THE DEVELOPMENT OF SWITCHABLE THULIUM DOPED FIBER LASER IN 2-MICRONMETER WAVELENGTH REGION

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**FACULTY OF SCIENCE
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ABSTRACT

Thulium doped fiber (TDF) laser is widely known for its ability to broaden its spectrum emission until 2.0 µm by with the range of wavelength between 1800 until 2100 nm which is almost into the infrared region. Laser diodes with the maximum power of 220 mW emission at the wavelength of 1550 nm will be used to provide the input power to the TDF with forward pumping configuration. A single pass and double pass configurations of TDF amplifier were implemented. In this study, the input test signal used are in the form of high signal (close to saturation) and low signal which are 0 dBm and -20 dBm respectively. The double pass configuration was able to give a high gain with low noise figure with the value of 28 dB and 3.48 dB respectively. Thus, it makes the efficiency of the amplifier from double pass amplification higher than the single pass configuration with the difference of 7.83%. The TDF laser has simply come from a closed laser cavity configuration with a laser diode at the wavelength of 1550 nm as the pump. The TDF laser was emitted at the wavelength of 1961 nm with a narrow 3-dB bandwidth of approximately 0.04 nm. A switchable TDF laser was proposed by employing an arrayed waveguide grating (AWG) as the wavelength selective mechanism. The emitted laser that can be tuned within the range of 17.27 nm in the region of 2 µm. The interval spacing between the adjacent channels is approximately 100 GHz where every laser emission at the selected wavelength is able to produce an acceptable SMSR value, which is within 58.75 dB and narrow band of 3-dB bandwidth with approximately of 0.06 nm. The research output can be used in many applications such as in telecommunication system, medical appliances and remote sensing.

ABSTRAK

Laser gentian berdop tulium (TDF) terkenal dengan keupayaan untuk melepaskan spektrum yang meluas sehingga 2.0 μm dengan julat panjang gelombang antara 1800 hingga 2100 nm yang hampir ke rantau inframerah. Diod laser dengan kuasa pelepasan maksimum 220 mW pada panjang gelombang 1550 nm akan digunakan untuk memberikan kuasa pengepaman kepada TDF dengan konfigurasi pam hadapan. Konfigurasi tunggal dan berganda penguat TDF telah dilaksanakan. Dalam kajian ini, isyarat ujian input yang digunakan adalah dalam bentuk isyarat yang tinggi (hampir tepu) dan isyarat rendah iaitu masing-masing 0 dBm dan -20 dBm. Konfigurasi berganda dapat memberi kenaikan yang tinggi dengan angka hingar yang rendah dengan nilai masing-masing 28 dB dan 3.48 dB. Oleh itu, ia membuatkan kecekapan penguat dari penguatan berganda lebih tinggi daripada konfigurasi tunggal dengan perbezaan 7.83%. TDF laser telah datang dari yang tertutup konfigurasi laser rongga dengan diod laser pada panjang gelombang 1550 nm sebagai pam. The TDF laser telah dipancarkan pada panjang gelombang 1961 nm dengan jalur lebar-3 dB yang sempit kira-kira 0.04 nm. TDF laser boleh suis telah dicadangkan dengan menggunakan satu pandu gelombang parutan (AWG) sebagai panjang gelombang mekanisme selektif. Laser dipancarkan yang boleh ditala dalam julat 17.27 nm di rantau 2 μm. Jarak selang antara saluran bersebelahan adalah kira-kira 100 GHz di mana setiap pelepasan laser pada panjang gelombang yang dipilih mampu menghasilkan nilai SMSR yang boleh diterima iaitu dalam lingkungan 58.75 dB dan jalur lebar-3 dB yang sempit dengan kira-kira 0.06 nm. Hasil penyelidikan boleh digunakan dalam pelbagai aplikasi seperti dalam sistem telekomunikasi, peralatan perubatan dan penderiaan jauh.

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LIST OF SYMBOLS AND ABBREVIATIONS

ASE	:	Amplified spontaneous emission
AWG	:	Arrayed waveguide grating
DWDM	:	Dense wavelength division multiplexing
EDF	:	Erbium doped fiber
FBG	:	Fiber Bragg grating
FPF	:	Fabry Perot Etalon filter/ Fabry Perot filter
FPR	:	Free propagation region
LIDAR	:	Light detection and ranging
MZI		Mach-Zehnder interferometer
NF	:	Noise figure
OC	:	Optical circulator
OCS	:	Optical channel selector
OPM	:	Optical power meter
OSA	:	Optical spectrum analyzer
SMF	:	Single mode fiber
SMSR	:	Side-mode suppression ratio
TDF	:	Thulium doped fiber
TLS	:	Tunable laser source
WDM	:	Wavelength division multiplexing

CHAPTER 1: INTRODUCTION

1.1 History of Optical Fiber Laser in Telecommunications / Optical Communications

Telecommunication comes from a two combined France's word. The 'tele' gives a meaning at a distance, whereas 'communication' bring a meaning to share. Simply, these telecommunications mean an activity of information delivery over a certain distance by the electromagnetic wave (Huurdeman, 2003). While, in optical fiber communication, the information transfer is achieved by using a light as the main information messenger (Agrawal, 2002).

The history of communication had started earlier than 150 BC, where; human used the smoke signal for the communication in a certain distance. Then the technology of telecommunications grew until the production of Chappe's telegraphs by a well-known French engineer, Claude Chappe in 1790s (Abd.Latif, 2013). The production of the telegraph had triggered other scientist and engineer to make a better technology in the telecommunication system. The first basic electrical signal transmission started in 1838 with the invention of electrical telegraph. The device had been installed successfully on the Great Western Railway over 13 km. In 1865, Abraham G. Bell produced a telephone (cable telephone) after spending 50 years of his lives. Due to the invention of the telegraph, people could send the first 'email', where, it can be sent via special codes before the codes change to word on a piece of paper. Prior to the invention of these devices for the public use, they were already used in the army. The code Morse was the pioneer in telecommunication where the code is widely used by military and sailors. This code is sent via a light signal. The sailor uses this Morse in sailing as the communication ways between the ship and the lighthouse. So, we can say that, the telecommunication had been employed since 18th century

(Huurdeman, 2003). In 1880, Alexander Graham Bell had invented a Photophone. The Photophone allows the transmission of communication in a beam of light and act the first Li Fi in the telecommunication industry (Abd.Latif, 2013; Flood, 1976). But, this device is not so practical since it is easy to be disturbed by clouds, fog, rain and snow. The first idea in total internal reflection of light is aroused in 1840 by Daniel Colladen and Jacques Baabinet. Then, in 1920s, John Baird and Clarence Hansell demonstrated the light guided by transparent rod for facsimile systems (Hecht, 1999).

1.2 History of 2 μm fiber laser

The rapid growth of optical fiber laser technology with the emission wavelength ranging from 800 nm until the 2 μm had become the major interest to many researchers. The improvement of fiber laser from an optical fiber with semiconductor dopant until the fiber laser with rare-earth dopant is very fast especially in telecommunication industries. Due to higher interest in emission at longer wavelength, laser operating at 2 μm was invented in 1965 by using bulk Tm-YAG pumped by laser diodes. This 2 μm laser was invented by Johnson et al (1963). However, in order to operate properly, the laser temperature should be kept very low, which is around -196 ^{o}C. It took several years to develop laser in 2 μm region that work properly in room temperature. In 1975, a research on pulsed laser by using Cr,Tm:YAG was successful in producing a laser which worked at room temperature. Since then, the development of laser in the 2 μm region has not shown any significant finding until 1990's where pulsed laser in 2 μm is invented by using Thulium doped silica fiber (Nelson et al., 1995; Sharp et al., 1996). Moreover, in recent years the research on of the 2 μm fiber laser for optical communication system has become the interest of various groups due to the predicted congestion faced by existing communication region 1.5 μm region (Li et al., 2012).

1.3 Application of 2 μm fiber laser

Fiber optics are widely known for its flexibility and high resistance in any condition. The application of fiber optics in any range of wavelength bandwidths keeps growing in many industries, especially in telecommunication , remote sensing and also in medical surgery (Scholle et al., 2010). For instance, the 1.0 μm optic laser bandwidth is popular in its ability to contain a huge sum of energy in the short wavelength and making the 1.0 μm laser suitable as a laser cutter (Suni et al., 1989). Meanwhile, 1.55 μm laser is very suitable in the telecommunication as the gain achieved in 1.55 μm wavelength is higher compared to the other wavelength band since the light were able to propagate through the silicon in optimum velocity (Castillo-Guzman et al., 2010) in that region. In addition to this, the 1.55 μm laser also can be adopted as the light source in the optical sensor system such as in LIDAR, and remote sensing (Geng et al., 2009). In 2 μm regions, there are some applications in this wavelength range such as in medicine, free space optical communication and remote sensing (Heidt et al., 2010.).

In medical field, 2 μm laser is widely known for the 'eye-safe' laser. Lasers in 2 μm regions have high absorption in water, thus when the laser injects into the eyes, its energy will then disperse after passing through the lens and absorbed into the liquid in vitreous humor before arriving onto the retina. Only a small volume of energy arrive on the retina will make the eye less damaged (Chiodini et al., 2014; Eguchi & Sato, 2005). High absorption in liquid also makes the laser having advantageous mostly during surgery as the laser will make the healthy cell to be undamaged and reduce bleeding during laser cutting by coagulation (Pal et al, 2013).

These optical sensors paired with 2 μm light source used in remote sensing and LIDAR system give a more precise calculation as the 2 μm laser has a longer range compared to the laser with a shorter wavelength (Scholle et al., 2010). Besides, high absorption in water also allows the 2 μm laser acts as the sensor in measuring the wind velocity. This will then allow it to provide high accuracy in measuring the water vapor in the air and the concentration of the carbon dioxide (CO_2). Moreover, the 'eye-safe' laser wavelength also give benefit in the production of Lidar, where the eye-safety is important in this field (A. Pal, 2013; B. Pal, 2010).

Tunable laser also widely used in the spectrometry. The narrow band of optical bandwidth with an ability to switch the wavelength enables the light to be used in spectroscopy. This can be done, for example, in two-beam spectrometers, where the light from the source is split into two beams. Only one beam (the sample beam), but not the reference beam, is sent through the medium under investigation, and the powers or intensities of both beams are measured. Particularly high sensitivities can be obtained with balanced photodetectors, where one directly measures the difference of photocurrents from the two beams. The theory of the absorption and emission of the light with high frequency resolution is used in making the spectroscopy.

1.4 Objectives

The study focuses on the diode pumped thulium doped fiber (TDF) laser operating in the 2 μm wavelength region, which is still in the early stage of research as compared to the other wavelength band such as in 1.0 μm or 1.55μm. In order to obtain an excellent TDF laser at 2 μm wavelength region, the correlation between the theoretical data and previous study will be highlighted. The main objectives of this research are:

- To determine the operation and performance of thulium doped fiber amplifier, which will be an important component in the fiber laser system.
- To characterize experimentally the operation and performance of single wavelength thulium doped fiber laser
- To design, develop and characterize a switchable thulium doped fiber laser operating at 2 μm region.

1.5 Scope of Research

In order to study and investigate the amplification process, a single pass and double pass configuration TDF amplifier were designed. A range of wavelength within the optimal operation region (1800 to 2000 nm) of the amplifier were tested for the amplification of both 0 and -20 dBm, which respectively represents the saturation signal and low input of the amplifier. This study will be able to show the absorption and emission performance of the TDF with 2 m long in the 2 μm region before the work to design and produce fiber laser with the same gain medium could proceed.

The investigation of the TDF absorption is followed by the characterization of a single wavelength TDF laser. This work is carried out by constructing a TDF laser in a ring configuration. The characterization of the TDF laser is performed experimentally by taking into account the spectrum of laser emission which emit at a certain wavelength with the highest efficiency.

In order to design and develop a switchable TDF laser with 19 different wavelengths, an arrayed waveguide grating (AWG) is employed as the wavelength selecting mechanism. The AWG, which works in 2 μm region, is the only device used to produce a stable laser emission that can be switched to different wavelength. To the best of the author's knowledge, this is the first reported work and results on switchable wavelength thulium doped fiber laser operating in the 2 μm region.

1.6 Thesis Overview

The thesis consists of five chapters. The first chapter focuses on the brief introduction of optical communication and the industrial application of the TDFL. Whereas, the chapter 2 is presents every literature that relates to the thesis. The working principle of the optical fiber will be discussed in detail. The theoretical understanding and physical principle of TDF amplifier and the TDF laser will be explained. In order to understand better the wavelength selective mechanism used in the study; AWG, is also discussed in chapter 2. Even though the AWG is the only a wavelength selective mechanism used, but a brief explanation about the other devices such as Fabry-Perot Filter (FPF) and Mach-Zehnder interferometer that worked in 2 μm region are also presented in chapter 2.

The experimental study of the amplifier for both single and double pass will be further explained in Chapter 3. The TDF amplifier is to study the ability of the TDF to provide an acceptable gain during amplification process. The main criteria of the amplifier are the gain achieved, noise figure and the efficiency of the amplifier. In order to carry out the comparison study of the TDF amplifier with the two different configurations, the study will use both saturated input signal at selected wavelength, 0 dBm and also the small signal input, -20 dBm. Before running the experiment of the TDF amplifier, characterization of the components is performed, so that, the insertion loss and laser emission of the components is within the permissible limits.

Chapter 4 will elaborate on the TDF laser in single ring cavity and its wavelength switching ability. The continuous wave (CW) single laser of TDF is implemented by using a single cavity of forward pumping with laser diode at the wavelength of 1550 nm. Properties such as the performance of the TDF laser emitted will be elaborated. As the characterization of the TDF laser is done, the switch-ability of the TDF laser will be studied by using AWG as the wavelength selective mechanism. Its efficiency and the wavelength region show the good switch ability of the laser. All the results will then be explained in details. Meanwhile, the final chapter will focus as the summary section of the study. It consists of the conclusion of research and also the suggestion for the future study.

CHAPTER 2: LITERATURE REVIEW

In this chapter, the literature review that relates to this work will be presented which includes the description of the existing telecommunication windows and their brief history, the potential of 2 μm band for future telecommunication window. The theory of photon generation in Thulium-doped fiber (TDF) in the 2 μm region, the concept of thulium doped amplifier and laser, and a detail explanation of the wavelength selective mechanism used.

2.1 Telecommunication Window

The optical fiber communication bandwidth can be divided into several bands, as shown in Table 2.1; O-band, E-band, S-band, C-band, L-band, U-band and 2 μm-band (Moulton & Moulton, 2001). The E and U band are not favorable for data transmission because they fall in the region of high transmission loss. The E-band is also known as the water peak region with high OH absorption, while U band resides at the edge of the transmission window of silica glass and this band is mostly used to accommodate the monitoring channels. However, recent researches have been looking into possibility to use the 2 μm region as the new telecommunication window to overcome the capacity limit of the existing band that might be fully utilized due to the exponential increase in the telecommunication traffic.

Table 2.1: Wavelength Bandwidth

Band	Description	Wavelength Range (λ, nm)
O	Original	1260-1350
E	Extended	1360-1460
S	Short wavelength	1460-1530
C	Conventional (Erbium)	1530-1565
L	Long wavelength	1565-1625
U	Ultra-long wavelength	1625-1675
2 µm	2 µm wavelength (Thulium/Holmium)	1700-2100

2.1.1 O and E –band

The first generation of the telecommunication window is in the range of 800 nm was introduced in the late 1970's. The system operating in this band was able to transmit 20 dB/km. During those years, the production of the semiconductor laser GaAs was able to make the system to be compact and reliable for the long distance data transmission. The telecommunication system that had been implanted in the big city of Turin in Italy was able to relay the data with the speed of 140 Mbit/s (Buzzelli et al., 1980; Huurdeman, 2003). Nevertheless, the laser production was at the shortest wavelength region had caused a huge energy loss as the light propagates along the fiber (Suni et al., 1989). Fortunately, the laser in that wavelength have high energy that can be applied in the major industry as a laser cutter or in welding manufacturing processes (Pfeifer et al., 2010).

