Performance Analysis of Hybrid Optical Amplifiers for multichannel WDM systems

A thesis submitted in partial fulfillment of the
Requirements for the award of degree of

Master of Engineering
in
Electronics & Communication Engineering

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June-2011

CERTIFICATE

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

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

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

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Acknowledgement

I am highly indebted to my thesis supervisor **Dr. R. S. Kaler**, Senior professor & Dean RPG, for giving me the opportunity to work under their supervision. They had encouraged me in period of distress and anxiety and guided me to accomplish this research work.

I am highly grateful to **Dr. A. K. Chatterjee**, Head, Department of Electronics & Communication engineering, Thapar University, Patiala, for provision this opportunity to carry out the present work.

My parents had kept me free from my duties at home so that I can devote more time to my research work. I acknowledge them for their blessings and support.

The copious help received from the technical staff of the department for their intellectual support is also acknowledging.

Finally, I sincerely thank all the persons who have helped and supported me directly or indirectly in the course of this work.

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ABSTRACT

For the need of higher capacity and speed optical fiber communication systems are being extensively used all over the world for telecommunication, video and data transmission purposes. Multimedia optical networks are the demands of today to carry out large information like real time video services. Presently, almost all the trunk lines of existing networks are using optical fiber. This is because the usable transmission bandwidth on an optical fiber is so enormous (as much as 50 THz) as a result of which, it is capable of allowing the transmission of many signals over long distances. However, attenuation is the major limitation imposed by the transmission medium for long-distance high-speed optical systems and networks. So with the growing transmission rates and demands in the field of optical communication, the electronic regeneration has become more and more expensive. The powerful optical amplifiers came into existence, which eliminated the costly conversions from optical to electrical signal and vice versa.

The hybrid optical amplifier have attracted much attention as they are amplifies the broad bandwidth. The hybrid optical amplifier has wide gain spectrum ease of integration with other devices and low cost.

This thesis is mainly concerned with the use of hybrid optical amplifiers in multichannel wavelength division multiplexing (WDM) optical communication system and network. The aim of investigation is to increase the transmission distance and amplify broad bandwidth optical networks by optimizing hybrid optical amplifiers.

The performance of various optical amplifiers and hybrid amplifiers and the performance have been compared on the basis of transmission distance, dispersion. Various types of configurations of hybrid optical amplifiers have been used for the better study of hybrid optical amplifier. It is observed that as we used less number of channels then SOA provide better results. By the increasing of channels SOA degraded the performance due of non-linearity induces. To overcome that problem the RAMAN amplifier is the best alternative.

We further optimized the hybrid optical amplifier (RAMAN) using different parameter of RAMAN and EDFA such as Raman fiber length, Raman pump wavelength, Raman pump power, EDFA noise figure and EDFA output power. Using this optimized hybrid optical amplifier we have achieved maximum single span distance for different dispersions.

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LIST OF ABBREVIATIONS

ALP	Adaptive-linear-prediction
APD	Avalanche photodiode
ASE	Amplified spontaneous emission
AWG	Arrayed waveguide gratings
BER	Bit error rate
DCF	Dispersion compensated fiber
DFA	Doped fiber amplifier
DFB	Distributed feedback
DRA	Distributed Raman amplifier
DS	Dispersion shifted
DWBA	Dynamic wavelength and bandwidth allocation
DWDM	Dense wavelength division multiplexing
EDFA	Erbium-doped fiber amplifiers
FDM	Frequency Division Multiplexing
FRA	Fiber Raman amplifier
FWM	Four-wave mixing
GRIN	Graded-refractive-index
GVD	Group velocity dispersion
HA	Hybrid amplilifier
ISI	Inter symbol interference
LED	Light emitting diode
NA	Numerical aperture
NB-HA	Narrow band hybrid amplifier
NDS	Normal dispersion shifted
NF	Noise figure
OADM	Optical add drop multiplexer
OAMP	Optical amplifier
OFA	Optical fiber amplifier
PIN	Positive-intrinsic negative
PMD	Polarization-mode dispersion
PON	Passive optical network
QoS	Quality-of service
RF	Radio frequency
RFA	Raman fiber amplifier
RWA	Routing and wavelength assignment

RZ	Return-to-zero
SBS	Stimulated Brillouin scattering
SMF	Single-mode fibers
SNR	Signal-to-noise ratio
SOA	Semiconductor optical amplifier
SPM	Self-phase modulation
SRS	Stimulated Raman scattering
SSF	Split step Fourier
SWB-HA	Seamless wide band hybrid amplifier
TDM	Time division multiplexing
TE	Transverse-electric
TM	Transverse-magnetic
UWB	Ultra wide band
VBR	Variable bit rate
WDM	Wavelength-division multiplexing
WLAN	Wireless local area networks
XPM	Cross-phase modulation

LIST OF SYMBOLS

λ	Wavelength of light
c	Velocity of light
h	Plank constant
µm	Micro meter
nm	Nano meter
Tb/s	Tera bits per second
ps	Pico second
Km	Kilometer
dB	Decibel
C_{mat}	Speed of light for a given material.
E1	Lower energy state
E2	Higher energy state
E	Photon energy
N1	Population density of lower level
N2	Population density of higher level
N	Carrier density
R	Run for fiber length
mW	Milli watt
G	Fiber path gain
i_m	Modulating current
η	Modulation sensitivity
β_2	Group velocity dispersion coefficient
γ	Self-phase modulation coefficient
T	Pulse width
z_0	Soliton period,
N	Soliton order
$\Delta\lambda$	Source line-width
D	Fiber dispersion
L	The fiber length
n_{mat}	The material's refractive index
ω	Angular frequency

CHAPTER 1

INRODUCTION

1.1 Development of Fiber Optic Systems

With the advancements in the communication systems, there is a need for large bandwidth to send more data at higher speed. Residential subscribers demand high speed network for voice and media-rich services. Similarly, corporate subscribers demand broadband infrastructure so that they can extend their local-area networks to the Internet backbone [1]. This demands the networks of higher capacities at lower costs. Optical communication technology gives the solution for higher bandwidth. By developing the optical networks, larger transmission capacity at longer transmission distance can be achieved. To accomplish higher data rates, these optical networks will be required fast and efficient wavelength conversion, multiplexing, optical splitter, optical combiner, arithmetic processing and add-drop function etc. [2].

In fiber optic communication, there is degradation of transmission signal with increased distance [3]. By the use of optoelectronic repeater, this loss limitation can be overcome. In optoelectronic repeater, optical signal is first converted into electric signal and then after amplification it is regenerated by transmitter. But such regeneration becomes quite complex and expensive for wavelength division multiplexing systems. So, to remove loss limitations, optical amplifiers are used which directly amplify the transmitter optical signal without converting it into electric forms. The optical amplifiers are used in linear mode as repeaters, optical gain blocks and optical pre-amplifiers. The optical amplifiers are also used in nonlinear mode as optical gates, pulse shaper and routing switches [2]. The optical amplifiers are mainly used for amplification of all channels simultaneously in WDM light wave system called as optical in-line amplifiers. The optical amplifiers are also bit rate transparent and can amplify signals at different wavelengths simultaneously. The optical amplifier increases the transmitter power by placing an amplifier just after the transmitter called power booster. The transmission distance can also be increased by putting an amplifier just before the receiver to boost the received power. The optical amplifier magnifies a signal immediately before it reaches the receiver called as optical pre-amplifier.

1.2 Development of DWDM Technology

Early WDM began in the late 1980s using the two widely spaced wavelengths in the 1310 nm and 1550 nm (or 850 nm and 1310 nm) regions, sometimes called wideband WDM [3]. The early 1990s saw a second generation of WDM, sometimes called narrowband WDM, in which two to eight channels were used. These channels were spaced at an interval of about 400 GHz in the 1550-nm window. By the mid-1990s, dense WDM (DWDM) systems were emerging with 16 to 40 channels and spacing from 100 to 200 GHz. By the late 1990s DWDM systems had evolved to the point where they were capable of 64 to 160 parallel channels, densely packed at 50 or even 25 GHz intervals, as shown in figure 1.1.

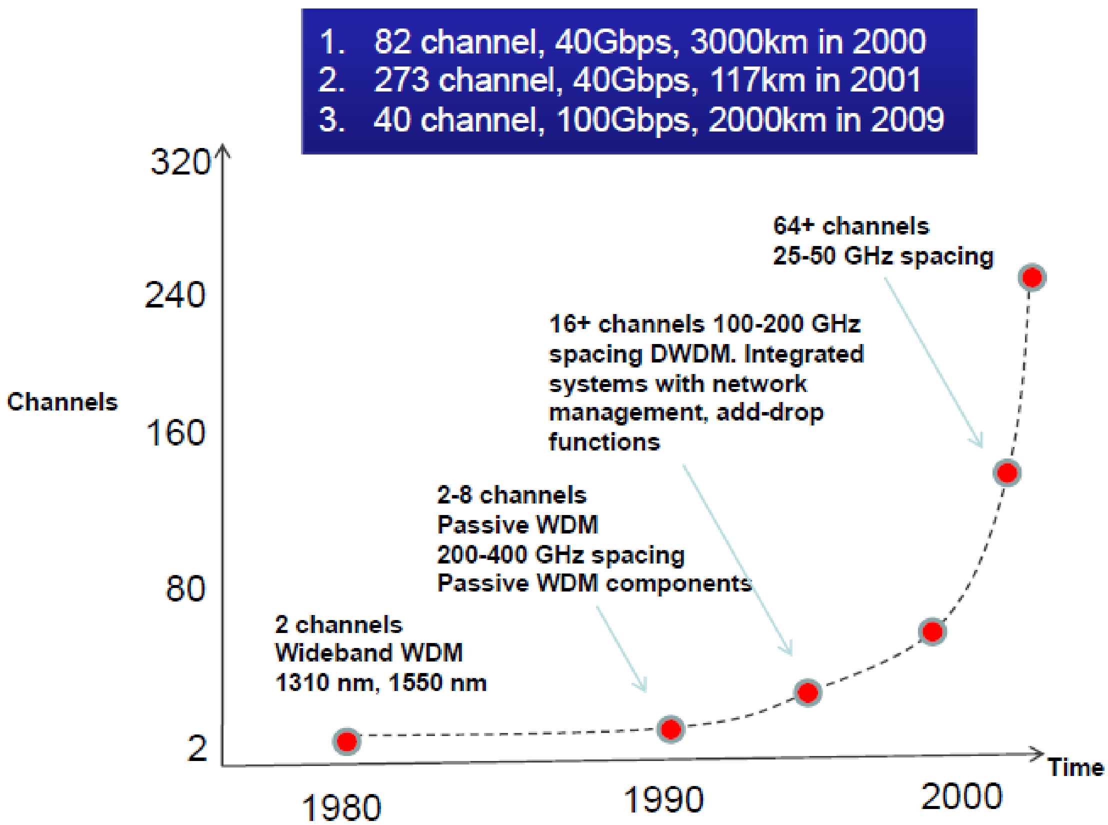


Figure 1.1: Development in WDM Technology [4]

1.3 Optical Transmission in Fiber

Before discussing optical components, it is essential to understand the characteristics of the optical fiber itself. Fiber is essentially a thin filament of glass which acts as a waveguide [5]. A waveguide is a physical medium or a path which allows the propagation of electromagnetic waves, such as light. Due to the physical phenomenon of total internal reflection, light can propagate the length of a fiber with little loss, which is illuminated as following [6]. Light travels through vacuum at a speed of c=3 × l0^8 m/s. Light can also travel through any transparent material, but the speed of light will be slower in the material than in a vacuum. Let c_{mat} be the speed of light for a given material [7]. The ratio of the speed of light in vacuum to that in a material is known as the material's refractive index (n), and is given by: $n_{mat}= \frac{c}{c_{mat}}$. Given that n_{mat} = 1.5 approximately for glass, the velocity of signal propagation in a fiber approximately equals 2 ×l0^8 m/s, which corresponds to a signal propagation delay of 5µs/km [5].When light travels from material of a given refractive index to material of a different refractive index (i.e., when refraction occurs), the angle at which the light is transmitted in the second material depends on the refractive indices of the two materials as well as the angle at which light strikes the interface between the two materials [6] . Due to Snell's Law, $n_a \sin\theta_a = n_b \sin\theta_b$ where n_a and n_b are the refractive indices of the first substance and the second substance, respectively; θ_a is the angle of incidence, or the angle with respect to normal that light hits the surface between the two materials; and θ_b is the angle of light in the second material. However, if $n_a > n_b$ and θ_a is greater than some critical value, the rays are reflected back into substance n from its boundary with substance 2nd [7].

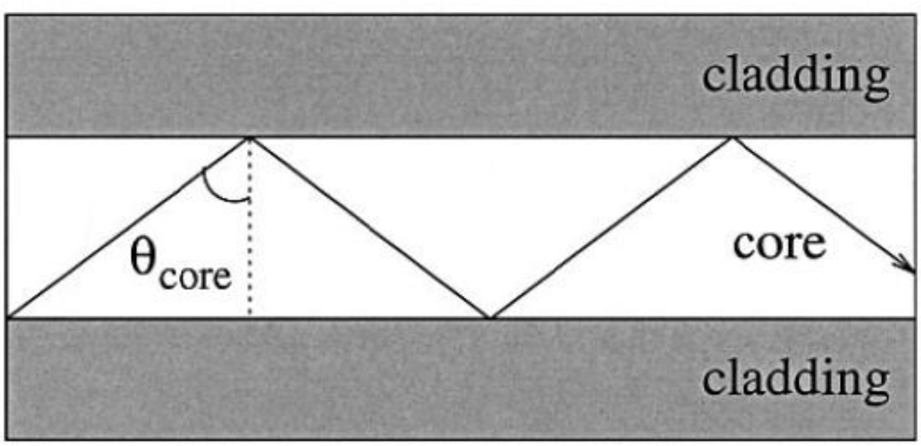


Figure 1.2: Light traveling via total internal reflection within a fiber [5].

Looking at Figures 1.2, we see that the fiber consists of a core completely surrounded by a cladding (both the core and the cladding consist of glass of different refractive indices). Let us first consider a step-index fiber, in which the change of refractive index at the core-cladding boundary is a step function [6]. If the refractive index of the cladding is less than that of the core, then total internal reflection can occur in the core and light can propagate through the fiber (as shown in Figure. 1.2). The angle above which total internal reflection will take place is known as the critical angle, and is given by θ_{core} which corresponds to θ_{clad} = 90'. From Snell's Law, we have:

$$\text{Sin}\theta_{clad}=\left(\frac{n_{core}}{n_{clad}}\right)\text{Sin}\theta_{core}$$

The critical angle is then:

$$\theta_{crit}=sin^{-1}(n_{clad}/n_{core}) \qquad (1.1)$$

So, for total internal reflection, we require:

$$\theta_{crit} > sin^{-1}(n_{clad}/n_{core})$$

In other words, for light to travel down a fiber, the light must be incident on the core-cladding surface at an angle greater than θ_{crit}

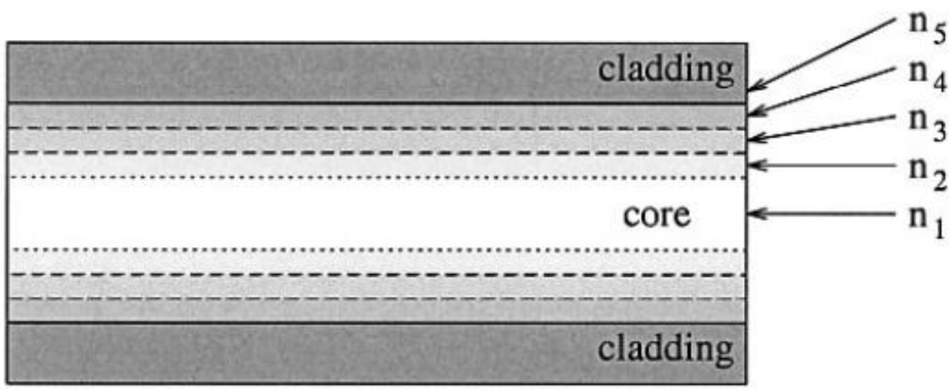


Figure 1.3: Graded-index fiber [6].

In some cases, the fiber may have a graded index in which the interface between the core and the cladding undergoes a gradual change in refractive index with $n_i > n_{i+1}$ (Figure. 1.3). A graded-index fiber reduces the minimum θ_{crit} required for total internal reflection, and also helps to reduce the intermodal dispersion in the fiber [7].

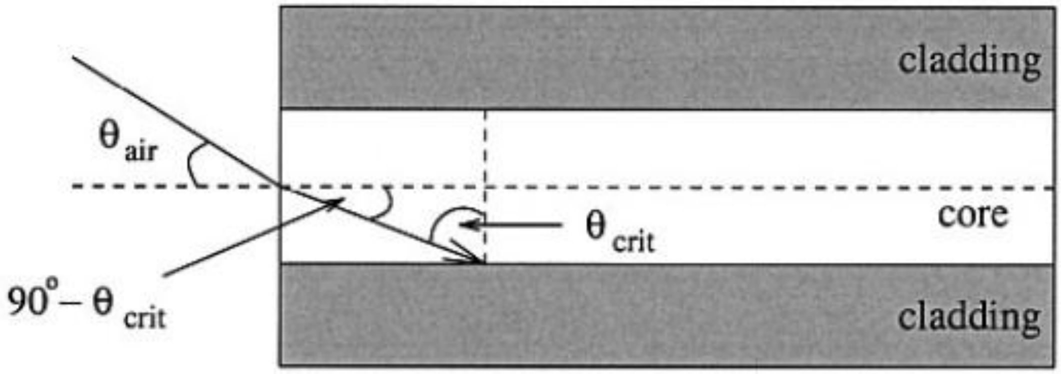


Figure 1.4: Numerical aperture of a fiber [6].

In order for light to enter a fiber, the incoming light should be at an angle such that the refraction at the air-core boundary results in the transmitted light being at an angle for which total internal reflection can take place at the core-cladding boundary [7].

As shown in Fig. 1.4, the maximum value of θ_{air} can be derived from:

$$n_{air} sin\theta_{air} = n_{core} \sin (90^0 - \theta_{crit})$$

$$= n_{core}\sqrt{1 - sin^2\theta_{crit}} \qquad (1.2)$$

From Eqn. (1.1), since $sin\theta_{crit} = (\frac{n_{clad}}{n_{core}})$, we can rewrite Eqn. (1.2) as:

$$n_{air} sin\theta_{air} = \sqrt{n_{core}^2 - n_{clad}^2} \qquad (1.3)$$

The quantity $n_{air} sin\theta_{air}$ is referred to as NA, the numerical aperture of the fiber and θ_{air} is the maximum angle with respect to the normal at the air-core boundary, so that the incident light that enters the core will experience total internal reflection inside the fiber. According to Snell's Law and fiber refractive index, typical delay of optical propagation in optical fiber is 5µs/km [3].

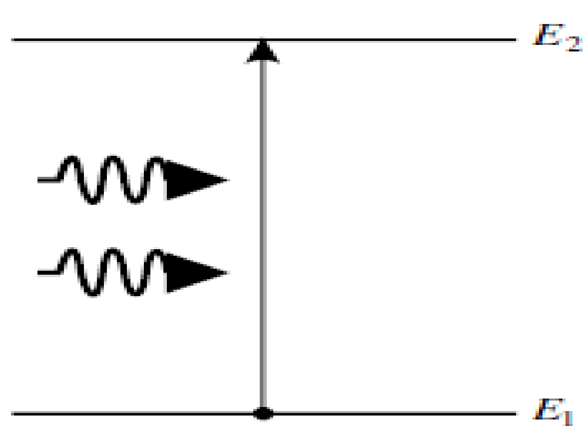
1.4 Optical Amplifier

1.4.1 Principle of optical amplifier

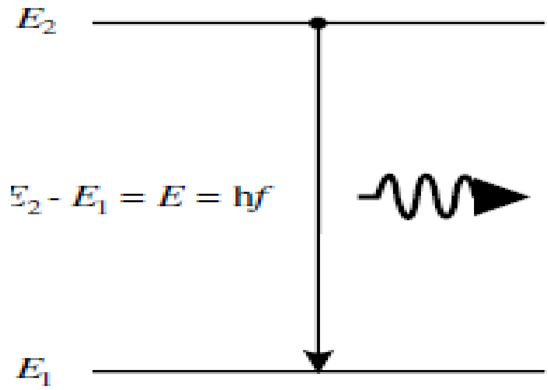
Atom exists only in certain discrete energy state, absorption and emission of light cause them to make a transition from one discrete energy state to another state and related to difference of energy E between the higher energy state E_2 and lower energy state E_1 as shown in figure 1.5(a). When photon energy E is incident on atom, it may be excited into higher energy state E_2 through absorption of photon called absorption as shown in figure 1.5(a). As atom in energy state E_2 is not remain stable, atom returns to lower energy state in random manner by generating a photon as shown in figure 1.5(b). This is called spontaneous emission.

Optical amplification uses the principle of stimulated emission, similar to the approach used in a laser [3]. The stimulated emission occurs, when incident photon having energy $E = hc/\lambda$ interact with electron in upper energy state causing it to return back into lower state with creation of second photon as shown in figure 1.5(c), where h is Plank constant, c is velocity of light and λ is the wavelength of light [2]. The light amplification occurs, when incident photon and emitted photon are in phase and release two more photons.

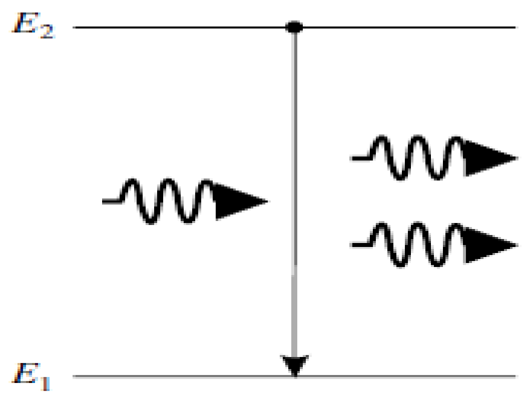
To achieve optical amplification, the population of upper energy level has to be greater than that of lower energy level i.e. $N_1 < N_2$, where N_1, N_2 are population densities of lower and upper state. This condition is known as population inversion. This can be achieved by exciting electron into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



(a)



(b)



(c)

Figure 1.5: Absorption, spontaneous emission and stimulated emission process. [8].

1.4.2 Types of Optical Amplifiers

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

1.4.2.1 Semiconductor Optical Amplifier

A semiconductor laser amplifier (see figure 1.6) is a modified semiconductor laser, which typically has different facet reflectivity and different device length [3]. Semiconductor optical amplifier is very similar to a laser except it has no reflecting facets. A weak signal is sent through the active region of the semiconductor, which, via stimulated emission, results in a stronger signal emitted from the semiconductor.

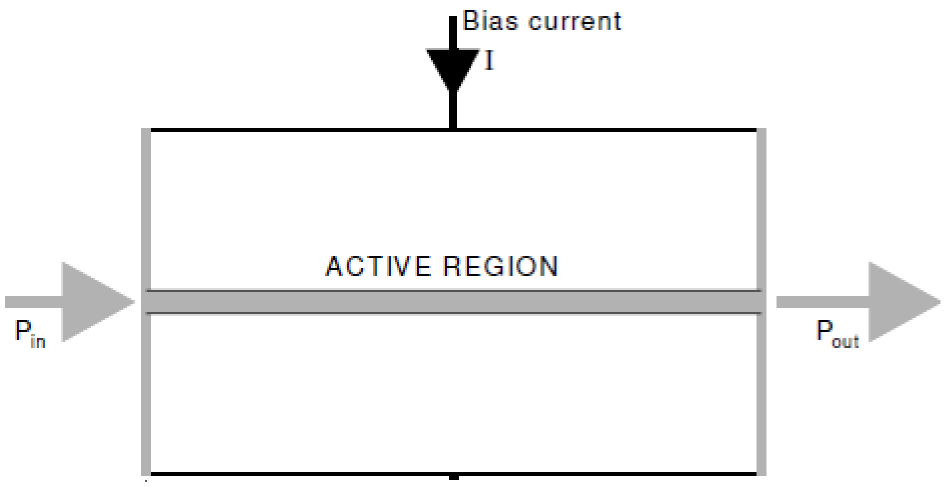


Figure 1.6: A Semiconductor Optical Amplifier [8]

SOA's are typically used in the following:

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

1.4.2.2 Erbium Doped Fiber Amplifier

The EDFA consists of three basic components: length of erbium doped fiber, pump laser and wavelength selective coupler to combine the signal and pump wavelengths as shown in figure 1.7. The optimum fiber length used depends upon the pump power, input signal power, amount of erbium doping and pumping wavelength [1]. Erbium doped fiber amplifiers (EDFAs) can be extensively used in optical fiber communication systems due to their compatibility with optical fiber. An EDFA has a comparatively wide wavelength range of amplification making it useful as transmission amplifier in wavelength division multiplexing systems. Theoretically EDFA is capable of amplifying all the wavelengths ranging from 1500 to 1600 nm. However practically there are two windows of wavelength. These are C and L band. This allows the data signal to stimulate the excited atoms to release photons [9]. Most erbium-doped fiber amplifiers (EDFAs) are pumped by lasers with a wavelength of either 980 nm or 1480 nm [3]. The 980-nm pump wavelength has shown gain efficiencies of around 10dB/mW, while the 1480-nm pump wavelength provides efficiencies of around 5dB/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.

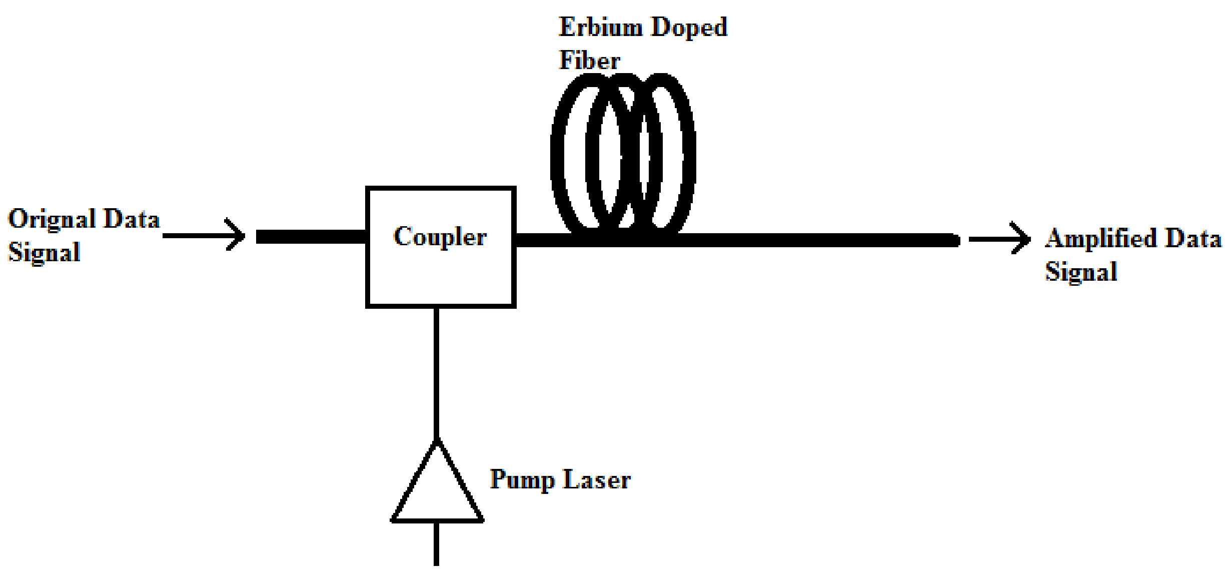


Figure 1.7: Erbium Doped Fiber Amplifier

1.4.2.3 RAMAN Amplifier

Raman gain in optical fibers occurs from the transfer of power from one optical beam to another through the transfer of energy of a phonon. A phonon arises when a beam of light couples with the vibration modes of the medium [10]. In this instance the optical fiber is the amplifying medium making the gain provided by Raman amplifiers dependent on the optical fiber's composition. In silica fibers, the Raman gain bandwidth is over 260 nm, with the dominant peak occurring at 86 nm from the pump wavelength. This makes Raman gain available across the entire transmission spectrum of the fiber as long as a suitable pump source is available. The gain presented by the Raman Effect in fused silica glass is polarization dependent; therefore gain only occurs if both the signal and pump beams is of the same polarization.

For a distributed Raman fiber amplifier (RFA), power is provided by optical pumping of the transmission fiber; the pump wavelength is shorter than the wavelength to be amplified by an amount that corresponds to an optical frequency difference of about 13.2 THz. The signal then experiences gain due to Stimulated Raman Scattering (SRS), a nonlinear optical process in which a pump photon is absorbed and immediately re-emitted in the form of a phonon and a signal photon, thus amplifying the signal as shown in figure 1.8.

Mohammed N. Islam [10] 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 and the gain is reasonably flat over a wide wavelength range.

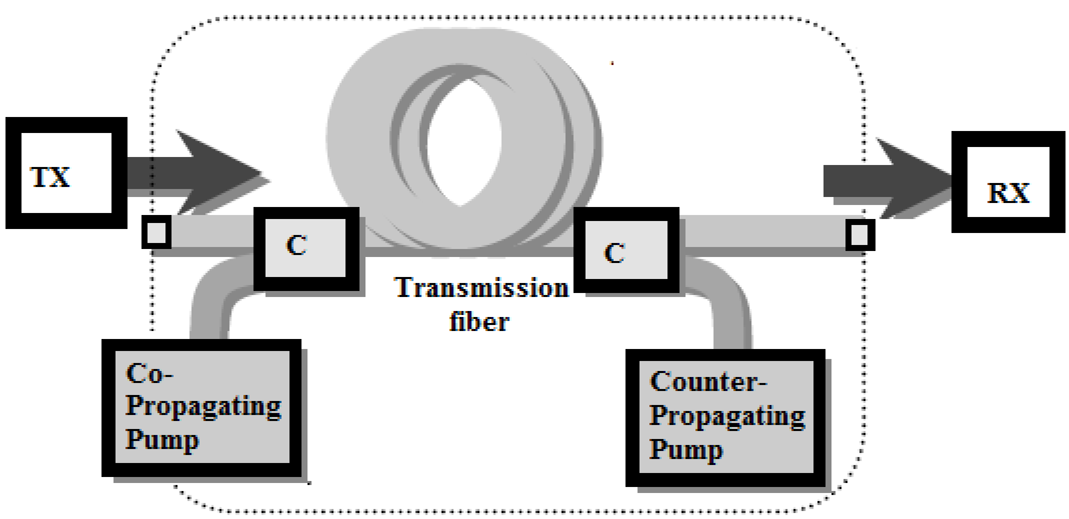


Figure 1.8: Schematic of a Raman fiber amplifier [11]; C: Coupler

Quantum Approach to Raman Scattering:

During Raman scattering, light incident on a medium is converted to a lower frequency. This is shown schematically in Figure 1.9. A pump photon ν p excites a molecule up to a virtual level (non-resonant state). The molecule quickly decays to a lower energy level emitting a signal photon ν s in the process. The difference in energy between the pump and signal photons is dissipated by the molecular vibrations of the host material. These vibration levels determine the frequency shift and shape of the Raman gain curve. Due to the amorphous nature of silica the Raman gain curve is fairly broad in optical fibers.

The Figure 1.10 shows the Scattering diagrams for Stokes and anti-Stokes Raman scattering. An incident photon of frequency ν_0 is scattered by a molecule exciting one quantum of vibrationaly energy **Ω** and producing a downshifted scattered photon of frequency $\nu_S = \nu_0 - \Omega$.

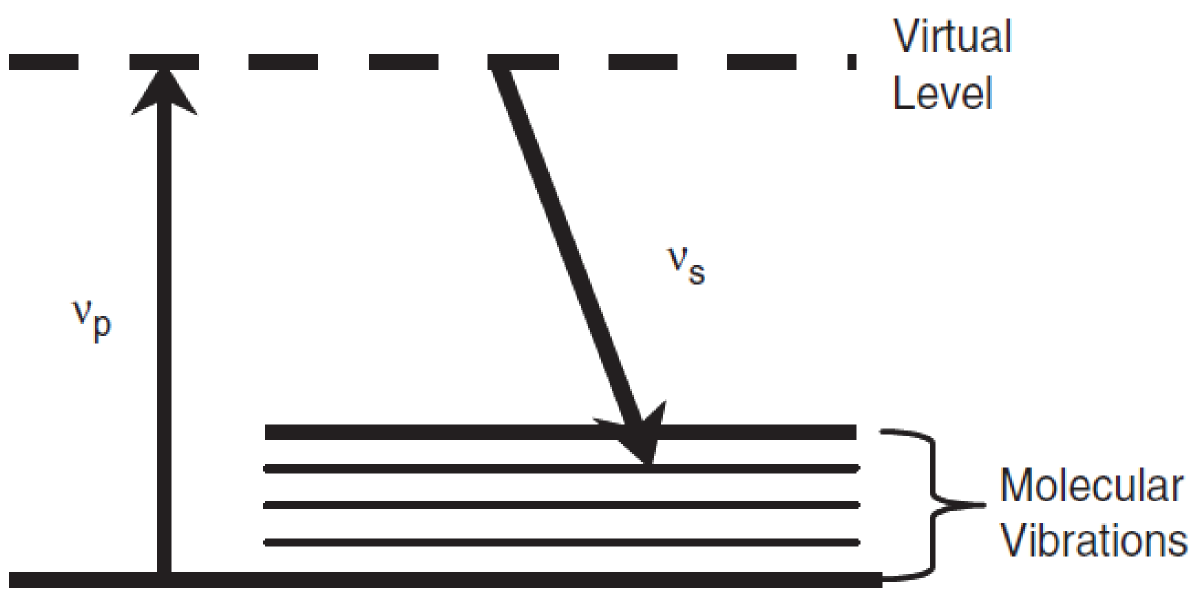


Figure 1.9: Schematic of the quantum mechanical process taking place during Raman scattering [12].

