

Performance Evolution of Hybrid Optical Amplifiers for WDM Systems

*A thesis submitted in partial fulfillment of the
requirements for the award of degree of*

**Master of Engineering
in
Electronics & Communication Engineering**

**Submitted by
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**Under the supervision of
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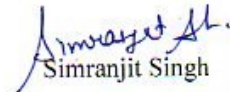
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June-2010**

CERTIFICATE

I hereby certify that the work which is being presented in this thesis entitled, "**Performance Evolution of Hybrid Optical Amplifiers for WDM Systems**", in partial fulfillment of the requirements for the award of degree of **Master in Engineering in Electronics & Communication Engineering** at **Thapar University, Patiala**, is an authentic record of my own work carried out under the supervision of **Dr. R. S. Kaler (Professor)** and refers other researcher's work which are duly listed in the reference section.

The matter embodied in this thesis has not been submitted for the award of any other degree to any other university.

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This is to certify that the above statement made by the candidate is correct and true to best of my knowledge.



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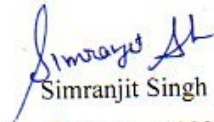
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ABSTRACT

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

Wavelength division multiplexing optical transport networks are expected to provide the capacity required to satisfy the growing volume of telecommunications traffic in a cost-effective way. This thesis is investigates the potential of optical amplifier operating at 16×10 Gb/s in optical communication system.

In this thesis, the 16 channel WDM systems at 10 Gbps have been investigated for the various optical amplifiers and hybrid amplifiers and the performance has been compared on the basis of transmission distance, dispersion and pumping. The amplifiers EDFA and SOA have been investigated independently and further compared with hybrid amplifiers like RAMAN-EDFA and RAMAN-SOA. It is observed that optical hybrid amplifier RAMAN-EDFA provides the highest output power (12.017dBm) and least bit error rate (1×10^{-40}) at 100 km for dispersion 2ps/nm/km and 4ps/nm/km as compare to other optical amplifier.

Four types of pumping have been investigated independently and compared. It is observed that pump 2 of RAMAN-EDFA provides the highest output power (12.048 dBm and 12 dBm) and least bit error rate (5.44×10^{-26} and 1.91×10^{-12}) at 140 km for dispersion 2ps/nm/km and 4ps/nm/km respectively as compare to other pumping amplifier. It is also observed that fiber length for pumping of the RAMAN-EDFA is acceptable only upto 30 kms (at this length power is 12.076dBm). After 30 Kms, the power is decreased instantly.

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LIST OF ABBREVIATIONS

ASE	Amplified spontaneous emission
BER	Bit error rate
CD	Chromatic dispersion
CNR	Carrier-to-noise ratio
DCF	Dispersion compensated fiber
DFA	Doped fiber amplifier
DFB	Distributed feedback
DRA	Distributed raman amplifier
DS	Dispersion shifted
EDFA	Erbium-doped fiber amplifiers
FRA	Fiber raman amplifier
FWM	Four-wave mixing
GVD	Group velocity dispersion
HA	hybrid amplilifier
ISI	Inter symbol interference
NB-HA	Narrow band hybrid amplifier
NDS	Normal dispersion shifted
NF	Noise figure
OADM	Optical add drop multiplexer
OAMP	Optical amplifier
OFA	Optical fiber amplifier
OXC	Optical cross connect
OXS	Optical cross switch
PMD	Polarization-mode dispersion
PON	Passive optical network
RF	Radio frequency
RWA	Routing and wavelength assignment
SBS	Stimulated Brillouin scattering
SMF	Single-mode fibers

SNR	Signal-to-noise ratio
SOA	Semiconductor optical amplifier
SPM	Self-phase modulation
SRS	Stimulated Raman scattering
SSF	Split step fourier
SWB-HA	Seamless wide band hybrid amplifier
WDM	Wavelength-division multiplexing
WLAN	Wireless local area networks
XPM	Cross-phase modulation

LIST OF SYMBOLS

λ	Wavelength of light
c	Velocity of light
h	Plank constant
μm	Micro meter
nm	Nano meter
ps	Pico second
Km	kilometer
dB	Decibel
E_1	lower energy state
E_2	Higher energy state
E	Photon energy
N_1	Population density of lower level
N_2	Population density of higher level
N	carrier density
R	Run for fiber length
mW	Milli watt
G	fiber path gain
i	modulating current
η	modulation sensitivity
β	group velocity dispersion coefficient
γ	self-phase modulation coefficient
T	pulse width
z	soliton period,
N	soliton order
$\Delta\lambda$	source line-width
D	fiber dispersion
L	the fiber length
ω	angular frequency

CHAPTER 1

INTRODUCTION

1.1 Development of Optical Fiber Communication

The progress of optical fiber communication has been advancing rapidly for the past two decades. Optical fiber communication systems have a long history and it was realized during the second half of the twentieth century that a greater transmission bandwidth could be achieved by employing optical waves as the carrier [1]. However, this possibility was not exploited until the invention of laser in the 1960s [2]. With the advent of the laser and thus the availability of a coherent optical source, a new era for optical communication was created. Initially, the extremely large losses (more than 1000 dB/km observed in the best optical fibers) made them appear impractical. A breakthrough was reached in 1966, when Kao and Hockham, and Werts discovered the high losses were a result of impurities in the fiber material and that the losses could be reduced by using glass-based optical waveguide [3]. This was realized in 1970, when Kapron, Keck and Maurer [2] succeeded in fabricating a silica fiber with an attenuation of approximately 20 dB/km. This made transmission of a few kilometers commercially feasible. At the same time, GaAs semiconductor lasers, operating continuously at room temperature were demonstrated [1].

First generation light wave systems operating near 0.8 μm became commercially available in 1980 [1] and the systems were operating a bitrate of 45 Mb/s with allowed repeater spacing of 10 km. In a span of a few years, second generation lightwave systems operating near 1.3 μm were developed. The advantages of operating at this wavelength could increase repeater spacing. It was also found that the optical fiber loss is below 1 dB/km and it exhibits minimum dispersion near 1.3 μm wavelength region [1]. Second generation system was developed using InGaAsP lasers and detector, but the bit rate was limited to below 100 Mbit/s due to the dispersion in multimode fibers. With the introduction of single mode fiber in the mid 80s, this limitation was overcome. By 1987, second generation lightwave systems were operating at a bit rate up to 1.7 Gb/s with a repeater spacing of 50 km. However, it was found that second generation systems were limited by the fiber loss at 1.3 μm , thus in order to achieve a faster data rate or longer distance it must operate near 1.55 μm where the loss of silica fibers is minimum. However, there

was another problem with conventional InGaAsP semiconductor lasers, as they could not be used because of pulse spreading which occurs as a result of simultaneous oscillation of several longitudinal modes. Two methods were introduced to cope with this dispersion problem. The first approach was the use of dispersion shifted fibers, which are designed to have a minimum dispersion near 1.55 μm and the second approach was to limit the laser spectrum to a single longitudinal mode. In 1990, third generation 1.55 μm systems were developed using these approaches and the systems were operating at a bit rate of 2.5 Gb/s. Despite the better performance of third generation systems, they have a major drawback: the need to regenerate the signal periodically by using electronic repeaters typically spaced 60-70 km apart [1]. This problem was overcome with the advent of fiber amplifiers in the early 90s. The fourth generation systems were developed using fiber amplifiers to increase the repeater spacing and bit rate. The development of erbium doped fiber amplifier (EDFA) was a major impetus to the research on active-fiber technology in the 1.55 μm wavelength region and it had a great impact on ultra-long haul transmission. Erbium doped fiber has made it possible to transmit optical signals over thousands of kilometers without electrical repeaters, simply by cascading optical amplifiers and fiber sections in a chain [4]. This technology has allowed systems to transmit data at longer distance and at a faster data rate. By 1996, it was reported in [1] that fourth generation systems were capable of transmitting over 11,300 km at a bit rate of 5 Gb/s. Although the optical amplifiers solve the loss problem, they worsen the dispersion problem since the dispersive effects accumulate over multiple amplification stages. Thus, the fiber dispersion remains in fourth generation systems while fifth generation systems are concerned with finding a solution. By the early part of the 2000s, almost every long-haul (typically between 300 and 800 km) or ultra-long-haul (typically longer than 800 km) fiber-optic transmission system uses Raman amplification. Raman amplifiers were not deployed until the late 1990s. The problem was a relatively poor efficiency of Raman amplifiers at lower signal powers. Erbium-doped fiber amplifiers required powers in the range of 1 to 10 mW, whereas Raman amplifiers required powers in the range of 1 to 5 W. Therefore, to achieve a gain of 20 dB or more required almost three orders of magnitude more pump power in Raman amplifiers [5]. Now days Optical hybrid amplifier provides high power gain. Mohammed N. Islam described that the total amplifier gain (G_{Hybrid}) is the sum of the two gains [6]: $G_{\text{Hybrid}} = G_{\text{EDFA}} + G_{\text{Raman}}$ if we are using RAMAN-EDFA hybrid amplifier. Recent efforts have been directed towards realizing greater capacity utilization

of fiber systems by multiplexing a large number of wavelengths. These systems are referred to as dense wavelength-division multiplexing (DWDM) system. This system aimed at reducing the wavelength separation of 0.8 nm which is currently in operation to less than 0.5 nm. Controlling the wavelength stability and development of wavelength de-multiplexing devices are critical to these efforts.

1.2 Optical Amplifier

1.2.1 Principle of optical amplifier

Atom exists only in certain discrete energy state, absorption and emission of light cause them to make a transition from one discrete energy state to another state and related to difference of energy E between the higher energy state E_2 and lower energy state E_1 as shown in figure 1.1(a). When photon energy E is incident on atom, it may be excited into higher energy state E_2 through absorption of photon called absorption as shown in figure 1.1(a). As atom in energy state E_2 is not remain stable, atom returns to lower energy state in random manner by generating a photon as shown in figure 1.1(b). This is called spontaneous emission.

Optical amplification uses the principle of stimulated emission, similar to the approach used in a laser [7]. The stimulated emission occurs, when incident photon having energy $E = hc/\lambda$ interact with electron in upper energy state causing it to return back into lower state with creation of second photon as shown in figure 1.1(c), where h is Plank constant, c is velocity of light and λ is the wavelength of light [8]. The light amplification occurs, when incident photon and emitted photon are in phase and release two more photons. The continuation of this process effectively creates avalanche multiplication and the amplified coherent emission is obtained.

To achieve optical amplification, the population of upper energy level has to be greater than that of lower energy level i.e. $N_1 < N_2$, where N_1 , N_2 are population densities of lower and upper state. This condition is known as population inversion. This can be achieved by exciting electron into higher energy level by external source called pumping.

1.2.2 Types of Optical amplifier

Optical amplifiers are classified on the basis of structure i.e. whether it is semiconductor based (Semiconductor optical amplifiers) or fiber based (Rare earth doped fiber amplifiers, Raman and Brillouin amplifiers). The optical amplifiers are also classified on the basis of device

characteristics i.e. whether it is based on linear characteristic (Semiconductor optical amplifier and Rare-earth doped fiber amplifiers) or non-linear characteristic (Raman amplifiers and Brillouin amplifiers).

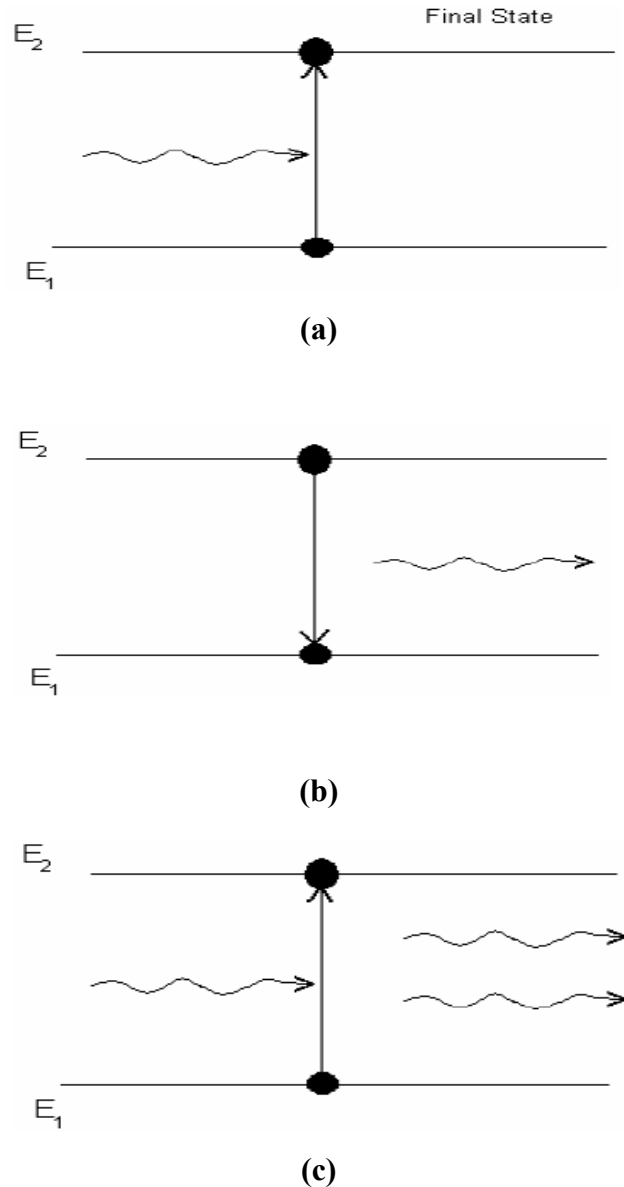


Figure 1.1: Absorption, spontaneous emission and stimulated emission process.

1.2.2.1 Semiconductor Optical Amplifier

A semiconductor laser amplifier (see figure 1.2) is a modified semiconductor laser, which typically has different facet reflectivity and different device length [7]. Semiconductor optical amplifier is very similar to a laser except it has no reflecting facets [9]. A weak signal is sent

through the active region of the semiconductor, which, via stimulated emission, results in a stronger signal emitted from the semiconductor.

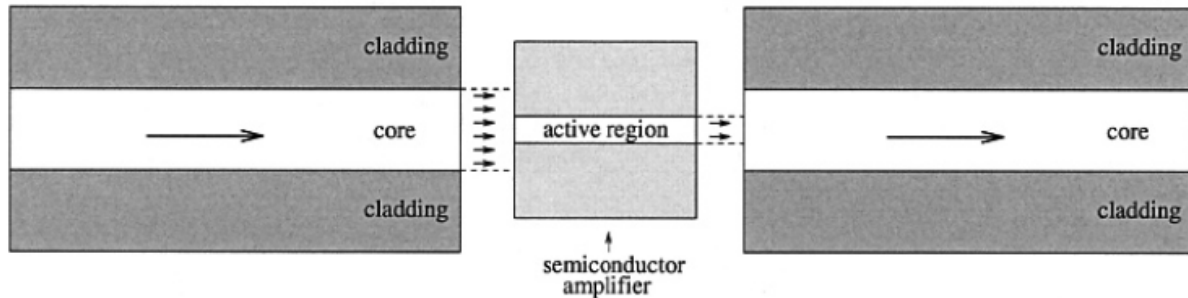


Figure 1.2: A Semiconductor Optical Amplifier [7]

SOA's are typically used in the following:

- Used as power boosters following the source (optical Post-amplifier).
- Provide optical amplification for long-distance communications (in-line amplification, repeaters).
- Pre-amplifiers before the photo detector.

1.2.2.2 Erbium Doped Fiber Amplifier

The EDFA consists of three basic components: length of erbium doped fiber, pump laser and wavelength selective coupler to combine the signal and pump wavelengths as shown in figure 1.3. The optimum fiber length used depends upon the pump power, input signal power, amount of erbium doping and pumping wavelength [1]. Erbium doped fiber amplifiers (EDFAs) can be extensively used in optical fiber communication systems due to their compatibility with optical fiber. An EDFA has a comparatively wide wavelength range of amplification making it useful as transmission amplifier in wavelength division multiplexing systems. Theoretically EDFA is capable of amplifying all the wavelengths ranging from 1500 to 1600 nm. However practically there are two windows of wavelength. These are C and L band. This allows the data signal to stimulate the excited atoms to release photons. Most erbium-doped fiber amplifiers (EDFAs) are pumped by lasers with a wavelength of either 980 nm or 1480 nm [7]. The 980-nm pump wavelength has shown gain efficiencies of around 10 dB/mW, while the 1480-nm pump wavelength provides efficiencies of around 5 dB/mW. Typical gains are on the order of 25 dB.

Typically noise figure lies between 4-5 dB with forward pumping and equivalent figures for backward pumping are 6-7 dB assuming 1480 nm pumping light was used [1].

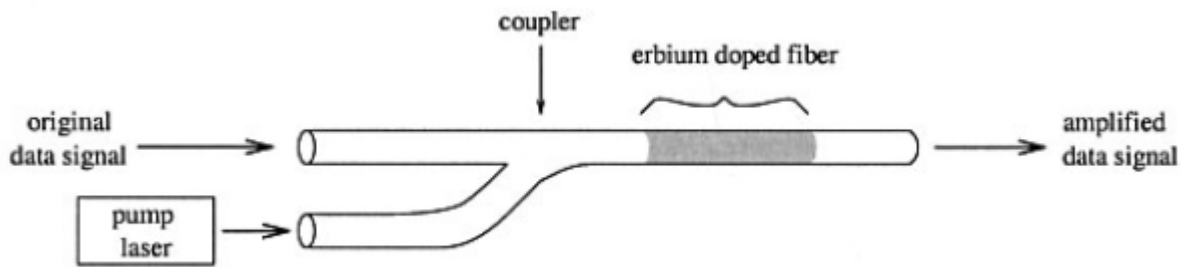


Figure 1.3: Erbium Doped Fiber Amplifier [7]

1.2.2.3 RAMAN Amplifier

Raman gain in optical fibers occurs from the transfer of power from one optical beam to another through the transfer of energy of a phonon. A phonon arises when a beam of light couples with the vibrational modes of the medium [7]. In this instance the optical fiber is the amplifying medium making the gain provided by Raman amplifiers dependent on the optical fiber's composition. In silica fibers, the Raman gain bandwidth is over 260 nm, with the dominant peak occurring at 86 nm from the pump wavelength. This makes Raman gain available across the entire transmission spectrum of the fiber as long as a suitable pump source is available. The gain presented by the Raman effect in fused silica glass is polarization dependent; therefore gain only occurs if both the signal and pump beams are of the same polarization.

For a distributed Raman fiber amplifier (RFA), power is provided by optical pumping of the transmission fiber; the pump wavelength is shorter than the wavelength to be amplified by an amount that corresponds to an optical frequency difference of about 13.2 THz. The signal then experiences gain due to Stimulated Raman Scattering (SRS), a nonlinear optical process in which a pump photon is absorbed and immediately reemitted in the form of a phonon and a signal photon, thus amplifying the signal as shown in figure 1.4.

Biswanath Mukherjee described in [7] fundamental advantages of Raman amplifier. First Raman gain exists in every fiber, which provides a cost-effective means of upgrading from the terminal ends. Second, the gain is nonresonant, which is available over the entire transparency region of

the fiber. The third advantage of Raman amplifiers is that the gain spectrum can be tailored by adjusting the pump wavelengths. For instance, multiple pump lines can be used to increase the optical bandwidth, and the pump distribution determines the gain flatness. Another advantage of Raman amplification is that it is a relatively broad-band amplifier with a bandwidth > 5 THz, and the gain is reasonably flat over a wide wavelength range.

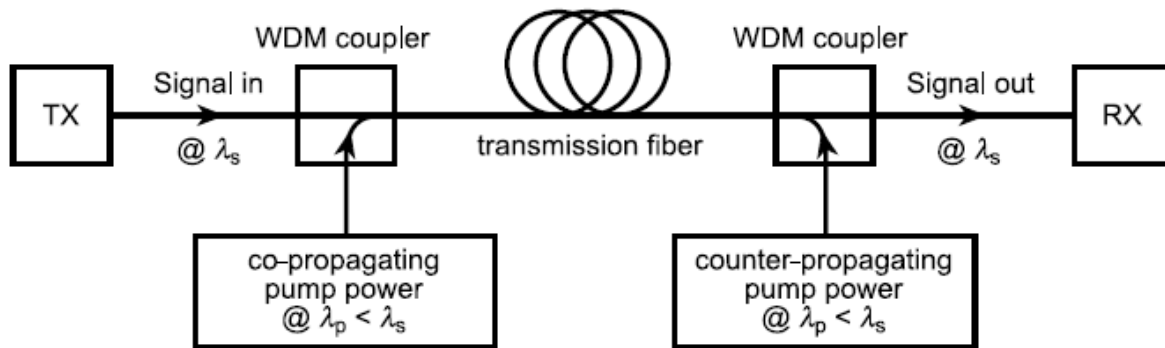


Figure 1.4: Schematic of a Raman fiber amplifier

1.2.2.4 Hybrid Optical Amplifier

The cascading an erbium-doped fiber amplifier (EDFA) and a fiber Raman amplifier (FRA or RA) is called a hybrid amplifier (HA), the RAMAN-EDFA. The cascading a semiconductor optical amplifier (SOA) and a fiber Raman amplifier (FRA or RA) is called a hybrid amplifier (HA), the RAMAN-SOA. Hybrid amplifier provides high power gain. Mohammed N.Islam described that the total amplifier gain (G_{Hybrid}) is the sum of the two gains [5]:

$$G_{\text{Hybrid}} = G_{\text{EDFA}} + G_{\text{Raman}}$$

Gain partitioning in hybrid amplifier is as shown figure 1.5.

Two kind of hybrid amplifier (HA) are: the narrowband HA (NB-HA) and the seamless and wideband HA (SWB-HA). The NB-HA employs distributed Raman amplification in the transmission fiber together with an EDFA and provides low noise transmission in the C- or L-band. The noise figure of the transmission line is lower than it would be if only an EDFA were used. The SWB-HA, on the other hand, employs distributed or discrete Raman amplification together with an EDFA, and provides a low-noise and wideband transmission line or a low-noise

and wideband discrete amplifier for the C- and L-bands. The typical gain bandwidth ($\Delta\lambda$) of the NB-HA is 30 to 40 nm, whereas that of the SWB-HA is 70 to 80 nm.

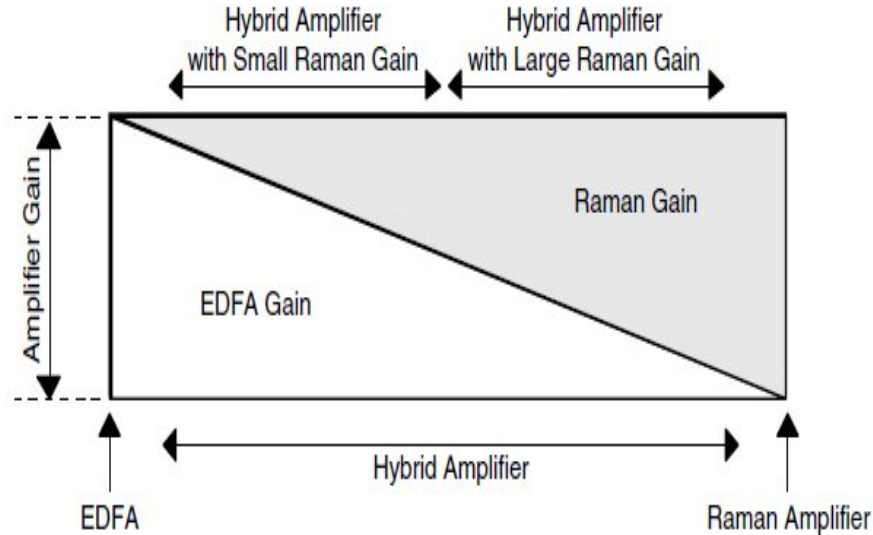
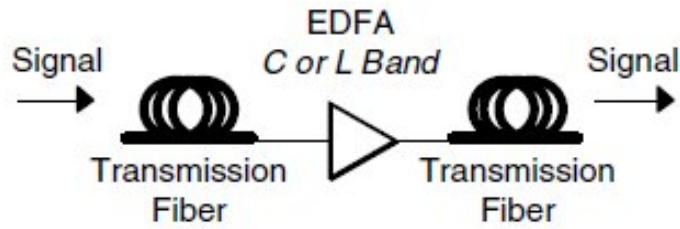


Figure 1.5: Gain partitioning in hybrid amplifier [5]

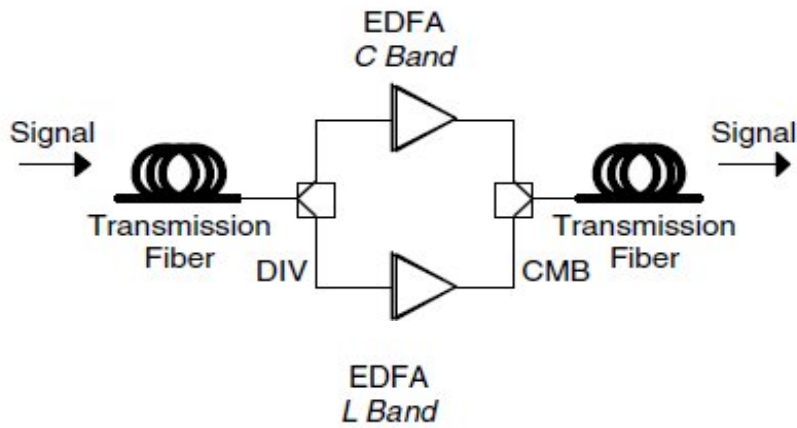
1.2.3 Basic configurations of a transmission line with an inline amplifier

Figure 1.6 shows some basic configurations of a transmission line with an inline amplifier. An EDFA is used as the repeater between two installed transmission fibers, and amplifies the input signal light figure 1.6 (a). The signal light usually consists of wavelength-division-multiplexed (WDM) multichannels, and the EDFA offers C or L-gain band coverage. The typical gain bands of C- and L-gain band EDFAs are the wavelength ranges of about 1530 to 1560 nm and 1570 to 1600 nm figure 1.6 (b) shows a two-gain band amplifier (EDFA) with C- and L-gain band EDFAs in parallel with each other. The combiner and divider connected to the EDFAs multiplex and demultiplex the WDM signal channels according to their wavelengths. The two-gain band EDFA has a gain bandwidth that is about twice that of the C- or L-band EDFA figure 1.6 (b). However, its cost and the number of optical components are about twice those of the C- or L-band EDFA. The NB-HA that offers C- or L-band coverage is shown in figure 1.6 (c). The NB-HA consists of a C- or L-band distributed Raman Amplifier (DRA), which is a transmission fiber itself, and a C- or L-band EDFA set after the transmission fiber as a repeater. Finally, figure 1.6 (d) shows a C and L-two-gain band HA. The two-gain band HA consists of a two-wavelength

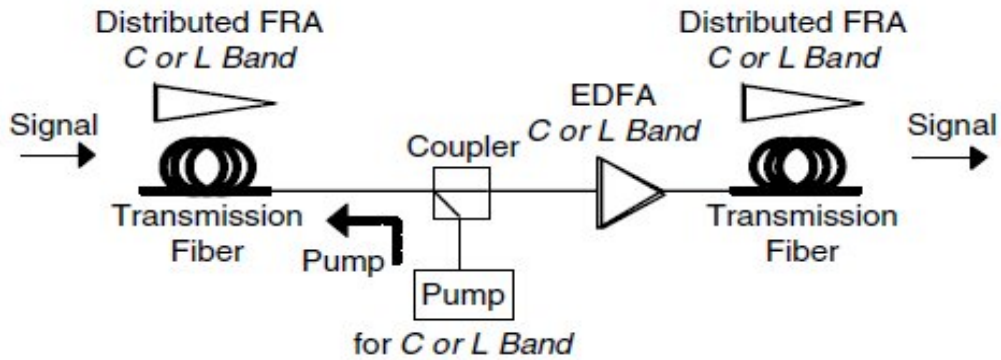
pumped DRA (C- and L-band) and a two-gain band EDFA. The pump lights for the C- and L-bands are multiplexed by a combiner and launched into the transmission fiber via a coupler.