Second generation of the telecommunication window is the O-band. This band occupies the wavelength ranging from 1270 until 1350 nm. Practically, O-band was introduced in 1980's by using InGaAsP semiconductor laser as it light source (Jain & Lind, 1983). In early 1990s, most of the doped fiber used in the production of laser in the range of 1.3 μm is made up from silicon or fluoride doped fiber of the praseodymium (Ishwar, 1999; Ohishi et al., 2010). The praseodymium doped fiber were able to emit the laser at the wavelength of O-band (original) and E-band (extended), from 1260 – 1360 nm and 1360 – 1460 nm respectively (Idachaba et al., 2014). Thus, making 'the upgraded' bandwidth which is better in low loss power emission and fiber chromatic dispersion compared to previous generation. Since then, optical communication was used globally with transmission data speed up to 1.7 Gb/s. Although the optical bandwidth is able to give a higher data transmission and minimizing of the dispersion broadening, but it is still having a low transmission range due to relatively high loss (Suni et al., 1989).

2.1.2 S- C and L-band

The 1500 nm wavelength bandwidth was introduced in 1990s as the third generation telecommunication window. S-band, C-band and L-band are the wavelength within the range of 1.5 μm. S-band comes with the wavelength ranging from 1460 until 1530 nm, C-band is the term for the wavelength in the region of 1530 until 1565 nm, whereas L-band is in the range of 1565 to 1625 nm. In order to give an emission in the 1.5 μm region, fibers doped with rare earth materials such as erbium, or thulium were used as the gain media (Koherentlab, 2007; Mahran, 2016). Jeremy group had presented a high gain of thulium doped fluoride fiber amplifier which around 20 dB for the generation of telecommunication with used of AlGaAs semiconductor laser (Carter et., 1991). Meanwhile, the erbium had become the first rare earth doped fiber used in telecommunication where it was able to give a good gain which up to 30 dB (Desurvire et al., 1990). As the performance of the erbium doped fiber amplifier less efficient in the L-band, researchers had find solutions such as by implementing of Raman amplifier. The Raman amplifier was capable in giving a maximum gain within 60 – 100 nm greater from the wavelength of the laser signal. Mostly, the laser signal used for the Raman amplifier in the S-band is 1485 nm (Simon, 1987). A research on L-band amplifier for the telecommunication service was been done by Stentz (1998), who was able to give a good data transmittance which around 10Gb/s via Raman amplification.

The erbium doped fiber (EDF) acts as a strong candidate in this wavelength region due to the large gain bandwidth with high efficiency (up to 50%), besides, EDF is easier to handle (less sensitive to any temperature and a stable signal amplification) (Suni et al., 1989). In addition, an ultra-long wavelength, U-band is classified for wavelengths in the range of 1625 until 1675 nm. Although, this U-band has not attracted many researchers as compared to the S, C and L band, but it is still covered in the region of 1.5 μm bandwidths. U-band has shorter bandwidth compared to the S, C and L band, which is only 50 nm and a special management is needed in order to produce signal amplification in the U-band region (Honda et al., 2009).

2.1.3 2 μm band

The 2 μm region occupies the wavelength from 1700 until 2100 nm. The invention of compact laser diode also able to replace the bulk laser, thus, reduces the cost of laser production. The 2 μm laser can be acquired by using Holmium Doped Fiber (HDF) or Thulium Doped Fiber (TDF). However, in this study, TDF is more favorable compared to the HDF because TDF can give an optimum laser emission within the range of 1820 until 2000 nm while the HDF is able to give an optimum laser emission at bandwidth from 1930 until 2400 nm.

Recent studies show some interests in developing light sources emitting in the 2 μm in various configurations to accomplish certain properties that can be utilized in many applications. One of the useful laser features is the ability to tune its wavelength which is important for data transfer in the wavelength division multiplexer (WDM) system and applicable in medical surgery industry (Huang et al., 2015; Pal, 2013; Samion et al., 2016). Some studies proposed tunable features in Thulium-Holmium doped fiber lasers that are able to give a steady emission with high output power (Billat et al., 2014).

In the previous study, the tune-ability of the laser emitting in the region of 2 μm is able to offer wide range of wavelength, approximately up to 250 nm of tuning range (Li., 2013) by utilizing a tunable band-pass filter. Other means to attain the wavelength tune-ability are by incorporating wavelength selective mechanisms such as arrayed waveguide grating (AWG), Mach-Zehnder interferometer or Fabry-Perot filter in the laser cavity

The congestion of data transfer in the telecommunication that runs in 1.55 μm wavelength region had forced the researcher to find solutions to overcome the issues. Emission of the laser operating in the 2 μm region bandwidth gives a potential in the telecommunication industries. Previous research on thulium doped fiber, which runs in longer region give possible results to the mess, where data transmission with achieving 8 Gbs/s and 20 Gbs/s, only give a low loss of window (Petrovich et al., 2012). Li et al (2012) gave a progress in this new optical communication bandwidth, where the researcher able to acquire a high gain that up to 35 dB with low than 6 dB loss within 110 nm bandwidth. It shows that this high efficiency of amplifier which operating in 2 μm wavelength region is the most promising idea for the future optical communication industries.

2.2 Fiber Laser

Fiber laser is a laser with optical fiber as its gain medium. In fiber lasers, most of its gain media are optical fibers doped with rare earth elements such as ytterbium, neodymium, erbium, thulium or holmium depend on the purpose of the study (Duarte, 2008). Fiber lasers have been an option in many of laser productions due to its outstanding heat dissipation capability, good beam quality, compactness, robustness and alignment free (Spiegelberg et al., 2004). These features enable fiber lasers to be better alternatives to the solid state and bulk laser which quite pricey and have bulk size setup (Pillai & Shriver, 1977). However, this study focuses on the single clad doped silica fiber, where, the fiber was doped with a thulium, which has an emission in the 2 μm wavelength regions.

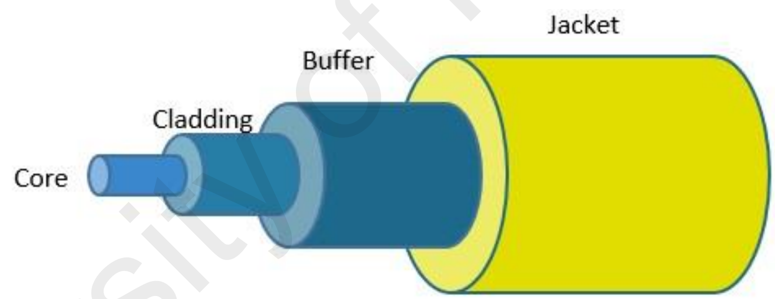


Figure 2.1: Cross section of single clad fiber laser

Single clad fiber as shown in Figure 2.1, consisting single rare earth doped core, cladding from either silica or fluoride, buffer was made up from plastic and outermost part of fiber; jacket, was made up from polyvinyl chloride (PVC) (Eichhorn & Jackson, 2008; Hideur et al., 2001; Traynor et al., 2002). The core of the fiber, has the smallest diameter, which in between of 5 to 9 μm depend on the manufacture products, while, the cladding diameter which made up from silica is in between of 120 to 200 μm of diameter (Pal, 2005). The silica was coated with PVC called buffer to protect the fiber from easily broken or evanescent loss of laser (power loss to surrounding during the study). These buffers will be stripped off when the fiber need to be spliced.

2.3 Single Wavelength

In this section, a single wavelength laser (also known as single frequency laser) will be studied. Single wavelength laser is a laser, which operates on a single resonator mode, thus emits quasi-monochromatic radiation. The emission of laser will have a very narrow line-width and low phase noise. Such line-width laser should be operating in stable frequency in long term without any mode hopping.

In determining the performance of the single wavelength fiber laser, several important criteria or characteristics need to be considered such as average output power, side-mode-suppression ratio (SMSR), tune-ability and stability. A sufficient input power is required to make the population inversion of thulium build up, hence, stimulated emission occurred which emits photon in selected wavelength region as the laser output. A lasing at the certain wavelength in the fiber laser actually is generated from the low signal gain coefficient, which is larger than its loss coefficient. A good performance of the laser output usually is able to attain at least -20 dB of its output peak power, and increase of input power will improve the performance.

In order to evaluate the degree of the output power of fiber lasers, the SMSR value is very crucial. A high value of the SMSR means the laser is giving a good performance. The typical SMSR value for any conventional laser diode is at least 40 dB, which is usually produced by a stable laser. High SMSR will affect the reduction in crosstalk in the WDM networks (act as the transmitters). The SMSR is simply defined as the difference of the main longitudinal mode, intensity with the maximum side mode intensity. By evaluating the power of the output laser mode with the side mode, this SMSR can be determined (Derickson, 1998);

$$SMSR(dB) = 10\log(\frac{I_{main}}{I_{side}})$$

$$= I_{main}(dBm) - I_{side}(dBm) \quad (2.1)$$

A switchable laser is important in allowing the wavelength selection in the fiber laser. This wide range wavelength selection gives many advantages in many industrial applications, especially in the dense wavelength division multiplexer (DWDM) communication system, medical appliances, sensor application (mostly as the LIDAR, temperature and displacement sensors).

In order to make a good fiber laser which switchable in a wide wavelength range, good stability performance of the output power of fiber laser over time must be taken into consideration. The stability test is very essential to ensure the fiber laser systems operating in good condition (without power deterioration) over significant period, and making a minimizing the additional cost operation.

2.4 Photon generation of TDF

Laser can be made up from difference state of matter such as gas, liquid, solid state or semiconductor (Asryan & Luryi, 2003; Hassan et al., 2016; Lagatsky et al., 2013; Liang et al., 2015; Redding et al., 2015; Wang et al., 2014). In early development of laser, most of the researches were focus on the use of the semiconductor material. By ignoring their different origin, all types of lasers share the basic principle in their action. The lasing action mainly can be divided into three key processes; photon absorption, spontaneous emission and stimulated emission. The processes are pictured with a simple two stage energy levels;

ground state and an excitation state. The transition energy during the process can be simply explained by using Plank's law, $h\nu_{12} = E_2 - E_1$.

Absorption process is triggered when the photon of energy collides with the electron at the ground state, E_1, thus resulting the electron to absorb the energy of photon resulting to the excitation of an electron to an excitation level, E_2; Figure 2.2. The electron at meta-stable state will drop to ground state subsequently, without any external simulation exert onto the system which then emitting a photon of energy, $h\nu_{12}$. This situation is called as spontaneous emission. The spontaneous emission is isotropic, thus, resulting to a narrow-band Gaussian outputs. As the electron been forced to make a downward transmission from the excited state to the ground state by inducing any external stimulation, the electron moves to the next stage of laser production which known as stimulated emission. The stimulated emission occurred when a photon of energy, $h\nu_{12}$ hits on the system (electron) while it is still at the excited state, the 'forced' will make the electron undergo the population inversion, hence, the electron drop to the ground state at once, and emits a photon of energy at certain wavelength as shown in Figure 2.2.

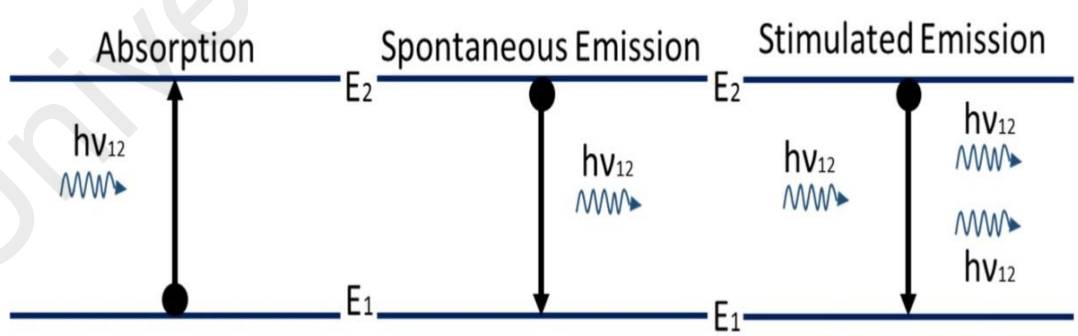


Figure 2.2: Photon generation in fiber laser

The pump signal (laser diode) must be shorter than the signal wavelength. In this case, this work was directed for the lasing to be in the 2 μm region and the pump signal at wavelength of 1550 nm is used. The 1550 nm pump used is to make the electron excite to its excitation level. Processes involve during the emission; spontaneous emission and stimulated emission had been explained in the previous paragraph with the assist of Figure 2.2.

The working principle of the photon generation with the TDF is clarified in three quasi level of the Thulium (Tsai et al., 2015) such as shown in Figure 2.3. Three quasi level represents the energy level of Thulium that occur during absorption and emission of light for the amplification. The pumping at 793 nm wavelength able to give an out-of-band pumping, while 1550 nm laser diode was able to make an in-band amplification process. When the 793 nm pumping inject into the gain medium, the electrons will be excited from the ground level to the $^3H_4$ level. The excited Tm^{3+} ions will then decay spontaneously in a second to the $^3F_4$ level, which emit a non-radiative photon. The ions will decay after all to the ground state that gives emission within the range of 1700 to 2100 nm. Additional of external power able to amplify the spontaneous emission along the fiber, which called Amplified Spontaneous Emission (ASE) with a wide range of photon emission from 1700 to 2100 nm.

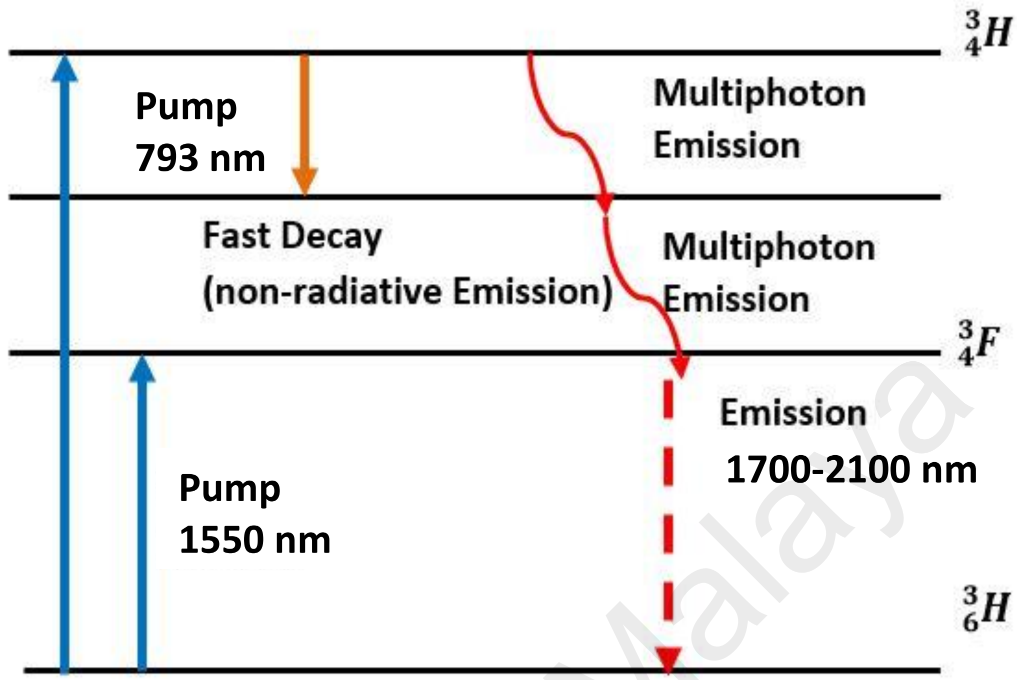


Figure 2.3: Three quasi level of TDF

The production of the photon emission from 1700 to 2100 nm also can be achieved by using 1550 nm wavelength pumping. Usually the 1550 nm pumping capable in making more powerful emission as compared to single pumping from at the wavelength of 793 nm. The laser signal emission within the range of 1700 to 2100 nm can be realized by making a ring cavity. The signal photon with the aid of laser pump will be amplified during the stimulated emission, thus, producing a stable laser signal along the cavity.

