Performance Analysis of Optical Amplifier and Its Hybrid Configuration

Dissertation Submitted in the partial fulfillment of requirement for the award of the Degree of

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In

ELECTRONICS & COMMUNICATION ENGINEERING

Submitted by

Deepak Goyal

Roll No. 801161008

Under the guidance of

Dr. Hardeep Singh

Assistant Professor, ECED

Department of Electronics & Communication Engineering

Thapar University, Patiala. (Punjab)

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DECLARATION

I, **Deepak Goyal** hereby declare that the work, which is being presented in the Dissertation, entitled **"Performance Analysis of Optical Amplifier and Its Hybrid Configuration"** in partial fulfillment of the requirements for the award of degree of Master of Engineering in **Electronics and Communication Engineering** from Thapar University, Patiala, is an authentic record of my own work carried out under the guidance of **Dr. Hardeep Singh.** I have not submitted the matter presented in the dissertation award of any other degree of this or any other university.

Deepak Goyal

Signature of student

Date: 09/7/13

Deepak Goyal

Roll no: 801161008

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

Dr. Hardeep Singh

Assistant Professor ,ECED

Thapar University, Patiala

Date: 09/07/13

Countersigned by.

Dr. Rajesh Khanna

Professor and Head ECED

Thapar University, Patiala.

Date ....

Dr. S.K. Mahopatra

Dean of Academic affairs

Thapar University, Patiala.

Date..........

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Deepak Goyal

Roll no. **801161008**

Abstract:

Optical fiber communication has become backbone of today data communication networks. Fiber communication allows multiple signals to be sent on same fiber simultaneously. Still the demand for the high data rate application is still increasing which can only be met by fiber communication because of its enormous bandwidth. Like other transmission media it also suffers from losses along the transmission. Losses like attenuation, distortion and other due to non-linearities limit the data rate as well as transmission rate. So a device is required which can amplify the signal so that it can travel long distance. This device should be able to regenerate as well reshape the signal. This gives development of optical amplifier. These amplifiers were transparent to data rate and modulation formats. So their invention brought a revolution in the optical communication. Data rate up to 1Tb/s is possible in optical system. Further their combination known as hybrid amplifier also developed which utilizes the advantage and weakness of each other. So with the event of optical amplifier it becomes possible to transmit wdm signal. So it becomes possible to send large no of signal simultaneously with good quality of communication. So optical amplifier has been the major factor behind the success of optical communication.

In this dissertation we have investigated the performance of 96 channels at 10 Gb/s using different optical amplifier and their hybrid combinations. Their performance has been evaluated on the basis of quality factor, bit error rate, eye opening and eye closure. At first we investigate the three amplifier and found that EDFA provide highest power and quality factor of as compared to other two amplifier. After 100 km SOA performs better than other two. Further we investigated the performance of hybrid amplifier for the same set up. We found that Raman-EDFA provide highest output power. At distance up to 100 km EDFA-EDFA performs good but after that Raman-Soa outperforms all other in term of quality factor, bit error rate, eye opening and closure. In the last section of the dissertation, we investigated different type of fiber like SMF, Ds-Anomalous, and Ds- Normal for Raman–EDFA amplifier. From the simulation works we find that Ds-Anomalous perform much better than the other fiber. Single mode fiber gives worst performance in terms of quality factor, eye opening and bit error rate.

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List of Symbol:

μm	micrometer
Nm	nanometer
Km	kilometer
mW	milli watt
N_1	population density at ground level
N_2	population density at upper level
E_1	energy at ground level
E_2	energy at upper level
h	plank constant
v	frequency of light
λ	wavelength of light
Fn	noise figure
M	number of channel
G	amplification factor
dB	decibel
n_{sp}	spontaneous noise factor

List of Abbreviations:

FPA	fabry perot amplifier
TWA	travelling wave amplifier
SWB-HA	seamless wideband hybrid amplifier
NWB-HA	narrow band hybrid amplifier
WDM	wavelength division multiplexing
CMB	combiner
DIV	divider
DWDM	dense wavelength division multiplexing
OAMP	optical amplifier
OADM	optical add drop multiplexer
OXC	optical cross connects
RWA	routing and wavelength assignment array
PON	passive optical network
OXS	optical cross switching
PMD	polarization mode dispersion
SSF	single mode fiber
OEO	optical electric optical
XGM	cross gain mixing
XPM	cross phase mixing
SNR	signal to noise ratio
RZ	return to zero
NRZ	non return to zero
DRA	distributed Raman amplifier

DSF	dispersion shifted fiber
ASE	amplified spontaneous emission
OSNR	optical signal to noise ratio
DCF	dispersion compensated fiber
LD	laser diode
HFA	hybrid fiber amplifier
NZDSF	non zero dispersion shifted fiber
OOK	on off keying
DBPSK	duobinary phase shift keying
DQPSK	quadrature phase shift keying
CRZ	chirp return to zero
VSRZ	vestigial sideband return to zero

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Chapter 1

Introduction

1.1 Development of Fiber Optic Communication System

A communication system transmits information from one place to another, whether separated by a few kilometers or by transoceanic distances. Information is often carried by an electromagnetic carrier wave whose frequency can vary from a few mega-hertz to several hundred tera-hertz. Optical communication systems use high carrier frequencies (100 THz) in the visible or near-infrared region of the electromagnetic spectrum. They are sometimes called light wave systems to distinguish them from microwave systems, whose carrier frequency is typically smaller by five orders of magnitude (1 GHz). Fiber-optic communication systems are lightwave systems that employ optical fibers for information transmission. The research phase of fiber-optic communication systems started around 1975. The enormous progress realized over the 25-year period extending from 1975 to 2000 can be grouped into several distinct generations.

The first generation [1] of lightwave systems operated near 0.8 nm and used GaAs semiconductor lasers. They operated at a bit rate of 45 Mb/s and allowed repeater spacing's of up to 10 km. The larger repeater spacing compared with 1 km spacing of coaxial systems was an important motivation for system designers because it decreased the installation and maintenance costs associated with each repeater.

Second generation, with in few year (1977-1979), a new optical window starts operating around 1.3 nm, where fiber loss was below 1 dB/km. Furthermore, optical fibers exhibit minimum dispersion in this wavelength region. This realization led to a worldwide effort for the development of InGaAsP semiconductor lasers and detectors operating near 1.3 nm. Bit rate was limited to below 100 Mb/s because of dispersion in multimode fibers [2]. This limitation was overcome by the use of single mode fibers. A laboratory experiment in 1981 demonstrated transmission at 2 Gb/s over 44 km of single-mode fiber [3]. By 1987, second-generation lightwave systems, operating at bit rates of up to 1.7 Gb/s with a repeater spacing of about 50 km, were easily available. The repeater spacing of the second-generation lightwave systems was limited by the fiber losses at the operating wavelength of 1.3 nm (typically 0.5 dB/km). Losses of silica fibers become minimum near 1.55 μm. A 0.2 dB/km loss was realized in 1979 in this spectral region [4]. But in this region suffered by large dispersion at 1.55 μm was considerably delayed by a large fiber. At this wavelength Conventional InGaAsP semiconductor lasers could not be used because of pulse spreading occur. This dispersion problem was overcome either by using (DSF) dispersion-shifted fibers designed to have minimum dispersion near 1.55 μm or by limiting the laser spectrum to a single longitudinal mode. By 1985, information at bit rates of up to 4 Gb/s over distances in excess of 100 km [5] was obtained. Third-generation lightwave systems operating at 2.5 Gb/s became available commercially in 1990. By combination of DSF and single mode laser a bit rate of up to 10 Gb/s [6] was achieved. But this generation used electronic repeaters spaced apart typically by 60–70 km. this was a drawback because signal has to be converted into electronics form and back to optical form. The fourth generation of lightwave systems

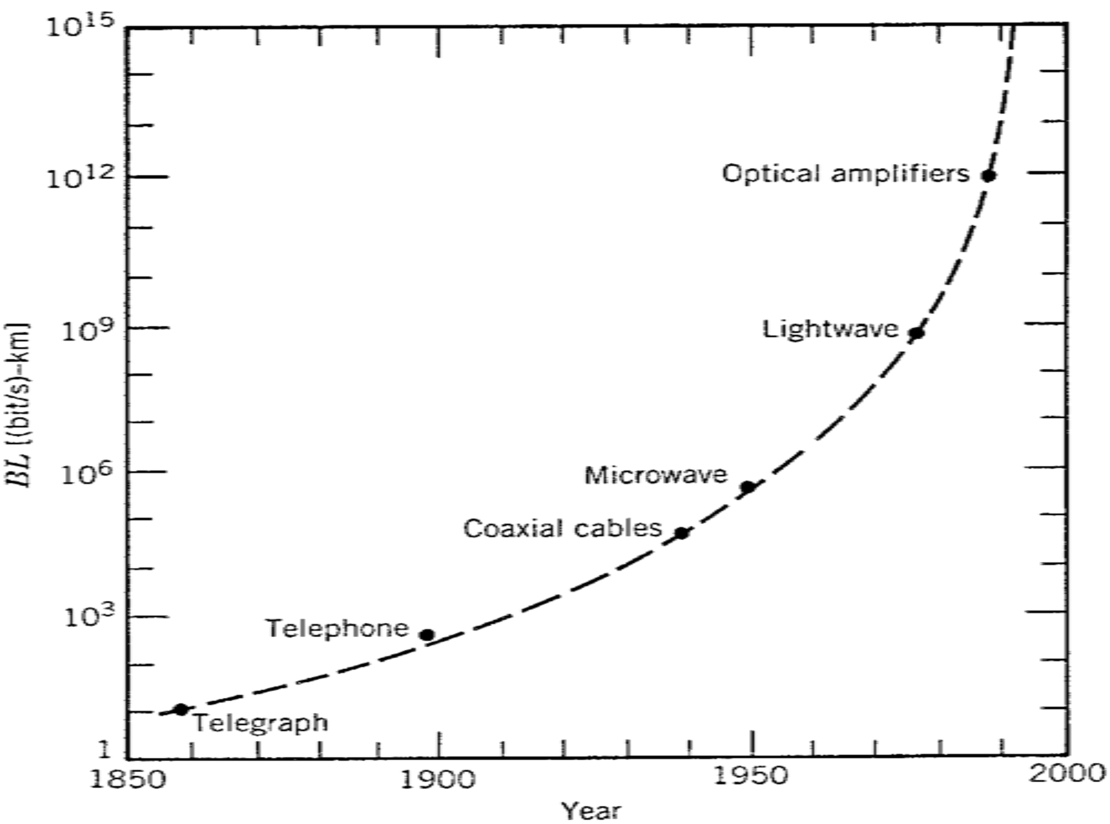


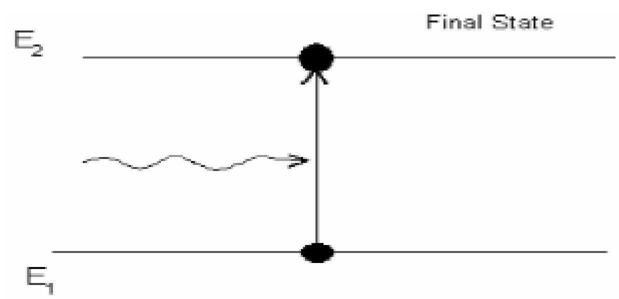
Figure 1.1: Increase in bit rate–distance product BL during the period 1850–2000[1]

makes use of optical amplification for increasing the repeater spacing and of wavelength-division multiplexing (WDM) for increasing the bit rate. With the invent of EDFA around 1990 greater bit rate was achieved. The current emphasis of WDM lightwave systems is on increasing the system capacity by transmitting more and more channels through the WDM technique. With increasing WDM signal bandwidth, it is often not possible to amplify all channels using a single amplifier. As a result, new kinds of amplification schemes are being explored for covering the spectral region extending from 1.45 to 1.62 μm.

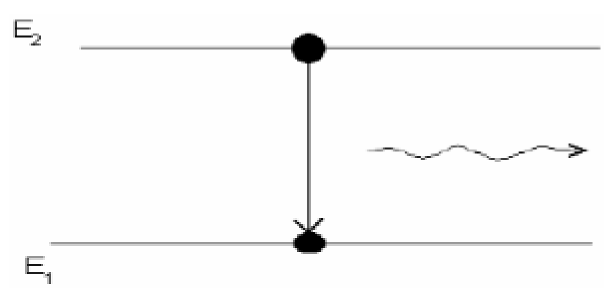
The fifth generation of fiber-optic communication systems is concerned with extending the wavelength range over which a WDM system can operate and bit rate simultaneously. The conventional wavelength window, known as the C band, covers the wavelength range 1.53–1.57 μm. It is being extended on both the long- and short-wavelength sides, resulting in the L and S bands, respectively. The Raman amplification technique can be used for signals in all three wavelength bands. Moreover, a new kind of fiber, known as the dry fiber has been developed with the property that fiber losses are small over the entire wavelength region extending from 1.30 to 1.65 μm [7]. Availability of such fibers and new amplification schemes may lead to lightwave systems with thousands of WDM channels. The fifth-generation systems also attempt to increase the bit rate of each channel within the WDM signal from 40 Gb/s to 160 Gb/s is also likely in the future. For this a new approach of Solition pulse arrives that maintain its shape during propagation. Later Raman amplifier was used for long distance transmission however it requires high pump power as compared to EDFA. For the same amplification 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, Raman required almost three orders of magnitude more pump power in Raman amplifiers [8]. Hybrid optical amplifiers (HOA) configuration of fiber provides higher output gain as described by Mohammed N. Islam. which is sum of the individual gain of amplifier described that the total amplifier $G_{Hybrid} = G_{EDFA} + G_{Raman}$.

1.2 Principle of Optical Amplifier:

Optical amplifier works on the principle of stimulated emission. To achieve optical amplification, the population of upper energy level has to be greater than that of lower energy level i.e. $N1 < N2$, where N1, N2 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. Every Atom has valance band and conduction band. Electrons in the ground state or valance band have low energy E_1, while electrons in the upper level have high energy E_2. To achieve optical amplification, the population of upper energy level has to be greater than that of lower energy level, i.e. $N_2 > N_1$, where N_1, N_2 is population density of lower and upper state. Electron in ground state can jump to upper level by absorbing energy $E = E_2 - E_1 = h\nu$ where h is plank constant and ν is frequency. After absorbing energy electron get existed to upper level. This is known as absorption as shown in figure. Since the life time of upper level is very small so they falls backs to ground state by emitting energy $h\nu$. This return to ground state occurs spontaneously in random direction. This is known as spontaneous emission as shown. When we force the upper level electron to ground state by incoming signal. These incoming photon causes the falling electron to emit a photon of same energy, direction and polarization as that of incoming photon, thus number of photon thus emitted keep on increasing causing amplification of light. Hence signal amplification takes place. During fiber amplification depletion of pump power takes place.



(a)



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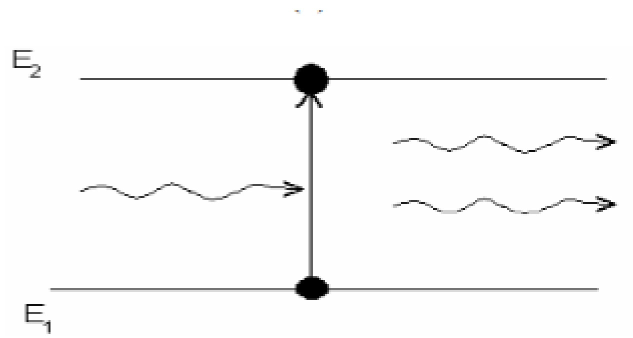


(c)

Figure 1.2: Absorption, spontaneous emission and stimulated emission Process [9]

The above figures are showing three mechanisms accruing in semiconductor. They are absorption process, spontaneous emission and stimulated emission. Stimulated process is responsible for the optical amplification of the incoming signal.

1.3 Amplifier Parameters:

1.3.1 Optical Gain: optical amplifier is a laser without feedback. The optical gain, in general, depends not only on the frequency (or wavelength) of the incident signal, but also on the local beam intensity at any point inside the amplifier. Details of the frequency and intensity dependence of the optical gain depend on the amplifier media. For a homogeneously broadened two-level system gain coefficient [10].

$$g(w)= \frac{g_0}{1+(w-w_0)^2\ T_2^2+\frac{P}{P_s}} \qquad (1)$$

g_0 is the peak value of the gain, w is the optical frequency of the incident signal, w is the atomic transition frequency, and P is the optical power of the signal being amplified. The saturation power P depends on gain-medium parameters such as the fluorescence time $T_{1.}$

1.3.2 Gain Spectrum and Bandwidth:

Optical gain provided by amplifier start decreasing in saturated region is given as

$$g(w)= \frac{g_0}{1+(w-w_0)^2\ T_2^2} \qquad (2)$$

This equation shows that the gain is maximum when the incident frequency coincides with the atomic transition frequency. Amplifiers with a relatively large bandwidth are preferred for optical communication systems because the gain is then nearly constant over the entire bandwidth of even a multichannel signal. Amplification factor is defined as

$$G = P_{out}/P_{in} \tag{3}$$

Where P_{in} and P_{out} are the input and output powers of the continuous-wave (CW) signal being amplified. We can obtain an expression for *G* by using equation

$$\frac{dP}{dz} = gP \tag{4}$$

where P(z) is the optical power at a distance *z* from the input end. A straightforward integration with the initial condition P(0)=P shows that the signal power grows exponentially as

$$P(z) = P_{in} \exp(gz) \tag{5}$$

Amplification factor for an amplifier of length *L* is given by

$$G(\omega) = \exp[g(\omega)L] \tag{6}$$

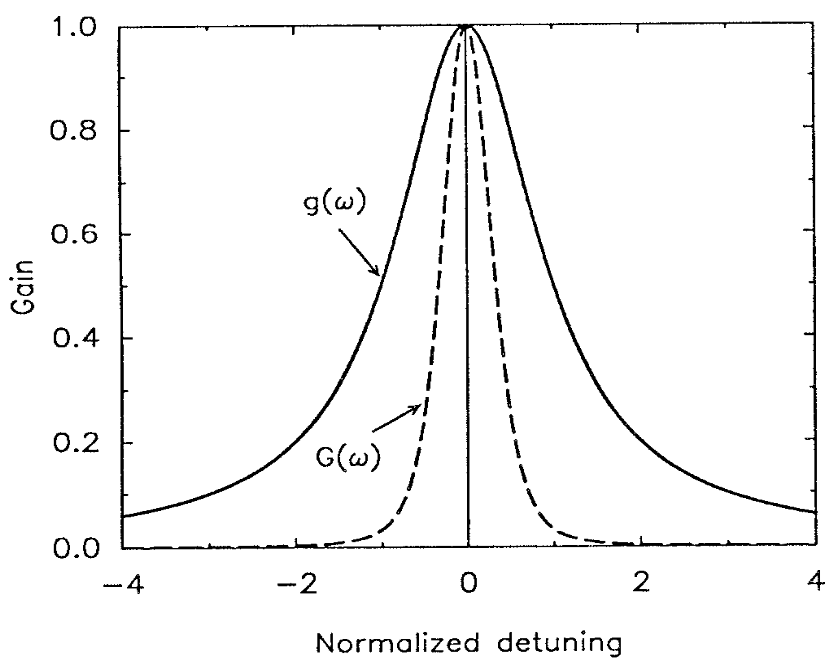


Figure 1.3: Gain variation vs. frequency

where the frequency dependence of both *G* and *g* is shown explicitly. Both the amplifier gain

G(ω) and the gain coefficient g(w) are maximum when $\omega = \omega_{0.}$ and decrease with the signal detuning. However, G (ω) decreases much faster than g(ω).

1.3.3 Gain Saturation: when signal power reaches around saturation power p_s then gain get reduced as indicated by equation (1). The amplification factor *G* decreases with an increase in the signal power. This phenomenon is called gain saturation. Consider the case in which incident signal frequency is exactly tuned to the gain peak $\omega=\omega_0$, equation (7) and (8) shows

$$\frac{dP}{dZ} = \frac{g_0 P}{1+\frac{P}{P_s}} \tag{7}$$

$$G = \exp\left(-\frac{G-1}{G} \times \frac{P_{OUT}}{Ps}\right) \tag{8}$$

hows the amplification factor G decreases from its unsaturated value G when Pout becomes comparable to Ps.

1.3.4. Amplifier Noise: All amplifier degrade the signal-to-noise ratio (SNR) of the amplifier signal because of spontaneous emission that adds noise to the signal during its amplification. The SNR degradation is quantified through a parameter Fn called the amplifier noise figure [11].

$$F_n = \frac{(SNR)_{in}}{(SNR)_{out}} \tag{9}$$

$$(SNR)_{in} = \frac{P_{in}}{2hv\,\Delta f} = \frac{<I^2>}{\sigma_S^2} \tag{10}$$

Where <I> is average photo current. R is called responsively with unit quantum efficiency. Parameter h is plank constant and Δf is bandwidth. To evaluate the SNR of the amplified signal, one should add the contribution of spontaneous emission to the receiver noise. The spectral density of spontaneous-emission-induced noise is nearly constant noise and can be written [11] as

$$S_{sp}(\nu) = (G-1) n_{sp} h\nu \tag{11}$$

$$n_{sp} = N_2/(N_2 - N_1) \tag{12}$$

where *v* is the optical frequency. The parameter n_{sp} is called the spontaneous-emission factor (or the population-inversion factor). Where N_1 and N_2 are the atomic populations for the ground and excited states, respectively. The effect of spontaneous emission is to add fluctuations to the amplified signal; these are converted to current fluctuations during the photo detection process. Use of optical amplifiers is to increase the transmitter power by placing amplifier just after the transmitter. Such amplifiers are called power amplifiers or power boosters, as their main purpose is to boost the power transmitted. A power amplifier can increase the transmission distance by 100 km or more depending on the amplifier gain and fiber losses. Transmission distance can also be increased by putting amplifier just before the receiver to boost the received power. Such amplifiers are called optical preamplifiers and are commonly used to improve the receiver sensitivity. Another application of optical amplifiers is to use them for compensating distribution losses in local-area networks.

Now days optical amplifiers are used for wavelength converter. Like Semiconductor optical amplifier can be used as a switch by biasing it above or below threshold value of current. Today optical amplifier has completely replaced their electronics counterpart. One major advantage of optical amplifier is that they are bit transparent. It means that they do not interfere with the data rate. But like electronics amplifier, these optical amplifier also has some limitations like gain saturation, pumping power requirement. These optical amplifiers have totally revolutionized the data communication.

1.4 Optical Amplifier

An optical amplifier is a device that amplifies an optical signal directly, without the need to first convert it to an electrical signal. An optical amplifier may be thought of as laser without optical cavity, or one in which feedback from the cavity is suppressed. Optical amplifiers are important in optical communication and laser physics. There are several different physical mechanisms that can be used to amplify light signal, which correspond to the major types of optical amplifiers. In doped fiber amplifiers and bulk, stimulated emission in the amplifier's gain medium causes amplification of incoming light. In semiconductor optical amplifiers (SOAs), electron-hole recombination occurs. In Raman, Raman scattering of incoming light with phonons in the lattice of the gain medium produces photons coherent with the incoming photons.

1.4.1 Semiconductor Optical Amplifier

A semiconductor laser amplifier (see figure 1.4) is a modified semiconductor laser, Which typically has different facet reflectivity and different device length [12]. Semiconductor optical amplifier is very similar to laser diode expect of facet reflectivity. A weak signal is sent through the active region of the semiconductor through the active region of the semiconductor, which, via stimulated emission, results in a stronger signal emitted from the semiconductor. SOA are of two different types. Fabry perot and travelling wave type. Both differ from each other in the reflectivity. FPA has a reflectivity of around 30% of the end mirror while TWA has about 0.01%. Out of these two TWA is most widely used due to its large bandwidth, high saturation power, and low polarization sensitivity. But TWA offer less gain due to low reflectivity than FPA.

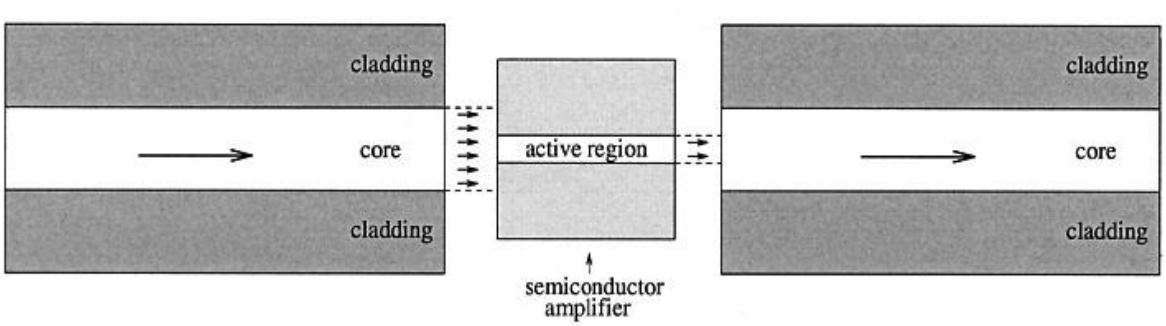


Figure 1.4: Semiconductor Optical Amplifier [12]

Amplification factor for FP-Soa is given by [13] [13]

$$G_{FP}(v) = \frac{(1-R_1)(1-R_2)}{(1-G\sqrt{R_1R_2})^2 + 4G\sqrt{R_1R_2}Sin^2[\pi(v-v_m)/\Delta v_L]}$$

where R_1 and R_2 are the facet reflectivities, v_m represents the cavity-resonance frequencies and Δv_L is the longitudinal-mode spacing, also known as the free spectral range of the FP cavity. Bandwidth of Soa is given by

$$\Delta v_A = \frac{2\Delta v_L}{\pi}\sin^{-1}\frac{(1-G\sqrt{R_1R_2})}{(4G\sqrt{R_1R_2})^{1/2}}$$

[14]

For large amplification $G\sqrt{R_1R_2}$ should be close to 1. Necessary condition for a FP-type Soa is

$$G\sqrt{R_1R_2} < 0.17$$

Although SOAs can be used to amplify several channels simultaneously, they suffer from a fundamental problem related to their relatively fast response. Ideally, the signal in each channel should be amplified by the same amount. In practice, several nonlinear phenomena in SOAs induce interchannel crosstalk, an undesirable feature that should be minimized for practical lightwave systems. Two such nonlinear phenomena are cross-gain saturation and four-wave mixing (FWM). Both of them originate from the stimulated recombination term.

$$P = 0.5\left|\sum_{j=1}^{m} Aj\exp(-iw_j t) + c.c\right|^2 \qquad [15]$$

Where c.c. stands for the complex conjugate, m is the number of channels, A_j is the amplitude, and w_j is the carrier frequency of the jth channel.

SOA's are typically used in the following applications.

1. Used as power boosters following the source (optical Post-amplifier).
2. Provide optical amplification for long-distance communications (in-line amplification, repeaters).
3. SOA can be used as a switch by biasing them above or below threshold current.

1.4.2 Erbium Doped Fiber Amplifier

A relatively high-powered beam of light is mixed with the input signal using a wavelength selective coupler. The input signal and the excitation light must be at significantly different wavelengths. The mixed light is guided into a section of fiber with erbium ions included in the core. This high-powered light beam excites the erbium ions to their higher-energy state. When the photons belonging to the signal at a different wavelength from the pump light meet the excited erbium atoms, the erbium atoms give up some of their energy to the signal and return to their lower-energy state. Most of EDFA are pumped either at 980 nm or 1480 nm. 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. Both C band 1525-1565 nm and L band 1570-1610 nm. DFA can be Doped with praseodymium, thallium. Gain spectra of EDFA are non uniform. A notch filter can be employed for gain flattening.

