NONLINEAR EFFECTS OF MULTI-WAVELENGTH FIBER LASER AND FOUR WAVE MIXING SIGNALS GENERATION IN FEW MODE FIBER AND HIGHLY NONLINEAR FIBER

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ABSTRACT

This thesis presents a study of nonlinear effects in few mode fiber (FMF) and highly nonlinear fiber (HNLF). The signal generation of multi-wavelength fiber laser (MFL) and four wave mixing (FWM) signals had been demonstrated in a 500 m of each FMF and HNLF. This study performs an MFL signal in a closed loop laser cavity incorporated with a passive erbium doped fiber amplifier (EDFA) and a Sagnac loop filter. A linear laser cavity with high power erbium doped fiber amplifier (HPEDFA) is utilized to perform signal generation of FWM. The formation of MFL signal in HNLF and FMF was discovered at 197 mW of EDFA output power with dual wavelength laser signals was observed in HNLF and triple wavelength laser signals has been observed in FMF. For HNLF, the first peak was observed at 1558.77 nm with -12.83 dBm peak power. The secondary peak was observed at 1561.27 nm with -13.16 dBm of peak power. For FMF, the first peak was at 1558.36 nm with -20.41 dBm peak power. The secondary peak was at 1560.94 nm with peak power of -9.44 dBm. The third peak was at 1563.57 nm and at -36.53 dBm of peak power. The signal generation of FWM in HNLF and FMF was performed at 398 mW output power of EDFA. For HNLF, as the pump peak was at 1551.09 nm and probe peak at 1552.06 nm, the first idler was discovered at 1550.13 nm with -51.25 dBm peak power. The secondary idler was obtained at 1553.02 nm with -52.03 dBm peak power. The generated signal of FWM in FMF was observed during the pump peak at 1550.68 nm and pump probe was at 1551.82 nm, first idler was formed at 1545.52 nm with -62.25 dBm peak power. The secondary idler was formed at 1552.98 nm with -60.91 dBm of peak power. The insertion of polarization controller in laser cavity generates low noise MFL signals. Greater suppression of the scattering phenomena in optical fiber should be taken into account in order to generate high OSNR of FWM signal.

ABSTRAK

Tesis ini membentangkan satu kajian kesan ketaklinearan di dalam gentian beberapa mod (FMF) dan gentian ketidaklinearan tinggi (HNLF). Penghasilan isyarat gentian laser pelbagai panjang gelombang (MFL) dan isyarat pencampuran empat gelombang (FWM) telah ditunjukkan dalam FMF dan HNLF yang berukuran 500 m panjang. Kajian ini menghasilkan satu isyarat MFL dalam rongga laser tertutup bersambung pengganda cahaya gentian optik berdop erbium (EDFA) dan satu penapis gelung Sagnac. Satu rongga laser linear dengan pengganda cahaya gentian optik berdop erbium berkuasa tinggi (HPEDFA) digunakan bagi penghasilan isyarat FWM. Pembentukan isyarat MFL dalam HNLF dan FMF ditemui pada 197 mW kuasa keluar EDFA dengan isyarat laser dua panjang gelombang diperhatikan dalam HNLF dan isyarat tiga panjang gelombang laser telah diperhatikan dalam FMF. Bagi HNLF, puncak pertama diperoleh pada 1558.77 nm dengan -12.83 dBm kuasa puncak dan puncak kedua diperoleh pada 1561.27 nm dengan -13.16 dBm kuasa puncak. Untuk FMF, puncak pertama adalah pada 1558.36 nm dengan -20.41 dBm. Puncak kedua adalah pada 1560.94 nm dengan kuasa puncak -9.44 dBm. Puncak ketiga adalah pada 1563.57 nm dan pada -36.53 dBm kuasa puncak. Daripada kajian ini penghasilan isyarat FWM dalam HNLF dan FMF ditemui pada 398 mW kuasa keluaran EDFA. Bagi HNLF ketika puncak pam pada 1551.09 nm dan puncak probe pada 1552.06 nm, idler pertama ditemui di 1550.13 nm dengan -51.25 dBm kuasa puncak. Idler kedua telah diperoleh pada 1553.02 nm dengan -52.03 dBm kuasa puncak. Isyarat FWM dijana dalam FMF diperhatikan ketika puncak pam pada 1550.68 nm dan puncak probe pada 1551.82 nm telah terhasil idler pertama adalah pada 1545.52 nm dengan -62.25 dBm kuasa puncak. Idler kedua telah terhasil pada 1552.98 nm dengan -60.91 dBm kuasa puncak. Kemasukan pengawal polarisasi bahagian dalam rongga laser menjana isyarat MFL pada hingar rendah. Pengawalan yang lebih terhadap fenomena penyerakkan gentian optik perlu diambil kira dalam usaha untuk menjana OSNR yang tinggi bagi isyarat FWM.

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LIST OF SYMBOLS AND ABBREVIATIONS

n	refractive index
I	electric field intensity
P	power
A_{eff}	effective area
Z	electromagnet impedance
μ	vacuum permeability
ε	vacuum permittivity
Δk	phase mismatch
λ_i	initial wavelength
$\emptyset$	phase shift
P	polarization
χ^3	third order susceptibility
ω	frequency
k_j	propagation constant
P_{NL}	nonlinear polarization
v	frequency
N	number of wavelength
M	number of cross mixing product
D	electric density
∇	del operator
ρ_f	total charge density

B	magnetic field
J	current density
NF	noise figure
SNR	signal to noise ratio
ASE	Amplified Spontaneous Emission
CW	Continuous Wave
DCF	Dispersion Compensating Fiber
DFG	Different Frequency Generation
DWDM	Dense Wavelength Division Multiplexing
EDFA	Erbium Doped Fiber Amplifier
FMF	Few Mode Fiber
FWHM	Full Wave Half Maximum
FWM	Four Wave Mixing
HPEDFA	High Power Erbium Doped Fiber Amplifier
HNLF	Highly Nonlinear Fiber
OSNR	Optical Signal to Noise Ratio
SMF	Single Mode Fiber
SMSR	Side Mode Suppression Ratio
SOA	Semiconductor Optical Amplifier
SPM	Self Phase Modulation
WDM	Wavelength Division Multiplexing
XPM	Cross Phase Modulation
2MF	Two Mode Fiber
4MF	Four Mode Fiber

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CHAPTER 1

INTRODUCTION

1.1 Background of the Problem

Communication is a vital procedure for human being to perform daily activities. The progressive growth of the broadband and internet applications drives the massive demand for bandwidth in the communication networks. In communication system, there are three components; the emitter, transmitter and receiver.