If the molecule already has vibration energy the incident photon can absorb a quantum of vibration energy producing an up shifted photon of frequency $\nu_A = \nu_0 + \Omega$. Both downshifted and up shifted frequencies are observed and called Stokes and anti-Stokes spectral lines.

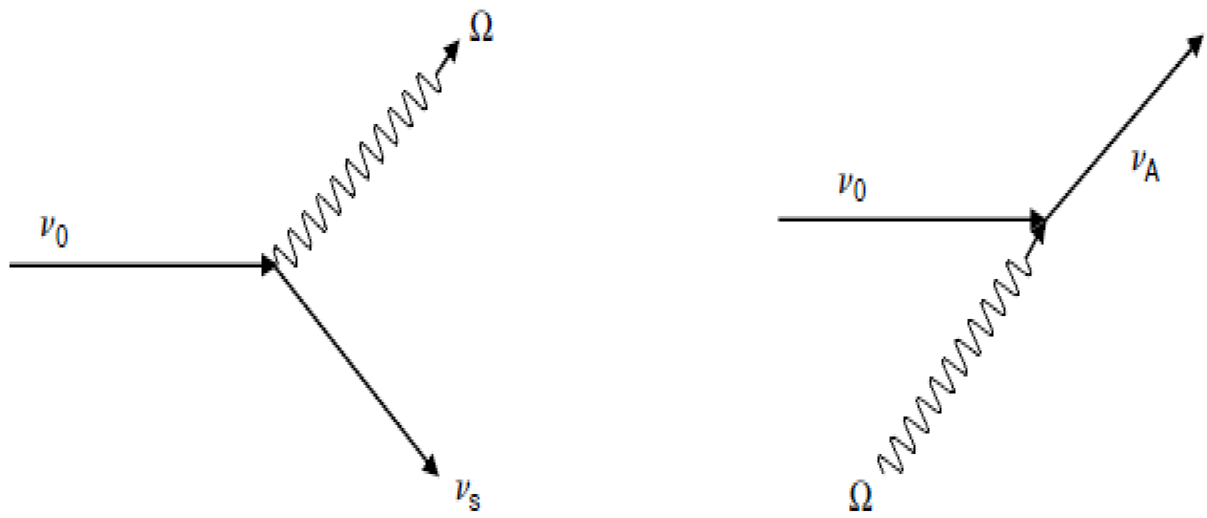


Figure 1.10: Scattering diagrams for Stokes and anti-Stokes Raman scattering.

1.5 Hybrid Optical Amplifier

The combination of more than one amplifier in a configuration is called hybrid optical amplifier. Mohammed N. Islam described that the total amplifier gain (G_{Hybrid}) is the sum of the two gains [10]:

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

Gain partitioning in hybrid amplifier is as shown figure 1.11.

Two kind of hybrid amplifier (HA) are: the narrowband HA (NB-HA) and the seamless and wideband HA (SWB-HA). The NB-HA employs distributed Raman amplification in the transmission fiber together with an EDFA and provides low noise transmission in the C- or L-band. The noise figure of the transmission line is lower than it would be if only an EDFA were used. The SWB-HA, on the other hand, employs distributed or discrete Raman amplification together with an EDFA and provides a low-noise and wideband transmission line or a low-noise and wideband discrete amplifier for the C- and L-bands. The typical gain bandwidth ($\Delta\lambda$) of the NB-HA is 30 to 40 nm, whereas that of the SWB-HA is 70 to 80 nm.

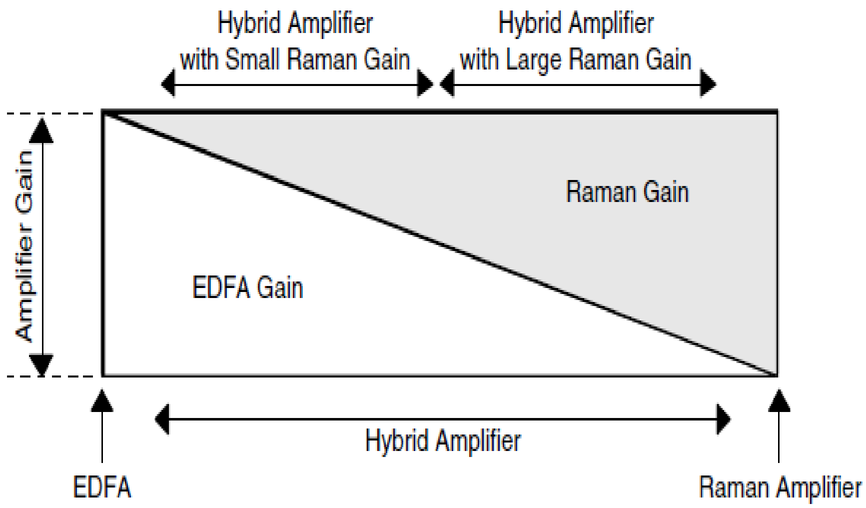


Figure 1.11: Gain partitioning in hybrid amplifier

Figure 1.12 shows examples of SWB-HA gain spectra.

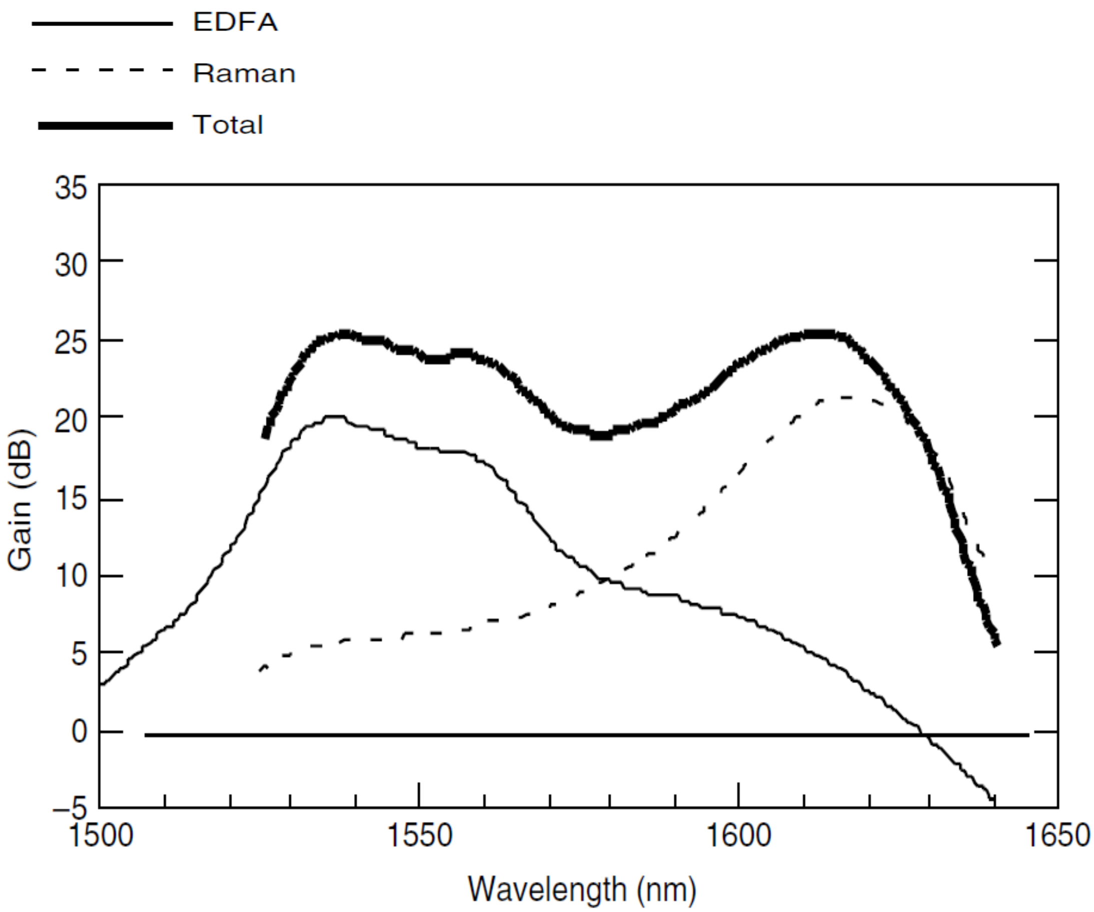


Figure 1.12: Gain spectra of a hybrid amplifier [13]

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.

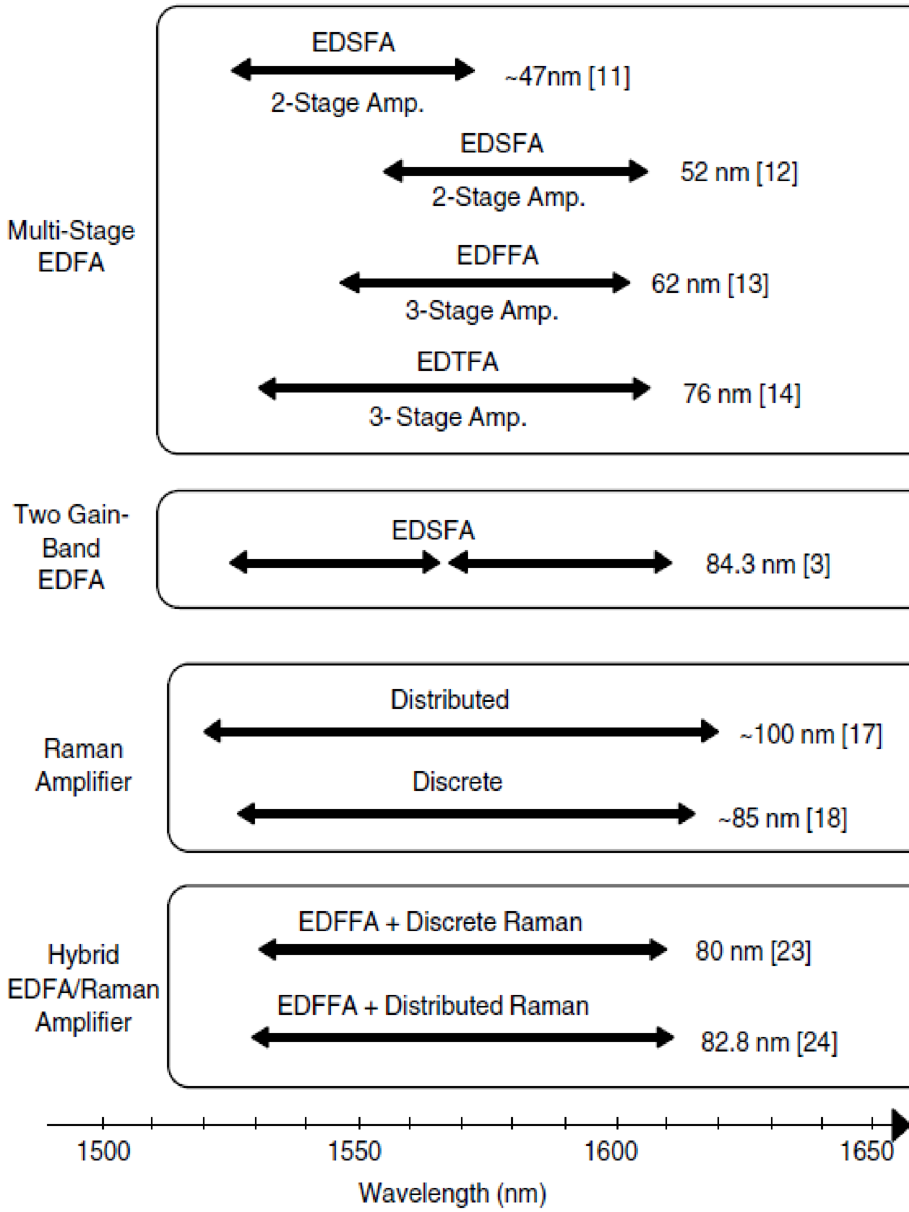


Figure 1.13: Gain bands of wideband fiber amplifiers. ED(S, F, T) FA: erbium-doped (silica, fluoride, telluride) fiber amplifier [10].

In figure 1.13 compares the gain bands of several types of wideband fiber amplifiers reported to date.

However, the bandwidth of the HA (Hybrid Amplifier) is limited by that of the EDFA or the RA (RAMAN Amplifier). Moreover, each of the EDFA and the RA needs many optical components so cost is high. Hybrid optical amplifiers have a simple structure with few optical components and so are cost effective. The EDFA and the RA have opposite gain spectral slopes over a wide wavelength region, the gain bandwidth of the SWB-HA (Seamless and Wideband Hybrid Amplifier) is as large as about 80 nm (1530 to 1610 nm). The 80 nm gain band seamlessly covers the two EDFA gain bands (the C- and L-bands).

1.6 Classification of Hybrid Optical Amplifiers

We can classify the SWB-HA into four types according to its G_{Raman} and gain types (distributed or discrete). Table 1.1 shows the classification with the four types [10].

Raman Gain	Distributed Gain	Discrete Gain
Small	Type 1	Type 3
Large	Type 2	Type 4

Table 1.1

The SWB-HA with small (large) distributed Raman gain is denoted as Type-1 (2). On the other hand, the SWB-HA with a small (large) discrete Raman gain is denoted as Type-3 (4).

The four types of SWB-HAs have different basic configurations as shown and thus have different gain, noise, and output characteristics. In this case the optical components such as isolators in the amplifiers are not shown for simplicity. As shown in figure the EDFs are forward pumped and the DCFs are backward pumped, because this approach is common. However, the opposite pump directions can be employed if needed. The basic amplifier configurations and the amplification characteristics of the four types are described below.

1.6.1 Type 1

First, the Type-1 amplifier has a two-stage EDFA with an intermediate GEQ (Gain equalizer) and a DCF as shown in figure 1.14. The two-stage EDFA configuration is employed because large EDFA gain is required. The amplifier also has a DRA (Distributed Raman Amplifier) with a transmission fiber as its gain medium in front of the EDFA. The peak loss of the GEQ is almost equal to that of the wideband two-stage EDFA.

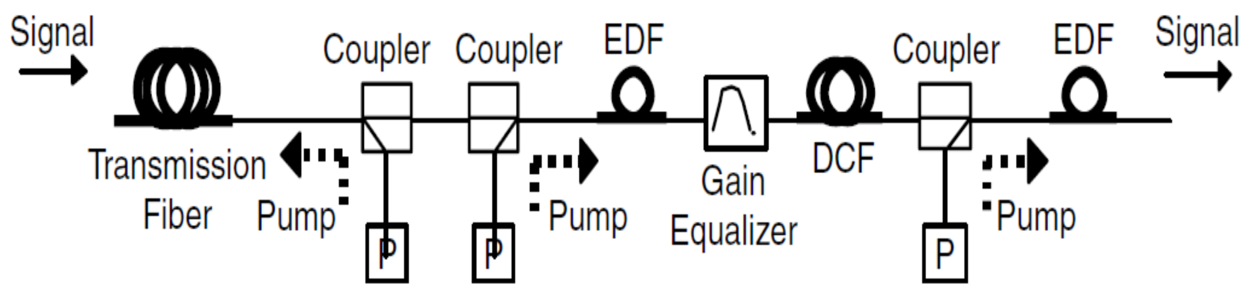


Figure 1.14: Type-1 with small distributed Raman gain

1.6.2 Type 2

The Type-2 amplifier has a single-stage EDFA with a GEQ and a DCF set in front of the EDF in the EDFA. The amplifier also has a DRA with a transmission fiber as its gain medium as shown in figure 1.15. The peak loss of the GEQ is small as is expected from the gain spectra. The effective NF spectrum of the amplifier is mainly determined by that of the DRA. However, both the single-stage EDFA and the DRA determine the output power.

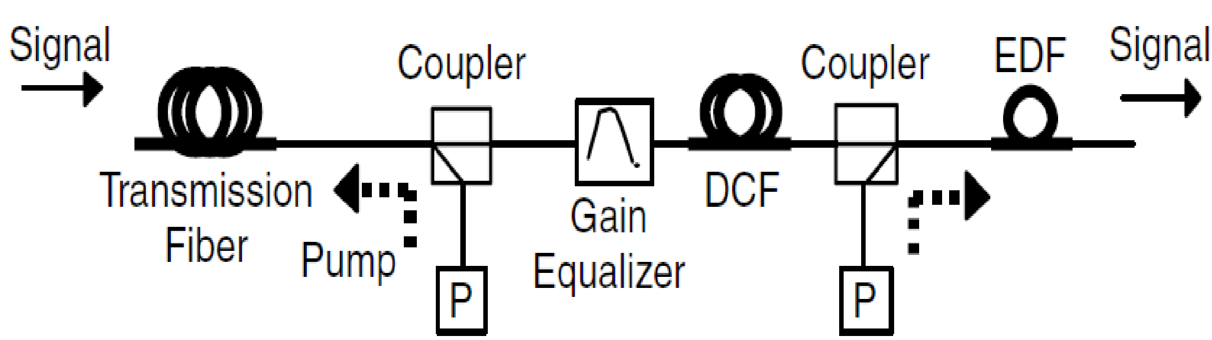


Figure 1.15: Type-2 with large distributed Raman gain

1.6.3 Type 3

The Type-3 amplifier has a two-stage EDFA with intermediate GEQ and DCF (shown in figure 1.16). The DCF is pumped and operates as an LRA.

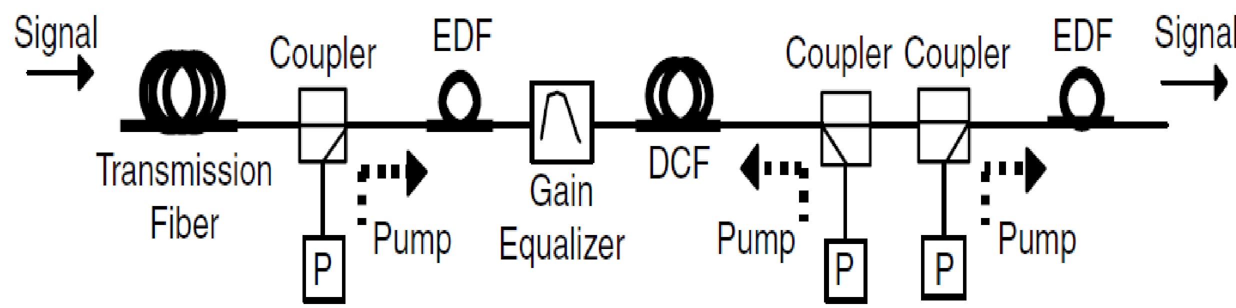


Figure 1.16: Type-3 with small discrete Raman gain

The peak loss of the GEQ is large. The NF spectrum of the amplifier is mainly determined by that of the first-stage EDF of the two-stage EDFA, but the output power is determined by the second-stage EDF.

1.6.4 Type 4

The Type-4 amplifier has a single-stage EDFA, a two-stage LRA, and an intermediate GEQ (shown in figure 1.17). The LRA has two DCFs as its gain media and generates a large Raman gain. The peak loss of the GEQ is small. The NF spectrum of the amplifier is determined by the NF spectra of the EDFA and the LRA.

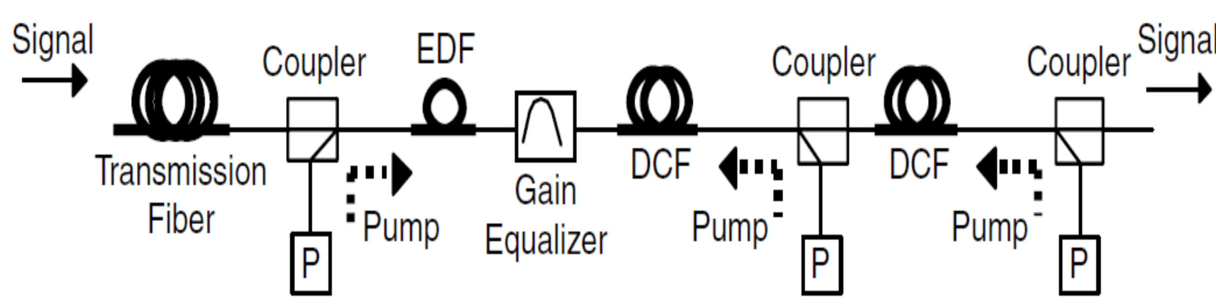
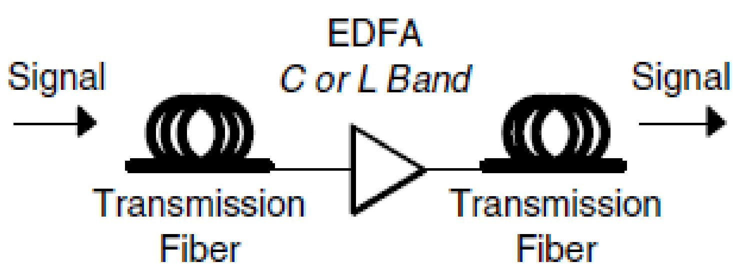


Figure 1.17: Type-4 with large discrete Raman gain

1.7 Basic configurations of a transmission line with an inline optical and Hybrid optical amplifier

The figure 1.18 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 1.18 (a). The signal light usually consists of wavelength-division-multiplexed (WDM) multichannel and the EDFA offers C or L-gain band coverage [10]. 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 1.18 (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 1.18 (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 1.18 (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 1.18 (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. Finally figure 1.18 (e) shows a hybrid amplifier recycling residual Raman pump in a cascaded EDF section after a DCF [14].

A	

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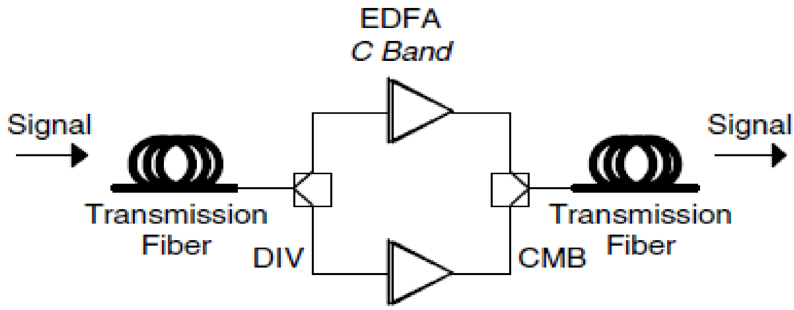
<tr><td>B</td><td>
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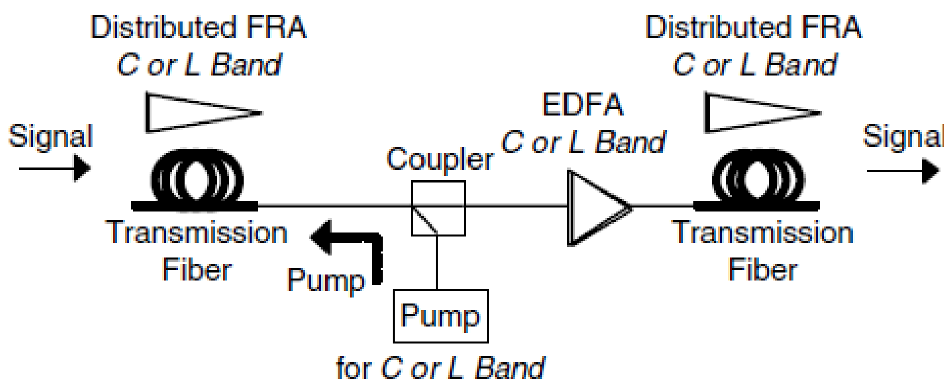
<tr><td>C</td><td>
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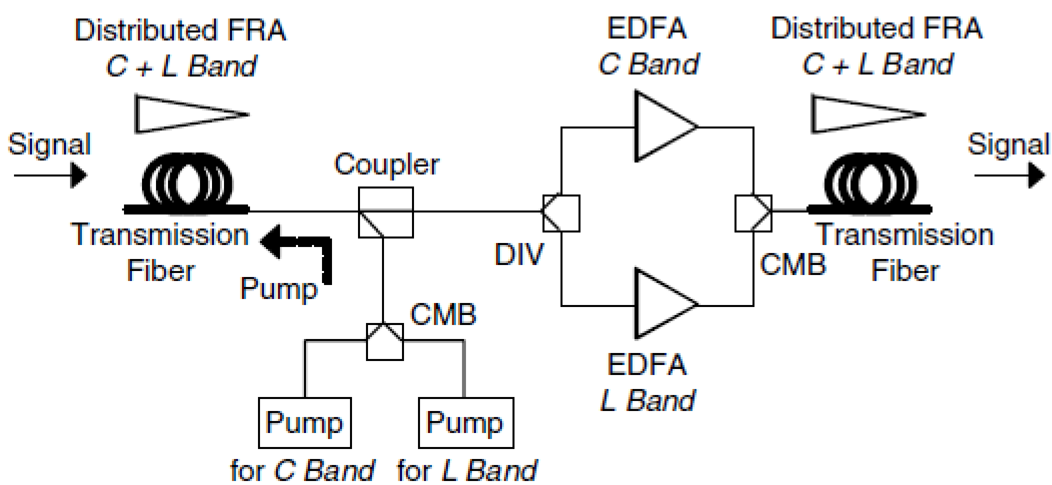
<tr><td>D</td><td>
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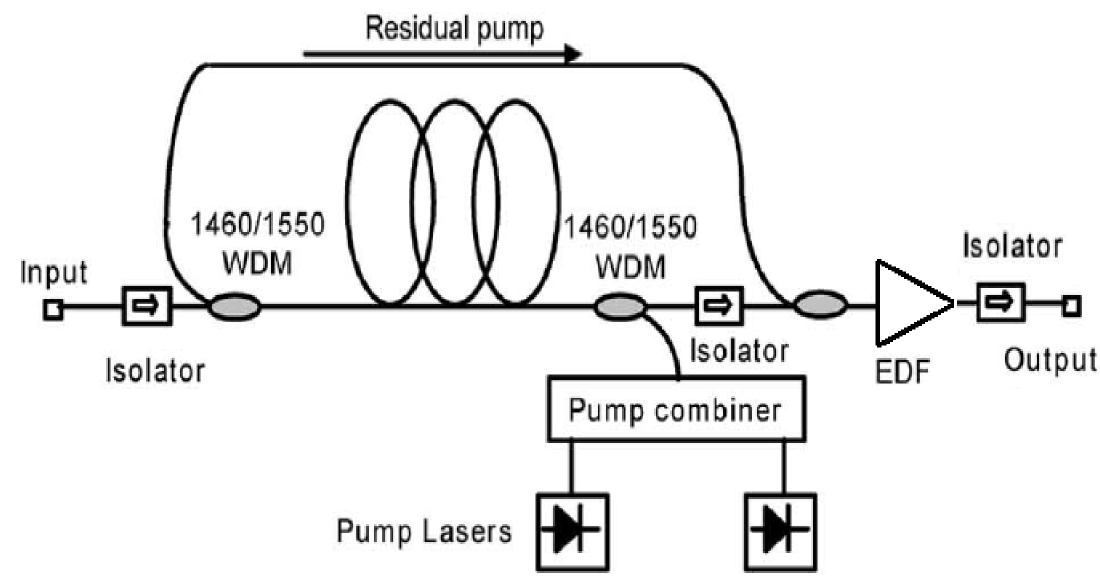

Figure 1.18: Basic configurations of a transmission line with an inline amplifier: (a) a EDFA; (b) a two-gain band amplifier (EDFA) with C- and L-band EDFAs in parallel; (c) a hybrid EDFA/distributed Raman amplifier with C- or L-band; and (d) a hybrid EDFA/distributed Raman amplifier with C- and L-bands in parallel (CMB: combiner, DIV: divider) [10]; (d) a hybrid Raman and EDFA amplifier with residual pump [14].

CHAPTER 2

LITERARURE SURVEY

2.1 Motivation

In the fiber optic communication, there is degradation in transmission signal with the increase in distance. To compensate signal degradation optoelectronic regenerators were used before the advent of optical amplifier. In optoelectronic regenerators, the optical signal is first converted into electric current and then regenerated by using a transmitter. But such regenerators become quite complex and expensive for wavelength division multiplexing systems. This reduces the reliability of networks as regenerator in an active device. Therefore, up gradation of multichannel WDM network will require optical amplifier. To remove loss limitations and to amplify the signal, the optical amplifiers are used which directly amplify the transmitter optical signal without conversion to electric forms as in-line amplifiers. The optical amplifiers are mainly used for WDM (Wavelength division multiplexing) light wave systems as all channels can amplify simultaneously. Optical amplifier increases the transmitter power by placing an amplifier just after the transmitter and just before the receiver. As the need of long haul unrepeated transmission distances and ultra fast broadband transmission is increasing, the advanced transmission methods have to be investigated. So, there is a demand to investigate the unrepeated all optical transmission and ultra fast broadband transmission over long distances. In order to achieve these objectives *i.e.* broadband and repeater less transmission of an optical communication system, it is of utmost importance to optimize the hybrid optical amplifier and then placement in optical networks. Therefore, it is of utmost important to study, analyze and optimize the optical amplifiers and hybrid optical amplifier in WDM optical communication network to improve the power budget for increasing the number of supported users.

2.2 Literature Survey

Increasing the gain-bandwidth of fiber amplifiers is the most effective way to increase the number of WDM channels. The gain-bands have been increased by (a) employing new fiber host materials for erbium-doped fiber amplifiers (EDFAs), (b) gain-equalizing optical filters [15] (c) parallel configurations for the two gain-bands of the EDFA [16] and (d) Raman amplifier with multiple wavelengths [17] (e) with multiple pump-wavelengths combination of EDFA with the distributed Raman amplification in the transmission fiber [18].

In 1992, J. M. P. Delavaux *et al.* [16] demonstrated of two efficient Hybrid EDFA (HEDFA) structures as power booster. The EDFA is pumped simultaneously by 980 and 1480 nm diode pump laser. Among other features, these HEDFAs exhibit a flat gain spectrum (+17dBm output saturated power) with a 1dB, bandwidth in excess of 35 nm which make them attractive as power boosters. They had also reported that hybrid pumping configurations prevent crosstalk problem for pumps of the same wavelength and offer the potential for pump redundancy. The use of concatenated EDFAs in WDM systems raises issues of gain tilt and longer term stability. As a result, a number of research groups, including that of the author, are investigating dynamic spectral equalization techniques for WDM.

The maximum 3dB gain-reduction bandwidth values reported till 1992 are 33nm centered at 1545nm (0.98mm pumping with an intermediate equalizer [17] and 40nm centered at 1580nm [19]. In 1997, H. Masuda *et al.* [18] reported the extremely large bandwidth of 65nm (1549-1614nm). This is obtained using a novel pumping scheme, a wideband gain equalizer and backward pumped Raman amplification in the transmission fiber. They also reported a bandwidth of 49nm (1556-1605nm) by using an optimized two-stage EDFA without Raman amplification. Very high pump power and the low gain compression of Raman amplifiers can induce unstable system performance. Therefore, if Raman amplification is combined with erbium doped fiber amplifier, the SNR can be improved while still keeping the high gain compression and output power provided by the erbium doped fiber amplifier**.**

In 1999, Shingo Kawai *et al.* [20] transmitted successfully fourteen 2.5-Gb/s signals over 900 km using highly gain flattened hybrid amplifier. They also reported that the optical SNR of the hybrid amplifier was 4.5–9.0 dB higher than that of the discrete EDFA with a 7-dB noise figure over the entire 1.5-dB gain-bandwidth.

In 2001, B. Zhu *et al.* [21] demonstrated the 3.08Tbit/s (77 x 42.7Gbit/s) WDM transmission over 1200 km fiber with 100 km amplifier spacing and l00GHz channel spacing. Error-free transmission of all 77 channels is achieved by employing dual C- and L-band hybrid Raman/ erbium-doped inline amplifiers. Till now amplification of C or L band using Raman, EDFA or RAMAN/EDFA hybrid amplifier had been discussed, now we are moving to shorter wavelength (1450-1520 nm) amplification, commonly termed as S band amplification.

Jowan Masum-Thomas *et al.* [22] 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 - 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.

In 2002, C. R. Davidsou *et al.* [23] first time demonstrated the transmission of two hundred and fifty six 10Gbps 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.* [24] 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 tellurite/silica fiber Raman amplifier. The amplifier was successfully used as a pre-amplifier in an 8 X 10Gbps 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 2 *et al.* [25] presented an experimental comparison of the performance of all-Raman vs. Raman/EDFA hybrid schemes at the line rate of 40Gbps. 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 40Gbps 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.* [26] 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.

In 2005 A. Guimaraes *et al.* [27] built the setup in which EDFA amplifiers used as a booster and inline amplifier and hybrid EDFA/FOPA (fiber optic parametric amplifier) used as a pre-amplifier. The results demonstrate that FOPAs have a comparable performance with Erbium doped fiber amplifiers (EDFAs) for in-line amplification. The hybrid EDFA+ FOPA pre-amplifier results in improved system performance in comparison with a conventional EDFA pre-amplifier. For a fixed error rate of 10^{-12}, the hybrid pre-amplifier provides an improving in the system power penalty of 3.2 dB when compared with the back-to-back values.

H S Chung *et al.* [28] demonstrated a long-haul transmission of 16 X 10Gbit/s over single-mode fiber (Span of 80 km) of 1040 km using combined Raman and linear optical amplifiers as inline amplifiers. All the span length used was 80 km (loss of 16 dB), but the span losses varied from 28 to 34 dB according to some additional loss elements. The measured Q-factors of the 16 channels after 1040 km (12.7–14.5 dB) were higher than the error-free threshold of the standard forward-error correction, which offers feasibility of the hybrid amplifiers including semiconductor optical amplifiers for the long-haul transmission. It is also observed the performance degradation of the transmitted channels under dynamic add drop situations after 560 km.

