization state. This is comparable to a conventional bulk half-wave or quarter-wave plate rotation with incoming light. Thus, the three loops rotate in the same way as a combination of  $\lambda/4$ ,  $\lambda/2$ , and  $\lambda/4$  plates. Furthermore, one may demonstrate that every input polarization state may be turned into any other output polarization state using these three combinations.



**Figure 3.8** Polarizer Controller used for the NPR technique

### 3.4.3 Wavelength Division Multiplexer (WDM)

A wavelength division multiplexer is a technique of multiplexing multiple optical carrier signals across a single optical fiber channel by varying the wavelength of laser beams. In WDM, two different sources of the optical signal are combined by a multiplexer, before transmitting through a single optical fiber strand. A demultiplexer will split the combined beam into each of their components and send it to the corresponding receiver at the receiving end.

### **3.4.4 Optical Isolator**

An optical isolator is a device that cannot allow light reflection, which the light will travel in a unidirectional transmission only. This device is very important to avoid the unwanted optical reflection that causes any damage to a laser source or causes it to a modulated light amplitude, or creating a frequency shift. In high power applications, the back reflection will cause instabilities and power spikes; thus, the optical isolator will help achieve a stable laser transmission throughout the propagation of light in the optical fiber cavity. It consists of an input polarizer, the Faraday rotator with magnet in the middle and then the output polarizer. The input polarizer will act as a filter that allows only linearly polarized light into the Faraday rotator. Then when it arrives at the Faraday rotator, the rod of the Faraday rotator will turn  $45^\circ$ , and the light will leave the output polarizer at  $45^\circ$  at the end.

### **3.4.6 Output Coupler (OC)**

The output coupler is an optical device that either split optical signals into multiple paths or combine numerous signals on one. An optical signal does not go through the receiver to the ground. Rather than that, a detector absorbs the signal flow at the receiver. Multiple receivers linked in series would get no signal once the first receiver absorbs the whole signal. As a result, numerous parallel optical output ports must split the signal in half, diminishing its size. A coupler is defined by the number of input and output ports stated as a  $N \times M$  arrangement.  $N$  denotes the number of input fibers, whereas  $M$  denotes the number of output fibers. In this experiment, the output coupler is used to change and divide the ratio of the light in the fiber into two by using the optical coupling method.

### **3.4.8 Photodetector**

A photodetector is a primary device in the front end of an optical receiver that will convert an optical signal into an electrical signal. It has been used extensively in optical communication as a photodetector can typically operate from visible to near-infrared wavelength. Due to the small size, rapid detection speed, and high detection efficiency, semiconductor photodetectors, generally referred to as photodiodes, are the most frequent photodetectors used in optical communication systems. Photodiodes similarly use PN junctions as laser diodes do.

### **3.5 Characterization of Laser Diode**

For a laser diode, the operational characteristics are a mixture of the five properties as electrical, spatial, spectral, optical and dynamic properties that will determine the performance and the efficiency of the diode. The characterization of the laser diode pump was required in the experiment to maintain the laser diode's performance stability. The first and most important characteristics are how the laser diode light output power ( $L$ ) responds to injected current ( $I$ ) where can be referred to as the L-I curve. By observing the curve, the significant parameter, including threshold current or the current at which the device begins to lase, can be determined. Besides, the output power typically is based on the product device responsivity and the nominal operating current. As for the lower-power devices, they can operate with a few 10's of mA to over 100mA, while the high-power devices or multimode laser diode can operate with more than 10A.

### **3.6 Characterization of Amplification Spontaneous Emission (ASE)**

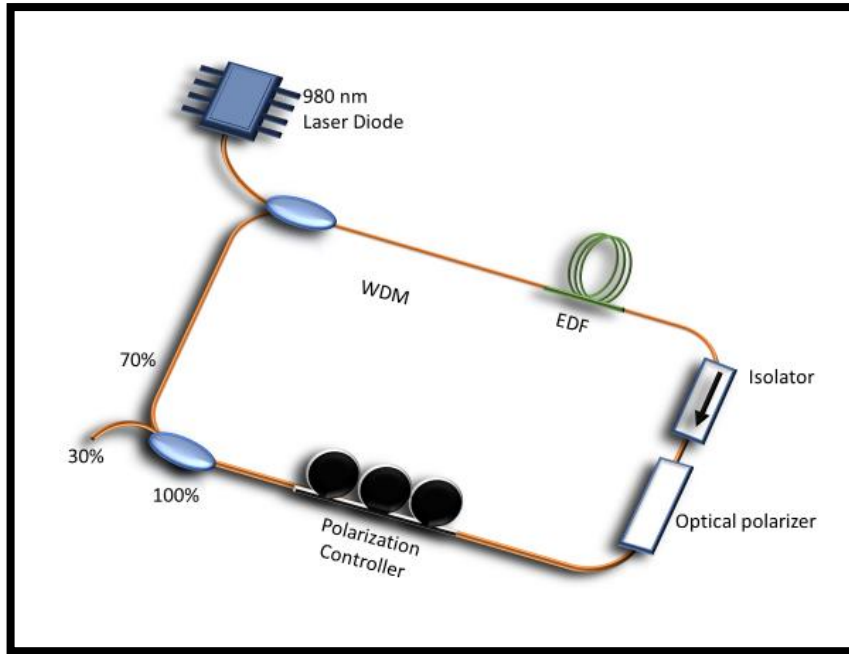
Amplification spontaneous emission is a process where the spontaneously emitted radiation is amplified. ASE is created when a laser gain medium is pushed to cause a population inversion. If the lasing threshold of the optical fiber laser's cavity is achieved, the ASE from the gain medium used will cause the stimulated emission to occur in the cavity, which substantially generates laser as the output. The ASE is used as a wideband light of the optical fiber cavity. However, due to the bandwidth of the gain medium, lasing will be inhibited if the cavity has no optical feedback, resulting in a high emission bandwidth, without the cavity laser output generated. In contrast to a laser, the ASE has a poor temporal coherence, whilst, output laser has a high temporal coherence leading to having a less speckle noise output.

### **3.7 Preparation of Laser Cavity for Mode-Locked Nonlinear Polarization Rotation Fiber Laser**

The experimental setup is used for the laser cavity preparation. The fiber laser used in this project was utilizing the Erbium (Er) doped fiber (EDF) as a gain medium. A 980 nm laser diode was pumped in a counter-clockwise direction. A wavelength division multiplexer (WDM) was connected to the 980 nm of the laser diode at the input leg, while the output was connected to the EDF. The optical isolator was connected to the polarization controller (PC) where the PC will act as the artificial saturable absorber by employing the nonlinear polarization rotation technique. The output cavity was extracted using the optical coupler (OC). The 70% will continue to circulate through the ring laser cavity to maintain the pulses. In comparison, another 30% will be divided into two sections, one for the Output Spectrum Analyzer (OSA) and autocorrelator output devices that will measure the pulses obtained.

### 3.8 Preparation of Nonlinear Polarization Rotation for Mode-Locked Fiber Laser.

Figure 3.9 illustrates the Mode-Locked Fiber Laser structure by employing the Nonlinear Polarization Rotation technique. An NPR technique can be applied by inserting the polarization controller in the cavity, which then the paddle of the PC will be adjusted and rotated. The laser diode acts as a pump to the gain medium which is the 15 m of a single-mode fiber in a ring configuration. A 3 m EDF is a gain medium connected through a fused wavelength division multiplexer (WDM) in the cavity. The 980 nm laser will be a pump in the system with a minimum power of 120 mW, and the maximum is 350mW. An isolator is used to prevent the light from moving backward and causing the other devices in the cavity to burn. A polarizer is located in the middle of the polarization controller (PC) and the isolator. A PC was adjusted to change the orientation of the fiber optic in order to obtain the ultra-short pulses. A 70:30 output coupler was used in this experiment where 70% of the light continue circulating in the cavity. The remaining 30% from the output coupler will be connected to the OSA, oscilloscope, and the OPM to extract the result.



**Figure 3.9** Experimental setup for Mode Locked Nonlinear Polarization Rotation Fiber Laser

### **3.9 Analysis characteristics of Mode-Locked Fiber Laser**

The characteristic of the Mode-Locked fiber laser can be determined by using the optical spectrum analyzer (OSA) and the autocorrelator. The analysis for the characteristics of the mode-locked fiber laser was obtained by considering the pulse repetition rate and the optical spectrum.

#### **3.9.1 Optical Spectrum Analyzer (OSA)**

An optical spectrum analyzer (OSA) is an instrument that is precisely used in measuring optical spectra. Besides, it is used in analyzing the output light beams from laser, light-emitting diode (LED) and other light sources. It is also used in some optical communication devices to ensure that the optical carrier includes only a single, spectrally pure wavelength. In this experiment, the fiber optic from the setup will be connected to the OSA using a fiber pigtail. Thus, the result will be obtained in the C-band region of the optical transmission window, which can be verified by the spectrum emission in the range of 1530 to 1550 nm wavelength.

#### **3.9.2 Oscilloscope for Pulse Repetition Rate measurement**

The pulse repetition rate is defined as the number of emitting pulses per second or is also defined as the inverse temporal pulse spacing. It requires a high pumping power and a short cavity length for a high repetition rate output to be generated in the cavity. As for the mode-locked fiber laser, the pulse repetition rate is usually between a few MHz and sometimes in GHz which is much higher compared to the Q-switching which is in kHz, which can be observed through the oscilloscope in our laboratory.

### 3.9.3 Optical Power meter (OPM)

An optical power meter is used as a testing instrument that can accurately measure the power of an optical signal passed through the fiber cable. It is made up of a calibrated sensor that measures the output power of the light from the cavity in the unit of milliWatts. It can be used to determine the power loss experienced by the optical signal as it travels down to an optical fiber. The optical power meter can be used by connecting directly to an optical transmission device through a fiber pigtail. Apart from determining the amount of power delivered by an optical fiber source, OPM is also used for continuity testing. It can be done by inserting an optical coupler where the main portion is connected to one of the ends of the fiber to a calibrated light source and the other end with a very small portion to an optical power meter for monitoring purposes.