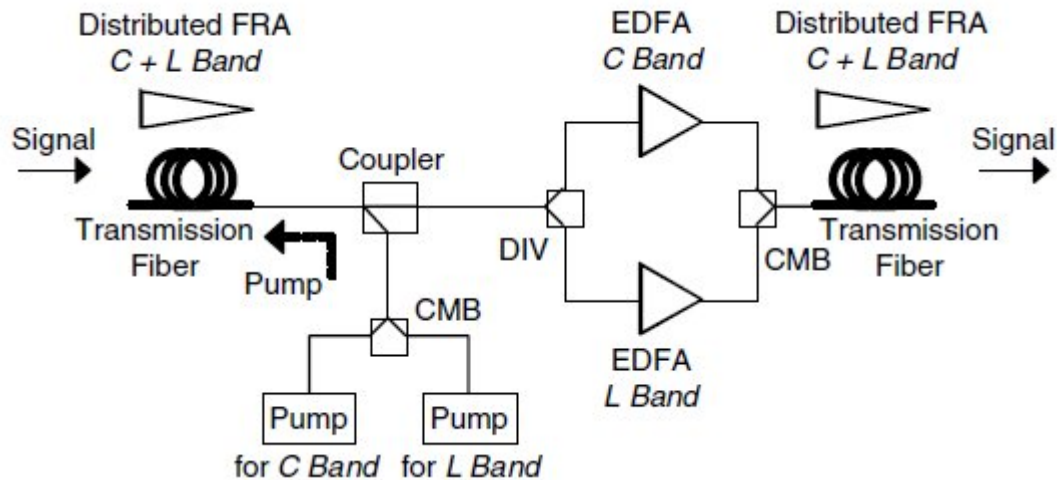
(a)



(b)



(c)



(d)

Figure 1.6: Basic configurations of a transmission line with an inline amplifier: (a) a EDFA; (b) a two-gain band amplifier (EDFA) with C- and L-band EDFAs in parallel; (c) a hybrid EDFA/distributed Raman amplifier with C- or L-band; and (d) a hybrid EDFA/distributed Raman amplifier with C- and L-bands in parallel (CMB: combiner, DIV: divider) [5].

1.3 Wavelength Division Multiplexing (WDM)

Wavelength-division multiplexing (WDM) is an approach that can exploit the huge optoelectronic bandwidth mismatch by requiring that each end user's equipment operate only at electronic rate, but multiple WDM channels from different end-users may be multiplexed on the same fiber.

WDM corresponds to the scheme in which multiple optical carriers at different wavelengths are modulated by using independent electrical bit streams (which may themselves use TDM and FDM techniques in the electrical domain) and are then transmitted over the same fiber. The optical signal at the receiver is demultiplexed into separate channels by using an optical technique.

Optical amplifier deployment of a completely new generation of system see figure 1.7. An advantage of EDFA is that they are capable of amplifying signals at many wavelengths simultaneously. This provide the another way to increasing the system capacity. At each

regenerator location, a single optical amplifier could replace an entire array of expensive regenerator, one per fiber.

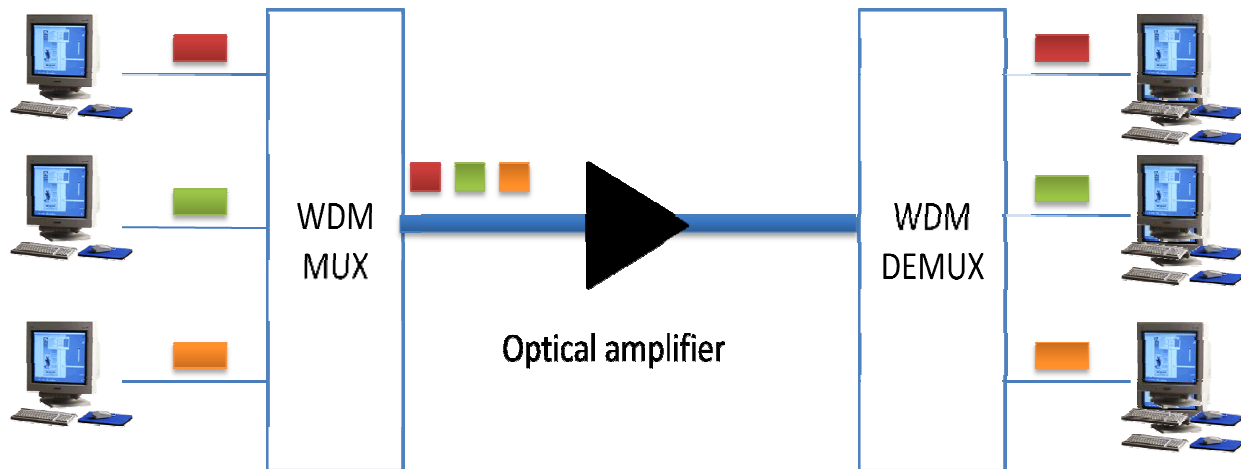


Figure 1.7 – A current generation WDM system using optical amplifiers instead of regenerators.

1.3.1 Evolution of WDM networks

The first generation of WDM networks provides only the point-to-point physical links, which are either static or manually configured see figure 1.8. The technical issues of the first-generation WDM include design and development of WDM lasers and optical amplifiers (OAMP) [10]. The second generation of WDM is capable of establishing connection oriented end-to-end lightpaths in the optical layer by introducing optical add/drop elements (OADM) and optical crossconnects (OXC). The ring and mesh topologies can be implemented using these OADMs and OXCs. The lightpaths are operated and managed based on a virtual topology over the physical fiber topology, and the virtual topology can be reconfigured dynamically in response to traffic changes [7]. The technical issues of second-generation WDM include the development of OADM and OXC, wavelength conversion, routing and wavelength assignment (RWA), interoperability among WDM networks, network control and management (recall the role of software) and so on. Both first-generation and second-generation WDM networks have been deployed in various carriers' operational networks [10]. The third generation of WDM is expected to support a

connectionless optical network. The key issues include the development of optical access network (such as passive optical network (PON)), and optical switching technologies, generically referred to as Optical "X" Switching (OXS), where X = P (for packet), B (for burst), L (for label), F (for flow), C (for cluster or circuit), Figure 1.8 shows the WDM network evolution. Traffic granularity refers to both the volume of the traffic and the size of each traffic unit. Traffic in access networks is aggregated/multiplexed before it rides over backbone networks [10].

A current generation is WDM system using multiple wavelengths at 1.55 μm and optical amplifiers instead of regenerators [11].

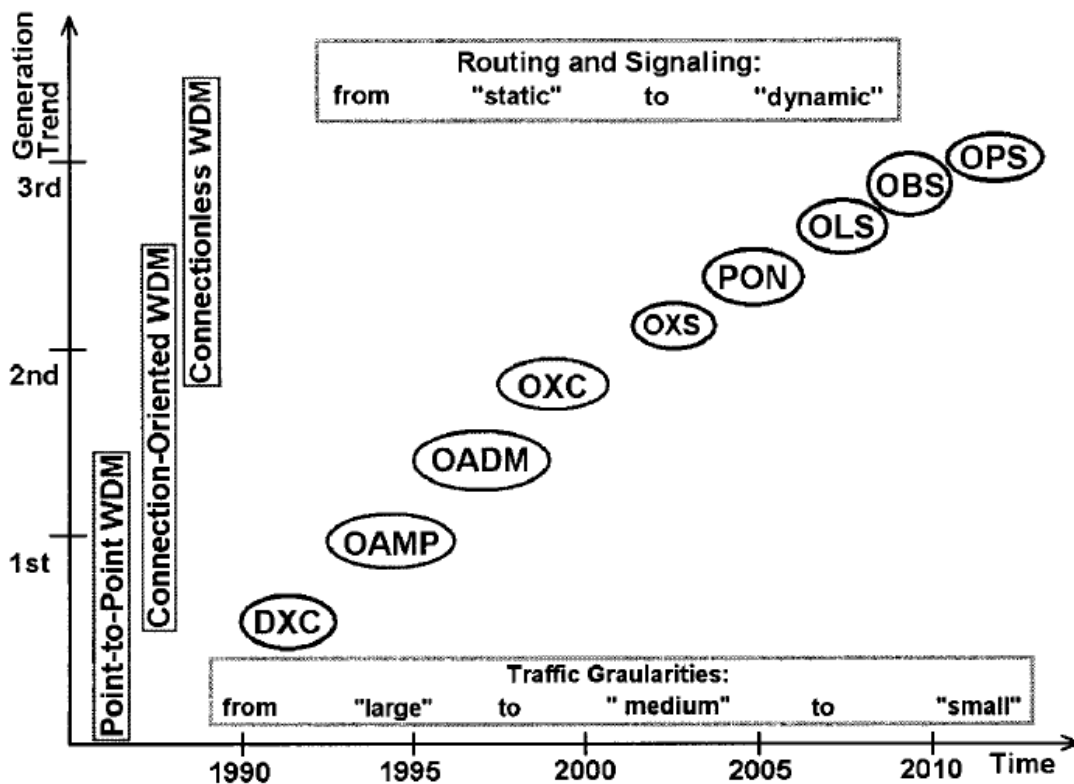


Figure 1.8: WDM network evolution [7]

1.4 OptSim

The core version of OptSim was first developed in 1983 by the Optical Communication Group of Politecnico di Torino [12]. The optical simulation software was originally known as TopSim, a transmission system simulation package, which was developed for mobile and satellite

communication. TopSim was further improved with the addition of a library for optical systems and after continuous refinement efforts by the simulation specialists of Politecnico di Torino, the simulation software was later known as OptSim. OptSim is an advanced vectorial fiber simulator tool that takes into account all important phenomena including fiber loss, chromatic dispersion, birefringence, polarisation mode dispersion (PMD), Kerr non-linearity and amplified spontaneous emission accumulation. OptSim is one of the two high-end commercial system simulators that are capable of calculating more than 15,000 km of non-linear fiber with high precision in a reasonable time. The fiber is simulated by solving the nonlinear Schrodinger equation using a modified version of the standard Split-Step Fourier (SSF) method, which solve the problems related to the cyclical numerical convolution effects intrinsic to the standard SSF method by implementing a true linear numerical convolution by means of component processing techniques (overlap-and-add algorithm) [13]. This method has allowed extremely long fiber links to be simulated on a large window (thousand of bits at standard bit rates) with excellent accuracy. OptSim is actually the fastest simulator because all the simulation components are based on a time domain computation [12]. With OptSim, it is possible to model very closely a “real” ultra-long haul system and achieve realistic results. In addition, continuous refinement of the design parameters can be performed to achieve optimal results, which is difficult to perform in the hardware implementation environment because it can be costly, time consuming and relatively inflexible.

1.4.1 System Requirements for Optsim:

The Windows versions require for Optsim Windows 2000/XP. OptSim is not guaranteed to work under Windows 95/98/NT. OptSim will also run under Linux and various UNIX using X Windows or XFree86 and Motif. Hardware requirements areas follow [14] :

- Pentium II 400 MHz .
- Minimum of 64 Mbytes of RAM for data processing. 128 Mbytes of RAM for faster processing time.
- 100 Mbytes of free space for complete OptSim installation.
- A PostScript compatible printer to print the schematics or graphs created with OptSim.
- A Color graphic display with resolution of 1024x768 pixels or higher.

1.4.2 Creating Optical Transmitter, Receiver and Hybrid Amplifier using Compound Component:

When designing a complex optical transmission link (i.e. WDM) that is made up of a large number of components, it is a tedious process to draw all the components in the provided drawing block. Another problem that may occur is that the drawing block may not be large enough to accommodate all of the components. The solution to these problems is to use the compound component. The advantage of implementing the compound component is that it makes the whole design look simpler and pleasant. The compound component is a useful feature that allows the user to group components as subsystems with identical structure but different numerical parameters. The compound component can be used as a standard block in OptSim that can have any number of inputs and outputs. Input and output will of any type (optical, electrical and logical). The compound component can also be used to group the transmitter section, optical link and the receiver sections. In this thesis, the 16 channel transmitter, receiver, and optical hybrid amplifier has been used as compound component (see figure 1.9).

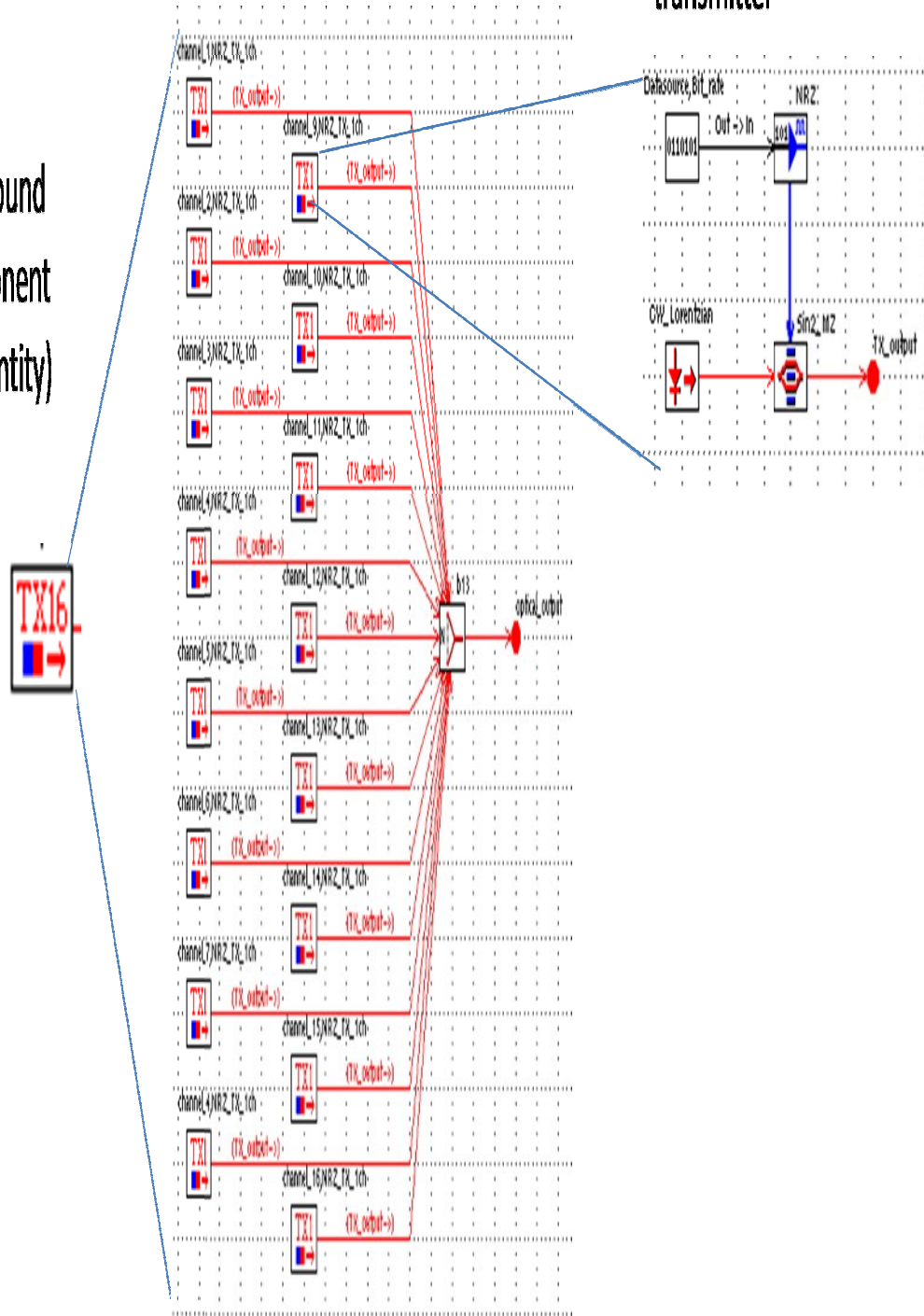
The procedures for creating the compound component for optical 16 channel transmitter, receiver and hybrid amplifier are as follows:

1. Click on the compound component icon on the menu bar and select “compound component” under the unit type.
2. Type the filename as t.opm, r.opm, ha.opm.
3. Under the simulation parameters, select dual polarization and click “Ok”. (This parameter is critical for this thesis and the wrong selection of the parameters would result in an error message to be displayed during VBS check).
4. Drag and place the required component for transmitter (laser diode, amplitude modulator, driver and data source), receiver (photo diode, optical and electrical filter) and optical hybrid amplifier (EDFA, SOA, RAMAN) into the drawing board and link all transmitters, receivers and optical amplifiers as shown in Figure 1.9.
5. Save the file.
6. To change the number of transmitters, receivers and optical amplifiers, right click the compound component and select open from the dialog box and it would bring the user to the drawing board of current hybrid amplifier simulation setup. After the changes have made, save the file.

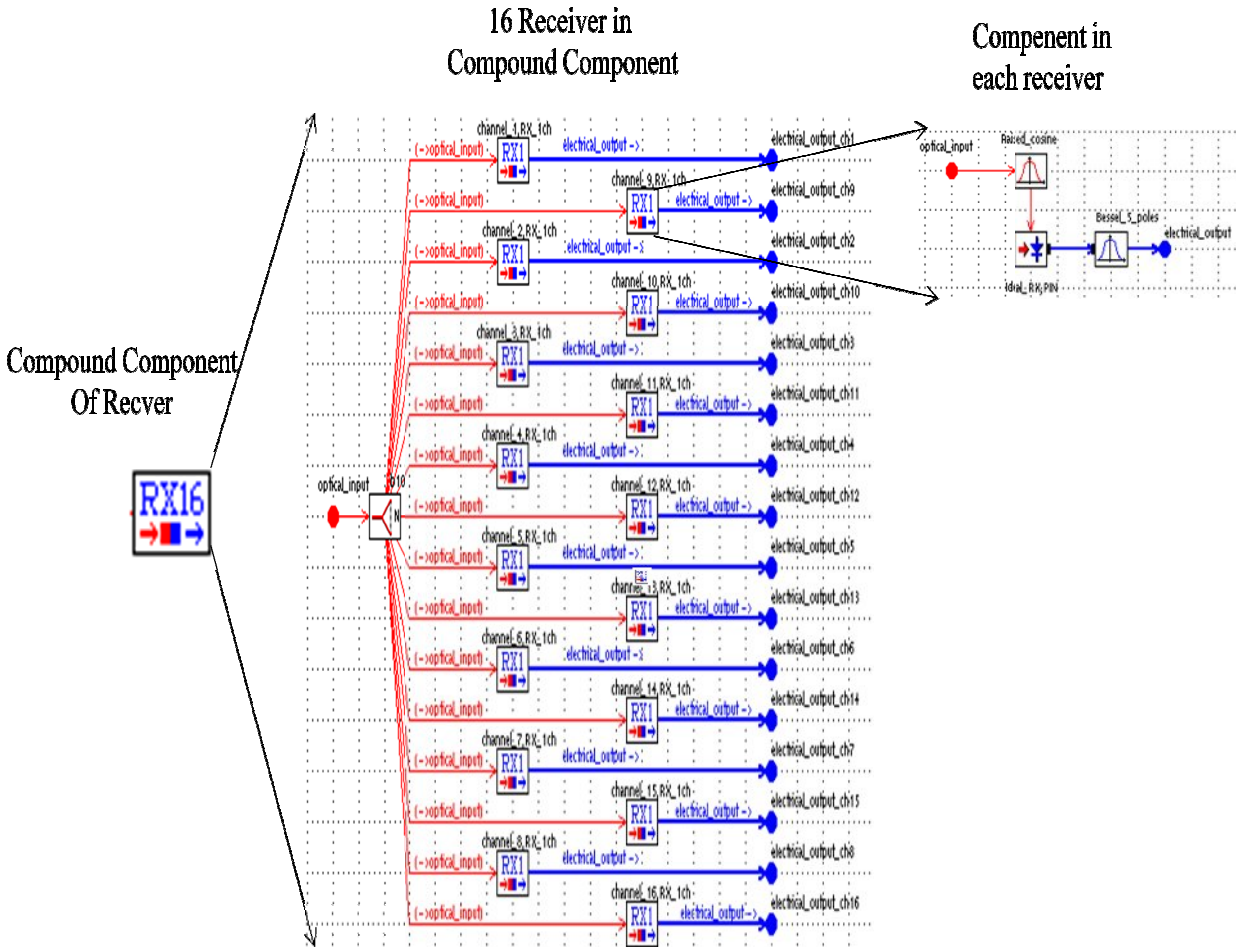
16 transmitter in compound component

Components in each transmitter

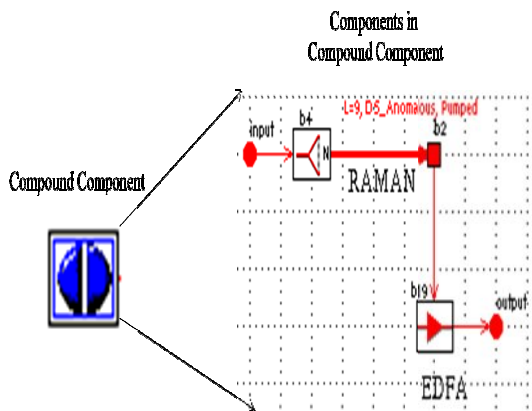
Compound component (one entity)



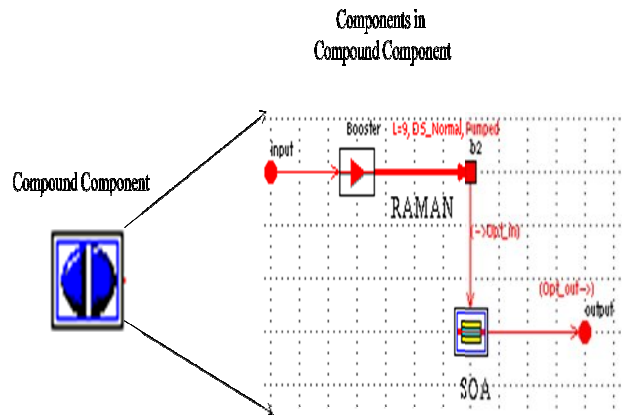
(a)



(b)



(c)



(d)

Figure 1.9: Compound Component of (a) Transmitter; (b) Receiver; (c) RAMAN-EDFA; d) RAMAN-SOA

1.4.3 Creating .DAT file for Raman Co and Counter propagating pumping:

All files used for the specification of fiber loss or dispersion versus frequency or wavelength must have the extension .DAT (i.e. in capital letters). The syntax used for these files must satisfy the following rules:

- (a) Files must be written in plain ASCII text.
- (b) A mandatory first line contains the keyword that identifies the file type and version. This keyword is OptSimFdisp for dispersion files, OptSimFloss for loss files and OptSimFRaman for Raman profile files (or nothing for k_{scale} files).
- (c) All comment lines must begin with a '#' character.
- (d) Comment lines are allowed only between the starting line and the '###' line.
- (e) Two separated data sections must contain co-propagating and counter-propagating pumps. The co-propagating pumps section must begin with the keyword Coprop and the number of co-propagating pumps, the counter-propagating pumps section must begin with the keyword Counterprop and the number of counter-propagating pumps. Almost one of the two sections is mandatory.
- (f) Each data section must contain two-column entries, the first column contains the frequencies or wavelengths of pumps, the second column contains the corresponding value of power in mW or dBm.