H. S Seo *et al*. [29] demonstrated the novel hybrid optical amplifier covering S+C+L bands with 105-nm total bandwidth using a silica fiber. It is reported through numerical calculations that the

S, C, and L bands could be amplified seamlessly and simultaneously through the two kinds of mediums. The first medium was an in-line hybrid optical fiber configured by an Er-doped cladding and a Ge-doped core. The second one was a combination of EDF and DCF. In case of the first medium, it is simple to configure the amplifier since there is no need to splice between mediums. Another advantage is that all optical signals in the entire band are amplified at the same time along the fiber. Therefore, the NF is easily controllable if we configure the amplifier in two stages by inserting an isolator. The Er/Raman fiber amplifier using the second medium can be more realistic approach in that it uses conventional EDF and DCF. However, it has splicing losses between EDFs and DCFs. Raman amplifiers based on dispersion-compensating fiber (DCF) have attracted huge research attention in recent years for their potential application in the future long-haul high-capacity optical communication systems due to the fact that both dispersion and loss compensation in transmission fiber spans can be obtained at the same time, and the amplification band expansion can be easily achieved within the transparency window of optical fiber simply by changing the pump wavelengths. Ju Han Lee *et al.* [30] demonstrated the hybrid optical amplifier in which DCF based Raman amplifier is used which is cascaded with EDFA. They show experimental performance comparison of three types of single-pump highly efficient dispersion-compensating Raman/erbium-doped fiber amplifier (EDFA) hybrid amplifiers with respect to gain, noise figure (NF), and stimulated Brillouin scattering (SBS)-induced penalty: Raman/EDFA hybrid amplifiers recycling residual Raman pump in a cascaded erbium-doped fiber located either after (Type I) or prior to (Type II) a dispersion-compensating fiber, and a Raman assisted EDFA (Type III).

Sun Hyok Chang *et al.* [31] compared the EDFA and Hybrid fiber amplifier (HFA) and reported that HFA can be an alternative to improve the performance of line amplifier instead of EDFA only. They described the configuration of HFA that has low noise figure and high output power. In the transmission experiments with circulating loop, HFA showed better transmission performance than EDFA when it was used as line amplifier. The Q-factor and OSNR (optical signal to noise ratio) in the case of HFA was higher by more than 1.0 dB.

Jien Chien [32] proposed a design approach for multistage gain-flattened fiber Raman amplifiers (FRAs) utilizing the multi wavelength- pumping scheme. The various pumping configurations for Raman amplifiers with hybrid dispersion-compensating fiber (DCF) and standard single-mode fiber (SMF) are discussed, with the objective of realizing flattened gain and noise performance simultaneously without using forward pumps.

Zhaohui Lie *et al.* [33] studded the noise and gain characteristics of Raman/EDFA hybrid amplifier based on dual-order SRS of a single pump. They illustrated the different span configuration of EDFA, SMF and DCF before Raman amplification and concluded best configuration is EDF is placed after 50km SMF from the span input end. It is reported that both gain and noise performance can be improved with 20m EDF placed in an optimal position along the span.

Shien-Kuei Liaw [34] proposed a hybrid EDFA/RFA for simultaneously amplifying the C-band EDFA and L-band RFA. The hybrid amplifier has many advantages: (1) the required DCF length for chromatic dispersion compensation is 50% safe. (2) By embedding the WDM-FBG at appropriate positions along the DCF, the dispersion slope mismatch values are -240 and +240 ps/nm at 1530 and 1595 nm, respectively, could be precisely dispersion compensated. (3) The reduction in gain variation from 9.8 dB to less than ±0.5 dB could be realized after optimizing the reflectivity of each FBG. (4) Pumping efficiency is improved by recycling the residual pumping power. With these merits, this hybrid amplifier may find vast application in WDM systems where both dispersion management and power equalization are the crucial issues.

G Charelt *et al.* [35] transmitted a flow of data at 7.2Tbit/s (72 X 100Gbps Channels) over a distance 7,040km with an information spectral density of 2 bit/s/Hz. The channel spacing between channels is 50 GHz and spacing between amplifiers is 80 km. In one re-circulated loop 11 spans of amplifiers are used. Modulation technique used in this setup is QPSK. The reported average Q^2-factor is 9.4dB, while the best is 10.2dB.

The results from M. M. J. Martini *et al.* [36] demonstrated that the Raman/EDFA hybrid amplifier under recycling residual Raman pump, allied with the properly chosen of the pump wavelengths and powers, enables the construction of broadband amplifiers with enhanced power conversion efficiency and high and flat gains. It is reported that best configuration considering two pump lasers is obtained with wavelengths 1425 nm and 1468.4 nm and powers of 296.3 mW and 61.3 mW, respectively.

Desurvire E et al. [37] demonstrates the potential of erbium-doped fiber amplifiers for application in wavelength-division multiplexed communication systems. It has low insertion loss, low crosstalk, high gain, polarization insensitive and low noise figure. An EDFA has a comparatively wide wavelength range of amplification making it useful as transmission amplifier in wavelength division multiplexing systems.

Theoretically EDFA is capable of amplifying all the wavelengths ranging from 1500 to 1600 nm. However practically there are two windows of wavelength. These are C and L band. The C band ranges from 1530 nm to 1560 nm and L band from 1560 nm to 1610 nm. The semiconductor laser pumping source at 980 nm wavelengths has proved to be the best in terms of efficiency and better noise performance [38].

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 [39, 40]. When increasing the numbers of pump wavelengths from two to eight, the gain profiles become flatter and the effective bandwidth becomes larger. Relative gain flatness of 1% could be achieved over bandwidths of up to 15.1 THz (corresponds to E-band) without any gain equalization devices [40, 35]. When increase the transmission distance, a simple EDFA makes a very serious accumulation noise. But, Fiber Raman amplifiers (FRA) in long-distance transmission line can not only enlarge the characteristics of the elimination of noise accumulation, gain relatively good noise characteristics, but also can expand the bandwidth of the gain. Raman amplifiers improve the noise figure and reduce the nonlinear penalty of fiber systems, allowing for longer amplifier spans, higher bit rates, closer channel spacing, and operation near the zero-dispersion wavelength.

EDFA and FRA broadband hybrid amplifier are becoming a hot research. Usually, the gain of EDFA is not flat [41].

To get higher OSNR Tuan Nguyen Van et al. [42] proposed three calculating models of Terrestrial cascaded EDFAs Fiber optical communication links using Hybrid amplifier.

2.3 Gaps in present study

- When increase the transmission distance, a simple EDFA makes a very serious accumulation noise.
- Semiconductors optical amplifiers have to be fully exploited for increased gain spectrum.
- There is need of work on L-band EDFA with reduction of crosstalk and gain improvement.
- Hybrid optical amplifier in long distance communication and in ultra high capacity.

- Imbalance of power amongst different channels.
- Placement of hybrid optical amplifier and increase single span distance.

2.4 Objectives

1. To investigate the performance comparison of optical amplifiers (RAMAN, EDFA and SOA) for 16 X 10, 32 X10 and 64 X 10Gbps WDM System at Different Transmission Distance and Dispersion.

2. To investigate the performance comparison of Hybrid optical amplifiers (RAMAN-EDFA, RAMAN-SOA and EDFA-SOA) for 16 X 10, 32 X10 and 64 X 10Gbps WDM System at Different Transmission Distance and dispersion.

3. To optimize the Hybrid Optical Amplifier (RAMAN-EDFA) and further find the maximum covered single span transmission distance.

2.5 Outline of Thesis

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

After carrying the principle and types in chapter 1.The literature review of optical amplifiers (EDFA, SOA, RAMAN-EDFA, RAMAN-SOA) has been studied in Chapter 2, different Optical amplifiers are modelled and analysed for transmission performance of 16 × 10Gb/s, 32 × 10Gb/s and 64 × 10Gb/s WDM systems at different transmission distance and dispersion have been presented in Chapter 3 and 4. The comparison between optical amplifiers and hybrid optical amplifiers have been shown. Additionally, it includes the simulation results for all amplifiers for different transmission distance (from 50 to 180 km) and dispersion (2 and 4ps/nm/km) in terms of output power, Q factor, BER and eye closure.

Chapter 4 is based on the optimization of RAMAN-EDFA. It includes the simulation result for optimized RAMAN-EDFA in the term of Q factor and Jitter. Further, found out the maximum covered single span transmission using this optimized hybrid optical amplifier.

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

CHAPTER 3

Simulation of WDM System Based on Optical Amplifiers

3.1 Abstract

In this chapter, 10Gbps WDM systems at 16, 32 and 64 channels have been investigated with EDFA, RAMAN and SOA amplifiers individually and the performance has been compared on the basis of transmission distance and dispersion with and without nonlinearities. It is demonstrated that when the dispersion is 2ps/nm/km and the number of channels are less, then SOA provide better results because as we increases the number of channels, the gain saturation problem arises due to cross gain modulation, the cross phase modulation and four wave mixing. When dispersion is increased from 2 to 10ps/nm/km, EDFA provides better results than SOA in the term of BER and output power, but it shows non uniform gain spectrum. It has been observed that RAMAN amplifier provides better results for L band amplification and gain flatting issue because it can substantially reduce the impact of fiber nonlinearity.

3.2 Introduction

The Current efforts of research and development are aiming at increasing the total capacity of medium and long haul optical transmission systems [5]. At the same time, deregulation of telecommunication markets and global success of the internet has driven the demand for higher and higher system capacity. The transmission distance of any fiber-optic communication system is eventually limited by fiber losses. For long-haul systems, the loss limitation has traditionally been overcome using optoelectronic repeaters in which the optical signal is first converted into an electric current and then regenerated using a transmitter. Such regenerators become quite complex and expensive for wavelength-division multiplexed (WDM) light wave systems. Currently the optical amplifiers are used which directly amplify the transmitter optical signal without conversion to electric forms as in-line amplifiers [43]. It amplifies the signals simultaneously and decreases the attenuation.

Fiber attenuation is the main reason behind power depletion of signal as it travels the distance. Also the fiber non-linearties are responsible for the signal power level depletion [5]. In 1990's the fourth generation of optical systems emerges ,the main technology behind this is the invention of optical fiber amplifiers were developed using fiber amplifiers to increase the repeater spacing and bit rate. EDFA has been used as booster and inline amplifier to transmit optical signals over thousands of kilometers [43]. EDFAs are having of low noise figure and have a good gain bandwidth and can amplify multichannel signals on different wavelengths simultaneously, so EDFA emerges as the implementing technology for WDM systems. It is also reported that under deeper saturation or having steeper saturation characteristic EDFA would result in less BER impairment [44].

Fiber Raman amplifiers (FRA) in long-distance transmission line eliminates noise accumulation. Raman amplifiers improve the noise figure and reduce the nonlinear penalty of fiber systems, this improves the overall system performance thus allows us longer amplifier spans, higher bit rates, closer channel spacing [11]. Another option for amplifications is Semiconductor optical amplifier.SOA have ultra wide band spectrum, low power consumption and low cost [45].

Chien-Hung Yeh et al. [46] investigated and demonstrated a new S- plus C-bands EDFA module in parallel structure over 96 nm gain bandwidth of 1480–1576 nm when the gain of >10 dB (the input signal power level could great than 5dBm) over the bandwidth of 1480–1576 nm. For the proposed EDFA, 30 dB peak gain with 8.2 dB noise figure and 36.2 dB peak gain with 7.2 dB noise figure can be observed at 1506 and 1532 nm, respectively, while the input signal power of -25dBm. In addition, this proposed amplifier module also can provide a broadband ASE light source from 1480 to 1578 nm while the optical output level above -40dBm.

Yonggyoo Kim et al. [47] successfully transmitted 10-Gb/s optical signals over 80 km through SSMF (Standard single mode fiber) with the transmitter using SOAs as booster amplifiers. They have further reported the find the appropriate parameters of input signals for SOAs, such as extinction ratio, rising/falling time, and chirp parameter to maximize output dynamic range and available maximum output power.

Surinder Singh et al. [48] have simulated the ten channels 100 GB/s DWDM using cascaded SOA with DPSK modulation format at 20GHz channel spacing. For this, they optimize the SOA model with low saturation power 21.36mW and to achieve low crosstalk 14.1 dB with high optical gain 36.5 dB. For 70km 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 100Gb/s RZ-DPSK signal at 17,227 km with power penalty 2.1 dB at good quality of signal.

Surinder Singh et al [49] concluded that the post-power compensation method shows good performance in terms of bit error rate, eye closure penalty and received power as compared to pre- and symmetrical power compensation methods. The bit error rate and eye closure penalty increases with increase in the signal input power.

Rajneesh Randhawa et al. [50] illustrated a novel channel allocation method, based on the optical Golomb ruler (OGR) that allows reduction of the FWM effect while maintaining bandwidth efficiency along with the algorithms has been presented in this paper. This channel allocation method generates unequal channel allocation in wavelength division multiplexing (WDM), resulting in reduction in the four-wave mixing (FWM) effect.

The investigation presented in [48, 50] for optical amplifier are restricted to number of channels. They have used only less than 16 channels.

In this chapter, the previous work in the context of 16, 32 and 64 channels for existing amplifiers used as pre-amplifiers has been extended. Further 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 has been investigated.

The chapter is organized into five sections. After discussion of abstract and introduction of this chapter, the optical simulation setup is described in Section 3.3. In Section 3.4, comparison results have been reported for the different modulation formats and finally in Section 3.5, conclusions are made.

3.3 Simulation Setup

In this chapter 16, 32, 64 channels have been transmitted at 10 GB/s data rate with 100 GHz channel spacing. NRZ data format (electrical driver) which converts the logical signal to corresponding electrical signal has been used. The logical signal has been fed into to the external Mach-Zehnder modulator ($\sin^2$_MZ for all configurations), where the input signals from data source is modulated through a carrier (optical signal from the laser source). The amplitude modulator is a sine square with an excess loss of 3 dB. A booster amplifier as preamplifier is used. After multiplexing signals are launched into DS-anomalous fiber at different transmission distance. A transmitter compound component (T) is built up using 16, 32, 64 transmitters. We have considered three cases, 16 transmitters, 32 transmitters, 64 transmitters. The channel spacing for all the three cases is kept 100 GHz. These beams have random laser phase and ideal laser noise bandwidth. The simulations setup consisting EDFA, SOA and RAMAN at different transmission distance and dispersion are shown in figure 3.1. This optical signal is transmitted and measured over different distance for 40, 80,120,160 and 200 Km (R) at 2ps/nm/km dispersion. Optical Power meter (P1, P2, and P3) and Optical probe (O1, O2, and O3) with splitters (S1, S2 and S3) are used for measuring the signal power and spectrum at different levels. The modulated signal is converted into original

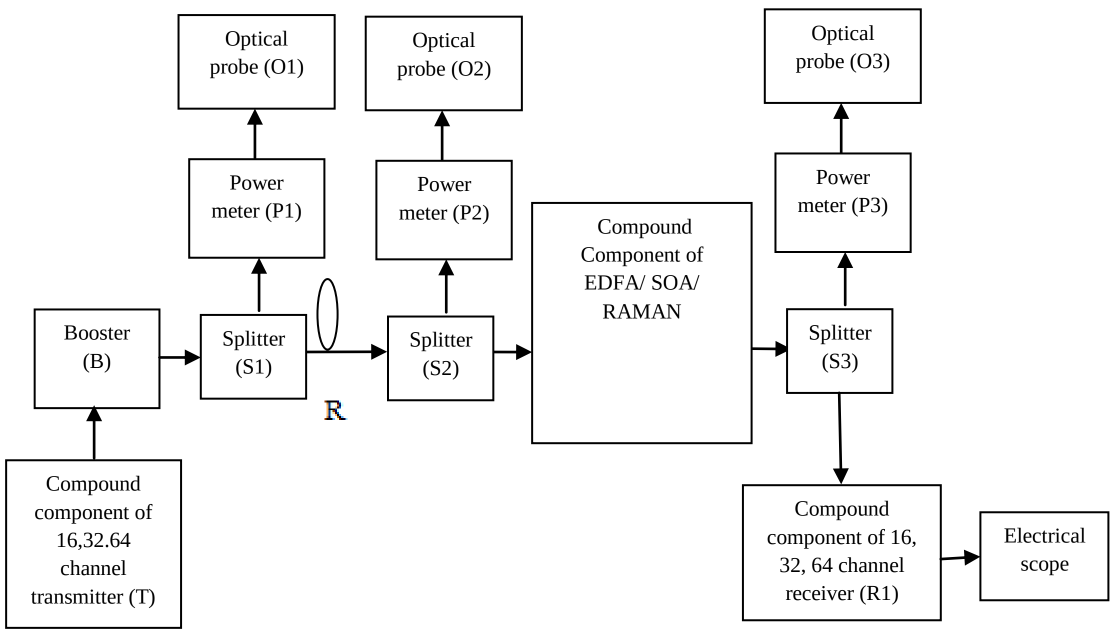

Figure 3.1: Block diagram for simulation setup

The optical signal is transmitted and measured over different distance for 40, 80,120,160 and 200 Km (R) at 2ps/nm/km dispersion individually. In the case of different dispersion (2, 4, 6, 8, 10ps/nm/km) the transmission distance is set at 50 Km. Optical Power meter (P1, P2, and P3) and Optical probe (O1, O2 and O3) 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 photodiode and filters. A compound receiver (R1) is used to detect all 16, 32, 64 signals and converts these into electrical form. Different types of optical amplifiers are also applied at the receiver side. The set up is repeated for measuring the signal strength by using different amplifiers i.e. EDFA/ SOA/ RAMAN. For all the cases maximum Q-factor, output power, minimum BER and Eye closure have been evaluated.

For DS Anomalous fiber the reference frequency is 193.414 THz and attenuation is 0.2dB/km .In this chapter fixed output power configuration EDFA has been used and its output power is 12dBm, gain shape is flat and noise figure is 4.5 dB. The various parameters for SOA are biased current is 100 mA, Amplifier length is 300×10^{-6}m, confinement factor is 0.35, insertion loss is 3 dB and output insertion is 3 dB. The various parameters for RAMAN are Raman fiber length is 10 km, operating temperature is 300 K, pump wavelength is 1480 nm and pump power is 300 mW.

3.4 Result and Discussion

The different optical amplifiers (RAMAN, EDFA, and SOA) have been compared for 16 X 10Gbps, 32 X 10 and 64 X 10Gbps WDM system in the term of received maximum Q Factor (dB), minimum eye closure (dB), minimum BER and maximum output power (dBm). To analyze the system, the results of the first channel have been taken.

Output power, BER and Q-factor for all cases can be seen for existing optical amplifiers that as the line is varied from 40 Km to 200 Km and dispersion varied from 2 to 10 ps/nm/km.

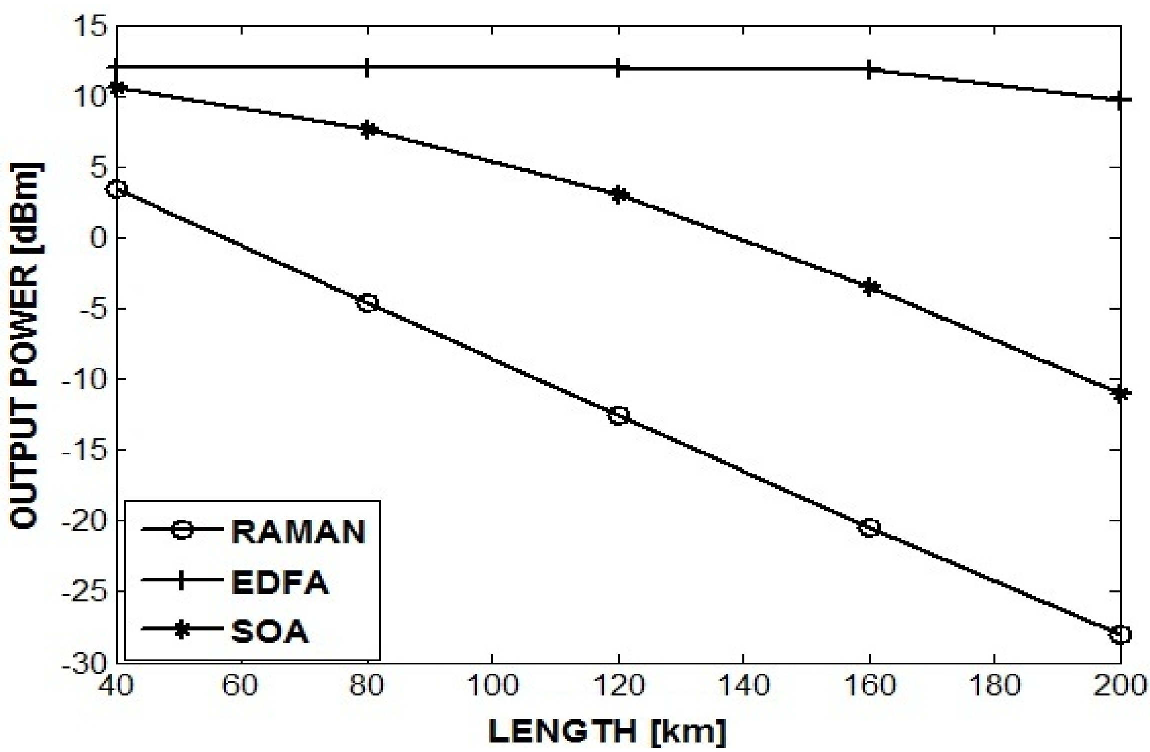

Figure 3.2: Output Power vs. Length for 16 channels in the presence of nonlinearities

The figure 3.2 shows the graphical representation of output power as a function of length in the presence of nonlinearities. The output power is decreases due to the fiber non-linearities and fiber attenuation. The better output power is provided by the EDFA amplifier (12.040 dBm) and also for the worst case (at 200 Km) it becomes 9.710 dBm.

The variation in output power for RAMAN, EDFA and SOA are 3.464 to -27.969 dBm, 12.040 to 9.710 dBm and 10.627 to -11.079 dBm respectively.

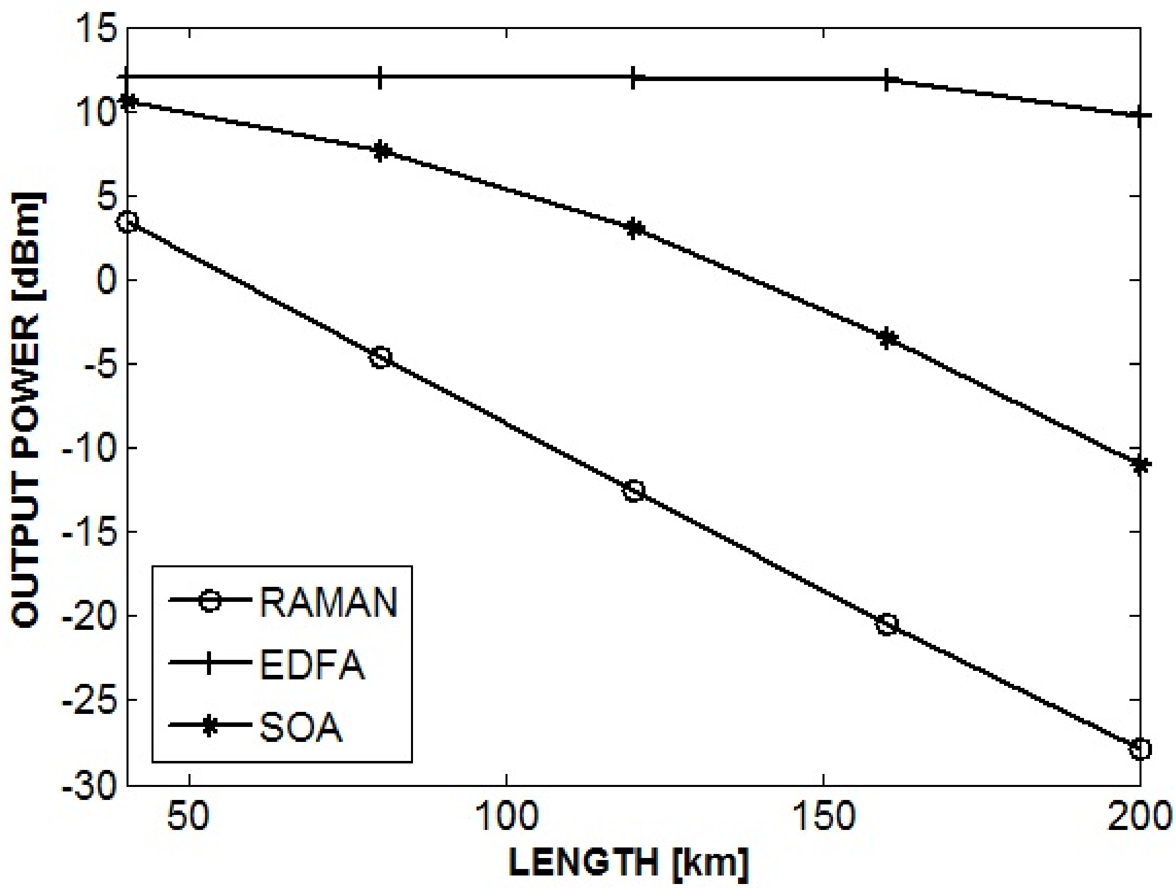

Figure 3.3: Output Power vs. Length for 16 channels in the absence of nonlinearities

If the nonlinearities not considered, better output power is provided by the EDFA amplifier (12.043 dBm) and also for the worst case (at 200 Km) it becomes 9.689 dBm as compare to other amplifiers as shown in figure 3.3. The variation in output power for RAMAN, EDFA and SOA are 3.465 to -27.945 dBm, 12.043 to 9.689 dBm and 10.628 to -11.076 dBm respectively.

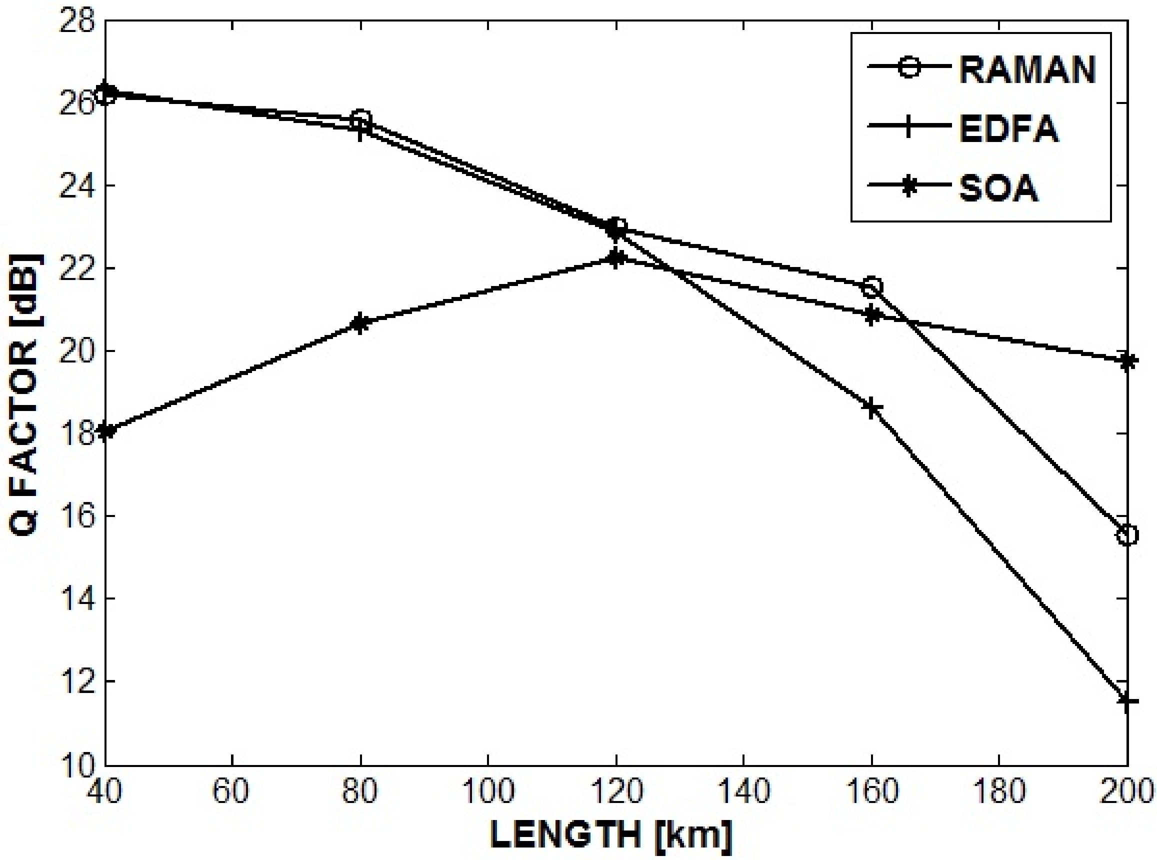

Figure 3.4: Q- factor vs. Length for 16 channels in the presence of nonlinearities

The figure 3.4 depict the graphical representation of Q Factor as a function of Length in the presence of non linearities . The better Q Factor is provided by the RAMAN amplifier (26.19 dB) and also for the worst case (at 200 Km) it becomes 15.54dB.In the distance range 40 to 120 km,RAMAN and EDFA amplifier have compareable Q-factor .Also at 120 km EDFA,RAMAN and SOA have almost the same Q-factor.

The variation in Q Factor for RAMAN, EDFA and SOA are 26.19 to 15.54 dB, 26.308 to 11.52 dB and 18.059 to 19.73 dB respectively. RAMAN provides the better result as compare to other amplifiers up to 160 km and at 200km SOA has highest Q-factor.

If nonlinearities are not considered, better Q Factor is provided by the RAMAN amplifier up to 120km and at 160 onwards SOA has highest Q-factor as shown in figure 3.5.

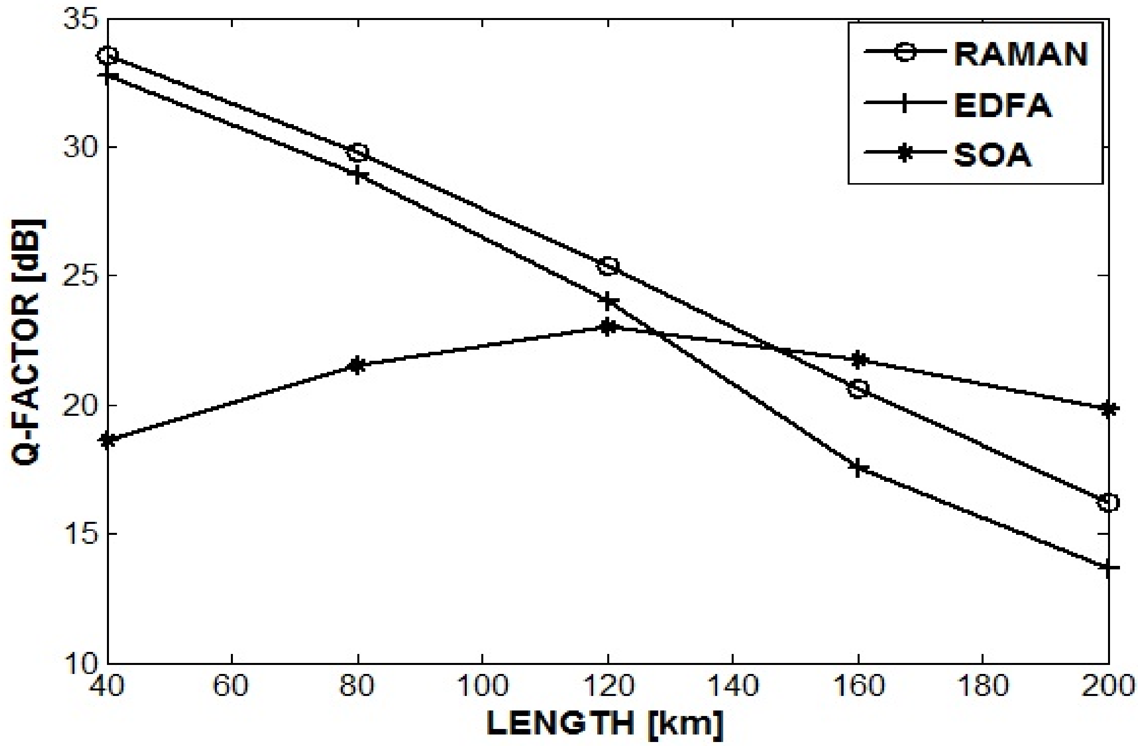

Figure 3.5: Q- factor vs. Length for 16 channels in the absence of nonlinearities

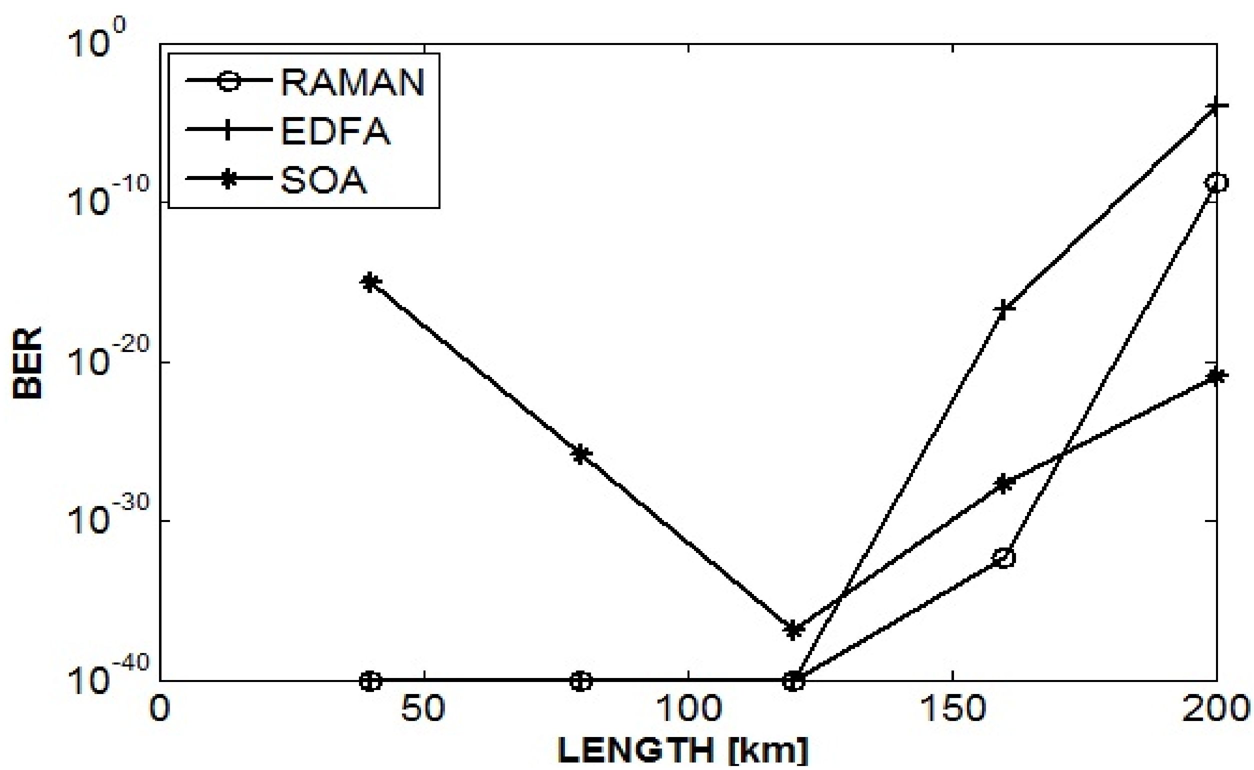

Figure 3.6: BER vs. Length for 16 channels in the presence of nonlinearities

The variation in Q Factor for RAMAN, EDFA and SOA are 33.57 to 16.23 dB, 32.76 to 13.64 dB and 18.66 to 19.82 dB respectively. At 120km EDFA, SOA and RAMAN have comparable Q-factor.

