YILDIRIM BEYAZIT UNIVERSITY

GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES

DESIGN AND ANALYSIS OF L-BAND ERBIUM DOPED FIBER AMPLIFIERS

M.Sc THESIS by

Mohammed Khaleel AWSAJ

Department of Electronics and Communication Engineering

March, 2015

ANKAR

DESIGN AND ANALYSIS OF L-BANDE RBIUM DOPED FIBER AMPLIFIERS

A Thesis Submitted to the

Graduate School of Natural and Applied Sciences of Yildirim Beyazit University

In Partial Fulfillment of the Requirements for the Degree of Master of Science in Electronics and Communication Engineering, Department of Electronics and Communication Engineering

by

Mohammed Khaleel AWSAJ

March, 2015

ANKARA

M.Sc THESIS EXAMINATION RESULT FORM

We have read the thesis entitled "DESIGN AND ANALYSIS OFL-BAND ERBIUM DOPED FIBER AMPLIFIERS" completed by MOHAMMED KHALEEL AWSAJ under supervision of ASSOC. PROF. DR. H. HALDUN GÖKTAŞ and we certify that in our opinion it is fully adequate, in scope and in quality, as a thesis for the degree of Master of Science.

Assoc. Prof. Dr. H. Haldun GÖKTAŞ

Supervisor

Prof. Dr. Fatih V. ÇELEBİ

(Jury Member)

Assoc. Prof. Dr. Murat Yücel

(Jury Member)

Prof.Dr. Fatih V. ÇELEBİ

Director

Graduate School of Natural and Applied Sciences

To the Great my messenger.

To the memory of my father.

To my mother with my love and gratitude.

To my brothers with my thanks.

To my wife and kids with my love.

ACKNOWLEDGMENTS

First of all, praise be to **ALLAH** for the support in all my life.

Special mention has to be made to my supervisor Dr. H. Haldun GÖKTAŞ, I offer him my deepest appreciation for his continuous work the preparation of the thesis. He tried hard to ensure the high quality of the work.

Special thanks are due to Dr. Murat Yucel in Gazi University, Dr. Thamer Fahed in Tikrit University, Dr. Salih Mohammed, Dr. Yousif Ismail in Al-Anbar University, and all who have helped me directly or indirectly in this work.

Special thanks to Dr. Naseer Noori Al-Alusi for support me to complete my study.

Special thanks are due to all staff of YILDIRIM BEYAZIT UNIVERSITY for helping me to complete my study.

Special thanks go to my mother and my brothers for their endless support and encouragement.

Last, but not least, special thanks go to my wife for supporting me all the time.

March, 2015 Mohammed Khaleel AWSAJ

CONTENTS

ABBREVIATIONS

ASE	Amplified Spontaneous Emission
BI	Bi-directional Pumping
BW	Backward Pumping
CS	Cross-Section
CW	Continuous Wave
DP	Double Pass
DFA	Doped Fiber Amplifier
ECS	Emission Cross-Section
EDF	Erbium Doped Fiber
EDFA	Erbium-Doped Fiber Amplifier
ESA	Excited State Absorption
FBG	Fiber Bragg Grating
FW	Forward Pumping
G	Gain
GSA	Ground State Absorption
LD	Laser Diode
LED	Light Emitting Diode
MUX	Multiplexer
NA	Fiber Numerical Aperture
NF	Noise figure
Pin	Input Signal Power
Pout	Output Signal Power
PP	Pump Power
R	Reflectivity
RL	Recirculating Loop
SNF	Saturated Noise Figure
SNR	Signal to Noise Ratio

TP	Triple Pass
WDM	Wavelength Division Multiplexing
WSC	Wavelength Selective Coupler

LIST OF TABLES

LIST OF FIGURES

DESIGN AND ANALYSIS OF L-BAND ERBIUM DOPED FIBER AMPLIFIERS

ABSTRACT

Optical Amplifiers are essential devices for long haul optical fiber communications. To extend optical communication window, wide band and flat gain optical amplifiers are needed. In this study, four types of erbium doped fibers, namely Fc-xsec, Fiber core, R31703, and ErFiber, were analyzed by using OptiAmplifier simulation program, with different pump powers, pump configurations and different input signal powers. These four types of EDF were applied to two types of new L- band EDFA configurations, namely double pass EDFA with wave selective coupler, and triple pass EDFA with passive EDF. The performance improvements have been achieved by the elimination of the residual pump power out of the signal and to realize high and flat gain and low noise figure. According to the simulation results the best result was obtained for the forward pumping ErFiber type EDF. Also, forward double pass EDFA with wave selective coupler (WSC) configuration was better with respect to gain, noise figure and gain flatness criteria. These results indicate increasing pump power lead to increase output power and decrease noise figure at the same time, as well as, the results are convergent for the bidirectional pumping. However, we found lower gain with higher noise figure for the backward pumping was used.

Keywords: *Double pass EDFA, Triple pass EDFA, L Band EDFA.*

ÖZET

Optik yükselteçler uzun mesafe fiber optic haberleşme için temel aygıtlardır. Optik iletişim penceresini genişletmek için düz kazançlı ve geniş bandlı optic yükselteçlere ihtiyaç vardır. Bu çalışmada OptiAmplifier optik simulasyon yazılımı kullanılarak farklı pompa güçleri, pompa konfigürasyonları ve giriş sinyal güçleri ile Fc-xsec, Fibercore, R31703, and ErFiber olarak adlandırılan dört tür erbiyum katkılı fiber çift geçişli EDFA ve üç geçişli EDFA olarak adlandırılan iki farklı yükseltece uygulanmıştır. Performans iyileştirmesi artık pompa gücünün elimine edilerek yüksek sinyal gücü ve düz kazanç ve düşük gürültü katsayısı elde edilmesiyle sağlanmıştır. Simulasyon sonuçlarına gore düz kazançlılık, yüksek kazanç ve düşük gürültü katsayısı kriterlerine gore en iyi sonuç çift geçişli EDFA için ErFiber türü EDF in kullanıldığı ileri pompalama konfigurasyonu ile elde edilmiştir. Bu sonuçların çift yönlü pompalama için de büyük ölçüde geçerli olduğu ve pompa gücünün artırılmasının çıkış gücünü artırdığı ve gürültü katsayısını azalttığı görülmüştür. Ancak geri yönlü pompalama konfigurasyonunun kazancı düşürüp gürültü katsayısını artirdiğl bulunmuştur.

Kelimeler: Çift geçişli EDFA, üç geçişli EDFA, L-band EDFA

CHAPTER ONE

1. INTRODUCTION

Human interactions depend principally on communication, which is the first step in social activities. For this reason, communication systems that enable the exchange of messages between distant places have become a topic of interest.

The basic motivation behind each new development is to increase data rate to enable more information to be sent and/or to increase transmission distance between communication points. Previously, communication systems had low information rates and mostly involved either visual or acoustical means. The invention of the telegraph by Samuel F. B. Morse in 1838 is considered the first step in a new epoch in communications (G. Keiser, 2000).

The telegraph could transfer only a few bytes per second, which was the norm for about fifty years until Alexander Graham Bell invented the telephone in 1878. Heinrich Hertz demonstrated long radio waves in 1895. Guglielmo Marconi implemented higher-frequency carrier waves with proportionally increased modulation speeds were implemented to improve and speed up communication based on electromagnetic waves (Schawlow, 1958).

This trend continued until the invention of higher electromagnetic frequencies, i.e., optical waves. In 1917, Albert Einstein showed that the process of stimulated emission must exist. And, Schawlow and Townes demonstrated the optical maser theory (Schawlow, 1958).

Laser action at optical frequencies in ruby was first demonstrated in 1960 by Theodore Maiman. Referring to Schawlow and Maiman Snitzer demonstrated the first experimental amplification of light in 1961 (Siegman, 1968).

Recently, continuous consumer demand has placed the telecommunications industry in a constant state of growth and change. Innovations in information technology are largely responsible for much of the activity in the industry. Increased competition among global telecommunication markets has increased equipment sales, while the cost of international calls and Internet communications have been reduced. In addition, photonic technology with better capabilities has revolutionized long-distance communications to support growth in the information market (Foo, 1999).

A communication channel transports an optical signal from a transmitter to a receiver without distortion. Most light wave systems used optical fibers as a communication channel because of silica fibers can transmit light with small losses at 0.2 dB/km. Optical power decreases to only 1% after 100 km. Fiber losses remain an important consideration in determining the amplifier or repeater (Agrawal, 1997**)**.

Optical transmission systems are basis of the principle that light can carrying more of information much a longer distance in a glass medium, while electrical signals can carrying information over coaxial or copper cables. Light is an electromagnetic waves, and an optical fiber is a waveguide. An optical amplifier is needed to compensate for the losses of optical fiber cables. Doped fiber amplifier (DFA) is an optical amplifier that uses rare-earth doping materials, such as erbium (Er3+), terbium (Te3+), neodymium (Nd3+), europium (Eu3+), samarium (Sm3+), praseodymium (Pr3+), lutetium (Lu3+), Thulium (Tm3+), ytterbium (Yb3+), lanthanum (La3+), gadolinium (Gd3+), dysprosium (Dy3+), promethium (Pm3+), cerium (Ce3+), and holmium (Ho3+), inside the fiber core.

Essentially, DFA is connected to a pump laser within a transmission line. The setup works on the principle that pump laser and stimulated emission are used to provide energy and excite ions to an upper energy level (Mohammed et al., 2011a, 2011b).The ions are then stimulated via the photon of the information signal and brought down to a low energy level. Subsequently, they emit photon energy exactly on the same wavelength as the input signal. The first rare earth-doped material of Nd3+ used in a single-mode fiber was demonstrated in 1960 (Ainslie, 1991). Some DFAs are obtained by doping fluoride-based fibers with elements such as Pr3+ with a 1300 nm window, Eu3+ with a 613 nm window, and Nd3+ with a 740 nm window (Naji et al., 2011). Temperature was analyzed depending on the configurations mentioned. Dependence on maximum spectral of EDFA gain with respect to temperature is obtained for single stage EDFA design while smaller spectral dependence of gains is obtained for both double stage and gain flatness double stage L-EDFA configurations (Yücel, 2011).

In optical fiber communication systems, the active medium of DFA that has less attenuation operates in the 1550 nm window that is create via doping a silica fiber core with Er3+. Currently, researchers focus more on erbium doping to decrease attenuation to a minimum because of the emission of Er3+ ions within a set of wavelengths of about 1550 nm, especially in silica-based fibers. This condition occurs when the silica fiber results in minimum attenuation of the information signal (Naji et al., 2011).

Becker (2002) presented the following important features of EDFAs:

1. They have the ability to pump devices at several different wavelengths.
2. EDFAs are highly transparent to signal format and bit rate.
3. Low coupling loss is achieved with a compatible fiber transmission medium.
4. The cylindrical shape of EDFs ensures low dependence of gain on light polarization.

1.1 Main concepts**:**

The effects of light amplification were first describe theoretical (Schawlow and Townes, 1958), and an analysis of rare earth-doped fiber characteristics are study and demonstrate in 1962 (Beckeret al., 2002). Subsequently, an investigation on erbium-doped fiber was first conducted (Mears and Payne, 1987) in the University of Southampton. EDFA was introduced as a commercial device in 1992 because many studies were being conducted by several researchers (Desurvire, 1987; Armitage, 1988; Bjarklevetal., 1989).

Each free ion of Er3+ represents a discrete energy level. This condition is attributed to the fact that anion contains an amount of a particular energy that corresponds either to emitted or absorbed energy. Emitted energy will decrease the energy level, whereas absorbed energy will raise it. Emitting photons are associated with emitting light in terms of amplification. Figure 1.1 shows the possible energy levels for pumping bands as well as possible Er3+ ions. Pump photon absorption results in a high energy state for Er3+ ions. The ions may dissipate energy radiatively at a high energy level by converting the energy in to heat or by releasing photons.

Each energy level has numbers of stark levels, and every ion experiences a different field strength and orientation, which will result in different stark splitting because of the randomness in glass molecular structure and according to the ion energy structure. Splitting is caused by large gain bandwidth of rare earth-doped fiber amplifiers. The numbers of stark split lines for every level are seven and eight for $^4I_{13/2}$ and $^4I_{15/2}$, respectively, which result in 56 possible transitions between lines that spread across a 1550 nm band at a low temperature (E. Desurvire, 1994).

The band has a sufficient overlap, which provides a smooth and continuous transition at a temperature of 300^0K. The increase of the energy gap between levels will also raise the tendency of photon radiation when jumping to lower energy levels. Thus, the transition between $^4I_{13/2}$ and $^4I_{15/2}$ is predominantly a radiative result at the1550 nm wavelength region. Spectroscopy studies on Er3+ glass show that pump wavelengths at 520 nm (Desurvire, 1987), 620 nm (Mears, 1987), 800 nm (Mearsetal, 1988), 980 nm (Liawetal., 1997; Haugenetal., 1992), and 1480 nm (Gabla et al., 1992) has been successfully demonstrate.

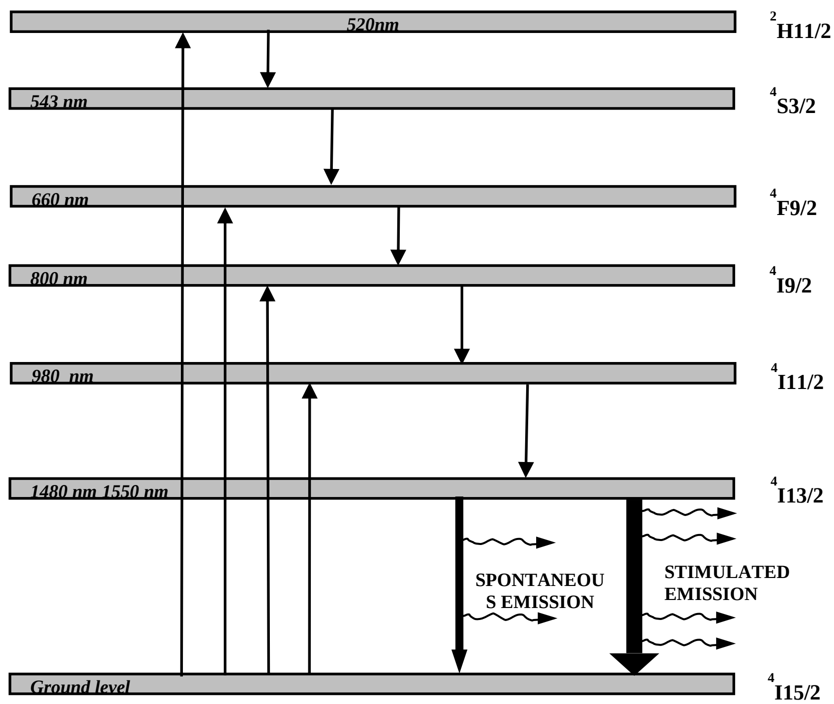


Figure 1.1 Energy level of erbium ions with the possible pump bands (Desurvire, 1994).

Pump laser diodes are available and grow mature at wavelengths of 1480 and 980 nm; therefore, these pump wavelengths are widely deployed (Franz and Jain, 2000). Pumps of 980 nm have narrow absorption bands. Thus, they provide low-noise amplifier output but require wavelength accuracy. By contrast, 1480 nm pumps have better power conversion efficiency than 980 nm pumps (Desurvire, 1994).

Figure 1.1 shows that discrete energy value via energy gaps, which follow the law of quantum physic. Ground level E ($^4I_{15/2}$) indicates the lowest level, and E ($^4I_{13/2}$) indicates the first level. The ion energy level may change because it can jump to another level discretely. The different energy Δ is the photon released as quantum energy when an atom moves from the upper to the lower level. The photon carring the energy of Ep and is defined as follows (Desurvire, 1994):

$$Ep = hf = E_2 - E_1 \quad (1.1)$$

Where:

E_2 and E_1 refer to the atom's discrete energy during transition between levels.

$h = 6.626\times10^{-34}$ J. is the Planck's constant, and photon frequency is denoted by f.

External energy is required to change the atom energy level from a lower to an upper level. The atoms absorb its energy and jumps to the upper level. Naturally, the atom attempts to surpass its lowest possible energy level. The process of providing an atom with external energy, known as pump, is depicted in Figure 1.2 (Naji et al., 2011).

Light absorption occurs when the atom relaxes at E_1which is the lowest energy level, and then applied external energy is absorbed via the atom and causes it to jump to a higher level E_2. Light emission occurs when the atoms from E_2 reach ground energy level. Light emission occurs either spontaneously or through stimulation processes. Spontaneous light emission occurs when an atom returns to the lower energy level randomly, while stimulated emission takes place when photon-shaving energy equals the energy difference between E_2 and E_1. The latter causes the atom to return to E_1, and more photons that have similar phases, polarizations, and frequencies with the ones that caused it are emitted. This condition is shown in a diagram in Figure 1.3.

Emission can occur in two ways:

1. Spontaneous emission, where atoms return to the lower energy level in a random manner. Spontaneous emission always involves transitioning from an upper to a lower energy state according to quantum mechanics theory. The spontaneous emission that is produced would become the noise generated via the amplifier and is referred to as amplified spontaneous emission (ASE) (Naji et al., 2011).

2. Stimulated emission is where the energy of a photon (energy carrying atom) is equal to the energy difference between E_2 and E_1, and interacts with the atom in E_2, thereby causing it to return to E_1 along with the creation of more photons. This condition is also referred to as avalanche multiplication.

The energy of a photon produced via stimulated emission is generally identical to that of the photon that caused it. Thus, the light associated with the produced photon is of the same phase, polarization, and frequency. Furthermore, when atoms are stimulated by an incident wave to emit light energy, the liberated energy could add to the wave in a constructive manner, thereby providing amplification (Naji et al., 2011).

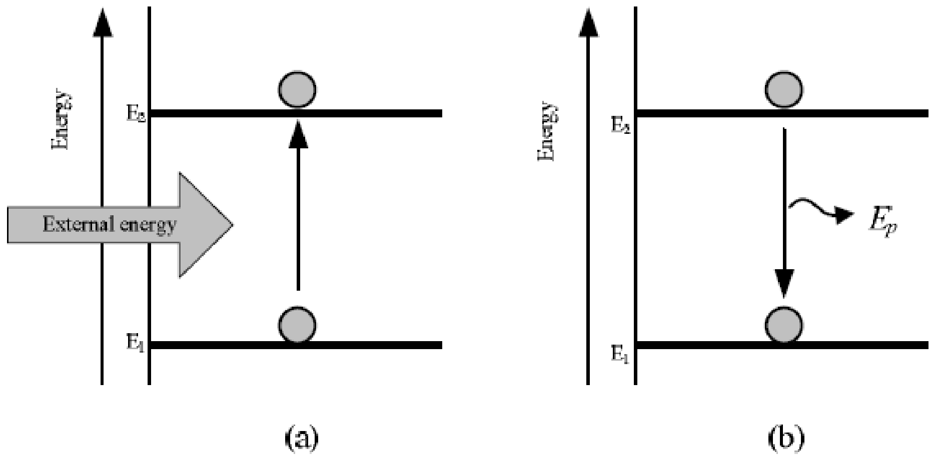


Figure 1.2 Atom with respective energy level: (a) light absorption and (b) light emission

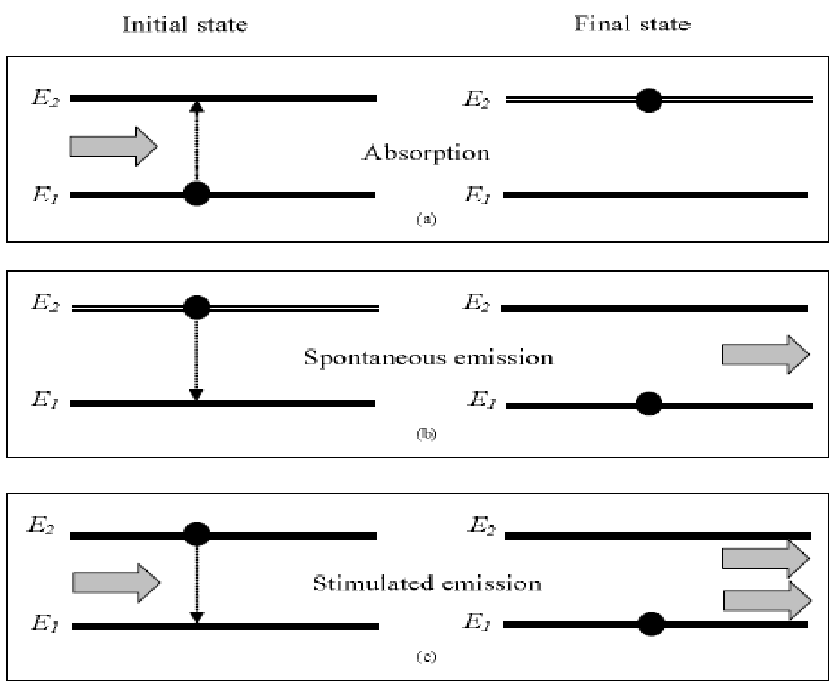


Figure 1.3 Schematic representations of absorption and emission between energy levels 1 and 2: (a) absorption, (b) spontaneous emission, and (c) stimulated emission. The black dot indicates the state of the atom before and after transition takes place, and the block arrow in (a) represents pump light, (b) ASE, and (c) signal light (Nadir et al., 2007d).

1.2 Literature survey

Many studies deal with the performance of erbium-doped fiber amplifiers in the L band, such as the following:

- Jung Mi Oh presented the bidirectional pumping scheme by incorporating a fiber Bragg grating (FBG) to achieve flat gain in L-band erbium-doped fiber amplifiers.

- Ahmet Altuncu analyzed EDFAs through simulations, which showed that gain and noise figure performance depend on EDF length. This paper provided a design and experimental characterization of high-performance C and L band EDFAs.

- S.W. Harun presented single- and double-pass systems in a new design of gain L-band EDFA. In addition, he presented gain enhancement in long wavelength band erbium-doped fiber amplifier (L-band EDFA), which was demonstrated by implementing a dual forward pumping scheme in a double-pass (DP) system. The small signal gain for a1580 nm signal can be improved by 13.5 dB unlike with the use of a single-stage single-pass scheme.

- J. H. Ji presented a new design of an all-optical gain-clamped L-band EDFA. The gain was clamped with a low-noise figure via DP configuration, which incorporated FBG and fiber ring laser configuration with an interleaver. The configuration improved the low-noise figure and the gain was clamped when the FBG is in DP configuration.

- K. H. Yla-Jarkko presented results on a low-cost cladding-pumped L-band amplifier based on side pumping (GT wave) fiber technology and pumped by a signal from a 980 nm multimode diode.

- L. L.Yi presented parallel C+L band EDFA through co-propagation configuration to obtain all-optical gain clamping. The gain and noise figure of the L-band signal were improved via DP configuration that incorporated an FBG.

- António Teixeira analyzed gain and noise figure of C and L band EDFAs. The behavior of the involved parameters as a function of power and wavelength was verified experimentally.

- Sulaiman Wadi Harun presented again-clamped DP L-band EDFA with high clamped gain and low-noise figure by using a ring laser. The broadband FBG that operates in the L-band region is used to retro-pass the test signal back into the system for enhanced gain.

- A.A. Rieznik presented the maximum gain of C and L band EDFAs for optimum fiber length with fixed pump power and showed that the optimum length depends on power and wavelength.

- Ali Sellami presented four configurations of EDFA, namely, possible passive single-pass, double-pass, triple-pass, and quadruple-pass, which were employed to improve gain and noise figure in the L-band.

- Yucel M presented flatten erbium doped fiber amplifiers (EDFA) gain by using many configurations. Gain and noise figure were analyzed using of one-stage, two-stage, two-stage with gain flattening filter, and double-pass L band EDFA configurations.

- A.W. Naji compared two configurations with different stages of EDFA, which produced triple-pass EDFAs. Triple-pass EDFA was analyzed for high performance gain and noise figure.

- Fowzia Akhter presented a multi-stage EDFA design with all possible triple-pass EDFA configurations to achieve high gain and low noise figure**.**

- Yucel, M Designed and optimized C and L band Erbium Doped Fiber Amplifiers (EDFA) are applied to three port filters and then input signals are separated into C and L bands in double pass configuration. For this purpose, 16 channels Wavelength Division Multiplexed (WDM) system with -30 dBm powers at the input signals (1530 nm-1610 nm).

- S. K. Liaw presented C + L bands, two types of a bidirectional fiber amplifier that used EDFA, and a hybrid fiber amplifier in C + L band. A single-wavelength pump source was used for both in this paper.

1.3 Aim of the work

EDFA is suitable to operate in the conventional (C) band from 1530 nm to 1570 nm, which can be considered the main limitation of EDFA as the C band is fully utilized. Long band EDFA is needed to operate in L-band EDFA with high pump power. However, the noise figure is higher than its value in the C-band EDFA. High EDFA concentration can also be used with the same EDFA length to achieve L-band EDFA. However, a higher noise figure is also observed. The main aim of this thesis is to design and simulate L-band EDFA with a low-noise figure as a high-quality optical amplifier for communication systems.

- This study also aims to design and analyze two new EDFA configurations.

- EDFA can operate in a wide-band region with high performance when we obtain a low-noise figure in the L band.

CHAPTER TWO

2. THEORY OF ERBIUM DOPED FIBER AMPLIFIER

Desurvire (1994) concluded that the theoretical study of the Erbium Doped Fiber Amplifier (EDFA) phenomenon is slightly complex due to the physical complexity, which includes:

1. The dependence of the energy level with light spectrum.
2. The Stark split.
3. The influence of the crystal field.

Based on the properties given above, a new design to decrease eliminate the residual energy is needed to enhance gain and noise figure of the amplifier. This will increase the efficiency of the amplifier as well as an increase in gain with a lack of noise figure at the same time. The theoretical study is important for getting better results in the amplifier. Besides, studying the properties of the amplifier and signal processing will increase the efficiency and disposal of high noise figure.

A lot of papers have been published since 1990s to explain the amplification phenomenon taking into consideration the parameters and factors affecting the phenomenon (Digonnet, 1990). This chapter represents Naji et al., 2011 of the theoretical studies behind the DFA and devices.

2.1 EDFA Evolution

During the second half of the previous century, a huge progress for fiber optic technology was experienced (Schawlow, 1958). The development of the fiber scope during the 1950's was considered an early success whereas the developed of laser technology was the next important step to initiate the optical communications. Lasers developed through several generations include the developing of the ruby laser and the helium-neon laser in 1960 (Maiman, 1960). In addition the semiconductor lasers were realized in 1962; which are the most widely used type in fiber optics today.

Maiman (1960) stated that the use of the laser enabled huge band widths for transmission systems. At that time, due to the high attenuation in silica glass fiber, optical communications did not emerge right away partly; therefore enormous efforts were made by several researchers to lower the losses in glass fiber. Researchers began to work on the problem of purifying glass.

A type of glass fiber that exhibited attenuation at less than 20 dB/km was developed, by Drs. Donald Keck, Robert Maurer and Peter Schultz (Maiman, 1960).

Optical fiber develops over the years in a series of generation that can be closely tied to wavelengths. Figure 2.1 shows three regions, the first one is the 850 nm region which was initially attractive because the technology to light emitter at this wavelength have already been perfect by LEDs (Ali, 2006).

Some companies jumped to the "second window" at 1310 nm because of low attenuation of about 0.5 dB/km, Nippon Telegraph and Telephone (NTT) developed the "third window" at 1550 nm. It offered the minimum optical loss for silica-based fibers, of about 0.2 dB/km (Keck et al., 1973).

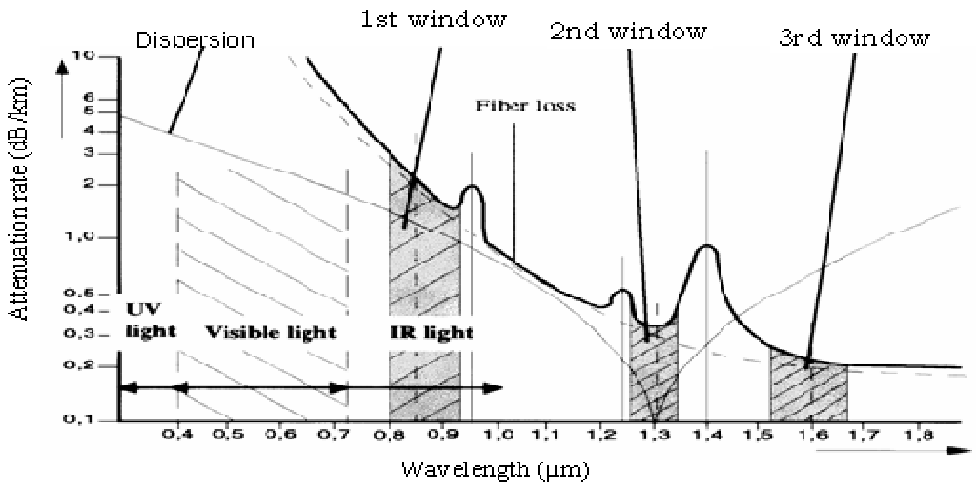


Figure 2.1 Three Wavelength Regions of Optical Fiber (Ali, 2006)

After getting a minimum loss window around 1550 nm for long haul communications. Optical gain at wavelengths near 1.55 nm need be realized. This can be achieved by doping with rare earth erbium and pumping the fiber with low power of visible light. This fact was firstly demonstrate in 1985, by a research group in the University of Southampton. The first applicable fiber amplifiers by using the EDFA has demonstrated in 1987 (Mears, 1987). Then, great effort have been poured into the development of optical amplifiers. Besides rare-earth doped amplifiers. Other techniques and materials for optical amplifiers has been developed.

Park et al (1988) stated that the EDFA is the most exceptional because of it can reach all the following advantages at once:

1- Minimal polarization sensitivity.
2- Temperature stabilization.
3- Quantum-bounded noise figure, and
4- Immunity to inter-channel crosstalk till at saturation region.

While (Karásek, 2001) demonstrate the rare-earth doped fiber amplifiers disadvantages are;

1- In contrast to Semiconductors Optical Amplifiers, they has to be pumped optically.
2- In addition, the gain flatness of the Erbium-Doped Fiber Amplifiers are not as good as that of Semiconductors Optical Amplifiers.
3- The lasing of photon by using Erbium Doped Fiber in conventional band and long band (C+L) bands respectively.

2.2 EDFA Operational Principles

The Erbium ions can exist in several energy states. For example, in case of the high energy state, a photon could be stimulated to give up some of its energy (as light), while by returning to a lower energy state (more stable state), photonic amplification is occurred. This phenomenon may consider as the basic operation principles of the EDFA (Agrawal, 1997).

2.2.1 Pump Wavelength and Absorption Spectrum

Based on the availability of these lasers sources, the pump wavelength can be either 1480 nm or 980 nm. Most of Erbium Doped Fiber Amplifiers using those two as their pumping wavelength. It is important here to explain that the Energy levels of the pump efficiency, Er3+, the absorption band of Er3+ and ionized erbium ion are serial states to which the erbium ions could be pumped using sources of different wavelengths such as those operating at 880 nm, 980 nm and 1480 nm. Figure 2.2 indicates these energy levels (Ali, 2006).

However, in real lightwave systems, the pump wavelength must be provide a high power to reach high gain in pump. The commonly available laser diode can operating at 800 nm, 980 nm and 1480 nm, while the pump efficiency can be rise more than 1 dB/mW with lower attenuation depending on the pump frequency.

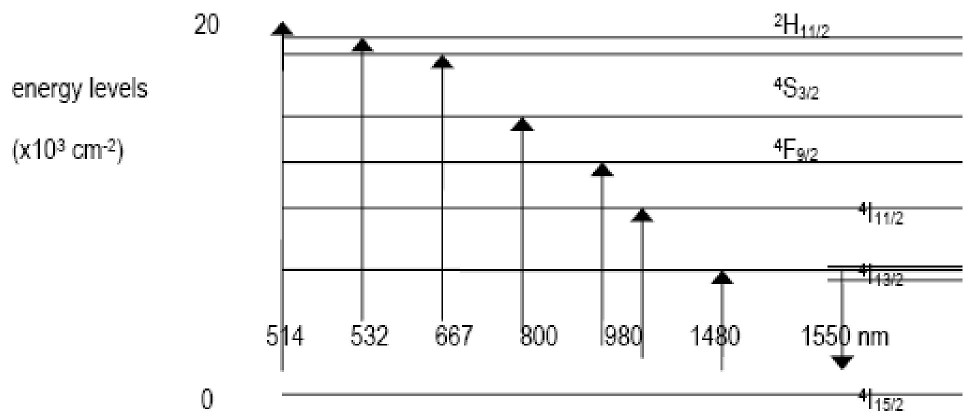


Figure 2.2 Erbium ion energy levels and pump spectra simplified model.

The only pump wavelength laser sources that are operating at 980 nm or 1490 nm can give a high pumping efficiency with lower attenuation. In practice, the 980 nm pump source is commonly used because its high gain coefficient (4dB/mW). The absorption and emission factors result in different effect of those two wavelength sources (Ali, 2006).

2.2.2 Pump Mechanism

The amplification mechanism plays a main role for developing the EDFA simulation model. During amplifier's pumping to achieve population inversion, the optical amplification gain are supplies via the excited erbium ions (Er^{3+}). Pumping scheme can be classified as a two level or three level scheme depending on the energy states of the dopant. The energy state occupied via the stimulated emission event governs the main difference between the two-level and three-level pumping schemes. In the case of a three-level scheme, the lower level is ground, where as it is in an excited state with a fast relaxation time in the two-level scheme. Figures 2.3 to 2.6, demonstrate that erbium ions are pumping to an upper energy level via the absorption of light wave energy from the pumping sources at either 980 nm or 1480 nm to regain the equilibrium distribution (Miniscalco, 1991).

Stage 1

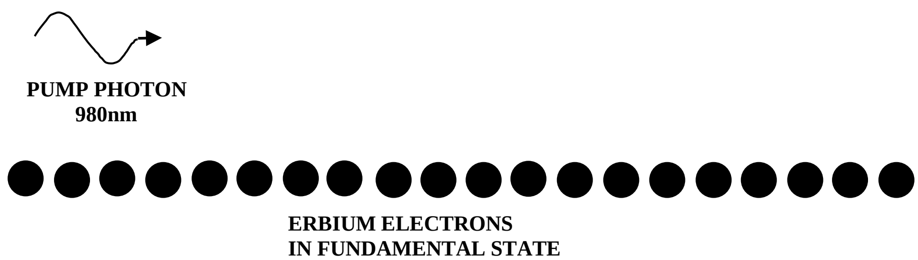


Figure 2.3 The erbium electrons lay on the fundamental state (Miniscalco, 1991)

Stage 2

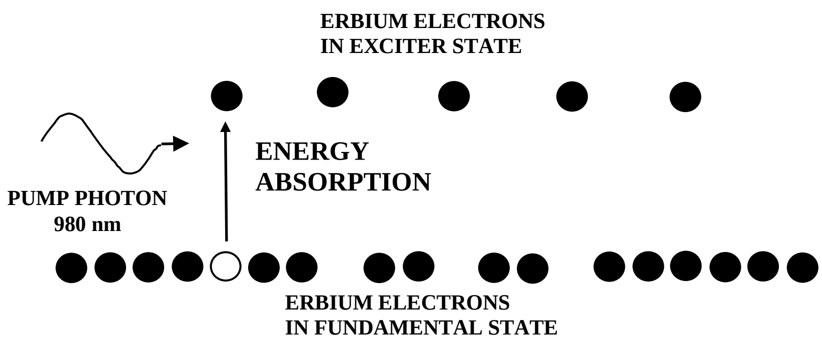


Figure 2.4 The erbium electrons which are pumped to higher-level energy states (Miniscalco, 1991).

Stage 3

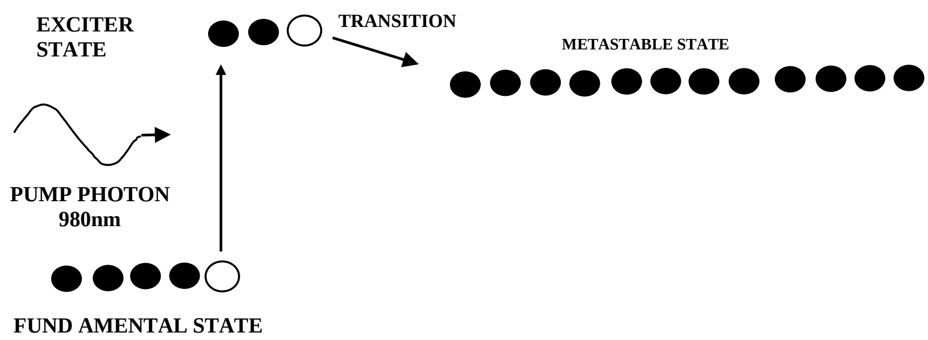


Figure 2.5 The erbium electrons now revert to lower states (metastable state) (Miniscalco, 1991).