## **CHAPTER 4:**

### **RESULT AND DISCUSSION**

#### **4.1 Introduction**

In this chapter, the result of the laser diode characterization, characterization of Amplified Spontaneous Emission (ASE) of Erbium-Doped Fiber Amplifier and the output performance in generating the ultra-short pulsed fiber laser by using a Nonlinear Polarization Rotation (NPR) technique will be discussed.

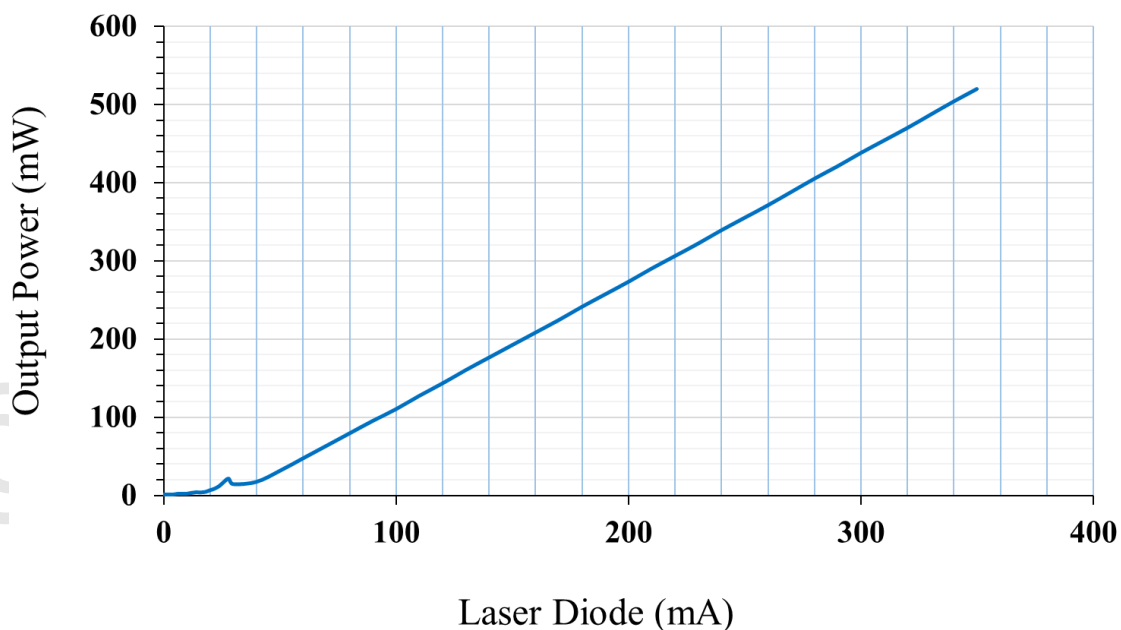
The main technique used in this experiment is by applying the Nonlinear Polarization Rotation technique where the polarization controller (PC) is adjusted and fixed. Begin with 160mA, the supplied current is enough to produce a self-starting mode locking pulse fiber laser. The current was increased uniformly for 20mA every increment which give a different result in a peak-to-peak, repetition rate, pulse width and the output spectrum for every current increased.

As for the stability of the pulse generated, the stability of the output spectrum was recorded in a 5 minutes of interval duration for an hour. This showed the stability of the pulses during the continuous operation.

## 4.2 Characterization of Laser Diode Pump

The primary purpose in characterizing the laser diode was to maintain the performance of the laser diode and to identify the output power of the laser when a certain amount of current was supplied into the device. The threshold current needs to be identified to know the minimum current needed for the laser to work with full power. The result can be observed in the output power (mW) graph against laser diode pump current (mA).

As shown in figure 4.1 below, the laser diode first was injected with the 10mA current, and the output power recorded showed a gradual increment. Therefore, it can be concluded that the laser diode is emitting light in the spontaneous emission process. At the current of 40mA and onward, the output power shows a rapid increment until the maximum power is applied. Thus, this shows that 40mA is a threshold current for the laser diode to begin lasing in full power, and the laser diode is operating in a stimulated emission process.



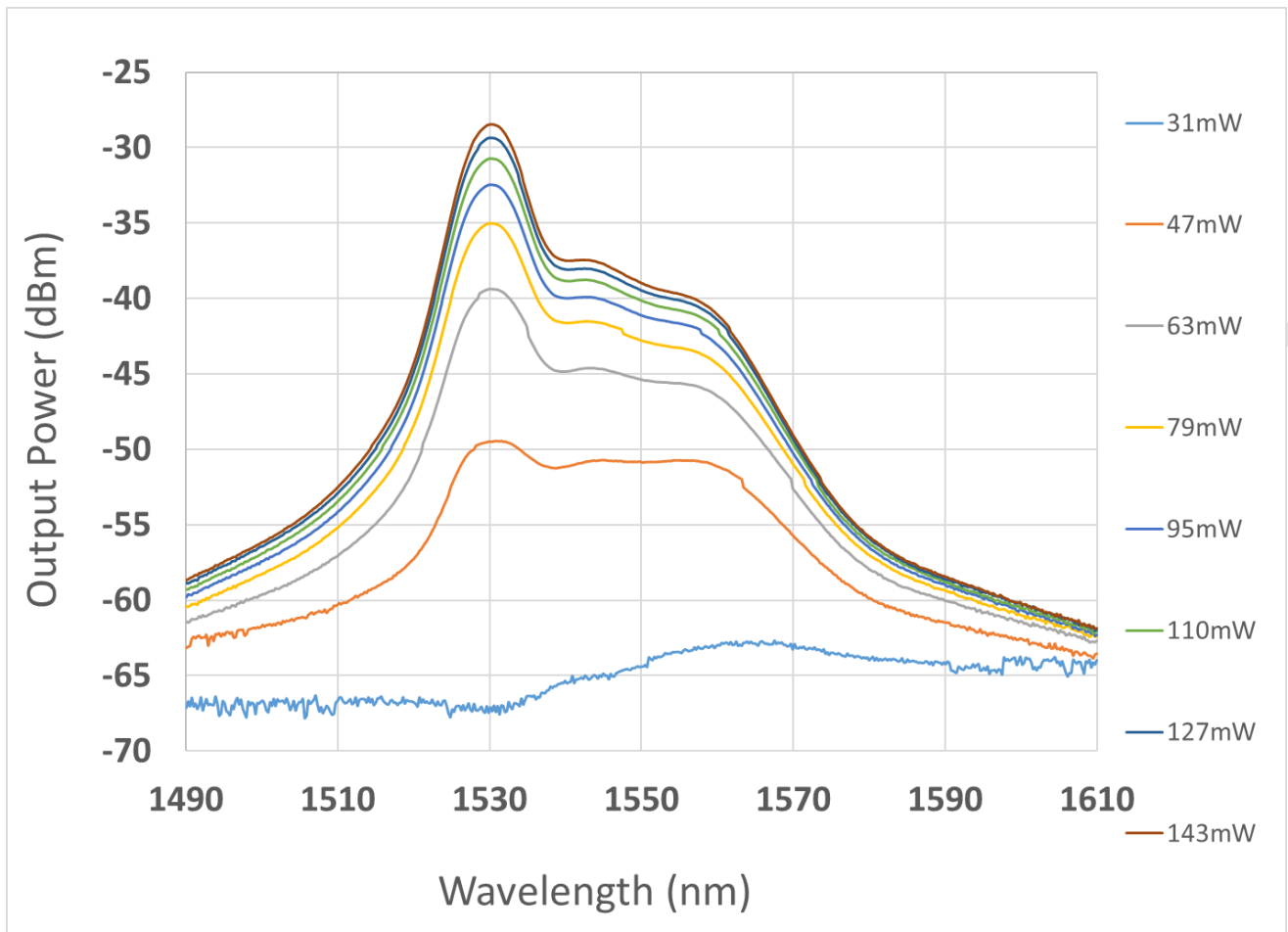
**Figure 4.1** Laser Diode Characterization

### 4.3 Characterization of Amplified Spontaneous Emission (ASE) of Erbium-Doped Fiber (EDF)

Compared to the other light sources, the amplified spontaneous emission (ASE) from a rare-earth-doped fibre has advantages in temperature stability, high output power and low polarization dependence. In this project, the Erbium-doped fiber (EDF) laser has been used to amplify light in the 1.5 $\mu$ m wavelength region efficiently.

Figure 4.2 illustrates the ASE spectra when a single 980 nm pump laser diode was pumped into the EDF. The result is obtained using an optical spectrum analyzer (OSA) by varying the eight different values of the laser diode, which is 31mW, 47mW, 63mW, 79mW, 95mW, 110mW, 127mW and 143mW. From the figure below, the photon starts to amplify at the pump power of 47mW, where we can conclude it as a threshold value for the ASE of EDF. As for the other pump power, when the current increase, the output power also increases simultaneously.

The graph shows that the erbium ions produce a mode-locking fiber laser at the wavelength ranging from 1530nm until 1560 nm, known as a Conventional band or C-band region, the region of the optical transmission system combined with the WDM and the EDF.