The figure 3.6 shows the graphical representation of BER as a function of Length in the presence of non linearities . It is observed that for distance from 40 to 120 km RAMAN and EDFA have almost same BER of the order of 10^{-40} .SOA has high BER of the order 10^{-15} at 40km and then it decreases linearly up to 120km.At 120km SOA have compareable BER with RAMAN and EDFA.After 120km BER for RAMAN,EDFA and SOA all starts increases and at 200km only SOA have BER less then 10^{-10} .It is obseved that RAMAN privides highest Q-factor among all in distance range from 40 to 160km .

The variation in BER for RAMAN, EDFA and SOA are 10^{-40} to 1.49 X 10^{-9}, 10^{-40} to 9.31 X 10^{-5} and 1.02 X 10^{-15} to 1.15 X 10^{-21} respectively.

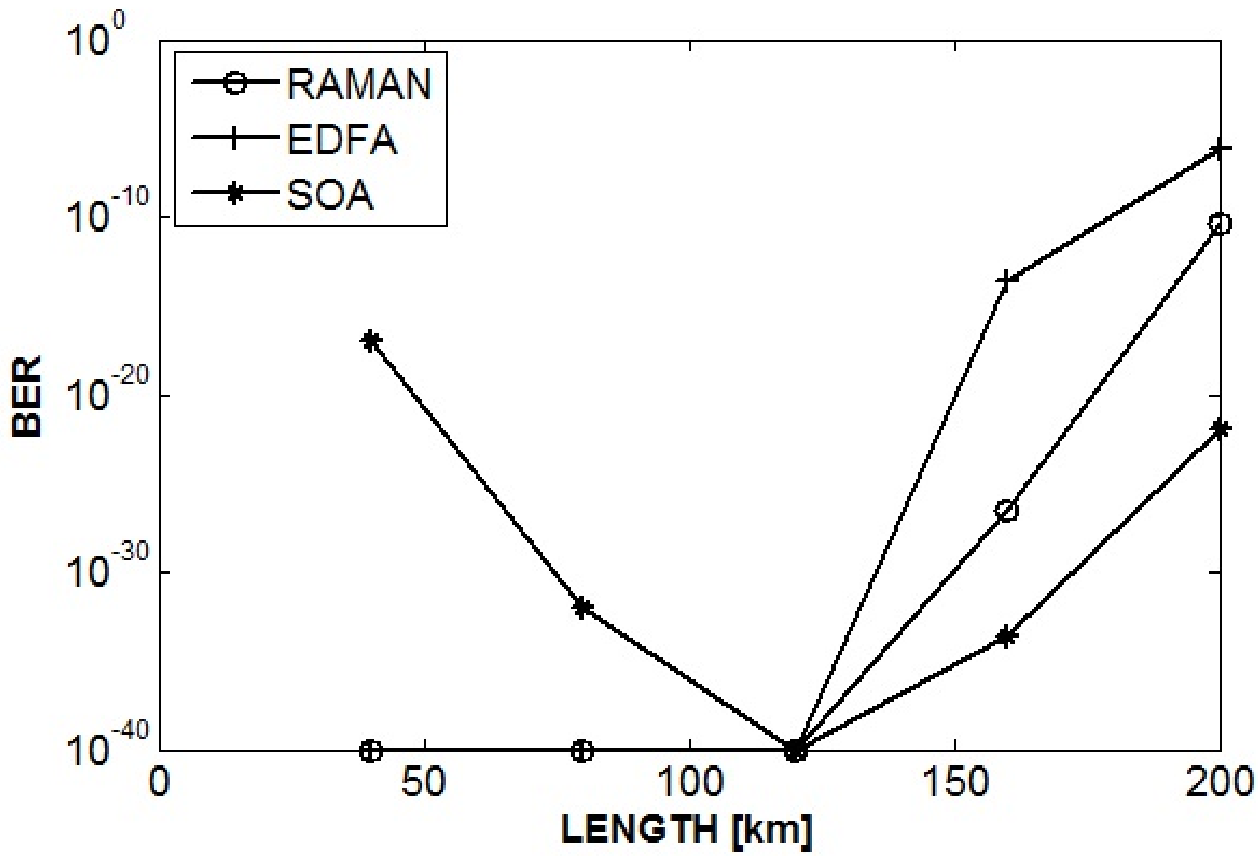

Figure 3.7: BER vs. Length for 16 channels in the absence of nonlinearities

If the nonlinearities not considered, better BER is provided by the SOA amplifier (1.10 X 10^{-17}) and also for the worst case (at 200 Km) it becomes 1.05 X 10^{-22}. But there is very much variation in BER as well as gain.So to mettigate this problem we required gain equalizer which increase the complexity and cost of the setup.So that RAMAN provides better results as shown in figure 3.7.

The variation in Q Factor for RAMAN, EDFA and SOA are 10^{-40} to 4.42 X 10^{-11}, 10^{-40} to 6.82 X 10^{-7} and 1.10 X 10^{-17} to 1.05 X 10^{-22} respectively.

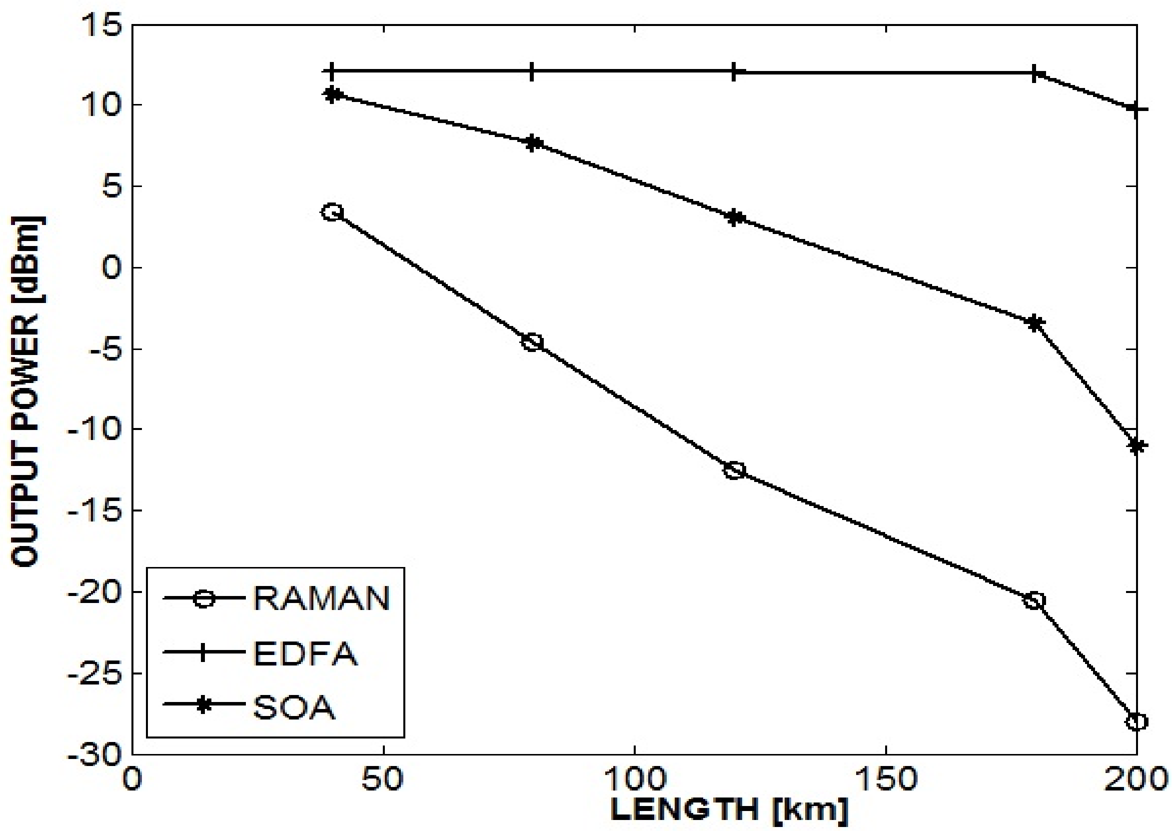

Figure 3.8: Output Power vs. Length for 32 channels in the presence of nonlinearities

In figure 3.8 Output power as a function of Length in the presence of non linearities is ploted for 32 channels.It is clear that EDFA has the higest and almost same output power for entire length range.EDFA amplifier provides 12.56 dBm at 40km and it becomes 9.7dBm at 200km.

The variation in Output power for RAMAN, EDFA and SOA are 3.393 to -28.036 dBm, 12.056 to 9.70 dBm and 10.638 to -11.063 dBm respectively. EDFA provides the better results as compared to other amplifiers.

If the nonlinearities effects are not considered,the better Output power is provided by the EDFA amplifier (12.063 dBm) at 40km as shown in figure 3.9.

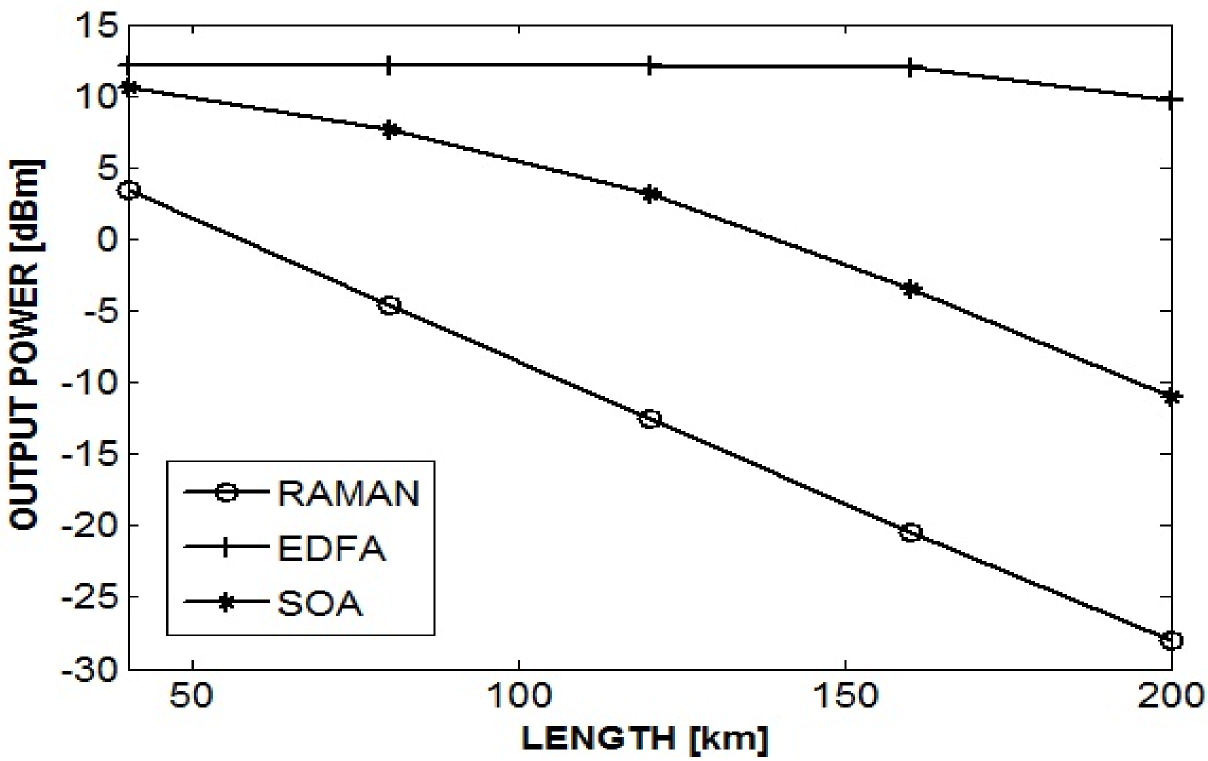

Figure 3.9: Power vs. Length for 32 channels in the absence of nonlinearities

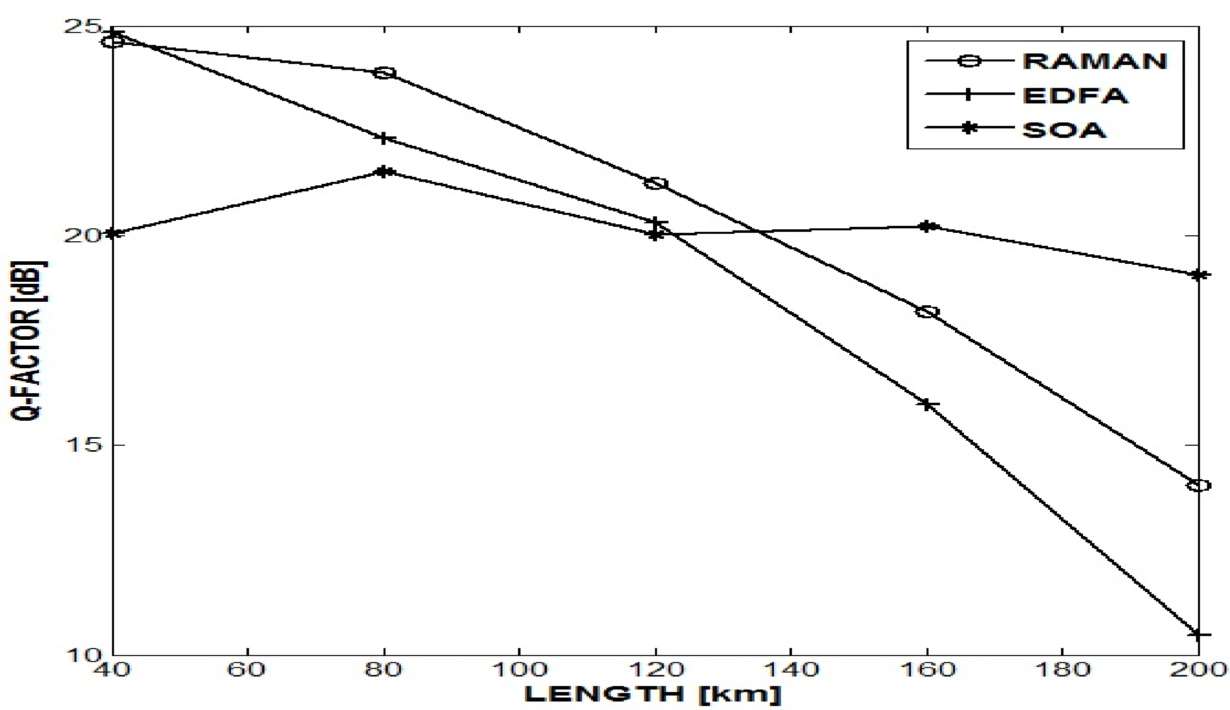

Figure 3.10: Q- factor vs. Length for 32 channels in the presence of nonlinearities

The figure 3.10 plots Q factor as a function of Length for 32 channels in the presence of non linearities . RAMAN amplifiers performs well up to 120km and after 120km SOA has highest Q-factor among all.

The variation in Q Factor for RAMAN, EDFA and SOA are 24.61 to 14.05 dB, 24.84 to 10.48 dB and 20.05 to 19.07 dB respectively.

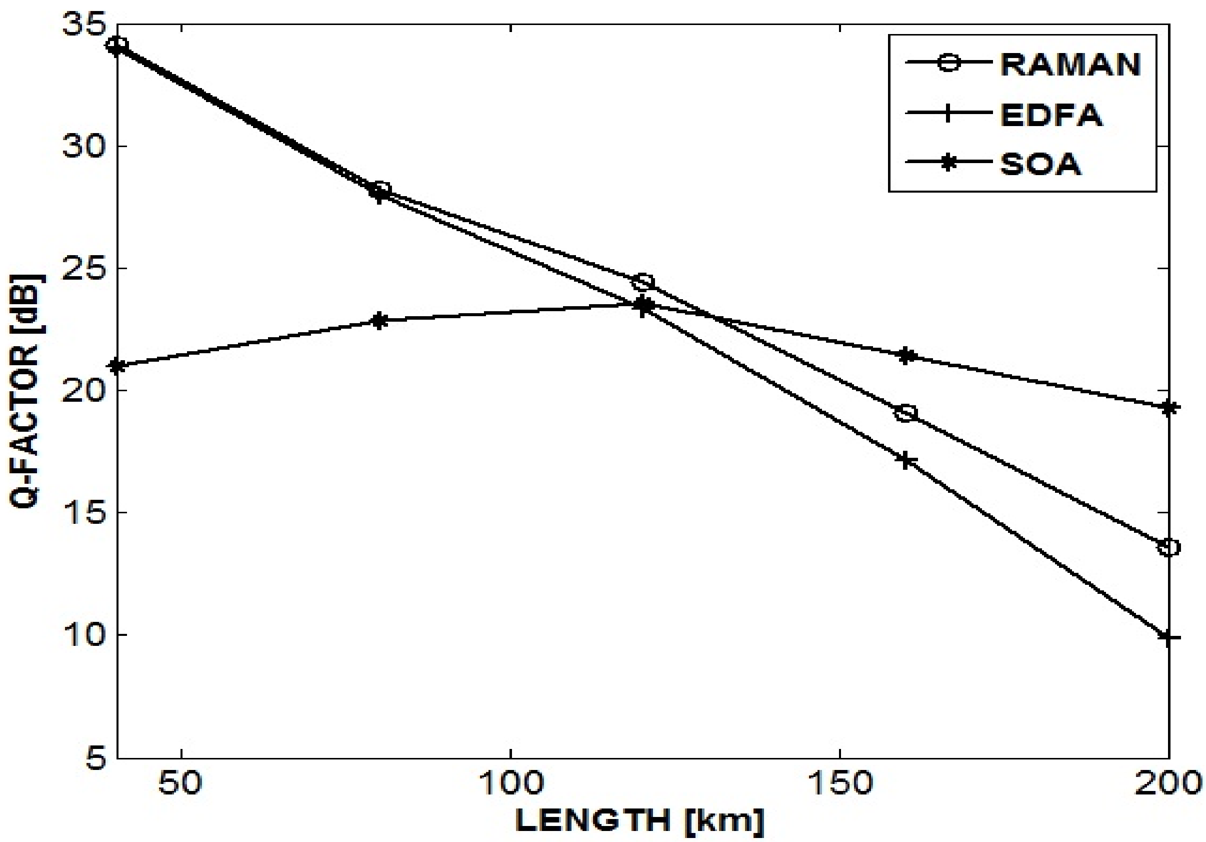

Figure 3.11: Q- factor vs. Length for 32 channels in the absence of nonlinearities

In figure 3.11,Q-factor vs.Length for 32 channel in absence of nonlinearties is plotted.It is observed that for distance up to 120km RAMAN and EDFA performs edge to edge,120km onwards SOA has the highest Q-factor among all and at 120km all the three amplifiers have compareable Q-factor.

The variation in Q Factor for RAMAN, EDFA and SOA are 34.13 to 13.57 dB, 34 to 9.91 dB and 20.97 to 19.32 dB respectively.

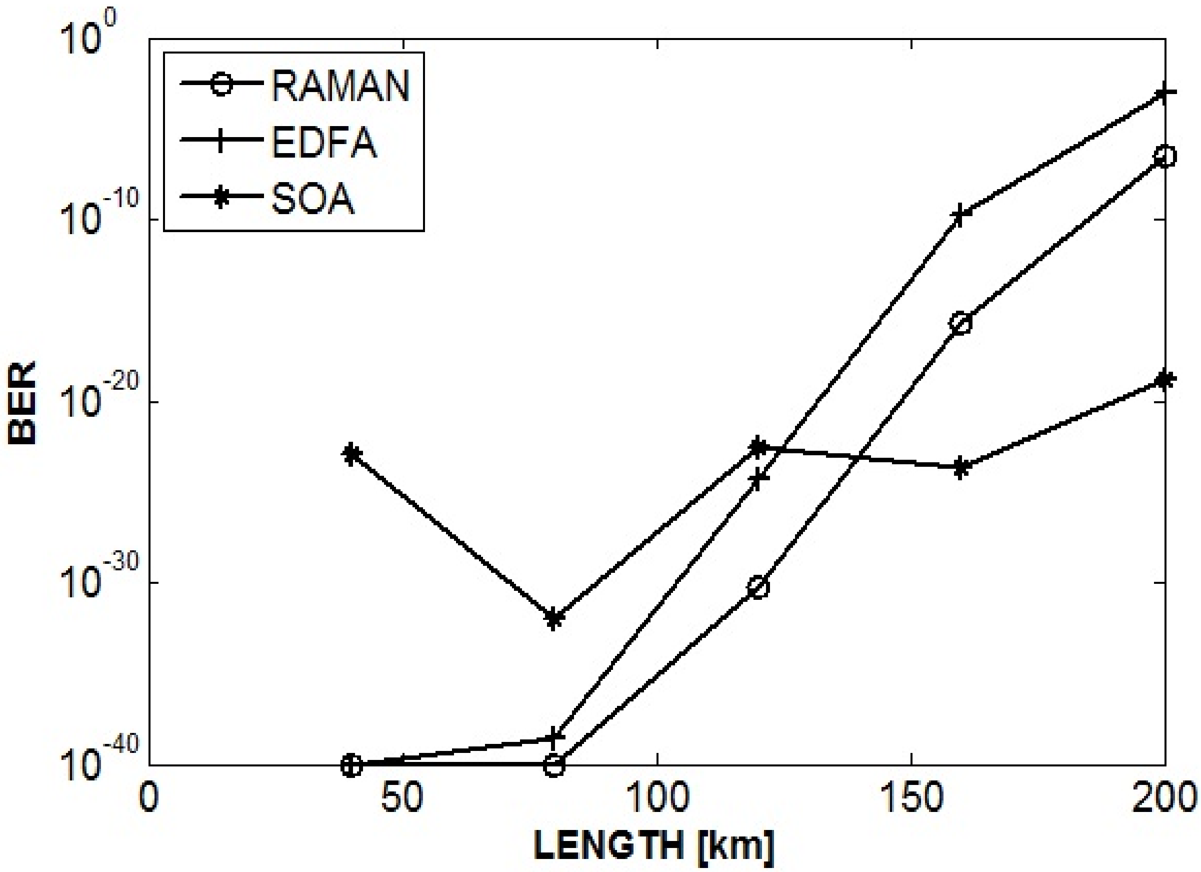

Figure 3.12: BER vs. Length for 32 channels in the presence of nonlinearities

The figure 3.12 shows the graphical representation of BER as a function of Length in the presence of non linearities . From this figure it is observed that RAMAN amplifier has lowest BER till 120km and 120km onwards SOA has lowest and also for the worst case (at 200 Km) it becomes 1.48 X 10^{-19}.But there is very much variation in BER as well as gain.So to mettigate this problem we required gain equalizer which increase the complexity and cost of the setup. So that RAMAN provides better results.

The variation in BER for RAMAN, EDFA and SOA are 10^{-40} to 3.45 X 10^{-7}, 10^{-40} to .001 and 1.063 X 10^{-23} to 1.48 X 10^{-19} respectively.

If the nonlinearities effects are not considered, from the figure 3.13 it is clear that at 40km RAMAN and EDFA have compareable BER of the order of 10^{-40} and SOA has some what high BER.At 80 and 120km all the three amplifiers have same BER of order 10^{-40} .At 120km onwards SOA perforns well and at it becomes 9.63 X 10^{-20} and is only amplifier with BER $<10^{-10}$.

The variation in BER for RAMAN, EDFA and SOA are 10^{-40} to 7.66 X 10^{-7}, 10^{-40} to .001 and 1.28 X 10^{-28} to 9.63 X 10^{-20} respectively.

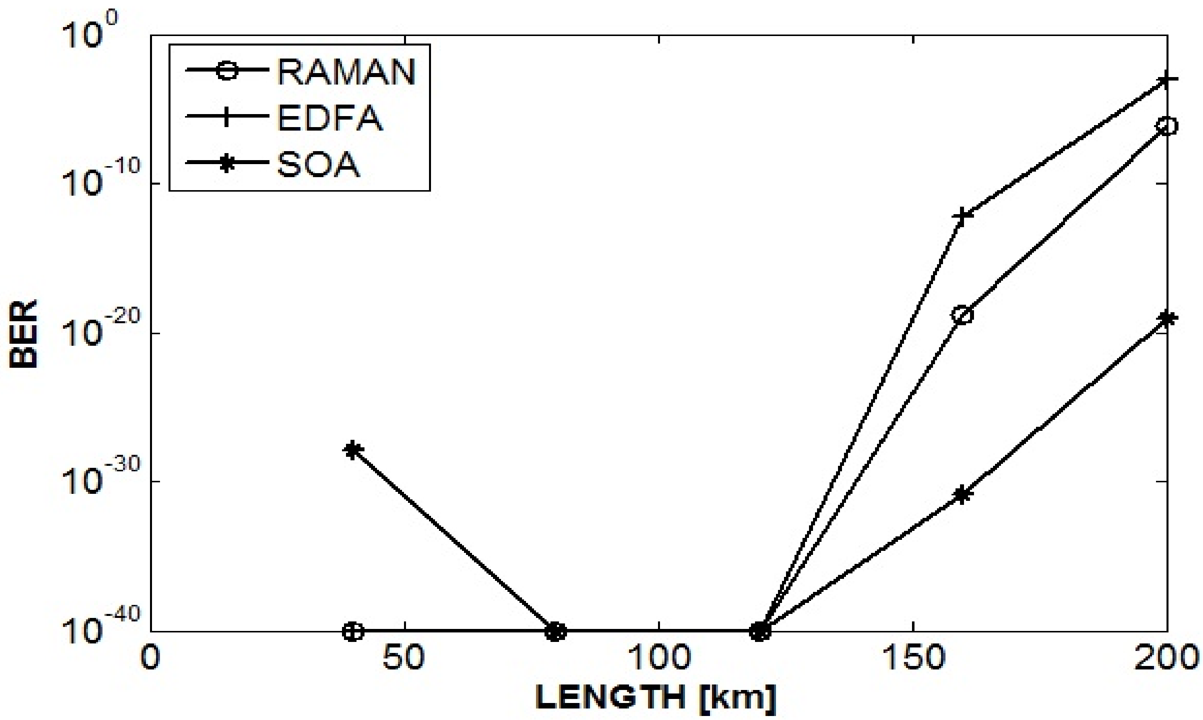

Figure 3.13: BER vs. Length for 32 channels in the absence of nonlinearities

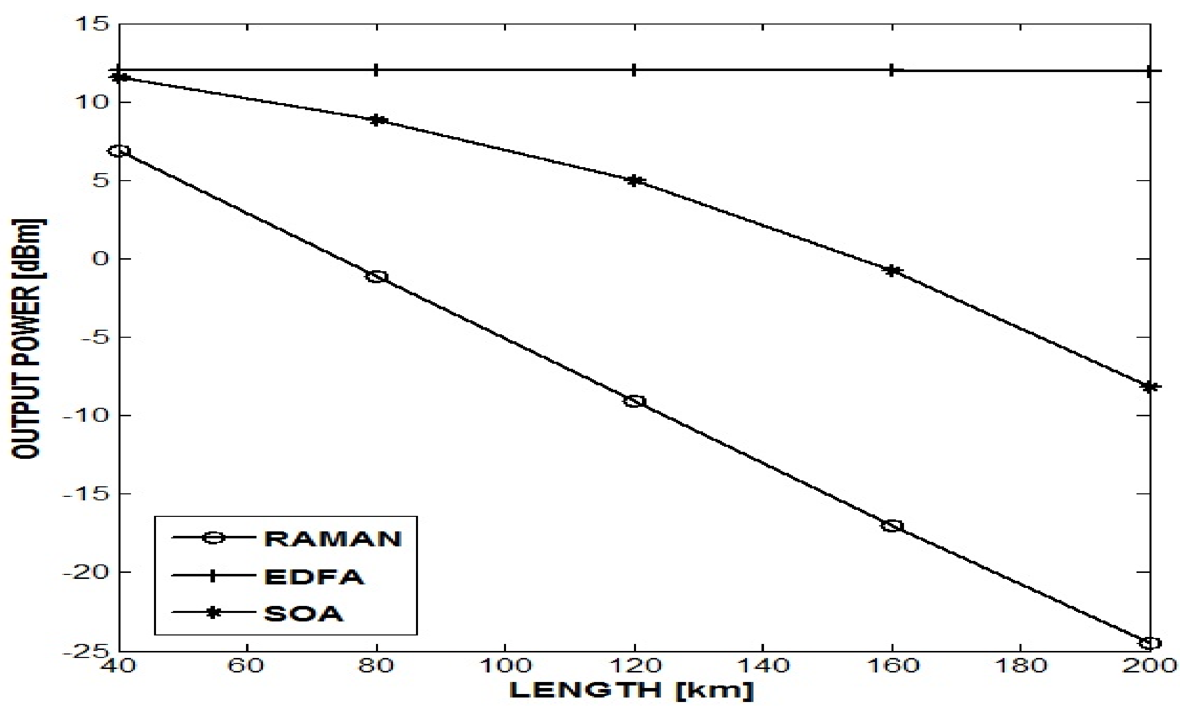

Figure 3.14: Power vs. Length for 64 channels in the presence of nonlinearities

The figure 3.14 shows the graphical representation of Output power as a function of Length in the presence of non linearities . The better Output power is provided by the EDFA amplifier (12.033dBm) and also for the worst case (at 200 Km) it becomes 11.957 dBm.

The variation in Output power for RAMAN, EDFA and SOA are 6.866 to -24.494 dBm, 12.033 to 11.957 dBm and 11.547 to -8.141 dBm respectively. EDFA provides the better result as compare to other amplifiers.

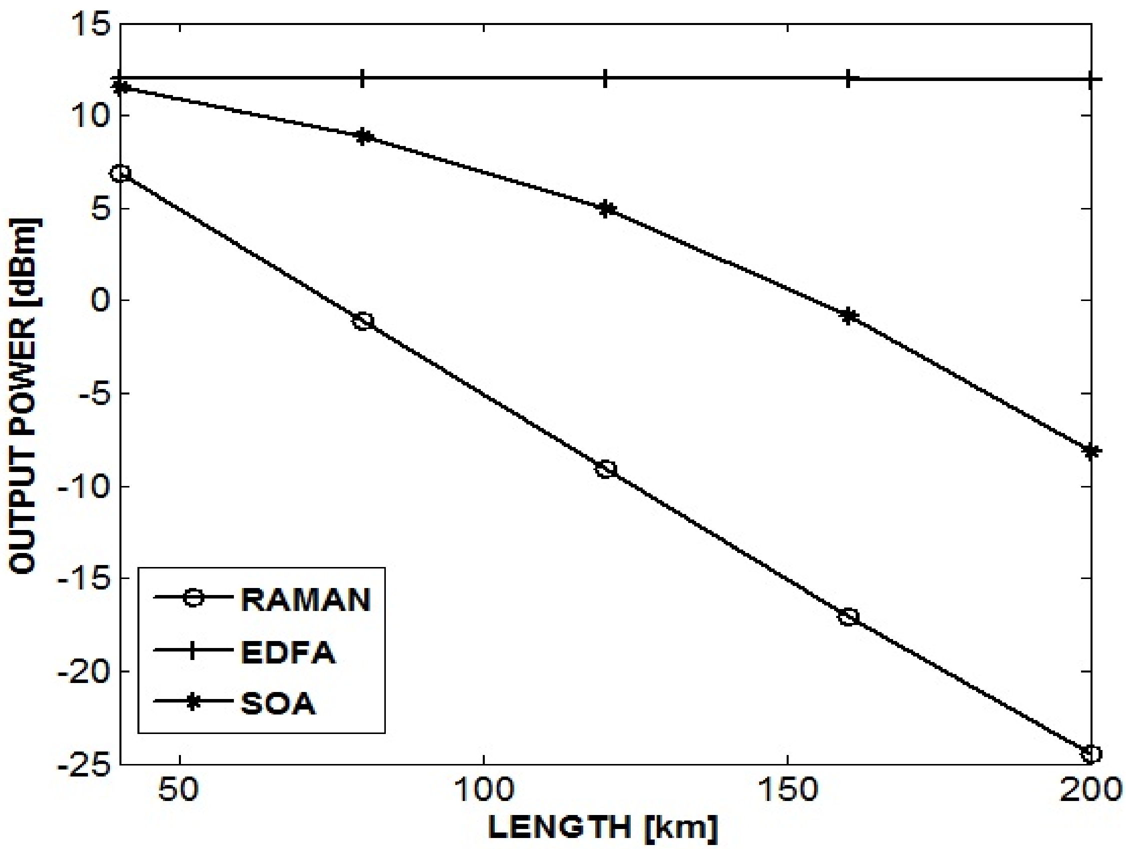

Figure 3.15: Power vs. Length for 64 channels in the absence of nonlinearities

If the nonlinearities effects are not considered, better output power is provided by the EDFA amplifier (12.045 dBm) and also for the worst case (at 200 Km) it becomes 11.947 dBm as shown in figure 3.15.

The variation in Output power for RAMAN, EDFA and SOA are 6.852 to -24.484 dBm, 12.045 to 11.947 dBm and 11.551 to -8.134dBm respectively.

