Performance Investigation of 64 × 20 Gbps and 100 × 10 Gbps DWDM System using Hybrid Optical Amplification for different Modulation Formats

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Declaration

I, Pardeep Kaur hereby declare that the thesis report entitled, **"Performance Investigation of 64 × 20 Gbps and 100 × 10 Gbps DWDM System using Hybrid Optical Amplification for different Modulation Formats"** is an authentic record of my study carried out as requirement for the award of degree of M.E (Master of Engineering) in Electronics and Communication Engineering Department, Thapar University, Patiala under the guidance of Dr. Hardeep Singh during January to June 2016

The matter presented in this report has not been submitted in any other university or institute for the award of any degree.

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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. In this chapter, WDM systems at 64 and 100 channels have been investigated at 20 Gbps and 10 Gbps date rates respectively, with Raman-EDFA amplifier and the performance has been investigated and compared on the basis of transmission distance and dispersion with and without nonlinearities for different modulation formats. Dual stage amplification is also observed for Raman-EDFA. It is observed that distributed RAMAN Amplifier provides flat gain spectra for narrow spaced channels and EDFA as second stage amplifier offers high gain. Further DWDM systems are compared base on modulation formats. Sixty four channels DWDM system is compared using NRZ, RZ and DPSK, while 100 channel DWDM system is investigated for NRZ and RZ in terms of quality factor, bit error rate and eye height. It observed that RZ offer good quality factor (minimum 14 and maximum 24.5), less eye closure (maximum 2.69), tolerable bit error rate (3.875 × 108) at individual distance as compared to other formats. Further we investigated gain performance of HOA (Raman EDFA) after each stage (first stage Raman amplifier and second stage EDFA provides gain nearby 5 dB and 17 dB respectively).

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List of Abbreviations

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

SNR	Signal to noise ratio
SOA	Semiconductor Optical Amplifier
SPM	Self-Phase Modulation
SRS	Stimulated Raman Scattering
SSF	Split step Fourier
SWB-HA	Seamless wide band HA
WDM	Wavelength division multiplexing
WLAN	Wireless local area networks
XPM	Cross-phase modulation

List of Symbols

λ	Wavelength of light
c	Velocity of light
h	Plank constant
µm	Micro meter
nm	Nano meter
ps	Pico second
km	kilometre
dB	Decibel
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	modulating current
β	modulation sensitivity
L	the fiber length
ω	angular frequency

Chapter 1

Introduction

1.1 Development of optical communication system (OCS)

Separated by a few kilometres or by long-haul distances, a communication network commits transformation of information from one place to another. An electromagnetic carrier wave, whose frequency may vary from a few megahertz to several hundred THz, carries the information signal. OCS uses high carrier frequencies upto100 (THz) in the infrared or visible constituency of electromagnetic spectrum. Optical communication sometimes called light wave system so as to discriminate it from microwave communication system, whose carrier frequency is smaller than former approximately 1 GHz. Fiber optical communication (FOC) systems are light wave systems that employ optical fibers for information transmission. High carrier frequency is used in optical fibers by virtue of which information capacity of communication system is increased by a factor of up to 10^3. This fact of increase in capacity can be understood by considering that optical fiber, is communication channel have very large BW, due to which it supports light wave to travel that carry the information signal. With 1% as the limiting value, FOC have the potential of carrying info at bit rates up to 1 Tbps [1].

1.1.1 Basic Block Diagram of OCS

As shown in Figure 1(a), the generic block diagram for an OCS. Common to all communication systems it consists of three elements: a transmitter, channel, and a receiver. Guided and unguided are two broad categories of Optical communication systems. For guided light system, optical beam emitted by the transmitter remains spatially restrained by using optical fibers. Since all guided optical communication systems currently use optical fibers, the commonly used term for them is fiber-optic communication systems. Optical transmitter is the phase of communication at which modulation of optical carrier signal is modulated according to the message signal as shown in the figure 1.1 (b). Optical signal and electrical input signal are provided to the modulator. Modulator superimposes the input signal on high frequency signal that is light wave. Then signal is ready to transmit through channel. Channel coupler is used as connector to couple the modulated signal to channel.

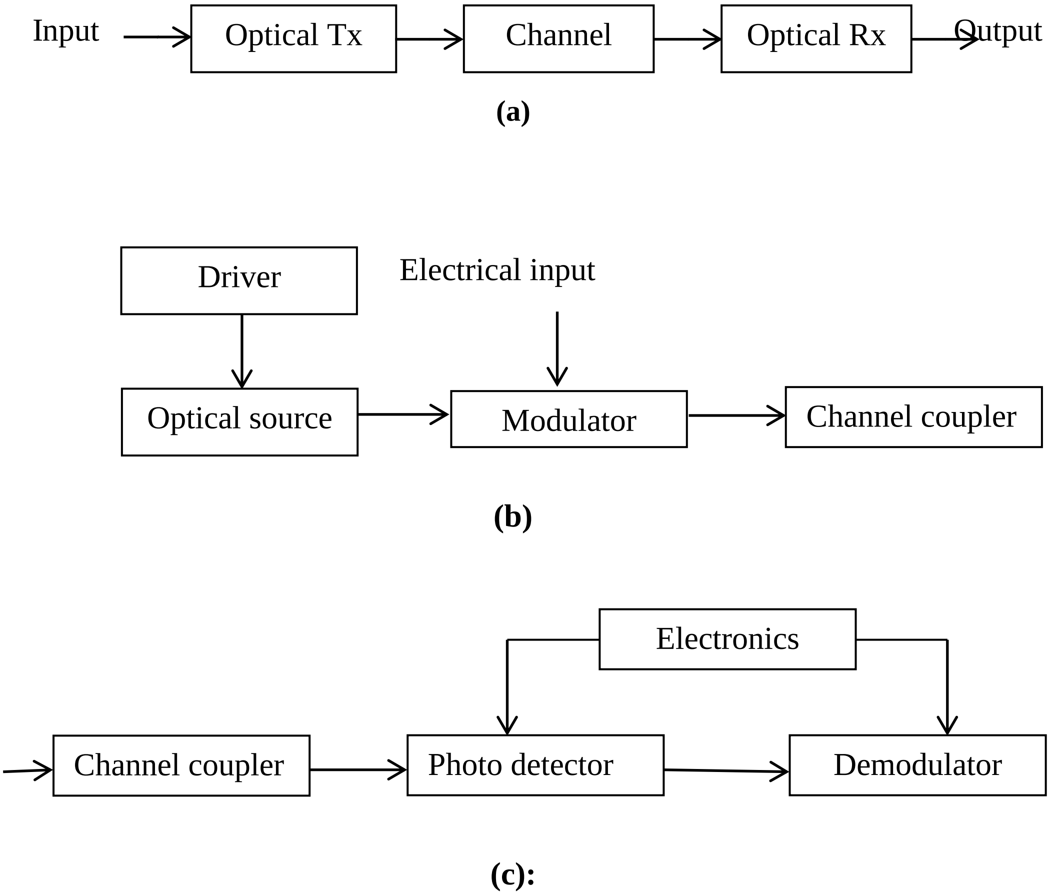


Figure 1.1 (a) Block diagram of optical communication system; (b) Optical transmitter; (c) Optical Receiver Components

Similarly communication channel transports the optical signal from transmitter to receiver without interference. FOC systems use optical fibers the communication channel because silica fibers can transmit light with small fatalities approximately 0.2 dB/Km. Even then, optical power reduces to only one per cent after hundred Km. Losses are still a chief design topic and require the repeater or amplifier in long-haul light wave system. Optical receiver consist channel coupler followed by photo detector and demodulator as shown in Figure 1.1 (c). Photo detector converts modulated optical signal into electrical signal. This electrical signal is then passed to modulator for demodulation.

By the progressions in the communication systems, there is a need for huge bandwidth to send more data at higher speeds. High speed network for voice and multimedia service areas are demanded by domestic users. Corporate subscribers demand broadband setup so that they can prolong LAN to the Internet [2]. This needs the higher capacity network at lower costs. FOC gives the key for higher bandwidth. By using the ON, enhanced transmission capacity at longer transmission distance can be realized. To attain this, these ON will be required fast and proficient wave-length conversion, multiplexing, optical splitter, optical combiner, arithmetic processing and add-drop function and so on [3]. In fiber optic communication, optical signal loses its strength due the fact that losses takes place with increase in transmission distance. Loss limitation can be improved by using optoelectronic conversion, using this approach amplification of signal is done after converting into electrical signal and then again transmitted for communication after reconversion into optical signal. But this approach becomes complex when large number of wavelengths are transmitted over single fiber. To solve this problem an alternative approach is used which directly amplify the transmitter optical signal without converting it into electric forms, called optical amplification and appropriate device is called optical amplifier. The optical amplifiers are used in three modes inline, power booster and pre-amplifiers. The OA are mainly used for amplification of all channels simultaneously in WDM light wave system known as optical in-line amplifiers. OAs are also bit rate transparent and also can amplify signals at different wavelengths simultaneously and they increases the transmitter power by placing an amplifier just after transmitter called power booster amplifier. The transmission spaces can also be increased by putting an amplifier just before the receiver to boost up the received power.

Attenuation in fiber results in the poor quality of signal. When one is designing a communication network for long haul communication, he has to consider the attenuation effects with transmitter (Tx) efficiency and receiver (Rx) sensitivity. Rx's sensitivity is the least power mandatory for a Rx to detect the signal. Let $P(L)$ be the power of the optical pulse at distance L Km from Tx and α be the attenuation constant of the fiber (in dB/Km). Attenuation is characterized by [1]:

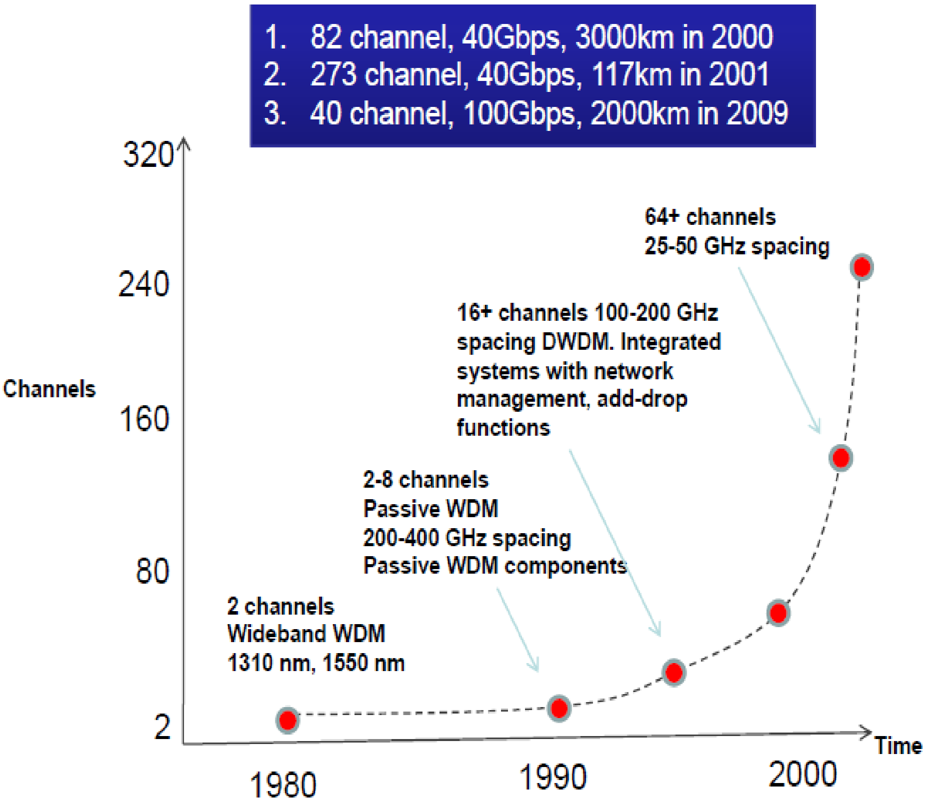
$$P(L) = 10^{-\alpha L/10} \times P(0) \qquad (1)$$

Where $P(0)$ is the optical power at the Tx, For a link length of L Km, $P(L)$ must be greater than or equal to $P(r)$, the receiver sensitivity. The maximum distance be tween the Tx and the Rx depends more heavily on the constant α than on the optical power at the input of Tx.

$$L_{max}= \frac{10}{\alpha}\log_{10}\frac{P(0)}{P(r)}. \qquad (2)$$

1.2 Development of WDM Technology

First WDM initiated in the late 1980s using the two widely spaced wavelengths in the 1310 nm and 1550 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 reached 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 1.2.