**Figure 4.2** Characterization of Amplified Spontaneous Emission of Erbium-Doped Fiber at different pump power injected

#### **4.4 Output Performance of Mode-locked Fiber Laser by Applying the Nonlinear Polarization Rotation technique.**

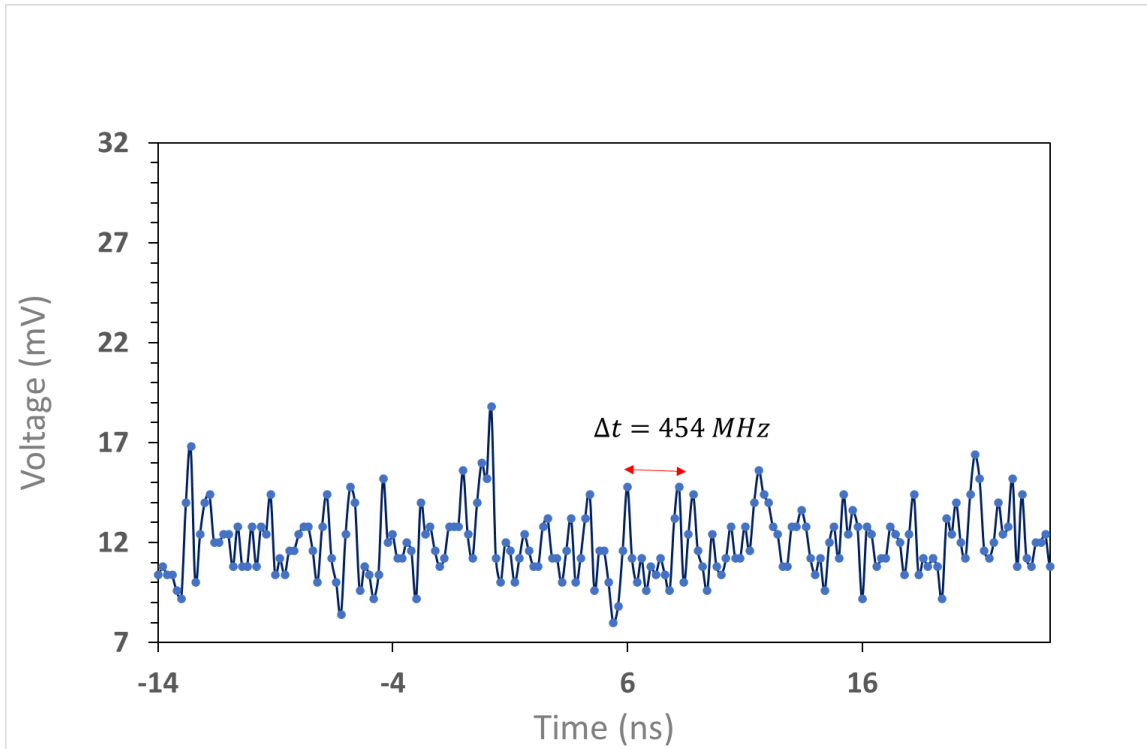
The operation of ultra-short pulse mode-locked will be discussed in this section. The output spectra of a mode-locked pulse generated in a fiber laser using the Nonlinear Polarization Rotation (NPR) technique are explained in this subtopic. Besides the output spectra, the peak-to-peak time duration, pulse repetition rate, and the pulse width with a different pump power injected such as 210 mW, 240 mW, 280 Mw, and 310 mW.

In addition, the spectrum stability with different pump power will be explained where the stability of the ultra-short pulsed mode-locking is also presented in this subsection. The stability of the spectra was taken at 5 minutes intervals for one hour starting from the 240 mW, 280 mW, 305 mW, 340 mW, and 370mW. The output performance of the mode-locking pulse was measured using the oscilloscope and the Optical Spectrum Analyzer (OSA). The result was extracted 30% from the 70:30 optical coupler.

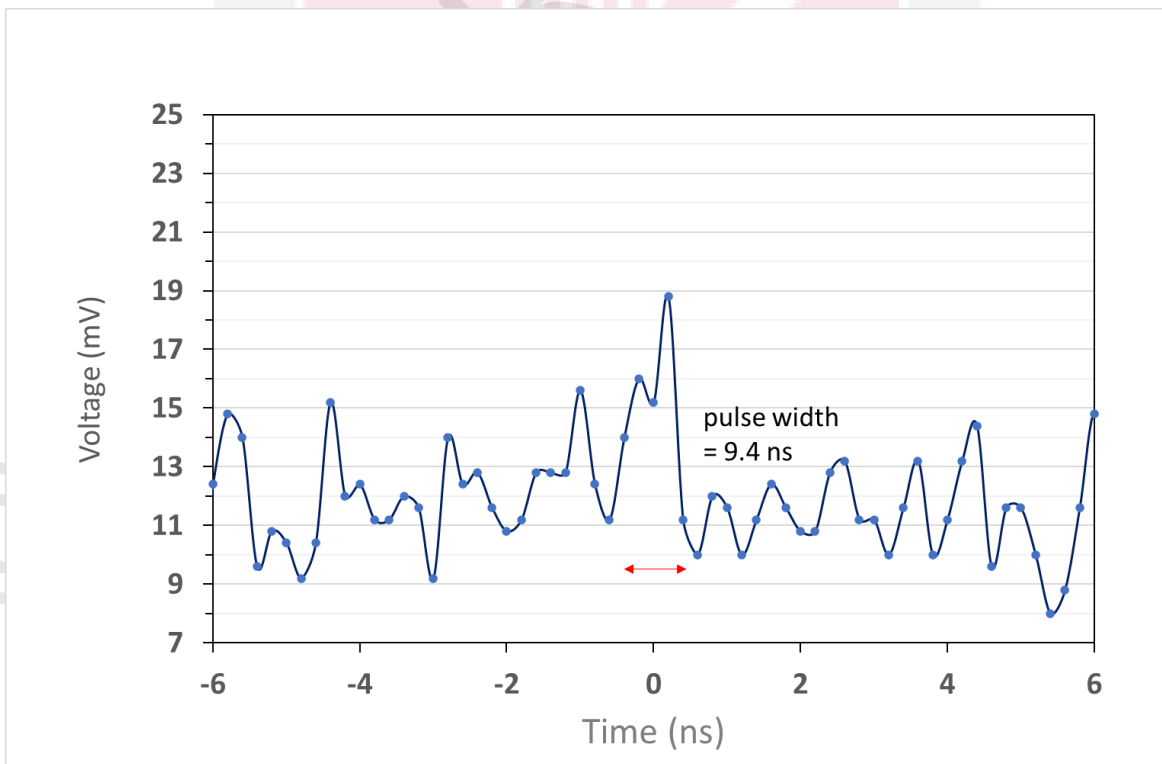
#### 4.4.1 Output of mode-locking ultra-short pulsed by employing Non-Linear Polarization Rotation method at different pump power.

Figure 4.3 shows the pulse obtained at 210 mW of pump power. At first, the repetition rate is 454 MHz was obtained, and the peak to peak was calculated to be at 2.2 ns. Next, a single random pulse calculated fullWidth at Half Maximum (FWHM). The calculated FWHM for 210 mW was 9.4 ns. Next, the pump power was then increased to 240 mW, as shown in figure 4.5, and the repetition rate obtained was 192.3 MHz. The peak to peak was calculated to be at 5.2 ns, and the calculated FWHM was 2.8 ns.

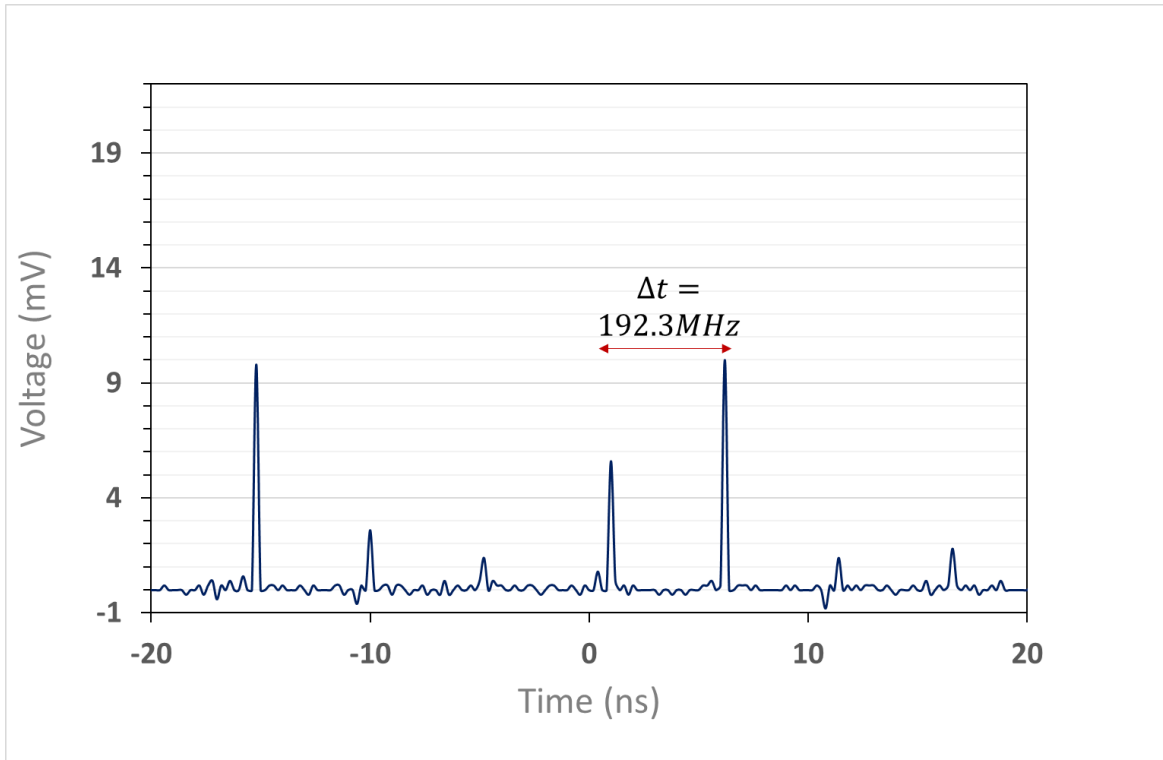
When the pump power increased to 280 mW (Figure 4.7), the repetition rate was 100 MHz, and the peak to peak was calculated to be at 10ns. The calculated FWHM was 0.64 ns. As for the last pump power, which is 310 mW (Figure 4.9), the highest pump power. The repetition rate is 104 MHz, and the peak to peak was calculated to be 0.96 ns. The FWHM obtained from the single pulse was calculated to be 0.08 ns. Both output power and pulse energy characteristics are observed to increase linearly as the pump power inside the cavity is raised.