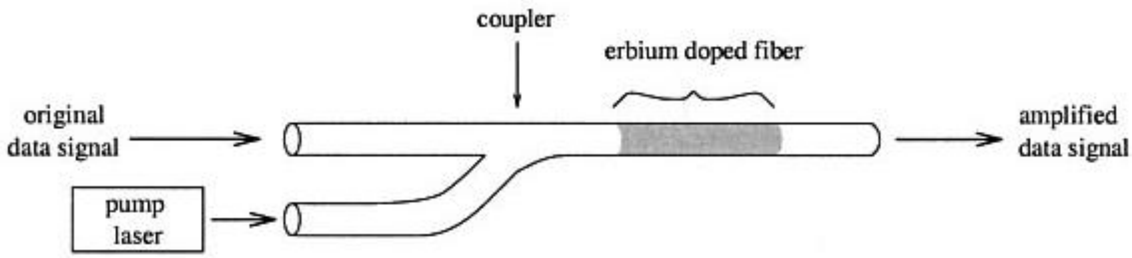


Figure 1.5: (a) Erbium doped fiber amplifier [12]

EDFA noise figure depend on both pump power and amplifier length for larger the pump power better will be the noise figure. EDFA Figure shows the variation of noise figure and gain with amplifier length for various value of pump power.

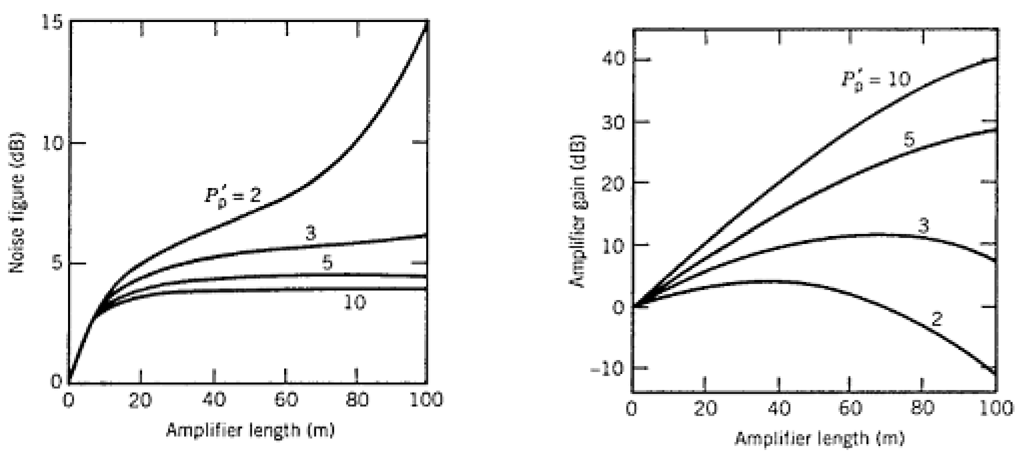


Figure 1.5: (b) Noise figure and gain variation with length for varying pump[14]

EDFA mathematical model for a two level system shows that ASE gets accumulated along the length of the erbium fiber. So larger the length more will be the amount of ASE generated.

This model is

$$\frac{n_2}{n_1} = \frac{\sum_{\lambda} \frac{P_\lambda(z)\alpha_\lambda^*}{h\nu_\lambda \xi}}{1+\sum_{\lambda} \frac{P_\lambda(z)(\alpha_\lambda^* + g_\lambda^*)}{h\nu_\lambda \xi}} \qquad [16]$$

$$\xi = \pi b_{eff}^2 n_t / \tau$$

$$\frac{dP_\lambda}{dz} = u_\lambda(\alpha_\lambda^* + g_\lambda^*)\frac{n_2}{n_1}P_\lambda(z) + u_\lambda g_\lambda^* \frac{n_2}{n_1} mh\nu_\lambda \triangle\nu_\lambda - u_\lambda(\alpha_\lambda^* + l_\lambda)P_\lambda(z) \qquad [17]$$

Where n_2 is the density of Erbium ions in the metastable state; n_1 is the density of all Erbium ions; P_λ is the power at wavelength λ and this can represent the pump power (λ = p) as well as the power of the m WDM channels (λ = i, with i = 1,2,... ,m) to be amplified; v_λ represents the frequency of field λ ; h is the Planck's constant; t is the fluorescence lifetime in the metastable level; ξ is the saturation parameter of the fiber. The parameters α_λ^* and g_λ^* are the absorption and emission coefficients, respectively; u, denotes either the forward (u_λ = l) or backward (u_λ = -1) propagating direction; m is the number of modes transmitted in the optical fiber and l_λ is the excess loss of the doped fiber.

1.4.3. Raman Amplifier

Raman amplifier is mostly used for long haul communication purpose. 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 [15]. Raman gain exists in every fiber. Raman amplifier use SRS (simulated Raman scattering). Atom or molecules in their crystal structure keep on vibrating. Their vibrating frequency (10^{12} to approximately 10^{14} Hz) lies in Infra red region. At any given instant, each molecule in a sample has a certain amount of vibrational energy. However, the amount of vibrational energy that a molecule has continually changes due to collisions and other interactions with other molecules in the sample. High intensity laser radiation with wavelengths in either the visible or near-infrared regions of the spectrum is passed through a sample. Photons from the laser beam are absorbed by the molecules, exciting them to a virtual energy state. When these molecules returns to a more stable state by releasing energy which is lower than the absorbed. Then the emitted photons are of lower energy than the incident photon. These waves of low frequency are known as stoke wave. . Mohammed N. Islam [8] described in 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 non-resonant, 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. Raman amplifiers are of two types. Discrete Raman amplifier and a distributed Raman amplifier. Further Raman can be used to amplify any signal provided a pump signal is available for that. Raman can be pumped from more than one pump i.e. multipump configuration. Multipump configuration can be used to gain broadening of Raman amplifier. Raman amplifier is most widely used in hybrid configuration.

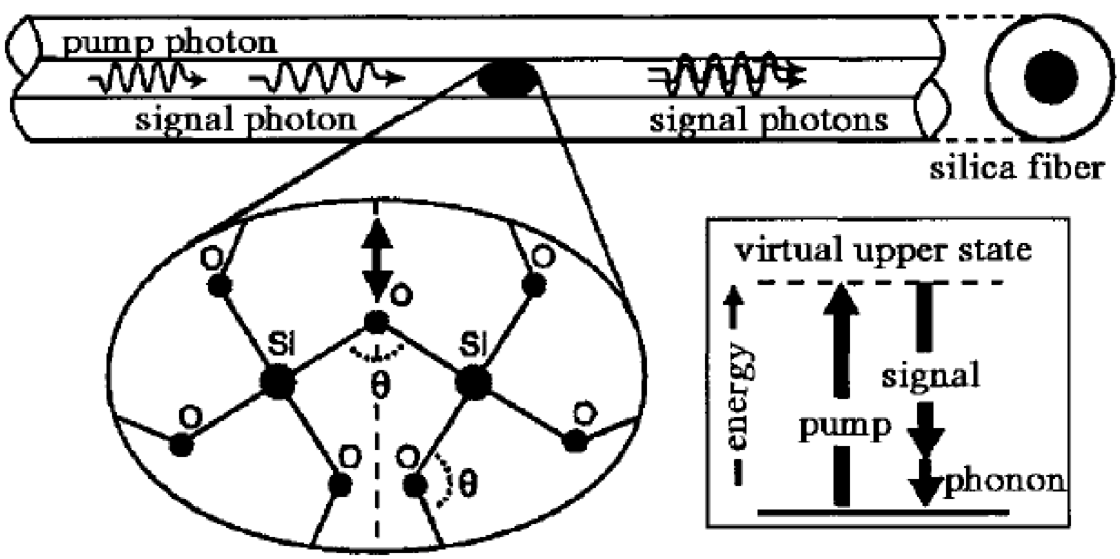


Figure 1.6: Raman amplifier [12]

One disadvantage of Raman amplifier is that it require high pump power. Further Raman can be pumped in three different methods. A co pumping mean pump signal and input signal both are in same direction. Counter pumping means pumping in opposite direction. A bidirectional pumping means pumping has to be done from both sides.

Raman gain spectrum is broadband. Raman gain is given by

$$g(w) = g_R(w)\left(\frac{P_P}{a_p}\right) \quad [18]$$

Where P_P is pump power and α_p is cross section of pump beam inside fiber. Since α_p varies with fiber so Raman gain varies with fiber used. Since Raman is a fiber amplifier so affect of fiber loss has to be taken into account. These variation of signal and pump power can be find out from

$$\begin{aligned} \frac{dP_s}{dz} &= -\alpha_s p_s + (g_R / a_P) p_p p_s \\ \frac{dP_p}{dz} &= -a_p p_p + (\omega_p / \omega_s)(g_R / a_P) p_p p_s \end{aligned} \quad [19]$$

α_s, a_P are represent fiber losses at the signal and pump frequencies ω_s and ω_p. In Raman amplifier signal power at the end of amplifier length varies according to the equation. Because of the fiber loss effective length (equation 20) of fiber is less than the actual length.

$$\begin{aligned} P_s(L) &= P_s(0)\exp[(g_R p_0 L_{eff} / a_P) - \alpha_s L] \\ L_{eff} &= [1 - \exp(-\alpha_p L)] / a_P \end{aligned} \quad [20]$$

In the absence of Raman amplification Raman gain reduces to

$$G_A = \frac{p_s(L)}{p_s(0)\exp(-\alpha_s L)} = \exp(g_0 L) \quad [21]$$

where

$$g_0 = g_r\left(\frac{p_0}{a_p}\right)\left(\frac{L_{eff}}{L}\right) \quad [22]$$

Raman amplifier performance is mainly limited by Rayleigh scattering. Due to this a small part of light is backscattered. Normally this is small and can be ignored but as the fiber length increases loss accumulates and becomes significant. Rayleigh scattering is main factor for power penalty in Raman fiber. It introduces noise as well as crosstalk. Rayleigh crosstalk is given by [16]

$$f_{DRS} = r_s^2 \int_0^z G^{-2}(z1)dz1 \int_{z1}^L G^2(z2)dz2 \qquad [23]$$

Where r_s Rayleigh coefficient which is nearly equal to 10^{-4} km^{-1}. G(z) is gain at a distance of z in backward pumping direction for a ampliifer of length L. Raman amplifier can work at any wavelength provided suitable pump power is available. While designing a Raman amplifier for a WDM system many features like pump –pump interaction, Rayleigh scattering, SRS has to be taken into account. Raman pump power variation in forward and backward pumping [17] is given by

$$\frac{dP_f(v)}{dz} = \int_{u>v} g_R(u-v)a_u^{-1}[p_f(u)+p_b(u)][p_f(u)+2hvn_{sp}(u-v)]du \qquad [24]$$
$$-\int_{u<v} g_R(v-u)a_u^{-1}[p_f(u)+p_b(u)][p_f(v)+2hvn_{sp}(v-u)]du$$
$$-a(v)p_R(v)+r_s p_b(v)$$

Where *u* and *v* denotes the optical frequencies. Subscripts *f* and b denotes the forward and backward pumping. Third and fourth term in right side is due to fiber loss and Rayleigh scattering.

1.5 Hybrid Optical Amplifier

Hybrid optical consists of two or more optical amplifier connected together which may be same or different type. There are varieties of hybrid amplifier. Hybrid amplifier provides higher gain than individual amplifier. According to Mohammed N. Islam total gain of hybrid amplifier is equal to the sum of individual gain [8].

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

Mainly we classify them into two categories. First is narrowband hybrid amplifier (NB-HA) and other is seamless wideband hybrid amplifier (SWB-HA). The NB-HA employs the use of

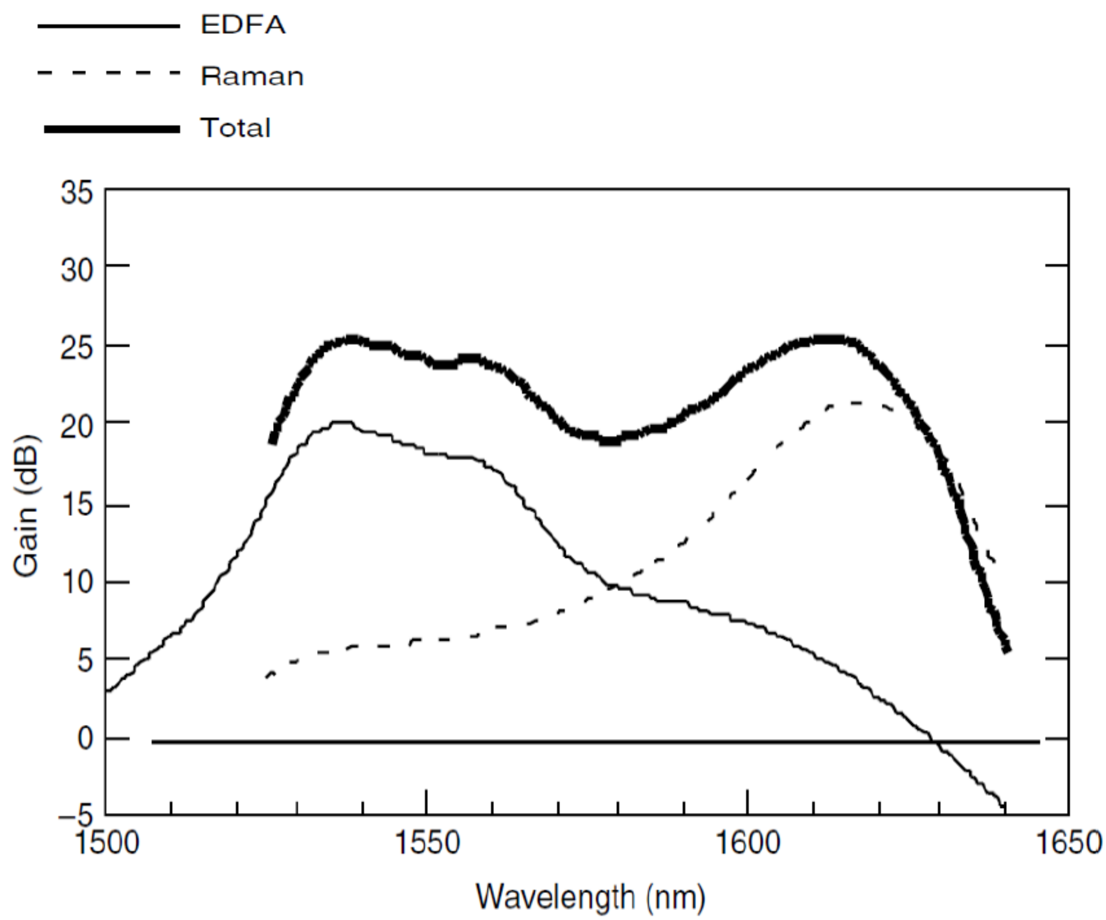
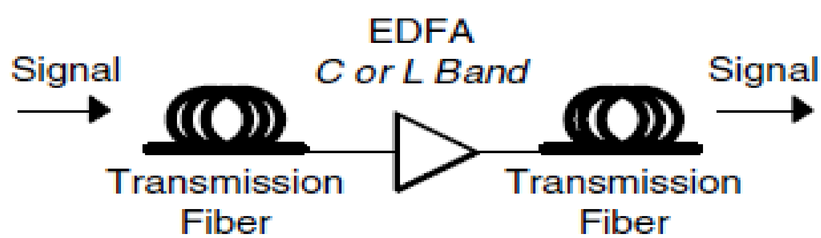


Figure 1.7: Gain spectra of a hybrid amplifier [18]

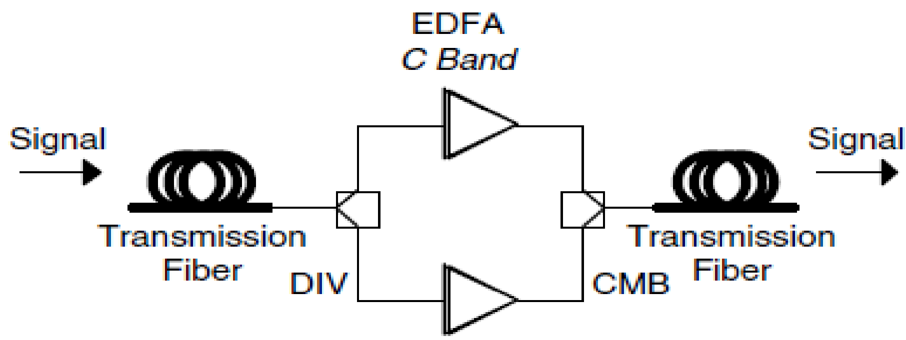
distributed Raman amplification in the Transmission fiber together with an EDFA and provides low noise transmission in the C- or L band. This configuration provides a low noise figure as compared to stand alone EDFA or Raman. SWB-HA may use both distributed as well as discrete Raman amplifier along with 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 of the NB-HA is 30 nm to 40 nm, whereas that of the SWB-HA is 70 nm to 80 nm. The significantly wider gain bandwidth of the SWB-HA, compared to the individual gain bandwidths of the EDFA and the RA, was obtained without a gain equalizer by the single wavelength pumping approach, because the gain spectra of the EDFA and RA have opposite gain slopes. Moreover, significantly improved gain flatness is obtained by the two-wavelength pumping if the optimum Raman and EDFA pump wavelength values are selected.

1.5.1. Classification of Hybrid Optical Amplifier

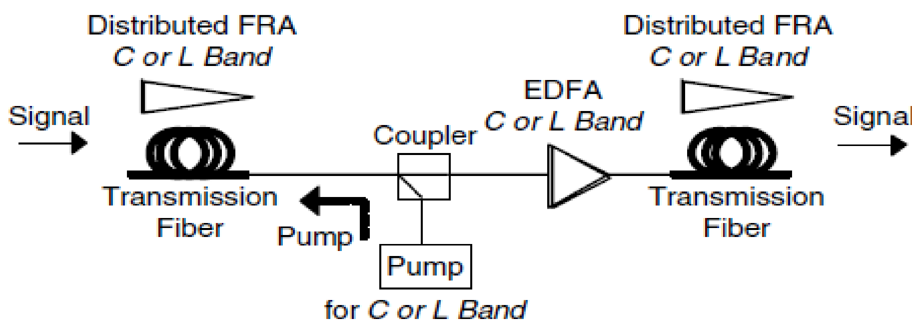
The figure 1.8 shows some basic configurations of a transmission line with an inline amplifier. An EDFA is used as the repeater between two installed transmission fibers and amplifies the input signal light figure 1.8 (a) The light signal usually consists of wavelength-division multiplexed (WDM) multichannel and the EDFA offers C or L-gain band coverage [5]. 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 1.8 (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 1.8 (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 1.8(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. The figure 1.8 (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.



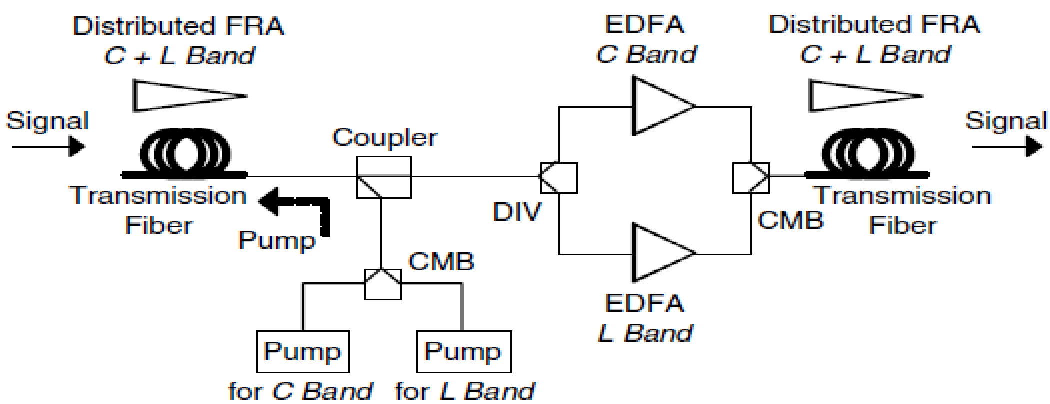
(a)


EDFA
C Band
Signal
Signal
Transmission
Fiber
DIV
CMB
Transmission
Fiber

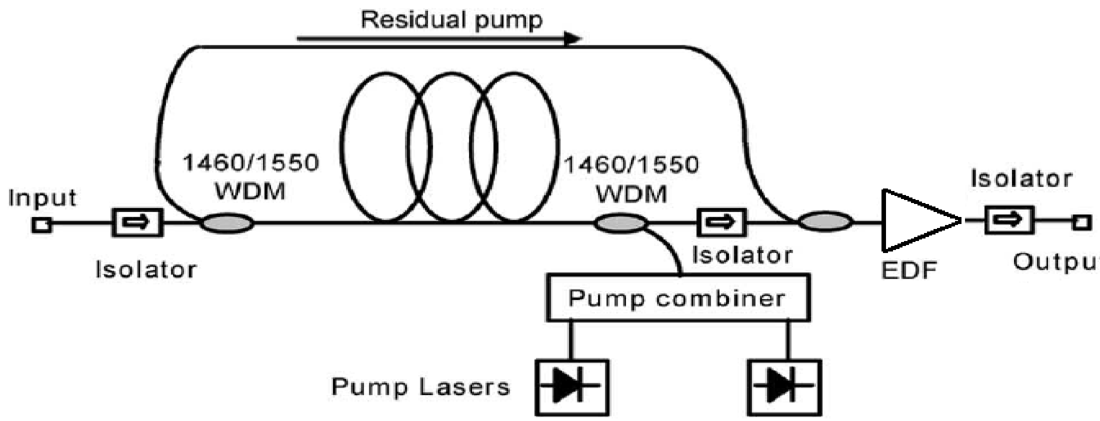
(b)


Distributed FRA
C or L Band
Distributed FRA
C or L Band
EDFA
C or L Band
Signal
Coupler
Signal
Transmission
Fiber
Pump
Pump
for C or L Band
Transmission
Fiber

(c)


Distributed FRA
C + L Band
EDFA
C Band
Distributed FRA
C + L Band
Signal
Coupler
Signal
Transmission
Fiber
Pump
DIV
CMB
Transmission
Fiber
CMB
Pump
for C Band
Pump
for L Band
EDFA
L Band

(d)



(e)

Figure 1.8: 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) 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) ; (d) a hybrid Raman and EDFA amplifier with residual pump[19].

1.6. Development in WDM Technology

WDM technology start around 1980 when only two channel were used at 1310 nm and 1550 nm this was known as wideband WDM because of large channel gap. Later on around 1985 number of channel increased from two to eight with reducing channel spacing around 400 GHz in 1550 nm window. This was called narrowband band WDM systems. By mid 90 number of channel further increased from 16 to 40 thus further decreasing channel spacing nearly 100 GHz. Around the year 1995 a new generation called DWDM came into existence which increases number of channel from 40 to 160 and even more with reducing channels spacing around 50 GHz or even 25 GHz. The first generation of WDM networks provides only the point-to-point physical links, The technical issues of the first generation WDM include the design and development of the WDM lasers and optical amplifiers (OAMP). 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 (WADM or OADM) and optical cross connects (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. The technical issues of second-generation WDM include the development of OADM and OXC, wavelength conversion, routing and wavelength assignment (RWA),

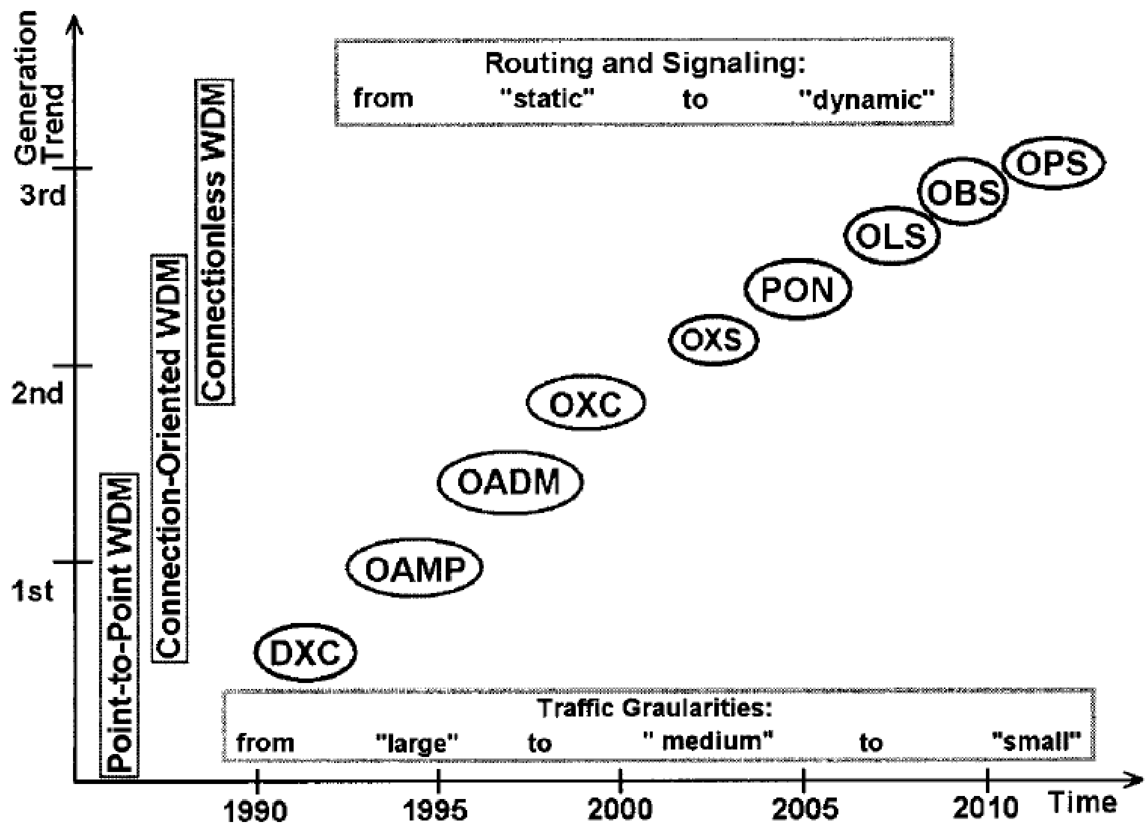


Figure 1.9 : Growth of WDM network[12]

Inter operability 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. 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), etc.

1.7 OptSim

The core version of OptSim was first developed in 1983 by the Optical Communication Group of Politecnico di Torino [20]. The optical simulation software was originally known as TopSim, a transmission system simulation package, which was developed for mobile and satellite communication. OptSim was furthered 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, polarization mode dispersion (PMD), and 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 solves 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). 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. 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.

1.7.1 System Requirements for OptSim:

The Windows versions require for OptSim Windows 2000/XP. OptSim is not guaranteed to work under Windows 95/98/NT. It can be installed in Window7 using V-WARE software. This will install virtual XP. OptSim will also run under Linux and various UNIX using X Windows or XFree86 and Motif. Hardware requirements areas follow [20].

- 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.