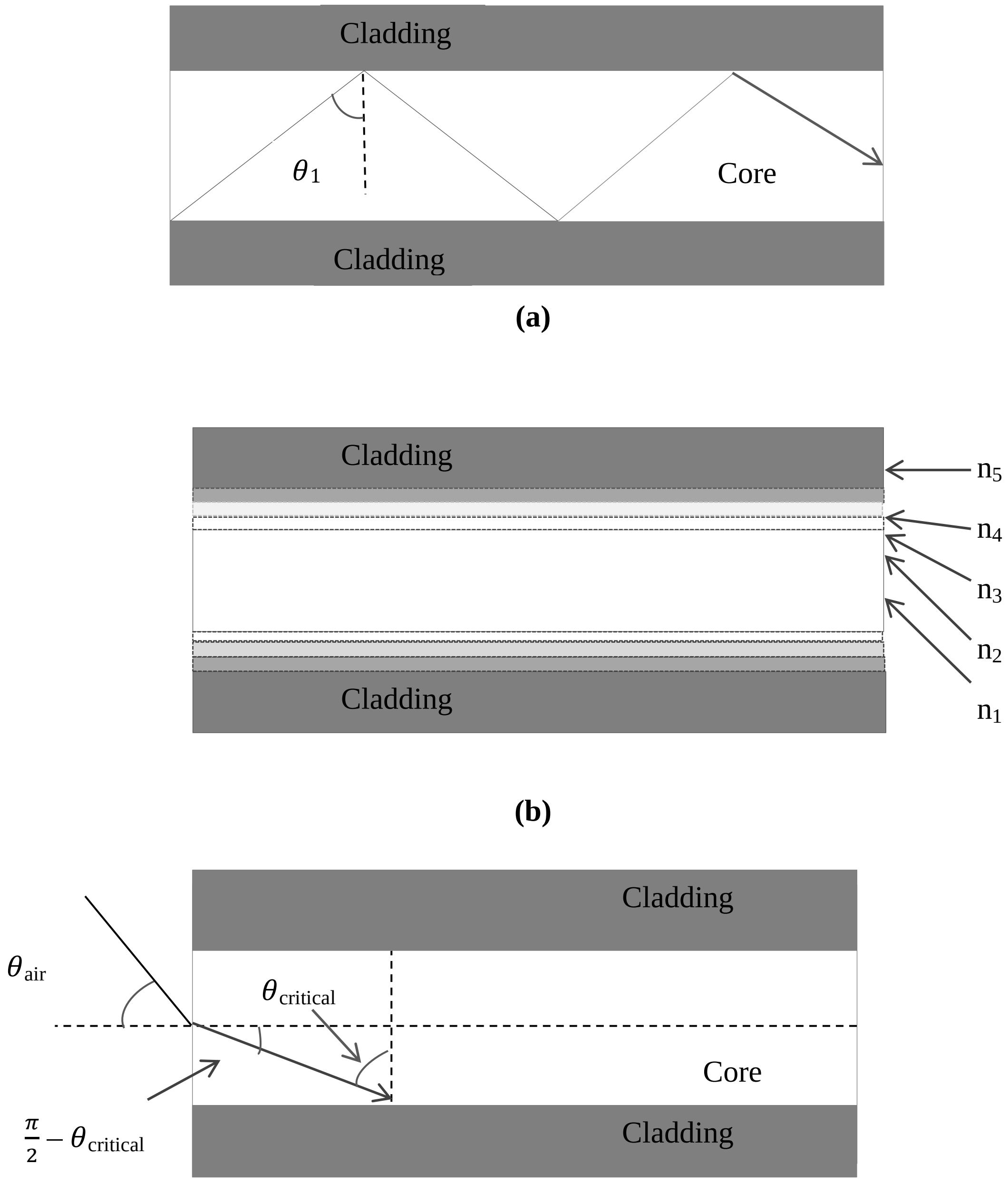


1. 82 channel, 40Gbps, 3000km in 2000
2. 273 channel, 40Gbps, 117km in 2001
3. 40 channel, 100Gbps, 2000km in 2009

Figure 1.2 Developments in WDM Technology [4]

1.3 Optical Transmission in Fiber

Before start discussing about optical components, it is necessary to understand the features of the optical fiber. Optical fiber or cable is basically thin filament made of glass material [5].



(a)

(b)

(c)

Figure 1.3 : TIR in Fiber :(a) Propagation of light through fiber using total internal reflection; (b) Graded-index optical fiber; (c) Numerical Aperture of optical fiber.

Due to the sensation of total internal reflection, light can propagate the length of a fiber with little loss, which is illuminated as following [6]. Speed of light in vacuum is c = 3×10^8 m/sec. speed of light in any other transparent material is less than its speed in vacuum. The refractive index (n) of a materia is measured by this equation [7]:

$$n = \frac{c}{v} \qquad (3)$$

Refractive index of glass is 1.5 and velocity of light in the glass is 2×10^8 m/sec, it results in propagation delay of 5µsec/Km [5]. When signal propagates from one material to another material (both materials having different refractive index), refraction of light signal takes place. The refractive index of both material and the angle at which light incident on the material decides the angle of refraction in second material [6]. If n_1 and n_2 are the refractive indices of material one and two respectively; θ_1 is the angle of incidence, θ_2 is the angle of light in second material. Snell's Law defines the relation between these parameters as: $n_1 \sin\theta_1 = n_2 \sin\theta_2$.

In Figures 1.3(a), we can see that the fiber comprises of a core fully enclosed by a cladding (together the core and cladding made of glass with different refractive indices). Fibers are of two types step index fiber and graded index fiber. in the first type the change in the refractive index from cladding to core is step change, but in second case refractive index changes gradually. If the cladding refractive index is less than that of the core the process of TIR takes place and the particular angle above which TIR takes place is called critical angle and is given by θ_1 (angle of incidence at core) which results in θ_2 (angle at cladding) becomes $\frac{\pi}{2}$ and according to Snell's Law:

$$\sin\theta_1 = \frac{n_2}{n_1}\sin\theta_2 \qquad (4)$$

$$\theta_{\text{Critical}} = \sin^{-1}\left(\frac{n_2}{n_1}\right) \qquad (5)$$

Angle of incidence should be greater than critical angle for TIR means $\theta_1 > \theta_{\text{Critical}}$. 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 $n_i > n_{i+1}$ as shown in fig 1.3(b). A graded index fiber reduces the minimum θ_{Critical} required for

TIR, and also helps to decrease the intermodal dispersion [7]. 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 TIR can take place at the core-cladding boundary [7].

As shown in Figure 1.3(c), the maximum value of θ_{air} can be derived from:

$$n_1 \sin\theta_1 = n_2 \sin\left(\frac{\pi}{2} - \theta_{critical}\right)$$
$$= n_1\sqrt{1 - \sin^2\theta_{critical}} \qquad (6)$$

Using equation (5), we can rewrite (6) as

$$n_{air} \sin\theta_{air} = \sqrt{{n_1}^2 - {n_2}^2} \qquad (7)$$

$n_{air} \sin\theta_{air}$ is referred to as numerical aperture denoted by NA and θ_{air} is extreme angle with respect to the normal at the air-core boundary, so that the incident light that enters the core will experience TIR inside the fiber.

1.4 Optical Amplifier

1.4.1 Principle of OA

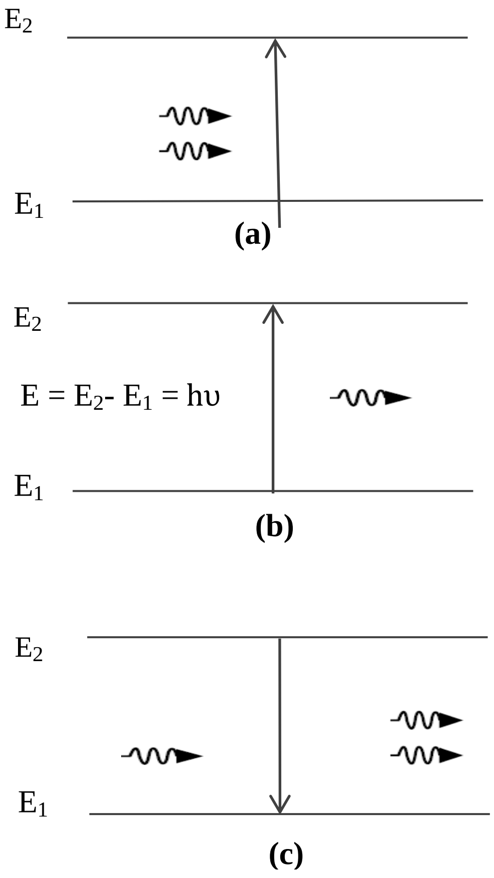


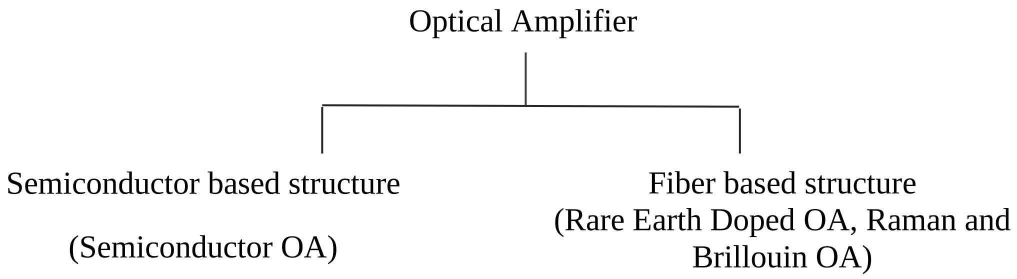
Figure: 1.4 (a) Absorption; (b) Spontaneous emission; (c) Stimulated emission;

Atom exists in certain discrete energy state, absorption and emission of light cause them to make a transition from one 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 1.4 (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 1.4(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 1.4(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 $E = \frac{hc}{\lambda}$ interact with electron in upper energy state causing it to return back into lower state with creation of second photon as shown in Figure 1.4(c), where h is Plank constant, c is velocity of light and λ is the wavelength of light [3]. The light amplification occurs, incidents 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.

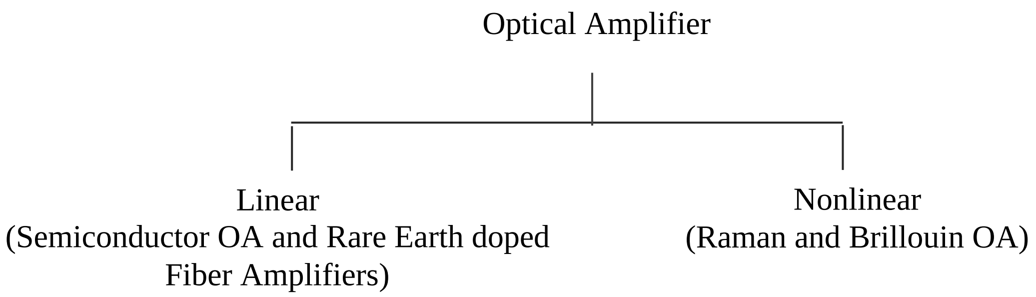
1.4.2 Types of Optical Amplifiers

Optical amplifiers are the basic need of today’s vast communication. There are so many types of optical amplifiers:

Based on their structure:



Based on their characteristics :



1.4.2.1 SOA

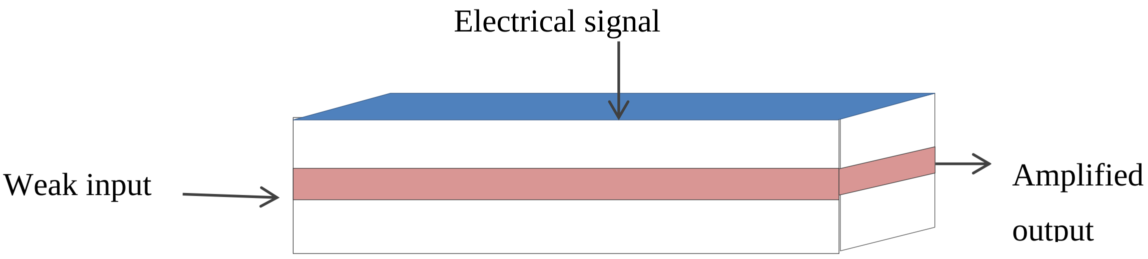


Figure 1.5: Semiconductor Optical Amplifier

Semiconductor optical amplifier (SOA) 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. SOA’s are typically used as power boosters following the source; provide optical amplification for long distance communications; preamplifiers before the photo detector. Semiconductor amplifiers are portable amplifiers because SOA can integrated in ICs.

SOA’s are typically used in the following:

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

1.4.2.2 EDFA

The (Erbium doped fiber amplifiers) EDFA comprises of three components: EDFA fiber, pump signal source and WDM coupler to combine the signal and pump wavelengths as shown in Figure 1.6. The optimum fiber length used depends upon the pump power, input signal power, amount of erbium doping and pumping wavelength [1]. EDFAs can be used in OFC systems because of their compatibility with optical fiber. An EDFA has a reasonably wide wavelength range of amplification making it useful as transmission amplifier in WDM systems. Ideally EDFA is capable of amplifying all the wavelengths ranging from 1500 to 1600 nm. However practically there are two windows of wavelengths that are C and L band. This allows the data signal to stimulate the excited atoms to release photons [4]. Most erbium doped fiber amplifiers (EDFAs) are pumped by lasers with a wavelength of either 980 nm or 1480 nm [4]. 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. 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.

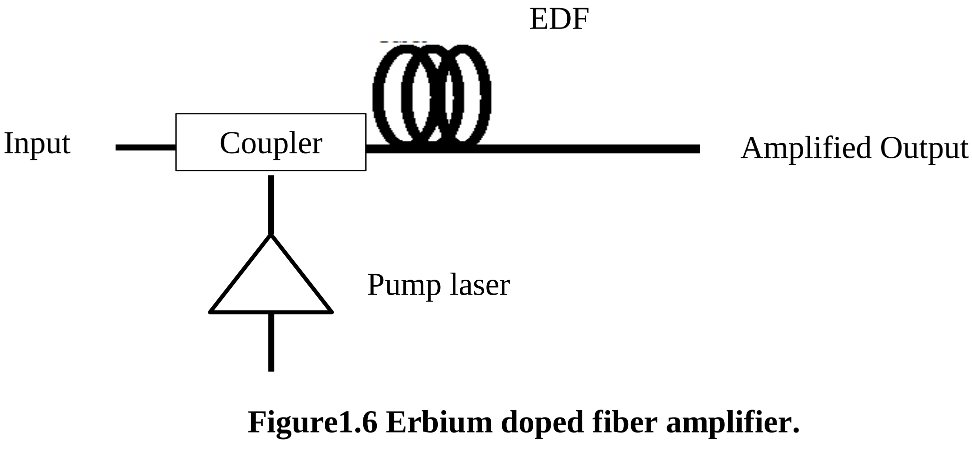
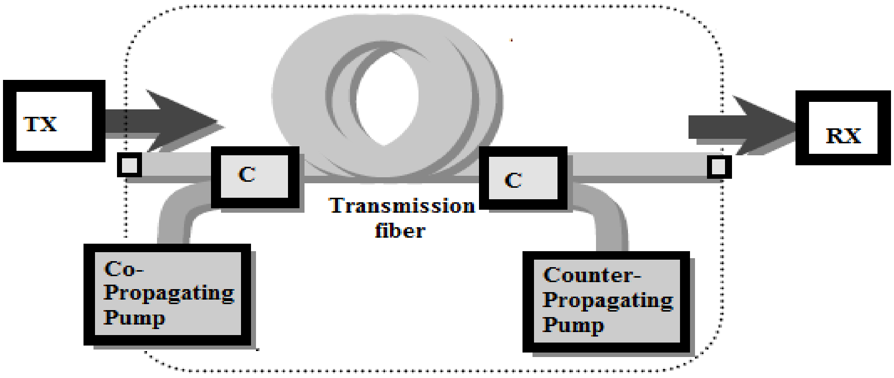


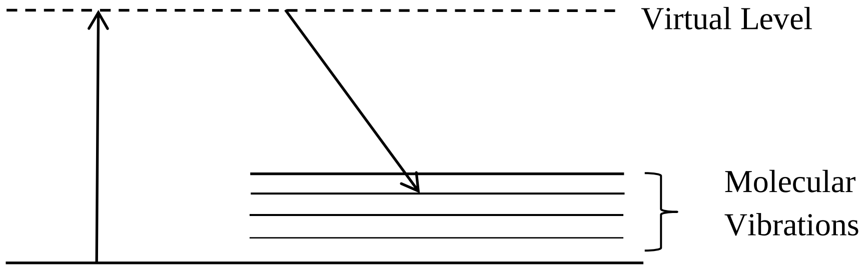
Figure1.6 Erbium doped fiber amplifier.

