DUALWAVELENGTH FIBER LASER

MOHAMED KHALIF ABDI

A project report submitted in partial
Fulfillment of the requirement for the award of the
Degree of Master of Electrical Engineering

Faculty of Electrical and Electronic Engineering
Universiti Tun Hussein Onn Malaysia

JULY, 2021

ACKNOWLEDGMENT

In the name of Allah, Most Gracious, Most Merciful. All praises be to Allah for blessing me and giving me the strength to complete this project.

Many thanks to my Supervisor Dr. NORAN AZIZAN BIN CHOLAN for his immense and timely help given during this project. This project would not have been possibly finished without his encouragement and support.

I would like to thank my family, especially my parents, for their love, courage, sacrifice and support. I would also like to thank my brothers and sisters, as well as all My friends and colleagues for providing me with ideas and support in completing this report. Thank you for your kindness and generosity. May Allah grant you paradise.

ABSTRACT

A Dual-wavelength erbium doped fiber laser (EDFL) is presented. The gain interest in recent decades due to their inherent characteristics such as narrow linewidth, high optical power. Generation of dual-wavelengths is realizable through Erbium Ytterbium Doped Fiber Amplifier (EYDFA) gain in the laser cavity. The lasing wavelength spacing is widely controlled in a range from 3 to 16.1 nm, which means the tunable can be achieved. The signal to noise ratio (OSNR) obtain as high as 60 dB. The fiber Bragg gratting FBG 1539.4 nm achieved and the output power of the EYDFA is fixed at 1 w. The Tunable BandPass Filter TBPF is put in the laser cavity. The laser FBG goes to port 1 then, TBPF will tune and passes to port 2. The FBG reflects only at the wavelength of 1539.4 nm and the rest passes through. The TBPF tuned from 1542.3 to 1555.5 nm. The TBPF is almost the same with FBG after thulium. The thulium function here is to stabilize and distribute energy from higher power to the low power. The minimum variation is 1.9 dB while the maximum is 2.87 dB. Hence, dual-wavelength fiber laser records the best performances with respect to the output power, the laser is found to be the most stable when applied enough power.

ABSTRAK

panjang gelombang ganda Erbium Doped Fiber Laser (EDFL) dipersembahkan. Peningkatan minat dalam beberapa dekad kebelakangan ini disebabkan oleh ciri-ciri yang wujud seperti garis sempit, daya optik yang tinggi. Penjanaan panjang gelombang ganda dapat direalisasikan melalui penambahan Erbium Ytterbium Doped Fiber Amplifier (EYDFA) di rongga laser. Jarak panjang gelombang lasing dikendalikan secara meluas dalam jarak antara 3 hingga 16.1 nm, yang bermaksud tunable dapat dicapai. Nisbah signal to noise (OSNR) memperoleh setinggi 60 dB. Serat Bragg grating FBG 1539.4 nm dicapai dan kuasa output EYDFA ditetapkan pada 1 w. TBPF Filter Tunable BandPass dimasukkan ke dalam rongga laser. Laser FBG menuju ke port 1 kemudian, TBPF akan menyesuaikan dan melintas ke port 2. FBG hanya memantulkan pada panjang gelombang 1539.4 nm dan selebihnya melewati. TBPF diselaraskan dari 1542.3 hingga 1555.5 nm. TBPF hampir sama dengan FBG selepas thulium. Fungsi thulium di sini adalah untuk menstabilkan dan mengedarkan tenaga dari daya yang lebih tinggi ke kuasa rendah. Variasi minimum ialah 1.9 dB sementara maksimum ialah 2.87 dB. Oleh itu, laser gentian dwi-gelombang mencatat prestasi terbaik sehubungan dengan daya output, laser didapati paling stabil apabila menggunakan daya yang cukup.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS AND ABBREVIATIONS

EDFL	-	Erbium doped fiber laser
EYDFA	-	Erbium ytterbium doped fiber amplifier
OSNR	-	Optical Signal to noise ratio
TBPF	-	Tunable Band Pass Filter
FBG	-	Fiber Brag Gratting
EDF	-	Erbium-doped fiber
DWDM	-	Dense wavelength division multiplexing
WDM	-	Wavelength division multiplexing
EYDFL	-	Dual wavelength fiber laser
OSA	-	Optical Spectrum analyzer
OPM	-	Optical power meter
LD	-	Laser diode
FRA	-	Fiber Raman Amplifier
PC	-	Polarization controller
SOA	-	Semiconductor Optical Amplifier
Er/Yb	-	Erbium & Ytterbium co Doped fiber
Yb	-	ytterbium
SMF	-	Single mode fiber
SOA	-	Semiconductor optical amplifier
SPM	-	Self-phase modulation
HR	-	High reflector
OC	-	output coupler
SLM	-	Single longitude mode
λ	-	Propagating wavelength

CHAPTER 1

INTRODUCTION

1.1 Background

Fiber optic sensors have been intensively studied for more than 30 years [1] and today have found applications in many fields such as medicine, defense, security and communication systems [2]. Among the fiber laser technologies, dual wavelength generation attracts community attention due to its great importance in optical sensors, microwave signal processing, optical instrumentation, and high- tech communication networks. The high speed internet is very essential for human being in this modern era. People today depend on to cater for their needs in their life; Therefore, the high-speed internet is no longer an option but a necessity in this modern lifestyle. When using high-speed Internet, huge bandwidth is required for it to work, as a result of downloading and uploading information at high data speed. To fulfill the need, dense wavelength Division Multiplexing (WDM) innovation is a serious competitor that is more than equipped for satisfying the need for quick and dependable transmission of voice, video and information signals.

To center for the demand of high speed internet, it is required to transmit data in terabits range which can be achieved by the performance of system components or devices used in an optical communication system [3] as result of an increase in the demand of large and fast data transmission, WDM coupler using optical fibers came as a popular and necessary choice as they offer huge transmission bandwidth [4]. Doping of ytterbium ions in EDFA make it as a popular choice for amplification gain enhancement using a shorter length of fiber. Erbium ytterbium doped fiber (EYDFA) is an only amplifier with different pump power configurations for achieving the maximum gain of 60 dB. In this amplifier the dual EYDFA and single pump with a pup power of 1000 mW have been to achieve the higher value of the

out power. The Erbium Ytterbium doped fiber laser (EYDFL) gives high efficiency with reduced power fluctuation while maintaining the tuning range. The efficiency of the EYDFL system easily beats higher and the power fluctuation was reduced as compared to the EDFL. This chapter describes theoretical background and descriptions of optical components, EYDFA and dual-wavelength Fiber laser EYDFL that are related to the research work.

1.2 Problem Statement

A Dual wavelength erbium ytterbium doped fiber laser EYDFL is one of the procedure for generating dual wavelength and compares to other techniques, it has an advantages in optical fiber sensing, for example microwave signals from photonic generation, and wavelength division multiplexing system. A particular problem arises through the gain dual wavelength fiber laser DWFL using an EDFL as the gain medium. The wavelength spacing of the two optical wavelength corresponds to the generated frequency based on the previous report, this technique need to be improve such as dual wavelength to generate an electrical signal with the frequency up to 1.66 THz [5]. This project will focus to perform an experiment that will produce a stable dual-wavelength laser.

Research on EYDFL mentioned to this point had, in particular, targeted on wavelength-based technique with the aid of using OSAs. In this thesis, three performances such as number of lasers, flatness, stability and threshold power are compered between these three cases.

1.3 Research Objectives

The main focus of this work is to generate a stable and uniform dual-wavelength erbium-doped fiber laser (EYDFL).

(i) To design dual-wavelength erbium ytterbium doped fiber laser (EYDFL) by conducting an experiment at the lab.

(ii) To compare the performances of the dual-wavelength EYDFL in terms tunibility, threshold power, number of channel and stability.

(iii) To analysis the outcome result measured by OPM and OSA.

1.4 Research Scope

Development of dual wavelength EDFL are studied and mentioned. The Erbium Ytterbium Doped Fiber Amplifier EYDFA is comprised of 10 m Erbium doped fiber and it is pumped by a 980 nm laser diode LD through a wavelength Division Multiplexer (WDM) coupler. In this configuration a 90/10 coupler is used to collect 10 percent of the laser power for the output while another 90 percent of the laser power is again transmitted into the cavity. The EDFA pump is supplied by a 980nm laser diode which produces a maximum power of 165 mW. Erbium ytterbium doped fiber (EYDFA) only amplifier with different pump power configurations for achieving the maximum gain of 60 dB. In this amplifier the dual wavelength EYDFA and single pump with a pup power of 1000 mW have been to achieve the higher value of the out power. In order to generate a number of laser lines in the laser cavity. In this simulation uses a 10 meter EYDFA with an input signal power of 30-dBm, and pump wavelength 980 nm. Records from the lasers will be obtained in the OSA to get the wavelength. For the lasers to overcome the losses incurred in the laser cavity, the oscillating signals gain power from an EYDFA that provides amplification from 1530 to 1565 nm. The efficiency of the EYDFL system easily beats higher and the power fluctuation was reduced as compared to the EDFL.

1.5 important of Studies

This research can be a reference to the improvement of measuring dual wavelength. The use of OPM and OSA makes those studies in value-effective interrogation of fiber laser on an EYDFL. As a result, this study has the benefit in the further improvement of strain measurement.

1.6 Thesis Organization

Overall, this thesis contains five chapters. The first chapter discusses the introduction of dual wavelength fiber laser for the application in optical telecommunication system and a brief background about the EYDFA. This chapter also highlights the problem statement, objective, research scope and thesis organization. Chapter 2 then extends the theoretical background of this research work. Specifically, this chapter covers the principle of EYDFA which includes the operation, material and structure. The previous developments of dual wavelength EDFLs are also reviewed in this chapter. Next, for Chapter 3 includes the research methodology of this work. In more details, in this part we outline the research strategy, the research method, the research process and description of the related devices in the experimental set.

As this thesis report is a comparison studies, Chapter 4 are devoted to the research work of dual wavelength. Each subtopic covers the explanation of experimental setup and the obtained laser performances such as the number of laser lines, threshold power, stability and tunability. Self-lasing cavity modes and Stokes evolution are also discussed in each chapter. The final chapter, Chapter 5 will conclude all the research work interms of tunability, threshold power, number of channels, and stability. The important of the improvement future work over the existing experiment is discussed in this chapter.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Dual wavelength fiber laser has attracted significant amount of research because of their potential applications in optical communications, optical instrument testing, and optical fiber sensors [6]. To center for the demand of high speed internet, it is required to transmit data in terabits range which can be achieved by the performance of system components or devices used in an optical communication system as result of an increase in the demand of large and fast data transmission, dense wavelength division multiplexing system using optical fibers came as a popular and necessary choice as they offer huge transmission bandwidth [7]. Doping of ytterbium ions in EDFA make it as a popular choice for amplification gain enhancement using a shorter length of fiber. Erbium ytterbium doped fiber (EYDFA) only amplifier with different pump power configurations for achieving the maximum gain of 60 dB. In this amplifier the dual EYDFA and single pump with a pup power of 1000 mW have been to achieve the higher value of the out power. This chapter describes theoretical background and descriptions of optical components, EDFA and dual-wavelength Fiber laser EDFL that are related to the research work. The theoretical backgrounds are important in understanding the experimental results that will be discussed in the next chapters. The optical devices can be characterized into two types, passive and active devices [8]. Examples of passive devices include isolators, circulators, couplers and optical fibers. Among device parameters being characterized are insertion loss, isolation, coupling ratio and bandwidth. On the other hand, the active

device utilized in this experimental work is a laser diode. Among the laser diode parameters being characterized are laser wavelength and optical power.

2.2 Optical Amplifiers

The transmission loss of the light passing through optical fiber is the very small value of less than 0.2 dB per km with a light wavelength in the 1,550 nm band. However, when the length of the optical fiber is a distance as long as 10 km or 100 km, that transmission loss cannot be ignored. When the light (signal) propagating a long-distance optical fiber becomes extremely weak, it is necessary to amplify the light using an optical amplifier. An optical amplifier amplifies light as it is without converting the optical signal to an electrical signal, and is an extremely important device that supports the long-distance optical communication networks of today. The major types of optical amplifiers include an EDFA, FRA, and SOA. The Erbium Ytterbium doped fiber laser (EDFL) gives high efficiency with reduced power fluctuation while maintaining the tuning range. The efficiency of the EYDFL system easily exceeds 300% higher and the power fluctuation was reduced up to 43.8% as compared to the EDFL [9].

2.2.1 Structure and Material EDFA

Erbium Doped Fiber (EDFA) is 1 type of OFA and is an optical amplifier with erbium ions added to the core of the optical fiber. It features high gain and low noise, is polarization independent, and can amplify optical signals in the 1550 nm band or 1580 nm band [10].

It was previously necessary to use an optical repeater to temporarily convert attenuated light into an electrical signal, electrically amplify and regenerate the waveform, then convert back to light and resend. In the 1990s, the debut of EDFAs enabled signals to be amplified as light [11].

Configuration EDFA irradiating a coupling module with light at 1480 nm enables the light to be internally stored as energy, and light in the 1550 nm band causes optical amplification when it propagates, and obtains a gain of 20 to 30 dB [12].