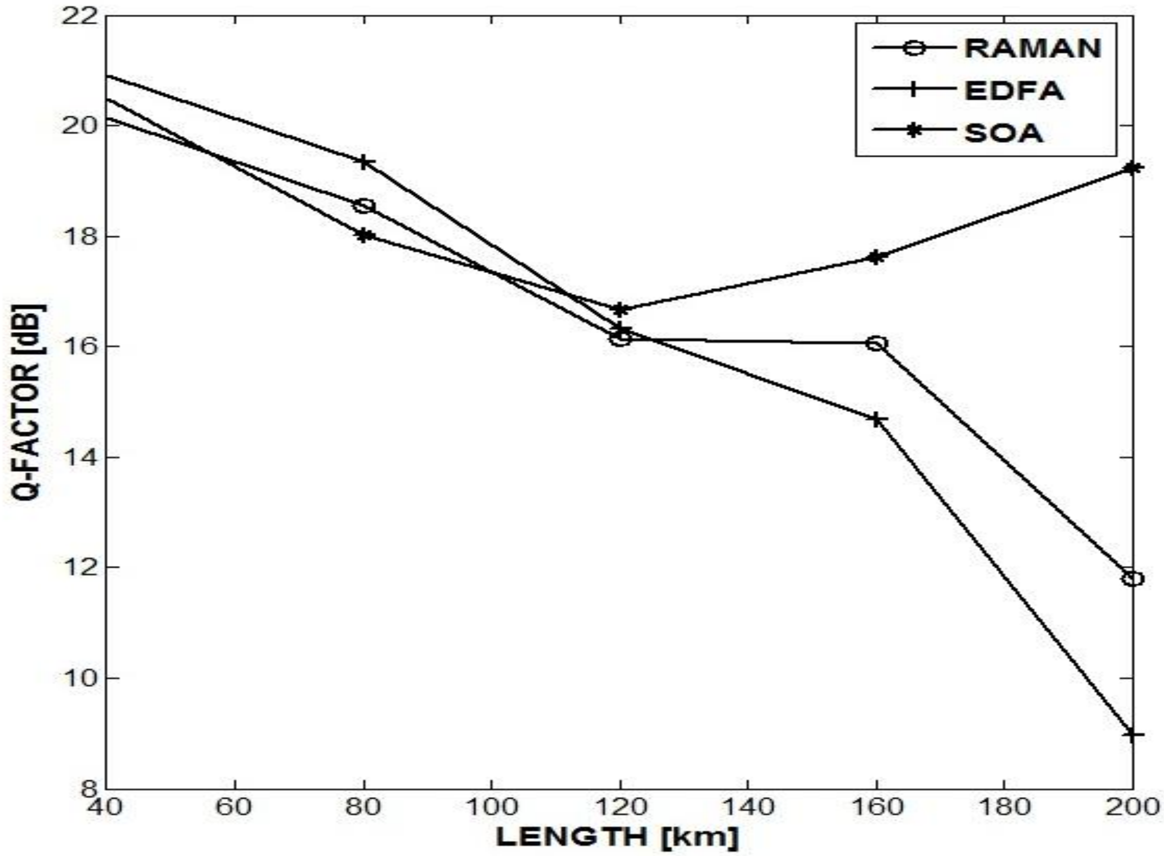

Figure 3.16: Q- factor vs. Length for 64 channels in the presence of nonlinearities

The figure 3.16 Q factor as a function of Length is ploted in the presence of non linearities .Up to 80km EDFA has highest Q-factor and at 120km all amplifiers have compareable Q-factor.SOA amplifier provides best Q-factor among all for distance 120km onwards and also for the worst case (at 200 Km) it becomes 19.23 dB.

The variation in Q Factor for RAMAN, EDFA and SOA are 20.13 to 11.8 dB, 20.89 to 8.97 dB and 20.48 to 19.23 dB respectively.

If the nonlinearities effects are not considered, up to 80km EDFA provides better Q factor among all and at 120km all the amplifiers have compareable Q-factor as shown in figure 3.17.SOA performs well after 120km to 200km. The variation in Q Factor for RAMAN, EDFA and SOA are 27.59 to 12.67 dB, 29.01 to 8.54 dB and 23.88 to 21dB respectively.

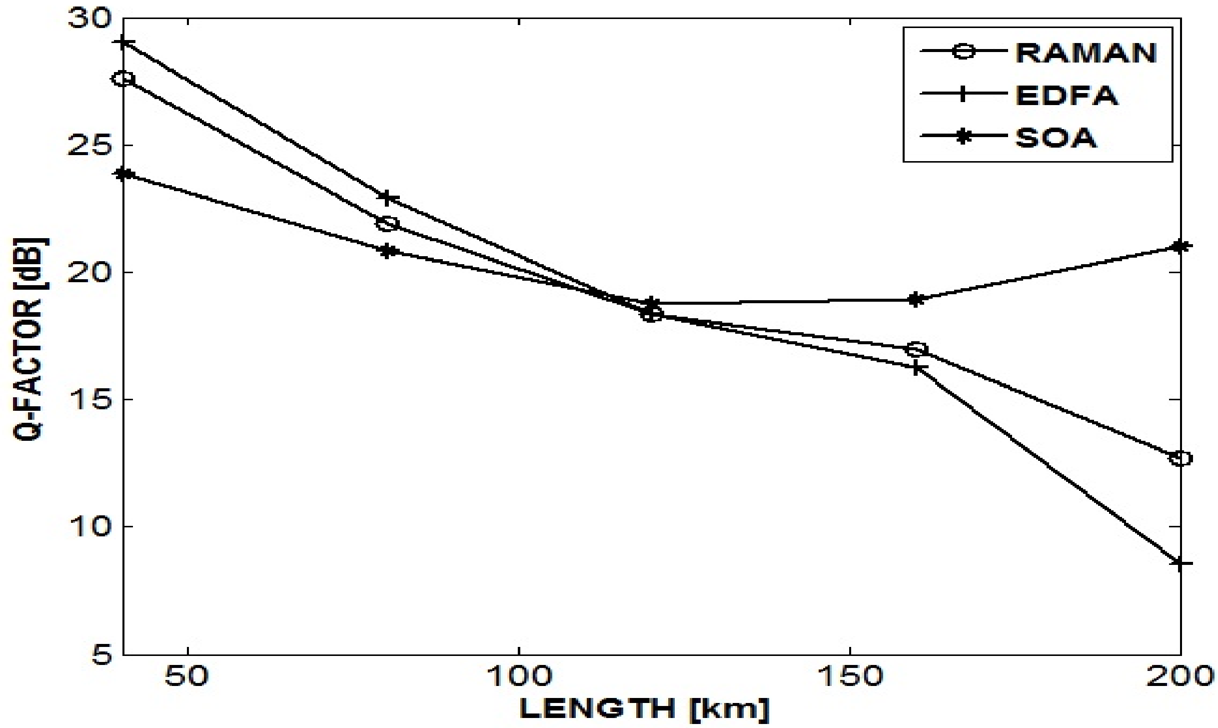

Figure 3.17: Q- factor vs. Length for 64 channels in the absence of nonlinearities

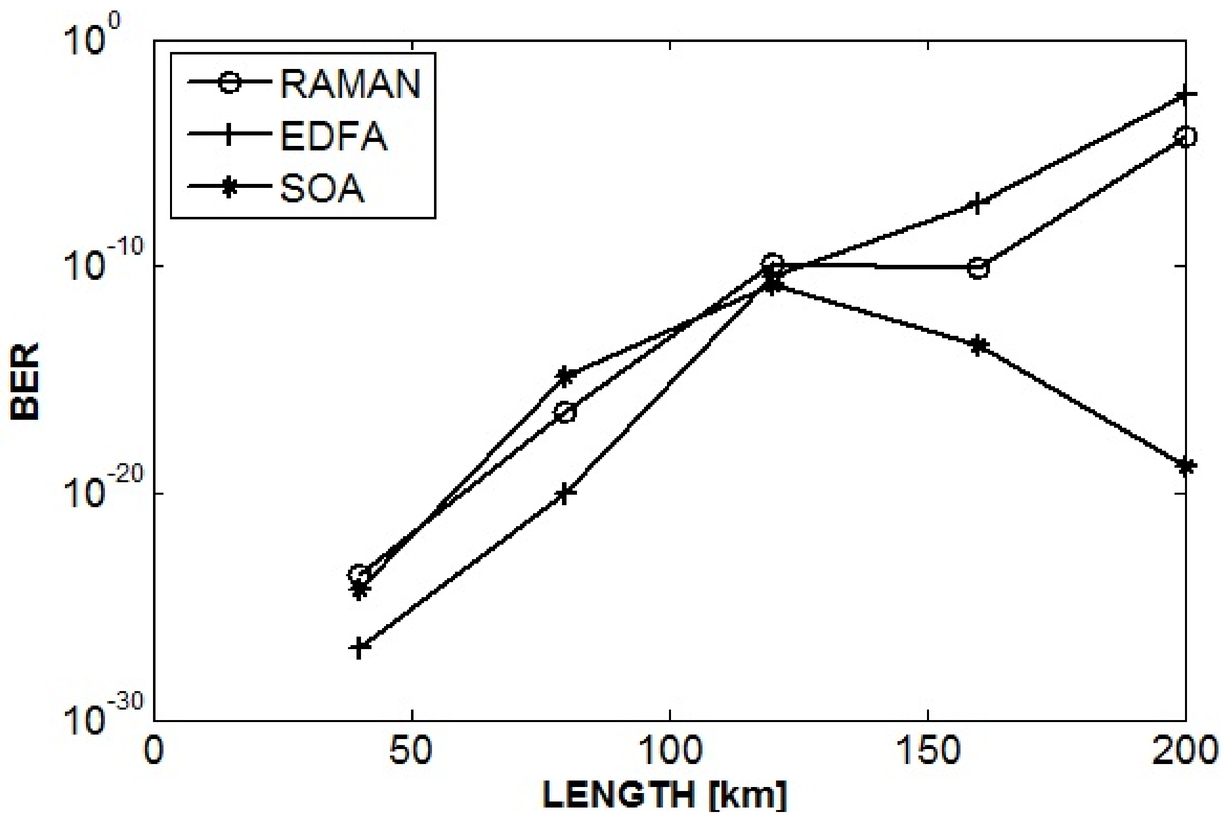

Figure 3.18: BER vs. Length for 64channels in the presence of nonlinearities

The figure 3.18 shows the graphical representation of BER as a function of Length in the presence of non linearities . Up to 80km EDFA has lowest BER and at 120km all the ampliofiers have compareable BER of the order of 10^{-10}. At 120km onwards SOA has lowest BER and at 200km it is only amplifier with BER <10^{-10} .

The variation in BER for RAMAN, EDFA and SOA are 2.39 X 10^{-24} to 4.79 X 10^{-5}, 1.47 X 10^{-27} to 4 X 10^{-2} and 5.29 X 10^{-25} to 1.61 X 10^{-19} respectively.

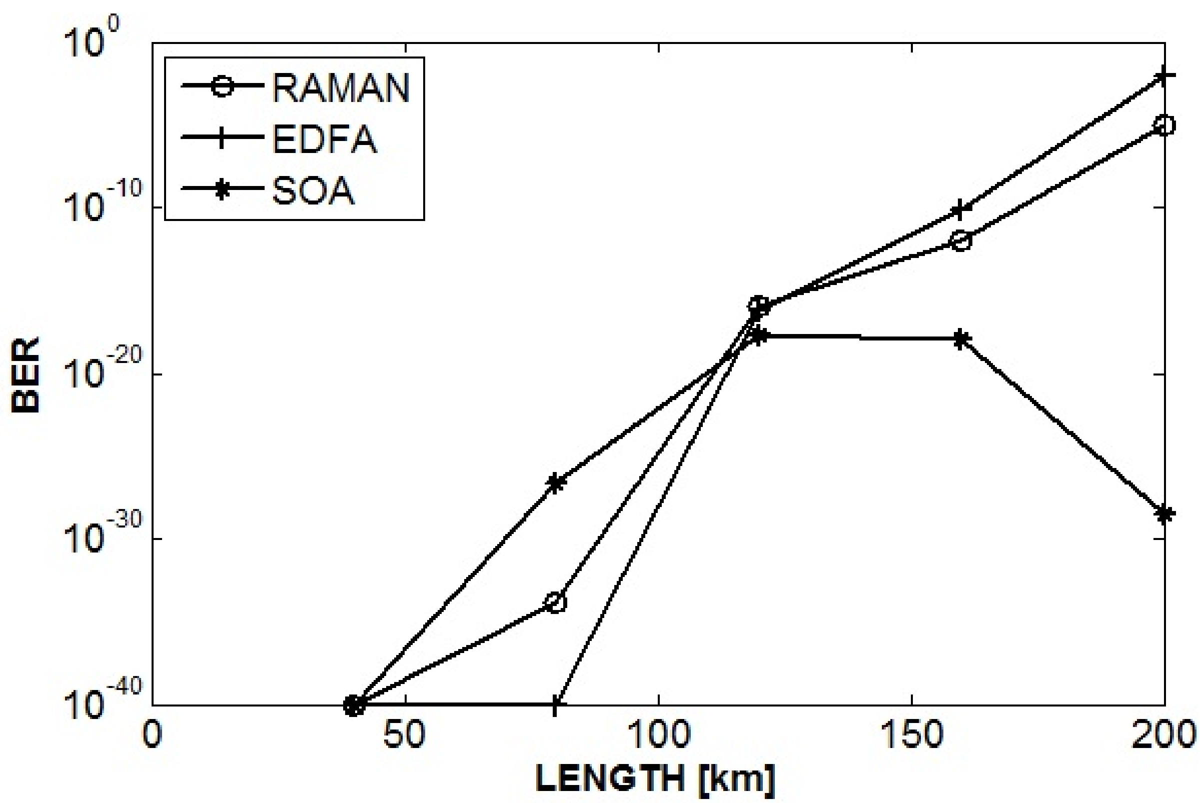

Figure 3.19: BER vs. Length for 64 channels in the absence of nonlinearities

If the nonlinearities effects are not considered, At 40km all the amplifiers have compareable BER and at 80km EDFA has lowest BER and 120km all the amplifiers have compareable BER.In the distance range 120km to 200km SOA has least BER among all amplifiers as shown in figure 3.19 .The variation in BER for RAMAN, EDFA and SOA are 10^{-40} to 8.83 X 10^{-6}, 10^{-40} to .01 and 10^{-40} to 3.38 X 10^{-29} respectively.

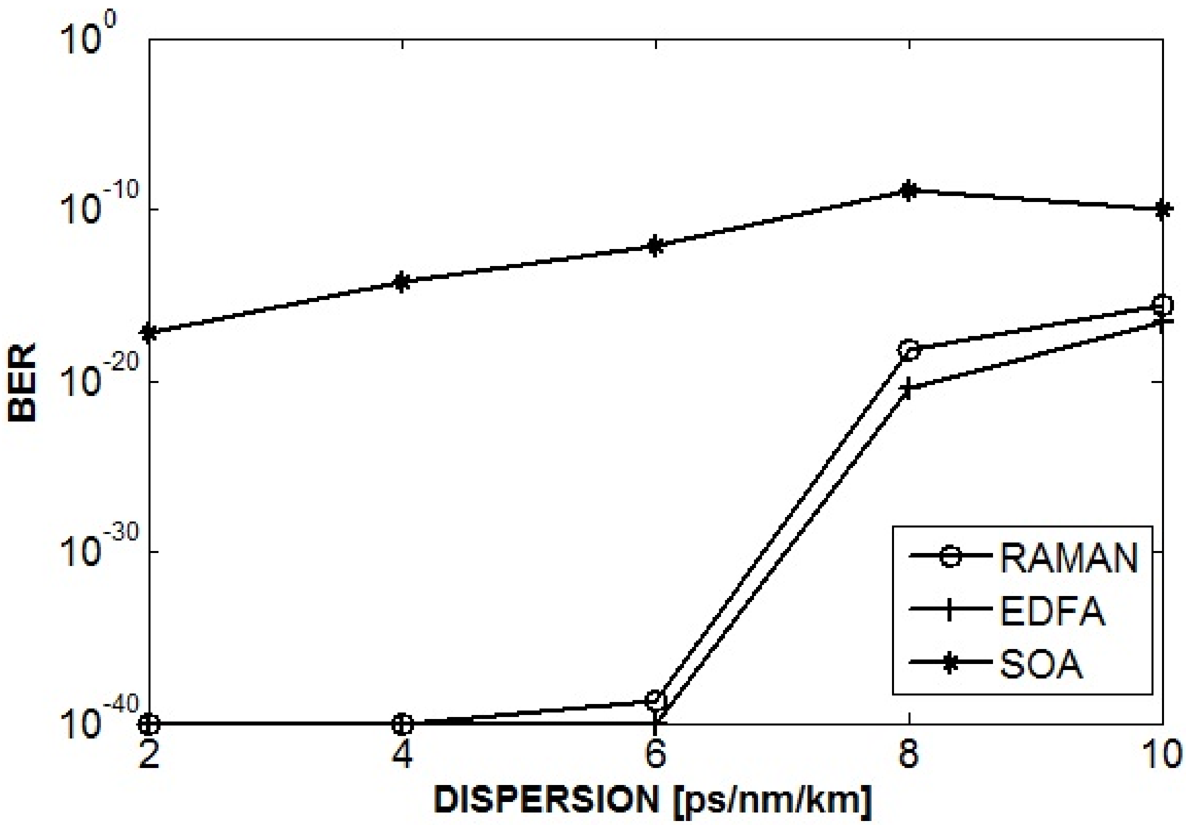

Figure 3.20: BER vs. Dispersion for 16 channels in the presence of nonlinearities

The figure 3.20 shows the graphical representation of BER as a function of Dispersion in the presence of non linearities . It is clear from the figure that EDFA and RAMAN provides better BER for dispersion varied from 2 to 10 ps/nm/km and SOA has high BER as compare to RAMAN and EDFA for all dispersion values.

The variation in BER for RAMAN, EDFA and SOA are 10^{-40} to 2.944 X 10^{-16}, 10^{-40} to 2.696 X 10^{-17} and 5.49 X 10^{-18} to 1.093 X 10^{-10} respectively.

If the nonlinearities effects are not considered, The better BER is provided by the both RAMAN and EDFA amplifiers for dispersion varied from 2 to 10 ps/nm/km as shown in figure 3.21.For dispersion values up to 6ps/nm/km EDFA and RAMAN have almost same BER and foe dispersion value 8 and 10 ps/nm/km EDFA have least BER.As in presence of nonlinearties here also, SOA has highest BER among all the amplifiers for all dispersion values.

The variation in BER for RAMAN, EDFA and SOA are 10^{-40} to 8.14 X 10^{-20}, 10^{-40} to 3.12 and 1.10 X 10^{-17} to 1.29 X 10^{-11} respectively.

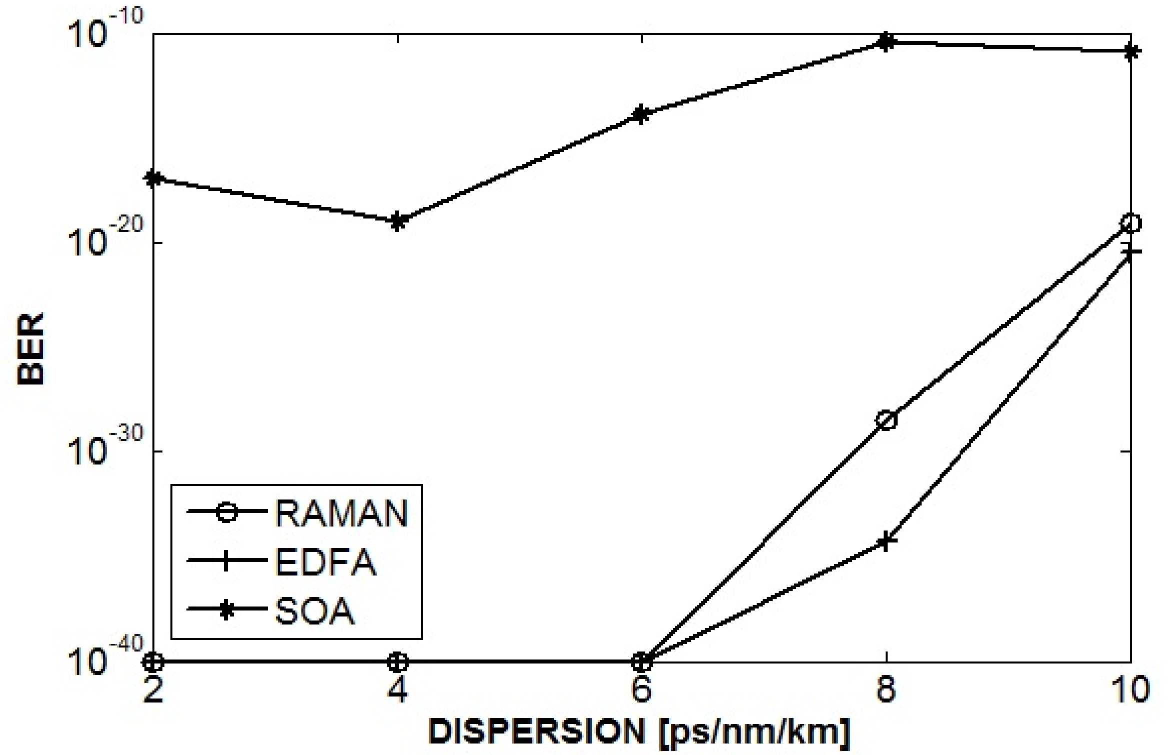

Figure 3.21: BER vs. Dispersion for 16 channels in the absence of nonlinearities

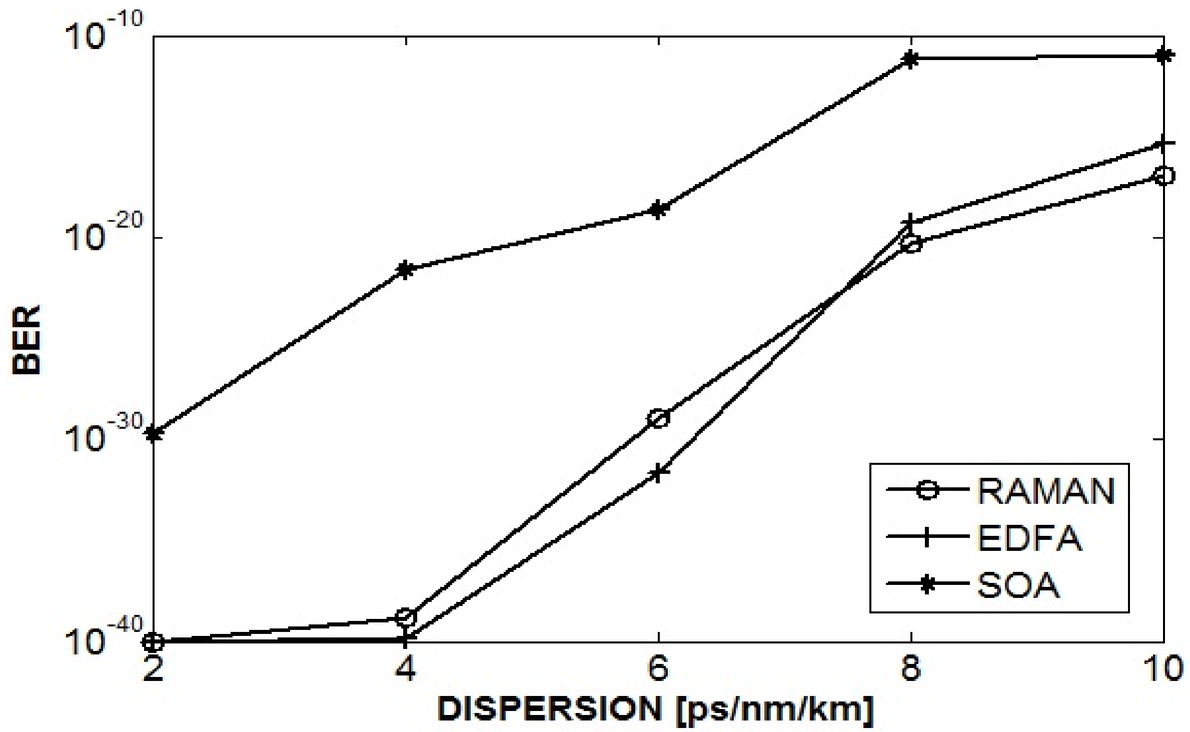

Figure 3.22: BER vs. Dispersion for 32 channels in the presence of nonlinearities

The figure 3.22 shows the graphical representation of BER as a function of Dispersion in the presence of non linearities. The better BER is provided by the both RAMAN and EDFA amplifiers and SOA has highest BER among all amplifiers. The variation in BER for RAMAN, EDFA and SOA are 10^{-40} to 1.05 X 10^{-17}, 10^{-40} to 3.97 X 10^{-16} and 1.83 X 10^{-30} to 1.02 X 10^{-11} respectively.

If the nonlinearities effects are not considered, again the better BER is provided by the both RAMAN and EDFA amplifiers for all dispersion values and SOA only have compareable performance at 2ps/nm/km and for higer dispersion SOA performs poorly as shown in figure 3.23.The variation in BER for RAMAN, EDFA and SOA are 10^{-40} to 1.23 X 10^{-23}, 10^{-40} to 1.59 X $10^{-21}$and 10^{-40} to 4.69 X 10^{-13} respectively.

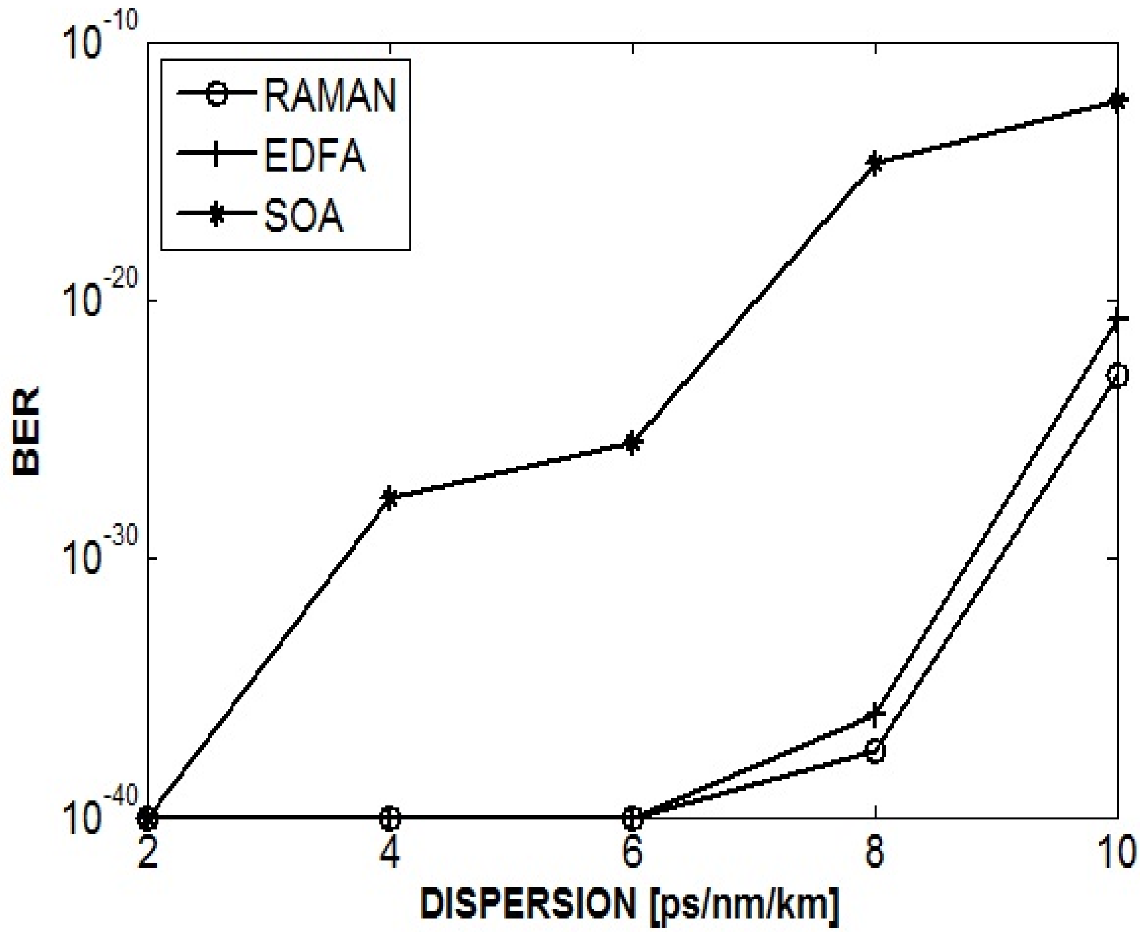

Figure 3.23: BER vs. Dispersion for 32 channels in the absence of nonlinearities

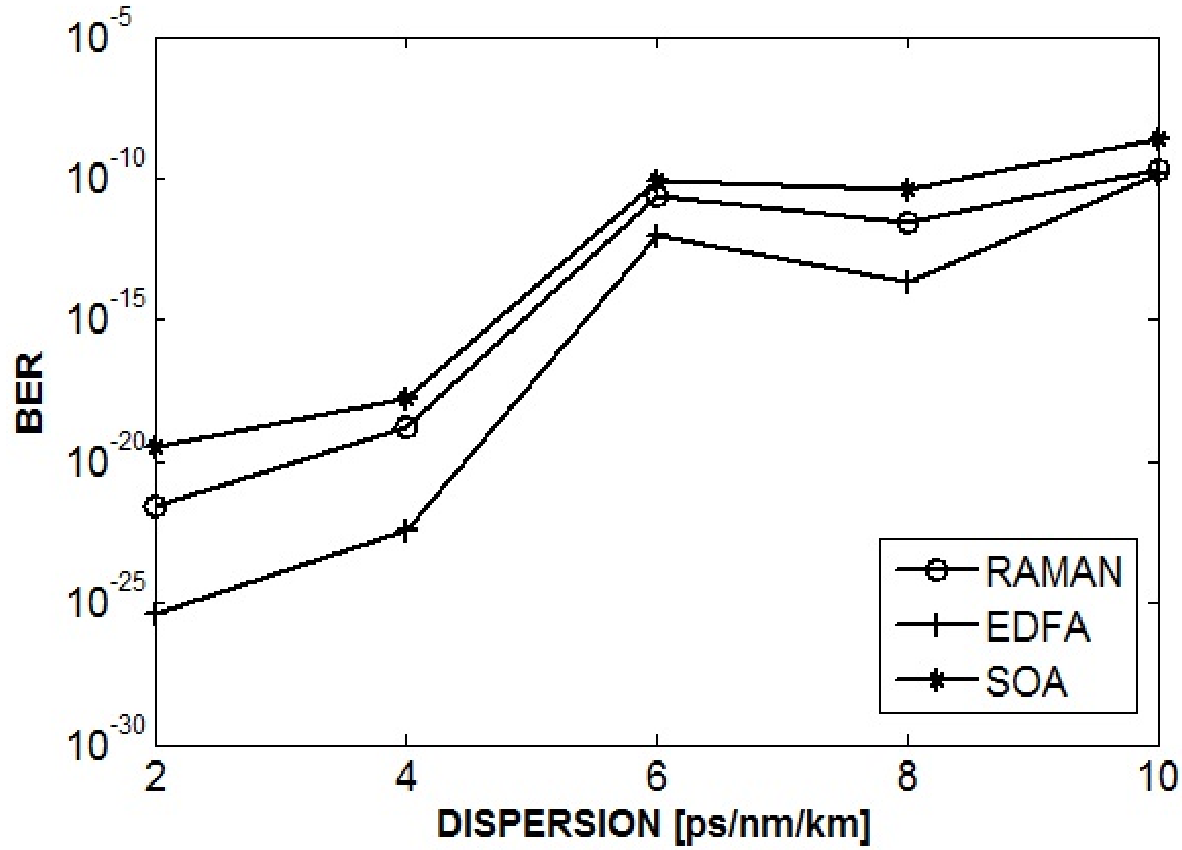

Figure 3.24: BER vs. Dispersion for 64 channels in the presence of nonlinearities

The figure 3.24 shows the graphical representation of BER as a function of Dispersion in the presence of non linearities . The better BER is provided by EDFA amplifier, SOA and RAMAN amplifiers also have good BER. The variation in BER for RAMAN, EDFA and SOA are 2.73 X 10^{-22} to 2.01 X 10^{-10}, 4.23 X 10^{-26} to 1.49 X 10^{-10} and 3.52 X 10^{-20} to 2.42 X 10^{-9} respectively.

If the nonlinearities effects are not considered For dispersion value 2ps/nm/km all the three amplifier have same BER, at 4ps/nm/km only RAMAN and EDFA have low and same BER,in this case BER for SOA is high.For dispersion value 6 and 8ps/nm/km EDFA has least BER among all and at 10ps/nm/km RAMAn and EDFA have compareable BER as shown in figure 3.25.The variation in BER for RAMAN, EDFA and SOA are 10^{-40} to 2.65 X 10^{-18}, 10^{-40} to 1.73 X $10^{-17}$and 10^{-40} to 1.29 X 10^{-14} respectively.

