PERFORMANCE ANALYSIS OF ERBIUM DOPED FIBER AMPLIFIER AT 980nm &1480nm PUMPING WAVELENGTHS.

HAUWA IBRAHIM KHALEEL

(SPS/13/MEE/00041)

A Dissertation Submitted to the Department Of Electrical Engineering, Bayero University, Kano, In Partial Fulfilment of the Requirements for the Award of Master Degree in Communications Engineering.

SUPERVISED BY:

PROFESSOR MUHAMMAD AJIYA, MNSE

DECEMBER, 2017

CERTIFICATION

This is to certify that the research work for this dissertation and the subsequent write-up by HAUWA IBRAHIM KHALEEL (SPS/13/MEE/00041) were carried out under my supervision

Signature and date...

Supervisor: Prof. Muhammad Ajiya, MNSE

Signature and date..

Head of department (H.O.D): Dr. Sabo Ibrahim Birnin Kudu

APPROVAL

This dissertation has been examined and approved for the award of masters in communications engineering.

Signature and date: ....

External examiner:

Signature and date: ....

Internal examiner:

Signature and date: ....

Supervisor: Prof. Muhammad Ajiya, MNSE

Signature and date: ....

Head of Department: Dr. Sabo Ibrahim Birnin Kudu

Signature and date: ....

Representative of the Board of the School of Post Graduate Studies

ACKNOWLEDGMENT

All praises are due to Allah The Almighty, The Lord of all that exists. May Allah's peace and blessings be upon His final Prophet and Messenger, Muhammad, his family and his companions

I am most grateful to the Almighty for the gift of life and many opportunities. He brought down all mountains in the way through my study of engineering.

My most profound appreciation goes to my ever supportive parents: Engr. I.K Inuwa FNSE, OFR, FAEng and Haj Amina Khaleel Inuwa for their moral support throughout the course of my study, jazakumullah khair. I pray to Allah the Almighty that He grants them Al jannatul firdaus.

I wish to specially acknowledge all the Staff of Electrical Engineering Department especially my able supervisor Engr. Prof. Muhammd Ajiya, MNSE for his patience and guide throughout the course of my thesis. I am grateful to all my colleagues for their support especially Abdulhakim Kabir, Yunusa Muhammad and Abduljalil Alao.

A special recognition of moral support to my gentle man, Mallam Tukur Sani Bunza, My beautiful daughters; Narjis and Nukhayla- the best reward in this world and in the hereafter, for having supported in every way possible.

I appreciate my siblings; Zainab, Umar, Aisha, Amina, Muhammad, Saadatu, Bilqees & Zainab for their unconditional love and support.

DEDICATION

I dedicate this research dissertation to my number one gentleman Mallam Tukur Sani Bunza, may Allah (S.W.A) grant him the best of both worlds, Ameen.

TABLE OF CONTENT: Page No:

Chapter one: Introduction

Chapter Two: Literature review

Chapter three: Methodology

ABSTRACT

Erbium Doped Fibre Amplifiers are used to provide amplification in long distance optical communication with fibre loss less than 0.2dB/Km by providing amplification in the long wavelength window near 1550nm.The performance of Erbium Doped Fibre Amplifier (EDFA) is dependent on numerous parameters which include Erbium ion doping concentration, pumping wavelength, fibre length and pumping power. EDFA basic says when an optical signal such as 1550nm wavelength signal enters the EDFA from input, the signal is combined with a pumping wavelength pump laser through a wavelength division multiplexer device. The input signal and pump laser signal pass through fibre doped with erbium ions. Here the 1550nm signal is amplified through interaction with doped erbium ions. Presently, the EDFA is being pumped by two pumping wavelengths of 980nm and 1480nm. The aim of this study were to analyse and validate performance of EDFA at 980nm and 1480nm pumping wavelengths. Subsequent to this, pumping wavelengths were chosen arbitrarily. In this study, it is clearly indicated that pump power applied to EDFA sharply reduces due to absorption in the erbium doped fibre, therefore there is strong dependence of gain and noise figure on the fibre length, pumping power and signal input power. The gain varies along the fibre length due to the pump power variation. This design gives comparison of the two pumping wavelengths i.e 980nm and 1480nm based on Gain and Noise Figure (NF) at different pump powers (15,50,100,150mW) and at different fibre lengths (10,50,100,150km). The operation is at a single channel in C-band, 1550nm wavelength, input power of -40dB , Er^{+3} ion density of $1^{+025}m^{-3}$. It is found that minimum NF occurs for 980nm pumping wavelength and high gain occurred at 1480nm pumping wavelength, this shows a trade-off. It is also seen that fibre length is proportional to pump power and when it is increased, the pump power should equally be increased in order to achieve high gain and minimum NF at a constant Er^{+3} ion density. The system is simulated on Opti- system software.

LIST OF FIGURES

LIST OF TABLES

CHAPTER ONE

INTRODUCTION

l.1 Background

Optical fiber communication is seen as one of the most reliable, fast and secure telecommunication technologies to achieve consumer needs for present and future applications. Optical Fiber communication has grown in importance exponentially in the present modern era. It is reliable in handling and transmitting data through hundreds of kilometers with an acceptable bit error rate which is 10^{-9} [1].

In traditional long-distance optical fiber communication systems, compensation of losses is usually accomplished by using electronic regenerators in which the optical signals are first converted into electrical signals, then processed and amplified in the electrical domain, and then reconverted into optical signals. Optical amplifiers play an exceptionally important role in long haul networks. Prior to the advent of optical amplifiers, the standard way of coping with the attenuation of light signals along a fiber span was to periodically space electronic regenerators along the line. Such regenerators consist of a photo-detector to detect the weak incoming light, electronic amplifiers, timing circuitry to maintain the timing of the signals, and a laser along with its driver to launch the signal along the next span. Such regenerators are limited by the speed of their electronic components. Thus, even though fiber systems have inherently large transmission capacities and bandwidths, due to their optical nature, they are limited by electronic regenerators in the event such regenerators are employed. Optical fiber amplifiers, on the other hand, are purely optical in nature and require no high-speed circuitry. The signal is not detected then regenerated; rather, it is simply optically amplified in strength by several orders of magnitude as it traverses the amplifier, without being limited by any electronic bandwidth. The shift from regenerators to amplifiers thus permits a dramatic increase in capacity of the transmission system. In addition, well-engineered amplified links can be upgraded in terms of bit rate from the terminal end alone, reusing the undersea cable and amplifiers. Since the introduction of optical amplifiers, rapid progress has been made in increasing the capacity of systems using such amplifiers. [3].

Whenever the system limitation is due to insufficient optical power, amplification of the signal and optical amplifiers can indeed perform this job. Optical amplifiers are devices that amplify the incoming optical signals in the optical domain itself without any conversion to the electrical domain; these devices have truly revolutionized long-distance fiber optic communications. Compared with electronic regenerators, optical amplifiers do not need any high-speed electronic circuitry, are transparent to bit rate and format, and most importantly can amplify multiple optical signals at different wavelengths simultaneously. Thus, their development has ushered in the tremendous growth of communication capacity using wavelength division multiplexing (WDM) in which multiple wavelengths carrying independent signals are propagated through the same single-mode fiber, thus multiplying the capacity of the link. Of course, compared with electronic regenerators, they have some drawbacks too: They add noise to the optical signal. [2]

The emergence of the fiber amplifier foreshadows the invention and development of further guided wave devices that should play a major role in the continuing increase in transmission capacity and functionality of fiber networks. [1]

Optical amplifiers can be used at many points in a communication link. Figure 1.1 shows some typical examples. A booster amplifier is used to boost the power of the transmitter before launching into the fiber link. The increased transmitter power can be used to attain longer reach in a link. The preamplifier placed just before the receiver is used to increase the receiver sensitivity. In-line amplifiers are used at intermediate points in the link to overcome fiber transmission and other losses. Optical amplifiers can also be used for overcoming splitter losses, for example, for distribution of cable televisions.

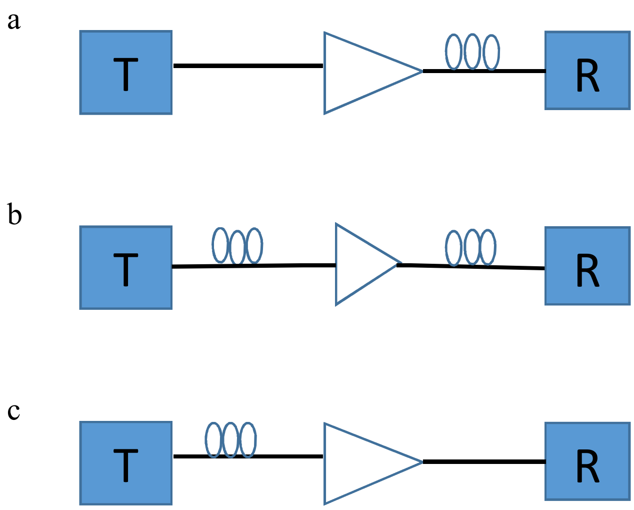


Figure 1.1 :Optical amplifiers in different forms: a-for boosting the transmitter power (booster amplifier), b-for use along the link (In line amplifier) and c-for use before the receiver (pre-amplifier). T- transmitter, R-receiver.

EDFAs can operate in a broad range within the 1550nm window at which the attenuation of silica fiber is minimum and therefore it is ideal for optical fiber communication systems operating at this wavelength range. According to the research performed in recent years, it is known that the pumping of erbium doped fiber at 980nm or 1480nm is the most efficient way [4].

The three main types of optical amplifiers are the Doped fiber amplifier, the Raman fiber amplifier (RFA), and the semi- conductor optical amplifier (SOA). Today, most optical fiber communication systems use EDFAs because of their advantages in terms of bandwidth, high power output, and noise characteristics. RFAs and SOAs are also becoming important in many applications [2].

In order to prevent signal degradation over long distance communication we need an optical amplifier with good gain and flat gain bandwidth. Thus Erbium Doped Fiber Amplifiers come into play. EDFA's have the major advantage of being optical amplifiers, with no conversion of the optical signal into electrical signal [7]. The erbium-doped fiber amplifier is emerging as a major enabler in the development of worldwide fiber-optic networks.

The purpose of this research is to investigate the performance of the erbium doped fiber amplifier under different pumping wavelengths (980nm and 1480nm) using forward pumping scheme, single mode fiber (SMF), various fiber lengths and pumping powers.

1.2 Problem statement

Erbium Doped Fiber Amplifier (EDFA) is the most prominent and adopted optical amplifier used in 1550nm low-loss window of the C-band. However, it is being pumped currently by two pumping wavelengths; 980nm and 1480nm. These pumping wavelengths each have its pros and cons that are still not clear.

1.3 Motivation

There is no distinct performance difference in the application of the two pumping wavelengths adapted for the excitation of the erbium ions in the Erbium doped fiber. To investigate and evaluate any difference in the performance parameters is the motivation to undertake the research/study.

1.4 Scope of the Work

In this Erbium doped fiber amplifier gain and noise figure analysis, simulation approach is used. The software used is Opti-system software. It is a comprehensive optical communications package developed by Opti-wave, Inc, USA.

1.4 Research Aim & Objectives

The aim of this research is to analyze and validate the performance of 980nm and 1480nm pumping wavelengths on EDFA.

The objectives of this research includes

1) Develop the simulation set-up in optisystem
2) Generation of EDF amplification scheme to obtain:
    a. Gain and
    b. Noise figure
3) Analyze and compare the two different pumping wavelengths, for:

a. Single mode fiber
b. Varying pumping power.
c. Varying fiber lengths.