Stage 4

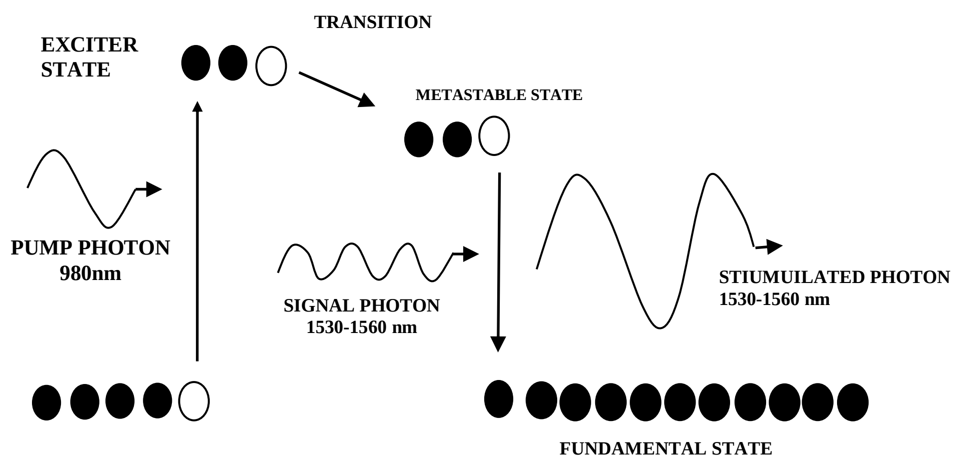


Figure 2.6 The erbium electron reverts to the fundamental state (Miniscalco, 1991).

Coherence of pumping sources and signals that means the incident photon and the stimulated one has the same phase, frequency, polarization and propagation direction (S. Yamashita, 2001). To achieve less noise figure with the highest optical must reach the pumping energy to the highest level of pumping, in this case will be the distribution inversion at the highest levels, upon the arrival of the ion to the upper level will take time 1 ms, then goes back to the meta-stable level, but there are many ions do not have enough energy to stay for 1 ms, which leads to fall of the ion to the ground level to produce the spontaneous emission, while ions which have enough energy to stay in the upper level will move to the meta-stable level and remains at this level time 10 ms, after this period will return the ions to the ground level to produce stimulated photon at wavelength of 1530-1560 nm .

2.2.3 Amplifier Noises

The noise is generated during the signal amplification process. The dominant amplification noise source is the amplified spontaneous emission noise (ASE noise). During the process of ions transition from the excited state to the ground state, some of excited erbium ions decay to the ground level state with spontaneous emission before amplifying the injecting signal photons. These photons are emitted with random direction and phase (Miniscalco, 1991).

As indicated in figure 2.7, the ASE spectral range are very broad and almost covers the C and L bands covering the gain spectrum of the amplifier. This will decrease the available gain for the signal field.

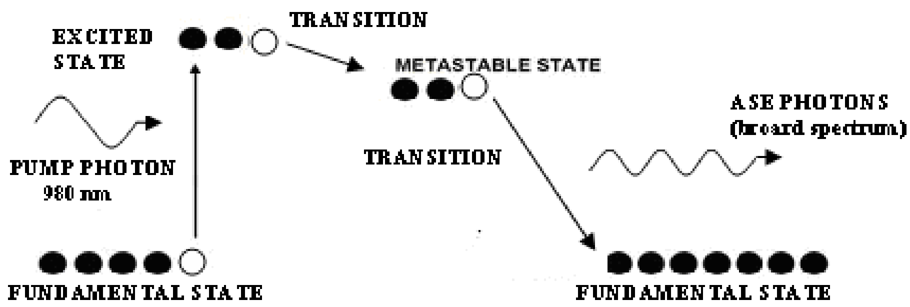


Figure 2.7 ASE photons Demonstration extracted (Chen, 1992)

Due to the incoherence of the signal photons with the excited erbium ions, the saturated gain has been reduced via the amplified spontaneous emission. V. Mehta graphically illustrated ASE noise spectrum as explained in Figure 2.8 (V. Mehta, 2003).

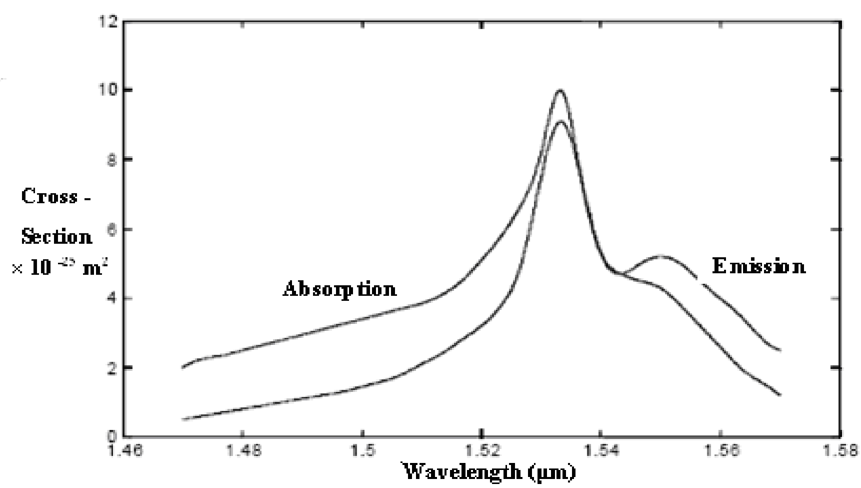


Figure 2.8 ASE noise spectrum (Mehta, 2003).

Erbium Doped Fiber Amplifier is employed in long-haul transmission systems; the Amplified Spontaneous Emission level grows after a cascade of amplifier and begins to saturate the optical amplifiers, hence decreasing the signal gain. This is attributed to the fact that, the total power almost equal to the pump power plus the Amplified Spontaneous Emission power as shown in figure 2.9.

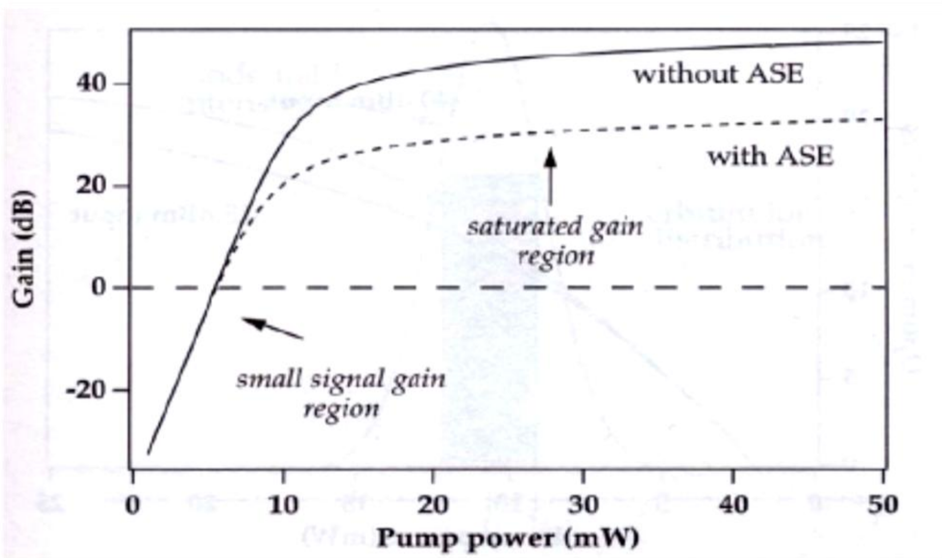
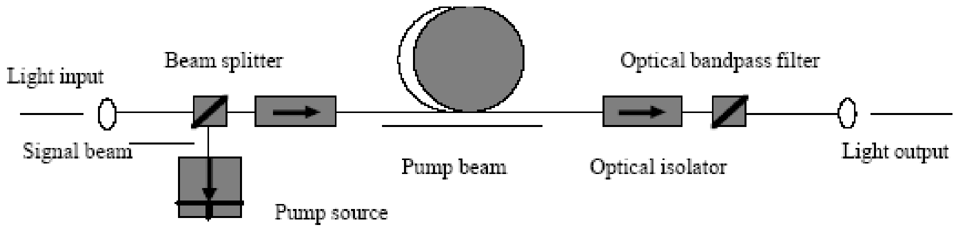


Figure 2.9 Optical gain reduction by the ASE (Mehta, 2003).

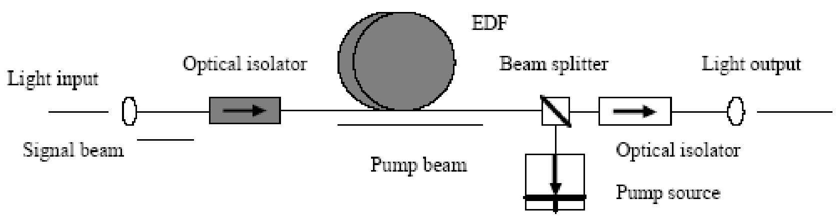
2.3 Construction of an erbium-doped fiber amplifier

An EDFA consists of a population inversion region and a means of supplying energy to this region, a means of suppressing laser oscillation, and optical filters for limiting the bandwidth. Figure 2.10 shows possible configurations, with an erbium-doped fiber form the population inversion region. The pumping beam must be launch into the fiber end and cause to propagate along it in the same way as the signal beam. Beam splitter and coupler are required to couple and separate the pump and the signal light (Ali, 2006).

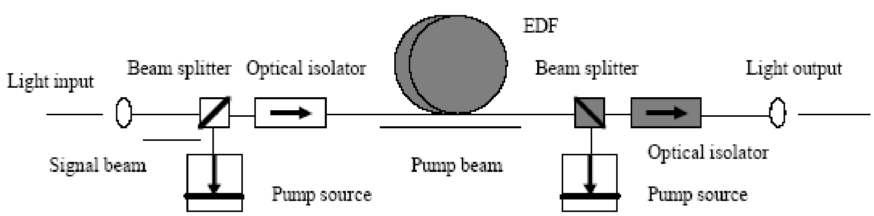
Erbium-doped fiber can be connect to other fibers through fusion splicing, which will cause reflectivity problem. At these points, a non-reciprocal circuit such as an optical isolator is essential for suppressing reflected signal.



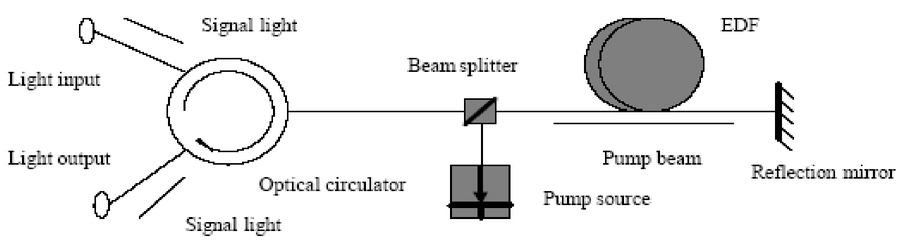
(a) Forward pumping (Gerd Keiser, 2000).



(b) Backward pumping (Gerd Keiser, 2000).



(c) Bi-directional pumping (Gerd Keiser, 2000).



(d) Reflection pumping (V. Mehta, 2003).

Figure 2.10 Configurations of erbium-doped fiber amplifiers

The configurations shown above in Figure 2.10 (a)-(d) are operating as traveling-wave amplifiers. When the pump beam travels in the same direction with the signal beam, this is called forward pumping (or co-propagation pumping) and called backward pumping (or back-propagation pumping) in case of the directions are opposite, while a combination of these two is called bi-directional pumping. The configuration using mirrors is known as reflection pumping. These configurations are all characterized according to the attenuation of the pump light as it propagates down the fiber and the occurrence of saturation induced by the signal light (Mehta, 2003).

2.4 Theoretical model of an EDFA

The transition levels of erbium ions optically pumped at any of the pump wavelength can be describe by use the standard three- levels laser system. Figure 2.11 indicates the laser system levels.

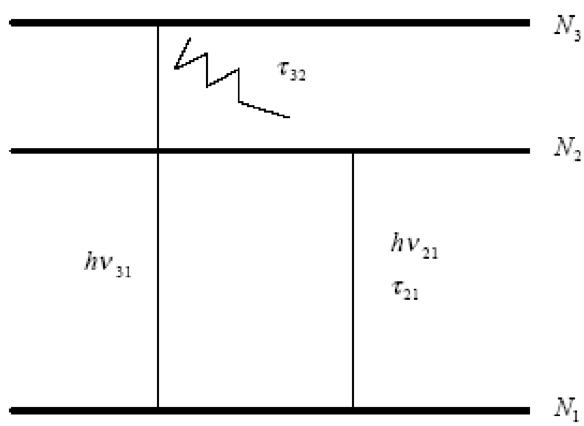


Figure 2.11 Three-level laser system for the erbium element

The relationship between the pump beam intensity I_P and the signal beam intensity I_S is given by the following equations (Yamashita, 2001).

$$\frac{dN_3}{dt} = \frac{\sigma_P I_P}{hv_p} N_1 - \frac{N_3}{\tau_{32}} \tag{2.1}$$

$$\frac{dN_2}{dt} = \frac{N_3}{\tau_{32}} - \frac{N_2}{\tau_{21}} - (\sigma_s N_2 - \sigma_a N_1) \frac{I_s}{hv_s} \tag{2.2}$$

$$\frac{dN_1}{dt} = -\frac{\sigma_P I_P}{hv_p} N_1 + \frac{N_2}{\tau_{21}} + (\sigma_s N_2 - \sigma_a N_1) \frac{I_s}{hv_s} \tag{2.3}$$

Where:

N_3, N_2 and N_1 are the ion density at the excited level, upper and fundamental levels respectively; σ_a is the absorption cross-section; σ_S is the stimulated emission cross-section; σ_P is the pump cross-section; τ_{21} is the level 2 to level 1 transition lifetime; τ_{32} is the level 3 to level 2 transition lifetime ($\tau_{32} \ll \tau_{21}$); *vp* is the pump frequency; *h* is Planck's constant; *vs* is the signal frequency; and the total ion densities will be N_T (Ali, 2006).

$$N_3 = \tau_{32} \frac{\sigma_P I_P}{hv_p} N_1 \ll N_1 < N_2 \tag{2.4}$$

Another:

$$N_T = N_1 + N_2 + N_3 \cong N_1 + N_2 \tag{2.5}$$

And furthermore:

$$N_1 = \frac{\frac{\sigma_s}{hv_s} I_s + \frac{1}{\tau_{21}}}{\frac{\sigma_p}{hv_p} I_p + \frac{(\sigma_a + \sigma_s)}{hv_s} I_s + \frac{1}{\tau_{21}}} N_T \tag{2.6}$$

$$N_2 = \frac{\frac{\sigma_p}{hv_p} I_p + \frac{\sigma_s}{hv_s} I_s}{\frac{\sigma_p}{hv_p} I_p + \frac{(\sigma_a + \sigma_s)}{hv_s} I_s + \frac{1}{\tau_{21}}} N_T \tag{2.7}$$

In the case of an Erbium Doped Fiber Amplifiers, there are the length waveguide structure in the fiber and the fact that it is only end pumped. Assuming the Erbium-Doped Fiber (EDF) to be uniform along its axis (*z* direction), ignore propagation loss, for a small fiber length dz, the following equations could be obtained (Ali, 2006).

$$\frac{dI_p}{dz} = -\sigma_p N_1 I_p \tag{2.8}$$

$$\frac{dI_s}{dz} = (\sigma_s N_2 - \sigma_a N_1) I_S \tag{2.9}$$

$$\pm \frac{dI^{\pm}{}_{ASE}}{dz} = (\sigma_s N_2 - \sigma_a N_1) I^{\pm}{}_{ASE} + hv\sigma_2 N_2 \Delta v \tag{2.10}$$

The '±' in Equation (10) refers to the Amplified Spontaneous Emission propagation direction. Where '+' indicate the ASE and pump light travel in the same direction, and '-' indicates opposite directions.

Δv is the spontaneous emission bandwidth and assuming homogeneous broadening of the spontaneous emission spectrum, the spectral function could be taken to has a Lorentzian shape given by (Ali, 2006).

$$g(v) = \frac{1}{\pi \Delta V} \frac{\Delta V^2}{(V - V_0)^2 - \Delta V^2} \tag{2.11}$$

It is take that the spontaneous emissions low enough to be ignored. Substituting Equations (6) and (7) and normalize by using the formulae given by:

$$I_{th} = \frac{hV_P}{\sigma_P \tau_{21}} I_P^{'} = \frac{I_P}{I_{th}} I_s^{'} = \gamma \frac{I_s}{I_{th}} \quad \gamma = \frac{\sigma_s V_P}{\sigma_P V_S} \quad \alpha = \frac{\sigma_a}{\sigma_S} \tag{2.12}$$

Equations (6) – (9) can be reformulate by:

$$N_1 = \frac{I_s^{'} + 1}{I_P^{'} + (\alpha + 1) I_s^{'} + 1} N_T \tag{2.13}$$

$$N_2 = \frac{I_P^{'} + 1}{I_P^{'} + (\alpha + 1) I_s^{'} + 1} N_T \tag{2.14}$$

$$\frac{dI_p^{'}}{dz} = -\frac{I_s^{'} + 1}{I_p^{'} + (\alpha + 1)I_s^{'} + 1} N_T \sigma_p I_p^{'} \tag{2.15}$$

$$\frac{dI_s^{'}}{dz} = \frac{I_s^{'} - \alpha}{I_p^{'} + (\alpha + 1)I_s^{'}} N_T \sigma_p I_s^{'} \tag{2.16}$$

From these definitions, *g (v)* the single-direction gain coefficient can be given by:

$$g(v) = \frac{I_p^{'} + \alpha}{I_p^{'} + (1 + \alpha)I_s^{'} + 1} N_T \sigma_s \tag{2.17}$$

Where I_P the pump light density is sufficiently high, the maximum gain coefficient (g_o) is given by:

$$g_0 = \frac{I_P^{'} - \alpha}{I_P^{'} + 1} N_T \sigma_S \leq N_T \sigma_S \tag{2.18}$$

From Equation (12), the gain coefficient are subject to saturation due to the amplify light signal I_S. If ' *sat* I_{sat} is defined as the signal light at which the gain coefficient is halved in value, then the following equation could be obtained:

$$I_{sat}^{'} = \frac{I_p^{'} + 1}{\alpha + 1} \tag{2.19}$$

$$g = \frac{g_0}{1 + I_s^{'}/I_{sat}^{'}} \tag{2.20}$$

In other words,

$$I_{sat} = \frac{I_p + I_{th}}{(\alpha + 1)\gamma} = \frac{\theta_p}{V_s}\frac{\sigma_p}{\sigma_a + \sigma_s}\left(I_p + I_{th}\right) \tag{2.21}$$

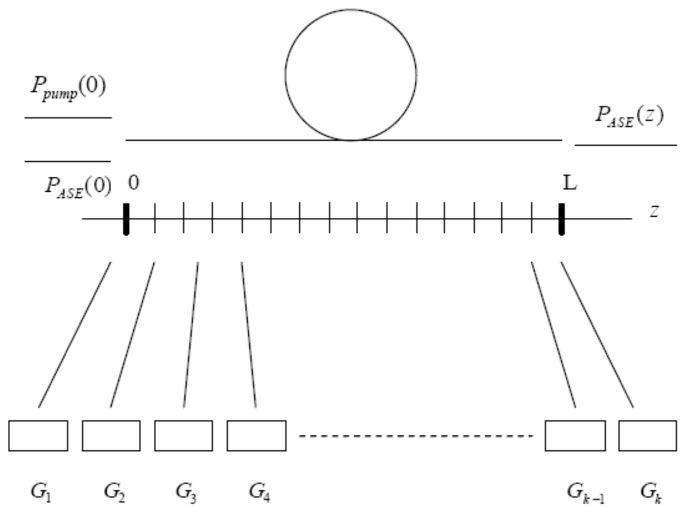
Where ($I_P >> I_{th}$).

The amplified signal beam producing saturation of the gain coefficient are proportional with the pump beam intensity. Furthermore, the population inversion parameter that determines the noise characteristics are given by (Ali, 2006).

$$n_{sp} = \frac{N_2}{N_2 - N_1}\frac{I_p^{'} + \alpha I_s^{'}}{I_p^{'} - 1 - (1 - \alpha)I_s^{'}} \tag{2.22}$$

With this value practically can reaching to1 when there are no signal ($I_P >> I_{th}$). The most important parameters in an Erbium Doped Fiber Amplifier of length L is the unsaturated gain G (L) and the noise figure F. The pump power P_{pump}, signal beam output P_S, ASE output $P_{ASE}(L)$,$G(L)$, and n_{sp} can be expressed via the following relationships, which can be understood by considering the distributed model of an EDFA in Figure 2.12 (Ali, 2006).

$$P_{pump} = I_p A_p$$



$$G(L) = G_1 \cdot G_3 \cdot G \cdots \cdot G_k$$

$$F = 2\left[n_{sp}^{(1)} \frac{G_1 - 1}{G_1} \times \frac{n_{sp}^{(2)}}{G_1} \frac{G_2 - 1}{G_2} \times \frac{n_{sp}^{(3)}}{G_1 G_2} \frac{G_3 - 1}{G_3} \times \cdots \times \frac{n_{sp}^{(k)}}{G_1 G_2 \cdots G_{k-1}} \frac{G_k - 1}{G_k} \right]$$

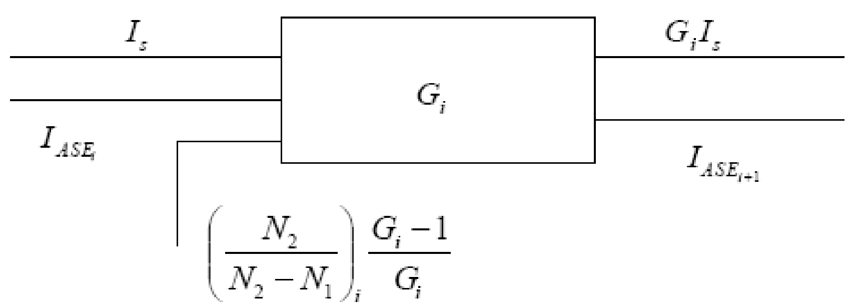


Figure 2.12 Divided model of erbium-doped fiber amplifiers (Ali, 2006)

$$P_s = I_s A_s \tag{2.23}$$

$$P_{ASE}^{\pm,E} = G(L)^{\pm} P_{ASE}^{\pm,0} \tag{2.24}$$

$$P_{ASE}^{0,L} = n_{sp}^{\pm}(L) h v \Delta v \frac{G(L)^{\pm} - 1}{G(L)^{\pm}} \cong n_{sp}^{\pm}(L) h v \Delta v \tag{2.25}$$

$$G(L) = \exp\left(\int_0^L g(z) dz\right) \tag{2.26}$$

$$n_{sp}^{\pm}(L) = \int_0^L \frac{g(z) n_{sp(z)}}{G(z)} dz \tag{2.27}$$

$$F^{\pm} = 2 \frac{P_{ASE}^{\pm}}{h v \Delta v G(L)} = 2 n_{sp}^{\pm}(L) \frac{G_L^{\pm} - 1}{G_L^{\pm}} \cong 2 n_{sp}^{\pm}(L) \tag{2.28}$$

$$G(L) \gg 1 \tag{2.29}$$

Where:

A_S *and* A_P are the effective cross-section of the signal beam and the pump beam respectively.

P_{ASE}^{0} is the equivalent incident noise power assuming that spontaneous emission light is input from the erbium-doped fiber end, and $n_{sp}^{\pm}(L)$ is the equivalent population inversion parameter in the direction of travels of the signal light.

When the incoming signal power are sufficiently great than P_{ASE}^{0}, equations that only consideration the pump light and signal light will accurately described the device operation (Ali, 2006).

2.5 The effect of input power on EDFA

2.5.1 The EDFA gain

The EDFA gain can be characterized by the following equation:

$$G = \frac{G_0}{1 + \left(\frac{P_{in}}{P_{sat}}\right)^{\alpha}} = \frac{G_0}{1 + \left(\frac{G_0 P_{in}}{P_{max}}\right)^{\alpha}} \tag{2.30}$$

Where:

G and G_0 are, the saturated gain and the small-signal gain for a given input signal power, respectively.

A P_{sat}^{in} and α are unknown parameters which characterized the gain saturation. Furthermore, it can be easily obtained from equation (30) that:

$$P_{max} = G_0 P_{sat}$$

Where:

P_{max} is maximum input power to EDFA.

The effect of rise the input power P_s^{in} on the EDFA gain can be characterize by the curve as shown in Figure 2.13.

In the small-signal regime which are often refers to as $P_s^{in} \leq P_{sat}^{in}$

Where, P_{sat}^{in} is the saturated input signal power and defined as the power at which the gain drops 3 dB below its maximum value.

In this so called linear gain region, G max -3 dB ≤ G ≤ G max, the Erbium Doped Fiber Amplifier operates near its peak gain performance. On the other hand, gain saturation are achieved when the Erbium Doped Fiber Amplifier characteristics depart from those linear relations. Figure 2.13 shows the theoretical results (X. Zhang, 2000).

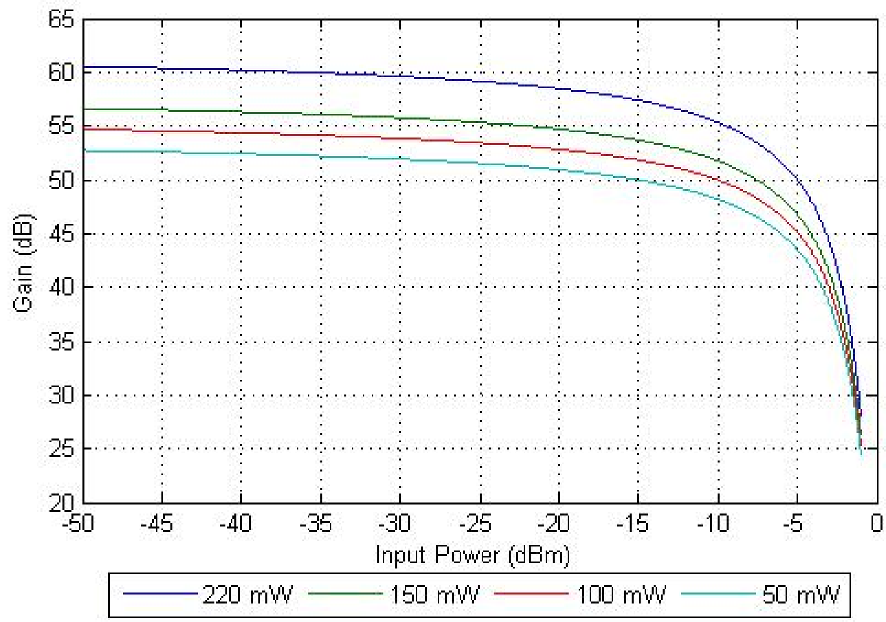


Figure 2.13 EDFA gain against input power (Ali, 2006)

2.5.2 The EDFA noise figure

Change of P_{in} not only changes the gain, but also changes the noise figure F_n. The following equation show the noise figure characteristic.

$$F_n = F_0 + K_1(\lambda)\exp[K_2(\lambda)(G_0dB - gdB)] \tag{2.31}$$

Where:

F_0 is small signal noise figure in dB.

F_n in noise figure in dB corresponds to the saturated gain g.

K_1 and K_2 are the parameters that depend on the wavelength. Figure 2.14 shows noise figure (NF) characteristics of EDFA in terms of $P_{in.}$ (X. Zhang, 2000).

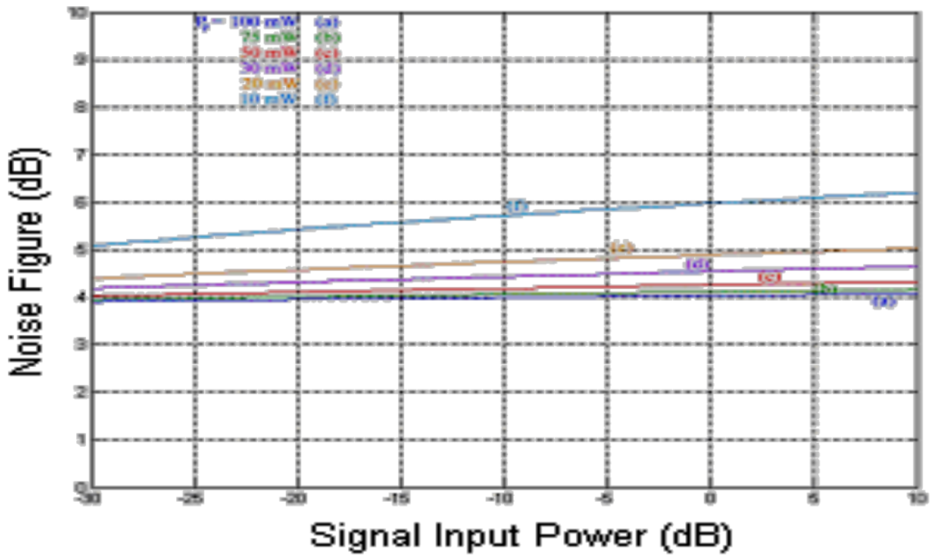


Figure 2.14 Noise Figure against Input Power (A.Cem ÇOKRAK)

2.6 The Effect of Pump Power on EDFA

2.5.3 The EDFA gain

The gain of Erbium-Doped Fiber is measure as a function of pump power; a laser is use as the pump source, operating at 980 nm for the fiber. As the pump power is rises, the output at the signal wavelength increase toward an upper limit.

By neglect the radial variations of both the dopant distribution and the optical fields, and also ignore variations along the length of the fiber, the gain G can be expressed by the following equation;

$$G = \exp\left[n_T . l \frac{W_{13\sigma E - \sigma_A/T}}{W_{13} + 1/T}\right] \quad (2.32)$$

Where:

$W_{13}$is the pump rate

r is the radiative lifetime, and

n_T is the number density of ions in the sample.

The above assumptions are justified for high pump powers, and short lengths of low doped fibers. The pump rate is directly proportional to the pump power ***P.*** In the case of no gain or loss (bleached condition), the pump rate is equal to $\sigma_{A\ /\ \tau}\sigma_E$, and the pump power to achieve it is P_{th}**.** Equation (32) can thus be re-written as:

$$G = \exp\left[n_T l \sigma_E \left(\frac{P - P_{th}}{p + P_{th}\frac{\sigma_E}{\sigma_A}}\right)\right] \quad (2.33)$$

Putting $R = P / P_{th}$**,** (33) becomes:

$$G = \exp\left[n_T l \sigma_E \left(\frac{R - 1}{R + \frac{\sigma_E}{\sigma_A} 1}\right)\right] \quad (2.34)$$

or, setting $n_T l \sigma_E$ to G_{max}**,** ***we*** have

$$G = \exp\left[\left(\frac{R-1}{R+\frac{\sigma_E}{\sigma_A}}\right)G_{max}\right] \tag{2.35}$$

Re-expressing the gain in decibels, we then have:

$$G = G_{max}\left(\frac{R-1}{R+\frac{\sigma_E}{\sigma_A}}\right) \tag{2.36}$$

Initially, σ_E / σ_A is set to 1**.** G_{max} may be predict from the experimental data by use (36). Figure 2.15 shows the characteristic of gain in terms of pump power. When the pump power are rise, the gain starts to increase in linear manner with pump power until the saturation occurs and then starts to stay constant (William L. Barnes, 1991).

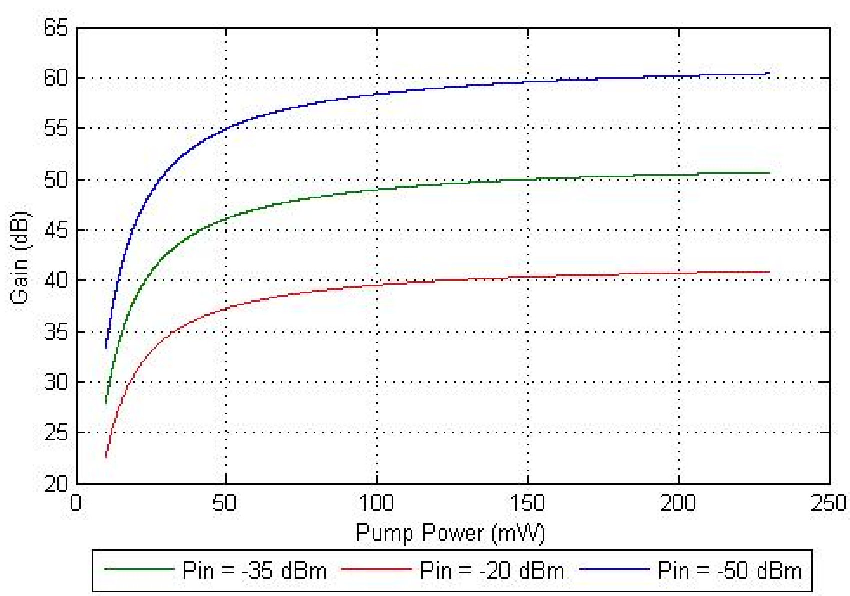


Figure 2.15 The gain against pump power (Ali, 2006)

2.5.4 The EDFA noise figure

The noise figure can be written as the following equation:

$$NF = \frac{(SNR)_{in}}{(SNR)_{out}} = \frac{P_{ASE}}{h\nu B.G} + \frac{1}{G} = 2n_{sp}\frac{(G-1)}{G} + \frac{1}{G} \approx 2n_{sp} \qquad (2.37)$$

Where;

n_{sp} is the spontaneous emission factor, can be determined using the equation below:

$$n_{sp} = \frac{N_2}{N_2 - S(\lambda_s)N_1} = \left\{1 - S(\lambda_s)/S(\lambda_p) - S(\lambda_s)P_p^{th}/P_p\right\}^{-1} \qquad (2.38)$$

Where:

$S(\lambda) = \sigma_a(\lambda_s) / \sigma_e(\lambda_p)$. The limit $\sigma_e(\lambda_p) \sim 0$ corresponds to the case of the three-level system, where $n_{sp} \approx [1 - S(\lambda_s) P_P^{th} / P_P]^{-1}$.

Figure 2.16 illustrates the dependence of NF on pump power. The curve shows that as the pump power is increased, the NF decreases and then starts to stay constant to reached a value of 3 dB for high pump power (Desurvire, 1990).

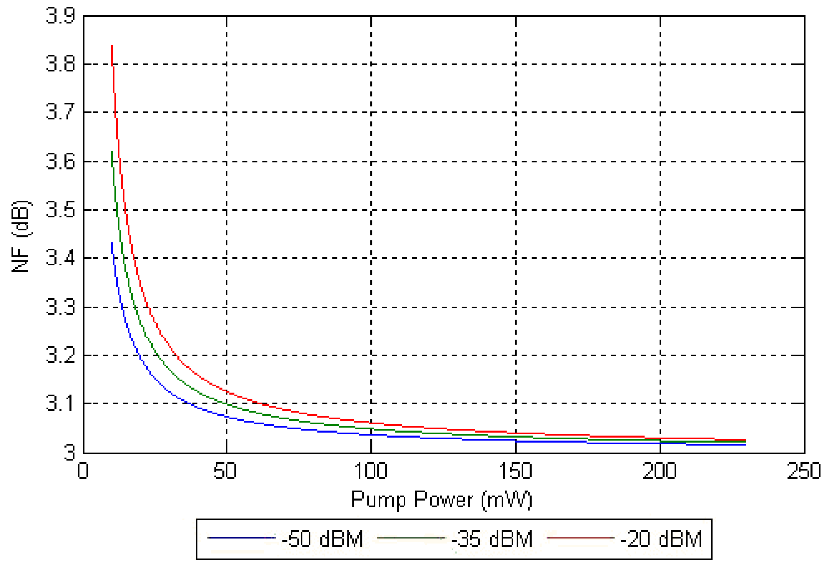


Figure 2.16 Noise Figure characteristic against pump power (Ali, 2006)

CAHPTER THREE

3. SIMULATION OF ERBIUM DOPED FIBER AMPLIFIER CONFIGURATION

3.1 Introduction

Erbium doped fiber amplifier (EDFAs) have elicited increasing attention for use them at wavelengths ranging from 1530 nm to 1560 nm bands at the third telecommunication window (H. Osanai et al., 1976). Significant progress has also been achieved in the development of high-yield EDFAs. Optical communication forms the backbone of communication because of its high-capacity communication systems. Given the intrinsic characteristics of various fiber materials, fiber systems still suffer from transmission loss. Thus, research should be directed toward adding new materials to improve the system and reduce losses (J. L. Zyskind et al., 1989). In this chapter, we introduced a double passes EDFA setup to eliminate the residual pump power out of the signal and attain optimal result, that is, high yield with low-noise figure by using WDM coupler as a wave selective coupler (WSC). This method reduces the effect of ASE self-saturation. We also demonstrate the effects of pump power on gain and noise figure, input signal power on gain and noise figure, and analysis gain and output power. The Figure 3.1 shows the progress of the signal in double pass configuration. The first pass went through Circulator1 port 1 into port 2, then traveling via EDFA to the amplified signal where it should be propagated. Thus, the first amplification event starts from the EFD. The signal reflects from Circulator2 and passes through the EDF second times and reaches to this receiver via WDM coupler and Circulator1.This setup was simulated using OptiAmplifer 4.0 and Matlab-based was used, as well as the program used are described in the Appendix.