1.4.2.3 Raman Amplifier

Raman amplifier's signal gain is based on the principle of transfer of energy from one signal to another via phonon. A phonon arises when a beam of light couples with the vibration modes of the medium. In this situation the optical is the amplifying medium making the gain provided by Raman amplifiers reliant on the optical fiber's composition. For silica fibers, the Raman gain BW is over 260 nm, with the foremost peak arising at 86 nm from the pump wavelength. This makes Raman gain available across the entire transmission spectrum of the fiber with the provision that a suitable pump source is available. The gain presented by the Raman Effect in fused silica glass is polarization dependent; so, 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 described in fundamental advantages of RFA. 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 for the entire transparency region of the fiber. The third benefit of RFA is that the gain spectrum can be tailored by fine-tuning the pump wavelengths. For illustration, manifold pump lines can be used to enhance the optical BW and the pump distribution, determines the gain flatness. Raman amplification has also advantage of its relatively wide band amplifier with a BW > 5 THz and also the gain is sensibly flat over a wide spectra.



(a)



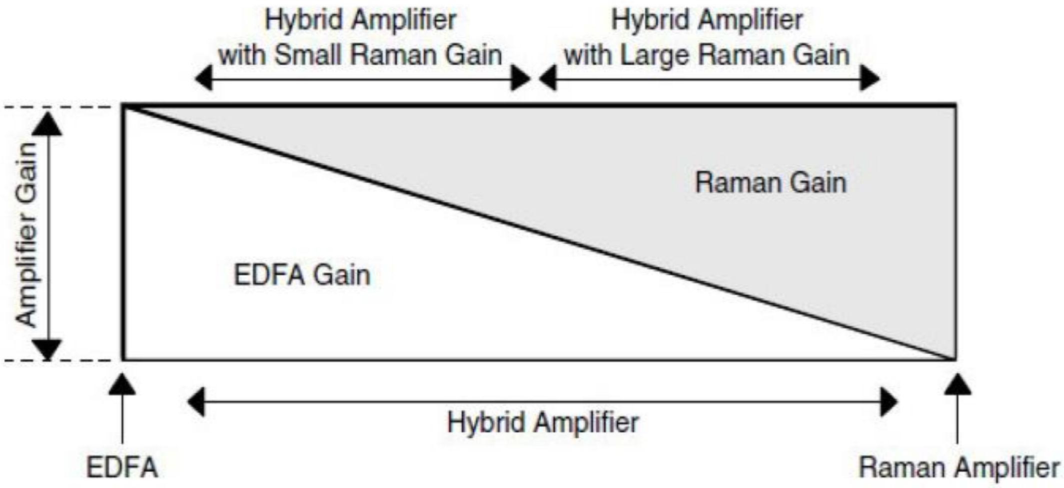
(b)

Figure 1.7 (a) Raman gain amplifier [29]; (b) Schematic of the quantum mechanical process taking place during Raman scattering

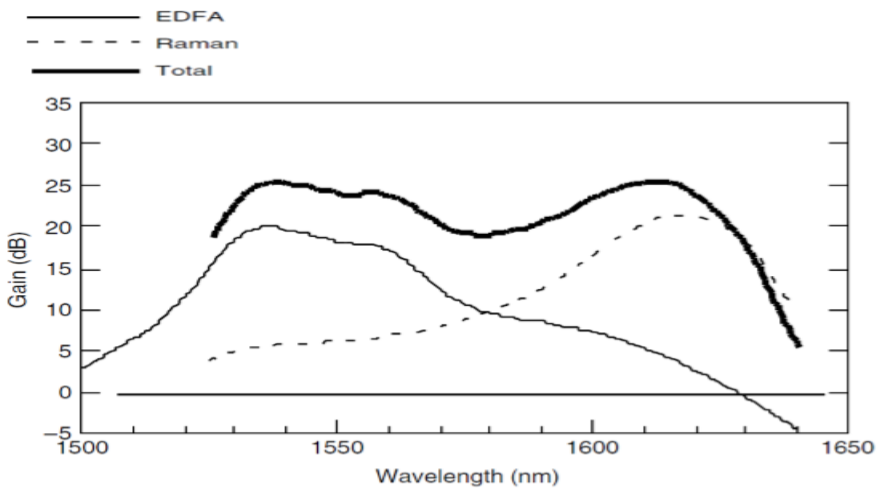
This is shown schematically in Figure 1.9 (a). Pump photon ν_p excites a particle up to a virtual level (non-resonant state). The molecule quickly decays to a lower energy state emitting a signal photon ν_s in the process. The difference in energy between the pump and also signal photons are dissipated 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 1.9 (b) shows the Scattering diagrams for Stokes and anti-Stokes Raman scattering. An incident photon of frequency ν0 is scattered by a molecule exciting one quantum of vibrational energy Ω and producing a downshifted scattered photon of frequency $v_s = \nu_0 - \Omega$.

1.4.3 Hybrid Optical Amplifier

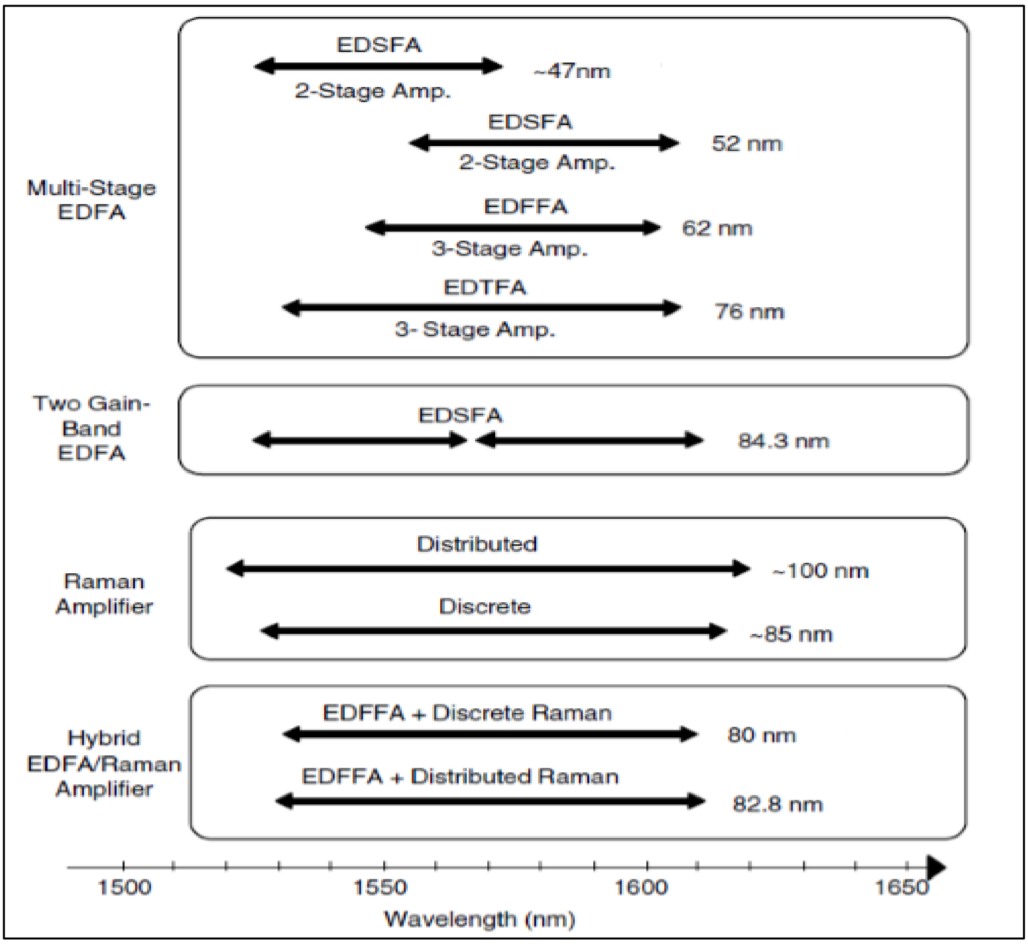
The combination of more than one amplifier in a configuration is called hybrid optical amplifier. Mohammed N. Islam described that the total amplifier gain (G_{Hybrid}) is the sum of the two gains [10]: $G_{Hybrid} = G_{EDFA} + G_{Raman}$. Gain partitioning in hybrid amplifier is as shown figure 1.8. 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 RA 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 (∆λ) of the NB HA is 30 to 40 nm, whereas that of the SWB HA is 70 to 80 nm. The significantly wider gain bandwidth of the SWB HA, compared to the individual gain bandwidths of the EDFA and the RA, was obtained without a gain equalizer by the single wavelength pumping approach, because the gain spectra of the EDFA and RA have opposite gain slopes. In Figure 1.10 compares the gain bands of several types of wideband fiber amplifiers reported to date. However, the bandwidth of the HA is limited by that of the EDFA or the RA. 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 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). 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. However, the bandwidth of the HA (Hybrid Amplifier) is limited by that of the EDFA or the Raman Amplifier (RA).



(a)



(b)



(c)

Figure 1.8: (a) Gain partitioning in hybrid amplifier; (b) Gain spectra of a hybrid amplifier [13]; (c) Gain bands of wideband fiber amplifiers. ED(S, F, T) FA: Erbium-doped (silica, fluoride, telluride) fiber amplifier [10]

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).

1.4.4 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	Type1	Type3
Large	Type2	Type4

Table 1.1

The SWB HA with small (large) distributed Raman gain is denoted as Type 1. On the other hand, the SWB HA with a small (large) discrete Raman gain is denoted as Type 3. 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 below 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. Types of hybrid amplifier are discussed as described below:

1.4.4.1 Type 1

First one is the Type 1 amplifier. It has dual stage EDFA with a midway GEQR (Gain equalizer) and a DCF (Dispersion Compensating fiber) as shown in Figure 1.9. 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 GEQR is almost equal to that of the wideband two tage EDFA.

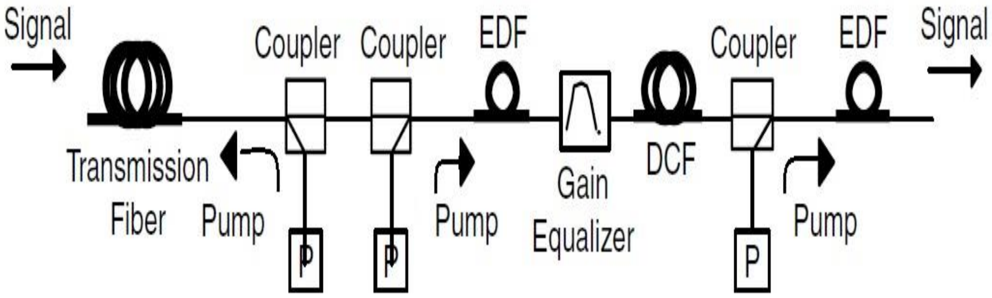


Figure 1.9: Type 1 with small distributed Raman gain

1.4.4.2 Type 2

The Type 2 amplifier has a single stage EDFA with a GEQR 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. 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 outpu power.

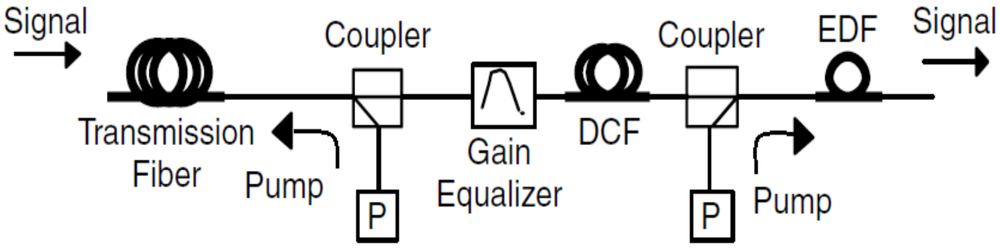


Figure 1.10: Type 2 with large distributed Raman gain [10]

1.4.4.3 Type 3

The Type 3 amplifier has a two stage EDFA with intermediate GEQ and DCF. The DCF is pumped and operates as an LRA. 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.

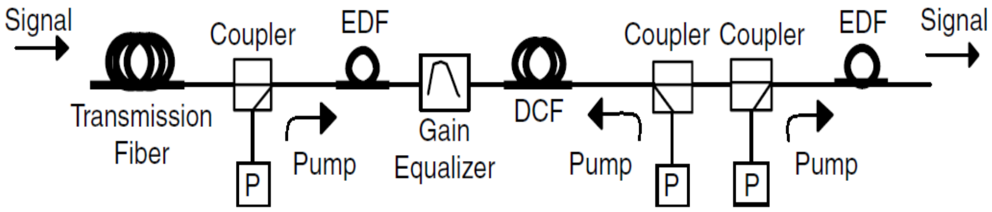


Figure 1.11: Type 3 with small discrete Raman gain [10]

1.4.4.4 Type 4

The Type 4 amplifier has a single stage EDFA, a two stage RA, and intermediate GEQ. The lumped RA has two DCFs as its gain media and generates a large Raman gain. The peak loss of the GEQ is small. The noise figure spectrum of the amplifier is determined by the NF spectra of the EDFA and the LRA.