1.7.2 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 96 channel transmitters, receiver, and optical hybrid amplifier has been used as compound component (see figure1.9).The procedures for creating the compound component for optical 96 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 .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. By right clicking on component its parameter can be set.
6. Save the file
7. To change the number of transmitters, receivers and optical amplifiers, right click the compound component

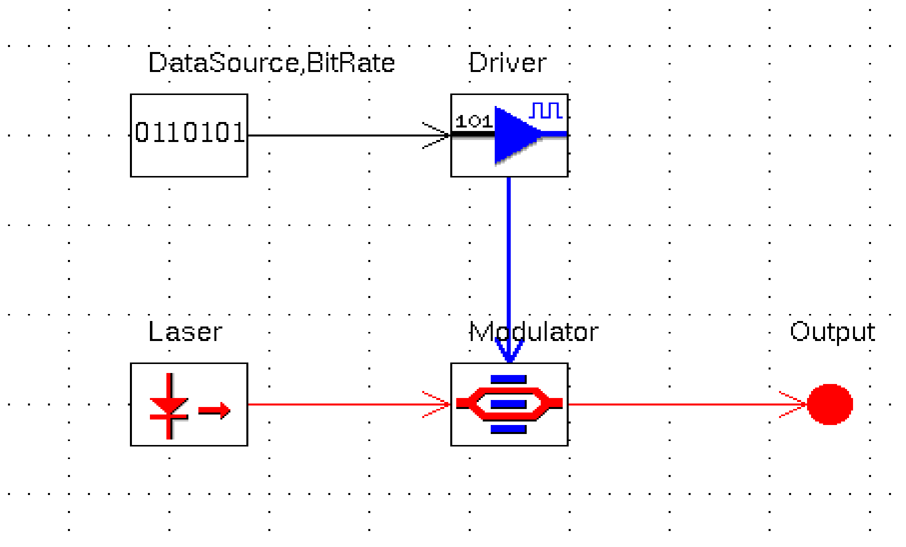


Figure 1.10: (a) Single channel transmitter

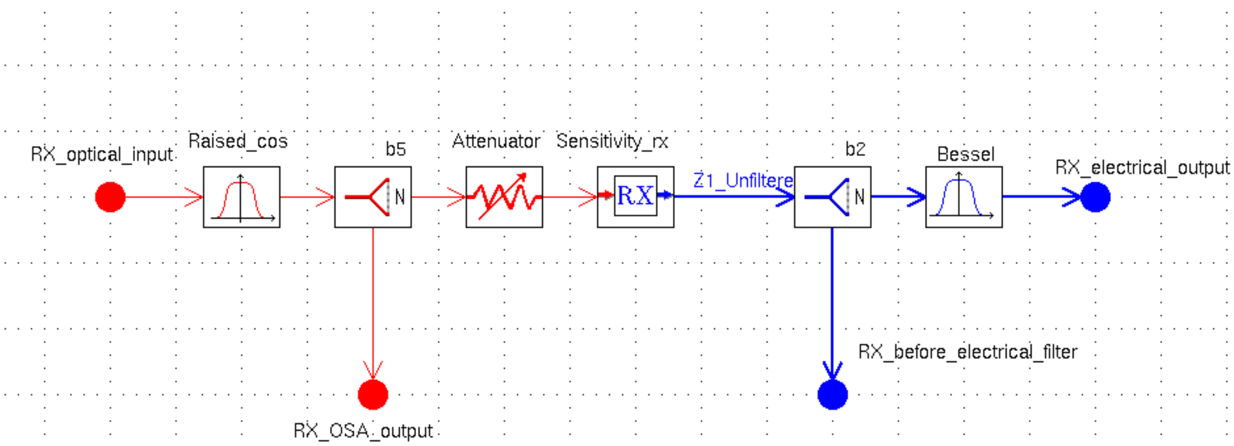


Figure 1.10: (b) Single channel receiver

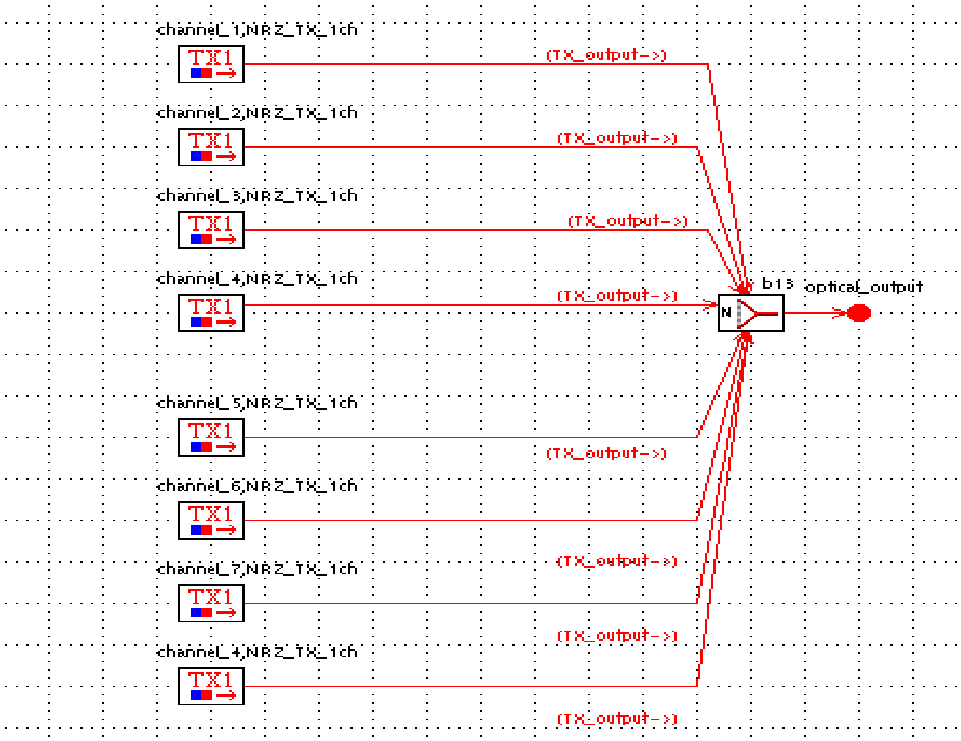


Figure 1.10 (c) Eight channel transmitter

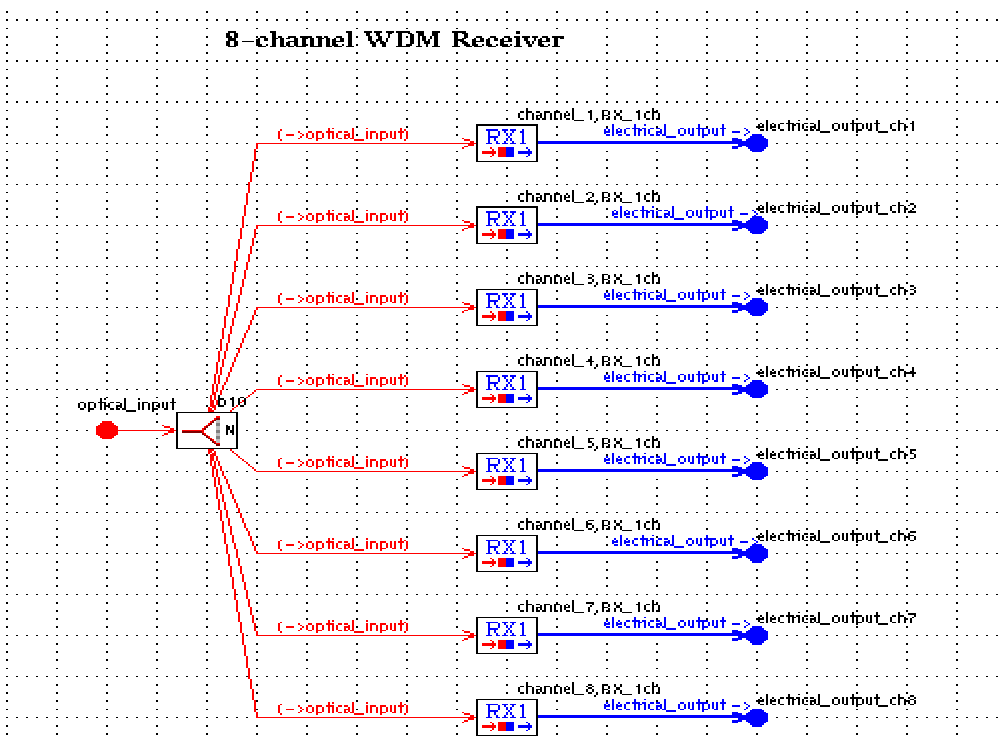


Figure 1.10 (d) Eight channel receiver

Chapter 2

Literature Survey

2.1 Motivation

Optical amplifier has now become backbone of today communication networks. Earlier before the invention of optical amplifier, electronics repeater was used. Drawback of such system was that optical signal needed to be converted back into electronics form then signal was electronically amplified. After this electronics signal is again converted into optical form. Thus this involves OEO conversion. 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. So the efficiency of such system was dependent on electronics hardware. To overcome this optical amplifier came into existence, these amplifier directly amplify the signal. Today WDM networks which are used for long distance communication totally depend on optical amplifier. Optical amplifier is transparent to bit rate, modulation format. Optical amplifier allows amplification of signal ire-respective of their modulation type or data rate. This is big advantage of optical amplifier. Now there are a variety of. Optical amplifiers which can be classify under two broad categories. One is semiconductor amplifier and other is fiber amplifier. Optical amplifier can be placed after the transmitter, in between the link or just before the receiver. These Optical amplifier increase the signal power so that signal can tolerate the loss occurred in the fiber link. The optical amplifiers are mainly used for WDM (Wavelength division multiplexing) light wave systems as all channels can amplify simultaneously.

2.2 Literature Survey

Optical amplifier is a device which amplifies the input optical signal. This device works on the principle of stimulated emission. 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 three types of OAs which are used in fiber optics communication system; semiconductor optical amplifiers (SOAs) and doped fiber amplifiers (DFAs), Raman amplifier .The SOAs are basically semiconductor lasers which operate below lasing threshold.

G. Nykolak et al. [21] carried out the experiment study of Erbium doped multimode fiber in 1991. For a 2 mtr length of Erbium with 13 μm core.they measure gain as high as 16 dB. This was done at signal wavelength of 1543 nm at pump power of 100 mW. In this paper they use pump wavelength of 980 nm. A mode scrambler was used to connect a single mode fiber to a multimode fiber. A plot of amplifier gain versus pump power for an input power of -11.84 dBm was plotted. They also calculated the gain versus output power for two different pump condition Ppump = 106 mw and 45 mw. Result of this paper is that a gain of 16 dB was obtained with 2 mtr length of EDFA with 13 um core.

A. S. Siddiqui et al. [22] obtained a further enhancement in optical gain. By using narrow band pass filter instead of isolator in the amplifier length .it is possible to increase the gain by more than 10 dB. This was done for a signal wavelength of 1.55 um. They also show that gain improvement for longer wavelength away from the amplifier gain peak is much higher than conventional EDFA. They also calculated the position of optical filter in the amplifier length. They found that the filter should be placed at 42% of the amplifier length from the input end. The used parameter for the EDFA was carrier life time = 10 ms, pump wavelength = 980 nm, pump power = 30 mw, signal power = -40 dBm, fiber core radius = 1.8 um, cut off wavelength = 920 nm. In this paper they compare the gain and noise figure for various filter position. Gain improvement of 4.5 dB at wavelength of 1531 nm and 11 dB at wavelength of 1550 nm was obtained. This paper clearly shows that gain improvement take place with optical filter. In the above analysis it was assumed that filter does not produce any insertion losses. However this is not the case in practice. Further they showed that gain improvement is more dependent on the pump less than the filter insertion loses. For pump loses of 1 dB significant gain improvement is obtained provided the insertion loses is less than 6 dB.

E. Willner [23] experimenting WDM system comprising of around 20 channel passive equalization of non uniform gain of EDFA was done with optical filter. Since in optical amplifier the amplified spontaneous noise is a big issue. It keeps on adding in a accumulated system so in cascaded system the total ASE become a big issue. Also the gain of the EDFA is non uniform. So with the inclusion of optical amplifier in a cascaded system of EDFA with each amplifier showing non uniform gain, we find a solution while maintaining minimum signal to noise ratio. In this paper a WDM system consisting of 20 channel intensity modulated at 2.5 Gb\s with a channel spacing of 0.5 nm was analyzed. They started with input power of -10 dBm per channel. The signals are input to a cascade of EDFA's with an input signal power of -10 dBm per channel. The center wavelength of the 10 nm wavelength range for the 20 channels is chosen to be 1557 nm, since this is the flattest part of the EDFA gain. The EDFA's are pumped at 1480 nm with a pump power of - 17 mW, thereby providing - 20 dB of small-signal gain for this 10 nm wavelength range; note that 980 nm pumping gives similar results for this paper. The link loss between amplifiers is 10.5 dB, which roughly corresponds to the saturated gain generated by each amplifier in a cascade; it was seen that ASE spectrum are non uniform over much of the spectrum. In this paper a result of 20 channel WDM system SNR with or without filter was compared. Filter used was Fabry perot centered at 1557 nm. The first fiber amplifiers were pumped by flash lamps and operated in a pulsed mode. In the mid 1995 the current emphasis of WDM light wave systems increased the system capacity by amplifying all channels by using single amplifier covering spectral region from 1460 nm to 1630 nm.

Jay M. Wiesenfeld et al. [24] transmitted data at 10 Gb/s from an input signal wavelength to another wavelength, either longer or shorter, using gain compression in a 1500 nm semiconductor optical amplifier for wavelength conversion. To achieve operation at such high bit rates, the probe (shifted) input must be intense enough to compress the gain of the amplifier significantly. This reduces the gain recovery time of the amplifier because of probe stimulated emission. A consequence of the intense probe is an extinction ratio deduction. Using moderate input powers, wavelength conversion is achieved over a 17 nm (2 THz) range, with 0.7 dB- 3 dB power penalties.

C. Joergensen et al. [25] improved the performance of [18] by transmitting at a bit rate higher than 10 Gb/s. They experimented at bit rates up to 40 Gb/s for both cross-gain modulation (XGM) and cross-phase modulation (XPM) in SOA's. For XGM, they have shown experimental evidence for a 50 GHz bandwidth using two 1200 mtr-long SOA's in cascade, each having a large confinement factor of 0.6. Additionally, negligible conversion penalty for both up and down conversion has been demonstrated by an optimized and compact 1.3 mm-long all-active MQW MI structure at 20 Gb/s. Moreover, experiments at 40 Gb/s using the MI wavelength converter demonstrated high-quality converted signals with > 10 dB extinction ratio and > 25 dB optical SNR (in 1 nm).

Wong C. S. et al. [26] demonstrated a high-extinction-ratio all-optical wavelength converter using birefringence switching in a semiconductor optical amplifier. The extinction ratio of the data-bearing wavelength-converted signal was improved by 9 dB compared to that of the input signal. The polarization change of the probe light in the presence of the input signal was measured. Bit error rate measurements at 10 Gb/s were performed and a power penalty of 2 dB was observed for the wavelength converter. The polarization sensitivity of the wavelength converter was 0.75 dB.

Chung Ghiu Lee. et al. [27] they showed that data can be changed from RZ to NRZ all optically by semiconductor optical amplifier (SOA) in a nonlinear optical loop mirror. The format conversion scheme is based on gain variation by an intensity-dependent phase change in an SOA-loop mirror. The input data stream acts as a control signal that induces the phase differences between clockwise and counterclockwise propagating data inside an SOA-loop mirror. It is possible to change the data format of the output data stream by controlling the phase differences of the clockwise and counterclockwise pulse in an SOA-loop mirror appropriately. From this method the output NRZ data at 10 Gb/s up to 78 km over single-mode fiber was transmitted. By comparing to the conventional NRZ transmission with the Mach-Zehnder modulation scheme, this shows an improved transmission performance. The NRZ-to-RZ conversion has clear eye openings up to 78 km as compared to 52 km of conventional RZ format. On the contrary, the conventional RZ binary data from a mode-locked laser has a nearly closed eye even at 52 km. The converted RZ data has a 2 dB conversion power margin to the injected NRZ data, which indicates an increase in the receiver sensitivity due to the signal format conversion. The improved transmission distance of the converted RZ signal is due to the duobinary coding effect of the SOA-loop mirror. The SOA has the possibility of high-speed operation over 40 Gb/s, and the SOA-loop mirror has the capabilities of format and wavelength conversions. Therefore, the SOA-loop mirror can be universal building block in future all-optical networks.

Katebi Jahromi and Farzin emami [28] 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. 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 Raman amplifier can be pumped either forward, backward or bidirectional in each of the configuration the type of transmission media plays a bigger role . So performance of DRA for Z fiber and DSF (dispersion shifted fiber) for each configuration for the optimized parameter such as pump power, pump power, ASE, noise figure was derived. Outcome of this paper was that we require minimum power and signal fluctuations when the DRA was used in backward configuration, which leads to minimum ripple in the output. They find that DSF fiber has better noise figure and more uniform gain with respect to Z fiber. Gain bandwidth of Raman amplifier determine by the pump power. Also multipumping scheme can be employed to broaden the bandwidth of Raman amplifier. In this paper the noise figure, ASE, distributed Rayleigh scattering for all three type of Raman configuration was evaluated. Parameter used for DSF was attenuation constant = 0.21 dB\km while for Z fiber it was 0.17 dB 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.

Beninca, M.O.L et al. [29] purposed a new design methodology for hybrid optical amplifiers operating simultaneously at C and L bands. This configuration uses an Erbium Doped Fiber Amplifier (EDFA) operating as a booster to obtain optical gain over the C-band and a Distributed Raman Amplifier (DRA) to provide gain over the L-band and control the gain ripple. The amplifier performance was computed in terms of on-off gain and ripple, Optical Signal to Noise Ratio (OSNR), and Noise Figure (NF). Our results show on-off gain from 17 dB with ripple up to 2 dB over a 65 nm bandwidth. The OSNR was higher than 35 dB with NF lower than 4 dB at 120 km. Fiber links from 90 km up to 180 km have been analyzed spans, in this paper simulation was a basic amplifier with one co propagating pump laser operating at 1480 nm wavelength with 100 mW of pump power. The amplification medium was of 1000 ppm Er^{3+} ion concentration in a 5 mtr doped fiber length. This low cost amplifier due to its basic layout is used as a booster in the C band with a 13 dB average gain and low noise figure (around 4 dB). This allows channels with -7.7 dBm, of input power each, to be launched throughout hundreds of kilometers, depending on the bit-rate and receiver sensitivity. For this model the power conversion efficiency, PCE = (P_{out} – P_{in})/P_{pump} was of 77 % where Pout and Pin are, respectively, output and input power. In this paper EDFA was used as a booster. EDFA characteristics Value Pump wavelength (nm) 1480 , Pump Power (mw) 100, Er3+ concentration(ppm) 1000 , Fiber Length (mtr) 5, Gain Range (dBm) 14.71 to 6.65, Noise Figure Range (dBm) 4.98 to 3.10 . In this paper for different fiber length the optical signal to noise ratio, noise figure, gain was calculated. It was found that EDFA and FRA broadband hybrid amplifier provide better result for than single EDFA.

Martini et al. [30] use residual pump power of RAMAN to feed EDFA then optimization of gain profile take place. It is based on the equalization of Erbium's gain spectrum by adjusting the flexible gain profile of a multi-pump Raman amplification stage. In this paper Raman with two and three pump amplifier has been studied.

Dumas, B. et al [31] further study hybrid amplifier in 2006. In this amplifier they use a two stage EDFA amplifier acting just like a in line amplifier. In this paper incorporate dispersion-compensating fiber (DCF) and optical components such as gain flattening filter, optical attenuator, and tap couplers. DCF is well known solution in compensating the fiber dispersion. However, high loss of DCF degrades noise figure of EDFA. In this paper they achieve a noise figure < 5 dB and a high output power of 23 dBm by using DCF as Raman fiber. They hybrid compare the performance of this configuration with conventional EDFA. HFA is composed of three stages: short-length EDFA pre-stage, DCF Raman amplifier (DCRA), and power boosting EDFA (B-EDFA). 4.5 mtr length of EDF (Er concentration - $8.1x10^{24}$ /m3) was used in pre-stage and it was pumped by 980 nm laser diode (LD). Insertion loss of IWDM and isolator was 0.8 dB and 0.3 dB. They use eighty channels ranging from 1530.33 nm to 1561.82 nm with 50 GHz spacing. The total input power was -2 dBm that corresponded to -21 dBm per channel. Pumping power was 100 mW, high enough to obtain high population inversion in EDFA. They found that noise figure was 2 dB better than EDFA. Transmission performance of each channels after 720 km SMF transmission when HFAs were used as line amplifiers in the circulating loop. Then, HFAs were replaced by EDFAs and the same experiment was performed. It shows the measured OSNR (optical signal to noise ratio). OSNR with HFA was higher than that with EDFA due to lower noise figure of HFA. Average OSNR was 22.8 dB and 21.0 dB. They showed the measured Q-factor after 720 km SMF transmission. The Q-factor in the case of HFA was higher by more than 1.0 dB. From these results, it can be concluded that HFA gives better transmission performance than EDFA.

Jowan Masum-Thomas et al. [32] designed a hybrid amplifier for short wavelength amplification. It is reported by cascading a Thulium doped fluoride fiber with a discrete Raman amplifier. Gain > 20 dB for a bandwidth 1445 nm - 1520 nm (75 nm) was achieved and also Gain > 30 dB and noise figures of between 7-8 dB were achieved for 50 nm bandwidth. They have achieved a flat gain without the usage of any gain flattening techniques due to the symmetric gain spectra of both amplifiers.

C. R. Davidsou et al. [33] first time demonstrated the transmission of two hundred and Fifty six 10 Gb/s WDM channels over 11,000 km in 80 nm of continuous optical bandwidth using a simple combination of distributed Raman gain and single-stage EDFA. The channel spacing across the bandwidth from 1527 nm to 1606.6 nm was 0.31 nm. This error free performance is achieved with the use of concatenated Reed-Solomon FEC coding. They have achieved the error free communication with least bit error rate ($< 10^{-10}$) good quality factor (> 9.1 dB).

H Masuda et al. [34] achieved the largest reported seamless gain bandwidth of 135 nm (from 1497 to 1632 nm) with a minimum gain more than 20 dB for optical fiber amplifiers with a novel hybrid telluride/silica fiber Raman amplifier. The amplifier was successfully used as preamplifier in an 8 ×10 Gb/s transmission experiment with signal wavelengths in the S, C, and L bands over an 80 km standard SMF with a BER of less than 10^{-11}. The amplifier also provided a dispersion equalization function because it had a built-in negative-slope dispersion compensation fiber as its silica Raman gain medium. A lot of interest was raised, as to whether all Raman amplification is better than widely used counter pumped Raman/EDFA hybrid amplification. But in this case Double Rayleigh scattering (DRS) was suggested as the major limiting factor for all-Raman systems.

Y Zhu et al. [35] presented an experimental comparison of the performance of all-Raman vs. Raman/EDFA hybrid schemes at the line rate of 40 Gb/s. Bi-directional pumping rather than counter-pumping, was used in the case of long-span evaluation to minimize the impact of DRS. In this work it is also reported that all Raman distributed amplification has allowed best transmission performance, compared to Raman/EDFA hybrid amplification. All Raman transmission yielded up to 1.3 dB system Q improvements in the 40 and 80 km span length systems, compared to the systems without Raman gain. In that same year they extended their own work by transmission of 16 channels of 40 Gb/s speed over 400 km using same Raman/EDFA hybrid optical amplifier. Single Raman pump wavelength having advantages over multiple pumps wavelengths are: a) simpler design and thus possible cost savings and b) Raman gain shape independent on channel loading. The second point is very important because the gain shape of saturated Raman amplifier with multiple pumps can be complex function of the channel present.

Maxim Bolshtyansky et al. [36] reported the first demonstration of a hybrid flat tilt free amplifier for use in a new wavelength rang L+ band (1610-1640 nm) using a single pump wavelength (1536 nm). They reported that to reduce the micro-bend loss at 1640 nm we have to improve Raman gain media.

P. P. Iannone et al. [37] further study of hybrid amplifier based on dynamic channel was done. Performance of HFA was studied under varying no of channel in the network. Since no of channel added or dropped has an effect on the transient effect. In this paper we study the performance of adding or dropping 17 channels in a 20 channel system. It was found that HFA gives much better and faster for forward HFA than backward. In this paper they analyses four different configuration of hybrid amplifier. A further study of WDM system at 100 GHz spacing for 96 channels for different fiber with varying distance has been studied. In this paper, we have investigated the performance comparison of different fibers by varying distance from 50 kms to 290 kms. The optimization has been done using 96 channels at the speed of 10 Gb/s.. It is observed that 290 kms is optimized distance for Ds-Anomalous fiber because up to this distance, it provides the best result. The system performs poorly for SMF due to less durability, insufficient quality and cost. In this paper analysis was done at fixed channel spacing.

R.S.Kaler [38] studied the effect of varying channel spacing. A varying channel spacing from 6.25 GHz to 75 GHz was analyzed. The effect of four wave mixing was considered. They found that eye opening keeps on increasing as we increases channel spacing. Optimize channel spacing was find out. The modulation format used was non return to zero. This format has advantages of narrow spectral width. So NRZ format has more immune to dispersion tolerance. In this paper the analysis was done at 10 Gb\s for varying channel spacing for a fixed format.

Sameksha Bhaskar [39] studied the performance Comparison of different hybrid amplifiers for different numbers of channels. The proposed configuration consists of 16, 32 and 64 Gb/s channels at speed of 10 Gb/s. It is observed that SOA-EDFA showed good performance as it can travel max distance of 220, 240, 260 km at 16, 32 and 64 channels respectively. Also, RAMAN-EDFA showed a good performance as it has a high Quality Factor (24.27) and BER (1×10^{-40}) at 16 channels. But all this has been done at a fixed bit rate.

Shveta singh [40] For high-speed optical communication, experimentally demonstrated the results for different data formats, viz. NRZ Rectangular, NRZ Raised cosine, RZ Rectangular and RZ Raised cosine. In the case of RZ Raised cosine its highest value of Q (26.33 dB), eye opening, lowest BER and its non-susceptibility at different chirps makes it the best choice among the data formats mentioned. Jitter value remains low for all the data formats in general and also been reported to be the best, however, it is also reasonably good (second best) for RZ Raised cosine.

2.3 Dissertation Scope

Optical amplifier plays a key role in today communication networks. Without optical amplifier transmission is restricted to limited distance. A review about optical amplifier has been done in section 2.2. Now a day's hybrid optical amplifier has becomes a hot topic in research area. In most of the optical books, hybrid amplifiers are not much discussed. Most of the work done on hybrid amplifier is available in research papers. Review of optical amplifier has been done in section 2.2. This review was essential in getting basic designing concept. Selecting the desired components from the OptSim simulation software and setting the desired set up for performance evaluation helps us to analyze various optical amplifiers. 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. Thus 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. To analyze the performance of hybrid optical amplifier like RAMAN-SOA, EDFA-EDFA, RAMAN-SOA, RAMAN-EDFA amplifier for 96×10 Gb/s system in the presence and absence of nonlinearity with changing transmission distance at a fixed dispersion value and find out which one provide better result in terms of quality factor, output power, eye opening , bit error rate.

2.4 Dissertation Objective

1 To analyze the performance of optical amplifier like SOA, EDFA, RAMAN amplifier for 96×10 Gb/s system in the presence and absence of nonlinearity with changing transmission distance at a fixed dispersion value and find out which one provide better result in terms of quality factor, output power, eye opening , bit error rate.

2 To analyze the performance of optical amplifier like SOA, EDFA, RAMAN amplifier for 96×10 Gb/s system in the presence and absence of nonlinearity with changing transmission distance at a fixed dispersion value and find out which one provide better result in terms of quality factor, output power, eye opening, bit error rate.