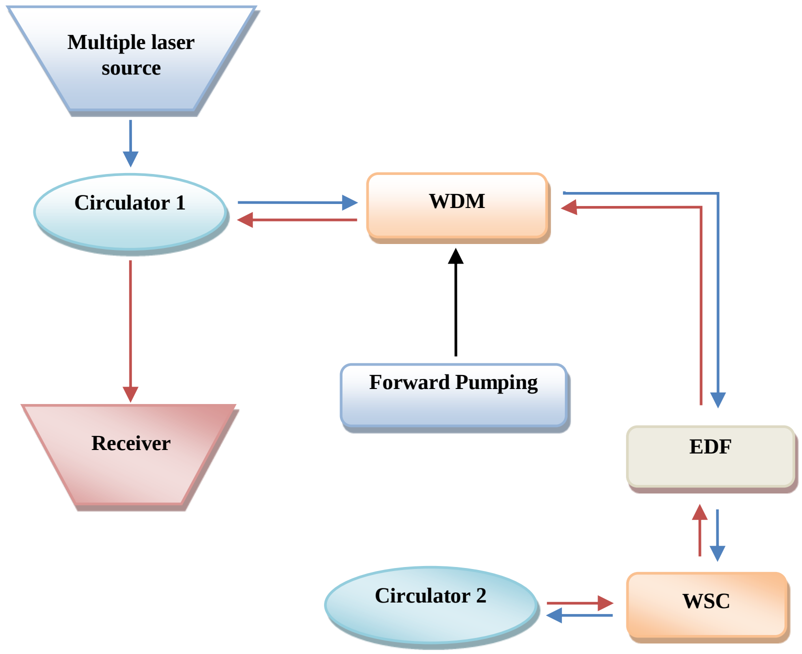


Figure 3.1 The progress of the signal in double pass EDFA with WSC

3.2 EDFA Parameters

EDFA parameters were divided into two parts: input parameters and output parameters. In the first part, the designer selective values were obtained from the engineering model. These parameters included input power, EDF length of the amplifier, pump power, and all parameter effects on the output power of the optical signal. The second part, which contained the output parameters, was used to evaluate the performance of the design and indicate the design's ability to satisfy functional requirements, such as the performances of gain and noise figure. The EDFA parameters control the EDFA performance. In this case, any changes in the design parameters also caused changes in the output of the optical signal and EDFA performance. The EDFA parameters discussed in this chapter are input power, erbium-doped fiber length, and pump power (Ali, 2006).

The length of the EDF is an important parameter for determining the performance and characteristics of the output optical signal, which include gain and noise figure.

Selecting the optimum length of the amplifier will attain the highest gain while reducing noise figure. Amplification of the signal by propagation through the EDF results in gain. The gain of an EDFA for an input signal depends directly on the overall average population inversion of Er^{3+} along the fiber. Another important figure indicates noise, and noise figure is generated by amplified spontaneous emission, thereby affecting the output optical signal.

Pump wavelength is very important because the EDFA efficiency is directly depends on the pump wavelength. The pump wavelength is also an important parameter for determining the performance and characteristics of the EDFA in optical communication. Pump power is the rate of energy pumped to excite the active ions in the active medium. Increasing the pumping energy will also increase the number of excited ions from the ground level to the upper level, thereby leading to a high rate of ion inversion. This thesis describes the effects of pump power on gain and noise figure.

3.3 The proposed configuration

3.3.1 Simulation Set-up

Simulations were performed to analyze the pump power dependence of gain and noise figure, as well as the effects of input signal power on gain and noise figure and analysis gain on output power performance in L-band EDFAs by using OptiAmplifer 4.0 simulation program. The high-yield behavior and characterization details of the new double-pass EDFA with WSC were also analyzed. The erbium-doped fiber (ErFiber.crs EDF) was used in the simulations. The numerical aperture was 0.31 with ion concentration of $1.4.10^{25}$ ion/m3. The core radius was 1 µm, and that of erbium doped fiber was also 1 µm. The lengths of EDF were 23, 30, and 36 m for the input power of −20, −30, and −40 dBm, respectively. An increase in yield indicated increases in output signal power and ratio of input signal power, thereby increasing sensitivity for the amplifiers (B. Bouzid et al., 2003). These results had been expounded to achieve the effects of the new setup on the decrease and increase of noise figure and yield, respectively. The circulator plays an important role in this configuration, and the optimal length was mainly responsible for the reduction of losses. Figure 3.2 shows the double-pass EDFA with WSC, and multiple laser sources used to inject signal light into the fiber. A circulator was used as an isolator to simultaneously separate the input signal from the output signal. A reflector was used to reflect the amplified signal back to the EDF and a receiver used to obtain the signal via circulator.

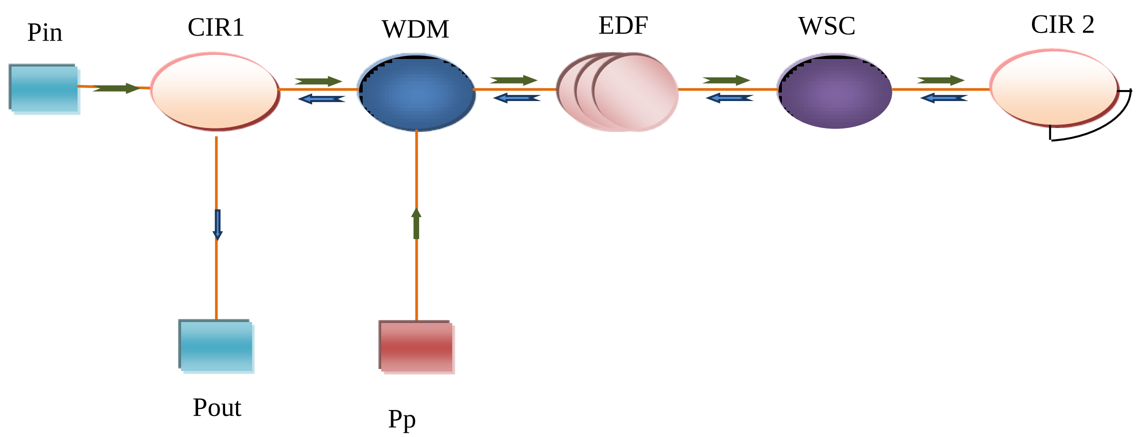


Figure 3.2 Double pass Erbium doped fiber with WSC

3.3.2 Principle of Operation

The configuration consists of circulator1 (CIR1) with three ports as follows: port1 for input signal power, port2 for connection with EDF, and port3 for output signal power. For signal feedback, CIR2 was used instead of a mirror because the simulation program contains no mirror. Multiple laser sources were used to inject signal light into the fiber. In this configuration, wavelength division multiplexing involves 16 channels. EDF is required for external pump sources to work. Thus, EDF was pumped by a pump laser operating at 980 nm. The first pass went through CIR1 port1 into port2, then traveling via EDF to the amplified signal where it should be propagated. Thus, the first amplification event starts from the EFDA. The second amplification occurs after passing the signal through CIR2 from port1 into port2, then passing WSC by traveling via EDF. Thus, the second amplification was an event that occurred via EDF. When the signal feedback from the CIR2 passive WSC arrived at EDF at this point, the residual pump power was eliminated, and the spontaneous emission decreased. In this case, the noise figure also decreases. After the second stage, in which the signal passed through EDF, the signal was sent to the output via port3 in CIR1.

3.3.3 Gain and Noise Figure against Pump Power

Figure 3.3 shows the relation between gain and pump power at 1590 nm wavelength with different input signal powers of −20, −30, and −40 dBm. The optimal lengths used for these powers were 23, 30, and 36 m, respectively. Thus, we used forward pump power with WSC Figure 3.3. We also used 12 different pump powers. The first power level is 20 mW, increases until 240 mW with the step of 20 mW. The gain increases gradually when the pump power was 20 mW and reached 80 mW for three signal powers. The pump power above 80 mW for the three signal powers slightly increased the gain. The highest recorded gain for −20, −30, and −40 dBm as 37.51, 43.73, and

47.45 dB, respectively, at 240 mW pump power. These findings suggest a direct correlation between gain and pump power for a given length. Table 3.1 shows the results of comparison of gain and noise figure for −20, −30, and −40 dB input signal powers with different pump powers for double-pass EDFA with WSC.

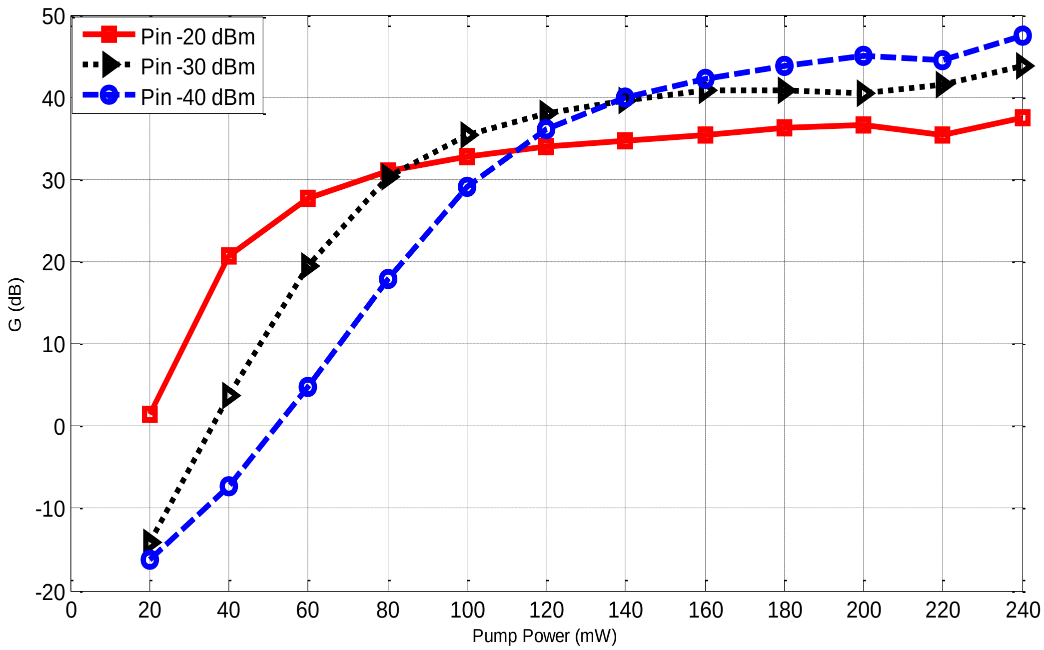


Figure 3.3 Gain against pump power at wavelength 1590 nm

Figure 3.4 shows the noise figure against pump power at 1590 nm wavelength with optimal length for three input signal powers of −20, −30, and −40 dBm. The noise figure gradually decreased as the pump power increased to 80 mW. Above 80 mW, the noise figure decreased slightly. The noise figure was very high at power pumping from 20 mW to 80 mW because the ions lack energy to remain in the upper level at 1 ms. The lowest noise figure for the input signal powers −20, −30, and −40 dBm showed 4.233, 4.262, and 4.282 dB, respectively. These findings suggest an inverse relationship between noise figure and pump power.

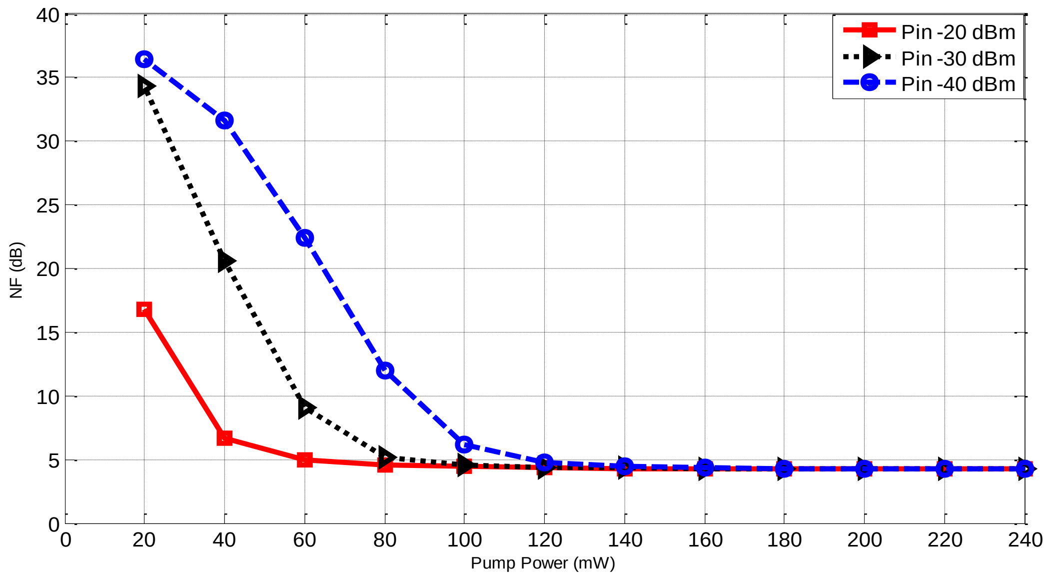


Figure 3.4 Noise figure against pump power at wavelength 1590 nm

Table3.1 Comparison between gain and noise figure for -20 dBm, -30 dBm and -40 dBm input signal power with different pump power for double pass EDFA with wave selective couple.

PUMP POWER	**INPUT POWER(-20dBm)**		**INPUT POWER (-30dBm)**		**INPUT POWER (-40dBm)**	
NM	G (dB)	NF (dB)	G (dB)	NF (dB)	G (dB)	NF (dB)
20	1.43	16.795	-14.14	34.3	-16.21	36.436
40	20.662	6.643	3.7	20.64	-7.35	31.674
60	27.734	4.945	19.54	9.076	4.7	22.392
80	30.929	4.572	30.26	5.187	17.92	12.005
100	32.753	4.428	35.47	4.563	29.062	6.137
120	33.934	4.354	38.1	4.398	36.1	4.766
140	34.765	4.31	39.61	4.332	39.91	4.463
160	35.395	4.282	40.8	4.274	42.17	4.357
180	36.251	4.277	40.87	4.275	43.78	4.285
200	36.577	4.263	40.55	4.271	44.96	4.288
220	35.316	4.243	41.46	4.287	44.43	4.282
240	37.51	4.233	43.73	4.262	47.45	4.282

3.3.4 Gain and Noise Figure against Input Signal Power

Figure 3.5 shows the relationship between the gain and input signal power for some pump powers at 1590 nm wavelength. The input signal power ranged from 0 dB to −40 dB, and the pump power involves four stages at 50, 100, 150, and 220 mW. The gain increases when the pump power increased with decreasing input signal power simultaneously because of the insignificant gain in the small signal regime. A maximum gain value recorded 39.93 dB for a pump power of 150 mW at -35 dB input signal power. For this configuration an optimal length of 23 m. was used. Apparently, the gain starts from 20.66 dB at 0 dBm input signal power, reaches into the value of 38.09 dB for -40 dBm input signal power. In this case, the gain increased gradually. Thus, an inverse relationship exists between gain and input signal power.

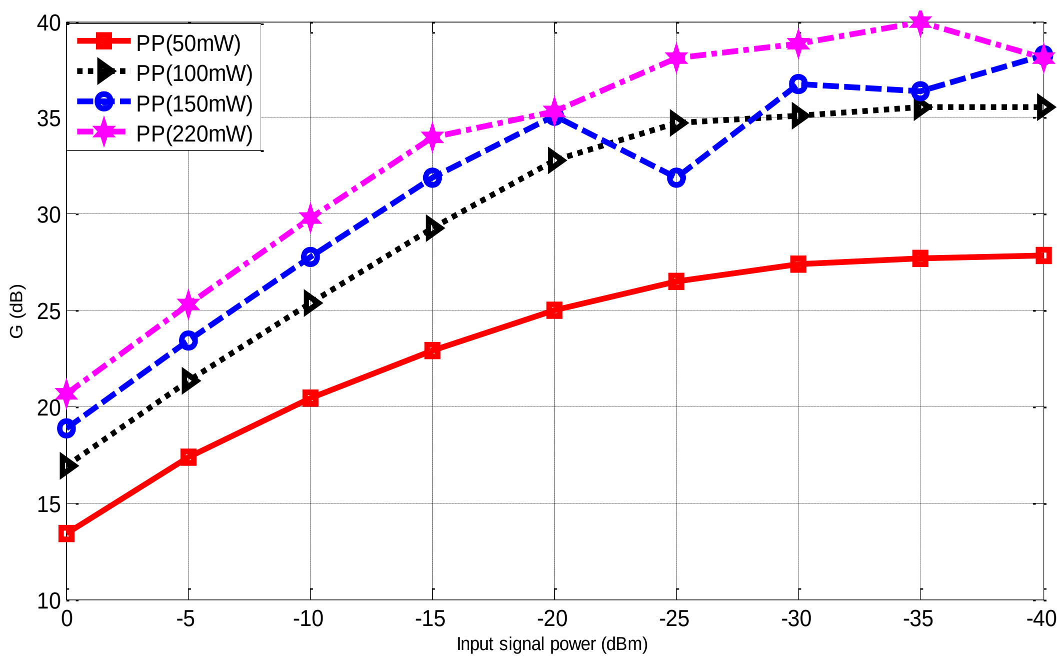


Figure 3.5 Gain versus input signal power for various pump powers at 1590 nm

An EDF length of 23 m was used for the simulations for fig 3.5 whereas an EDF length of 30 m was used that of figure 3.6 when the pump power was 50 mW, the gain increased gradually for the input signal power from 0 to -40 figure 3.5. By contrast, the gain increases gradually between 0 to -10 dB input signal levels and decreases between -10 to -40 because of the low pump power for the EDF length of 30 m. Figure 3.6 shows that this pump level is not suitable. In this case, the ions lack energy to stay in the upper level, leading to the fall of the ions to the ground level to generate the noise figure. Table 3.2 shows the results of comparison of gain and noise figure for 50, 100, 150, and 220 mW pump powers with different input signal powers for double-pass EDFA with WSC.

Table3.2 Comparison of gain and noise figure for 50 mW, 100 mW, 150 mW and 220 mW pump powers for double pass EDFA with EDF length of 23 m with different input signal powers

INPUT SIGNAL POWER	**PUMP POWER (50 mw)**		**PUMP POWER (100mW)**		**PUMP POWER (150mW)**		**PUMP POWER (220 Mw)**	
	G (dB)	NF (dB)	G (dB)	NF (dB)	G (dB)	NF (dB)	G (dB)	NF (dB)
0	13.42	7.55	16.95	6.294	18.89	5.748	20.66	5.334
-5	17.36	6.6913	21.33	5.528	23.42	5.083	25.3	4.77
-10	20.4	6.152	25.36	4.997	27.75	4.65	29.79	4.439
-15	22.93	5.751	29.29	4.632	31.91	4.399	33.96	4.277
-20	25.02	5.424	32.75	4.428	35.08	4.295	35.31	4.243
-25	26.52	5.194	34.73	4.357	31.85	4.314	38.09	4.273
-30	27.37	5.072	35.132	4.381	36.75	4.315	38.86	4.288
-35	27.72	5.023	35.57	4.337	36.35	4.342	39.93	4.291
-40	27.85	5.006	35.54	4.361	38.22	4.325	38.09	4.294

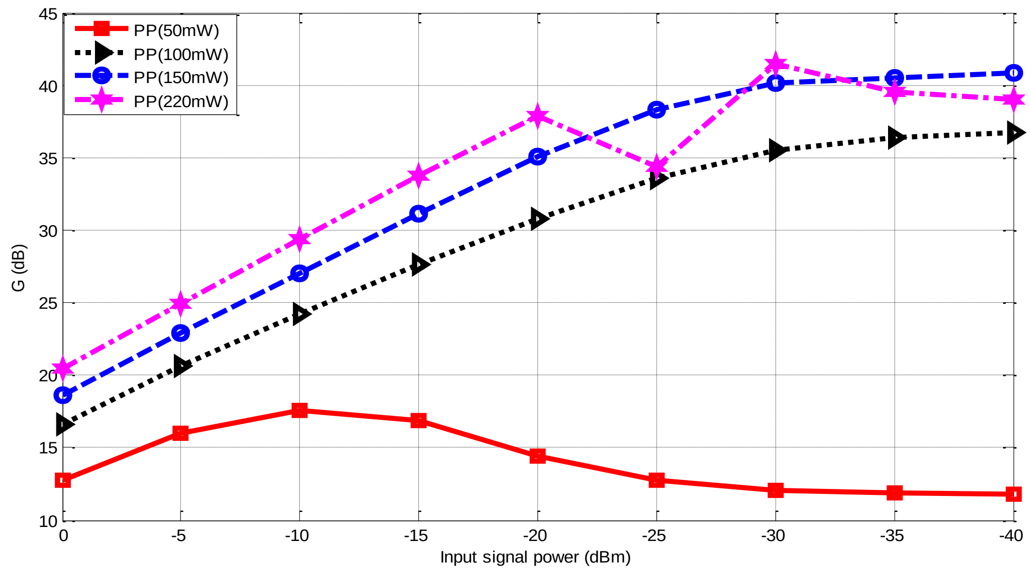


Figure 3.6 Gain against input signal power at wavelength 1590 nm

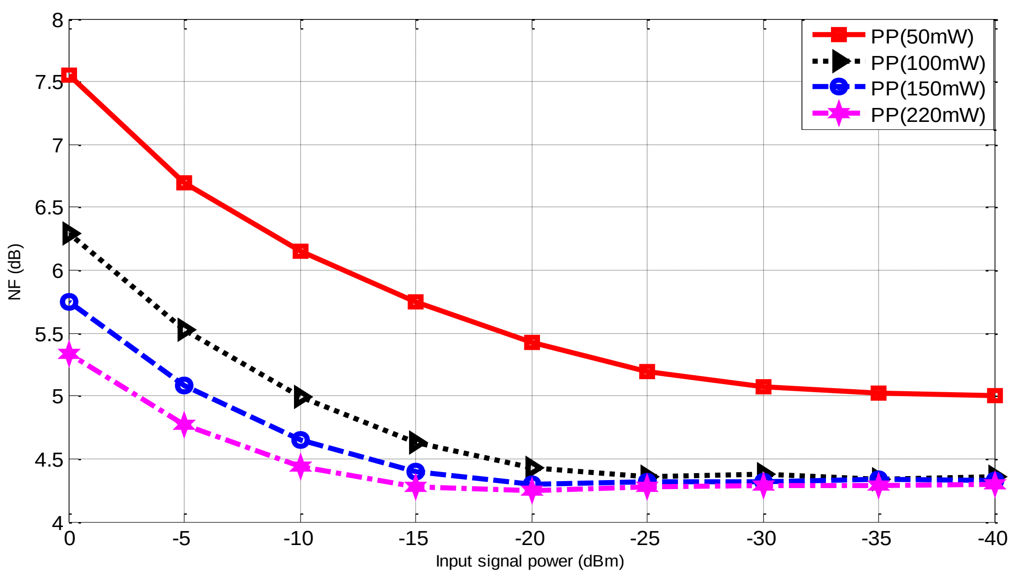


Figure 3.7 Noise figure against input signal power at wavelength 1590 nm

Figure 3.7 illustrates the relation between noise figure and input signal power for different pump power levels at 1590 nm. Apparently, the noise figure decreases gradually with increasing pump power, and a positive relationship exists between noise figure and input signal power. The lowest noise figure was at 4.243 dB when the pump power reached 220 mW at −20 dB input signal power for the EDF length of 23 m.

Figure 3.8 shows the relation between noise figure and input signal power for EDF length of 30 m, to determine the difference between the optimal length and the normal length. Notably, for the EDF length of 23 m, the pump power level of 50 mW, the noise figure decreases gradually from 7.5 dB to 5 dB, and while the input signal power was changing from 0 dB to −40 dB figure 3.7. However, for the EDF length of 30 m for the pump power level was 50 mW, the NF is very high for all levels of input signal. This means that 50 mW pump cannot use in practice. Table 3.3 shows the results of comparison of gain and noise figure for 50, 100, 150, and 220 mW pump power and EDFA length of 30 m with different input signal powers for double-pass EDFA with WSC.

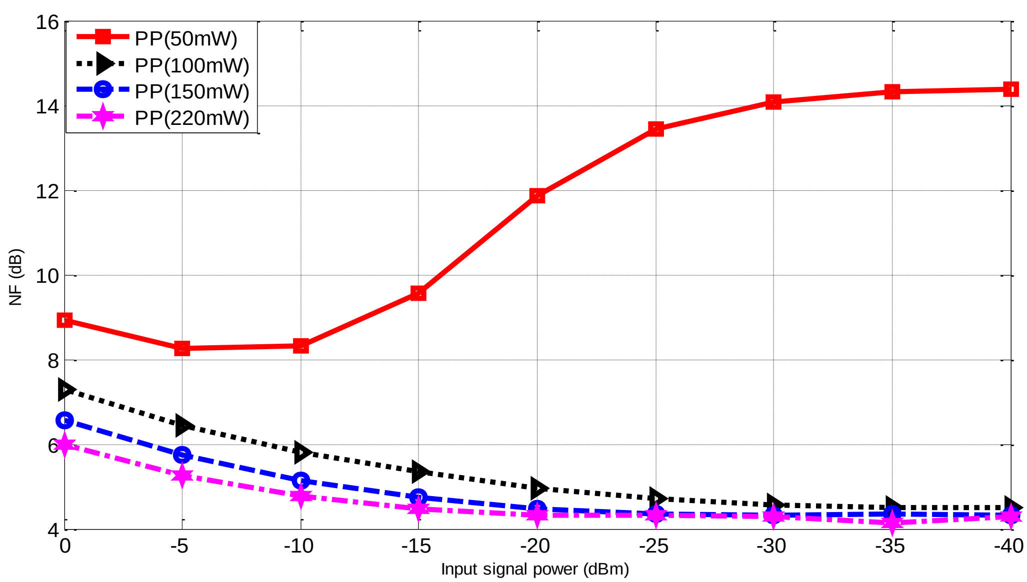


Figure 3.8 Noise figure against input signal power at wavelength 1590 nm

Table3.3 Comparison of gain and noise figure for 50mW, 100mW, 150mW and 220mW pump power and EDF length of 30m with different input signal power for double pass EDFA with wave selective coupler.

INPUT SIGNAL POWER	PUMP POWER (50mW)		PUMP POWER (100mW)		PUMP POWER (150mW)		PUMP POWER (220 Mw)	
	G (dB)	NF (dB)	G (dB)	NF (dB)	G (dB)	NF (dB)	G (dB)	NF (dB)
0	12.77	8.923	16.57	7.284	18.6	6.559	20.44	5.999
-5	15.99	8.252	20.62	6.437	22.93	5.745	24.96	5.26
-10	17.55	8.316	24.21	5.814	27.04	5.149	29.36	4.759
-15	16.88	9.546	27.6	5.334	31.12	4.734	33.75	4.457
-20	14.44	11.854	30.81	4.956	35.06	4.479	37.85	4.31
-25	12.77	13.431	33.57	4.697	38.3	4.354	34.33	4.311
-30	12.08	14.08	35.47	4.563	40.17	4.311	41.466	4.287
-35	11.848	14.311	36.39	4.51	40.47	4.34	39.49	4.143
-40	11.76	14.38	36.74	4.492	40.83	4.315	38.97	4.296

3.3.5 Gain and Output Power Analysis

Figure 3.9 illustrates the analysis of gain and input signal power at 1590 nm wavelength. The gain and input signal power increases with increasing pump power, also the gain increases with decreasing input signal power.

For the pump powers of 50, 100, 150, and 220 mW, unsaturated gains 27.919, 35.96, 38.267, and 40.207 dB were obtained, respectively. A maximum power at 20.86 dBm was achieved when the pump power of 220 mW was obtained for 10 dBm input signal power.

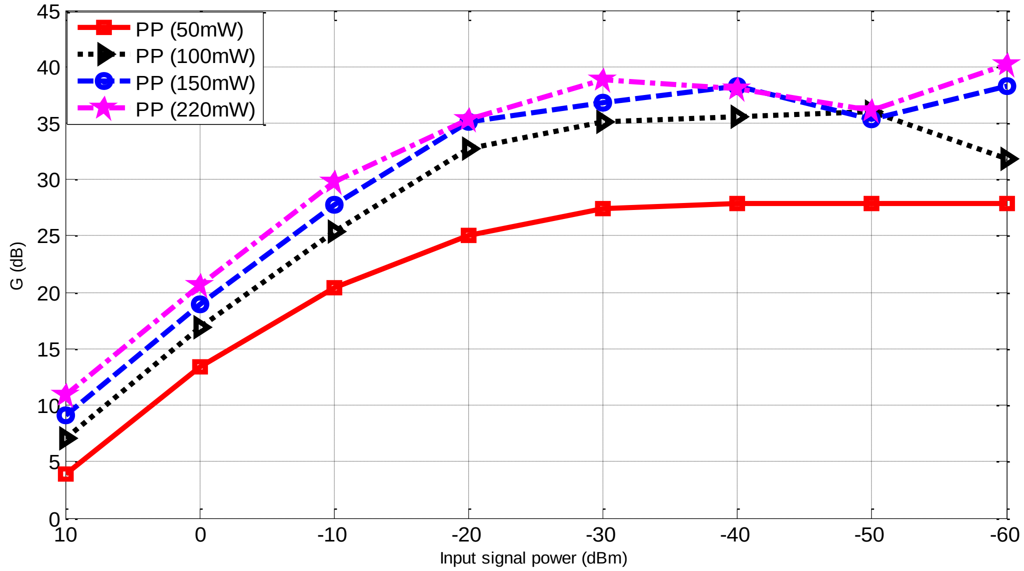


Figure 3.9 Gain and output power at wavelength 1590 nm

Figure 3.10 shows the output signal power against input signal power at 1590 nm wavelength, for pump power of 50, 100, 150, and 220 mW. The output signal power increases with increasing input power, In this case, a positive relationship existed between input and output signal powers. The highest output value was recorded at 20.86 dBm when the pump power reached 220 mW at 10 dBm input signal power. Overall, considering all the figures have shown the changes in pumping power, the input signal power and the length of fiber are the main elements of the effect on the output (gain, output, and noise figure). For the best results, the optimal values of these three factors (pump power, input signal power, and the EDF length) should be selected. Table 3.4 shows comparison of gain and output signal power for 50, 100, 150, and 220 mW pump power and EDF length of 23 m with different input signal powers for double-pass EDFA with WSC.

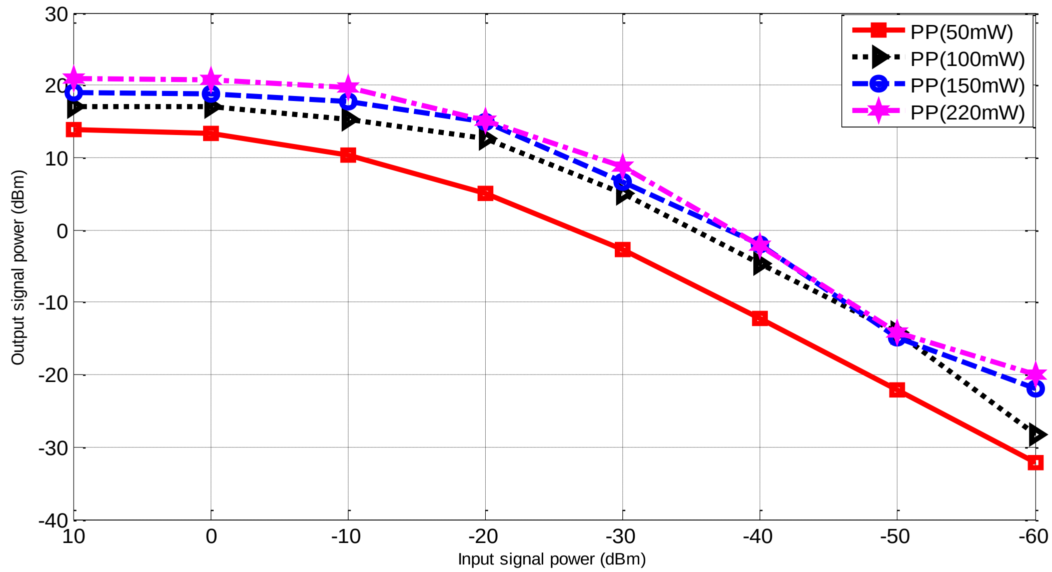


Figure 3.10 Output signal power versus input signal power at wavelength 1590 nm

Table3.4 Comparison of gain and output signal power for different pump powers of an EDFA having an EDF length of 23 m with different input signal power for double pass EDFA with wave selective coupler.

INPUT SIGNAL POWER	PUMP POWER (50 mW)		PUMP POWER (100 mW)		PUMP POWER (150 mW)		PUMP POWER (220 mW)	
	G	Pout	G	Pout	G	Pout	G	Pout
10	3.909	13.907	7.114	17.112	9.049	19.047	10.866	20.865
0	13.425	13.423	16.959	16.956	18.894	18.891	20.667	20.664
-10	20.405	10.4	25.369	15.357	27.756	17.737	29.799	19.771
-20	25.024	5.009	32.753	12.689	35.087	14.981	35.316	15.17
-30	27.37	-2.654	35.132	4.991	36.756	6.59	38.869	8.674
-40	27.857	-12.17	35.548	-4.586	38.22	-1.949	38.098	-2.101
-50	27.914	-22.113	35.96	-14.169	35.366	-14.802	36.102	-14.097
-60	27.919	-32.108	31.821	-28.309	38.267	-21.903	40.207	19.993

In this chapter have been the relationship between each of the pump power, input signal power, gain, noise figure, and output power by using a new method forward double pass EDFA with WSC to reduce the noise figure and get the highest gain, as well as the most important parameters have been identified input power, EDF length, and pump power to be able to improve performance characteristics in L band.

CHAPTER FOUR

4. SIMULATION RESULTS

4.1 INTRODUCTION:

In this chapter, two configurations were introduced to eliminate the residual pump power out of the signal in L-band EDFA by using the first setup, namely, double-pass EDFA with wave selective coupler (WSC), and the second setup, namely, triple-pass EDFA with passive EDF. Four types of erbium doped fiber were used including Fc-xesc, Fibercore, R31703, and ErFiber. Moreover, two input signal powers, namely, −20 dB and −30 dB, were used with optimal EDF length for each case. The laser diode pump was operated at 980 nm with three stage pump powers (forward, bidirectional, and backward) at 225, 150, and 100 mW, respectively, for each stage. Table 4.1 shows the specifications for all EDF types used. In this chapter, the relationship between gain and wavelength is presented on the one hand, whereas the relationship between noise and wavelength is presented on the other hand. The results were analyzed for four types of fiber by performing three ways of pumping. Figure 4.1 shows the progress of the signal for double-pass EDFA with WSC, from the input signal, which passes through the EDF, to its arrival in the receiver. Figure 4.2 illustrates the progress of the signal for triple pass EDFA with passive EDFA, from the input signal, which passes through the EDF, to its arrival in CIR1 and to passes through the EDF passive to arrival the receiver. Moreover, the comparison was demonstrated among all types of fiber, as shown in Table 4.2. All results presented through the figures, which were designed with MATLAB, are reported in the Appendix. All the values used in this chapter are also found in the Appendix (A-P).