Focusing on the transmitter signal system, there are many fabrication and many manufacturing of transmitter devices such as planar waveguide, slab waveguide and optical fibre. Enhancing the communication system using optical approach in speed of light, serve us another alternative way of dwindling the noise effects on interline communication. Enabled by modern optical technology, optical fibre emerges as the quickest and most cost-effective element to maximize and expand network capabilities.

In the mean of expanding the capacity of data transmission, the ability of nonlinear effects had been examined lately. Nonlinear effect in optical fiber is referring to the effect that acts as a hindrance of pulse propagation due to the change of refractive index with optical power and energy field [1].

The nonlinear effects are greatly discovered in optical fiber due to the changes of refractive index of the fiber as the optical wave carrier as the presence of high intensity of light. The main factor of massive utilization of optical fiber in optical communication system is its reliability to transfer data with the speed of light efficiently and perform low loss for a long haul distance data transfer as compared with the conventional metal wire which is affected with the electromagnetic interference [2]. The capacity of single mode fiber (SMF) is excessively approaching the capacity limits foisted by combination of Shannon's information theory and nonlinear fiber effects [3]. Recently, a new type of optical fiber had been introduced to market and which is known as few mode fiber (FMF). This type of optical fiber has smaller core diameter than multimode fiber, however it is able to perform as SMF with more than one mode can be transmitted through. The world first FMF in passive optical network had been demonstrated in 2014 [4]. As a result, the utilization of mode multiplexing has been the successfully adapted to eliminate the combining losses for upstream traffic. Thus, the FMF becomes a new attraction in optical communication and a lot of research works are based on this type of fiber had been executed to serve global users with highly efficient technology in optical communication. Currently, few mode fiber had been used in mode converter system [5], optical filter [6] and to exploit the space division multiplexer (SDM) [7].

1.2 Statement of the Problem

In the data transmission, the pulse width, pulse duration and the transmission length play their role in order to perform an acceptable output signal. Dealing with continuous wave, we need to transform it into a pulse wave to recognize a signal in a data transmission. After a signal had been recognized, the receiver will be able to read the information before distributing it into another form to another places. The invention of FMF leads us to extend the applications of the optical pulse propagation in more modes compared with the SMF [8].

Huge data transmission in optical systems is exposed to the emergence of blocking probability in a same streaming wavelength. A simple wavelength conversion is an alternative approach to reduce the blocking probability and it can be performed by using four wave mixing (FWM) technique and multi-wavelength fiber laser (MFL) system. Due to many applications such as optical switch, wavelength converter and optical fiber sensors, a stable and high signal to noise ratio (SNR) of FWM signals and MFL signals have a large room for improvements in terms of reliability and cost effectiveness by implementing various systems based on optical fiber [9].

This study investigates the nonlinear effects produced in a highly nonlinear fiber (HNLF) and FMF by introducing FWM signal and MFL signal to both fibers. The generation of FWM is obtained from the transmission of the light waves from two input tunable laser sources (TLS) before pumping it into a high power erbium doped fiber amplifier (HPEDFA). However, the signal generation of multi-wavelength is originated from the transmission of light waves from a tunable laser diode (LD) into a ring cavity laser incorporated with Sagnac loop fiber ring. The transmission distance is limited to 500 m each using an FMF and HNLF. This length of optical fibers had been selected due to the limited type of optical fibers in our laboratory and the longest FMF which is available to be tested is a 500 m step index FMF and HNLF.

One of the crucial parts in this study is to generate the signals of FWM and MFL signals in FMF and HNLF. As modes are classified as slow mode and fast mode, the existence of these modes can be utilized to enhance the number of data transmission at the same time interval in FMF but not in HNLF which is used for single mode optical transmission. The different characteristics of fiber are expected to exhibit different type of nonlinear effects at the output of the optical fibers.

1.3 Objective of the Study

The main aim of this research is to study the nonlinear effect of MFL signals and FWM signals generation in FMF and HNLF. The objectives are outlined as follow :

1. To investigate the nonlinear effects in FMF and HNLF.
2. To design signals of MFL and FWM signals in FMF and HNLF
3. To perform comparison of the signals generation of MFL and FWM in FMF and HNLF**.**

1.4 Scope of the Study

This study focuses on the signal generation of FWM and MFL signals in two different type of optical fibers; 500 m step index HNLF and FMF. The MFL signals generation is delimited by an optical laser propagation in a close loop cavity (figure of eight cavity). The system for MFL is delimited to only a single set of tunable LD to function as light source. The system for FWM signals generation is delimited to two input TLS as light sources which are setting up under C-band (wavelength between 1530 nm-1560 nm) in an open cavity (linear cavity).

1.5 Significance of the Study

The demand for heavy information capacity in the full speed of light is a world trend recently. Less noise and less power loss are important characteristics in an optical communication system in order to transmit data. Nonlinear effects such as FWM signals and MFL signals open a new window to global users in extending the ability of high speed data transmission in optical fibers. FWM signals and MFL signals in FMF have the capability to extend the capacity of a data carrier in terms of wavelength expansion and space mode division (SDM). Proper investigation about FWM and MFL in terms of nonlinear response of its peak power, SNR and side mode suppression ratio (SMSR) are highly recommend to provide a functional data transmitter system for heavy and multi-link optical communication purposes.

1.6 Thesis Outline

This thesis is divided into five chapters. Chapter 1 provides the research introduction, research objectives, scope of the study and significance of study. Chapter 2 describes the background of this study, fundamental of nonlinear effects in optics and brief explanation about MFL and FWM. Chapter 3 consists of research methods and processes of the experiment through out the study. Chapter 4 provides results and data analysis on the formation of MFL signals and generated signals of FWM in FMF and HNLF. Based on the laser cavity, the highest OSNR, peak power and stable spectrum are detailed and discussed. The works presented in this thesis are summarized and concluded in Chapter 5. A recommendation for future research is also proposed in this chapter.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Nonlinear optics is a study of optical phenomena that emerged due to any consequence of the modification of optical properties in a material by the presence of light intensity. Technically only laser is sufficiently intense to modify the properties of a material [10]. The beginning of the nonlinear optics field was in 1961 as the second-harmonic generation had been discovered [11]. This was achieved a year after the first laser successfully invented [12]. A lot of waveguide such as planar crystal and optical fiber was massively developed since then. The nonlinear fiber effect influenced the capacity of single mode fiber which is downgraded to reach a limit point of usage [3].

Optical fiber is an effective medium as field intensities of several milliwatts are focused into the small fiber core of 209-215 μm^2 through tens to hundreds of kilometres. The effect of nonlinear refraction is to produce nonlinear phase shift that is dependent on the input power of the optical propagated pulse.