.DAT files for Pump 1, Pump 2, Pump 3, Pump 4 and attenuation are as follows:

<p>(a) Pump1.DAT</p> <pre>OptSimFPumps 1 # frequency in nm # Power in mW ### Coprop 1 1365 250 Counterprop 1 1453 500</pre>	<p>(b) Pump2.DAT</p> <pre>OptSimFPumps 2 # frequency in nm # Power in mW ### Coprop 1 1365 300 Counterprop 1 1453 500</pre>
---	---

<p>(c) Pump3.DAT</p> <p>OptSimFPumps 3</p> <pre># frequency in nm # Power in mW ## Coprop 1 1365 400 Counterprop 1 1453 500</pre>	<p>(d) Pump4.DAT</p> <p>OptSimFPumps 4</p> <pre># frequency in nm # Power in mW ## Coprop 1 1365 500 Counterprop 1 1453 500</pre>
<p>(e) Attenuation.DAT</p> <p>OptSimFloss 1</p> <pre># frequency in nm # attenuation in dB/km ## 1365 0.3 1450 0.3 1465 0.3</pre>	

CHAPTER 2

Literature Survey

2.1 Motivation

In the fiber optic communication, there is degradation in transmission signal with the increase in distance. The number of users can be increased by increasing the power budget or reducing the losses in the network by using optoelectronic regenerators. In optoelectronic regenerators, the optical signal is first converted into electric current and then regenerated by using a transmitter. But such regenerators become quite complex and expensive for wavelength division multiplexing systems. This reduces the reliability of networks as regenerator in an active device. Therefore, upgradation of multichannel WDM network will require optical amplifier. To remove loss limitations and to amplify the signal, the optical amplifiers are used which directly amplify the transmitter optical signal without conversion to electric forms as in-line amplifiers. The optical amplifiers are mainly used for WDM (Wavelength division multiplexing) light wave systems as all channels can amplify simultaneously. Optical amplifier increases the transmitter power by placing an amplifier just after the transmitter and just before the receiver.

2.2 Literature Survey

Optical amplifier is a device which amplifies the input optical signal. This device works on the principle of stimulated emission [15]. Hidenori Taga et al. [16], discussed that until the optical amplifiers were developed, only the short distance (up to a few tens kilometers) WDM system was in focus, because the optical repeaters for the WDM transmission were considered to be not practical. The advent of the optical amplifiers made it possible to construct the long distance. There are two types of OAs which are used in communication system; semiconductor optical amplifiers (SOAs) and doped fiber amplifiers (DFAs). The SOAs are basically semiconductor lasers which operate below lasing threshold [1].

R. Boudreau et al. [17] reproducibly demonstrated a simple, high-gain (19 to 21 dB) semiconductor optical amplifier package in which stable, reworkable fiber attachment is

achieved by soldering. A two temperature- zone package, with thermoelectric coolers, is used to solder each fiber without affecting the other.

T. Toyonaka et al. [18] proposed the use of a high NA aspheric lens for coupling optics, and have fabricated a high-gain polarization-insensitive SOA module. A coupling loss as low as 3dB/facet, a net gain of 22dB, and a polarization sensitivity of less than 0.5 dB are also demonstrated.

Jay M. Wiesenfeld et al. [19] has been translated data at 10 Gb/s from an input signal wavelength to another wavelength, either longer or shorter, using gain compression in a 1.5- μm semiconductor optical amplifier for wavelength conversion. They are described that using moderate input powers; wavelength conversion is achieved over a 17 nm (2 THz) range, with 0.7-3 dB power penalties.

Surinder Singh and R.S. Kaler [20] investigated post-, pre- and symmetrical power compensation methods for different positions of the SOA in fiber link. This research is deals with the placement of semiconductor optical amplifier for 10 Gb/s non-return to zero format in single mode and dispersion-compensated fiber link. The effect of increase in signal input power for the three power compensation methods is compared in terms of eye diagram, bit error rate, eye closure penalty and output received power. They are found that the post-power compensation method is superior to pre- and symmetrical power compensation methods. As a result they are find the maximum transmission distance observed for post-power compensation method is 945 km.

The first fiber amplifiers were pumped by flash lamps and operated in a pulsed mode. In the mid-1980s, the group led by D.N. Payne [21] at the University of Southampton, developed a technology of rare earth ions deposition in single-mode silica fibers and the first EDFA was reported in 1987. They are observed that Gains of up to 28 dB have been attained in the important wavelength region of 1.54 μm .

The current emphasis of WDM light wave systems increased the system capacity by amplifying all channels by using single amplifier covering spectral region from 1.45 to 1.62 μm . Bergano et al. [22] successfully demonstrated transmission of 640 Gb/s over 7200 km by using a recirculating loop. Results from this paper indicate that 5 Gbit/s all-optical EDFA transmission systems are capable of achieving transoceanic distances at very low error rates.

Vareille et al. [23] demonstrated the transmission capacity of 340 Gb/s over 6380 km on a straight-line test bed. They are fully representative of systems using 32 channels plus 2 additional wavelengths used for N+ 1 network protection schemes.

The SOA is used as a functional device in the area of long haul optical communication. The nonlinearities in optical amplifiers i.e. ASE noise power, gain saturation, cross gain modulation (XGM), four wave mixing (FWM) and cross phase modulation (XPM) limits its use for long distance optical fiber communication as an in-line amplifier. It also shows limitation for use as pre- and booster amplifiers. Jennen et al. [24] demonstrated that the SOAs are used as functional device in the area of long-haul optical transmission. In this paper the simulations also demonstrate that the worst WDM system incorporating SOAs is a two-channel one.

Durhuus T et al. [25] showed that wavelength conversion at 2.5 Gb/s has penalty of 0.7 dB by using cross gain modulation in SOA. The wavelength converter based on cross gain modulation has permitted transmission distance of 50 km by using normal dispersion shift (NDS) fiber with 3 dB penalty for 5 Gb/s

Desurvire E et al. [26] demonstrates the potential of erbium-doped fiber amplifiers for application in wavelength-division multiplexed communication systems. It has low insertion loss, low crosstalk, high gain, polarization insensitive and low noise figure. An EDFA has a comparatively wide wavelength range of amplification making it useful as transmission amplifier in wavelength division multiplexing systems.

Theoretically EDFA is capable of amplifying all the wavelengths ranging from 1500 to 1600 nm. However practically there are two windows of wavelength. These are C and L band. The C band ranges from 1530 nm to 1560 nm and L band from 1560 nm to 1610 nm. The semiconductor laser pumping source at 980 nm wavelength has proved to be the best in terms of efficiency (more than 10 dB gain per mW pump power) and better noise performance [27].

Raman amplifiers provide a simple single platform for long-haul and ultralong-haul amplifier needs. Raman amplifiers are broad-band and wavelength agnostic. Raman amplifiers can be distributed, lumped or discrete, or hybrid. Also, in Raman amplifiers the amplification and dispersion compensation can be combined in the same fiber length. For high channel count systems, as will be deployed in the next few years, Raman amplifiers' efficiency actually exceeds even 1480-nm pumped -band EDFAs. Consequently, Raman amplifiers should see a wide range of deployment in the next few years [6].

EDFA and SOA are not providing gain flatness as compare to the Raman amplifier. When increasing the numbers of pump wavelengths from two to eight, the gain profiles become flatter and the effective bandwidth larger [28, 29]. When increasing the numbers of pump wavelengths from two to eight, the gain profiles become flatter, and the effective bandwidth becomes larger. Relative gain flatness of 1% could be achieved over bandwidths of up to 15.1 THz (corresponds to E-band) without any gain equalization devices [29]. When increase the transmission distance, a simple EDFA makes a very serious accumulation noise. But, Fiber raman amplifiers (FRA) in long-distance transmission line can not only enlarge the characteristics of the elimination of noise accumulation, gain relatively good noise characteristics, but also can expand the bandwidth of the gain. Raman amplifiers improve the noise figure and reduce the nonlinear penalty of fiber systems, allowing for longer amplifier spans, higher bit rates, closer channel spacing, and operation near the zero-dispersion wavelength [6].

EDFA and FRA broadband hybrid amplifier are becoming a hot research. Usually, the gain of EDFA is not flat [30]. Shingo Kawai et al. [31] investigated a 1.5-dB gain-flatness over 67 nm is achieved with a novel hybrid amplifier comprised of a distributed Raman amplifier pumped at two wavelengths and an erbium-doped fluoride fiber amplifier.

Hiroji Masuda et al. [32] achieves the widest seamless 3.0-, 1.3-, and 1.0-dB bandwidths of 80, 76, and 69 nm with a novel discrete Hybrid amplifier.

H. Masuda et al. [33] demonstrated the first terrestrial field trial to use six novel 1.48 mm pumped hybrid (two-stage-type remotely-pumped EDF/distributed Raman) inline type amplifiers is successfully demonstrated. It offers 1.28 Tbit/s capacity and 100 GHz spacing over a record 528 km (6×88 km) of installed-DSF in a straight line in the L-band.

Ken-Ichi Suzuki et al. [34] demonstrate error free transmission of a 128 x 8 split and 60 km long-reach PON system over 12 hours; a loss budget of over 60-dB is achieved by combining a hybrid burst-mode optical fiber amplifier (OFA). They achieve high gain, over 27-dB, and excellent dynamic range, over 16.5-dB.

T. Matsuda et al. [35] was shown that the hybrid optical amplifier described herein improved the transmission performance in the L-band. They has been experimentally demonstrated the 54×42.7 Gbit/s L and U-band WDM signal transmission. In-line hybrid optical amplifiers consisting of L-band EDFAs and U-band distributed Raman amplifiers enable 2.2 Tbit/s WDM

signals to be transmitted over three spans of 75 km DSF. They experimentally verified that U-band transmission was superior to C-band transmission for the DCF line.

To get higher OSNR Tuan Nguyen Van et al. [36] proposed three calculating models of Terrestrial cascaded EDFAs Fiber optical communication links using Hybrid amplifier.

H. S. Seo et al. [37] demonstrated through numerical calculations that the S, C, and L bands could be amplified seamlessly and simultaneously through mediums. The medium was an in-line hybrid optical fiber configured by an Er-doped cladding and a Ge-doped core. The medium is simple to configure the amplifier since there is no need to splice between mediums. Another advantage is that all optical signals in the entire band are amplified at the same time along the fiber. Therefore, the NF is easily controllable if we configure the amplifier in two stages by inserting an isolator.

Sun Hyok Chang et al. [38] described the transient phenomena of hybrid Raman/erbium-doped fiber amplifier upon optical channel add-drop is investigated. The transient responses of surviving channels are resulted from the combined dynamics of Raman amplifier and EDFA. The transient-suppressing hybrid Raman/EDFA is proven to be enough for wavelength-division-multiplexing networks including reconfigurable optical add-drop multiplexer and/or transparent optical cross-connect, if the optical switching speed is carefully chosen.

2.3 Thesis Scope

The formulation of this thesis consisted of several main stages. These are represented in the figure 2.1. Initially, a review work of theoretical groundwork on optical amplifiers was carried out. As Optical hybrid amplifier is now hot research, many books do not mention this and much of the effort was spent reading and extracting information from relevant journal articles. Following that, a literature review of the optical amplifier and hybrid optical amplifier has been done. The literature review was beneficial in understanding the operation of optical transmission using optical amplifier. Selected the component which was able to support 10 Gb/s optical transmission. After all of the optical components had been selected, a block diagram of the optical amplifiers model and optical hybrid amplifier model was developed so as to enable the designer to have a better visualization of the whole system structure and the components to be used. Then, the optical amplifiers design model was implemented into OptSim whereby the eye

diagrams, BER, power, Q factor and eye opening results were obtained. Both the simulation results for optical amplifier and hybrid optical amplifier were analyzed and compared.

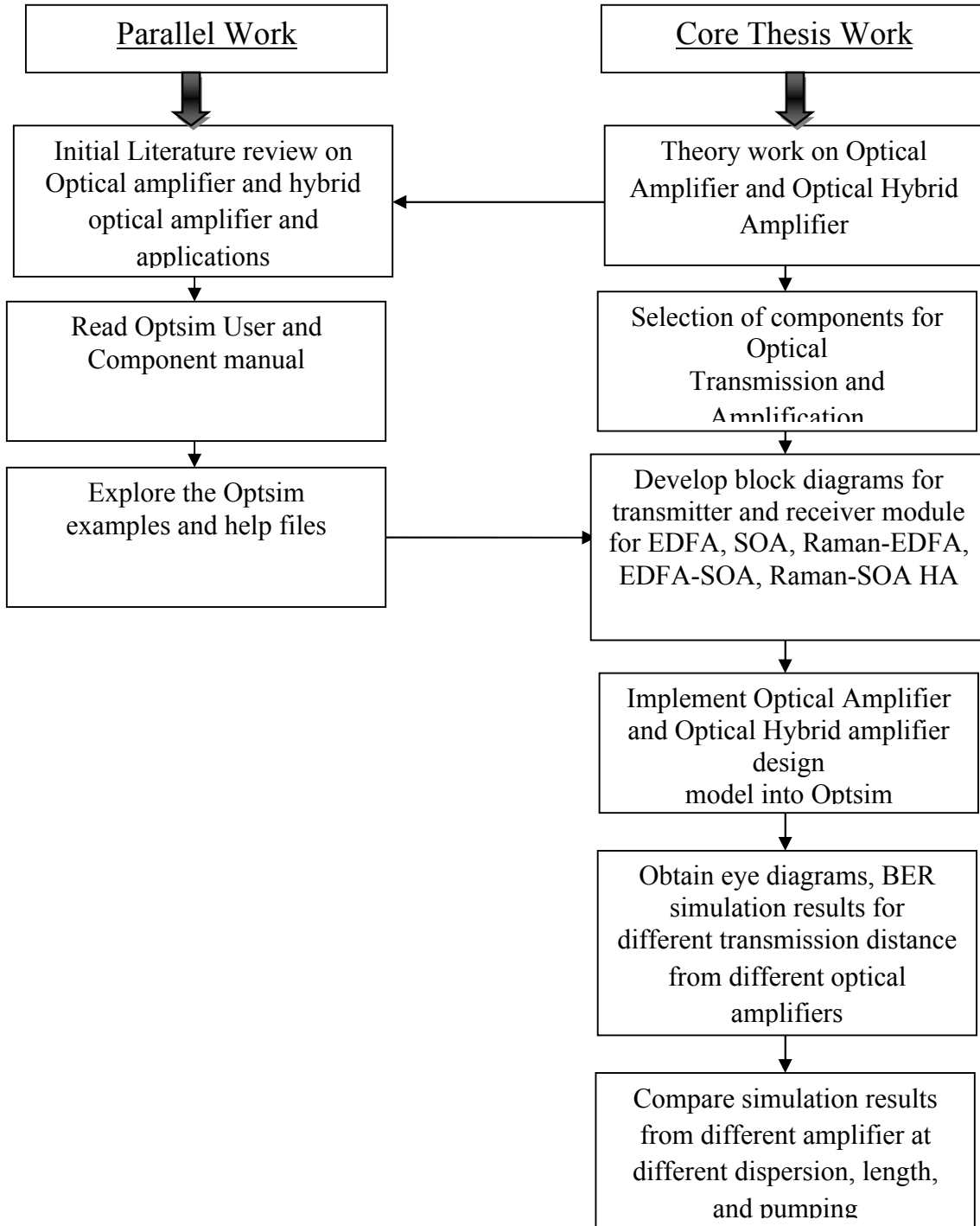


Figure 2.1: Main stages in thesis

2.4 Objectives

1. To investigate the performance of optical amplifier (EDFA, SOA) and hybrid optical amplifier (RAMAN-EDFA, RAMAN-SOA) for different transmission distance and dispersion. Compare all amplifiers and find which one is provide better result in the term of high output power, least BER, high Q factor and large eye opening.
2. To investigate placements of RAMAN-EDFA HA after source in 16×10 Gb/s WDM optical communication system.
3. To analysis the performance of RAMAN-EDFA HA at different raman pumping and pumping power.
4. To investigate the effect on RAMAN-EDFA HA by varies the raman fiber length. Find the optimize raman fiber length before which HA provide maximum power, acceptable BER and Q factor.

2.5 Outline of Thesis

The thesis has been organized into five chapters. Contents of each chapter are briefly described as under:

After carrying the principal and types in chapter 1. The literature review of optical amplifiers (EDFA, SOA, RAMAN-EDFA, RAMAN-SOA) has been studied in Chapter 1, different Optical amplifiers modeling and analysis for transmission performance of 16×10 Gb/s WDM signals at different distance and dispersion have been presented in Chapter 3. It has been shown that the comparison between optical amplifiers and placement (in Km) of RAMAN-EDFA. It also includes the simulation results for all amplifiers for different transmission distance (from 75 to 180 km) and dispersion (2 and 4 ps/nm/km) in terms of output power, Q factor, BER and eye opening.

Chapter 4 is based on the optimization of RAMAN-EDFA at different pumping and pumping power. It has been shown the effect on performance of RAMAN-EDFA by vary the raman fiber length (from 10 to 30). It also includes the simulation result for RAMAN-EDFA for different pumping, pumping power and raman fiber length in terms of output power, BER and eye opening.

Finally, the Chapter 5 highlights the conclusions of the thesis and provides the future scope of the work.

CHAPTER 3

Simulation of 16×10 Gbps WDM System Based on Optical Amplifiers at Different Transmission Distance and Dispersion

3.1 Abstract

In this chapter, the 16 channel WDM systems at 10 Gbps have been investigated for the various optical amplifiers and hybrid amplifiers and the performance has been compared on the basis of transmission distance and dispersion. The amplifiers EDFA and SOA have been investigated independently and further compared with hybrid amplifiers like RAMAN-EDFA and RAMAN-SOA. It is observed that optical hybrid amplifier RAMAN-EDFA provides the highest output power (12.017dBm) and least bit error rate (1×10^{-40}) at 100 km for dispersion 2ps/nm/km and 4ps/nm/km as compare to other optical amplifier.

3.2 Introduction

Wavelength Division Multiplexing (WDM) has been now widely used to demonstrate the transmission of high capacity based on 10 Gbit/s modulation per wavelength [39, 40, 41]. As attenuation, loss of optical signal has been compensated by the use of optical amplifiers. But increasing the number of wavelengths however raises in particular the problems of signal-to-noise ratio, output power reduction and optical amplifier gain equalization. Using Raman amplification features we improve the optical amplifier noise figure and to provide active gain equalization. A Raman Amplifier was used to enhance the OSNR and extend the repeaterless transmission distance with low receiver penalty [42]. This technique however requires very high pump power and the low gain compression of Raman amplifiers can induce unstable system performance. Therefore, if Raman amplifier cascaded with Erbium doped fiber amplifier called hybrid amplifier (HA), the SNR, Q factor and output power can be improved and bit error rate will be decreases. Raman amplifiers are better to any other alternatives for optical amplification in terms of high signal transmission performance. Erbium-doped fiber amplifiers (EDFAs), which have been widely used in the actual optical transmission systems now in service. EDFAs is the more mature technology, mainly used in 1.5~1.6 μ m band amplification. EDFAs are of low

noise, compact, highly efficient with high gain, and capable of amplifying multichannel signals on different wavelengths at a time, and hence quite economical for WDM transmissions. But it working under deeper saturation or having steeper saturation characteristic would result in smaller BER [43]. However, when increase the transmission distance, a simple EDFA makes a very serious accumulation noise. But, Fiber raman amplifiers (FRA) in long-distance transmission line can not only enlarge the characteristics of the elimination of noise accumulation, gain relatively good noise characteristics, but also can expand the bandwidth of the gain. Raman amplifiers improve the noise figure and reduce the nonlinear penalty of fiber systems, allowing for longer amplifier spans, higher bit rates, closer channel spacing, and operation near the zero-dispersion wavelength [6]. Another alternative of optical amplification is the semiconductor optical amplifier (SOA), which is nominally an optical amplifier device with an active waveguide integrated onto a compound semiconductor. SOA is superior in the sense of high integration and additional functionality such as wavelength conversion and all-optical regeneration. In order to improve the performance of amplifiers, EDFA and FRA broadband hybrid amplifier are becoming a hot research. Usually, the gain of EDFA is not flat [30]. Shingo Kawai et al. investigated a 1.5-dB gain-flatness over 67 nm is achieved with a novel hybrid amplifier comprised of a distributed Raman amplifier pumped at two wavelengths and an erbium-doped fluoride fiber amplifier [31]. Hiroji Masuda et al. achieves the widest seamless 3.0-, 1.3-, and 1.0-dB bandwidths of 80, 76, and 69 nm with a novel discrete Hybrid amplifier [32]. Due to the nonlinear nature of the propagation, the system performance depends upon power levels [44] and good power level is achieved by hybrid optical amplifier as compare to EDFA and SOA. The sufficient power levels depend upon the placement of the optical amplifier in optical communication [20]. Here, by using optimized hybrid amplifier, we find the placement of hybrid amplifier and the results of different optical amplifier are compared on the basis of bit error rate, eye diagram, output power and Q factor, for different transmission distances and dispersion.

3.3 Simulation Setup

In this model, sixteen users transmitted their data over a bandwidth of 3.2 THz at 10 Gb/s speed with channel spacing of 100 GHz. Each input signal is modulated in NRZ format and pre-amplified by a booster. The amplified signals send to the channel where these signal are

transmitted over DS-anomalous fiber of different transmission distance. A transmitter compound component is built up using sixteen transmitters.

This transmitter compound component consists of the data source, electrical driver, laser source and external Mach-Zehnder modulator in each transmitter section. The data source is generating signal of 10 Gb/s with pseudo random sequence. The electrical driver converts the logical input signal into an electrical signal. The CW laser sources generate the 16 laser beams at 191.9 THz to 193.4 THz with 100 GHz channel spacing. These beams have random laser phase and ideal laser noise bandwidth. The signals from data source and laser are fed to the external Mach-Zehnder modulator (\sin^2_MZ for all configurations), where the input signals from data source is modulated through a carrier (optical signal from the laser source).

The simulations setup of EDFA, SOA, RAMAN-EDFA (C1), RAMAN-SOA (C2) using compound component at different transmission distance and dispersion are shown in figure 3.1.

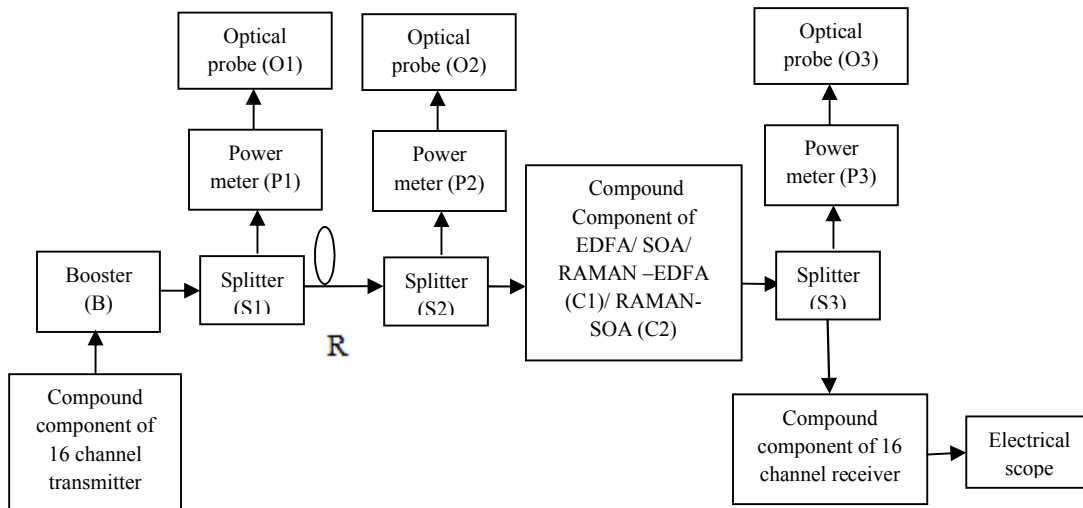
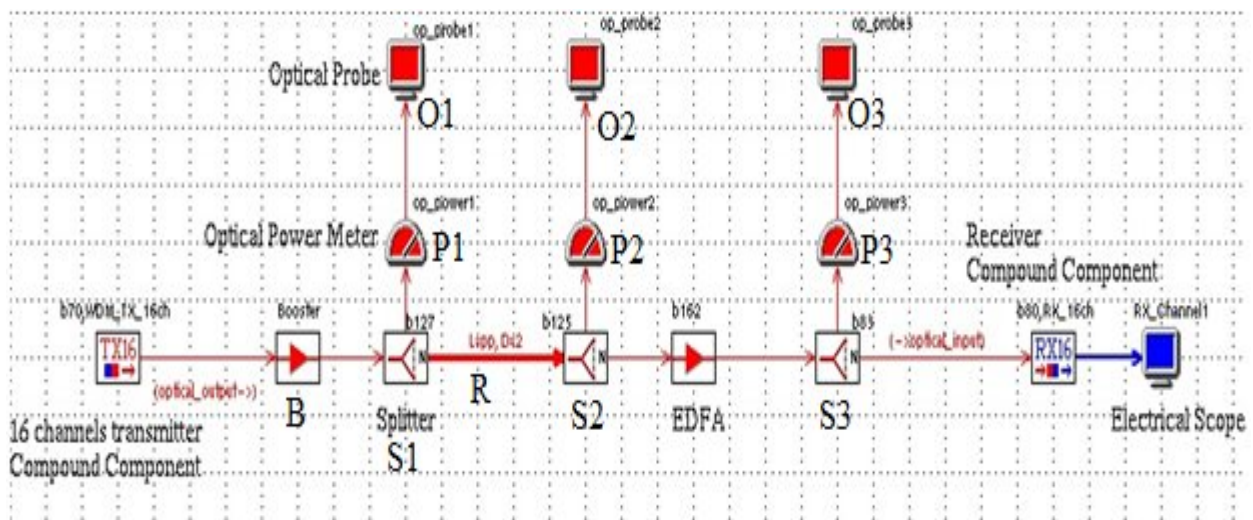


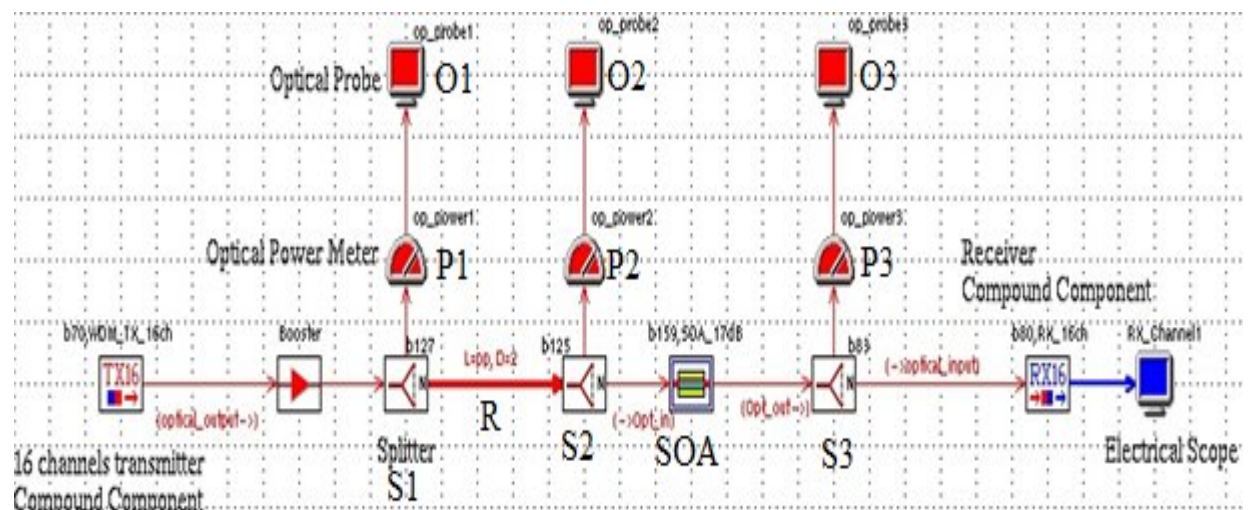
Figure 3.1: Block diagram for simulation setup

The output optical signal of the modulator is fed to the channel where a booster is used to boost the signal. This optical signal is transmitted and measured over different distance for

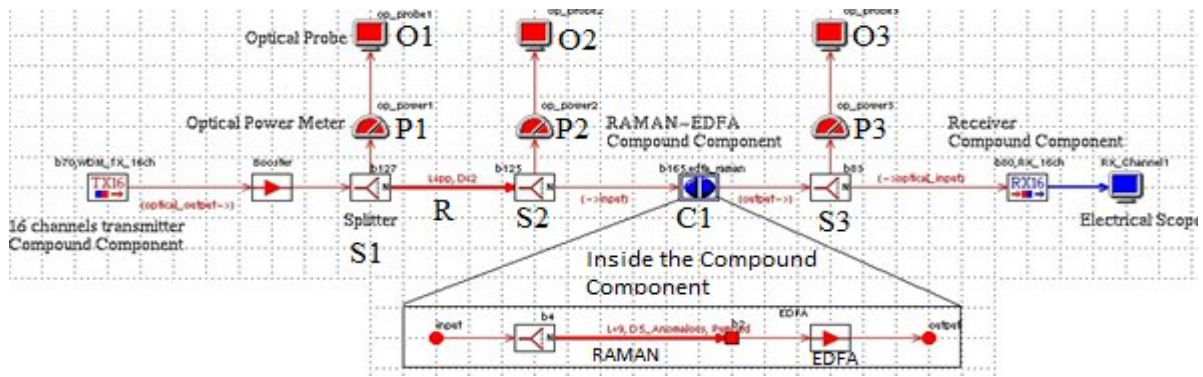
75,100,120,140,150,160,180 Km at 2 ps/nm/km and 4 ps/nm/km dispersion individually. Different types of optical amplifiers are also applied at the receiver side. The set up is repeated for measuring the signal strength by using different amplifiers i.e. EDFA/ SOA/ RAMAN–EDFA/ RAMAN-SOA. Different results like Eye diagram, Q-factor and BER show that Raman – EDFA is the most suitable amplifiers in the all proposed amplifiers. Optical Power meter (P1, P2, P3) and Optical probe (O1, O2, O3) with splitters (S1, S2, S3) are used for measuring the signal power at different levels.