2.5 Amplification Gain

The amplification gain is the most important operation of the TDF, which determines the ability of the TDF to amplify the incoming signals. The saturation gains (mostly known as gain) can be intrinsic or fiber-to-fiber gain. The intrinsic gain, G is a ratio of the power of the signal at the input facet to the power of the signal at the output facet. These fiber-to-fiber gain can also be defined as the ratio of the output signal, P_{out}, to the signal, P_{in} (Baney, Gallion, & Tucker, 2000; Derickson, 1998);

$$G(v) = \frac{P_{out}}{P_{in}} \tag{2.2}$$

The signal gain of a TDF at an optical frequency of ƒ can be written as;

$$G(f) = \frac{(1-R_1)(1-R_2)G_s}{(1-\sqrt{R_1R_2}G_2)^2 + 4\sqrt{R_1R_2}G_2 sin^2[\frac{(f-f_O)L}{v}]} \tag{2.3}$$

Where;

G_s is the signal-pass amplifier gain, R_1 and R_2 are the reflectivity of the input and output facets, f_o is the center frequency and ν is the velocity of the light when travelling in the TDF (ν can be obtained by the ratio of the speed of light in air, f to the refractive index of material, n so that $v = \frac{c}{n}$). The TDF and facets are forming a reflective cavity, giving a rise to resonant frequencies, which in turn will affect the gain of the TDF during the amplification process. Resonant frequencies occur when the sin^2 factor is 0, giving a minimum gain. The signal pass gain, G_s can be measured in terms of the material gain coefficient, confinement factor Γ, absorption coefficient α and active region length L as;

$$G_s = \exp[(\Gamma g_m - \alpha)L] \tag{2.4}$$

Where;

g_m is a material gain, while the α is the material-loss coefficient.

The mathematical Equation in (2.4) is simply by taking the reflectivity to be the same, so $R_1 = R_2 = R$. This will make;

$$G(f) = \frac{(1-R)^2 G_s}{(1-RG_2)^2 + 4RG_s sin^2[\frac{(f-f_O)L}{v}]} \tag{2.5}$$

The mathematical Equation (2.5) is the key formula for the calculation of signal gain in the TDF, where it is applicable to the gain achieved in TDF amplifier and AWG where the reflectivity is not a concern.

Other than reflectivity and frequency, input signal power also plays a role in maximizing the signal gain in the TDF. This is because as the signal power increases, the gain collected in TDF decreases due to the gain saturation. The relation between the input signal power dependent gains, $G(p)$ and the input signal power can be given by;

$$G(p) = G_0 \exp[\frac{(G-1)P_{out}}{GP_{sat}}] \quad (2.6)$$

Where;

G is given, while P_{sat} is obtained from the saturation power of the TDF.

By using this mathematical Equation (2.6), the signal gain for the TDF can be predicted under various drive currents, input wavelengths and input powers. However, these equations are only applicable in certain conditions. TDF can only exhibit a low signal gain at certain input power, but as the power of the input signal increases, these mathematical formulas become invalid. Meanwhile, the gain will keep increasing as the bias current increases until the saturation currents point, thus making the gain remains the same as the drive current is increased. As mentioned in the section 2.5, the wavelength of the signal that the TDF can amplify is limited to the TDF bandwidth region.

The optimum gain value of the TDF depends on the maximum bias current that had been injected into the TDF (as gain medium), thus these input signals will then be amplified by the TDF (depending on the power and wavelength region).

In comparison to the Equation (2.5) and (2.6), which indicate that the signal of any power, which constantly amplified in the TDF, but in reality the gain of the TDF, is limited by the input signal saturation power. This is because signal frequency and power were depended on the material gain, which is given by;

$$g(f,P) = \frac{g(f)}{1+\frac{P}{P_{sat}}} \tag{2.7}$$

Equation (2.7) shows that the material gain coefficient depends on the input signal power. As the input power increases, the gain coefficient of the material used will begin to decrease. Only half of the maximum gain coefficient can be obtained when the signal is fully saturated. From these material gain coefficients, the gain can be calculated as;

$$G_s = 1 + \left(\frac{P_{sat}}{P_{in}}\right) ln \frac{G_s^{max}}{G_s} \tag{2.8}$$

Where;

G_s^{max} is G_s at ω_0 and P_{sat} is the saturation power. The saturation power defines as the signal power at which the gain of the TDF is half (3-dB) of the low signal gain.

2.6 Noise Figure and ASE

As well as saturation gain of the study, another important parameter in determining the efficiency of the Thulium doped fiber is the noise figure, NF where TDF laser with best saturation gain during operation will generate the noise figure as low as reasonably achievable are the most sought after.

The NF is the ratio input to output's signal-to-noise ratio, of an optical amplifier. It is essential in quantifying the performance of an optical amplifier, and generally given by (Analyzer, 2000);

$$NF = \frac{(\frac{S}{N})_i}{(\frac{S}{N})_o} \tag{2.9}$$

Where;

$(\frac{S}{N})_i$ is the input signal-to-noise ratio and $(\frac{S}{N})_o$ is the output signal-to-noise ratio. In the case of this TDF, the NF can be expressed as in terms of the TDF amplifier gain and ASE power as;

$$NF = \frac{1}{G} + \frac{P_{ASE}}{Gh\nu\Delta\nu} \tag{2.10}$$

Where;

h is a Plank constant, while ν is the signal frequency and Δν is the bandwidth. From a mathematical Equation in (2.10), the noise figure of the TDF amplifier is inversely proportional to the saturation gain of the TDF; thus, the higher the saturation gain collected, the lower the noise figure of the TDF. Meanwhile, the P_{ASE} is the result of the carriers that spontaneously decay from the upper energy level of the TDF, from the process of proton released that have random phases and directions. Although these photons fall within the same frequency range (signal), their random phases and directions does not contribute to amplifying the passing signal, instead generating the noise value.

The average peak of ASE can be obtained by using this formula;

$$P_{ASE} = 2n_{SP}h\nu G\Delta\nu \tag{2.11}$$

The factor of two in the mathematical Equation (2.11) is due to the fact that the ASE will propagate equally in both forward and backward directions, thus the ASE power measured at either end of the TDF is only half of the total ASE power generated.

2.7 Switchable wavelength mechanism

Tunable laser or switchable laser is widely known for its ability in producing wavelength that is able to tune into selected wavelength. Single tunable laser or multi tunable laser is widely used in industrial due to its low-cost production, compact and versatile. The application of the wavelength-slicing device depends on the purpose of the study.

The basic concept of the wavelength slicing mechanism is by allowing only one particular wavelength to be transmitted while the other propagating wavelength will be blocked. There are several types of the wavelength slicing mechanism works in the 2 μm region such as arrayed waveguide grating (AWG), Fabry-Perot Etalon filter (FPF) and Mach-Zehnder interferometer. Each type of the wavelength slicing mechanism practicing a different optics principle in filtering and selecting (used in the optical resonator) the wavelength.

In this section, brief theory and working principle of the wavelength slicing mechanism work in the 2 μm region will be discussed.

2.7.1 Fabry-Perot Etalon filter

The Fabry – Perot interferometer filter, also known as Fabry-Perot Etalon filter (FPF) is an optical resonator that confines and stores light energy at selected frequencies which shown in Figure 2.4. This optical transmission system incorporates feedback, whereby, the light is repeatedly reflecting within the system, thus, circulates without escaping the system. Typically, a transparent plate with two reflecting surfaces builds the FPF or some productions use two parallel highly reflecting mirrors with a spaced fixed distance apart, d. So, in order to prevent the rear surfaces from producing interference fringes, the flats in an interferometer is made in a wedge shape, while the rear surfaces also have anti-reflective coating. This FPF filter is widely used in telecommunications, lasers and spectroscopy to control and measure the wavelengths of lights.

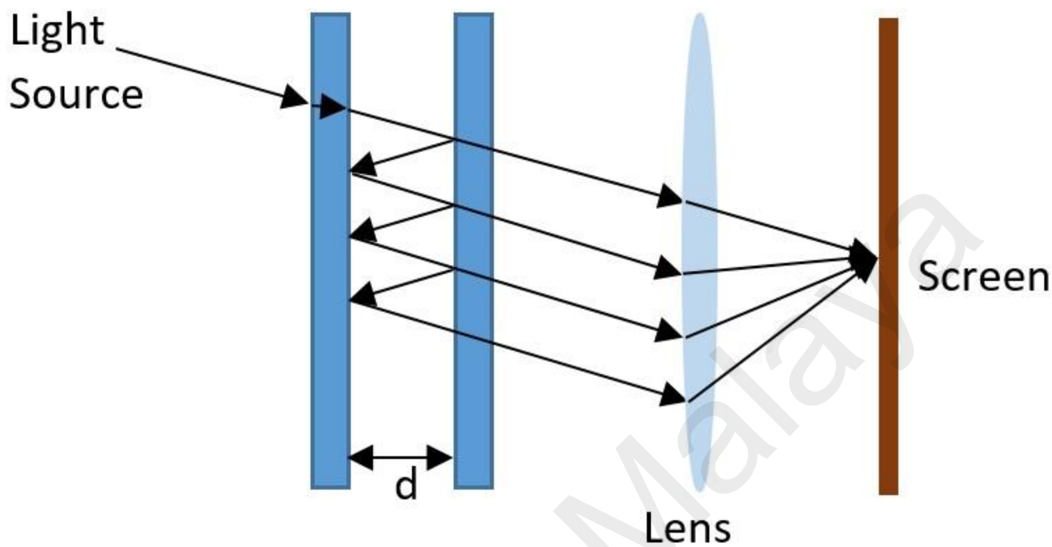


Figure 2.4: Geometry of Fabry-Perot etalon filter

2.7.2 Mach Zehnder Interferometer

The production of tunable laser can also be realized by using Mach-Zehnder interferometer. Compared to the wavelength selective filters that are wavelength dependent filters, the interferometer is the filter, which is independent to the wavelength used. The working process of the interferometer is slightly different compared to the Fabry-Perot interferometer. A beam (laser input) enters the system will then split into two with the existence of two beam splitters (see Figure 2.5). The lights will recombine again at the second beam-splitters. The recombined light then emitted a laser at the certain wavelength (laser output 1 and 2). Tune-ability of the wavelength is achieved by changing the path length of the mirror (slightly adjusted the mirror position) and make the different result of the reflection of light along the path.

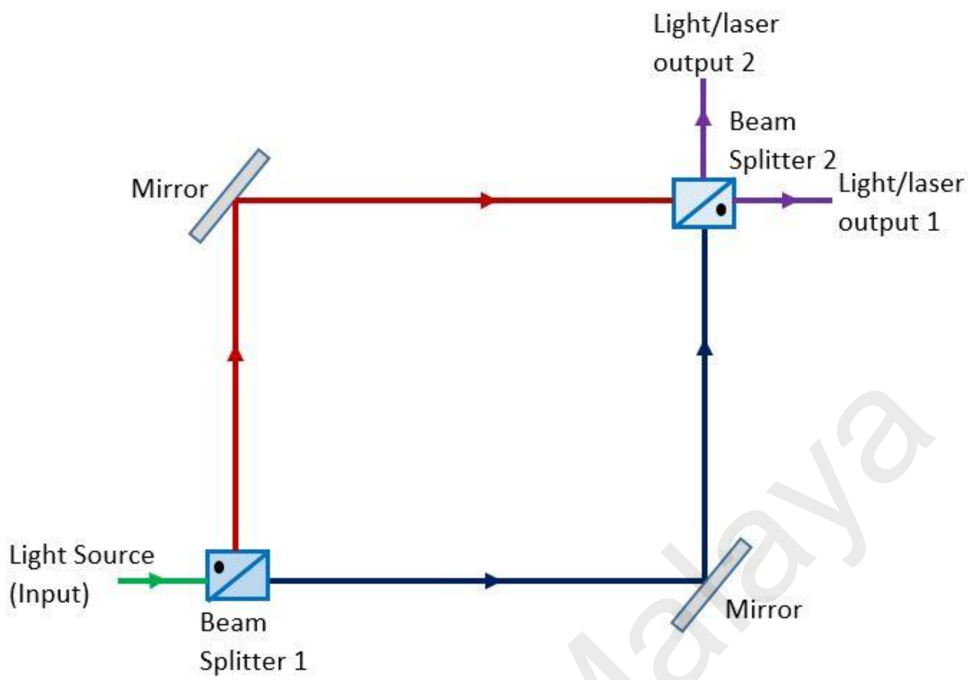


Figure 2.5: Geometry of Mach-Zehnder interferometer

2.7.3 Arrayed Waveguide Grating

Most of the wavelength selective filters have specific operating wavelength region. However, in the case of the AWG, the wavelength selectivity is independent of operating wavelength. The wavelength slicing mechanism in this study works properly in 1.5 μm wavelength region but it also can be used in 2 μm wavelength region. The AWG multiplexers or de-multiplexers are the planar device, which works based on the array of waveguides in both imaging and dispersive properties.

This is the first study on tunable single laser working in 2 μm region by using AWG as a wavelength selective filter. The ability of producing tunable multi-wavelength laser had shown the capability of the AWG as a wavelength selective mechanism. The AWG had convinced by Harith et al (2011) in producing stable multi-wavelength laser that work accordingly in 1 μm region by using Ytterbium doped fiber, where each laser gave an SMSR value of 59.65 dB (Ahmad et al., 2011). Demonstration of AWG not only fixes in continuous wave laser, but it is also competent in tunable pulsed laser production. Hayashi et al., (2003) had made multi-wavelength active mode locked pulsed laser by using 16 channels of AWG with spacing of 100 GHz. Moreover, Samion et al., (2016) shows that the AWG was used to make a tunable pulsed laser, which operates properly in 2 μm region.

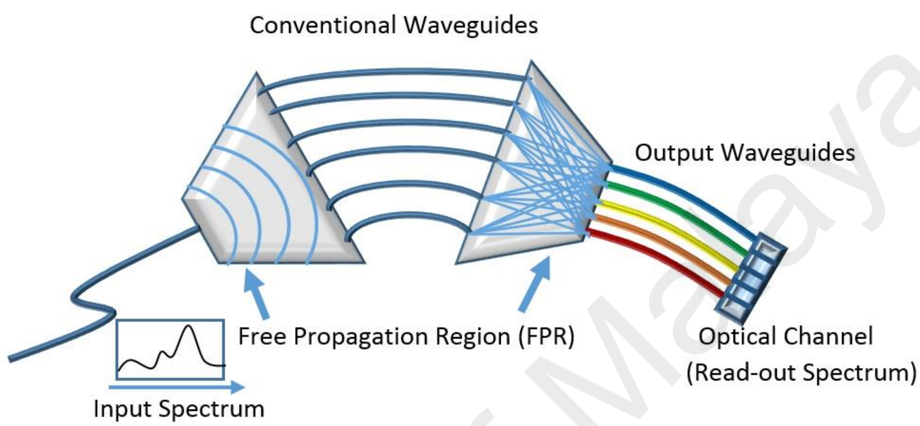


Figure 2.6: Geometry of AWG

The AWG used consist of 24 channels with a minimum insertion loss of about 3 dB at 2000 nm. This is due to the original design which supposed to operate at 1550 nm. Figure 2.6 shows the AWG with split incident beams where the image of the input waveguide onto an array of the output waveguides in such a way that the different wavelength signals present in the input waveguide are imaged onto different output waveguides.

The production of the AWG consists of the certain number of transmitter or receiver waveguides, two focusing objects and image planes, arrayed waveguides with a constant path length difference, ΔL between neighboring waveguides and number of optical channel at the receiver (read-out spectrum). As the input beam is injected through the transmitter's waveguide enter the free propagation region (FPR), the beam will automatically diverge into the output aperture (conventional waveguide region) of the arrayed waveguides. The multi-number of beams will then propagate trough the single array waveguides towards the output aperture and finally goes to the image plane.

The output of the AWG will be connected to the OCS which acts as the channel selector. The channel interspacing is based on the receiver of FPR. The formulae involve in the production of wavelength at a certain number of channels will be explained below.

The light emitting from the output waveguides must satisfy the mathematical grating equation;

$$n_s d \sin\theta + n_c \Delta L = m\lambda \tag{2.12}$$

Where;

m = diffraction order of grating

Meanwhile, the channel spacing in the AWG can be in terms of frequency or wavelengths. Both spacing employs different calculation, $\Delta\nu$ and $\Delta\lambda$ respectively.

$$\Delta\nu = \frac{x}{L_f}\frac{n_s c d}{m\lambda^2}\frac{n_c}{n_g} \tag{2.13}$$

Where the group index of the AWG;

$$n_g = n_c - \lambda\frac{dn_c}{d\lambda} \tag{2.14}$$

$$\Delta\lambda = \frac{x}{L_f}\frac{\lambda_{0d}}{\Delta L}\frac{n_s}{n_g} \tag{2.15}$$

Where;

L_f = focal length of the lens

ΔL can be calculated by using the following formula;

$$\Delta L = m\frac{\lambda_c}{n_c} \tag{2.16}$$

Where;

λ_c = central wavelength in the vacuum

The channel spacing of the AWG is more stable as compared to the other because spacing is rigid during the device manufacturing process. In a meantime, the AWG can be used in splitting the line formation in the optical spectrum of super-continuum source. In this study, the use of AWG is able to give a selected wavelength in the 2 μm region, which make the laser to have the wavelength tune-ability.