The time independence of the input power causes the nonlinear phase shift to vary with time, resulting in frequency chirping, which means the carrier frequency of the input pulse change with time. Thus, affect the pulse shape through group velocity delay. Hence, power dependence of the refractive index can be a limiting factor for the optical communication performance. This nonlinear phase shift is responsible for the effects is induced by the optical field itself and known as self-phase modulation (SPM). SPM leads to the spectral broadening of pulses propagating inside an optical fiber.

2.2 Nonlinear Effect in Optical Fiber

Figure 2.1 shows the previous achievements and contributions of many successful researchers who had obtained important knowledge in photonics field of study. On the early days, many theories had been proposed and discussed. The significant Maxwell's equation in late 1880 for example, had been introduced to state the fundamentals of electromagnetism [13]. Around the same year, Kerr effect had been proposed to show the changes of refractive index of a material in response to the square of applied electric field [14]. In 1900's, the Pockel's effect had been introduced. This effect shows the birefringence is proportional to the applied electric field but it is only applied for the material which is lack of inversion symmetry such as lithium niobate and another non-centro symmetry media [16].

In 1920's, researchers found the Brillouin and Raman scattering and also two photon absorption theory (TPA) [17]-[19]. All of these achievements had expanded the understanding in nonlinear phenomena as compared to the years back. The growth of nonlinear optics applications are seemingly in an exponential rate. This growth originates with the invention of first laser in 1958 which leads to the demonstration of ruby laser by Maiman in 1960 [12]. After the invention of the first laser, vast publications of theoretical descriptions of nonlinear phenomena occurred and a lot of findings had been proposed since then [21]-[26]. The remarkable Maxwell's equation [13] is the key to understand the energy exchange in light waves and the interaction of polarizations in optical medium.

A laser also had been demonstrated in 1970's to track polar motion. A laser ranges to the Beacon Explorer C spacecraft from a single Goddard Space Flight Center tracking system were utilized to determine the change in latitude of the station arising from polar motion. A precision of measurement was obtained for the latitude during a five-month period in 1970 [28].

In 2000, a group of researcher fabricated zinc oxide diode using an excimer-laser doping process. The technique which was used to form a p-type ZnO layer on an n-type ZnO substrate is subjected to excimer-laser pulses [30]. Ten years later, for the first time, an ångstrom-wavelength free electron laser had been demonstrated [31]. Lately, in 2015 a research of anti-dark solitons in an inhomogeneous optical fiber had been published [32].

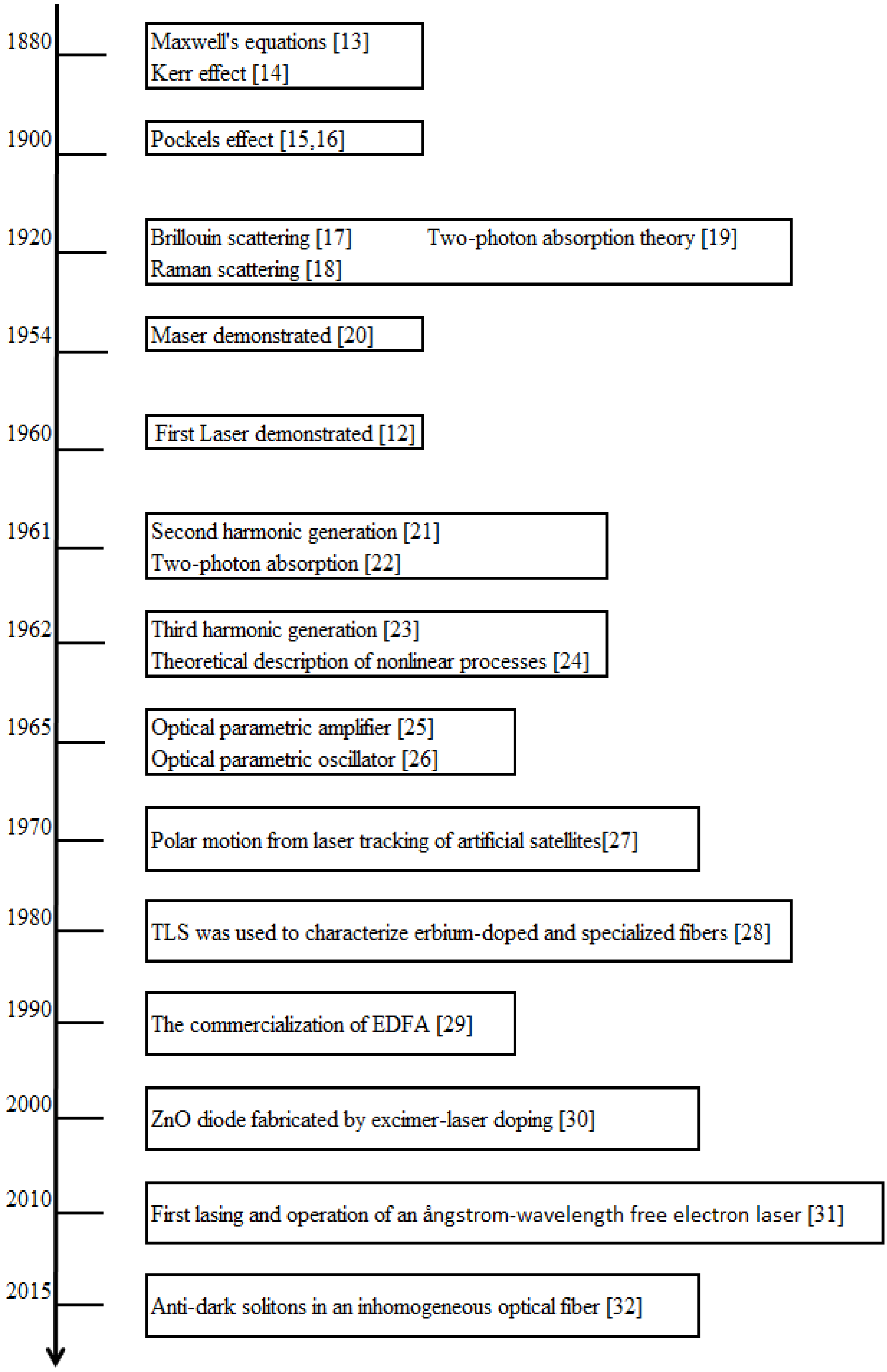

Figure 2.1 Timeline illustrating the history of nonlinear optics and laser study.

2.2.1 Kerr effect

The optical fibre should not always be considered as linear transmission waveguide or channel. A linear term in optics mean intensity-independent phenomena and a nonlinear term refer to intensity-dependent phenomena. The larger the injected power and the longer the transmission distance, the faster the non-linear effects begin to emerge. Execution of optical high-power signal into an optical fiber results the linearity of the optical response to lost and giving rise to diverse non-linear effects. Nonlinear effects in optical fiber occur due to two factors; due to change in refractive index of medium with optical intensity and the other one is due to inelastic scattering phenomenon.