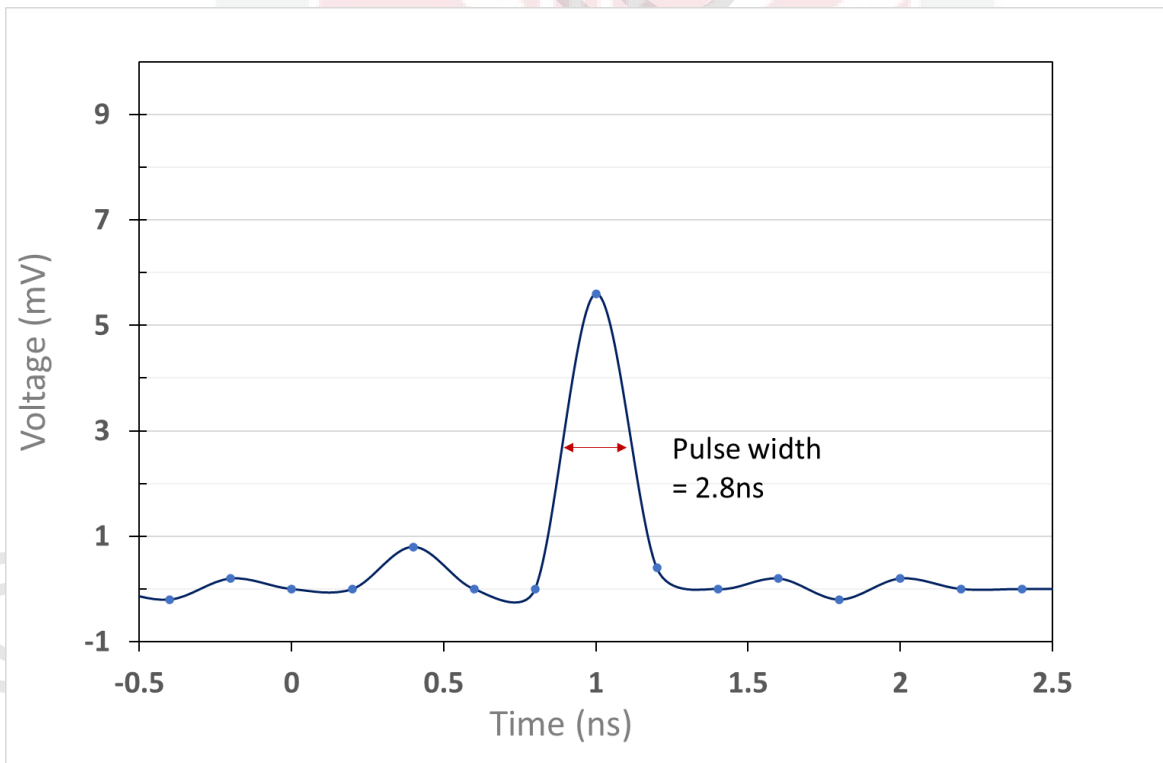
**Figure 4.3** Repetition rate for mode-locking pulse at pump power 210 mW



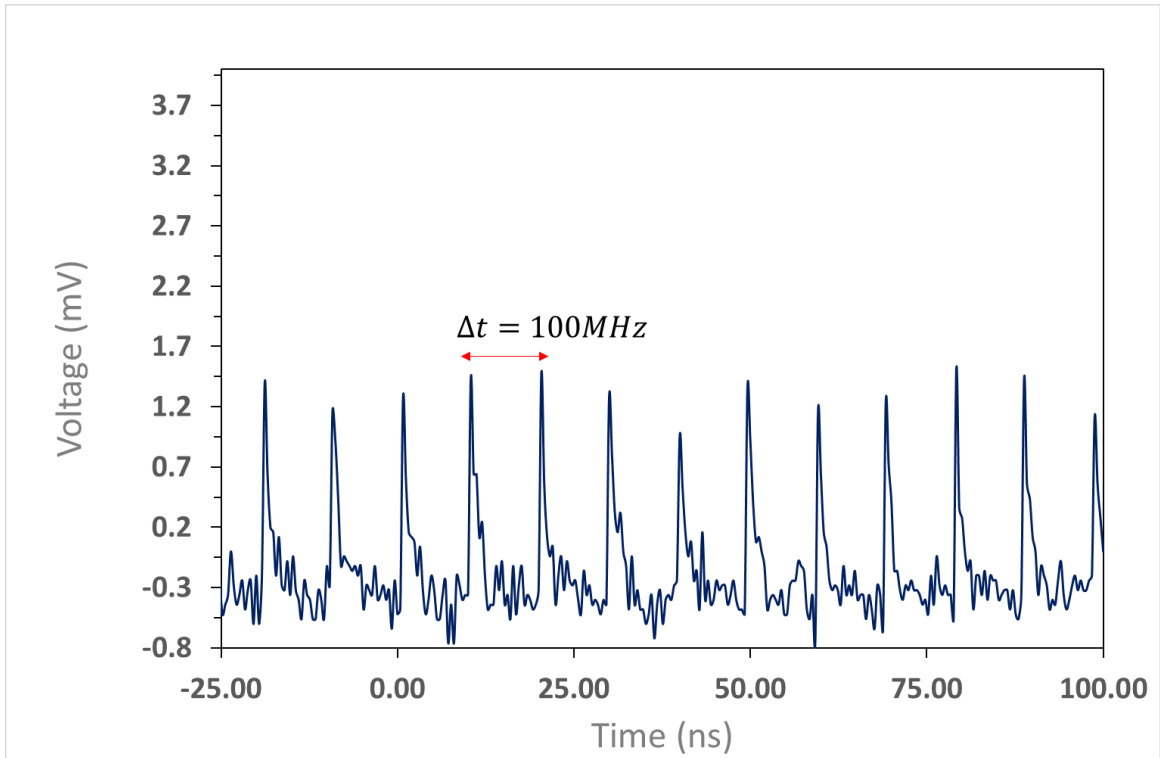
**Figure 4.4** Pulse width for mode-locking pulse at pump power 210 mW



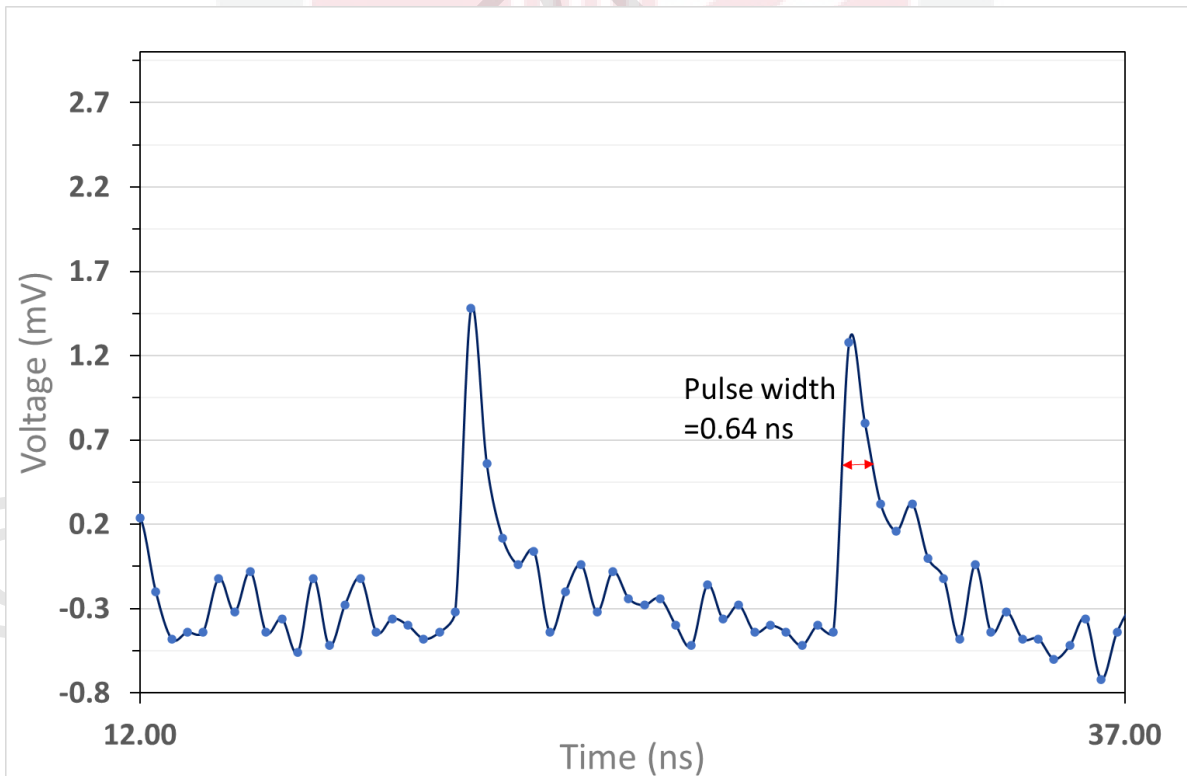
**Figure 4.5** Repetition rate for mode-locking at pump power 240mW