3 To investigate various type of transmission fiber for RAMAN-EDFA.

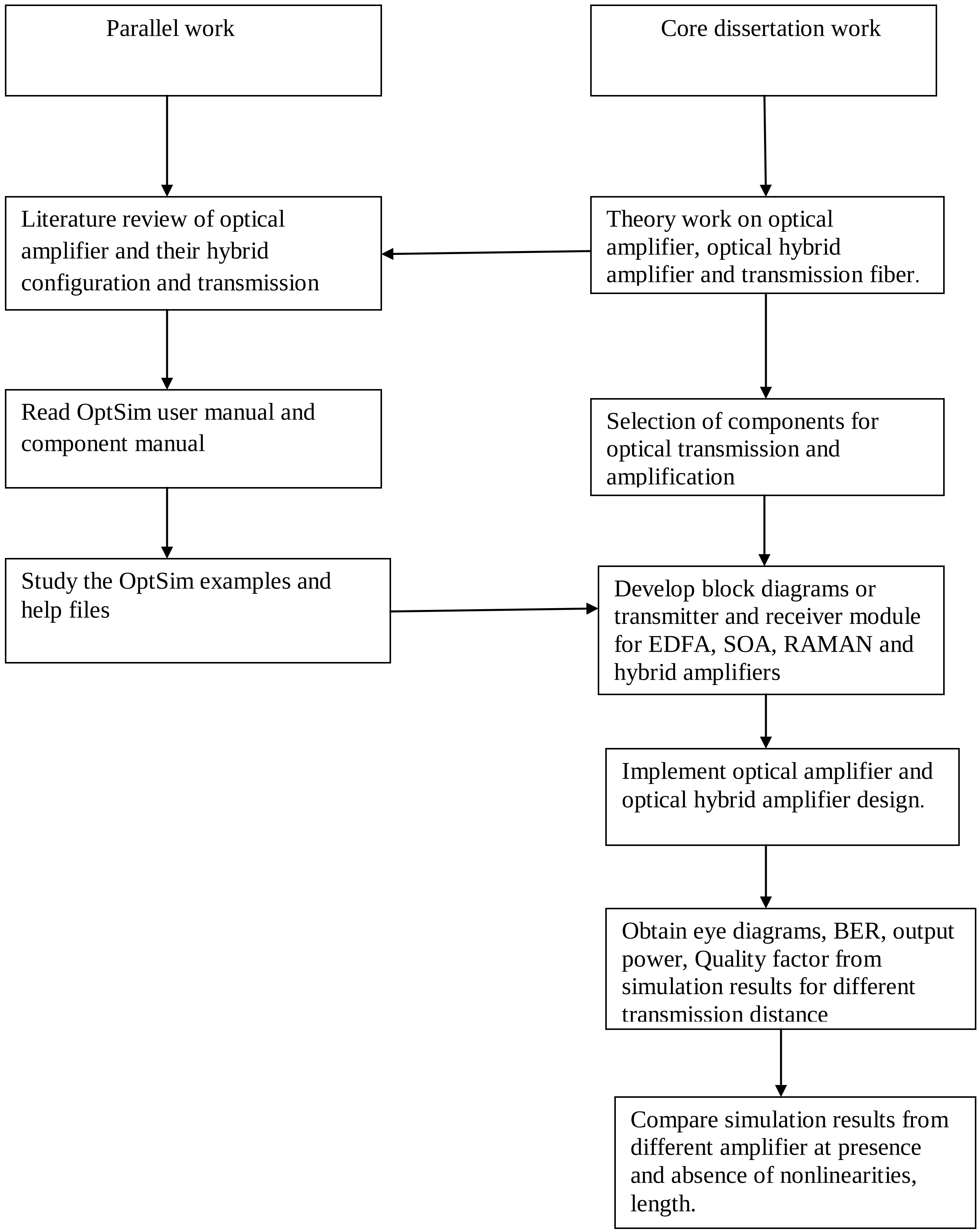


Figure 2.1: Dissertation frame work

Chapter 3

Simulation of 96×10 Gbps WDM Signal using Optical Amplifiers

3.1 Abstract

We have investigated the performance of the optical amplifier individually. Performance has been compared at a dispersion value of 2 ps/nm/km by varying the transmission distance from 60 to 180 km with and without nonlinearities. In the presence of nonlinearities EDFA provide almost constant power while SOA and Raman provide a varying power with transmission distance. Among these optical amplifiers EDFA provides a highest power output of 13.98 dBm. In term of Quality factor all three provide almost same value of 25.61 dB at 100 km. After 100 km SOA provide better Q-value. At 160 km SOA provide highest Q-value of 24.9 dB as compared to EDFA and RAMAN which provide a value of 16.45 dB and 21.4 dB respectfully. SOA also provide a minimum eye closure of 0.44 dB while EDFA and RAMAN have eye closure of 2.48 dB and 0.90 dB. However in the absence of nonlinearities, simulation gives better results. Quality factor at 100 km distance becomes around 28.42 dB, 28.9 dB, 28.6 dB for EDFA, SOA and RAMAN respectively.

3.2 Introduction

Wavelength Division Multiplexing (WDM) has been now widely used to demonstrate the transmission of high capacity based on 10 Gb/s modulation per wavelength. It is possible to increase capacity while reducing system costs [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. Optical amplifier increases the transmitter power by placing an amplifier just after the transmitter and just before the receiver. EDFA has low noise figure and has a very good gain bandwidth. So it can operate on large band [42]. EDFA is suitable to operate at the conventional (C) band from about 1530 to 1565 nm [43]. Since the entire C band of optical channels and wider optical bandwidth urges EDFA technology to develop beyond its present limits. To extend the optical bandwidth and increase the number of WDM channels, L-band optical amplifiers are used to operate in longer wavelength from about 1570 to 1605 nm.

EDFA by itself has a very low-gain at the L-band, most realizations of L-band EDFA implement a long length of erbium-doped fiber (EDF) to pump up its gain. A typical L-band EDFA also has larger noise figure than C-band EDFA [44]. But working under deeper saturation or steeper saturation characterization would result in less BER impairment [45]. An efficient [46] gain-flattened L-band optical amplifier is demonstrated using a hybrid configuration with a distributed Raman amplifier (DRA) and an erbium-doped fiber amplifier (EDFA) for 160 ×10 Gb/s dense wavelength division multiplexed system at 25 GHz interval. With an input signal power of 3 mW, a flat gain of > 10 dB is obtained across the frequency range from 187 THz to 190.975 THz with a gain variation of < 4.5 dB without using any gain-flattening technique. The output power obtained at 3 mW optimum input power is also the highest value > 8.9 dBm ever reported for a DRA–EDFA hybrid optical amplifier at reduced channel spacing. So they obtain the highest output power at the reduced channel spacing with the optimum value of input power of 3 mW. RFA has several advantages including lower noise figure (NF), flexibility on the selection of gain medium, and wide gain bandwidth [47], especially that RFA has the capability to distribute the gain over a long distance in the transmission fiber. Kim et.al [48] transmitted 10 Gb/s signal over 80 km using SSMF using SOA as a booster. They have found parameter of input signal such as extinction ratio, rising/falling time and chirp to maximize output power and dynamic range. Further simulation [49] of the ten channel 100 Gb/s DWDM using cascaded SOA with DPSK modulation format at 20 GHz channel spacing is done. For this, we optimize the SOA model with low saturation power 21.36 mW, and achieved low crosstalk of 14.1 dB with high optical gain 36.5 dB. For 70 km transmission distance, there is improvement in output signal power using optimized SOA inline amplifier at same quality without using inline amplifier. Using optimum span scheme it is possible to transmit 100 Gb/s RZ-DPSK signals at 17,227 km with power penalty 2.1 dB at good quality of signal. EDFA gain depends on the pump power and pump wavelength for a given length of EDFA. Simulation results [50] shows EDFA length of 10 mtr and with 980 nm pump of power 0.22 W gives the gain of 40.17 dB and for the same length of EDFA with 980 nm pump of power 0.62 W gives the optimized gain of 44.3 dB and also with 980 nm pump of power 1W gives the maximum optimized gain of 46 dB and compared the results of Gain and noise figure with the wavelength of 1480 nm and also with different lengths. RAMAN gain [51] is higher in bidirectional pumping than in counter pumping, the gain changes with increasing the fiber length while the noise figure remain the same for short fiber lengths and the gain saturates differently for different pumping configuration at different fiber lengths and power levels of the signal. The fiber parameters have strong effects [52] on the operation of multi-pump distributed Raman Amplifiers, because of their nonlinearities. Two types of fibers are used in simulation; Z-fiber and dispersion shifted fiber (DSF). In each case the optimum parameters such as pump and signal powers, amplified spontaneous emission and noise figure are derived. We found that there is minimum total input power for backward case and there is minimum fluctuation in signal power along the fiber which leads to having the lowest ripple in signal to noise ratio. Indeed, DSFs have proper noise figure level and more uniform signal gain relative to the Z fibers. We further investigated the performance comparison of SOA, RAMAN and EDFA for different dispersion and distance in the term of bit error rate (BER), Q-factor, eye closure and output power.

3.3 Simulation Set up

In this model, ninety six channels are transmitted at data rate of 10 Gb/s with 100 GHz channel spacing. 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 (T1) is built up using ninety six transmitters. In transmitter compound component each transmitter section consists of the data source, electrical driver, laser source and external Mach–Zehnder modulator. 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 96 laser beams at 188.88–197.64 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 (sin2 MZ for (Optical signal from the laser source). The amplitude modulator is a sine square with an excess loss of 3 dB. The simulations setup of EDFA, SOA and RAMAN at different transmission distance with 2 ps/nm/km dispersion shown in Figure 3.1. 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 60, 80, 100, 120, 140, 160 and 180 km (R) at 2 ps/nm/km dispersion. Optical power meter (p1, p2, p3) and optical probe (op1, op2, op3) with splitters (s1, s2, s3) are used for measuring the signal power and spectrum at different levels. The modulated signal is converted into original signal with the help of PIN photo diode and filters. A compound receiver (R1) is used to detect all signals and converts these into electrical form. Different types of optical amplifiers are also applied at the receiver side. The setup is repeated for measuring the signal strength by using different amplifiers.

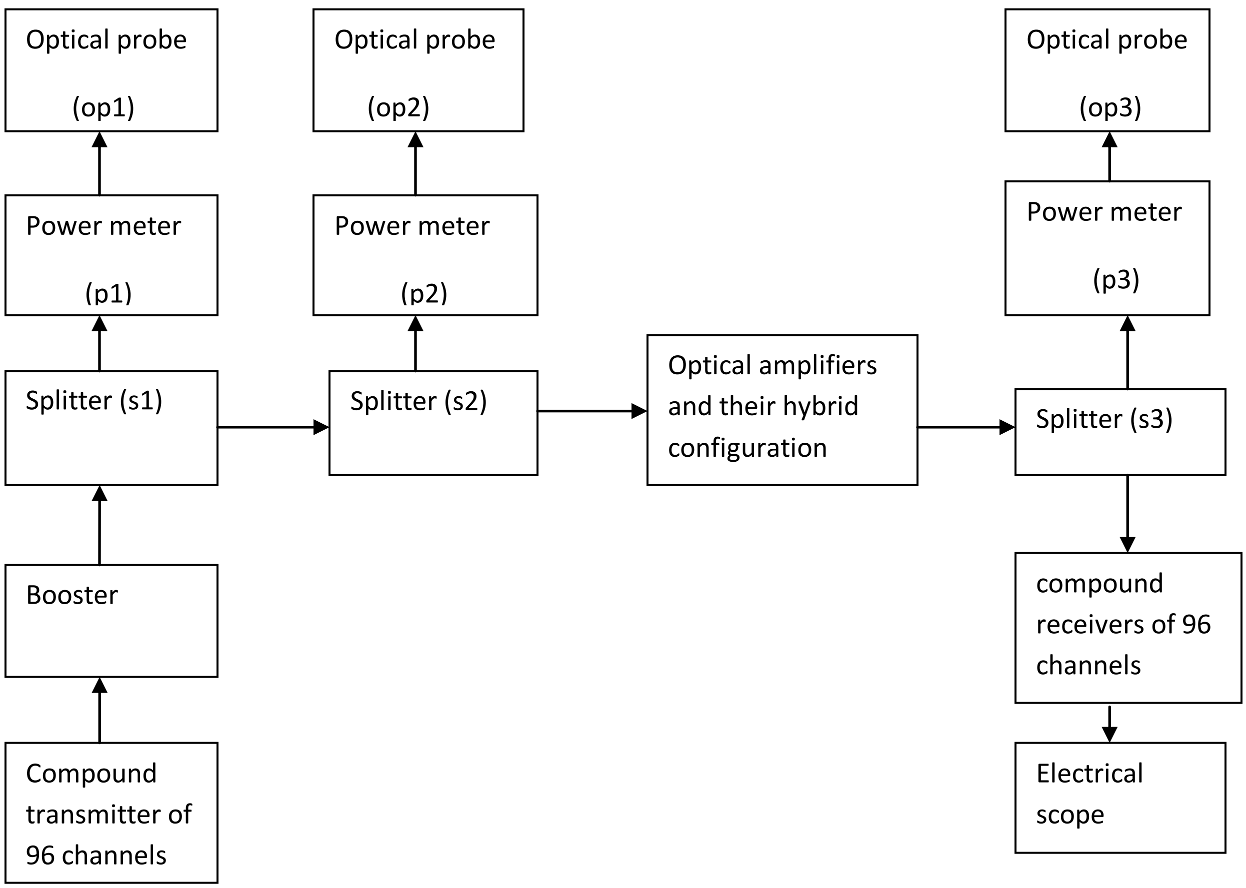
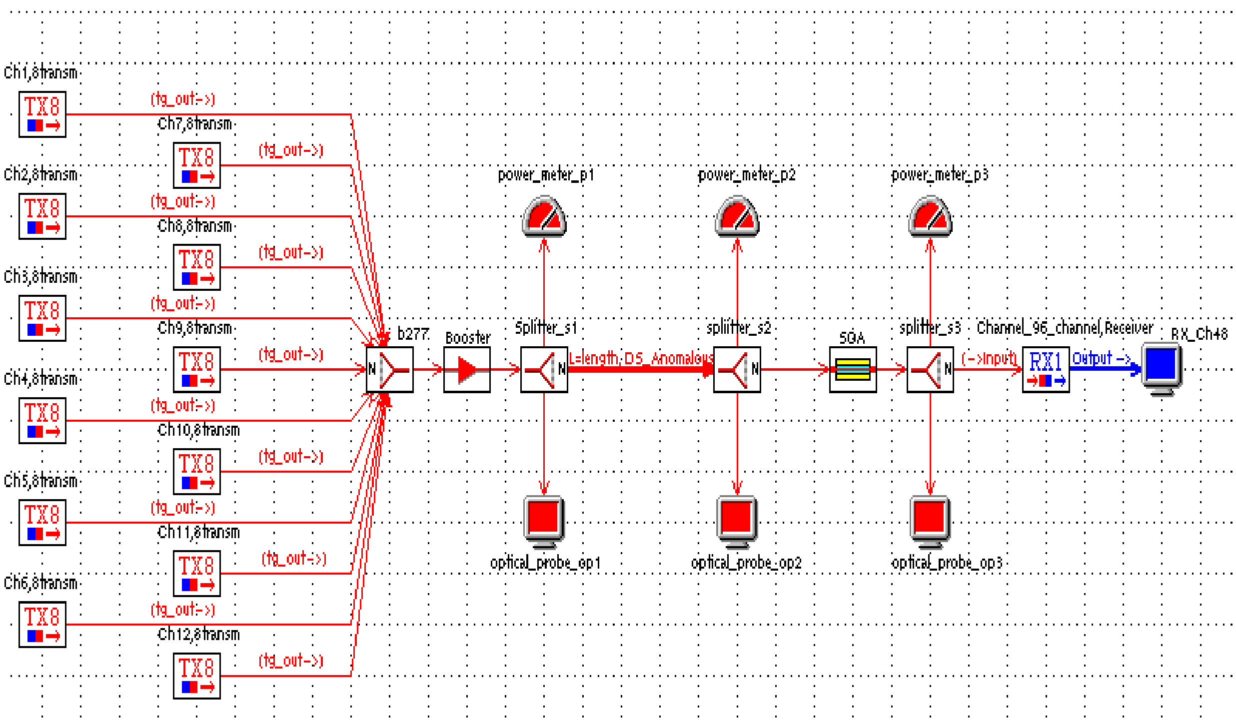
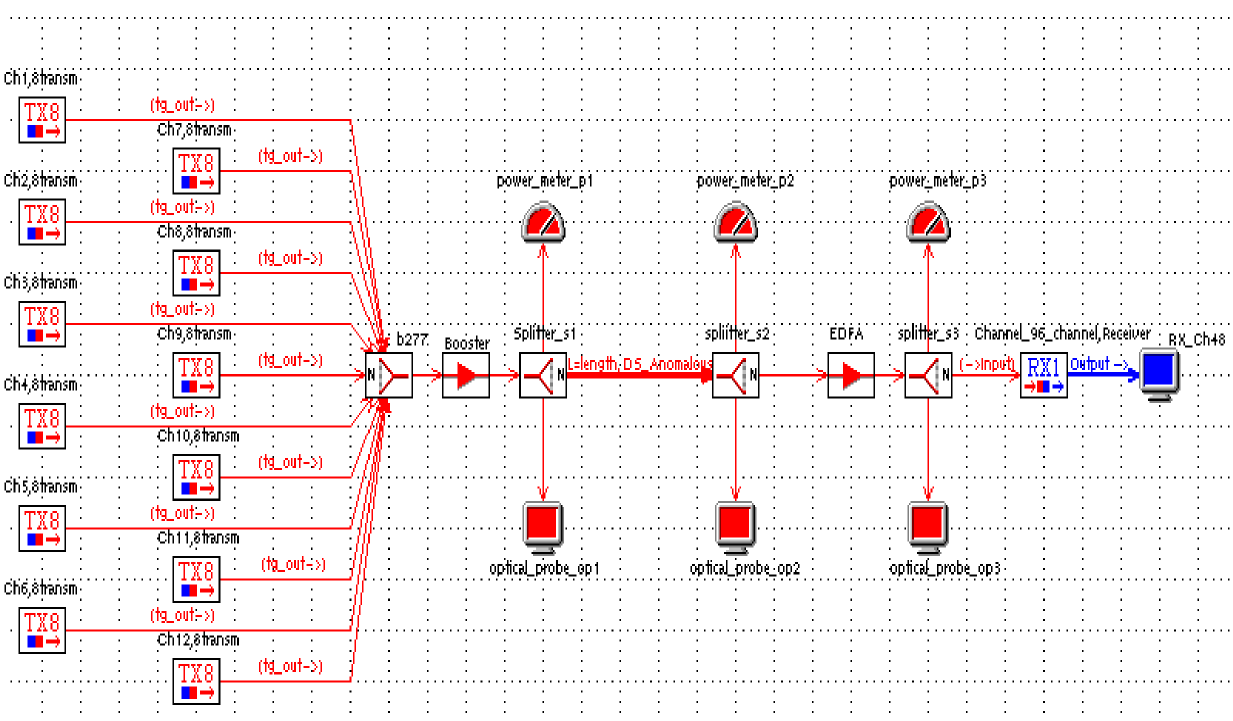


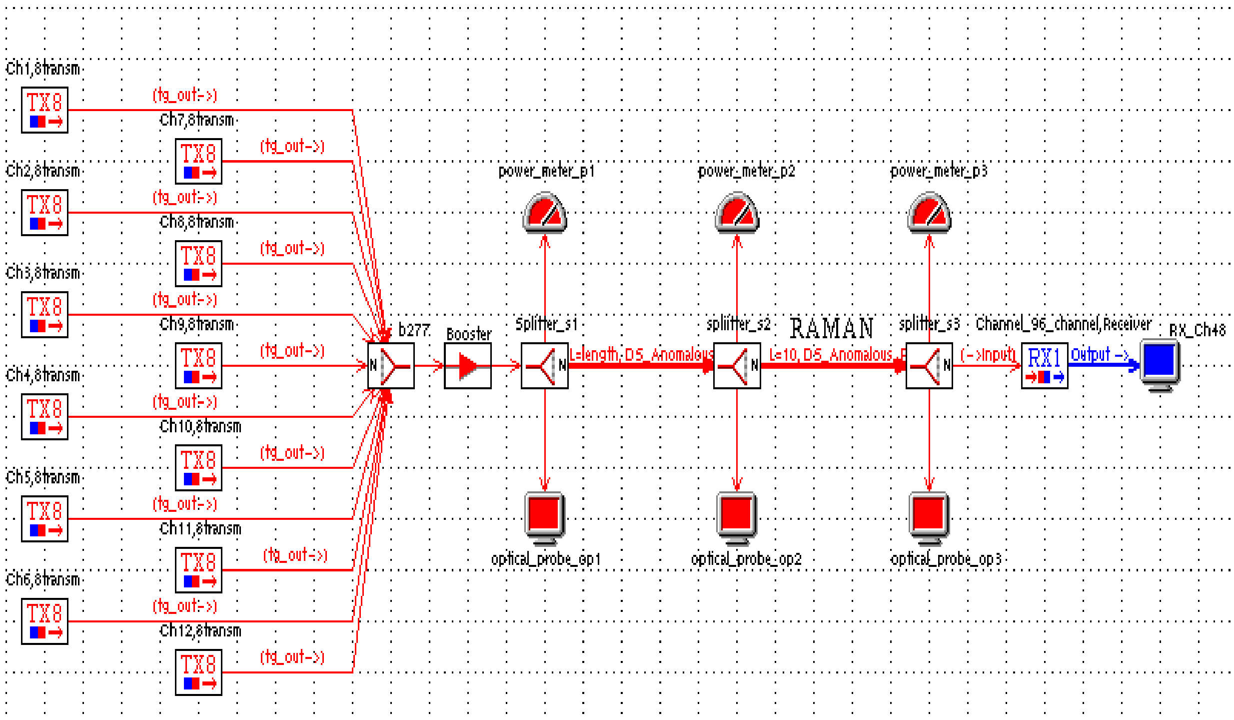
Figure 3.1: Block diagram of simulation set up


Ch1,8transm
Ch2,8transm
Ch3,8transm
Ch4,8transm
Ch5,8transm
Ch6,8transm
Ch7,8transm
Ch8,8transm
Ch9,8transm
Ch10,8transm
Ch11,8transm
Ch12,8transm
TX8
(tg_out->)
b277
Booster
Splitter_s1
L=length_DS_Anomalous
splitter_s2
SOA
splitter_s3
Channel_96_channel,Receiver
(->input)
RX1
Output ->
RX_Ch48
power_meter_p1
power_meter_p2
power_meter_p3
optical_probe_op1
optical_probe_op2
optical_probe_op3

(a)


Ch1,8transm
Ch2,8transm
Ch3,8transm
Ch4,8transm
Ch5,8transm
Ch6,8transm
Ch7,8transm
Ch8,8transm
Ch9,8transm
Ch10,8transm
Ch11,8transm
Ch12,8transm
TX8
(tg_out->)
b277
Booster
Splitter_s1
L=length_DS_Anomalous
splitter_s2
EDFA
splitter_s3
Channel_96_channel,Receiver
(->input)
RX1
Output ->
RX_Ch48
power_meter_p1
power_meter_p2
power_meter_p3
optical_probe_op1
optical_probe_op2
optical_probe_op3

(b)



(c)

Figure 3.2: Simulation set up (a) SOA (b) EDFA (c) Raman amplifier.

3.4 Simulations and Results:

Different types of optical amplifiers are also applied at the receiver side. The setup is repeated for measuring the signal strength by using different amplifiers i.e. EDFA, SOA, RAMAN. Different results like eye diagram, Q-factor and BER are obtained to find out the most suitable amplifier. Different component used in the set up has different parameters as listed in the tables.

Parameter of Ds- Anomalous fiber

Dispersion correlation length	20 mtr
Polarization mode dispersion	0.1 ps/km$^{0.5}$
Fiber core effective area	55 um^2
Fiber average beat length	5 mtr
Dispersion	2ps/nm/km

(a)

Parameter of Amplitude modulator

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

(b)

Parameter of SOA

Bias current	100 mA
Amplifier length	300×10^{-6}m
Active layer width	1.5×10^{-6}m
Input insertion loss	3 dB
Output insertion loss	3 dB
Confinement factor	0.35
Spontaneous carrier life time	0.3 ns
Active layer width	0.15×10^{-6}m

(c)

Parameter of EDFA

Output power	25 mW
Gain type	Flat
Small signal gain	35
Noise figure	4.5

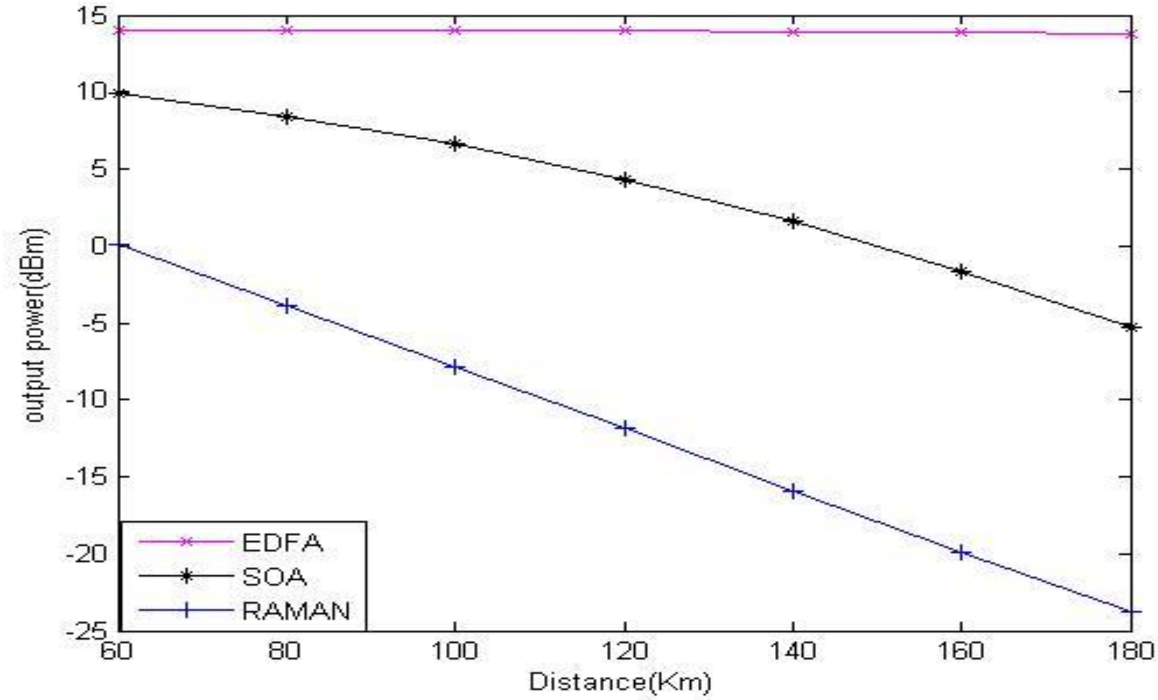
(d)

Parameter of RAMAN amplifier

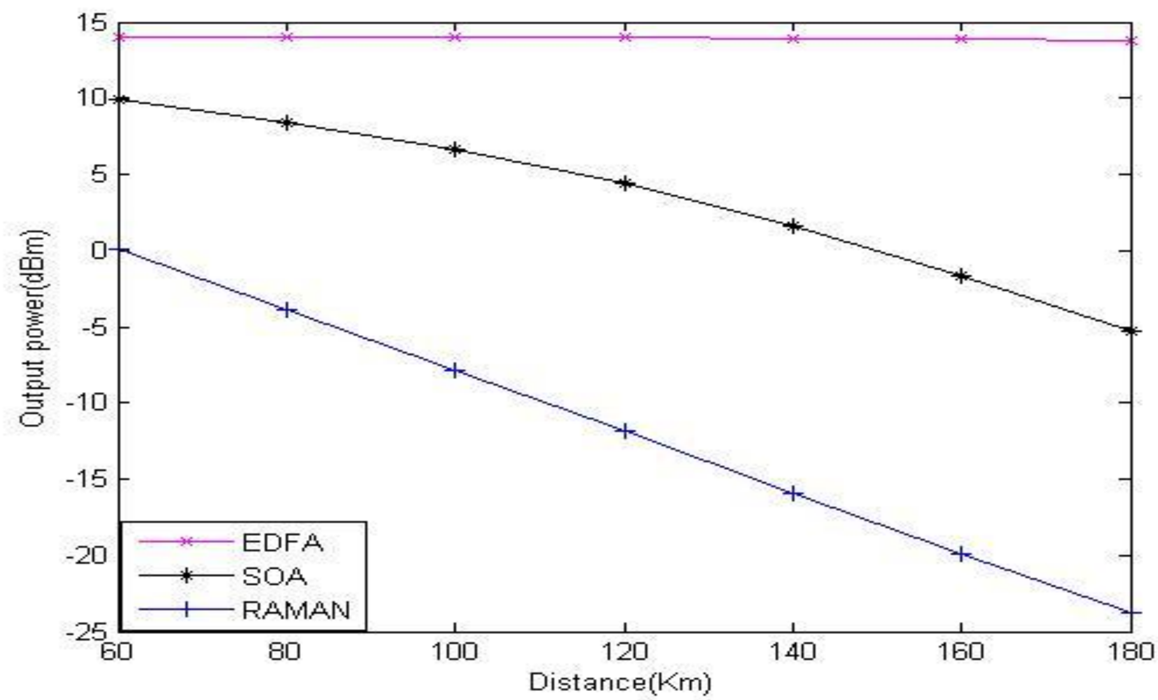
Raman length	10 m
Operating temperature	300 K
Operating frequency	1550 nm
Pump power	300 mW
Attenuation	1.2 dB/km

(e)

Table 1.1-1.5: Parameters of various components



(a)



(b)

Figure 3.3: Output powers vs. distance (a) in the presence of nonlinearities (b) in the in the absence of nonlinearities.