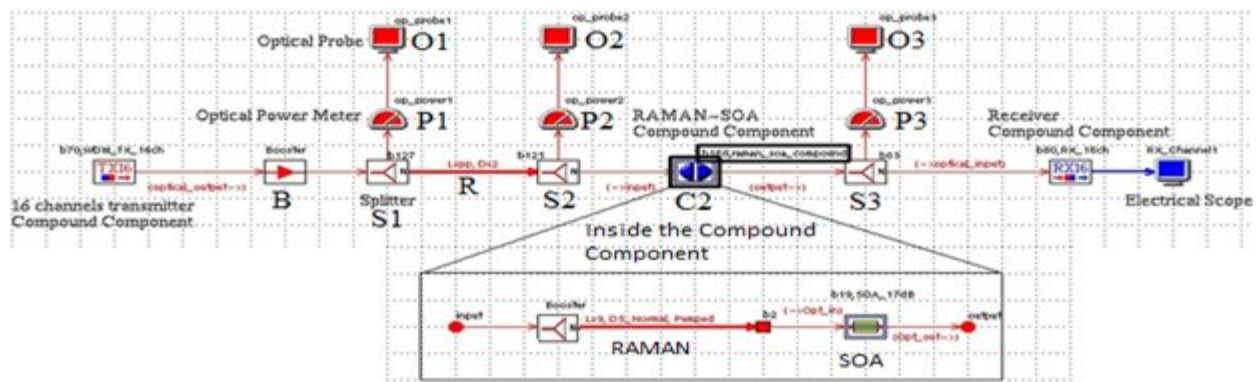
(a)



(b)



(c)



(d)

Figure 3.2: Simulation setup for (a) EDFA, (b) SOA, (c) RAMAN-EDFA HA, (d) RAMAN-SOA HA

Figure 3.2 shows the various simulation set ups for different amplifiers. In figure 3.2 (a) optical signals are amplified using EDFA amplifier. The signal power is measured by power meter and optical probe. This set up is repeated for different distance from 75 km to 180 km by varying the fiber length i.e. R. These set ups are further repeated for SOA, RAMAN–EDFA and RAMAN–SOA. The modulated signal is converted into original signal with the help of PIN photodiode and filters. A compound receiver is used to detect all sixteen signals and converts these into electrical form.

3.4 Result and Discussion

Performance of different amplifiers EDFA/ SOA/ RAMAN–EDFA/ RAMAN–SOA are compared at different distance. The optical signal is connected to different optical amplifier

through a splitter. Different components have different operational parameters. The parameters for external Mach-Zehnder modulator are described in the table 3.1.

The electrical filter is of raised cosine band pass filter with 40 GHz bandwidth, raised cosine exponent is 1 and raised cosine roll off is 0.1. The responsivity of the PIN detector is 1A/W and quantum efficiency is 0.79819.

Table 3.1: Parameters for amplitude modulator are:

Maximum transmissivity offset voltage	2.5 V
Average power reduction due to modulation	3dB
Excess loss	3dB

The DS Anomalous fiber is used to transmit the optical signal. Its various parameters are shown in Table 3.2.

Table 3.2: Parameters for DS Anomalous fiber are:

Reference frequency	193.414THz
Attenuation	0.2 dB/km
Dispersion correlation length	20 km
Fiber nonlinearity coefficient	1.84 1/W/km
Non linear refractive index	$2.5e-20 \text{ m}^{2/W}$
Fiber polarization mode dispersion	$0.1 \text{ ps/km}^{0.5}$

The EDFA is used to amplify the optical signal. Its various parameters are shown in Table 3.3.

Table 3.3: Parameters for EDFA are:

Output power	16 mW
Gain shape	flat
Maximum small signal gain	35dB
Noise figure	4.5dB

The SOA is used to amplify the optical signal. Its various parameters are shown in Table 3.4.

Table 3.4: Parameters for SOA are:

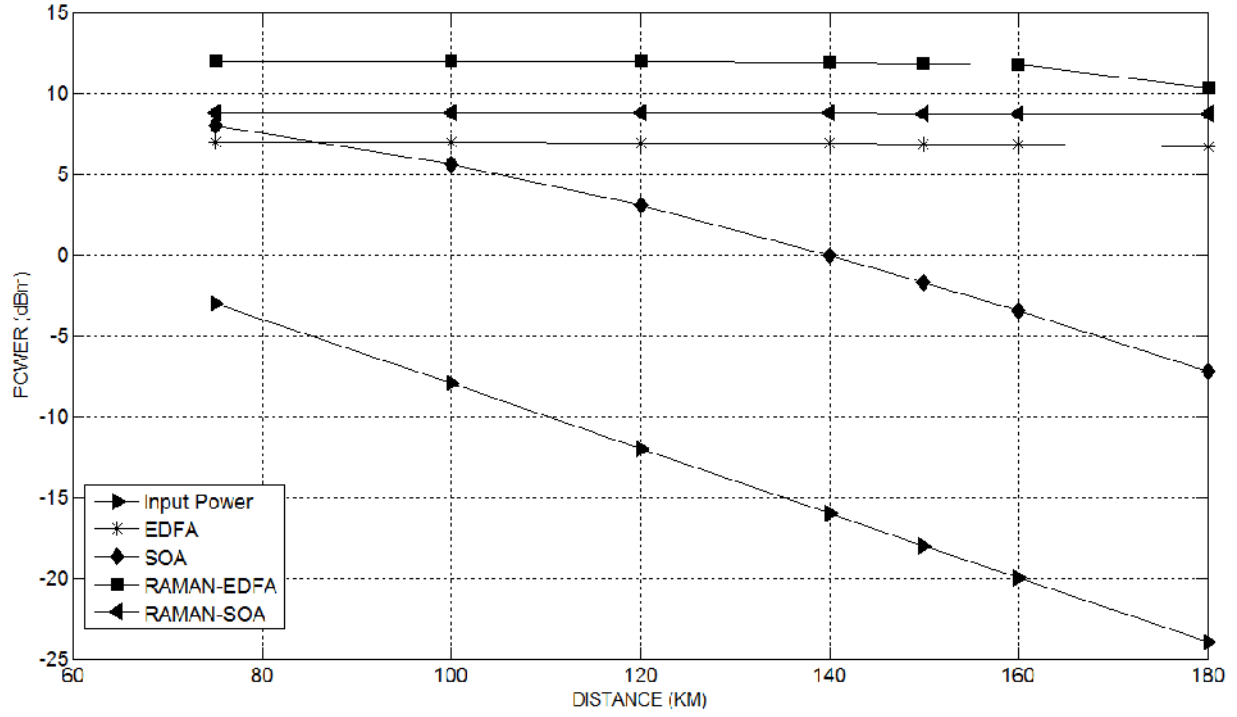
Biased current	100mA
Amplifier length	300 10^{-6} m
Active layer width	300 10^{-6} m
Active layer thickness	0.15 10^{-6} m
Confinement factor	0.35
Spontaneous carrier lifetime	0.3 ns
Insertion loss	3dB,
Output insertion	3dB

The RAMAN amplifier is used to amplify the optical signal. Various parameters for RAMAN are shown in Table 3.5.

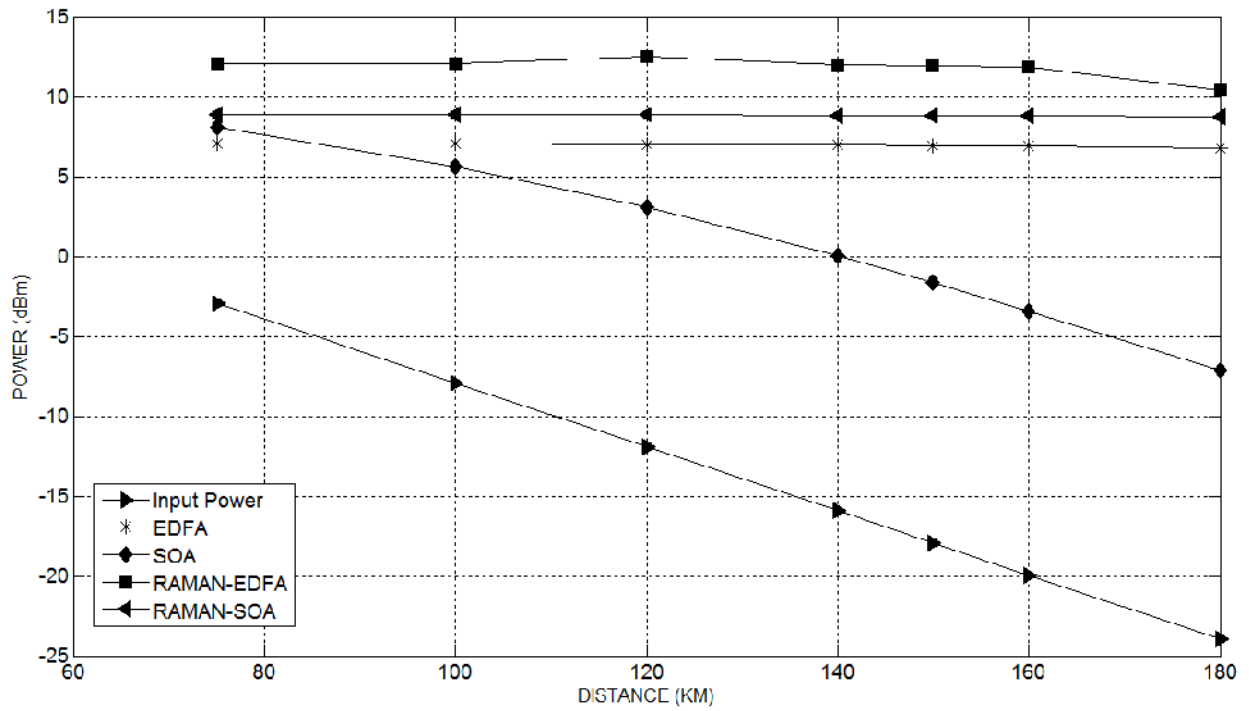
Table 3.5: Parameters for RAMAN fiber are:

RAMAN fiber length	9 km
Operating temperature	300K
Pump power	150 mW
Pump wavelength	1550 nm
Pump attenuation	1.2 dB/km

In order to observe the performance of different amplifiers (EDFA, SOA, RAMAN-EDFA, RAMAN-SOA), the output power versus transmission distance graph are shown for different dispersion. These graphs show that as we increase the transmission distance from 75 to 180 km, the output power decreases simultaneously. The variation in output power from different optical amplifiers at dispersion $D=2$ ps/nm/km is 6.966 to 6.726 dBm for EDFA, 8.038 to -7.184 dBm for SOA, 12.011 to 10.334 dBm for RAMAN-EDFA, 8.830 to 8.696 dBm for RAMAN-SOA. The variation in output power from different optical amplifiers at dispersion $D=4$ ps/nm/km is 7.045 to 6.750 dBm for EDFA, 8.072 to -7.171 dBm for SOA, 12.087 to 10.384 dBm for RAMAN-EDFA, 8.856 to 8.708 dBm for RAMAN-SOA.



(a)



(b)

Figure 3.3: Power vs Distance for (a) $D=2$ ps/nm/km (b) $D=4$ ps/nm/km

The output power results from different optical amplifiers at dispersion $D=2, 4$ ps/nm/km are shown in figure 3.3. It is observed that maximum output power is obtained from RAMAN-EDFA i.e. 12.017 dBm at 100 km transmission distance. The transmission distance is varied with R ($R=75, 100, 120, 140, 150, 160, 180$ km). The input of optical amplifiers is -2.980 to -23.954 dBm for $D=2$ ps/nm/km and -2.911 to -23.966 dBm is for $D=4$ ps/nm/km corresponding to different transmission distance.

Optical spectrum of signal after EDFA at 100 km distance with 2 ps/nm/km and 4 ps/nm/km is shown in figure 3.4. The optical output power for dispersion 2 ps/nm/km and 4 ps/nm/km is 6.983 dBm and 7.046 dBm respectively.

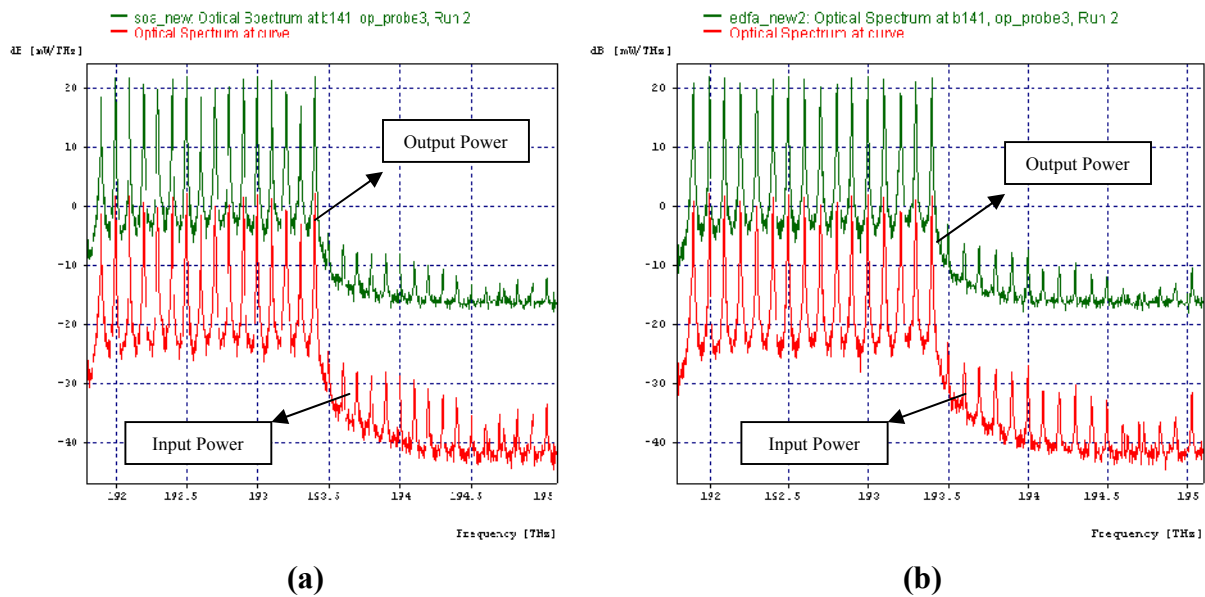
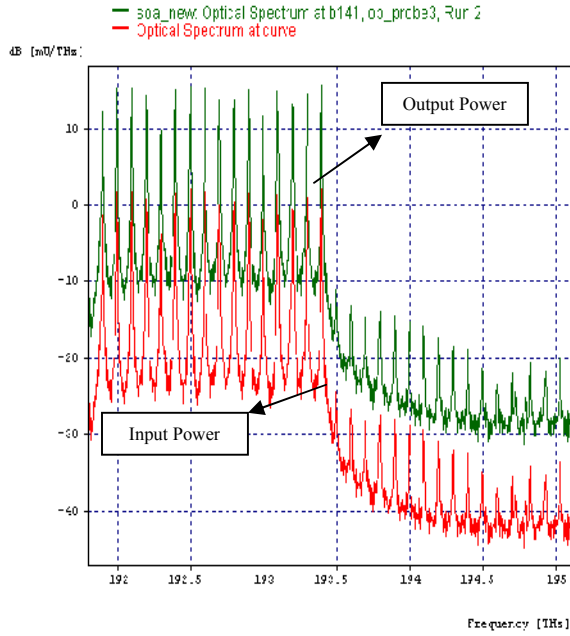


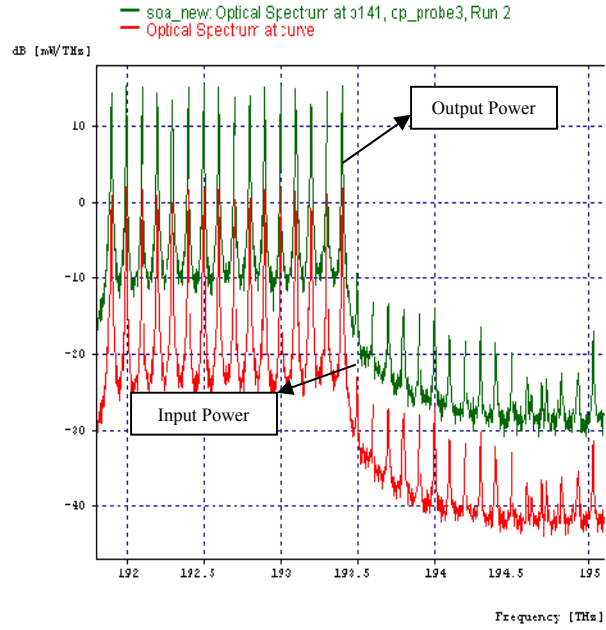
Figure 3.4: Optical Spectrum from EDFA at 100 km for (a) $D=2$ ps/nm/km (b) $D=4$ ps/nm/km

Optical spectrum of signal after SOA at 100 km distance with 2 ps/nm/km and 4 ps/nm/km is shown in figure 3.5. The optical output power for dispersion 2 ps/nm/km and 4 ps/nm/km is 5.587 dBm and 5.618 dBm respectively.

Optical spectrum of signal after RAMAN-EDFA at 100 km distance with 2 ps/nm/km and 4 ps/nm/km is shown in figure 3.6. The optical output power for dispersion 2 ps/nm/km and 4 ps/nm/km is 12.017 dBm and 12.088 dBm respectively.

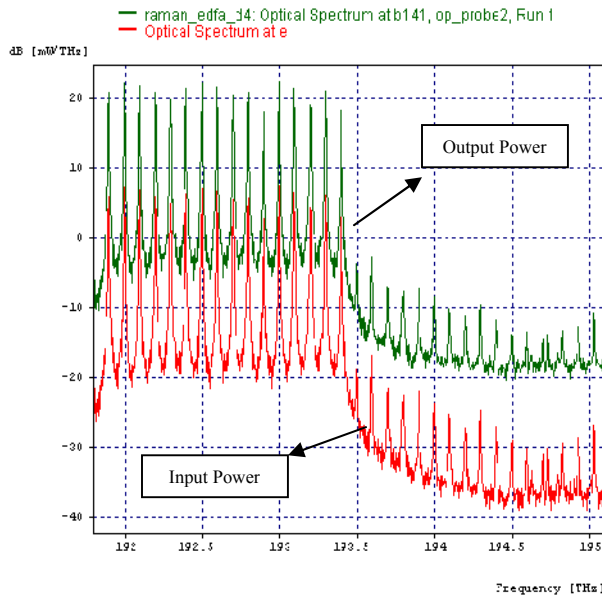


(a)

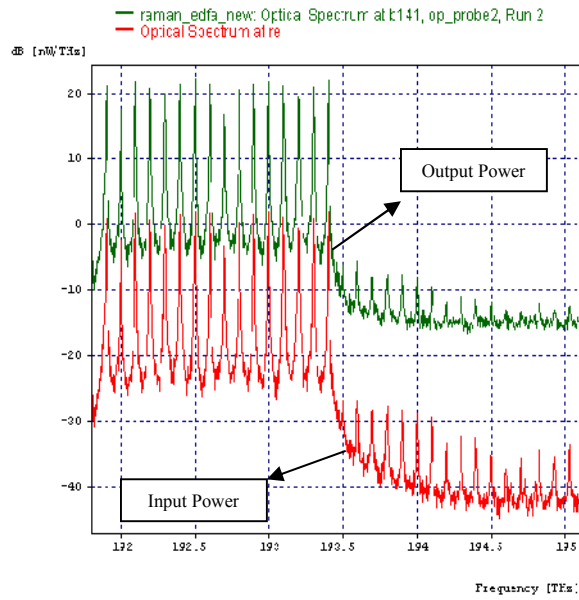


(b)

Figure 3.5: Optical Spectrum from SOA at 100km for (a) $D=2$ ps/nm/km (b) $D=4$ ps/nm/km



(a)



(b)

Figure 3.6: Optical Spectrum from RAMAN-EDFA at 100 km for (a) $D=2$ ps/nm/km (b) $D=4$ ps/nm/km

Optical spectrum of signal after RAMAN-SOA at 100 km distance with 2 ps/nm/km and 4 ps/nm/km is shown in figure 3.7. The optical output power for dispersion 2 ps/nm/km and 4 ps/nm/km is 8.834 dBm and 8.856 dBm respectively.