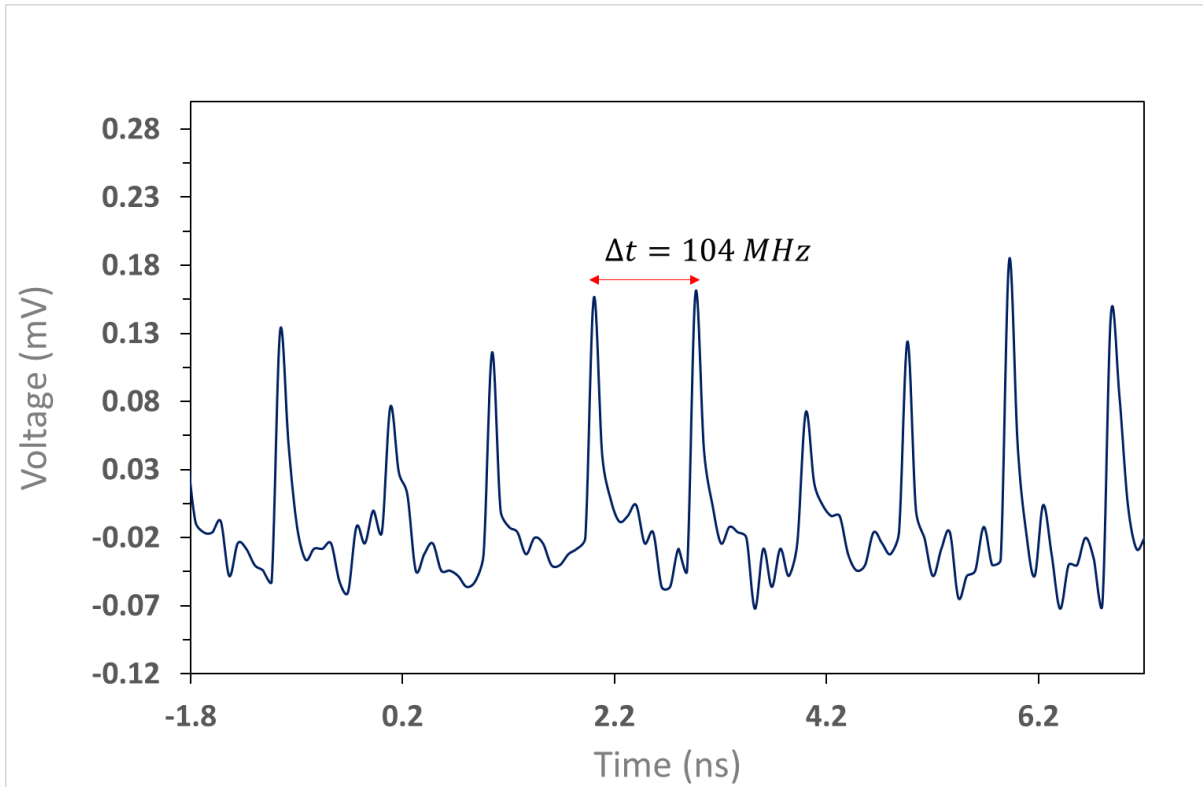
**Figure 4.6** Pulse width for mode-locking at pump power 240mW



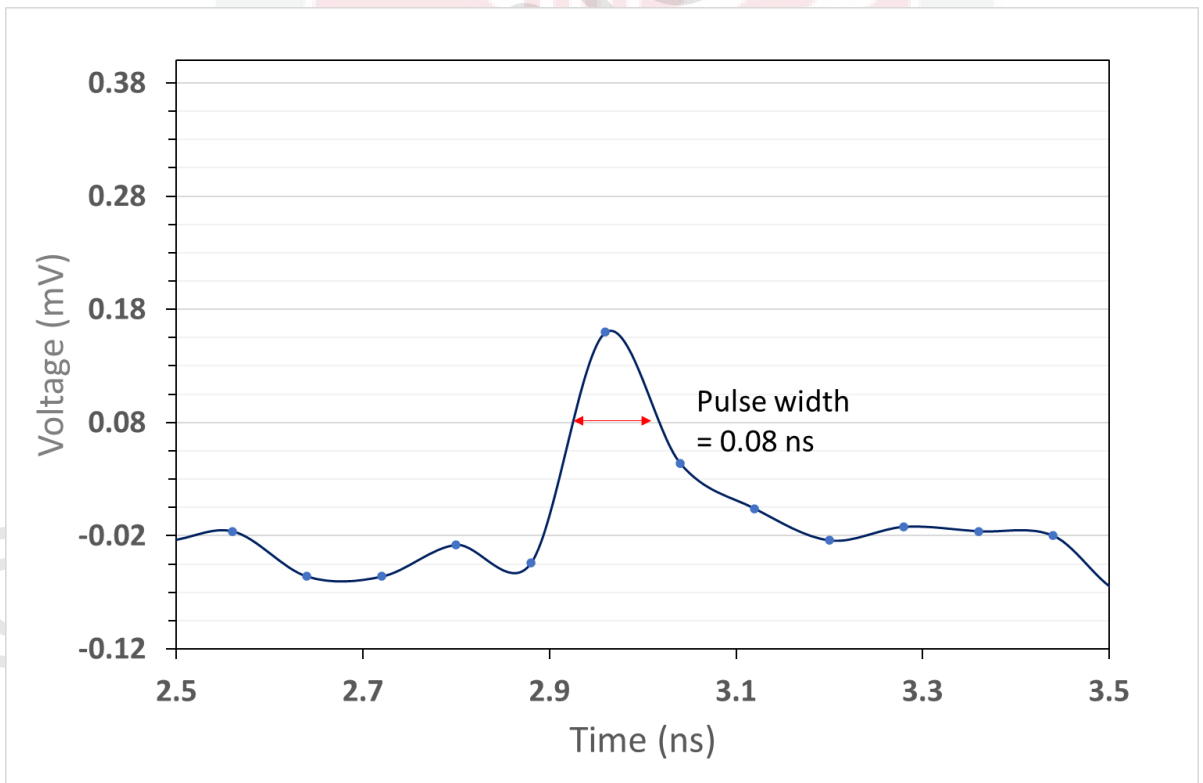
**Figure 4.7** Repetition rate for mode-locking pulse at pump power 280mW



**Figure 4.8** Pulse width for mode-locking at pump power 280 mW



**Figure 4.9** Repetition rate for mode-locking pulse at pump power 310 mW



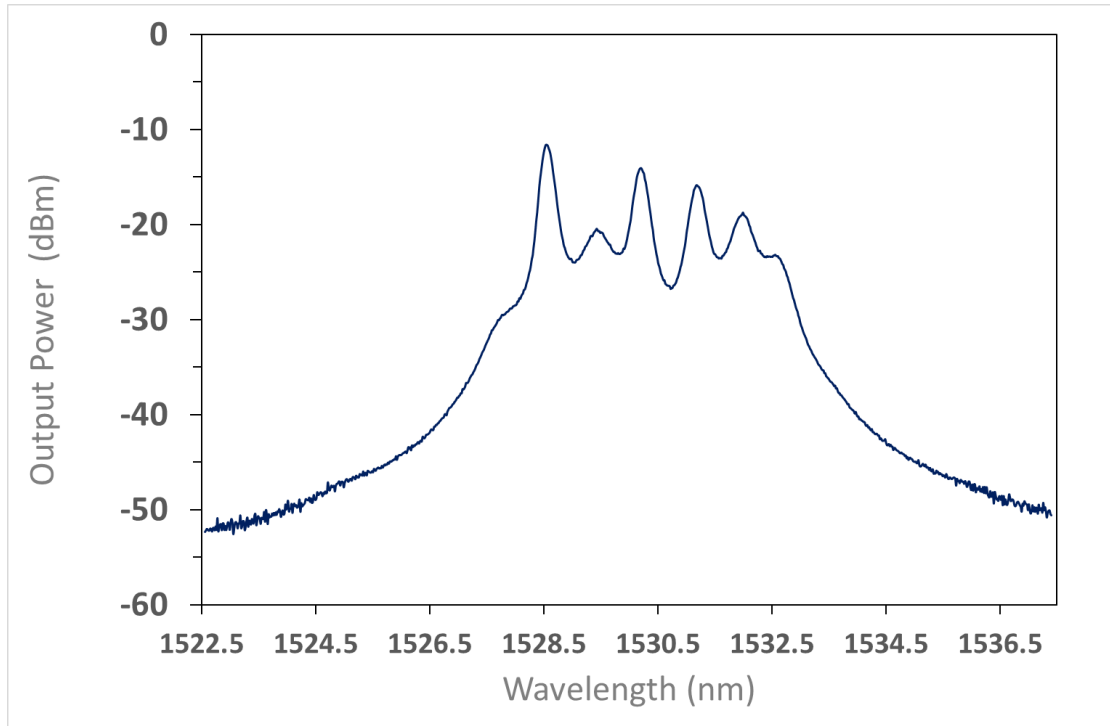
**Figure 4.10** Pulse width for mode-locking pulse at pump power 310mW

#### **4.4.2 Optical spectra for Mode-Locked in a Fiber Laser with Nonlinear Polarization Rotation technique with different pump power.**

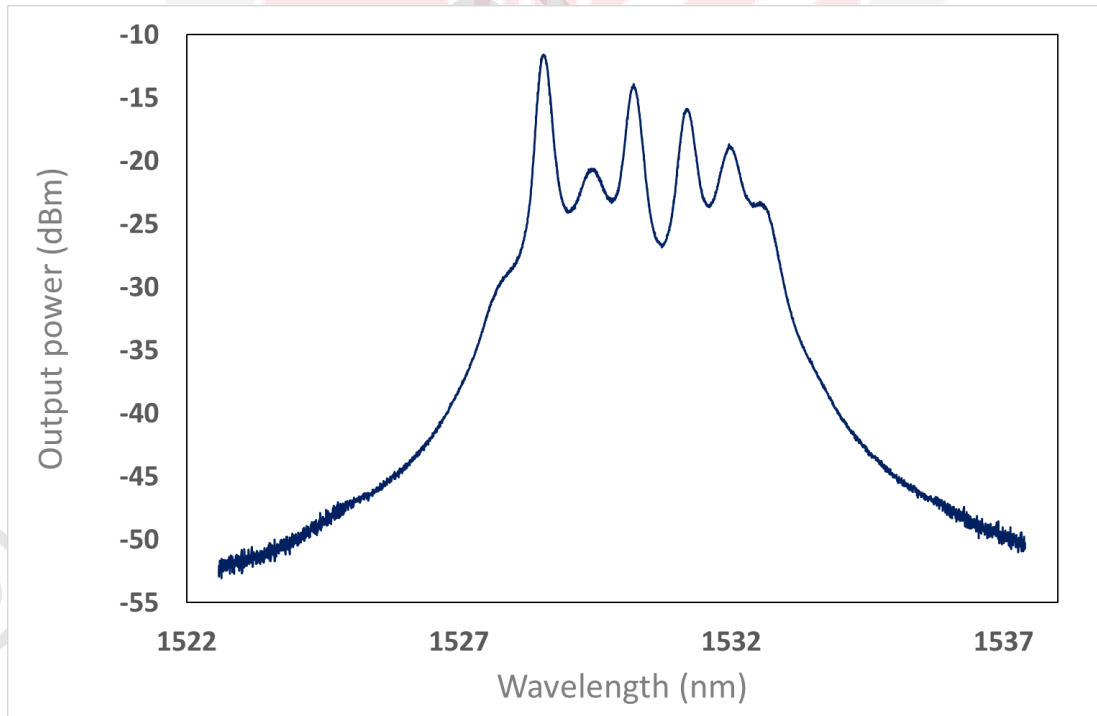
Figure 4.11-4.14 shown below is the spectra of output pulse generated from Mode-Locking in a Fiber Laser with the Nonlinear Polarization Rotation technique. The result is taken via 30% output of a fused optical coupler and connected to the Optical Spectrum Analyzer. As the pump power increases, the mode-locked pulse is observed to be more stable as a sufficient amount of power needed is supplied during the increment of the pumping power.