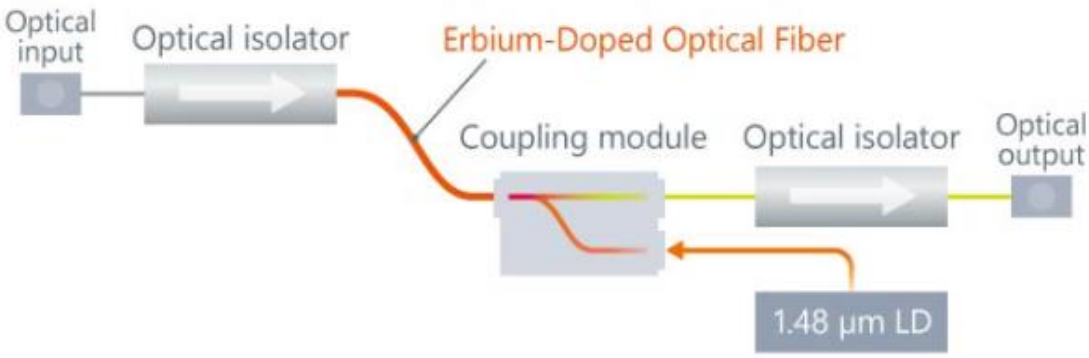

Figure 2.1: Erbium Doped Optical Fiber [13]

2.2.2 Working principles

Figure 2.2 shows a basic energy level that shows how the amplification happen at the wavelength 1550 nm. There are two types wavelengths to pump an EDFA which are 980 or 1480 nm [14].

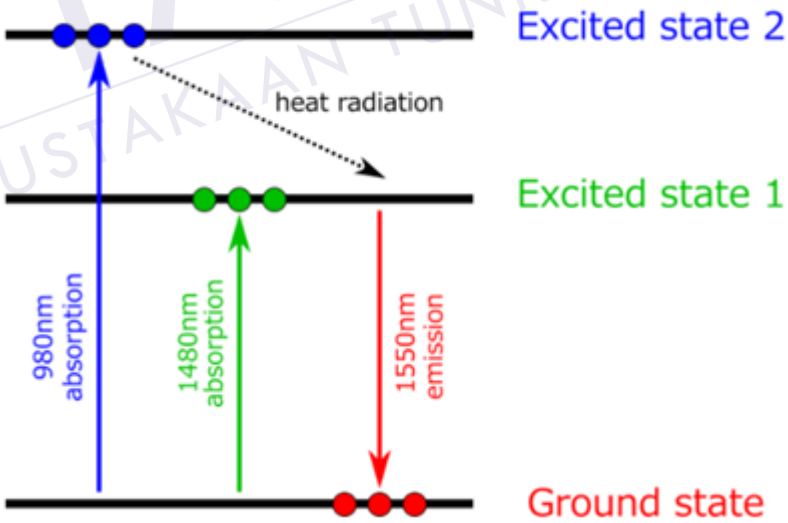

Figure 2.2: Erbium energy level [14]

When an EDFA pumping is required to trigger the electrons at the higher energy levels. Photons are used to race electrons into higher energy state so photons will be triggering them to come into lower energy state. It requires three energy levels, ground state, exited state 2 and in between we have exited state 1, from the ground

they will reach to the top most energy level which is the exited level and after that as soon as they reach their will be a dropping of the electrons to the exited state 1 and the electrons can accumulate for a longer duration of time. The signal photon is going to stimulate emission, if we supply photon which is having the wavelength identical to the stimulated band gap then we are generating a new photon and it will be having the same wavelength then the signal photon and stimulated emission will be taking place so, the pumping wavelength is shorter than the signal wavelength in this case because for the pumping required energy gap in between the top most energy level exited state 2 and the ground energy level. There are two principles we have, an exited state 1 and the pumping levels. The exited state 1 separated from bottom of ground state level by energy gap 0.814 electron volt at bottom of exited state 1 to 0.841 electron volt at the top. The pumping is required to trigger the electrons at the higher energy levels. Photons are used to race electrons into higher energy state so photons will be triggering them to come into lower energy state. It requires three energy levels, ground state, exited state 2 and in between we have exited state 1, from the ground they will reach to the top most energy level which is the exited level and after that as soon as they reach their will be a dropping of the electrons to the exited state 1 and the electrons can accumulate for a longer duration of time. The signal photon is going to stimulate emission, if we supply photon which is having the wavelength identical to the stimulated band gap then we are generating a new photon and it will be having the same wavelength then the signal photon and stimulated emission will be taking place so, the pumping wavelength is shorter than the signal wavelength in this case because for the pumping required energy gap in between the top most energy level exited state 2 and the ground energy level. There are two principles we have exited state 1 and the pumping levels. The exited state 1 separated from bottom of ground state level by energy gap 0.814 electron volt at bottom of exited state 1 to 0.841 electron volt at the top. Since the an EDFA diode pump protested in 1989 [15], exclusive exertion has been made to prepare a highly reliable laser diode pump. When an EDFA signal 980 nm send to the pump band which is the highest energy level with the help of pumping transition absorption, the electron from the ground pump to the exited state 2, when the electron from the exited state 2 comes to the exited state 2 we will have non radiative decay there will not be any heat radiations provided [14]. When we supply the wavelength 1400 nm energy to the electron, the electron can directly move to the exited state 2 only. When

it comes to the exited state 2 and it comes all decay to the lower state then we can have spontaneous emission and radiating 1550 nm wavelength signal [16].

2.2.3 Erbium Ytterbium Doped Amplifier EYDFA for High Power Operation

The Erbium Ytterbium doped fiber laser (EYDFL) gives high efficiency with reduced power fluctuation while maintaining the tuning range. The efficiency of the EYDFL system easily exceeds 300% higher and the power fluctuation was reduced up to 43.8% as compared to the EDFL. Cladding-pumping configuration is a popular choice for high-power operation, and so-called "erbium/ytterbium co-doped" fiber amplifier [17] is often used. In this scheme, ytterbium (Yb) is co-doped as a sensitizer to increase the absorption, as the absorption becomes much smaller in cladding-pumping configuration due to poor overlap between the core and pump. The operation principle of an Er/Yb co-doped fiber is shown in Figure 2.3. The Er ions are excited by the following two steps: (1) pump photons excite the Yb ions first, and (2) the excited Yb ions transfer the energy to the Er ions, raising them to the Excited state 2 [18].

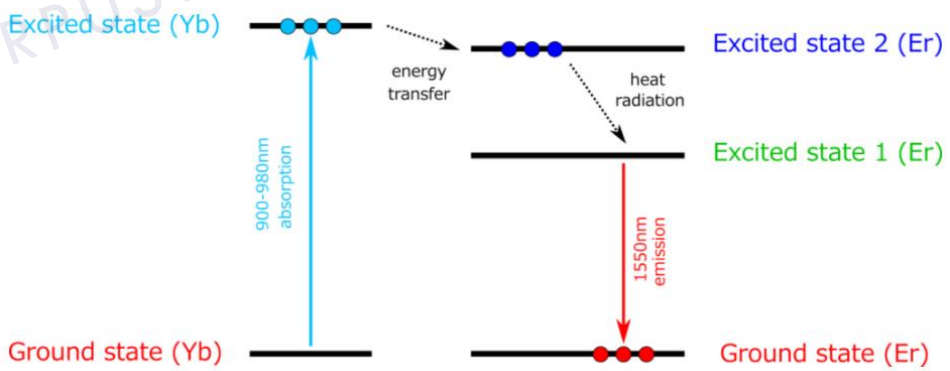

Figure 2.3: Energy diagram of Er/Yb co-doped fiber [18]

2.2.4 Internal configuration

The basic structure of an EDFA is composed of an erbium-doped fiber, a pump laser, an optical isolator and a WDM coupler as depicted in Figure 2.4. The type of EDF fiber used in this study is FSC-EDF-021C-Model P980 and this is where the amplification process takes place. The EDFA is optically pumped and therefore it requires a pump source, which is usually a high-power semiconductor laser diode. The WDM coupler is used to combine the short wavelength pump with the longer wavelength signal. The reason to use a WDM combiner instead of a simple optical coupler is to avoid the combination loss. The optical isolator is used to minimize the impact of optical reflections from the interfaces of optical components [19].

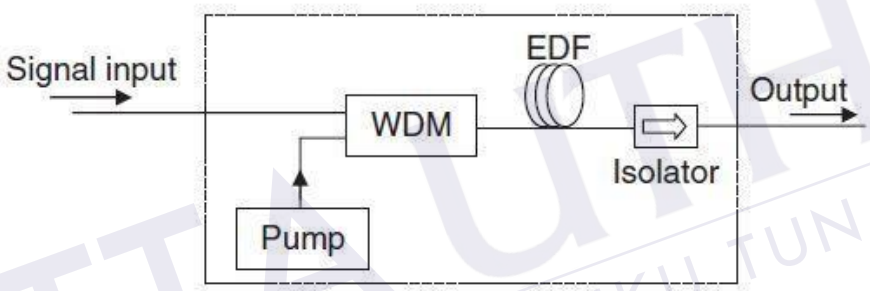

Figure 2.4: Common configuration of EDFA [19]

2.3 Dual-wavelength fiber lasers

Dual wavelength fiber lasers have involved in a huge number of research interest because of their possible applications in optical communication, optical fiber sensors and optical instrument testing. Particularly, dual wavelength erbium ytterbium doped fiber EYDFL which has been considered as a significant source for microwave signal, accomplished by beating the dual wavelengths in a photodiode. Nonetheless, erbium- doped fiber (EYDF) is a homogeneous expanding acquire medium at room temperature, and a long laser cavity is normally included, which leads laser operation instability. To accomplish a stable SLM fiber laser operation, the solid homogeneous expanding and cross-gain saturation of the EDF ought to be eliminated [20]. One of the strategies is to utilize a semiconductor optical amplifier along with a section of EDF as the hybrid gain medium. On the other hand, the polarization hole burning

(PHB) impact existed in the polarization maintaining EDF is utilized to wipe out the mode rivalry [21]. as shown Figure 2.5.

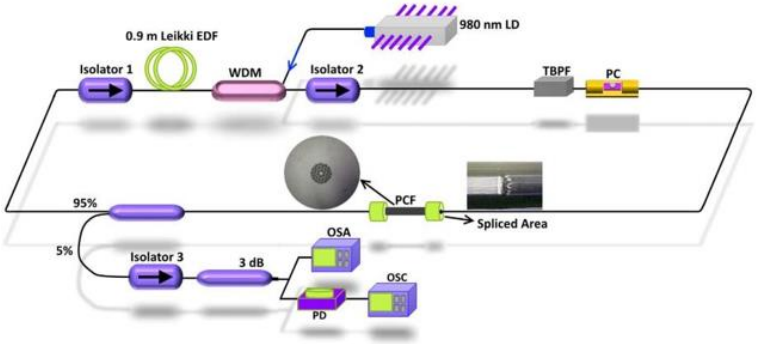

Figure 2.5: Stable dual-wavelength fiber laser [22]

2.4 Fiber Bragg Gratings (FBG) in fiber lasers

shown Figure 2.6. Fiber Bragg Grating (FBG) mirrors in a fiber laser system distributed reflectors fabricated in an optical fiber the advancement of high force fiber lasers has produced another arrangement of applications for fiber Bragg gratings (FBGs), working at power levels that were previously thought inconceivable. On account of a basic fiber laser, the FBGs can be used as the high reflector (HR) and output coupler (OC) to frame the laser cavity [23]. The gain for the laser is given by a length of uncommon earth doped optical fiber, with the most widely recognized structure utilizing Yb ions as the active lasing ions in the silica fiber. These Yb-doped fiber lasers previously worked at the 1 kW CW power level in 2004. Based on free space cavities yet were not appeared to work with fiber Bragg grinding cavities until some other time.

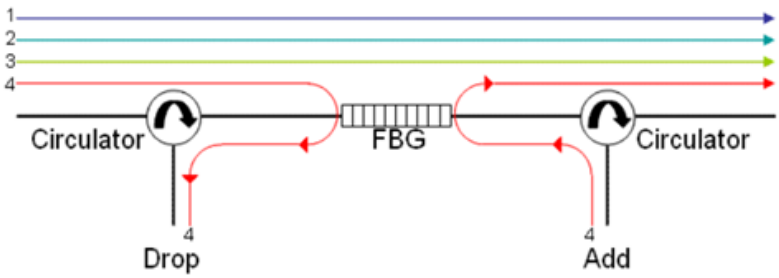

Figure 2.6: Fiber Bragg Grating FBG [23]

2.5 Past Similar Research

2.5.1 Tunable and Switchable Dual-Wavelength Single-Longitudinal-Mode Erbium-Doped Fiber Lasers.

Therese is a two types of erbium-doped fiber laser based on sagnac interferometer incorporated with fiber gratting are proposed in this research. The sagnac interferometer with fiber grating plays the role as a narrowband comp filter, while unpumped EDF together with the tunable FBG essentially forms a passive self-tracking filter to ensure a stable single-longitudinal-mode. The transmission spectrum of the Sagnac interferometer with CFBG controlling the PC in the ring, the dual-wavelength asing at 1560.42 nm and 1560.50 nm, with the pump power of 153 mW, was monitored for 20 min by OSA, at a time interval of 2 min, and the results obtained. The output power is dBm and the SMSR is 40 dB. At room temperature, the wavelength fluctuation is near several picometers and the output power fluctuation is 1 dBm. Such a fluctuation may be partially related with the instability of the pump laser and surrounding temperature. The performance can be further enhanced by use of a careful temperature control.