Table 4.1 The specifications of Erbium doped fibers

Type	Core Radius	Erbium Radius	Concentration	Numerical Aperture
Fc-xesc	1.7 μm	1.6 μm	9.10^{24} ion/m^3	0.31
Fibercore	1.7 μm	1.6 μm	9.10^{24} ion/m^3	0.22
R31703	1.45 μm	1.38 μm	9.10^{24} ion/m^3	0.24
ErFiber	1 μm	1 μm	$1.4.10^{25}$ion/m^3	0.31

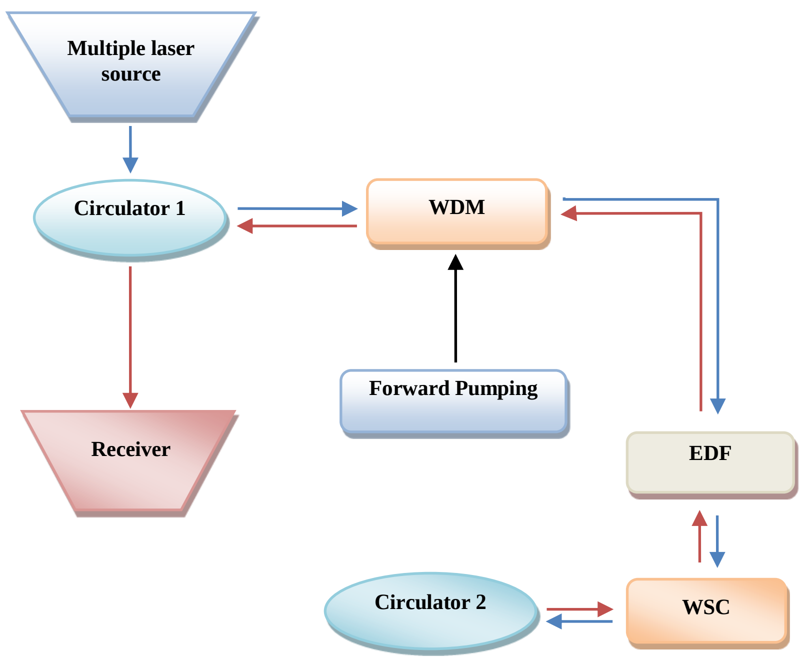


Figure 4.1 The progress of the signal in Double pass EDFA with WSC

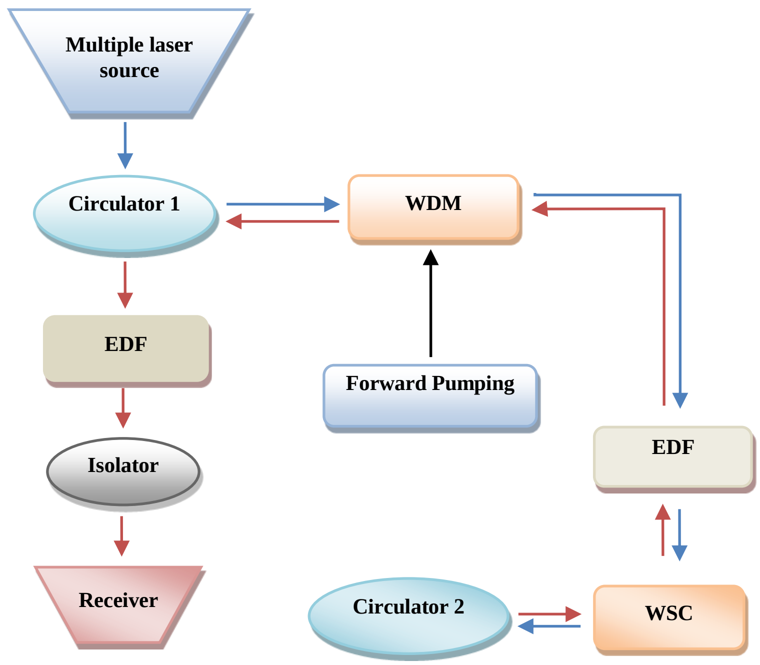


Figure 4.2 The progress of the signal Triple pass EDFA with passive EDF

4.2 Double pass EDFA with Wave Selective Coupler Configuration:

Double-pass EDFA with WSC was introduced. Figure 4.3 shows the first configuration. This configuration consists of multiple laser sources used to inject signals into the fiber. A circulator was used as an isolator to separate the input signal from the output signal. A reflector that was used to obtain the second pass and triple pass in order to reflect the amplified signal back to EDF. In this configuration circulator was used as a mirror reflector. The pump power was operated at 980 nm with a laser diode to excite the ions in EDF. Simulations are performed to analyze the pump power dependence of gain and noise figure as well as the effect of input signal power on gain and noise figure. Moreover, gain and output power performances in L-band EDFAs were analyzed by using OptiAmplifier 4.0 simulation program. This configuration resulted with the elimination of the residual pump power out of the signal by using double-pass EDFA with WSC. To obtain the best result encompassing high gain with a low noise figure. This result is obtained by using a WDM Coupler as a WSC. This setup was operated in double pass through the EDF. The optical signal passes through Circulator1, WDM coupler, EDF, and WSC. It reflects back from Circulator2 and passes through WSC, EDF, WDM Coupler and Circulator1. Thus, the first amplification event starts from the EDF. So, the second amplification was an event when the signal feedback from Circulator2 passive WSC arrived at EDF. The WSC has been used to extract residual pumping in the circuit where it allows the signal to return are not allowed to pump residual return within the circle which causes extra noise figure. At this point, the spontaneous emission was decreased. In this case, the noise figure also decreases.

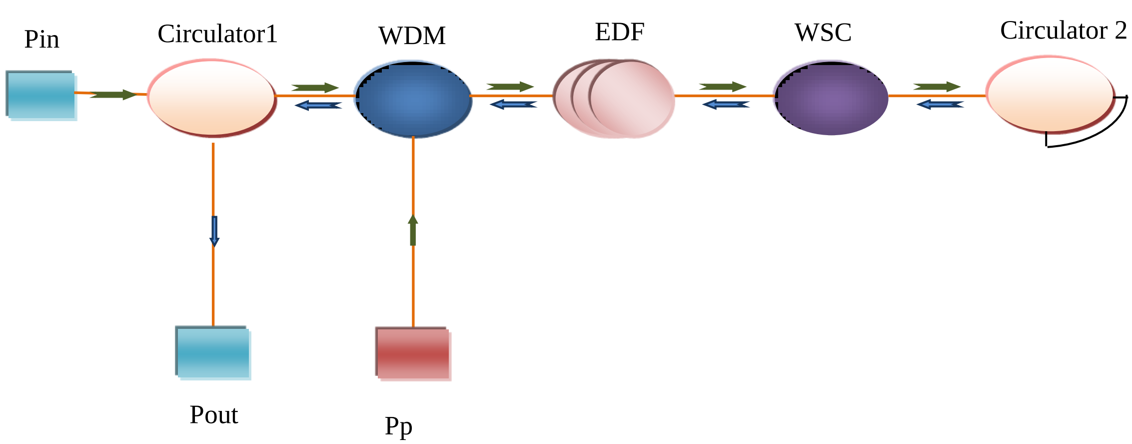


Figure 4.3 Double pass EDFA with wave selective coupler

4.2.1 Performance of Fc.xesc.crs type EDF:

This type of fiber was used in the first setup. Double-pass EDFA with WSC configuration was introduced. The effects of pump power were demonstrated on gain and noise figure by using forward, bidirectional, and backward pump powers. For each case, 225, 150, and 100 mW were used to analyze this configuration. The parameters of erbium-doped fiber (Fc.xesc.crs EDF) were used in the simulations. The numerical aperture was 0.31 with ion concentration of 9.10^{24} ion /m^3. The core radius was 1.7 µm, and that of erbium was 1.6 µm. The input powers were −20 dBm and −30 dBm with different EDF length for each case.

- *Forward pump power for Fc-xesc.crs EDF With -20 dB:*

Forward double pass EDFA with WSC configuration was introduced. Figure 4.4 shows the relationship between gain and noise figure against for three different pump powers, namely 225, 150, and 100 mW. 16 WDM channels were used between 1570–1600 nm. The EDF length was 23.5 m and the input signal power was −20 dBm. The highest magnitudes of gain for 225, 150, and 100 mW pump powers were 29.539, 26.832, and 26.258 dB, respectively. Figure 4.4 illustrates that the gain record was high when the pump power was 225 mW with gain flatness of 1.97 dB. Moreover, the gain flatness was 2.2 dB for the pump power 150 mW. These results indicate that an increased pump power led to increased gain. As shown in Figure 4.4 the lowest the noise figure magnitudes recorded for 225, 150, and 100 mW pump powers were 3.923, 3.944, and 4.008 dB. The noise figure at 225 mW was lower that of the other pump powers. Therefore, the noise figure and pump Power had an inverse relationship. Moreover, Figure 4.4 illustrates that the noise figure decreases gradually with increases wavelength. These findings suggest that the wavelength and noise figure had an inverse correlation.

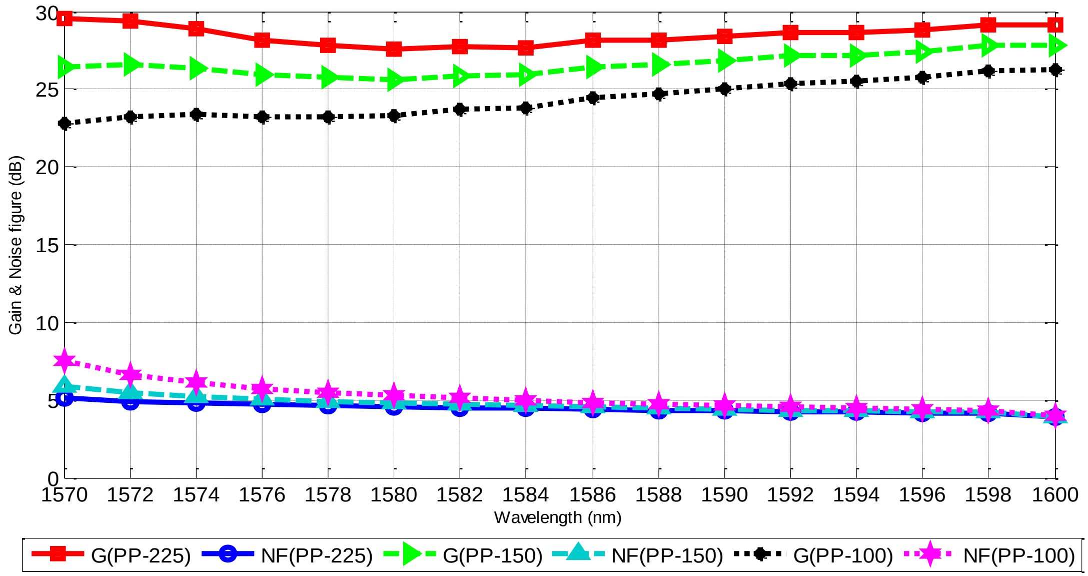


Figure 4.4 Gain and noise figure versus wavelength for different forward pump powers for 23.5 m EDF length.

- *Forward pump power for Fc-xesc.crs EDF With -30 dB:*

Same simulations were performed using a different type of EDF whose information is given by Fc-xesc.crs. Figure 4.5 illustrates the relationship between gain versus wavelength, for three different pump powers, such as 225, 150, and 100 mW. 16 channels were used between 1570-1600 nm and the EDF length for −30 dB was 30.5 m. The highest magnitudes of gain for 225, 150, and 100 mW pump powers were 38.01, 36.01, and 33.01 dB, respectively. The highest magnitude was recorded at 225 mW. In this case, gain and pump powers have a positive correlation. Moreover, the gain flatness was 2.37 dB at 225 mW. Figure 4.5 shows the relationship between noise figure against wavelength. The lowest noise figure magnitudes were recorded as 3.756, 3.728, and 3.756 dB for 225, 150, and 100 mW pump powers, respectively. At 225 mW pump power, the noise figure starts from 5.41 dB the wavelength was 1570 nm, and decreases gradually until 3.756 dB at 1600 nm. At 150 mW, the noise figure for the first channel starts from 6.841 dB and decreases gradually to the level of 3.756 dB. Therefore, the noise figure decreases when the wavelength and pump power increased at the same time.

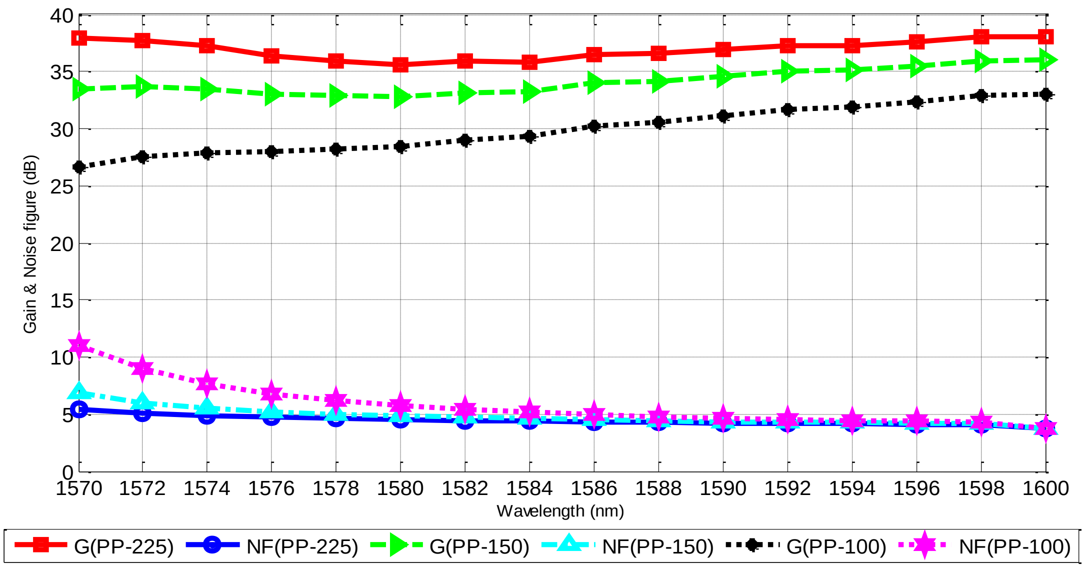


Figure 4.5 Gain and noise figure versus wavelength for different forward pump powers for 30.5 m EDF length.

- *Bidirectional pump power for Fc-xesc.crs EDF With -20 dB:*

Bidirectional double pass EDFA with WSC configuration was introduced. Figure 4.6 shows the relationship between gain versus wavelength, also show results of simulation for three different pump powers. Firstly, 225mW forward and 75 mW backward pump powers were used. Secondly,150 mW forward and 125 mW backward pump powers were used. Finally, 100 mW forward and 225 mW backward pump powers were used. For all cases, input signal was −20 dBm and EDF length was 24 m. In the bidirectional pump configuration, the highest of gain was recorded as 29.415, 27.988, and 26.398 dB for the first, second, and third cases, respectively. The highest gain was recorded at the first case with gain flatness of 1.79 dB. These findings suggest a positive correlation between gain and pump power. Meanwhile, gain and wavelength also have a positive relationship. Figure 4.6 illustrates the relationship between the wavelength and noise figure and the inverse correlation between them. The low noise figure recorded 3.898, 3.921, and 3.988 dB for the first, second, and third cases, respectively. Therefore, the results were convergent during forward and bidirectional pumping because the amplifier reached saturation in the bidirectional pump.

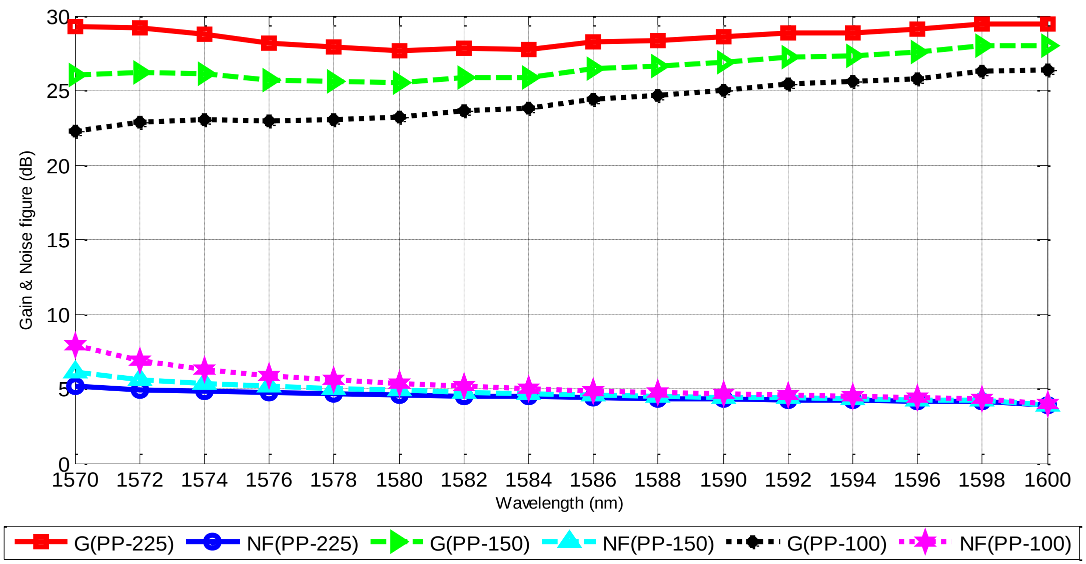


Figure 4.6 Gain and noise figure versus wavelength for different bidirectional pump powers for 24 m EDF length.

- *Backward pump power for (Fc-xesc.crs) EDF With -20 dB:*

Backward double pass EDFA with WCS configuration was introduced for −20 dB input signal power and EDF length was 24 m. Figure 4.7 shows the relation between gain and noise figure versus wavelength for three different pump powers namely 225, 150, and 100 mW. 16 channels were used between 1570–1600 nm. The highest magnitudes of gain for 225, 150, and 100 mW pump powers were 29.50, 28.17, and 26.51 dB, respectively. These results indicate an increased pump power that leads to increased gain. However, the noise figure in figure 4.7 is significantly higher than that of the previous figures because backward pump power was used. In backward pumping, the ion cannot obtain enough energy to stay 1 ms in upper state, thereby leading to high noise figure in backward pumping. The lowest magnitudes were recorded for 225, 150, and 100 mW pump powers were 7.205, 7.392, and 7.644 dB. The noise figure at 225 mW was lower than that of the other pump powers. Therefore, the noise figure and pump power have an inverse relationship. Moreover, Figure 4.7 illustrates that the noise figure decreases gradually with increasing wavelength. These findings suggest an inverse correlation between the wavelength and noise figure.

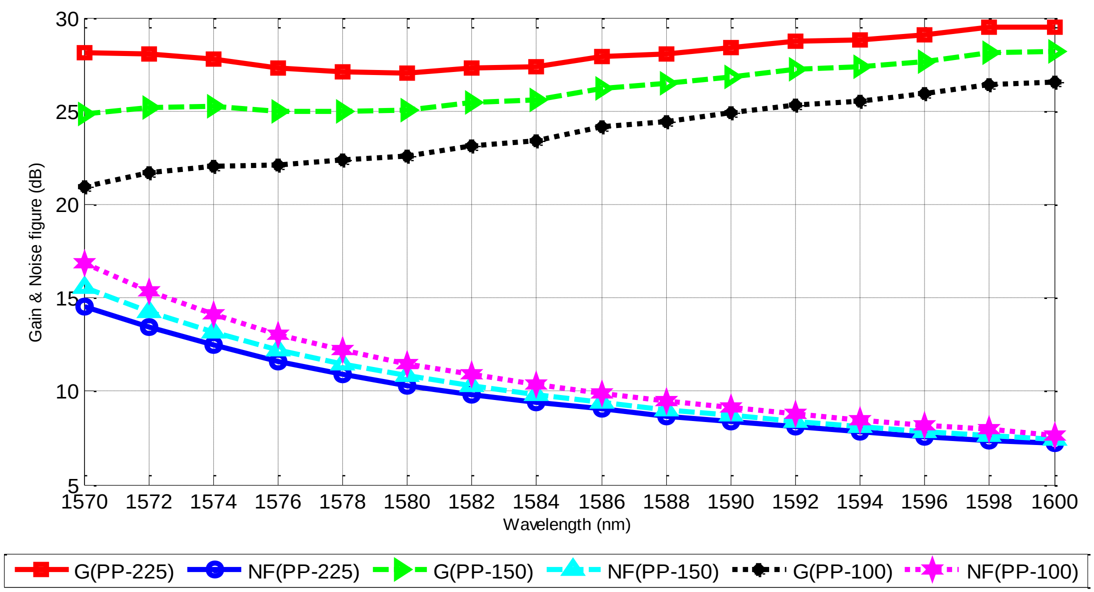


Figure 4.7 Gain and noise figure versus wavelength for different backward pump powers for 24 m EDF length.

4.2.2 Performance of Fibercore.crs type EDF:

This type of fiber was used in the first setup. Double pass EDFA with WSC configuration was introduced. The effects of pump power were demonstrated on gain and noise figure by using forward, bidirectional, and backward pump powers. For each case 225, 150, and 100 mW were used to analyze this configuration. The parameters of erbium doped fiber (Fibercore.crs EDF) were used in the simulations. The numerical aperture was 0.22 with ion concentration of 9.10^{24}ion/m^3. The core radius was 1.7 μm, and that of erbium was 1.6 μm. The input signal powers were −20 dBm and −30 dBm with different EDF length for each case.

- *Forward pump power for Fibercore.crs EDF with −20 dB:*

Forward double pass EDFA with WSC configuration was introduced. Figure 4.8 illustrates results of simulation for three different pump powers, such as 225, 150, and 100 mW. Moreover, the relationship between gain and noise figure against wavelength was shown. 16 DWM channels were used between 1570–1600 nm. The EDF length was 33.5 m, and the input signal power was −20 dBm. The highest magnitudes of gain for 225, 150, and 100 mW pump powers were 29.560, 27.694, and 25.958 dB, respectively. According to the simulation results the highest gain obtained for the pump power of 225 mW with gain flatness of 1.73 dB. Moreover, the gain flatness for the pump power of 150 mW was 2.08 dB. These results indicate increased pump power lead to increased gain. Moreover, Figure 4.8 illustrates that the lowest noise figure record magnitudes of 3.823, 3.85, and 3.929 dB for 225, 150, and 100 mW pump powers, respectively. The noise figure at 225 mW was lower than that of the other pump powers. Therefore, the noise figure and pump power have an inverse relationship. Moreover, Figure 4.8 illustrates that the noise figure decreases gradually with the increases of wavelength. These findings suggest an inverse correlation between the wavelength and noise figure.

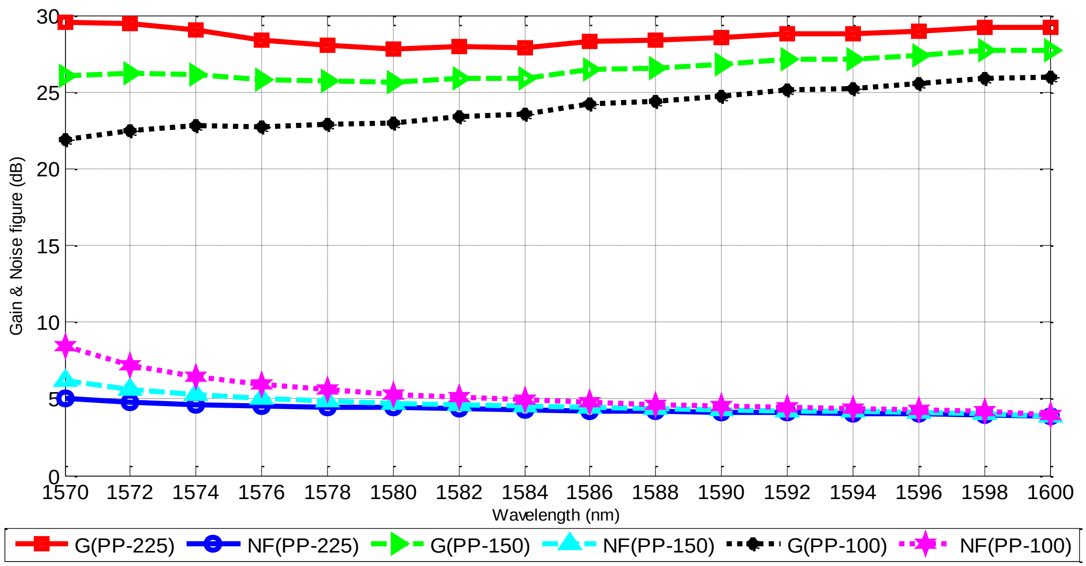


Figure 4.8 Gain and noise figure versus wavelength for different forward pump powers for 33.5 m EDF length.

- *Forward pump power for Fibercore.crs EDF With -30 dB:*

Forward double pass EDFA with WSC configuration was introduced. Figure 4.9 illustrates the relationship between gain versus wavelength for the input signal power −30 dBm and the EDF length was 42.5 m, also show results of simulation for three different pump powers, such as 225, 150, and 100 mW. 16 WDM channels were used between 1570–1600 nm. The highest magnitudes of gain were 37.65, 34.72, and 30.37 dB for 225, 150, and 100 mW pump powers, respectively. The highest magnitude was recorded at 225 mW. In this case, gain and pump power have positive correlation. Moreover, the gain flatness was 1.84 dB at 225 mW. Figure 4.9 shows the relationship between the noise figure against wavelength. The lowest noise figure magnitudes were recorded 3.689, 3.668, and 3.773 dB for 225, 150, and 100 mW pump powers, respectively. At 225 mW pump power, the noise figure starts from 5.364 dB at 1570 nm and decreases gradually to 3.689 dB at 1600 nm. At 150 mW, the noise figure for the first channel starts from 7.837 dB and decreases gradually to reaches the last channel at

3.668 dB. Therefore, the noise figure decreases when the wavelength and pump power increases at the same time.

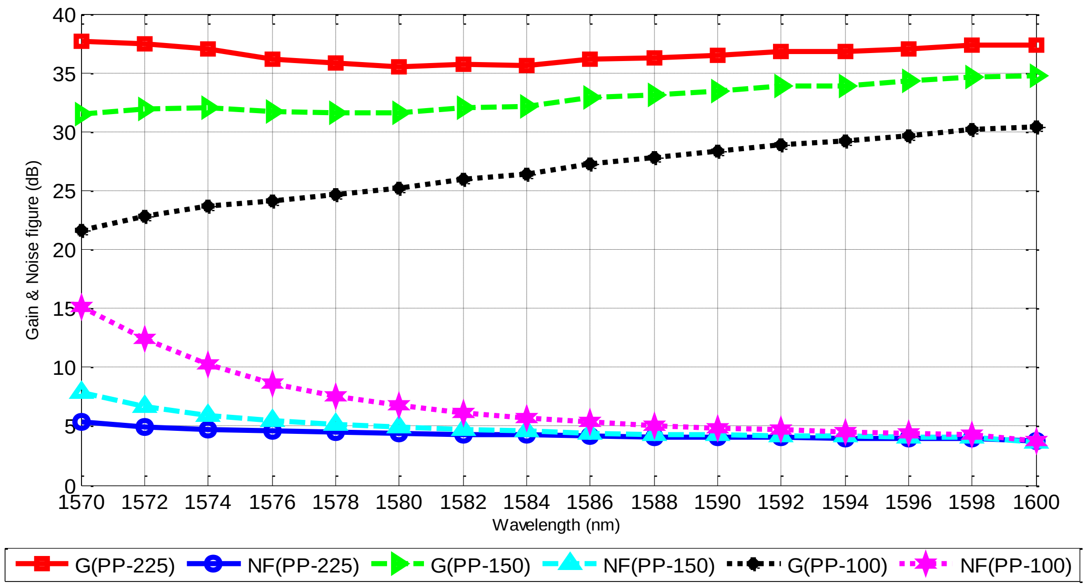


Figure 4.9 Gain and noise figure versus wavelength for different forward pump powers for 42.5 m EDF length.

- *Bidirectional pump power for Fibercore.crs EDF With -20 dB:*

Bidirectional double pass EDFA with WSC configuration was used in this simulation. Figure 4.10 shows the relationship between gain and noise figure versus wavelength for three different pump powers namely. Firstly, 225 mW forward and 75 mW backward pump powers were used. Secondly, 150 mW forward and 125 mW backward pump powers were used. Finally, 100 mW forward and 225 mW backward were used. For all cases, −20 dBm input signal power with 35.5 m EDF length was used. In the bidirectional pump, the highest gain was recorded as 31.459, 31.122, and 32.794 dB for the first, second, and third cases, respectively. The highest gain was recorded at the third case. Gain flatness of 1.92 dB, 1.80 dB, and 2.51 dB were recorded for the first, second, and third cases, respectively. These findings suggest a positive correlation between gain and pump power. Meanwhile, gain and wavelength have a positive relationship. Moreover, figure 4.10 show the inverse correlation between noise figure and wavelength. The lowest noise figure values were recorded for the first, second, and third cases were 4.153, 4.999, and 5.835 dB, respectively. Therefore, the gain in this type was higher than that of the first type because the length of the fiber in the second type was longer than that of the first fiber.

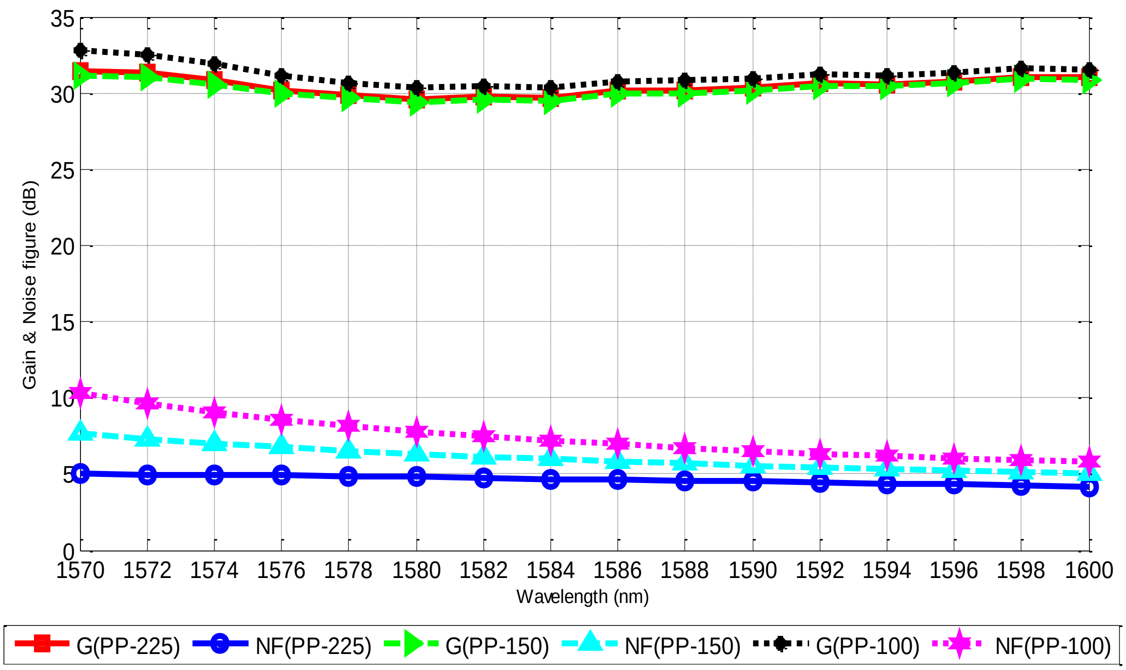


Figure 4.10 Gain and noise figure versus wavelength for different bidirectional pump powers for 35.5 m EDF length.

- *Backward pump power for Fibercore.crs EDF With -30 dB:*

Backward double-pass EDFA with WSC configuration was introduced for −30 dBm input signal power and EDF length 43 m was used. Figure 4.11 shows the relationship between gain and noise figure against wavelength, for three different pump powers namely 225, 150, and 100 mW. 16 WDM channels were used between 1570–1600 nm.

The highest magnitudes of gain for 225, 150, and 100 mW pump powers were 37.33, 36.38, and 34.69 dB, respectively. These results indicate an increases pump power lead to increases gain. According to the simulation results the lowest noise figure obtained for the pump power of 6.580, 6.622, and 6.864 dB for 225, 150, and 100 mW pump powers, respectively. The noise figure at 225 mW was lower than that of the other pump powers. Therefore, the noise figure and pump power have an inverse relationship. Moreover, figure 4.11 illustrates that the noise figure decreases gradually with increasing wavelength. These findings suggest that wavelength and noise figure have an inverse correlation.

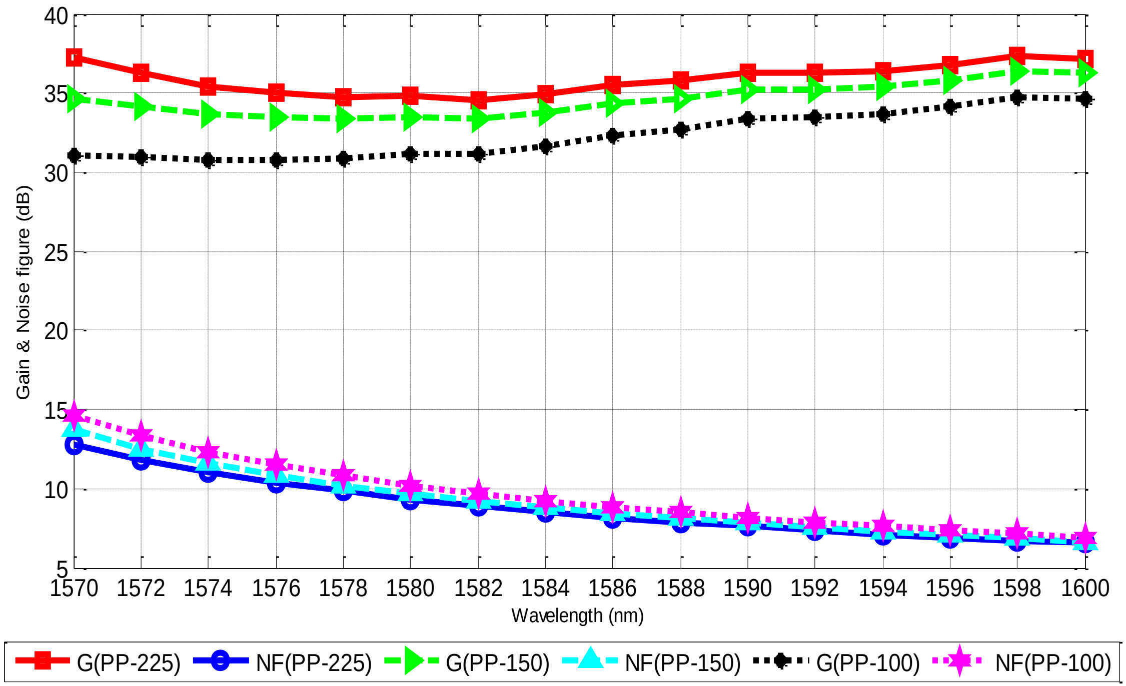


Figure 4.11 Gain and noise figure versus wavelength for different backward pump powers for 43 m EDF length.

4.2.3 Performance of R31703.crs type EDF:

This type of fiber was used in the first setup, double pass EDFA with WSC configuration was introduced. The effects of pump power were demonstrated on gain and noise figure by using forward, bidirectional, and backward pump powers. For each case, 225, 150, and 100 mW were used to analyze this configuration. The parameters of erbium doped fiber (R31703.crs) were used in the simulation. The numerical aperture was 0.24 with ion concentration of 9.10^{24}ion/m^3. The core radius was 1.45 µm, and that of erbium was 1.38 µm. The input powers were −20 dBm and −30 dBm with different EDF length for each case.

- *Forward pump power for R31703.crs EDF with −20 dB:*

Forward double-pass EDFA with WSC configuration was used in this simulation. Figure 4.12 illustrates the relationship between gain and noise figure versus wavelength, for three different pump powers, such as 225, 150, and 100 mW. 16 WDM channels were used between 1570–1600 nm. Moreover, the input signal power was −20 dBm, and EDF length was 23 m. The highest magnitudes of gain for 225, 150, and 100 mW pump powers were 28.989, 27.745, and 26.196 dB, respectively. According to the simulation results the highest gain obtained for the pump power of 225 mW with the gain flatness of 1.77 dB and the gain flatness was 1.99 dB for the pump power of 150 mW. These results show that increased pump power led to increased gain. Moreover, in Figure 4.12 the lowest noise figure magnitudes for 225, 150, and 100 mW pump powers were 4.298, 4.384, and 4.542 dB, respectively. The noise figure at 225 mW was lower than that of the other pump powers. As expected, the noise figure and pump power have an inverse relationship. Moreover, Figure 4.12 illustrates that the noise figure decreases gradually with increases wavelength. These findings suggest an inverse correlation between wavelength and noise figure.

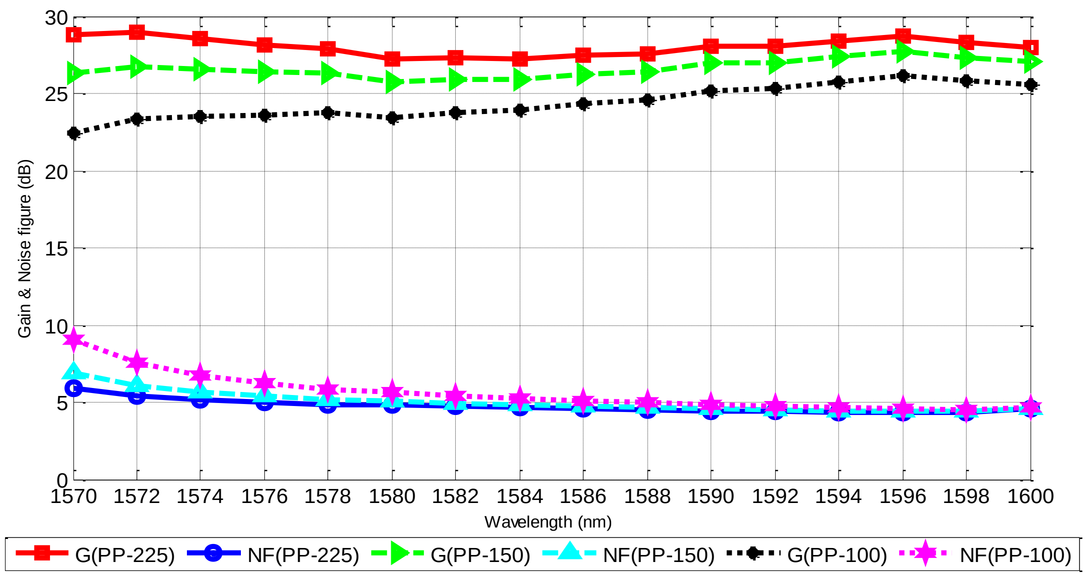


Figure 4.12 Gain and noise figure versus wavelength for different forward pump powers for 23 m EDF length.