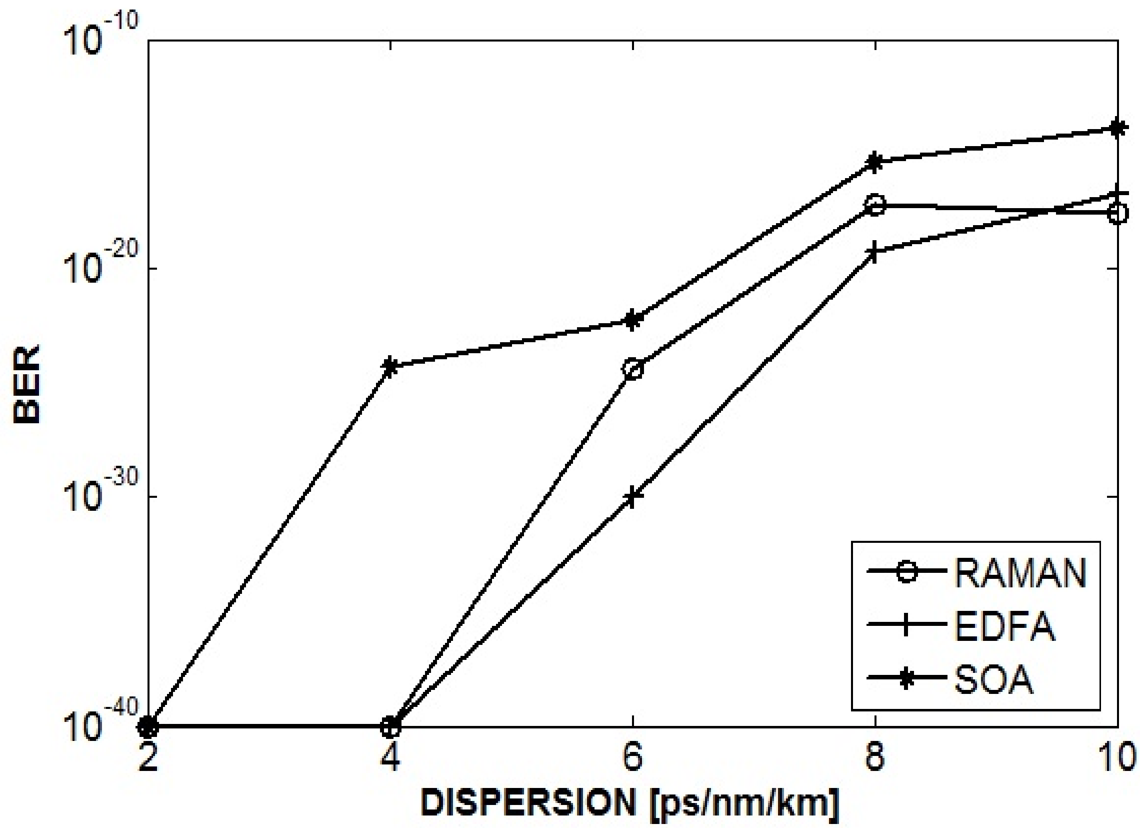

Figure 3.25: BER vs. Dispersion for 64 channels in the absence of nonlinearities

3.5 Conclusion

This chapter investigates 16 X 10, 32 X 10 and 64 X 10Gbps WDM light wave system using optical amplifiers (RAMAN, EDFA and SOA) with and without non linearities. Both the cases with and without nonlinearities are implemented to compare optical amplifiers by varying transmission distance (40 to 200 Km) and dispersion (2 to 10ps/nm/km) in the term of output power, BER, Q factor and eye closure. From this work it is concluded that when the dispersion is 2ps/nm/km then SOA provide better results but as we increase the number of channels it degraded the performance because gain saturation problem arises. If we increase the dispersion and number of channels then EDFA provides better results than SOA. It has also observed that RAMAN amplifier gives low output power than other existing amplifiers and it can be give better results for higher wavelengths.

CHAPTER 4

Simulation of WDM System Based on Hybrid Optical Amplifiers

4.1 Abstract

In this chapter, the performance of different combinations of optical amplifiers (Hybrid optical amplifiers) for 16, 32 and 64 channels at 10Gbps WDM systems has been investigated. These comparisons have been done on the basis of transmission distance and dispersion. It has been observed that RAMAN-EDFA provides better results as we increases the numbers of channels. For the gain flatness issue RAMAN-EDFA is better alternative than other existing hybrid optical amplifiers. By using RAMAN-EDFA the SNR can be improved while still keeping the high gain compression and output power provided by the erbium doped fiber amplifier.

4.2 Introduction

The growing demand for transmission capacity on optical fiber trunk lines in wave- length division multiplexing (WDM) systems increases: channel speed, channel number, and spectral efficiency need to be upgraded [43]. To overcome these problems, the WDM systems have been demonstrated using several types of wideband amplifiers. EDFA, SOA and RAMAN amplifiers are the main amplifiers having good amplification response and good gain bandwidth [11,43, 49].The erbium-doped fiber amplifier (EDFA) has been utilized in WDM systems since the 1980s [51]. EDFA alone has been used as booster and inline amplifier to transmit optical signals over thousands of kilometers [43]. Semiconductor optical amplifier.SOA have ultra wide band spectrum, low power consumption and low cost [49] and Fiber Raman amplifiers (FRA) in long-distance transmission line eliminates noise accumulation and improves the noise figure and reduce the nonlinear penalty of fiber systems . But overall performance can be enhanced by cascading two amplifiers, this leads to term Hybrid optical amplifier. Hybrid amplifiers have many advantages over individual amplifiers, like wide gain bandwidth and more flat gain profile; Hybrid amplifier provides high power gain.

Mohammed N.Islam [11] described that the total amplifier gain (G_{Hybrid}) is the sum of the two gains

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

Also other important hybrid amplifier is the RAMAN-SOA. Yihong chen et.al [52] demonstrated a hybrid SOA-Raman amplifier scheme with over 40 nm operational bandwidth.

Ju Han Lee et al [53] investigated transient effects of their proposed Raman/EDFA hybrid amplifier recycling residual Raman pump, and demonstrated the use of a FBG based alloptical gain clamping technique to efficiently suppress the output power transients. There proposed single pump, Raman/EDFA hybrid amplifier was found to have a significantly long transient response time of ~ 2 ms compared to the conventional separate pump, Raman/EDFA hybrid amplifiers.

Ju Han Lee et al [54] demonstrated the hybrid optical amplifier in which DCF based Raman amplifier is used which is cascaded with EDFA. They show experimental performance comparison of three types of single-pump highly efficient dispersion-compensating Raman/erbium-doped fiber amplifier (EDFA) hybrid amplifiers with respect to gain, noise figure (NF), and stimulated Brillouin scattering (SBS)-induced penalty: Raman/EDFA hybrid amplifiers recycling residual Raman pump in a cascaded erbium-doped fiber located either after (Type I) or prior to (Type II) a dispersion-compensating fiber, and a Raman assisted EDFA (Type III).

S. H. Wang et al. [55] proposed a hybrid amplifier by cascading a Raman-assisted fiber optical parametric amplifier and a fiber optical parametric amplifier. The proposed hybrid amplifier can increase the gain of a RA-FOPA (Raman Amplifier- Fiber Optic Parametric Amplifier) which uses the same length of fiber and the same Raman and parametric pump powers. By optimizing the length of the first section of the hybrid amplifier, gain enhancement can be obtained by maximizing the parametric pump power.

Rajneesh Randhawa et al. [56] compared the different dispersion mapping techniques like pre-compensated, post-compensated or hybrid- compensation in the presence of fiber nonlinearities in 10 and 40Gbps carrier-suppressed return to zero (CSRZ) systems. It is observed that the hybrid-compensation is the best in dispersion mapping technique, which reduces the bit error rate (BER), produced due to the fiber nonlinearities to the more extent than that of pre- and post-compensations. By using the hybrid-compensation, the repeater length is increased almost up to double than that of pre- and post-compensations. It is also observed that with increase in the input bit rate and input power, the BER for hybrid is better as compared to other mapping techniques.

Rajneesh Kaler et al. [57] investigated the Gain and Noise figure performance comparison of Physical EDFA and Compact EDFA at 10Gbps for optical long haul link. It has been noticed that in link consisting of the chain of EDFA and Compact EDFA amplifiers, the Compact EDFAs has the higher gain levels with the minimum loss when the pump power is varied and up-conversion co-efficient values. Further it has also been investigated that noise figure obtained is higher in case of cascaded Physical EDFAs than Compact EDFAs on varying the EDFA length from 10 to 100 m.

Rajneesh Randhawa et al. [58] analyzed the impacts of Polarization Mode Dispersion (PMD) on the performance of high-speed optical communication system have been reported at different bit rates. The two systems are modeled using older fibers with same PMD coefficient at different bit rates and third is with the new fiber with less PMD coefficient than that of the previous two. The attenuation, chromatic dispersion and non-linear effects have been disabled, so that all the variation of the results is due to PMD. The bit rate is varied from 2.5 to 40Gbps and the length is varied from 1000 to 20,000 km. It is shown that the impact of PMD increases with the bit rate of system. It is also reported that the impact of PMD becomes intolerable at the bit rates of more than 40Gbps. And also the PMD produces very minute impact on the system performance for same bit rate with the variation in the fiber length.

The previous work [27, 56] restricted to less number of channels. We can further extend this work to study the effect on performance by using hybrid optical amplifier at more number of channels.

In this chapter, the previous work in the context of 16, 32 and 64 channels for existing hybrid optical amplifiers has been extended. Further, the performance comparison of RAMAN-SOA, EDFA-SOA and RAMAN-EDFA for different dispersion and distance in the term of bit error rate (BER), Q-Factor and output power has been investigated.

The chapter is organized into five sections. After discussion of abstract and introduction of this chapter, the optical simulation setup is described in Section 4.3. In Section 4.4, comparison results have been reported for the different modulation formats and finally in Section 4.5, conclusions are made.

4.3 Simulation Setup

In this chapter 16, 32, 64 channels are transmitted at 10 GB/s data rate with 0.1 THz channel spacing. We have used NRZ format and the launched signal after multiplexer is pre-amplified by a booster .The multiplexed signal is launched into DS-anomalous fiber of different transmission distance. A transmitter compound component (T) is built up using 16, 32, 64 transmitters. We have considered three cases, 16 transmitters, 32 transmitters, 64 transmitters ,The channel spacing for all the three cases is kept 100 GHz. These beams have random laser phase and ideal laser noise bandwidth. The signals from data source and laser are fed to the external Mach-Zehnder modulator (sin^2_MZ for all configurations), where the input signals from data source is modulated through a carrier (optical signal from the laser source). The amplitude modulator is a sine square with an excess loss of 3 dB. A booster amplifier as preamplifier is used. The simulations setup of RAMAN-EDFA, EDFA-SOA and RAMAN-SOA using compound component at different transmission distance and dispersion are shown in figure 4.1.

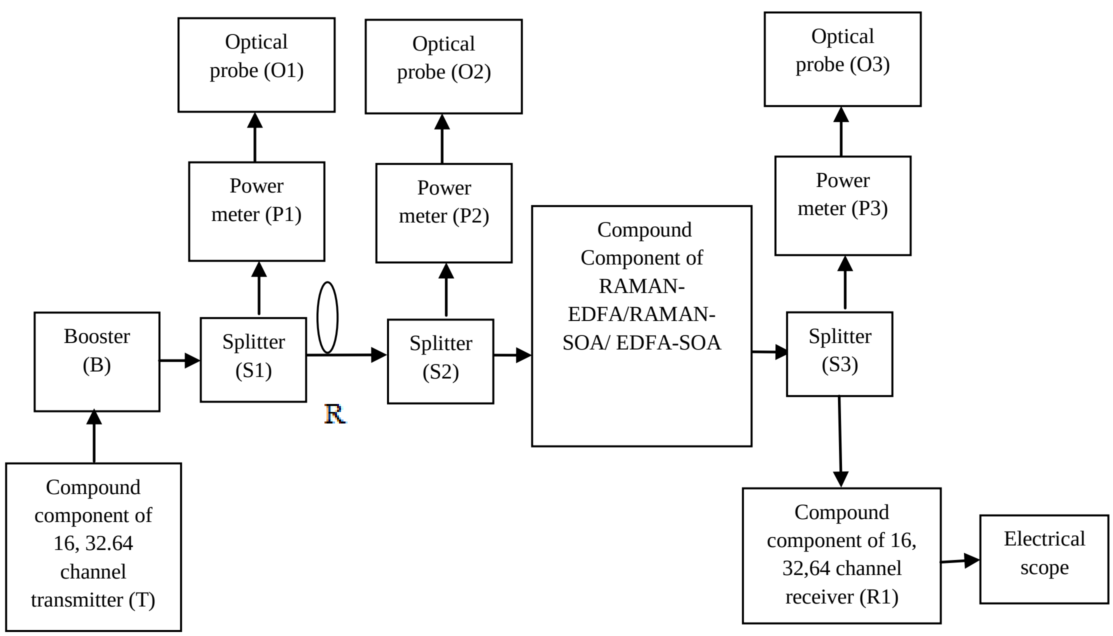

Figure 4.1: Block diagram for simulation setup

This optical signal is transmitted and measured over different distance for 40, 80,120,160 and 200 Km (R) at 2ps/nm/km and 8ps/nm/km dispersion individually. Optical Power meter (P1, P2, and P3) and Optical probe (O1, O2, and O3) with splitters (S1, S2, and 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 photodiode and filters. A compound receiver (R1) is used to detect all sixteen signals and converts these into electrical form. Different types of optical amplifiers are also applied at the receiver side. The set up is repeated for measuring the signal strength by using different hybrid amplifiers i.e. RAMAN-EDFA/ RAMAN-SOA/ EDFA-SOA. For all the cases maximum Q-factor, output power and minimum BER have been evaluated.

In DS Anomalous fiber the reference frequency is 193.414 THz, attenuation is 1.2dB/km and fiber polarization mode dispersion is 0.1ps/km$^{0.5m}$ are set .In this chapter fixed output power configuration EDFA and its output power is 12 dBm, gain shape is flat and noise figure is 4.5 dB used. The various parameters for SOA are biased current is 100 mA, Amplifier length is 300×10^{-6m}, confinement factor is 0.35, insertion loss is 3 dB and output insertion is 3 dB. The various parameters for RAMAN are Raman fiber length is 10 km, operating temperature is 300 K, pump wavelength is 1480 nm and pump power is 300 mW.

4.4 Result and Discussion

The Performance of different hybrid amplifiers RAMAN-EDFA/ RAMAN-SOA/ EDFA-SOA are evaluated and compared for 16 X 10Gbps , 32 X 10 and 64 X 10Gbps WDM system in the term of received maximum Q Factor (dB), minimum eye closure(dB), minimum BER and maximum output power(dBm) at different transmission distance and dispersion. The distance varied from 40 to 200 km in steps of 40 km and dispersion varies from 2 to 10ps/nm/km. To analyze the system, the results of the first channel have been taken.

The figure 4.2 shows the graphical representation of output power as a function of length in the presence of nonlinearities. The output power is decreased due to the fiber non-linearities and fiber attenuation. The better output power is provided by the RAMAN-EDFA and EDFA-SOA amplifier for entire distance range. At 40km output power provided by RAMAN-EDFA and RAMAN-SOA are 12.041dBm and 12.031dBm and also for the worst case (at 200 Km) it becomes 9.703dBm and 12.026dBm. The variation in output power for RAMAN-EDFA, RAMAN-SOA and EDFA-SOA are 12.041 to 9.703dBm, 10.037 to -11.637 dBm and 12.031 to 12.026 dBm respectively.

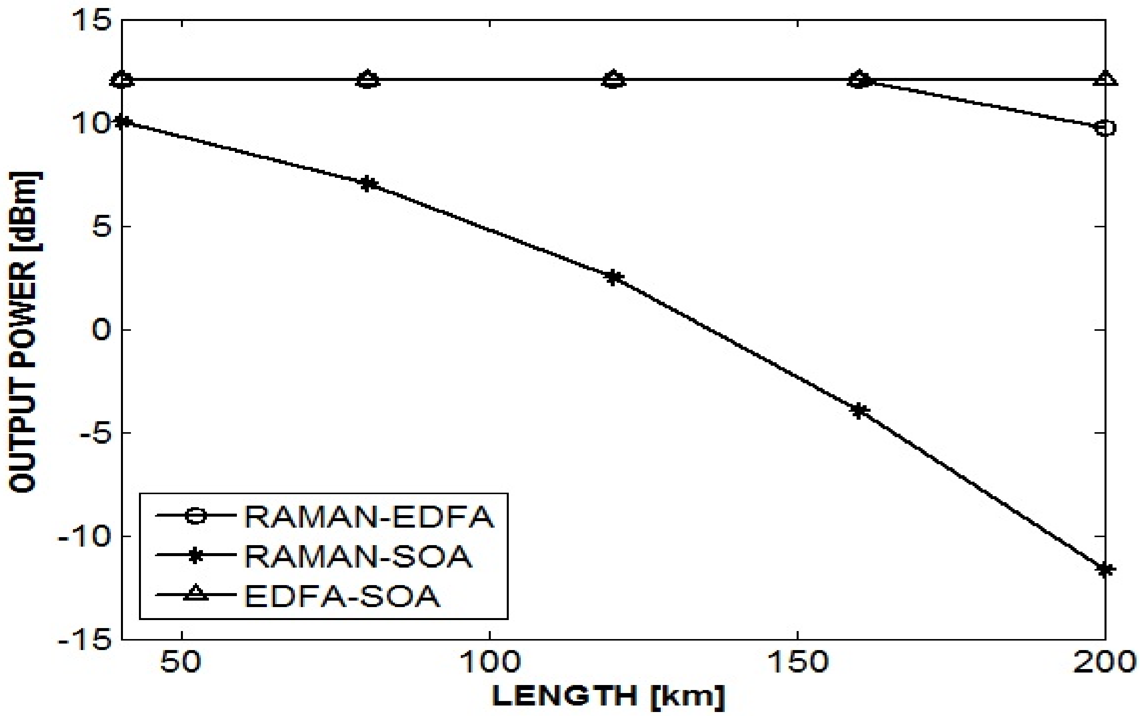

Figure 4.2: Output Power vs. Length for 16 channels in the presence of nonlinearities

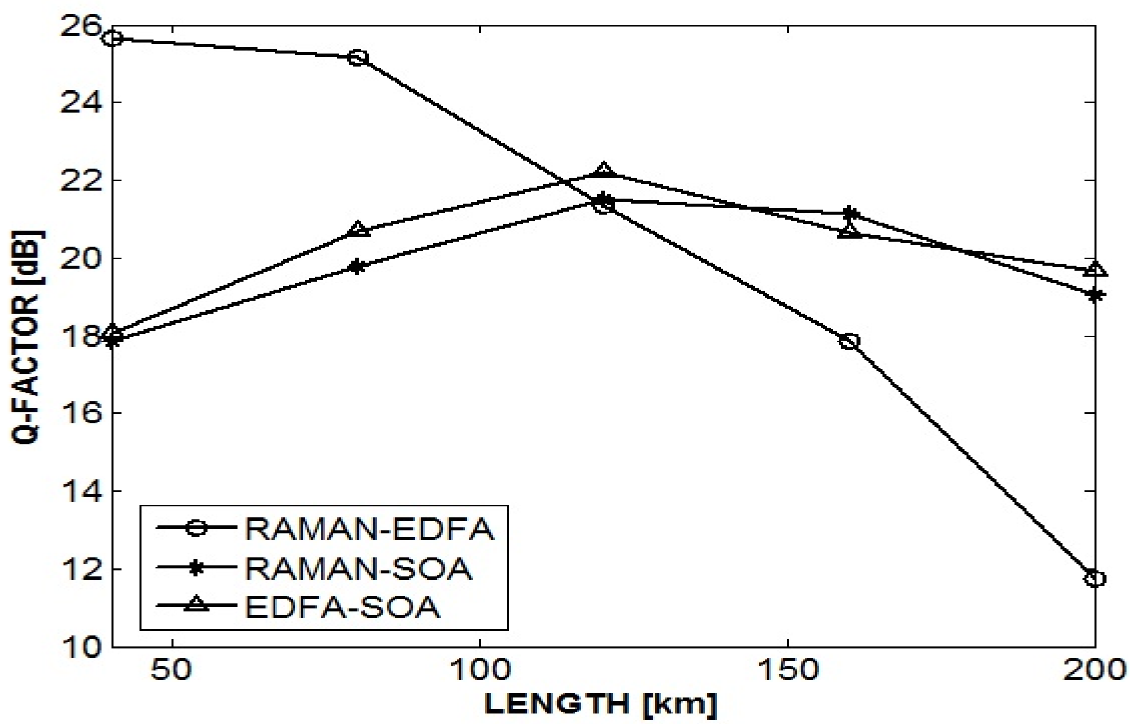

Figure 4.3: Q- factor vs. Length for 16 channels in the presence of nonlinearities

The figure 4.3 shows the graphical representation of Q factor as a function of length in the presence of nonlinearities.The better Q factor is provided by the RAMAN-EDFA amplifier at 40km (25.67 dB) and also for the worst case (at 200 Km) it becomes 11.75 dB.At 100km all the three amplifiers configurations have compareable Q-factor, but as the distance increases RAMAN-SOA and EDFA-SOA provides better result .

The variation in Q factor for RAMAN-EDFA, RAMAN-SOA and EDFA- SOA are 25.67 to 11.75 dB, 17.864 to 19.05 dB and 18.05 to 19.65 dB respectively.

The figure 4.4 depicts the plot of BER vs.Length in the presence of nonlinearities. The better BER is provided by the RAMAN-EDFA amplifier (10^{-40}) at 40km and also for the worst case (at 200 Km) it becomes 6.68 X 10^{-5}.RAMAN-SOA and EDFA-SOA also provides the acceptable results but there is very much variation in BER.

The variation in BER for RAMAN EDFA,RAMAN-SOA and EDFA-SOA are 10^{-40} to 6.68 X 10^{-5},2.06 X 10^{-15} to 1.802 X 10^{-19} and 1.114 X 10^{-15} to 1.84 X 10^{21}.

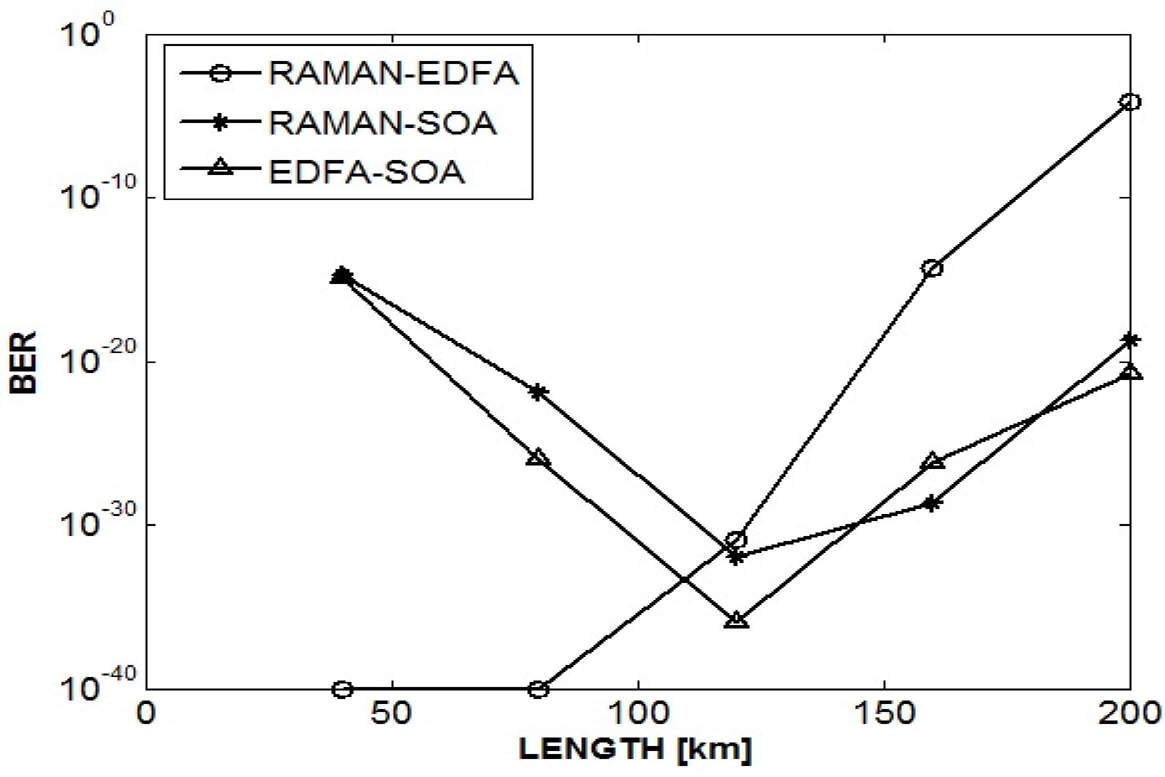

Figure 4.4: BER vs. Length for 16 channels in the presence of nonlinearities.

The figure 4.5 shows the output power as a function of length is plotted in the presence of nonlinearities. The output power is decreased with distance due to the fiber non-linearities and fiber attenuation. For distance range RAMAN-EDFA and EDFA-SOA amplifier provides almost comparable and better results. At 40km, RAMAN-EDFA and EDFA-SOA amplifier have 12.078dBm and 13.170dBm respectively; also for the worst case (at 200 Km) it becomes 9.648dBm and 12.40dBm respectively.

The variation in output power for RAMAN-EDFA, RAMAN-SOA and EDFA-SOA are 12.078 to 9.648 dBm, 10.431 to -11.139 dBm and 13.170 to 12.404 dBm respectively.

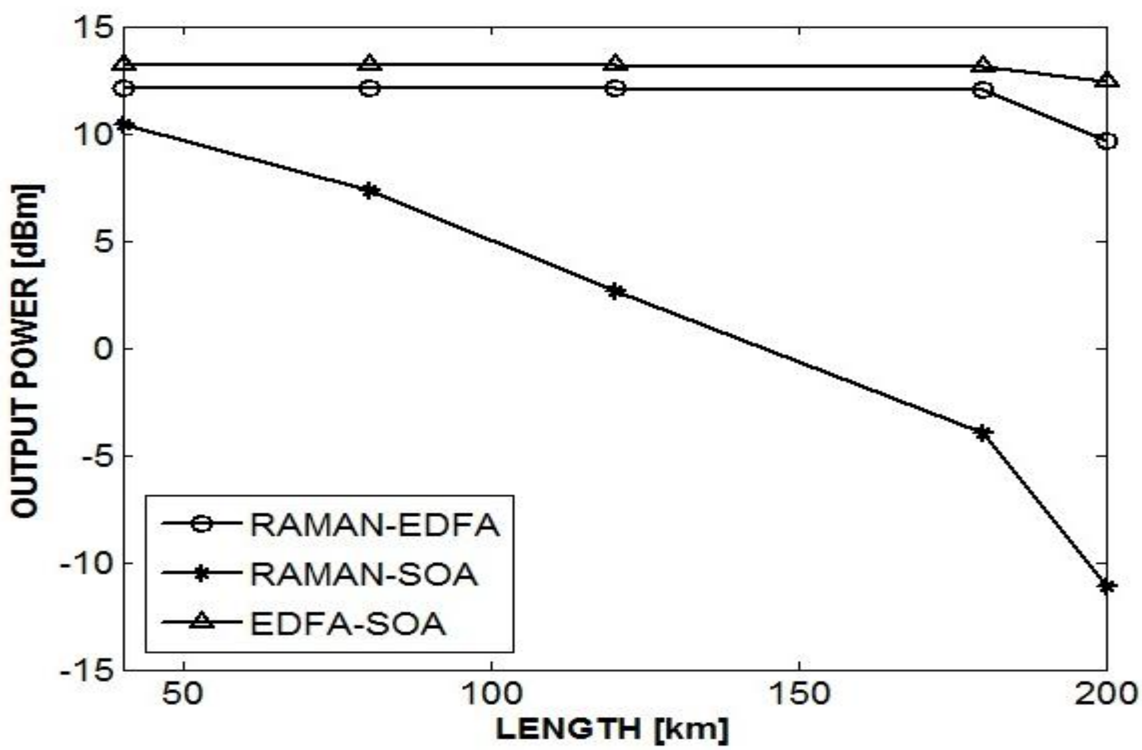

Figure 4.5: Output Power vs. Length for 32 channels in the presence of nonlinearities

In the figure 4.6 Q-factor as a function of length is plotted for 32 channels in the presence of nonlinearities. At 40km the better Q factor is provided by the RAMAN-EDFA amplifier (24.64dB) and also for the worst case (at 200 Km) it becomes 8.34dB .As the distance has increased beyond 120km RAMAN-SOA provides the better results among all.

The variation in output power for RAMAN-EDFA, RAMAN-SOA and EDFA-SOA are 24.64 to 8.34 dB, 20.96 to 12.54 dB and 19.56 to 10.37 dB respectively.

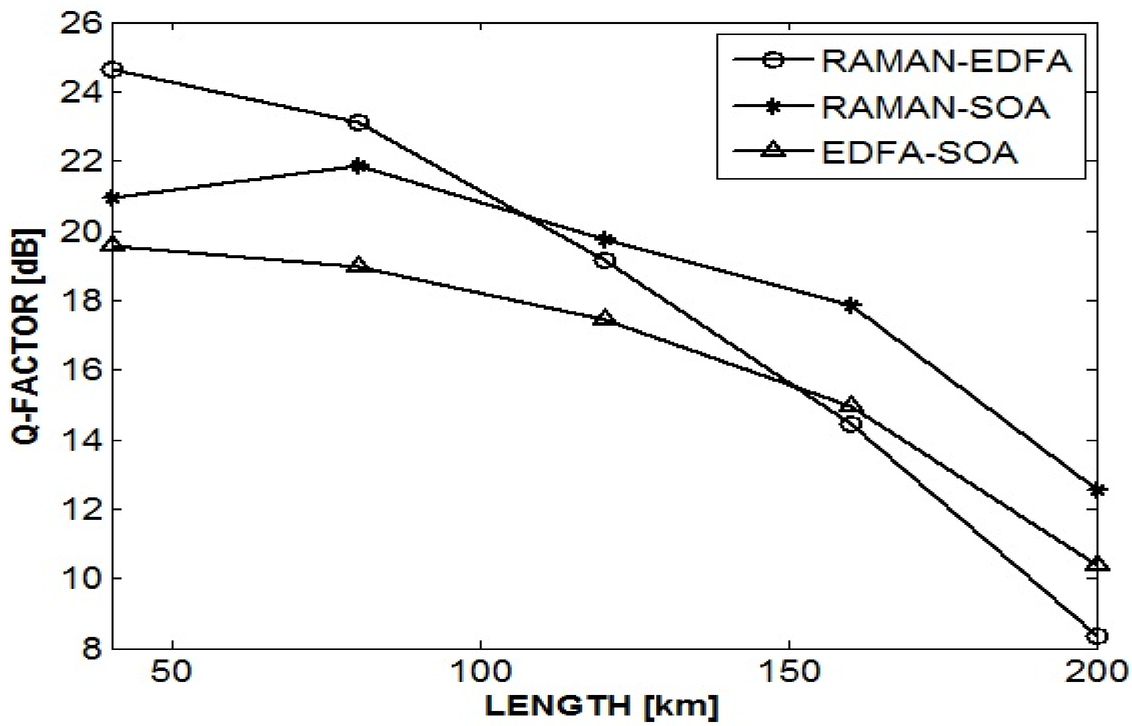

Figure 4.6: Q- factor vs. Length for 32 channels in the presence of nonlinearities

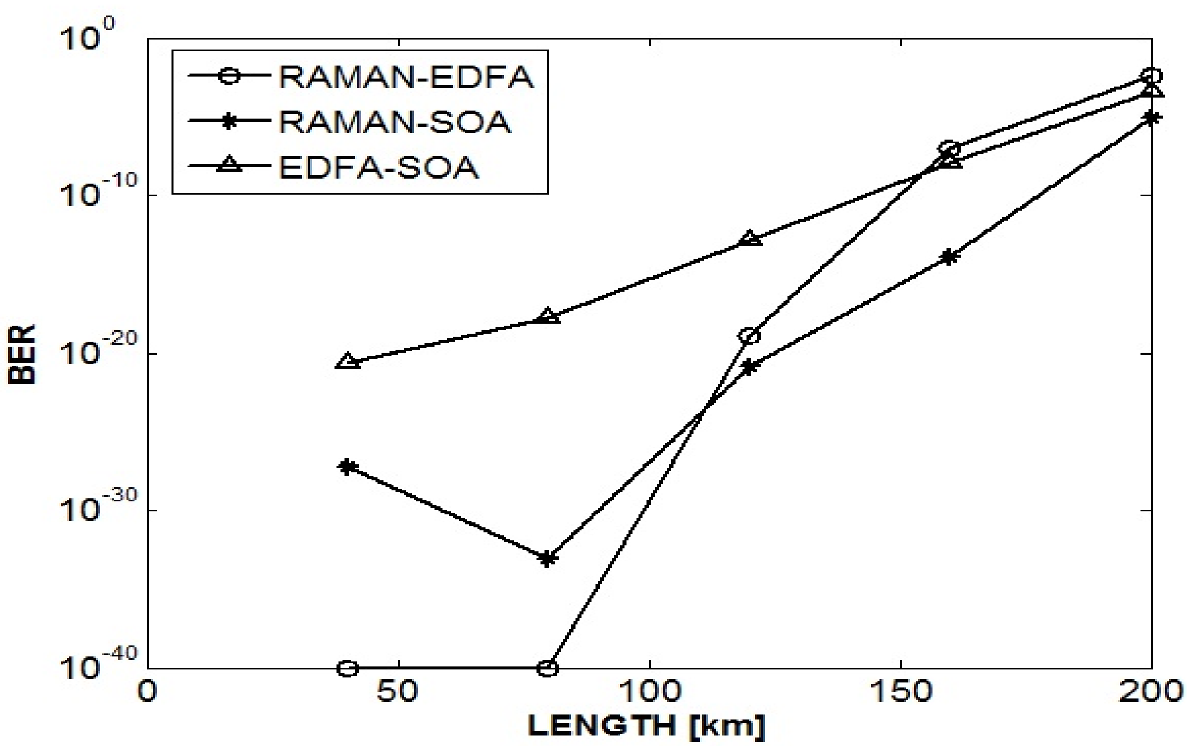

Figure 4.7: BER vs. Length for 32 channels in the presence of nonlinearities

The figure 4.7 shows the graphical representation of BER as a function of length in the presence of nonlinearities. At 40km the better BER is provided by the RAMAN-EDFA amplifier (10^{-40}) and also for the worst case (at 200 Km) it becomes 0.004 .RAMAN-SOA also provides the acceptable result but there is very much variation in BER.It is also observed that at 160km only RAMAN-SOA has BER <10^{-10} .