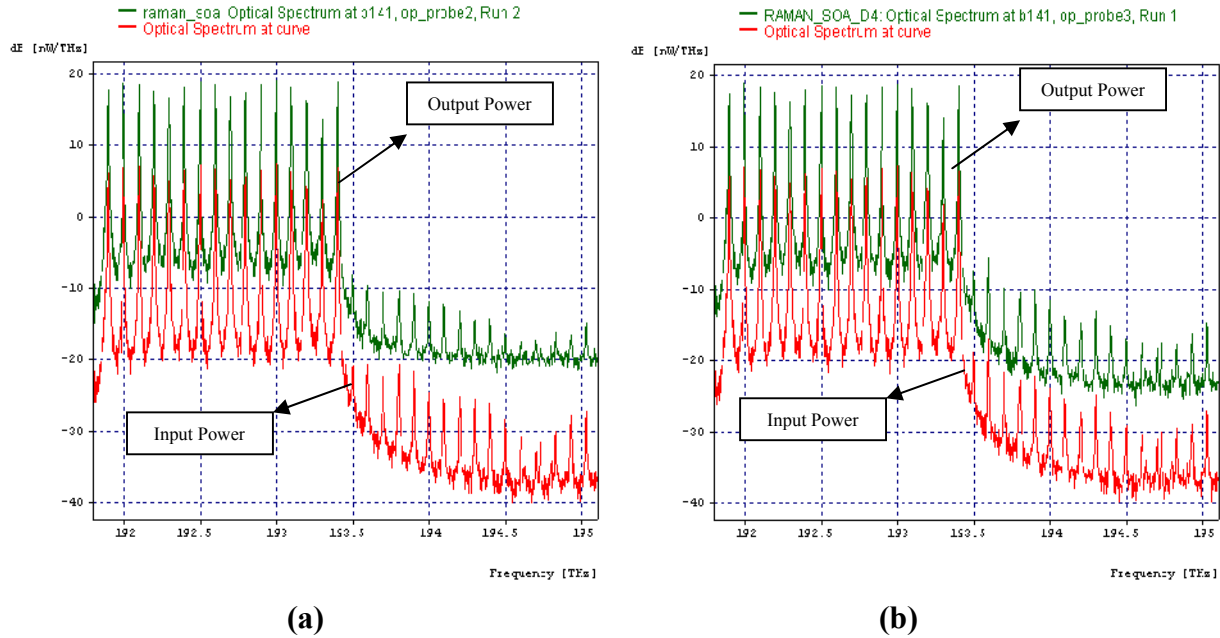
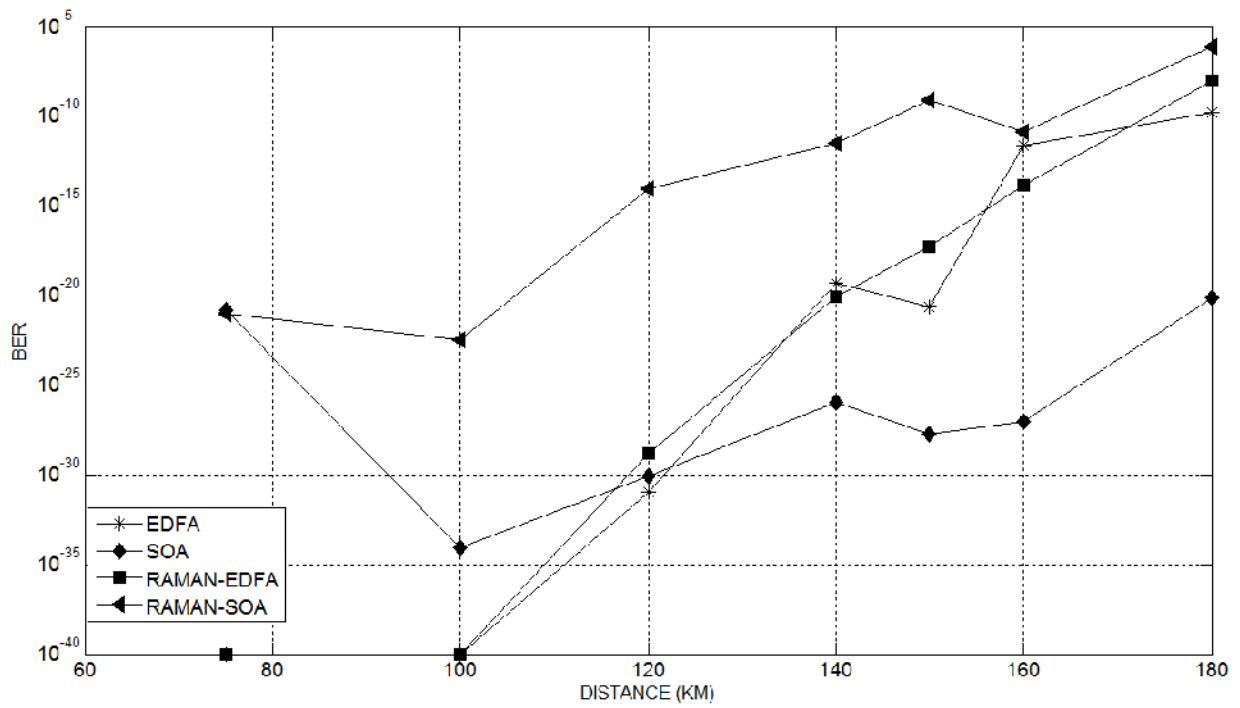


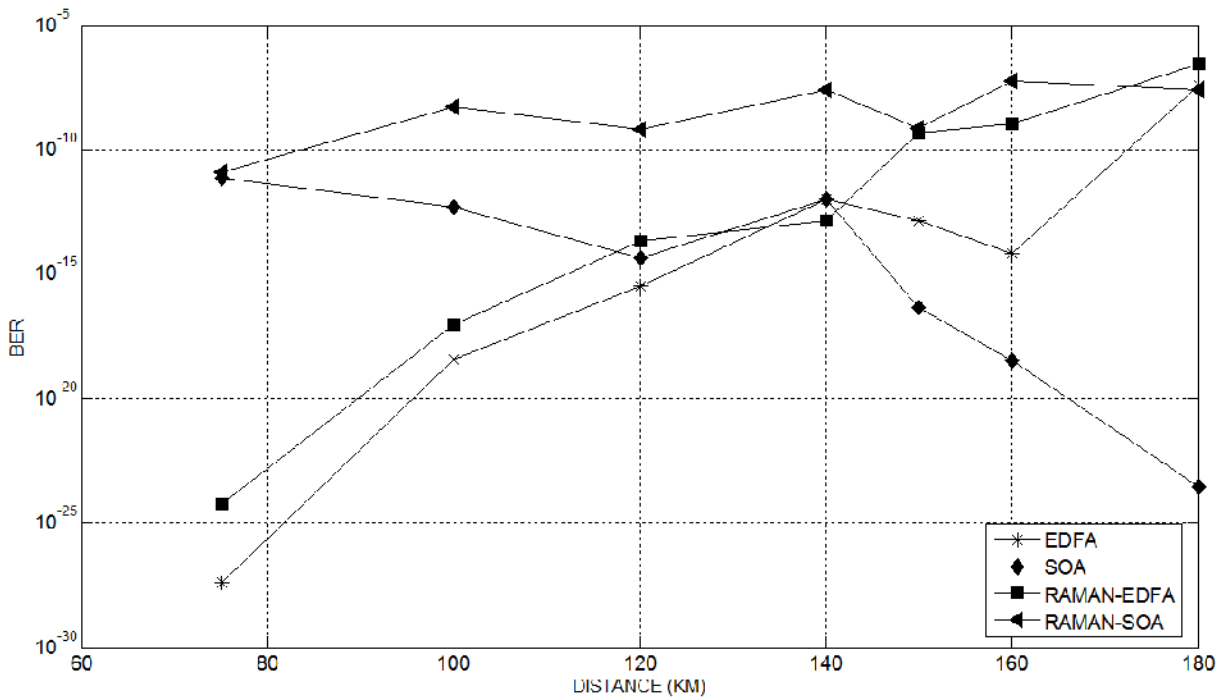
Figure 3.7: Optical Spectrum from RAMAN-SOA at 100 km for (a) D=2 ps/nm/km (b) D=4 ps/nm/km

This comparison shows that output power of 12.017 dBm at 100 km transmission distance is the maximum output power obtained by RAMAN- EDFA hybrid amplifier.

The acceptable bit error rate (BER) for optical transmission is 1×10^{-9} . The BER versus transmission distance for different dispersion is shown in figure 3.8. It is observed that by increasing the transmission distance from 75 to 180 km, BER is also increasing. The variation in BER from different optical amplifiers at dispersion $D=2$ ps/nm/km is 1×10^{-40} to 1.53×10^{-10} for EDFA, 1.50×10^{-21} to 7.75×10^{-21} for SOA, 1×10^{-40} to 9.16×10^{-9} for RAMAN-EDFA (HA), 9.85×10^{-22} to 7.53×10^{-7} for RAMAN-SOA (HA). The variation in BER from different optical amplifiers at dispersion $D=4$ ps/nm/km is 4.10×10^{-28} to 3.77×10^{-8} for EDFA, 6.95×10^{-12} to 2.91×10^{-24} for SOA, 5.71×10^{-25} to 2.68×10^{-7} for RAMAN-EDFA (HA), 1.17×10^{-11} to 2.52×10^{-8} for RAMAN-SOA HA.



(a)

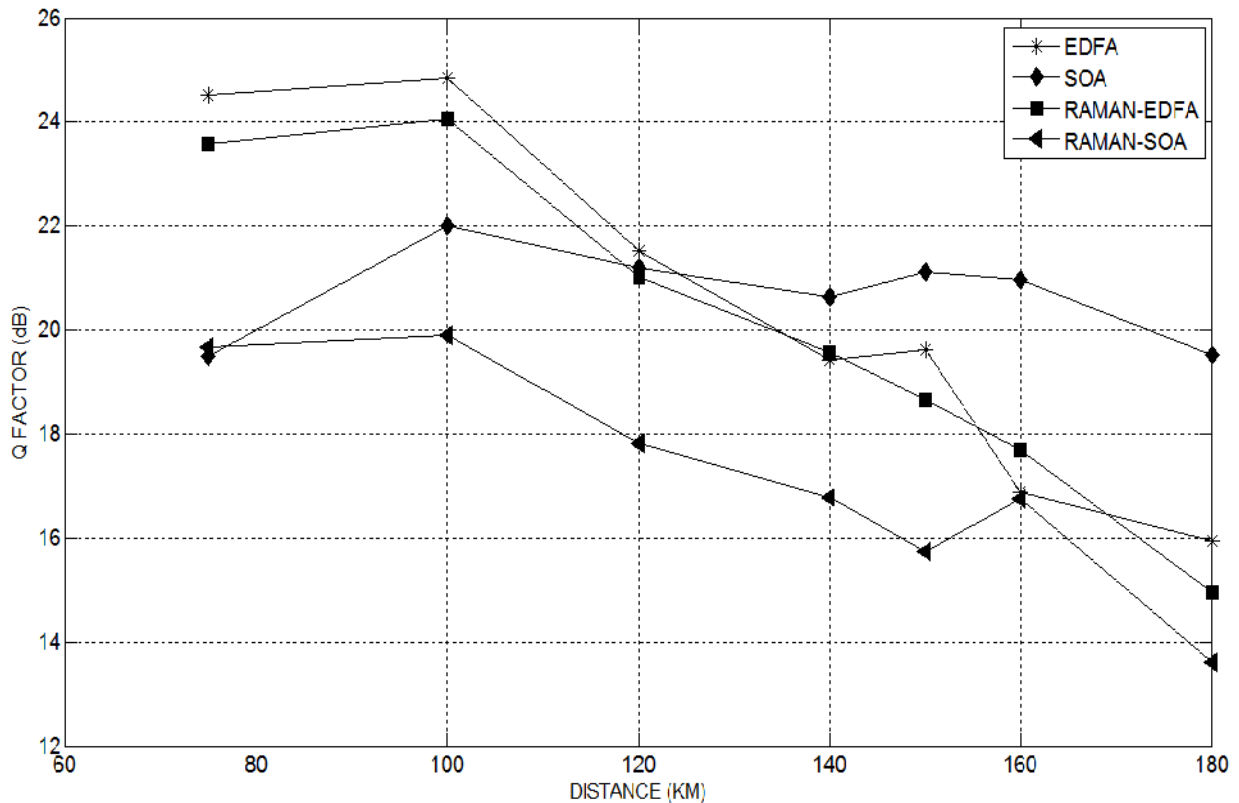


(b)

Figure 3.8: BER vs Distance for (a) $D=2$ ps/nm/km (b) $D=4$ ps/nm/km

It is observed from the simulation result that minimum BER value is obtained from RAMAN-EDFA and EDFA which is 1×10^{-40} at 100 km transmission distance. The results show that the minimum BER is provided by SOA for all distance but it provides very less power. Minimum BER and maximum output power both are achieved from RAMAN-EDFA at distance 100km.

The Q Factor versus transmission distance for different dispersion is shown in figure 3.9. It is observed that by increasing the transmission distance from 75 to 180 km, Q factor is decreasing. The variation in Q factor at dispersion $D=2$ ps/nm/km is 24.514 to 15.947 dB for EDFA, 19.486 to 19.519 dB for SOA, 23.586 to 14.953 dB for RAMAN-EDFA, 19.679 to 13.611 dB for RAMAN-SOA. The variation in Q factor at dispersion $D=4$ ps/nm/km is 21.020 to 14.721 dB for EDFA, 16.725 to 20.226 dB for SOA, 20.470 to 13.966 dB for RAMAN-EDFA, 16.447 to 14.762 dB for RAMAN-SOA.



(a)

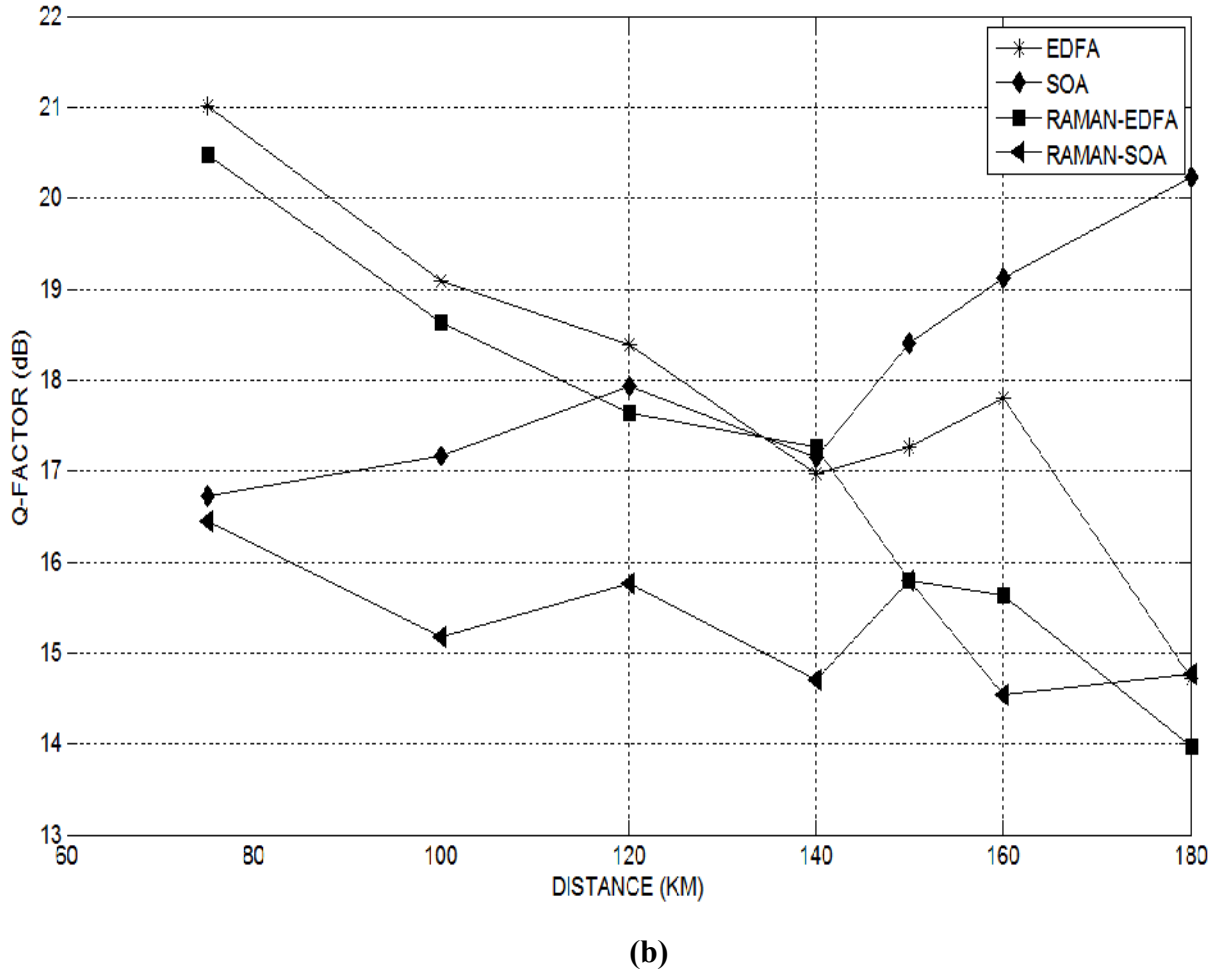
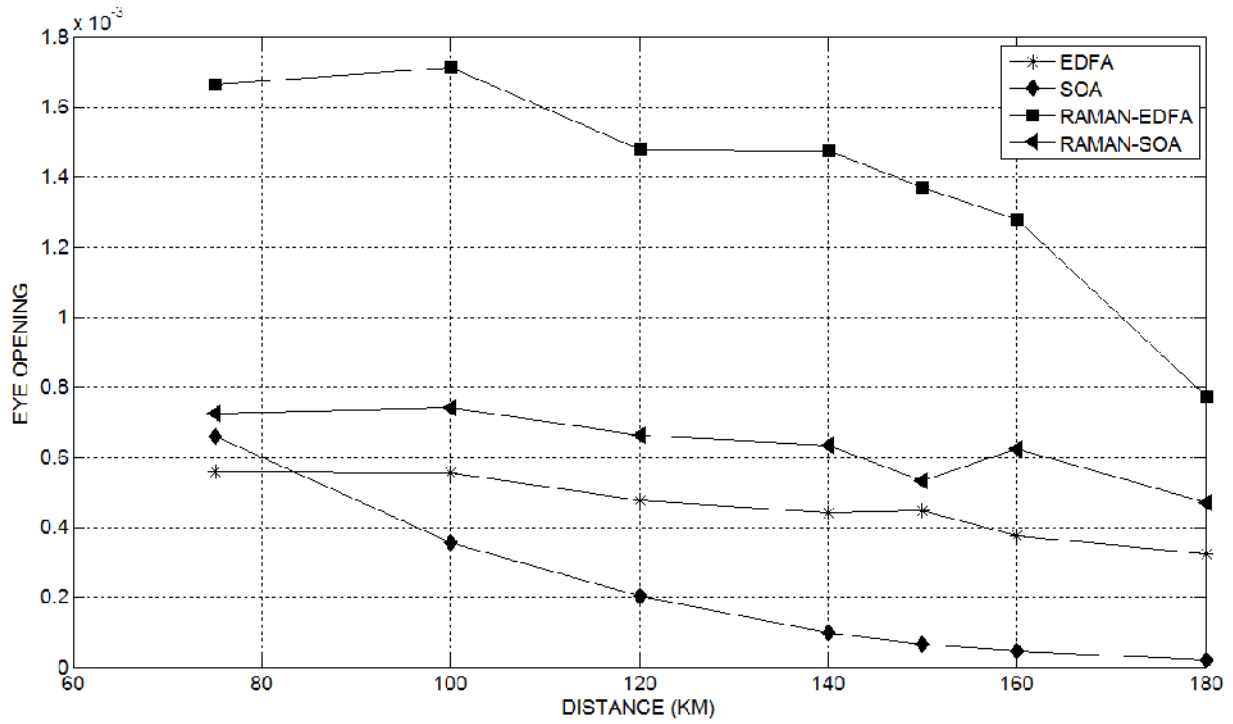


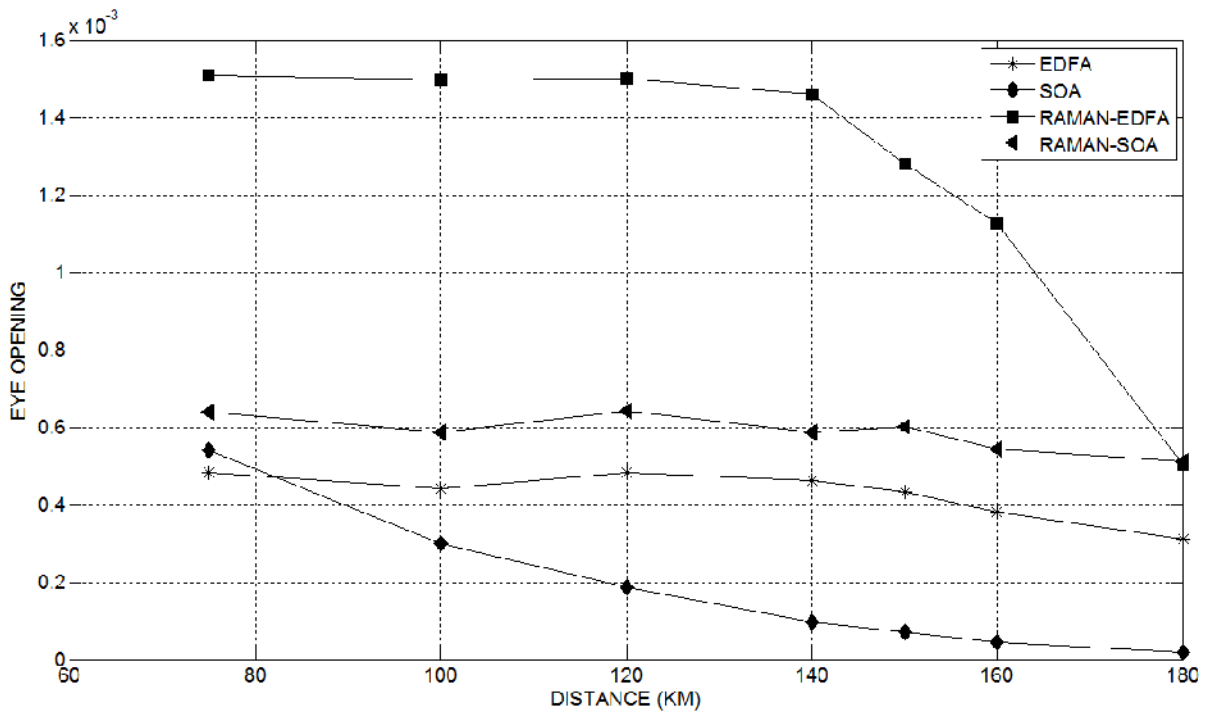
Figure 3.9: Q Factor vs Distance for (a) D=2 ps/nm/km (b) D=4 ps/nm/km

It is observed from the simulation result that maximum Q factor is obtained from EDFA and RAMAN-EDFA hybrid amplifier is 24.841 and 24.067 dB at 100 km transmission distance.

The eye opening from different amplifiers versus transmission distance is shown in figure 3.10. Large eye opening means less BER and good communication. It is observed that by increasing the transmission distance from 75 to 180 km, eye opening is also decreasing. The variation in eye opening from different optical amplifiers at dispersion $D=2$ ps/nm/km is 5.59×10^{-4} to 3.25×10^{-4} for EDFA, 6.60×10^{-4} to 1.96×10^{-005} for SOA, 1.66×10^{-3} to 7.74×10^{-4} for RAMAN-EDFA, 7.24×10^{-4} to 4.69×10^{-4} for RAMAN-SOA. The variation in Eye opening from different optical amplifiers at dispersion $D=4$ ps/nm/km is 4.82×10^{-4} to 3.10×10^{-4} for EDFA, 5.41×10^{-4} to 1.83×10^{-005} for SOA, 1.50×10^{-3} to 4.04×10^{-4} for RAMAN-EDFA, 6.39×10^{-4} to 5.10×10^{-4} for RAMAN-SOA.



(a)



(b)

Figure 3.10: Eye opening vs Distance for (a) $D=2$ ps/nm/km (b) $D=4$ ps/nm/km

It is observed from the simulation result that maximum eye opening is obtained from RAMAN-EDFA is 1.71×10^{-3} , 1.56×10^{-3} for $D=2$ or 4 ps/nm/km at 100 km transmission distance.

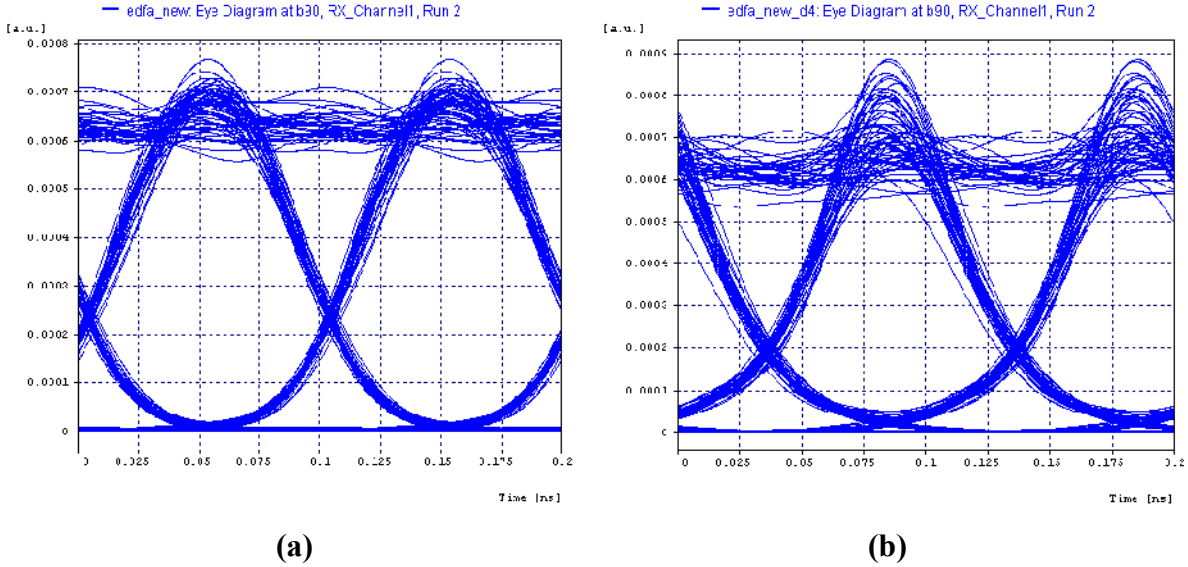


Figure 3.11: Eye diagram for EDFA at 100 km for (a) $D=2$ ps/nm/km (b) $D=4$ ps/nm/km

Eye diagram of signal after EDFA at 100 km distance with 2 ps/nm/km and 4 ps/nm/km is shown in figure 3.11. The eye opening for dispersion 2 ps/nm/km and 4 ps/nm/km is 5.56×10^{-4} and 4.41×10^{-4} respectively.