Performance of various optical amplifiers has been analyzed with varying transmission distance at 2 ps/nm/km dispersion. As figure 3.3 showing EDFA provides almost a constant power level irrespective of transmission distance. EDFA provide highest power around 14 dBm. At 100 km distance power output of three is 13.97 dBm, 6.6 dBm, -7.9 dBm respectively. Variation in power is from 13.98 dBm to 13.77 dBm, 9.95 dBm to -5.34 dBm, 0.1 to -23.8 for EDFA, SOA and RAMAN respectively. Even in the absence of nonlinearities output power remains almost same.

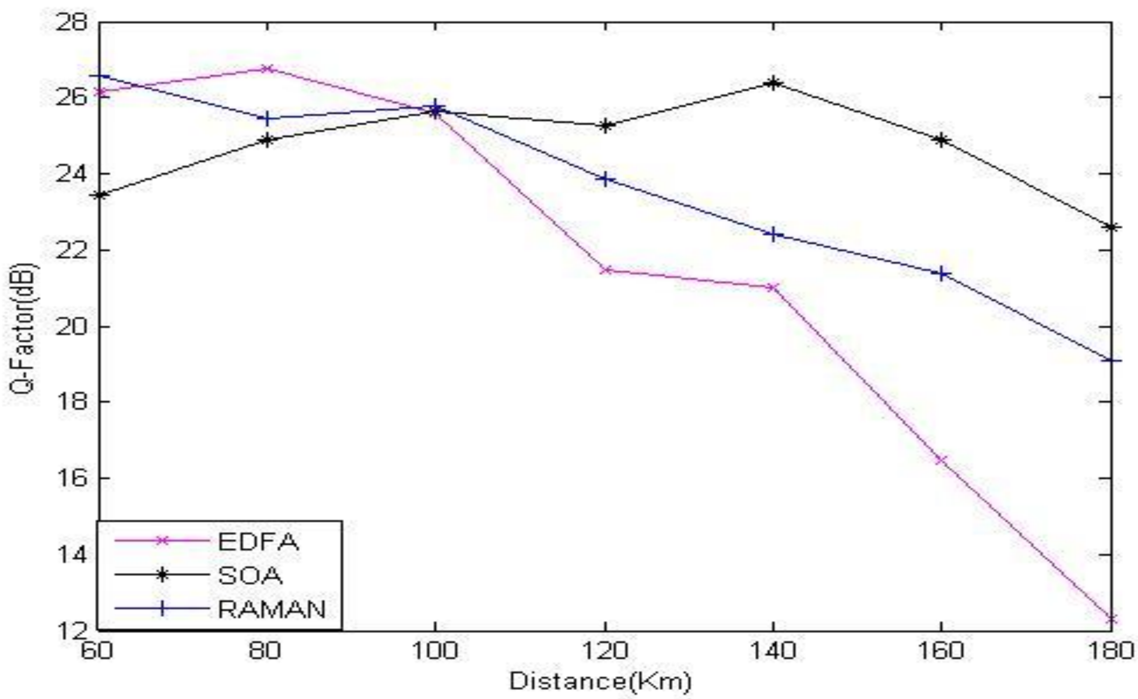
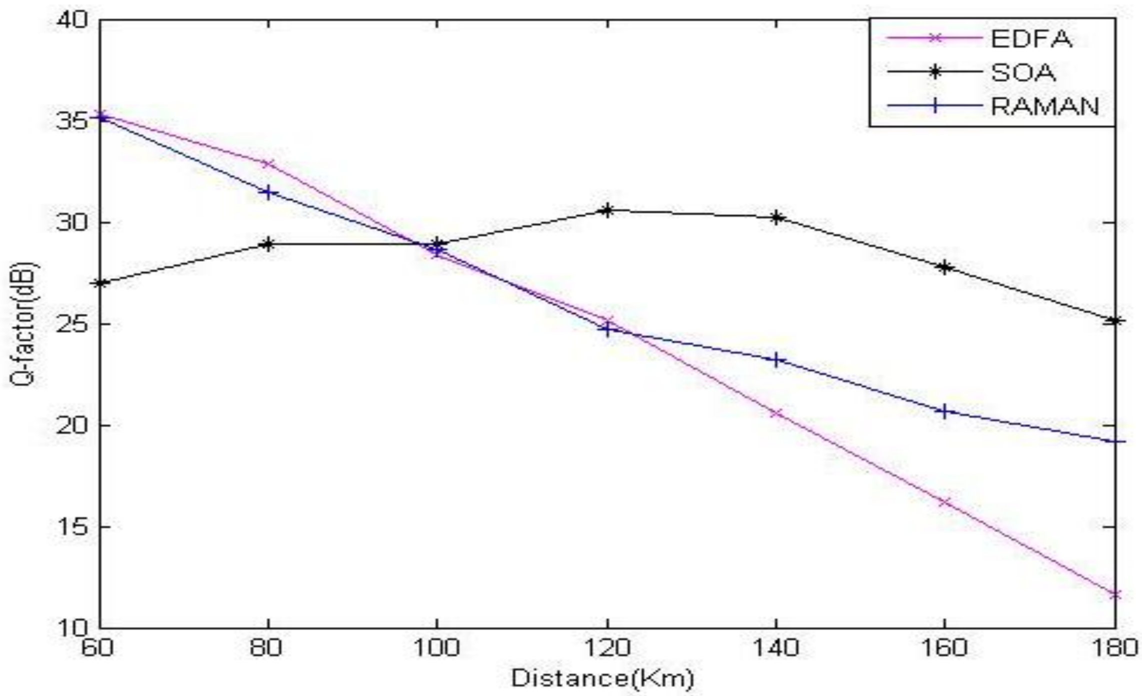


Figure 3.4: (a)

Figure 3.4 shows the variation in Q-factor with distance. Q–factor at 100 km for all three amplifiers is almost same. At 100 km Q-factor is 25.61 dB, 25.62 dB and 25.78 dB. As the distance increases Q-factor degrade for EDFA. At 160 km it reduces to 12.29 dB only. However SOA gives much consistent Q-factor. At 160 km Q-factor is 22.6 dB while for RAMAN amplifier it reduces to 19.11 dB. So for length more than 100 km SOA gives improved performance as compared to the other two. In the absence of nonlinearities Quality factor varies from 35.34 dB to 11.6 dB, 27 dB to 25.17 dB, 35.14 to 19.17 dB for the EDFA, SOA and RAMAN respectfully.



(b)

Figure 3.4: Quality factor vs. distance (a) in the presence of nonlinearities (b) in the in the absence of nonlinearities.

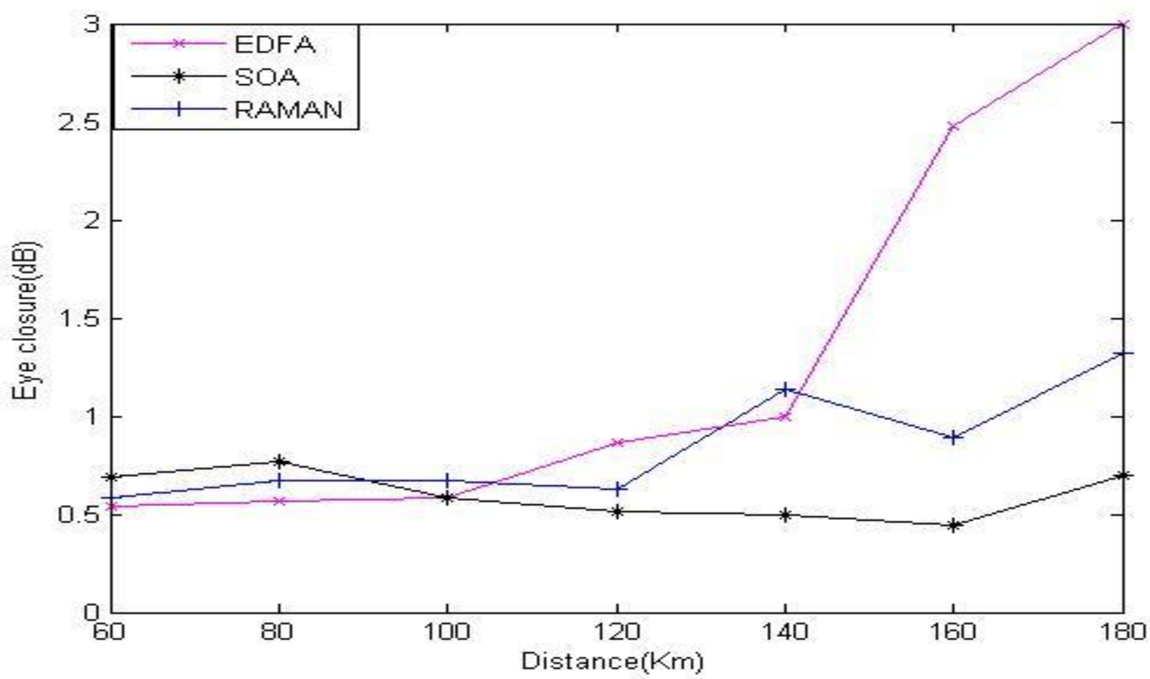


Figure 3.5: (a) Eye closure vs. distance in the presence of nonlinearities

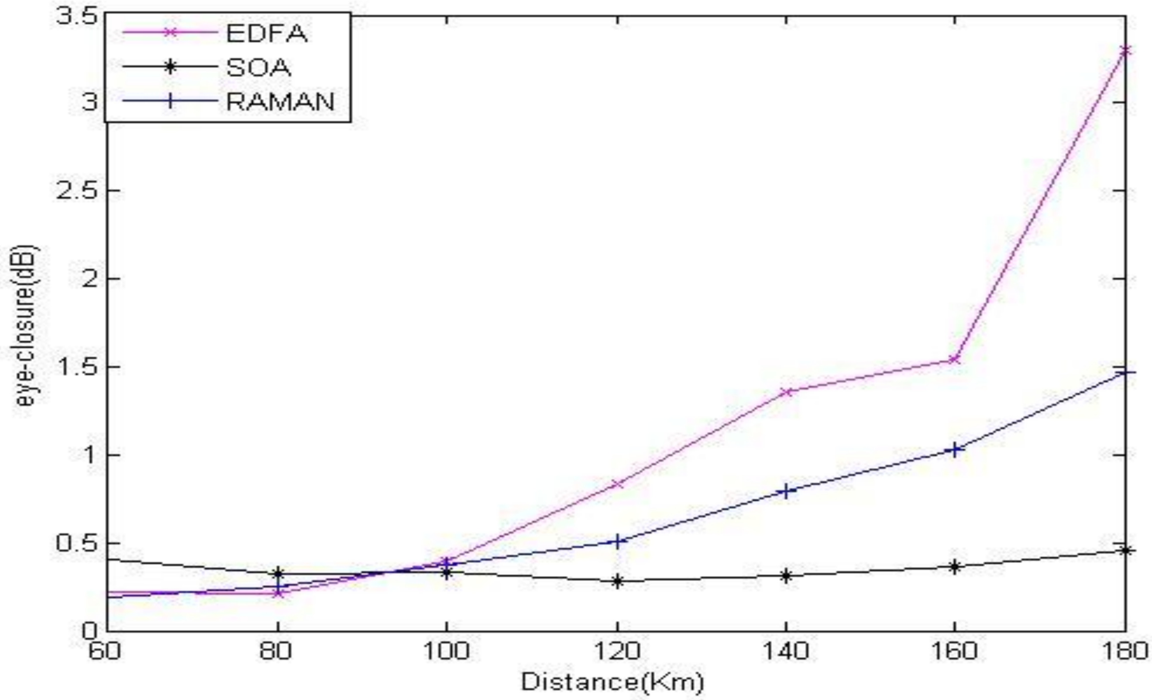


Figure 3.5: (b) Eye closure vs. distance in **the absence of nonlinearities**

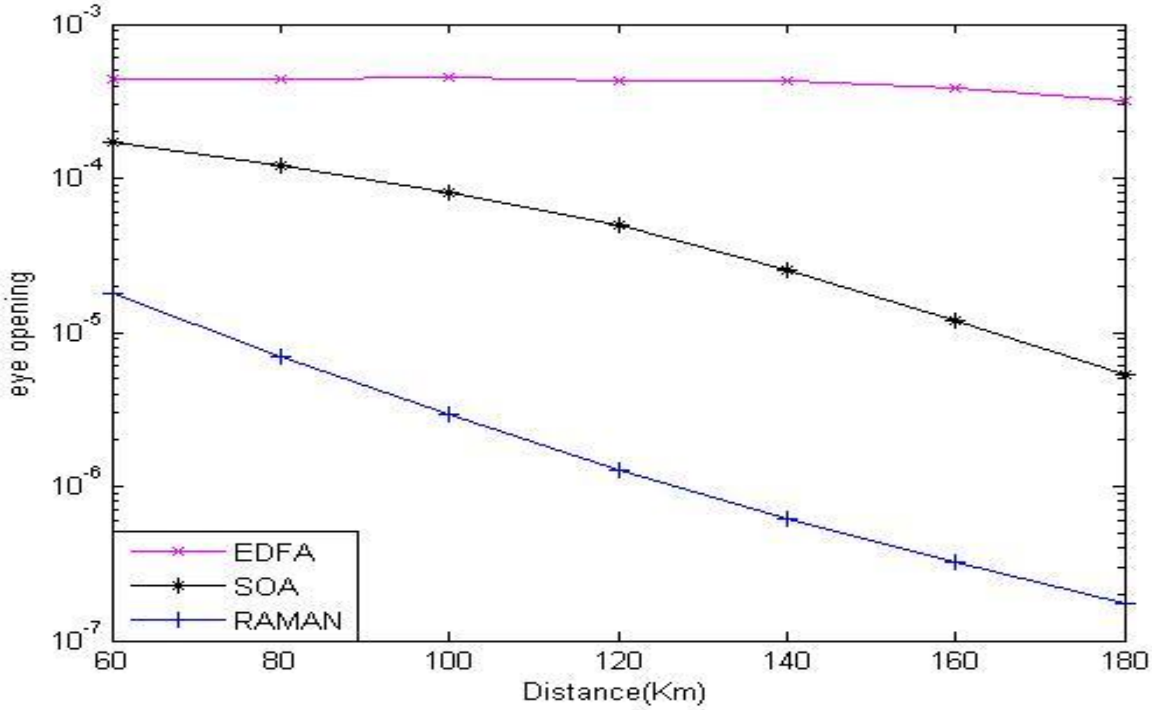


Figure 3.6: (a) Eye opening in the presence of nonlinearities

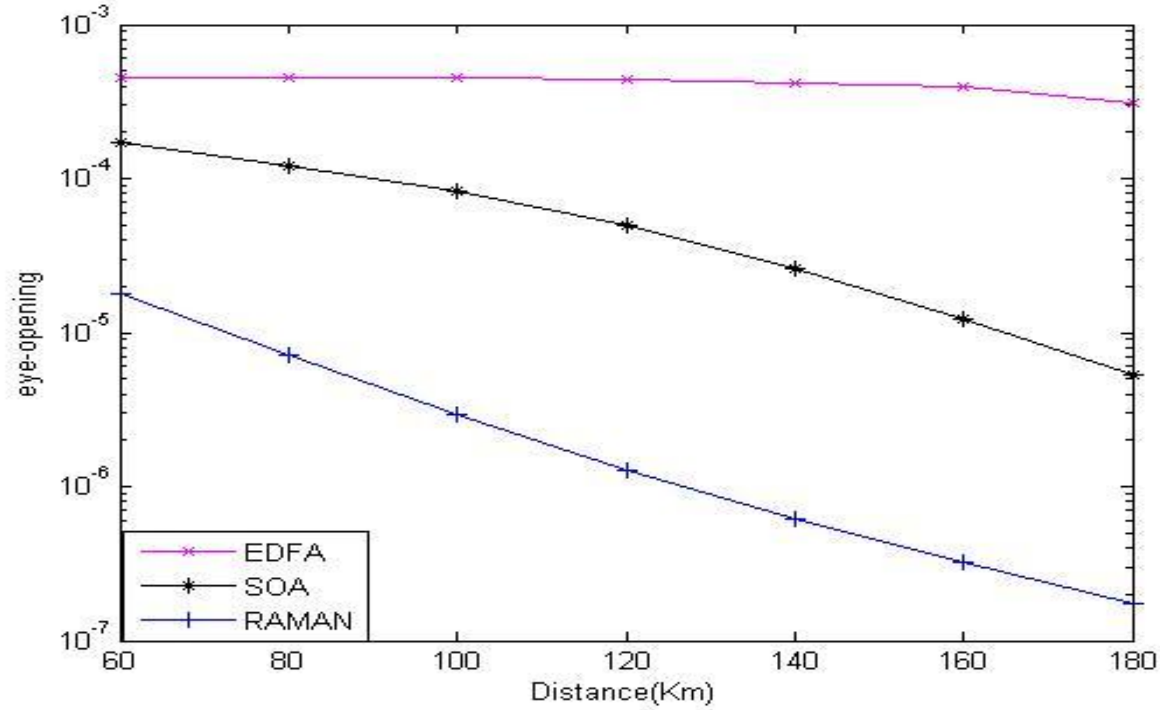


Figure 3.6: (b) Eye opening in the absence of nonlinearities

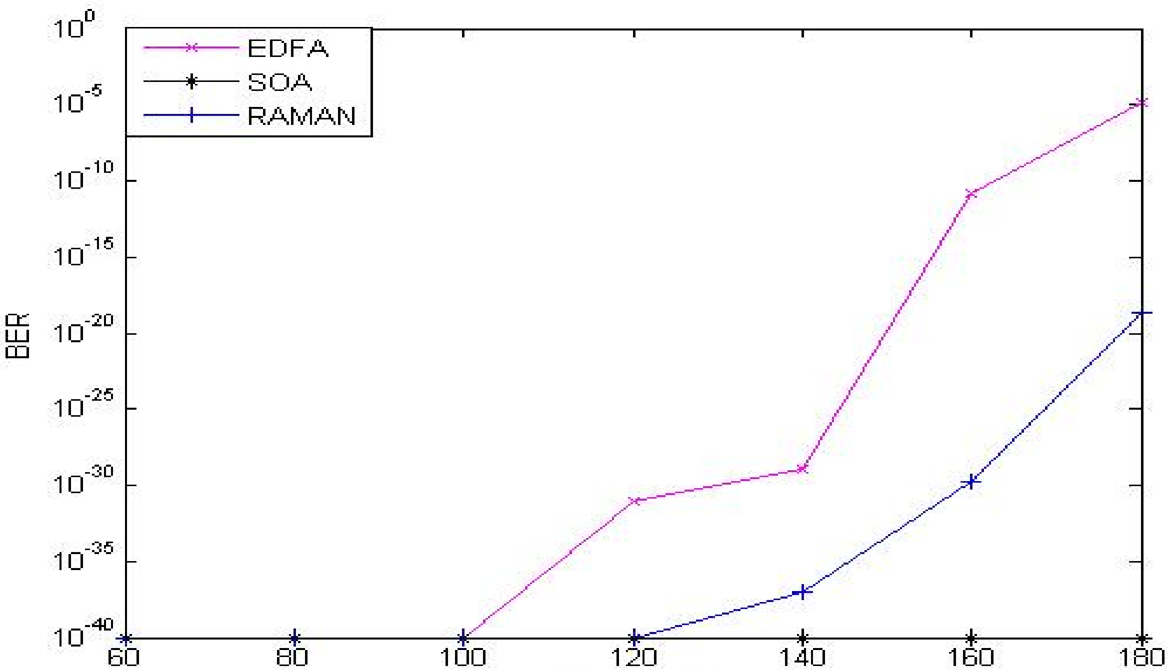


Figure 3.7: (a)

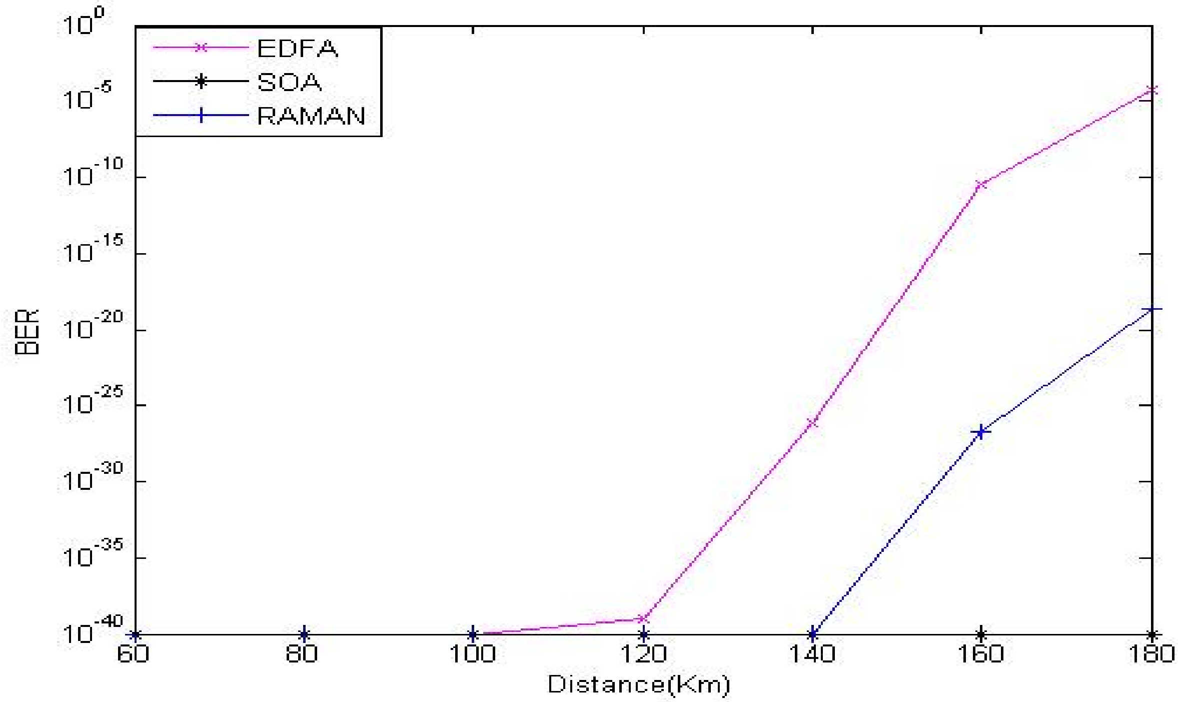


Figure 3.7: Bit error rate vs. distance (a) in the presence of nonlinearities (b) in the absence of nonlinearities.

Figure 3.5 and 3.6 shows variation in eye opening and eye closure with distance. Again SOA provide least eye closure among all three. At 160 km SOA provide an eye closure of 0.70 dB while EDFA and RAMAN provide an eye closure of 3 dB and 1.32 dB respectively. Larger the eye closure lesser will be the quality of communication. At 100 km all three provide almost similar eye closure value of 0.58 dB. Variation in eye closure is form 0.53 dB to 3 dB, 0.69 dB to 0.70 dB and 0.58 dB to 1.32 dB for EDFA, SOA, and RAMAN respectfully. Eye opening variation shows that EDFA has largest eye opening. Larger the eye opening better will be the communication quality. Eye variation is from 4.4×10^{-4} to 3.2×10^{-4}, 1.7×10^{-4} to 5.3×10^{-6} and 1.78×10^{-5} to 1.72×10^{-7} for EDFA, SOA, RAMAN respectively. Figure 3.7 shows bit error rate for the amplifiers. SOA gives a minimum but error rate of 1×10^{-40} .

At 100 km all three provide identical bit error rate of 1×10^{-40} . As the distance increases from 60 to 180 km, SOA outperforms other two. At 160 km EDFA and RAMAN has a bit error rate of 1.5×10^{-11} and 1.7×10^{-30} respectively.

Conclusion:

We have investigated the performance of optical amplifier for a WDM system equally spaced at 10 Gb/s. we have simulated different amplifier with varying transmission distance. EDFA provide highest output power around 14 dBm which remain constant throughout the distance while for the other two amplifier output power decrease with distance. In SOA main limiting factor is crosstalk and polarization sensitivity. While in RAMAN it is Rayleigh crosstalk limit the performance. At 100 km all three provide similar quality factor but after that Soa gives better quality factor. Soa also provide less eye closure and minimum bit error rate. So for distance up to 100 km EDFA gives better results but beyond that quality factor falls rapidly.

Chapter 4

Simulation of 96×10 Gbps WDM System using Hybrid Optical Amplifiers

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4.1. Abstract

The performance and feasibility of Hybrid Optical Amplifiers operating at the bit rate of 10 Gb/s for 96 channels. Performance has been investigated for varying the distance at the dispersion value of 2 ps/nm/km with and without nonlinearity. It is demonstrated that for short distance up to 100 km EDFA-EDFA provide better result as compare to other configurations. At 100 km EDFA-EDFA provides highest Q-factor of 26 dB, while EDFA-SOA provides a Q-factor of 20 dB in presence of non-linearities. For longer distance i.e. at 160 km RAMAN-SOA provide better communication reliability. RAMAN-SOA provides Q-factor of 22.5 dB as compared to EDFA-EDFA which provides a Q-factor of 17 dB in presence of non-linearities. RAMAN-SOA also provides a minimum bit error rate of 5.6×10^{-40} at a distance of 160 km in presence of non-linearities. In absence of non-linearities system shows much better performance as compared to system with non-linearities.

4.2 Simulation and Results:

Same simulation (figure 3.1) set up has been used to simulate the performance of hybrid optical amplifier as that for the optical amplifier. In the simulation set up we use 96 channels both at the transmitter and receiver side. At the transmitter side signal are modulated using NRZ modulations. This modulation scheme has an advantage over RZ format. These different signals are then pre-amplified by booster before transmission. After preamplification signals are transmitted at a dispersion value of 2 ps/nm/km. after that signal is passed through the various hybrid optical amplifiers like EDFA-EDFA, RAMAN-EDFA, RAMAN-SOA, EDFA-SOA. Transmission distance is varied from 60 to 180 km. at the receiver side received signal is demodulated back using photo detector into electrical form. Various power meters are used to obtain the power of signals at various points. At the receiver we analyze parameter like bit error rate, output power, eye closure, eye opening in the presence and absence of impurities. Simulation set up for various configurations has been shown in figure 4.1.