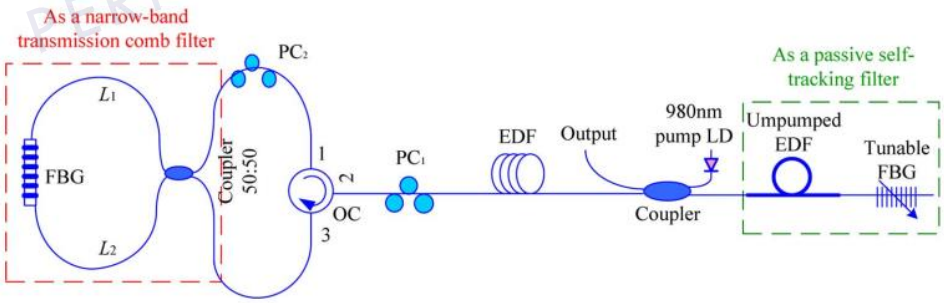

Figure 2.7: Schematic diagram of the proposed tunable and switchable EDFL with a simple linear cavity; FBG: fiber Bragg grating, PC: polarization controller, OC: optical circulator, EDF: erbium-doped fiber [24]

2.5.2 Widely tunable single-/dual-wavelength fiber lasers with ultra-narrow linewidth and high OSNR using high quality passive subring cavity and novel tuning method

As shown in Figure 2.8 a High stability single and dual wavelength compound cavity erbium doped fiber lasers with ultra narrow linewidth, high OSNR and fiber rings as secondary cavities. The pump power is 150 mW, OSA was measured the spectrum with resolution of 0.02 nm. The lasing centered at the wavelength of 1549.464 nm is slightly different with the reflecting center wavelength of UFBG. The 3-dB bandwidth delta wavelength is 0.009 nm which is less than the OSA resolution. The ultra high OSNR of 73 dB indicates the excellent mode selecting capability of the PSC. The repeated of 16 times spectra scans OSA at 2 minutes intervals where the measurement shows stable operation. Along with the increase of pump power the OSA changed OSNR measured at the pump power of 150 mW. During six hours experimental time investigated the stability of the EDFL with an interval of data sampling 20 minutes. The measured wavelength and output power fluctuations are less than 0.015 nm and 0.06 dB respectively, which indicates a very stable operation. [25].

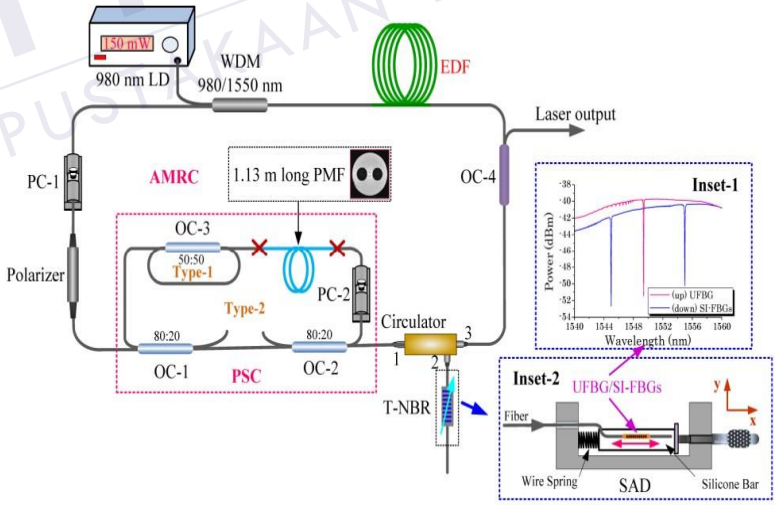

Figure 2.8: Experimental configuration of the proposed EDFL [25]

2.5.3 Swithcable and tunable dual-wavelength single-longitudinal-mode erbium-doped fiber laser with special subring-caity and superimpose fiber Bragg grattings.

The Experimental result shows the dual-wavelength operation of the laser with lasing wavelengths 1543.218 and 1543.553 nm, respectively, corresponding to the two reflection peak wavelengths of the PMFBG. The measured OSNR was greater than 52 dB. The 3 dB bandwidth measured by using an OSA with a wavelength resolution of 0.01 nm is 0.012 nm for both wavelengths. Sixteen times repeated scans at 5-min intervals in nearly one and half an hour. The amplitude variation of the two lasing wavelengths was less than 0.2 dB. The single wavelength operation of the laser. The lasing spectra of 1543.218 and 1543.553 nm wavelength operation, respectively. The 3 dB bandwidth measured by using an OSA with a wavelength resolution of 0.01 nm is 0.012 nm for both wavelengths. The amplitude variation was also measured to be less than 0.2 dB in each single-wavelength operation and the OSNR was for both over 45 dB. In the experiment, no significant drift in wavelength or amplitude variation was discovered under an invariant pump. Note that higher output power, efficiency and OSNR can be achieved by optimizing the reflectivity of the PMFBG and the coupling ratio which provides the output power.

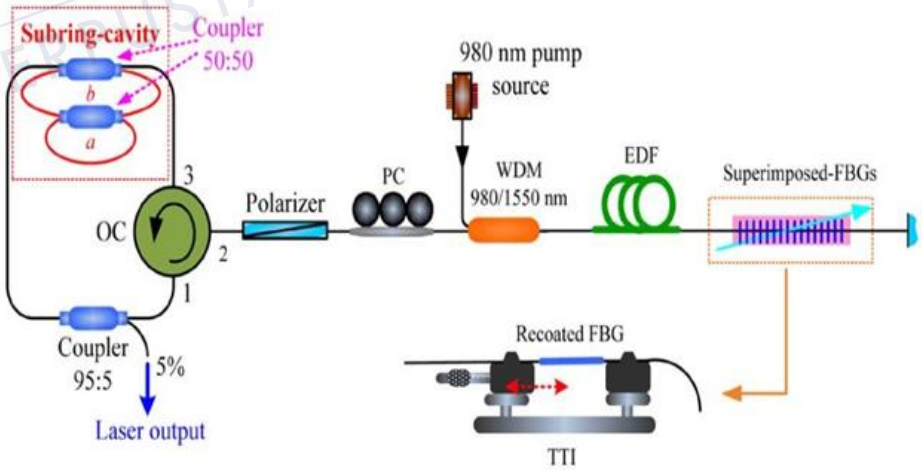

Figure 2.9: The experimental configuration of the proposed dual-wavelength EDFL [26]

2.5.4 Dual-wavelength Thulium Floride Fiber Laser Based on SMF TMSIF-SMF Interferometer as potential source for microwave Generation in 100-GHz Region.

This experiment SMS interferometer using Thulium fluoride fiber laser the laser lines spacing of 8.8 nm. The output spectrum is filtered in the laser cavity using TBPF to get a stable DWFL in the S-band region. By consuming FDTD simulation method, the dual wavelength oscillation is long stablished in 100 GHz frequency. With the use of TBPF, the microwave signal generated can be tuned from 105.678 GHz to 106.524 GHz while the continuous step of 0.15 GHz.

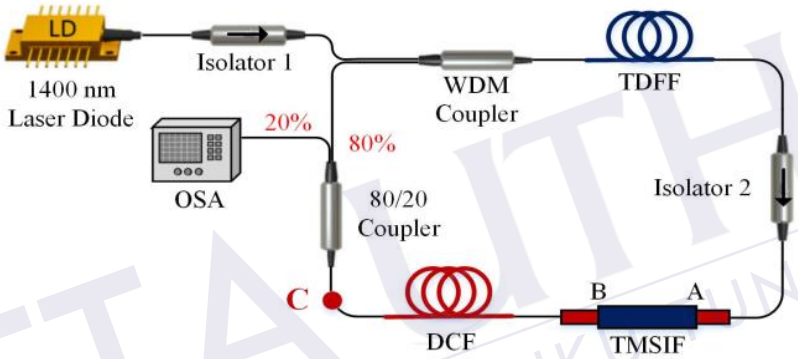

Figure 2.10: Experimental setup of S-band multi-wavelength TDFF laser [27]

2.5.5 Chapter Summary Dual-wavelength Erbium-Doped Fiber Laser with a Simple Linear Cavity and Its Application in Microwave Generation

In A FBG with two ultranarrow transmission bands is incorporated to guarantee SLM operation. As the theoretical analysis predicted, dual-wavelength oscillation can be achieved due to the gain grating formed by the standing wave pattern. The gain grating reduces the gain of the mode that generates it, while making it possible for other modes to reach their thresholds. The laser can be stable for more than half an hour at room temperature (in general, SLM dual-wavelength operation in ring laser can only last for a few seconds at room temperature). By heterodyning the laser output, a microwave signal with a 3-dB linewidth narrower than 20 kHz is generated without any feedback. The proposed laser in this letter has potential applications for

microwave generation, high-resolution spectroscopy, and fiber-optic sensing because of its simple configuration, low cost, as well as SLM operation.

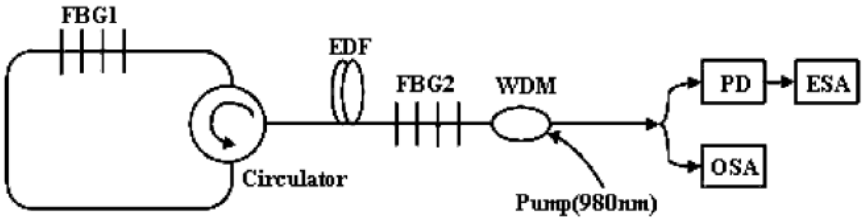

Figure 2.11: Schematic diagram of the dual-wavelength fiber laser.
FBG1: dual-phase-shift grating. FBG2: fiber grating reflector.
PD: photodetector [28]

2.5.6 Dual-wavelength Fiber Laser Sensor System for Measurement of Temperature and Strain

This research the sensor system was reserved under room temperature conditions 22 degree Celsius, and the axial strain was applied to the PM-FBG using an MM. Figure 2.12 shows the output spectrum of the dual wavelength fiber laser with a wavelength separation of 2 nm using a pump power of delta wavelength 0.6 nm 85 mW when no strain was practical applied to the PM-FBG. The denial ratios of the wavelength and the lasing are over 40 dB. When the PM-FBG was stretched, the lasing wavelength separation was decreased due to a reduction of the birefringence of the Hi-Bi fiber, and where the wavelength separation was reduced to 0.266 nm. By further stretching the PM-FBG, a stable lasing wavelength separation of as small as 0.05 nm was obtained.

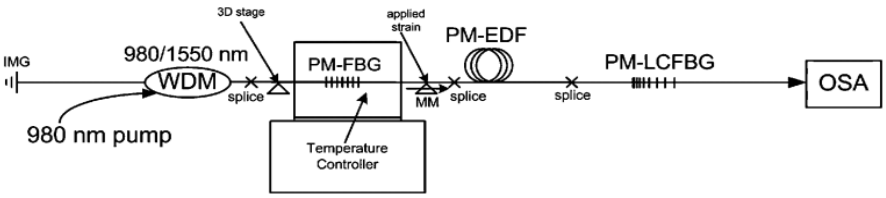

Figure 2.12: Schematic diagram of the dual-wavelength fiber laser sensor system for temperature and strain measurements [29]

2.5.7 All-fiber dual-wavelength Q-swithced and mode-locked EDFL by SMFTHDF-SMF structure as a saturable obsorber

Figure 2,13 shows the dual-wavelength mode-locking operation generated by adding 195 m long SMF in the same cavity. The dual-wavelength Q-switch EDFL generates lasing at 1555.14 nm and 1557.64 nm with FSR of 2.5 nm under 12–100 mW pump power. The repetition rate increases from 14.45 to 78.49 kHz as corresponds to this pump power range, where the pulse duration decreases from 35.84 µs to 6.94 µs. At maximum pump power, the pulse energy is about 32.87 nJ which correspond to the maximum output power of 2.58 mW. Under 166–201 mW pump power, the dual-wavelength mode-locked. EDFL produces lasing at 1530.34 nm and 1532.84 nm with FSR of 2.5 nm. The highest pulse energy is about 1.57 nJ, which corresponds to the maximum output power of 1.57 mW and repetition rate of 1 MHz. The pulse duration is 128 ns with the SNR of 62 Db. Figure 2.13 shows (a) Schematic diagram of dual-wavelength pulsed lasers. Mode-locked operation obtained by adding 195 nm long SMF. (b) SMF-THDF-SMF structure. Insert is an image of the SMF-THDF structure before fusion splicing. (c) Linear absorption profile of 19 cm THDF [30].