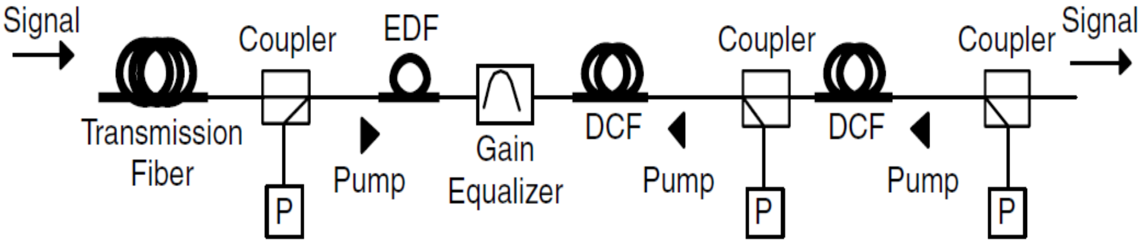
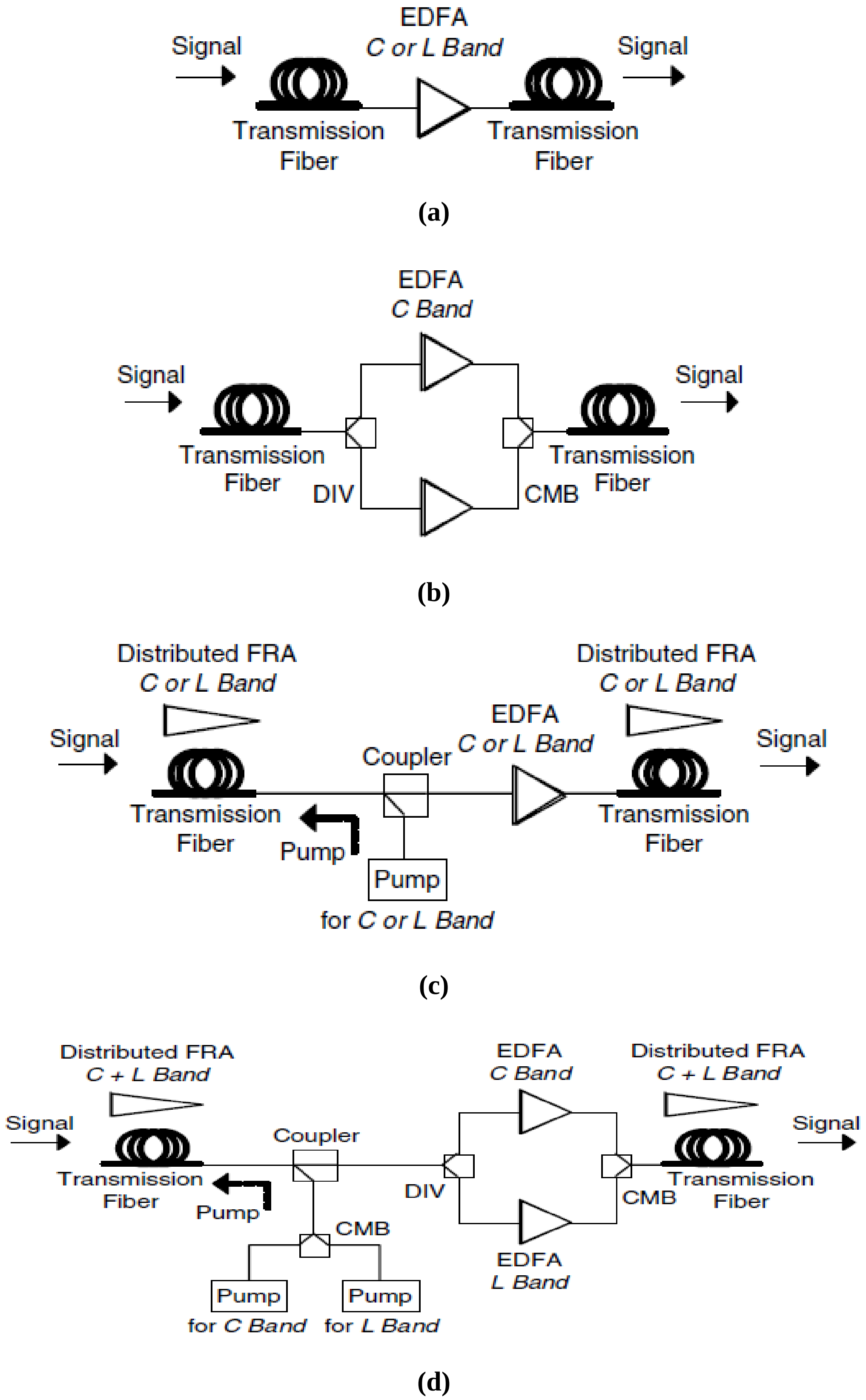


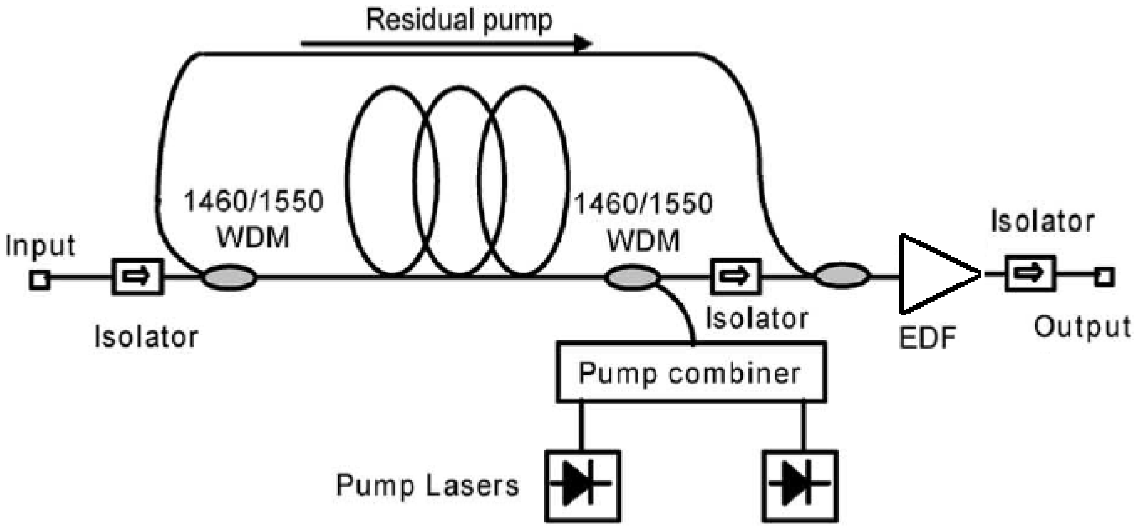
Figure 1.12: Type 4 with large discrete Raman gain [10]

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

The Figure 1.5 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 1.13 (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 1530 to 1560 nm and 1570 to 1600 nm Figure 1.13 (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 de multiplex 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 1.13 (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 1.13 (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 transmission fiber as a repeater. The figure 1.13 (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 or the C and L bands are multiplexed by a combiner, and launched into the transmission fiber via a coupler. Finally Figure 1.13 (e) shows a hybrid amplifier recycling residual Raman pump in a cascaded EDF section after a DCF [14].





(e)

Figure 1.13: Basic configurations of inline amplifier in optical transmission line (a) EDFA; (b) Dual gain band EDFA in C and L band; (c) Hybrid Raman EDFA with C or L band; (d) Hybrid EDFA/distributed Raman amplifier with C and L bands in parallel (CMB: combiner, DIV: divider) [10]; (e) Hybrid Raman and EDFA amplifier with residual pump [14].

Chapter 2

Literature survey

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. This becomes 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 channels can amplify simultaneously. Optical amplifier increases the Tx power by placing an amplifier just after the transmitter and just before the receiver. As the need of long haul unrepeated transmission distances and ultrafast broadband transmission is increasing, the advanced transmission methods have to be known. There is demand to investigate the unrepeated optical transmission & ultrafast 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, analyse and optimize the optical amplifiers and hybrid optical amplifier in WDM communication network to improve the power budget for increasing the number of supported users.

Increasing the gain bandwidth of fiber amplifiers is the most effective way to raise the number of WDM channels. The gain bands have been increased by employing new fiber host materials for erbium-doped fiber amplifiers (EDFAs), gain-equalizing optical filters [13], parallel configurations for the two gain-bands of the EDFA [14], Raman amplifier with many wavelengths [15] and with multiple pump wavelengths combination of EDFA with the distributed Raman amplification in the transmission fiber [16].

In 1992, J. M. P. Delavaux et al. [14] demonstrated that, two efficient Hybrid EDFA structures as power booster. The EDFA is pumped simultaneously by 980 nm and also 1480 nm diode pump laser. Among other features, these EDFAs 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 reduction in in gain and bandwidth values reported till 1992 are 33nm centred at 1545 nm and 0.98 mm pumping with an intermediate equalizer [15] and 40nm centred at1580 nm

In 1997, H. Masuda et al. [16] reported the extremely large bandwidth of 65 nm (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 nm to 1605 nm) by using an optimized two stage EDFA without Raman amplification. Very high pump power and the low gain compression of Raman amplifiers can induce the 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, Juhan Lee, Uh-Chan Ryu[10] observed that A novel structure, which utilizes detrimental backward amplified spontaneous emission as a secondary pump source is suggested for a silica based fiber amplifier, operating at a wavelength range from 1570 to 1610 nm. By using the secondary pumping effect from the strong, wasted 1550 nm band amplified spontaneous emission power in the unpumped section of the erbium doped fiber, it was possible to achieve a considerable improvement in power conversion efficiency, increasing small signal gain by more than 4dB. The suggested pump structure was also shown to be useful in overall conversion ability improvement for L band EDFA’s, regardless of pump wavelength choice. In 1999, S. Kawai et al. [18] 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 to 9.0 dB higher than that of discrete EDFA with a 7 dB noise Figure over the entire 1.5 dB gain bandwidth.

In 2001, B. Zhu et al. [19] demonstrated the 3.08 Tbps (77 x 42.7 Gbps) WDM transmission over 1200 km fiber with 100 km amplifier spacing and 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 ofC 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 termed as S band amplification.

Jowan Masum-Thomas et al. [20] 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 to 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. Davidson et al. [21] first time demonstrated the transmission of two hundred and fifty six 10 Gbps WDM channels over 11,000 Km in 80 nm of 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 and good quality factor (> 9.1 dB).

H Masuda et al. [22] achieved the largest reported seamless gain bandwidth of 135 nm (from 1497 to 1632 nm) with gain more than 20 dB for optical fiber amplifiers with novel hybrid telluride/silica fiber Raman amplifier. The amplifier was used as a preamplifier in an 8 X 10 Gbps 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. [23] presented an experimental comparison of the performance of all Raman vs Raman EDFA hybrid schemes at the rate of 40 Gbps. Bidirectional 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 act, compared to Raman EDFA hybrid amplification. All Raman transmission yielded up to 1.3 dB system Q improvements in the 40 and 80 Km span length systems, compared to the systems without Raman gain. In that same year they extended their own work by transmission of 16 channels of 40 Gbps 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. [24] 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. [25] built the setup in which EDFA amplifiers used as a booster and inline amplifier and hybrid EDFA FPA (fiber parametric amplifier) used as a preamplifier. The results demonstrate that FPAs have a comparable performance with Erbium doped fiber amplifiers (EDFAs) for in line amplification. The hybrid EDFA + FOPA preamplifier results in improved system performance in comparison with a conventional EDFA preamplifier. 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. [26] demonstrated a long haul transmission of 16 × 10 Gbps 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 (12.71–14.55 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. In 2011, Akihide Sano, Hiroji Masuda, Takayuki Kobayashi[10] demonstrated that high capacity transmission based on spectrally efficient multi level modulation wideband optical amplification techniques. 21.4 G baud polarization division multiplexed (PDM) 16 ary quadrature amplitude modulation (QAM) the signals are generated by utilizing an optical synthesis technique, wavelength multiplexed with 25 GHz spacing by optical pre filtering, and received by an intra dyne coherent receiver based on digital signal processing (DSP) with pilotless algorithms. These techniques realize a spectral efficiency (SE) of 6.4b/s/Hz. Furthermore, a hybrid amplification technique that combines distributed Raman and dual band EDFA amplifiers realizes 10.8 THz signal bandwidth in C and extended L bands. By using these techniques, we successfully demonstrate 69.1 Tbps transmissions over 240 km of low loss pure silica core fibers.

In 2002 Mohammed N. Islam Raman amplifiers are being deployed in almost every new long haul and ultra long haul fiber optic transmission systems, making them one of the first widely commercialized nonlinear devices in telecommunications. This paper reviews some of the technical reasons behind the wide spread acceptance of Raman technology. Distributed 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. Lumped or discrete Raman amplifiers are primarily used to increase the capacity of fiber optic networks, opening up new wavelength windows for WDM such as the 1300 nm, 1400 nm, or short wavelength band. As an example, using a cascade of band lumped amplifiers, a 20 channel, OC 192 system is shown that propagates over 867 Km of standard, single mode fiber. Raman amplifiers provide a simple single platform for long haul and ultra long haul amplifier needs and therefore, should see a wide range of deployment in the next few years. Matsuda et al. [30] compared non return to zero (NRZ) and return to zero (RZ) signal formats for single channel extended distance transmission in an in line amplifier system with dispersion management providing average zero dispersion and local non zero dispersion at an interval equal to the in line amplifier spacing. It is reported that with linear amplified spontaneous emission (ASE) accumulation, signal waveform distortion due to the combined effect of higher order group velocity dispersion (GVD) and self phase modulation (SPM) dominates the performance. Bosko et al. [31] investigated the ultra dense wavelength division multiplexing (UDWDM) scenario at 40 Gbps using NRZ, RZ, and carrier suppressed return to zero (CSRZ) modulation formats. It is reported that NRZ modulation does not benefit from the introduction of atransmission optical filter, it takes advantage of the orthogonal polarization launch of adjacent channels, but its performance is still worse than the RZ and CSRZ performance in a UDWDM scenario. Singh et al. [32] investigated the return to zero (RZ) pulse duty cycle for single channel standard single mode fiber (SSMF), nonzero dispersion shifted fibers (normal NZDSF and anomalous NZDSF fiber) for 10 Gbps optical fiber communicationsystem.

Malhotra et al. [33] investigated the performance of the optical system consisting of chain of EDFA amplifiers for different data formats as NRZ, RZ and Manchester. Their effect on the spectral loss variations produced in fiber output is analysed. It is reported that the NRZ raised cosine modulation format best compensates spectral loss variations in case of 3 channels WDM system which is amplified by cascaded EDFAs.

Hayee et al. [34] compared NRZ with RZ modulation format for WDM systems operating at data rates up to 40 Gbps. It is reported that in 10-40 Gbps dispersion-managed systems singl mode fiber alternating with dispersion compensating fiber.

Delavaux *et al.* [36] demonstrated the two efficient hybrid EDFA structures as power booster. The two simulations pumps (tuned at 980 nm and 1480 nm) are used to pump the proposed amplifier. The offered amplifier provides large gain over broad spectrum (> 35 nm) with better gain flatness (i.e. 1 dB) and output power (17 dBm). They carried a new hybrid pumping scheme to avoid inter channel crosstalk effect for pumps of the same wavelength with different pumping power.