- Forward pump power for R31703.crs EDF With -30 dB*:*

Forward double-pass EDFA with WSC configuration was used in this simulation. Figure 4.13 illustrates the relationship between gain versus wavelength at −30 dB and 30 m as the EDF length. The results were analyzed by using three different pump powers, such as 225, 150, and 100 mW. 16 WDM channels were used between 1570–1600 nm. According to the simulation results the highest gain obtained for 225, 150, and 100 mW pump powers were 38.15, 35.85, and 32.99 dB, respectively. The highest magnitude was recorded at 225 mW. Therefore, gain and pump power have positive correlation. Moreover, the gain flatness was 2.3 dB at 225 mW. Figure 4.13 shows the relationship between noise figure against wavelength. The lowest noise figure magnitudes were recorded 4.195, 4.260, and 4.429 dB for 225, 150, and 100 mW pump powers, respectively. At 225 mW pump power, the noise figure starts from 6.345 dB the wavelength was 1570 nm and decreases gradually to 4.195 dB at 1600 nm. At 150 mW, the noise figure for the first channel starts from 8.145 dB and decreases gradually to 4.429 dB at the last channel. Therefore, the noise figure decreased when the wavelength and pump power increased at the same time.

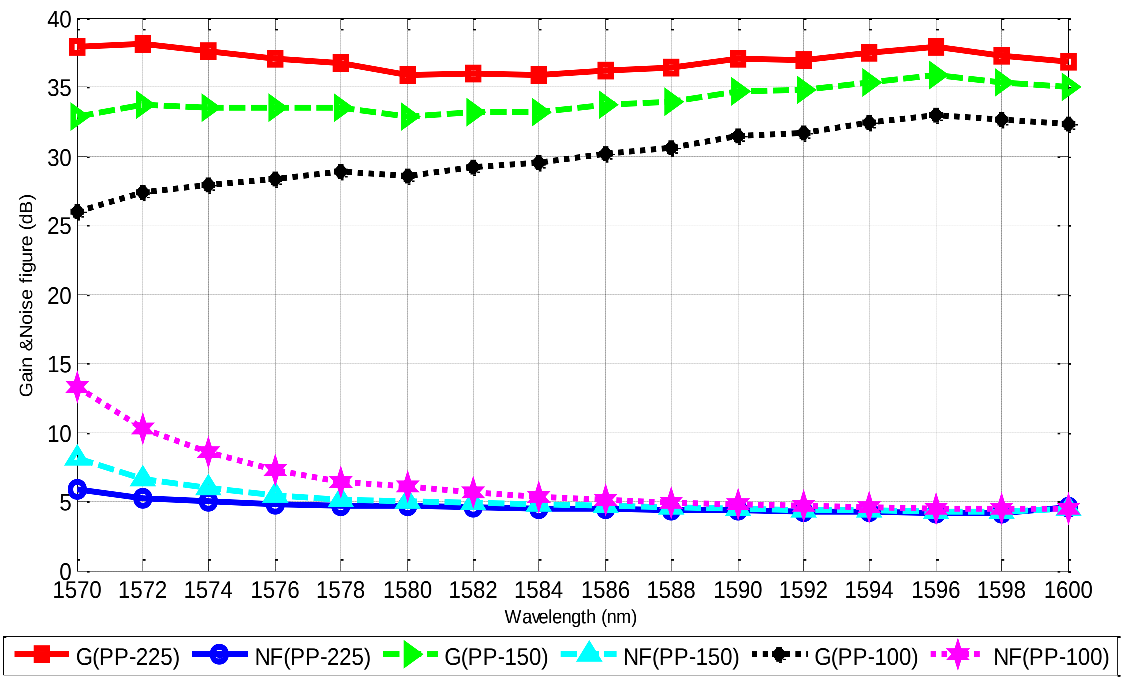


Figure 4.13 Gain and noise figure versus wavelength for different forward pump powers for 30 m EDF length.

- *Bidirectional pump power for R31703.crs EDF With -20 dB:*

Bidirectional double-pass EDFA with WSC configuration was introduced. Figure 4.14 shows the relationship between gain against wavelength by using three different for pump powers namely, the firstly, 225 mW forward and 75 mW backward pump powers were used. Secondly, 150 mW forward and 125 mW backward pump powers were used. Finally, 100 mW forward and 225 mW backward were used. For all cases were used −20 dBm input signal power and 25 m EDF length. For the bidirectional pump, the highest values for gain were recorded as 31.102, 31.666, and 31.189 dB for the first, second, and third cases, respectively. The highest gain was recorded at the third case. The gain flatness was recorded as 1.76, 1.95, and 1.79 dB in the first, second, and third cases, respectively. These findings suggest a positive correlation between gain and pump power. Meanwhile, gain and wavelength have a positive relationship. Moreover, Figure 4.14 illustrates the relationship between wavelength against noise figure as well as an inverse correlation between them. The lowest noise figure was recorded for the first, second, and third cases were 4.659, 5.279, and 6.380 dB, respectively.

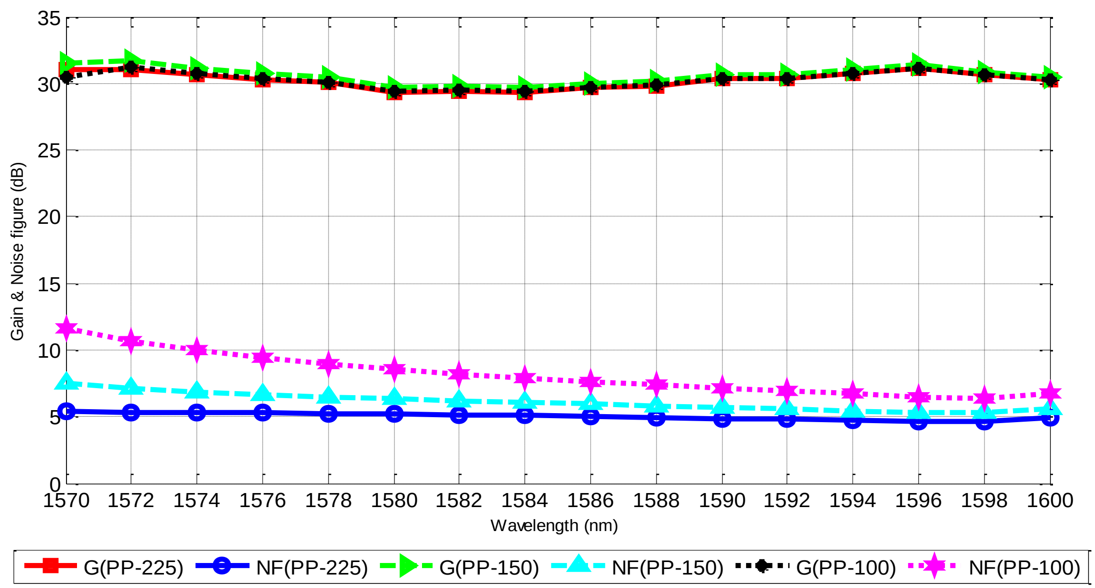


Figure 4.14 Gain and noise figure against wavelength for different bidirectional pump powers for 25 m EDF length.

- *Backward pump power for R31703.crs EDF With -20 dB:*

Backward double-pass EDFA with WSC configuration was introduced. Figure 4.15 shows the relationship between gain and noise figure versus wavelength. 16 WDM channels were used between 1570–1600 nm for −20 dB input signal power with 23 m

EDF length. The results were analyzed by using three different pump powers namely 225, 150, and 100 mW. The highest gain magnitudes were recorded for 225, 150, and 100 mW pump powers as 29.02, 27.75, and 26.25 dB, respectively. These results indicated an increases pump power that led to increases gain. According to the simulation results the gain flatness for 225 and 150 mW pump powers were 1.89 and 2.01 dB, respectively. The lowest noise figure magnitudes were recorded 7.610, 7.772, and 8.347 dB for 225, 150, and 100 mW pump powers, respectively. The noise figure for 225 mW was lower than that of the other pump powers. Therefore, the noise figure and pump power have an inverse relationship. Moreover, Figure 4.15 illustrates that the noise figure gradually decreases with increasing wavelength. These findings suggest an inverse correlation between the wavelength and noise figure.

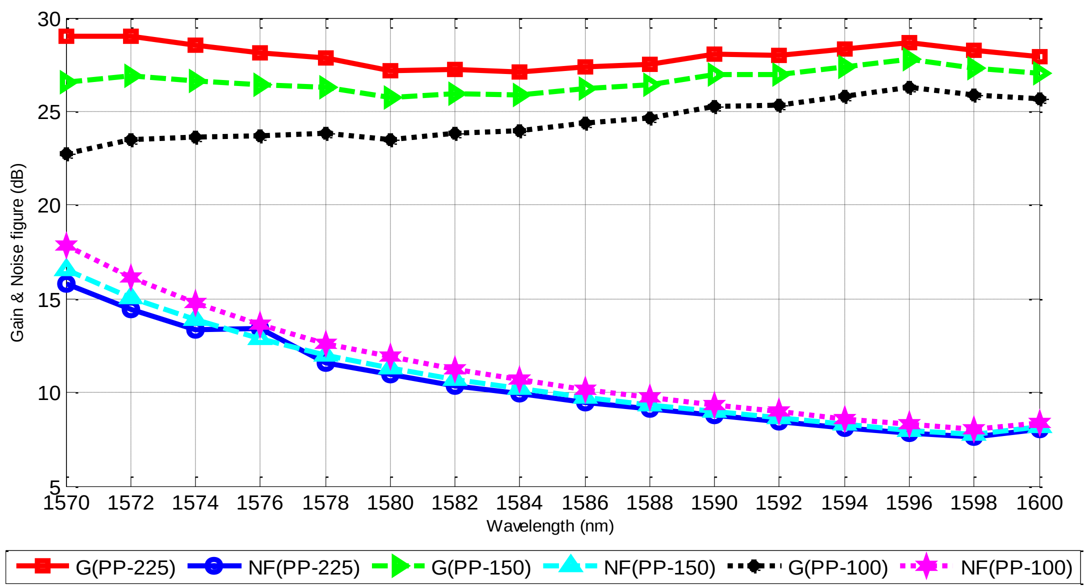


Figure 4.15 Gain and noise figure against wavelength for different backward pump powers for 23 m EDF length.

4.2.4 Performance of ErFiber.crs type EDF:

This type of fiber was used in the first setup. Double-pass EDFA with WSC configuration was introduced. The effects of pump power were demonstrated on gain and noise figure by using forward, bidirectional, and backward pump powers. We used 225, 150, and 100 mW pump powers for each case to analyze this configuration. The parameters of erbium-doped fiber were used in the simulations. The numerical aperture was 0.31 with ion concentration of $1.4.10^{25}$ ion/m^3. The core radius was 1 µm, and that of erbium was 1 µm. The input powers were −20 dBm and −30 dBm with different EDF length for each case.

- *Forward pump power for ErFiber.crs EDF with −20 dB:*

Forward double-pass EDFA with WSC configuration was introduced. Figure 4.16 shows the relationship between gain and noise figure versus wavelength, for three different pump powers namely 225, 150, and 100 mW. 16 WDM channels were used between 1570–1600 nm. Moreover, the input signal power was −20 dBm and EDF length 30.5 m was used. The highest gain magnitudes were recorded for 225, 150, and 100 mW pump powers were 29.46, 28.14, and 26.65 dB, respectively. According to the simulation results the highest gain obtained for the pump power of 225 mW with gain flatness of 1.48 dB. Moreover, the gain flatness for the pump power of 150 mW was 2.09 dB. These results indicated increased pump power that led to increased gain. Moreover, figure 4.16 illustrates that the lowest noise figure magnitudes were recorded for 225, 150, and 100 mW were 3.801, 3.811, and 3.853 dB, respectively. The noise figure at 225 mW was lower than that of the other pump powers. Moreover, Figure 4.16 illustrates that noise figure gradually decreases with increasing wavelength. These findings suggest an inverse correlation between the wavelength and noise figure.

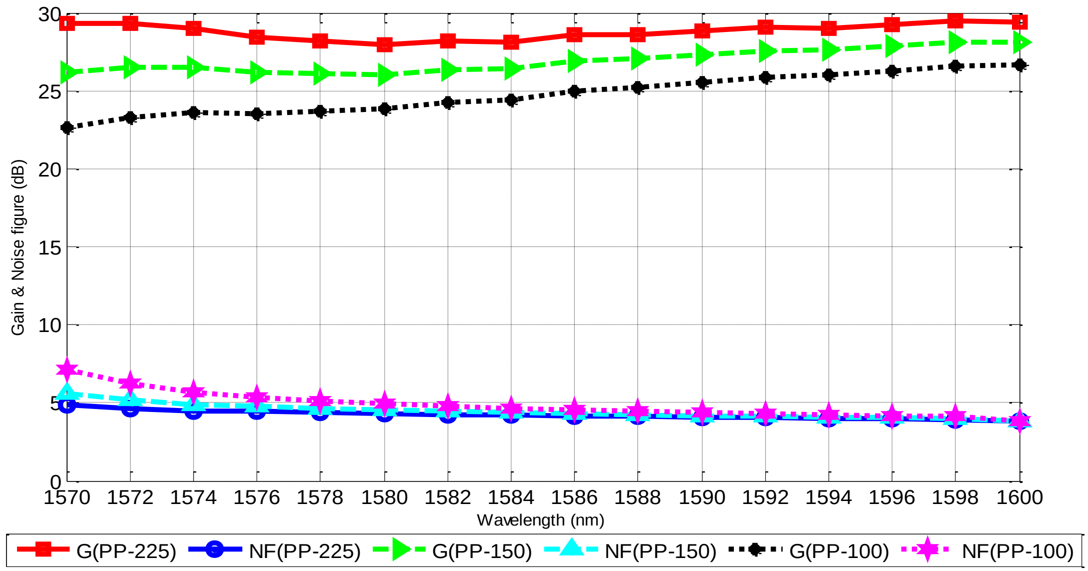


Figure 4.16 Gain and noise figure versus wavelength for different forward pump powers for 30.5 m EDF length.

- *Forward pump power for ErFiber.crs EDF With -30 dB:*

Forward double-pass EDFA with WSC configuration was introduced. Figure 4.17 illustrates the relationship between gain against wavelength for −30 dB input signal power and EDF length of 38.5 m was used. The results were analyzed by using three different pump powers, such as 225, 150, and 100 mW. 16 WDM channels were used between 1570–1600 nm. According to the simulation results the highest gain obtained for pump powers magnitudes of 225, 150, and 100 mW were 37.72, 36.28, and 34.11 dB, respectively. The highest magnitude was recorded at 225 mW. Therefore, gain and pump power have positive correlation. Moreover, the gain flatness was 2.04 dB at 225 mW. Figure 4.17 shows the relationship between noise figure versus wavelength. The lowest noise figure magnitudes were recorded 3.671, 3.644, and 3.631 dB for 225, 150, and 100 mW pump powers, respectively. At 225 mW pump power, the noise figure starts from 4.838 dB the wavelength was 1570 nm and decreased gradually to reach 3.671 dB at 1600 nm. At 150 mW, the noise figure for the first channel starts from 5.750

dB and decreased gradually to 3.644 dB at the last channel. Therefore, the noise figure decreased when the wavelength and pump power increased at the same time.

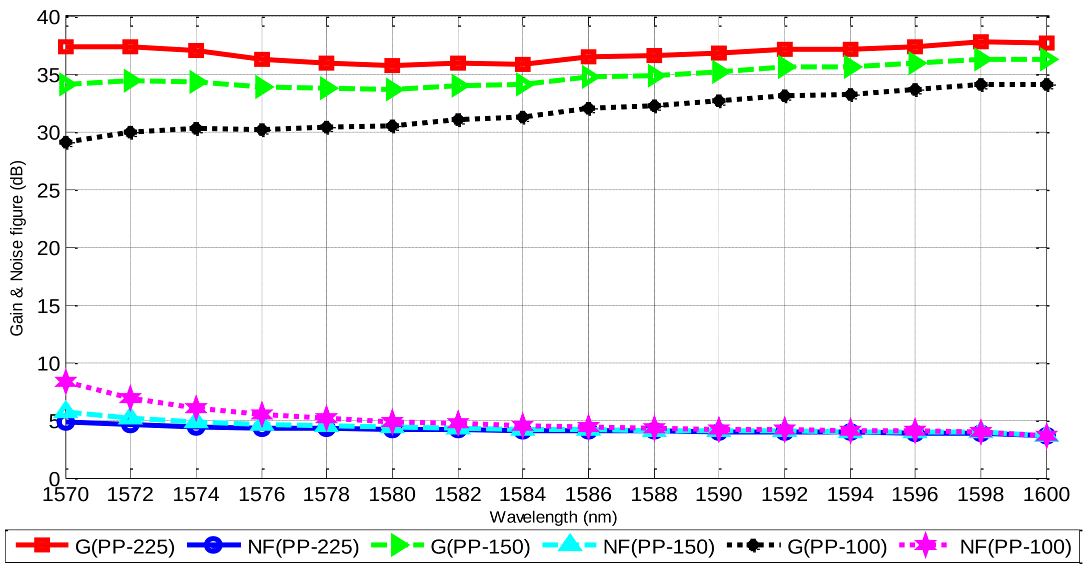


Figure 4.17 Gain and noise figure versus wavelength for different forward pump powers for 38.5 m EDF length.

- *Bidirectional pump power for ErFiber.crs EDF With -20 dB:*

Bidirectional double-pass EDFA with WSC configuration was used in this simulation. Figure 4.18 shows the relationship between gain against wavelength, by using three different for pump powers. Firstly, 225 mW forward and 75 mW backward pump powers were used. Secondly, 150 mW forward and 125 mW backward pump powers were used. Finally, 100 mW forward and 225 mW backward pump powers were used. For all cases -20 dBm input signal power and 30.5 m EDF length were used. For the bidirectional pump, the highest gain values were recorded as 32.15, 31.99, and 33.05 dB for the first, second, and third cases, respectively. The highest gain was recorded at the third case. The gain flatness was recorded as 2.4 dB and 2.3 dB for the first and second cases, respectively. These findings suggest a positive correlation between gain and pump power and a positive relationship between gain and wavelength. Moreover, Figure 4.18 illustrates the relationship between the noise figure versus wavelength and an inverse correlation between them. The lowest noise figure magnitudes were recorded of 4.30, 5.12, and 5.84 dB for the first, second, and third cases, respectively.

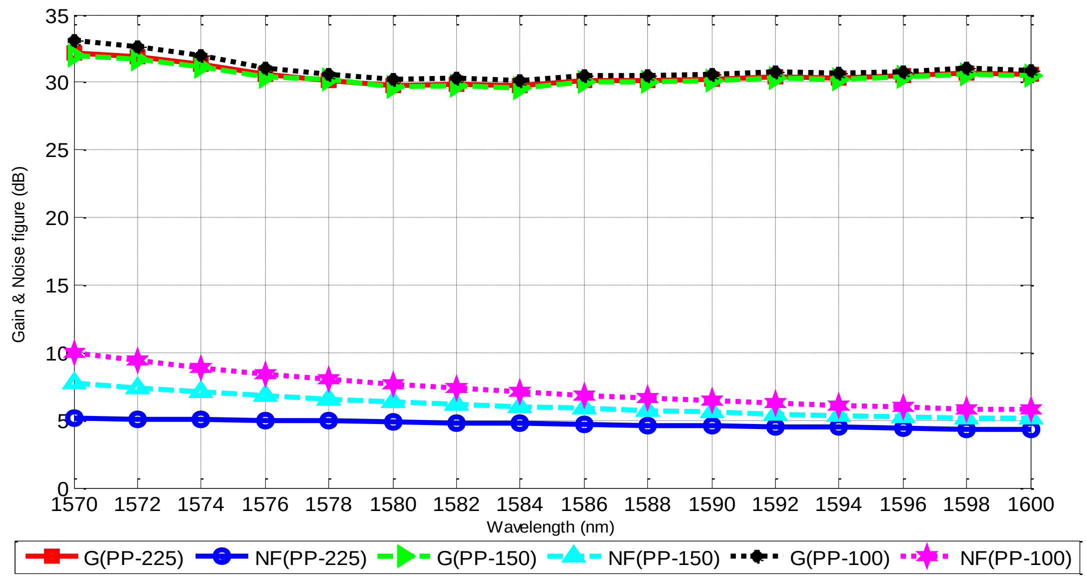


Figure 4.18 Gain and noise figure against wavelength for different bidirectional pump powers for 30.5 m EDF length.

- *Backward pump power for ErFiber.crs EDF With -20 dB:*

Backward double-pass EDFA with WSC configuration was introduced for −20 dBm input signal power and the EDF length 30.5 m. Figure 4.19 shows the relationship between the gain and noise figure versus wavelength, for three different pump powers namely 225, 150, and 100 mW. 16 WDM channels were used between 1570–1600 nm. The highest magnitudes of gain were recorded for 225, 150, and 100 mW pump powers were 30.57, 28.57, and 27.11 dB, respectively. These results indicate an increased pump power that led to increased gain. The gain flatness for 225 and 150 mW was 1.89 and 2.01 dB, respectively. The lowest noise figure magnitudes were recorded of 6.83, 6.97, and 7.14 dB for 225, 150, and 100 mW, respectively. The noise figure at 225 mW was lower than that of the other pump powers. Therefore, the noise figure and pump power have an inverse relationship. Moreover, Figure 4.19 illustrates that the noise figure decreased gradually with increasing wavelength. These findings suggest an inverse correlation between the wavelength and noise figure.

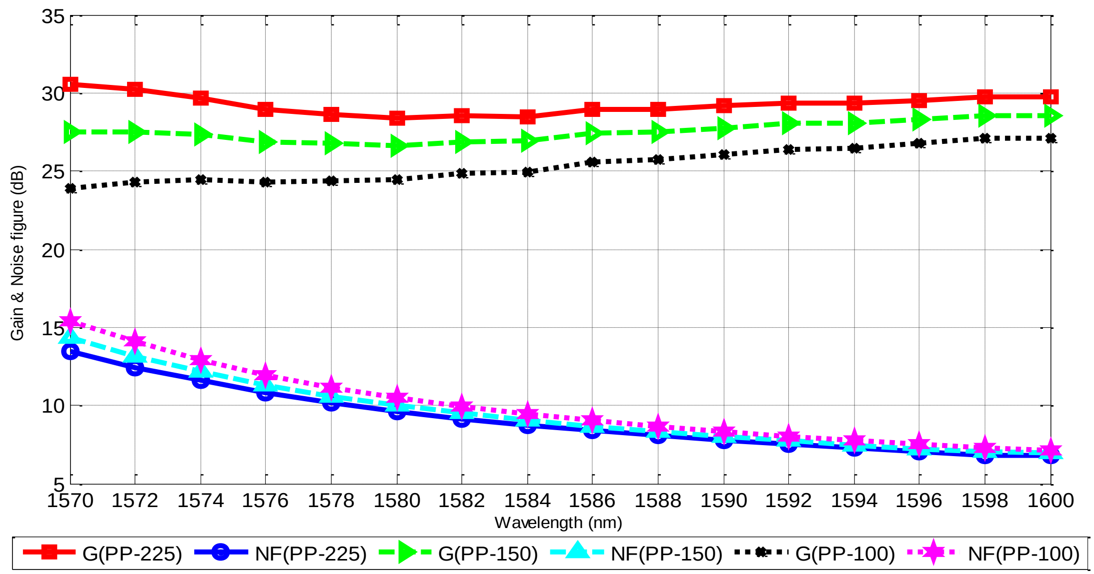


Figure 4.19 Gain and noise figure versus wavelength for different backward pump powers for 30.5 m EDF length.

Table 4.2 shows the comparison between four types of EDF for double-pass EDFA with WSC by using forward, bidirectional, and backward pump powers for −20 dBm and −30 dBm input signal powers with different EDF length for each case. Three different magnitudes for each case of pump power were (225, 150, and 100 mW). According to the simulation table 4.2 shows the highest and lowest magnitudes for gain and noise figure. The results in the table illustrate that the gain and noise figure were acceptable with theoretical and practical results using in chapter one and convergent with four types (Fc-xsec, Fibercore, R31703, and ErFiber) of EDFA when forward pumping was at 225 mW. According to the simulation results in double pass EDFA with

Table 4.2 Comparisons between four types EDF for double pass EDFA with WSC.

	Forward									Bidirectional					Backward						
	P.P	-20				-30				p.p	-20				p.p	-20			-30		
		G.	NF.	F.G.	L.	G.	NF.	F.G.	L.		G.	NF.	F.G.	L.		G.	NF.	L.	G.	NF.	L.
FC-XSEC	225	29.53	5.10	2	23.5	38.01	5.41	2.3	30.5	225 F	29.41	5.19	1.79	24	225	29.50	14.51	24			
		27.56	3.92			35.64	3.75			75 B	27.62	3.89				27.00	7.20				
	150	27.81	5.90	2.2	23.5	36.01	6.84	-	30.5	150 F	27.98	6.13	2.46	24	150	28.17	15.53	24			
		25.61	3.94			32.77	3.72			125B	25.52	3.92				24.86	7.39				
	100	26.25	7.52	-	23.5	33.01	10.98	-	30.5	100 F	26.39	7.93		24	100	26.51	16.86	24			
		22.80	4.00			26.66	3.75			225B	22.27	3.98				20.92	7.46				
Fibercore	225	29.56	5.03	1.73	33.5	37.65	4.95	2.1	42.5	225 F	31.45	5.04	1.86	35.5	225				37.33	12.76	43
		27.82	3.82			35.49	3.69			75 B	29.59	4.15							34.57	4.35	
	150	27.69	6.15	2	33.5	34.72	7.83	3	42.5	150 F	31.12	7.59	1.74	35.5	150				36.38	13.70	43
		25.60	3.85			31.54	3.66			125B	29.37	4.99							33.33	4.41	
	100	25.95	8.39	-	33.5	30.37	15.16	-	42.5	100 F	32.79	10.31	2.44	35.5	100				34.69	14.64	43
		21.90	3.92			21.67	3.77			225B	30.34	5.83							30.73	4.55	
R31703	225	28.98	5.92	1.77	23	37.36	6.34	2.3	30	225 F	31.10	5.44	1.76	25	225				29.02	15.82	23
		27.21	4.29			35.04	4.19			75 B	29.34	4.65							27.13	7.61	
	150	27.74	6.91	1.99	23	35.83	8.14	3	30	150 F	31.66	7.47	1.95	25	150				27.75	16.57	23
		25.75	4.38			32.83	4.26			125B	29.70	5.27							25.75	8.16	
	100	26.19	9.07	-	23	32.99	13.23	-	30	100 F	31.18	11.63	1.79	25	100				26.25	17.82	23
		22.47	4.54			25.97	4.42			225B	29.39	6.38							22.74	8.04	
Erfiber	225	29.46	4.88	1.48	30.5	37.72	4.83	2.04	38.5	225 F	32.15	5.16	2.44	30.5	225	30.57	13.43	30.5			
		27.97	3.80			35.66	3.76			75 B	29.71	4.30				28.38	6.83				
	150	28.14	5.62	2.09	30.5	36.28	5.75	2.06	38.5	150 F	31.99	7.73	2.38	30.5	150	28.57	14.32	30.5			
		26.04	3.81			34.01	3.64			125B	29.61	5.12				26.61	6.97				
	100	26.65	7.10		30.5	34.11	8.30		38.5	100 F	33.05	10.01	2.95	30.5	100	27.11	15.41	30.5			
		22.61	3.85			29.10	3.63			225B	30.10	5.80				23.85	7.14				

WSC by using forward and bidirectional pump powers for 225 mW and optimal EDF length for -20 dBm or -30 dBm input signal power, we can get high gain and gain flatness with low noise figure, while, in backward pump power we can get lower gain with higher noise figure. The results can be improved when by adding fiber Bragg grating to the setup; it could not be placed in the present study because of limitations of the user program. In bidirectional double pass, the magnitude convergent and the gain and noise figures are acceptable in theory at 225 mW and 75 mW for forward pumping and backward pumping, respectively.

4.3 Triple pass EDFA with passive EDFA Configuration:

Triple-pass EDFA with passive EDFA configuration was introduced. Figure 4.20 shows the second configuration used in this chapter. This configuration consists of multiple laser sources used to inject signal light into the fiber. A circulator was used as an isolator while separating the input signal from the output signal. A reflector was used to reflect the amplified signal back to EDF. In this configuration, a circulator was used, and pump power operated at 980 nm via laser diode to excite the ions in EDF and enable the receiver to receive the signal. The simulations were performed to analyze the pump power dependence of gain and noise figure as well as the effect of input signal power on gain and noise figure. Moreover, gain and output power performances in L-band EDFAs were analyzed by using OptiAmplifer 4.0 simulation program. This configuration resulted with the elimination of the residual pump power from the signal by using triple-pass EDFA with passive EDFA to obtain the best result encompassing high gain with low noise figure. The optical signal passes through Circulator1, WDM Coupler, EDF, and WSC. It reflect to from Circulator2 and passes through WSC, EDF, WDM Coupler, and Circultor1.Then passes through Circulator1 to arrive passive EDF. Thus, the first amplification event starts from the EDF. So, the second amplification was an event when the signal feedback from Circulator2 passive WSC arrived at EDF at. Thus, the third amplification occurred when the signal arrived from EDF to Circulator1 and then passed through the passive EDF. The higher absorption in passive EDF between 1530-1550 nm, so, we can achieved to eliminate the residual energy and also the signal which is located frequency in L band often cannot be absorbed within this amplifier. At this spontaneous emission decreased. In this case, the noise figure also decreased.

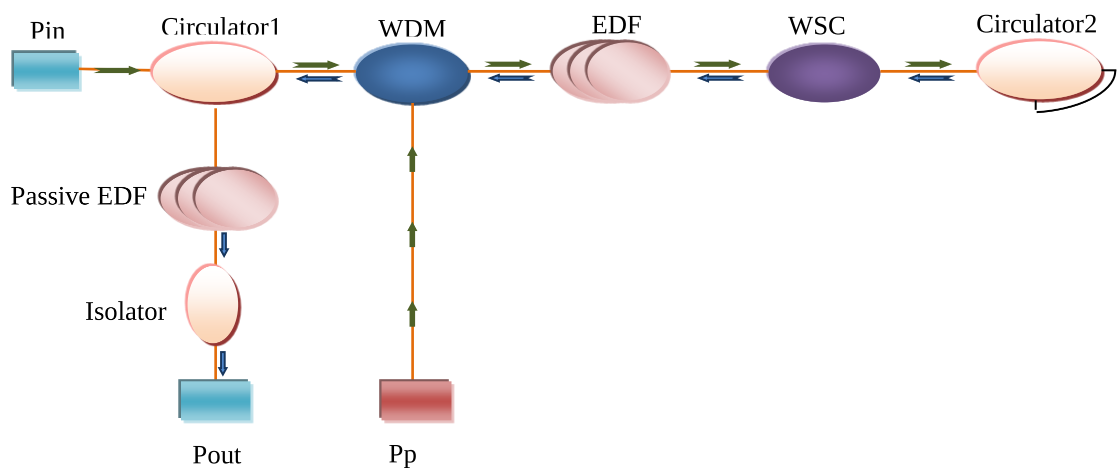


Figure 4.20 Triple pass EDFA with passive EDFA

4.3.1 Forward pump power for (Fc.xesc.crs) EDF With -20 dB:

Forward triple pass EDFA with passive EDFA configuration was introduced. Figure 4.21 shows the relationship between gain and noise figure versus wavelength for three different pump powers namely 225, 150, and 100 mW for -20 dBm input signal power and the EDF length was16 m and the passive EDF length was 12 m. 16 WDM channels were used between 1570 – 1600 nm. The highest gain values were recorded for 225, 150, and 100 mW pump powers as 28.860, 27.390, and 25.809 dB, respectively. According to the simulation results the highest gain obtained for pump powers 225 mW with gain flatness 1.79 dB, and the gain flatness for 150 mW pump power was 1.88 dB. These results indicate an increase pump power lead to increased gain. Also in the figure 4.21 the lowest magnitudes of noise figure were recorded for 225, 150, and 100 mW pump powers as 4.812, 4.947, and 4.841 dB. The noise figure at 225 mW was the lower than that of the other pump powers, from these we can say that an inverse relationship exists between the noise figure and pump power. Also in the figure below see decrease noise figure gradually with increase wavelength, these findings suggest an inverse correlation between the wavelength and noise figure.

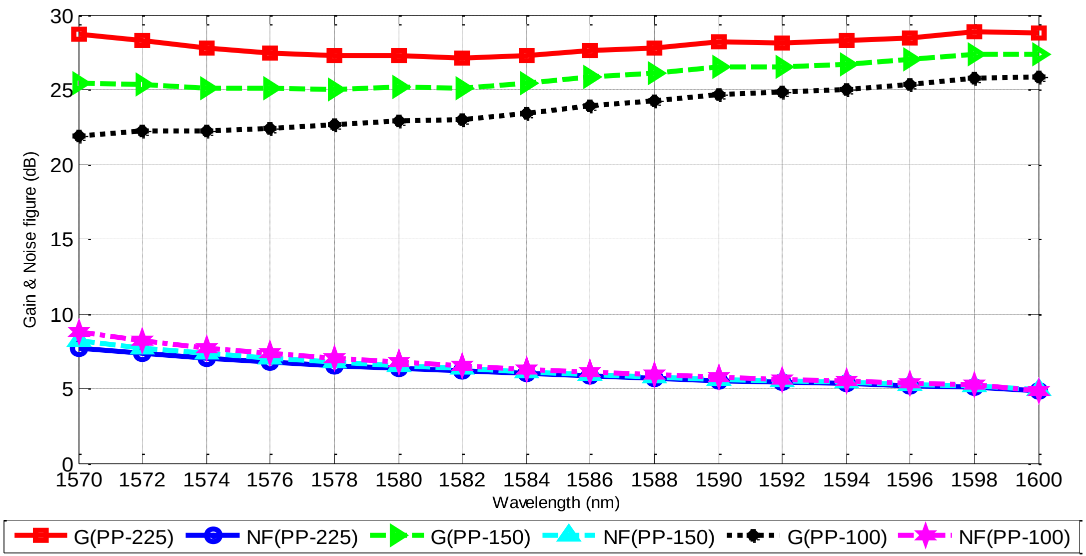


Figure 4.21 Gain and noise figure versus wavelength for different forward pump powers for 16 m EDF length and 12 m passive EDF length.

4.3.2 Forward pump power for (Fc.xesc.crs) EDF With -30 dB:

Forward triple pass EDFA with passive EDFA configuration was introduced. Figure 4.22 illustrate the relationship between gain against wavelength, by using three different pump powers were 225, 150, and 100 mW. Input signal power was -30 dBm, with the EDF length was 23 m and the passive EDF length 12 m. The highest values of gain were recorded for 225, 150, and 100 mW pump powers as 38.323, 37.313, and 35.727 dB, respectively. According to the simulation results the highest gain obtained for the pump power 225 mW, thus, the positive correlation between gain and pump power. Also the gain flatness were 2.37 dB and 2.78 dB for 225 and 150 mW respectively. Figure 4.22 shows the relation between noise figure versus wavelength. The lowest magnitudes of noise figure were recorded for 225, 150, and 100 mW pump powers as 4.321, 4.373, and 4.365 dB, respectively. At 225 mW pump power, the noise figure starts from 6.252 dB for the wavelength of 1570 nm and decreases gradually to 4.321 dB at 1600 nm. Similarly, for 150 mW pump power the noise figure for the first channel changes between 6.448 dB and 4.373 dB. For all pump power levels, the noise figure decrease with the increasing wavelength and pump power.

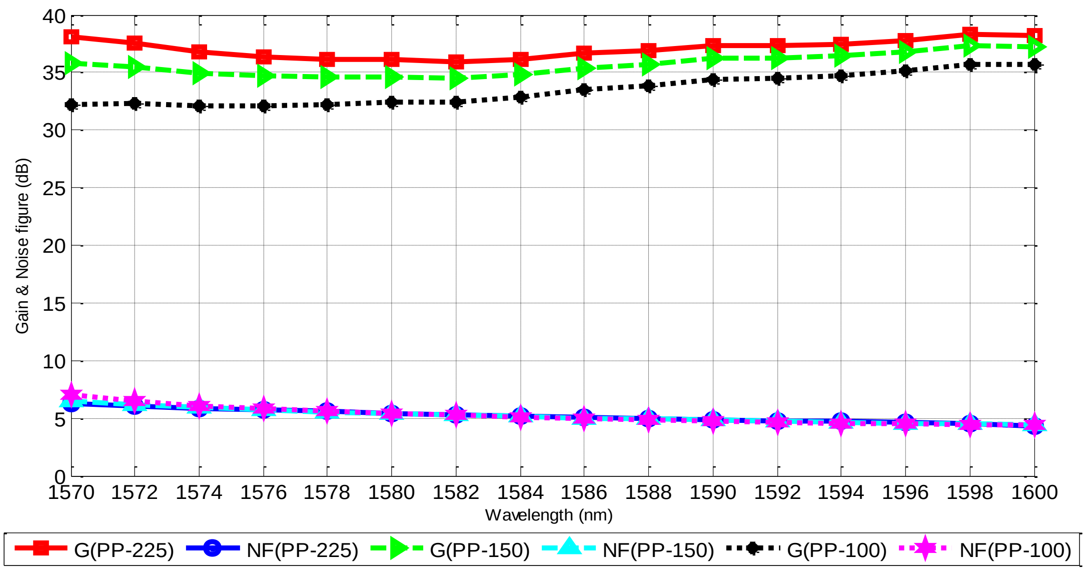


Figure 4.22 Gain and noise figure against wavelength for different forward pump powers for 23 m EDF length and 12 m passive EDF length.