2.8 Summary

This chapter briefly discusses on the topics that involve in the production of TDF laser and TDF amplifier. The beginning part of the chapter explains the telecom window available in the industry, which is from 1-micron bandwidth until 2-micron wavelength bandwidth. The 1 μm bandwidth and lower bandwidth are developed in the early stage of the development of optical fiber. The 1 μm laser is made up from Ytterbium as its gain media. As the laser is only able to propagate in shorter wavelength, the laser power will degrade drastically along the fiber, thus, making the 1 μm fiber laser unsuitable for metro network communication. On the other sides, the 1 μm provide a high amount of energy compared to the longer wavelength region, which allows it to act as laser cutter in the industry.

Before the production of 2 μm fiber laser, 1.5 μm had become a novel topic to the scientist and engineer. The 1.5 μm give a bandwidth from the wavelength 1440 nm until 1650 nm where it can be separated into 3-different bands; S-band, C-band, and L-band. The S-band needs Thulium or Erbium as its gain medium while the C-band and L-band use Erbium-doped fiber as the gain media. This 1.5 μm fiber laser is the main bandwidth in the construction of the optical communication industry due to the high gain achieved along the system. The stability and durability of the Erbium-doped fiber laser make the laser to be acts successfully in producing a pulse laser, Q-switched or mode-locked, thus, allowing them to produce an ultrafast laser (Terahertz laser). Pulsed laser either active or passive production of the Erbium-doped fiber also have several applications in the industries; medical, telecommunication, remote sensing or in free-space industry. However, due to the high traffic in telecommunication from the use of 1.5 μm wavelength bandwidth, the researcher had found an alternative, which is a 2 μm wavelength bandwidth.

The 2 μm fiber laser is made up from Holmium or Thulium. A large bandwidth of 2 μm fiber laser (1800 until 2200 nm) gives them a high number of wavelength tune-ability by using wavelength selective mechanism. As explained in section 1.3, the 2 μm can be applied in several fields such as remote sensing, LIDAR, medicine and in free space optical communication. In comparison to the Erbium-doped fiber amplifier, which only able to achieve 30 dB of saturation gain, the TDF amplifier is able to achieve more than 60 dB for the saturation gain with lower noise figure production.

Amplification of the TDF is based on the laser pumping used in the system, whilst the 1550 nm laser diode is made the electron to be exciting to the certain energy level. The laser production can be divided into three stages; absorption, spontaneous emission and stimulated emission. Spontaneous emission and stimulated emission emit a number of photons along the photons. The spontaneous emission does not need any external force drop the electron in the ground state, whereas the stimulated emission needs additional external forces to drop the electrons. As compared to the spontaneous emission which resulting a noise in the laser emission, the stimulated emission gives a laser with preferred wavelength. Gain and noised figure achieved during the study is explained by using calculated from the formula.

Final section of the chapter is focused on the working principle of the wavelength selective mechanism. AWG is the only wavelength selective mechanism used for the study. The wavelength dependent mechanism is able to give a tune-ability along the wavelength bandwidth.

CHAPTER 3: THULIUM DOPED FIBER AMPLIFIER

The research methodology for this work is divided into three major stages; (a) characterization of components used, (b) design and fabrication of TDF amplifier that produce higher amplification gain with low noise figure by the means of single pass or double pass configuration and, (c) design and fabrication of switchable wavelength laser with the laser emission approaching infrared by considering wavelength slicing mechanism.

In this section, the characterization process of all component used for the study are further explained. The components are the 1550 nm laser diode pump, wavelength division multiplexer (WDM), TDF, amplified spontaneous emission (ASE), TDF laser and tunable laser source (TLS). This characterization is carried out to record and determine the insertion loss of the component used. Insertion loss will degrade the power of the light propagates along the cavity. Moreover, the fabrication and design of TDF amplifier with single pass and double pass amplification processes are needed to understand more the light amplification process in the gain medium and at the same is quite useful to produce an optimum gain with minimum noise figure. The result for both single pass and double pass TDF amplifier will then be compared with each other.

3.1 The 1550 nm LD pump

In this study, a laser diode by the Princeton Lightwave with the model number of PSL-450 (as shown n Figure 3.1), working at the wavelength of 1550 nm and connected to a single mode fiber (SMF-28) is used. The laser diode is capable to deliver an output power of more than 250 mW at the temperature of 25°C, fully controlled by a laser driver manufactured by Thorlabs with the model number of CLD1015.

Figure 3.1: Laser diode Princeton Lightwave

As been explained in 2.4, the 1550 nm laser diode pump will allow the thulium electron to excite from level $^3H_6$ to $^3F_4$, thus giving a stimulated laser emission in the range of 2 μm. The characterization of the laser diode by using an optical power meter (OPM) is used to study the amount of pump power (Figure 3.2). The result of emission rate will be compared with the characterization of the WDM.

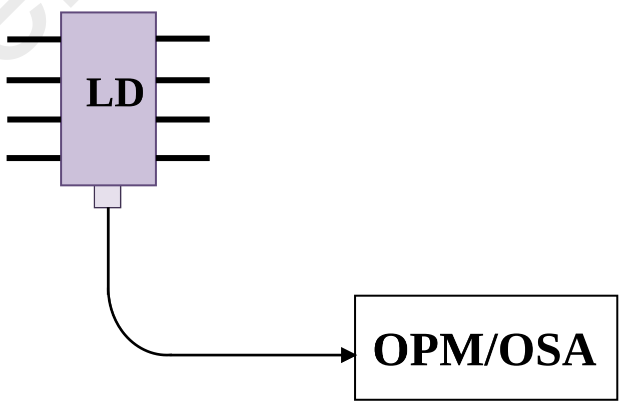


Figure 3.2: Experimental setup for characterization of laser diode

Schematic diagram of the setup for the characterization of the laser diode is shown in Figure 3.2. The laser diode output is simply connected to the OPM. The measurement of the emission is recorded from the OPM, while, the OSA was used to verify the wavelength, which is fixed at 1550 nm throughout the characterization of the laser diode.

Figure 3.3 shows the efficiency of the average power emission for the laser diode laser diode, where the power was increased simultaneously with the increment drive current of 50 mA until the maximum drive current of 1400 mA. It shows that the power threshold started at 8 mW. Power threshold of the laser diode shows when the power emission is started to increase uniformly without any occurrence of power drop. The maximum power was achieved at 250 mW when the power emission starts to be constant at one point. The graph also shows the determination coefficient (R^2) value for the 1550 nm LD pump is 0.9998. This valued is close to one which indicating that the line is almost linear where the power emission of the LD is in stable condition.

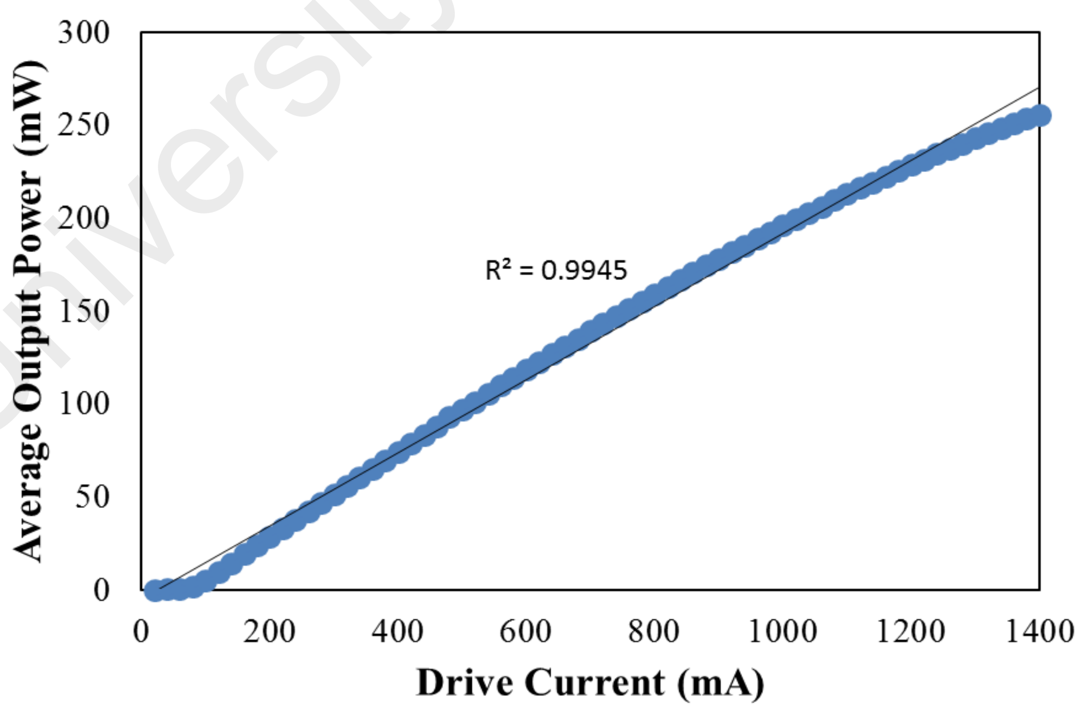


Figure 3.3: Graph of the laser diode characterization over output power

3.2 Characterization of WDM

Wavelength division multiplexer (WDM) is a device that enables different signal wavelength to be transmitted along the same optical fiber. This mechanism is widely used in optical fiber communication in transmitting data in several wavelengths or commands over one single fiber. Thus, increase the transmission capacities of the fiber optic links. The research used a WDM in allowing different wavelengths (1550 nm and 2000 nm) to be propagated into a single fiber. The Figure 3.4 shows the experimental setup for the characterization of WDM 1550/2000 nm.

The WDM used in allowing both 1550 nm wavelength laser from the laser diode and the 2000 nm of laser wavelength in the cavities to propagate over one strand of optical fiber. Prior to the laser production with the emission in 2 μm region, the characterization of WDM is required. The 1550 nm fiber of WDM was coupled to output of laser diode, while the output of WDM was read out by the OPM which schematically diagram shown in Figure 3.4. This characterization is necessary in studying the insertion loss of the WDM. Besides, the characterization will provide the range of input power for the experimental study.

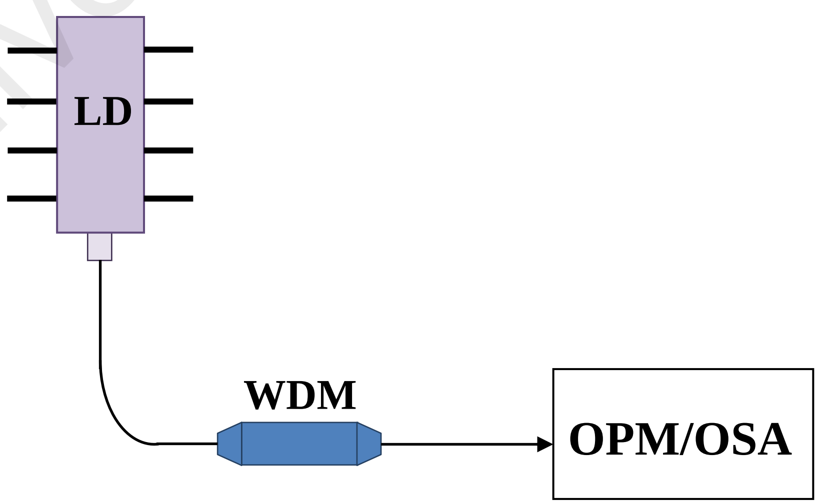


Figure 3.4: Experimental setup for characterization of WDM

Figure 3.5 shows the comparison between the efficiency of power before and after the insertion of WDM. The graph shows that the WDM only able to provide a maximum 0.6 dB of power loss which indicates an insertion loss of the WDM. The R^2 values for the laser pump of 1550 nm and the WDM are 0.9945 and 0.9944 respectively, which denote to the steady power emission for both components. Moreover, after the WDM, the laser is able to provide a maximum of 220 mW of pump power.

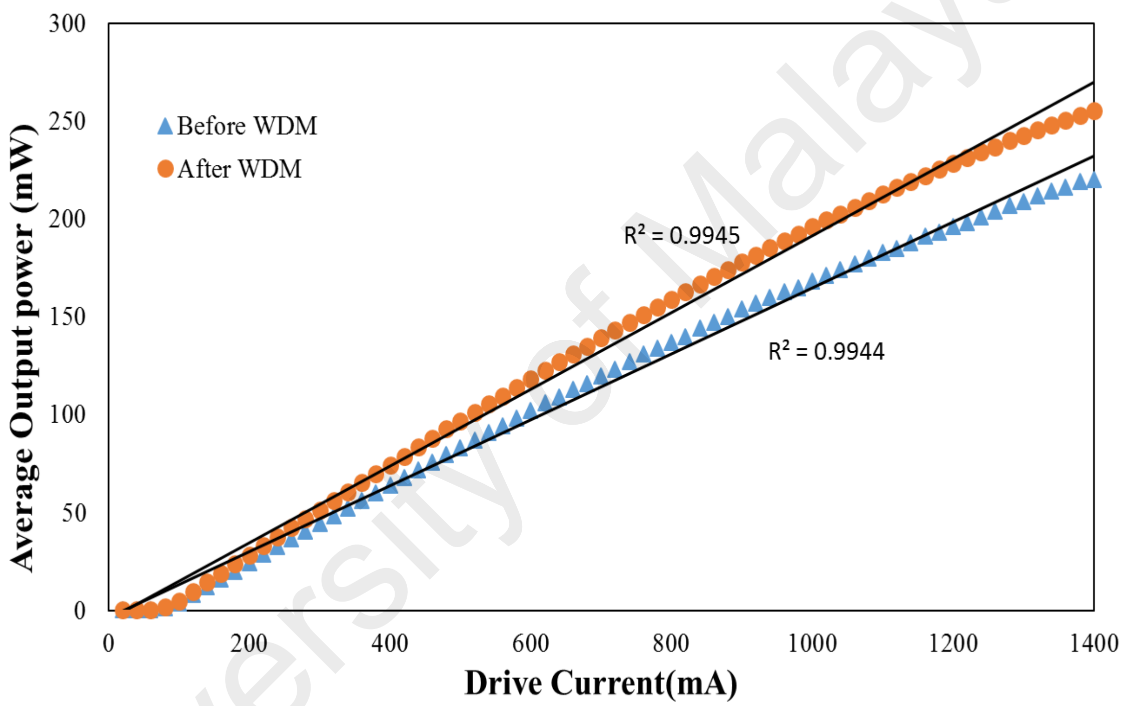


Figure 3.5: Graph of characterization of WDM

3.3 ASE of the 2 m long TDF

Amplified spontaneous emission, ASE (also known as super-luminescence) is produced by spontaneous emission of optical photon occurred during amplification in the TDF. The ASE is produced when the gain medium is pumped to create a population inversion.

The ASE of the 2-m long TDF was achieved by a configuration which is shown in Figure 3.6. The laser diode at 1550 nm was used as the main pump source of the experiment in this study. The pump laser will propagate along the 1550/2000 WDM and enter the 2-m long of TDF. The pump, the WDM and the gain media will be spliced together in order to reduce the insertion losses that might be occurred. All spliced region was fixed and bending loss that might happen along the fiber must be reduced, so that the power loss can be minimized throughout the experiment. The TDF is connected to the coupler and the 10% is tapped out and connected to the OSA or OPM.