1.5 Structure of the Thesis

This thesis deals with the simulation research work on analysis and comparison of 980nm and 1480nm pumps based on Erbium doped fiber amplification gain and noise figure. The simulation is carried out using Optiwave optisystem optical simulation software. There are basically five chapters in this report, with each contents briefed below:

In the first chapter, the general layout of the project has been presented. It has the background as well as introduction to Optical communications. The problem statement, scope, aims & objectives of the project are stated clearly in this chapter.

Chapter two deals with the literature review of optical amplifiers. Theory of Erbium doped fiber amplifiers is discussed. Gain and noise figure of the amplifier for varying pump power, fiber lengths and different fiber types is analyzed.

Chapter three discusses the methodology of the project. It discusses the operation of the EDFA used in this thesis. The component details and specification are discussed in this chapter. Varying pump power, fiber lengths and different fiber types are stated as the input parameters in this chapter.

Chapter four present the results of simulation using Optiwave optisystem version 7.0 optical system software. Performance analysis is presented through graphs plotted using Optiwave software with the results obtained from simulation. Summarized results of all the analysis is presented in this chapter.

Chapter five concludes the research findings for the simulation. It makes provision for future research and further development.

CHAPTER TWO

THEORY AND REVIEW OF RELATED STUDY

2.1 Introduction

Signals in optical communications network travelled through fibers for very large distances with insignificant attenuation. When these distances become hundreds of kilometers, amplification of the signal is required .Optical fiber amplifiers provide in-line amplifications of optical signals by effecting stimulated emission of photons by rare earth ion implanted in the core of the optical fiber. EDFAs are used to provide amplification in long distance optical communication with fiber loss less than 0.2dB/Km by providing amplification in the long wavelength window near 1550nm. [4]. Compared with electronic regenerators, optical amplifiers do not need any high-speed electronic circuitry, are transparent to bit rate and format, and most importantly can amplify multiple optical signals at different wavelengths simultaneously.

Thus, their development has ushered in the tremendous growth of communication capacity using wavelength division multiplexing (WDM) in which multiple wavelengths carrying independent signals are propagated through the same single-mode fiber, thus multiplying the capacity of the link. Of course, compared with electronic regenerators, they have some drawbacks too: They do not compensate for dispersion accumulated in the link and also add noise to the optical signal. This noise leads to a maximum number of amplifiers that can be cascaded so that the received signal-to-noise ratio (SNR) is within the limits. Optical amplifiers can be used at many points in a communication link. [3]

2.2 Uses of Optical Amplifiers

Optical amplifiers can be used at many points in a communication link. A booster amplifier is used to boost the power of the transmitter before launching into the fiber link. The increased transmitter power can be used to attain longer reach in a link. The preamplifier placed just before the receiver is used to increase the receiver sensitivity. In-line amplifiers are used at intermediate points in the link to overcome fiber transmission and other losses. Optical amplifiers can also be used for overcoming splitter losses, for example, for distribution of cable televisions.

The three main types of optical amplifiers are the erbium-doped fiber amplifier (EDFA), the Raman fiber amplifier (RFA), and the semi- conductor optical amplifier (SOA). Today, most optical fiber communication systems use EDFAs because of their advantages in terms of bandwidth, high power output, and noise characteristics. RFAs and SOAs are also becoming important in many applications. In the following it is a basic introduction to the characteristics of EDFAs; detailed discussions on EDFAs can be found in many texts [1]

2.3 Comparison of Optical Amplifier Devices

Various optical amplifiers have been proposed and characterized since the advent of optical communications. The ideal goal is to have an amplifier that has a very large bandwidth, high, polarization independent gain with modest power requirements, and that adds no noise to the actual signal or signals. Of course, the ideal amplifier does not exist, although the erbium-doped fiber amplifier comes close. A brief detour here to compare the most prevalent optical amplifiers to date, in particular from the point of view of their noise performances.

2.3.1 Raman Fiber Amplifier (RFA)

In Raman scattering a photon is annihilated to create an optical phonon and a lower frequency photon (Stokes photon). For sufficiently high optical powers, the process becomes stimulated (stimulated Raman scattering or SRS), and optical gain is generated at the Stokes frequency. In Raman amplifiers utilizing silica fiber, the Stokes shift between the pump and the signal frequency where gain occurs is approximately 15 THz. Since the gain peak can be shifted by varying the center wavelength of the pump, a Raman amplifier is tunable. The gain is proportional to the pump power, so that gain flatness to the extent of the gain width of the optical phonon band can be ensured. The noise for a Raman amplifier is derived from an equivalent n_{sp}, given by [19]

$$n_{sp} = \quad 1/ (1- \quad e^{-h\nu s} /kT) \qquad 2.1$$

where Vs is the Stokes shift. [18] Typically, hvs »kT so that Usp ≃ 1 and the noise is close to the quantum limit. The pump powers needed for Raman amplifiers are quite high, on the order of 0.5W to 1W. In addition, Raman amplifiers can exhibit large crosstalk between different wavelength signals, via gain saturation, which, in contrast to erbium-doped fiber amplifiers, is not damped by a slow population response time. Raman amplifiers, in particular for 1.3 /µm amplification purposes, have recently witnessed a resurgence of interest with the advent of high-power solid state laser pump sources. [19, 20]

2.3.2 Brillouin Amplifiers

Brillouin amplifiers are analogous to Raman amplifiers with the difference that acoustical phonons are involved in the gain process [21]. In the case of Brillouin amplifiers, the Stokes wave propagates backward. The Stokes shift for Brillouin scattering is typically very small ≃ 11 GHz in silica fiber. Therefore, using equation 2.1, the spontaneous emission factor n_{sp} is large, about 500. The Brillouin gain bandwidth is only about 20 MHz, which makes Brillouin amplifiers attractive for narrowband selective amplification but, because of the poor noise performance, Brillouin amplifiers have not found wide use in communication applications.[22] As with Raman amplifiers, Brillouin amplifiers are tunable via the pump wavelength. The threshold power for stimulated Brillouin scattering is only a few mW in single-mode fiber and is one of the main effects that limit the usable optical power in communication systems.

2.3.3 Semiconductor Optical Amplifier (SOA)

Semiconductor laser amplifiers have the advantage that they can be directly pumped electrically and require very low electrical pump power. Semiconductor laser amplifiers were the optical amplifiers of choice prior to erbium-doped fiber amplifiers, and much of the early research done on optically amplified systems was performed with semiconductor laser amplifiers. Some of the basic results concerning spontaneous emission noise derived for the fiber amplifier remain valid for semiconductor amplifiers.[15, 23, 24] Semiconductor laser amplifiers can be fabricated at most of the wavelengths of interest (1.5 /µm and 1.3 /µm). The bandwidth of semiconductor laser amplifiers is very large, and they have large small signal gains. The intrinsic noise performance of semiconductor laser amplifiers is quite good. However, they suffer from coupling loss to the adjoining fiber transmission line. This coupling problem is a technically difficult problem; it impairs the gain and noise figure and adds components that are not necessary with fiber amplifiers. For a semiconductor laser amplifier, typically $n_{sp} \simeq 2$ and is wavelength dependent. Polarization sensitivity is also an issue. Another drawback of semiconductor laser amplifiers is multi-wavelength crosstalk. It has been shown that four-wave mixing is a particularly strong effect in semiconductor laser amplifiers and gives rise to large inter-signal modulation and information distortion, unless the wavelengths are separated by unreasonably large frequency gaps. This restricts the information-carrying capacity in wavelength division multiplexed systems. Crosstalk from gain saturation is also a concern for these amplifiers. The carrier lifetime in an typical semiconductor laser amplifier is a few ns (compared to 10ms in erbium-doped fiber amplifiers), which results in crosstalk that extends to several 100 MHz through cross-channel gain saturation. The short lifetime also results in pulse distortion when the amplifier is operated in deep gain saturation.

2.3.4 Erbium Doped Fiber Amplifier (EDFA)

Historical Development of Erbium-Doped Fiber Amplifiers

The basic concept of a traveling wave optical amplifier was first introduced in 1962 by Geusic and Scovil. Shortly thereafter, optical fiber amplifiers were invented in 1964 by E. Snitzer, then at the American Optical Company. Demonstrated a neodymium doped fiber amplifier at 1.06/µm. The fiber had a core of 10 /µm with a 0.75 to 1.5 mm cladding, a typical length of 1 m, and was wrapped around a flash-lamp that excited the neodymium ions. The fiber ends were polished at an angle to prevent laser oscillation, a technique that was used again by workers in the field more than twenty years later. Application to communications, and the appearance of noise from spontaneous emission, was mentioned by Snitzer in the conclusion of his paper. This work laid dormant for many years thereafter. It emerged as an exceedingly relevant technological innovation after the advent of silica glass fibers for telecommunications. Snitzer also demonstrated the first erbium-doped glass laser. [36].

EDFA Architecture

An optical fiber consists of a doped fiber, one or more pump lasers, a passive wavelength coupler, optical isolators and tap couplers. The wavelength selective coupler couples both the pump and signal optical power efficiently into the fiber amplifier. The tap couplers are wavelength insensitive and are generally used on both sides of amplifier to compare the incoming signal with the amplifier output. The optical isolators stop the amplified signal from bouncing back into device which results in increase in amplifier noise and decreases its efficiency. Typically, the EDFA configuration can be categorized by pumping schemes into three particular arrangements. These schemes are forward-pumped (co-pumped), Backward-pumped (counter-pumped) and Bi-directional pumped (Dual-pumped). Gain through population inversion is achieved when pumping is done at a suitable wavelength. The gain spectrum is dependent on the pumping scheme as well as presence of other dopants, such as germanium, and alumina within the fiber core [1].

For co-pumped, the pump and input signals co-propagate in same direction inside the fiber core The input signal and the pump are mixed by a pump combiner or a wavelength selective coupler. The input signal absorbs the pump energy and is therefore amplified at the output of the amplifier. Isolators are used to ensure no feedback of signal occurs by making sure the signal travel in only one direction.

For counter-pumping, the input signal and pump signal propagate in opposite direction inside the fiber.

Erbium doped fiber is a conventional silica fiber heavily doped with active erbium ions as the gain medium. Erbium ions ($Er3+$) are having the optical fluorescent properties that are suitable for the optical amplification. There are practically two wavelength widows C-Band (1530nm-1560nm) and L-Band (1560nm-1600nm). EDFA can amplify a wide wavelength range (1500nm-1600nm) simultaneously, hence is very useful in wavelength division multiplexing for amplification. EDFA basic says when an optical signal such as 1550nm wavelength signal enters the EDFA from input the signal is combined with a 980nm or 1480nm pump laser through a wavelength division multiplexer device. The input signal and pump laser signal pass through fiber doped with erbium ions. Here the 1550nm signal is amplified through interaction with doped erbium ions [37].

The erbium-doped fiber amplifier has a theoretical quantum limited noise figure due to spontaneous emission. This noise figure of 3 dB has been achieved experimentally, although realistic values lie in the range of 3.5 to 6 dB. The gains accomplished with the erbium-doped amplifier are extremely high. Gains of up to 45 dB have been achieved with two-stage erbium-doped fiber amplifiers [4].

However, the erbium-doped fiber amplifier exhibits some very slight polarization sensitivity, which can be a factor in system performance when many (e.g., hundreds of) amplifiers are cascaded in series. The saturation characteristics are very good, because the saturation power can be linearly increased with the pump power. The long 10ms upper-state lifetime is unique to E^{+3} and dramatically distinguishes the erbium-doped fiber amplifier from all the other amplifiers. It is responsible for several of the key advantages of the erbium-doped fiber amplifier. Because the upper state can integrate the pump power for such long time, the pump power required to store sufficient energy in the amplifier is typically very low $\simeq$ 10 mW to 20 mW for a 30 dB small signal gain. For signals at different wavelengths, multichannel crosstalk in the amplifier is also very low due to the long upper-state lifetime, which ensures that the population in the upper state cannot respond to fast signal changes that would other- wise be carried over to another signal via the population inversion. For the same reason, the erbium-doped fiber amplifier is still a non-distorting amplifier even when operating deep in saturation. Obviously, the erbium-doped fiber amplifier can obviously easily be integrated in a fiber network since it is already a silica-based fiber component. The major drawback of the erbium-doped fiber amplifier is that the gain spectrum is not inherently flat but peaked, so the gain is not equal at different wavelengths [3].

