Sudan University of Science & Technology

College of Graduate Studies

Performance Evaluation of Hybrid Optical Amplifier for Wavelength Division Multiplexing Transmission

تقييم أداء المكبرات الضوئية الهجين للإرسال باستخدام التبديل بتقسيم الطول الموجي

Thesis Submitted in Partial Fulfillment of the Requirements of the Degree of M.Sc.in Electronics Engineering (Communication Engineering)

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الآيـة

بسم الله الرحمن الرحيم

قال تعالى:

{يَرْفَعِ اللهُ الَّذينَ آمَنُوا مِنْكُم والَّذينَ
أوتُوا ٍالعلمَ دَرَجَاتٍ والله بما تعْمَلُون خَبِيرٌ}

المجادلة 11

Dedication

Dedication to my mother…

Dedication to my father…

Dedication to my Husband

Dedication to my daughter

Dedication to my sisters..

Dedication to my friends

Dedication to all my teachers …

In whom I believe so much

Acknowledgments

First, we need to thankfully our god (Allah) that without his blessing this work will not complete.

Then I thank my supervisor **Dr. Fath Elrhman Ismael** for his patience and countless hours and valuable efforts to guide and advise to complete the work in his fair way. I extend my thanks to all who stood with me to achieve this research which it come because of grace of God. Lastly, I need to thank our teachers in department of electronic engineering for their efforts in helping and support.

Abstract

To fulfill the need of higher bandwidth, enhanced number of users, enhanced speed of communication of today's users, the concept of wavelength division multiplexing (WDM) and fiber optic are developed. In which the multiple input signals are combined together and transfers as a single input. It uses the concept of multiplexing and de-multiplexing. WDM system comprises of amplifiers that are used to enhance the performance of the optical fiber system. This study analyzes a hybrid configuration of Raman amplifier and erbium-doped fiber amplifier (EDFA) which proposed to obtain a better performance in term of gain, noise figure and flat gain. It is based on the optimum parameter configuration of Raman amplifier and EDFA. The simulation is done by using optisystem software. The hybrid amplifier consists of Raman amplifier with multi-pump power set up and pump power of EDFA with the pump wavelength of 980 nm is designed and simulated in order to obtain higher gain and lower noise figure. From the simulation of the hybrid configuration, the optimum output has been achieved. The hybrid configurations exhibit the average gain of 46.1dB and average noise figure of 3 dB. The flat gain obtained in wide bandwidth between 1530 nm to 1600 nm which include C-Band and L-Band frequency with the gain bandwidth of 70 nm.

المستخلص

تلبية للحاجة إلى عرض نطاق ترددي أكبر ، وبسبب زيادة عدد المستخدمين ، ولتعزيز سرعة الاتصال بين مستخدمي اليوم ، تم تطوير مفهوم دمج وتقسيم الطول الموجي وتطوير الألياف البصرية. حيث يتم الجمع بين إشارات الإدخال المتعددة وتحويلها لتدخل كمدخل واحد، وفي ذلك يستخدم مفهوم التبديل وإلغاء التبديل. يتكون نظام دمج وتقسيم الطول الموجي من مكبرات تُستخدم لتعزيز أداء نظام الألياف البصرية. يحلل هذا البحث تكوين هجين من المكبر الضوئي الذي يسمى رامان و المكبر الضوئي خليط أربيوم .اقترح للحصول على أداء أفضل من حيث الكسب والكسب المسطح ورقم الضوضاء ، واستند إلى المعاملات المثالية لتكوين مكبر رامان و المكبر الضوئي خليط أربيوم. تمت المحاكاة باستخدام برنامج (أوبتي سيستم). يتألف المكبر الهجين من مكبر رامان مع قدرة ضخ متعددة القيم وقوة ضخ المكبر الضوئي خليط أربيوم مع الطول الموجي للمضخة البالغ 980 نانومتر وتم تصميمه ومحاكاته للحصول على كسب أعلى ورقم ضوضاء أقل. من المحاكاة للمكبر الضوئي الهجين نجد أنه قد تحقق الخرج الأمثل. وتبين متوسط الكسب البالغ46.1 ديسيبل ومتوسط ضوضاء بلغ 3 ديسبيل. قيمة الكسب المسطح الذي تم الحصول عليه في نطاق واسع بين 1530 نانومتر إلى 1600 نانومتر والتي تشمل ترددات نطاق الحزمة (سي) ونطاق الحزمة (إل) و عرض نطاق الكسب 70 نانومتر.

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LIST OF ABBREVIATION

ASE	Amplified Spontaneous Emission
DRA	Distributed Raman Amplification
EDF	Erbium Doped Fiber
EDFA	Erbium Doped Fiber Amplifier
GFF	Gain Flattening Filter
HOA	Hybrid Optical Amplifier
NF	Noise Figure
NSP	Noise Power Spectral Density
OSA	Optical Spectrum Analyzer
OSNR	Optical Signal to Noise Ratio
SNR	Signal to Noise Ratio
SRS	Stimulated Raman Scattering
SOA	Semiconductor Optical Amplifiers
RA	Raman Amplifier
WDM	Wavelength Division Multiplexing

LIST OF SYMBOLES

G	Gain
P_{out}	Output Power
P_{in}	Input Power
X	Amplified Signal
Y	Noise
G_{EDFA}	EDFA Gain
L	EDFA Length
λp	Pump Wavelength
λs	Signal Wavelength
r_p	Cross Section Ratio
σ_{pa}	Pump Absorption
σ_{pe}	pump Emission
σ_{sa}	Signal Absorption
σ_{se}	Signal Emission
G_{RAMAN}	RAMAN Gain
Pp	Pump Power
Ps	Signal Power
Z	Longitudinal Position along the fiber
As	Rayleigh Scattering coefficient.
G_{Hybrid}	Gain of Hybrid Amplifier
F	frequency

CHAPTER ONE

INTRODUCTION

1.1 Preface

For several years now, optical fiber communication systems are being extensively used all over the world for telecommunication, video and data transmission purposes. The demand for transmission over the global telecommunication network will continue to grow at an exponential rate and only fiber optics will be able to meet the challenge. Presently, almost all the trunk lines of existing networks are using optical fiber. This is because the optical fiber capable of allowing the transmission of many signals over long distances. However, attenuation is the major limitation imposed by the transmission medium for long-distance high-speed optical systems and networks. So with the growing transmission rates and demands in the field of optical communication, the electronic regeneration has become more and more expensive.

In optical fiber network, amplifiers are used to regenerate an optical signal, amplify and then retransmitting an optical signal. In long-haul optical systems, many amplifiers are needed to prevent the output of signal seriously attenuated. The powerful optical amplifiers came into existence, which eliminated the costly conversions from optical to electrical signal and vice versa [1].

Due to the need of longer and longer unrepeated transmission distances wavelength division multiplexing optical transport networks are expected to provide the capacity required to satisfy the growing volume of telecommunications traffic in a cost-effective way. WDM multiplexes a number of optical carrier signals onto a single optical fiber by using different wavelengths at speed in Gbps.

In this work study performance evaluation of hybrid amplifier (Raman Amplifier and Erbium Doped Fiber Amplifier (EDFA) in term of gain for WDM applications.

1.2 Problem Statement

In optical fiber communication system signal traveling for long distances inside the fiber suffers from various losses which increases the demand of high gain amplifiers and flat gain in wide bandwidth. There are many amplifiers available now but there is a need to evaluate their performance in long haul communication link.

1.3 Proposed Solution

This research considers hybrid amplifiers compose Raman amplifier and erbium-doped fiber amplifier (EDFA) and evaluate their performance for WDM applications.

1.4 Aim and Objectives

❑ The main aim is to design hybrid configuration of Raman amplifier and erbium-doped fiber amplifier and evaluate its performance in term of gain, then determine the design parameters affecting the hybrid amplifier performance.

❑ The objectives are:

- To Increase the gain for hybrid amplifier.
- To decrease the noise figure for both hybrid amplifiers RAMAN and EDFA
- To increase the bandwidth of flat gain.

1.5 Methodology

The type of hybrid optical amplifier has been determined by study the design parameters for this hybrid optical amplifier. Next optimize these design parameters for both hybrid amplifiers RAMAN and EDFA.

Optisystem software has been used in order to design and simulate the configuration of EDFA, Raman amplifier and hybrid EDFA-Raman amplifier. Firstly the simulation will be started with the configuration and optimization of EDFA .Secondly Raman amplifier will be simulated .Finally by using the optimum parameter of both amplifiers, a hybrid optimum Raman-EDFA will be configured and simulated then evaluate the performance of this hybrid amplifier and discuss the results of simulation.

1.6 Thesis Outlines

This thesis contains of five chapters, Chapter One contains introduction that shows the problem statement, objectives, and the scope work of research .Chapter Two presents literature Review which is gives the background of optical amplifier and related works to the design of hybrid optical amplifier .Chapter Three describes methodology of this research by using optisystem software to simulate the design and explains the simulation process by change in simulation parameters. Chapter Four include the simulation results and discussion of these results. Chapter Five shows the conclusion for the whole research, and recommendation for future work.

CHAPTER TWO

LITREATURE REVIEW

This chapter gives an overview of optical fiber communication system. The optical amplifiers will be discusses first then discusses its types, also the design principle for every type of optical amplifier which is used with WDM applications.

2.1 Background

2.1.1 Introduction of Fiber Optic Communication System

Optical fiber is a medium for carrying information from one point to another in the form of light. A basic optical fiber system consists of a transmitting device that converts an electrical signal into a light signal, an optical fiber cable that carries the light, and a receiver that accepts the light signal and converts it back into an electrical signal. The communication system shows in Fgure2.1 consists of a transmitter or modulator linked to the information source, the transmission medium, and a receiver or demodulator at the destination point [1].

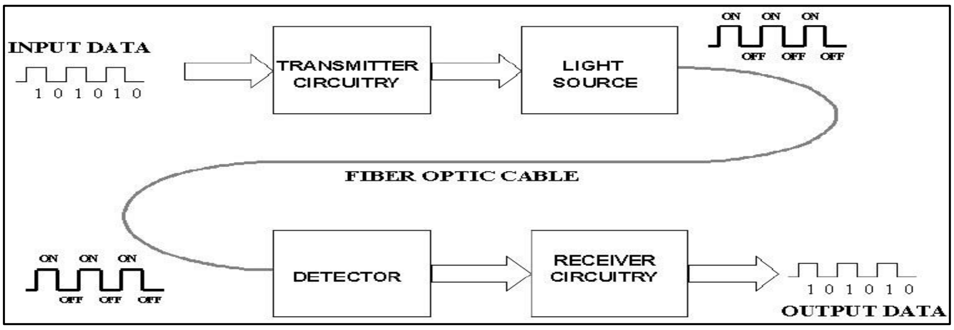

Figure 2.1: Component of optical fiber communication system [2]

2.1.2 Advantages of Optical Fiber Communication

Fiber-optic communication systems can be used to transmit more information than copper cables and are well-suited for use with digital communications .The optical carrier frequency in the range 1013 to 1016 Hz. Optical fibers offer low power loss, Signals can be transmitted further, It incurs low loss to the signal usually 0.3 dB/Km .Fiber optic cables are made of glass or plastic, and they are thinner than copper cables These make them lighter and easy to install. Optical fibers are cheap than the conventional wires [1].