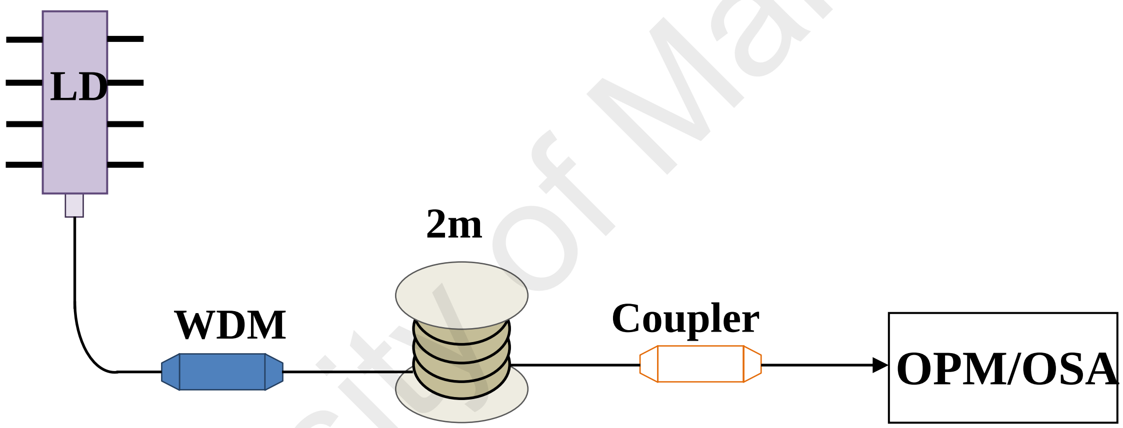


Figure 3.6: Experimental setup for the ASE of the TDF

Figure 3.7 shows the ASE produced by the TDF when pumped by a 1550 nm laser diode at different pump power; 50 mW, 100 mW, 150 mW, 200 mW and 220 mW (maximum input power). Characterization of the ASE was carried out at room temperature (~25℃) to avoid any disturbance to the results due to the temperature changes. For instance, the ASE diagram also shows that the peak is within the region 1850 until 1900 nm. At the lowest drive power, 50 mW, the peak is approximately -63 dBm. The increment of about 5 dB is achieved from the drive power of 50 mW to power 100 mW. The output power increases gradually by approximately 4 dB as the input drive was raised from 100 to 150 mW and also 200 mW. Here, it shows a slight change in ASE for 200 mW and 220 mW input power which is due to the TDF has almost achieved its saturation gain point, thus further increase in the drive current over 200 mW will yield only a small increment in the ASE peak value. As has been explained in section 2.5, the ASE shows the bandwidth of the TDF emission from 1700 mW until 2100 mW, thus, the region of the study will be within that region.

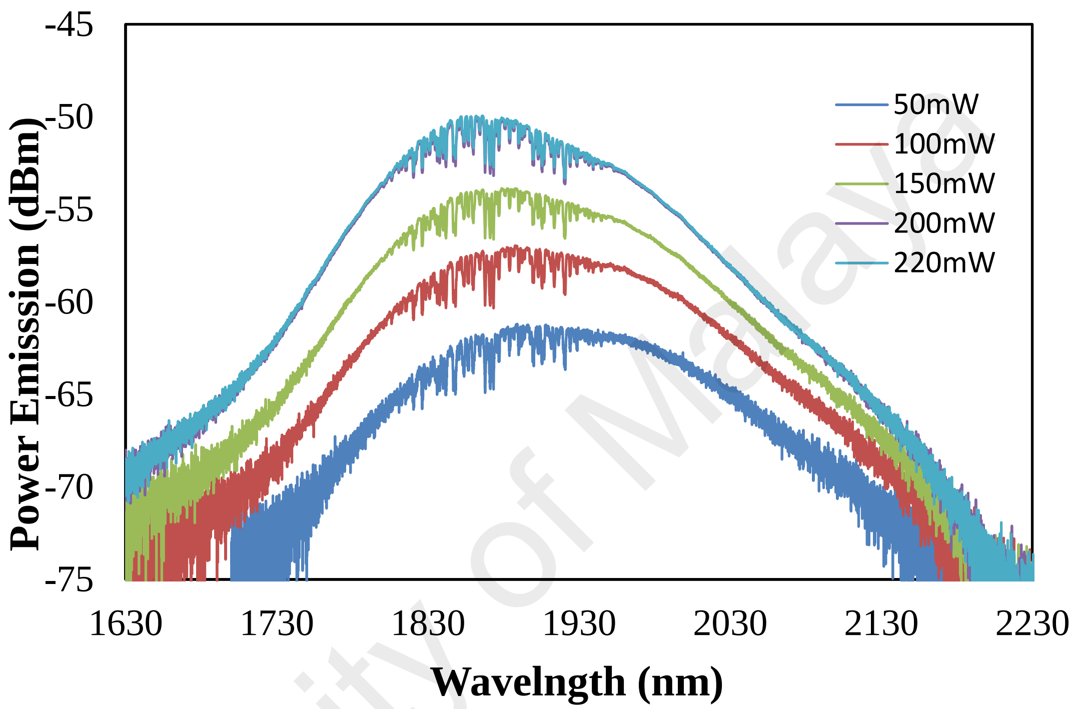


Figure 3.7: The ASE of TDF with different pump power

3.4 Characterization of tunable laser source

The tunable laser source (TLS) manufactured by Thorlabs Inc was used in this study, where the user can tune the TLS manually or control via computer. The TLS acts as the seed laser for the experiment that give a laser signal within 2 μm regions which is from 1910 to 2000 nm. As the characterization was already run by the manufacturer, the user need to redo the characterization to check any changes in the power emission and wavelength of the laser. In this study, the characterization is carried out with the assistance of the computerized motor controller with a special software known as APT-user from the Thorlab Corp. The output power of the seed laser can go up to 3 mW. In order to tune the wavelength, the computer motor controller assisted in channel selection, which is from channel 1 to 10, with the smallest increment of 1.2 nm.

Figure 3.8 shows the experimental setup used in the characterization of the TLS, whereby the output of TLS was measured through the OPM and OSA. The OPM used to study the average output power of the TLS for every tuned wavelength, while the OSA showed the spectrum of laser emission. The TLS is able to give a low seed signal with the power emission of -45 dBm and give a high signal which is more than 0 dBm, whereby the signal is mainly used for the study on the TDF amplifier. Nevertheless, the study used -20 dBm and 0 dBm for low and high input signal respectively with 11 selected wavelengths of the laser emission within the range of 1910 until 2000 nm.

Figure 3.8: The setup of TLS characterization

3.5 Single pass Thulium doped fiber amplifier

In order to study the properties and performance of the thulium doped fiber (TDF) in signal amplification, the TDF amplifier was designed. As has been mentioned in section 2.6, the most crucial parts of the TDF amplifier are gain collected and noise figure produced along the amplification process. Basically, a good TDF amplifier will yield higher gain with low noise figure. As been explained in section 2.5, the 1550 nm laser diode was used to make an in-band pumping for amplification in the energy level of the TDF, which contribute to a more efficient TDF amplifier (Shukla & Kaur, 2013).

Based on previous study by Parekhan & Banaz, (2008), a TDF amplifier can be composed of three different pumping schemes; forward pumping, backward pumping or bidirectional pumping (dual-pumped). Forward and backward pumping have different effects on the noise figure (NF) and gain collected. The forward pumping is proven to be able to give low NF as compared to the backward pumping, which is based on the formula; n_{sp2}/n_{sp1}-1 where the value is always positive (Desurvire et al., 1990; Harun et al., 2002; Jung et al, 2012; Sakamoto et al., 2000). Thus, to provide a high gain with low of NF value, the forward pumping configuration is selected to get a TDF amplifier worked in 2 μm wavelength region.

The fabrication and characterization of the TDF amplifier is by making a single-pass TDF amplifier employing a 2-m long of TDF as shown in Figure 3.9. The TLS with both low and high pump signal (-20 dBm and 0 dBm) were used for injecting the laser signal at certain selected wavelengths into the cavity. The wavelengths were from 1910 to 2000 nm with the spacing of 1.2 nm. An isolator was placed after the TLS to allow unidirectional laser propagation. The isolator will then connected to the WDM with the aid of a connecter. In a meantime, the laser diode with the wavelength of 1550 nm was spliced with the WDM. They were spliced together, so that any unwanted loss of power signal could be avoided. The output of WDM will be spliced to the 2 m of TDF whereby the gain medium is tapped out to the OSA (with spectral resolution of 0.05 nm) and OPM to observe it performance.

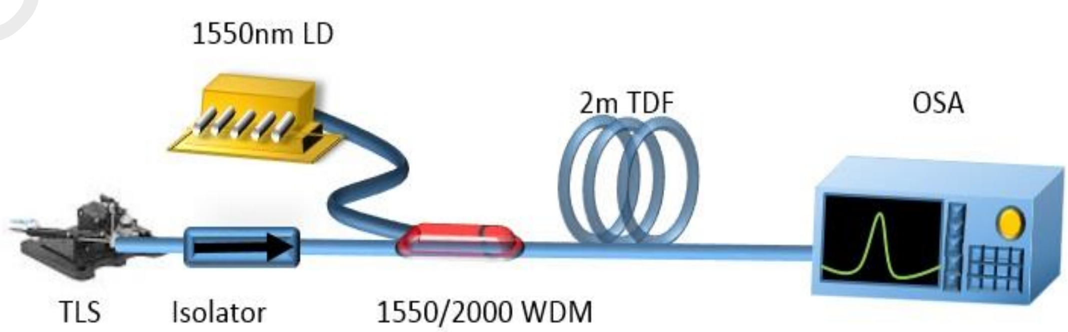


Figure 3.9: Experimental setup for single pass TDF amplifier

3.6 Double pass TDF amplifier

The experimental setup for double pass TDF amplifier is shown in Figure 3.10.

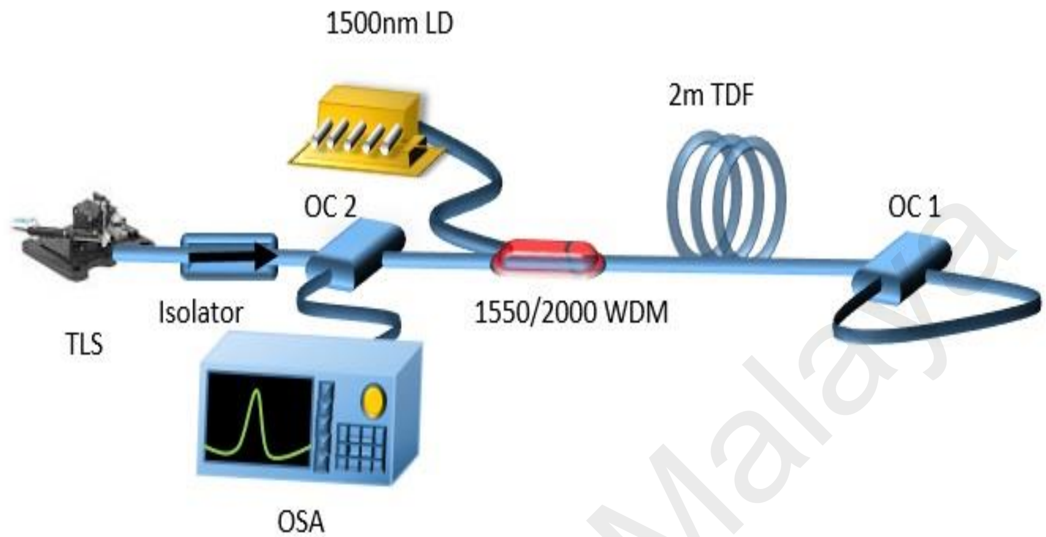


Figure 3.10: Experimental setup for double pass TDF amplifier

A double pass amplifier needs an additional component such as mirror, circulator or fiber Bragg grating (FBG). In this study, two circulators were used to realize a double pass configuration TDF amplifier. The first circulator was placed at the output of the gain media to make the double amplification process, whereby port 1 and port 3 of the circulator are spliced together. On the other hand, the second circulator will be placed after the isolator before the WDM, thus the port 3 of the second circulator will be tapped out to the OSA and OPM to observe its performance. Data recorded by the OSA and the OPM will then be evaluated for the study. Just as the single pass of TDF amplifier, the double pass TDF amplifier will use the same low input power, -20 dBm and high input power, 0 dBm from the signal laser, whereas the wavelength of the laser will be in the same region of the chosen wavelengths during the single pass of TDF amplifier. The results of studies such as saturation gain, noise figure, and efficiency will then be compared between those configurations.

3.7 Single and double pass configuration of Thulium doped fiber amplifier

This comparison will show the best gain achieved and the efficiency of both configurations. Besides, the efficiency of the low input signal and high input signal for amplification will then be analyzed.

The amplified spontaneous emission (ASE) of both single and double pass is shown in Figure 3.11. From the graph, it shows that the peak of ASE of double-pass amplifier is slightly higher compared to peak of the ASE of single pass. Both configurations are run at the maximum input power, 220 mW at 1550 nm pumping. Double pass TDF amplifier has higher ASE peak because it allows double propagation or two stage of amplification of the laser power. Both double and single pass configurations of the TDF amplifier produced the ASE wavelength with the bandwidth of more than 2000 nm. However, the ASE bandwidth of the single pass is longer than the double pass ASE by 100 nm differential. The ASE of the single pass configuration is within the range of 1880 until 2200 nm, whereas the double pass configuration has wider range of ASE which is from 1600 until 2200 nm.

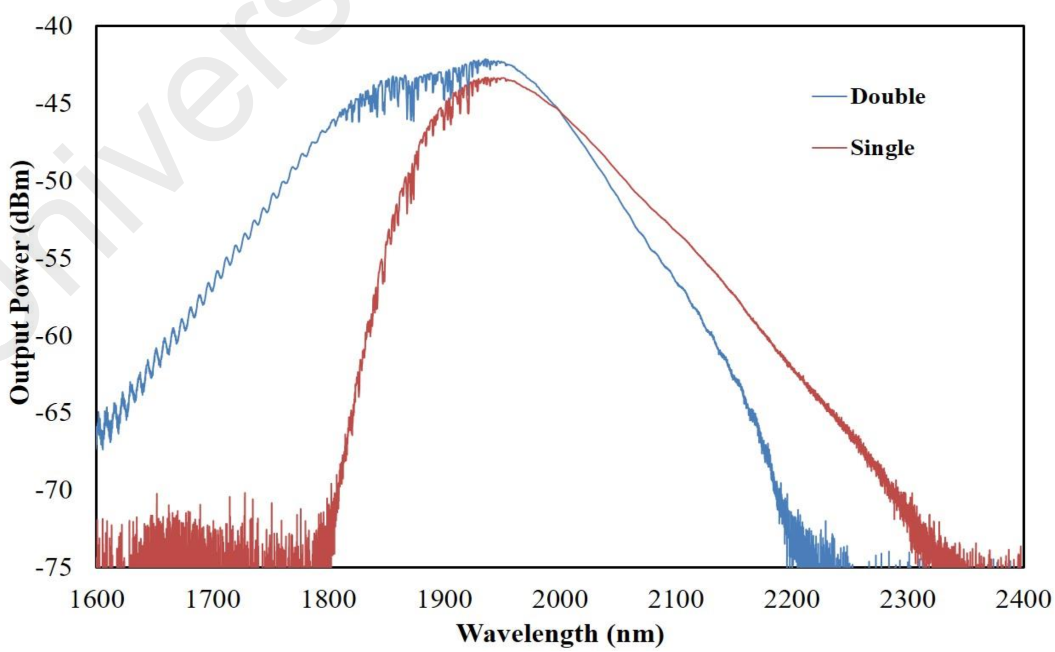
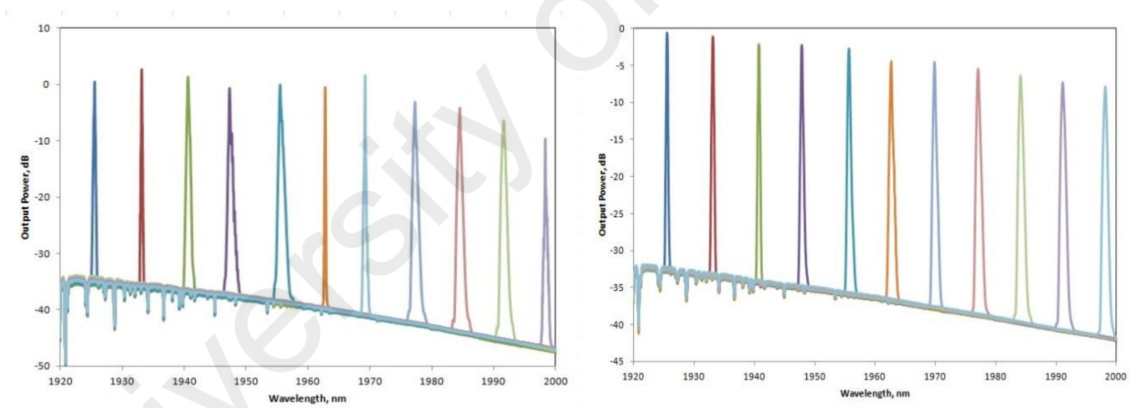


Figure 3.11: ASE for both single pass and double pass of TDF amplifier

The wavelengths of the TLS were switched from 1925 until 1998 nm with a 7 nm interval between two consecutive wavelengths with the aid of computerized motor controller. Both TDF amplifier configurations at low and high input signals are using the same wavelength emission. Previous study from Li et al, (2013) had used the switchable wavelength between 1900 to 2100 nm. This has contributed to the production of the two different bands in the region of 2 μm which the shorter band occupied the wavelength region from 1900 to 1960 nm, whereas the longer band starts from the wavelength of 1960 to the 2000 nm. The result of laser amplification with an input pump of 220 mW from the laser diode is shown in Figure 3.12. The graph showed that each tunable peak lasers is different. The lowest floor resulting the lowest laser peak emission. The highest floor able to emit the highest peak laser emission. The floor of the laser is based on the shape of the ASE.