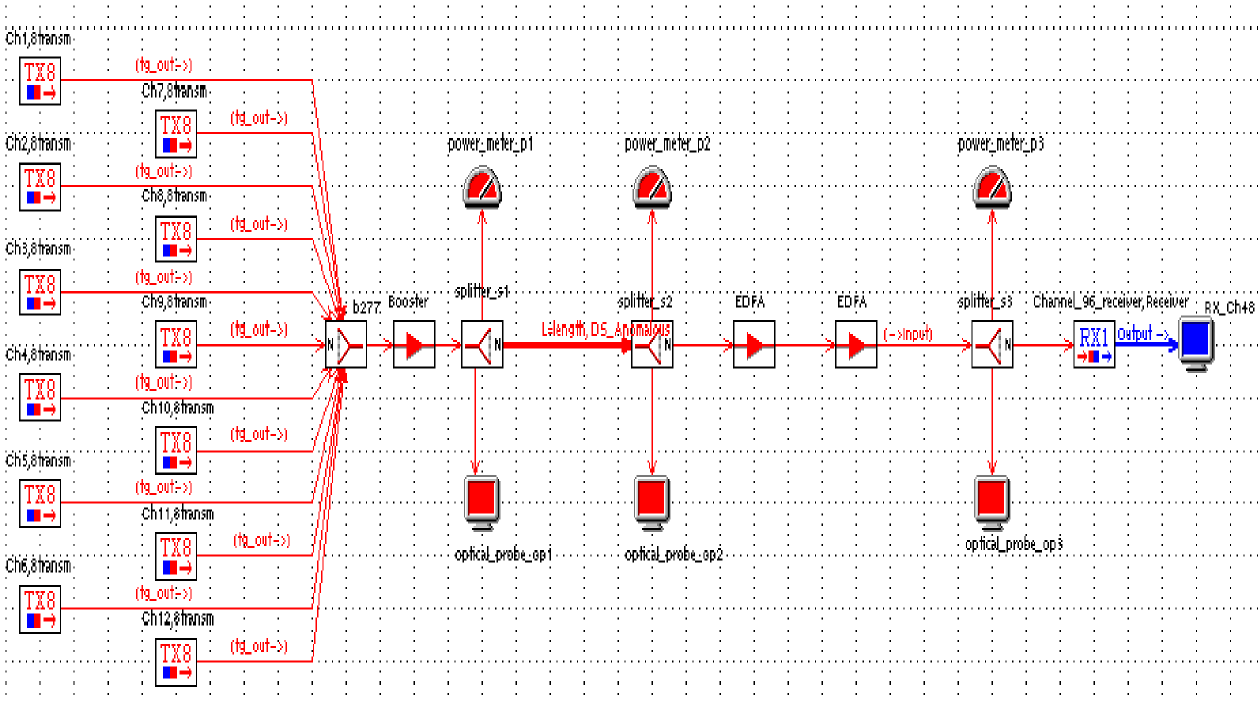


Figure 4.1: (a)

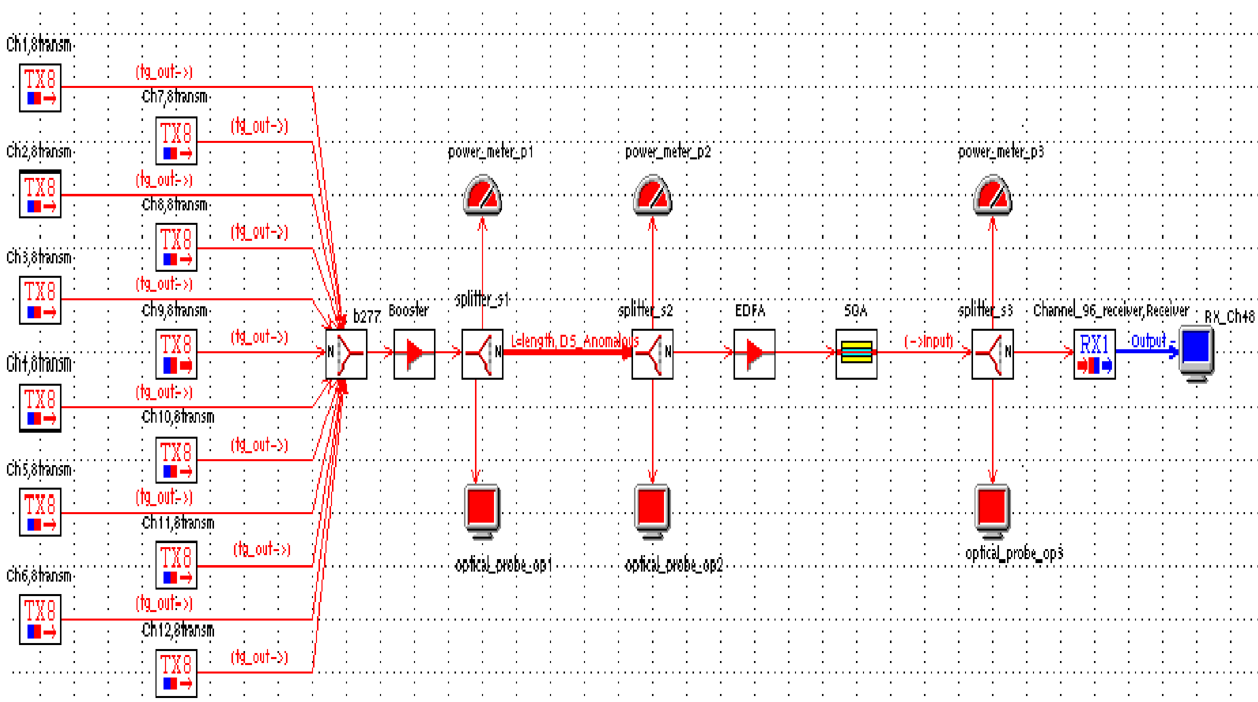


Figure 4.1: (b)

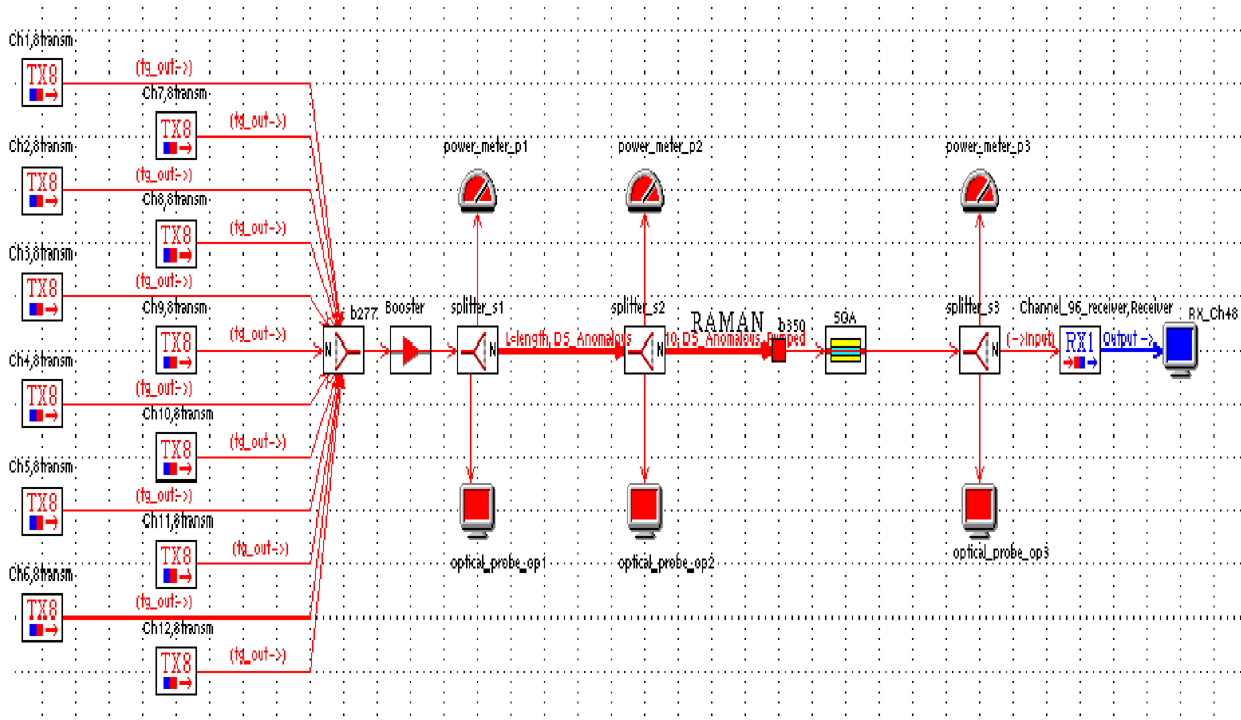


Figure 4.1: (c)

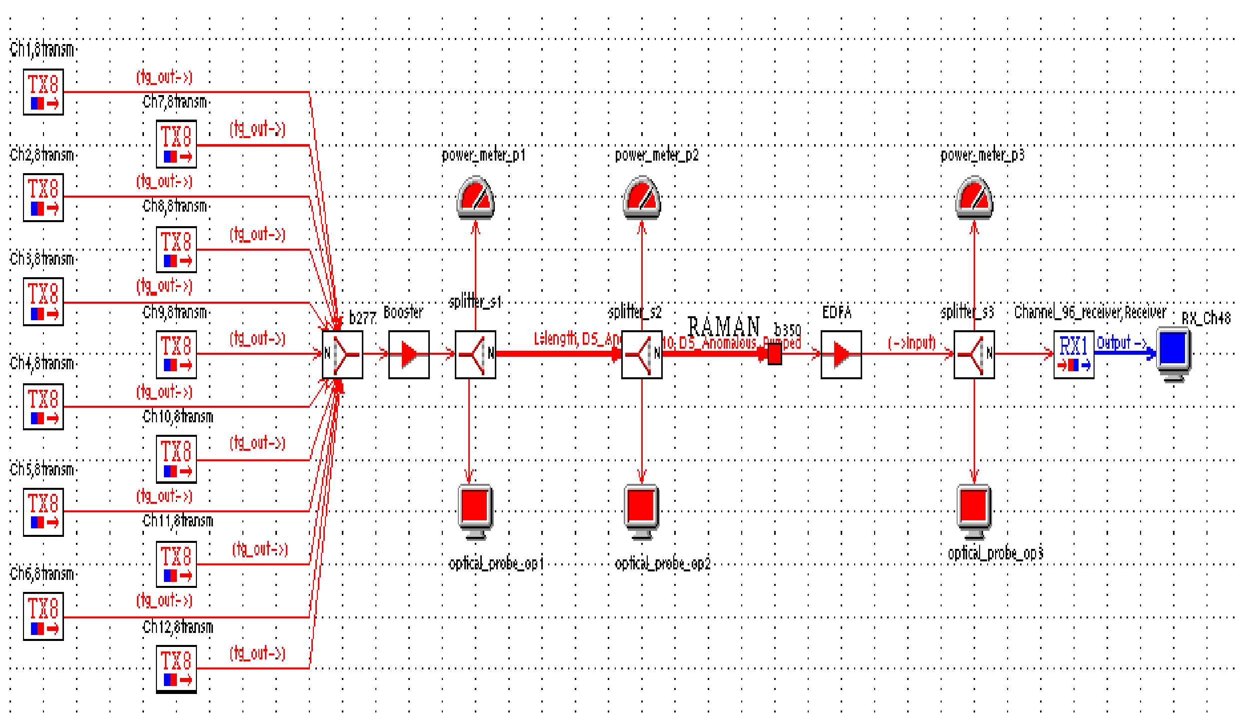


Figure 4.1: Simulation set up for (a) EDFA-EDFA, (b) EDFA-SOA, (c) RAMAN-SOA (d) RAMAN-EDFA.

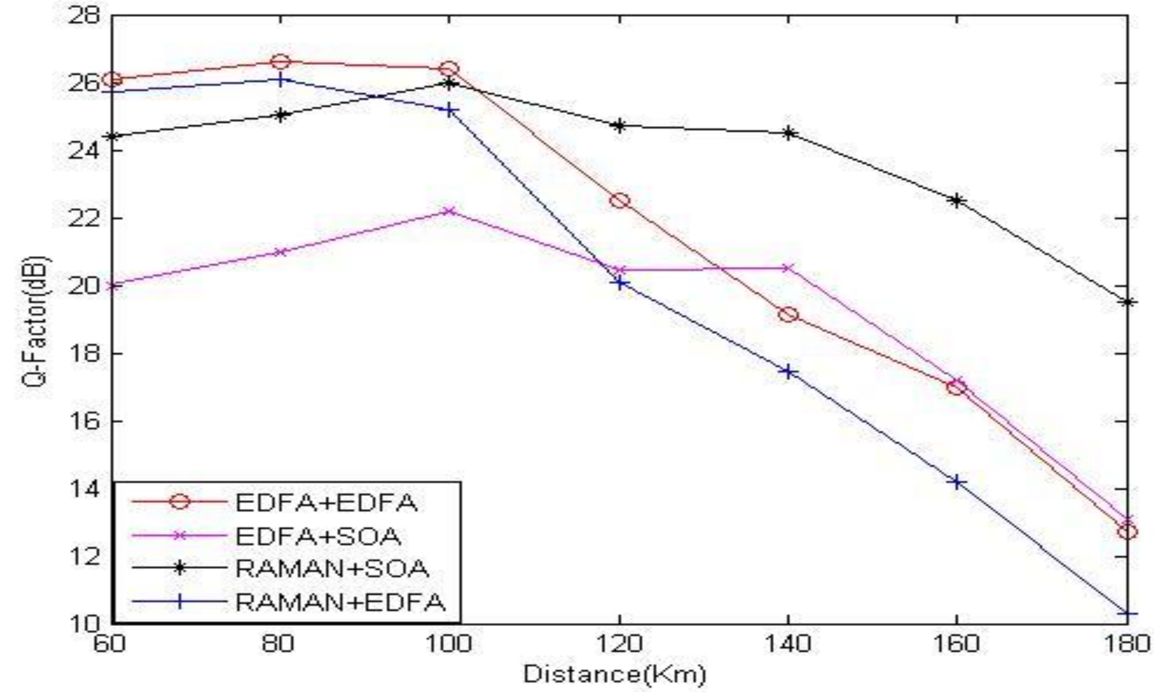


Figure 4.2: (a) Quality factor vs. distance in presence of nonlinearities.

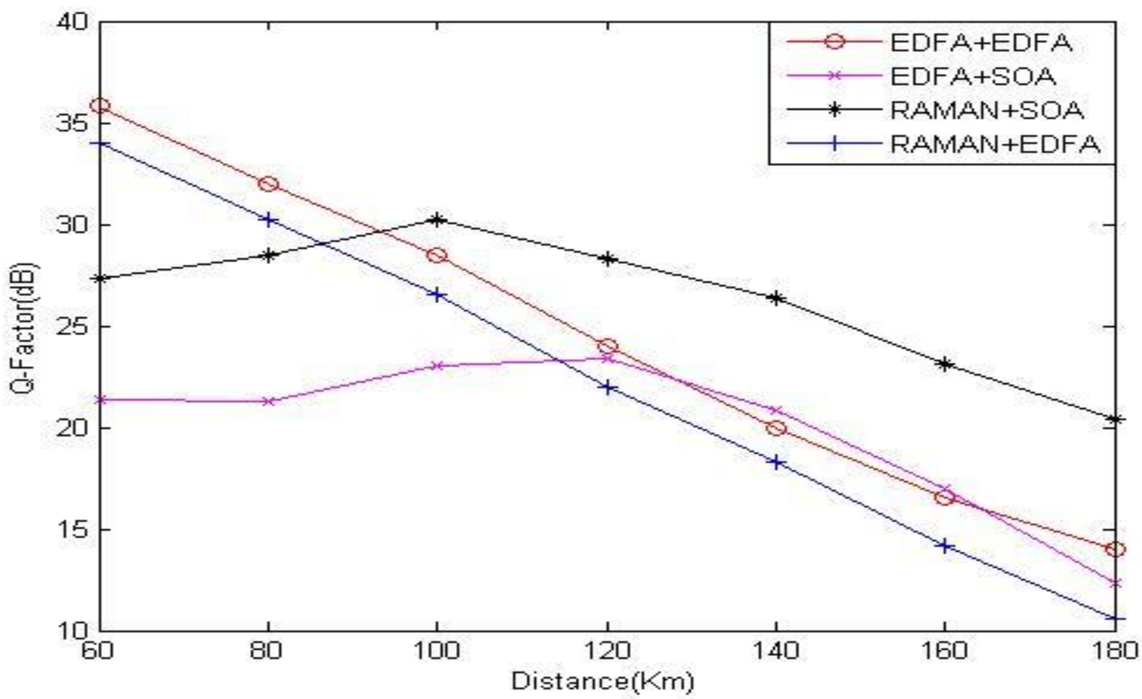


Figure 4.2: (b) Quality factor vs. distance in the absence of nonlinearities.

We observed that Q-Factor is highest; 26.06 dB for EDFA-EDFA and lowest for RAMAN-SOA 20 dB at 60 km. But after 100 km RAMAN-SOA amplifier perform better than other configurations. If non- linearity is not considered then a Q-Factor of 35.8 dB is shown by EDFA-EDFA and 34 dB by RAMAN–SOA. For distance for more than 100 km again RAMAN-SOA outperforms the all other configurations. We also observe that Q-Factor decreases with distances. Variation in value is 26.06 dB to 12.72 dB, 20 dB to 13.08 dB, 25.7 dB to 10.29 dB, 24.37 dB to 19.5 dB for EDFA-EDFA, EDFA-SOA, RAMAN-EDFA, and RAMAN-SOA in the presence of non-linearity.

However in the presence of non-linearity variations are from 35.8 dB to 14 dB, 21.4 dB to 12.34 dB, 27.34 dB to 20.43 dB, 34 dB to 10.6 dB for EDFA-EDFA, EDFA-SOA, RAMAN-SOA, RAMAN-EDFA respectfully. So in term of Quality factor for both the cases EDFA-EDFA yields better result for short distance up to 100 km. for longer distance around 160 km RAMAN-SOA provides better outcomes. Even at 180 km RAMAN-SOA provide a Q-factor of 19.5 dB.

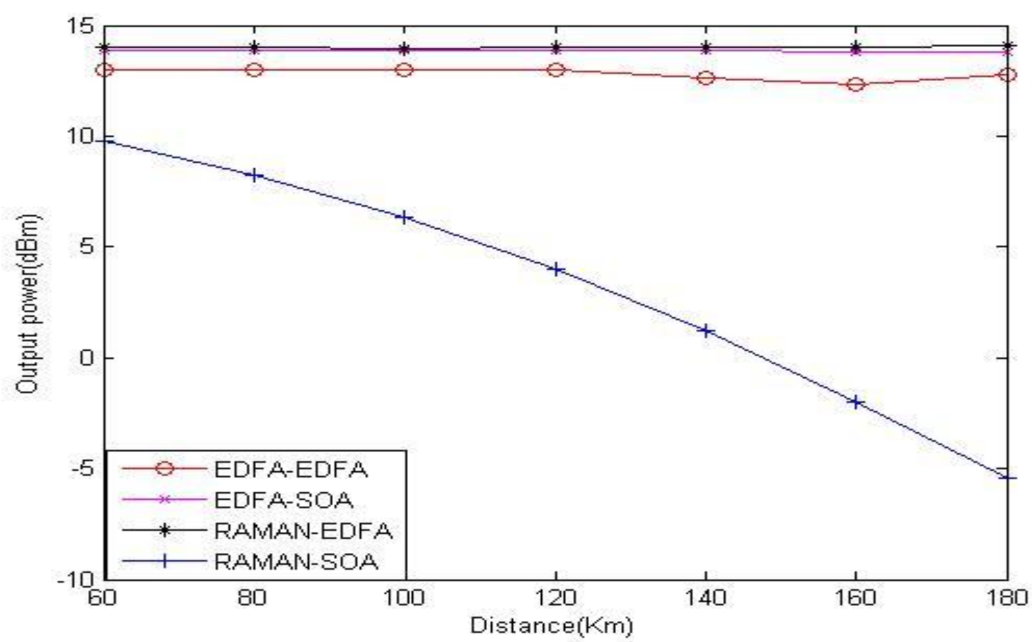


Figure 4.3: Output power vs. distance

Figure 4.3 show that RAMAN-EDFA provides highest power for all distance. It provides around 14 dBm output power. EDFA-EDFA, EDFA-Soa also provides good output power. RAMAN- SOA provides least output power. It varies from 9.7 dBm at 60 km to -5.4 dBm at

180 km. in the absence of impurities output power almost remains same as that of with nonlinearities.

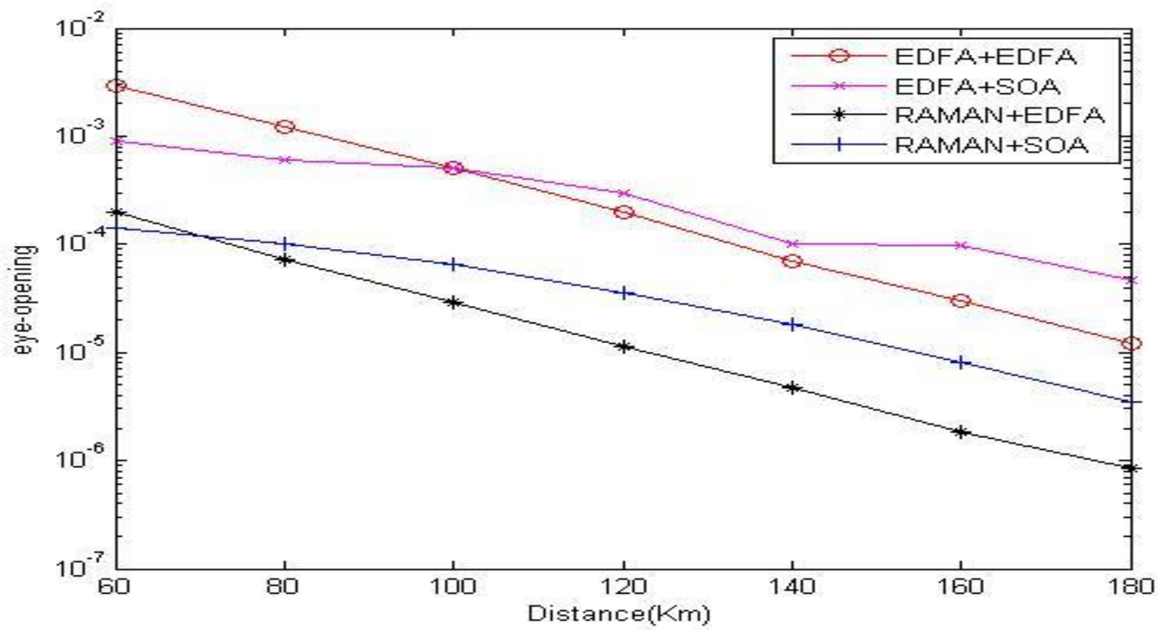


Figure 4.4: (a) Eye opening vs. distance in the presence of nonlinearities.

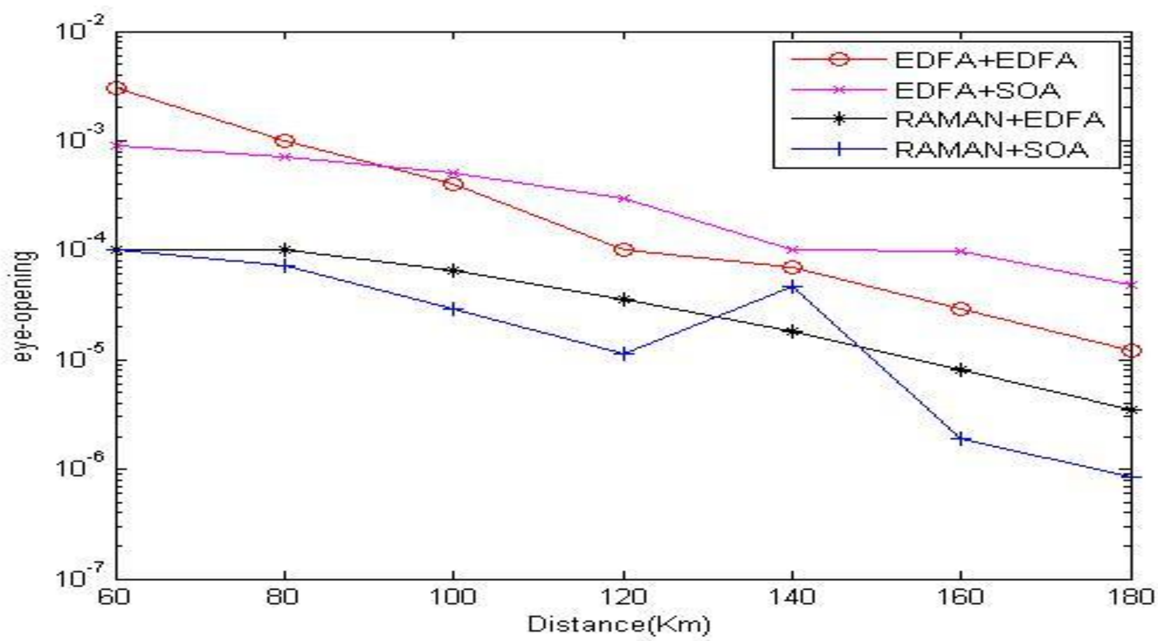


Figure 4.4: (b) Eye opening vs. distance in the absence of nonlinearities.

In figure 4.4 Eye opening vs. transmission distance is plotted. It is shown that eye opening decrease with distance. Larger eye opening means good quality of communication. Eye opening varies from 2.9×10^{-3} to 1.15×10^{-5}, 0.9×10^{-3} to 4.6×10^{-5}, 0.2×10^{-3} to 8.38×10^{-7}, 0.14×10^{-3} to 3.55×10^{-6} for EDFA-EDFA, EDFA-SOA, RAMAN-EDFA, RAMAN-SOA in the presence of non-linearity.

However in the absence of non linearities eye opening varies from 3×10^{-3} to 1.2×10^{-5}, 0.9×10^{-3} to 4.8×10^{-5}, 0.1×10^{-3} to 3.5×10^{-6}, 0.1×10^{-3} to 8.55×10^{-7} for EDFA-EDFA, EDFA-SOA, RAMAN-EDFA, RAMAN-SOA in the absence of non-linearity.

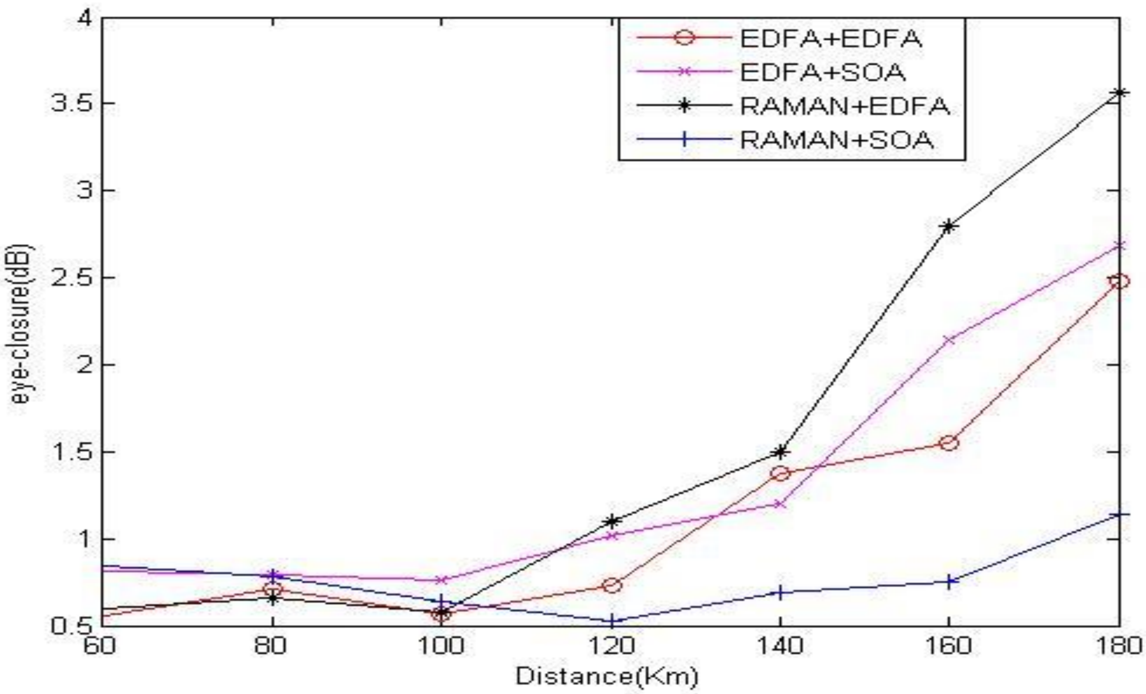


Figure 4.5: (a) Eye closure vs. distance in the presence of nonlinearities.