2.2 Optical Amplifier

An optical amplifier is a device which amplifies the optical signal directly without ever changing it to electricity the light itself is amplified. Optical amplifiers are a key enabling technology for optical communication networks. Together with wavelength-division multiplexing (WDM) technology, which allows the transmission of multiple channels over the same fiber, optical amplifiers have made it possible to transmit many terabits of data over distances from a few hundred kilometers and up to transoceanic distances, providing the data capacity required for current and future communication networks. An ideal optical amplifier is designed to directly amplifier any input optical signal, without needing to transform it first to an electronic signal. It can amplify all WDM channels together, also it is generally transparent to the number of channels, their bit-rate, and modulation format [3].

2.2.1 Applications of optical amplifiers

Optical amplifiers have found many applications ranging from ultra-long undersea links to short links in access networks [4]:

- **In-line amplifier:** This is used as a repeater along the link at intermediate points. It can be used to compensate for transmission loss and increase the distance between regenerative repeaters, as shown in Figure 2.2

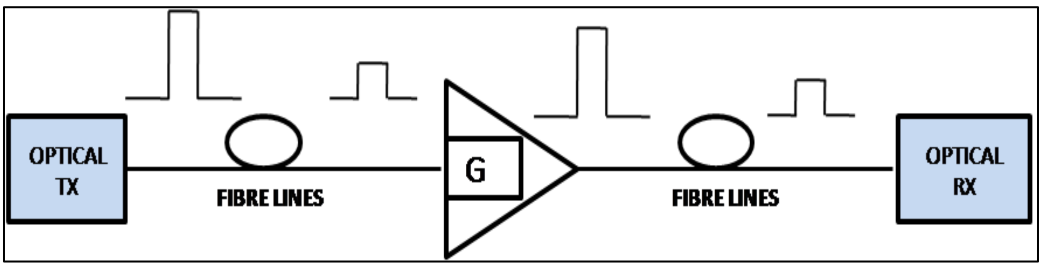

Figure2.2: Optical Amplifier as In-Line Amplifier [4].

- **Pre-amplifier:** This is used before the photo detector at the receiver in order to strengthen the weak received signal. This increases the sensitivity of the detector effectively. This configuration is shown in Figure 2.3

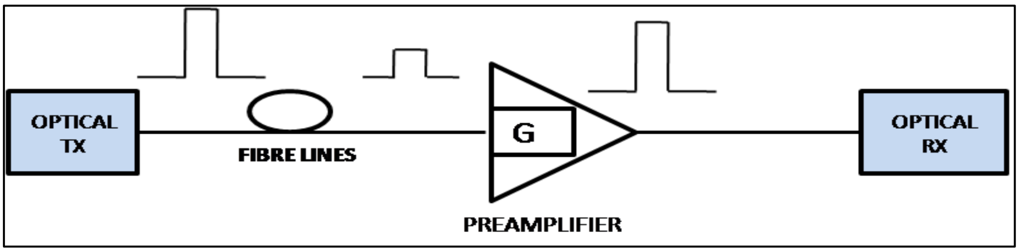

Figure. 2.3: Optical Amplifier as Preamplifier [4].

- **Post -amplifier:** This is used at the transmitting end, after the source and operates near the saturation region. The power launched into the fiber is enhanced and so the repeater span can become large. This serves to increase the transmission distance by 10- 100km depending on the amplifier gain and fiber loss. This configuration is shown in Figure 2.4.

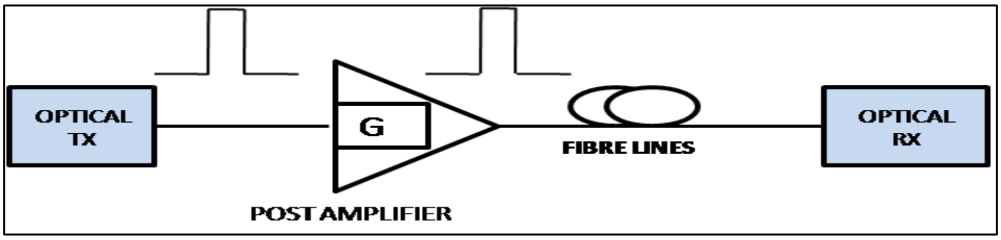

Figure. 2.4: Optical Amplifier as Post amplifier [4].

2.2.2 Types of Optical amplifier

Optical amplifiers are classified on the basis of structure i.e. whether it is semiconductor based (Semiconductor optical amplifiers) or fiber based (Rare earth doped fiber amplifiers, Raman). The optical amplifiers are also classified on the basis of device characteristics i.e. whether it is based on linear characteristic (Semiconductor optical amplifier and Rare-earth doped fiber amplifiers) or non-linear characteristic (Raman amplifiers) [5].

2.2.3 Semiconductor Optical Amplifiers (SOAs)

SOAs are amplifiers which use a semiconductor to provide the gain medium. They operate in a similar manner to standard semiconductor lasers (without optical feedback which causes lasing), and are packaged in small semiconductor “butterfly” packages. SOAs amplify incident light through stimulated emission. When the light traveling through the active region, it causes these electrons to lose energy in the form of photons and get back to the ground state. Those stimulated photons have the same wavelength as the optical signal, thus amplifying the optical signal. Figure2.5shows the basic working principle of SOA.

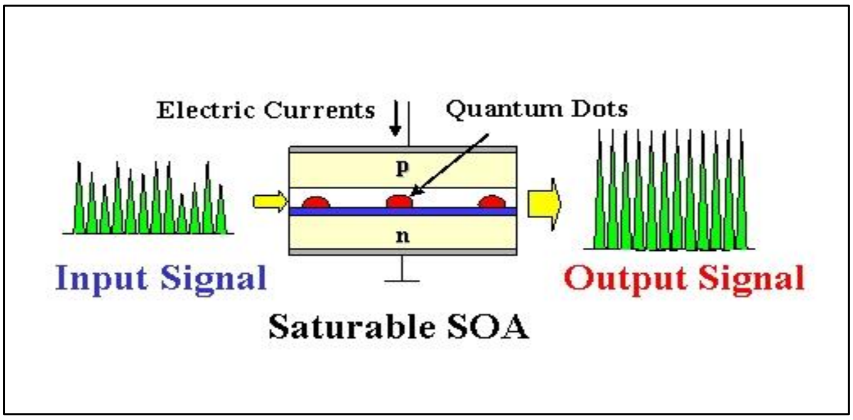

Figure 2.5: Semiconductor Optical Amplifiers [6].

Despite their small size and potentially low cost due to mass production, SOAs suffer from a number of drawbacks which make them unsuitable for most applications. In particular, they provide relatively low gain (<15 dB), have a low saturated output power (<13 dBm), and relatively high NF. Furthermore, the fast response time of SOAs means that when operating near the saturation level they suffer from signal distortion for single channel operation, and noise due to cross-gain modulation for multi-channel WDM operation. These drawbacks make the SOAs largely unsuitable for multichannel WDM applications. However, they can suit some applications such as single channel booster amplifiers which don’t require high gain or high output power [7].

2.2.4 Erbium Doped Fiber Amplifier (EDFA)

Erbium doped fiber amplifier is most common optical amplifier, commercially available since the early 1990's. It is a most stable optical amplifier with operating bands 1525 – 1565 nm wavelength region. It works best in this range with gain up to 40 dB. For communication, there are two windows 1530-1560nm(C-band) and 1560- 1610nm (L band) [7].

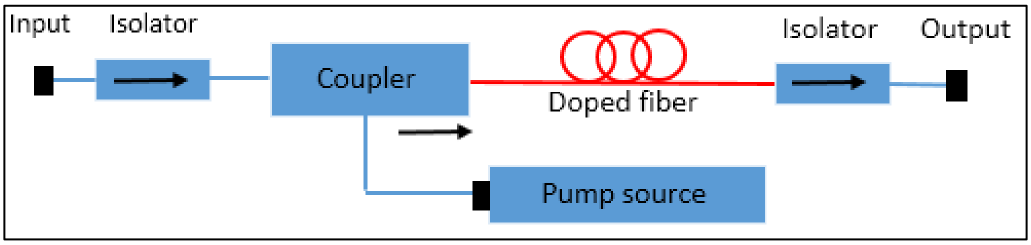

Figure: 2.6: Symbolic diagram of a simple Doped fiber Amplifier [8]

2.2.4.1 Physical Principle of EDF Amplification

At the heart of EDFA technology is the Erbium Doped Fiber (EDF), which is a conventional Silica fiber doped with Erbium. When the Erbium is illuminated with light energy at a suitable wavelength (either 980nm or1480nm) it is excited to a long lifetime intermediate state so it decays back to the ground state by emitting light within the 1525-1565 nm band. If light energy already exist within the 1525- 1565nm band, for example due to a signal channel passing through the EDF, then this stimulates the decay process (so called stimulated emission), resulting in additional light energy. Thus, if a pump wavelength and a signal wavelength are simultaneously propagating through an EDF, energy transfer will occur via the Erbium from the pump wavelength to the signal wavelength, resulting in signal amplification. Figure 2.6 shows that the Erbium can be either pumped by 980nm light, in which case it pass through an unstable short lifetime state (E3) before rapidly decaying to a quasi-stable state (E2), or by 1480nm light in which case it is directly excited to the quasi-stable state. Once in the quasi-stable state, it decays to the ground state by emitting light in the 1525-1565nm band. This decay process can be stimulated by pre-existing light, thus resulting in amplification. When a 980 nm pump laser diode beam is fed into an erbium-doped fiber, Er3+ will be excited from the ground state E1 to the higher level E3. The excited Er3 ions on E3 will rapidly decay to energy level E2 through non radiative emission. The excited ions on E2 eventually return to ground state E1 through spontaneous emission, which produces photons in the wavelength band 1525 – 1565 nm. The spontaneous emission will be amplified as it propagates through the fiber, especially when the pump laser power is increasing. As amplified spontaneous emission (ASE) covers a wide wavelength range 1525 – 1565 nm, we can use it as a broadband light source.

If a laser signal with a wavelength between 1525 and 1565 nm, and a 980 pump laser are fed into an erbium-doped fiber simultaneously as shown in Figure 2.7, there are three possible outcomes for the signal photon: i) stimulated absorption: signal photon excites an erbium ion from the state E1 to a higher level E2 and become annihilated in the process; ii) stimulated emission: signal photon stimulates an erbium ion at state E2 to decay to E1, producing another identical photon. Thus the signal is amplified; iii) signal photon can propagate unaffected through the fiber. In the meanwhile, spontaneous emission always occurs between level E2 and level E1. When pump laser power is high enough that the population inversion is achieved between the energy level E2 and E1 of erbium-doped fiber, the input laser signal passing through the fiber is then be amplified [9].