Kawai *et al.* [37] successfully transmitted the 14 × 2.5 Gbps WDM signals over 900 km using highly gain flattened hybrid amplifier. In this investigation, the proposed hybrid amplifier provides better results as compared to single or discrete EDFA.

Thomas *et al.* [38] proposed a hybrid Thulium dope fluoride amplifier (TDFA) and DRA for short wavelength amplification. Using the offered hybrid amplifier, the gain of greater than 20 dB over broad bandwidth (that is 75 nm ranging from 1445 nm to 1520 nm) was achieved with the noise figures of between 7 dB to 8 dB. Also, due to the similar gain 18 profile of these amplifiers, the expensive gain flattening techniques are exempted to achieve large gain flatness.

In Raman amplifier, it is better to use single pump wavelength instead of multiple pumps because: (i) It is easy to design with minimum cost and (ii) The profile of the Raman gain spectrum is independent to channel loading. Among these two, the second point is very important because the gain shape of saturated Raman amplifier with multiple pumps can be complex function of the present channels.

Bolshtyansky et al. [39] demonstrated the hybrid flat or tilt free amplifier in a new wavelength range (i.e. L+ band ranging from 1610 nm to 1640 nm) using a single pump tuned at 1536 nm. It was suggested that, to reduce the micro bend losses, the Raman gain media should be improved by optimizing the parameters.

Zimmerman et al. [40] studied several gain flattening approaches through numerical simulation. These methods consist the hybrid Al codoped with EDFA, Raman EDA HOA and also gain equalizer optical filters. After comparison it was reported that the gain equalizer filter was the utmost appropriate method to increase the GBW product of the EDFAs with gain flatness. On the other hand, Raman EDFA HOA provided the maximum reachable bandwidth without using any high cost or power inefficient optical filters.

Guimarles et al. [41] built the setup in which EDFAs are used as a booster and as inline amplifier. The hybrid EDFA and fiber optic parametric amplifier (FOPA) was used as a preamplifier. It was reported that, for inline amplification, the FOPAs shows better results as good as EDFAs. After comparison it was observed that the hybrid EDFA and FOPA delivers improved performance as compared EDFAs. The performance has been improved in the term of gain, gain bandwidth, NF etc. As compared to back to back values, the proposed hybrid optical pre amplifier also improved the system power penalty by 3.2 dB.

Seo et al. [42] demonstrated the novel broad band HOA covering 105 nm of gain bandwidth. For this investigation silica fiber has been used as transmission channel. By numerical designs and simulations it was observed that the S, C, and L bands could be amplified simultaneously with the proposed mediums. The first medium was an in line HOA constructed by an Er doped cladding and a Ge doped core. The second medium was a combination of EDF and DCF. In case of the first medium, it is simple to construct the amplifier since the splicer was not used between the mediums. Also the whole optical signals in the entire band are amplified at the same time along the fiber. The noise figure 19 can be easily controlled if the inline isolator is used between mediums. The hybrid Raman EDFA using the second medium was reported as more realistic approach.

Martini et al. [43] demonstrated the Raman EDFA HOA in the scenario of cost effective recycling residual pumps by choosing the optimized pump wavelength and power. This allows the structure of amplifiers with large gain bandwidth product, gain flatness and with high power conversion efficiency. It was observed that the proposed Raman EDFA HOA provides best results when it was pumped with two pump lasers (which were tuned at 1425 nm and 1468.4 nm, respectively) with the pump powers of 296.3 mW and 61.3 mW, respectively.

Tiwari et al. [44] characterized the hybrid Raman and EDFA in the terms of gain variation and noise figure measurement. In this work, three types of HOAs are for proposed multichannel WDM system and it was observed that the multi channel gain spectrum of the HOAs are quite different from the case of single channel. However BER performanceshown by Raman EDFA is better in Type 1 Hybrid optical amplifier. But the better bit error rate enactment had been shown by hybrid I configuration, which is a combination of Raman and EDFA, pumped by the residual Raman pump in a co propagating geometery. Rocha et al. [45] proposed a cost effective optical amplification over the S+C bands using a hybrid fiber amplifier (HFA). The cost factor has also been reduced by using single pump wavelength to pump the proposed HFA. The HFA is basically EDFA which provide gain over C band and distributed Raman amplifier attain gain over S band. The HFA was numerically characterized and its optimal configuration was calculated using the optimization procedures based on genetic algorithms. They found an optimum EDFA length, which allows a HFA configuration to 20 operate for several transmission This configuration can operate up to 100 km achieving a higher gain with an average NF of 5dB over the analysed wideband

Hsu et al. [46] proposed and demonstrated a 100 Km dual band HFA in the bridge-type scheme. The proposed HFA consists of C band EDFA and an L band RFA using double pass dispersion compensators in a loo back scheme. Power equalization was realized by adjusting the pump ratio and optimizing the FBG reflectivity for the corresponding channels. On the other hand, the chromatic dispersion for all C+L band channels was optimally compensated to achieve flat power spectrum. After comparing simulation and experimental results, it was recommended that proposed hybrid EDFA and RFA may find vast applications in WDM long haul systems and in optical networks where power equalization, power budget and dispersion crucial issues.

Yuan et al. [47] introduced a configuration of the hybrid Raman EDFA. They also made some restriction conditions to yield the optimum design. The influence of various Raman amplifier noises (amplified spontaneous emission and Rayleigh) on the SNR of the receiver had also been determined in the depth. In this work various important conclusions have been made, such as, with the same span length and with different large nonlinear weight, the value of Q actor is larger. On the other hand, the quality degrades, if the same nonlinear weight has been chosen with different span distance. The Quality factor degrades with respect to the increment in the span length which yields the amplified spontaneous emission (ASE) and Rayleigh noise.

Li et al. [48] investigated the performance of return to zero differential phase shift keying (NRZ DPSK) modulated DWDM system when a saturated SOA is used as booster. By introducing time interleaving, they suppressed the crosstalk induced by SOA nonlinearities and WDM component. It was reported that by providing proper time delay between the even and odd channels, the induced linear crosstalk be mitigated. To reduce self phase modulation (SPM) and cross phase modulation (XPM), the time interleaving strategy is used in which the intensity summed over all the channels would remain constant.

Shah *et al.* [49] investigated and mitigated the inter channel crosstalk, especially cross gain modulation (XGM) and four wave mixing (FWM). The suppression of these undesired effects has been done by properly time interleaved channels. The simulation and experiment of 2 × 20 Gbps WDM system has been conducted and further the acceptable and comparable results have been described.

Shien-Kuei Liaw [50] proposed a hybrid Raman EDFA for simultaneously amplifying the C band EDFA and L band Raman amplifier. 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 and power equalization are the crucial issues.

Chapter 3

Statement of Problem based on Identified Research Gaps

3.1 Gaps

Research Gaps based on the literature survey:

The current efforts of research and development are aiming at increasing the total capacity of medium and long-haul optical transmission systems. Need to design the hybrid optical amplifiers for long distance communication systems with flat gain response and less distortion. Hybrid optical amplifiers can be analysed with different combinations to improve flatness of gain. Earlier work has been done by using limited combinations of different amplifiers. Imbalance of power amongst the different channels occurs. Whenever power variations occur at the input of WDM channels then serious problem of nonlinearity effects in the fiber for high input signals occurs, this need to be overwhelmed.

3.2 Objectives

From literature survey and gaps:

1. To review the enactment of hybrid optical amplifiers (Raman EDFA) in DWDM systems at reduced channel spacing, at increased distance for different modulation formats.
2. To reanalyse the performance of Hybrid optical amplifiers Raman-EDFA for 64 × 10 Gbps and 100 × 10 Gbps WDM System at Different Transmission distance.
3. To investigate the Hybrid Optical Amplifier to find the maximum covered single span transmission distance for reduced input power (nonlinear effects are less dominating in DWDM systems at low input power).

Chapter 4

Proposed Methodology, Results and discussion

4.1 Abstract

In this chapter, WDM systems at 64 and 100 channels have been investigated at 20 Gbps and 10 Gbps date rates respectively, with Raman-EDFA amplifier and the performance has been investigated and compared on the basis of transmission distance and dispersion with and without nonlinearities for different modulation formats. Dual stage amplification is also observed for Raman-EDFA. It is observed that distributed RAMAN Amplifier provides flat gain spectra for narrow spaced channels and EDFA as second stage amplifier offers high gain. Further DWDM systems are compared base on modulation formats. Sixty four channels DWDM system is compared using NRZ, RZ and DPSK, while 100 channel DWDM system is investigated for NRZ and RZ in terms of quality factor, bit error rate and eye height. It observed that RZ offer good quality factor (minimum 14 and maximum 24.5), less eye closure (maximum 2.69), tolerable bit error rate (3.875 × 108) at individual distance as compared to other formats. Further we investigated gain performance of HOA (Raman EDFA) after each stage (first stage Raman amplifier and second stage EDFA provides gain nearby 5 dB and 17 dB respectively).

4.2 Optsystem Overview

Optsystem software is an innovative optical communication system simulation package that designs, tests, and optimizes virtually any type of optical link in the physical layer of a broad spectrum of optical networks, from analog video broadcast systems to large scale intercontinental backbones (Optisystem reference guide 2002). Optisystem is a stand alone product that does not rely on other model framework. It is physical layer simulator based on the realistic modeling of FOC. It possesses a powerful new simulation environment and a truly hierarchical definition of systems and components. Its capabilities can be extended easily with the addition of user components, and can be seamlessly interfaced to a wide range of tools. The extensive library of active and passive components includes realistic, wavelength dependent parameters. Parameter sweeps allow the user to investigate the effect of particular device specifications on system performance. Optisystem calculates signal using the appropriate algorithms related to the required simulation by determining the order of execution of component modules according to the selected data flow model. The main data flow model that addresses the simulation of the transmission layer is the Component Iteration Data Flow (CIDF). CIDF domain uses run time scheduling, supporting conditions, data dependent iteration and true recursion. In order to predict the system performance, Optisystem software calculates parameters such as BER, Eye opening, Q-Factor using analysis or semi-analytical techniques for systems which are limited by inter symbol interference and noise.

4.3 Performance Investigation of 64 channel and 100 channel DWDM System using Hybrid Optical Amplification for NRZ, RZ and DPSK Modulation Formats

DWDM is today's need of networks where high transmission capacity is the core requirement and use of hybrid optical amplifiers enhanced the performance of DWDM systems. In DWDM systems different wavelengths carry information are multiplexed together and are passed over single optical fiber. Instead of deploying different fibers for different users, single thread of fiber is used in WDM systems. By reducing the channel spacing between adjacent channels, given BW can be used effectively. Hence data rate will be increased without any need of more BW. In this technology each user is assigned with unique wavelength, are wavelengths carry different information signal. Typically channel spacing is 1 nm more or less. In DWDM system, channels should be narrowly spaced so as to enhance the transmission capacity. This pressurize on optical amplifier (OA) to provide broad band gain and flat gain for these tightly spaced channels. Hybrid optical amplifiers (HOA) are promising technology for long haul DWDM. These amplifiers had shown good characteristics in today long haul DWDM technology, as shown in the recent research work. There is the technique of employing OA for optimum utilization of available fiber BW i.e. by way of using various combinations of optical amplifiers in different wavelength range. The HOA can be connected either in parallel or in series and configuration is referred to as HOA. The HOA has wide gain spectrum. This amplifier increases the link distance and gain flatness, which is limited by fiber loss in an optical communication system. However, the amplifiers also introduce nonlinear effects, which not only limits the bit rate but also the propagation distance in an optical fiber link. HOAs are available to effectively use the bandwidth and to achieve significant gain up to wide range of BW. There are several combinations of optical amplifiers, such as EDFA & Raman, EDFA & SOA etc. among all EDFA & Raman shows effective gain performance up to C and L band [33]. Recently research has been done on DWDM technology using hybrid optical amplifiers, also effective performance of system is analysed. It is also observed that RAMAN-EDFA has good multichannel gain. The gain spectrum of RA can be varied by adjusting the pump power and pump wavelength. This property is used to enhance the bandwidth of EDFA. Noise figure of RA is lower than that of EDFA, Therefore to achieve a higher gain with lower noise figure or wide band amplification, use an EDFA in combination with a distributed Raman amplifier (RA). Dual stage RA-EDFA amplifier provided wide gain spectra. This HOA has been investigated in DWDM system with 25 GHz channel spacing. Control

Matsuda et al. [30] compared non return to zero (NRZ) and return to zero (RZ) signal formats for single channel long distance transmission in an in-line amplifier system with dispersion control providing average zero dispersion and local nonzero dispersion at an interval equal to the in line amplifier spacing. It is reported that with linear amplified spontaneous emission accumulation,signal waveform distortion due to the combined effect of higher order group velocity dispersion (GVD) and S PM dominating the performance.

Bosko et al. [31] exam ined the ultra dense wavelength division multiplexing (UDWDM) scenario at 40 Gb/s using NRZ, RZ, and carrier suppressed return to zero (CSRZ) modulation layouts. It is reported that NRZ modulation does not benefit from the introduction of a broadcast optical filter, while it takes advantage of the orthogonal polarization unveiling of adjacent channels; however its enactment is still worse as compared to the RZ and CSRZ in a UDWDM consequence.