Eye closure for various configurations has been obtained for different configurations. Eye closure increases with distance as shown. Eye closure is maximum for RAMAN-EDFA and minimum for RAMAN-SOA. Eye closure varies from 0.56 dB to 2.48 dB, 0.81 dB to 2.69 dB, 0.6 dB to 3.57 dB and 0.84 dB to 1.138 dB for EDFA-EDFA, EDFA-SOA, RAMAN-EDFA, RAMAN-SOA in the presence of non-linearity.

In the absence of non linearities, eye closure varies from 0.15dB to 2.97dB, 0.68 dB to 2.98 dB, 0.51 dB to 1.28 dB and 0.18 dB to 3.5 dB, for EDFA-EDFA, EDFA-SOA, RAMAN-EDFA, RAMAN-SOA .

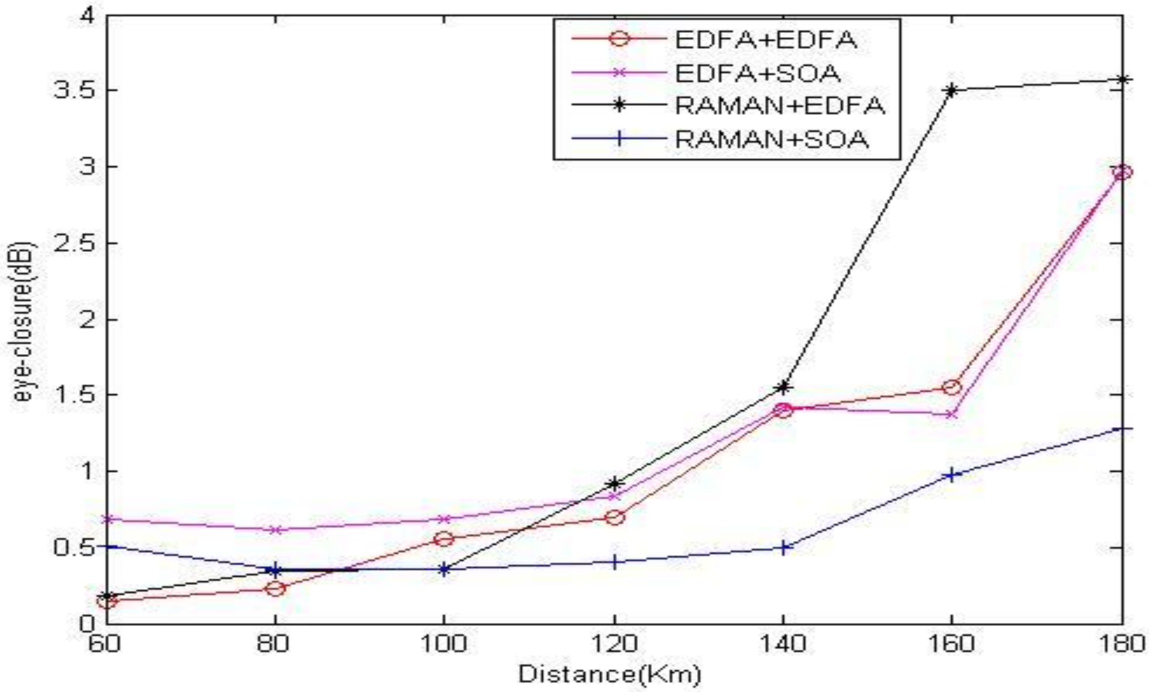


Figure 4.5: (b) Eye closure vs. distance in the absence of nonlinearities.

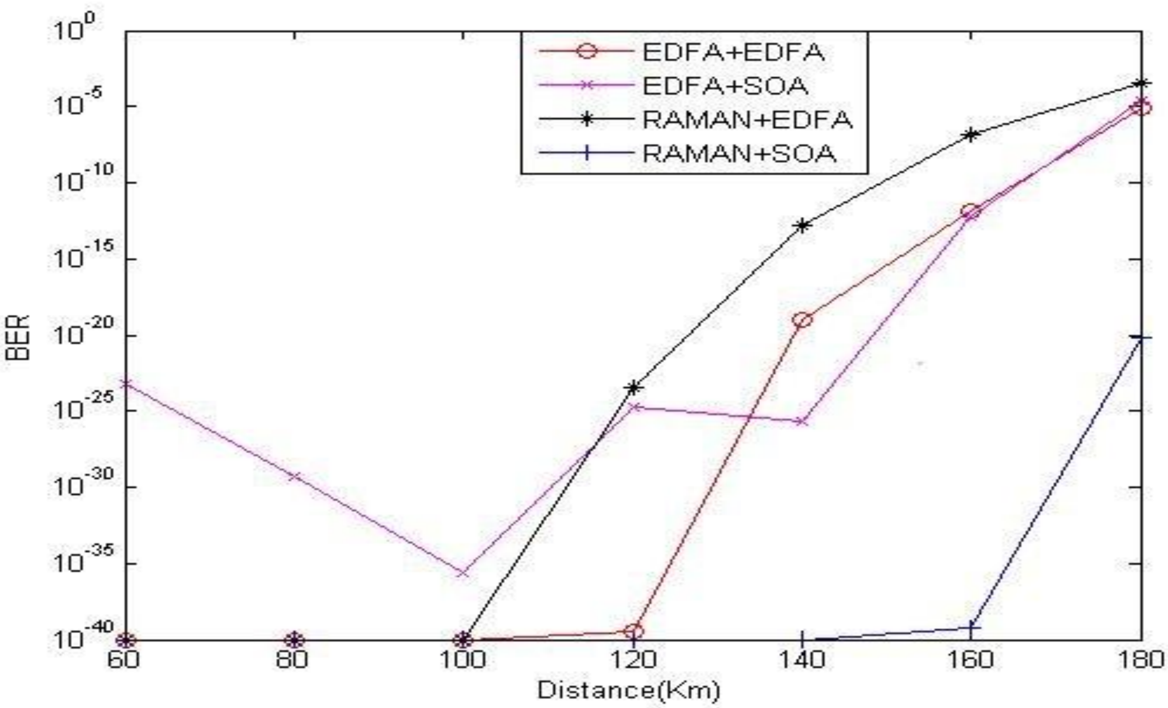
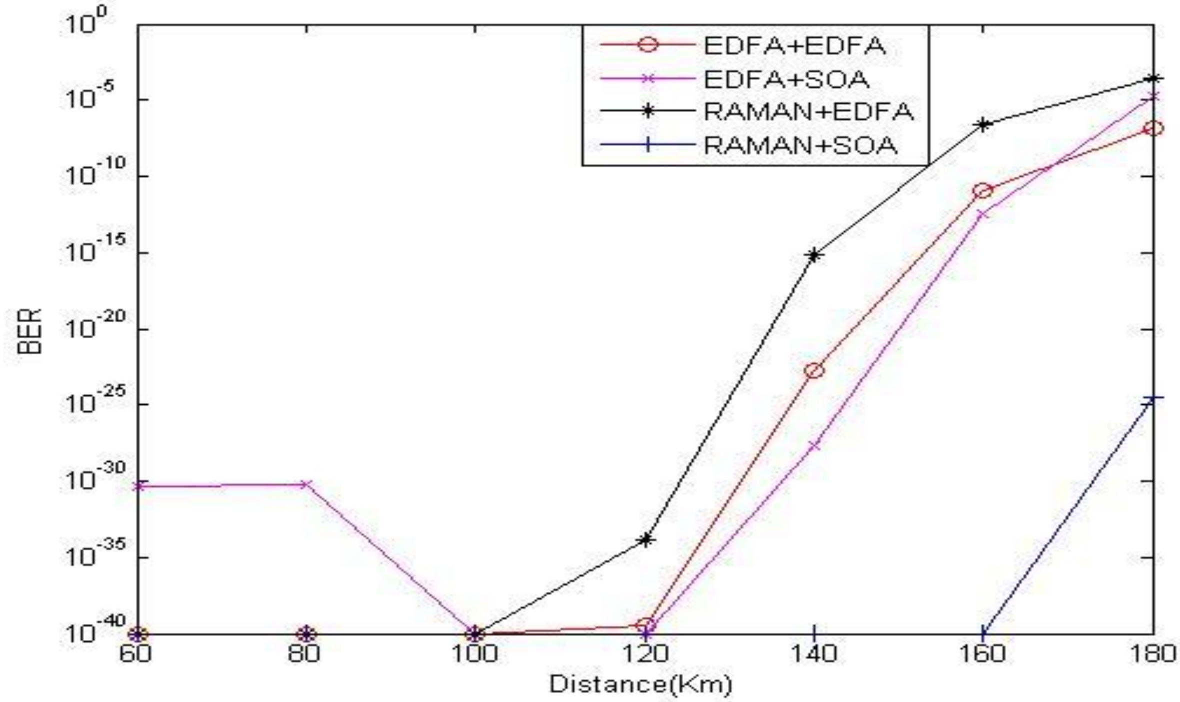


Figure 4.6 (a) Bit error rate vs. distance in the presence of nonlinearities.



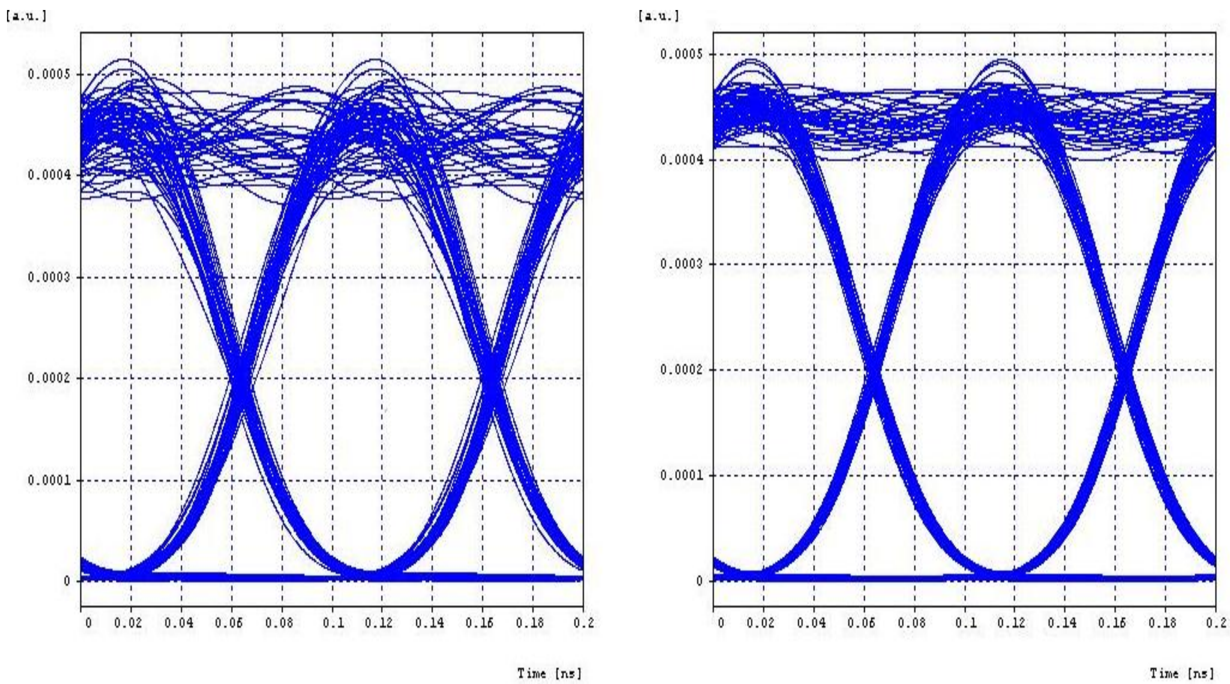
(b)

Figure 4.6: (b) Bit error rate vs. distance in the absence of non-linearities.

The acceptable bit error rate (BER) for optical transmission is 1×10^{-10}. Larger the bit error rate means there is more distortion in the detected signal. The BER versus transmission distance is shown in figure. It is observed that by increasing the transmission distance from 60 to 180 km in the absence of non- linearity BER degrades.

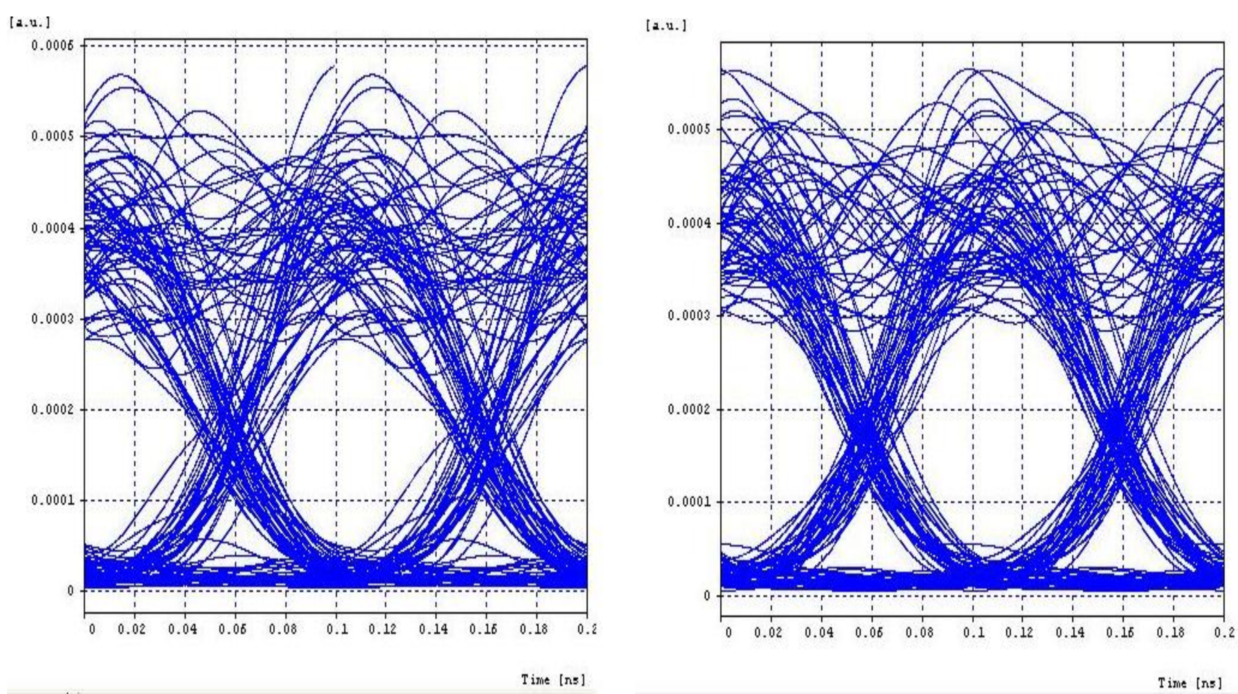
BER increase with distance from 1×10^{-40} to 8.2×10^{-6} for EDFA-EDFA and 1×10^{-40} to 6.7×10^{-21} for RAMAN- SOA. Further for EDFA-SOA, BER increases from 6.8×10^{-24} to 2.4×10^{-06}. for RAMAN-EDFA variation is form 10^{-40} to 4×10^{-4} in the presence of nonlinearities.

In the absence of non linearities it varies from 1×10^{-40} to 1.56×10^{-7} for EDFA-EDFA and 1×10^{-40} to 3×10^{-25} for RAMAN- SOA. Further for EDFA-SOA, BER increases from 5×10^{-31} to 1.8×10^{-5}. For RAMAN-EDFA variation is form 10^{-40} to 4×10^{-3} in the presence of nonlinearities.



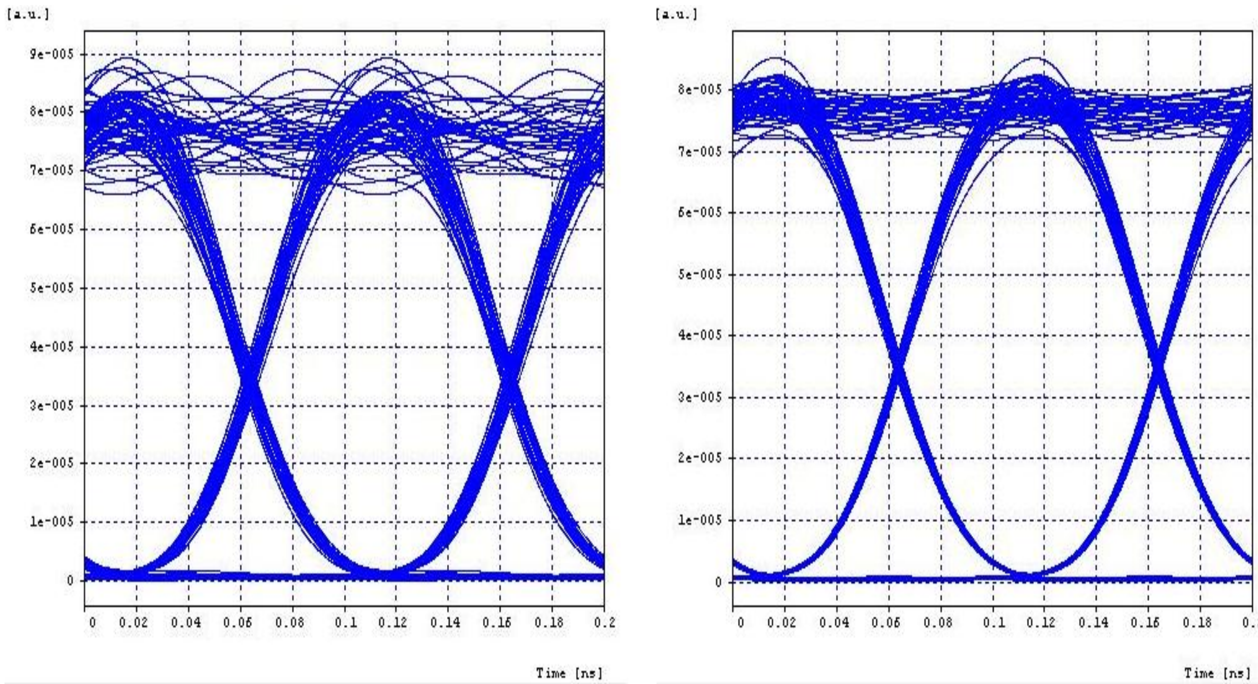
(a) **(b)**

Figure 4.7: Eye diagram for RAMAN-EDFA at 100 km (a) in the presence of nonlinearities (b) in the absence of nonlinearities.



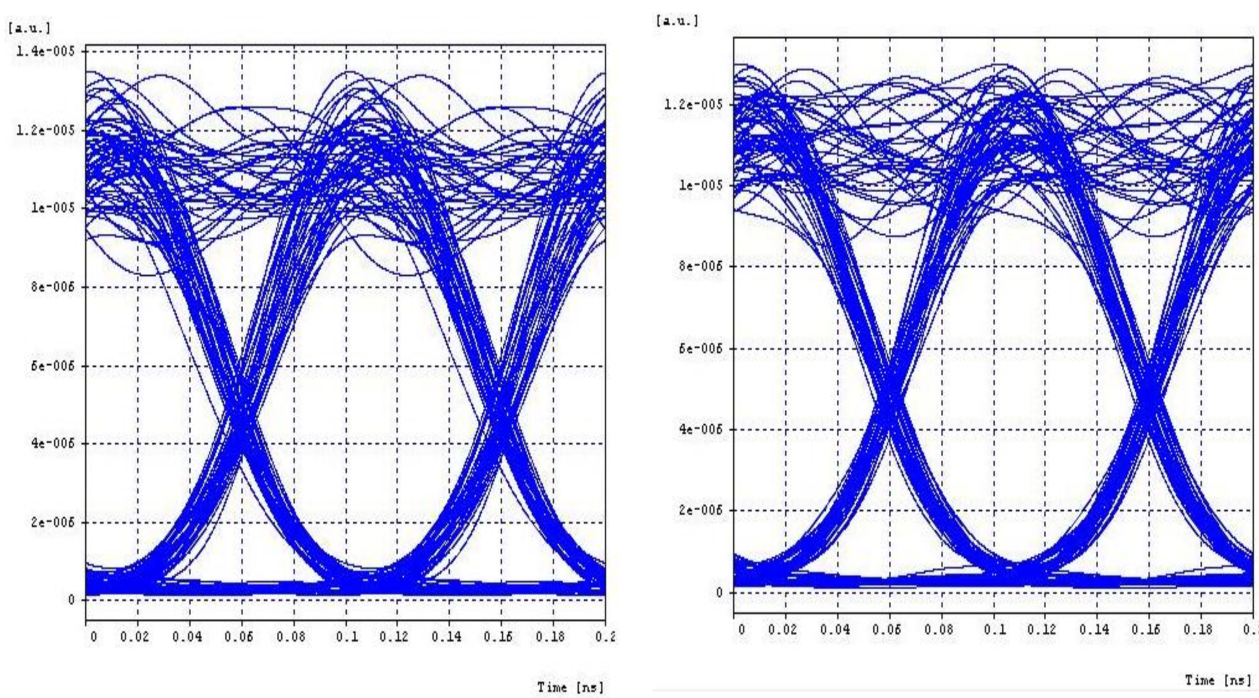
(a) **(b)**

Figure 4.8: Eye diagram for Raman-EDFA at 160 km (a) in the presence of nonlinearities (b) in the absence of nonlinearities.



(a) (b)

Figure 4.9: Eye diagram for RAMAN-SOA at 100 km (a) in the presence of nonlinearities (b) in the absence of nonlinearities.



(a) (b)

Figure 4.10: Eye diagram for RAMAN-SOA at 160 km (a) in the presence of nonlinearities (b) in the absence of nonlinearities.

Conclusion:

We have designed and implemented hybrid optical amplifiers by using OptSim. We carried out simulation for different hybrid amplifier in the presence and absence of nonlinearities by varying the transmission distance and finding out most suitable among them the performance of optical amplifiers was evaluated using the eye patterns, BER measurement, average eye opening and Q factor. The simulation results show that RAMAN–EDFA provide highest output power as compared to other hybrid amplifier. But as the distance increases beyond 100 km RAMAN-SOA performs better as compared to other in term of quality factor, bit error rate, eye closure and eye opening. At 160 km RAMAN –SOA provide a Q- Factor of 17 dB as compared to 13 dB, 11.55 dB, and 11.23 dB of EDFA-EDFA, EDFA-SOA, and RAMAN–EDFA. At 160 km RAMAN–SOA provide minimum eye closure of 1.7 dB, which is much better than the other as shown in figure 4.5 (a) and 4.5 (b). From eye diagram shown in figure we see that RAMAN-SOA provide maximum eye opening. So RAMAN-SOA is promising alternative for distance around 160 km.

Chapter 5

Simulation of Various Types of Transmission Media for 96×10 Gbps WDM System for Raman-EDFA Fiber

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5.1 Abstract:

In this chapter, the 96 channel WDM systems at 10 Gbps have been investigated for the various type of transmission fiber for RAMAN–EDFA optical amplifiers. Different type of fiber like Ds-Anomalous, Ds-Normal, Standard single mode fiber has been used for transmission. Performance has been compared on the basis of fiber. It is found that Ds-Anomalous provide best communication.

5.2 Introduction:

Type of fiber that we are using for transmission plays a very significant role in communication networks. WDM is mostly used around 1550 nm window. The transmission fibers are usually classified according to their dispersion characteristics [53]. Transmission fibers are classified by their dispersion characteristic, standard single mode fibers (SMF's), dispersion-shifted fibers (DSF's) and nonzero dispersion-shifted fibers (NZDSF's). SMF's have low dispersion in the 1300 nm window, while the DSF's and NZDSF's have low dispersion in the 1550 nm window. Dispersion-compensating fibers (DCF's) are fibers with large negative dispersion, often used to compensate the dispersion of SMF in the 1550 nm window. Another interesting fiber is a dispersion-flattened fiber [54]-[55], which has low dispersion in both windows. Its relatively high attenuation, 0.28–0.3 dB/km, prevented its widespread use. To avoid four-wave mixing penalties in WDM systems, NZDSF's were developed [56]-[57]. Their dispersion is designed to be nonzero in the erbium-doped amplifiers gain band but small enough to avoid large dispersion penalties.

With the advent of erbium doped fiber amplifiers, it became possible to amplify multiple signals simultaneously, and optically amplified WDM systems with transmission capacities greater than 1 Tb/s have been demonstrated in the laboratory [58]-[60]. The impact of these nonlinear effects on the system performance will depend on the fiber dispersion [61]-[62]. The exception is the stimulated Brillouin scattering effect, which can be avoided by broadening the signal line width

[63]. The major impact of self-phase modulation, cross phase modulation, and modulation instability is to broaden the signal spectral width, increasing the distortions due to the fiber dispersion [61]-[65]. Furthermore, unlike in the linear case, the induced penalties cannot be fully recovered by dispersion compensation. Fiber dispersion is not all undesirable, since it can reduce cross-talk penalties due to stimulated Raman scattering and four-wave mixing [61].

[66] shown the performance of high data rate and high capacity long-haul DWMD light wave system using a methodology for finding the optimum modulation format that can enhance the system performance without major changes in the existing infrastructure . They showed a 42.7 Gb/s, 80 Km × 16 spans DWDM light wave system including transmitter, different fiber types (SSMF, LEAF, and TW-RS), amplifiers, and receiver is designed. They use four different modulation four formats: NRZ-OOK, optical duo binary, differential binary phase shift keying (NRZ-DBPSK), and differential quadrature phase shift keying (RZ-DQPSK). Simulation results show that the overall system's performance using a combination RZ-DQPSK with the LEAF based on reduced channel spacing (50 GHz with spectral efficiency of 0.8 bit/s/Hz) provides a remarkable improvement (approximately 50% in the transmission distance) over implementations based on other fiber and modulation format combinations.

[67] Further compare the transmission performance of three different modulation formats, return-to-zero (RZ), chirped RZ (CRZ) and vestigial sideband RZ (VSRZ) on using standard single mode fiber (SSMF) and all Erbium-doped fiber amplifiers (EDFAs). This link is composed of wavelength division multiplexed (WDM) channels at 10 Gb/s over 24 times 100 km amplifier spans without using new types of fibers and Raman amplifiers. The generation of each modulation format in experiments is optimized for more reasonable comparison, and their optical characteristics are investigated by comparing with simulation results.

[68] Performing simulations of nonlinear RZ and NRZ transmission we have assessed the potential benefit of RZ coding with respect to NRZ for 10 and 40 Gb/s transmission on standard and non-zero dispersion shifted fiber. For standard fiber we find an increase of the maximum number of spans of 2 dB at l0 Gb/s and up to 6 dB at 40 Gb/s. Employing non-zero dispersion shifted fiber a benefit of 3 dB is observed at 10 Gb/s whereas at 40 Gb/s a maximum increase of the span count of only 2 dB occurs. The widely reported single-channel benefit of NZDSF at 40

Gb/s can be equally achieved by RZ coding on SSMF while SSMF has known benefits for multi-channel limited WDM systems.