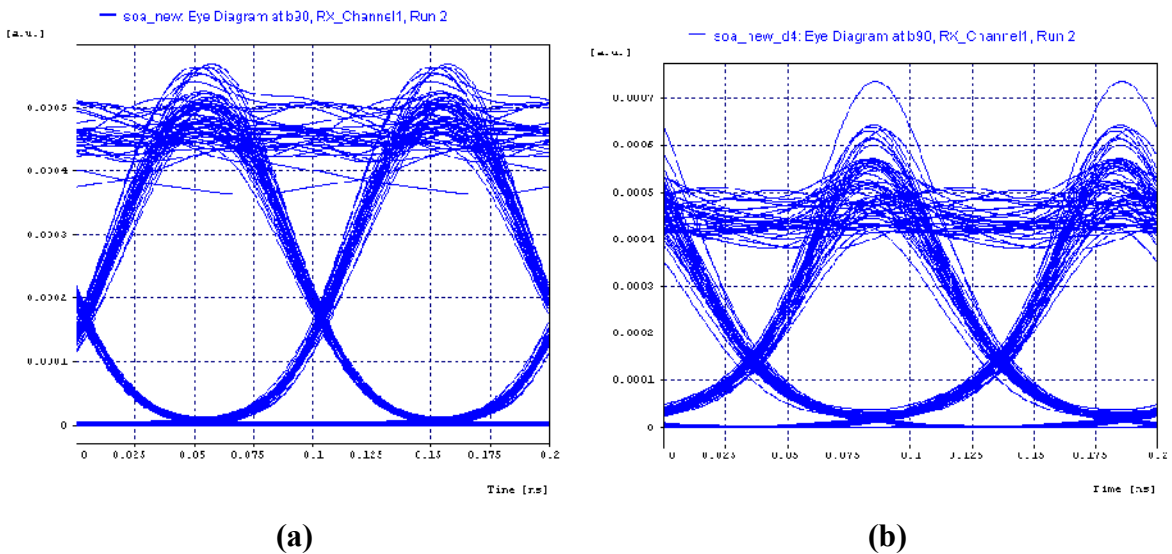


Figure 3.12: Eye diagram for SOA at 100 km for (a) $D=2$ ps/nm/km (b) $D=4$ ps/nm/km

Eye diagram of signal after SOA at 100 km distance with 2 ps/nm/km and 4 ps/nm/km is shown in figure 3.12. The eye opening for dispersion 2 ps/nm/km and 4 ps/nm/km is 3.55×10^{-4} and 3.01×10^{-4} respectively.

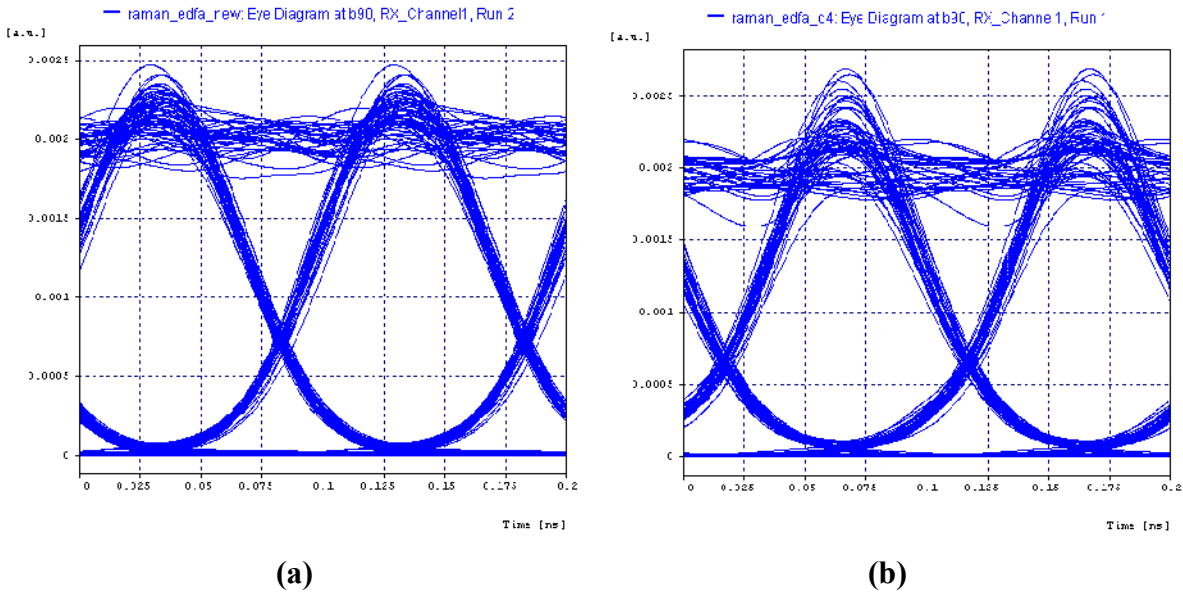


Figure 3.13: Eye diagram for RAMAN-EDFA at 100 km for (a) D=2 ps/nm/km (b) D=4 ps/nm/km

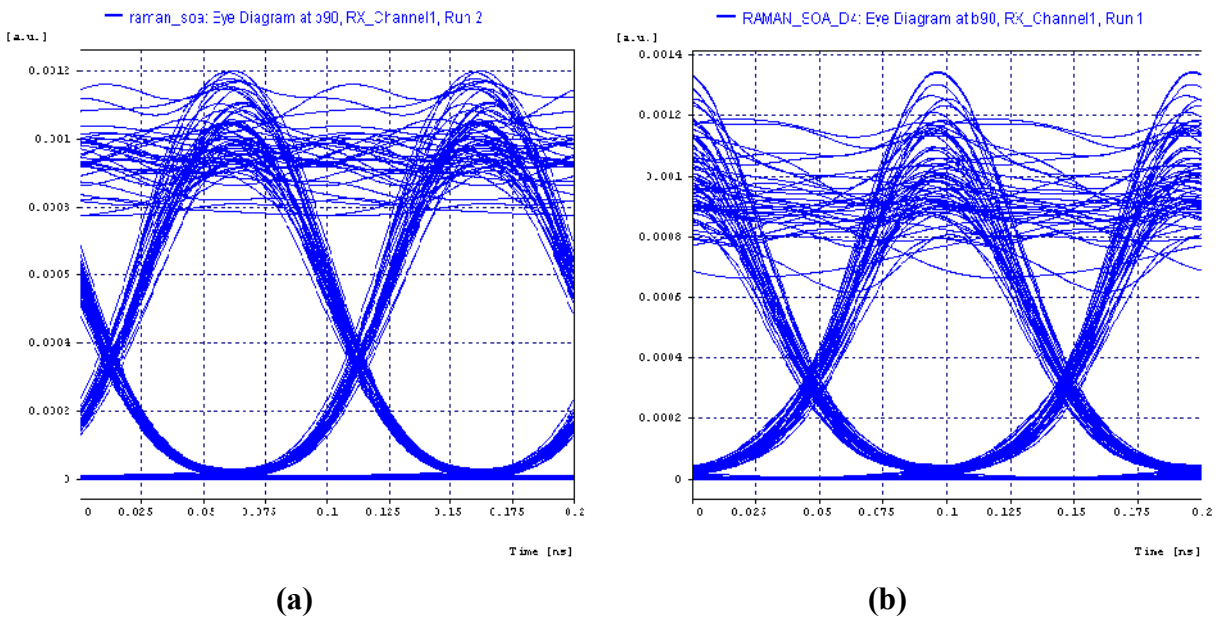


Figure 3.14: Eye diagram for RAMAN-SOA at 100 km for (a) D=2 ps/nm/km (b) D=4 ps/nm/km

Eye diagram of signal after RAMAN-EDFA at 100 km distance with 2 ps/nm/km and 4 ps/nm/km is shown in figure 3.13. The eye opening for dispersion 2 ps/nm/km and 4 ps/nm/km is 1.71×10^{-3} and 1.49×10^{-3} respectively.

Eye diagram of signal after RAMAN-SOA at 100 km distance with 2 ps/nm/km and 4 ps/nm/km is shown in figure 3.14. The eye opening for dispersion 2 ps/nm/km and 4 ps/nm/km is 7.40×10^{-4} and 5.88×10^{-4} respectively.

3.5 Conclusion

The optical amplifiers and hybrid optical amplifiers design models were successfully designed and implemented into OptSim. The main motivation of this work is to optimize the optical amplifiers for different dispersion and transmission distance.

The performance of optical amplifiers was evaluated using the eye patterns, BER measurement, eye opening and Q factor. The simulation results show that RAMAN-EDFA performed better than EDFA, SOA, RAMAN-SOA optical amplifier. RAMAN-EDFA provide high power (12.011 to 10.334 dBm for D=2ps/nm/km and 12.087 to 10.384 dBm for D=4ps/nm/km), least BER (1×10^{-40} to 9.16×10^{-9} for D=2ps/nm/km and 5.71×10^{-25} to 2.68×10^{-7} for D=4ps/nm/km), large Q factor (23.586 to 14.953 dB for D=2ps/nm/km and 20.470 to 13.960 dB for D=4ps/nm/km) and good eye diagram for different transmission distance ranging from 75 to 180 km. These results are valid upto 100 Kms. Above 100 km distance, there is more distortion in the detected signal. The output power, Q factor and eye opening are decreasing above this. Also, there is an increment in BER after 100 Km. So, this proposed model is best suited for 100 km distance.

In conclusion, this model has demonstrated that RAMAN-EDFA is a promising alternative to EDFA, SOA, RAMAN-SOA in optical transmission.

CHAPTER 4

Simulation of 16×10 Gbps WDM System Based on RAMAN-EDFA

HA at Different Pumping and Dispersion

4.1 Abstract

In this chapter, the 16 channel WDM systems at 10 Gbps have been investigated for the various RAMAN-EDFA optical amplifiers pumping and its power. The performance has been compared on the basis of different fiber length and dispersion. Four types of pumping have been investigated independently and compared. It is observed that pump 2 of RAMAN-EDFA provides the highest output power (12.048 dBm and 12 dBm) and least bit error rate (5.44×10^{-26} and 1.91×10^{-12}) at 140 km for dispersion 2ps/nm/km and 4ps/nm/km respectively as compare to other pumping amplifier. It is also observed that fiber length for pumping of the RAMAN-EDFA is acceptable only upto 30 kms (at this length power is 12.076dBm). After 30 Kms, the power is decreased instantly.

4.2 Introduction

Regardless of the reckless bursting of the so-called wavelength division multiplexing (WDM) in now days, Internet traffic has ever been increasing and this trend seems to stay unchanged for the foreseeable future. Behind the constant increase of Internet traffic, various applications have emerged one after another, exploiting higher bandwidth per user. Wavelength Division Multiplexing (WDM) has been now widely used to demonstrate the transmission of high capacity based on 10 Gbit/s modulation per wavelength [40, 45, 46].

There are plenty of ways in different network layers, ranging from optimizing the network architecture to the use of better fiber links, to enhance the connectivity. In any of these approaches, the portion of the data staying in the optical rather than the electric domain would increase in the future networks with higher data capacity and efficiency. The more the data is in the optical domain, the more the optical transmission performance of the system has to be well maintained and fast. The performance of the optical transmission is determined by optical

transmission links consisting of optical data transmitters and receivers, optical fiber cables, optical switches, couplers, and optical amplifiers. This chapter focuses on RAMAN-EDFA at different pumping and pumping power, which are an emerging technology and in fact being gradually deployed for the commercial services.

Raman amplifiers are better to any other alternatives for optical amplification in terms of high signal transmission performance. Erbium-doped fiber amplifiers (EDFAs), which have been widely used in the actual optical transmission systems now in service. EDFAs are of low noise, compact, highly efficient with high gain, and capable of amplifying multichannel signals on different wavelengths at a time, and hence quite economical for WDM transmissions. Another alternative of optical amplification is the semiconductor optical amplifier (SOA), which is nominally an optical amplifier device with an active waveguide integrated onto a compound semiconductor. SOA is superior in the sense of high integration and additional functionality such as wavelength conversion and all-optical regeneration.

Now days Optical hybrid amplifier provides high power gain. Mohammed N.Islam described that The total amplifier gain (G_{Hybrid}) is the sum of the two gains [6]:

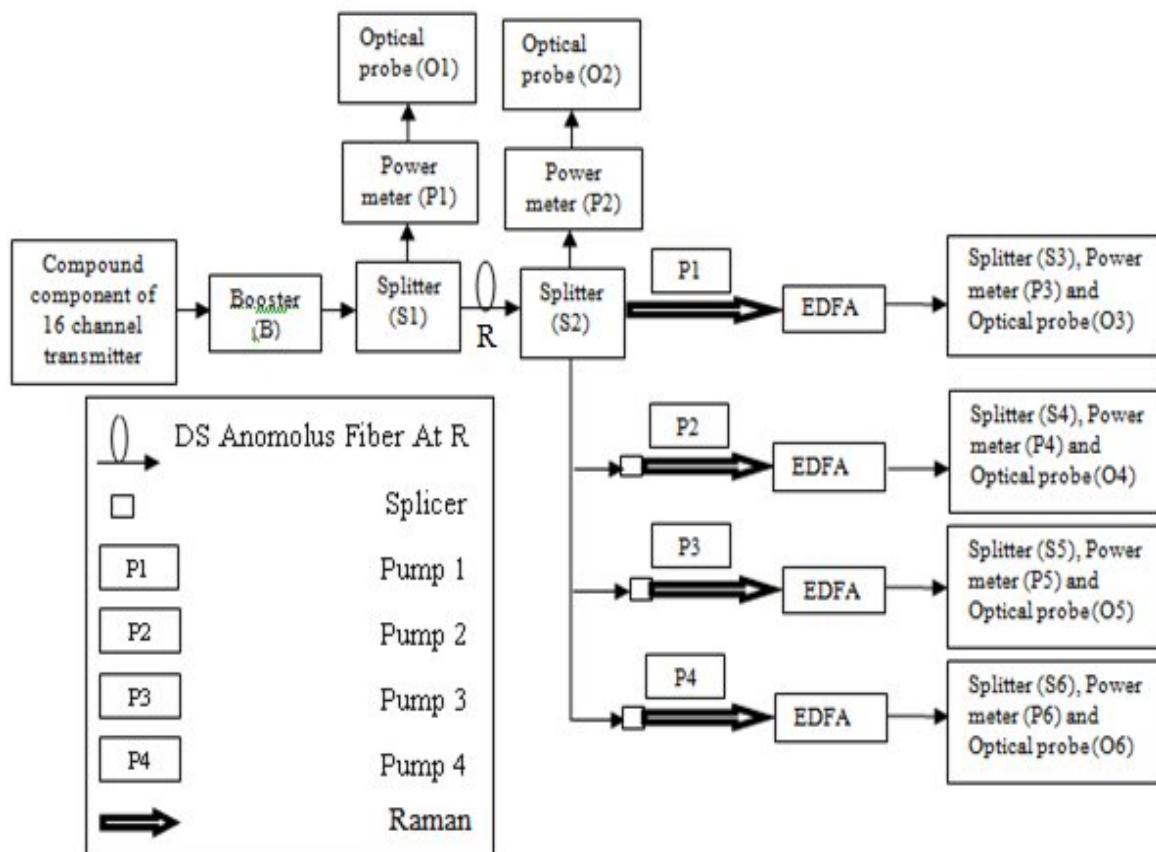
$$G_{\text{Hybrid}} = G_{\text{EDFA}} + G_{\text{Raman}}$$

Ju Han Lee et al. [47] also experimentally demonstrated a dispersion-compensating Raman/EDFA hybrid amplifier recycling residual Raman pump for increase of overall power conversion efficiency. They achieve the significant enhancement of both signal gain and effective gain-bandwidth by 15 dB (small signal gain) and 20 nm, respectively, compared to the performance of the Raman-only amplifier. JB. Leroy et al. [48] obtained the Q factor improvement when turning on the 100 mW Raman pumps is 1.3dB with +10 dBm amplifier output.

4.3 Simulation Setup

The block diagram of different configuration of RAMAN-EDFA for pumping is shown in figure 4.1. In this model, sixteen users transmitted their data over a bandwidth of 3.2 THz at 10 Gb/s speed with channel spacing of 100 GHz. Each input signal is modulated in NRZ format and pre-amplified by a booster. The amplified signals send to the channel where these signal are transmitted over DS-anomalous fiber of different transmission distance. A transmitter compound component is built up using sixteen transmitters. This transmitter compound component consists

of the data source, electrical driver, laser source and external Mach-Zehnder modulator in each transmitter section. The data source is generating signal of 10 Gb/s with pseudo random sequence. The electrical driver converts the logical input signal into an electrical signal. The CW laser sources generate the 16 laser beams at 191.9 THz to 193.4 THz with 100 GHz channel spacing. These beams have random laser phase and ideal laser noise bandwidth. The signals from data source and laser are fed to the external Mach-Zehnder modulator (\sin^2_MZ for all configurations), where the input signals from data source is modulated through a carrier (optical signal from the laser source).



**Figure 4.1 Block Diagram of RAMAN EDFA with different pumping systems
(Where R= 75,100,120,140,150,160,180)**

The output optical signal of the modulator is fed to the channel where a booster is used to boost the signal. This optical signal is transmitted and measured over different distance for 75,100,120,140,150,160,180 Km at 2 ps/nm/km and 4 ps/nm/km dispersion individually. Optical

Power meter (P1, P2, P3 etc.) and Optical probe (O1, O2, O3 etc) with splitters (S1, S2, S3 etc) are used for measuring the signal power at different levels. RAMAN EDFA amplifier is used for amplifying the optical signal. Different types of pumping in RAMAN EDFA are applied at the receiver side. The set up is repeated for measuring the signal strength by using different four pumps named Pump1, Pump2, Pump3, Pump4. Different results like Eye diagram, Q-factor and BER show that Pump 2 in RAMAN-EDFA amplifier is the most suitable pump in the all proposed pumps. Fiber nonlinearities, polarization mode dispersion, birefringence are considered in simulation but raman crosstalk is not consider.

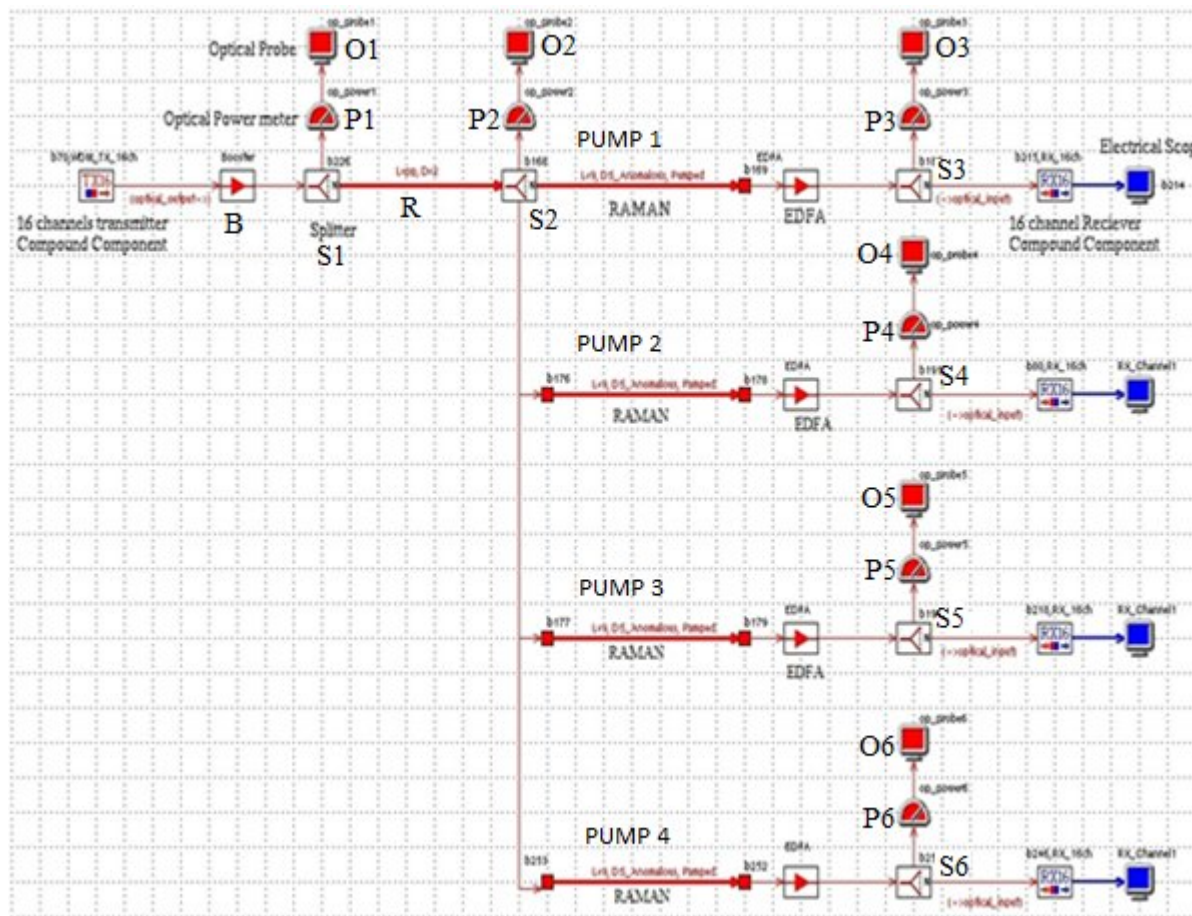


Figure 4.2: Simulation Setup for RAMAN-EDFA HA at different Pumping

The simulation set up for different pumps is shown in figure 4.2. The optical signals are generated by sixteen transmitter compound component and this signal is fed to RAMAN EDFA

via booster and DS Anomalous fiber. The signal power is measured by power meter and optical probe. This set up is repeated for different distance from 75 km to 180 km by varying the fiber length i.e. R. The modulated signal is converted into original signal with the help of PIN photodiode and filters. A compound receiver is used to detect all sixteen signals and converts these into electrical form.

4.4 Result and Discussion

Performance of different pumps in RAMAN EDFA amplifier is compared at different distance. The optical signal is connected to different pumps through a splitter. Different components have different operational parameters. The parameters for external Mach-Zehnder modulator are described in the table 4.1.

Table 4.1: Amplitude modulator parameter

Maximum transmissivity offset voltage	2.5 V
Average power reduction due to modulation	3dB
Excess loss	3dB

The DS Anomalous fiber is used to transmit the optical signal. Its various parameters are shown in Table 4.2.

Table 4.2: DS Anomalous fiber parameters

Reference frequency	193.414THz
Attenuation	0.2 dB/km
Dispersion correlation length	20 km
Fiber nonlinearity coefficient	1.84 1/W/km
Non linear refractive index	$2.5e-20 \text{ m}^{2/W}$
Fiber polarization mode dispersion	$0.1 \text{ ps/km}^{0.5}$

The RAMAN amplifier is used to amplify the optical signal. Various parameters for RAMAN are shown in Table 4.3.

Table 4.3: RAMAN amplifier parameters

RAMAN fiber length	9 km
Operating temperature	300K
Pump power	150 mW
Pump wavelength	1550 nm
Pump attenuation	1.2 dB/km

The EDFA is used to amplify the optical signal. Its various parameters are shown in Table 4.4.

Table 4.4: EDFA parameters

Output power	16 mW
Gain shape	flat
Maximum small signal gain	35dB
Noise figure	4.5dB

Table 4.5: Various power parameters of all proposed pumps:

Pump	co-propagating pumping (nm)	co-propagating pump power (mW)	counter propagating pumping (nm)	counter propagating pump power (mW)
Pump 1	1365	250	1453	500
Pump 2	1365	300	1453	500
Pump 3	1365	400	1453	500
Pump 4	1365	500	1453	500

The electrical filter is of raised cosine band pass filter with 40 GHz bandwidth, raised cosine exponent is 1 and raised cosine roll off is 0.1. The responsivity of the PIN detector is 1A/W and quantum efficiency is 0.79819.

In order to observe the performance of different pumps, the output power versus transmission distance graph is shown for different dispersion. These graphs show that as we increase the

transmission distance from 75 to 180 km, the output power decreases simultaneously. The variation in output power from different pumps at dispersion $D=2$ ps/nm/km for pump 1 is 12.074 to 10.293 dBm, for pump 2 is 12.073 to 10.280 dBm, for pump 3 is 12.073 to 10.322 dBm and for pump 4 is 12.072 to 10.290 dBm as shown in figure 4.3. The variation in output power from different pumps at dispersion $D=4$ ps/nm/km for pump 1 is 12.023 to 10.347 dBm, for pump 2 is 12.026 to 10.347 dBm, for pump 3 is 12.024 to 10.339 dBm and for pump 4 is 12.023 to 10.336 dBm as shown in figure 4.3.

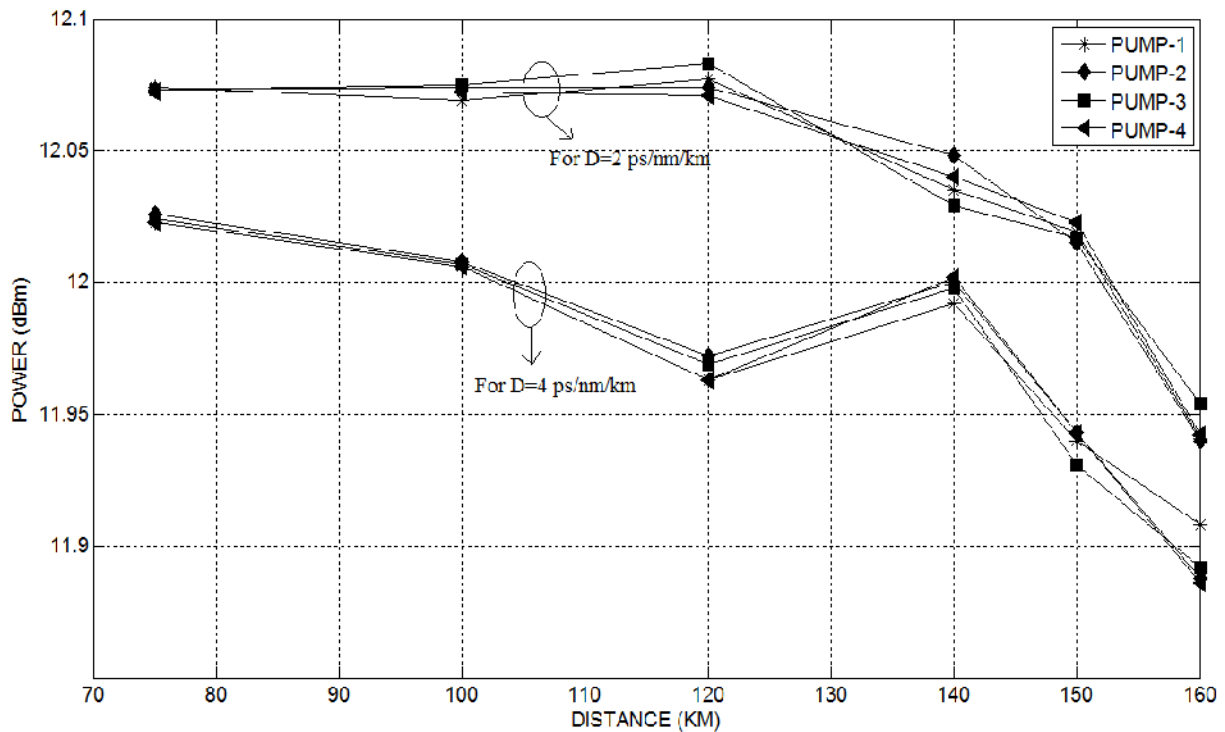


Figure 4.3: Power from RAMAN-EDFA HA for $D=2$ and 4 ps/nm/km at different pumping

Optical spectrum of pump 1 signal after RAMAN EDFA at 140 km distance with 2 ps/nm/km and 4 ps/nm/km is shown in figure 4.4. The optical output power for dispersion 2 ps/nm/km and 4 ps/nm/km is 12.035 dBm and 11.992 dBm respectively.