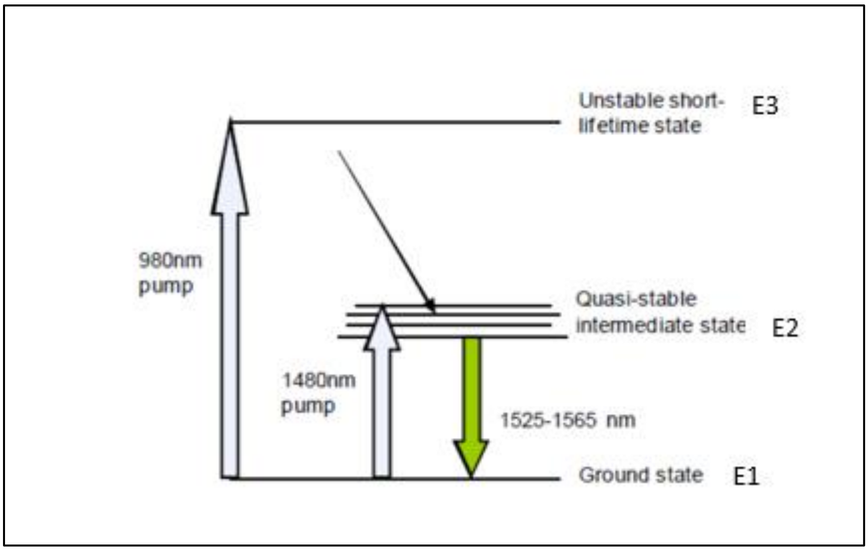

Figure 2.7: The energy levels of the Erbium with the EDF [9].

2.2.4.2 Basic EDFA Design

In its most basic form the EDFA consist of a length of EDF (typically 2-30m), a pump laser, and a component (often referred to as a WDM) for combining the signal and pump wavelength so that they can propagate simultaneously through the EDF. In principle EDFA's can be designed such that pump energy propagates in the same direction as the signal (forward pumping), the opposite direction to the signal (backward pumping), or both direction together. The pump energy may either by 980nm pump energy, 1480nm pump energy, or a combination of both. Practically, the most common EDFA configuration is the forward pumping configuration using 980nm pump energy, as shown in Figure 2.8.This configuration makes the most efficient use of cost effective, reliable and low power consumption 980nm semiconductor pump laser diodes, thus providing the best overall design with respect to performance and cost trade-offs [10].

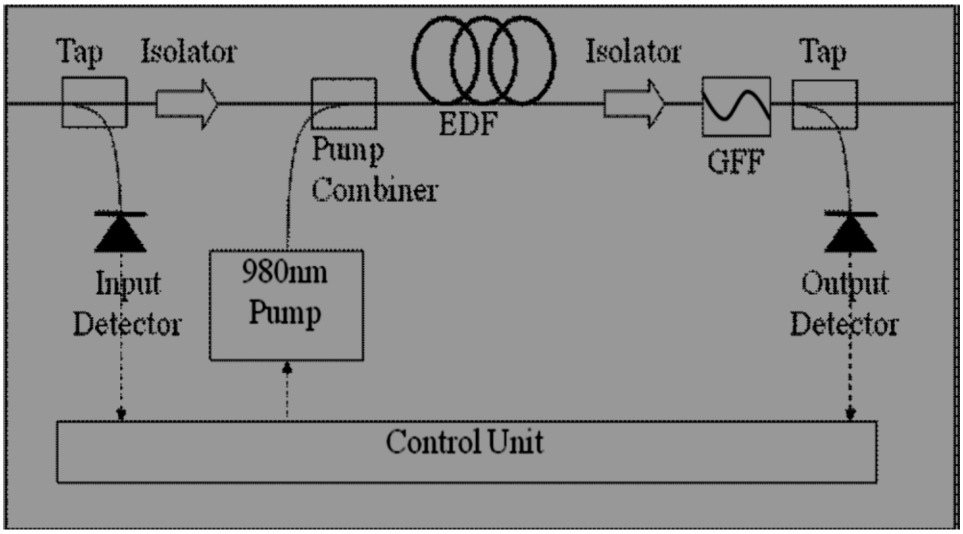

Figure 2.8: Diagram of a typical single stage EDFA [10].

Besides the three basic components described above, figure 2.8 also shows additional optical and electronic components used in a basic single stage EDFA. The signal enters the amplifier through the input port, and then passes through a tap which is used to divert a small percentage of the signal power (typically 1-2%) to an input detector. The signal then passes through an isolator, before being combined with pump energy emitted by the 980nm pump laser diode. The combined signal and pump energy propagate along the EDF, where signal amplification occurs, and then the amplified signal exits the EDF and passes through a second isolator. The purpose of the two isolators, which allow light to pass only in a single direction, is to ensure that lasing cannot take place within the EDF. Furthermore, the output isolator also acts as a filter for 980nm light propagating in the forward direction, thus stopping the 980nm light from exiting the amplifier output port.

In a multi-channel WDM amplifier, a Gain Flattening Filter (GFF) is usually placed following the output isolator in order to flatten the gain spectrum, as shown in Figure 2.9. The attenuation spectrum of the GFF is designed to match the Gain spectrum of the EDF (operating at a given fixed gain), such that the combination of the two produces a flat gain.

Following the GFF the signal passes through an output tap used to divert a small percentage of the output power (typically 1-2%) to the output detector. The output and input detectors are used to monitor the input and output power respectively, and thus provide feed-back to the control unit, which controls the amplifier by setting the pump laser current, and thus the amount of pump power injected into the EDF.

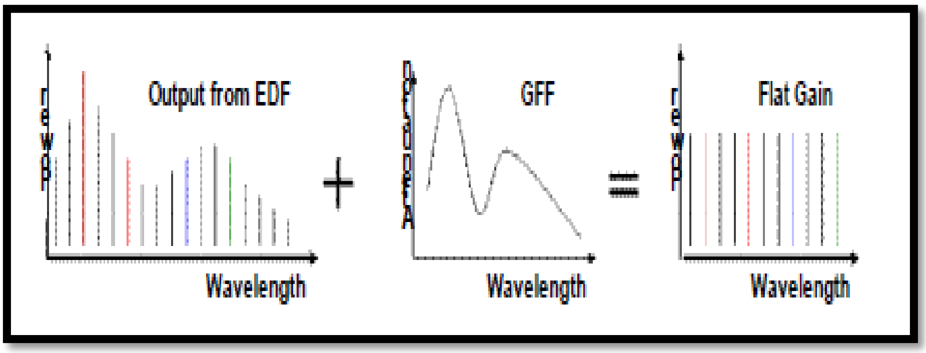

Figure 2.9: Use of a Gain Flattened Filter (GFF) to achieve a flat gain spectrum [11].

2.2.4.3 Saturation and EDFA Gain

There are two main differences between the behavior of electronic amplifiers and of EDFAs in gain saturation:

1. As input power is increased on the EDFA the total gain of the amplifier increases slowly. An electronic amplifier operates relatively linearly until its gain saturates and then it just produces all it can. This means that an electronic amplifier operated near saturation introduces significant distortions into the signal.

2. An erbium amplifier at saturation simply applies less gain to all of its input regardless of the instantaneous signal level, thus it does not distort the signal. There is little or no crosstalk between WDM channels even in saturation.

EDFA is in saturation if almost all Erbium ions are consumed for amplification. Then the total output power remains almost constant, regardless of input power changes, shows as Figure 2.10[12].

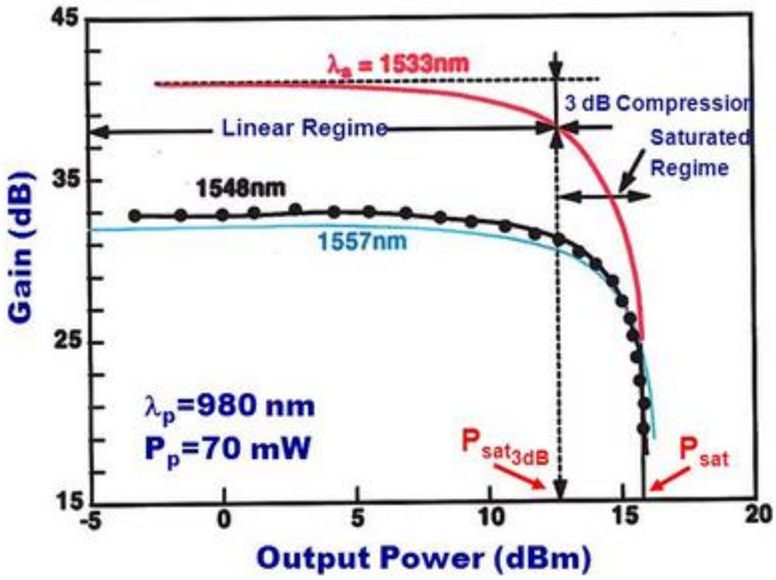

Figure 2.10: EDFA Gain [12].

The ratio between output power to input power is defines as Amplification factor equation 2.1 shows this factor and the total output power is defines as Amplified signal with Noise ASE , equation 2.2 shows total power

$$G = {P_{out}}/{P_{in}} \tag{2.1}$$

$$P_{out} = X + Y \tag{2.2}$$

Where P_{out} is the Output Power, P_{in} is the input Power, X is Amplified Signal and Y is Noise.

Also the gain can be calculated as

$$G_{EDFA} = G_{max}(L, \lambda p, \lambda s) = expL\frac{r_p * (\lambda p) - r(\lambda s)}{1 + r_p(\lambda p)} \tag{2.3}$$

Where the dependence of Gmax on λp (pump wavelength) and λs (signal wavelength), appear explicitly in the cross-section ratios

$$r_p = {\sigma_{pa}}/{\sigma_{pe}} \text{ (Pump absorption/pump emission).} \tag{2.4}$$

$$r_p = {\sigma_{sa}}/{\sigma_{se}} \text{(Signal absorption/signal emission).} \tag{2.5}$$

2.2.4.4 Noise and Noise Figure

The ASE noise generated in an EDFA can be the limiting performance factor in an optical transmission link. It is therefore important to quantify this effect. For an amplifier with gain G, the ASE noise power spectral density at the output at optical frequency f is where NSP, the spontaneous emission factor, is a function of the state population and approaches its minimum value of 1 with full population inversion. The ASE noise spectrum for an EDFA is roughly the same shape as the gain profile. The significance of the ASE noise is most clearly expressed in terms of SNRs and the amplifier noise figure NF. These quantities are defined in terms of electrically detected signals in an ideal system as shown in the following Figure 2.11[13].