The nonlinearities in optical fiber fall into two different categories same as shown in the Figure 2.2. One is the stimulated scattering (Raman and Brillouin), and the other is the optical Kerr effects. Kerr effects are originated by changing in the refractive index with optical power (refractive index power dependence). The stimulated scatterings are responsible for intensity dependent gain or loss while the nonlinear refractive index is responsible for intensity dependent phase shift of the optical signal in an optical system or laser cavity. One main difference between scattering effects and the Kerr effect is the stimulated scatterings have a threshold power levels at which the nonlinear effects manifest themselves while the Kerr effect does not have a threshold. This is a self-induced effect in which the phase velocity of the wave depends on the wave's own intensity. Kerr effect describes change in a refractive index of fiber due to an electrical perturbation.

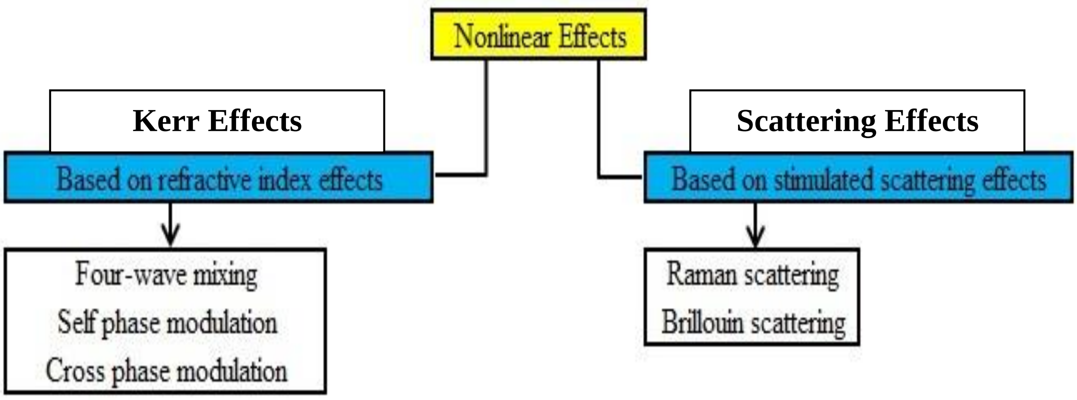

Figure 2.2: Nonlinear effects separation

The intensity of electric field intensity varies in time with the transmitted pulse train. It induces intensity dependent modulation of the refractive index, hence modulation of the phase of the transmitted pulse train.

It is also known that the Kerr effect is a state which the refractive index of optical fiber is slightly dependent on the electric field intensity (input signal) that passing through the optical fiber as shown in Equation 2.1.

$$n = n_{\circ} + n_2 I \quad (2.1)$$

Where is n the refractive index of a fiber, $n_{\circ}$ is the linear refractive index, n_2 is the nonlinear refractive index, I is the electric field intensity, and it is a ratio of optical power, P to the effective mode area, A_{eff} as shown in Equation 2.2.

$$I = P/A_{eff} \quad (2.2)$$

Somehow, the refractive index can be shown in Equation 2.3.

$$n = n_0 + n_2 \frac{|E|^2}{Z_I} = n + n_2 I \quad (2.3)$$

Where E is the energy field, Z_I is the fiber electromagnetic impedance, n_0 and n_2 are linear and nonlinear refractive index respectively. The risen of Kerr nonlinearity effects depends on the shape of the injected field into the fiber. Since the optical signal feeds into the fiber, the signal frequency will interact and perform a complicated behaviour [33].

Kerr effects are three different types of phenomena; self-phase modulation (SPM), cross phase modulation (XPM), and the four-wave mixing (FWM). The SPM is an effect that changes the refractive index of the transmission medium which is caused by the intensity of the pulse. The FWM is an effect, in which mixing of optical waves rise a fourth wave, which can occur in the same wavelength as one of the mixed wave. The XPM is an effect where wave of light can change the phase of another wave of light with different wavelength. This effect causes spectral broadening.

2.3 Multi-wavelength Fiber Laser (MFL)

Lasers in term of time domain is divided into two groups, a continuous wave laser and a pulse wave laser. Laser is term of wavelength domain is divided into two segments, a single wavelength laser and a MFL.

Multi-wavelength is a nonlinear phenomenon which is created from the light wave interference in a waveguide [34]. Multi-wavelength lasing is achievable by using a fiber ring laser system [35]-[36]. A fiber ring laser is constructed by a closed fiber loop to form an optical ring resonator. Commonly a simple fiber ring laser includes an erbium doped fiber as the laser gain medium which allows the occurrence of an optical gain within a spectral range in response to an optical pump signal from a laser diode at 980 nm. The fiber ring provides an optical feedback to circulate the photons at different wavelengths.

A laser oscillation in the fiber ring occurs at a laser wavelength of 1550 nm which had been tuned from 980 nm within a gain spectral range when two operating conditions are met. First, the total optical gain at that laser wavelength exceeds the total optical loss in the fiber ring, and secondly, the optical phase delay associated with a round trip within the fiber ring is 360 degrees or a multiple of 360 degrees. The gain spectral range of the doped fiber, such as erbium (Er)-doped fibers, usually has a large bandwidth and hence allows multiple modes at different frequencies to oscillate at the same period. A single-mode oscillation can be obtained by utilizing one particular mode to oscillate while suppressing other modes.

Various applications require single model laser oscillations. For example, wavelength-division-multiplexing (WDM) has been used to expand the capacity of a fiber communication link by simultaneously transmitting different optical waves at different WDM wavelengths. One commonly-used WDM wavelength standard is the International Telecommunication Union (ITU) standard, where the WDM wavelengths of different optical waves are required to match ITU grid frequencies. Hence, each laser transmitter needs to operate in a single mode at a designated WDM wavelength. Other applications for single-mode laser oscillations include precision spectroscopic measurements, short nonlinear optical processes, among others.

Fiber ring lasers are erupting as a new generation of compact, inexpensive and robust laser sources to produce single-mode oscillations for WDM systems and other applications where a single-mode laser oscillation is desirable. Performance of multi-wavelength signals in the optical fiber laser is depending on the polarization state of light wave. A polarization controller is suggested to be applied in the laser cavity to control the polarization state in a laser system.

2.3.1 Sagnac loop mirror

The Sagnac effect is named after French physicist Georges Sagnac. It is a phenomenon encountered in interferometry that is generated by optical rotation. Sagnac effect is very significance to the modern gyroscope as providing a promised sensor operation as utilizing the difference time propagation between beams of light travels in counter-clockwise and clockwise directions in a closed optical system [37]. The Sagnac effect forms in a setup called a ring interferometer. A beam of light is split and the two beams propagate in the same path but in opposite directions. In return to the point of entry, the two light beams are allowed to exit the ring and undergo interference.