The variation in BER for RAMAN-EDFA,RAMAN-SOA and EDFA-SOA are 10^{-40} to .004,6.20 X 10^{-28} to 9.16 X 10^{-6} and 2.25 X 10^{-21} to .0004.

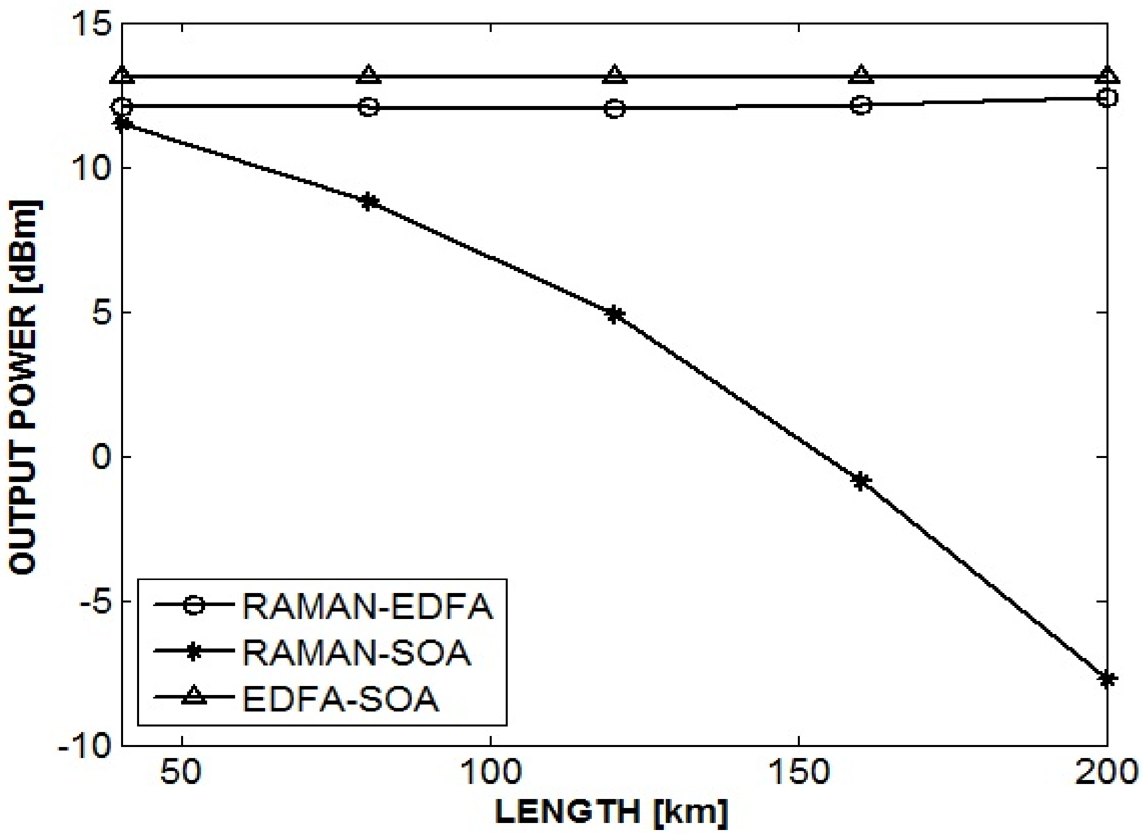

Figure 4.8: Output Power vs. Length for 64 channels in the presence of nonlinearities

The figure 4.8 depicts the plot of output power as a function of length in the presence of nonlinearities. The output power is decreased due to the fiber non-linearities and fiber attenuation. At 40km the better output power is provided by the RAMAN-EDFA and EDFA-SOA amplifier (12.055dBm and 13.134dBm) and also for the worst case (at 200 Km) it becomes 12.381dBm and 13.11dBm.It is observed that output power for RAMAN-EDFA and RAMAN-

SOA remains almost constant for entire distance range .But for RAMAN-SOA output power decreases linearly with distance.

The variation in output power for RAMAN-EDFA, RAMAN-SOA and EDFA-SOA are 12.055 to 12.381dBm, 11.494 to -7.703 dBm and 13.134 to 13.110 dBm respectively.

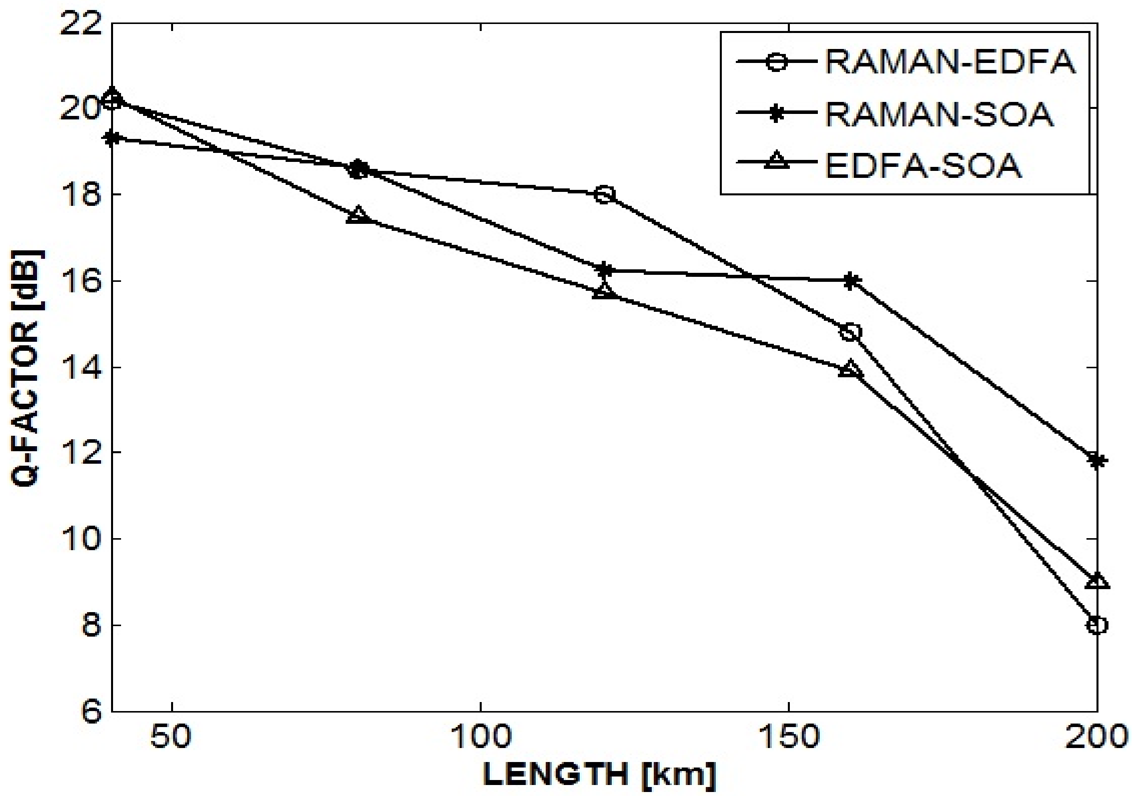

Figure 4.9: Q- factor vs. Length for 64 channels in the presence of nonlinearities

Q-factor vs. Length for 64 channels in the presence of nonlinearities is plotted in figure 4.9. At 40km the better Q factor is provided by the RAMAN-EDFA and RAMAN-SOA amplifier (20.16 dB and 19.31dB) and also for the worst case (at 200 Km) it becomes 7.99 dB and 11.82dB respectively.

The variation in output power for RAMAN-EDFA, RAMAN-SOA and EDFA-SOA are 20.16 to 7.99dB, 19.31 to 11.82 dB and 20.24 to 8.99 dB respectively.

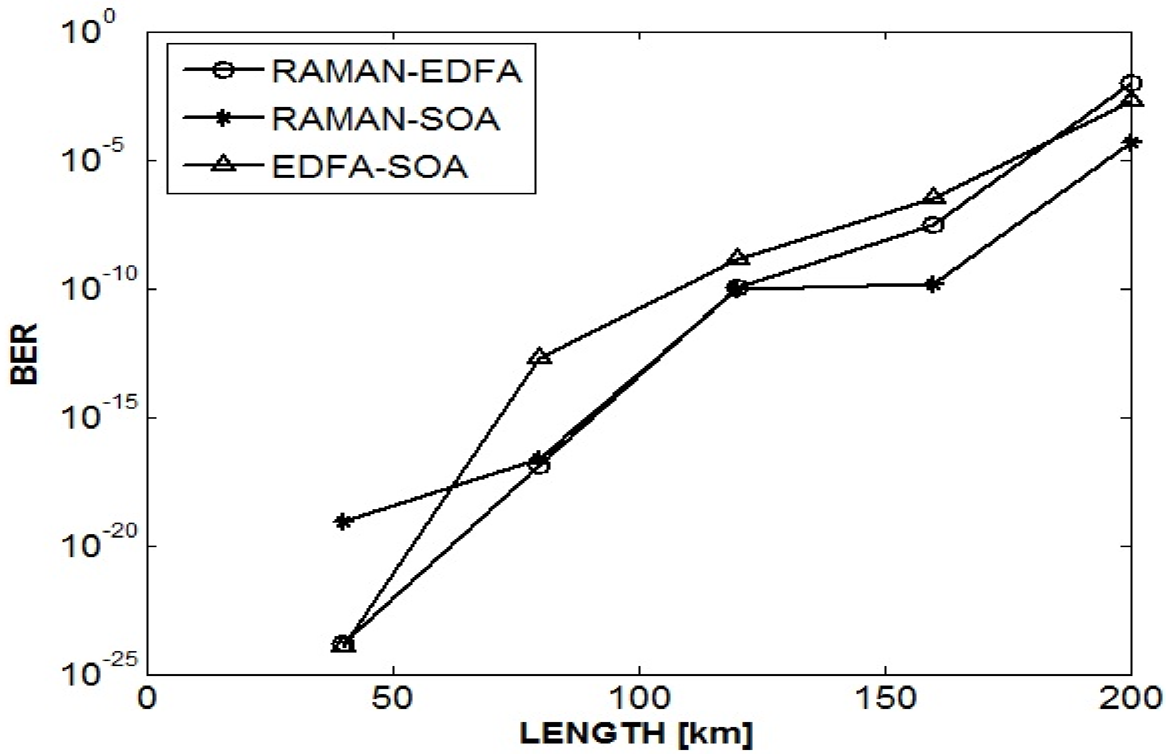

Figure 4.10: BER vs. Length for 64channels in the presence of nonlinearities

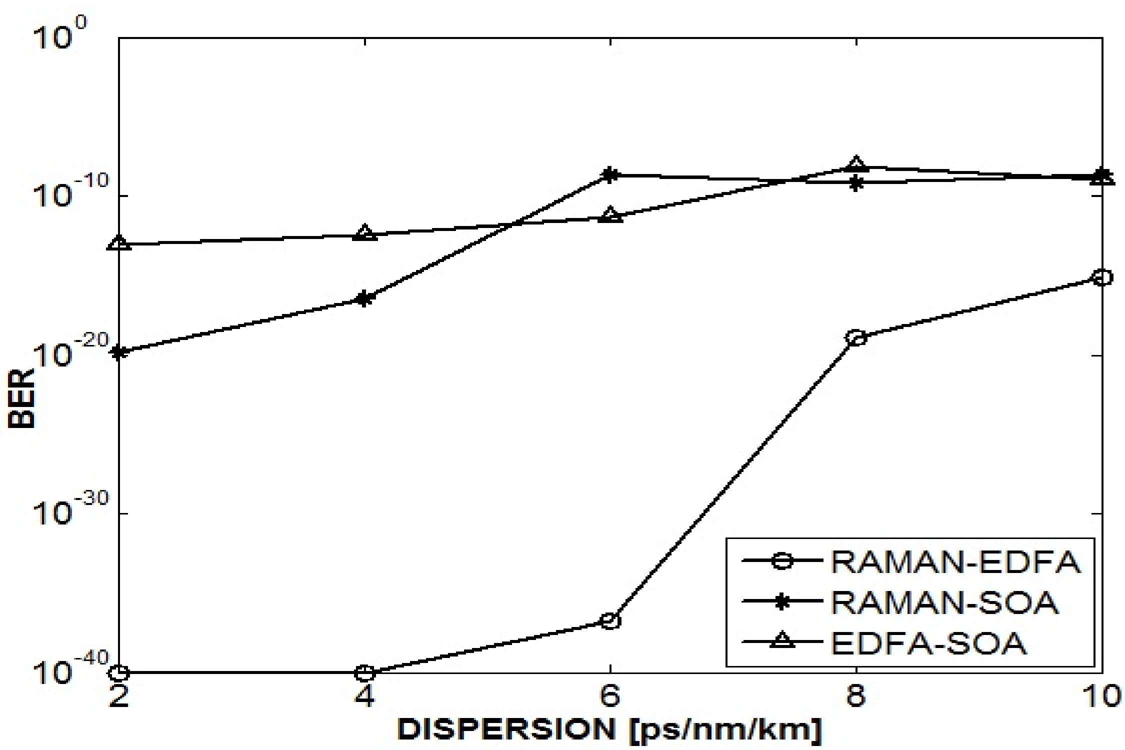

Figure 4.11: BER vs. Dispersion for 16 channels in the presence of nonlinearities

The figure 4.10 shows the graphical representation of BER as a function of length in the presence of nonlinearities. At 40km the better BER is provided by the RAMAN-EDFA and RAMAN-SOA amplifier (1.53 X 10^{-24} **)** and also for the worst case (at 200 Km) it becomes 0.01 The variation in BER for RAMAN-EDFA,RAMAN-SOA and EDFA-SOA are 1.53 X 10^{-24} to .01,8.16 X 10^{-20} to 4.67 X 10^{-5} and 1.07 X 10^{-24} to .002.

In the figure 4.11, BER as the function of dispersion is plotted in the presence of nonlinearities. It is observed that RAMAN-EDFA has the least BER for all the dispersion values ranging 2 to 10 ps/nm/km.The better BER is provided by the RAMAN-EDFA amplifier (10^{-40}) at 40km and also for the worst case (at 200 Km) it becomes 6.685 X 10^{-16}.

The variation in BER for RAMAN-EDFA,RAMAN-SOA and EDFA-SOA are 10^{-40} to 6.685 X 10^{-16},1.334 X 10^{-20} to 2.29 X 10^{-9} and 8.22 X 10^{-14} to 1.11 X 10^{-9}.

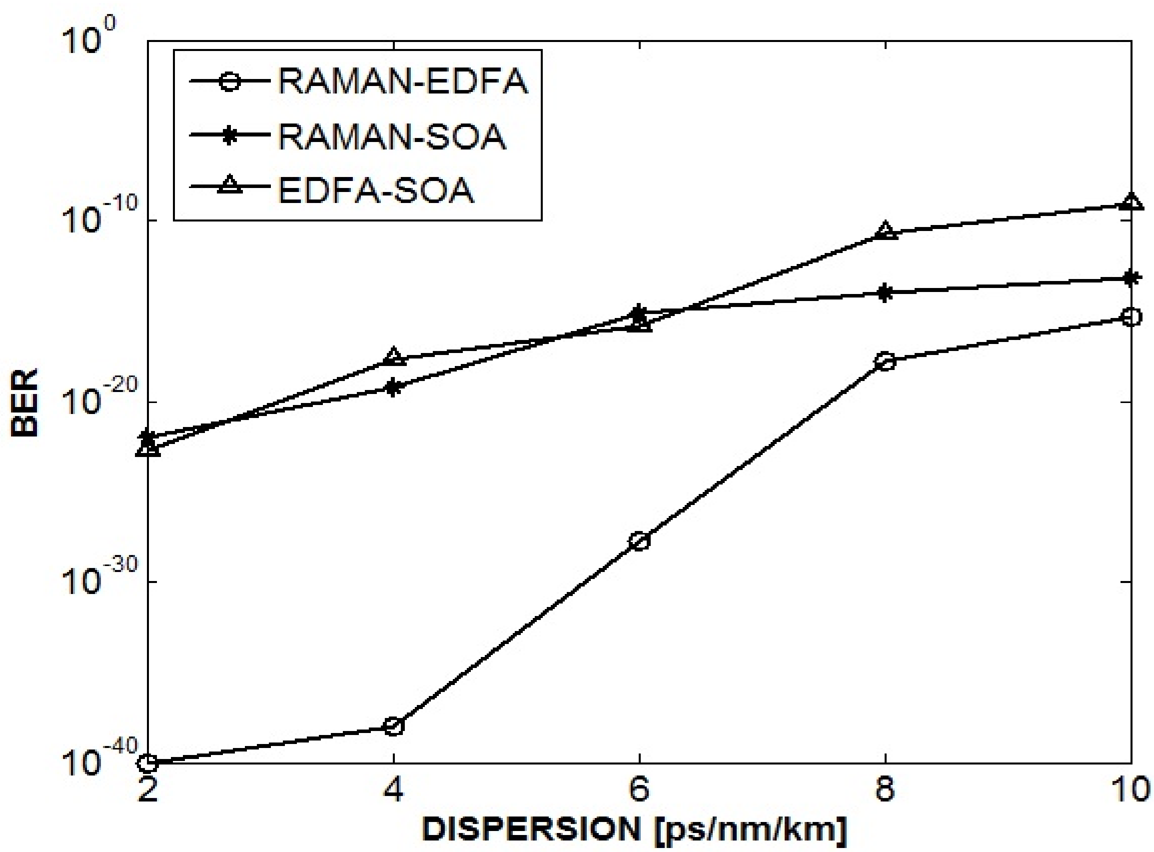

Figure 4.12: BER vs. Dispersion for 32 channels in the presence of nonlinearities

In the figure 4.12 BER vs. dispersion is plotted in the presence of nonlinearities. For all the dispersion values the better BER is provided by the RAMAN-EDFA amplifier .RAMAN-EDFA provides BER of 10^{-40} at dispersion 2ps/nm/km and BER increases with increases in dispersion .For the worst case (at 10ps/nm/km) it becomes 5.08 X 10^{-16} .

The variation in BER for RAMAN-EDFA,RAMAN-SOA and EDFA-SOA are 10^{-40} to 5.08 X 10^{-16},1.03 X 10^{-22} to 5.96 X 10^{-14} and 1.73 X 10^{-23} to 7.76 X 10^{-10}.

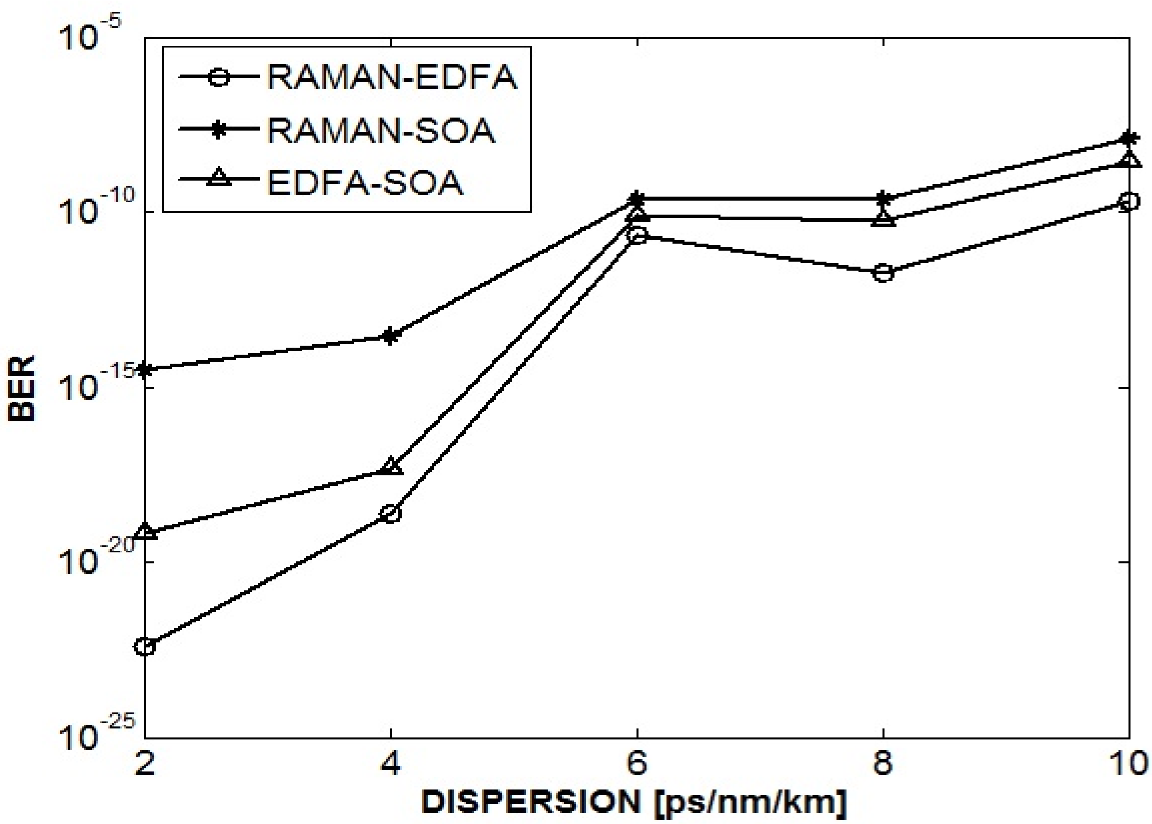

Figure 4.13: BER vs. Dispersion for 64 channels in the presence of nonlinearities

The figure 4.13 shows the graphical representation of BER as a function of dispersion in the presence of nonlinearities. For dispersion values varied from 2 to 10ps/nm/km RAMAN-EDFA provides the better BER.At 2ps/nm/km RAMAN-EDFA provides BER of 3.701 X 10^{-23} and also for the worst case (at 10ps/nm/km) it becomes 2.14 X 10^{-10}.It is also observed that for dispersion 6ps/nm/km all the three confegurations have compareable BER.

The variation in BER for RAMAN-EDFA,RAMAN-SOA and EDFA-SOA are 3.701 X 10^{-23} to 2.14 X 10^{-10},3.19 X 10^{-15} to 1.24 X 10^{-8} and 6.88 X 10^{-20} to 2.71 X 10^{-9}.

4.5 Conclusion

In this chapter, the 16, 32 and 64 X 10Gbps channel WDM system have been investigated for the various hybrid optical amplifiers and the performance has been compared on the basis of transmission distance and dispersion. The performance of hybrid optical amplifier was evaluated using the power level, eye patterns, BER measurement and Q factor. It is observed that for 16 channels RAMAN-SOA provides better result but as the numbers of channels increases then it degrades the performance because gain saturation problem arises due to cross gain modulation, the cross phase modulation and four wave mixing. For 64 channels system RAMAN-EDFA shows best performance in the terms of BER and Q factor.

CHAPTER 5

Optimization of Hybrid Raman/Erbium-Doped Fiber Amplifier for WDM system

5.1 Abstract

In this chapter, Hybrid optical amplifier (RAMAN-EDFA) has been optimized. It is being shown that when the optimized parameters (such as noise figure, output power for EDFA and Raman fiber length, Raman pump wavelength, pump power for RAMAN amplifier) are used then the lesser noise is induced and provide better quality of the signal. The parameters have been optimized in the term of high Q factor and least jitter. Further it observed the maximum single span distance using optimized hybrid optical amplifier.

5.2 Introduction

The growing demand for higher transmission capacity in wavelength division multiplexing (WDM) systems increases, channel speed, number of channels and spectral efficiency need to be upgraded [57]. To overcome these problems optical amplifiers (RAMAN, EDFA, and SOA) are playing an important role. Raman amplifiers have become essential in overcoming the limitations of the bandwidth, noise figure (NF), and output power of conventional doped fiber amplifiers [59].The erbium-doped fiber amplifier (EDFA) has been utilized in WDM systems since the 1980s, for every long-haul or ultra-long-haul fiber-optic transmission system [51] and SOA have ultra wide band spectrum, low power consumption and low cost [49]. The overall performance can be enhanced by cascading two amplifiers, this leads to term Hybrid optical amplifier. Hybrid amplifiers have many advantages over individual amplifiers, like wide gain bandwidth and more flat gain profile [22, 24]. Hybrid amplifier provides high power gain. By appropriately choosing wavelengths and powers of pump signals, Raman fiber amplifiers can provide broader amplification bandwidth and flexible center wavelength compared with pure EDFAs. Hybrid RAMAN-EDFA is a promising technology for future dense wavelength-division-multiplexing (DWDM) multiterabit systems. Hybrid Raman/erbium-doped fiber amplifiers are designed in order to maximize the span length or to minimize the impairments of fiber nonlinearities and to enhance the bandwidth of erbium-doped fiber amplifiers (EDFAs) [60].

Jowan Masum-Thomas *et al.* [22] 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 - 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 achieved a flat gain without the usage of any gain flattening techniques due to the symmetric gain spectra of both amplifiers.

H S Chung *et al.* [28] demonstrated a long-haul transmission of 16 channels X 10Gbit/s over single-mode fiber (Span of 80 km) of 1040 km using combined Raman and linear optical amplifiers as inline amplifiers. All the span length used was 80 km (loss of 16 dB), but the span losses varied from 28 to 34 dB according to some additional loss elements. The measured Q-factors of the 16 channels after 1040 km (12.7–14.5 dB) were higher than the error-free threshold of the standard forward-error correction, which offers feasibility of the hybrid amplifiers including semiconductor optical amplifiers for the long-haul transmission. In this work EDFA is used as a pre-amplifier.

Sun Hyok Chang *et al.* [31] compared the EDFA and Hybrid fiber amplifier (HFA) and reported that HFA can be an alternative to improve the performance of line amplifier instead of EDFA only. They described the configuration of HFA that has low noise figure and high output power. In the transmission experiments with circulating loop, HFA shown better transmission performance than EDFA when it was used as line amplifier. The Q-factor and OSNR (optical signal to noise ratio) in the case of HFA was higher by more than 1.0 dB

A. Guimaraes *et al.* [27] investigated the performance of hybrid optical amplifier when it is used as pre-amplifier and described its application on 40Gbps systems. In this work it is shown that hybrid pre-amplifier provides an improving in the system power penalty of 3.2 dB when compared with the back-to-back values. The higher performance obtained with the hybrid pre-amplifier is due to the fact that they designed the FOPA to operate in the saturated regime, therefore it is acting as a noise limiter.

Single Raman pump wavelength having advantages over multiple pumps wavelengths are: simpler design and thus possible cost savings and Raman gain shape independent on channel loading. A. Carene *et al.* [61] discussed the optimal configuration of hybrid Raman/erbium-doped fiber amplifiers. They has been evaluated a maximum reachable distance as a function of the span length and nonlinear weight, given a target optical signal-to-noise ratio. The single pump signal at 1453 nm with pump power of 1000 mw has been used and covered maximum distance with span length of 50 km.

Johann Gest *et al.* [62] theoretically analyzed the dynamic response of amplifier cascades involving combinations of unclamped and gain-clamped discrete fiber Raman amplifiers (DFRAs) in the worst possible case of power transients. In this paper the discrete fiber RAMAN amplifier is used as a pre-amplifier to increase the system performance. Using the APA technique, they were able to reduce the computation time by at least one order of magnitude compared to the direct Runge‑Kutta approach and with a precision within 2%.

Surinder *et al.* [49] investigated placement of semiconductor optical amplifier for 10 GB/s non-return to zero format in single mode and dispersion-compensated fiber link. In this work power different compensation methods (pre-, post- and symmetrical) for different positions of the SOA in fiber link has been described. The effect of increase in signal input power for these three power compensation methods are compared in terms of eye diagram, bit error rate, eye closure penalty and output received power. It is found that the post-power compensation method is superior to pre- and symmetrical power compensation methods when SOA is used.

The investigation presented in [27] for hybrid optical amplifier is restricted to number of channels and repeater spacing. They have used only one channel and repeater spacing of 49 and 92 km.

In this chapter, the previous work has been extended by increase the single span distance when the optimized hybrid optical amplifier is used which amplifies 64 channels simultaneously. These results have been checked in the term of Q factor, BER and eye closure by varying the transmission distance and dispersion.

The chapter is organized into five sections. After discussion of abstract and introduction of this chapter, the optical simulation setup is described in Section 5.3. In Section 5.4, comparison results have been reported for the different modulation formats and finally in Section 5.5, conclusions are made.

5.3 Simulation Setup

The simulation setup for 64 channels pre-amplified by amplified by hybrid optical amplifier shown in figure 5.1. As shown in figure sixty four signals from CW laser sources, modulated by NRZ format, are transmitted over a medium hall link. The laser power is set to 0 dBm because at higher power the wavelengths tend to overlap each other causing more dominance of non-linear effects like XPM and FWM [49]. The 64 channels (1531.01-1601.56 nm) are spaced at 100 GHz. The input signal spectrum occupies a bandwidth of 6.4 THz. The signals are transmitted over DS-anomalous fiber at different dispersions and distance. The variation of the dispersion is from 2 to 16ps/nm/km and distance is from 50 to 160 km. At the receiver section, the performance of one of the 64 channels is evaluated using the optical spectra, eye diagram and BER and Q value measurement.

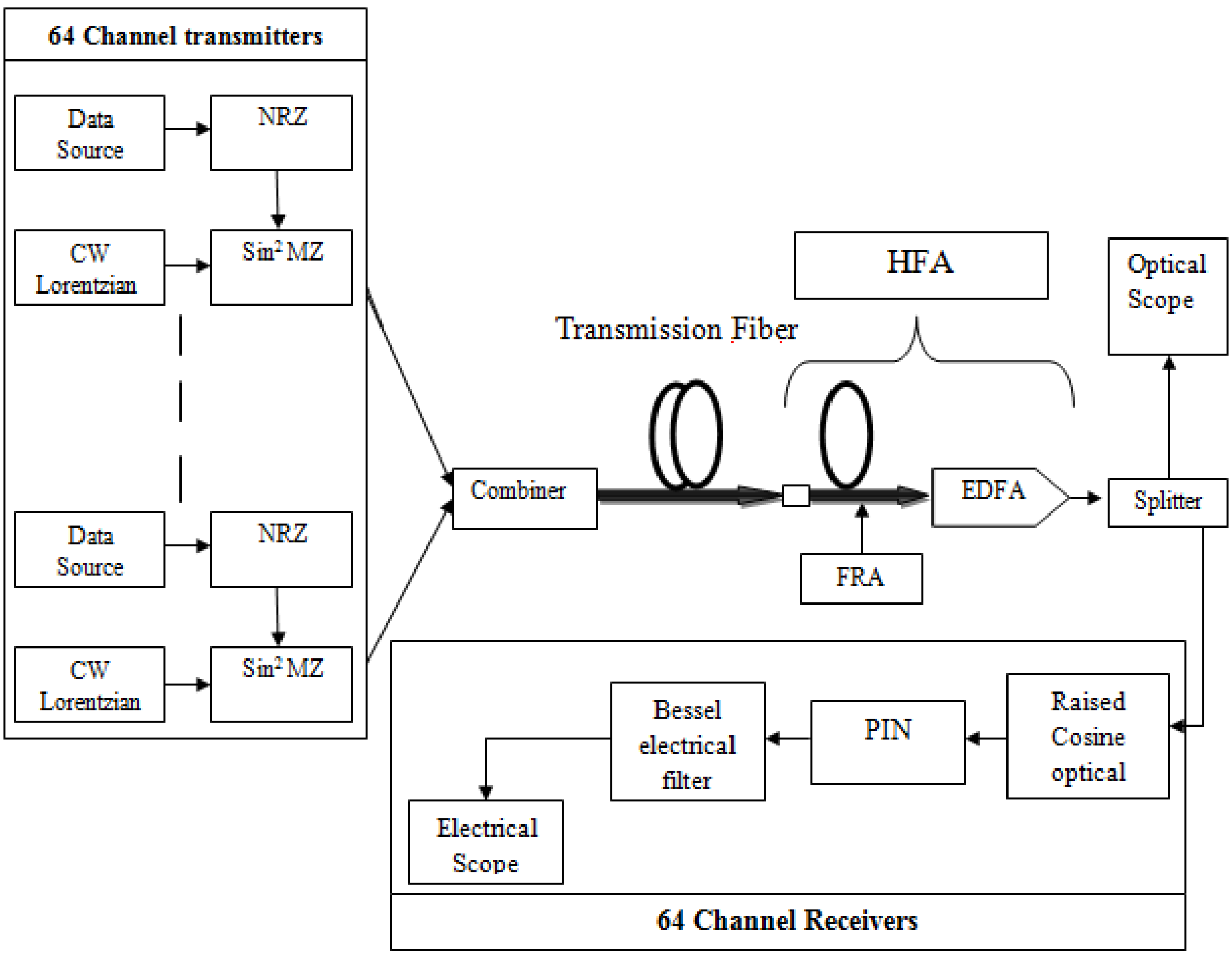

Figure 5.1: Simulation Setup for 64 WDM channels; FBG: Fiber Bragg Grating; FRA: Fiber Raman Amplifier; HFA: Hybrid Fiber Amplifier.

The parameters of basic attribute sections taken are 10Gbps bit rate, number of bit per symbol is 1 and the pseudo-random sequence is selected. Data source simulates a pseudo-random or a deterministic logical signal generator. The period length of the corresponding pseudo-random sequence is 2^D-1 bits, where D is the degree set by the Degree parameter. Electrical driver is converts logical input signal, binary sequences of zeros and ones into an electrical signal. Here we are using NRZ electrical drivers. For NRZ rectangular format the fraction of bit duration is set to 1 and signal dynamics low level is -2.5 and high level is 2.5.

FRA consist a DS- anomalous fiber which is counter pumped by optimized pump wavelength and pump power [61] which is 1453 nm at 1000 mW pump power. In this fiber the non linearity, fiber PMD and fiber birefringence are considered. Here we vary the fiber length from 50 to 160 Km to check optimize the single span distance. The RAMAN amplified signals are further amplified by EDFA.

The fixed output power EDFA with the 20 mW output power and 5 dB noise figure is used to amplify the signals after FRA. The gain shape of EDFA is flat. Maximum small signal gain of the amplifier can give to the signal to ensure the requested output power is 35 dB. These amplifies signals are received by the optical receiver.