For the output pulse spectrum as shown in figure 4.11, at the pump power of 210 mW as the injected light source, the wavelength recorded to be a range from 1527 until 1532 nm. For figure 4.12, as the power increased, the wavelength was recorded at range 1528-1532 nm. At the pump power of 280 mW and 310 mW, the spectra' wavelength ranges 1522-1537 nm and 1522-1537 nm, respectively. It can be concluded that the spectrum obtained from the experiment is not stable because the location of each of the wavelengths is not in the region of the C-band, which is 1530-1565 nm.

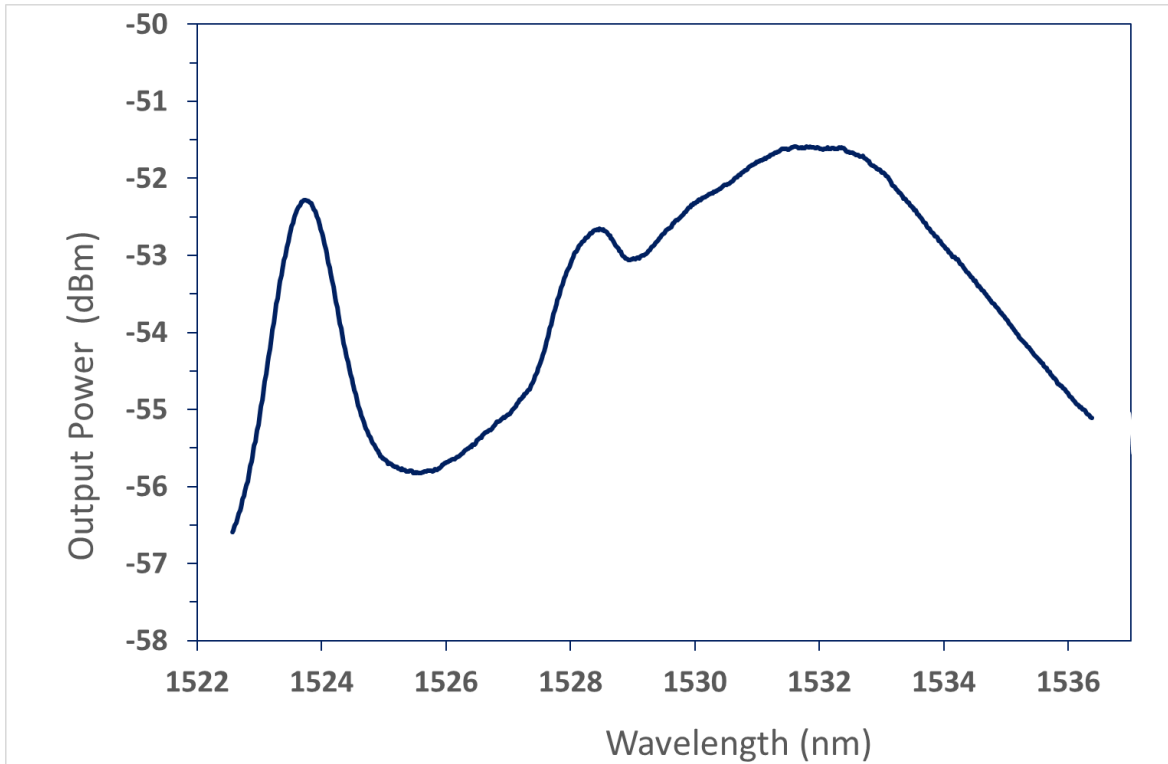
In this experiment, due to the existence of the artificial birefringent filter caused by the NPR technique, the centre of the wavelength of the fibre laser can be tuned when the birefringence is tuned by rotating the paddle on the polarizer controller.



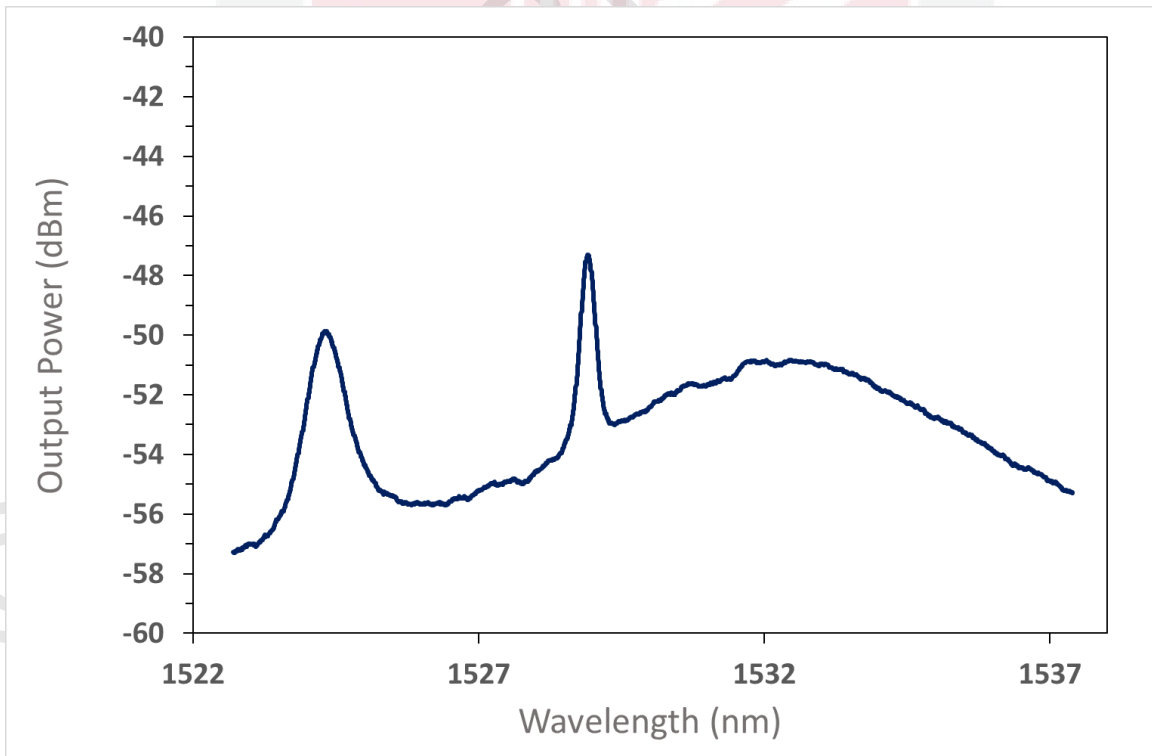
**Figure 4.11** Optical Spectrum for Mode Locked in a fiber laser with a nonlinear polarization rotation technique at pump power of 210 mW



**Figure 4.12** Optical Spectrum for Mode-Locked in a Fiber Laser with a Nonlinear Polarization Rotation Technique at pump power of 240 mW



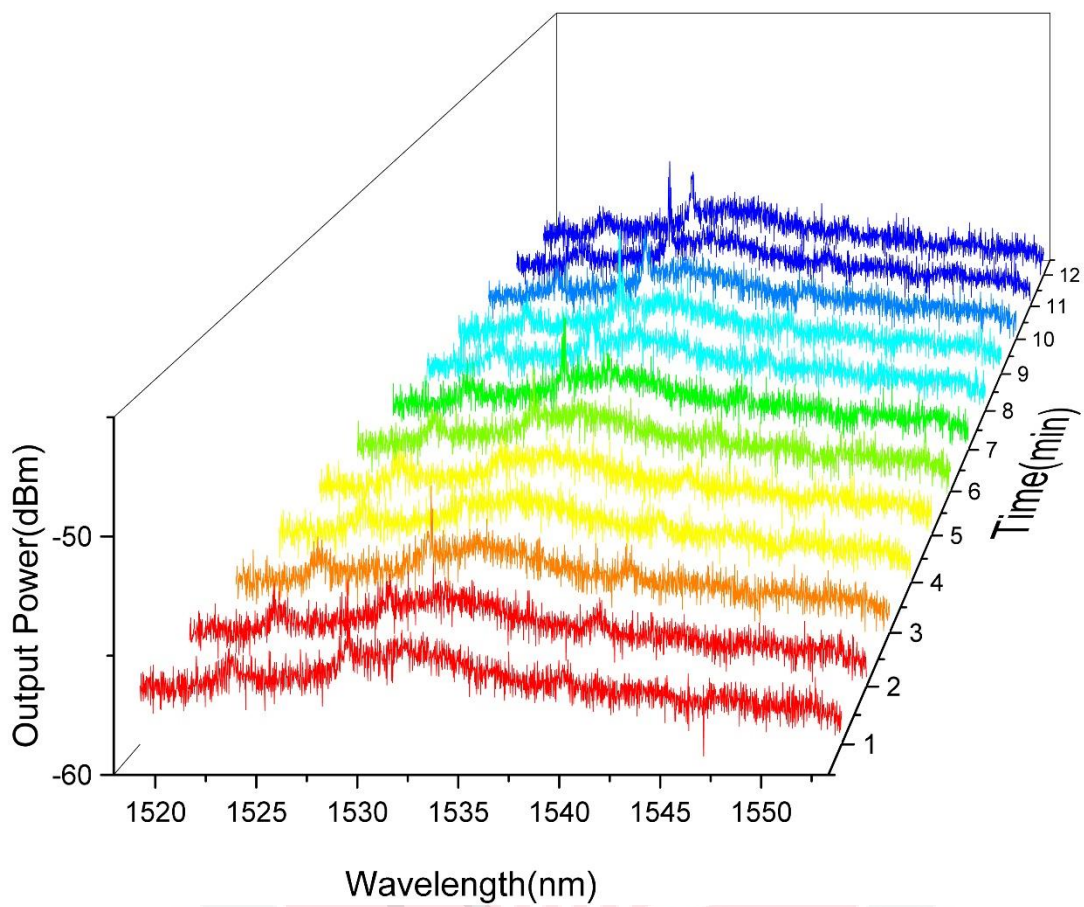
**Figure 4.13** Optical Spectrum for Mode-Locked in a Fiber Laser with a Nonlinear Polarization Rotation Technique at pump power of 280 mW