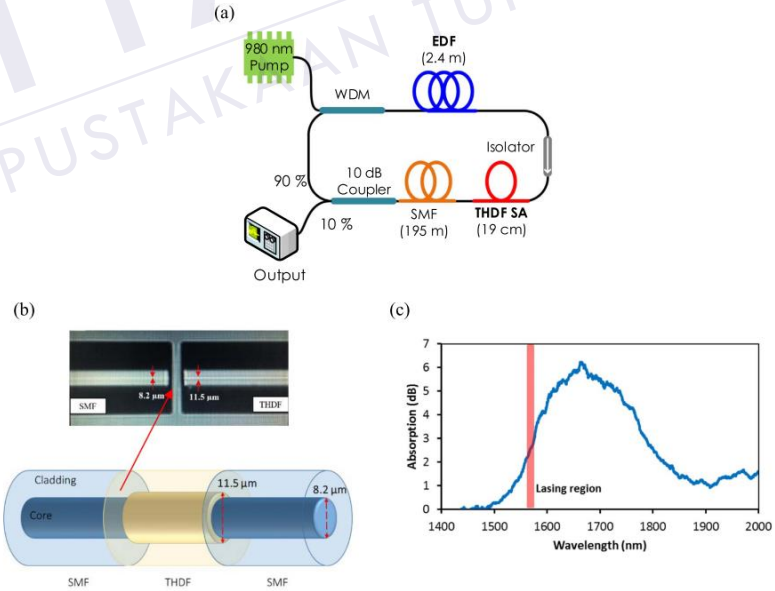

Figure 2.13: (a) Schematic diagram of dual-wavelength pulsed lasers. (b) SMF-THDF-SMF structure (c) Linear absorption profile of 19 cm THDF [30]

2.5.8 Stable and Widely Tunable Single-Longitudinal-Mode Dual-Wavelength Erbium Doped Fiber Laser Fo Optical Beat Frequency Generation

As shown Figure 2.14 there is two FBGs were fabricated by using a photosensitive fiber co-doped with Ge and B effectively controlled, which is resulting from the wavelength shift of two FBGs. When the moving stage moves from the -8 to the +8 mm, the wavelength spacing of the dual-wavelength laser can be continuously tuned in a range from ~13.2 nm to ~3.46 nm, which is corresponding to the CW tunable THz beat signal in a range from 1.66 to 0.43 THz. The output power difference was measured to be less than 0.8 dB in the whole tuning range.

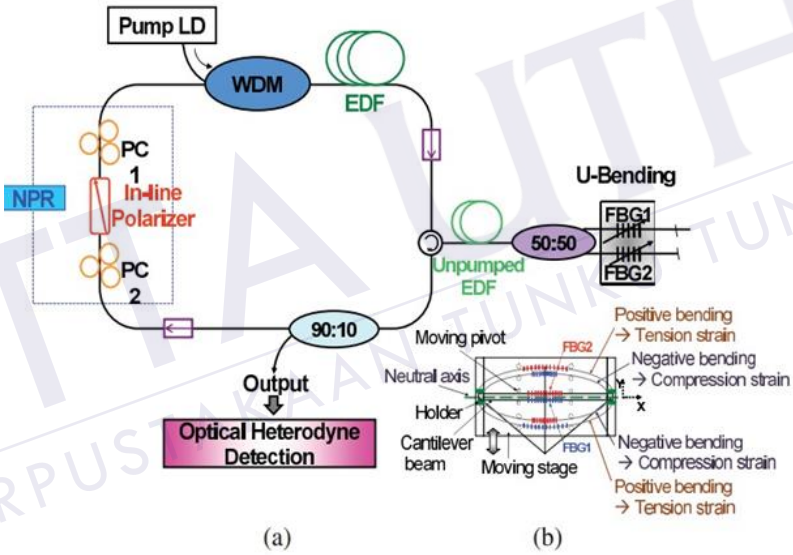

Figure 2.14: (a) Experimental scheme for tunable single-longitudinal-mode dual-wavelength EDF laser. (b) U-bending technique [31]

2.5.9 Photonic generation of microwave signal by beating a dual-wavelength single longitudinal mode erbium0doped fiber ring laser based on the polarization maintaining fiber bragg grating

This experiment was conducted a Single-longitudinal mode dualwelength erbium doped fiber ring laser based on one polarization maintaining enhanced by the

PMFBG, as shown in Figure 2.15 the laser can be designed to operate in stable dual-wavelength oscillation with a wavelength spacting of 0.182 nm at room temperature by adjusting a polarization controller. The dual-wavelength operation of the fiber laser with lasing wavelengths 1543.365 and 1543.547 nm, respectively, corresponding to the two reflection peak wavelengths of the PMFBG. The 3 dB bandwidth of the laser spectrum measured using the OSA with a wavelength resolution of 0.01 nm is 0.012 nm for both wavelengths. The measured optical signal-to-noise ratio was greater than 50 dB. Sixteen times repeated scans of the fiber laser at 5-min intervals in nearly one and half an hour. The amplitude variation of the two lasing wavelengths was less than 0.5 dB, suggesting good stability at the fiber laser output.

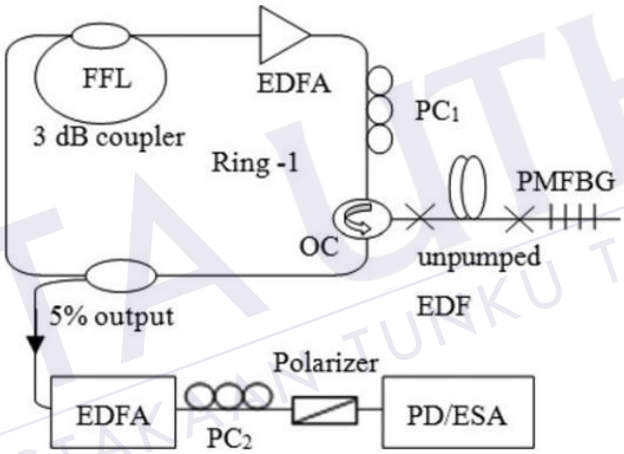

Figure 2.15: Schematic diagram of the proposed fiber laser [32]

2.6 Chapter Summary

This chapter provides the fundamental of theoretical explanation and the description of fiber EYDFL. The basic fundamental of fiber EYDFAs is discussed and it is followed by the explanation of working principles. Based on the previous work, the progress of dual wavelength EDFL with respect to the design structure and performance stability are then described. Eventually, the chapter ends with some reviews on dual wavelength EDFL based on selected research works. In the review section, the output, tuning range and pulse duration weakness of the previous works are discussed.

CHAPTER 3

METHODOLOGY

This chapter covering the detailed execution of the work is illustrated using an operative outline. The development process of this system which includes background theory of the instrument that is used, design process and experiment setup are included.

3.1 Introduction:

The Fiber have found rapid development since their inception in 1961 [33]. and until now, it has become one of the intense research activities due to its contribution in security, medicine, defense, industry and communication systems [34]. They come with many varieties in technologies and among them are Raman fiber laser, fiber optical parametric oscillator, erbium-doped fiber laser(EDFL).

Among these approaches, EDFLs have some interesting characteristics over the others in that they have low threshold, a large number of laser lines and wide tunibility [24]. Cowle and Stepanov demonstrated erbium doped fiber amplifier (EDFA). Since then, Sagnac loop filter, ring cavity, self-seeded design, dual wave mixing and composite cavity and many other techniques have been demonstrated to improve the performances.

This chapter starts off with the research methodology that applies for all the experimental work reported in this thesis. The research methodology basically explains the general guideline on how the research work is carried out from device characterization and experimental setup development to the optimization of laser performances [5]. The next part

of the chapter will then cover the optical components that are used in the experiment of dual-wavelength EDFLs for further understanding of experimental design. The chosen type of optical component is then listed in this chapter and its operating mechanism is explained.

3.2 Project description

The research work starts off with the characterization of optical devices. The optical devices can be categorized into two types; passive and active devices. Examples of passive devices include isolators, circulators, couplers and optical fibers. Among device parameters being characterized are insertion loss, isolation, coupling ratio and bandwidth. On the other hand, the active device utilized in this experimental work is a laser diode. The research methodology is illustrated in Figure 3.1.

The steps are repeated as to improve the achievement of stable EYDFA. The result from OPM and OSA could be presented and discussed thoroughly in chapter 4. Finally, the documentation process where the thesis writing is achieved.

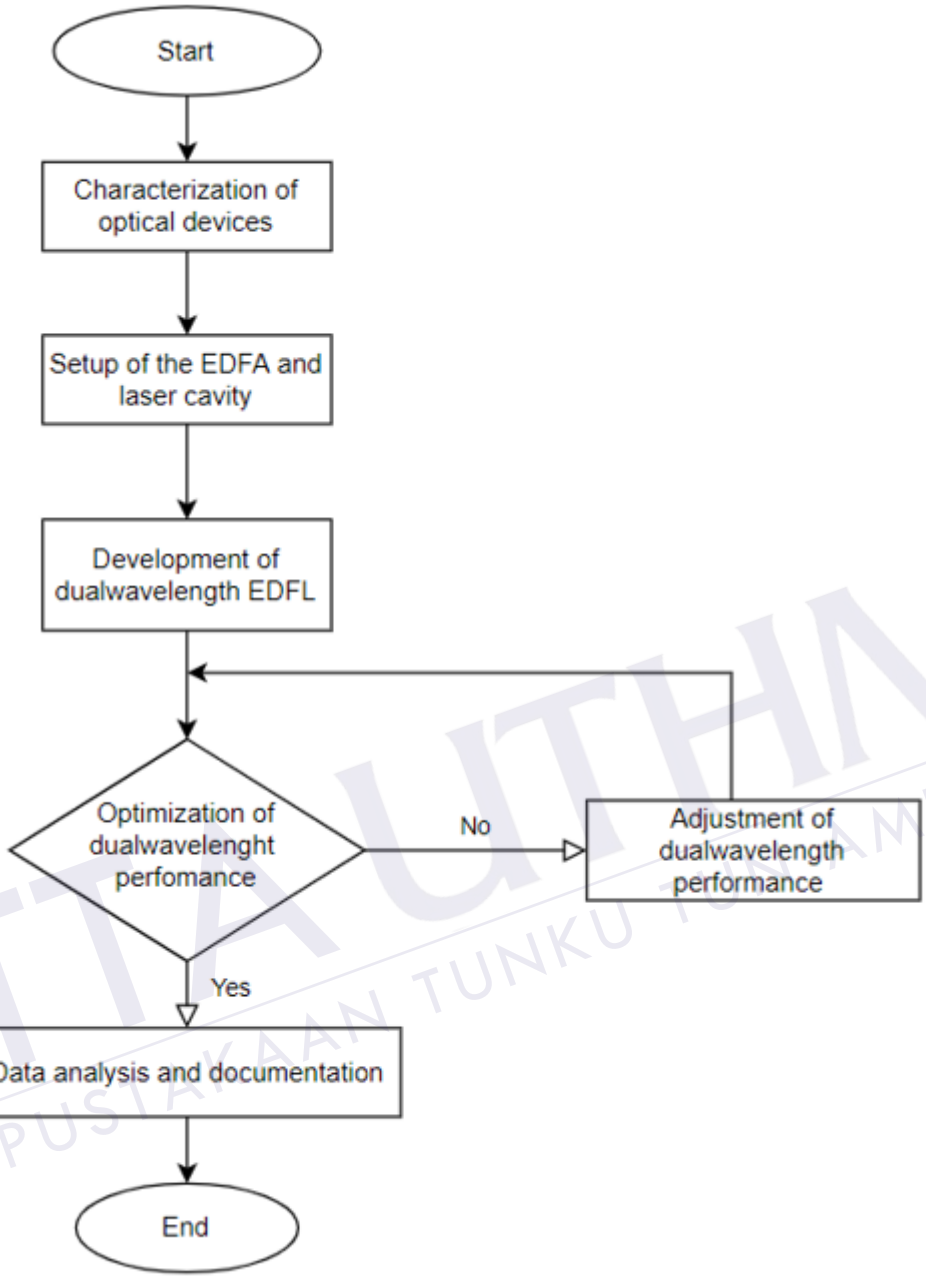

Figure 3. 1 : Flow chart of the project

3.3 Instruments and Measurement Devices

The main function of optical components is to alter the state of light by focusing, filtering, reflecting, or polarizing. In the industry, there are many applications for testing and measurement that uses the integrated optical components such as microscopy [35], imaging [36], and interferometry [37]. Besides, optical component has the capability to optimize the performance of electromagnetic spectrum that includes the designated ultraviolet [38], visible [39], infrared wavelength [40], and wavelength ranges [41], by using specific substrates or anti-reflection. In this work, optical component plays an important role as it takes a majority part of the component in the setup configuration. The optical components used are coupler, laser diode, optical fiber, circulator and isolator and the details for each optical component is discussed.

3.3.1 Optical Coupler

A device that can distribute and combine from one fiber to another fiber known as a coupler. The distribution and combination can be from one fiber to dual fibers or from dual fibers to one fiber. The special ability of the coupler is that most of the input signal is attenuated as it is divided among the output ports. Using the 1 x 2 fiber optic coupler for example, when the input signal enters this type of coupler, the output power of each ports is less than one-half of the input signal. There are many types of coupler such as 50/50 optical coupler, 90/10 optical coupler, WDM optical coupler and the couplers can be characterized either active or passive couplers.

The power distribution of the output light when entering the input fiber is dependent on the wavelength and polarization [42]. However, in this case, there is a physical restriction on the performance of the coupler. It happens when combining the inputs that have the same frequency into one single-polarization output. On the other hand, it is possible to combine the inputs at the different wavelength into one single polarization output, as there are couplers that are wavelength-sensitive such as WDM couplers.

Passive and active coupler is the classification of optical couplers. Passive fiber optic couplers to redistribute the signal without optical to electrical conversion, as they require no

power for operation [43]. Meanwhile, for active fiber optic couplers, they need electrical power to determine the splitting ratio of the optical couplers [44]. In this work, the type of optical couplers used are 90/10 coupler and WDM coupler, which are categorized as passive devices.