The relative phases of the two exiting beams and the position of the interference fringes are shifted according to the angular velocity of the apparatus. Phase difference between the light beams is generated. This arrangement is also notified as Sagnac loop mirror (SLM). This SLM is utilized in the formation of multi-wavelength laser. Generation of a multi-wavelength laser signal with the SLM only need a single light source and a sufficient input optical power.

In order for optical path to support lasing activity, there must be an integral number of wavelengths around the path and oscillation of photon at a specific frequency, f which obey the requirement. The differential in frequency between the two travelling waves, the beat frequency Δf is noted in the following relationship based on Equation 2.4.

$$\Delta f = \frac{4A\Omega}{\lambda_S P} \tag{2.4}$$

Where A is the area, P is the perimeter of the ring cavity, λ_S is the wavelength of light in lasing medium and Ω is angular rate of rotation.

In term of phase difference between two counter-propagating beams, $\Delta\phi$, can be understand based on Equation 2.5.

$$\Delta\phi = \frac{4A\Omega}{\lambda_S v} \qquad (2.5)$$

Where v is the speed of propagated beams in the Sagnac loop, A is the area, P is the perimeter of the ring cavity, λ_S is the wavelength of light in lasing medium and Ω is angular rate of rotation.

2.3.2 Polarization controller (PC)

Polarization controller is a device which allows us to control the state of polarization of light within fibers. Polarization controller or normally known as PC is widely utilized in various optical research experiments [38]-[41] due to its ability in dealing with the state of polarization in linear even closed loop laser cavity [8][42]-[64]. PC had been inserted into laser cavity to adjust the state of polarization [65]-[67]. All propagated waves in a cavity may achieve same polarization state with the incorporated of PCs in the cavity [68].

The PC is very useful as it was applied into a fiber ring laser cavity as a lasing wavelength tuner to select identical lasing wavelength as reported previously [39]. The combination of PCs in a laser cavity in between of SMF has created a situation of intensity independent loss as reported recently [69]. Periodic filter in a laser cavity is created by the insertion of PC which is one of the core components as reported before [9]. PC also had been used to increase the side-mode suppression ratio above than a minimal value of 20 dB [70]. Enhancement of four-wave mixing in experiment with the installation of PC was reported [48].

The famous type of PC is the three plate type or known as “bat-ear” controller with bent single mode fiber. These PC operates with three manual paddles, which can be rotated into a different angle. Each of the paddles had been classified as the quarter wave plate, half wave plate, and quarter wave plate which respect to the position of the paddle as shown in the Figure 2.3. The half wave plate is in the middle of both quarter plates. This type of PC utilizes stress-induced birefringence to alter and control the state of polarization in a single mode fiber.

The combinations of a quarter-wave plate, half-wave plate, and quarter-wave plate in series allow the transformation of an arbitrary polarization state into any other polarization state. The first quarter-wave plate would transform the input polarization state into a linear polarization state, next is the half-wave plate which the function is to rotate the linear polarization state. The last quarter-wave plate would transform the linear state into an arbitrary polarization state. The fast axis of the fiber is in the plane of the spool, allowing an arbitrary input polarization state to be adjusted by rotating the paddles. Commercial polarization controllers accept bare and ≤ 900 μm diameter of jacketed single mode fibers.

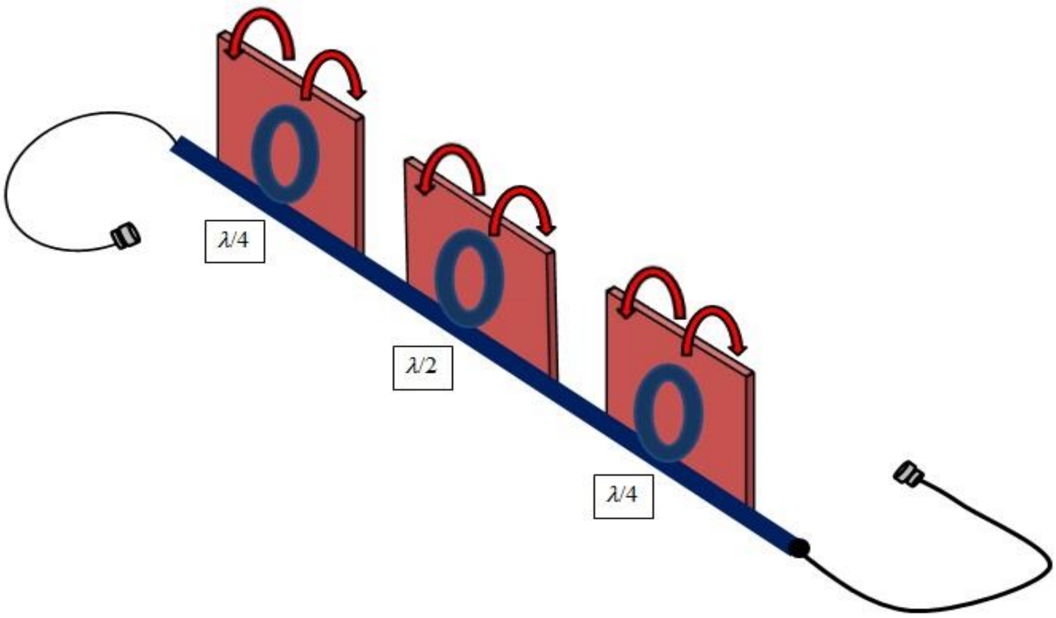

Figure 2.3 The “bat-ear” polarization controller.

2.3.3 Side mode suppression ratio (SMSR)

The definition of side mode suppression ratio is the amplitude difference between the main mode and the largest side mode in the unit of decibels. It is the relation of power between a centre peak of longitudinal mode with the nearest higher order mode. SMSR is a vital factor for the use of the optical pulse propagation in optical communication systems. The insufficient of SMSR value will result in a large amount of amplitude noise on the transmitted pulses due to the interaction of mode partition effect with either fiber dispersion or spectral filtering [71]. Figure 2.4 shows the definition of side mode suppression ratio. It implies as the difference of optical intensity between two peaks.