Optical spectrum of pump 2 signal after RAMAN EDFA at 140 km distance with 2 ps/nm/km and 4 ps/nm/km is shown in figure 4.5. The optical output power for dispersion 2 ps/nm/km and 4 ps/nm/km is 12.048 dBm and 12 dBm respectively.

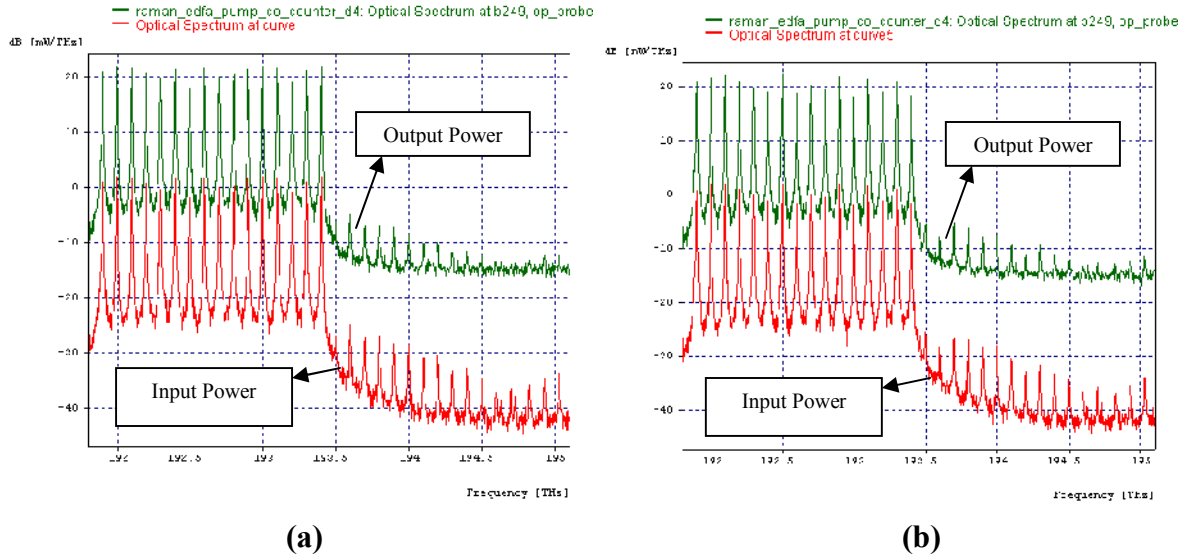


Figure 4.4: Optical Spectrum from Pump 1 at 140 km for (a) $D=2$ ps/nm/km; (b) $D=4$ ps/nm/km

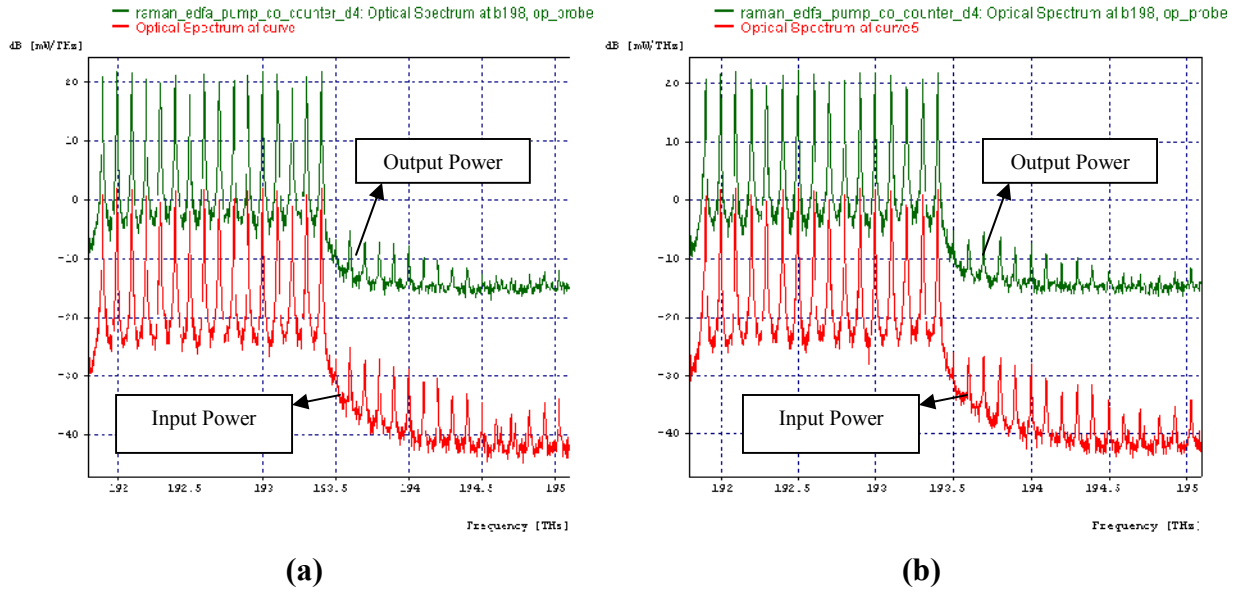
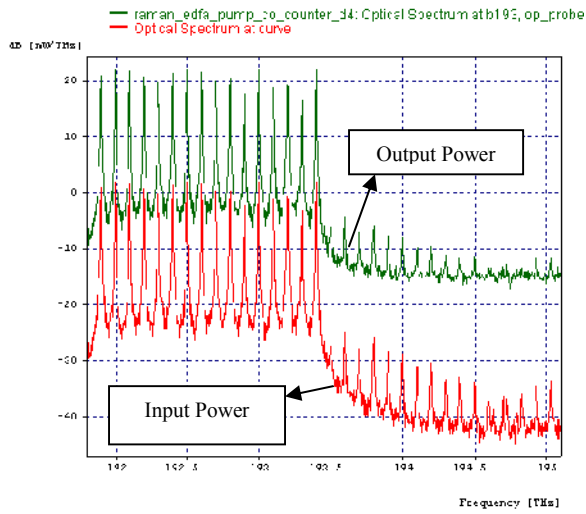
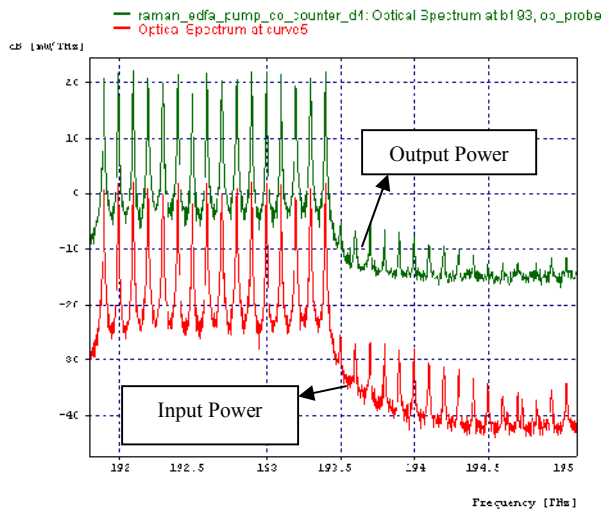


Figure 4.5: Optical Spectrum from Pump 2 at 140 km for (a) $D=2$ ps/nm/k; (b) $D=4$ ps/nm/km

Optical spectrum of pump 3 signal after RAMAN EDFA at 140 km distance with 2 ps/nm/km and 4 ps/nm/km is shown in figure 4.6. The optical output power for dispersion 2 ps/nm/km and 4 ps/nm/km is 12.029 dBm and 11.998 dBm respectively.



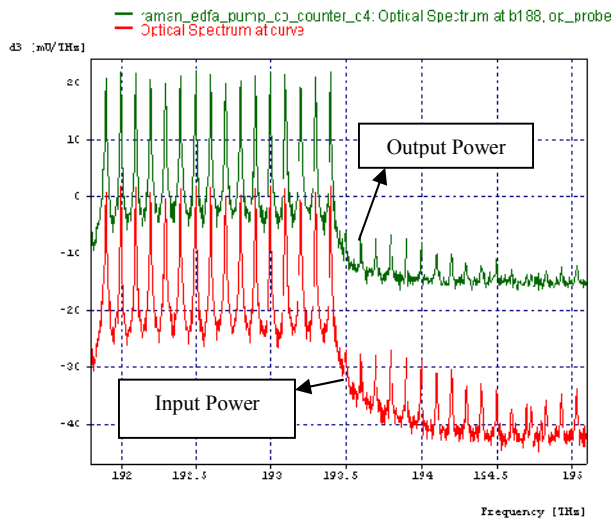
(a)



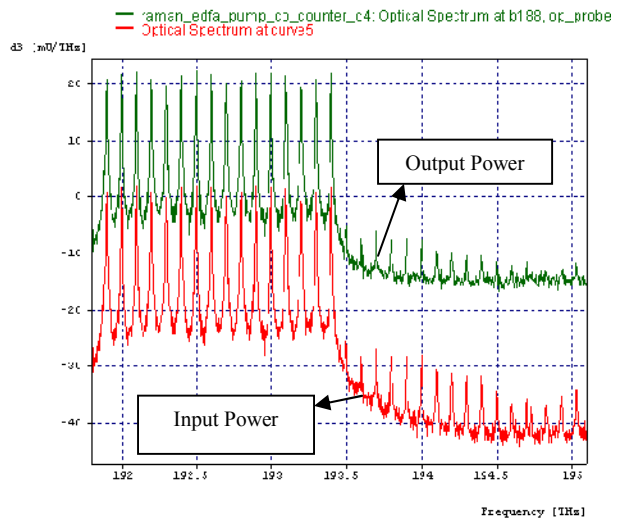
(b)

Figure 4.6: Optical Spectrum from Pump 3 at 140 km for (a) $D=2$ ps/nm/km; (b) $D=4$ ps/nm/km

Optical spectrum of pump 4 signal after RAMAN EDFA at 140 km distance with 2 ps/nm/km and 4 ps/nm/km is shown in figure 4.7. The optical output power for dispersion 2 ps/nm/km and 4 ps/nm/km is 12.040 dBm and 12.002 dBm respectively.



(a)

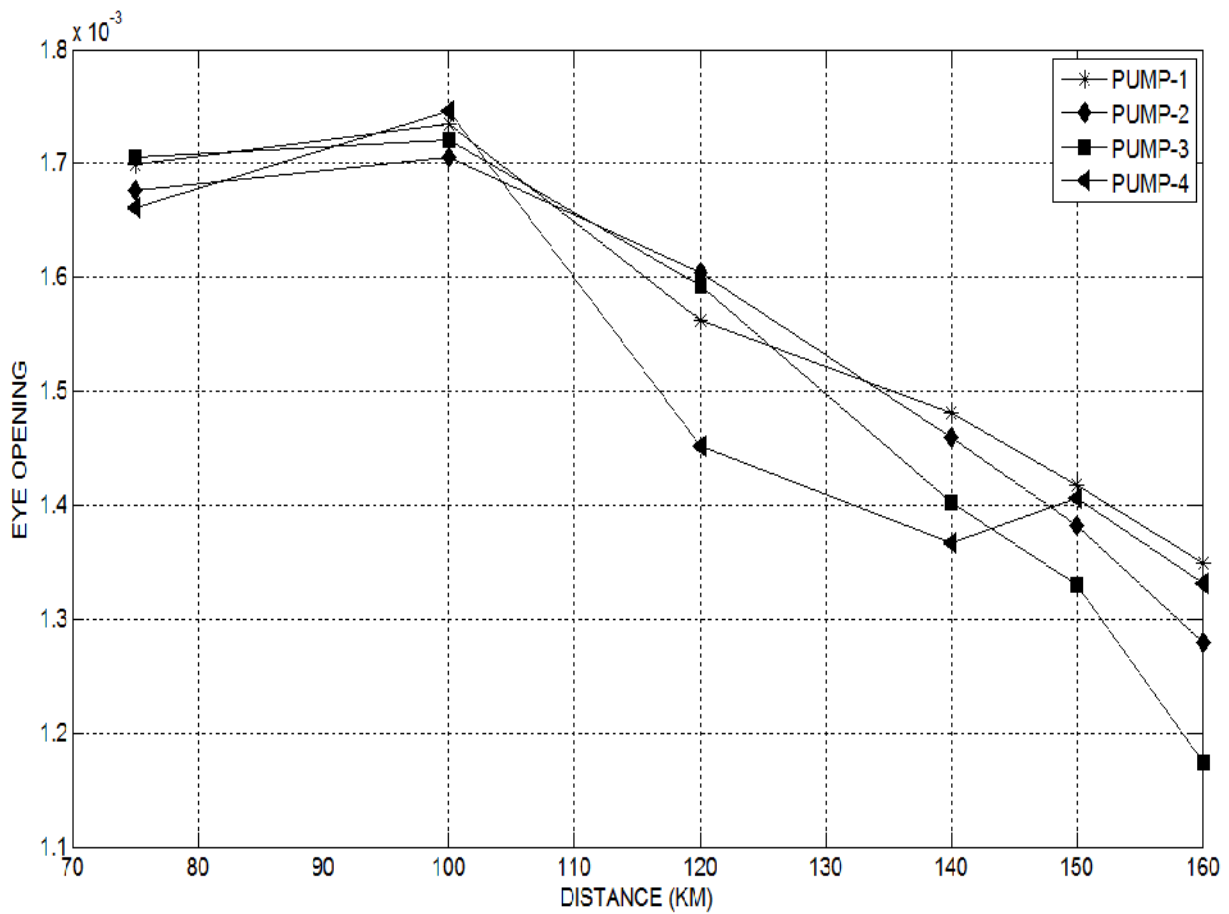


(b)

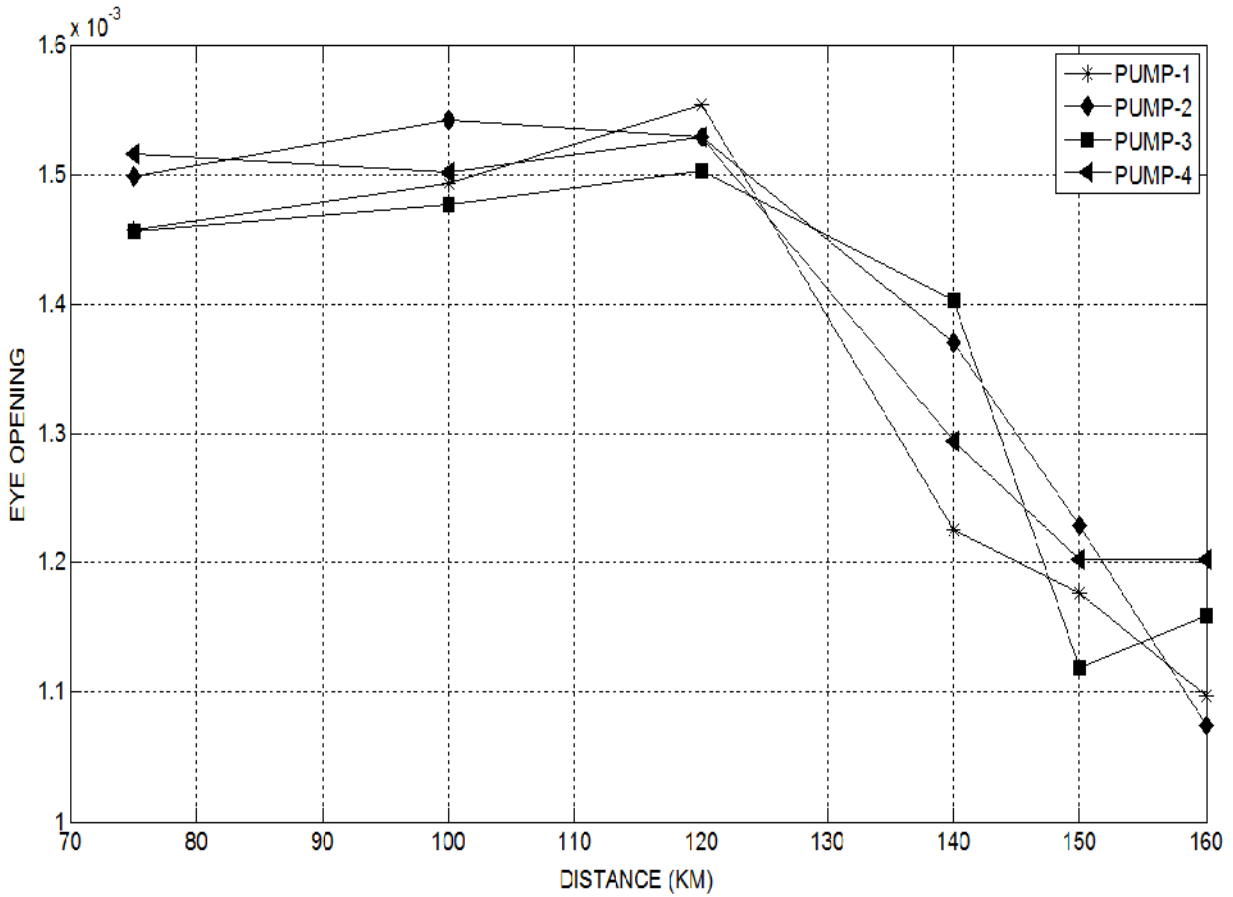
Figure 4.7: Optical Spectrum from Pump 4 at 140 km for (a) $D=2$ ps/nm/km (b) $D=4$ ps/nm/km

This comparison shows that output power of 12.048 dBm at 140 km transmission distance is the maximum output power obtained by pump2.

The eye opening from different pumps verses transmission distance is shown in figure 4.8. Large eye opening means less BER and good communication. It is observed that by increasing the transmission distance from 75 to 180 km, eye opening is also decreasing. The variation in Eye opening from different pumps at dispersion $D=2$ ps/nm/km is 1.69×10^{-3} to 1.34×10^{-3} for Pump 1, 1.67×10^{-3} to 1.28×10^{-3} for Pump 2, 1.70×10^{-3} to 1.17×10^{-3} for Pump 3, 1.66×10^{-3} to 1.33×10^{-3} for Pump 4. The variation in Eye opening from different pumps at dispersion $D=4$ ps/nm/km is 1.69×10^{-3} to 4.62×10^{-3} for Pump 1, 1.67×10^{-3} to 7.14×10^{-4} is for Pump 2, 1.70×10^{-3} to 6.29×10^{-3} for Pump 3, 1.66×10^{-3} to 6.66×10^{-3} for Pump 4.



(a)



(b)

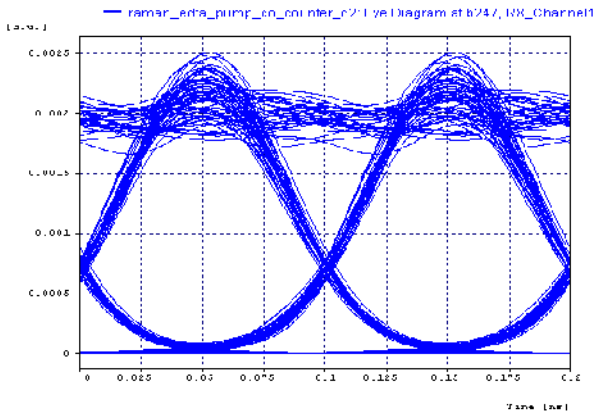
Figure 4.8: Eye opening vs Transmission distance for (a) $D=2$ ps/nm/km (b) $D=4$ ps/nm/km

It is observed from the simulation result that maximum Eye opening is obtained from pump 2 is 1.45×10^{-3} and 1.36×10^{-3} for $D=2$ or 4 ps/nm/km at 140 km transmission distance.

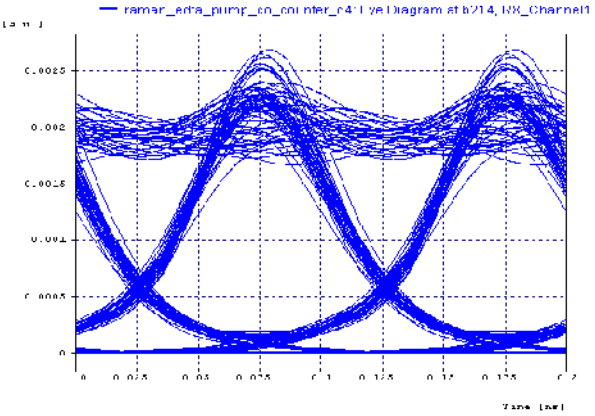
Eye diagram of signal after pump1 at 140 km distance with 2 ps/nm/km and 4 ps/nm/km is shown in figure 4.9. The eye opening for dispersion 2 ps/nm/km and 4 ps/nm/km is 1.48×10^{-3} and 1.22×10^{-3} respectively.

Eye diagram of signal after pump2 at 140 km distance with 2 ps/nm/km and 4 ps/nm/km is shown in figure 4.10. The eye opening for dispersion 2 ps/nm/km and 4 ps/nm/km is 1.45×10^{-3} and 1.36×10^{-3} respectively.

Eye diagram of signal after pump3 at 140 km distance with 2 ps/nm/km and 4 ps/nm/km is shown in figure 4.11. The eye opening for dispersion 2 ps/nm/km and 4 ps/nm/km is 1.40×10^{-3} and 1.40×10^{-3} respectively.

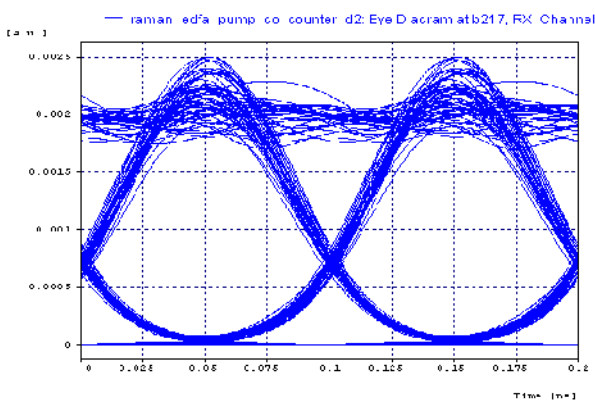


(a)

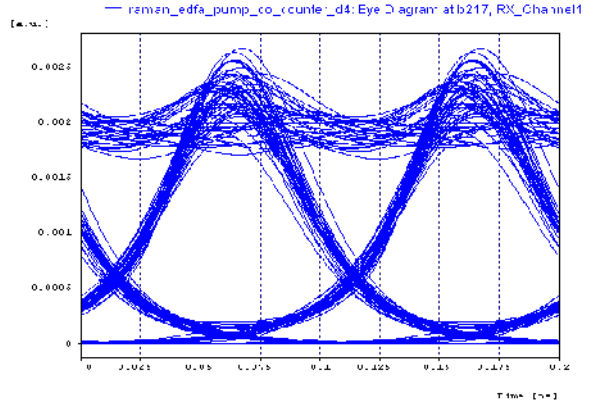


(b)

Figure 4.9: Eye diagram for Pump 1 at 140 km for (a) $D=2$ ps/nm/km (b) $D=4$ ps/nm/km

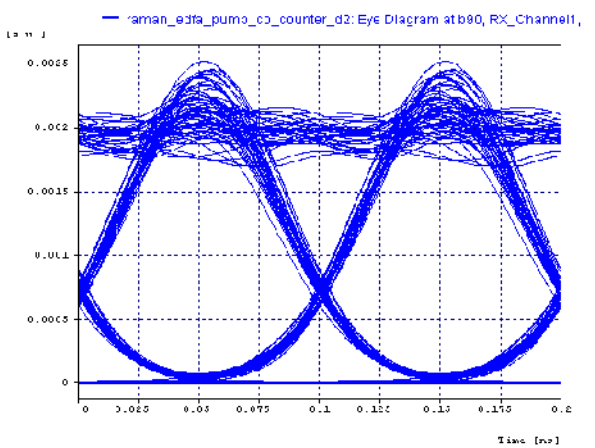


(a)

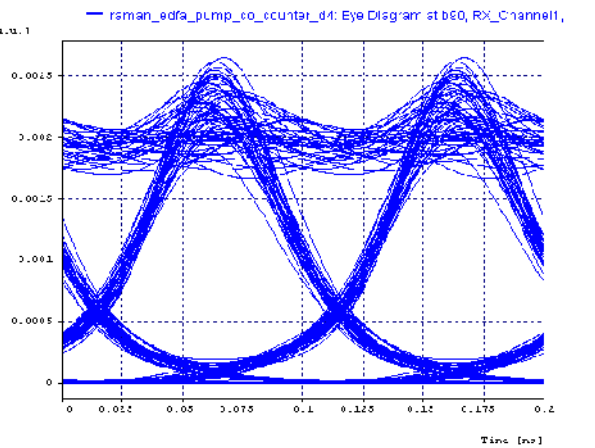


(b)

Figure 4.10: Eye diagram for Pump 2 at 140 km for (a) $D=2$ ps/nm/km (b) $D=4$ ps/nm/km



(a)



(b)

Figure 4.11: Eye diagram for Pump 3 at 140 km for (a) $D=2$ ps/nm/km (b) $D=4$ ps/nm/km

Eye diagram of signal after pump3 at 140 km distance with 2 ps/nm/km and 4 ps/nm/km is shown in figure 4.12. The eye opening for dispersion 2 ps/nm/km and 4 ps/nm/km is 1.36×10^{-3} and 1.29×10^{-3} respectively.