An EDFA consists of a short piece of erbium doped fiber that is pumped by 980nm or 1480nm laser diode through a WDM coupler. Signals around 1550nm wavelength get amplified as they propagate through the pumped doped fiber [3] as depicted in figure 2.1

Figure 2.1 below shows amplification principle in an EDFA.

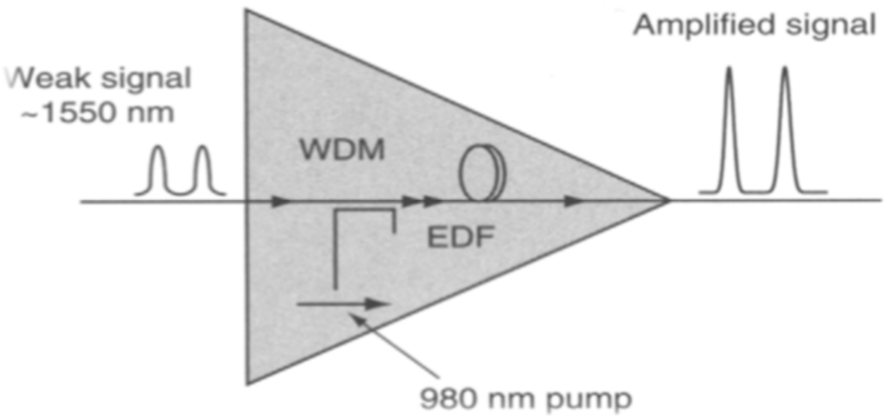


Figure 2.1: Amplification Principle in EDFA

Amplification Principle of Erbium Doped Fiber Amplifier

Optical amplification by EDFA is based on the process of stimulated emission, which is the basic principle behind laser operation. In fact, a laser without any optical feedback is just an optical amplifier. Figure 2.2 shows two levels of an atomic system: the ground level with energy E1 and an excited level with energy E2. Under thermal equilibrium, most of the atoms are in the ground level. Thus, if light corresponding to an appropriate frequency (v -- (E2 - E1)/h, h being Planck's constant) falls on this collection of atoms, then it will result in a greater number of absorptions than stimulated emissions and the light beam suffers attenuation. On the other hand, if the number of atoms in the upper level could be made more than those in the lower level, then an incident light beam at the appropriate frequency could induce more stimulated emissions than absorptions, thus leading to optical amplification.

Figure 2.2 shows schematic representation of signal attenuation and amplification. Under thermal equilibrium, the lower levels are more populated than the upper levels, which leads to absorption of an incoming beam. On the other hand, if the upper level has greater population than the lower level, then optical amplification can take place. [3]

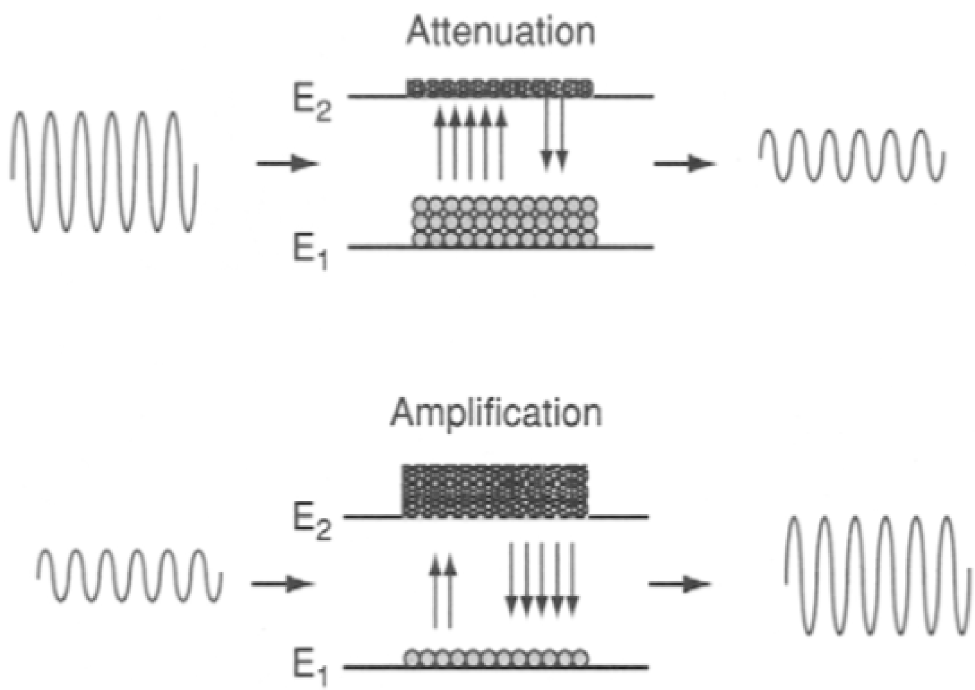


Figure 2.2: Amplification process in an EDFA.

Figure 2.3 shows the three lowest lying energy levels of erbium ion in silica matrix. A pump laser at 980 nm excites the erbium ions from the ground state to the level marked E3. The E3 level is a short- lived level, and the ions fall back to the level marked E2 after less than a microsecond. The life-time of level E2 is much larger and is about 12ms. Hence, ions brought to level E2 stay there for a long time. [3]

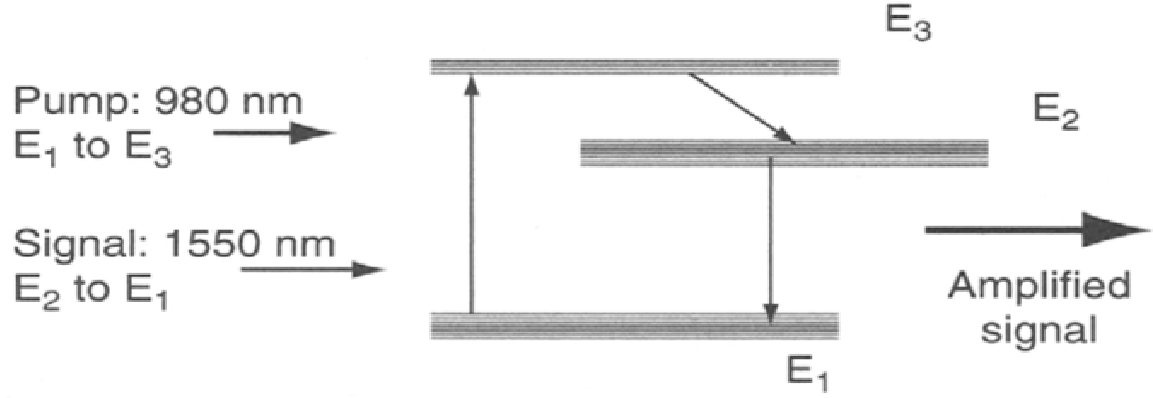


Figure 2.3: Principle of Amplification in an EDFA [3]

Thus, by pumping hard enough, the population of ions in the E2 level can be made larger than the population of E1 level and thus achieve population inversion between the E1 and E2 levels. In such a situation, a light beam at a frequency v0--(E2- E1)/h incident on the collection of erbium ions gets amplified. For erbium ions, the frequency v0 falls in the 1550-nm band and thus is an ideal amplifier for signals in the 1550-nm window, which is the lowest-loss window of silica-based optical fibers. In the case of erbium ions in a silica matrix, the energy levels are not sharp but are broadened due to interaction with other ions in the silica matrix. Hence, the system is capable of amplifying optical signals over a band of wavelengths. [3]

Population Inversion and optical amplification

If N1 is the number of erbium ions per unit volume in the ground level and if light of intensity Iv at a frequency v interacts with the ions, then the number of absorptions per unit time per unit volume from level E1 to E2 can be written as [3]

$$\frac{dN1}{dt} = -\sigma a\ (\upsilon)\ \frac{I\upsilon}{hv} N1 \qquad (2.1)$$

where σa is called the absorption cross-section (has dimensions of area) and is a function of the frequency. Similarly, if N2 is the number of ions per unit volume in the level E2, then the number of stimulated emissions per unit volume per unit time from level E2 to E1 can be written as [3]

$$\frac{dN2}{dt} = -\sigma e\ (\upsilon)\ \frac{I\upsilon}{hv} N2 \qquad (2.2)$$

where σe is called the emission cross section. The absorption and emission cross sections depend on the specific ion as well as on the pair of levels for a given ion. Similarly, an atom in the excited state E2 can emit a photon spontaneously and get de-excited to the level El. The number of such emissions per unit volume per unit time is given by [3]

$$\frac{dN2}{dt} = -\frac{N2}{tsp} \qquad (2.3)$$

where tsp is called the spontaneous lifetime of the level E2.

Consider the propagation of a light beam as depicted in figure 2.4 at frequency v through a collection of these ions. Let Iv(z) be the intensity of the light beam at the plane PI (of cross-sectional area S) and let Iv (z + z) be the intensity of the light beam on the plane P2

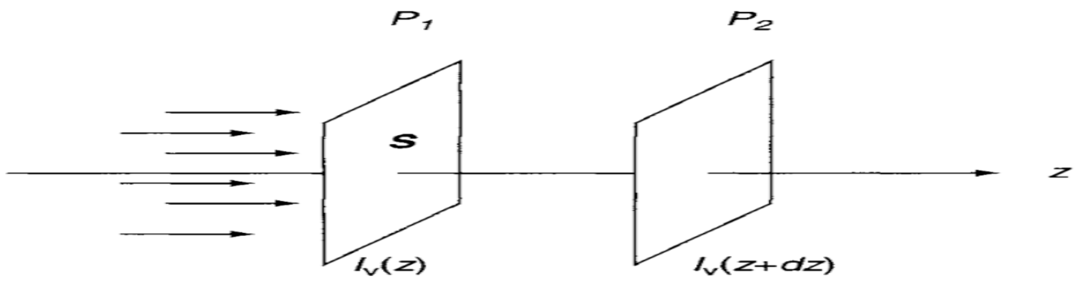


Figure 2.4: Principle of light beam propagation

Source: [3]

The intensity of the propagating light beam changes due to absorption and stimulated emission. The difference in energy entering and leaving the volume lying between planes P1 and P2 must be due to the above processes. Thus, we can write [3]

$$Is\ (z)S - Iv\ (z + dz)S = -\frac{dIv}{dz} = (\sigma aN1 - \sigma eN2)IvSdz \tag{2.4}$$

Which gives the following equation for the evolution of light intensity with distance [3]:

$$\frac{dIv}{dz} = -(\sigma aN1 - \sigma eN2)Iv \tag{2.5}$$

Hence, for optical amplification must have o'eN2 > o'aN1. If σa =fie (which is usually the case), then for optical amplification it needs to be N2 > N1, that is, have population inversion. Figure 2.5 shows the spectral variation of absorption and emission cross-sections in the spectral region of 1550 nm of erbium ions in silica matrix. Notice that the absorption and emission spectra are broad, and this is what leads to the broad gain spectrum of EDFAs.