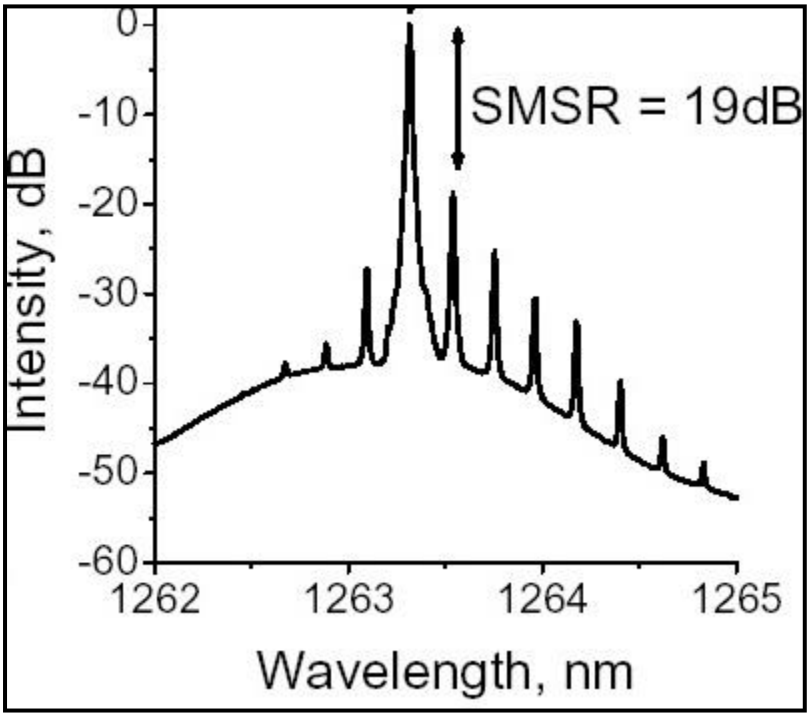

Figure 2.4: The side mode suppression ratio allocation

2.4 Four Wave Mixing (FWM) Signal Generation

Launching two input signals in a same optical fiber theoretically will generate FWM. FWM is also a parametric interaction among waves satisfying phase matching. It is a process of energy conversion taken by the photon pairing in a high irradiance beam upon scattering off the host material. As the process excludes material resonances, total photon energy is necessary to be preserved for significant FWM gain. The induced power transfer from the main pump beam to such satellite spectral sidebands of FWM comes into limitation when it emerges in pulse fiber laser and pulse fiber amplifier meant to retain high spectral brightness. Another necessary condition for efficient FWM is the total photon momentum be preserved, which is known as the phase matching condition and is quantified as in Equation 2.6.

$$\Delta k = 2\emptyset_0 - \emptyset_1 + \emptyset_2 = 0 \qquad (2.6)$$

Where phase shift, $\emptyset_i$ is defined based on Equation 2.7.

$$\emptyset_i = \frac{2\pi n_{eff}(\lambda_i)}{\lambda_i} + \emptyset_{NL(i)} \qquad (2.7)$$

Here the symbols of Δk, λ_i, $n_{eff}(\lambda_i)$, and $\emptyset_{NL(i)}$ indicates the phase shift, wavelength, fiber refractive index and non-linear phase shift for each beam respectively.

FWM in optical fiber has many applications. FWM is usable for wavelength conversion, phase conjugation, quantum noise reduction, supercontinuum generation [33] and optical sampler [72]. FWM had been used dramatically during 1990's because of its potential application in WDM light wave systems [73]-[76]. The application of phase conjugation is to be utilized for dispersion compensation in optical communication process [74]-[79], and it was only introduced for the first time in 1979 [80]. FWM has led to the reduction of quantum noise via squeezing phenomenon [81]-[83].

The fundamental of an applied parametric process lies in the nonlinear response of bound electrons of a material to an applied optical field. The parametric process is classified into two terms; second order and third order depend on the susceptibility of the process. FWM is a third order nonlinearity and is derived in third order susceptibility (χ^3).

FWM is easily observable due to the process of third order is unlike the second order which this one is allowed in all media. The theory of FWM follows closely the general theory of optical mixing. The formation of this effect is drawn by the formation of two photons. In quantum-mechanical terms, the FWM appears when single or more waves are annihilated and other photons are created at different frequencies which obeys the conservation of net momentum and energy during the parametric interaction.

FWM is a practical process to generate new waves. On a fundamental stage, the harmonic motion of bound electrons under influence of an applied filed caused total polarization P induced by electric dipoles is not linear in the electric field and relies on Equation 2.8.

$$P = \varepsilon_0 \left(\chi^1 \cdot E + \chi^2 : EE + \chi^3 \vdots EEE + \dots \right), \tag{2.8}$$

P is the total polarization, ε_0 is the vacuum permittivity, χ^j = (j = 1,2,3,…) is jth order susceptibility and E is the energy field. The third order susceptibility χ^3 is responsible for third harmonic generation, nonlinear refraction and FWM. Most of the nonlinear effects in optical fiber have relation with the intensity dependence of refractive index which is known as nonlinear refraction. The total refractive index, $\tilde{\eta}$ can be written as in Equation 2.9.

$$\tilde{\eta} = n(\omega) + n_2 |E|^2 \tag{2.9}$$

Where n (ω) is the linear part and $|E|^2$ is the optical intensity inside fiber, and n_2 is the nonlinear-index coefficient with relation to third order susceptibility, χ^3 by the Equation 2.10.

$$n_2 = \frac{3}{8n} \operatorname{Re} \left(\chi^3 \right) \tag{2.10}$$

Where Re is the real part and optical field is assumed to be linearly polarized so that only one component of third order susceptibility, χ^3 of four rank tensors contributes to refractive index. The third order susceptibility of χ^3 is able to affect the polarization properties of optical input through nonlinear birefringence. Consider four waves oscillating at frequencies $\omega_1, \omega_2, \omega_3$, and ω_4 and linearly polarized along same axis. The total electric field refers to Equation 2.11.

$$E = \frac{1}{2} \hat{x} \sum_{j=1}^{4} E_j \exp[\, i(k_j z - \omega_j t)] + c.c., \tag{2.11}$$

Where the k_j is the propagation constant E_j (j = 1,2,3 and 4) electric field, i is the wave number, ω_j frequency (j = 1,2,3, and 4), k_j (j = 1,2,3 and 4) is propagation constant, and t is time. Four waves are assumed to be propagating in same direction. We notice that the third order polarization term is given in Equation 2.12.

$$P_{NL} = \varepsilon_0 \chi^3 \vdots \text{ EEE} \tag{2.12}$$

Where P_{NL} is the induced nonlinear polarization, ε_0 is the vacuum permittivity, χ^3 is third order susceptibility and E is the electric field. For the induced nonlinear polarization form can be expressed in Equation 2.13.

$$P_{NL} = \frac{1}{2} \hat{x} \sum_{j=1}^{4} P_j \exp[\, i(k_j z - \omega_j t)] + c.c., \tag{2.13}$$

With two input frequency components are coupled into a coupler another two additional frequencies are created. In general for *N* number of wavelengths of input channel will produce *M* number of cross mixing products and are given by the Equation 2.14.

$$M = \frac{N^2}{2}(N-1) \tag{2.14}$$

As mentioned by Liu et.al [84], FWM effect in the cavity is related to three parameters of optical fiber, the length, the dispersion and the nonlinearity coefficient. Based on the theory, the HNLF is highly recommended as compared to SMF to increase the FWM effect in cavity. The fiber non-uniformity plays a vital role for suppressing the FWM process efficiency in a longer fiber [85].