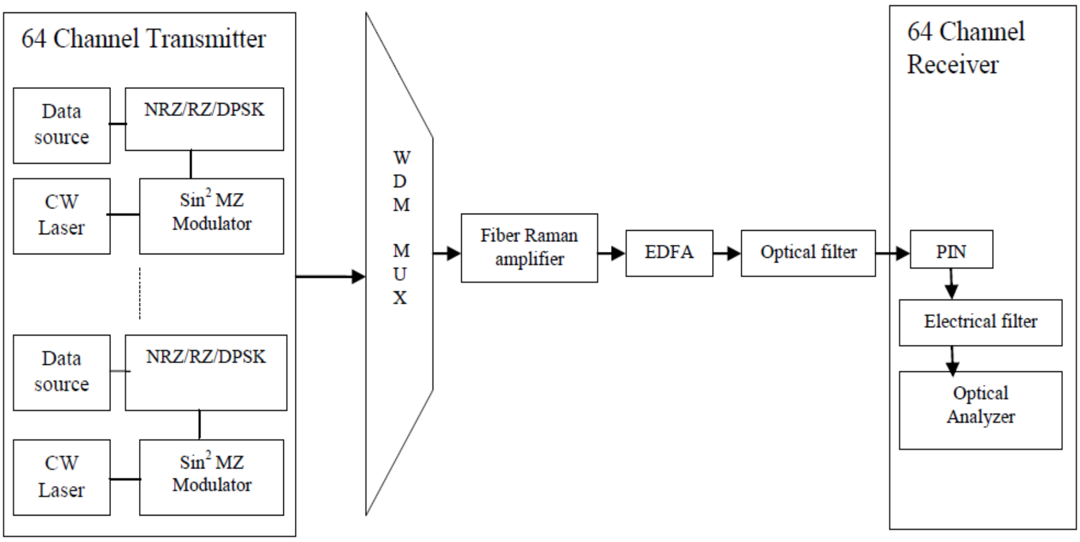
Malhotra et al. [33] examined the performance of the fiber optical system consisting of sequence of EDFA amplifiers for various data formats such as NRZ, RZ and Manchester. Their consequence on the spectral loss variations produced in fiber output is analysed. It is stated that the NRZ raised cosine modulation format best recompenses the spectral loss variations in case of 32 channels WDM system which is amplified by cascaded EDFAs. In this chapter, same target is pursuing, but in the perspective of 64 DWDM which is amplified by HOA (Raman EDFA). Each simulated channel has 20 Gbps data speed. We further investigated the enactment comparison of HOA, Raman EDFA with different modulation formats in the term of Q factor, bit error rate (BER), output power and eye closure and optimize the extreme single span transmitted distance.

Hayee et al. [34] compared NRZ with RZ modulation format for WDM systems operating at data rates up to 40 Gbps. It is described that in 10 to 40 Gb/s dispersion managed systems SMF alternating dispersion compensating fiber (DCF). Singh et al. [35] explored the return to zero (RZ) pulse duty cycle for single-channel standard single mode fiber (SSMF), nonzero dispersion shifted fibers (normal NZDSF and anomalous NZDSF fiber) for 10 Gbps for each optical channel, in the designed optical fiber communication system.

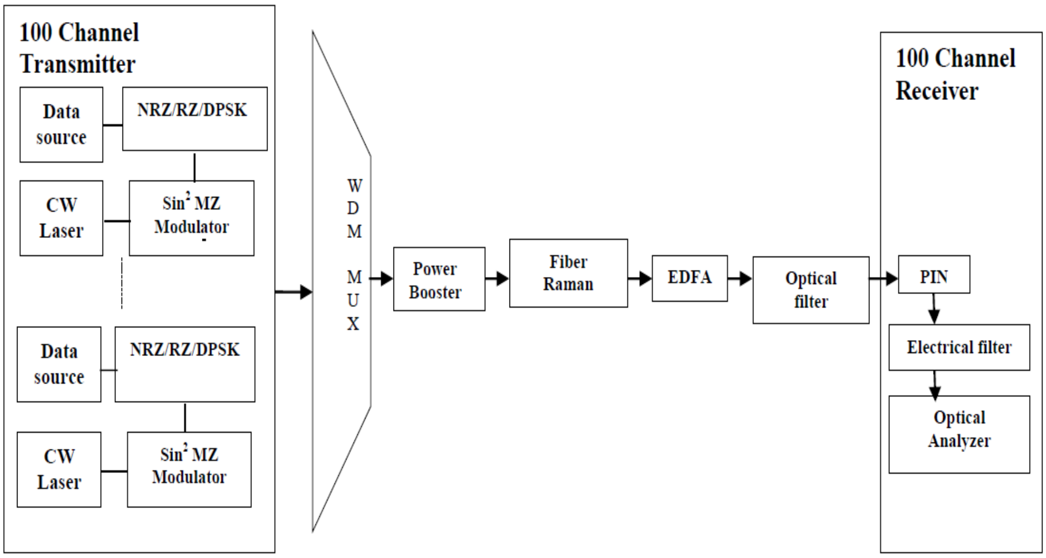
The chapter is organized into four sections. In Section 1, the optical simulation set-up is described. In Section 2, comparison results have been reported for the different modulation formats and finally in Section 4, conclusions are made and future work is mentioned as future scope.

4.3.1 Simulation Setup

In this chapter 64 and 100 channel DWDM systems are investigated at 20 Gbps and 10 Gbps data speeds respectively. This is done at channel spacing of 25 GHz channel spacing. The data source is of different modulation formats changed after one another according to the analysis work (NRZ, RZ, and DPSK) at data rate 20 Gbps for 64 channel and 10 Gbps for 100 channel DWDM. The output of the modulator is fed to an optical link with the Raman EDFA. The laser power is set to 0 dBm because at higher power the wavelengths tend to overlap each other causing more dominance of nonlinear effects like cross phase modulation and four wave mixing [33]. The 64 channels spaced at 30 GHz starting from 187 THz. The input signal spectrum occupies a bandwidth of nearby 1.9 THz. The signals are first amplified by a power booster amplifier and transmitted over fiber at different distances from 50 to 200 Km. the fiber is distributed Raman fiber. This fiber is pumped by 1480 nm with 300 mW power, amplified by Raman-EDFA. Dispersion is totally compensated by deploying fiber brag grating. At the output node, the performance of one of the 64 channels is evaluated using the optical spectra eye diagram, bit error rate BER and Q value measurement. 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. For RZ rectangular format the duty cycle is set to 0.5. For DPSK the centre frequency is set using the condition which is centre frequency $< \frac{BW}{4}$. For 64 channel system the used band width is 2.625 THz (187.18–189.81 THz). Then selected DPSK centre frequency and real symbol period are 2.1 THz. The external modulator used is Sin^2 Machzehnder modulator which has 5 dB insertion loss, 30 dB extinction ratio and 0 chirp factor. The modulated optical signals are amplified by fiber Raman amplifier (FRA) after pre amplification by the booster. The CW Lorentzian laser is deployed in this model. The parameters for CW Lorentzian laser are: center emission wavelength is 1551.1 nm; CW power is 0 dBm and laser phase is random. The amplitude modulator is a sine square using an excess loss of 3 dB. Data formats are altered. The simulated bit rate is 10 Gbps with pseudorandom binary sequences. The PIN detector dark current is 0.11 nA. The frequency domain simulations are performed at the center wavelength of 188 THz with a bandwidth of 1.9 THz. The cascade Raman EDFA (Hybrid optical amplifier) is used to amplify the optical signal. The parameters for Raman fiber are: length is 50 to 200 Km, operating temperature is 300 K, and counter-propagating pump wave-length is 1480 and pump power is 300 mW. The fixed output power EDFA is used after Raman amplifier. EDFA parameters are: power at output is 35 mW, gain shape is flat and noise figure is 4.5 dB. The same setup is repeated for various modulation formats (NRZ, RZ and DPSK).



(a)



(b)

Figure 4.1: Simulation setup: (a) 64 × 20 Channel DWDM System at channel spacing of 30 GHz; (b) 100 × 10 Channel DWDM System at Channel Spacing of 25 GHz;

Similarly same setup is made for 100 channel DWDM system as shown in the figure 4.1 (b). All parameters of setup are same as previous except number of channels and channel spacing (now 25 GHz channel spacing is used). In the second case NRZ and RZ modulation formats are compared only the reason is explained later in the chapter.

4.3.2 Results and Discussion

In this experiment simulations are made for both 64 channel and 100 channel DWDM systems. First of all the results are compared for 64 channel DWDM system for different modulation formats. It is investigated that highest level produced at the output with minimum noise and maximum single span distance covered is in the case of RZ rectangular data format for 64 channels DWDM system. The different data formats have been compared for 64 × 20 Gbps DWDM system in the term of received maximum Q value (dB), minimum eye closure, minimum BER and maximum output power. To analyse the system, the results of the first channel have been taken. At first approach gain after first stage and second stage is compared. It is observed that gain after first stage is almost flat but of less value only up to 5 dB and after second stage of amplification it reaches the value of 17 dB with a tilt of less than 2 dB. Fig. 4.2 shows gain flatness of DWDM system for dual stage HOA.

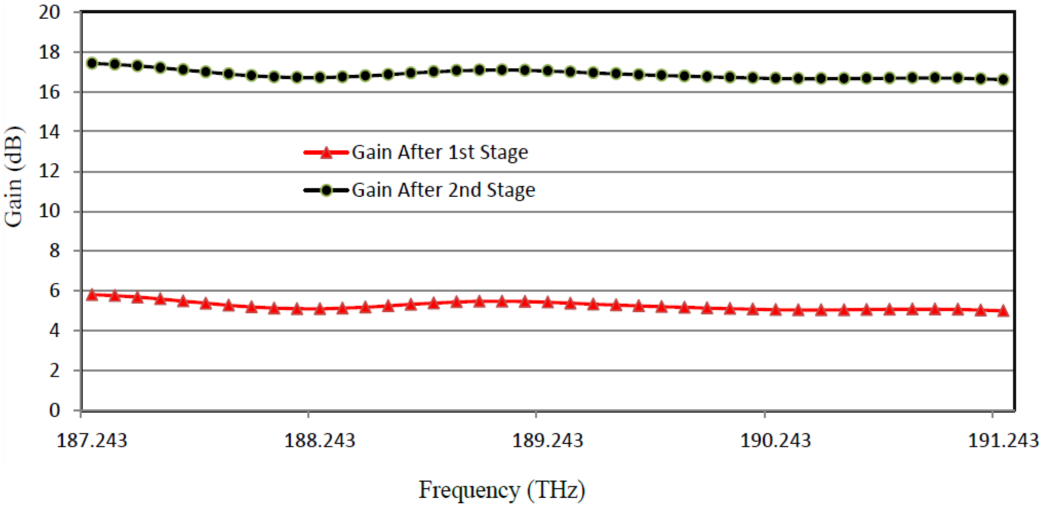


Figure 4.2: Dual stage hybrid optical amplifier flat gain spectra of Raman-EDFA in DWDM system

It can be seen that gain after first stage is completely flat not sufficiently large, but after second stage it is acceptable gain of approximately 17 dB. Flat gain performance is the basic need of DWDM systems.

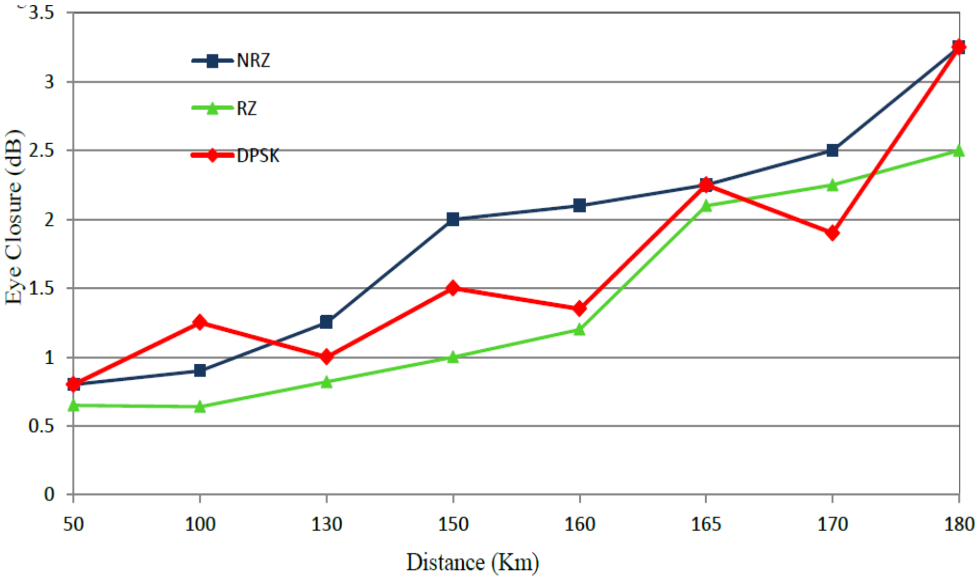


Fig. 4.3: Distance versus eye opening for 64 channels DWDM system

Fig. 4.3 indicates the eye closure penalty. Because of ASE problem in EDFA eye closure penalty is high in DPSK and NRZ. On the other hand RZ offers least value of eye closure (2.5 dB maximum at 180 Km). Also it is found that eye closure penalty goes on increasing as we increase the transmission distance. This shows good agreement with the result [32]. As the eye closure penalty goes on increase, the quality goes on decreasing. It means as the distance is increases system performance decreases based on eye closure plot.

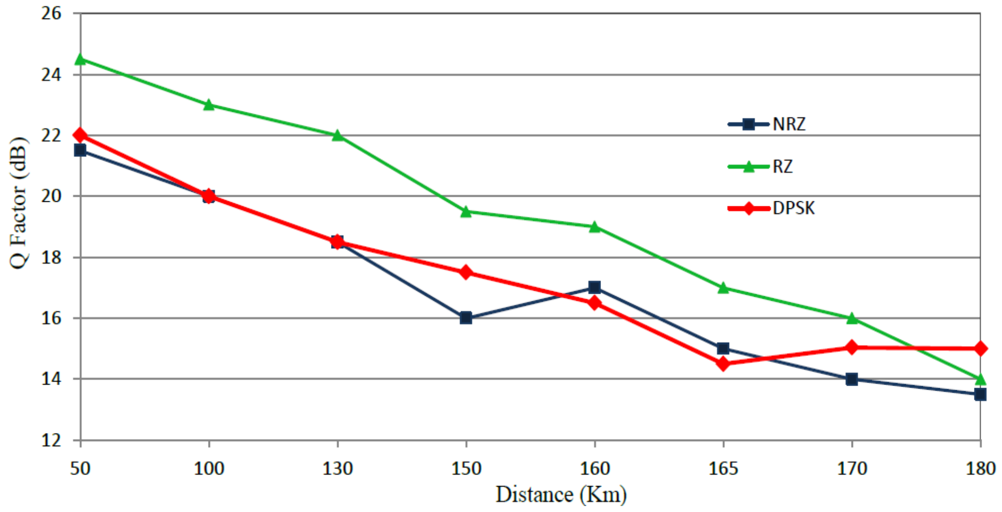


Figure 4.4: Q factor versus distance for 64 channels DWDM system.