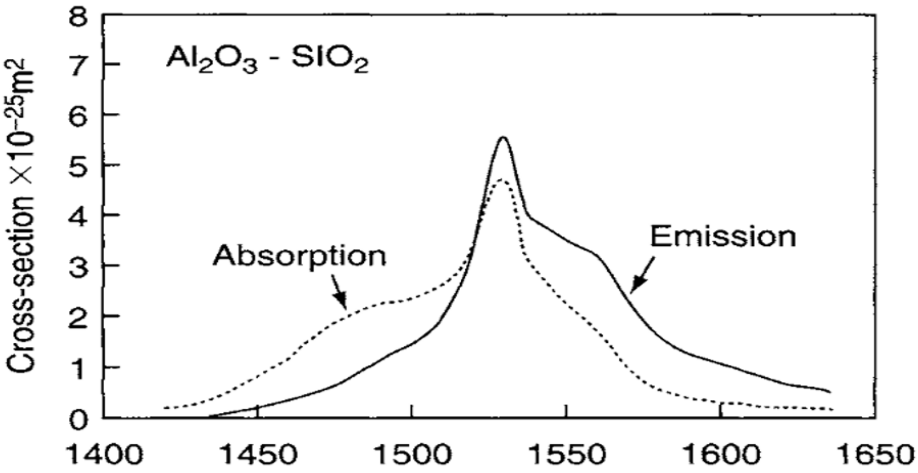


Figure 2.5: Spectral Absorption and Emission Cross Section of EDFA in 1550nm region

©IEEE 2005

Optical Amplification in EDFAs

Now consider the evolution of pump and signal in an erbium-doped fiber. Considering an erbium-doped fiber and let Ip (z) and Is(z) represent the variation of intensity of the pump at frequency Vp (assumed to be at 980 nm) and the signal at frequency Vs assumed to be in the region of 1550 nm. As the beams propagate through the fiber, the pump would induce absorption from E1 to E3, whereas the signal would induce absorption and stimulated emissions between levels E2 and El. The population of the various levels would depend on the fiber length, that is, z, because the intensities of the beams would be z dependent. Assume that the lifetime of level E3 is very small so that neglecting the population density N3 of level E3 and put N3 = 0. Thus, the ions are either in level E1 or in level E2. Now write the rate of change of population of level E2 as [3]:

$$\frac{dN1}{dt} = -\frac{N2}{tsp} + \frac{\sigma paIp}{hvp}N1 - (\sigma seN2 - \ \sigma saN1)\frac{Is}{hvs} \qquad (2.6)$$

The various terms on the right-hand side of the above equation correspond to the following: term 1, spontaneous emission; term 2, pump absorption; and term 3, absorption and stimulated emission due to signal. Subscripts p and s correspond to pump and signal, respectively. Neglecting the population of level E3, gives [3]:

$$\frac{dN1}{dt} = -\frac{dN2}{dt} \tag{2.7}$$

The pump and signal intensity variations with z are caused due to absorption and stimulated emission and can be described by the following equations [3]:

$$\frac{dIp}{dz} = -\sigma paN1\mathrm{I}p \tag{2.8}$$

$$\frac{dIs}{dz} = -(\sigma paN1 - \sigma seN2)Is \tag{2.9}$$

In the case of optical fibers, because the pump and signal beams propagate in the form of modes, we should describe amplification in terms of powers rather than in terms of intensities. The optical powers at the pump and signal are given by [3]:

$$Pp, s\ (z, t) \int Ip, s\ (r, z, t) 2\pi r\ dr \tag{2.10}$$

EDFA Power Conversion Efficiency and Gain

The energy conversation and gain of the EDFA set the upper limits on what is available from the amplifier based on the pump and signal wavelength and strength. The gain is actually limited by several physical effects such as the limit due to energy conversion principle and the finite number or erbium ions existing in the medium. In practice, EDFA gain properties are also limited by commonly called second-order effects including pimp excited-state absorption (ESA), self-saturation by amplified spontaneous emission (ASE), concatenation quenching and inhomogenous broadening. It is clearly known that the pump conversion to signal is always less than one. Therefore, the power conversion efficiency can be obtained from energy conversation as shown in equation [38]:

$$P_{s,out} \leq P_{s,in} + (\lambda_p/\lambda_s)P_{p,in} \tag{2.11}$$

Where, $P_{s,out}$, $P_{s,in}$ and $P_{p,in}$ are the output power, input power of signal and pump power respectively. Then λ_p *and* λ_s are pump and signal wavelengths.

The power conversion efficiency (PCE) is shown [38]

$$PCE = (P_{s,out} - P_{s,in})/\, P_{p,in} \leq (\lambda_p/\lambda_s) \leq 1 \tag{2.12}$$

The quantum conversion efficiency (QCE) can be obtained as shown in equation

$$QCE = (\lambda_p/\lambda_s)PCE \tag{2.13}$$

The gain is given as shown in equation [38]

$$G = P_{s,out}/P_{s,in} \leq (\lambda_p/\lambda_s)P_{p,in}/P_{s,in} \tag{2.14}$$

The maximum possible gain is the obtained as shown in equation [38]

$$G = P_{s,out}/P_{s,in} \leq 1 + (\lambda_p/\lambda_s)P_{p,in}/P_{s,in} \tag{2.15}$$

Also, the maximum output power can be given as shown in equation [38]

$$P_{s,out} \leq P_{s,in} + (\lambda_p/\lambda_s)P_{p,in} \tag{2.16}$$

2.4 Review of Erbium Doped Fiber Amplifier/ EDFA pumping Schemes

Carrying capacity of fiber optical communication seems to have undergone rapid growth in the last few years due to the need for very large capacity for data transmission [16]. Commercial systems are now able to transport more than 100 channels over a single fiber with the availability of WDM components [17]. Thus, readily installed systems can be upgraded so many times without the need for a new fiber, making it realistic to build WDM systems that are inexpensive with greater capacity [18]. Optical signal de-multiplexing components with greater values of optical attenuation come into play when the number of channels of such systems are increased. Signals are highly attenuated in long distances as a result of these components, therefore, optical signal amplification is sought to restore the optical power budget. Erbium doped fiber amplifiers are a choice for the signal amplification in wavelength division multiplexing due to their negligible sensitivity to polarization of the signal, low noise and can be relatively simply realized [19].

EDFA consists of a fiber with a silica glass host core doped with active Er ions as the gain medium [32]. The erbium doped fiber is usually pumped by semiconductor lasers at 980nm or 1480nm. The signal is amplified while propagating along a short span of the fiber [21]. A simplified scheme of an EDFA is shown in figure 2.7 [19]

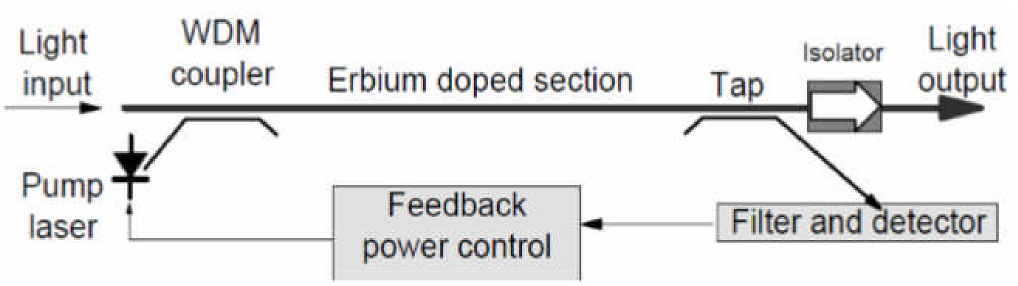


Figure 2.7: Amplification scheme of an EDFA [19]

In the scheme, the amplifier is pumped by a semiconductor laser, which is complemented with a wavelength selective coupler (also known as WDM coupler) that combines the pump laser light with the signal light. The pump light either propagates in same direction as the signal (co-propagation) or in opposite direction (counter-propagation). Optical isolators are used to prevent oscillations and excessive noise due to unwanted reflections [22].

The main condition that should be fulfilled to ensure the optical power transfer to the erbium atoms are to be in the excited state. The excitation is performed using a powerful pumping laser with corresponding radiation wavelength of 980nm or 1480nm. The pump laser diode generates a high-power beam of light at such a wavelength that the erbium ions absorb it and reach excited state, as the photons of the signals meet the excited erbium atoms, the atoms give up a portion of their energy to the signal. Erbium gives up its energy in the form of additional photons with exactly same phase and direction as the signal being amplified. This means signal is amplified along its direction of travel only. Pumping laser power is controlled through a feedback [23]. EDFA can operate in a broad range of the 1550nm [24] window at which the attenuation of silica fiber is minimum and therefore it is ideal for the optical fiber communications systems operating at this wavelength range. Making it very useful in WDM for amplification [25]

It is found that minimum NF occurs for both forward and bidirectional pumping configuration whereas flat gain is obtained using bidirectional pumping configuration [26]. The forward pumping direction provides the lowest NF. In fact, the noise is sensitive to gain and the gain is highest when the input power is lowest. [27]

CHAPTER THREE

METHODOLOGY

3.1 Introduction

This chapter describes the methodology of the C-band single channel EDFA performance analysis. It is divided into three sections; the first section describes the experimental setup and principle of operation of an EDFA. The second section presents the parameters under study (design parameters and performance parameters); on the course of this study the design parameters will be optimized to produce the best performance of the EDFA. The third section deals with all related EDFA components; they are explained in order to have a better understanding of the construction of the EDFAs.

3.2 Simulation set-up

The simulation set up of the C-Band single channel Erbium Doped Fiber Amplifier performance analysis is depicted in Figure 3.1. The set up consists of continuous wave Laser of wavelength 1550nm and pump laser at varying wavelength (of 1480nm and 980nm) and input power of -40dBm. Erbium Doped Fiber Amplifier (EDFA) is fixed at length of 9m, Single mode fiber (SMF) of varying lengths (10km, 50km, 100km &150km), attenuation of 25dB, 16.75ps/nm/km of dispersion and Optical Spectrum Analyzer (OSA) of 0.01nm resolution bandwidth. The circuit is implemented in OPTISYSTEM optical system simulation software. The continuous wave laser with a signal of 1550nm and a pump laser of varying pump powers (15mW, 50mW, 100mW &150mW) and pumping wavelengths (980nm and 1480nm). Both the pump power and continuous laser frequency are passed through co-propagating pump coupler, at whose output an EDFA is attached to amplify the signal before passing through the optical fiber. A dual port wavelength division multiplexer (DWDM) analyzer is connected across the output of the Pump coupler and the optical fiber to detect the gain, noise figure, output signal, output noise and the optical signal to noise ratio (OSNR) of the amplifier. Other output components used are the optical spectrum analyzer and the optical time domain.