2.4.1 Phase matching

Phase matching is a crucial part to develop a four wave mixing technique in performing wavelength conversion. Phase-matching is imperative requirement for coherent nonlinear optical processes such as parametric amplification and frequency conversion, allowing nonlinear sources to combine constructively, resulting in more efficient emission. In contrast, phase mismatch prevents microscopic nonlinear sources from combining effectively, resulting in destructive interference and thus lead to low efficiency.

Phase matching is a group of applied technique to generate efficient nonlinear interactions in a medium. It is ensuring that a proper phase relationship between the interacting waves is maintained along the propagation direction in an optical transmission system. Only if that condition is fulfilled, amplitude contributions from different locations to the product wave are all in phase at the end of the nonlinear crystal [86].

The usual technique for achieving phase matching in nonlinear crystals is birefringence phase matching, where one exploits birefringence to cancel the phase mismatch. This technique comes in many variations: Type I phase matching means that, for example in sum frequency generation the two fundamental beams have the same polarization, perpendicular to that of the sum frequency wave. Conversely, in type II phase matching, the two fundamental beams have different polarization directions; this can be appropriate when the birefringence is relatively strong (over-compensating the dispersion in a type I scheme) or the phase velocity mismatch is small.

The distinction between type I and type II similarly applies to frequency doubling, and to processes such as degenerate or non-degenerate parametric amplification. The different polarization arrangements can have various practical implications, for example for the combination of several nonlinear conversion stages, or for intra-cavity frequency doubling.

Critical phase matching means that an angular adjustment of the crystal (or the beam) is used to find a phase-matching configuration, whereas in noncritical phase matching all polarization directions are along the crystal axes, and the angular position is then not a sensitive parameter.

The wave vector of all involved beams may have the same direction (collinear phase matching) or different directions (non-collinear phase matching), where, however, the vector sum of the generating beams equals the wave vector of the product beam. A special case is a chromatic phase matching where at least one of the interacting beams is angularly dispersed so that each frequency component of the signal is properly phase-matched.

A special technique of significant importance is quasi-phase matching, where real phase matching does not occur, but high conversion efficiencies are nevertheless obtained in a crystal where the sign (or strength) of the nonlinearity varies periodically.

At the stage of achieving the phase match, the group velocities of the interacting waves are in general still not matched; there is a certain group velocity mismatch, which limits the interaction length for pulses and the spectral range. In addition, there is only a finite range of angles beams where phase matching works and particularly for critical phase matching. This range of angles is usually called the angular phase-matching bandwidth.

2.5 Previous Works of Multi-wavelength Fiber Laser (MFL)

The occurrence of two or more high peak power photons from a nonlinear system in an optical fiber based on lasing which is launched from a single optical light source is called MFL. The photon is characterized based on their optical power and their optical wavelength.

Fiber lasers can be used to generate continuous wave radiation as well as ultra-short optical pulses [87]. The wavelength division multiplexing (WDM) techniques have shown to unlock the available fiber capacity and to increase the performances of broadband optical access networks. One of the essential components is the creation of new low-cost laser sources. Candidates for such applications are multi-wavelength fiber ring lasers as they have simple structure, are low cost, and have a multi-wavelength operation. Recently, multi-wavelength lasers have caused considerable interests due to their potential applications such as wavelength converter [88], fiber sensors [89] and fiber-optics instrumentations.

Requirements for multi-wavelength sources include; stable multi-wavelength operation, high signal to noise ratio and channel power flattening. Compared to a system that uses a number of discrete semiconductor diode laser [90], it is physically easier to produce a multiple wavelength source using a single gain medium including a wavelength selective element. In order to define lasing wavelengths, wavelength selective comb filters have been included in the laser cavity. A MFL is highly desirable for the cost and size reduction, improvement of system integration and compatible with optical communication networks. For the past one decade or so, EDFs have been extensively studied and developed as a gain medium for the multi-wavelength laser.

MFL operations around 1550 nm have been generated in erbium-doped fiber lasers by utilizing Mach–Zehnder comb filter [35] or Fabry–Perot filter [36], fiber Bragg grating (FBG) cavities [91], four-wave-mixing effect in highly nonlinear fiber [92]-[93] and nonlinear polarization rotation (NPR) [94]. Multi-wavelength fiber lasers or MFLs have become a great interest since their potential as cost effective multi-wavelength sources which is practical for wavelength-division multiplexing (WDM) optical sensors, gas detection and optical communication have been explored lately [9],[95]-[96]. MFL is able to be applied as wavelength converter and for that purpose a commercial Fabry Perot laser had been effectively used as cheap wavelength converter [97].

A good performance of MFL with proper set up had been recorded [98]. Wavelength tunability in laser has been explored by optimization in laser cavity [99]. Erbium doped fiber ring laser had been used to produce tunable dual wavelength laser [100]. The gain competition leads to the instability of laser output due to the homogeneous gain broadening of erbium-doped fibers (EDFs). Several methods have been introduced to palliate the gain competition [101]-[102]. MFLs experiment which applied FWM in dispersion shifted fibers (DFSs) and photonic crystal fibers (PCFs) to stabilize the laser outputs have been reported [95]. Instead dual wavelength, triple wavelength also had been reported using Sagnac loop application [103]. Four-wave mixing also had been applied to obtain stable dual wavelength [104] and various methods had been founded to stabilize dual wavelength [105].

2.6 Previous Works of Four Wave Mixing (FWM)

The most common news on four-wave mixing is the wide applications based on this nonlinear effect. FWM had been utilized in wavelength conversion with large spacing and wide tunability [106]. Even in MFL scope, FWM signals had been experimentally demonstrated as the basic technique to generate multi-wavelength in single mode fiber (SMF) and HNLF in 2013 to investigate the lasing stability [102]. In 2016, FWM technique had been applied to microfiber to enhance the phase matching condition [107]. It is almost known the advantages of FWM should not be wasted and a deeper research need to carry out to provide us with better nonlinear optics applications in daily life.

2.7 Amplified Spontaneous Emission (ASE)

Amplified spontaneous emission or super-luminescence is light, produced by spontaneous emission that has been optically amplified by the process of stimulated emission in a gain medium. It is inherent in the field of random lasers.