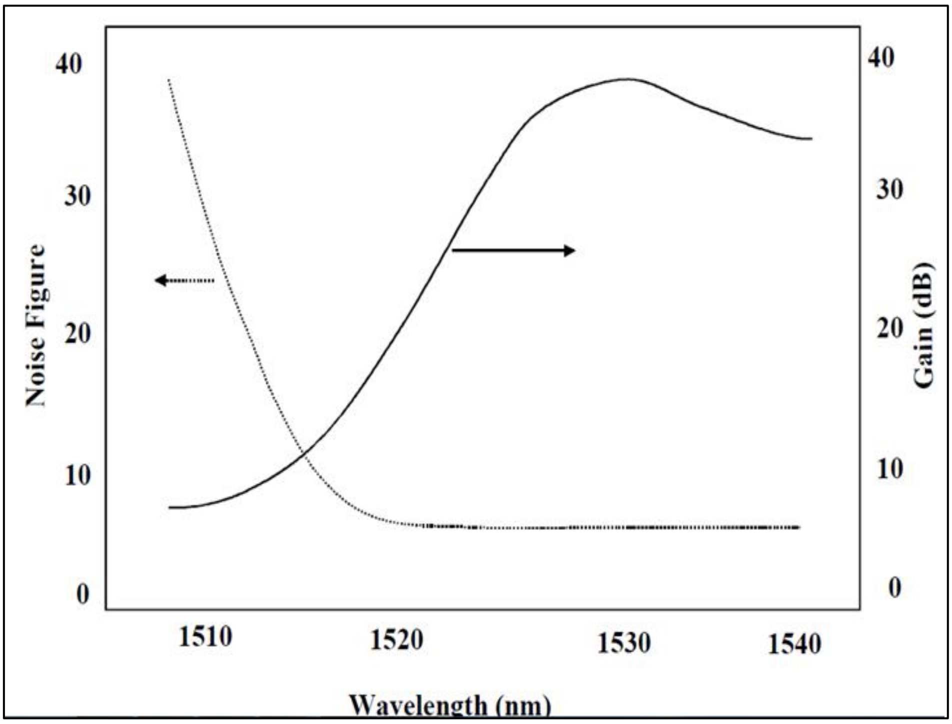

Figure2.11: Noise Figure [13]

The noise figure is defined as where SNR in is the electrical SNR seen when a signal of power Pin is converted to a photocurrent at the output of an ideal photo detector .The noise in this case is shot noise due to the fact that the ideal detector is counting photons, which arrive randomly at the detector. (The detection process must be an integral part of any noise calculation, reflecting the quantum limits of light wave transmission.

2.2.4.5 Advantages of EDFAs are

Advantages of the EDFA are low noise, high saturation power, High gain (~50dB), High output power (>100mW), Less gain variation Low noise figure (~4dB, and its cost effectiveness compared to repeaters [13].

2.2.4.6 Disadvantages of EDFAs

Cannot be easily integrated with other devices, relatively large devices (km lengths of fiber). Cross-talk effects in addition gain saturation effects also amplified spontaneous emission (ASE - there is always some output even with no signal input due to some excitation of ions in the fiber – spontaneous noise).[14]

2.2.5 RAMAN Amplifier

In a Raman amplifier, the signal is amplified due to stimulated Raman scattering (SRS). Raman scattering is a process in which light is scattered by molecules from a lower wavelength to a higher wavelength. When sufficiently high pump power is present at a lower wavelength, stimulated scattering can occur in which a signal with a higher wavelength is amplified by Raman scattering from the pump light. SRS is a nonlinear interaction between the signal (higher wavelength; e.g. 1550 nm) and the pump (lower wavelength; e.g. 1450 nm) and can take place within any optical fiber. In most fibers however the efficiency of the SRS process is low, meaning that high pump power (typically over 1 W) is required to obtain useful signal gain. Thus, in most cases Raman amplifiers cannot compete effectively with EDFAs.

On the other hand, Raman amplification provides two unique advantages over other amplification technologies. The first is that the amplification wavelength band of the Raman amplifier can be tailored by changing the pump wavelengths, and thus amplification can be achieved at wavelengths not supported by competing technologies. A second, more important, advantage is that amplification can be achieved within the transmission fiber itself, enabling what is known as distributed Raman amplification (DRA) [15].

2.2.5.1 Basic principles in RAMAN Amplifier

In particular the broad gain– bandwidth associated with Raman amplification is attractive for current wavelength division multiplexed (WDM) systems since fiber Raman amplifiers in comparison with doped fiber amplifiers provide gain over the entire fiber band (i.e. 0.8 to 1.6 μm)

The pump signal optical wavelengths in Raman fiber amplifiers are typically 500 cm−1 higher in frequency than the signal to be amplified, and the pumping signal can propagate in either direction along the fiber. A schematic representation of both the forward and backward pumping capability of Raman fiber amplifiers is shown in Figure 2.12.

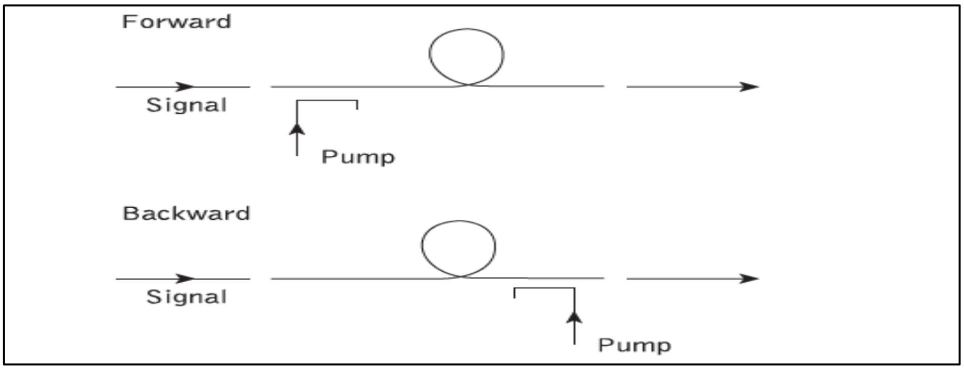

Figure 2.12: Illustrations of the forward and backward pumping capability associated with the Raman amplifier [15].

Moreover, continuous-wave Raman gains exceeding 20 dB have been demonstrated experimentally in silica fiber which in principle exhibits a broad spectral bandwidth of up to 100 nm with suitable doping of the fiber .In addition, Raman gain in excess of 40 dB has been obtained using fluoride glass fiber in which the Raman shift is 590 cm−l. Raman fiber amplifiers have been investigated for WDM system applications.

2.2.5.2 RAMAN Gain

In a Raman amplifier the power spectrum of the optical signal is affected by Raman pumping (only counter propagation is considered here), Raman amplified spontaneous emission (ASE) noise and Rayleigh back- scattering. The pump power does not remain constant along the Raman fiber length. When these effects are included, the Raman amplification process is governed by the set of two coupled equations described in

$$G_{RAMAN} = G(Z) = \frac{P_s(z)}{P_s(0)} = exp(g_r \int_0^z P_p\,(z)dz - \alpha_s z) \qquad (2.6)$$

Where Pp and Ps are the pump and signal power, respectively. On the other hand, z is the longitudinal position along the fiber and αs is the Rayleigh scattering coefficient [16]

2.2.6 Comparison of Optical Amplifiers

After talking about these three types of optical amplifiers, we make a comparison of them as the following Table 2.1.

Table 2.1: Comparison of Optical Amplifiers [5]

.NO.	Parameter	Semiconductor Optical Amplifier (SOA)	Erbium Doped Fiber Amplifier (EDFA)	Raman Amplifier (FRA)
1.	**Gain(dB)**	>30	>40	>25
2.	**Bandwidth (3dB)**	60	30-60	Pump dependent
3.	**Noise Figure (dB)**	8	5	5
4.	**Pump Power**	<400mA	25dBm	>30dBm
5.	**Wavelength(nm)**	1260-1650	1530-1560	1260-1650
6.	**Cost factor**	Low	Medium	High
7.	**Max. Saturation (dBm)**	18	22	0.75 X pump

2.2.7 Hybrid Optical Amplifier

The cascading an erbium-doped fiber amplifier (EDFA) and Raman amplifier (RA) is called a hybrid optical amplifier (HOA), the RAMAN-EDFA. The cascading a semiconductor optical amplifier (SOA) and a fiber Raman amplifier (FRA) is called a hybrid optical amplifier (HA), the RAMAN-SOA. Hybrid amplifier provides high power gain. The total amplifier gain (G_{Hybrid}) is the sum of the two gains: [17]

$$G_{Hybrid} = G_{EDFA} + G_{Raman} \tag{2.7}$$

Gain partitioning in hybrid amplifier is as shown Figure 2.13.

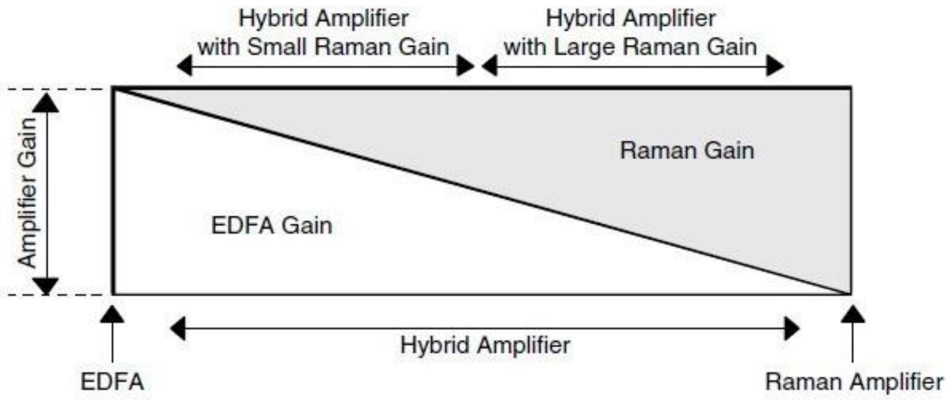

Figure 2.13: Gain partitioning in hybrid amplifier [17]

2.3 Wavelength Division Multiplexing (WDM)

Wavelength-division multiplexing (WDM) is an approach that can exploit the huge opto- electronic bandwidth mismatch by requiring that each end user's equipment operate only at electronic rate, but multiple WDM channels from different end-users may be multiplexed on the same fiber. WDM corresponds to the scheme in which multiple optical carriers at different wavelengths are modulated by using independent electrical bit streams (which may themselves use TDM and FDM techniques in the electrical domain) and are then transmitted over the same fiber. The optical signal at the receiver is demultiplexed into separate channels by using an optical technique.

Optical amplifier deployment of a completely new generation of system see Figure 2.14 an advantage of EDFA is that they are capable of amplifying signals at many wavelengths simultaneously. This provide the another way to increasing the system capacity. At each regenerator location, a single regenerator, one per fiber optical amplifier could replace an entire array of expensive [18].

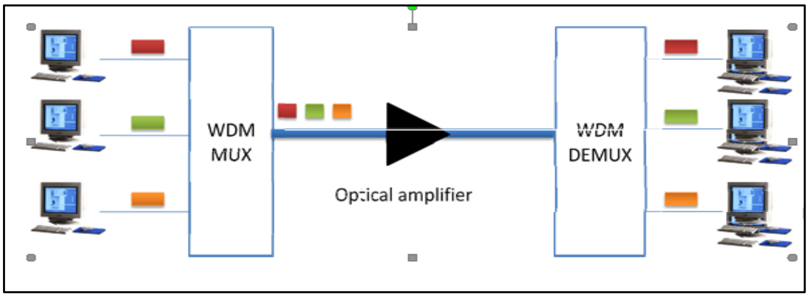

Figure 2.14: A current generation WDM system using optical amplifiers instead of regenerators [19]

2.4 Related Work

The author of [20], introduced a hybrid two stage Raman-EDFA amplifier can give a flat gain of L-Band. The increasing of input power increase the gain variation over the bandwidth. Flat gain of greater than 10 dB is achieved using the input power of 3 mW for the frequency between 187 to 190.975 THz.