4.3.3 Bidirectional pump power for (Fc.xesc.crs) EDF With -20 dB:

Bidirectional triple pass EDFA with passive EDFA configuration was introduced. Figure 4.23 shows the relation between gain against wavelength, by using three different pump powers. Firstly, 225 mW forward and 75 mW backward pump powers were used. Secondly, 150 mW forward and 125 mW backward pump powers were used. Finally, 100 mW forward and 225 mW backward pump powers were used. And, for all cases -20 dBm input signal power, the 16 m EDF length, and 13 m passive EDF length were used. The highest values of gain were recorded 30.357, 30.324, and 30.792 dB for first, second, and third cases, respectively. The highest value of gain was recorded at the third case. These findings suggest a positive correlation between gain and pump power, at the same time a positive relationship between gain and wavelength. Also the figure 4.23 illustrates the relation between the wavelength versus noise figure. The lower values of noise figure were recorded for first, second, and third cases were 4.079, 4.381, and 4.672 dB, respectively.

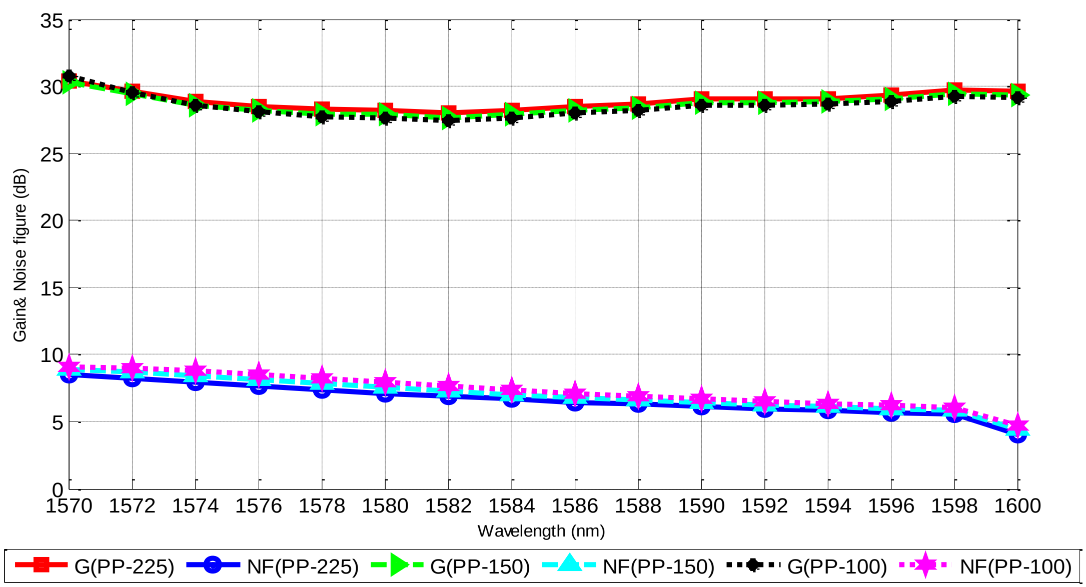


Figure 4.23 Gain and noise figure against wavelength for different bidirectional pump powers for 16 m EDF length and 13 m passive EDF length.

4.3.4 Backward pump power for (Fc.xesc.crs) EDF With -30 dB:

Backward triple pass EDFA with passive EDFA configuration was introduced. Figure 4.24 shows the relation between gain and noise figure versus wavelength for three different pump powers namely 225, 150, and 100 mW were used. And, for all cases -30 dBm input signal power, the 21.5 m EDF length and the 16 m passive EDF length were used. The highest values of gain were recorded for 225, 150, and 100 mW pump powers as 37.001, 36.074, and 34.547 dB. These results indicate an increase pump power lead to increased gain. But, at the same time the noise figure in this figure very high compared to the previous figures, the reason is use of backward pump power. In the backward pumping the ion cannot get enough energy to stay 1 ms in upper state, that is lead to high noise figure in backward pumping. The lowest magnitudes record for 225, 150, and 100 mW pump powers as 9.563, 9.838, and 10.338 dB. The noise figure at 225 mW was the lower than that of the other pump powers, from these we can say that an inverse relationship exists between the noise figure and pump power. These findings suggest an inverse correlation between the wavelength and noise figure.

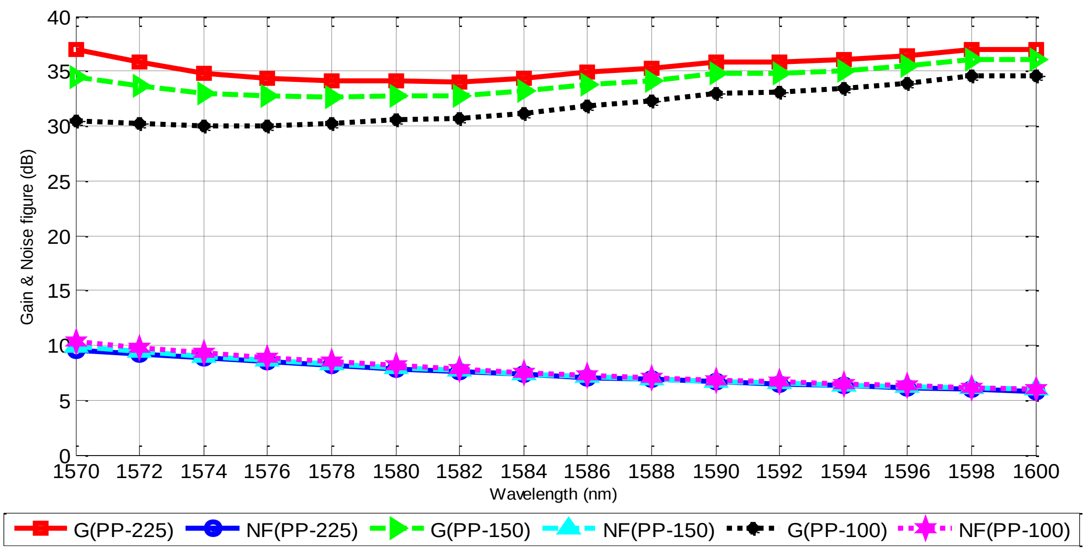


Figure 4.24 Gain and noise figure versus wavelength for different backward pump powers for 21.5 m EDF length and 13 m passive EDF length**.**

4.3.5 Forward pump power for (Fibercore.crs) EDF With -20 dB:

Forward triple pass EDFA with passive EDFA configuration was introduced. Figure 4.25 shows the relationship between gain and noise figure versus wavelength for three different pump powers namely 225, 150, and 100 mW were used. And, for all cases the -20 dBm input signal power, the 23.5 m EDF length and the 18.5 m passive EDF length were used. The highest gain magnitudes were recorded for 225, 150, and 100 mW pump powers as 28.731, 27.050, and 25.373 dB, respectively. The highest values of gain were recorded for the pump power of 225 mW with gain flatness 1.72 dB, and the gain flatness for the pump power 150 mW was 2.12 dB. Also the Figure 4.25 the lowest magnitudes of noise figure were recorded for 225, 150, and 100 mW pump powers as 4.524, 4.604, and 4.824 dB. The noise figure at 225 mW was the lower than that of the other pump powers, from these results we can say that an inverse relationship exists between the noise figure and pump power. These findings suggest an inverse correlation between the wavelength and noise figure.

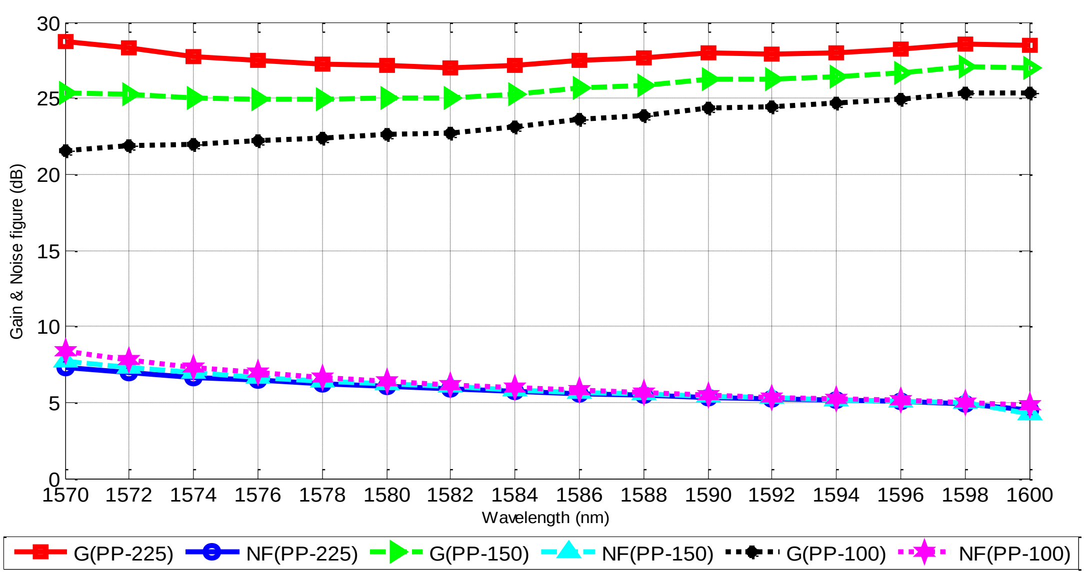


Figure 4.25 Gain and noise figure versus wavelength for different forward pump powers for 23.5 m EDF length and 18.5 m passive EDF length.

4.3.6 Forward pump power for (Fibercore.crs) EDF With -30 dB:

Forward triple pass EDFA with passive EDFA configuration was introduced. Figure 4.26 illustrates the relationship between gain against wavelength, for three different pump powers as 225, 150, and 100 mW. And, for all cases -30 dBm input signal power, the 32.5 m EDF length and the 23 m passive EDF length. 16 WDM channels were used between 1570 – 1600 nm. The highest magnitudes of gain were recorded for 225, 150, and 100 mW pump powers as 38.692, 36.997, and 35.207 dB, respectively. Therefore, the positive correlation between gain and pump power. Also the gain flatness were 2.3 dB and 2.7 dB for 225 and 150 mW respectively.

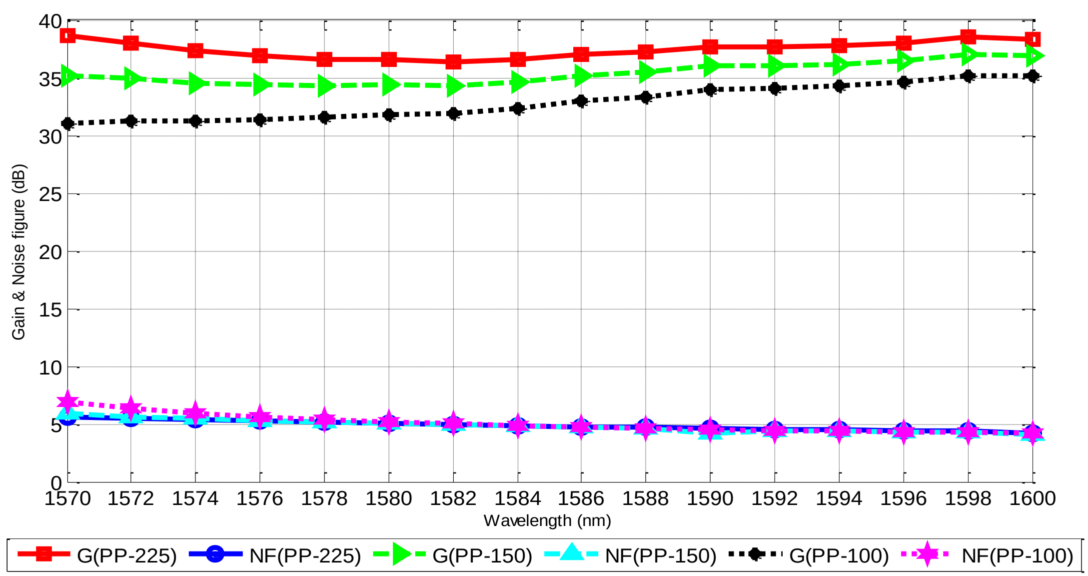


Figure 4.26 Gain and noise figure versus wavelength for different forward pump powers for 32.5 m EDF length and 23 m passive EDF.

Also figure 4.26 shows the relation between noise figure versus wavelength. The lower values of noise figure were recorded for 225, 150, and 100 mW pump powers as 4.172, 4.227, and 4.289 dB, respectively. At 225 mW pump power, the noise figure starts from 5.627 dB the wavelength was 1570 nm and decreases gradually to reached 4.172dB at 1600 nm, at 150 mW the noise figure for the first channel starts from 5.936 dB and decreases gradually to 4.227 dB at the last channel. The noise figure decreases with the increasing wavelength and pump power at the same time.

4.3.7 Bidirectional pump power for (Fibercore.crs) EDF With -30 dB:

Bidirectional triple pass EDFA with passive EDFA configuration was used in this simulation. Figure 4.27 shows the relationship between gain noise figure versus wavelength by using three different pump powers. Firstly, 225 mW forward and 75 mW backward pump powers were used. Secondly, 150 mW forward and 125 mW backward pump powers were used. Finally, 100 mW forward and 225 mW backward pump powers were used. And, for all cases -30 dBm input signal power, the 34.5 m EDF length and 24.5 m passive EDF length were used. The highest values of gain were recorded 39.553, 38.936, and 40.426 dB for first, second, and third cases, respectively. The highest value of gain was record at the third case. The gain flatness for the first case was 2.8 dB. These findings suggest a positive correlation between gain and pump power, at the same time a positive relationship between gain and wavelength. The lowest values of noise figure were recorded for first, second, and third cases were 5.200, 5.517, and 5.714 dB, respectively. These results indicate an inverse correlation between noise figure and wavelength.

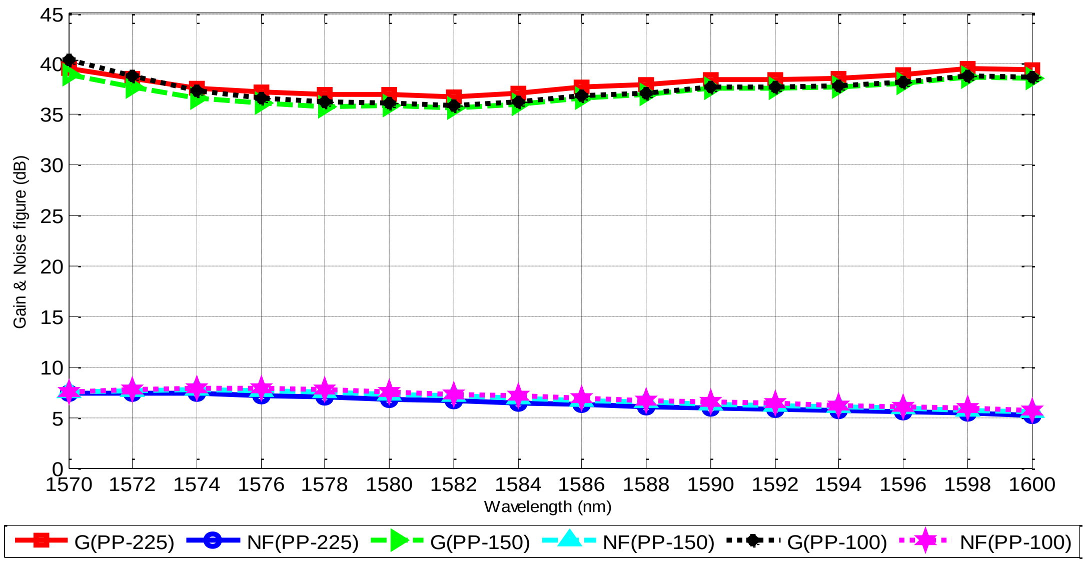


Figure 4.27 Gain and noise figure versus wavelength for different bidirectional pump powers for 34.5 m EDF length and 24.5 m for passive EDF length**.**

4.3.8 Backward pump power for (Fibercore.crs) EDF With -30 dB:

Backward triple pass EDFA with passive EDFA configuration was introduced. Figure 4.28 shows the relation between gain and noise figure versus wavelength for three different pump powers namely 225, 150, and 100 mW were used. And, for all cases -30 dBm input signal power, the 32 m EDF length and the 24 m passive EDF length. 16 WDM channels were used between 1570 – 1600 nm. The highest magnitudes of gain were recorded for 225, 150, and 100 mW pump powers as 37.133, 35.664, and 34.048 dB, respectively. These results indicate an increase pump power lead to increased gain. According to the simulation results the lowest noise figure obtained for 225, 150, and 100 mW pump powers as 9.805, 10.337, and 11.044 dB. The noise figure at 225 mW was the lower than that of the other pump powers, from these we can say that an inverse relationship between the noise figure and pump power. These findings suggest an inverse correlation between the wavelength and noise figure.

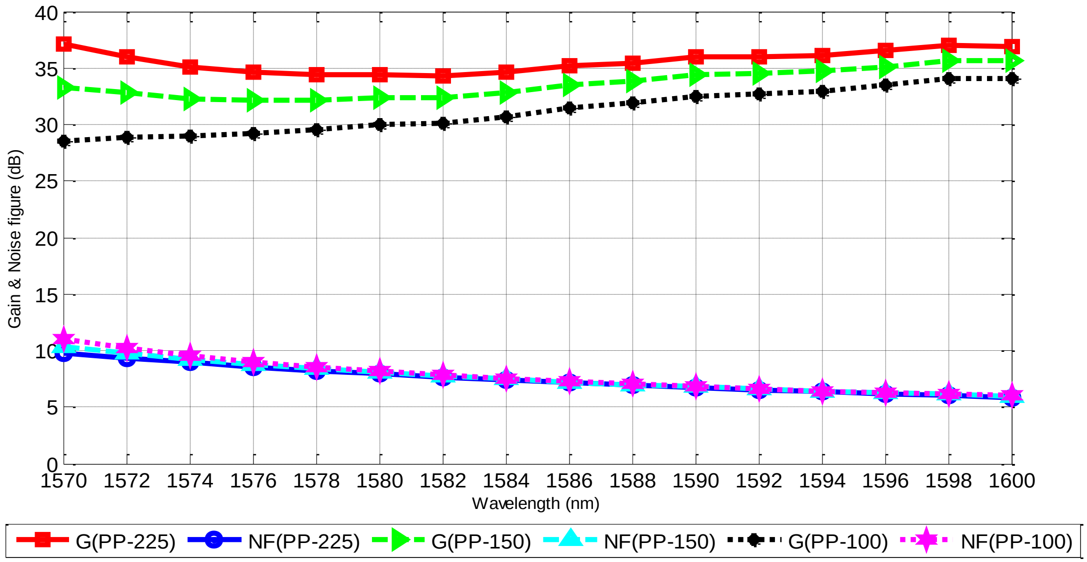


Figure 4.28 Gain and noise figure versus wavelength for different backward pump powers for 32.5 m EDF length and 24 m passive EDF length.

4.3.9 Forward pump power for (R31703.crs) EDF With -20 dB:

Forward triple pass EDFA with passive EDFA configuration was introduced. Figure 4.29 shows the relationship between gain and noise figure versus wavelength for three different pump powers namely 225, 150, and 100 mW were used. And, for all cases the input signal power was -20 dBm, the 16.5 m EDF length and 12.5 m passive EDF length. The highest values of gain were recorded 225, 150, and 100 mW pump powers as 27.811, 26.838, and 25.364 dB, respectively. The highest values of gain was recorded for the pump power 225 mW with gain flatness 1.76 dB, and the gain flatness for the pump power 150 mW was 2.2 dB. These results indicate an increase pump power lead to increased gain. According to the simulation results the lowest magnitudes of noise figure were recorded of 225, 150, and 100 mW pump powers as 5.568, 5.602, and 5.659 dB. The noise figure at 225 mW was the lower than that of the other pump powers, from these we can say that an inverse relationship exists between the noise figure and pump power. These findings suggest an inverse correlation between the wavelength and noise figure.

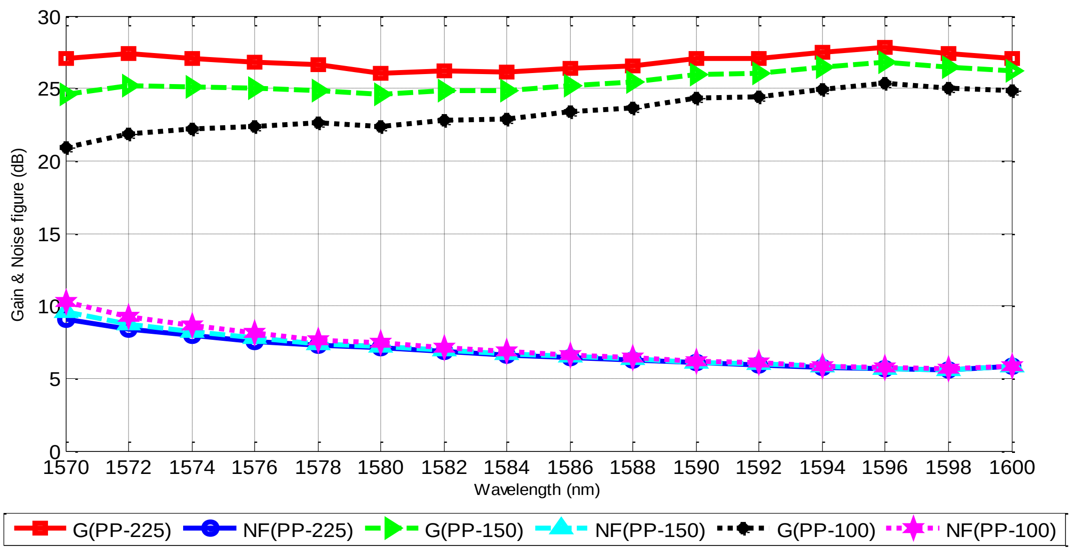


Figure 4.29 Gain and noise figure against wavelength for different forward pump powers for 16.5 m EDF length and 12.5 m passive EDF length.

4.3.10 Forward pump power for (R31703.crs) EDF With -30 dB:

Forward triple pass EDFA with passive EDFA configuration was introduced. Figure 4.30 illustrate the relationship between gain versus wavelength for three different pump powers were 225, 150, and 100 mW were used. And, for all cases -30 dBm input signal power, the 22.5 m EDF length and the 16 m passive EDF length. 16 WDM channels were used between 1570 – 1600 nm. The highest magnitudes of gain were recorded 225, 150, and 100 mW pump powers as 38.155, 36.733, and 35.251 dB, respectively. According to the simulation results the highest gain obtained for the pump power of 225 mW, thus, the positive correlation between gain and pump power and the gain flatness were 2.2 dB at 225 mW and 2.8 dB, at 150 mW. Also the figure 4.30 shows the relation between noise figure versus wavelength. The lower magnitudes of noise figure recorded

225, 150, and 100 mW pump powers as 4.887, 4.804, and 4.741 dB, respectively. At 225 mW pump power, the noise figure starts from 6.714 dB the wavelength was 1570 nm and decreases gradually to reached 4.887 dB at 1600 nm, at 150 mW the noise figure for the first channel starts from 7.150 dB and decreases gradually to 4.804 dB at the last channel. Finally, the noise figure decreases with the increasing wavelength and pump power at the same time.

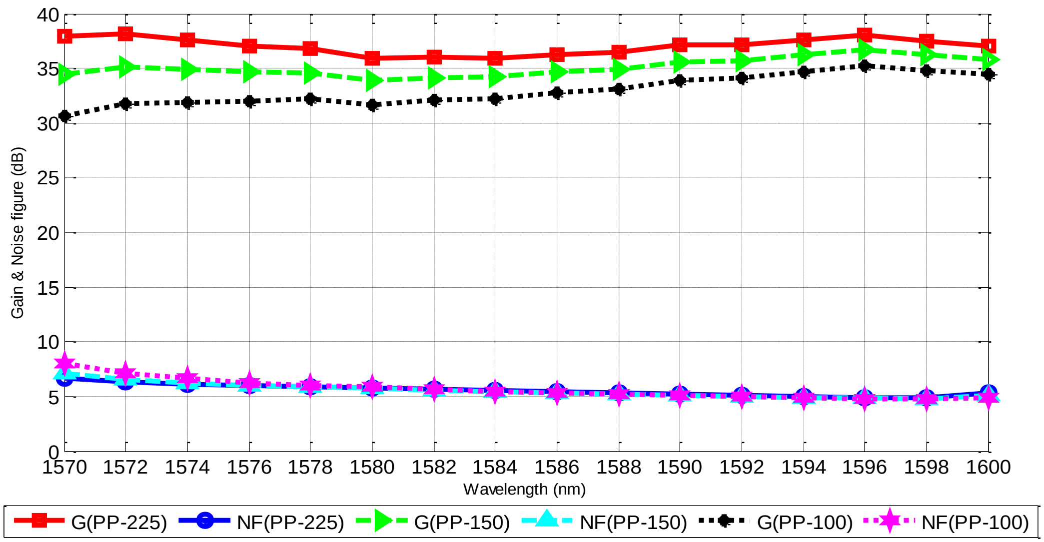


Figure 4.30 Gain and noise figure versus wavelength for different forward pump powers for 22.5 m EDF length and 16 m passive EDF length.

4.3.11 Bidirectional pump power for (R31703.crs) EDF With -20 dB:

Bidirectional triple pass EDFA with passive EDFA configuration was introduced. Figure 4.31 shows the relationship between gain against wavelength by using three different pump powers. Firstly, 225 mW forward and 75 mW backward pump powers were used. Secondly, 150 mW forward and 125 mW backward pump powers were used. Finally, 100 mW forward and 225 mW backward pump powers were used. And, for all cases -20 dBm input signal power, the 17.5 m EDF length and 12.5 m passive EDF length were used. The highest values of gain were recorded 29.075, 28.164, and 28.534 dB, for first, second, and third cases, respectively. According to the simulation results the highest gain obtained for the first case pump power and the gain flatness was 1.82 dB for the first case and was 2.2 dB for the second case. These findings suggest a positive correlation between gain and pump power, at the same time a positive relationship between gain and wavelength. Also the figure 4.31 illustrates the relation between the noise figure against wavelength. The lower values of noise figure were record for first, second, and third cases were 6.319, 6.643, and 7.008 dB, respectively.

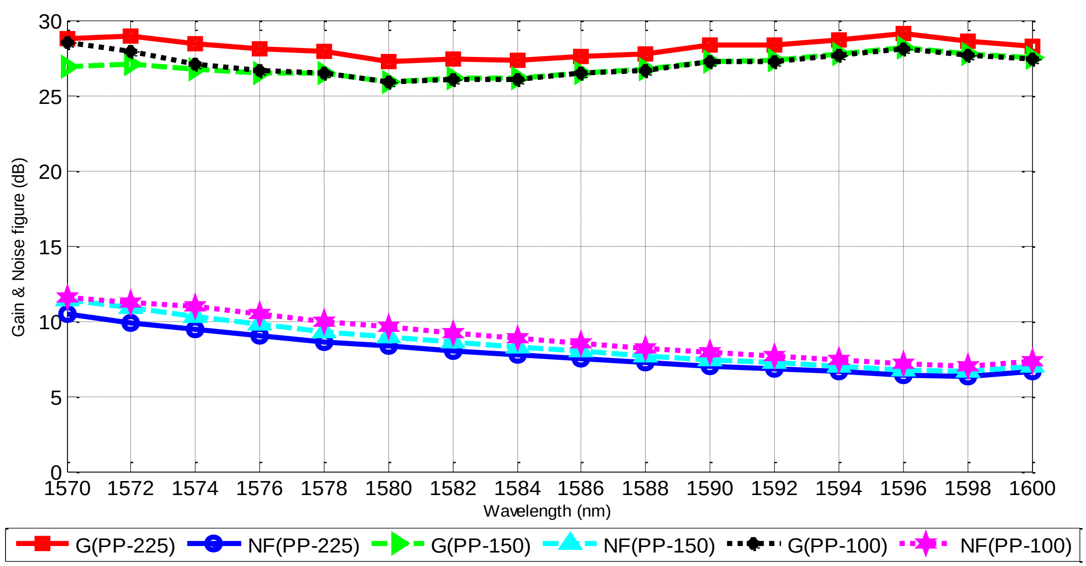


Figure 4.31 Gain and noise figure versus wavelength for different bidirectional pump powers for 17.5 m EDF length and 12.5 m passive EDF length.

4.3.12 Backward pump power for (R31703.crs) EDF With -30 dB:

Backward triple pass EDFA with passive EDFA configuration was introduced. Figure 4.32 shows the relationship between gain and noise figure versus wavelength for three different pump powers namely 225, 150, and 100 mW were used. And, for all cases -30 dBm input signal power, the 22 m EDF length and the 16.5 m passive EDF length were used. 16 WDM channels were used between 1570 – 1600 nm, The highest magnitudes of gain were recorded 225, 150, and 100 mW pump powers as 35.539, 34.240, and 32.740 dB, respectively. These results indicate an increase pump power lead to increased gain. The lowest magnitudes of noise figure were recorded 225, 150, and 100 mW pump powers as 11.449, 11.978, and 12.634 dB. The noise figure at 225 mW was the lower than that of the other pump powers, from these results we can say that an inverse relationship exists between the noise figure and pump power. These findings suggest an inverse correlation between the wavelength and noise figure.

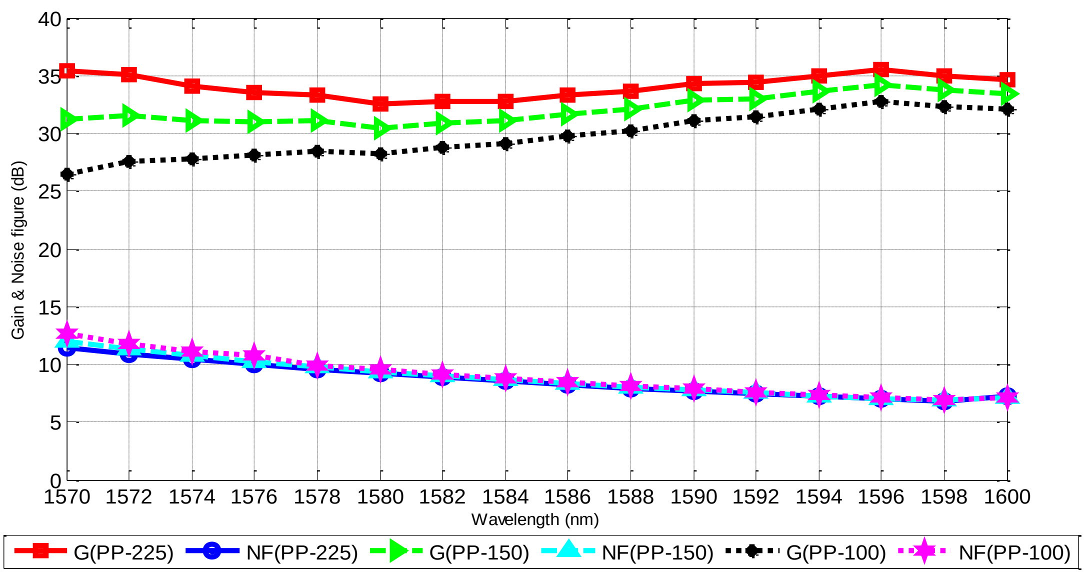


Figure 4.32 Gain and noise figure against wavelength for different backward pump powers for 22 m EDF length and 16.5 m passive EDF length.

4.3.13 Forward pump power for (ErFiber.crs) EDF With -30 dB:

Forward triple pass EDFA with passive EDFA configuration was introduced. Figure 4.33 shows the relationship between gain and noise figure versus wavelength, for three different pump powers were 225, 150, and 100 mW were used. And, for all cases -30 dBm input signal power, the 16.5 m EDF length and 9.5 m passive EDF length were used. 16 WDM channels were used between 1570 – 1600 nm. The highest values of gain were recorded 225, 150, and 100 mW pump powers as 38.232, 36.438, and 34.708 dB, respectively. According to the simulation results the highest gain obtained for the pump power 225 mW with gain flatness 2.58 dB. These results indicate an increase pump power lead to increased gain. Also in the figure 4.33 the lowest magnitudes of noise figure were recorded for 225, 150, and 100 mW as 4.167, 4.103, and 4.082 dB. The noise figure at 100 mW was the lower than that of the other pump powers. In the figure below see decrease noise figure gradually with increase wavelength, these findings suggest an inverse correlation between the wavelength and noise figure.

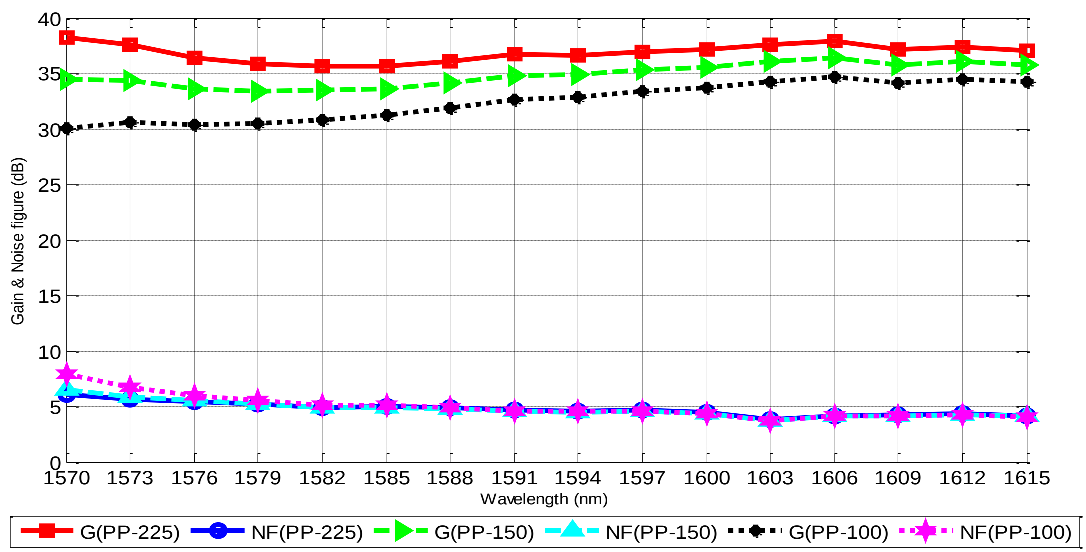


Figure 4.33 Gain and noise figure versus wavelength for different forward pump powers for 16.5 m EDF length and 9.5 m passive EDF length.

Table 4.3 shows comparison between four types of EDF. Three different pump configurations and two different signal powers used in the simulation. Results of gain and noise figure in this table are consistent with the theoretical results (Fc-xsec, Fibercore, R31703, and ErFiber) EDFA, when it is forward pumping at 225 mW. According to the simulation results in triple pass EDFA with passive EDFA by using forward and bidirectional pump powers for 225 mW with optimal EDF length for -20 dBm or -30 dBm input signal power, we can get higher gain and gain flatness with low noise figure, while, in backward we can get low gain with high noise figure. The results can be improved when by adding fiber Bragg grating to the setup; it could not be placed in the present study because of limitations of the user program. In bidirectional double pass, the magnitude convergent and the gain and noise figures are acceptable in theory at 225 mW and 75 mW for forward pumping and backward pumping, respectively.