ASE is produced when a laser gain medium is pumped to produce a population inversion. Feedback of the ASE by the laser's optical cavity may produce laser operation if the lasing threshold is reached. Excess ASE is an unwanted effect in lasers, since it is not coherent, and limits the maximum gain that can be achieved in the gain medium. ASE creates serious problems in any laser with high gain and/or large size. In this case, a mechanism to absorb or extract the incoherent ASE must be provided. Otherwise, the excitation of the gain medium will be depleted by the incoherent ASE rather than by the desired coherent laser radiation.

2.8 Optical Pulse Propagation

Optical pulses are defined as flashes of light. The pulse is often generated with laser and delivered in the form of laser beam. Continuous wave is able to be transformed into pulse wave type by certain process. Different input power (amplitude) over propagated wavelengths is one of the characteristics of pulse wave.

In this section, the basic propagation equation for single mode optical fiber is presented. Following the introduction of nonlinear Schrodinger equation, NLSE, a discussion on pulse propagation governed by group velocity dispersion, GVD, self-phase modulation, SPM, and combination of both SPM and GVD.

The process of light field propagation in fiber is able to be explained by Maxwell’s equations. The equations can be utilized to predict the existence of any entity called electromagnetic wave. This wave travelled in space and time with the velocity of light. The Maxwell’s equations can be derived from the fundamental laws of Faraday and Ampere which founded from experiments. Conceptually, Maxwell’s equations describe how electrical charges and electrical currents act as sources for the electric and magnetic fields. It describes how a time varying electric field generates a time varying magnetic field and vice versa.

Gauss's law describes how the fields emanate from charges. In details, this law describes the relationship between an electric field and the generating electric charges as refer in Equation 2.15.

$$\nabla .\ D = \rho_f \qquad (2.15)$$

D is the electric field density, ρ_f is the total charge density. Gauss's law for magnetism states that there are no magnetic changes and it is similar to electric charges as refer to Equation 2.16.

$$\nabla .\ B = 0 \qquad (2.16)$$

where B is magnetic field. In terms of field lines, this equation states that the field lines neither begins nor ends but makes loops or extend to infinity.

Faraday's law describes how a time varying magnetic field induces the electric field as refer to Equation 2.17.

$$\nabla \times E = -\frac{\partial B}{\partial t} \qquad (2.17)$$

This equation implies that the curl, $\nabla \times$ of electric field, E is equal to the magnetic derivative of the magnetic field, ∂B with respect changes in time, ∂t. Ampere's law with Maxwell's correction states that magnetic field can be generated by electrical current and by changing electric field as refer to Equation 2.18.

$$\nabla \times H = J + \frac{\partial D}{\partial t} \qquad (2.18)$$

where J is a current density, D electric density, and ∂t time differential of the electric field [107].

2.9 Type of Optical Fibers

Optical fiber is a type of waveguide to allow propagation of optical signal from a transmitter to a receiver. Based on the concept of internal reflection, fiber optics now had grown diversely to satisfy our modern demand especially in communication technology. Its high bandwidth capabilities and low attenuation characteristics make it ideal for gigabit transmission and beyond.

Years back, in 1970's the demand for optical fiber was tremendously grown. Nowadays, there are a lot of optical fibers manufacturers in the current market such as Furukawa, Thorlabs, AFL, FibreFab and Optical Cable Corporation (OCC). The applications for optical fiber is also numerous. The advantages of optical fiber are suitable for long haul data transmission, exhibits as non-conductivity material, small diameter but large bandwidth and light in weight.

The most well-known and commonly use optical fiber is the single mode fiber (SMF). An SMF only allows one mode of light to propagate along the fiber channel. There are also several types of optical fiber which had been introduced into market for various purposes. FMF is an optical fiber which can allow more than one mode of light wave to propagate into the channel. Most recent years, there has been a growing interest in the development of FMF for mode division multiplexing (MDM), which is founded to be a promising solution for scaling the data-carrying capacity of networks system [108]. FMFs are demonstrated as a good compromise as they are sufficiently resistant to mode coupling compared to standard multimode fiber. A standard multimode fiber has larger core diameter as compare with SMF. In terms of dispersion and loss, they have the same performance as SMF. Due the absence of mode interaction it is possible to use this fiber in the single-mode operation where all the data is carried in only one of the spatial modes throughout the fiber. An experiment for single-mode operation was carried out by splicing SMF to both ends of a 35-km-long FMF at 1310 nm. After 35 km of transmission, no modal dispersion or excess loss was observed [109].

HNLF is another type of fiber. HNLF leads to novel nonlinear effect. This type of fiber is constructed from SMF. The main advantage of applying the HNLF as a nonlinear media is its ultrafast nonlinear response. This nature of nonlinear can be utilized in ultrafast switching and ultrafast signal processing. Its small magnitude in normal dispersion regime is due to rapid pulse broadening [110].

Optical power in fiber optics sytem is expressed in term of dBm. The decibel term implies the assumption of input power is 1 mW. The optical output power from an optical fiber can be obtained after subtracting the optical power loss from the input power given. The input power with 1 mW is expressed as 0 dBm and highly addressed in research. For every 3 dB power loss, means the power amount is reduce into half of the value from the initial power given or input power.

2.10 Erbium doped fiber amplifier (EDFA)

In optical communication system the output power will suffer of pulse broadening and power loss when across a long haul data transmission system. Thus, these deficits promote a need of signal amplification and signal reshaping to compensate this issue. Signal amplification is commonly used in practical to overcome this problem. Optical amplifiers are divided into two categories. The first is semiconductor laser amplifier or semiconductor optical amplifier (SOA). It is an amplified optical signal based on the semiconductor gain medium. The second type of optical amplifier is based on active fiber or doped fiber amplifier. EDFA is a common amplifier which is widely used among researchers and belongs to this category.

The most important part in the invention of optical amplifier is the noise figure (*NF*) and gain. They are related to each other. Low *NF* and higher gain are the main ideas to produce a practical and effective amplifier [11]. The *NF* for an optical amplifier is defined in Equation 2.19.

$$NF \equiv \frac{SNR_{in}}{SNR_{out}} \tag{2.19}$$

Where SNR_{in} and SNR_{out} are the signal-to-noise ratios at the amplifier input and output respectively. The origin of optical amplifier noise is amplified spontaneous emission. All amplifiers add noise, and it can be shown that even the ideal optical amplifier has a noise figure of 3 dB. Typical values for EDFAs are 4 to 6 dB.

This amplifier is based on a single mode optical fiber and had been doped with erbium ions which act as active fiber [111]-[112]. The optical operation takes place three level system. A pump photon is absorbed by an erbium ion at the ground

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