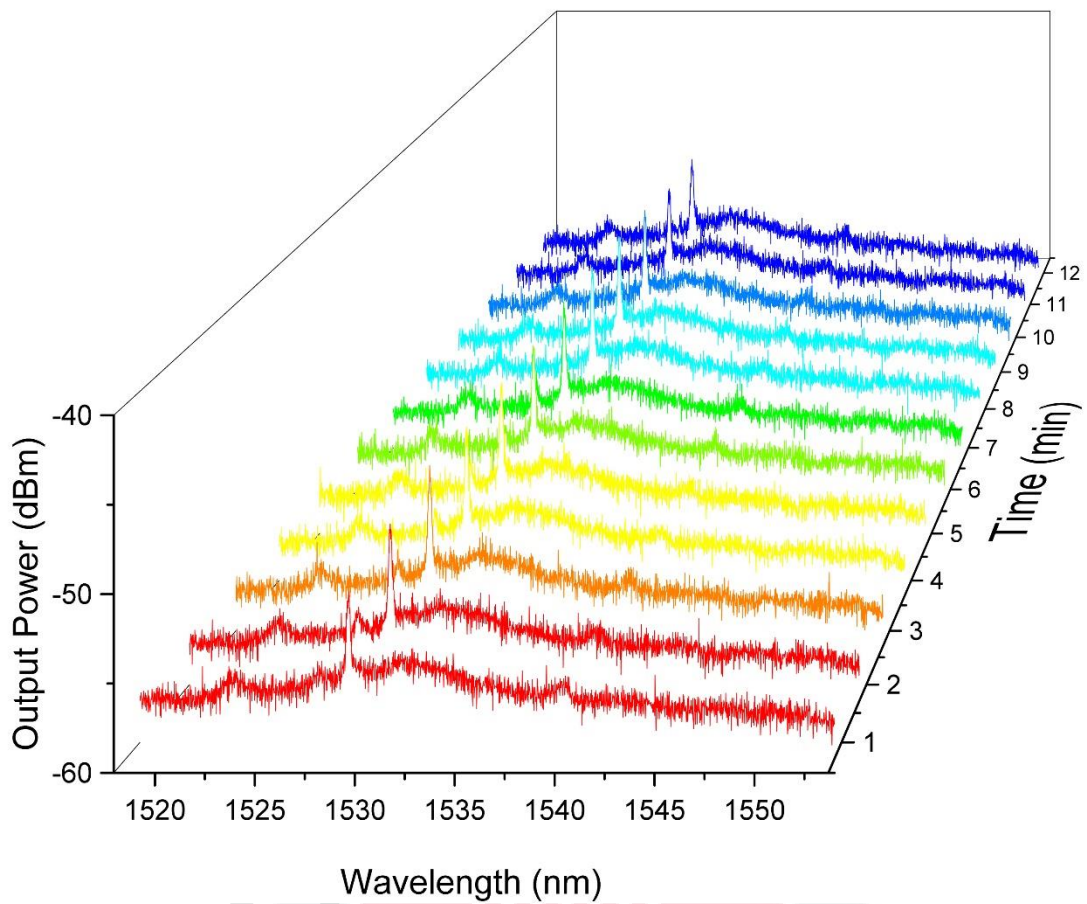
**Figure 4.14** Optical Spectrum for Mode-Locked in a Fiber Laser with a Nonlinear Polarization Rotation Technique at pump power of 310 mW

#### **4.4.3 Stability Measurement for Mode-Locking in a Fiber Laser with Nonlinear Polarization Rotation Technique.**

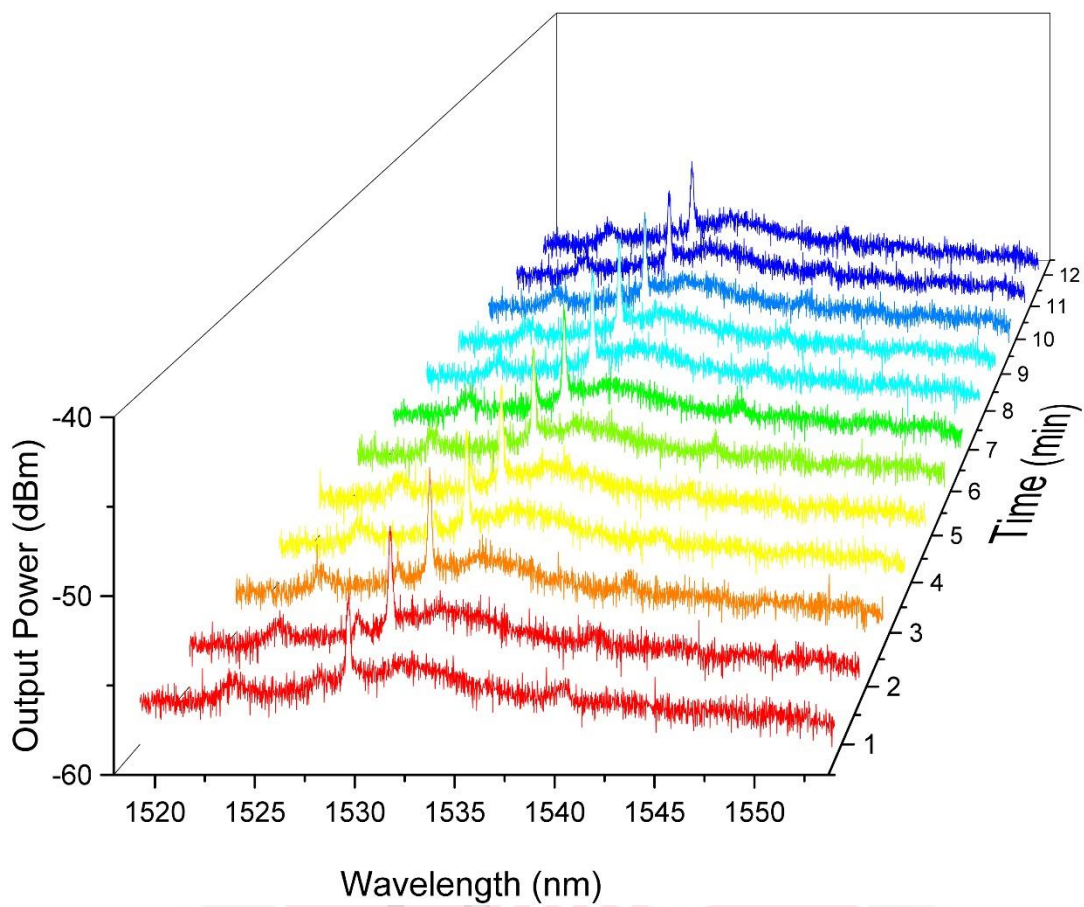
The figure shows the output spectra of mode-locking in a fiber laser with nonlinear polarization rotation taken at 5 minutes intervals for 12 readings of continuous operation. Figures 4.15 and 4.16 show output spectra of mode-locked in a fiber laser with nonlinear polarization rotation taken at 5 minutes intervals for reading of continuous operation for 240 mW and 280 mW pump power. In figure 4.17, the pump power was increased to 305 mW, and the stability of the spectra was recorded. As for the pump power at 310 mW and 370mW, figure 4.18 and 4.19 shows the stability in 5 minutes intervals for a one-hour operation. Based on the result, the output stability of this mode-locked pulse by employing the NPR technique was maintained over time. For each pump, it is observed that the central wavelength is in the 1530 nm until 1550 nm. The spectral development towards time graphs demonstrates that the optical spectrum for each pump power is steady, as shown by the observed stability performance.