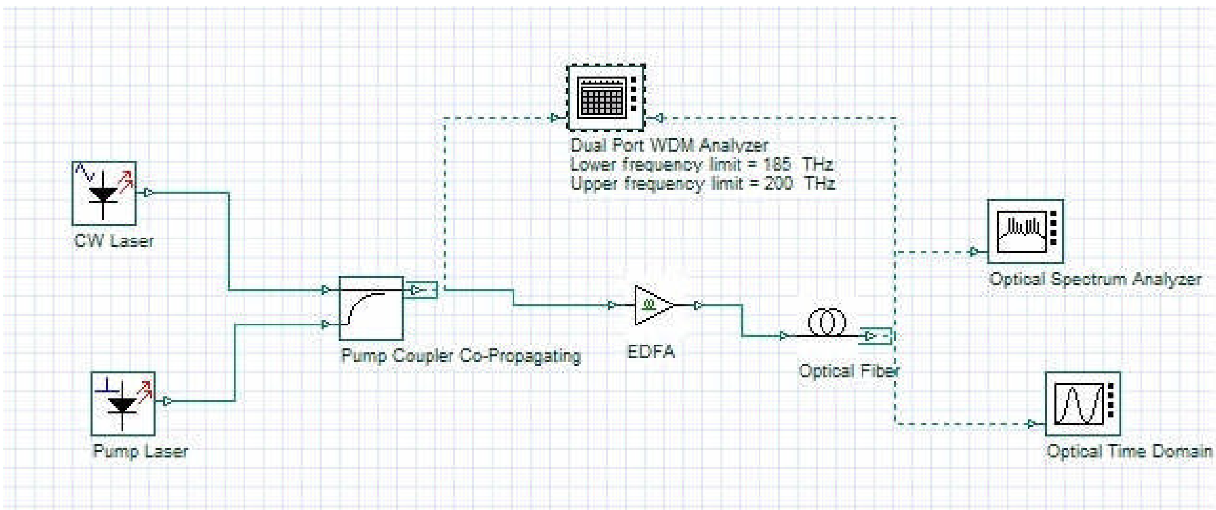


Figure 3.1: EDFA Simulation Set Up in Optisystem

3.3 Principle of Operation

A relatively high-powered beam of light is mixed with the input signal using a wavelength selective coupler. The input signal and the excitation light must be at significantly different wavelengths. The mixed light is guided into a section of fiber with erbium Er^{+3} included in the core. The high-powered light beam excites the Er^{+3} to their higher-energy state. When photons belonging to the signal at a different wavelength (λ_p) from the pump light meet the excited Er^{+3} atoms, the Er^{+3} atoms give up some of their energy to the signal and return to their lower-energy state.

3.4 Components of Erbium Doped Fiber Amplification Scheme

The configuration of this type of fiber laser consist of pump power and continuous wave laser mainly put in place as light source for lasing process to be initiated. The other components used in this research includes co-propagating pump coupler, EDF Amplifier, single mode fiber (SMF), optical spectrum analyzer (OSA), Power meter, WDM analyzer. All the components used here are picked from the components library of optisystem software. The details of the components are discussed in the following subsections.

3.4.1 Continuous wave Laser

Lasers are semiconductors which are used for converting electrical current into light. Lasers are used in optical communication because it has several advantages. One of the most important advantages is that they are small in size and have long life and can be modulated easily. LED diodes are also used but lasers have the following advantages on LED diodes. The speed of laser is faster and provides high bandwidth and also spectral width provided by the laser is narrow as compare to LED [29]. In this research the CW laser with assistance of EDFA as amplifying medium is considered as a tunable laser source that is used as Erbium Doped Fiber pump.

3.4.2 Optical Isolator

Optical isolators are devices that allow light to pass through them in only one direction. This is important in a number of instances to prevent scattered or reflected light from travelling in the reverse direction. One common application of an optical isolator is to keep such light from entering a laser diode and possibly causing instabilities in the optical output.

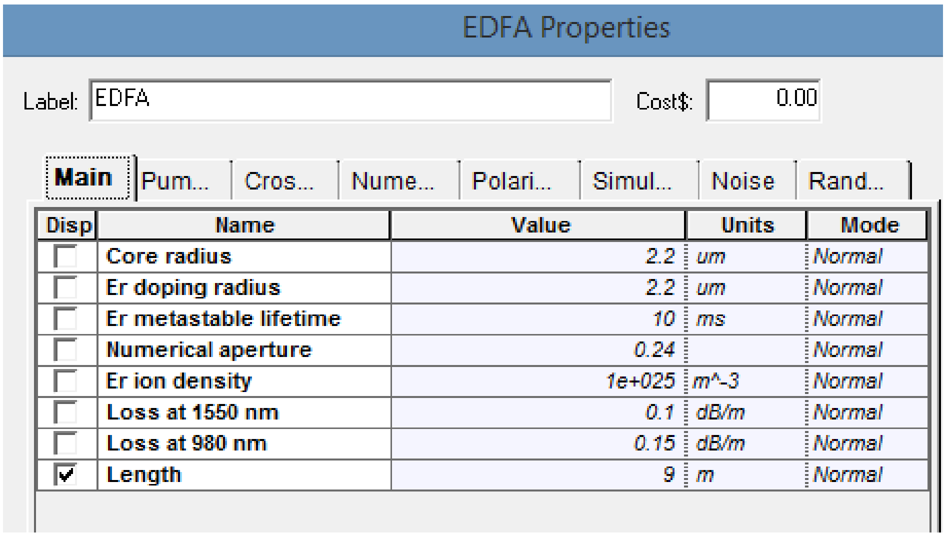
3.4.3 Optical Amplifier

Optical amplifier enables the design of amplifiers, including EDFAs that consider pre-defined operational conditions. This means that expected gain, Noise Figure and amplifier output power can be specified. The amplifier presents the same facilities as a block box model, which enables to select the operation mode with gain control, power control, or to perform simulations under saturated conditions. It defines the expected amplifier performance as well. In this project, the amplifier is operated in expected gain mode i.e. the amplification is taking place by pre-determined the gain of the amplifier.

3.4.3.1 EDFA Properties

The properties of the Erbium doped fiber are set to the values shown in Table 3.1 below. These include fiber core radius, Erbium doping radius, numerical aperture, Erbium ion density, the length of the fiber used and fiber losses at different wavelengths.

Table 3.1: EDFA Properties



EDFA Properties

Label: EDFA   Cost$: 0.00

Main | Pum... | Cros... | Nume... | Polari... | Simul... | Noise | Rand...

Disp	Name	Value	Units	Mode
☐	Core radius	2.2	um	Normal
☐	Er doping radius	2.2	um	Normal
☐	Er metastable lifetime	10	ms	Normal
☐	Numerical aperture	0.24		Normal
☐	Er ion density	1e+025	m^-3	Normal
☐	Loss at 1550 nm	0.1	dB/m	Normal
☐	Loss at 980 nm	0.15	dB/m	Normal
☑	Length	9	m	Normal

3.5 Design Parameters

The design parameters refer to as input parameters of the CW laser and pump laser that alter for the purpose of the analysis. The design parameter considered in this study includes input power, pumping wavelength, pump power and fiber length. The modification of the EDFA as a result of change in any of these parameters result in changing the output performance of the EDFA. The details about these parameters are discussed as follows.

3.5.1 Pump Power

This is a parameter of high importance. It is the energy of the input signal. The pump power gives the signal the strength to travel in the optical fiber. It is directly proportional to the amplifier gain, the higher the pump power, the higher the gain. The signal is always less than the actual input power injected because of pump depletion. The pump source used throughout the whole works of this study was taken from continuous wave laser diodes which its output is amplified by optical amplifier (EDFA).

3.5.2 EDFA Pump Wavelength

EDFA pump wavelength is a very useful parameter in performance analysis of the EDFA. In order to analyze the amplifier, pumping wavelength must be tuned to the one of the current pumping wavelengths; 1480nm or 980nm. Commonly 980nm or 1480nm lasers are used to optically pump Er ions to higher energy bands. The purpose of optical pumping is to achieve population inversion, where there are more ions in higher energy band than there are in the ground energy band. It is necessary for optical gain, otherwise the rate of optical signal photons absorbed by the erbium doped fiber will be greater than the rate generated by simulated emission. The pump wavelength in this study is tuned within the C-band ranges of 1525nm to 1565 nm.

3.5.3 Simulation parameters of SMF

The simulation parameters of the single mode fiber (SMF) are two: attenuation which is constant and length which varies as shown in the Table 3.2 below

Table 3.2: Simulation Parameters of SMF

Parameter	Value
Attenuation	0.2dB/km
Length	10, 50, 100 &150km

3.6 Performance parameters

The performance parameter as discussed earlier is the output parameters used to analyze or measure the performance of the EDFA. In this thesis various performance parameters were considered to evaluate and represent the working conditions pumping wavelengths. The performance parameters are: EDFA gain, gain saturation, pump saturation, saturation output power and Noise figure, output noise, signal and OSNR.

3.6.1 Optical Signal to Noise Ratio (OSNR)

OSNR is the key performance parameters in optical network that predict the bit error rate (BER) of the system. OSNR is measured by comparing the peak power of the generated channels with the highest noise level. The noise power and channel peak power in this study are measured by DWDM analyzer and Optical spectrum analyzer respectively. The OSNR increases as the peak power of the channel increases. The higher the EDFA gain, the lower will be the OSNR and vice versa.

3.6.2 EDFA (small-signal) gain

The gain of an amplifier is defined as the ratio of output signal power to input signal power with the output signal power corrected for the ASE noise of the EDFA. [7]

$$G = (P_{OUT} - P_{ASE}) / P_{in} \quad (3.1)$$

P_{in} and P_{out} are respective input and output signal powers in watts

P_{ASE} is the ASE noise power in watts at the signal wavelength.

However, where the input signal power is sufficiently large, ASE noise adjustment is negligible and can said to be zero.

The small-signal gain region is considered the range of input signal powers where the signal amplification does not significantly reduce the gain of the amplifier. In this situation, it is assumed that the rate of erbium ions excited into the metastable energy level is greater than the rate of stimulated emission. Therefore the gain will remain constant as the input signal is increased.

3.6.3 Gain Saturation

Gain saturation is experienced when the metastable energy level population is severely depleted by a high rate of stimulated emission, as when the input signal power is sufficiently high. For a fixed pump power, the rate of erbium ions excited for population inversion will be constant. As the input signal power is increased past the small-signal gain region, the more photons will enter the erbium-doped fiber stimulating emission of photons and depleting the metastable energy level faster than it can be filled. Therefore, the amplification will reach a limit and the gain will decrease with increasing input signal power.

3.6.4 Saturation output Power

Saturation output power is the output power at which gain has been reduced by 3dB of its small-signal gain. This parameter shows the maximum power capabilities of the EDFA for a fixed pump power, and is an outcome of gain saturation. So as the input power is increased past the small-signal region, the gain will decrease even as the output signal power increases.

3.6.5 Pump Saturation

Pump saturation occurs when the pump power is large enough to significantly deplete the ground energy bond, which reduces the pumping rate of the erbium ions. Gain will increase with pump power, but will flatten out as pump saturation takes over.

3.6.6 Noise Figure

Noise figure quantifies the signal-to-noise ratio degradation experienced by an optical signal passing through the amplifier. The NF will always be greater than 1 since the EDFA adds noise during the amplification process in the form of Amplified Spontaneous Emission (ASE). So the output SNR is always less than the input SNR. In theory, the best NF is achieved by an EDFA is 3dB. [7]

$$NF = SNR_{in} / SNR_{out} \qquad (3.2)$$

CHAPTER FOUR

RESULT AND DISCUSSION

4.1 Introduction

The performance parameters considered in this study includes amplifier gain and Noise figure. The measuring tools used in the simulation includes optical spectrum analyzer, DWDM analyzer and optical time domain visualizer.

In this research, the variation of gain and Noise Figure for EDFA is analyzed by using single pumping (forward pumping) for the current pumping wavelengths (980nm & 1480nm) at a constant Er ion density. The variation of gain and NF is also analyzed for different EDF length (10, 50, 100 &150km) and at different pumping power (15, 50, 100 & 150mW). The length of the EDF depends on the pump power, signal power and the signal and pump wavelengths.

At 1480nm pumping wavelength, it is clear that the output power is increased with increase with increase in pump power as shown in table 4.1.

Table 4.1: Transmitted and Received Power with Different Pump Power at a Fixed Fiber Length of 50km and Pumping Wavelength of 980nm.