(a) (b)

Figure 3.12: Spectrum for the double pass TDF amplifier (a) low input signal, -20 dBm and (b) high input signal, 0 dBm.

Meanwhile, Figure 3.12 (a) shows the laser spectrum of TDF amplifier with double pass configuration at high input signal, 0 dBm. Meanwhile, Figure 3.12 (b) shows the laser signal tuned between the wavelength of 1925 to 1998 nm at low input signal, -20 dBm.

The correlation between gain and noise figure (NF) in each wavelength for both double pass and single pass are shown in Figure 3.13. The highest gain was recorded at the wavelength of 1933 nm with double pass configuration, whereby the accumulated gain is 23.84 dB. On the other hand, the lowest NF value was recorded at the wavelength of 1969 nm with the value of 3.24 dB. The recorded gain tends to decrease for both configurations as the wavelength was tuned farther from the short wavelength. This is caused by reduction in the population inversion of the TDF, which subsequently increases the NF penalty. In the double pass configuration, there is a sudden high gain at the wavelength of 1969 nm. The anomaly in the graph trend is most probably caused by the sudden fluctuation in the gain medium absorption and emission during the amplification process, thus resulting in sudden increase in gain and decrease in NF.

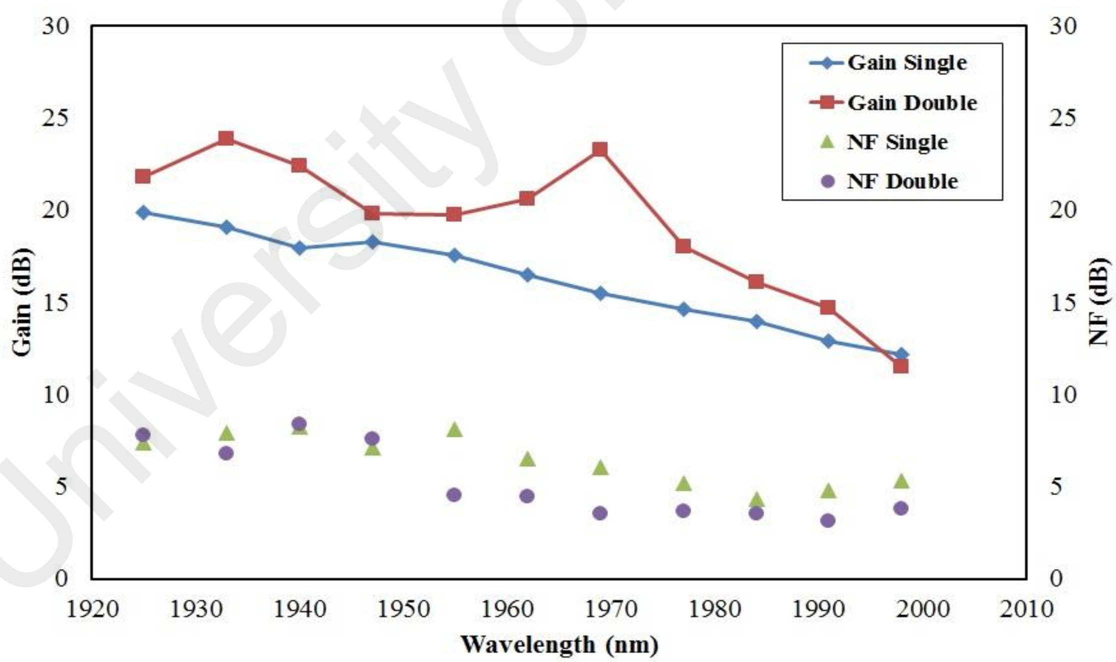


Figure 3.13: Gain and noise figure (NF) acquired for both single and double pass at every wavelength

Figure 3.14 shows the gain and NF for both single and double pass configurations at the center wavelength of 1969 nm with various of pump power, which are 50 mW, 100 mW, 150 mW, 200 mW and the maximum of the input power of 220 mW. Improved amplification attained in the double pass configuration as compared to the single pass, thus contribute to higher gain with the lower NF values. As the pump power increases, the gain will rise which resulting to a decrement in the NF value. This scenario only happens before the amplification reach the saturated gain, whereby preventing any amplification, where any additional input power will make the gain and NF to remain at plateau.

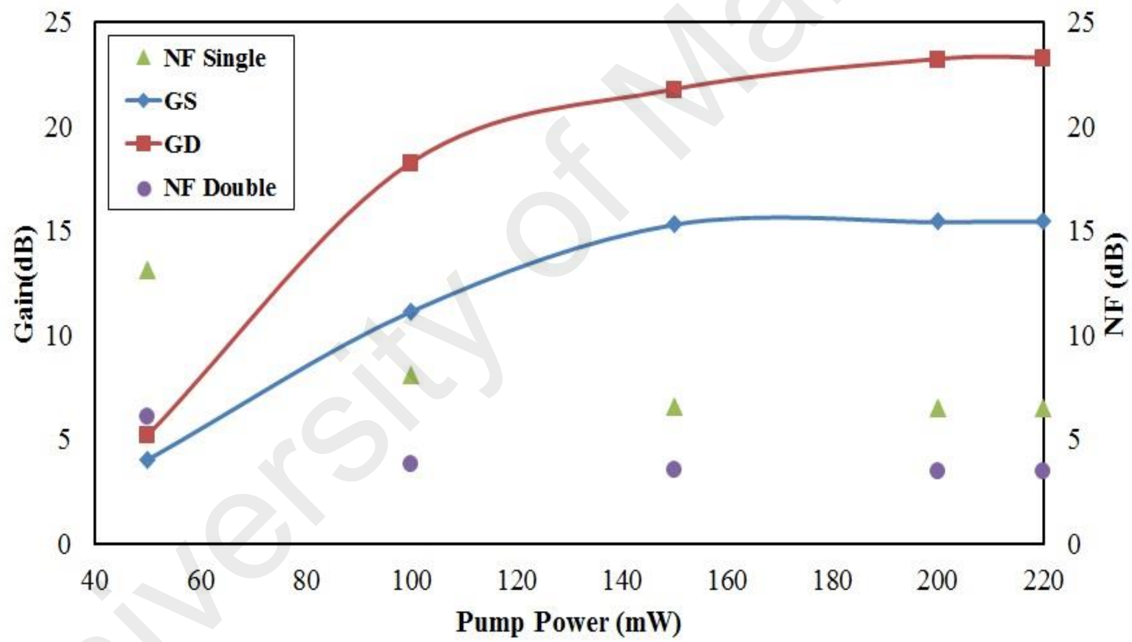


Figure 3.14: Gain and noise figure (NF) acquired for both single and double pass with varies pump power

Figure 3.15 shows the comparison of the performances of output power between both double and single pass configurations when -10 dBm of input signal is pumped at center wavelength of 1965 nm. The efficiency of the single pass configuration for TDF amplifier is 9.36%, where the difference between double pass with single pass configuration of TDF amplifier is about 7.36%. So, the percentage of efficiency for the double pass configuration is around 16.53%. The values of efficiency for double pass configuration can be considered high which is approximately of 30 mW as compared to the single pass configuration which less than 25 mW. This obey the theoretical behavior of the double pass configuration for TDF amplifier which is able to produce higher power emission during the amplification process. Both graphs give an almost linear graph, where the R^2 value for single and double pass configuration are 0.9967 and 0.9997 respectively.

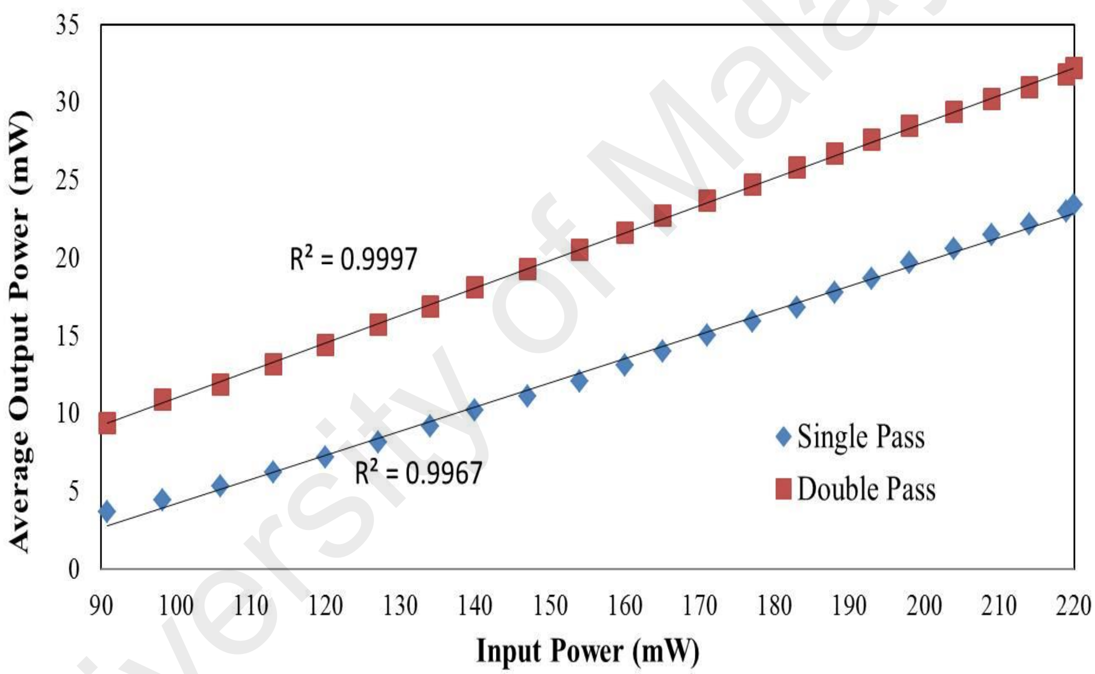


Figure 3.15: Performance of TDF amplifier

Meanwhile, Figure 3.16 shows the performance of the double pass between two different input signals at -10 dBm and -20 dBm. Both signals were chosen in enabling in differentiating of efficiency of the TDF during the amplification. It shows that the -10 dBm input signal, resulting a high efficiency up to 16% compare to the -20 dBm input signal with approximately 13% of the efficiency. Although, the efficiency of -20 dBm of input signal for double pass configuration is lower than the -10 dBm of input signal at the same configuration, yet it still higher compared to the efficiency of -10 dBm of input signal for the single pass configuration. The efficiency at the maximum input power of 220 mW shows the best with more than 16% of efficiency and at the lowest of input power of 50 mW shows the least because low input power is insufficient in enabling more population inversion in the TDF to emit more energy.

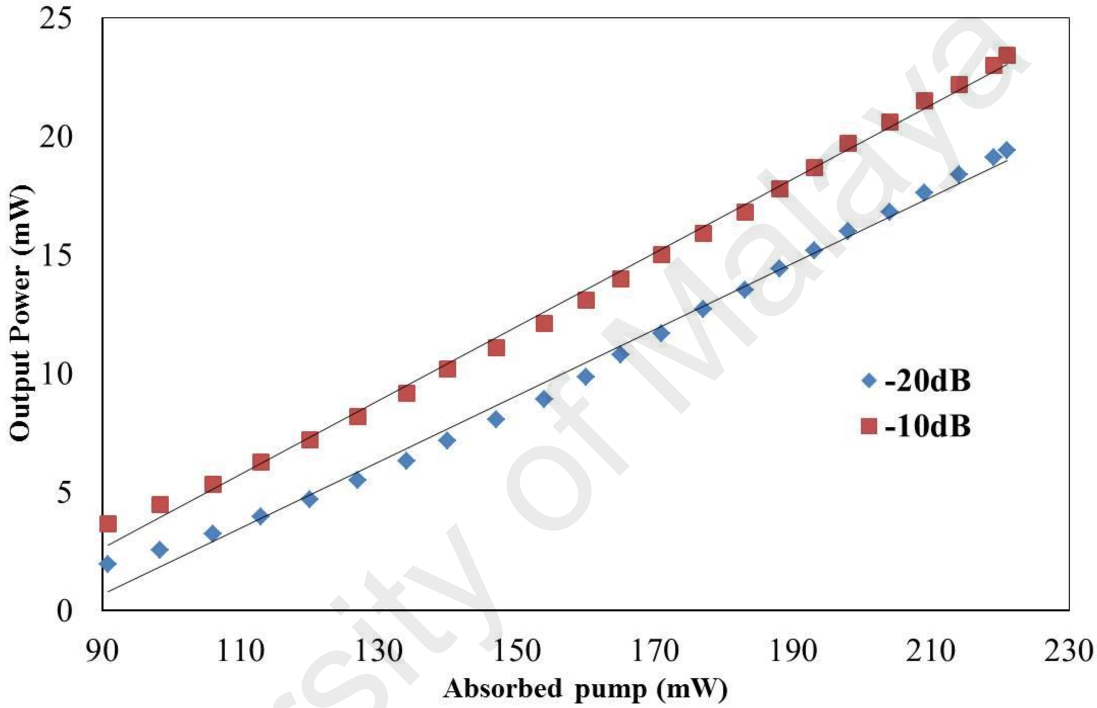


Figure 3.16: Performance of TDF amplifier for double pass with -10 dB and -20 dB input signal

3.8 Summary

This chapter concerns on the fabrication and characterization for all the component that were used throughout the study. The characterization of the components such as, LD, WDM, gain medium used, TLS is to determine the insertion loss and the power emission of the signal. The analysis shows that the insertion loss of the WDM is approximately 0.6 dB. Characterization of the TLS which is fully controlled by the computerized motor is accustomed to examine the wavelength of signal at both low and high input signal which are -20 dBm and 0 dBm.

The amplification of the TDF by using double and single pass configurations were clearly explained, where the double pass TDF amplifier is able to obtain high gain which is up to 28 dB with the lowest noise figure of 3.48 dB. Gain saturation occurred at the pump power more than 200 mW for both configurations. The comparisons of the efficiency for both double pass and single pass had shown that the high signal have a higher signal compare to the low signal with the difference of 7.83 %. Both of the double pass and single pass used two types of laser signal, which are low signal, and high signal, -20 dBm and 0 dBm respectively. In this study, the low signal has lower efficiency compared to the high signal.

CHAPTER 4: THULIUM DOPED FIBER LASER

This chapter focuses on the emission of Thulium-doped fiber (TDF) laser and its ability to switch the operating wavelength. The chapter consists of two sub-topics; (a) which explains on the TDF laser in a ring configuration, (b) the tune ability of TDF laser by using AWG as the wavelength selective mechanism.

4.1 Characterization of the TDF laser

A good laser emission (narrow 3 dB bandwidth with high side mode suppression ratio (SMSR) value) can be identified by characterized the TDF laser. The characterization is done by simply making a single ring cavity fiber laser with 2-m long of TDF manufactured by Nufern with the model of SM-TSF-9/125. A single ring TDF laser has been designed as depicted in Figure 4.1. The characterization of the TDF using a laser diode from Princeton Lightwave with the maximum of the 220 mW pump power at the wavelength of 1550 nm with a single forward pumping configuration.