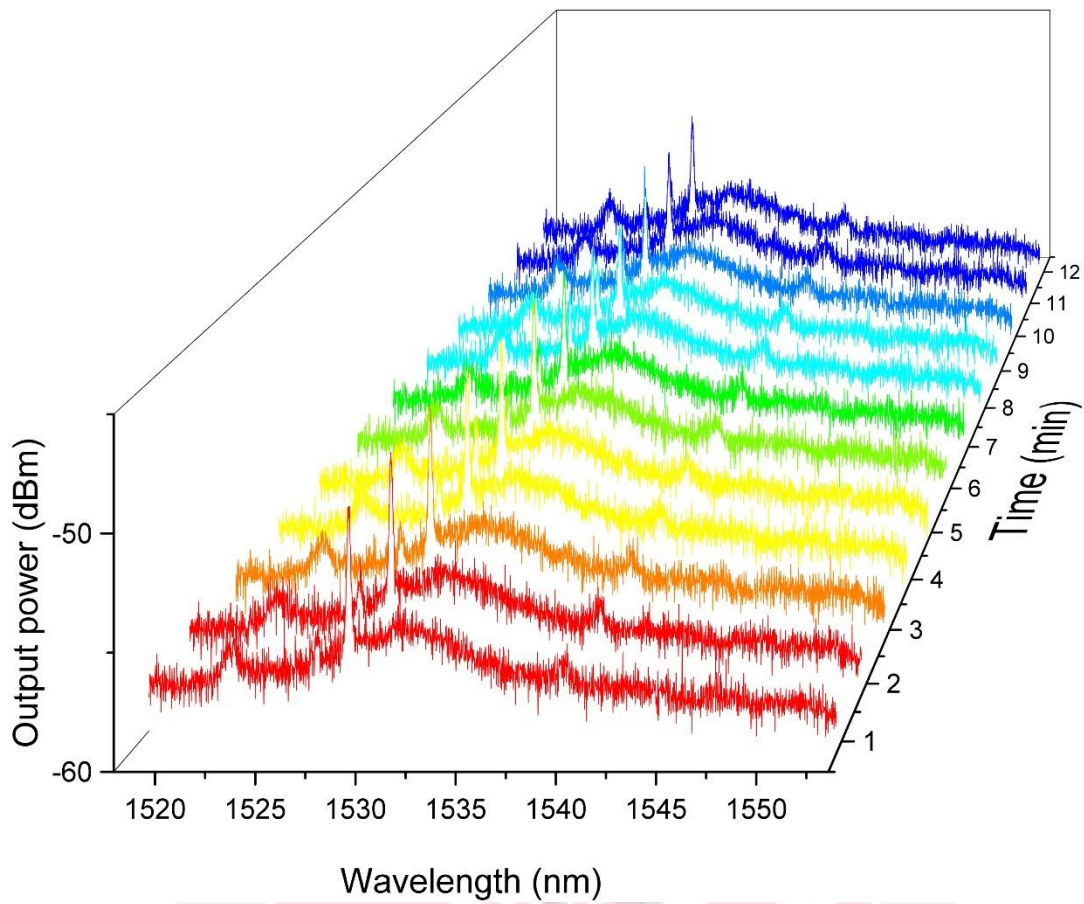
**Figure 4.15** Spectrum evolution for Mode-Locking in a Fiber Laser with a Nonlinear at pump power of 240 mW



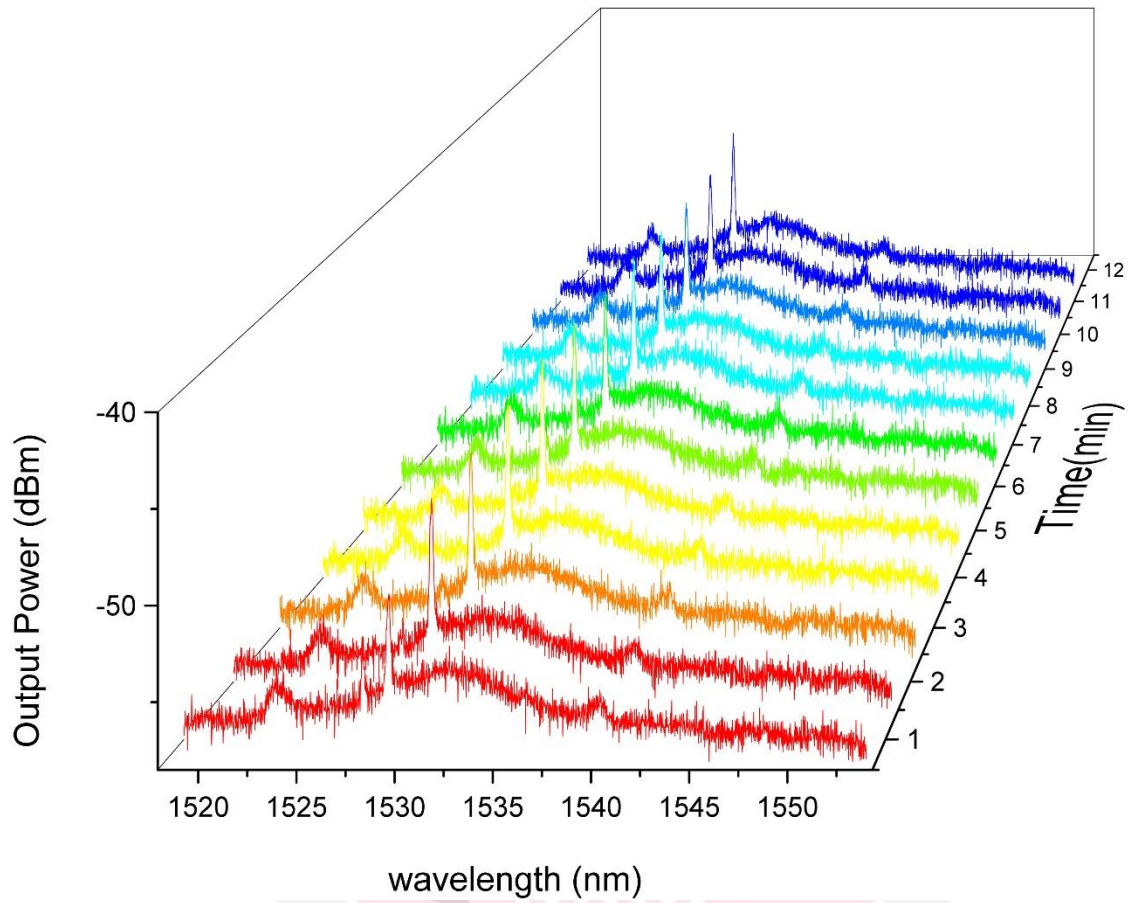
**Figure 4.16** Spectrum evolution for Mode-Locking in a Fiber Laser with a Nonlinear at pump power of 280 mW



**Figure 4.17** Spectrum evolution for Mode-Locking in a Fiber Laser with a Nonlinear at pump power of 305 mW



**Figure 4.18** Spectrum evolution for Mode-Locking in a Fiber Laser with a Nonlinear at pump power of 340 mW



**Figure 4.19** Spectrum evolution for Mode-Locking in a Fiber Laser with a Nonlinear at pump power of 370 mW

#### 4.5 Comparison Between Repetition Rate and FWHM Obtained from Different Pump Power.

In this point, the comparison between all of the pump power injected will be discussed. It involves the repetition rate and the FWHM values resulting from this project. Different currents will give a different repetition rate, resulting in the different FWHM calculated values. The decreasing value of FWHM may be caused by the dispersion managed by the cavity structure and the change of effective laser gain with the rotating PC paddles. From the table shown below, the FWHM value decreases as the pump power injected into the cavity increases(Luo et al., 2014).

Pump power (mW)	Repetition rate (MHz)	FWHM (ns)
210	454	9.4
240	192.3	2.8
280	100	0.64
310	104	0.08

**Table 4.1**

**Table 4.1** Output performance of ultra-short pulse mode-locked by employing the Nonlinear Polarization Rotation technique at different pump power.

## CHAPTER 5

### CONCLUSION

In this final chapter, the conclusion and the summary of the experiment in achieving an ultra-short pulsed mode-locking fiber laser by employing the Nonlinear Polarization Rotation technique will be concluded. The recommendation in conducting future research also will be discussed.

#### 5.1 Conclusion

An ultra-short pulsed fiber laser is successfully demonstrated using a nonlinear polarization rotation technique and a 4m long erbium-doped fiber laser as a gain medium. An ultra-short pulsed mode-locking was first obtained at the pump power of 240 mW, where we can see the pulse start to lock at a specific frequency as the current increased, stable pulsed were forming. From the previous research, the NPR technique has the maximum average output power at 80mw, but for this experiment the cavity needs to be supplied at least the output power is at 210 mw in order to obtain the mode locked pulse. This may due to the combination of the high-pump power source and the optimization of the cavity length.

The ultra-short pulse can be obtained by rotating the paddle of the polarization controller as the nonlinear polarization rotation technique was applied in this experiment. It is a compact and straightforward solution for mode-locking in fiber laser in multi-wavelength mode. However, the pulsed obtained should be in the C-band region, but from the previous chapter's result, the pulsed spectrum recorded to be at the range from 1522- 1537 nm. It may result due to some error while experimenting. however, the pulsed obtained in this experiment shown that we were successfully demonstrated an ultra-short pulsed where it can be used in

various application such as optical communication as it is compact and low-cost designed structure.

The NPR technique is an artificial saturable absorber which is known to be very sensitive to the environment. The environment variation such as temperature and humidity changes will affect the birefringence of fibers and will degrades the long-term stability. However, the characteristic of fiber laser by employing the nonlinear polarization rotation technique can be observed, such as a repetition rate, peak-to-peak time duration and pulse width. In addition, the output spectrum and the stability performance result were included.

A stable mode-locked ultra-short pulsed was observed by increasing the pump power from this experiment. This result was analyzed and collected from the 30% of the 70:30 output coupler connected to the oscilloscope, optical spectrum analyzer and optical power meter. The pulsed first was obtained at the pump power is 240mW. As the current increased, a more stable pulsed were recorded, and the repetition rate and the pulse width. From this experiment, the highest repetition rate obtained for the stable pulsed was 104 MHz when the pump power is 310 mW, and the calculated FWHM is 0.08 ns.

## **5.2 Recommendation for future work.**

From the previous study, a lot of the generation of ultra-short pulsed fiber laser by employing a nonlinear polarization rotation technique was carried out. In the future, the researcher will find out the most stable output pulses with the lowest output power can be achieved to create a more compact and efficient fiber laser. Furthermore, the preparation of the cavity and the experiment equipment can be modified, or another suitable method can create a compact, low-cost but powerful fiber laser. The environment while using an NPR can be improved to optimize the efficiency of the cavity as the NPR has high sensitivity.

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FIELD OF STUDY : PENTAKSIRAN TINGKATAN 3 (PT3)

SCHOOL : SMK SULTAN ABDULLAH



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