The authors of [21] demonstrated a wideband and finely gain flattened hybrid fiber amplifier. The amplifier consists of an erbium doped fiber amplifier and a discrete Raman amplifier, which has two, isolated Raman fibers pumped simultaneously at three wavelengths. Here the amplifier yields optical noise under 6dBand total output power13.8dB. The relative gain variation is 11.3dB.

The authors of [22] proposed configuration of hybrid amplifier using 20x50 Gbps WDM system with the range from 1560 nm to 1577 nm wavelength but this is narrow bandwidth . The input power use is 15 dBm the result shows that gain and noise figure variation will increase as the input power, number of pump and pump wavelength increases.

The authors of [23], introduced Hybrid combination of EDFA and Raman ,the configuration consists of 16 channels with 50GHz channel spacing, the system has a WDM transmitter with first channel is at 193.5THz ,the input power is 20dBm .So the overall gain for given frequency band is increased from 12.41dB to 16.21dB by using this combination.

The authors of [24] proposed hybrid configuration of Raman amplifier and EDFA exhibit the average gain of 40 dB and average noise figure of 3 dB. The flat gain obtained is between 1530 nm to 1600 nm which include C-Band and L-Band frequency with the gain bandwidth of 70 nm.

CHAPTER THREE

SIMULATION SETUP

3.1 Overview

This chapter contain the details explanation of methodology that has been used in this research. It describes in details the simulation by using optisystem software. Simulation composed of three parts: part 1, include design and simulation of EDFA. Part 2 include the configuration of RAMAN amplifier part3 include hybrid EDFA-Raman amplifier.

The simulation started with the configuration and optimization of EDFA and followed by Raman amplifier. Then, using the optimum parameter of both amplifiers, a hybrid optimum Raman-EDFA is configured and simulated.

3.2 Simulation Tool Description

This section describes the tools that is used in optisystem software to obtain the configuration of hybrid Amplifiers shown in Figure 3.1 and Figure3.3:

WDM Transmitter

The WDM Transmitter generates multiple channels in different frequenciesIt encapsulates different components, allowing users to select different modulation formats and schemes for multiple channels in one single component. It is a transmitter array that allows for different modulation types and schemes as shown in Figure 3.1 as number (1).

Ideal Mux

Multiplexers a user-defined number of input WDM signal channels. It is equivalent to an ideal adder, since there is no power splitting and filtering as shown in Figure 3.1 as number (2).

EDFA Amplifier

Optical amplification is required to overcome the fiber loss and also amplify the input signal from WDM Transmitter. It have received great attention due to their characteristics of high gains, bandwidth, low noise and high efficiencies as shown in Figure 3.1 as number (3).

RAMAN Amplifier

An input signal can be amplified while co- or counter propagating with a pump beam, the wavelength of which is typically a few tens of nanometers shorter as shown in Figure 3.1 as number (4).

Dual Port WDM Analyzer

This visualizer automatically detects, calculates and displays the optical power, noise, OSNR, Gain, noise figure, frequency and wavelength for each WDM channel at the visualizer inputs, the visualizers in the project generate graphs and results based on the signal input as shown in Figure 3.1 as number (5).

Optical Spectrum Analyzer

An Optical Spectrum Analyzer (or OSA) is a precision instrument designed to measure and display the distribution of power of an optical source over a specified wavelength span. An OSA trace displays power in the vertical scale and the wavelength in the horizontal scale as shown in Figure 3.1 as number (6).

Pump Laser Array

An array of pump lasers use to generate an optical parameterized signal to be used for optical amplifier pumping.

Isolator

The optical isolator prevents the amplified signal from reflecting back into the device as shown in Figure 3.3 as number (8).

Gain Flattering Filter

EDFAs have a wavelength-dependent gain; i.e., some wavelengths are amplified more than others. A gain flattening filter restores all wavelengths to approximately the same intensity as shown in Figure 3.3 as number (9).

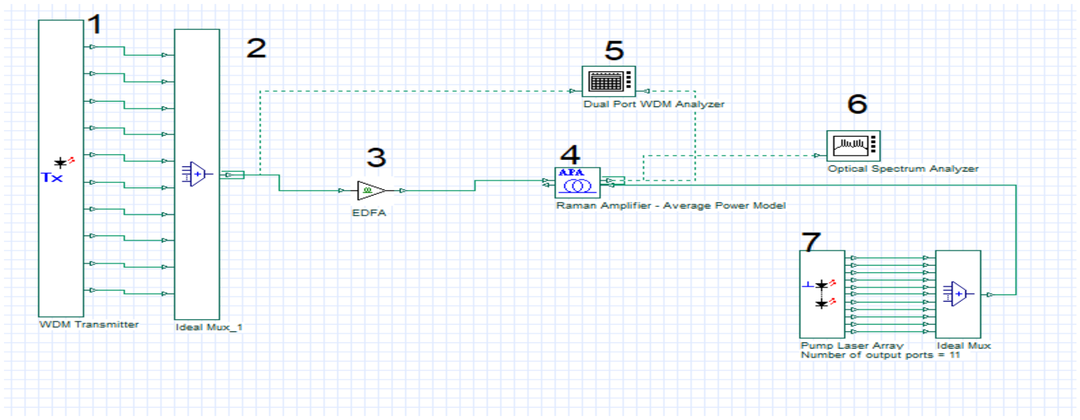

Figure3.1: General component in optisystem

3.3 Simulation Setup

3.3.1 Configuration of Erbium Doped Fiber Amplifiers (EDFA):

Figure 3.2 shows the proposed configuration of EDFA. The parameter involves to be tested in this configuration are pump wavelength, erbium ion density, EDFA length, pump power and input signal power. These parameters will be varied in order to check for the best amplifier performance for the design configuration. The frequency for the WDM channel is from 1530 nm to 1620 nm with 19 channels of 5 nm spacing. The frequency is the range for C-Band and L-Band. The pump wavelength of the EDFA can be 980 nm or 1480 nm, so the parameters are set as shown in Table 3.1.

Table 3.1: EDFA Amplifier Design specifications

Parameter	Value
Input signal power	-41dBm
EDFA length	5m
Bit Rate	10 Gbits/sec
Erbium ion density	1000ppm~wt
pump power	980dBm
pump wavelength	300nm

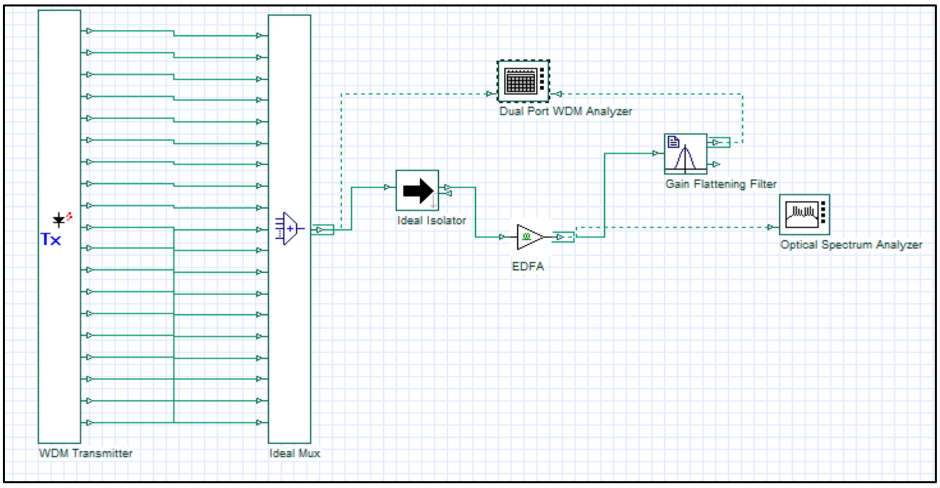

Figure 3.2: Simulation of EDFA Amplifier

3.3.2 Parameter optimization for EDFA amplifier

In optimizing to enhance the performance of EDFA amplifier, the EDFA length is varied between 1 m to 40 m. Then, for input signal power of WDM transmitter optimization, the power is varied between -200 to 0 dBm to obtain the best input signal power. For the optimum erbium ion density, the density is varied between 100 to 2500 ppm-wt while the pump configuration is set to optimum which is 980 nm pumping. The optimized parameter was set to the configuration of EDFA amplifier is shown in Figure 3.3 below.

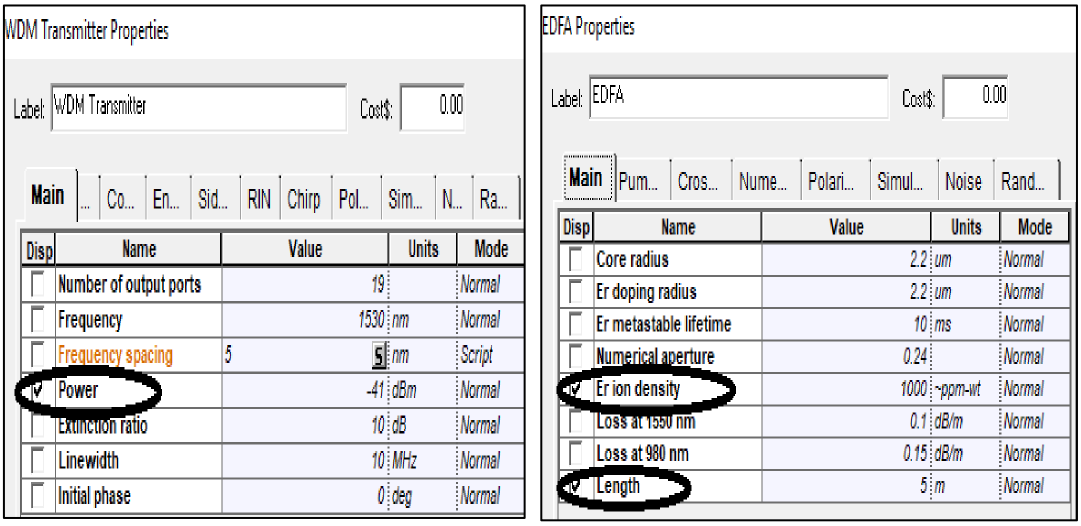

Figure 3.3: Parameter optimization for EDFA Amplifier

3.3.3 Configuration of Raman Amplifier

Figure3.4 shows the proposed configuration of Raman amplifier. The WDM transmitter uses the frequency range between 1530 nm to 1620 nm with 10 nm spacing. The input signal power of -41 dBm is set to constant throughout this simulation. In this simulation, the optimum Raman length and pump power have been observed. There are 11 pump laser arrays of various frequencies ranging from 1420 nm to 1520 nm with increment of 10 nm. The difference between pump wavelength and signal wavelength should be 100 nm to obtain high Raman gain coefficient. The values has been used in the configuration is shown in Table 3.2