Both 50/50 coupler and 90/10 coupler function as light combiner or splitter for the input light. The difference is that the 50/50 coupler split the input light evenly, whereas the 90/10 couplers split the input light into 90% at the one output and the rest of 10% to another output [45]. Both of these optical couplers are bidirectional, which mean the couplers have the ability to combine the input with one side and the splits it on the other side. It does not matter which side as the input since the other side will automatically serves as an output. For example, Figure 3.2, when the input is launched to the port 1 or 4, the port 2 and 3 becomes the output ports and vice versa [45].

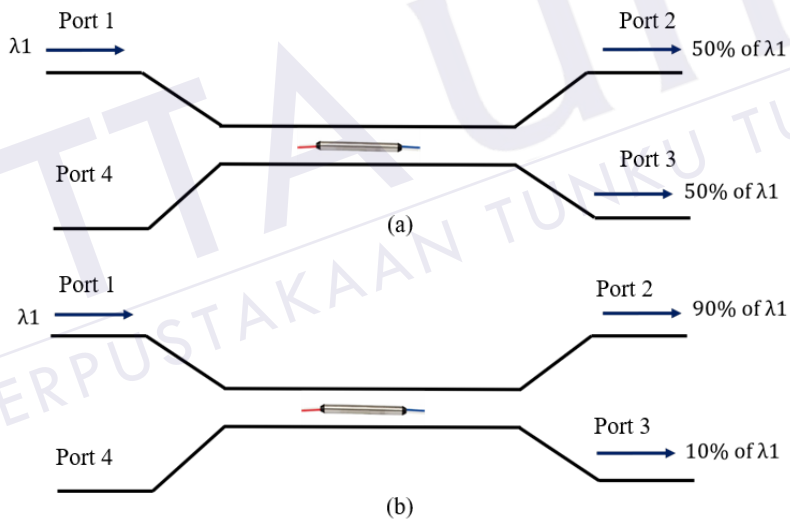

Figure 3. 2: The schematic diagram of the (a) 50/50 and (b) 90/10 coupler [46]

WDM coupler is one of the common coupler that has been widely used in EDFA. WDM coupler can act as a wavelength splitter or combiner as illustrated in Figure 3.3. When two different wavelengths (λ1 and λ2) are injected into the same input port, λ1 and λ2 exits at the different output ports. This the case where the WDM coupler behaves as a wavelength splitter. On the other hand, the WDM coupler behaves as a wavelength combiner when two different

wavelengths are injected into different input ports. In this case, both λ1 and λ2 exit at the same output port. The mechanism how the WDM coupler behaves as the wavelength splitter is shown in Figure 3.4. In the WDM coupler, there exists a coupling region over which the energy is transferred back and forth repeatedly. For the WDM coupler to function as a wavelength splitter, the interaction length of the coupler *L* is chosen such that one wavelength has 100% transmission whereas the other wavelength has 0% transmission. Meanwhile, the mechanism how the WDM coupler behaves as the wavelength combiner is shown in Figure 3.5. For the WDM coupler to function as a wavelength combiner, the interaction length of the coupler *L* is chosen such that both wavelengths have 100% transmission.

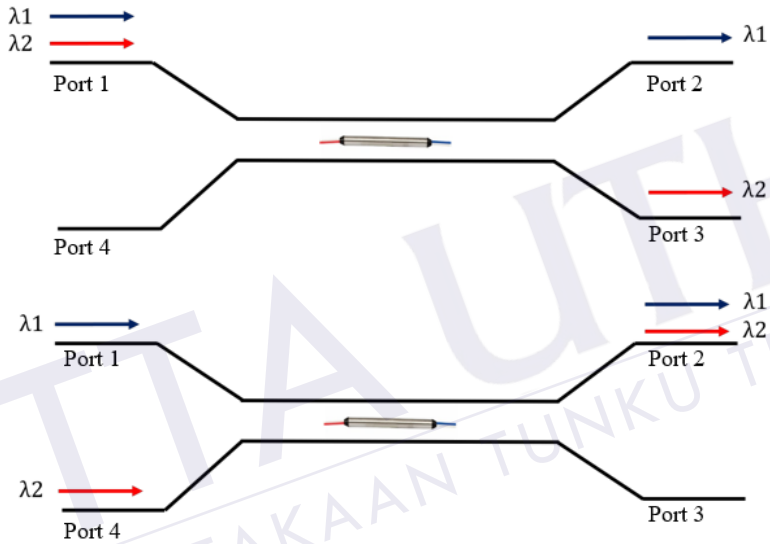

Figure 3.3: The function of WDM coupler as wavelength splitter and combine [46]

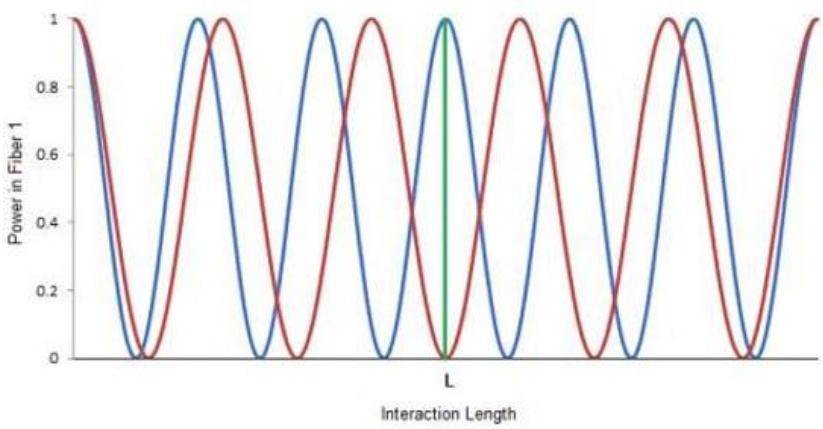

Figure 3.4: Energy transfer in WDM coupler that functions as wavelength splitter [47]

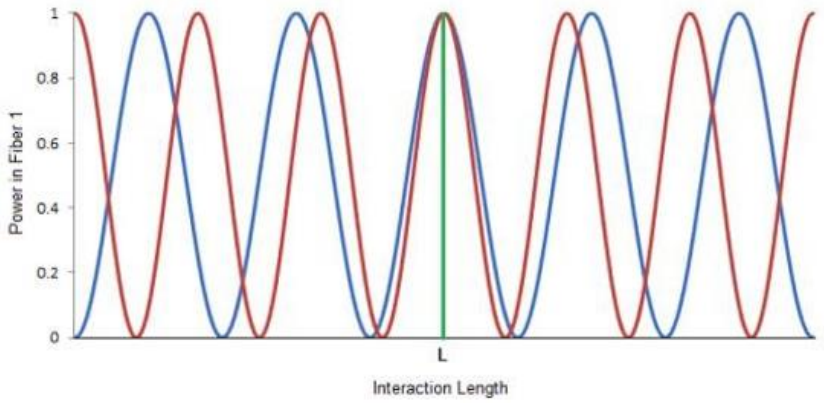

Figure 3.5: Energy transfer in WDM coupler that functions as wavelength combiner [47]

In this research work, the type of coupler used is the Oplink 90/10 coupler and Oplink WDM coupler. The Oplink 90/10 coupler offers high performance and high reliability over wide bandwidth in optical signal coupling and splitting. The accuracy provided by this coupler is very useful in this experimental setup. Moreover, the Oplink WDM coupler allows bi-directional coupling and can be used to either split or combine signals which is efficient to be used in EDFA application. The function of WDM coupler takes place in which 980nm pump and the 1550nm signals are combined before being launched into an erbium-doped fiber (EDF). The advantages of using the Oplink WDM couplers includes wide operating wavelength range, compact in size, low optical loss and environmentally stable which are important to secure good experimental results.

3.3.2 Laser Diode

Laser diodes become highly demanded devices in many applications regarding commercial and industrial use. This is due to the advantages that laser diodes offer such as their optical characteristics, small size, ruggedness and output brightness. Nowadays, a cubic inches small laser diode has the capability to operate under continuous wave (CW) with a power of hundreds of watts. These devices are suitable for cable TV transmission [48], high definition TV development [49], and medical applications [50] due to this special characteristic. In communication system, laser diodes provide an advantage in high-speed data communications as they can be modulated at high frequency. For example, the output of laser

diode can be modulated at high frequencies up to several GHz by modulating the drive current. Laser diodes have two types which are low power laser diodes and high-power laser diodes. Both of them come in different types of packages. Most of the low power laser diodes are integrated with a monitor photodiode and the light emitted by laser diode comes from the end of their cavity as shown in Figure 3.6. In order to maintain the laser at a constant power, the rear facet output beam of the laser needs to be monitored [51]. On the other hand, in high power laser diodes, a high-power focused coherent beam of light is emitted. The coherent beam of light is achieved by tuning the laser diode to the absorption band of the dielectric crystal that increases the pumping efficiency of the laser rod [52]. This beam can be used in a variety of industrial, medical, and military applications.

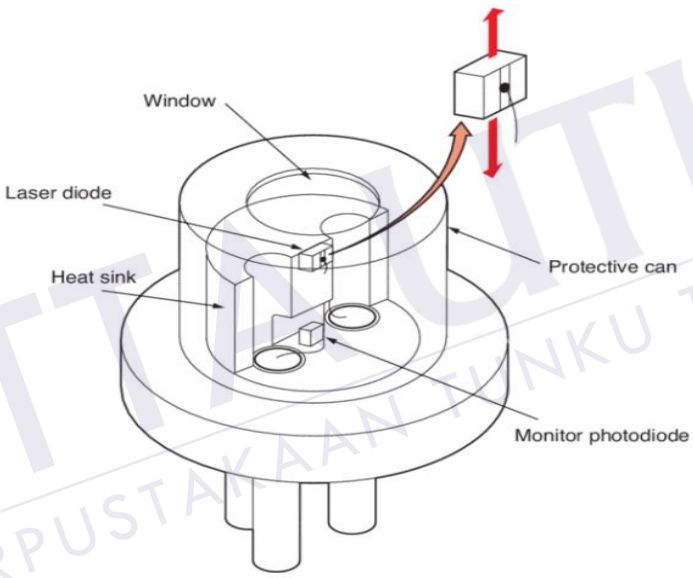

Figure 3.6: The arrangement of low power laser diode: a laser diode with a monitor photodiode [40]

Single frequency laser diode is in the low power laser diode family. It is the device that is very useful for spectroscopy [54] and high bandwidth communications [55] as it has lower threshold currents and required lower power. Figure 3.7 show the distributed feedback (DFB) laser diode as one of the structures and the output light is emitted between 1300 nm and 1550 nm of the optics wavelength. This type of laser diode is suitable to use for sensing and spectroscopy due to the emission of light over a narrow wavelength range.

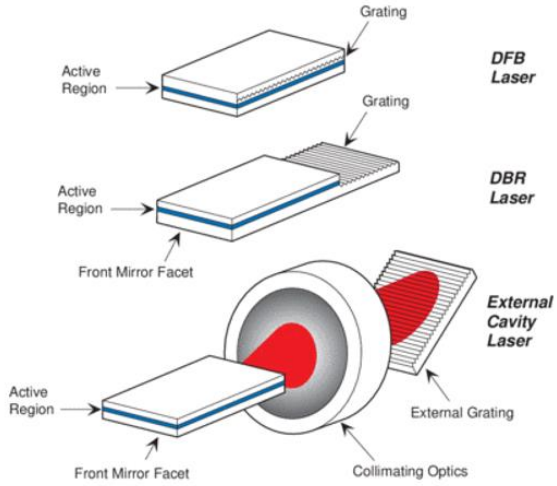

Figure 3.7: A DFB, a distributed Bragg reflector (DBR) and an external grattin device in a single frequency semiconductor laser [26]

The high power laser diodes meet the specific criteria involving the pumping of solid-state laser rods that are needed [52] is used as a pump source at the wavelength of 980 nm. The 1550 nm wavelength signal propagetes a long with the pump power for optical amplification along –haul telecommunication lines. By using this method, the electric-to-light conversion can be avoided by eliminating the electrical amplifying circuits.

3.3.3 Optical Circulator and Isolator

Optical circulator and isolator are both categorized as passive devices. They function as the device that delivers signal with low loss. The optical circulator is a three-port circle device that is needed to ensure the optical signal that enters any port exit another port in a one-way direction. This action is able to eliminate any unintended direction of the optical signal. For example, in a three- port circulator, the input signal launched at the port 1 is transmitted to the port 2, and the signal from the port 2 goes to the port 3 as shown in Figure 3.8. There are many applications that need the use of circulators such as optical amplifier, the optical and drop system [56], the dense wavelength division multiplexing (DWDM) network [57] networks and the optical time domain reflectometers (OTDRs) [58]

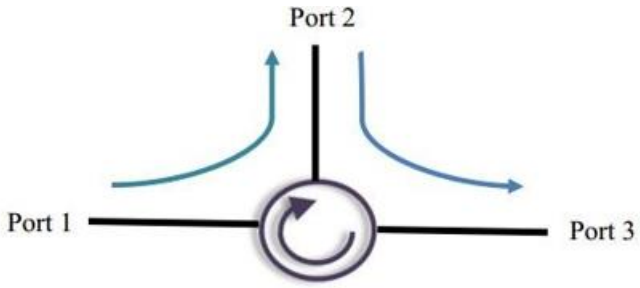

Figure 3.8: The behavior of an optical circulator [56]

Optical isolator has the same function as optic isolator but it has only two ports. It means that there is no reverse direction of the propagating light an isolator can transmit light wave with a low attenuation in one direction but it suffers much attenuation if light goes in the reverse direction. Many applications utilize optical isolator such as optical amplifier [59], integral component laser diode [60], in-line component laser diode multipath reflection in high-bit rate [61] and analog transmission [62]. Based on Figure 3.9, the polarizers and Faraday rotators are the main working principle in the optical isolator.