Pump power (mW)	Input power (dBm)	Output power (dBm)
15	-40	-11.3644
50	-40	-10.0892
100	-40	-8.82614
150	-40	-7.90834

At 980nm pumping wavelength, it is clear that the output power is increased with increase with increase in pump power as shown in table 4.2

Table 4.2: Transmitted and Received Power with Different Pump Power at a Fixed Fiber Length of 50km and Pumping Wavelength of 1480nm

Pump power (mW)	Input power (dBm)	Output power (dBm)
15	-40	-10.2644
50	-40	-8.31611
100	-40	-6.8307
150	-40	-5.86613

Amplified spontaneous emission (ASE) noise generated during amplification process is added to the signal leading to decrease in signal to noise ratio (SNR) at the amplifier output. SNR reduction from input to output of the amplifier is defined as Noise figure, which is also used for electronic amplifiers. Table 4.3 shows it for 980nm pumping wavelength.

Table 4.3: Transmitted and Received OSNR with Different Amplifier Gain at a Fixed Fiber Length of 50km and Pumping Wavelength of 980nm.

Gain (dB)	Input OSNR (dB)	Output OSNR (dB)
28.640548	60	13.2416
29.915721	60	13.204
31.178773	60	13.1731
32.096574	60	13.1546

Amplified spontaneous emission (ASE) noise generated during amplification process is added to the signal leading to decrease in signal to noise ratio (SNR) at the amplifier output. SNR reduction from input to output of the amplifier is defined as Noise figure, which is also used for electronic amplifiers. Table 4.3 shows it for 1480nm pumping wavelength.

Table 4.4: Transmitted and Received OSNR with Different Amplifier Gain at a Fixed Fiber Length of 50km and Pumping Wavelength of 1480nm.

Gain (dB)	Input OSNR (dB)	Output OSNR (dB)
29.740498	60	13.1561
31.688848	60	12.9986
33.170842	60	12.9029
34.138785	60	12.8635

The graph for output power (dBm) vs. length (km) is depicted in Figure 4.1 which show a drop in the output power as the fiber length is increased for the pumping wavelengths, 980nm and 1480nm. The resultant output power for λ_p=1480nm ranges from 2.13396dBm to -30.2644dBm while that for λ_p=980nm ranges from 0.0917159dBm to -31.3644dBm. Thus, it can be said that λ_p=1480nm has a higher output power for corresponding pump powers and fiber lengths since its peak value is higher than that of 980nm by 95.7020% and the least value by 3.5072% .

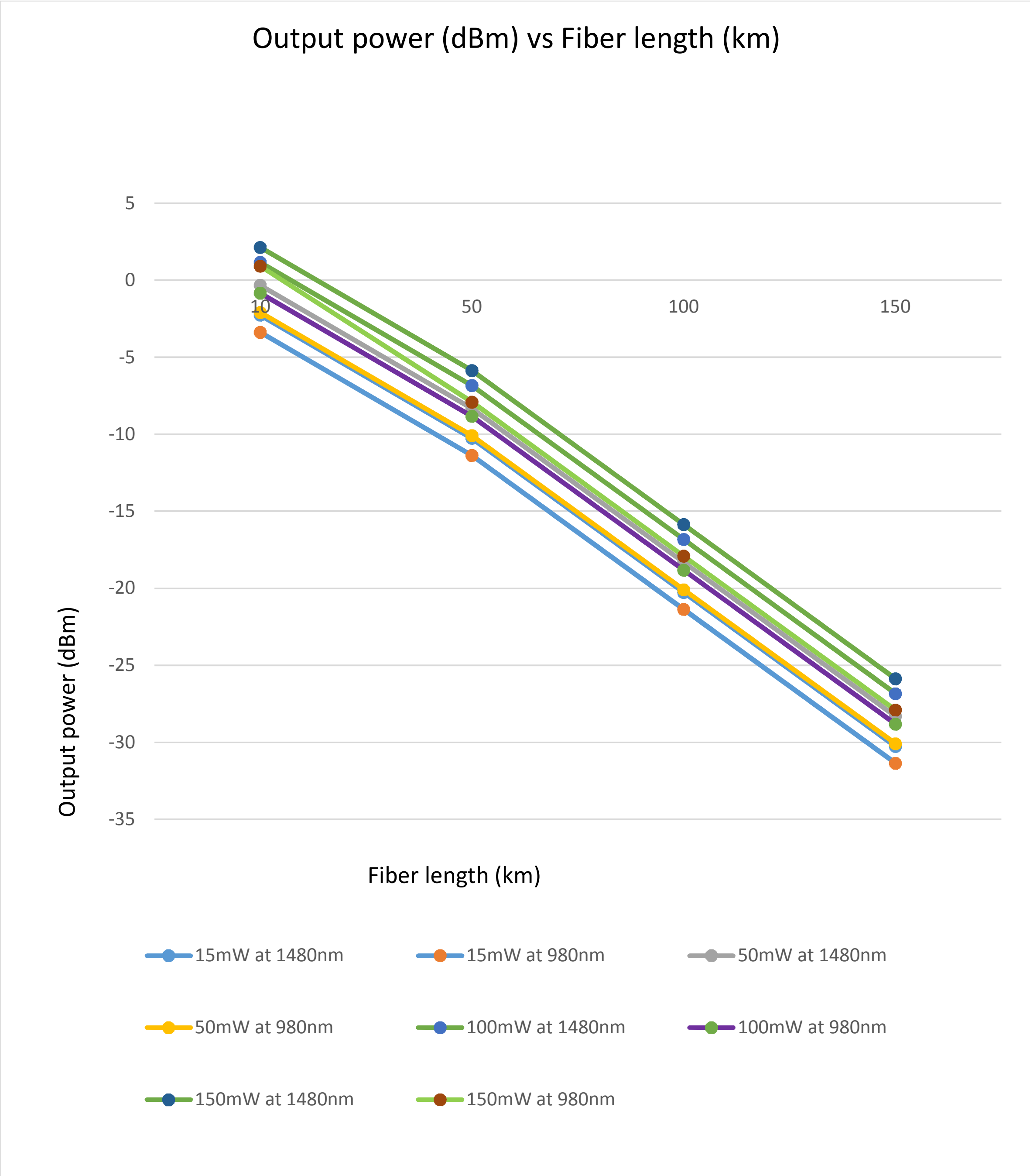


Figure 4.1: Output Power vs. Fiber Length @ λ_p=1480nm and λ_p=980nm

4.2 Gain Characteristics

Gain of an Erbium doped fiber with length $\boldsymbol{L}$ is the ratio of signal power at the fiber output to the signal power injected at the signal input as [8]:

$$\boldsymbol{G} = \frac{P_S\,(L)}{P_S\,(0)} \tag{4.1}$$

Figure 4.2 below shows variation of gain with fiber length for different pump powers and different pumping wavelength with constant signal input power, signal wavelength, and erbium density. The gain obtained from the amplifier for the four different pump power levels were given for 150km long EDF when a signal of 40mW is applied to the active fiber. As it is seen, the gain varies along the fiber length because of pump power variations. The reason for the decrease in gain is insufficient population inversion due to higher losses than the provided gain at the signal wavelength due to high total loss of Erbium doped fiber (fiber background loss + Er absorption loss).

Comparing the graphs for each pumping wavelengths, the peak value for λ_p=1480nm is a gain of 42.138872dB and its lowest is at 9.7404933dB, while the peak value of λ_p=980nm is at 40.096627 and the lowest value at 8.6405438. 1480nm pumping wavelength has a higher gain than 980nm by 4.8464% for their corresponding peak values and 11.2925% for their least values.

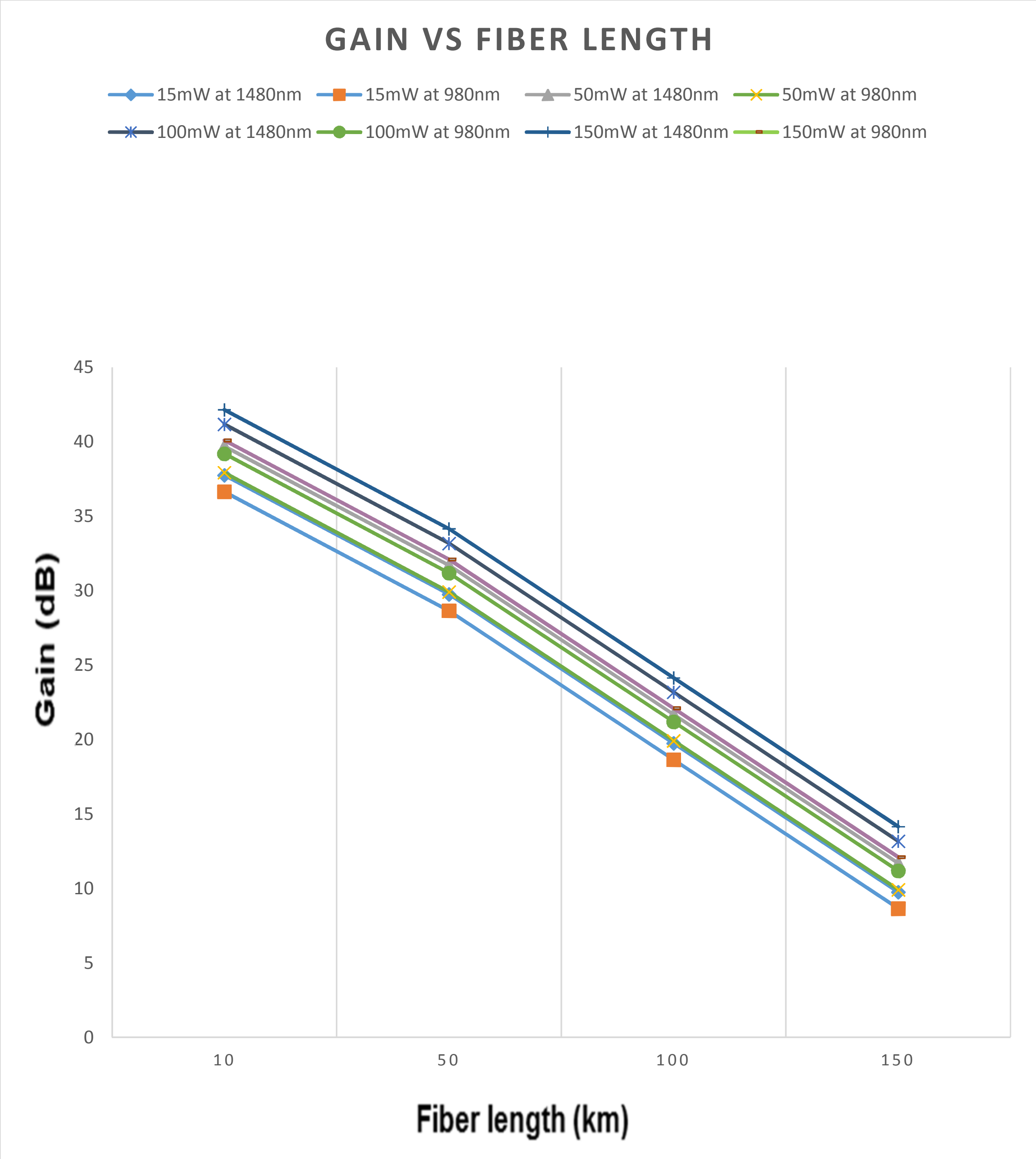


Figure 4.2: Gain vs. Fiber Length @ λ_p=1480nm and λ_p=980nm

Figure 4.3 show variation of gain with pump power for different fiber lengths at 1480nm and 980nm pumping wavelengths respectively. It is seen that higher gain is recorded for 1480nm pumping wavelength with respect to pump power for each fiber length. This graph is an inversion of the previous graphs therefore it gives same percentage increase for the peak and lowest values, 1480nm pumping wavelength has a higher gain by 4.8464% . This graph is presented to show the relationship between pump power and gain. The higher the pump power, the higher the gain recorded for the same input power and fiber length.