Table 3.2: RAMAN Amplifier Design specifications

Parameter	Value
Frequency	1530nm
Frequency Spacing	10nm
Input signal power	-41dBm
RAMAN length	40km
Power of pump Laser Array	150 dBm
Wavelength of pump Laser Array	1420-1520nm
Bit rate	10Gbit/sec

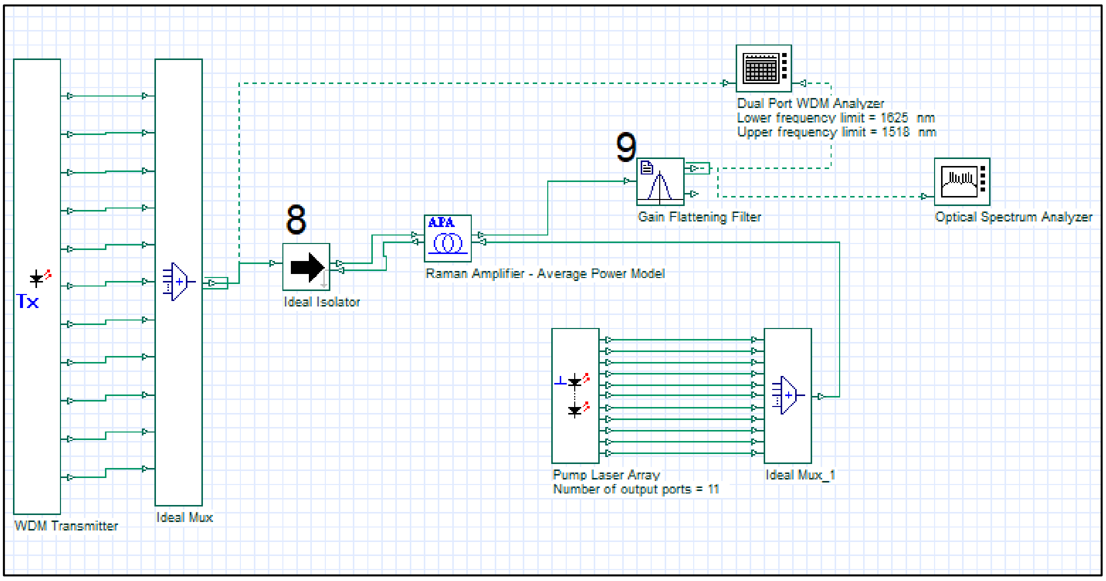

Figure 3.4: Simulation of RAMAN Amplifier

3.3.4 Parameter optimization for Raman Amplifier

The optimization of Raman length is done by varying the length from 10 km to 100 km. Besides, in optimizing the pump power, the amplifier length is set to the optimum length obtained previously which is 40 km with variation of pump power for pump laser array from 50 to 250 mW. Figure 3.5 shows the optimum length and pump power was been achieved.

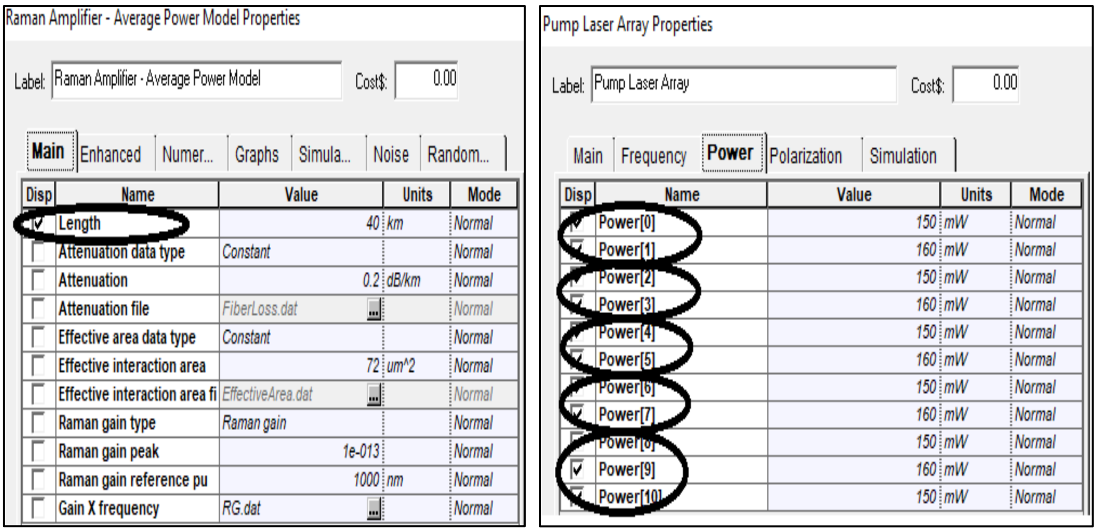

Figure 3.5: Parameter optimization for RAMAN Amplifier

3.3.5 Configuration of Hybrid EDFA-Raman amplifier

The basic configuration consists of 10 channels with 50nm channel spacing, the system has a WDM transmitter with first channel is at 1530nm and increases as the number of channels increases, the input power of WDM transmitter is -41dBm. All the channels are transmitted into the WDM multiplexer with zero insertion loss, here all the light signals are combined and transmitted over the erbium doped fiber of length 5m.The erbium doped fiber amplifier is counter pumped at 980nm.The counter pumping scheme gives more gain than that of co-propagating pumping scheme. The pump power at which the EDFA pumped is 300mw. The output then fed into the Raman amplifier of length 45km which is counter pumped from 1420 to 1520nm with constant pump power of 150mW.The overall amplified signal is fed into the optical spectrum analyzer to analyze the optical spectrum. The dual port WDM analyzer is placed after the Raman amplifier which gives the values of gain and noise figure. The simulation setup of hybrid optical is shown in the given Figure 3.6.

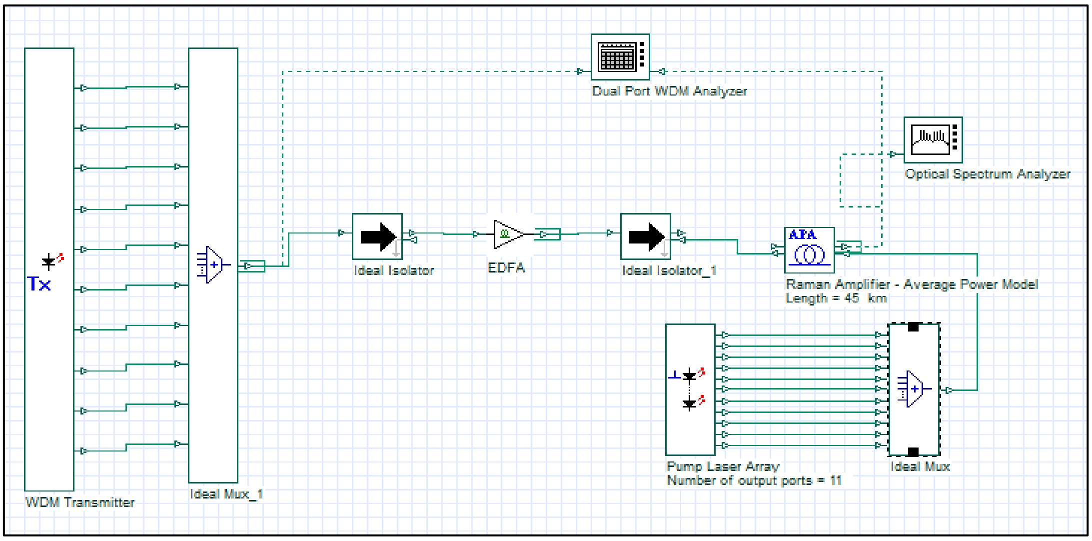

Figure 3.6: Simulation of Hybrid Amplifier

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Overview

This chapter summarized the process of analyzing the simulation of optical amplifiers Erbium doped fiber amplifier, RAMAN amplifier and Hybrid combination (EDFA, RAMAN) using optisystem simulation tools, discusses the results of simulation then evaluate the performance and compare the all values.

4.2 Simulation Results

Although mainly we focused on gain characteristic but noise figure is also analyzed for each amplifier at same parameters values.

4.2.1 EDFA Amplifier

4.2.1.1 Gain and Noise Figure for EDFA amplifier

Figure 4.1 shows the gain and noise figure performances for EDFA. It is shown that the flat gain can be obtained from 1540 nm to 1560 nm with the average gain around 41.8 dB and average noise figure of 3.81 dB. The achievable flat gain bandwidth is 20 nm. This optimum EDFA is obtained based on the 300 mW pump power with 980 nm pump wavelength. In terms of pumping configurations, the best configuration is by using bidirectional pumping as it will provide higher gain and lower noise figure. The optimum erbium ion density used to obtain this result is 1000ppm-wt. For this configuration, 5 m EDFA length is chosen as the optimum length as it gives highest gain, lowest noise figure and flat gain compared to other length. When longer length is used, the gain will decrease as the pump power does not have sufficient energy to produce complete population inversion. The optimum input signal power used is -41 dBm which is the threshold input signal. If the input signal is higher than the threshold, the gain will decrease.

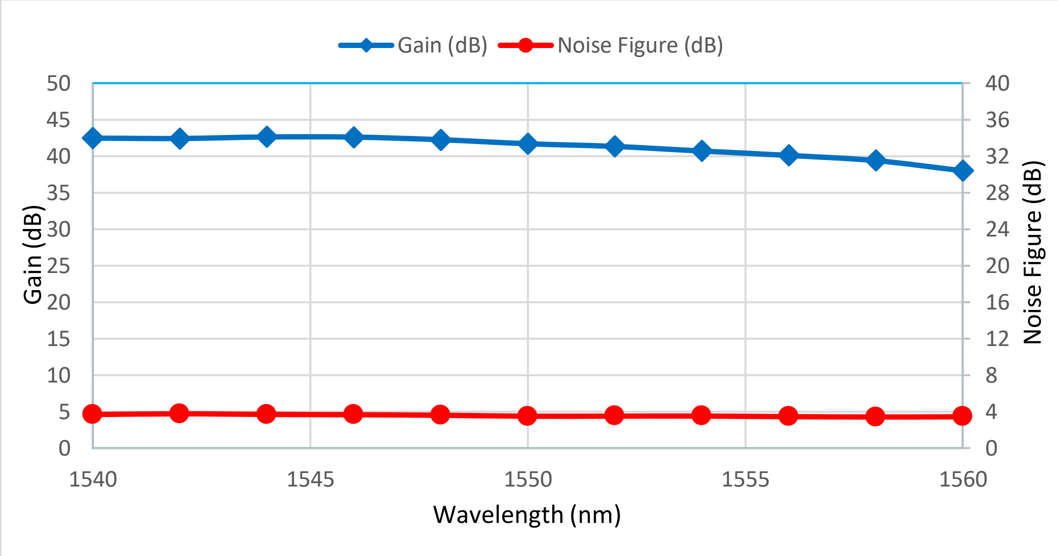

Figure 4.1: Gain and Noise Figure of EDFA Amplifier.