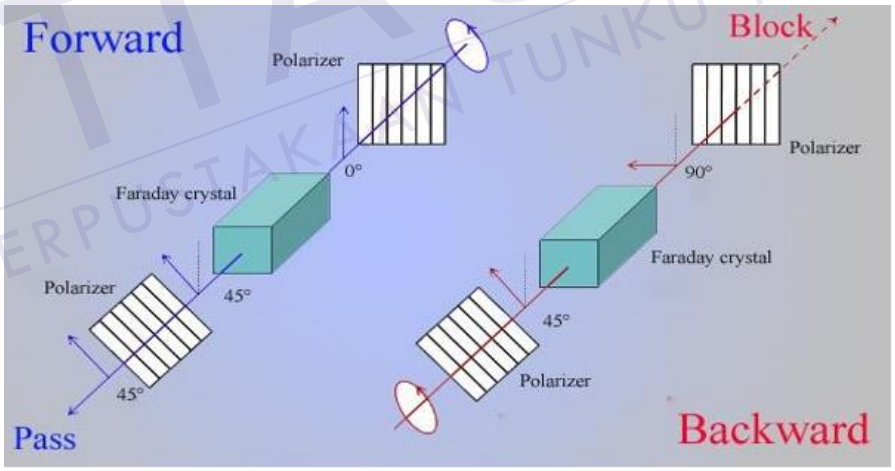

Figure 3.9: The working principle of optical isolator [63]

3.3.4 Erbium Doped Fiber Amplifier (EDFA)

This EDFA is utilized to generate C-band ASE source. It consists of an essentially of an extraordinary earth doped fiber, which is generally quartz glass fiber. This EDFA is injected with a laser of relevant wavelength. Consequently, a population inversion and optical benefit can be completed inside the EDFA.

EDFA offer amplification of in-line signal with non-electronics excessive electrical intensity transfer capability from the pump to power signal and the amplification is not relying on of data rate. For the used on long distance, EDFA can be cascaded and the gain is relatively uniform. At the drawback, the system is massive. Similarly, there's gain saturation and also existence of ASE. Figure 3.10 shows the picture of the EDFA, an ASE-UPM-C100 which was invented by UPM [64]. This broadband source is used is because it produces a wide bandwidth of wavelength compare to a laser source deliver a narrow bandwidth of wavelength.

Figure 3. 10: Erbium Doped Fiber Amplifier (EDFA) [64]

Table 3.1: Specification Erbium Doped Fiber Amplifier (EDFA)

Name	**Specification**
Fiber Type	Erbium Doped
Mode Field Diameter (MFD)	3.8 – 4.7 @ 1550nm
Numerical Aperture (NA)	≥ 0.30
Core Index	Call

Cladding Index	Call
Cut-Off	900 – 102nm
Attenuation	≤100dB/km @488nm
Cladding Diameter	80±1µm
Coating Diameter	160±10µm
Length	2m

3.4 Optical Power Meter (OPM)

The OPM is an apparatus that applied to compute the power in an optical signal. It is normally referred to a tool for check common power in fiber-optic systems. As shown in figure 3.11. OPM-100 optical power meter [65] is a chargeable portable power meter with a huge power measurement scale. The OPM-100 series power is used rechargeable Lithium-ion battery and operate with its low electrical power consumption. The OPM-100 is design with a strong frame structure that is best for outdoor as well as laboratory utilizes.

Figure 3.11: Optical Power Meter OPM-100 [65]

3.5 Optical Spectrum Analyser (OSA)

The AQ6370B Telecom Optical Spectrum Analyzer 600nm - 1700nm uses a latest of high-performance technology in order to achieve high wavelength resolution [66], which is 0.02nm and broad focused dynamic level of 70dB. OSA is used in the measurement of the

wavelength moves due to the modification in the strain. The record take from OSA is tabled in .xls format. Figure 3.12 suggests the image of OSA.

Figure 3.12: Optical Spectrum Analyser AQ6370B [66]

3.6 Operation Principles

Absorption happens when lower state energy atoms absorb radiation and transit to the upper energy excited state level. Then, at the exited state, the atoms spontaneously emit electromagnetic radiation and de-excite themselves back to the lower state. This process is called spontaneous emission. On the other hand, stimulated emission is a process where the incoming wave forces the excited atoms to go down to the lower level. Figure 3.13. illustrate the processes of absorption, spontaneous and stimulated emission.

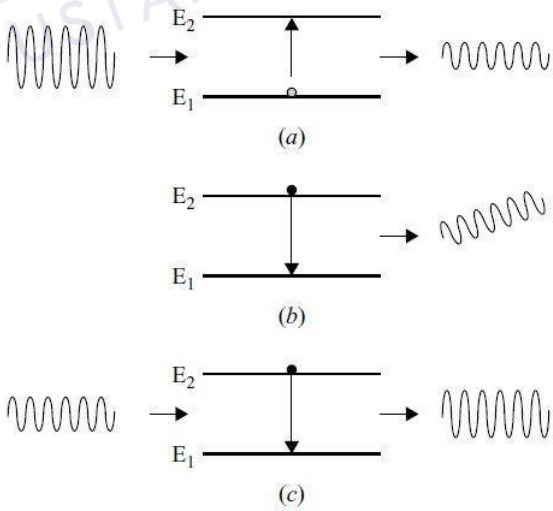

Figure 3.13: Three different emissions at a certain energy level (a) absorption, (b) spontaneous emission, (c) stimulated emission [67]

The energy level of erbium ions located with silica is illustrated in Figure 3.14. Light from the laser diode at 980 nm excites the erbium ions from the lower state to the upper state. Afterwards, the erbium ions fall down from E3 to E2 and non- radiative emission is released. The lifetime of energy level E2 is 12 ms, so the erbium ions stay at E2 for a longer time. With the longer time, population inversion can be achieved as the number of population at E2 is higher than that at E1. The 1550 nm signal photons then trigger stimulated emission in the gain medium, thus the 1550 nm signal gets amplified as a result of the coherent emission of the stimulated emission process.

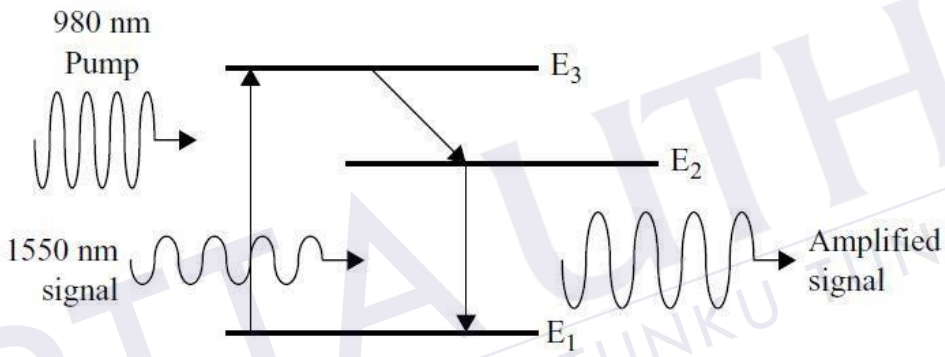

Figure 3.14: The energy bands of an erbium ion in silica matrix [67]

Table 3.2: Comparison of features of the reading equipment

Interrogator / Features	OSA AQ6370	OPM-100
Cost	RM100k-200k	~RM300
Size	Very large & Bulky	Small
Weight	Very heavy	Light
Battery operable	No	Yes
Wavelength Range	600 - 1700nm	800~1600nm

3.7 Experimental Setup

3.7.1 Erbium Doped Fiber Amplifier (EDFA)

The experimental setup of the proposed dual wavelength EYDFL configuration is shown in Figure 3.15. An Erbium-doped fiber amplifier or also known as EDFA is responsible to provide the gain medium for laser cavity as well as to act as the optical amplifier. Before characterizing the EDFA output, the setup of the EYDFA needs to be developed. The EDFA is developed through the combination of WDM coupler, 10 m of Erbium doped fiber EDF. The laser diode LD of 980 nm is pumped to the EDF through WDM coupler, it will cause the erbium ion in the EYDF to get dual wavelength spectra output power. Figure 3.16 shows the two power inputs and an output of the experiment. Polarization controller PC, in polarizer line, an un-pumped EDF a securable absorber, fiber Bragg gratting FBG with center wavelength, an optical circulator, a 90/10 coupler output. An amplifier is placed after the polarization controller PC to amplify an optical signal directly, without losses in the cavity. The propagating light isolator can transmit light wave with low attenuation in one direction however, it suffers much attenuation if light goes in the reverse direction. By improving the quality of the components mainly the thermal effect, the oscillation laser stability can be improved. By setting the pump power at 240 mW, by placing the tunable TBPF, tunable dual wavelength laser can be secure. The light source injected at port 2 of an optical circulator after that through the FBG and transmitted (1539.4 nm). A tuned bandpass filter (1542.3 nm) is back-reflected at port 3 which both transmitted and reflected is measured using OSA.

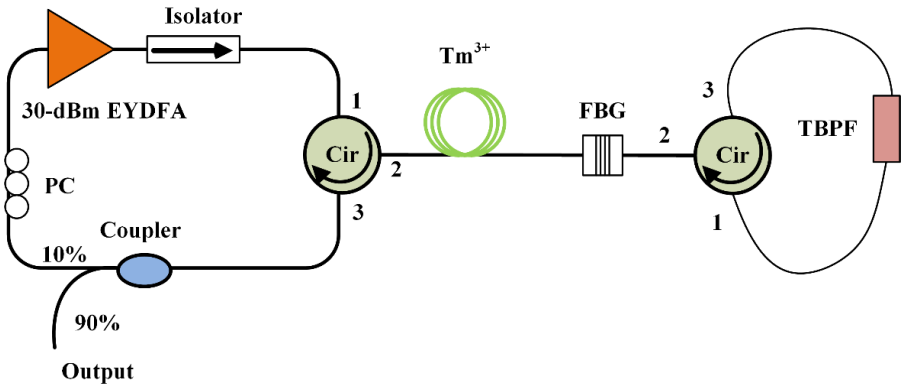

Figure 3.15: Experiment setup of dual wavelength EYDFL configuration

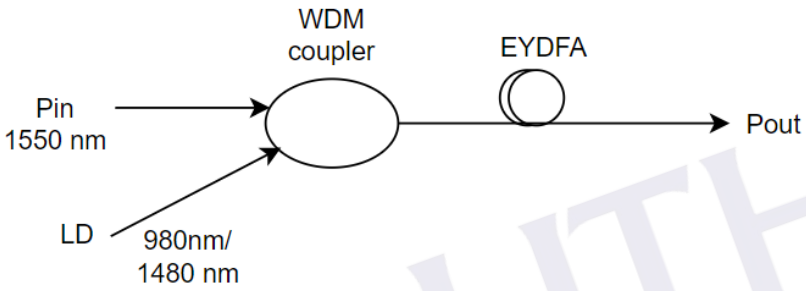

Figure 3.16: Experimental Input and output

CHAPTER 4

RESULTS AND DISCUSSIONS

On this chapter, the experimental results are recorded using OSA and OPM. The outcome achieved is plotted graph in the Microsoft Excel software with a purpose to be analyzed and discussed in this chapter. The testing and measurement of dual wavelength of fiber laser were performed at Optoelectronic Laboratory, FKEE UTHM.

4.1 Introduction

This chapter will discuss further the output of the experiment of dual wavelength EDFL with tunable bandpass filter TBPF. Several of experimental procedures are conducted in order to ensure that it would realize the standards and the validity of the results. The discussion starts off with some result explanation of the experimental setup for dual wavelength EYDFL with TBPF. The investigations of the dual wavelength performance including self-lasing cavity modes, the number of channels, threshold power, tunability and stability of the outputs are explained for each setup and the theoretical explanations are considered afterwards. After thorough discussion regarding the experimental results, the chapter will end with the summary of all experimental works.

4.2 Experimental Result

The Characterization of EYDFA the laser output power increases from 0 to 1000 mW is then investigated as shown Figure 4.1. The output power is measured with an optical power meter, replacing the OSA point in the schematic. The EYDFA voltage increases from 0 to 3000 In the starting of the experimental stage, EDFAs has an inter base of voltage, when the voltage is

increased gradually, the output power also increases. The recorded EYDFA output power for the 1000 mW. The output power is measured with an optical power meter, replacing the OSA point in the schematic. Nevertheless, when the pump power exceeds the threshold power, stimulated emission dominates over spontaneous emission, thus triggering signal oscillation in the laser cavity. Consequently, more EDF power is needed for amplification, thus resulting in high threshold power to have flat wavelength wavelength. The first lasing is occurred at 1535 nm. The explanation for the high EYDFA contributes more power to the oscillating.