Table 4.3 Comparison between four types EDF for triple pass EDFA with passive EDF

		Forward								Bidirectional								Backward			
	P.P	-20				-30				p.p	-20				-30			p.p	-30		
		G.	NF.	G.F.	L.	G.	NF.	G.F.	L.		G	NF.	G.F.	L.	G.	NF	L.		G.	NF.	L.
FC-XSEC	225	28.860	7.672	1.79	16/12	38.323	6.252	2.46	23/12	225 F 75 B	30.357	8.481	2.37	16/13				225	37.001	9.563	21.5/16
		27.070	4.812			35.859	4.321				27.984	4.079							33.982	5.812	
	150	27.390	8.185	1.88	16/12	37.313	6.448	2.78	23/12	150 F 125B	30.324	8.932	2.65	16/13				150	36.074	9.563	21.5/16
		25.031	4.947			34.525	3.373				27.673	4.381							32.627	5.8121	
	100	25.809	8.800		16/12	35.727	7.002		23/12	100 F 225B	30.792	9.068		16/13				100	34.547	10.338	21.5/16
		21.922	4.841			32.1001	4.365				27.456	4.672							29.972	6.022	
Fibercore	225	28.732	7.257	1.72	23.5/18.5	38.692	5.627	2.3	32.5/23	225 F 75 B			2.8		39.553	7.410	34.5/24.5	225	37.133	9.805	32.5/24
		27.003	4.524			36.311	4.172								36.751	5.200			34.244	5.803	
	150	27.050	7.727	2.12	23.5/18.5	36.997	5.936	2.7	32.5/23	150 F 125B					38.963	7.764	34.5/24.5	150	35.664	10.337	32.5/24
		24.922	4.604			32.285	4.227								35.663	5.517			32.169	5.929	
	100	25.373	8.360		23.5/18.5	35.207	6.951		32.5/23	100 F 225B					40.426	7.913	34.5/24.5	100	34.042	11.049	32.5/24
		21.586	4.824			31.077	4.289								35.931	5.714			28.507	6.044	
R31703	225	27.811	9.103	1.76	16.5/12.5	38.155	6.714	2.2	22.5/16	225 F 75 B	29.075	10.450	1.82	17.5/12.5				225	35.539	11.449	22/16.5
		26.042	5.568			35.884	4.887				27.252	6.319							32.509	6.846	
	150	26.838	9.550	2.2	16.5/12.5	36.733	7.150	2.8	22.5/16	150 F 125B	28.164	11.411	2.2	17.5/12.5				150	34.240	11.978	22/16.5
		24.583	5.605			33.904	4.804				25.904	6.643							30.493	6.908	
	100	25.364	10.314		16.5/12.5	35.251	8.051		22.5/16	100 F 225B	28.534	11.265		17.5/12.5				100	32.740	12.634	22/16.5
		20.909	5.659			30.683	4.741				25.901	7.008							26.483	6.953	
Erfiber	225			2.58		38.232	6.041		16.5/9.5												
						35.665	4.167														
	150					36.438	6.520		16.5/9.5												
						33.421	4.103														
	100					34.708	7.952		16.5/9.5												
						30.080	4.082														

CHAPTER FIVE

5. CONCLUSION

5.1 Conclusion

In this study the analysis of two types new L band EDFA configurations, namely double pass EDFA with wave selective coupler, and triple pass EDFA with passive EDFA, has been simulated. The performance improvements have been achieved by the elimination of the residual pump power out of the signal. Depending on three types of pump power such as, forward, bidirectional, and backward 980 nm pump laser with the best EDF length for each case, help us to realize flat and high gain and low noise figure. Four types of EDF have been applied to these configurations and having various, input signal powers, pump powers, and EDF lengths, have been tested in order to get the best results. Through the analysis of results by using four types EDF fiber for different pump powers, found the best result at the forward pumping with increases pump power to reach under of saturation. Increase pumping lead to increase gain and decrease noise figure at the same time, as well as, the results are convergent when the bidirectional pumping. But, we found lower gain with higher noise figure when the backward pumping were used.

Two configurations with high gain, gain flatness, and low noise figure have been designed and simulated. We can use these results in practice to get better results in the L -band leading to improve performance in long haul communications.

5.2 Future work

The resulting theoretical results can be used in practice through the use of configurations as well as we can improve configurations results in future work to improve the performance, below a proposal for the future work is given.

- Improving characteristics of EDFA, high gain flatness and low noise figure using FBG in the configurations.
- Through analysis four types of EDFA, new EDFA configurations can be designed.
- EDFA and other Rare earth doped fiber amplifier designs can cover the other bands such as U band.

REFERENCES

Agrawal, G. P. (1997). Fiber-Optic Communication Systems (2nd Ed). John Wiley And Sons, Sydney.

Altuncu Ahmet, Arif Başgümüş, Burçin, Uzunca Ekim, Haznedaroğlu (2003) " Desıgn and Characterızatıonof hıgh performance C and L Band Erbıum Doped Fıber Amplıfıers (C,L-EDFAs)".

Armitage JR (1988). Three-Level Fiber Laser Amplifier: A Theoretical Model. Appl. Optics., 27(23): 4831-4836.

Becker PC (2002), Erbium Doped Fiber Amplifiers Fundamentals And Technology. Acad. Press

Bjarklev AS, Hansen L, Povlsen JH (1989), Large Signal Modeling Of An Erbium-Doped Fiber Amplifier, Proceedings SPIE, Fiber Laser Sources And Ampli., 1171: 118-129.

Chen, D.N.; Desurvire, E.. (1992, Jan). Noise Performance Evaluation Of Distributed Erbium-Doped Fiber Amplifiers With Bidirectional Pumping At 1480 Nm. IEEE Photonics Technology Letters, Vol. 4, No. 1, 52 -55.

ÇOKRAK A.Cem, ALtuncu Ahmet.(2004) . Gaın and Noıse Fıgure performance of Erbıum Doped Fıber Amplıfıers (EDFA).journal of electrıcal & electronıcs engıneerıng, Vol. 4, No.2, 2004.

Desurvire E (1994). Erbium-Doped Fiber Amplifier: Principles And Applications. John WIley And Sons, Inc. New York.

Desurvire E (1987). High Gain Erbium- Doped Traveling Wave Fiber Amplifier. Opt. Lett., 12:888-890.

Desurvire. E. (1990, Mar). Spectral Noise Figure Of Er3+-Doped Fiber Amplifiers. IEEE Photonics Technology Letters: Vol. 2, No, 3.

Digonnet. M. J. F. (1990, Oct). Closed-Form Expressions For The Gain In Three-And Four-Level Laser Fibers. IEEE Journal Of Quantum Electronics: Vol. 26, No. 10.

Fowzia Akhter*, A.W.Naji, M.I. Ibrahimy And H.R. Siddiquei (2012) " Characterization Of Triple Pass Erbium-Doped Fiber Amplifiers" International Conference On Computer And Communication Engineering (ICCCE 2012), 3-5 July 2012, Kuala Lumpur, Malaysia.

Franz JH, Jain VK (2000). Optical Communications Components And Systems: Alpha Sci.,

Fujiwara. M, H. Nishimoto, T. K, Masataka. I, And Shuji. S. (1991, Feb). Studies On Semiconductor Optical Amplifiers For Line Capacity Expansion In Photonic Space-Division Switching System. Journal Of Lightwave Technology: Vol. 9, No. 2, Pp. 155 -160.

Gabla PM, Pamart JL, Uhel R, Leclerc E, Frorud JO, Ollivier FX , Borderieux S (1992). 401km 622Mb/S And 357km, 2.488Gb/S IM/DD Repeaterless Transmission Experiences Using Erbium-Doped Fiber Amplifiers And Error Correcting Code. IEEE Photo. Technol. Lett., 4(10):1148-1151.

Gerd Keiser. (2000). Optical Fiber Communications (3rd Edn.). Mcgraw-Hill Company.

Harun. S. W, N Tamchek, P Poopalan And H Ahmad (2003) " High Gain L-Band Erbium-Doped Fiber Amplifier With Two-Stage Double-Pass Configuration" Indian Academy Of Sciences Vol. 61, No. 1.

Harun. S. W, H. Ahmad (2003) "Gaın Clampıng In Sıngle-Pass And Double-Pass L-Band Erbıum-Doped Fıber Amplıfıers" Acta Physica Slovaca Vol. 54 No. 1, 81 – 88.

HarunSulaiman Wadi And Harith Ahmad (2004) " An Efficient And Low Noise L-Band Erbium-Doped Fiber Amplifier " The 4th Annual Seminar Of National Science Fellowship 2004.

J. H. Ji, L. Zhan, L. L. Yi, C. C. Tang, Q. H. Ye, And Y. X. Xia (2005) " Low Noise-Figure Gain-Clamped L-Band Double-Pass Erbium-Doped Fiber Ring Lasing Amplifier With An Interleaver " Journal Of Lightwave Technology, VOL. 23, NO. 3.

James BA (1991). A Review Of The Fabrication And Properties Of Erbiumdoped Fibers For Optical Amplifiers. J. Lightw. Technol., 9(2): 220-227.

Ji JH (2005). Low Noise-Figure Gain-Clamping L-Band Double-Pass Doped Fiber Ring Lasing Amplifier With Interleaver. Journal Of Lightwave Technology, 23(3): 1375-1379.

Jung Mi Oh, Hyun Beom Choi, Donghan Lee, Seong Joon Ahn, Soo Jin Jung, And Sang Bae Lee (2002) " Demonstration Of Highly Efficient Flat-Gain L-Band Erbium-Doped Fiber Amplifiers By Incorporating A Fiber Bragg Grating" Journal Of Lightwave Technology, VOL. 14, NO. 9, September 2002.

Karásek. M And M. Menif. (2001, Sep). Serial Topology Of Wide –Band Erbium-Doped Fiber Amplifier For WDM Applications. IEEE Photonics Technology Letters: Vol. 13, No. 9, 939-941.

Keck. D. B, R. D. Maurer, And P. C. Schultz. (1973). On The Ultimate Lower Limit Of Attenuation In Glass Optical Waveguides. Appl. Phys. Lett: 22, 307-309.

L .L .Yi , L . Zhan , C . S .Taung , S . Y .Luo , W . S .Hu , Y . K . Su And Y .X . Xia (2005) " Low Noise Figure All- Optical Gain- Clamped Parallel C+L Band Erbium Doped Fiber Amplifier Using An Interleaver " Optical Society Of America.

Liaw SK, Lee CC, Chen YK, Ho KP, Chi S (1997). Chirped-Fiber-Grating- Integrated Optical Limiting Amplifier F Or Dispersion Compensation. Proceedings Of The IEEE Lasers And Electro-Optics Society Annual Meeting., 1: 26-27.

Liaw. S. K, Y. L. Yu, Y. C. Wang, W. F. Wu, And R. Y. Liu (2013) "Investigation Of Two Bidirectional C + L Band Fiber Amplifiers With Pumping Sharing And Wavelength Reused Mechanisms" PIERS Proceedings, Taipei, March 25{28, 2013}.

Maiman. T. H. (1960, Aug). Stimulated Optical Radiation In Ruby. Nature 187, 493-496.

Mears RJ, Reekie L, Jauncey IM, Payne DN (1988). Optical Fiber Amplifiers For 1.5 Mm Operation. Proceedings Of The Optical Fiber Comm. Conf., Pp. 3-5.

Mears RJ (1987). High Gain Rare-Earth-Doped Fiber Amplifier At 1.54 µm. Proceedings Of The Optical Fiber Comm. Conf., 3(12): 167-169.

Mehta. V. (2003). Amplified Spontaneous Emission Tutorial. ECE1654: Optical NetworksUniversity Of Toronto.

Miniscalco. W.J. (1991). Erbium-Doped Glass For Fiber Amplifiers At 1500nm. IEEE J. Lightwave Tech: 9,234.

Mohammed MJ, Sarah TA, Zaidan AA, BB Zaidan, Naji AW, Ibraheem TA (2011a) “Overview Of Laser Principle, Laser–Tissue Interaction Mechanisms And Laser Safety Precautions For Medical Laser Users“, Int. J. Pharmacol., (IJP), 7(2):149-160.

Mohammed MJ, Sarah TA, Zaidan BB, Zaidan AA, Ibraheem TA, Naji AW (2011b) “An Overview: Laser Applications In Dentistry “, Int. J. Pharmacol., (IJP), 7(2):189-197.

Nadir H (2007d). Modeling of Hybrid EDFA/DRA for Long Haul Optical Fiber Commuication System. Msc dissertation, Multimedia Uni, Malaysia.

Naji. A.W, H.F.H. Ibrahim*, Belal Ahmed, S.W. Harun And M.A. Mahdi (2010) " Theoretical Analysis Of Triple-Pass Erbium-Doped Fiber Amplifier" International Conference On Computer And Communication Engineering (ICCCE 2010), 11-13 May 2010, Kuala Lumpur, Malaysia.

Rieznik. A.A, H.L. Fragnito , M.B. Costa E Silva , J.P. Von Der Weid (2006) " Study On Optimum Fiber Length For Maximum Gain In C- And L-Band Edfas" Optics Communications 266 (2006) 546–551.

Sellami Ali, Khalid A. Al-Khateeb And Bouzid Belloui(2006) " The Influence Of EDFA's Configurations On The Behavioral Trends Of Gain And Noise Figure" Vol. II, 9-11 May 2006, Kuala Lumpur, Malaysia.

Sellamı, Ali. (2006) Desıgn and Analysıs of new Erbıum Doped Fıber Amplıfıer and Laser. Msc dissertation, International Islamic University Malaysia.

Schawlow AL, Townes CH (1958). Infrared And Optical Masers. Phys. Rev. Lett., 112(6): 1940-1949.

Siegman , A.E. (1968). An Introduction To Laser And Masers. Mcgraw- Hill.

Sik Heng Foo. (1999). Statistical Properties Of Filtered Amplifier Spontaneous Emission Noise Of Erbium-Doped Fiber Amplifiers. Msc dissertation, University of Alberta.

Stentz, A.J.; Grubb, S.G.; Headley, C.E.; Simpson, J.R.; Strasser, T.; Park, N. (1996). Raman Amplifier With Improved System Performance. Optical Fiber Communications, 1996. OFC '96, 16 -17.

W. Naji1, B. A. Hamida, X. S. Cheng , M. A. Mahdi, S. Harun, S. Khan, W. F. AL-Khateeb, A. A. Zaidan ,B. B. Zaidan, And H. Ahmad (2011) Review Of Erbium-Doped Fiber Amplifier. International Journal Of The Physical Sciences Vol. 6(20), Pp. 4674-4689, 23 September

William L. Barnes, Richard I. Laming, Eleanor J. Tarbox, And P. R. Morkel. (1991,Apr). Absorption And Emission Cross Section Of Er3+Doped Silica Fibers. IEEE Journal Of Quantum Electronics: Vol. 27, NO. 4.

Yucel, M., Aslan Z., Celebi FV, Göktas, HH. Gain and Noise Figure Enhancements of both C and L Bands Double Pass Erbium Doped Fiber Amplifier. ELECO 2013 8th International Conference On Electrical and Electronics Engineering; 28-30 November 2013, Bursa, TURKEY.

Yucel M., Goktas H. H., "Gain Flattening Configurations at the L Band Erbium Doped Fiber Amplifiers", Signal Processing and Communications Applications,. SIU 2007. IEEE 15th, Page(s):1 – 4, Eskişehir, 11-13 June 2007.

Yücel M., Göktaş H.H., "L Band Ekfy'lerin Sıcaklığa Bağımlı Fiber Boyu Ve Kazancının Bulanık Mantık Kullanılarak İncelenmesi", Akademik Bilişim 2007, 31 Ocak-2 Şubat 2007, Kütahya.

Yücel M., Göktaş H.H. and Çelebi Fatih. V., "Temperature independent length optimisation of L band EDFAs providing flat gain", OPTİK, Optik, Cilt 122, Sayı 10, 872-876, (2011).

Yamashita. S And M. Nishihara. (2001, Feb). L-Band Erbium-Doped Fibre Amplifier Incorporating An Inline Fibre Grating Laser' IEEE J. Quantum Electronics: Vol 07, No1

Yla-Jarkko, K.H.,Codemard. C., Singleton. J., Turner. P.W.,Godfrey.I.,Alam. S.U., Nilsson.J., Sahu.,J.K., And Grudinin.A.B ()" Low Noise Intelligent Cladding – Pumped L- Band EDFA "

Zhang. X And A. Mitchell. (2000, Jan). A Simple Black Box Model For Erbium-Doped Fiber Amplifiers. IEEE Photonics Technology Letters: Vol.12, No 1, Pp.28-30.

APPENDIX

Fc_xsec.crs. Setup 1

Forward pump power

Pump Power (225 mw)						Pump Power (150 mw)						Pump Power (100 mw)					
Pin(-20db) L (23.5 m)			Pin(-30db) L (30.5 m)			Pin(-20db) L (23.5 m)			Pin(-30db) L (30.5 m)			Pin(-20db) L (23.5 m)			Pin(-30db) L (30.5 m)		
N.M	G.	NF.	N.M	G.	NF.	N.M	G.	NF.	N.M	G.	NF.	N.M	G.	NF.	N.M	G.	NF.
1570	29.539	5.10814	1570	37.9239	5.41075	1570	26.4531	5.90074	1570	33.4229	6.84166	1570	22.8027	7.52102	1570	26.6632	10.9881
1572	29.3452	4.89699	1572	37.7525	5.0591	1572	26.5576	5.47029	1572	33.6712	6.00751	1572	23.259	6.6355	1572	27.4954	8.9982
1574	28.8802	4.77154	1574	37.2108	4.85288	1574	26.3578	5.21454	1574	33.5154	5.52186	1574	23.3722	6.08943	1574	27.9024	7.66963
1576	28.1883	4.69706	1576	36.3606	4.72617	1576	25.9068	5.05885	1576	33.0225	5.22834	1576	23.2056	5.74459	1576	27.9364	6.79933
1578	27.852	4.62595	1578	35.9684	4.62452	1578	25.7487	4.92739	1578	32.8903	5.01161	1578	23.2581	5.48128	1578	28.1954	6.19247
1580	27.5699	4.56749	1580	35.64	4.54626	1580	25.6159	4.82499	1580	32.7799	4.85468	1580	23.3019	5.28468	1580	28.4143	5.76641
1582	27.7274	4.49518	1582	35.8847	4.46521	1582	25.8765	4.71355	1582	33.1688	4.70857	1582	23.6848	5.09694	1582	29.0274	5.4177
1584	27.6493	4.44409	1584	35.8154	4.40663	1584	25.9028	4.63512	1584	33.2499	4.60694	1584	23.8347	4.96336	1584	29.3381	5.17449
1586	28.1233	4.37232	1586	36.4739	4.33617	1586	26.4381	4.53527	1586	33.9867	4.49483	1586	24.4432	4.81317	1586	30.2034	4.94416
1588	28.1728	4.32665	1588	36.5682	4.28854	1588	26.5646	4.47136	1588	34.1899	4.42167	1588	24.6608	4.71416	1588	30.5746	4.79084
1590	28.3821	4.27909	1590	36.8733	4.24188	1590	26.8327	4.40761	1590	34.5744	4.35337	1590	24.9988	4.62085	1590	31.0847	4.65931
1592	28.643	4.2326	1592	37.2475	4.19746	1592	27.1448	4.34694	1592	35.0155	4.2908	1592	25.3718	4.53489	1592	31.6335	4.54554
1594	28.6285	4.19994	1594	37.2506	4.16432	1594	27.1891	4.30462	1594	35.1031	4.24622	1594	25.4856	4.47434	1594	31.8499	4.46539
1596	28.8488	4.16137	1596	37.5685	4.12802	1596	27.4509	4.25615	1596	35.4747	4.19828	1596	25.7968	4.4086	1596	32.3082	4.38574
1598	29.16	4.12199	1598	38.0106	4.0919	1598	27.796	4.20753	1598	35.9566	4.15155	1598	26.1822	4.34435	1598	32.8575	4.31169
1600	29.1386	3.92347	1600	37.9999	3.75698	1600	27.8195	3.94461	1600	36.011	3.72891	1600	26.2588	4.00828	1600	33.0106	3.7568

Comparison between gain and noise figure versus wavelength for different forward pump powers for 23.5 m EDF length with -20 dBm input signal power and 30.5 m with -30 dBm input signal power for double pass EDFA with WSC.

Fc_xsec.crs. Setup 1 / Bidirectional pump power Pin(-20dBm) &L(24m)								
F.W 225& B.W 75 mW			F.W 150 & B.W 125 mW			F.W 100 & B.W 225 Mw		
NM	G (dB)	NF (dB)	NM	G (dB)	NF (dB)	NM	G (dB)	NF (dB)
1570	29.3091	5.19585	1570	25.9947	6.13382	1570	22.2775	7.93185
1572	29.1964	4.95443	1572	26.2021	5.62461	1572	22.8426	6.91455
1574	28.7972	4.81177	1574	26.0875	5.3227	1574	23.0466	6.284
1576	28.1592	4.72682	1576	25.7081	5.13871	1576	22.9567	5.88492
1578	27.8666	4.64827	1578	25.6068	4.98803	1578	23.0698	5.58579
1580	27.621	4.58463	1580	25.5216	4.87241	1580	23.1644	5.36476
1582	27.8115	4.50804	1582	25.8228	4.75048	1582	23.5902	5.15864
1584	27.7616	4.45408	1584	25.885	4.66487	1584	23.7782	5.01223
1586	28.2636	4.37969	1586	26.4528	4.55862	1586	24.4205	4.85134
1588	28.3362	4.33236	1588	26.6081	4.49052	1588	24.6686	4.74504
1590	28.5671	4.28346	1590	26.9021	4.42337	1590	25.0337	4.64601
1592	28.8485	4.2359	1592	27.2385	4.35992	1592	25.432	4.55543
1594	28.8506	4.20252	1594	27.3037	4.31571	1594	25.568	4.49164
1596	29.0878	4.16331	1596	27.5854	4.2655	1596	25.734	4.42307
1598	29.4157	4.12341	1598	27.9496	4.21537	1598	26.3053	4.35641
1600	29.4068	3.89888	1600	27.9889	3.92184	1600	26.3986	3.98873

Comparison between gain and noise figure versus wavelength for different bidirectional pump powers for 24 m EDF length for double pass EDFA with WSC.

Fc_xsec.crs. Setup 1 / Backward pump power Pin(-20dBm) &L(24m)								
Pump power (225)mW			Pump power (150)mW			Pump power (100)mW		
NM	G (dB)	NF (dB)	NM	G (dB)	NF (dB)	NM	G (dB)	NF (dB)
1570	28.1358	14.5125	1570	24.8634	15.533	1570	20.9279	16.8663
1572	28.084	13.4127	1572	25.2002	14.2559	1572	21.6826	15.382
1574	27.8009	12.4483	1574	25.2272	13.1648	1574	22.0609	14.1314
1576	27.2932	11.5966	1576	24.9844	12.2143	1576	22.1284	13.0508
1578	27.1309	10.9105	1578	25.0091	11.457	1578	22.3784	12.1968
1580	27.0015	10.3238	1580	25.0341	10.8127	1580	22.5912	11.4735
1582	27.2996	9.84183	1582	25.4363	10.287	1582	23.1221	10.8873
1584	27.3427	9.39621	1584	25.5857	9.80136	1584	23.4022	10.3465
1586	27.9363	9.03184	1586	26.2394	9.40707	1586	24.1315	9.91036
1588	28.0856	8.67719	1588	26.4665	9.02257	1588	24.4548	9.48483
1590	28.3873	8.37217	1590	26.8269	8.69301	1590	24.8883	9.12142
1592	28.7362	8.09103	1592	27.2266	8.3899	1592	25.3515	8.78803
1594	28.7932	7.82387	1594	27.3432	8.10164	1594	25.5418	8.47105
1596	29.0858	7.59212	1596	27.677	7.85252	1596	25.9271	8.1981
1598	29.4687	7.37966	1598	28.093	7.62462	1598	26.3848	7.949
1600	29.5008	7.20582	1600	28.1707	7.39217	1600	26.5189	7.64492

Comparison between gain and noise figure versus wavelength for different backward pump powers for 24 m EDF length for double pass EDFA with

R31703.crs Setup 1

FORWARD PUMP POWER

Pump Power (225 mw)						Pump Power (150 mw)						Pump Power (100 mw)					
Pin(-20dB) L (23 m)			Pin(-30dB) L (30 m)			Pin(-20dB) L (23 m)			Pin(-30dB) L (30 m)			Pin(-20dB) L (23 m)			Pin(-30dB) L (30 m)		
N.M	G.	NF.	N.M	G.	NF.	N.M	G.	NF.	N.M	G.	NF.	N.M	G.	NF.	N.M	G.	NF.
1570	28.8138	5.92898	1570	37.9094	5.88648	1570	26.333	6.91393	1570	32.898	8.14558	1570	22.4709	9.07792	1570	25.9754	13.2337
1572	28.9894	5.40406	1572	38.1503	5.26218	1572	26.7767	6.06506	1572	33.6588	6.65649	1572	23.331	7.56259	1572	27.3968	10.2952
1574	28.5443	5.16226	1574	37.5637	4.97988	1574	26.5665	5.65162	1574	33.5482	5.92528	1574	23.4857	6.74865	1574	27.928	8.5026
1576	28.1627	4.99814	1576	37.0631	4.79894	1576	26.3805	5.37502	1576	33.445	5.46461	1576	23.6041	6.20217	1576	28.3717	7.28182
1578	27.9201	4.87049	1578	36.7483	4.66811	1578	26.3008	5.16845	1578	33.4596	5.14983	1578	23.7779	5.80665	1578	28.8448	6.43639
1580	27.2386	4.83751	1580	35.8477	4.62669	1580	25.7519	5.09866	1580	32.834	5.02859	1580	23.4355	5.64167	1580	28.5976	6.04959
1582	27.3096	4.73969	1582	35.9484	4.53877	1582	25.9251	4.95684	1582	33.1383	4.84917	1582	23.7678	5.40008	1582	29.189	5.61453
1584	27.2114	4.68094	1584	35.8232	4.48642	1584	25.911	4.87087	1584	33.1826	4.74403	1584	23.8846	5.25157	1584	29.4709	5.35707
1586	27.4656	4.59921	1586	36.1672	4.41865	1586	26.2334	4.76195	1586	33.66	4.62578	1586	24.3134	5.08377	1586	30.1387	5.10551
1588	27.6021	4.53952	1588	36.3543	4.36959	1588	26.4287	4.68327	1588	33.9631	4.54366	1588	24.6003	4.96389	1588	30.6063	4.93563
1590	28.0831	4.46195	1590	37.0032	4.30831	1590	26.9533	4.58663	1590	34.6925	4.45019	1590	25.1931	4.82799	1590	31.4539	4.7642
1592	28.0536	4.42281	1592	36.9687	4.27589	1592	26.9772	4.53603	1592	34.7657	4.40033	1592	25.3002	4.75231	1592	31.678	4.66717
1594	28.4084	4.35779	1594	37.4517	4.22439	1594	27.3772	4.45695	1594	35.3339	4.32751	1594	25.7711	4.64447	1594	32.3698	4.54373
1596	28.7398	4.30255	1596	37.9048	4.18067	1596	27.7455	4.39093	1596	35.8553	4.26822	1596	26.1969	4.55669	1596	32.9906	4.44856
1598	28.2788	4.29885	1598	37.2862	4.17516	1598	27.3293	4.38436	1598	35.3346	4.26026	1598	25.8503	4.54274	1598	32.6022	4.42955
1600	27.9388	4.59375	1600	36.8321	4.53802	1600	27.0289	4.61821	1600	34.9653	4.49358	1600	25.6114	4.68369	1600	32.3486	4.48776

Comparison between gain and noise figure versus wavelength for different forward pump powers for 23 m EDF length with -20 dBm input signal power and 30 m with -30 dBm input signal power for double pass EDFA with WSC

R31703.crs Setup 1 Pin(-20dBm) & L (25 m)								
BIDIRECTIONAL PUMP POWER								
F.W (225 mW) B.W (75mW)			**F.W (150 mW)B.W (125mW)**			**F.W (100 mW) B.W(225mW)**		
N.M	**G (dB)**	**NF (dB)**	**N.M**	**G (dB)**	**NF (dB)**	**N.M**	**G (dB)**	**NF (dB)**
1570	30.8161	5.44646	1570	31.4831	7.47423	1570	30.9849	11.6307
1572	31.0731	5.34268	1572	31.6661	7.10975	1572	31.1893	10.7102
1574	30.6449	5.30293	1574	31.1739	6.88136	1574	30.7328	10.0248
1576	30.2766	5.26215	1576	30.7531	6.68039	1576	30.3501	9.44332
1578	30.0521	5.21095	1578	30.4853	6.48888	1578	30.1173	8.93258
1580	29.3417	5.20538	1580	29.7392	6.38579	1580	29.399	8.59167
1582	29.4442	5.1358	1582	29.815	6.21482	1582	29.4989	8.21214
1584	29.3579	5.08696	1584	29.7067	6.0876	1584	29.4099	7.92065
1586	29.6519	5.01117	1586	29.9831	5.93614	1586	29.7033	7.62313
1588	29.8154	4.94978	1588	30.1315	5.81242	1588	29.866	7.37762
1590	30.3512	4.86874	1590	30.6565	5.67328	1590	30.4029	7.13395
1592	30.3324	4.81982	1592	30.6237	5.57253	1592	30.3826	6.9295
1594	30.7311	4.74331	1594	31.0112	5.44074	1594	30.7821	6.69597
1596	31.1026	4.67598	1596	31.3736	5.32751	1596	31.1545	6.49886
1598	30.6103	4.65966	1598	30.869	5.27905	1598	30.6586	6.38033
1600	30.2491	4.97025	1600	30.4969	5.63725	1600	30.2946	6.77831

Comparison between gain and noise figure versus wavelength for different bidirectional pump powers for 25 m EDF length for double pass EDFA with WSC

R31703. Setup 1 / Backward pump power Pin (-20 dBm) & L (23 m)								
Pump power (225)mW			**Pump power (150)mW**			**Pump power (100)mW**		
NM	**G (dB)**	**NF (dB)**	**NM**	**G (dB)**	**NF (dB)**	**NM**	**G (dB)**	**NF (dB)**
1570	28.9932	15.8246	1570	26.5525	16.5772	1570	22.7419	17.8269
1572	29.0248	14.4545	1572	26.8886	15.0717	1572	23.5197	16.1109
1574	28.5047	13.3419	1574	26.615	13.8634	1574	23.6172	14.7458
1576	28.095	13.39	1576	26.4001	12.836	1576	23.7039	13.5948
1578	27.8439	11.56	1578	26.3075	11.95	1578	23.8597	12.61
1580	27.1528	10.96	1580	25.7453	11.31	1580	23.5001	11.89
1582	27.2288	10.37	1582	25.9187	10.68	1582	23.8279	11.2
1584	27.1334	9.91	1584	25.9034	10.1897	1584	23.94	10.665
1586	27.3945	9.46355	1586	26.2291	9.72178	1586	24.3686	10.154
1588	27.5361	9.09336	1588	26.4264	9.33103	1588	24.6546	9.72802
1590	28.0259	8.74939	1590	26.9569	8.96922	1590	25.2506	9.33555
1592	27.999	8.43312	1592	26.9809	8.63606	1592	25.3554	8.97
1594	28.361	8.09654	1594	27.3855	8.28269	1594	25.8283	8.59171
1596	28.6989	7.814	1596	27.7581	7.98647	1596	26.2564	8.27221
1598	28.2345	7.61074	1598	27.3368	7.77	1598	25.9033	8.04066
1600	27.893	8.05524	1600	27.0333	8.16371	1600	25.66	8.34731

Comparison between gain and noise figure versus wavelength for different back ward pump powers for 23 m EDF length for double pass EDFA with WSC.

ErFiber.crs Setup 1																	
FORWARD PUMP POWER																	
Pump Power (225 mw)						**Pump Power (150 mw)**						**Pump Power (100 mw)**					
Pin(-20 dBm) L (30.5 m)			**Pin(-30 dBm) L (38.5 m)**			**Pin(-20 dBm) L (30.5 m)**			**Pin(-30 dBm) L (38.5 m)**			**Pin(-20 dBm) L (30.5 m)**			**Pin(-30 dBm) L (38.5 m)**		
N.M	**G.**	**NF.**	**N.M**	**G.**	**NF.**	**N.M**	**G.**	**NF.**	**N.M**	**G.**	**NF.**	**N.M**	**G.**	**NF.**	**N.M**	**G.**	**NF.**
1570	29.2771	4.85675	1570	37.3233	4.83835	1570	26.1899	5.62173	1570	34.1148	5.75079	1570	22.6187	7.1086	1570	29.1086	8.30708
1572	29.2873	4.62657	1572	37.3475	4.57146	1572	26.5045	5.16391	1572	34.4415	5.15302	1572	23.2848	6.20345	1572	29.8976	6.85487
1574	28.9899	4.49703	1574	36.9683	4.41909	1574	26.4773	4.90334	1574	34.3428	4.82348	1574	23.5699	5.66657	1574	30.228	5.98907
1576	28.4405	4.42409	1576	36.2593	4.32861	1576	26.1729	4.75086	1576	33.8957	4.63339	1576	23.5485	5.33949	1576	30.1782	5.46844
1578	28.1953	4.35905	1578	35.949	4.25947	1578	26.1095	4.62897	1578	33.7741	4.49543	1578	23.6952	5.09971	1578	30.3504	5.11699
1580	27.9789	4.30771	1580	35.6757	4.20721	1580	26.0456	4.53717	1580	33.6591	4.39691	1580	23.8077	4.92557	1580	30.4824	4.87684
1582	28.1638	4.245	1582	35.9269	4.15241	1582	26.3366	4.43949	1582	34.0125	4.30238	1582	24.2218	4.76273	1582	31.0033	4.6758
1584	28.1117	4.20174	1584	35.8673	4.11269	1584	26.3914	4.37189	1584	34.0617	4.23743	1584	24.4004	4.64848	1584	31.2248	4.53891
1586	28.574	4.14033	1586	36.485	4.06353	1586	26.9179	4.28612	1586	34.732	4.16192	1586	25.0016	4.52095	1586	31.9905	4.40149
1588	28.6231	4.10199	1588	36.5586	4.02987	1588	27.0462	4.23184	1588	34.8842	4.11323	1588	25.2218	4.43753	1588	32.2688	4.31244
1590	28.8146	4.06189	1590	36.8211	3.99628	1590	27.2989	4.17776	1590	35.203	4.06641	1590	25.5454	4.35915	1590	32.6819	4.23328
1592	29.0494	4.02258	1592	37.1426	3.96368	1592	27.5871	4.12625	1592	35.5714	4.02255	1592	25.8958	4.28692	1592	33.1311	4.16298
1594	29.0156	3.99506	1594	37.1055	3.93861	1594	27.614	4.0903	1594	35.5967	3.99103	1594	25.9929	4.23592	1594	33.2543	4.11368
1596	29.199	3.96232	1596	37.3589	3.91099	1596	27.841	4.04905	1596	35.8887	3.95618	1596	26.2705	4.18055	1596	33.6121	4.0623
1598	29.4642	3.92877	1598	37.7241	3.88322	1598	28.1422	4.00758	1598	36.2816	3.92159	1598	26.6136	4.12635	1598	34.0563	4.01314
1600	29.4091	3.80113	1600	37.6567	3.67149	1600	28.1337	3.81147	1600	36.2637	3.64495	1600	26.659	3.85321	1600	34.1145	3.63107

Comparison between gain and noise figure versus wavelength for different forward pump powers for 30.5 m EDF length with -20 dBm input signal power and 30.5 m with -30 dBm input signal power for double pass EDFA with WSC

Fiber Core.crs Setup 1 Pin(-20db)& L (35.5 m)								
BIDIRECTIONAL PUMP POWER/ SETUP 1								
Pump F.W (225 mw) Pump B.W (75 mw)			Pump F.W (150 mw) Pump B.W (125 mw)			Pump F.W (100 mw) Pump B.W (200 mw)		
N.M	**G.**	**NF.**	**N.M**	**G.**	**NF.**	**N.M**	**G.**	**NF.**
1570	31.4593	5.04587	1570	31.122	7.69654	1570	32.7948	10.3145
1572	31.3124	4.97759	1572	31.0045	7.31641	1572	32.4626	9.63767
1574	30.8764	4.92917	1574	30.5965	7.01393	1574	31.8889	9.0634
1576	30.2005	4.89445	1576	29.947	6.76225	1576	31.1001	8.56624
1578	29.873	4.84669	1578	29.6397	6.53842	1578	30.6965	8.15384
1580	29.5929	4.79836	1580	29.3768	6.3403	1580	30.3547	7.79741
1582	29.7501	4.733	1582	29.5466	6.15164	1582	30.4727	7.49005
1584	29.6661	4.67928	1584	29.4748	5.98576	1584	30.3472	7.21073
1586	30.134	4.60733	1586	29.9509	5.82242	1586	30.7946	6.96698
1588	30.1714	4.55334	1588	29.9976	5.68105	1588	30.8023	6.73956
1590	30.3665	4.49762	1590	30.2001	5.55086	1590	30.9759	6.53923
1592	30.6113	4.44204	1592	30.4516	5.42737	1592	31.2026	6.35274
1594	30.577	4.39686	1594	30.4244	5.31824	1594	31.1451	6.17996
1596	30.7765	4.348	1596	30.6293	5.21451	1596	31.3298	6.02519
1598	31.0656	4.29887	1598	30.9232	5.11563	1598	31.6079	5.88133
1600	31.0192	4.15324	1600	30.8821	4.99984	1600	31.5434	5.83508

Comparison between gain and noise figure versus wavelength for different bidirectional pump powers for 35.5 m EDF length for double pass EDFA with WSC.