4.2.1.2 Power Spectrum for Output Signal

Figure 4.2 shows power spectrum of output signal which the maximum value of signal power is11.83 that is obtained from optical spectrum analyzer.

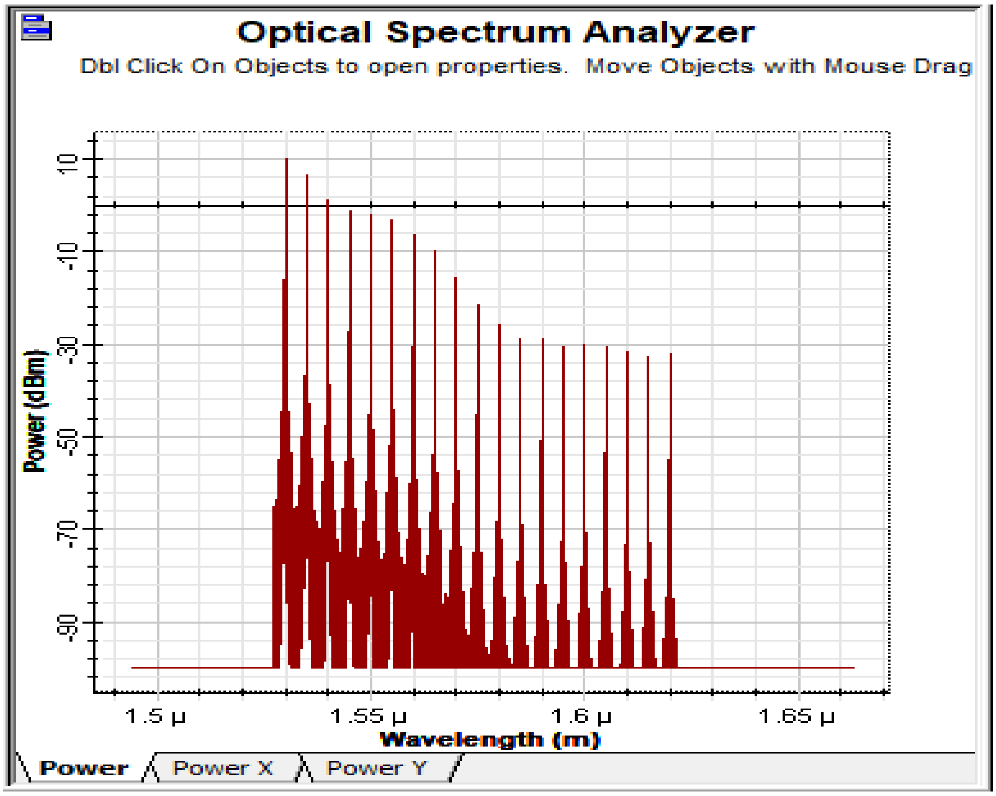

Figure 4.2: Signal spectra at the output of the EDFA Amplifier

4.2.2 Raman Amplifier

4.2.2.1 Gain and Noise Figure for Raman amplifier

Figure 4.3 shows the performance of Raman amplifier. As in the figure, the flat gain is obtained from 1600 nm to 1620 nm with the bandwidth of 20 nm. The average gain obtained from the flat gain is 38.7 dB while the average noise figure is -23 dB. This shows that Raman amplifier will gives better noise figure compared to EDFA. In this configuration, the optimum Raman length used is 40 km as it obtained the highest gain for the signal wavelength of 1600 nm. Gain increases with the increasing Raman length and decreases when the length is longer than 40 km. The optimum pump power for each of the pump laser is 150 mW as it gives less gain variation when compared with 200mW pump power.

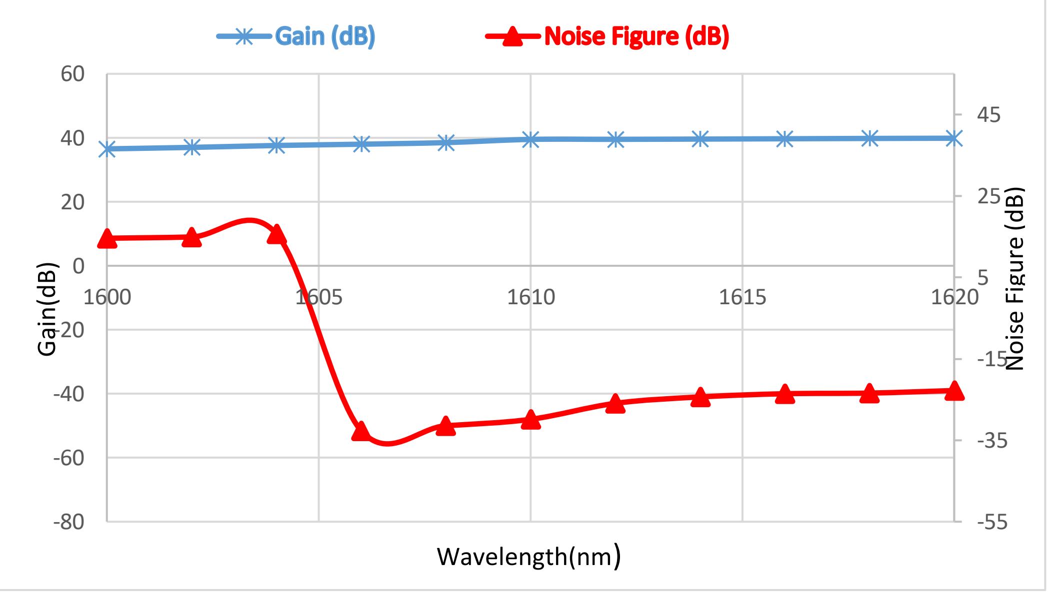

Figure 4.3 Gain and Noise Figure of Raman Amplifier.

4.2.2.2 Power Spectrum for Output Signal

Figure 4.4 shows power spectrum of output signal which the maximum value of signal power is -3.8 that is obtained from optical spectrum analyzer.

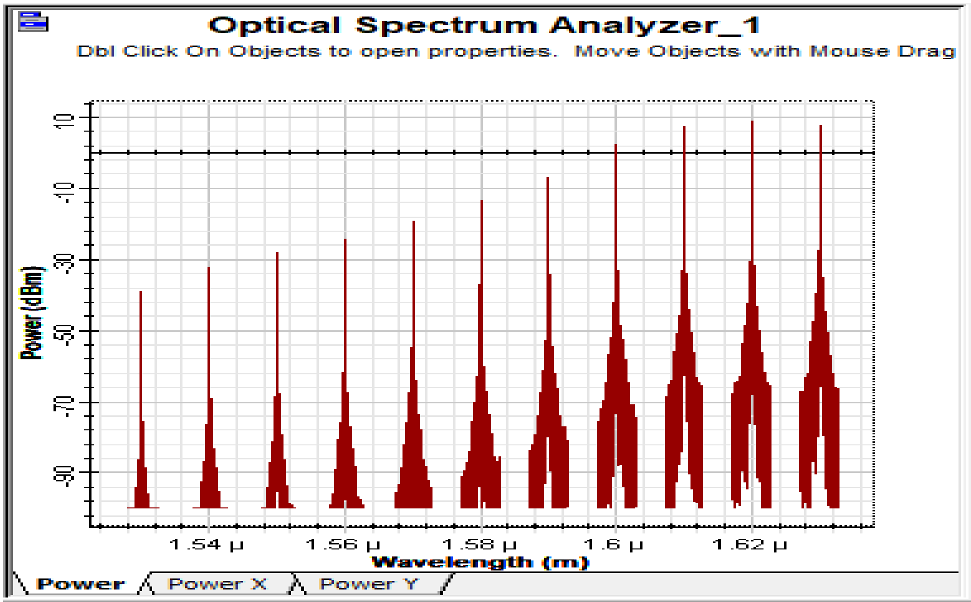

Figure 4.4: Signal spectra at the output of the RAMAN Amplifier

4.2.3 Hybrid Amplifier

4.2.3.1 Gain and Noise Figure for Hybrid amplifier

Figure 4.5 shows the performance of Hybrid Raman amplifier. The flat gain can be obtained from 1530 nm to 1600 nm which is 70 nm bandwidth. The best performances of Hybrid Raman amplifier is the configuration of hybrid EDFA-Raman as is gives the highest average gain of 46.1 dB and lowest noise figure of 3 dB as compared to optimum singly-based EDFA and Raman as well as hybrid Raman- EDFA.

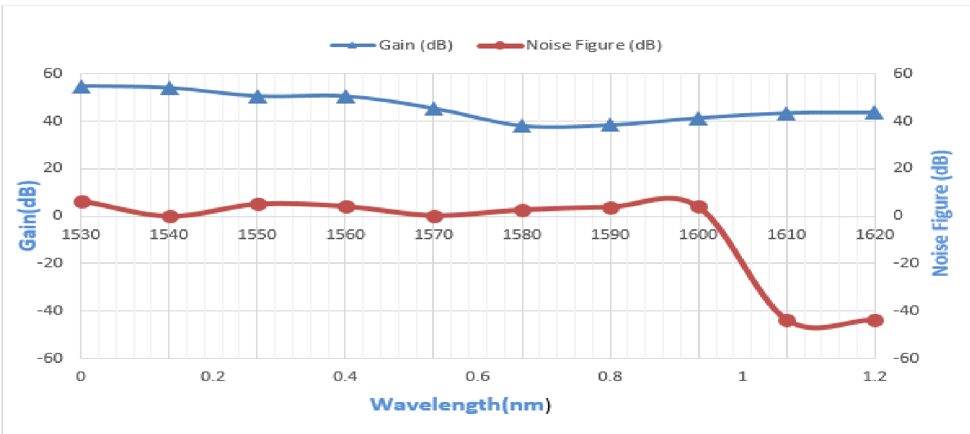

Figure 4.5: Gain and Noise Figure of Hybrid (Raman -EDFA) Amplifier

4.2.3.2 Power Spectrum for Output Signal

Figure4.6 show power spectrum of output signal which the maximum value of signal power 11.1 that is obtained from optical spectrum analyzer.