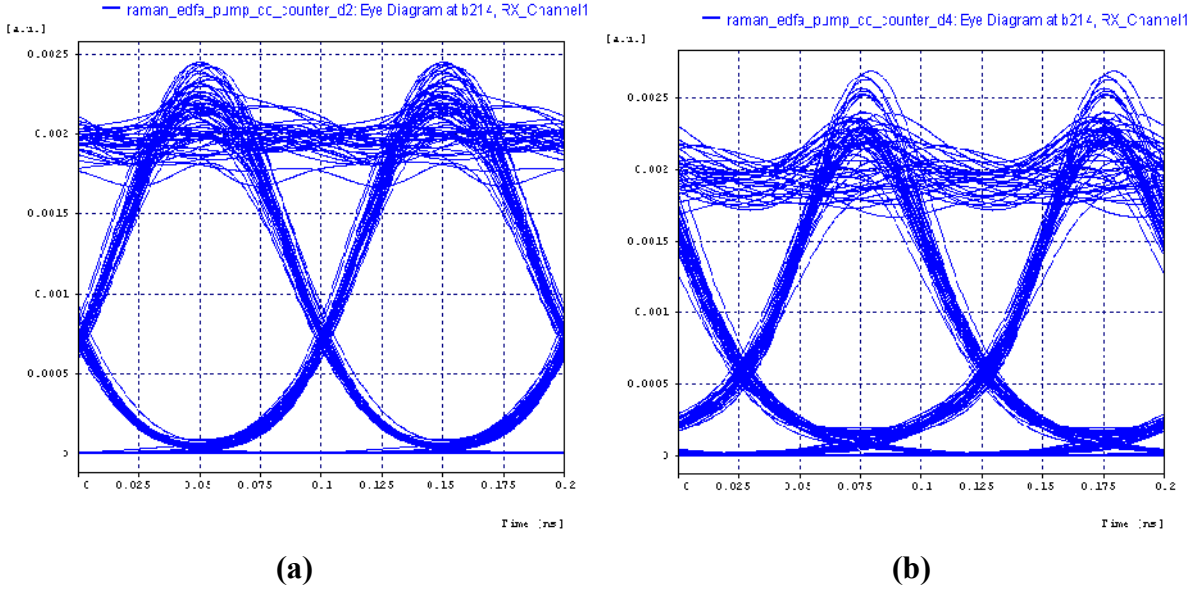
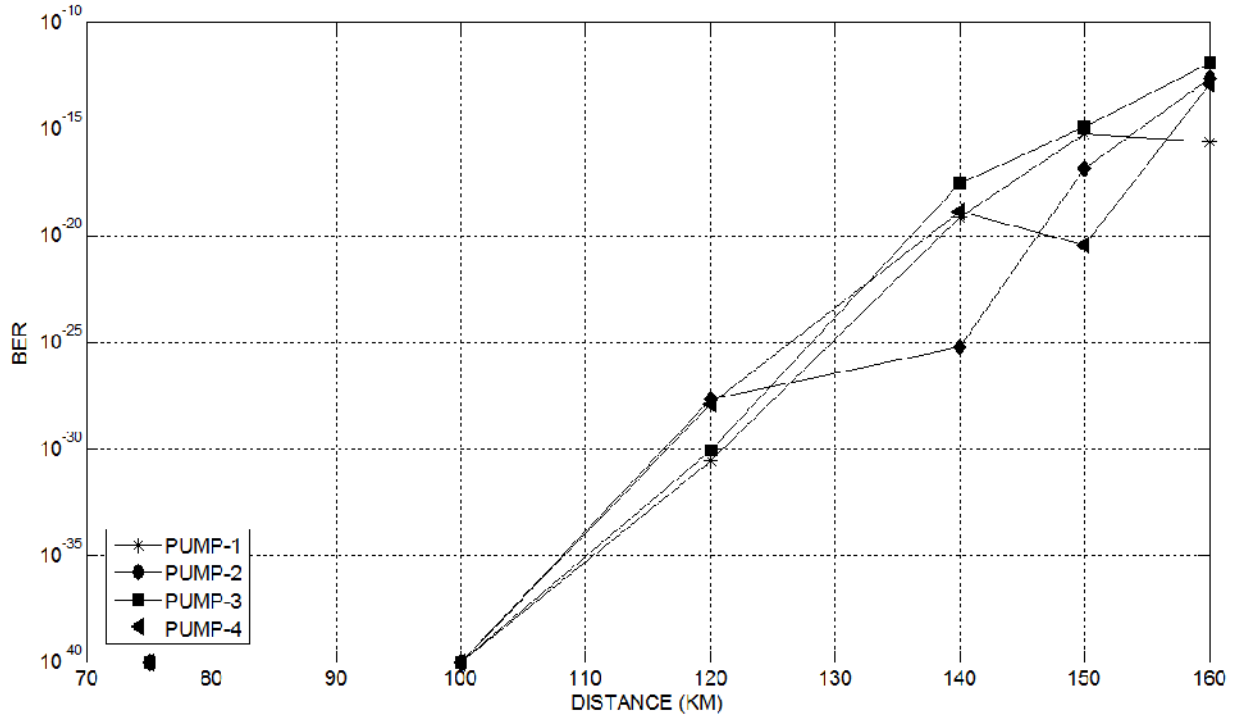


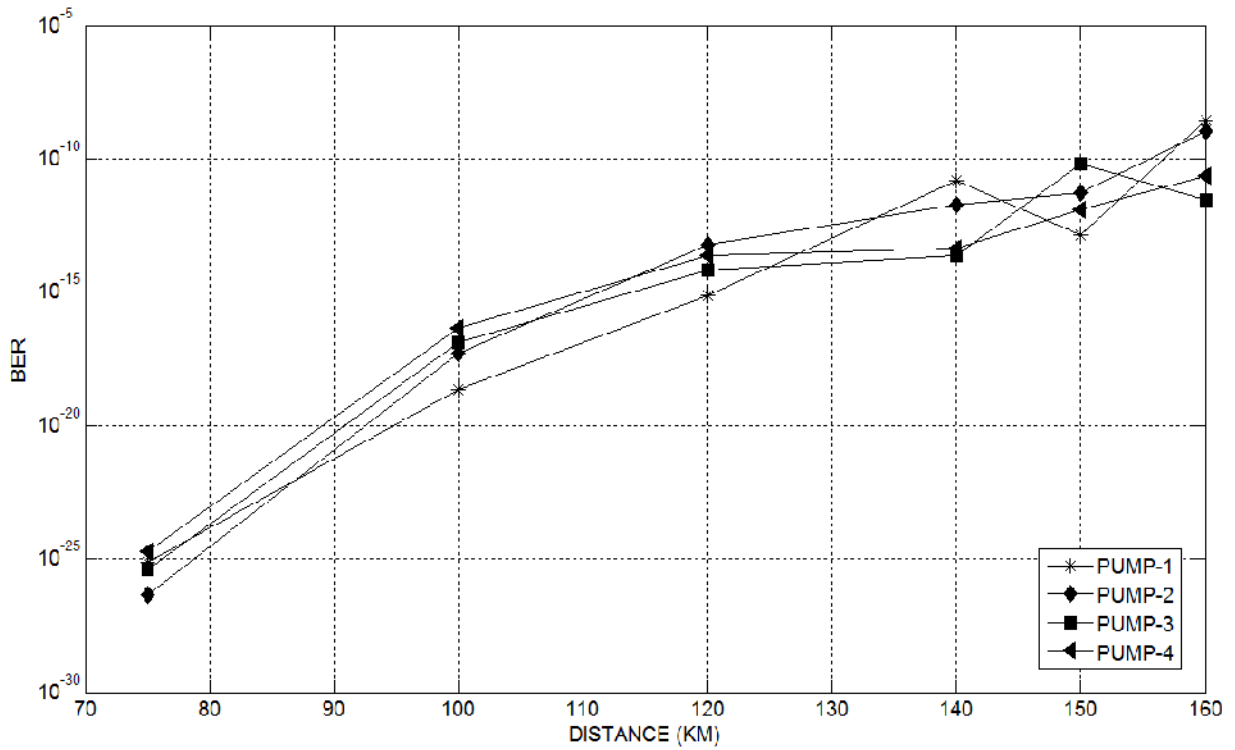
Figure 4.12: Eye diagram for Pump 4 at 140 km for (a) D=2 ps/nm/km (b) D=4 ps/nm/km

The acceptable bit error rate (BER) for optical transmission is 1×10^{-9} . The BER versus transmission distance for different dispersion is shown in figure 4.13. It is observed that by increasing the transmission distance from 75 to 180 km, BER is also increasing. The variation in BER from different pumps at dispersion D=2 ps/nm/km is 1×10^{-40} to 6.32×10^{-7} for pump 1, 1×10^{-40} to 9.95×10^{-8} for pump 2, 1×10^{-40} to 4.96×10^{-8} for pump 3 and 1×10^{-40} to 3.35×10^{-7} for pump 4. The variation in BER from different pumps at dispersion D=4 ps/nm/km is 7.42×10^{-26} to 3.89×10^{-7} for pump 1, 4.65×10^{-27} to 4.15×10^{-7} for pump 2, 3.90×10^{-26} to 1.91×10^{-6} for pump 3 and 1.82×10^{-25} to 3.92×10^{-7} for pump 4.

It is observed from the simulation result that minimum BER value is obtained from pump2 is 5.44×10^{-26} at 140 km transmission distance. The results show that the minimum BER is provided by pump 1 for all distance but it provides very less power. Minimum BER and maximum output power both are achieved from pump 2 at distance 140km.



(a)



(b)

Figure 4.13: BER vs Distance for (a) $D=2$ ps/nm/km (b) $D=4$ ps/nm/km

The power versus Raman Fiber length for dispersion $D = 2\text{ps/nm/km}$ is shown in figure 4.14. It is observed that by increasing the Raman Fiber length from 10 to 30 km, power is also increasing. But above this length, there is sudden fall in power output. The variation in output power is 112.043 to 12.076 dBm. In this model, the raman pumping is done at co-propagating pumping of 1365 nm with 500 mW pump power and counter propagating pumping of 1453 nm with 500 mW pump power.

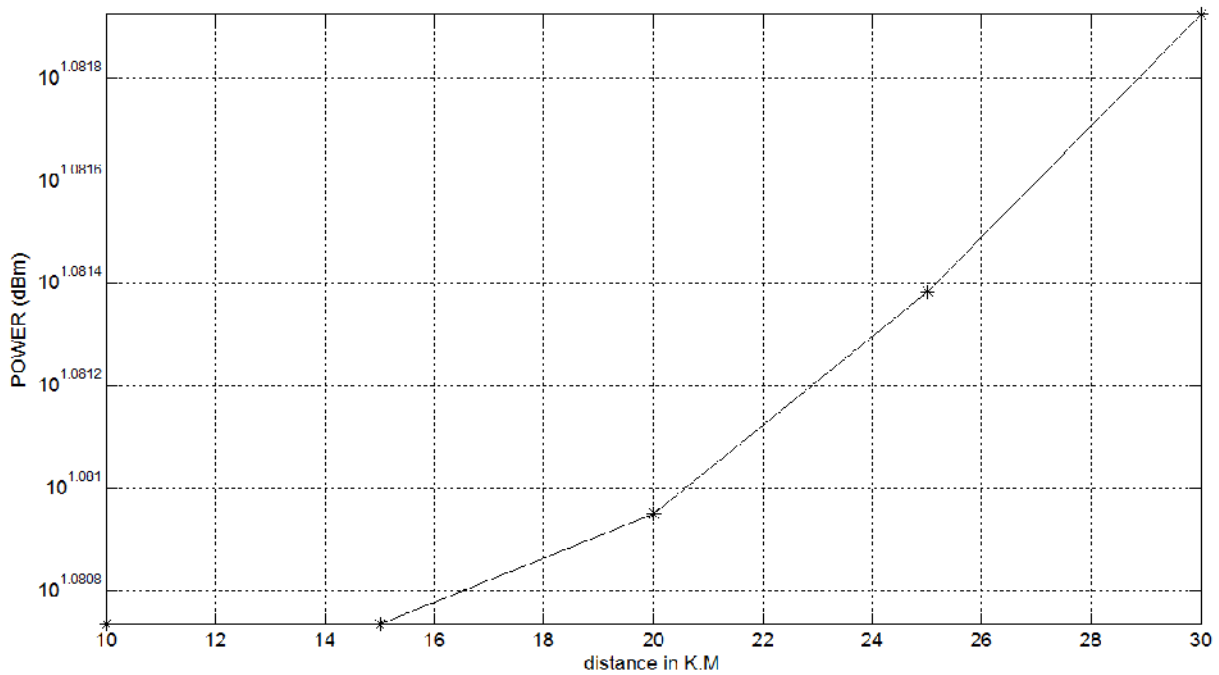


Figure 4.14: Output Power vs RAMAN fiber length for $D=2\text{ ps/nm/km}$

The BER versus Raman Fiber length for dispersion $D = 2\text{ps/nm/km}$ is shown in figure 4.15. It is observed that by increasing the Raman Fiber length from 10 to 30 km, BER is also increasing. But above this length, there is sudden raise in BER. The variation in BER is 1×10^{-40} to 1.2×10^{-25} . The Q factor versus Raman Fiber length for dispersion $D = 2\text{ps/nm/km}$ is shown in figure 4.16. It is observed that by increasing the Raman Fiber length from 10 to 30 km, Q factor is decreasing. But above this length, there is sudden fall in Q factor. The variation in Q factor is 22.7366 to 20.3909 dB.

After 30 km the output power and Q factor decrease with respect to raman fiber length and BER increases which is not required.

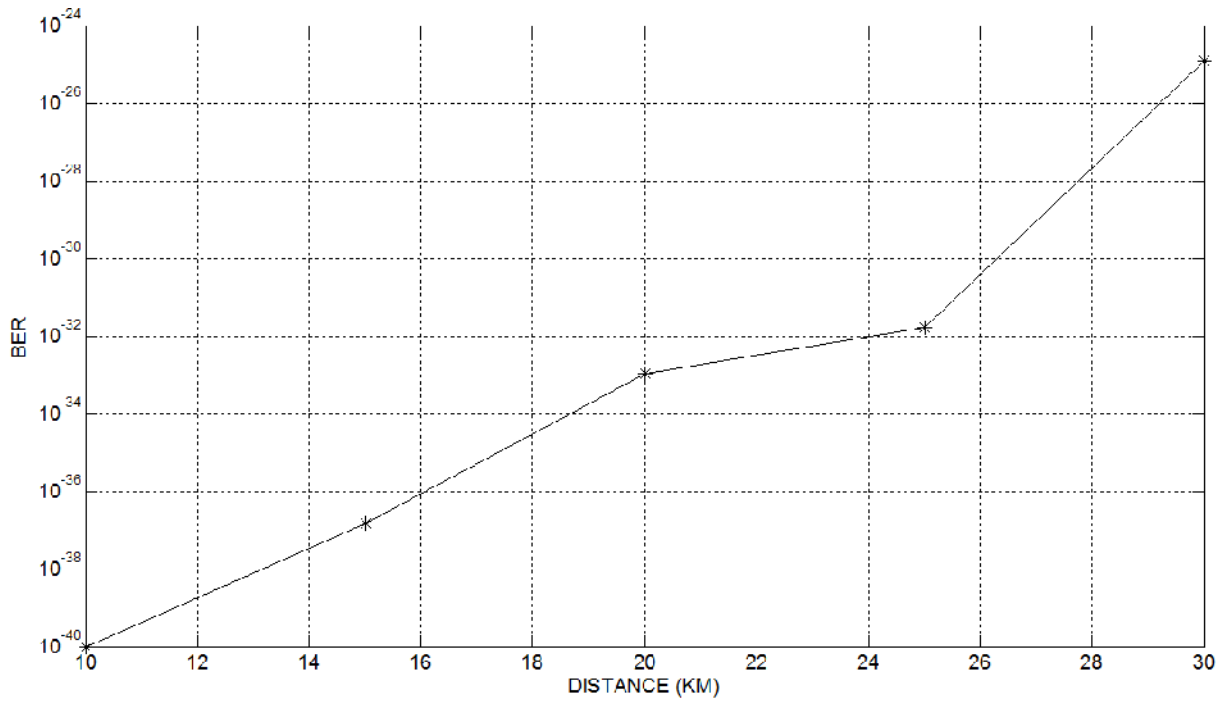


Figure 4.15: BER vs RAMAN fiber length for $D=2$ ps/nm/km

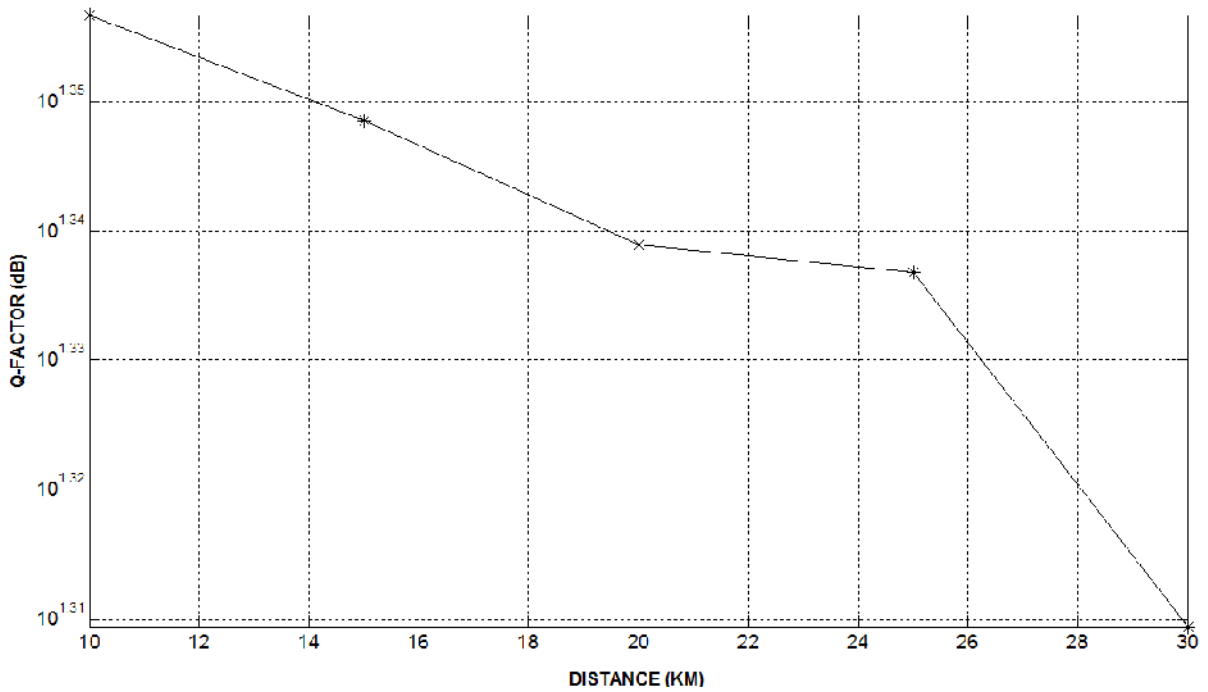


Figure 4.16 :Q Factor vs RAMAN fiber length for $D=2$ ps/nm/km

4.5 Conclusion

The hybrid optical amplifiers (RAMAN-EDFA) design model were successfully designed and implemented into OptSim. The main motivation of this work is to optimize the optical amplifiers for different dispersion, pumping, raman fiber length and transmission distance.

The performance of RAMAN-EDFA HA is evaluated using the eye patterns, BER, eye opening and Q factor measurement. The simulation results have shown the variation in output power, BER, Q Factor and eye opening with respect to transmission distance and different pumping (Pump 1, Pump2, Pump 3, Pump 4). The variation in output power is 12.074 to 10.293 dBm for pump 1 and for pump 2 is 12.073 to 10.280 dBm, for pump 3 is 12.073 to 10.322 dBm and for pump 4 is 12.072 to 10.290 dBm. The variation in Eye opening is 1.69×10^{-3} to 1.34×10^{-3} for Pump 1, 1.67×10^{-3} to 1.28×10^{-3} for Pump 2, 1.70×10^{-3} to 1.17×10^{-3} for Pump 3 and 1.66×10^{-3} to 1.33×10^{-3} for Pump 4. The variation in BER is 1×10^{-40} to 6.32×10^{-7} for pump 1, 1×10^{-40} to 9.95×10^{-8} for pump 2, 1×10^{-40} to 4.96×10^{-8} for pump 3 and 1×10^{-40} to 3.35×10^{-7} for pump 4. The variation in Q Factor is 23.5185 to 13.77 dB for pump 1, 23.1458 to 14.3844 dB for pump 2, 23.5122 to 14.4916 dB for pump 3 and 23.2860 to 13.9034 dB for pump 4. These variation is for dispersion $D=2$ ps/nm/km and acceptable upto 140 km transmission distance.

When we change the raman fiber length from 10 to 30 km then the output power and BER are increase but Q Factor decreases. The variation in output power is 112.043 to 12.076 dBm, in Q Factor is 22.7366 to 20.3909 dB and in BER is 1×10^{-40} to 1.2×10^{-25} with respect to raman fiber length (10 to 30 km) at dispersion ($D=2$ ps/nm/km). The raman fiber length is acceptable up to 30km after this it will give less output power, Q factor and increase in BER.

CHAPTER 5

CONCLUSION AND FUTURE WORK

5.1 Conclusion

The optical amplifiers and hybrid optical amplifiers design models were successfully designed and implemented into OptSim. The 16 channel WDM systems at 10Gbps have been investigated for the various optical amplifiers and pumping systems and the performance has been compared on the basis of transmission distance and dispersion. It is observed that optical hybrid amplifier RAMAN-EDFA provides the highest output power (12.017dBm) and least bit error rate ($1e-040$) at 100 km for dispersion 2ps/nm/km and 4ps/nm/km as compare to other optical amplifier. The RAMAN – EDFA is further analyzed with respect to pump system. The various results show that pump 2 gives the best performance upto 140 km at dispersion 2 ps/nm/km in comparison of all proposed pumps.

The performance of optical amplifiers was evaluated using the eye patterns, BER measurement, eye opening and Q factor. The simulation results show that RAMAN-EDFA performed better than EDFA, SOA, RAMAN-SOA optical amplifier. RAMAN-EDFA provide high power (12.011 to 10.334 dBm for $D=2\text{ps/nm/km}$ and 12.087 to 10.384 dBm for $D=4\text{ps/nm/km}$), least BER (1×10^{-40} to 9.16×10^{-9} for $D=2\text{ps/nm/km}$ and 5.71×10^{-25} to 2.68×10^{-7} for $D=4\text{ps/nm/km}$), large Q factor (23.5868 to 14.9537 dB for $D=2\text{ps/nm/km}$ and 20.4707 to 13.960 dB for $D=4\text{ps/nm/km}$) and good eye diagram for different transmission distance ranging from 75 to 180 km. These results are valid upto 100 Kms. Above 100 km distance, there is more distortion in the detected signal. The output power, Q factor and eye opening are decreasing above this. Also, there is an increment in BER after 100 Km. So, This proposed model is best suited for 100 km distance.

The variation in output power is 12.074 to 10.293 dBm for pump 1 and for pump 2 is 12.073 to 10.280 dBm, for pump 3 is 12.073 to 10.322 dBm and for pump 4 is 12.072 to 10.290 dBm. The variation in Eye opening is 1.69×10^{-3} to 1.34×10^{-3} for Pump 1, 1.67×10^{-3} to 1.28×10^{-3} for Pump 2, 1.70×10^{-3} to 1.17×10^{-3} for Pump 3 and 1.66×10^{-3} to 1.33×10^{-3} for Pump 4. The variation in BER is 1×10^{-40} to 6.32×10^{-7} for pump 1, 1×10^{-40} to 9.95×10^{-8} for pump 2, 1×10^{-40} to 4.96×10^{-8} for

pump 3 and 1×10^{-40} to 3.35×10^{-7} for pump 4. The variation in Q Factor is 23.5185 to 13.77 dB for pump 1, 23.1458 to 14.3844 dB for pump 2, 23.5122 to 14.4916 dB for pump 3 and 23.2860 to 13.9034 dB for pump 4. These variation is for dispersion $D=2$ ps/nm/km and acceptable upto 140 km transmission distance.

When we change the raman fiber length from 10 to 30 km then the output power and BER are increase but Q Factor decreases. The variation in output power is 112.043 to 12.076 dBm, in Q Factor is 22.7366 to 20.3909 dB and in BER is 1×10^{-40} to 1.2×10^{-25} with respect to raman fiber length (10 to 30 km) at dispersion ($D=2$ ps/nm/km). The raman fiber length is acceptable up to 30km after this it will give less output power, Q factor and increase in BER.

5.2 Future Scope

In this thesis, The modal is investigated hybrid amplifier which is combination of RAMAN and EDFA but this work can be extend for other hybrid amplifiers like amplifiers combined with other gain media, including combination of RAMAN with fibers doped with different rare earths (e.g., Nd and Yb). The set up is demonstrated for transmission of 16-channel WDM system at 10 Gb/s channel data rate but this simulation can be implemented for DWDM channels at very high data rate. The channel spacing is also a major concern. The modal of RAMAN-EDFA can also be explored in optical network topologies and broadcast topologies. The proposed system investigated the RAMAN-EDFA by changing the raman fiber length and can also investigates the RAMAN-EDFA by vary Erbium-doped fiber length. There is also scope for increasing the performance of hybrid amplifiers by combining more than two amplifiers.

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