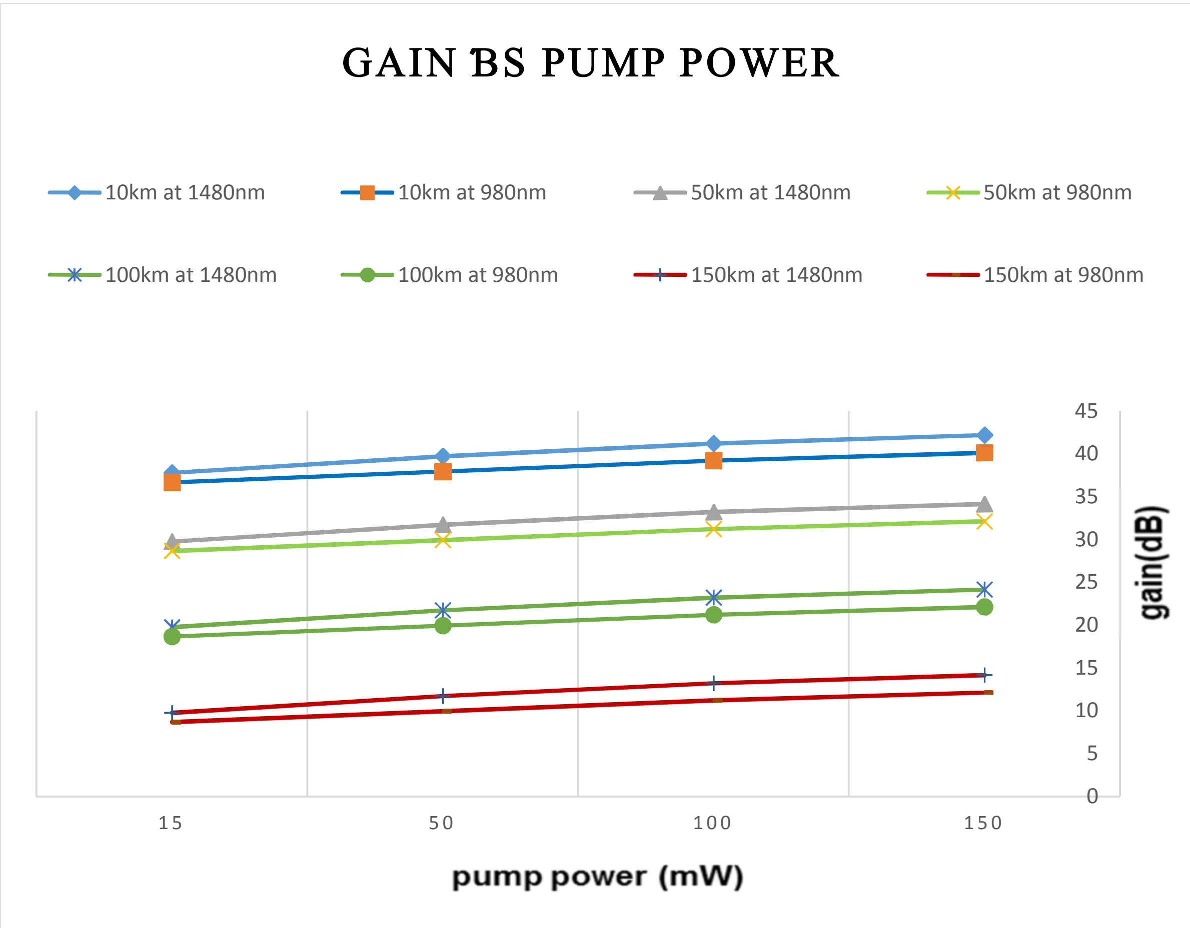


Figure 4.3: Gain vs. Pump Power @ λ_p=1480nm and λ_p=980nm

4.3. Noise figure Characteristics

Amplified spontaneous emission (ASE) noise generated during amplification is added to the signal leading to decrease in signal to noise ratio (SNR) at the amplifier output. The reduction ratio of SNR from input to output of the amplifier is called Noise Figure [8]

$$\boldsymbol{NF} = \frac{(\boldsymbol{SNR})_{\boldsymbol{in}}}{(\boldsymbol{SNR})_{\boldsymbol{out}}} \tag{4.2}$$

Noise figure can also be expressed in terms of gain and spontaneous emission factor (n_{sp}) [8]

$$\boldsymbol{NF} = \frac{\boldsymbol{2n_{SP}(G-1)}}{\boldsymbol{G-2n_{sp}}} \tag{4.3}$$

$$\boldsymbol{n_{sp}} = \frac{\boldsymbol{n2}}{\boldsymbol{n2-n1}} \tag{4.4}$$

n_1 and n_2 are ionic population in two energy levels.

The noise figure of different pump power is varied along with the fiber length at the two pumping wavelengths and the NF of different fiber lengths is also varied along with the pump power, having constant Er doping concentration, signal input power and signal wavelength, 1550nm (C-band).

Figure 4.4 shows a slight increase in NF with increase in fiber length for each pump power. Pumping at 1480nm gives a higher noise figure than pumping at 980nm, this can be verified due to the recorded increase of 4.9598% for the peak values and an increase of 1.7829% for lowest values. Thus, it can be said that the longer the distance, the higher the NF. Pumping at 980nm wavelength has a better NF.

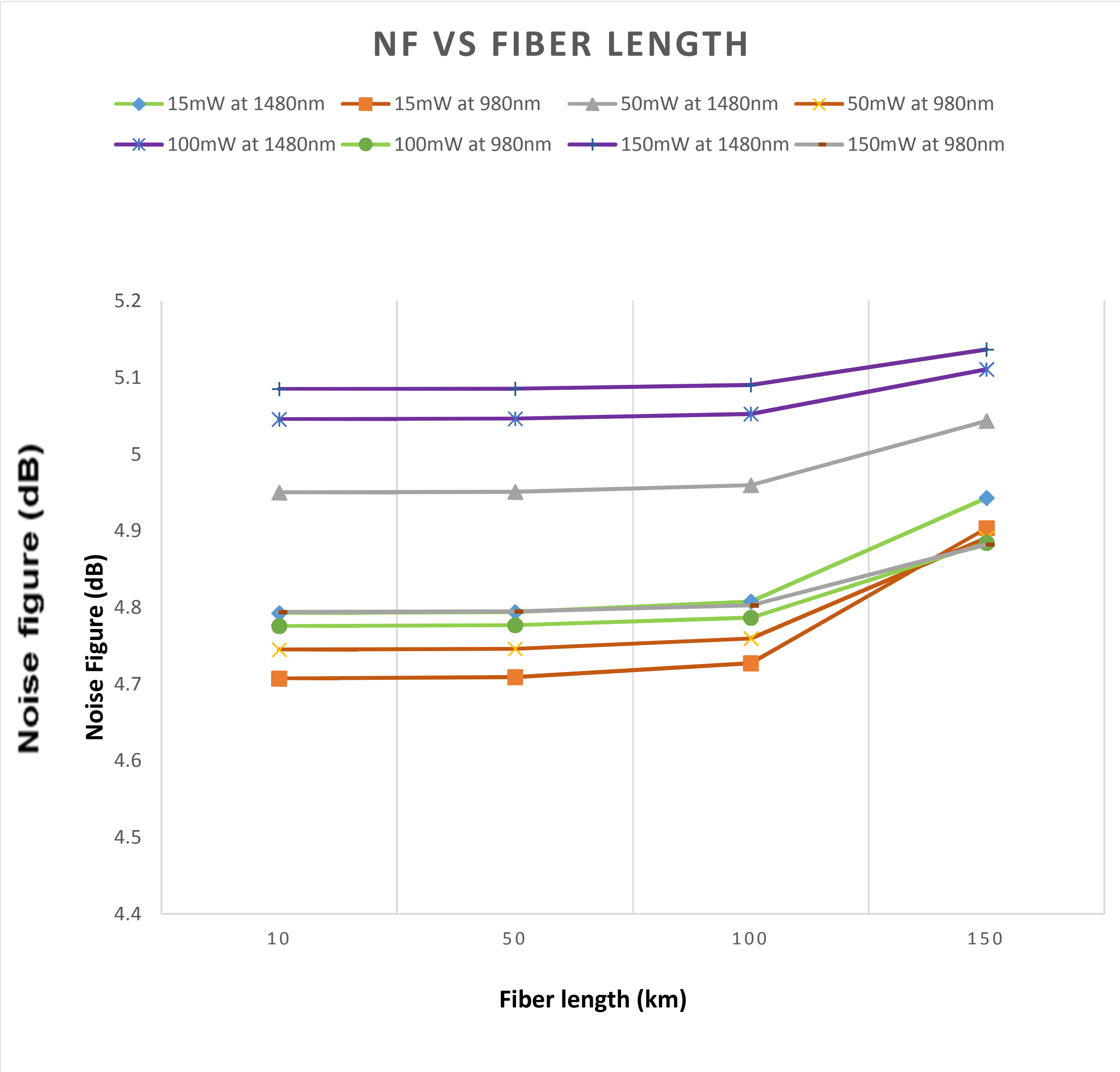


Figure 4.4: Noise Figure vs. Fiber Length @ λ_p=1480nm and λ_p=980nm

Figure 4.5 shows the dependency of the output power on pump power, there is always an increase in output power as the pump power is increased. From the graph obtained, it can be concluded that the output power is greater for 1480nm by 5.1488% for peak values and 11.4037% for lowest values as compared to that of 980nm.

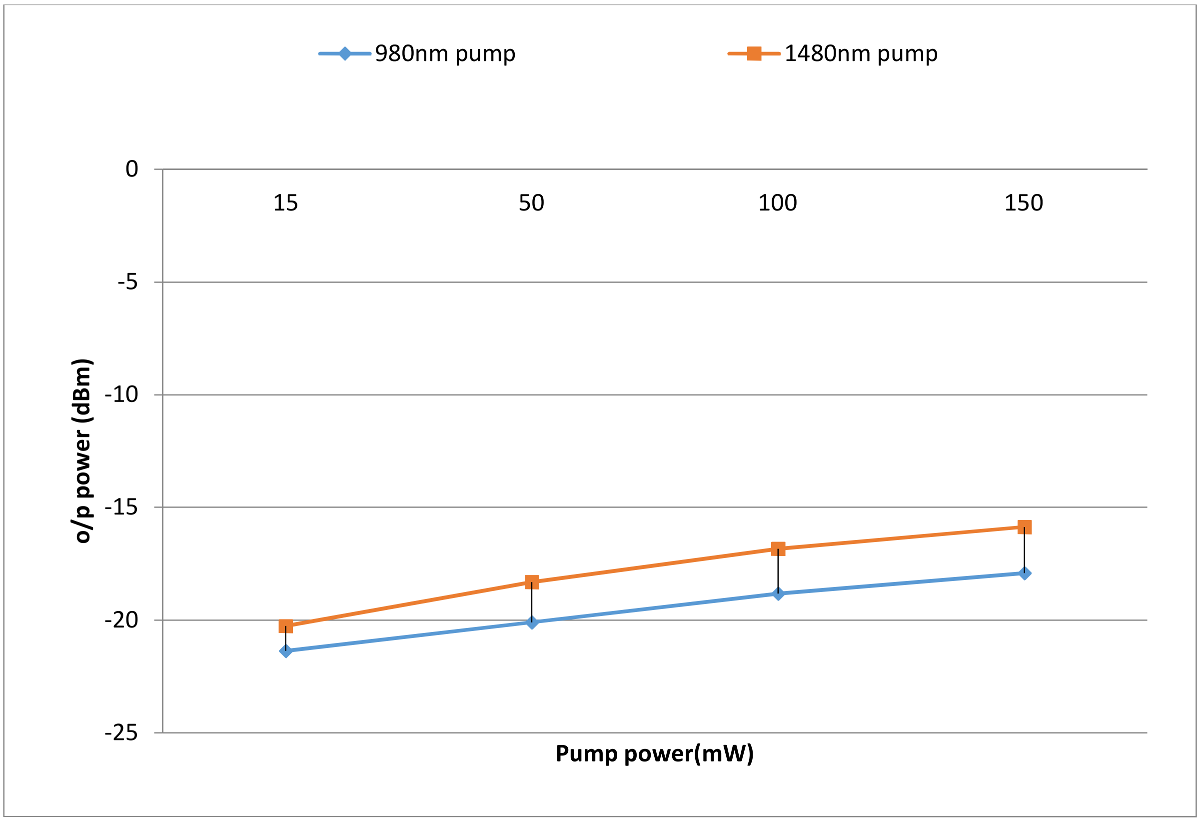


Figure 4.5: Output power vs. Pump Power @ ʎ=1480nm and ʎ= 980nm

4.4 Comparison with previous works

Shukla & Kaur,[27] in their work compared the three pumping configuration schemes i.e forward, backward and bidirectional pumping based on gain and noise figure at different pump power and fiber lengths operating in C-band, 10dBm signal input power, 980nm pumping wavelength, Er^{+3} ion density of 1e+025m^3. It was found that minimum Nf occurs for both forward and bidirectional pumping configurations whereas flat gain is obtained by using bidirectional pumping.