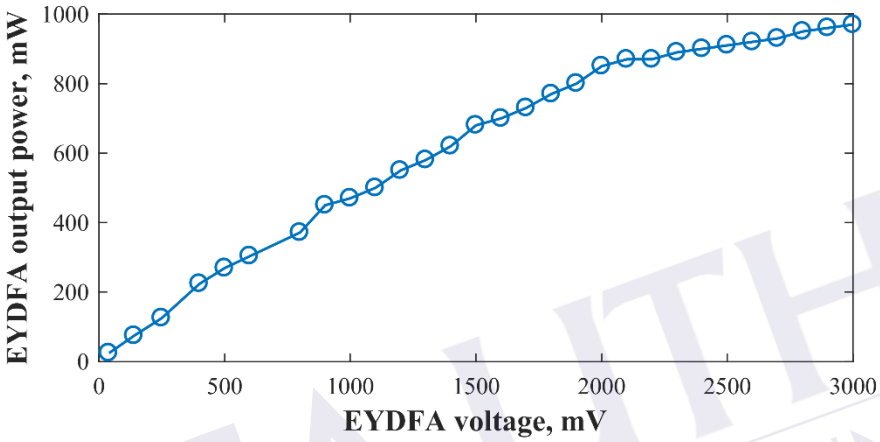

Figure 4.1: EYDFA characterization

4.3 Effect of EYDFA output power on dual wavelength lasing

The behavior of the laser output power as the EDF pump power increases from 0 to 1000 mW is then investigated as shown in Figure 4.2. In this observation, the output powers are set at 1 W, whereas the wavelength is fixed at 1550 nm. The output power is measured by using an optical power meter. Based on Figure 4.2, it is noticeable that there is little output power before the onset of the threshold power. The laser from 24.5 mW to 304 mW has less enough power then laser between 900 mW to 1000 mW. This is due to the spontaneous emission dominating the laser cavity. However, once the stimulated emission dictates the spontaneous emission, the output power increases exponentially. Another important thing to note from Figure 4.2 is that the EYDFA voltage increases from 0 to 3000 In the starting of the experimental stage, EDFAs has an inter base of voltage, when the voltage is increased gradually, the output power also increases. The laser wavelengths between24.5 nm and 900

nm are not flat and requires enough power to reach stable. The wavelengths between 930 nm and 1000 nm, are stable and they have enough power.

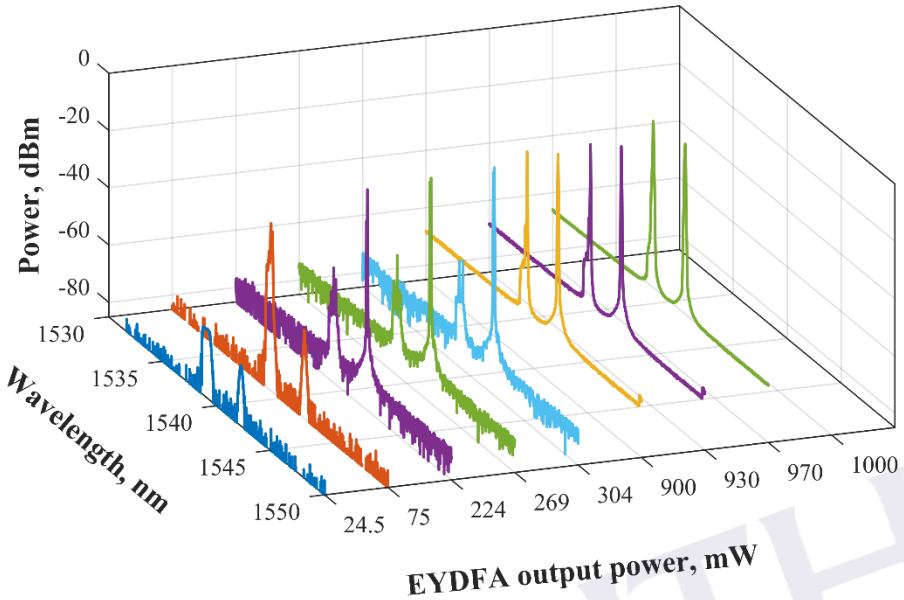

Figure 4.2: dual wavelength spectra at different EYDFA output power

4.4 EYDFA output power

OSNR is 60dB for both wavelengths. Based on the same principle of wavelength-tuning in dual-wavelength operation, the EDFL had the same wide wavelength-tunable range of 3nm in dual-wavelength operation as marked in Figure 4.3. As long time experimental results indicated, the laser outputs also had high stabilities in both wavelength and power in the dual-wavelength operation. The linewidths of the laser outputs in dual-wavelength operation at λ1 (1539.4 nm) and λ2 (1542.3nm) were measured are almost the same. The EYDF output power spectra is 1 w with a constant spacing of 3 nm. The higher the SNR the better.

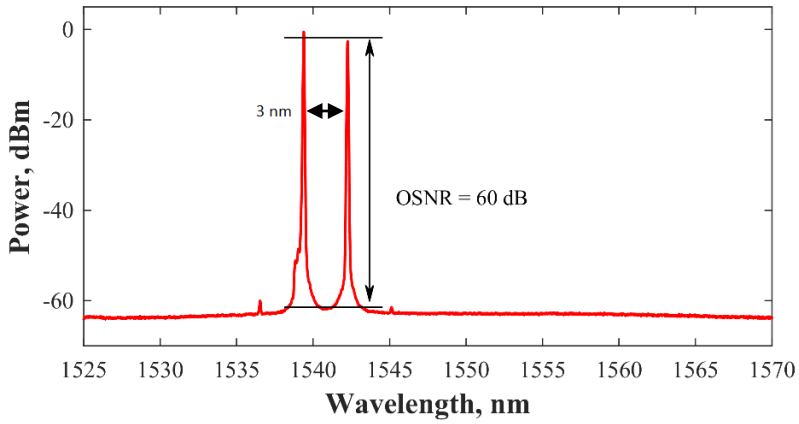

Figure 4.3: dual wavelength spectra at 1 W EYDFA output power

4.5 Tuning range performance

The tunibility performance of the EYDFA is investigated. The first lasing happens where 1539.4 nm at the pump power of 1 w, where 1539.4 nm closes to peak of the gain range, the other laser line increase when the pump power increases. 8 lasing line oscillation are twisted at the power of 1 w from 1539.4 nm to 15555.5 nm with the continuous interval space of 3 nm. The dual wavelength can be attuned to parallel strength. The TBPF is shifted from 1520 nm to 1570 nm with a constant spacing of 3 nm to reach a dual wavelength laser that are cantered wavelength at 1535, 1538, 1541, 1544, 1547, 1550, 1553 and 1556 nm respectively, as shown in Figure 4.4. The function of thulium here is to stabilize, they distribute energy from higher power to the lower power, the wavelength 1535 nm has low power and 1538 nm is high power, after the thulium they both have almost the same. The FBG spectrum transmit has two wavelengths 1535 nm and 1538 nm, the BandPass filter was initially tuned at 1538 nm at the central wavelength. The FBG and transmitted (1539.4 nm). A tuned bandpass filter (1542.3 nm) is back-reflected at port 3 which both transmitted and reflected is measured using OSA.

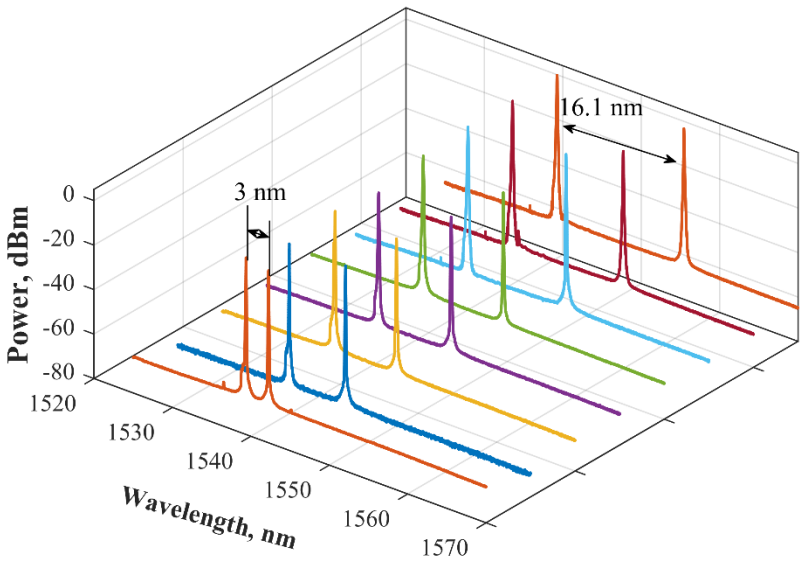

Figure 4.4: tuning rang performance of the dual wavelength EYDFL at EYDFA output power of 1 W

As shown Figure 4.5. The output power at different wavelengths is one of the investigations of this work. The least power at the peak of -28.2 dBm which is located at the wavelength 1535 nm, and the maximum power is 18.2 dBm achieved at the wavelength of 1538 nm. The FBG is cantered at 1539.4 nm and EYDFA output power is fixed at 1 W. The TBPF wavelength is tuned from 1542.3 to 1555.5 nm using optical power meter to measure laser power in order to study the tunibility of the dual wavelength EDFL. The 20 mW pump power at the wavelength of 1542.3 nm is close to the top emission of the TBPF gain range. The laser line increases when the pump power increase at the highest power of 240 mW.

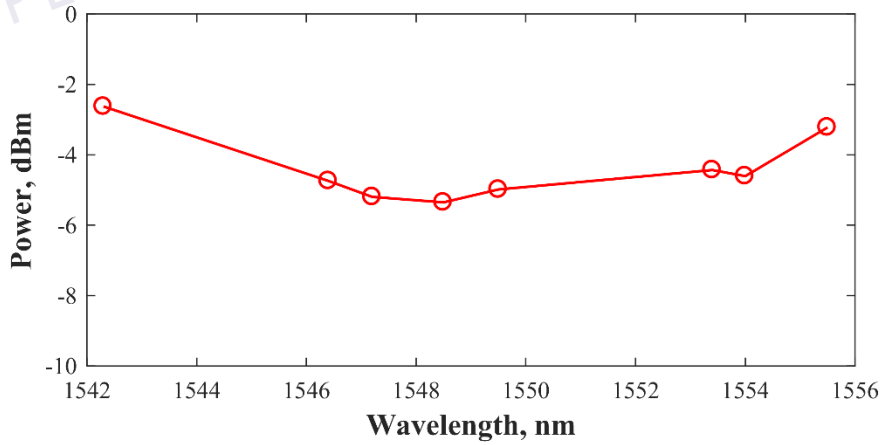

Figure 4.5: The output power at different wavelengths

4.6 1-Stability Measurements

The stability of proposed dual wavelength EDFL is then investigated. Figure 4.6 shows the output of 1-Stability measurement at 1539.4 nm and 1542.3 nm. EYDFA output power is fixed at 1 W. The stability by monitoring the fluctuation in 12 minutes within an interval of five minutes, the power is 60 dBm. The output spectra are plotted for a 12 minutes-duration with step 2 minute. In this observation, the EDF pump power is set at 1 w, while the bandpass wavelength centered 1542.3 nm.

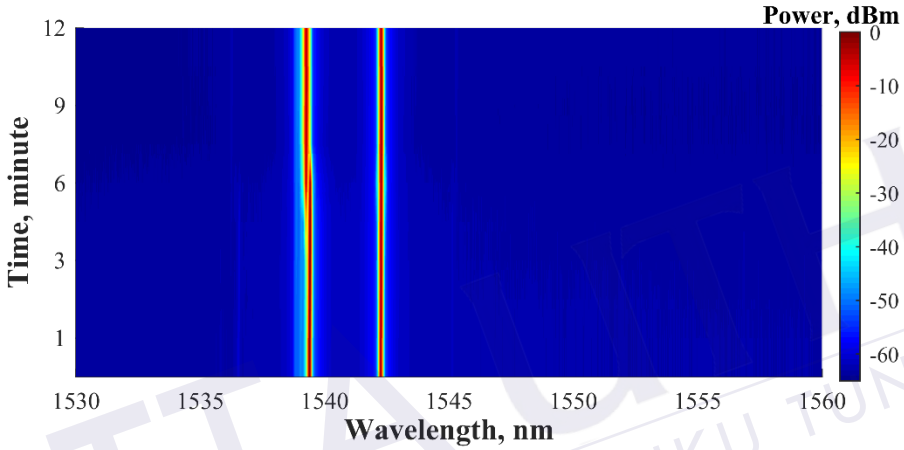

Figure 4.6: Stability measurement

The measurement of 1-Stability at 1539.4 nm and 1542.3 nm: EYDFA output power is fixed at 1 W. the stability by monitoring the fluctuation in 10 minutes within an interval of five minutes. The pump power edge of 20 mW where 1549.73 nm is closer to the peak emission of the TBPF gain range. When we tune at tunable band pass filter the laser line become almost the same at the maximum power of 240 mW as shown Figure 4.9 and Figure 4.10.