The graphical representation of Q value is shown in Fig. 4.4. It is shown as a function of transmission distance. Q value can be seen for all the modulation formats that as the line is vary from 40 Km to 180 Km then the Q factor is ecreased due to the fiber nonlinearities. The better Q value is provided by the RZ data format (24 dB) and also for the worst case (at 180 Km) it becomes 14 dB. The variation in Q-factor for NRZ, RZ and DPSK are 21 15 dB, 24.34–13.81 dB and 22.31–14.41 dB, respectively, RZ is better among all.

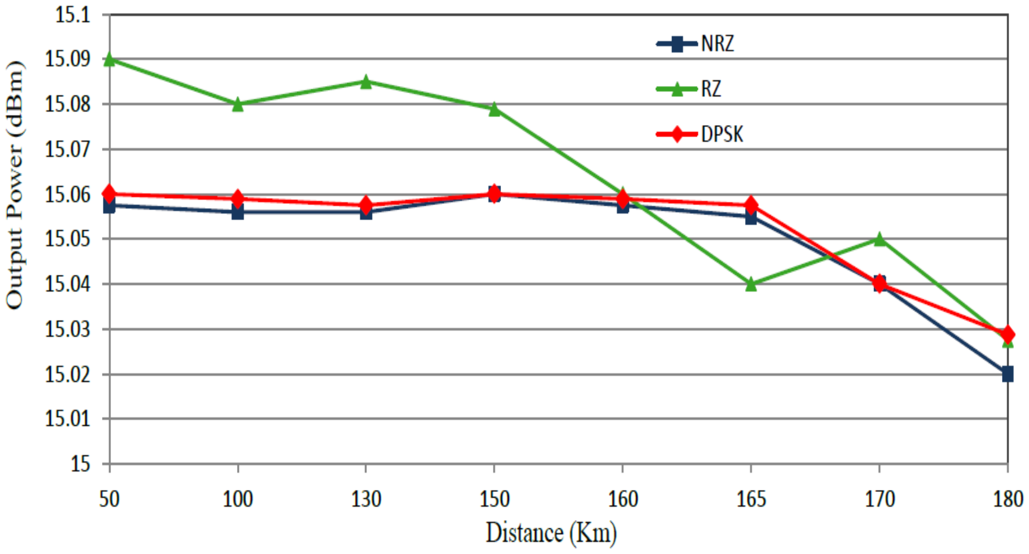


Figure 4.5: Distance versus output power for 64 channels DWDM system

Fig. 4.5 reported the output power versus transmission distance. RZ data format provide better output power (15.09 and 15.01 dBm for 50 and 180 Km respectively). We further investigate the maximum single span distance for different modulations. For 64 channels DWDM system the maximum distance is covered by RZ (180 Km) by suitable power level and better quality. Similarly for both NRZ , DPSK covered distance is 170 Km.

Further the research is extended up to 100 channel closely packed DWDM system. Simulation set up is as shown in figure 4.1 (b). In this experiment power boosting stage is added before Raman amplification. Power booster is simply an EDFA. For 100 channels DWDM system we are considering only RZ and NRZ modulation format only.

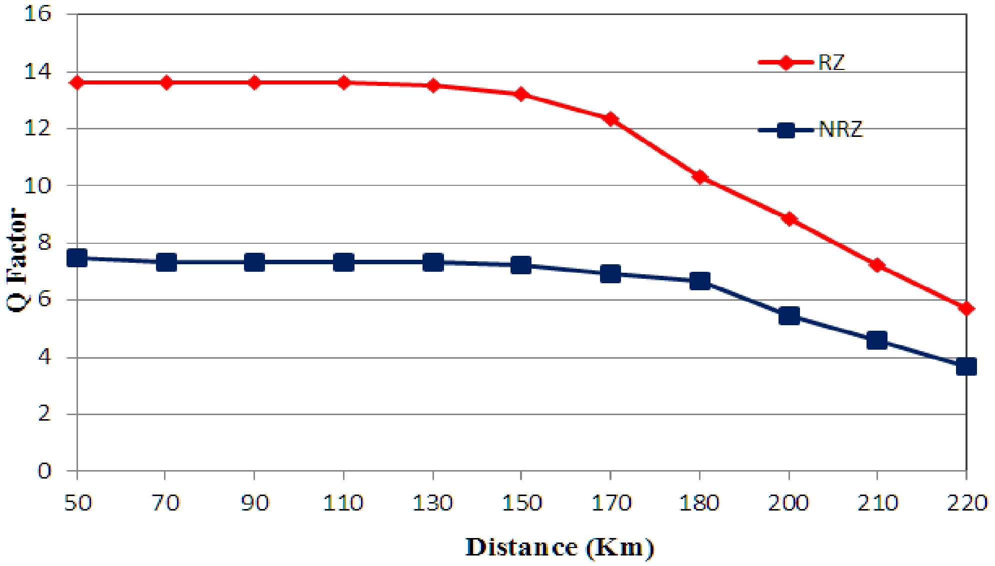


Figure 4.6: Q factor versus distance for 100 channels DWDM system

Fig. 4.7 indicates the eye high. RZ offers high value of eye high (0.0777 maximum at 50 Km) and it is better than NRZ (0.0599) Also it is found that eye high goes on decreasing as we increase the transmission distance. This shows good agreement with the result [32]. It means as the distance is increases system performance decreases. It is investigated that BER performance of RZ is better than NRZ format as shown in figure 4.8. RZ have BER penalty of 10^{-50} (at 50 Km) in worst case it is 1×10^{-9} (at 220 Km), while in case of NRZ it is 9.03×10^{-43} (50 Km) and in worst case it is 4.09×10^{-09} (at 220 Km). Hence it is concluded that RZ is better than NRZ modulation formats in terms of BER, Q factor and eye height.

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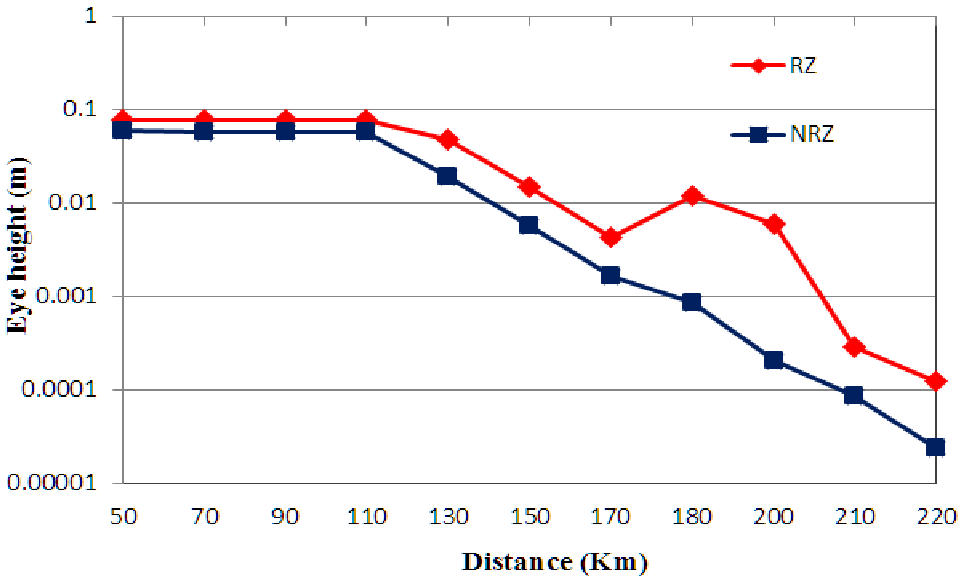


Fig. 4.7: Distance versus eye opening for 100 channels DWDM system

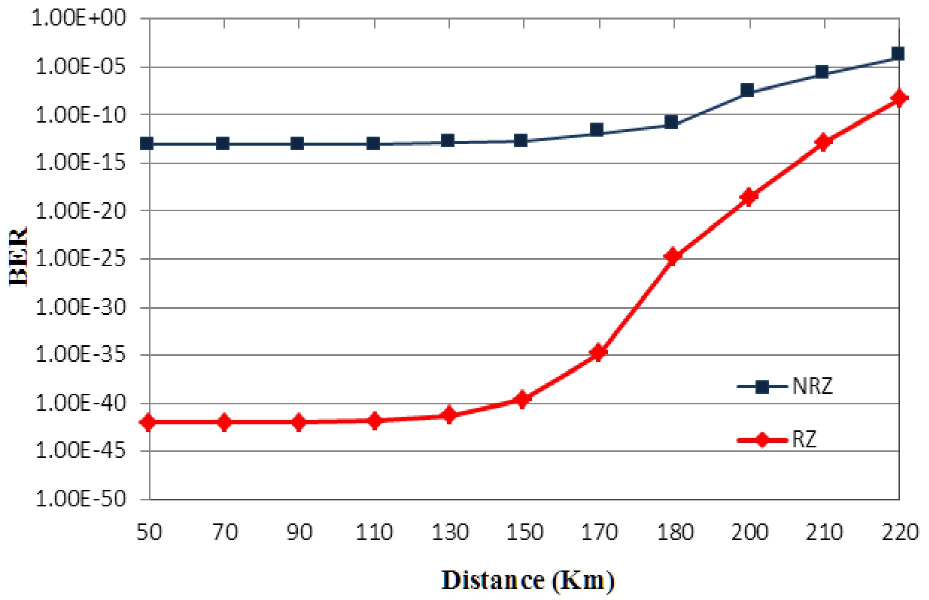
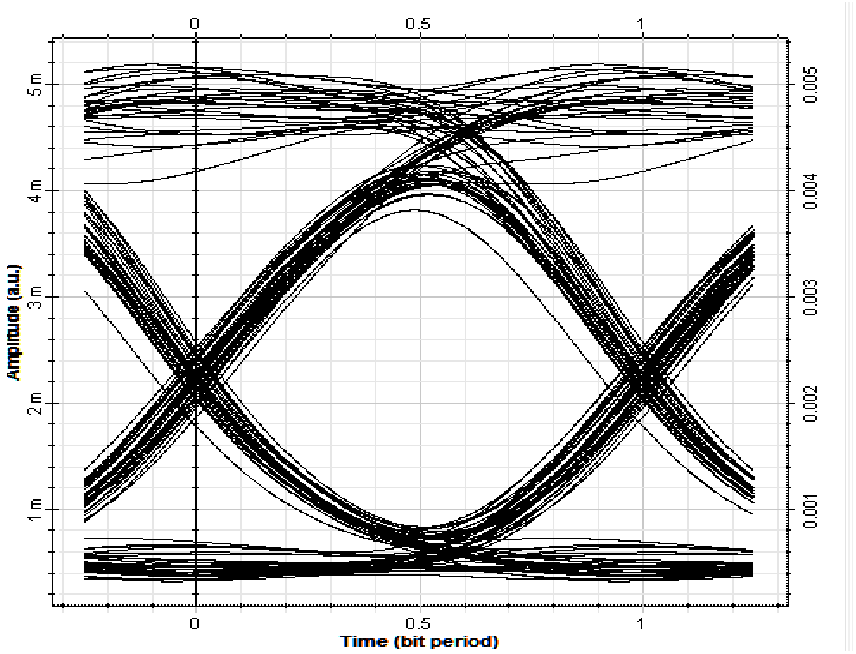


Figure 4.8 Distance versus BER plot for 100 channels DWDM system.

Eye diagram is the final solution to study the combined effect of inter-symbol interference; non linarites in the fiber etc. eye pattern is defined as the experimental tool to study the communication system imperfections. An eye pattern provides a great deal of useful information about the performance of data transmission system. Here the eye pattern for both 64 and 100 channel DWDM systems are presented for NRZ and RZ modulation format for 50 Km and 200 Km. Eye pattern for 64 × 20

Gbps system are shown in Figure 4.9. It is investigated that at 50 to 200 Km RZ modulation provides great eye opening. Eye pattern is best at 50 Km.



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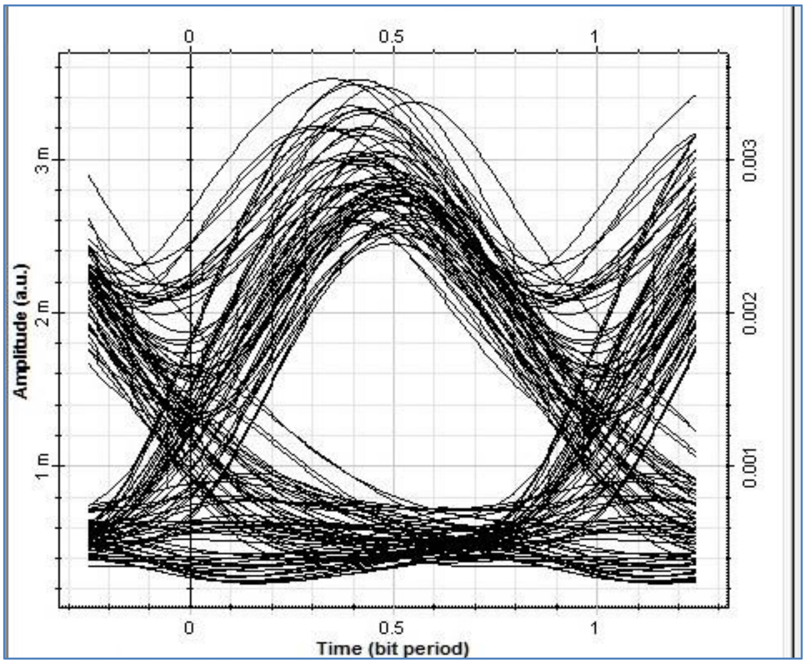