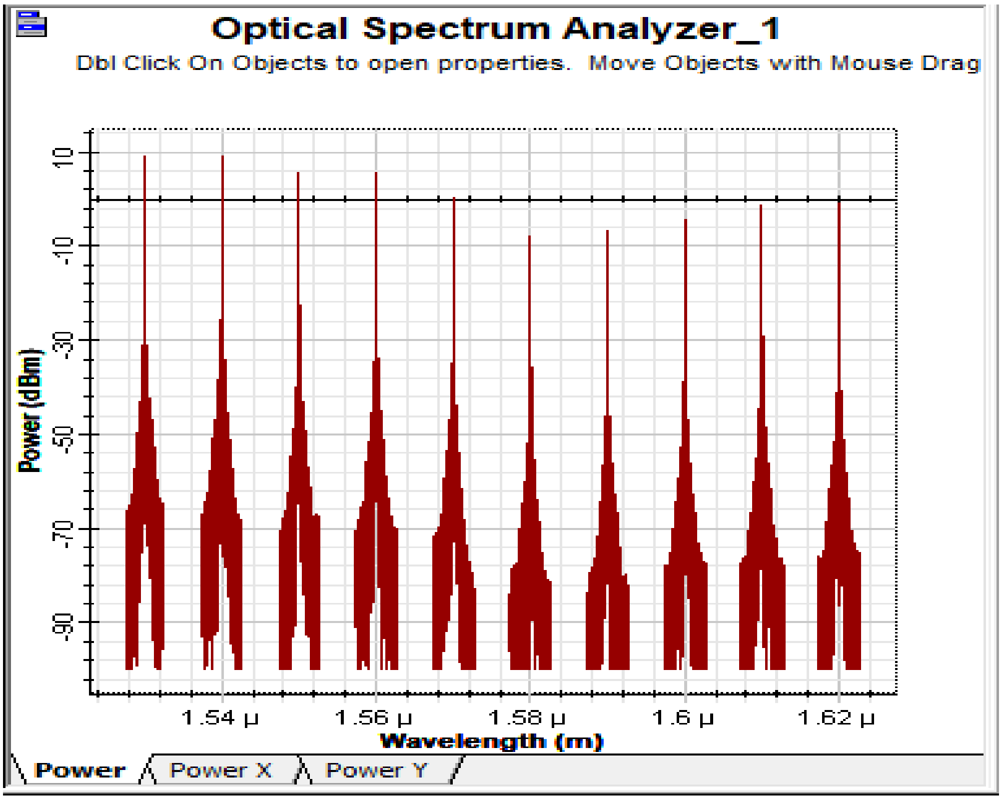

Figure 4.6: Signal spectra at the output of the Hybrid (RAMAN-EDFA) Amplifier

4.2.4 Evaluation of amplifiers gain

The gain profile of amplifiers shown in Figure 4.7 It exhibits that EDFA amplifier gives flat gain in C band (1530-1590nm) and RAMAN amplifier gives flat gain in L band (1600-1620nm). In contrast using of hybrid configuration of RAMAN and EDFA obtained higher gain.

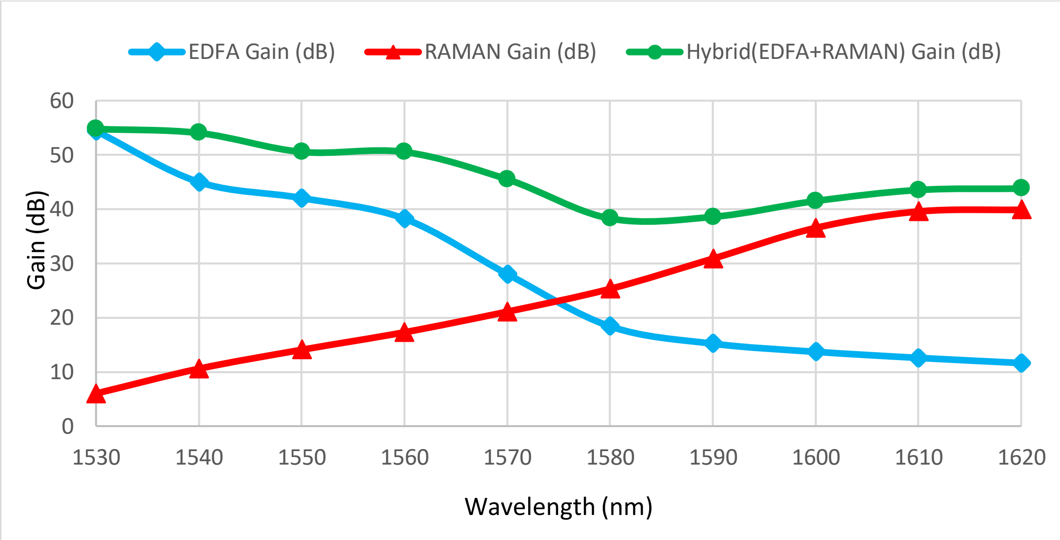

Figure 4.7: Gain vs. wavelength curve for EDFA, Raman and Hybrid Amplifier

4.2.5 Evaluation of amplifiers noise figure

Figure 4.8 show niose figure curve for EDFA ,RAMAN,and Hybrid amplifiers. It appear that using hybrid configuration of RAMAN and EDFA obtained low noise figure in both C band, L band below 3dB.

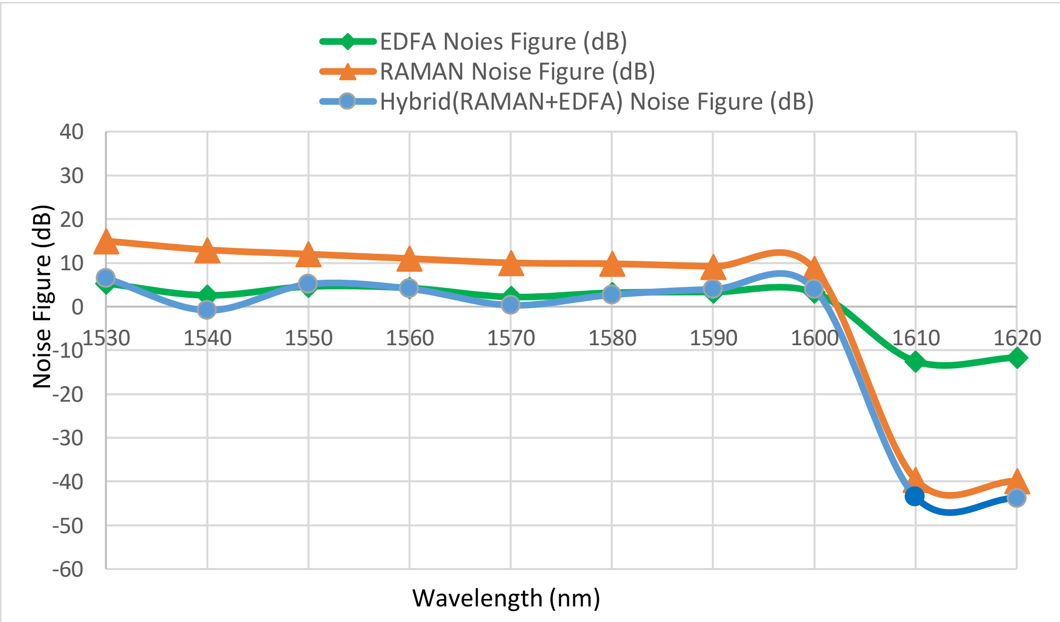

Figure 4.8: Noise Figure vs. wavelength curve for EDFA, Raman and Hybrid Amplifier

4.2.6 Evaluation of optical signal to noise ratio

In Figure 4.9 the optical signal to noise ratio (OSNR) is plotted against the signal wavelength for Hybrid (EDFA/Raman), EDFA and Raman amplifier. The lower values of OSNR obtained for Raman amplifier only in the range of signal wavelength (1530-1590) which mean that the gain of Raman amplifier is low in comparison to EDFA and hybrid amplifier (EDFA/Raman) in this range, In contrast EDFA amplifier gave lower value of OSNR in the range of wavelength (1600-1620) which indicate that the gain of EDFA amplifier is low in comparison to Raman and hybrid amplifier (EDFA/Raman). So using hybrid configuration of RAMAN and EDFA enhanced the OSNR.

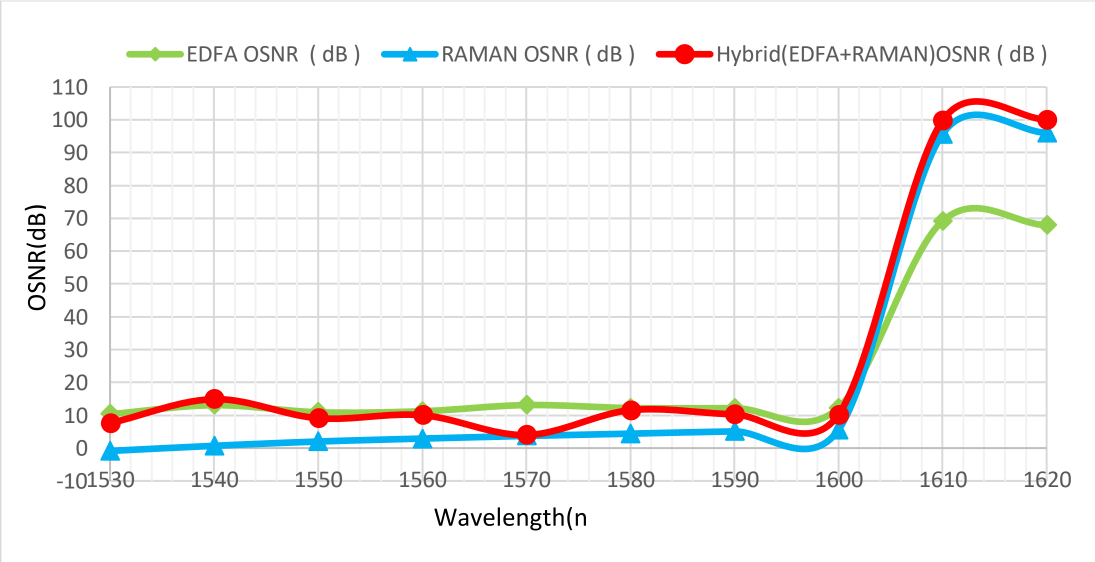

Figure 4.9: OSNR vs. wavelength curve for EDFA, Raman and Hybrid Amplifier

CHAPTER FIVE

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

In conclusion, the optical amplifiers and hybrid optical amplifiers design models were successfully designed and implemented into Optisystem. The optimization of hybrid EDFA-Raman amplifier performance improved significantly in terms of flat gain bandwidth as well as higher gain of transmission system. The design of optimum hybrid amplifiers was very important in obtaining a broad flat gain and better noise performances. The parameters which optimized the EDFA's performance in term of noise figure and gain are erbium ion density, EDFA length, input signal power, pump power and pump wavelength while the parameters optimized the Raman amplifier are Raman length and pump power. The hybrid amplifier performance was evaluated in terms of gain and noise figure considering WDM input signals. It was give low noise figure and a better flat gain bandwidth. The hybrid configurations gave the highest average gain of 46.1 dB and lowest average noise figure of 3 dB as compared to optimum singly-based EDFA and Raman as well as hybrid Raman- EDFA. The flat gain obtained is between 1530 nm to 1600 nm which included C-Band and L-Band frequency with the gain bandwidth of 70 nm.

5.2 Recommendations

There are many types of optical amplifier can be used for WDM application to fulfill the need of higher bandwidth, and enhanced speed of communication of today's users. So it required to evaluate their performance. Therefor in future research it recommended to increase the number of channels in transmitter for EDFA and RAMAN amplifiers, to extend the work for different frequency spacing and data rate, and using another rare earth optical amplifier with Raman amplifier.

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