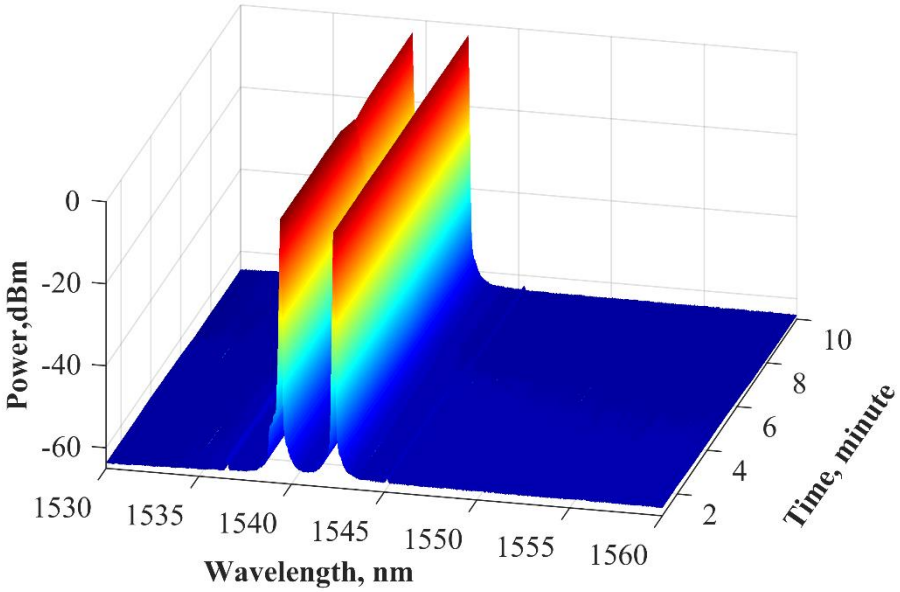

Figure 4.7: Stability measurement

4.7 1-Stability Variation Measurements

The EDFL stability is additional examined by monitoring in 30 minutes' time running with the interval of five minutes. To avoid dismissal similar characteristics, the dual wave length fiber laser results at 1539.4 nm and 1542.3 nm are showed in Figure 4.8. through the monitoring of 27 minutes the two wavelengths have no significant drifting and power fluctuation. The experimental wavelength drifting is less than 0.1 nm, while the power variation is less than 2 dB. The OSNR is then 60 dB. 8 times repeated the OSA measured OSNR changes along with the pump power increase. In order to have a closer look on the laser stability, the peak power fluctuation for each channel at the power of 4.6 dBm is plotted in Figure 4.8. The higher order Stokes signals have more significant fluctuations. The lowest and highest peak powers recorded are 1.90 dB and 2.87 dB correspondingly. The peak power variation of less than 3.00 dB shows that the dual wavelength EDFL.

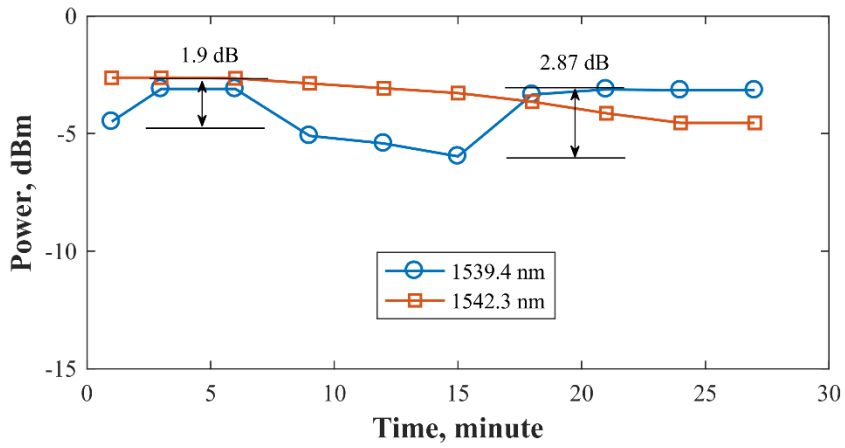

Figure 4.8: Stability measurement

4.8 2-Stability Measurements

The measurement of 2-Stability Erbium doped fiber laser, the FBG is centered at the wavelength of 1539.4 nm, while the TBPF wavelength is centered at the wavelength of 1549.73 nm: EYDFA output power is fixed at 1 W. the stability by monitoring the fluctuation in 27 minutes within an interval of five minutes. The 20 Mw pump power of 1549.73 nm is nearer to the top emission of the Tunable Band Pass Filter gain range. As shown Figure 4.9 and Figure 4.10 the lasing line increased as the power increase. The maximum pump power is 240 Mw. By adjusting in terms of intensity the tunable bandpass filter TBPF passes through the centered wavelength of 1549.73 nm the FBG reflected back the wavelength of 1542.3 nm as shown Figure 4.94.

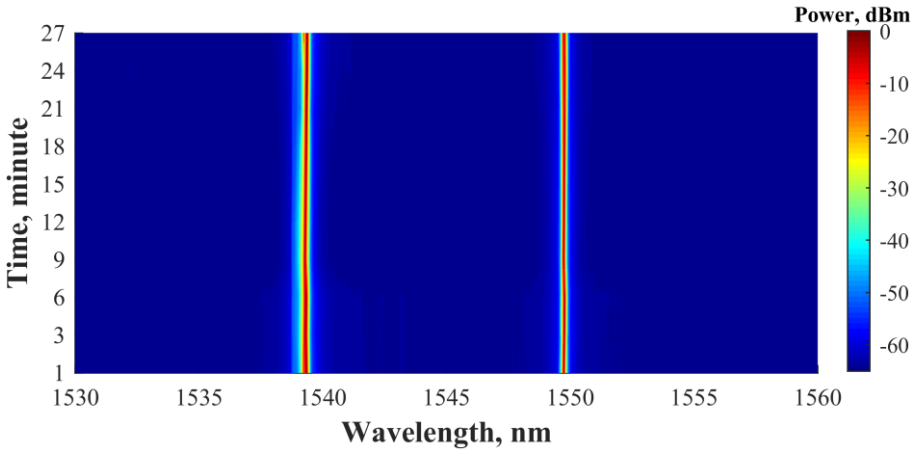

Figure 4.9: Stability measurement

The wavelengths of 2-Stability measurement at 1539.4 nm and 1549.73 nm with EYDFA output power is fixed at 1 W. By monitoring the fluctuation in 27 minutes within an interval of five minutes, the power is 60 dBm. The output spectra planned for 27 minutes, the interval minutes are 2 minutes' time. The EYDFA pump power is set at 1, the TBPF is centered at the wavelength 1549.73 nm the FBG reflected back the at the wavelength of 1542.3 nm while the rest passes through to the TBPF. The exited Erbium ions generated a stable wavelength after the TBPF.

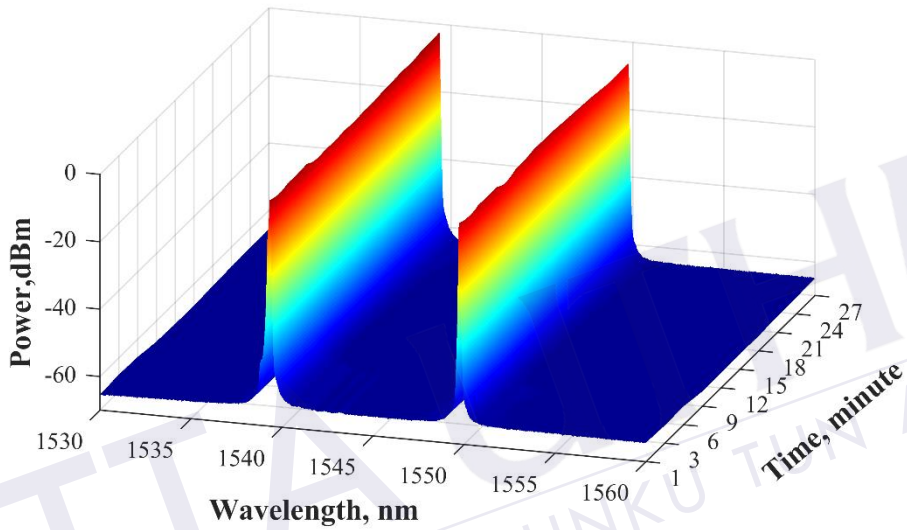

Figure 4.10: Stability measurement

4.9 2-Stability Variation Measurements

As shown Figure 4.11. The measurement of dual wavelength stability running for 30 minutes' period at the spacing interval of 5 minutes. Through the wavelengths 1539.4 nm and 1549.73 nm both wavelength lasing shows no drifting after monitoring 27 minutes' center wavelengths' fluctuations wavelengths are both less than 2.5 dB, the EYDFL shows a good stability there are almost no observable fluctuations in both output spectrum and it suggesting that the output spectra are stable thulium. Based on the plotted peak power fluctuation for each channel, the minimum variation is 2.3 dB, whereas the maximum variation is 2.4 dB. It can be concluded that the peak power fluctuations are not significant as their variation is less than 2.5 dB.

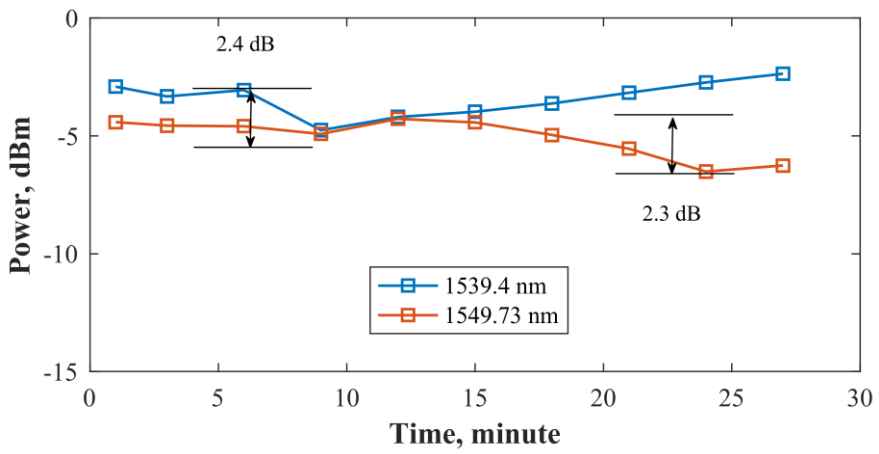

Figure4.11: Stability measurement

This chapter all the result work and outcomes are proposed. The experimental shown a new interrogation setup was achieved, the dual wavelength peak is stable, both lasing wavelengths FBG and TBPF are almost the same while tuning one using TBPF. The minimum variation is 1.9 dB while the maximum is 2.87 dB. The EYDFL can be observed by using OSA and OPM.

Chapter 5

CONCLUSION AND RECOMMENDATIONS

This chapter gives a summary to all the research that has been achieved. In essence, the early objectives for this project are well achieved.

5.1. Conclusion

The motivation of this thesis is the generation of Dual-wavelength erbium-doped fiber laser (EDFL). The generated output is then observed and recorded using the OSA. Based on the collected data, all the characteristics of the out spectra are investigated and analyzed. The data afterwards is analyzed and the reasoning behind the behavior is provided by physic-based explanation. Finally, all the results are concluded in this chapter.

The conclusion of this thesis is in accordance with the two sub-objectives stated in the first chapter. The first objective is to design a Dual-wavelength erbium-doped fiber laser (EDFL) by conducting experiment at the lab.

The second achieved objective is to compare the performances of the Dual-wavelength EDFL. and to compare the performance of Dual-wavelength EDFL in terms of tunibility, threshold power, number of channels and stability measurement. Consequently, the location of the EDFA is adjusted. All of these schemes are shown in Chapter 4. For, FBG centered wavelength and TBPF tunibility, Nevertheless, there are certain parameters in which other schemes have better performance. The performance parameters being compared are Tuning rang performance of the dual wavelength EDF at EYDFA, laser threshold power, tunability, the number of channel stability and OSNR wide tuning range. All of these performance parameters are stated in chapter 4 for Dual-wavelength stability and tuning range performance. A great improvement of laser output quality was achieved, especially for the linewidth and OSNR. The Dual-wavelength fiber laser was achieved to stabilize TBPF after

thulium, and 8 laser lines with a constant spacing of 3 nm are achieved. The dual wavelength output spectrum is further filtered in the laser cavity using a tunable bandpass filter to achieve stable dual-wavelength lasing. the linewidth for both wavelengths were less than 1kHz

Finally, the main objectives of this mission are dual wavelength fiber laser using EYDFA was proposed and experimentally demonstrated. The dual wavelength performs nicely and stable. The signal to noise ratio OSNR as high as 60 dB which is good, the output power fluctuation achieved both 1-stability and 2-stability measurements to get properly results of stable dual wavelength. The wavelength peak in the output spectrum changed from 1539.4 nm to 1555.5 nm and the constant spacing of 3 nm, this result changed into acquired stable dual wavelength laser.

For the conclusion of experiment, the sensitivity of dual wavelength EYDFL monitor by using tuning the laser. The tunable band pass filter TBPF tuned from 1542.3 to 1555.5 nm and the FBG centered at the wavelength of 1539.4 nm while it could be concluded that the experiment sucessfull. As stated in the objective, the motive of doing this project is to obtain a dual wavelength fiber laser EYDFA, which can be monitored via OSA and OPM. In general, dual wavelength EYDFA is successfully analyzed and established.

5.2. Recommendation and Future work

For future work, several experimental designs can contribute to further improvement of research work. It could be interesting to see whether the laser performances can be improved as they have unique characteristics. This could be achieved by enough power to reach the laser wavelength stable and flat. For example, when the EYDFA voltage increase gradually the output power also increases as explained in chapter 4. Another way to improve the performance is to study the effect by polarization, usually we change the polarization and see the power effect. therefore, it is interesting to see if other fiber stability will improve the laser performances.

Another recommendation is the realization of a simpler setup which can be implemented by using fewer optical devices. For instance, the isolator that acts as a mirror can be removed by changing the existing experimental setup configuration from the closer peak emission of the TBPF gain spectrum. Introducing such feature could produce the laser oscillation in the cavity without the function of the mirror.

Another way for improvement is to use different gain medium in the laser cavity such as Raman amplifier, parametric amplifier and semiconductor optical amplifier. These