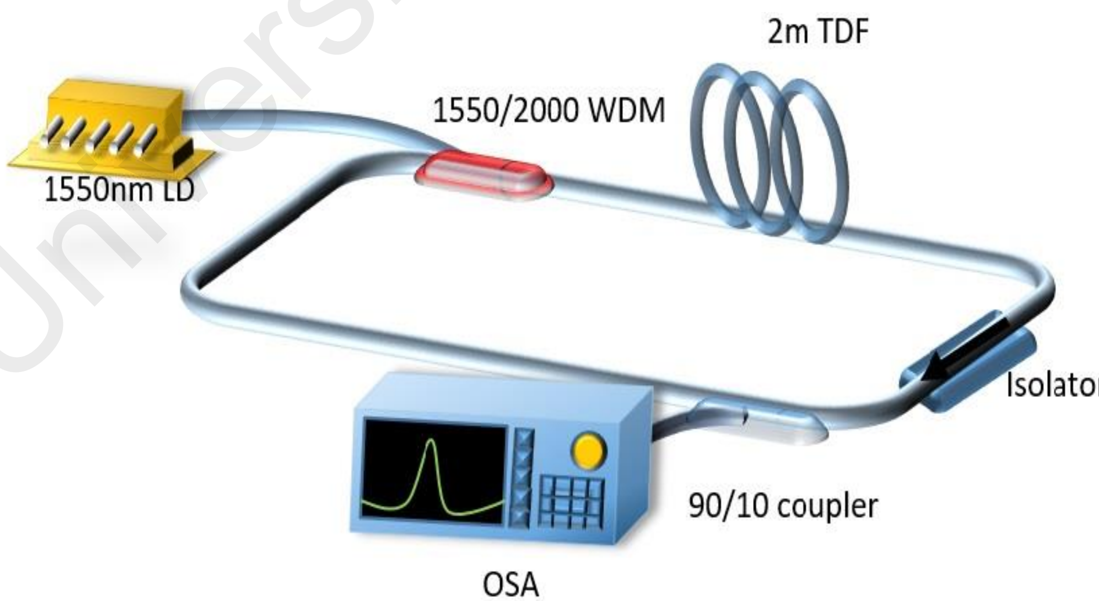


Figure 4.1: The set-up of the TDF laser

The pump will be coupled to the TDF via 1550/2000 nm wavelength division multiplexer (WDM) coupler. The light from the laser diode will propagate into the gain medium, thus provide a sufficient energy to excite the thulium ions, then generates the amplified spontaneous emission (ASE). Forward pumping configuration was tested thoroughly before running the experiment by studying the ASE properties of the TDF with a forward pumping configuration. Forward pumping is capable in generating high gain with low noise figure (NF) compared to the backward pumping (Prachi, & Preet, 2013). The 1550 nm laser diode was chosen because the in-band pumping is able to achieve more efficient laser as compared to the out-of-band pumping by using laser diode at the wavelength of 793 nm (Shukla & Kaur, 2013). In general, the TDF laser was configured by using a pump source, a 2-m length of TDF as the gain medium, a wavelength division multiplexer (WDM), an isolator to allow unidirectional laser propagation in a ring and a coupler (90/10 coupler). The 10% output of the coupler was tapped out to the optical spectrum analyzer (OSA), manufactured by Yokogawa model AQ 6375. The OSA spectral resolution was set at 0.05 nm where the resolution can be selected at the OSA's setting program. The 90% output port of the coupler is then connected to the WDM with the assistance of the adapter to make a closed loop cavity. In order to obtain an optimized TDF laser, it can be verified through the efficiency and side-mode suppression ratio (SMSR) of the laser; some key parameters such as input power, output power, laser lasing region and the bandwidth of amplification will be taken into consideration. The amplification bandwidth and the lasing region have been extensively covered in chapter 3.

Firstly, the characterization of the TDF laser was carried out with the highest input power of 220 mW. The power absorbed at the input power of 220 mW shows that the laser peak spectrum shown by the OSA gives the value of 2.56 dB, at the wavelength of 1961 nm as shown in Figure 4.2. TDF laser spectrum shows the narrow band of 3-dB bandwidth and high number SMSR with approximately 0.04 nm and 60.18 dB, this indicate that the laser emission of the TDF is stable. The maximum output power recorded by the OPM resulted a higher power emission of TDF laser at 220 mW, which approximately 6.8 dBm, which includes the excessive ASE produced by the TDF (Ahmad et al., 2009).

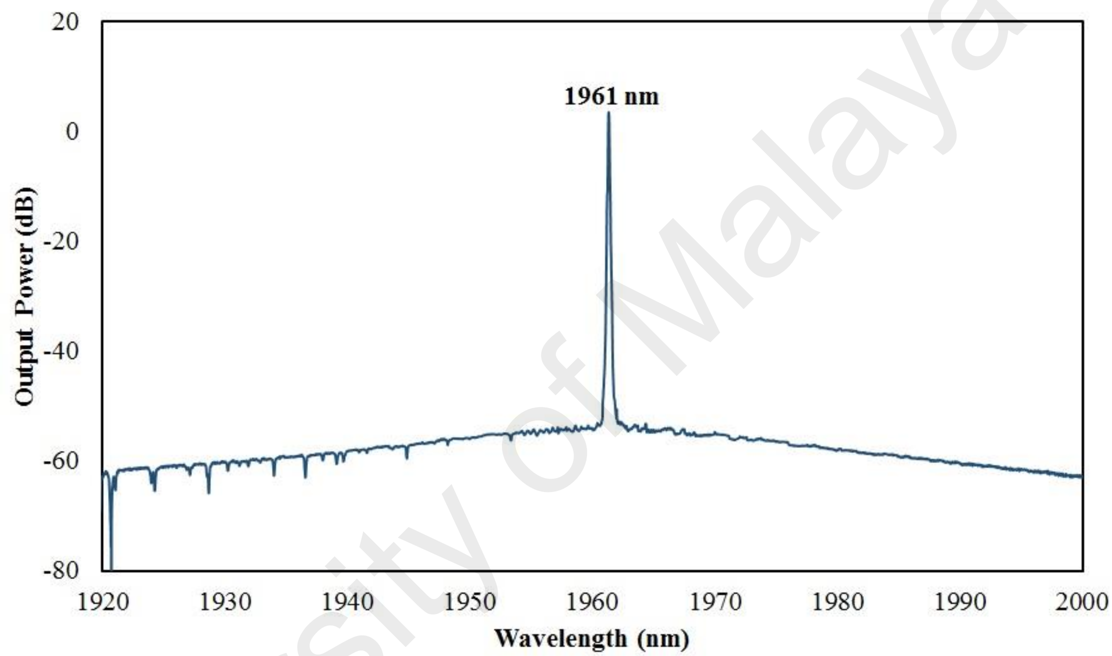


Figure 4.2: Laser peak spectrum of TDF

4.2 Switchable TDF laser at 2 µm

Tunable wavelength TDF laser can be achieved by implementing a wavelength slicing mechanism, which is provided by an arrayed wavelength grating (AWG) with an expected intra-channel spacing of 100 GHz (Pal, 2005).

The TDF laser emission is in the region of 2 µm region (Agger & Povlsen, 2006). The AWG will give out a laser, which has a tune-ability in the region of 2 µm by changing the channel of AWG. Figure 4.3 shows the proposed setup for the tune-able wavelength of TDF laser. The setup used a 2-m long of Nufern (SM-TSF-9/125) TDF. The 1550 nm pump will be coupled to the 1550/2000 nm WDM coupler. An isolator is inserted into the cavity to provide unidirectional propagation, thus, depressing the backward ASE of the TDF and enhancing the SMSR of the laser emission. The output of the isolator is then connected to a coupler, whereby, the AWG will be connected at the output of 90% of the coupler. The cavity will have a forward pumped which was spliced directly to the TDF via WDM, whereas the 10% of output coupler will then be tapped out and connected to the OSA and OPM. The AWG (model OPLINK) has a 100 GHz narrow band interval spacing which correspond to approximately 1 nm wavelength interval between two adjacent channels, but in this study, the interval is approximately 0.96 nm. The channel of the AWG gives a different wavelength, which result a tunable wavelength from the 1st channel until the last 19th channel.

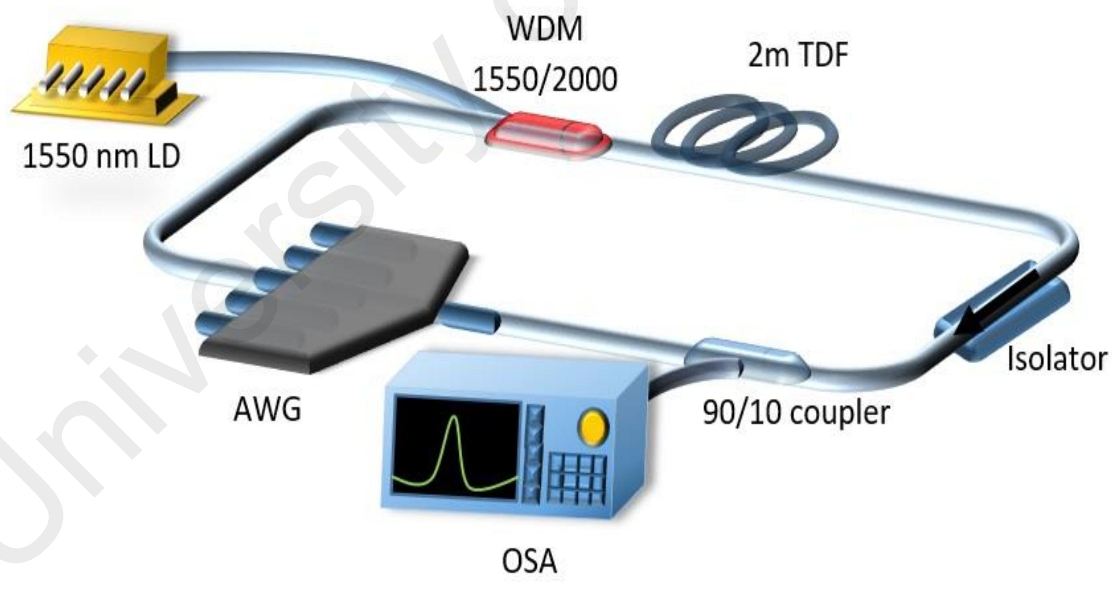


Figure 4.3: Setup for switchable 2 μm TDF laser

In this study, the single wavelength output spectrum achieved from a channel in the AWG at the pump power of 220 mW was shown in Figure 4.4. The laser emits at channel 1 lies on the wavelength of 1888.92 nm with a peak power of -10.90 dBm. The reduction of peak power in the output laser incorporating the AWG as compared to prior insertion of the AWG is due to several factors, including higher insertion loss experienced by the cavity due to inclusion of AWG and the wavelength filtering process that occurs in the AWG. Laser emission was detected by using OSA with 0.05 nm spectral resolution and it's producing a good stable laser with side-mode suppression ratio (SMSR) of approximately 56 dB for channel 1. A stable laser can be calculated from the SMSR value; where, the value must be higher than 40 dB (Chien et al., 2005). Besides, a good laser emission can be shown by the 3-dB bandwidth of the emitted laser, thus, from the graph of the laser emission at channel 1, it shows that its 3-dB bandwidth is 0.06 nm.

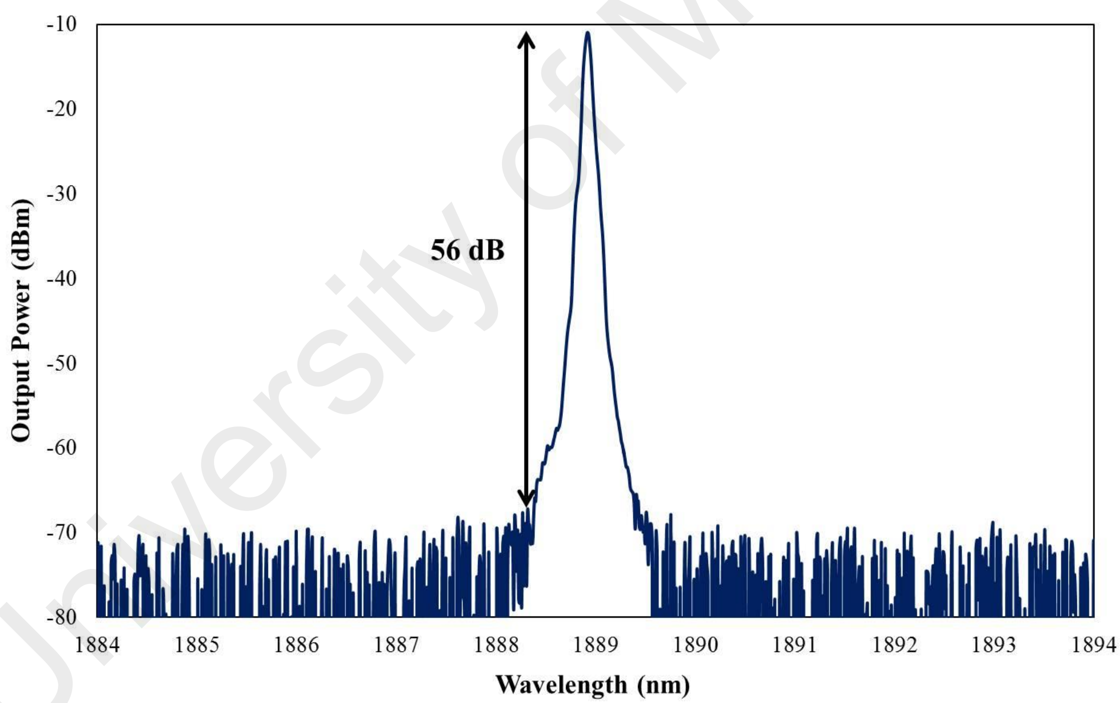


Figure 4.4: TDF laser of a channel in AWG

Figure 4.5 shows the wavelength of laser emission tuned from channel 1 until channel 19 as taken from the OSA with model from Yokogawa AQ 6375 with the fixed input power of 220 mW. The tuned wavelength is moving to shorter wavelengths as the channel increase, by which it starts from channel 1 with the wavelength of 1888.93 nm and moves consecutively towards the shorter wavelength until the last channel (channel 19) with the wavelength of 1871.66 nm. The 1x19 AWG produced stable inter-channel wavelength spacing of approximately 0.96 nm (100 GHz). The AWG covers the tunable wavelength within the range of approximately 17.27 nm from channel 1 until channel 19. The tuning range of the AWG can be increased by expanding the number of channel in the AWG. The tunable wavelengths by using AWG are able to maintain its emission power with approximately 3.36 dB of variation different between the maximum laser amplitude with the minimum laser peak amplitude. From the graph, it shows that the maximum peak laser emission occurred at channel 1 with the wavelength of 1888.93 nm. Channel 1 emits the laser with a peak value of -10.98 dBm. Furthermore, the minimum laser emission of -14.53 dBm occurred at the wavelength of 1873.56 nm that corresponds to the channel 17 of AWG. It can be seen that the variation of peak laser emission across the wavelength follows the pattern of the ASE spectrum of the TDF. The output power's losses between the tuning wavelengths is caused by some external factors such as bending loss or insertion loss. However, this loss is still considered low compared to the other study by Latif *et al*, (2011) which used an EDF to produce tunable wavelength by using the same wavelength selective mechanism, AWG. The 3-dB bandwidth of the wavelength produced by the AWG is approximately 0.06 nm, indicates the stability of laser emission in each channel. The narrow 3 dB bandwidth of the laser spectrum makes it suitable for application such as in the DWDM system with the 0.8 nm interval between two adjacent channels.