Fiber Core.crs Setup 2 Pin(-30db) & L (32.5 &23 m)								
FORWARD PUMP WITH PASSIVE EDFA SETUP 2								
F.W PUMP (225 mW)			F.W PUMP (150 mW)			F.W PUMP (100 mW)		
N.M	G.	NF.	N.M	G.	NF.	N.M	G.	NF.
1570	38.6923	5.62774	1570	35.1562	5.93641	1570	31.0778	6.95154
1572	38.0397	5.48076	1572	34.9255	5.64449	1572	31.2963	6.33652
1574	37.2892	5.37201	1574	34.5201	5.44112	1574	31.2702	5.91802
1576	36.8919	5.26268	1576	34.3698	5.27189	1576	31.3986	5.60793
1578	36.6083	5.16141	1578	34.2851	5.13062	1578	31.5415	5.36837
1580	36.5556	5.0583	1580	34.3869	5.00066	1580	31.8221	5.16815
1582	36.3113	4.9771	1582	34.2867	4.90161	1582	31.8888	5.01882
1584	36.5757	4.87636	1584	34.6481	4.78893	1584	32.3641	4.86816
1586	37.036	4.7763	1586	35.1815	4.68122	1586	32.9839	4.73201
1588	37.2401	4.69709	1588	35.4623	4.59745	1588	33.3547	4.62735
1590	37.7042	4.61215	1590	35.9826	4.51	1590	33.9416	4.52341
1592	37.6309	4.55493	1592	35.9846	4.4519	1592	34.0318	4.45354
1594	37.736	4.49464	1594	36.1492	4.39184	1594	34.2663	4.38432
1596	38.036	4.43148	1596	36.494	4.32969	1596	34.6642	4.31497
1598	38.5063	4.37219	1598	36.9974	4.27202	1598	35.2071	4.25162
1600	38.6324	4.32194	1600	37.4523	4.24231	1600	35.6154	4.2254

Comparison between gain and noise figure versus wavelength for different bidirectional pump powers for 32.5 m EDF length and 23 passive EDF length for triple pass EDFA with passive EDF.

ErFiber.crs Setup 1 / Bidirectional pump power Pin(-20dbm)& L(30.5)								
F.W 225& B.W 75 mW			F.W 150 & B.W 125 mW			F.W 100 & B.W 225 mW		
NM	G (dB)	NF (dB)	NM	G (dB)	NF (dB)	NM	G (dB)	NF (dB)
1570	32.1599	5.16562	1570	31.9934	7.73675	1570	33.0595	10.0193
1572	31.8834	5.08555	1572	31.7228	7.36058	1572	32.6056	9.40281
1574	31.3318	5.02768	1574	31.1817	7.0571	1574	31.94	8.86727
1576	30.552	4.98519	1576	30.4139	6.80201	1576	31.0767	8.39792
1578	30.1373	4.93194	1578	30.22	6.5758	1578	30.6119	8.00403
1580	29.779	4.87895	1580	29.6612	6.37535	1580	30.2148	7.66228
1582	29.8663	4.81	1582	29.7562	6.18594	1582	30.2798	7.36584
1584	29.7151	4.75261	1584	29.6122	6.01832	1584	30.104	7.09664
1586	30.1198	4.67796	1586	30.0225	5.85516	1586	30.4991	6.86045
1588	30.0957	4.62088	1588	30.0041	5.7124	1588	30.4579	6.64067
1590	30.2314	4.56255	1590	30.1446	5.58141	1590	30.5821	6.44669
1592	30.4176	4.50449	1592	30.3353	5.45724	1592	30.7589	6.26593
1594	30.3277	4.45667	1594	30.2495	5.34659	1594	30.6553	6.09865
1596	30.4714	4.40563	1596	30.3967	5.24211	1596	30.7911	5.9485
1598	30.7044	4.35449	1598	30.6331	5.14272	1598	31.0188	5.80878
1600	30.6059	4.30903	1600	30.5376	5.12843	1600	30.9094	5.84486

Comparison between gain and noise figure versus wavelength for different bidirectional pump powers for 30.5 m EDF length for double pass EDFA with WSC.

ErFiber.crs Setup 1 / Backward pump power Pin(-20dbm)& L(30.5)								
Pump power (225)mW			Pump power (150)mW			Pump power (100)mW		
NM	G (dB)	NF (dB)	NM	G (dB)	NF (dB)	NM	G (dB)	NF (dB)
1570	30.5736	13.4302	1570	27.4891	14.3226	1570	23.852	15.4113
1572	30.2089	12.4574	1572	27.5319	13.1733	1572	24.3172	14.0708
1574	29.6814	11.5827	1574	27.3204	12.1777	1574	24.451	12.9357
1576	28.9775	10.7973	1576	26.8786	11.3024	1576	24.3074	11.951
1578	28.6569	10.1568	1578	26.7384	10.5997	1578	24.3801	11.1694
1580	28.3878	9.60606	1580	26.6167	9.99958	1580	24.4348	10.5057
1582	28.5527	9.15287	1582	26.8801	9.50947	1582	24.8186	9.96728
1584	28.473	8.73275	1584	26.9011	9.0556	1584	24.9617	9.46954
1586	28.9368	8.39042	1586	27.4218	8.68834	1586	25.5536	9.06932
1588	28.9692	8.05576	1588	27.5281	8.32875	1588	25.75	8.67732
1590	29.1535	7.76827	1590	27.7683	8.02085	1590	26.0591	8.3428
1592	29.3843	7.50355	1592	28.0476	7.73793	1592	26.3984	8.03613
1594	29.3358	7.25066	1594	28.0558	7.46753	1594	26.4758	7.74315
1596	29.5154	7.03225	1596	28.2751	7.23478	1596	26.7442	7.49177
1598	29.7814	6.83257	1598	28.5733	7.02241	1598	27.0826	7.26288
1600	29.7139	6.84285	1600	28.5494	6.97497	1600	27.112	7.14497

Comparison between gain and noise figure versus wavelength for different back ward pump powers for 30.5 m EDF length for double pass EDFA with WSC.

Fibercore.crs Setup 1 / Backward pump power Pin(-30dbm) & L (43 m)								
Pump power (225)mW			Pump power (150)mW			Pump power (100)mW		
NM	G (dB)	NF (dB)	NM	G (dB)	NF (dB)	NM	G (dB)	NF (dB)
1570	37.2589	12.764	1571	34.6585	13.7095	1571	31.0131	14.6466
1572	36.3085	11.86	1573	34.1936	12.53	1573	30.9476	13.3832
1574	35.4165	11.065	1575	33.64	11.58	1575	30.7361	12.34
1576	35.0176	10.408	1577	33.4412	10.83	1577	30.7802	11.51
1578	34.7694	9.83846	1579	33.3393	10.19	1579	30.8766	10.81
1580	34.7797	9.34413	1581	33.4526	9.66143	1581	31.1423	10.22
1582	34.5786	8.91	1583	33.3499	9.18552	1583	31.1881	9.69409
1584	34.9236	8.52473	1585	33.7503	8.78036	1585	31.6802	9.24508
1586	35.4771	8.19054	1587	34.3398	8.42829	1587	32.3326	8.85573
1588	35.7472	7.88721	1589	34.654	8.10659	1589	32.72	8.50102
1590	36.3028	7.61157	1591	35.2343	7.81783	1591	33.3449	8.18348
1592	36.2587	7.35403	1593	35.2407	7.54268	1593	33.4321	7.88129
1594	36.4095	7.12137	1595	35.4274	7.29646	1595	33.6781	7.61149
1596	36.7748	6.91053	1597	35.8148	7.07551	1597	34.1036	7.37007
1598	37.3331	6.72249	1599	36.3831	6.88022	1599	34.6912	7.15704
1600	37.1729	6.5805	1601	36.2639	6.62	1601	34.6384	6.86

Comparison between gain and noise figure versus wavelength for different forward pump powers for 43 m EDF length for double pass EDFA with WSC.

Fibercore.crs Setup 1 / forward pump power Pin (-20 dBm) & L (33.5 m)								
Pump power (225)mW			Pump power (150)mW			Pump power (100)mW		
NM	G (dB)	NF (dB)	NM	G (dB)	NF (dB)	NM	G (dB)	NF (dB)
1570	29.5601	5.03852	1570	26.038	6.15877	1570	21.9055	8.39681
1572	29.4277	4.78899	1572	26.2495	5.5822	1572	22.5186	7.18986
1574	29.0224	4.64152	1574	26.1498	5.23809	1574	22.7764	6.42604
1576	28.391	4.55237	1576	25.7954	5.02531	1576	22.7467	5.93356
1578	28.0856	4.47287	1578	25.6955	4.85871	1578	22.8877	5.57778
1580	27.8245	4.4089	1580	25.6066	4.73257	1580	23.0009	5.31811
1582	27.9739	4.33509	1582	25.8757	4.60694	1582	23.4107	5.08979
1584	27.8963	4.28214	1584	25.9187	4.51709	1584	23.5955	4.9246
1586	28.337	4.2122	1586	26.4315	4.41214	1586	24.1933	4.75545
1588	28.3732	4.16639	1588	26.557	4.3425	1588	24.4237	4.63924
1590	28.5572	4.1198	1590	26.8096	4.2427	1590	24.7572	4.53428
1592	28.7878	4.07466	1592	27.1002	4.21273	1592	25.1184	4.43949
1594	28.7562	4.042	1594	27.1368	4.16754	1594	25.2351	4.37042
1596	28.944	4.00472	1596	27.3734	4.1181	1596	25.5292	4.29945
1598	29.2157	3.96708	1598	27.6852	4.06933	1598	25.8884	4.23161
1600	29.1725	3.82367	1600	27.6943	3.85093	1600	25.9588	3.92905

Comparison between gain and noise figure versus wavelength for different forward pump powers for 33.5 m EDF length for double pass EDFA with WSC

Fibercore.crs Setup 1 / forward pump power Pin (-20 dBm) & L (42.5 m)								
Pump power (225)mW			Pump power (150)mW			Pump power (100)mW		
NM	G (dB)	NF (dB)	NM	G (dB)	NF (dB)	NM	G (dB)	NF (dB)
1570	37.6501	5.3646	1570	31.5407	7.83797	1570	21.6798	15.1607
1572	37.5	4.95721	1572	31.9642	6.61543	1572	22.8458	12.3747
1574	36.9954	4.72108	1574	31.9866	5.87707	1574	23.6741	10.2215
1576	36.1969	4.57669	1576	31.6742	5.42148	1576	24.1375	8.64832
1578	35.8184	4.46436	1578	31.6528	5.10342	1578	24.7008	7.53982
1580	35.4951	4.3794	1580	31.629	4.87935	1580	25.1714	6.74686
1582	35.7005	4.29495	1582	32.0373	4.68785	1582	25.9219	6.13906
1584	35.6115	4.23397	1584	32.1567	4.55368	1584	26.389	5.69913
1586	36.1934	4.16328	1586	32.8546	4.41897	1586	27.2901	5.32789
1588	36.2505	4.11518	1588	33.0645	4.32872	1588	27.7567	5.06525
1590	36.4993	4.06882	1590	33.4278	4.24826	1590	28.3156	4.85367
1592	36.8093	4.02503	1592	33.8362	4.17641	1592	28.8939	4.67731
1594	36.7763	3.99219	1594	33.9213	4.12446	1594	29.1755	4.54879
1596	37.03	3.95678	1596	34.255	4.07127	1596	29.6473	4.43206
1598	37.3947	3.92178	1598	34.6826	4.02063	1598	30.1863	4.32836
1600	37.3449	3.69829	1600	34.724	3.66808	1600	30.3786	3.77394

Comparison between gain and noise figure versus wavelength for different forward pump powers for 42.5 m EDF length for double pass EDFA with WSC.

ErFiber.crs / Setup 2 Forward pump power Pin (-30 dBm) & L (16.5&9.5 m)								
Pump power (225)mW			Pump power (150)mW			Pump power (100)mW		
NM	G (dB)	NF (dB)	NM	G (dB)	NF (dB)	NM	G (dB)	NF (dB)
1570	38.2324	6.04199	1570	34.4893	6.52084	1570	30.0806	7.95212
1573	37.5421	5.67181	1573	34.3389	5.90717	1573	30.5661	6.74995
1576	36.3815	5.38156	1576	33.6216	5.48995	1576	30.3708	6.0105
1579	35.8801	5.17324	1579	33.421	5.21101	1579	30.5246	5.54717
1582	35.6783	4.89313	1582	33.4456	4.89418	1582	30.8157	5.12271
1585	35.6651	4.98318	1585	33.6092	4.94239	1585	31.1878	5.07751
1588	36.1195	4.85881	1588	34.1862	4.79992	1588	31.9092	4.88246
1591	36.6717	4.62601	1591	34.8362	4.56227	1591	32.6744	4.61608
1594	36.5768	4.575	1594	34.8525	4.50497	1594	32.8217	4.53428
1597	36.93	4.63538	1597	35.2822	4.55565	1597	33.3415	4.55981
1600	37.102	4.45198	1600	35.5277	4.37772	1600	33.6734	4.37738
1603	37.5558	3.76782	1603	36.0356	3.71874	1603	34.245	3.73926
1606	37.9085	4.18794	1606	36.4389	4.12039	1606	34.708	4.11124
1609	37.1518	4.21429	1609	35.7647	4.14663	1609	34.1309	4.1317
1612	37.4086	4.30922	1612	36.0624	4.23612	1612	34.4769	4.20946
1615	37.0458	4.16757	1615	35.7559	4.10362	1615	34.2366	4.08292

Comparison between gain and noise figure versus wavelength for different forward pump powers for 16.5 m EDF length and 9.5 m passive EDF length for triple pass EDFA with passive EDFA.

R31703.crs / Setup 2 Backward pump power Pin (-30 dBm) & L (22&16.5m)								
Pump power (225)mW			Pump power (150)mW			Pump power (100)mW		
NM	G (dB)	NF (dB)	NM	G (dB)	NF (dB)	NM	G (dB)	NF (dB)
1570	35.4202	11.45	1570	31.2535	11.978	1570	26.4835	12.63
1572	35.0879	10.91	1572	31.5674	11.32	1572	27.5609	11.78
1574	34.1225	10.47	1574	31.1554	10.78	1574	27.7782	11.0978
1576	33.5431	10.0186	1576	30.9864	10.26	1576	28.0668	10.78
1578	33.3122	9.56253	1578	31.0595	9.75	1578	28.4785	9.91701
1580	32.5079	9.23482	1580	30.4934	9.38987	1580	28.1783	9.52
1582	32.7784	8.84713	1582	30.9232	8.98025	1582	28.7878	9.08508
1584	32.7969	8.53925	1584	31.0707	8.65614	1584	29.0814	8.74569
1586	33.2843	8.22218	1586	31.656	8.327	1586	29.7781	8.40648
1588	33.5933	7.95579	1588	32.0491	8.05083	1588	30.2672	8.12208
1590	34.3472	7.69331	1590	32.8611	7.78	1590	31.1459	7.84739
1592	34.4202	7.46464	1592	33.0108	7.54448	1592	31.3833	7.60369
1594	35.0051	7.20698	1594	33.657	7.2	1594	32.0997	7.33414
1596	35.5395	6.98835	1596	34.2408	7.05591	1596	32.7403	7.10609
1598	35.0105	6.85	1598	33.7773	6.90846	1598	32.3518	6.95331
1600	34.6407	7.18403	1600	33.4639	7.15775	1600	32.103	7.09884

Comparison between gain and noise figure versus wavelength for different back ward pump powers for 22 m EDF length and 16.5 m passive EDF length for triple pass EDFA with passive EDFA.

R31703.crs / Setup 2 Bidirectional pump power Pin (-20 dBm) & L (17.5& 12.5m)								
F.W 225& B.W 75 mW			F.W 225& B.W 75 mW			F.W 225& B.W 75 mW		
NM	G (dB)	NF (dB)	NM	G (dB)	NF (dB)	NM	G (dB)	NF (dB)
1570	28.8106	10.45	1570	26.9419	11.41	1570	28.5341	11.56
1572	28.8997	9.89169	1572	27.0784	10.85	1572	27.9039	11.21
1574	28.4386	9.43861	1574	26.7294	10.33	1574	27.111	10.94
1576	28.0906	9.00632	1576	26.5115	9.81103	1576	26.676	10.5
1578	27.901	8.6	1578	26.4466	9.31683	1578	26.5044	9.99653
1580	27.2524	8.32461	1580	25.9047	8.97405	1580	25.9012	9.62548
1582	27.3781	7.99422	1582	26.118	8.58292	1582	26.0908	9.19223
1584	27.3208	7.73874	1584	26.1336	8.27816	1584	26.0915	8.85
1586	27.6218	7.46931	1586	26.4954	7.96626	1586	26.4471	8.49977
1588	27.796	7.24595	1588	26.722	7.70696	1588	26.6694	8.20767
1590	28.3189	7.01865	1590	27.2849	7.45041	1590	27.2323	7.92305
1592	28.3184	6.83	1592	27.3321	7.23183	1592	27.2765	7.67412
1594	28.7114	6.61238	1594	27.7666	6.98	1594	27.7111	7.39655
1596	29.0754	6.42631	1596	28.1644	6.77343	1596	28.1095	7.16203
1598	28.6242	6.32	1598	27.7527	6.64356	1598	27.6952	7.00853
1600	28.2957	6.67	1600	27.4596	6.95324	1600	27.4008	7.33571

Comparison between gain and noise figure versus wavelength for different bidirectional pump powers for 17.5 m EDF length and 12.5 m passive EDF length for triple pass EDFA with passive EDFA.

R31703.crs / Setup 2 Forward pump power Pin (-30 dBm) & L (22.5&16m)								
Pump power (225)mW			Pump power (150)mW			Pump power (100)mW		
NM	G (dB)	NF (dB)	NM	G (dB)	NF (dB)	NM	G (dB)	NF (dB)
1570	37.9341	6.72	1570	34.4747	7.15065	1570	30.683	8.05109
1572	38.1552	6.32	1572	35.1098	6.56068	1572	31.7466	7.11933
1574	37.5513	6.13767	1574	34.8659	6.26048	1574	31.8809	6.61535
1576	37.061	5.98139	1576	34.6619	6.02908	1576	31.9845	6.24745
1578	36.7687	5.83174	1578	34.6002	5.82924	1578	32.1746	5.95376
1580	35.8844	5.78432	1580	33.904	5.76	1580	31.6842	5.83212
1582	36.0108	5.64082	1582	34.1692	5.59067	1582	32.1035	5.62108
1584	35.9054	5.54439	1584	34.1782	5.48156	1584	32.2396	5.48478
1586	36.2685	5.41409	1586	34.6324	5.34119	1586	32.7956	5.32162
1588	36.4708	5.31318	1588	34.9134	5.23453	1588	33.1645	5.20035
1590	37.1302	5.18832	1590	35.6296	5.1054	1590	33.9448	5.05926
1592	37.1078	5.11428	1592	35.6793	5.0299	1592	34.075	4.97688
1594	37.598	5.00358	1594	36.2293	4.91837	1594	34.6921	4.85908
1596	38.0541	4.90906	1596	36.7338	4.82424	1596	35.2512	4.76138
1598	37.4509	4.88796	1598	36.1924	4.80471	1598	34.7783	4.74143
1600	37.0093	5.26633	1600	35.8048	5.09215	1600	34.4508	4.92862

Comparison between gain and noise figure versus wavelength for different forward pump powers for 22.5 m EDF length and 16 m passive EDF length for triple pass EDFA with passive EDFA.

R31703.crs / Setup 2 Forward pump power Pin (-20 dBm) & L (16.5 & 12.5 m)								
Pump power (225)mW			Pump power (150)mW			Pump power (100)mW		
NM	G (dB)	NF (dB)	NM	G (dB)	NF (dB)	NM	G (dB)	NF (dB)
1570	27.0621	9.10358	1570	24.6101	9.55004	1570	20.9096	10.31
1572	27.372	8.38492	1572	25.1905	8.71185	1572	21.8951	9.27184
1574	27.0569	7.94138	1574	25.1106	8.19092	1574	22.168	8.61583
1576	26.788	7.57718	1576	25.0362	7.77151	1576	22.3864	8.09946
1578	26.6404	7.25505	1578	24.82	7.40851	1578	22.6435	7.66476
1580	26.0423	7.0828	1580	24.583	7.21278	1580	22.3742	7.42758
1582	26.1717	6.82538	1582	24.8132	6.93247	1582	22.7569	7.10756
1584	26.1235	6.63977	1584	24.8479	6.73148	1584	22.9168	6.87993
1586	26.4145	6.42739	1586	25.2063	6.50486	1586	23.3771	6.62892
1588	26.5837	6.25818	1588	25.4334	6.32519	1588	23.6918	6.43141
1590	27.0844	6.07187	1590	25.9772	6.12913	1590	24.301	6.21892
1592	27.0862	5.94021	1592	26.0317	5.99056	1592	24.4351	6.06866
1594	27.4628	5.77	1594	26.4531	5.81289	1594	24.9243	5.87838
1596	27.8113	5.62624	1596	26.838	5.66325	1596	25.3645	5.71915
1598	27.3821	5.57	1598	26.4527	5.60296	1598	25.0453	5.65482
1600	27.0695	5.87923	1600	26.1788	5.85167	1600	24.8301	5.80928

Comparison between gain and noise figure versus wavelength for different forward pump powers for 16.5 m EDF length and 12.5 m passive EDF length for triple pass EDFA with passive EDFA.

Fibercore.crs / Setup 2 Backward pump power Pin (-30 dBm) & L (32&24 m)								
Pump power (225)mW			Pump power (150)mW			Pump power (100)mW		
NM	G (dB)	NF (dB)	NM	G (dB)	NF (dB)	NM	G (dB)	NF (dB)
1570	37.1331	9.80559	1570	33.2415	10.34	1570	28.5077	11.0496
1572	36.0429	9.36651	1572	32.7706	9.75496	1572	28.8452	10.19
1574	35.0679	8.95829	1574	32.2828	9.24	1574	28.965	9.50025
1576	34.6353	8.58369	1576	32.1731	8.79935	1576	29.2469	8.97
1578	34.3879	8.24	1578	32.1691	8.41	1578	29.5351	8.52318
1580	34.4119	7.91909	1580	32.3704	8.0618	1580	29.9477	8.14467
1582	34.2448	7.63023	1582	32.364	7.74906	1582	30.1337	7.80595
1584	34.6039	7.36631	1584	32.824	7.47174	1584	30.7127	7.51863
1586	35.1563	7.12859	1586	33.4492	7.22501	1586	31.4229	7.26759
1588	35.4394	6.91206	1588	33.8101	6.99905	1588	31.8759	7.03502
1590	35.9829	6.71061	1590	34.4078	6.79138	1590	32.5368	6.82541
1592	35.9735	6.52396	1592	34.4753	6.59608	1592	32.6964	6.62
1594	36.1413	6.35218	1594	34.702	6.41799	1594	32.9931	6.44037
1596	36.5016	6.19393	1596	35.1053	6.25529	1596	33.4467	6.27608
1598	37.0302	6.05219	1598	35.6643	6.11041	1598	34.0407	6.13144
1600	36.9139	5.8032	1600	35.6041	5.92914	1600	34.0483	6.0448

Comparison between gain and noise figure versus wavelength for different backward pump powers for 32 m EDF length and 24 m passive EDF length for triple pass EDFA with passive EDFA.

Fibercore.crs / Setup 2 Bidirectional pump power Pin (-20 dBm) & L (34.5 & 24.5 m)								
F.W 225& B.W 75 mW			F.W 225& B.W 75 mW			F.W 225& B.W 75 mW		
NM	G (dB)	NF (dB)	NM	G (dB)	NF (dB)	NM	G (dB)	NF (dB)
1570	39.5535	7.38472	1570	38.9634	7.47	1570	40.4262	7.57947
1572	38.5532	7.41077	1572	37.6875	7.68925	1572	38.7824	7.80147
1574	37.618	7.35354	1574	36.5789	7.76417	1574	37.3552	7.91387
1576	37.1912	7.20202	1576	36.0873	7.66872	1576	36.661	7.85133
1578	36.9325	7.02292	1578	35.8121	7.50874	1578	36.245	7.71
1580	36.9446	6.82494	1580	35.8376	7.30563	1580	36.1823	7.51788
1582	36.7511	6.64976	1582	35.6635	7.12018	1582	35.9312	7.33485
1584	37.1084	6.45264	1584	36.0538	6.90035	1584	36.2884	7.11293
1586	37.6711	6.26182	1586	36.6503	6.68477	1586	36.8689	6.89379
1588	37.9509	6.10003	1588	36.9596	6.502	1588	37.1552	6.70583
1590	38.5073	5.93551	1590	37.5463	6.31476	1590	37.7335	6.51353
1592	38.4795	5.80696	1592	37.5434	6.16871	1592	37.7045	6.35988
1594	38.6402	5.67939	1594	37.7291	6.02301	1594	37.8745	6.20705
1596	39.0065	5.55324	1596	38.1193	5.88	1596	38.2578	6.05667
1598	39.5528	5.43447	1598	38.6884	5.74232	1598	38.8266	5.91501
1600	39.4146	5.20028	1600	38.5702	5.51722	1600	38.6904	5.71416

Comparison between gain and noise figure versus wavelength for different bidirectional pump powers for 34.5 m EDF length and 24.5 m passive EDF length for triple pass EDFA with passive EDFA.

Fibercore.crs / Setup 2 Forward pump power Pin (-30 dBm) & L (32.5&23m)								
Pump power (225)mW			Pump power (150)mW			Pump power (100)mW		
NM	G (dB)	NF (dB)	NM	G (dB)	NF (dB)	NM	G (dB)	NF (dB)
1570	38.6923	5.62774	1570	35.1562	5.93641	1570	31.0778	6.95154
1572	38.0397	5.48076	1572	34.9255	5.64449	1572	31.2963	6.33652
1574	37.2892	5.37201	1574	34.5201	5.44112	1574	31.2702	5.91802
1576	36.8919	5.26268	1576	34.3698	5.27189	1576	31.3986	5.60793
1578	36.6083	5.16141	1578	34.2851	5.13062	1578	31.5415	5.36837
1580	36.5556	5.0583	1580	34.3869	5.00066	1580	31.8221	5.16815
1582	36.3113	4.98	1582	34.2867	4.90161	1582	31.8888	5.01882
1584	36.5757	4.87636	1584	34.6481	4.78893	1584	32.3641	4.86816
1586	37.036	4.78	1586	35.1815	4.68122	1586	32.9839	4.73201
1588	37.2401	4.69709	1588	35.4623	4.59745	1588	33.3547	4.62735
1590	37.7042	4.61215	1590	35.9826	4.2	1590	33.9416	4.52341
1592	37.6309	4.55493	1592	35.9846	4.45	1592	34.0318	4.45354
1594	37.736	4.49464	1594	36.1492	4.39184	1594	34.2663	4.38432
1596	38.036	4.43148	1596	36.494	4.32969	1596	34.6642	4.31497
1598	38.5063	4.37219	1598	36.9974	4.27202	1598	35.2071	4.25162
1600	38.3427	4.1721	1600	36.8903	4.0276	1600	35.1661	4.1617

Comparison between gain and noise figure versus wavelength for different forward pump powers for 32.5 m EDF length and 23 m passive EDF length for triple pass EDFA with passive EDFA.

Fibercore.crs / Setup 2 Forward pump power Pin (-20 dBm) & L (23.5 & 18.5 m)								
Pump power (225)mW			Pump power (150)mW			Pump power (100)mW		
NM	G (dB)	NF (dB)	NM	G (dB)	NF (dB)	NM	G (dB)	NF (dB)
1570	28.7345	7.25763	1570	25.3355	7.74	1570	21.586	8.36075
1572	28.2925	6.93206	1572	25.2505	7.29339	1572	21.8884	7.75826
1574	27.756	6.67345	1574	25.0182	6.95	1574	21.9883	7.30605
1576	27.461	6.44706	1576	24.9514	6.66988	1576	22.1719	6.94725
1578	27.2445	6.24665	1578	24.9229	6.42795	1578	22.3506	6.64954
1580	27.1955	6.05999	1580	25.0234	6.20969	1580	22.6159	6.39
1582	27.0062	5.90332	1582	24.9731	6.02897	1582	22.719	6.17679
1584	27.1907	5.74	1584	25.2547	5.84662	1584	23.108	5.96888
1586	27.5201	5.59	1586	25.659	5.68	1586	23.5954	5.77886
1588	27.6624	5.46	1588	25.878	5.53542	1588	23.8992	5.62092
1590	27.9959	5.32922	1590	26.2698	5.39522	1590	24.3555	5.47
1592	27.9359	5.22845	1592	26.2835	5.28616	1592	24.4509	5.34734
1594	28.0073	5.12965	1594	26.4142	5.18014	1594	24.6472	5.23244
1596	28.2224	5.03236	1596	26.6752	5.07644	1596	24.959	5.12095
1598	28.5626	4.94228	1598	27.0507	4.98057	1598	25.3737	5.01814
1600	28.4383	4.52404	1600	26.9812	4.20447	1600	25.3649	4.82436

Comparison between gain and noise figure versus wavelength for different forward pump powers for 23.5 m EDF length and 18.5 m passive EDF length for triple pass EDFA with passive EDFA.

Fc-xsec.crs / Setup 2 **Backward pump power Pin (-30 dBm) & L (21.5&16m)**								
Pump power (225)mW			**Pump power (150)mW**			**Pump power (100)mW**		
NM	**G (dB)**	**NF (dB)**	**NM**	**G (dB)**	**NF (dB)**	**NM**	**G (dB)**	**NF (dB)**
1570	36.9982	9.56369	1570	34.5104	9.83827	1570	30.4212	10.34
1572	35.8394	9.1857	1572	33.7109	9.41408	1572	30.2226	9.79813
1574	34.8176	8.82594	1574	32.9819	9.01143	1574	29.9724	9.30477
1576	34.364	8.48173	1576	32.7281	8.64	1576	30.0421	8.87
1578	34.1106	8.15614	1578	32.6279	8.28738	1578	30.1897	8.48
1580	34.1397	7.85159	1580	32.77	7.96589	1580	30.515	8.13277
1582	33.9843	7.57399	1582	32.718	7.67387	1582	30.6305	7.81723
1584	34.362	7.31605	1584	33.1608	7.40635	1584	31.1796	7.53528
1586	34.938	7.08211	1586	33.7839	7.16518	1586	31.8796	7.28376
1588	35.2474	6.86961	1588	34.1436	6.95	1588	32.3217	7.05388
1590	35.8209	6.67054	1590	34.7523	6.74129	1590	32.9879	6.842
1592	35.8417	6.48766	1592	34.823	6.55229	1592	33.1401	6.64364
1594	36.0426	6.31842	1594	35.0621	6.38	1594	33.4418	6.46238
1596	36.4391	6.16177	1596	35.4863	6.21769	1596	33.9116	6.29647
1598	37.0073	6.02094	1598	36.074	6.07374	1598	34.5312	6.14839
1600	36.9268	5.81219	1600	36.0301	5.97487	1600	34.5475	6.02289

Comparison between gain and noise figure versus wavelength for different backward pump powers for 21.5 m EDF length and 16 m passive EDF length for triple pass EDFA with passive EDFA.

Fc-xsec.crs / Setup 2 Bidirectional pump power Pin (-20 dBm) & L (16 &13 m)								
F.W 225& B.W 75 mW			F.W 150 & B.W 125 mW			F.W 100 & B.W 225 mW		
NM	**G (dB)**	**NF (dB)**	**NM**	**G (dB)**	**NF (dB)**	**NM**	**G (dB)**	**NF (dB)**
1570	30.3573	8.48171	1570	30.324	8.93223	1570	30.7922	9.06861
1572	29.6167	8.20661	1572	29.4062	8.72456	1572	29.5389	9.02751
1574	28.9029	7.91072	1574	28.6112	8.432	1574	28.5559	8.81055
1576	28.5224	7.62187	1576	28.2049	8.11777	1576	28.0665	8.51213
1578	28.2581	7.35098	1578	27.935	7.81367	1578	27.7554	8.20085
1580	28.1892	7.09892	1580	27.8702	7.52845	1580	27.673	7.89901
1582	27.9847	6.87209	1582	27.673	7.26876	1582	27.4657	7.61877
1584	28.1796	6.65858	1584	27.8769	7.02839	1584	27.6694	7.36
1586	28.5313	6.46352	1586	28.2371	6.81073	1586	28.0323	7.1247
1588	28.6913	6.28815	1588	28.4054	6.61	1588	28.2029	6.91
1590	29.0542	6.12184	1590	28.7759	6.42843	1590	28.5771	6.71041
1592	29.0086	5.97287	1592	28.7384	6.25911	1592	28.542	6.52423
1594	29.1027	5.83365	1594	28.8398	6.1025	1594	28.6468	6.35296
1596	29.3487	5.7	1596	29.0922	5.95743	1596	28.9029	6.19544
1598	29.7275	5.58545	1598	29.4764	5.82722	1598	29.2908	6.05462
1600	29.6222	4.07951	1600	29.3779	4.38129	1600	29.1953	4.67208

Comparison between gain and noise figure versus wavelength for different bidirectional pump powers for 16 m EDF length and 13 m passive EDF length for triple pass EDFA with passive EDFA.

Fc-xsec.crs / Setup 2 Forward pump power Pin (-30 dBm) & L (23 & 12m)								
Pump power (225)mW			Pump power (150)mW			Pump power (100)mW		
NM	G (dB)	NF (dB)	NM	G (dB)	NF (dB)	NM	G (dB)	NF (dB)
1570	38.1445	6.25275	1570	35.8125	6.45	1570	32.2487	7.00233
1572	37.496	6.0382	1572	35.4435	6.13849	1572	32.2766	6.47067
1574	36.7559	5.87598	1574	34.9328	5.91471	1574	32.1001	6.10312
1576	36.3739	5.72044	1576	34.7138	5.72	1576	32.1241	5.81904
1578	36.1094	5.57897	1578	34.5801	5.55513	1578	32.1879	5.59204
1580	36.0783	5.43982	1580	34.6495	5.39981	1580	32.4111	5.39532
1582	35.8596	5.33	1582	34.5252	5.27758	1582	32.4312	5.24496
1584	36.1496	5.19838	1584	34.877	5.14105	1584	32.8792	5.08873
1586	36.6379	5.07226	1586	35.4108	5.01073	1586	33.4846	4.94491
1588	36.8733	4.97079	1588	35.6949	4.90689	1588	33.8447	4.83215
1590	37.3706	4.86481	1590	36.2267	4.8	1590	34.4309	4.71905
1592	37.3319	4.79011	1592	36.237	4.72	1592	34.5169	4.64067
1594	37.4731	4.71347	1594	36.4162	4.64872	1594	34.7553	4.56
1596	37.8115	4.635	1596	36.7823	4.57117	1596	35.165	4.48432
1598	38.3231	4.56	1598	37.3133	4.49876	1598	35.727	4.41209
1600	38.1978	4.32	1600	37.2251	4.37345	1600	35.6961	4.36573

Comparison between gain and noise figure versus wavelength for different forward pump powers for 23 m EDF length and 12 m passive EDF length for triple pass EDFA with passive EDFA.

Fc-xsec.crs / Setup 2 Forward pump power Pin (-20 dBm) & L (16 &12 m)								
Pump power (225)mW			Pump power (150)mW			Pump power (100)mW		
NM	G (dB)	NF (dB)	NM	G (dB)	NF (dB)	NM	G (dB)	NF (dB)
1570	28.7117	7.67231	1570	25.4432	8.18506	1570	21.9229	8.80032
1572	28.2688	7.31895	1572	25.3455	7.71763	1572	22.1886	8.19293
1574	27.7414	7.02926	1574	25.1107	7.34731	1574	22.2646	7.72283
1576	27.4621	6.77459	1576	25.0496	7.03675	1576	22.4369	7.34309
1578	27.2646	6.54802	1578	25.0314	6.76821	1578	22.6113	7.02282
1580	27.237	6.33827	1580	25.1457	6.52605	1580	22.8785	6.74098
1582	27.0708	6.15949	1582	25.1116	6.32185	1582	22.9868	6.50582
1584	27.2801	5.97905	1584	25.4125	6.12058	1584	23.3867	6.27945
1586	27.6362	5.81049	1586	25.8388	5.93484	1586	23.889	6.07317
1588	27.8062	5.66641	1588	26.0809	5.77671	1588	24.2093	5.89835
1590	28.1693	5.52439	1590	26.4983	5.62238	1590	24.6855	5.73
1592	28.1381	5.40973	1592	26.5369	5.49784	1592	24.7994	5.59338
1594	28.2397	5.29883	1594	26.6942	5.37833	1594	25.017	5.46385
1596	28.4867	5.19106	1596	26.9839	5.26292	1596	25.3531	5.33961
1598	28.8609	5.09177	1598	27.3905	5.15675	1598	25.7949	5.22554
1600	28.7673	4.81232	1600	27.3487	4.94707	1600	25.8091	4.84103

Comparison between gain and noise figure versus wavelength for different forward pump powers for 16 m EDF length and 12 m passive EDF length for triple pass EDFA with passive EDFA.