From their findings, the choice of forward pumping configuration was made.

Altuncu & Cokrak [26] solved the rate and propagation equations characterizing an EDFA operating in C-band and pumped at 1480nm in forward direction and results were graphically displayed. It is seen that the pump power applied to EDFA sharply reduces due to absorption in erbium doped fiber; in addition, gain and NF are strongly dependent on the fiber length, pumping power, signal input power and Erbium ion density. When the EDFA is supplied with sufficient pump power, it was shown that EDFA could be operated in saturation regimes leading to maximum gain and minimum NF. From the results obtained from this paper, we know why pump power applied to an EDFA reduces sharply

Ajibodu *et al*, [32] concluded that for an EDFA to be used as an amplifier, the ASE characteristics of EDFA must be considered, for it was observed that as the ASE increased, gain of the amplifier reduced and hence by extension the OSNR reduced.

Kumar *et al* [2] concluded that M-5 fiber is the most suitable fiber for four- stage implementation of EDFA. The same EDFA has been implemented in Optisystem with further customizable parameters. The pump power was varied. Analyzing the gain and noise figure spectrum for the EDFA under different pump powers, it was concluded that 0.75W gave a better result. This EDFA design can be used in booster applications due to high gain recorded.

CHAPTER FIVE

CONCLUSION

5.1 Summary

According to our result, it is clearly indicated that pump power applied to EDFA sharply reduces due to absorption in the erbium doped fiber, therefore there is strong dependence of gain and noise figure on the fiber length, pumping power and signal input power. The gain varies along the fiber length due to the pump power variation.

The simulation of EDFA has been demonstrated through optical simulation software version 7.0. The goal of the simulation study stated to include development of the switching set-up, generation of amplification scheme and analysis of performance parameters through the modification by input/design parameters including EDFA length, fiber length, pump power and input power have been achieved.

5.2 Conclusion

This design gives comparison of the two pumping wavelengths i.e 980nm and 1480nm based on Gain and Noise Figure (NF) at different pump powers (15,50,100,150mW) and at different fiber lengths (10,50,100,150km). The operation is at a single channel in C-band, 1550nm wavelength, input power of -40dB , Er^{+3} ion density of $1^{+025}m^{-3}$. It is found that minimum NF occurs for 980nm pumping wavelength and high gain occurred at 1480nm pumping wavelength, this shows a trade-off. It is also seen that fiber length is proportional to pump power and when it is increased, the pump power should equally be increased in order to achieve high gain and minimum NF at a constant Er^{+3} ion density.

5.3 Significant Contribution

1. The output power is greater for 1480nm by 5.1% for peak values and 11.4% for lowest values as compared to that of 980nm.

2. Pumping at 1480nm gives a higher noise figure than pumping at 980nm, this is due to the recorded increase of 5% for the peak values and an increase of 1.8% for lowest values. Thus, it can be said that the longer the distance, the higher the NF. Pumping at 980nm wavelength has a better NF.

3. Higher gain is recorded for 1480nm pumping wavelength with respect to pump power for each fiber length. 1480nm pumping wavelength has a higher gain by 4.8%. The higher the pump power, the higher the gain recorded for the same input power and fiber length.

5.4 Recommendations for future works

Although this research target has been fulfilled, there are many other avenues in which the research can continue. Key among the future works would be:

1. Conduct same research for other fiber types (PCF, DCF, MMF etc) and study the outcome.
2. Vary Er iron concentration to see its effect on the output signal.
3. The research can also be carried out on a multichannel system and flatten its gain.

References

1. Becker P.C, Olsson N.A and Simpson J.R *" Erbium Doped Fiber Amplifiers, Fundamentals and Technology"* Academic Press , San Diego, 1999

2. G.R Kumar, I. Sadhu and N. Sangeetha, *"Gain and Noise Figure Analysis of Erbium Doped Fiber Amplifier by Four stage Enhancement and Analysis"* International journal of Scientific and Research Publications Vol 4, Iss 4, 2014

3. K. Thyagarajan *"Guided Wave Optical Components and Devices"* , Academic Press, New York, 2006

4. Desuvire, E. " *Erbium Doped Fiber Amplifiers",* Academic Press, New York, 1994

5. Ghatak, A.K and Thyagarajan, K. *" Introduction to Fiber Optics"* , Cambridge University Press, UK , 1998

6. M M Ismail et al , "*EDFA-WDM Optical Network Design Systems*", In Sci Verse Science Direct, Malaysian Technical Universities Conference on Engineering And Technology 2012, MUCET2012

7. B. S Wang "*Novel Erbium Doped Fiber for High Power Applications "* OFS Laboratory, 25 Schoolhouse Road, Somerset, NJ 08873, USA, Published in SPIE APOC2004

8. Emmanuel Desurvire "Erbium Doped Fiber Amplifiers" Principles And Applications, Republished in New York by Colombia University1994

9. R. H. Stolen and E. P Ippen "*Raman Gain in Glass Optical Waveguides "*, Applied Physics Letters volume 22, No 6 (1973).

10. N. A. Olsson and J. Hegarty, *"Noise Properties of a Raman Amplifier"* Journal of light-wave Technology volume 4, 396 (1986).

11. S. G. Grubb, T. Erdogan, V. Mizrahi, T. Strasser, W. Y. Cheung, W. A. Reed, P J. Lemaire, A. E. Miller, S. G. Kosinski, G. Nykolak, and P C. Becker, *"1.3 /µm cascaded Raman amplifier in germanosilicate fibers, in Optical Amplifiers and Their Applications"*, Vol. 1o, 1994 OSA Technical Digest Series, (Optical Society of America, Washington, D.C., 1994)

12. A. J. Stentz, *"Progress on Raman amplifiers,"* in Optical Fiber Communication Conference, Vol. 6, 1997 OSA Technical Digest Series (Optical Society of America, Washington D.C.,1997)

13. N. A. Olsson and J. P Van der Ziel,*"Fiber Brillouin Amplifiers with Electronically Controlled bandwidth" Electronic Letters* 22, 488 (1986).

14. A. R. Chraplyvy and R. W. Tkach, " *Regimes of Feedback effects in 1.5µm distributed feedback lasers" Electronic Letters volume* 22, 1084 (1986).

15. J. C. Simon, /. *"GaInAsP Semiconductor laser amplifiers for single mode fiber" Lightwave Technology* volume 5, issue 9 (1987).

16. T. Mukai, Y. Yamamoto, and T. Kimura, *"Optical amplification by semiconductor lasers, in Semiconductors and Semimetals"*, Vol. 22, Part E, W. T. Tsang, Ed. (Academic Press, New York, 1985)

17. Cisco Systems . *"Cisco Visual Networking Index- Forecast ad Methodology 2009-2014"*. White Paper 2010

18. Bobrovs V, Jelinskis J, InanovsG, Lauks G " *Research Of Traffic Management in FTTx optical communications systems"*. Latvian J. Phys Technical Sci 2(46): 2009

19. Azadeh, M. *" Fiber Optics Engineering"* . New York: Springer, 374: 3, 2009

20. Dutta AK, Dutta NK, Fujiwara M, *"WDM Technologies: Passive optical Components"*. USA: Academic Press, 2003

21. Becker PC, Olsson NA, Simpson JR. *"Erbium Doped Fiber Amplifiers".* Academic Press, 1999

22. Agrawal GP " *Fiber Optic communication systems* ". New Jersey : John Wiley and Sons, 2002

23. Mukherjee B, *"Optical WDM Networks"* Springer Science & Business media , 2006

24. Trifonovs I, Bobrovs V, Ivanovs G *"Optimization of a Standard Bidirectional DWDM Solution."* Journal Of Electrical & Electronic Engineering, vol. 9, 2011

25. Schiopu P., Vasile F. " *The Performance with Gain versus Pump Power*" IEEE Semiconductor Conference, vol. 4, 2004

26. Cokrak A.C, Altuncu A *"Gain and Noise Performance Of Erbium Doped Fiber Amplifiers* " Journal Of Electrical & Electronic Engineering, vol 4, 2004

27. P. Shukla and K.P Kaur, " *Performance Analysis of EDFA for Different Pumping Configurations at High Data Rate"* International Journal Of Engineering and Advanced Technology (IJEAT), Vol. 2 Issue 5

28. Giles C.R, Desuvire E., " *Modeling Erbium Doped Fiber Amplifiers*", journal of Light wave Technology Letters , Vol. 9, No 2, 1991

29. Sun, Y., Zyskind, J.L. and Srivastava, A. "*Average inversion level, modeling, and physics of erbium doped fiber amplifiers"* , IEEE J. SeL Topics Quant. Electron. 3, 1997

30. T. Morioka, K. Mori, and M. Saruwatari, (1993) "*More than 100-wavelength-channel picosecond optical pulse generation from single laser source using super-continuum in optical fibers,"* Electron.Lett., Vol. 29, no. 10.

31. Optisystem Optical Communication System Design Software.

http.//www.optiwave.co.kr/product/optisystem.htm

32. Franklin Ajibodu, Zacchaeous Adetona and Babajide Ojo "*Performance analysis of EDFA and FWM characteristics in a passive Optical Network"* International Journal of Optoelectronic Engineering Vol 6, Iss 1, 2016

33. Bellemare A, Karasek M, Rochette M, La Rochelle S and Tetu M (2000) Light-wave Journal. Technol. Vol. 18

34. N. A. Olsson, *"Lightwave Systems with Optical amplifier"* Journal of Lightwave Technology volume 7, issue 7 (1989).

35. R. H. Stolen, E. P. Ippen, and A. R. Tynes, *"Raman Oscillation in Glass Optical Waveguide"* Applied Physics Letters volume 20 (1972).

36. E. Snitzer and R. Woodcock "*Yb^{3+}-Er^{3+} Glass Laser"* Applied Physics Letters volume 6 Issue 3 (1965)

37. X. S Cheng, R. Parvizi, H. Ahmed "*Wide-Band Bismuth based Erbium Doped Fiber Amplifier with a flat-Gain Characteristics "* volume 1, 2009

38. Alao Abduljaleel, "Development of variable channel spaced L-band Erbium multi wavelength fiber laser" 2016