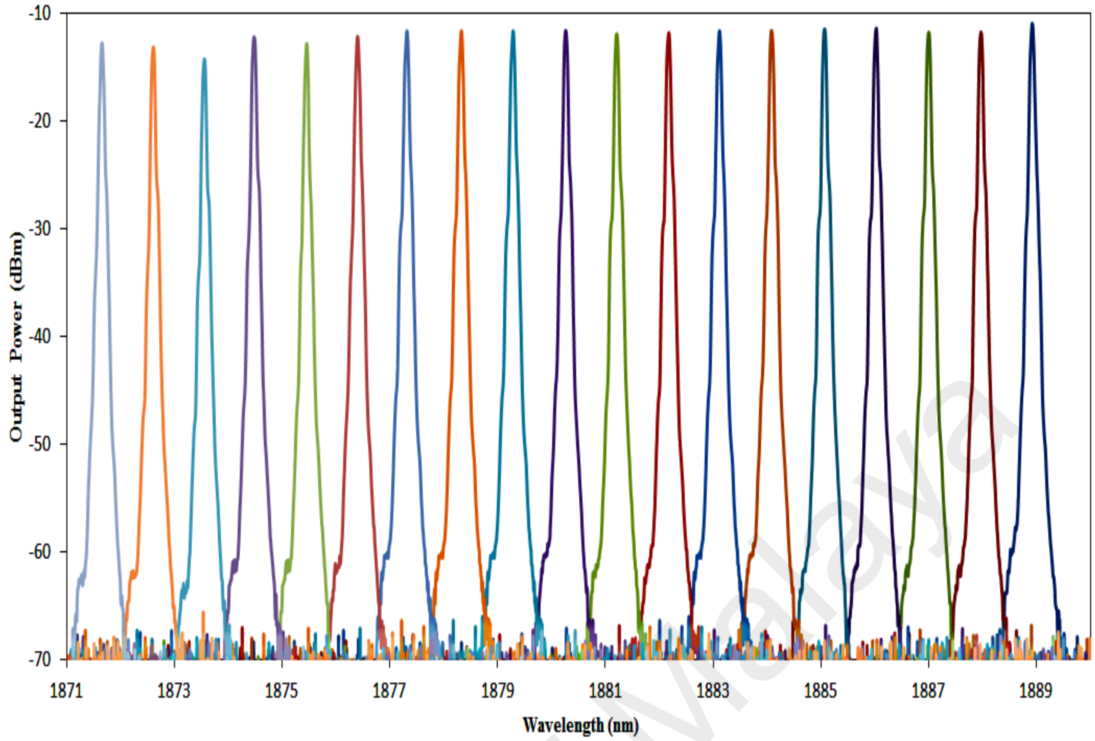


Figure 4.5: TDF laser of every channel in AWG

The side-mode suppression ratios (SMSR) for the tunable wavelength is shown in Figure 4.6. The SMSR value can be read via OSA or mathematically calculated as the difference between the highest peak of the laser's amplitude and its lowest position for each wavelength. The graph shows that the average value of the SMSR is 58.75 dB. The highest SMSR value was obtained at the laser emission at the channel 1 which corresponding to the wavelength of 1888.93 with the value of 60.18 dB. Whereas, the lowest recorded value of the SMSR was obtained from the laser emission at channel 17 which corresponds to the wavelength of 1873.56 nm with the value of 56.89 dB at a pump power of 220 mW, hence giving a difference of 3.29 dB from the maximum value of SMSR. Thus, it is shown that the low fluctuation of the SMSR occurred with respect to the wavelength. The fluctuations of the SMSR along the channels are because of the AWG quality issues, which probably resulted from the insertion loss between the connectors or bending loss of the fiber itself. The

3.29 dB is a slightly higher compared to the other study by Latif *et al* with high input power might. The results are caused by the quality issues of the AWG, the TDF ASE level and the difference in the input power (Ahmad et al., 2009). As shown in the graph, the value of SMSR is stable in term of laser emission or output peak power with ASE level, which is higher than 56 dB for each output wavelength.

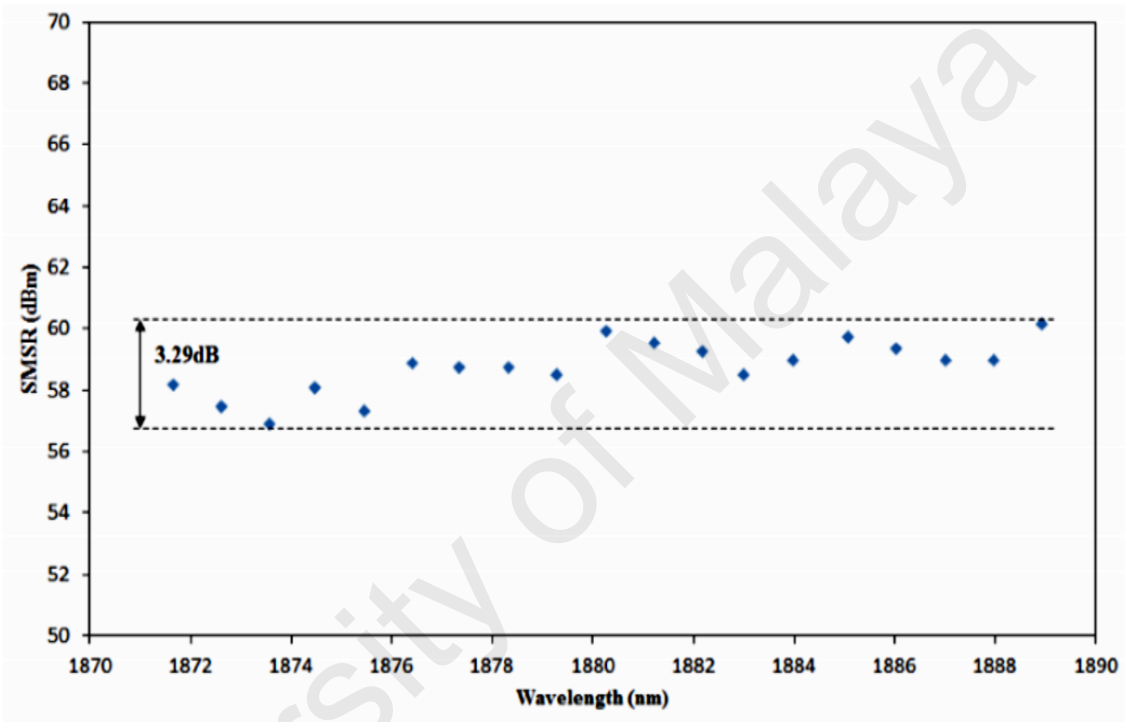


Figure 4.6: SMSR of the channel TDF laser

Figure 4.7 shows the output power of each tunable wavelength by using an optical power meter (OPM) versus its wavelength. The result shows that the variation of the output power for every wavelength tuned is approximately of 0.49 dB only. The value can be considered low compared to the result collected by the OSA (shown previously in Figure 4.5). The highest laser output is obtained from channel 1 with -4.44 dBm whereas the lowest output power of laser is emitted at channel 17 which is -4.94 dBm. The difference in the output wavelength is due to the insertion and bending loss between the connectors at the channel 17 of the AWG as compared to the other channels. The output power of the laser emission can be further increased by having higher pump power or by employing a bi-directional pumping configuration.

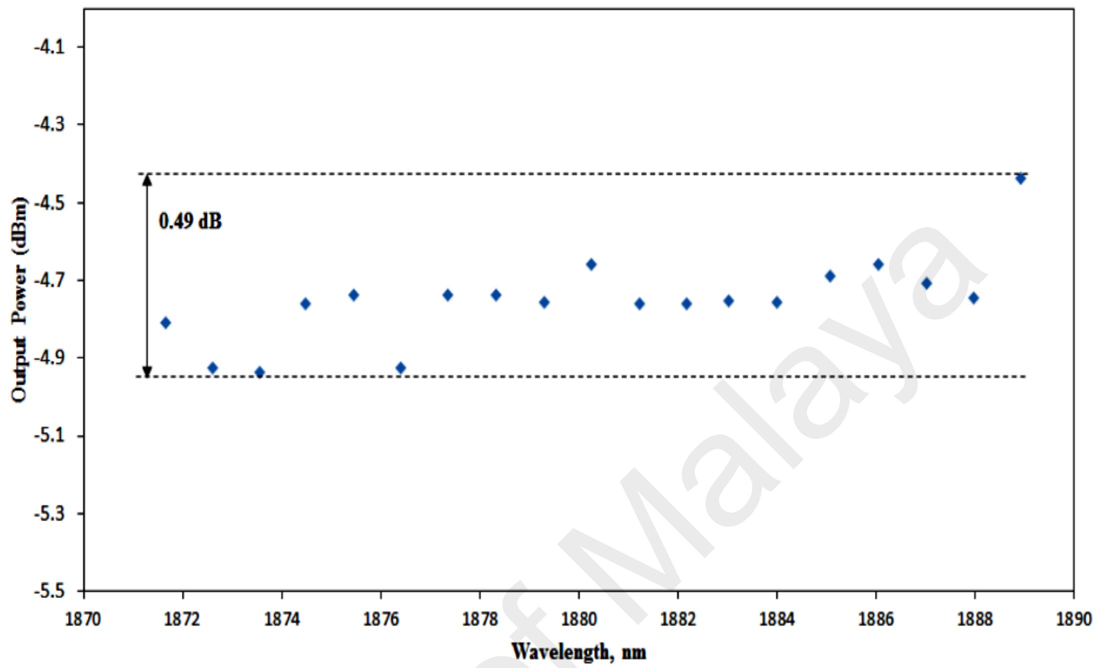


Figure 4.7: Stability of TDF laser at every channel

4.3 Summary

The TDF laser is in the form of a single ring cavity with the 2-m long TDF. The value of input or pump power used in this setup is variable, so that the research can examine more closely on the laser behavior. Lasing threshold starts at the input power of 50 mW able to give laser emission at the wavelength of 1960 nm. The maximum input power provides a good laser emission with the SMSR of approximately 60 dB. Meanwhile, the switch-ability of the TDF laser is achieved by incorporating a wavelength selective mechanism, which is an arrayed wavelength mechanism (AWG) into the laser cavity.

The AWG used is able to provide a tunable laser emitting 19 different wavelengths in the 2 μm regions. The laser wavelength could be detuned from 1871.66 nm to 1888.96 nm with the spacing of the intra-channel of 0.96 nm. Each switchable laser emitted consider as a stable laser with SMSR value of approximately 58.75 dB. Moreover, the power of laser emitted at each channel is practically the same because the variance in the peak of the laser emitted at each channel shown by the OPM is around 0.49 dB.

CHAPTER 5: CONCLUSION AND FUTURE WORKS

The main objective of this research work is to develop a switchable wavelength TDF laser working in the 2 μm region. Generally, this work has been divided into three stages. The first stage is to study the amplification ability of the TDF. Second stage is about the properties of a single wavelength TDF laser in a ring configuration, whereas the final is on the switch ability of the TDF laser, which is working in 2 μm wavelength region.

A good TDF amplifier is determined based on the achievable gain during the amplification process and minimum noise figure accumulated. From this work, single and double pass configuration TDF amplifier were able to give an acceptable accumulated gain with a minimum amount of noise figure. The experiment is accomplished by passing low and high input signal, which are -20 dBm and 0 dBm respectively into the amplifier's cavity. Based on the study, the double pass configuration is able to acquire higher gain as compared to the single pass configuration. The highest gain, 23.84 dB is obtained at the wavelength of 1933 nm, though the lowest NF occurred at the wavelength of 1969 nm with the NF value of 3.24 dB. The TDF amplifier shows that the efficiency of the single pass TDF amplifier is 9.36% while the double pass TDF amplifier able to achieve 16.53% of degree of efficiency.

In order to obtain a good TDF laser, part of this work is to investigate the achievable side-mode suppression ratio (SMSR) level and the 3-dB bandwidth of the laser emission. In this work, the TDF laser peaks at the wavelength of 1961 nm with 60.18 dB of the SMSR and 0.04 nm of it 3-dB bandwidth. Based on the results, it shows that the laser emission is considered very good because of high SMSR value with narrow 3-dB bandwidth.

In the final stage of the research work, the ability of the TDF laser to switch its wavelength in the 2 μm wavelength region is investigated. This is accomplished by using a AWG with 100 GHz of interval as the wavelength selective mechanism. The wavelength of the TDF laser can be switched within the 19 channels provided by the AWG, ranging from 1871.66 to 1888.93 nm. The work is able to achieve a good laser emission at each tune wavelength, where the average of the SMSR is approximately 57 dB and the attainable 3-dB bandwidth is as narrow as 0.06 nm. The fabricated the laser is able to give a good output power, which is recorded by the OPM. It shows that the highest output power, -4.44 dBm and was recorded at the wavelength of 1888.93 nm, while the lowest output power happened at the wavelength of 1873.56 nm with the value of -4.94 dBm. Thus, its shows that the emission of the output power for each tuning wavelength is stable whereby the variance of the output power between channels is only 0.49 dB.

5.1 Future Works

Research on lasers and optical amplifiers in 2 μm region is relatively new compared to the shorter wavelength region. The 2 μm lasers have many advantages in wide range of applications such as in medical surgery, LIDAR, sensor mechanism and free space telecommunication.

In general, factors such as gain and noise figure are the factors to define a good TDF amplifier. Several key factors need to be taken into consideration in order to build a good amplifier; such as the amount of the pump power and the length of the gain medium. For instance, increasing the pump power, which is the output power of the laser diode is an option. Higher pump power is able to increase the percentage of the population inversion of the thulium ions, thus increase the gain accumulated but once the gain achieved it saturation point, the gain will at remain with the increasing of input power. Therefore, future work might consider raising the pump power by employing more laser diodes as the pump source. To realize this, the laser diodes can be coupled into the cavity by making several types of configurations such as the backward or bi-directional pumping configuration. The use of pump combiner with the number of laser diodes also can increase the pump power. Hence, increasing the maximum power of the laser diode.

The length of the gain medium is one of many factors in determining the capability of the amplifier. Longer gain medium could lowered the gain if the pump power is not adequate because generally longer gain medium requires more pump power to excite the ions and make the population inversion to occur within the length of the gain medium. However, on the positive side, longer gain medium can prevent the early gain saturation All these factors can be considered in future works.

Furthermore, the operating wavelength of the laser diode used as the pump source also play a role in generating good laser emission. As explained before, 2 μm emission in TDF laser can be generated by using 1550 nm and 793 nm pumping wavelength. The out-of-band pumping or the 793 nm pump is good to excite the ions into the highest energy level, while the in-band pumping able to excite higher number of ions to the excitation level. In this case, the used of both types of pumps into cavity make the laser emission to be more efficient. The use of integrated pumping can be explored in future work.

In providing a switchable laser emission, the researcher can use various alternatives of the wavelength switching mechanism such as fiber Bragg grating, Mach-Zehnder interferometer, fabry-Perot filter and many more. Every mechanism used will emit laser that can be tuned with different properties.

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LIST OF PUBLICATIONS AND PAPER PRESENTED

1) Ahmad, H., **Muhamad, A**., Sharbirin, A. S., Samion, M. Z., & Ismail, M. F. (2017). Tunable Q-switched thulium-doped fiber laser using multiwall carbon nanotube and Fabry-Perot etalon filter. *Optics Communications*, *383*, 359-365.

2) Ahmad, H., Samion, M. Z., **Muhamad, A**., Sharbirin, A. S., & Ismail, M. F. (2016). Passively Q-switched thulium-doped fiber laser with silver-nanoparticle film as the saturable absorber for operation at 2.0 µm. L*aser Physics Letters, 13(12)*, 126201.

3) Samion, M. Z., Ismail, M. F., **Muhamad, A**., Sharbirin, A. S., Harun, S. W., & Ahmad, H. (2016). Tunable passively Q-switched thulium-doped fiber laser operating at 1.9µm using arrayed waveguide grating (AWG). *Optics Communications, 380*, 195–200.

4) Ahmad, H., Sharbirin, A. S., **Muhamad, A**., Samion, M. Z., Reduan, S. A., Zulkifli, A. Z., & Ismail, M. F. (2017). Aluminized film as saturable absorber for generating passive Q-switched pulses in the two-micron region. *Journal of Lightwave Technology, 35(12)*, 2470-2475.

5) **Muhamad, A**., Ismail, M., F., Zulkifli., M., Z., Ahmad, H. (2015, May). *Switchable wavelength thulium doped fiber laser at 1900nm by using AWG.* Paper presented at the 10th International Symposium on Modern Optics and Its Applications 2015 (ISMOA'15), Bandung, Indonesia.