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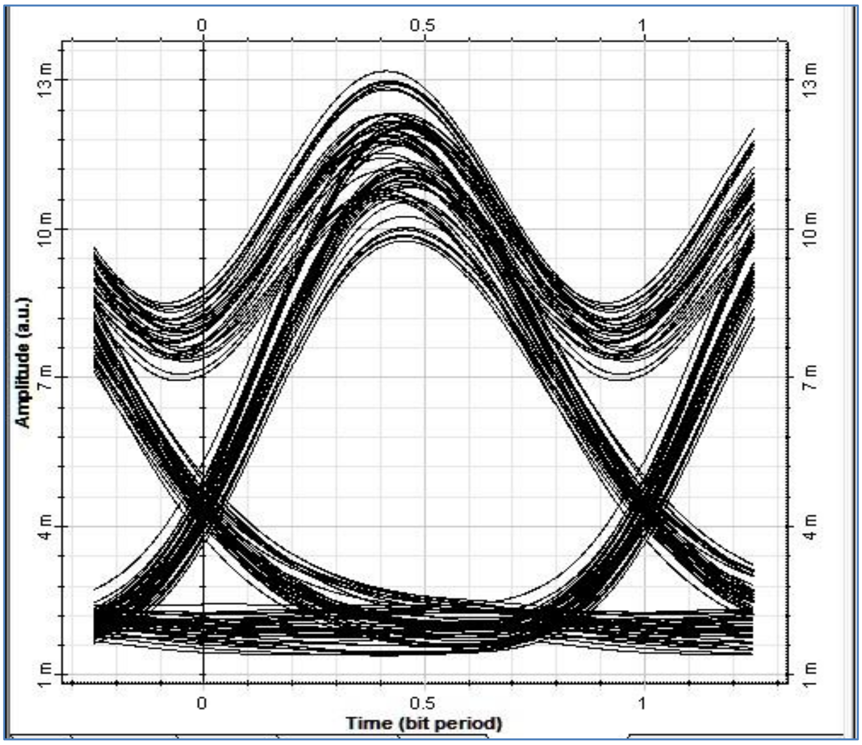

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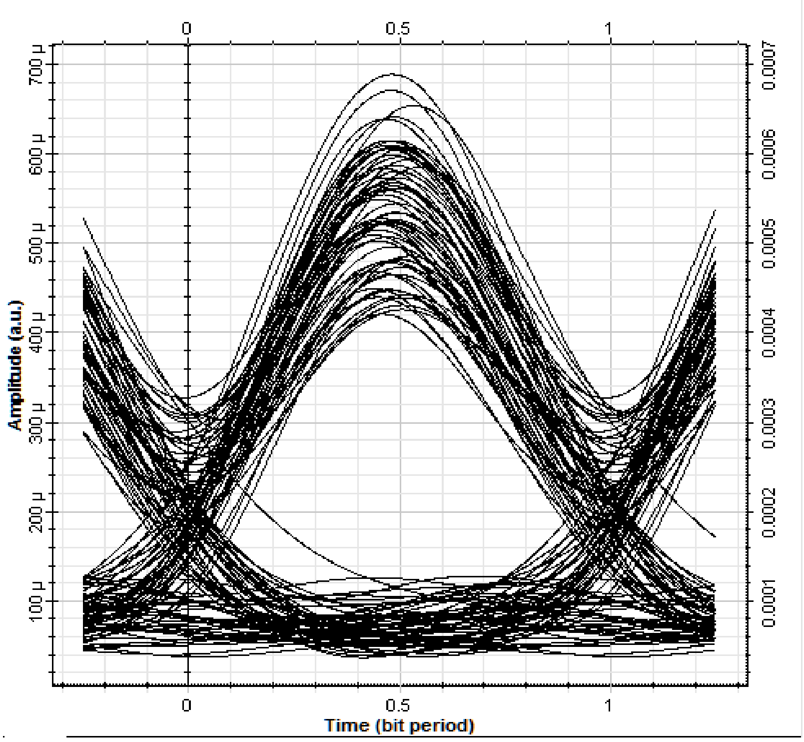
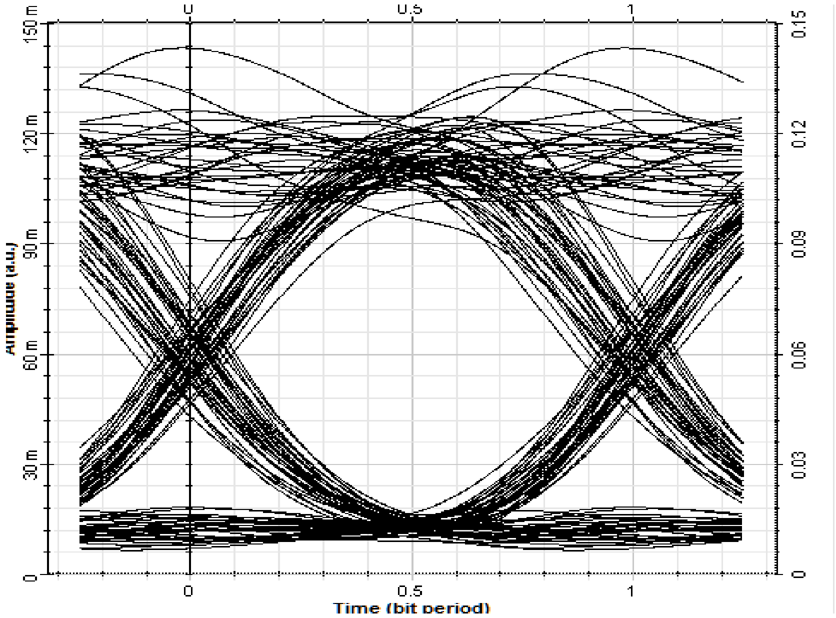


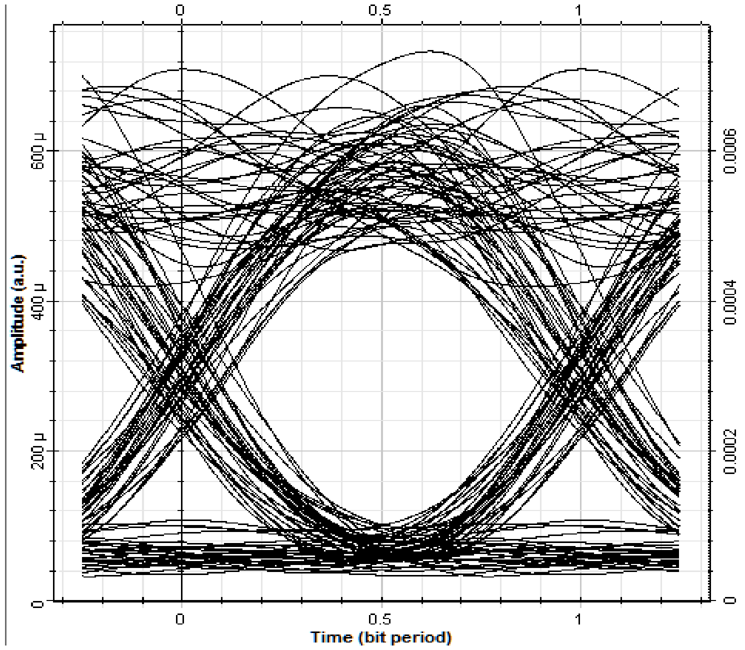
(d)

Figure 4.9: Eye Diagram for 64 channel DWDM system (a) RZ modulation format at 50 Km (b) RZ modulation format at 200 Km respectively; (c) NRZ modulation format at 50 Km (d) NRZ modulation format 200 Km respectively;

It also indicates that eye penalty is high for NRZ format even at 50 Km, this occurs due to ASE at indicates the eye closure penalty which is high for NRZ because of ASE noise power. Because the impulse width of NRZ is the largest, so inter symbol interference easily occurs, is sensitive to transmission loss, influencing the non-linear effect. The duty factor of the RZ code will reduce; impulse width is smaller than NRZ, which can restrain the non linear effect of optical fiber, suitable to work in the high power and long distance transmission condition.



(a)



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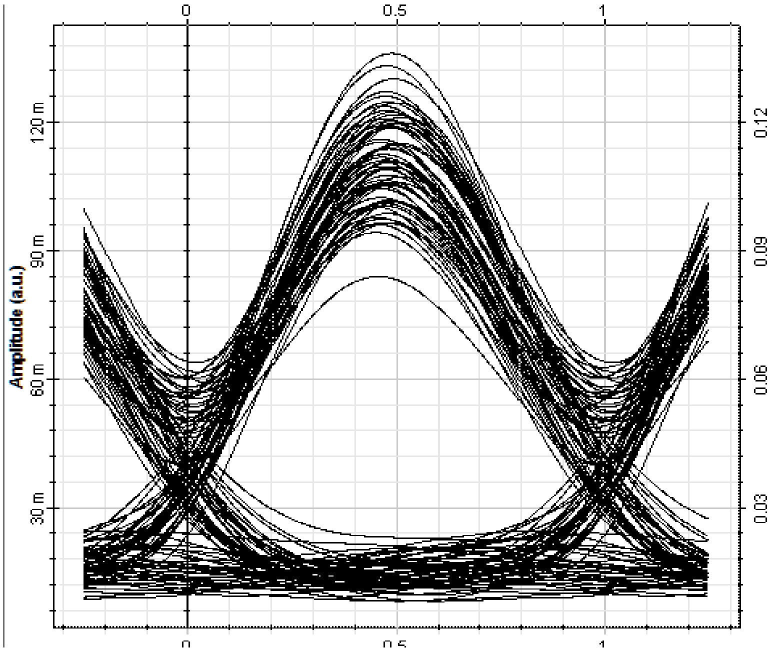

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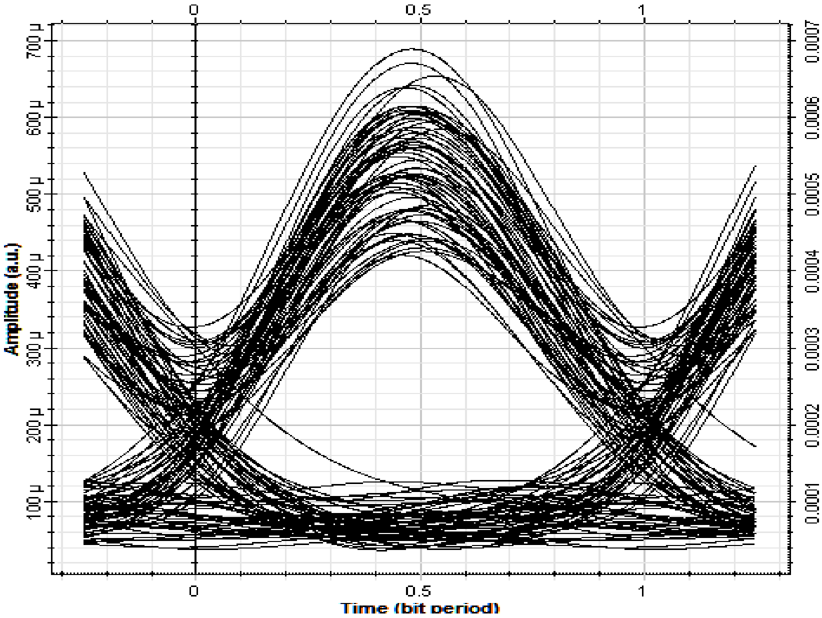

(d)

Figure: 4.10 Eye diagram for 100 channel DWDM system: (a) For RZ modulation format at 50 Km; (b) RZ modulation format at 200 Km; (c) NRZ modulation format at 50 Km; (d) NRZ modulation format at 200 Km.

We further investigate the eye pattern for 100 channel DWDM system. As the distance is increased the eye pattern shows less eye opening. NRZ shows same performance but RZ is better. RZ shows better results than NRZ due same reason as explained before.

In this chapter, we investigated the enactment of 64 × 20 and 100 × 10 Gbps dense WDM optical system consisting of hybrid optical amplifier Raman EDFA for distinct data format such as non return to zero (NRZ), return to zero (RZ) and differential phase shift keying (DPSK). It has been noticed that in link consisting of the Raman-EDFA amplifiers, the RZ raised cosine modulation format has the highest power levels with the minimum loss which is indicated by the reduction of the noisy spikes at the output of the receiver and BER estimator. We further investigated the maximum single span distance for different modulation formats. RZ provided the better results and covered 200 Km and 180 for 64 and 100 channels DWDM system, respectively. We further investigate the maximum single span distance for different modulation formats. For 64 channels DWDM system the maximum distance is covered by RZ (180 Km) with acceptable BER and good quality and power level. In same system both NRZ and DPSK covered 180 Km distance. Similarly for 100 channels RZ is again covered the maximum distance (200 Km) as compare to NRZ (180 Km).

Chapter 5
Concluding Remarks and Future scope

5.1 Conclusion

A hybrid optical amplifier with flat gain characteristics is anticipated using dual stage configuration with a midway isolator. This proposed hybrid optical amplifier is investigated for DWDM system 25 GHz channel spacing and increased data rate. The gain equalization technique is applied, and the hybrid optical amplifier that has a gain of greater than 17 dB. It is found that the gain is less and almost flat after the first stage of amplification. Nevertheless after second stage satisfactory gain is attained. This means grouping of EDFA and Raman amplifier is cause to increase the gain spectra and EDFA is used to increase the gain. It is also used to significantly reduce the influence of fiber non-linearity. Flat gain is realized for reduced channel spacing as it is essential for the DWDM structures. Also it is originated that with the upswing in frequency from 187 THz, the overall gain varies with a tilt of less than 2 dB. It is clear from the results that increase in the stages of HOA upgrades the system performance in terms of gain, gain BW product and gain flatness.

We investigated the performance of 64 × 20 and 100 × 10 Gbps DWDM optical system consisting of hybrid optical amplifier Raman EDFA for different data format such as non return to zero (NRZ), return to zero (RZ) and differential phase shift keying (DPSK). It has been noticed that in link consisting of the Raman EDFA amplifiers, the RZ raised cosine modulation format has the highest power levels with the minimum loss which is indicated by the reduction of the noisy spikes at the output of the receiver and BER estimator. We further investigated the maximum single span distance for different modulation formats. RZ provided the better results and covered 200 and 180 for 64 and 100 channels DWDM system, respectively. We further investigate the maximum distance for different modulation formats. For 64 channels DWDM system the maximum distance is covered by RZ (180 Km) with acceptable BER and good quality and power level. In same system both NRZ and DPSK covered 180 Km distance. Similarly for 100 channels RZ is again covered the maximum distance (200 Km) as compare to NRZ (180 Km).

5.2 Future scope

The this thesis we analyzed hybrid amplifier, which is combination of RAMAN and EDFA in DWDM system but this work can be extend for other hybrid amplifiers like amplifiers combined with other gain media, including combination of RAMAN with fibers doped with different rare earths (e.g., Nd and Yb). The setup is demonstrated for transmission of 100 channel DWDM system at 10 Gbps channel data rate but this simulation can be implemented for DWDM channels at very high data rate. The channel spacing is also a major concern. The modal of RAMAN-EDFA can also be explored in optical network topologies and broadcast topologies. The proposed system investigated the RAMAN-EDFA by changing the Raman fiber length and can also investigates the RAMAN-EDFA by vary Erbium-doped fiber length. There is also scope for increasing the performance of hybrid amplifiers by combining more than two amplifiers.

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