[69] Analyzed the system limitations of WDM transmission when using various types of optical fiber to manage dispersion and nonlinearities. In our model, from two to eight, 10 Gb/s WDM channels are transmitted through a cascade of EDFA's experiencing dispersion, stimulated Raman scattering, and self- and cross-phase modulation. Three types of fibers include: conventional single-mode fiber, dispersion-shifted fiber, and dispersion-compensating fiber. These fibers have different dispersion spectral profiles and are combined to manage dispersion to produce a total zero dispersion for a certain fiber span while eliminating four-wave mixing. We find that a system using dispersion-shifted fiber and conventional single-mode fiber exhibits the best performance, with the combination of dispersion and cross-phase modulation as the dominant effects. Furthermore, conventional single-mode fiber combined with dispersion compensating fiber system exhibits the worst performance, with the combination of dispersion and self-phase modulation as the dominant effects**.**

5.3 Simulation Setup and Result:

In this model, ninety six channels are transmitted at data rate of 10 Gb/s with 100 GHz channel spacing. 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 fiber of different transmission distance. A transmitter compound component (T1) is built up using ninety six transmitters. In transmitter compound component each transmitter section consists of the data source, electrical driver, laser source and external Mach–Zehnder modulator. The data source is generating signal of 10 Gb/s with pseudo random sequence. Thus data from all the 96 users is collected at the transmitter side and passed through a booster amplify it before transmission. The transmission distance is varied by parametric run value. In this section of work the fiber cable is changed from one to other type. The CW laser sources generate the 96 laser beams at 188.29 THz–198.29 THz with 100 GHz channel spacing.

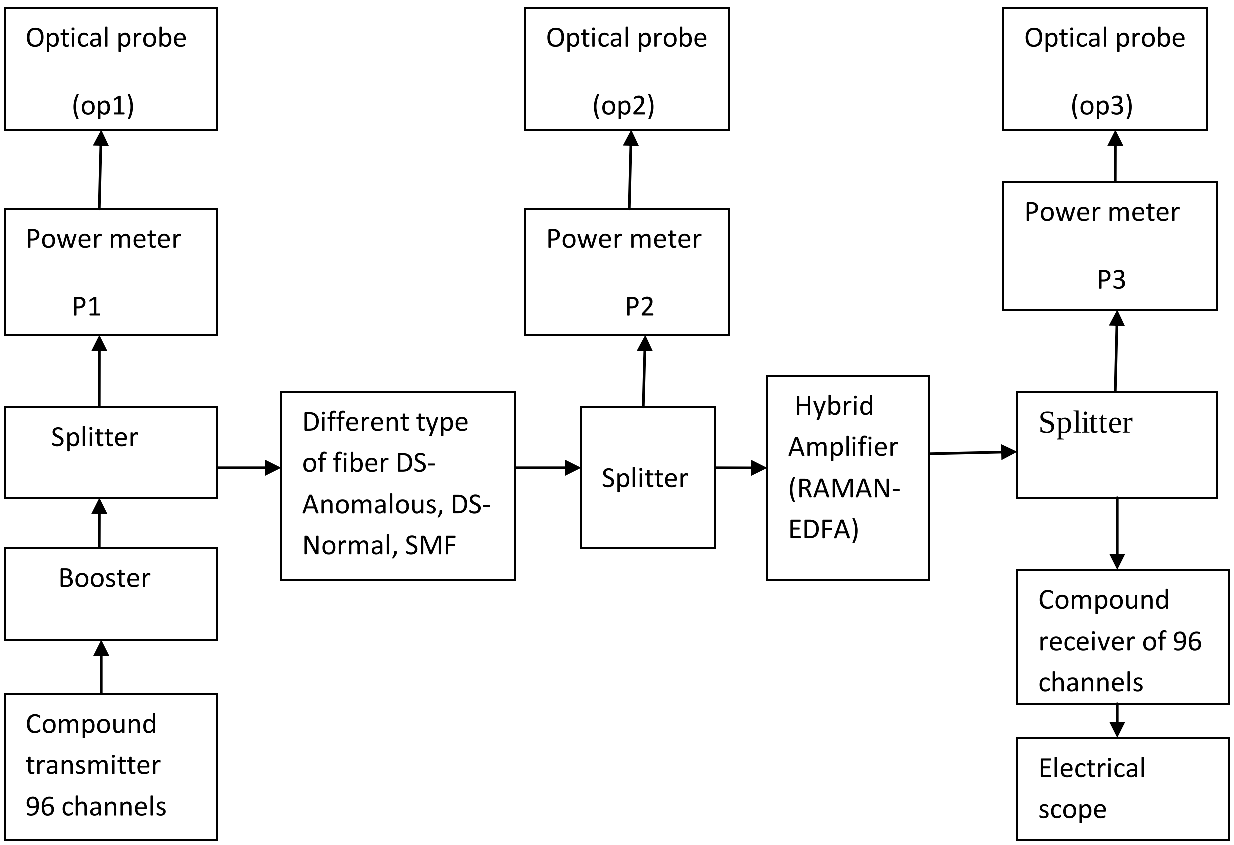


Figure 5.1: Simulation set up

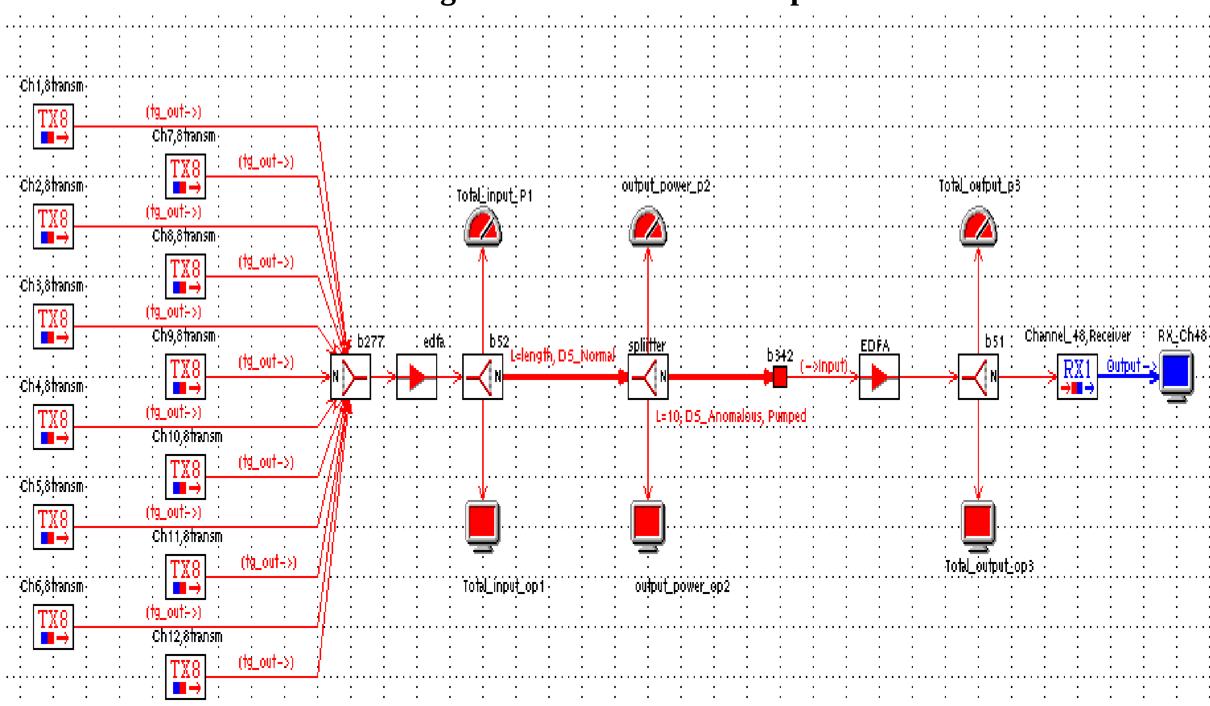


Figure 5.2: Simulation set up

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 (sin2 MZ for (Optical signal from the laser source). In this set up we have used different transmission fiber like DS-Anomalous, DS- Normal and Single mode fiber. RAMAN –EDFA is used as a optical amplifier since this amplifier provide better result as compared to other combinations.

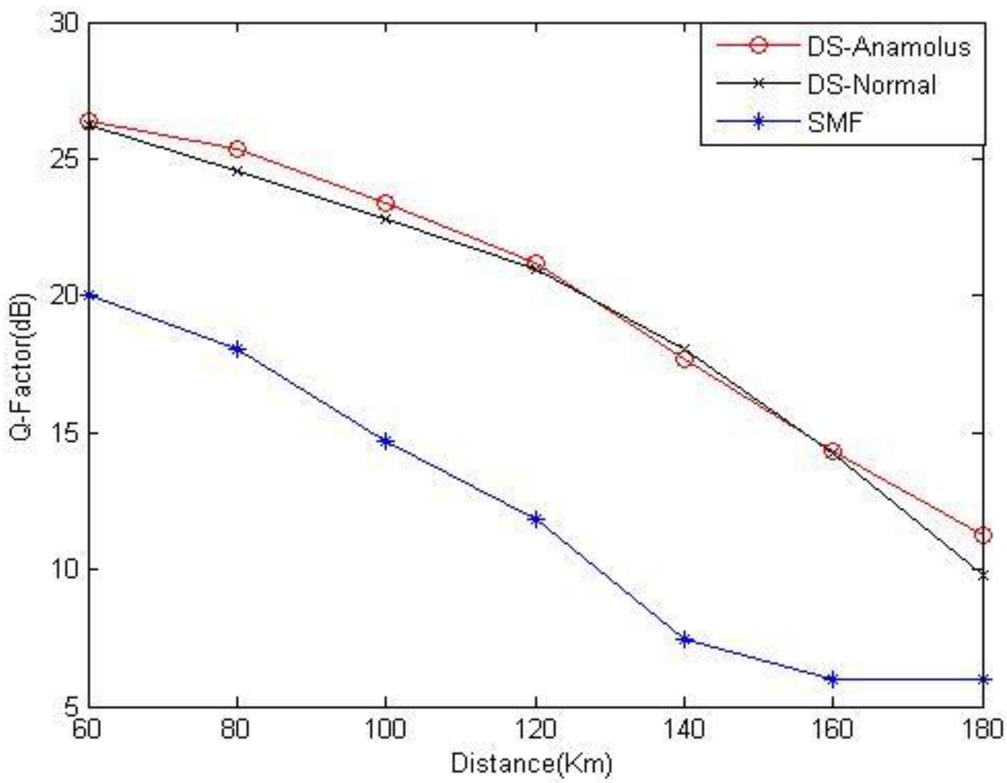


Figure 5.3: Q-factor vs. distance.

We find that as we increases the transmission distance the q-factor decrease. Q-factor is highest for DS-Anomalous fiber. Its value is 24 dB at the 100 km as compared to 22.79 dB and 14.66 dB for the DS- Normal and single mode fiber. For SMF decrease is sharp. At 160 km onwards Q-factor becomes 6 dB making it unsuitable for transmission. Among the three alternative, DS-Anomalous provide better communication. Figure 5.4 shows that DS-Anomalous provide minimum eye closure. More the closure of eye means less suitability for data transmission. Eye closure is worst in SMF. It rises very sharply after a distance of 120 km.

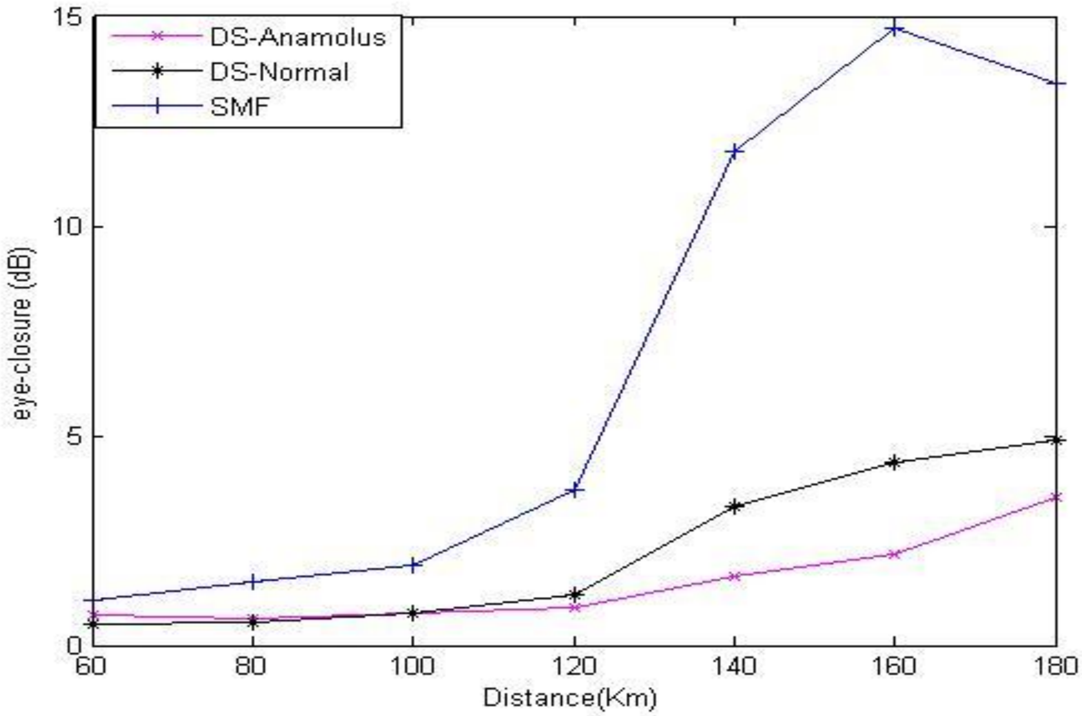


Figure 5.4 Eye closure vs. transmission distance.

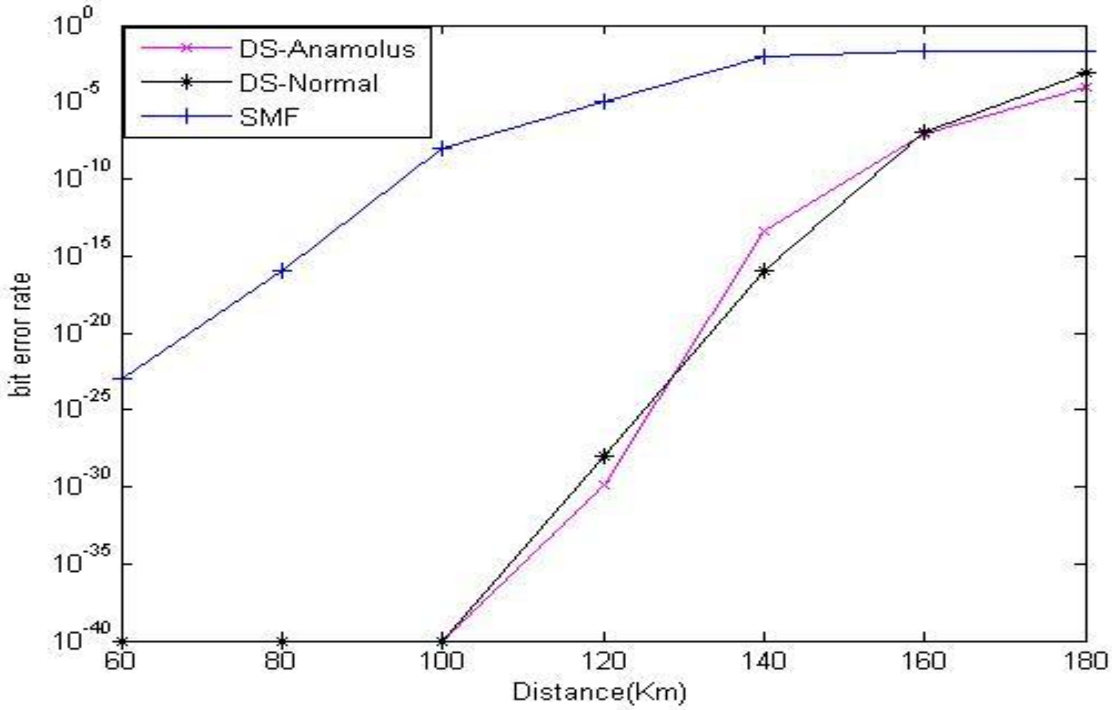
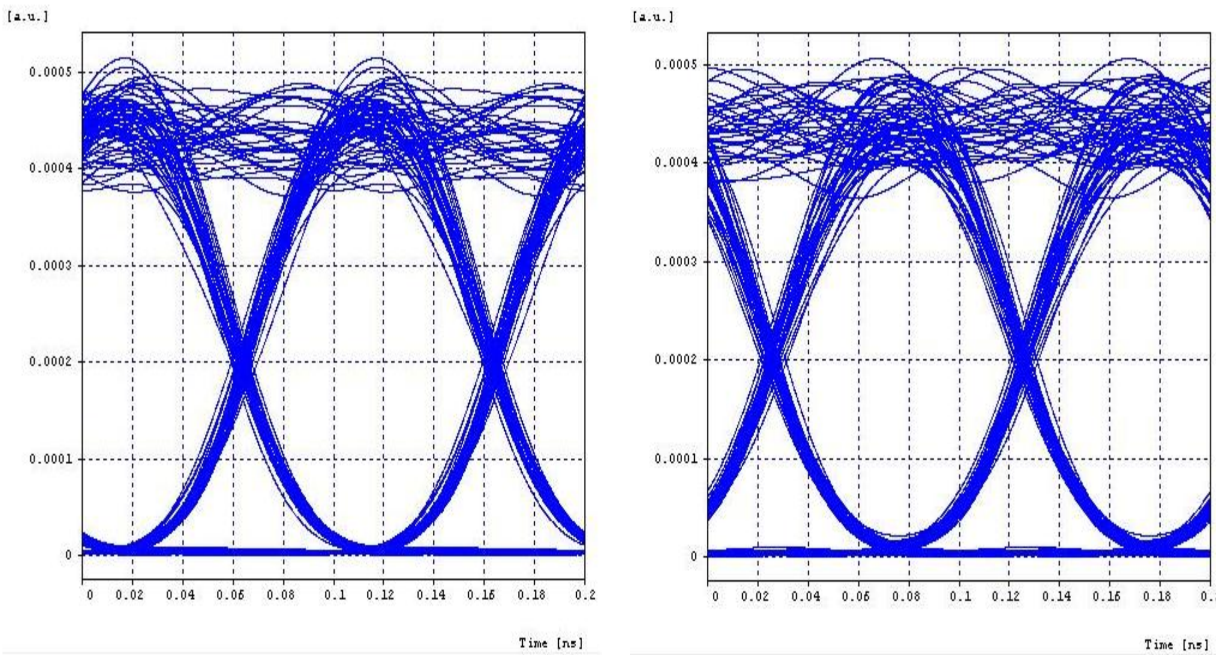
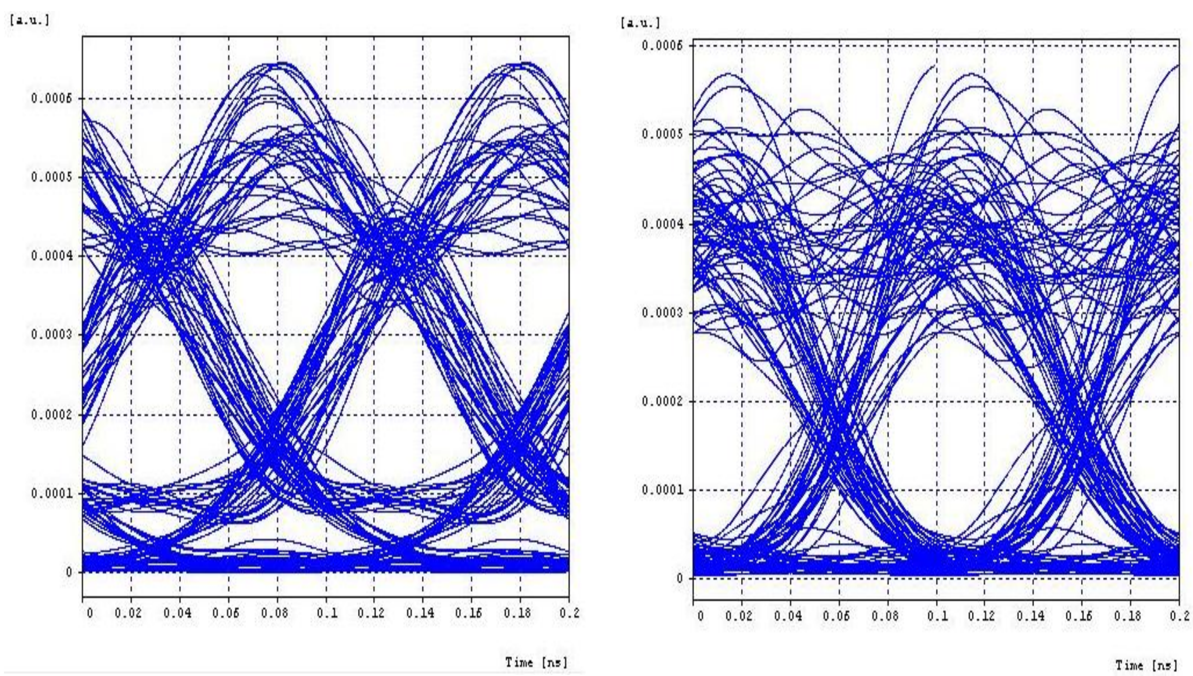


Figure 5.5 Bit error rate vs. distance.



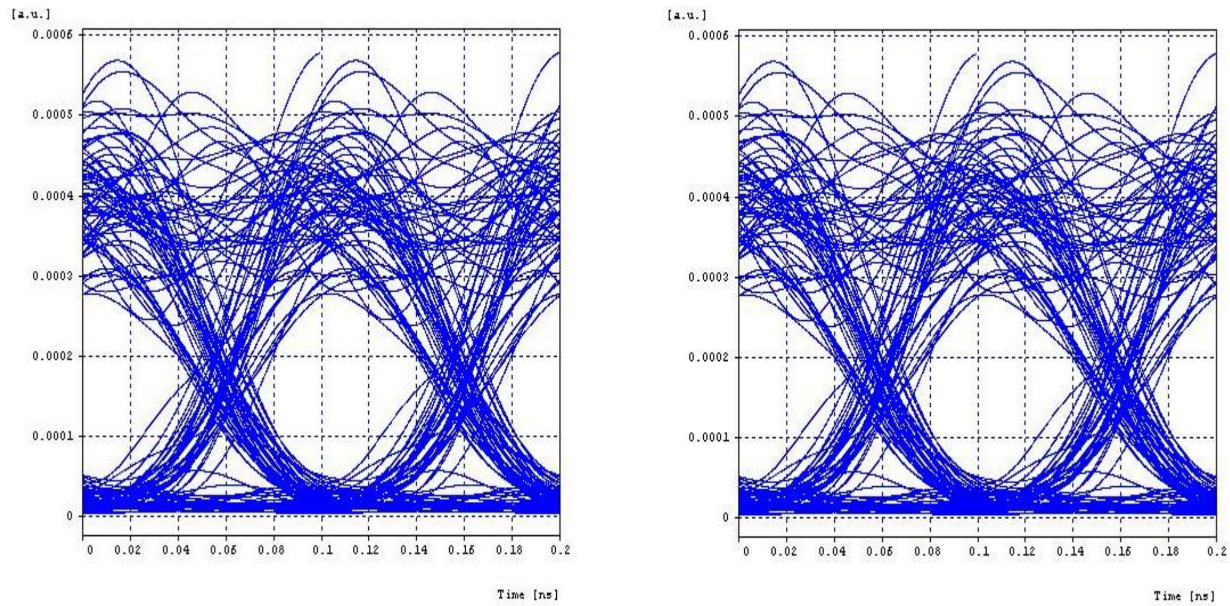
(a) **(b)**

Figure 5.6 Eye diagram for DS-Anomalous fiber at (a) 100km (b) 160 km.



(a) **(b)**

Figure 5.7 Eye diagram for Ds-Normal fiber at (a) 100km (b) 160km.



(a) **(b)**

Figure 5.8 Eye diagram for SMF at (a) 100km (b) 160 km.

Conclusion:

We investigated the performance of three different type of fiber on with Raman-EDFA hybrid amplifier. We found that Ds-Anomalous provide best result in term of quality factor, eye opening and bit error rate. Ds- Anomalous provide highest quality factor of 24 dB as compared to 22.8 dB of Ds- Normal, and 14.66 dB of single mode fiber. Ds- Anomalous also provide minimum eye closure as compared to other two fiber. From eye diagram at 100 km and 160 km it is quite clear that Ds-Anomalous fiber has best eye diagram i.e. maximum eye opening hence minimum distortion. So Ds- Anomalous fiber provide good communication. So the three Ds-Anomalous is better fiber to choose among the three.

Chapter 6

Conclusion and Future Scope

6.1 Conclusion: We have investigated the performance of optical amplifier for a WDM system equally spaced at 10 Gb/s. We have simulated different amplifier with varying transmission distance. EDFA provide highest output power around 14 dBm which remains constant throughout the distance while for the other two amplifiers, output power decreases with distance. For RAMAN and SOA at 100 km, output power becomes -7.913 and 6.6 dBm respectively. In SOA, main limiting factor is crosstalk and polarization sensitivity, while in RAMAN, it is Rayleigh crosstalk which limits the performance. At 100 km, all three provide similar quality factor but after that SOA gives better quality factor. SOA also provides less eye closure of (0.70) dB and minimum bit error rate (1×10^{-35}) at 160 km. So, for distance up to 100 km EDFA gives better results but beyond that quality factor falls rapidly.

Further simulation of hybrid amplifier shows that RAMAN–EDFA provides highest output power as compared to other hybrid amplifiers. But as the distance increases beyond 100 km RAMAN- SOA performs better as compared to other in terms of quality factor, bit error rate, eye closure and eye opening. At 160 km RAMAN –SOA provides Q- Factor of 17 dB as compared to 13 dB, 11.55 dB and 11.23 dB of EDFA-EDFA, EDFA-SOA, and RAMAN–EDFA respectively. At 160 km, RAMAN –SOA provides minimum eye closure of 1.7 dB, which is much better than the others.

In chapter 5, we investigated the performance of three different types of fiber with RAMAN-EDFA hybrid amplifier. We found that Ds-Anomalous fiber provides best result in term of quality factor, eye opening and bit error rate. Ds-Anomalous fiber provide highest quality factor of 24 dB as compared to 22.8 dB of Ds-Normal and 14.66 dB of single mode fiber. Ds-Anomalous also provide minimum eye closure as compared to other two fibers. From eye diagram at 100 km and 160 km, it is quite clear that Ds-Anomalous fiber has best eye diagram i.e. maximum eye opening hence, minimum distortion. So Ds-Anomalous fiber provides good communication. So among the three fibers, Ds-Anomalous is better fiber for communication.

6.2 Future Scope:

In this dissertation, the parameters: bit error rate, eye opening, eye closure and quality factor have been evaulated for 96 WDM channels, 100 GHz spaced. Channel spacing can be reduced to 50 GHz and even to 25 GHz. Work can be extended for more numbers of channels and fiber can be doped with other rare earth material like Thulium, Praseodymium, and Ytterbium. We have investigated the performance using NRZ format which can be changed to solition pulse, raised cosine. This simulation work is done at 10 Gb/s which can be increased to much higher bit rate like 20 Gb/s to 40 Gb/s. Effect of equal and unequal channel spacing on the performance of optical amplifier can also be studied. There is also scope of combining more than two optical amplifiers.

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