PIN photo diodes with Quantum efficiency 0.798 are used to detect the amplified signals.

5.4 Result and Discussion

In this chapter, the 64 channels are used to transmit the data with the speed of 10Gbps which is amplified by hybrid optical amplifier (RAMAN) after covering the single span distance.

Firstly, the parameters of EDFA (noise figure and output power) and RAMAN amplifier (Raman fiber length) have been optimized. The optimization of parameter has been done on the basis of Q factor and jitter. Then further maximum single span distance for different dispersions (2, 4, 8, 16ps/nm/km) using optimized hybrid optical amplifier has been investigated.

Figure 5.2 and 5.3 shows the graphical representation of optimization of noise figure (EDFA parameter) on the basis of Q factor and Jitter. This optimization is also has been done using same setup but without any transmission fiber.

From figure 5.2 and 5.3 it is observed that at 5 dB of noise figure of EDFA, the system provides better results. The results have been observed in the term of Q factor and Jitter.

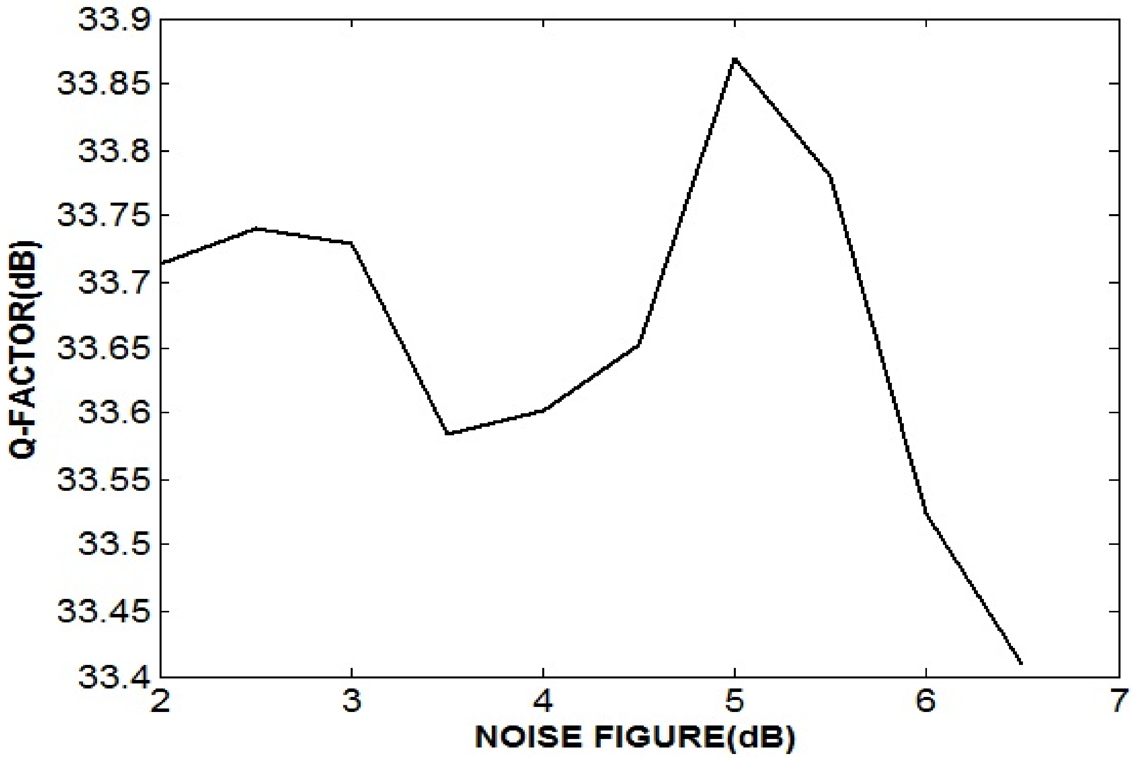

Figure 5.2: Optimization of noise figure in the term of Q Factor

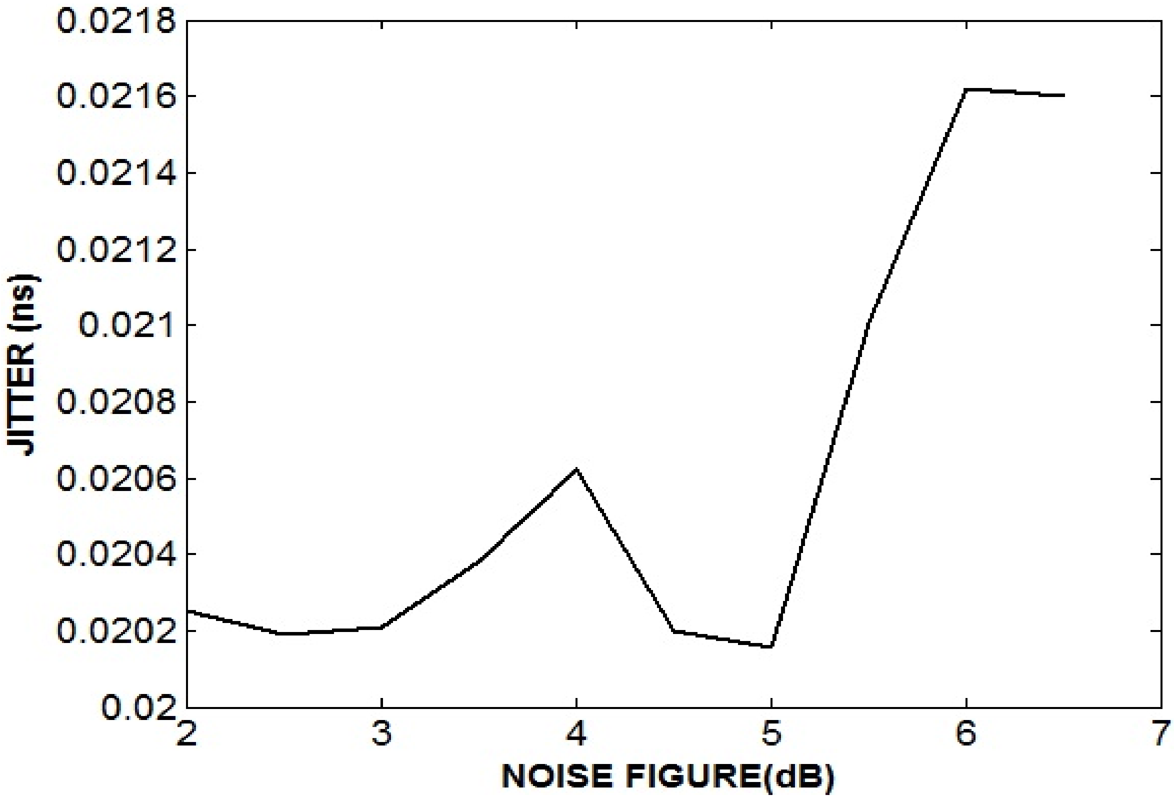

Figure 5.3: Optimization of noise figure in the term of Jitter.

From Figure 5.2 and 5.3 it is observed that. at 5 dB of noise figure the system provide high Q factor (29.70 dB) and least amount of jitter (0.01808 ns). Then 5 dB is the optimized noise figure.

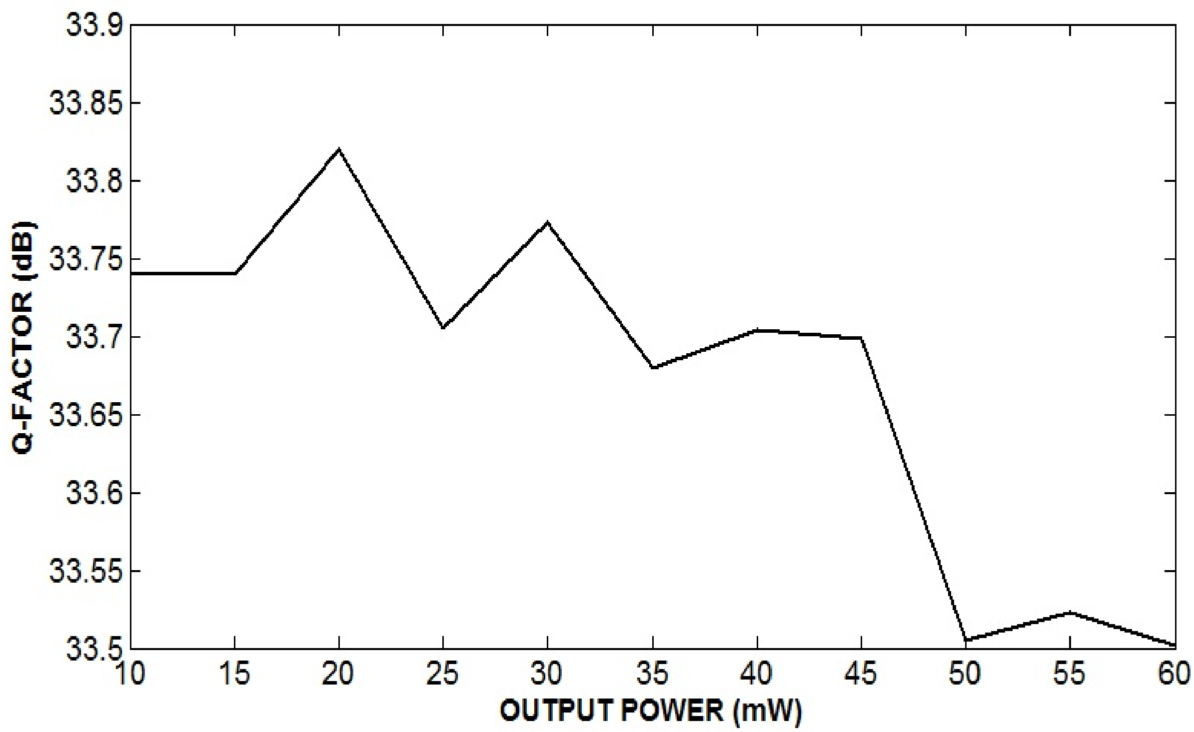

Figure 5.4: Optimization of output power in the term of Q Factor

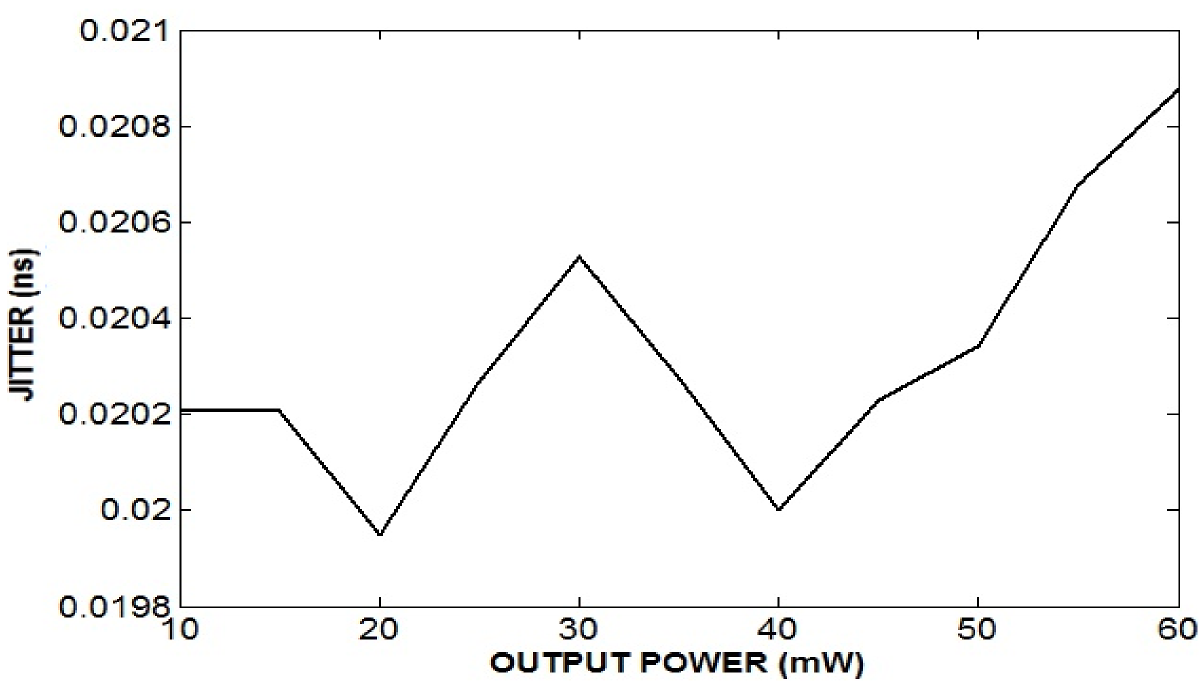

Figure 5.5: Optimization of output power in the term of Jitter.

Further the output power of EDFA has been optimized on the basis of Q factor and jitter as shown in figure 5.3 and 5.4. It is observed that at 20 mW of output power of EDFA, the system provide better results. The results have been observed in the term of Q factor and Jitter. At 20 mW of output power the system provides high Q factor (33.81 dB) and least amount of jitter (0.02019 ns). Then 20 mW is the optimized noise figure.

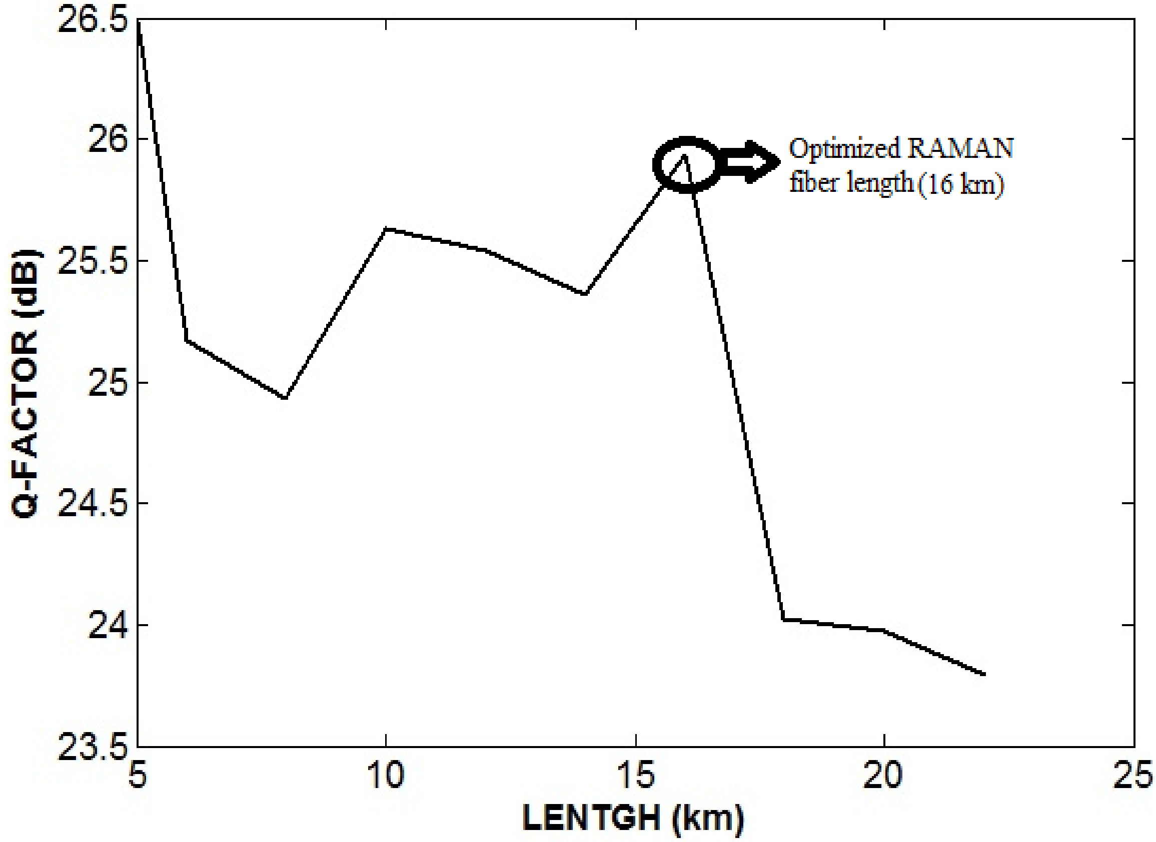

Figure 5.6: Optimization of Raman Fiber Length in the term of Q Factor

Next the RAMAN fiber length has optimized. It is shown that (in figure 5.6 and 5.7) 16 km is the optimized fiber length at which is provide the better results in the term of Q factor and Jitter. At 16 km of Raman fiber length system provide better results as Q factor is 25.93 dB and jitter is 0.01974 ns.

In this setup the RAMAN amplifier is pumped at 1453 nm with 1000 mw of pump power. This optimized pump and power is used by A. Carene *et al.* [61] and shows better result.

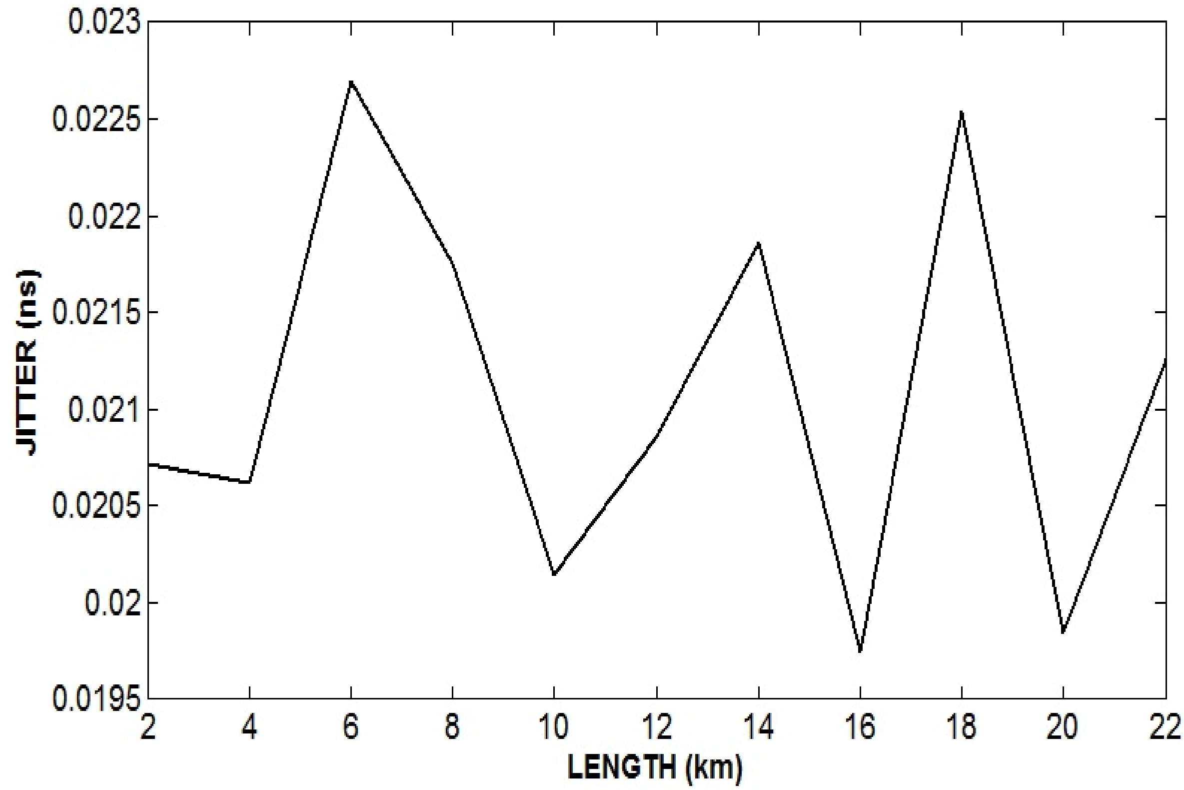

Figure 5.7: Optimization of Raman Fiber Length in the term of Jitter.

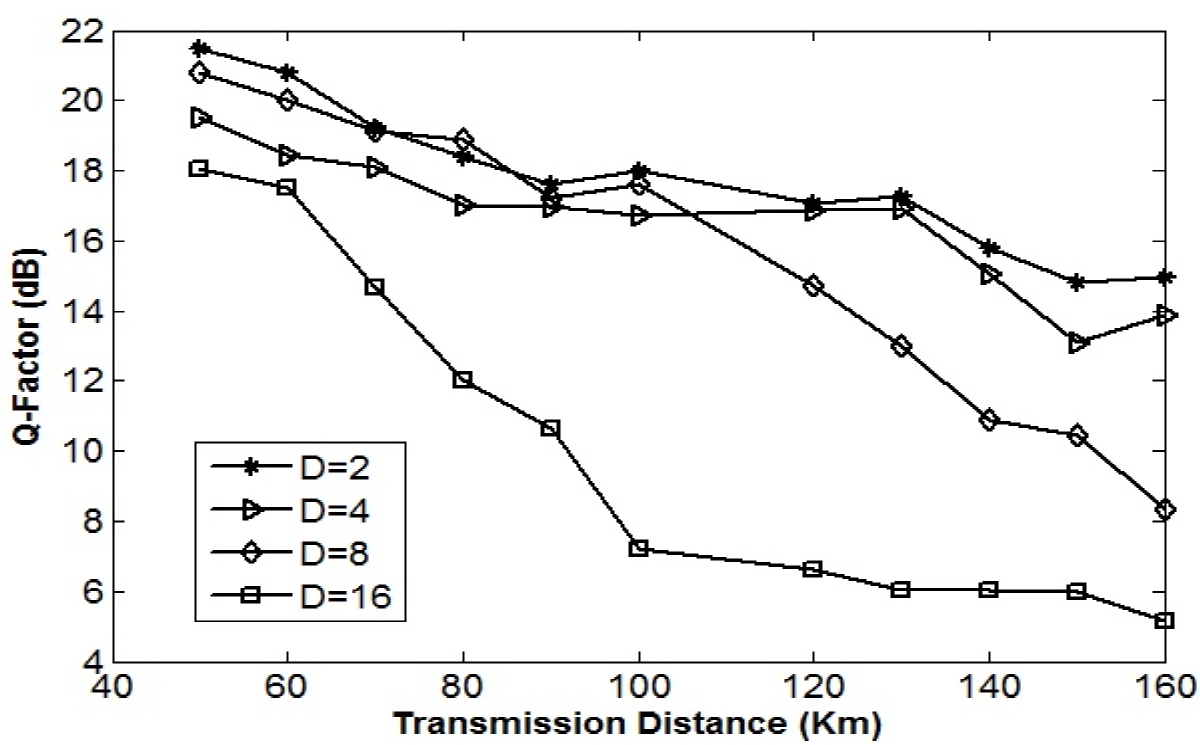

Figure 5.8: Q-Factor versus distance for 64 channels DWDM system.

Further the maximum single span distance by using the optimized hybrid optical amplifier for different dispersions individually has been finding.

The figure 5.8 shows the graphical representation of Q value as a function of transmission distance. Q value can be seen for all the dispersions that as the line is varying from 50 Km to 160 Km then the Q-factor is decreased due to the fiber non-linearities. The better Q value is provided by the dispersion at 2ps/nm/km (21.48 dB) and covered maximum distance (150 km) with the acceptable Q value of 14.82 dB. The other dispersions at 4, 8 and 16ps/nm/km achieved 150, 120 and 70 km of single span distance, respectively

As shown in figure 5.9 the BER is increased as the transmission distance increases. The better BER is provided by the dispersion at 2ps/nm/km (8.67 x 10^{-32}) and covered maximum distance (150 km) with the acceptable BER of 2.61 x 10^{-9}. The other dispersions at 4, 8 and 16ps/nm/km achieved 150, 120 and 70 km of single span distance, respectively.

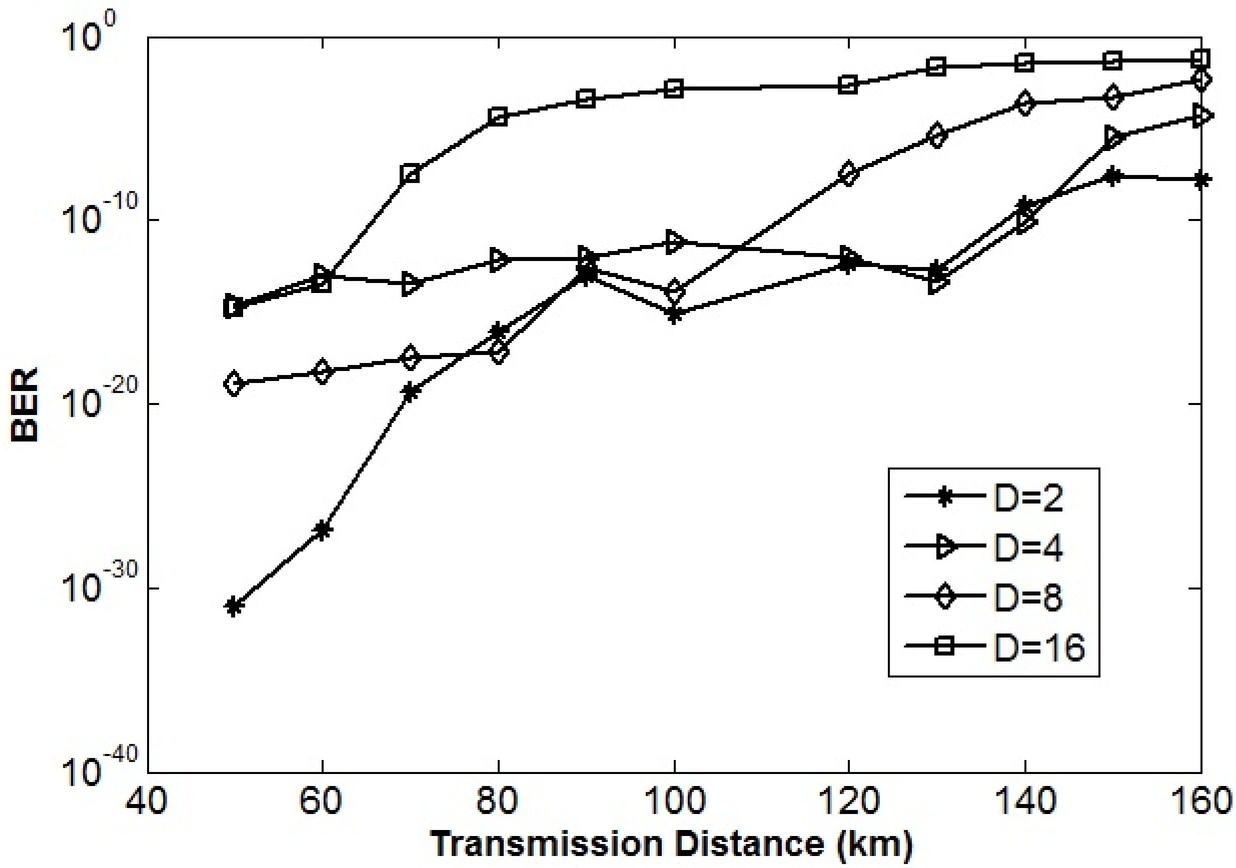

Figure 5.9: Distance versus BER for 64 channels DWDM system.

Figure 5.10 indicates the eye closure penalty which is very high for dispersion 16ps/nm/km because of ASE noise power. It has observed that dispersion at 2ps/nm/km provides least eye closure also in worst case at 150 km (1.979 dB). Means as increases the transmission distance, the eye closure penalty goes on increasing. As the eye closure penalty goes on increase, the quality goes on decreasing.

It is observed from figures that the dispersions at 2 , 4, 8, 16ps/nm/km achieves 150, 150, 120 and 70 km of single span distance respectively with the acceptable Q factor, BER and eye closure.

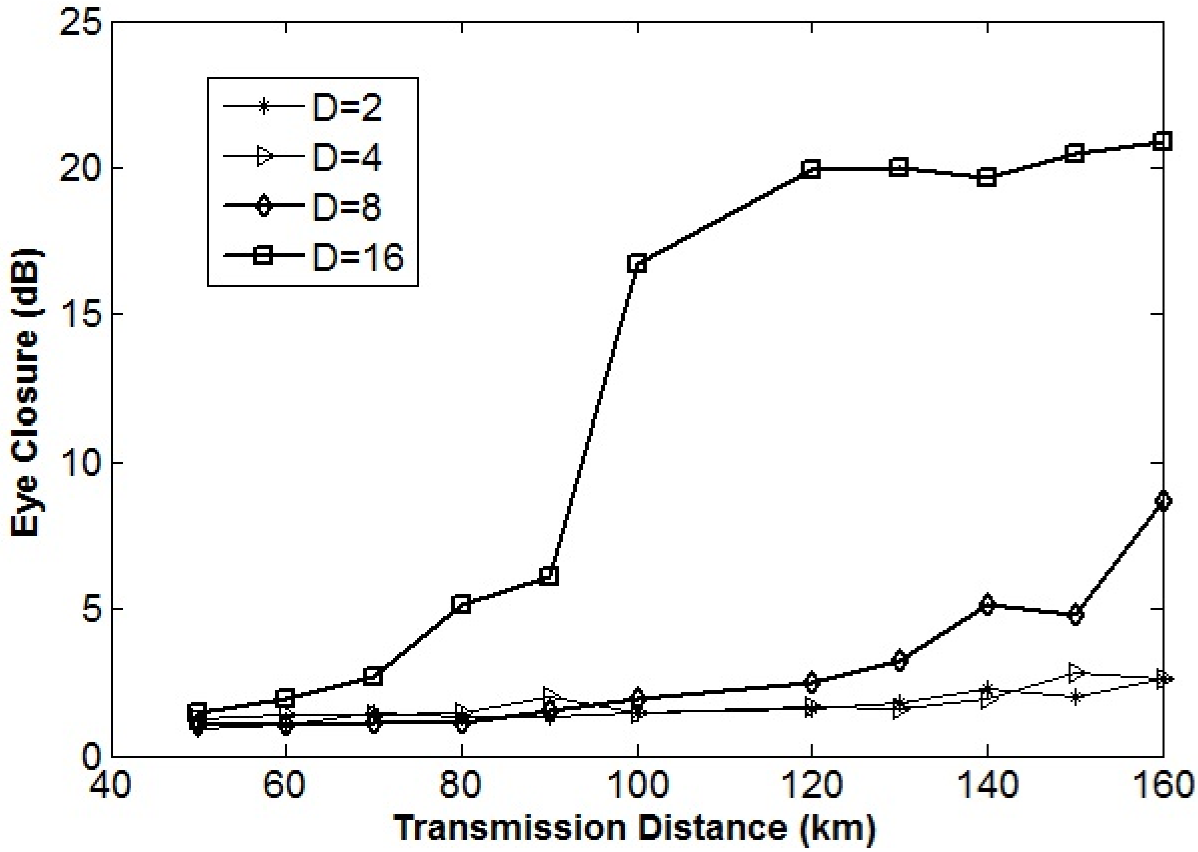

Figure 5.10: Distance vs. Eye Closure for 64 channels DWDM system.

5.5 Conclusion

The all-optical fiber communication optical amplifier plays an important role. To amplify broad bandwidth the hybrid optical amplifier is the best alternative.

In this chapter, the hybrid optical amplifier has been optimized and using it, the performance of 64 channel WDM optical system for different dispersions has been investigated. It is being shown that when the optimized parameters (such as noise figure, output power for EDFA and Raman fiber length, Raman pump wavelength, pump power for RAMAN amplifier) are used the hybrid optical amplifier provide better result. It is observed that using optimized hybrid optical amplifier the dispersions at 2 , 4, 8, 16ps/nm/km achieves 150, 150, 120 and 70 km of single span distance respectively with the acceptable Q factor, BER and eye closure.

CHAPTER 6

Conclusion and Future scope

6.1 Conclusion

In past years, various techniques and methods were presented to flatten the gain of optical amplifiers to push the bit rate and transmission distance longer and longer. The Hybrid Optical amplifiers are the key components for increasing the flexibility and capacity of broadcast optical networks.

In this thesis the performance of optical amplifier and hybrid optical amplifier have been compared for different channels, distances and dispersions. The performance of optical amplifiers was evaluated using the eye patterns, BER measurement, eye opening and Q factor. From the comparison of optical amplifiers (EDFA, SOA, RAMAN) it is conceded that at lesser number of channels the SOA provide better results but as increases the number of channels it degraded the performance because gain saturation problem arises. If increases the dispersion and number of channels then EDFA provides better results than SOA. Also observed that RAMAN amplifier gives low output power than other existing amplifiers and it can be give better results for higher wavelengths. Further, compared the different configuration of hybrid optical amplifier then also concluded that RAMAN-EDFA provides better results.

To achieve better results it is of utmost importance to optimize the optical amplifier. Then the various parameters of hybrid optical amplifier such as Raman pump wavelength (1453 nm), RAMAN pump power (1000 mw), Raman fiber length (16 km), EDFA noise figure (5 dB) and EDFA output power (20 mw) have been optimized. Then further, it has covered 150, 150, 120 and 70 km of single span distance for 2, 4, 8, 16ps/nm/km respectively.

Therefore, this study establishes that the use of optimized optical amplifiers in the optical communication networks results in revolutionary growth of internet traffic for large number of users and long transmission distance.

6.2 Future scope

1. There is need of detailed study for the XGM, XPM, and FWM in Raman amplifier for multichannel WDM transmission system. The structural parameter optimization of EDFA and Raman Amplifier is evaluated by reducing theses nonlinearities in doped fiber amplifiers for long haul WDM transmission at higher bit rate.
2. The research work can be extended for S + C + L band amplification simultaneously using hybrid optical amplifiers.
3. In this work, the optical amplifiers are used as in cascaded form. We can extend this work by using different configuration of optical amplifier for better performance.
4. The hybrid optical amplifiers explored in broadcast topologies including multilevel topologies for increasing number of users.

6.3 Recommendation

1. The hybrid optical amplifier model can be recommended for WDM transmission system as compared to single optical amplifier and complex regenerator.
2. The same setup for hybrid optical amplifier can also be applied to more number of channels. Therefore, with this approach high bit rate distance product is achieved and applicable for wideband optical system.
3. The hybrid optical amplifier is recommended for long haul DWDM transmission system by using cascaded optimized Hybrid amplifiers.

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