

# **“Performance analysis of Transient aspects for EDFA Amplifiers”**

**A Thesis**

*Submitted in partial fulfilment of the  
requirement for the award of degree of*

**Master of Engineering  
in  
Electronics and Communication Engineering**

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### Certificate

I hereby certify that the work which is being presented in the thesis entitled, "Performance analysis of Transient aspects for Erbium Doped Fiber Amplifiers", in the partial fulfilment of the requirements for the award of degree of Masters 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 and refers others researchers 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 of this or nay other university.

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## ABSTRACT

Information revolution implies that multimedia networks need high bandwidth real-time communication services. At present, optical fibre is the only transmission medium offering such large bandwidth with low loss communication links. To amplify an optical signal with a conventional repeater, one performs photon to electron conversion, electrical amplification, retiming, pulse shaping, and then electron to photon conversion. Although this process works well for moderate speed single wavelength operation, it can be fairly complex and expensive for high speed multiple wavelength systems. Thus a great deal of effort has been expended to develop all-optical amplifiers. These devices operate completely in the optical domain to boost the power levels of multiple light wave signals over spectral bands of 30 nm. Optical amplifiers are in general bit rate transparent and can amplify signals at different wavelength simultaneously. Optical amplifiers are mainly of two types i.e. Semiconductor optical amplifiers and Fiber amplifiers and further classified into travelling wave's semiconductor optical amplifier, fabry-perot semiconductor optical amplifier, Erbium doped fiber amplifier, Raman & Brillouin fiber amplifiers.

First, the technique to control the transients by means of channel adding/dropping in cascades of erbium doped fiber amplifiers (EDFAs) in optical communication system is discussed. It is seen that as EDFAs are gradually added in the optical link, the transients are also reduced significantly. Also that when we use cascade of six EDFAs and note the transient reduction, it is not as much as in case of chain of ten edfa s in which the transients are greatly suppressed . Using the same model, the comparison of transient response of Compact EDFAs and Transient EDFAs is presented. It is observed that suppression of transients is much in Compact EDFAs than Transient EDFAs. Secondly the performance of the optical system consisting of chain of EDFA amplifiers for different data formats such as non return to zero (NRZ), return to zero (RZ) and Manchester are discussed. Their effect on the spectral loss variations produced in fiber output is analysed. It is seen that when the RZ raised cosine and Manchester raised cosine modulation formats are used, the non linear ties are produced in power spectrum plots which severely distort the signals obtained at the output of the chain of the EDFA amplifiers. On the other hand, the NRZ raised cosine modulation format best compensates the spectral loss variations in the power spectrum plots obtained at the output. Also NRZ raised cosine has good eye opening as compared to other modulation formats.

Finally, we investigate the gain and noise figure characteristics of Physical EDFAs and Compact EDFAs in an optical system consisting of cascade of both the amplifiers. The Gain, Noise Figure variations of a forward pumped EDFA and Compact EDFA as functions of  $\text{Er}^{3+}$  fiber length, injected pump power and up-conversion coefficient is demonstrated. It is observed that the Gain becomes

constant when the length of both the amplifiers reaches above 20m. The comparison shows that the higher gain with flatter output is obtained in case of Compact EDFAs than Physical EDFAs in a system consisting of chain of both the amplifiers. It is further investigated that the agreement between the Compact and Physical EDFA models is good up to 10 m with the no up-conversion co-efficient. Also, the noise figure obtained in case of Physical EDFA is higher than Compact EDFA when same amplifier length is more than 20 m and then becomes constant for both the amplifiers.

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# CHAPTER 1

## Optical Fiber Communication

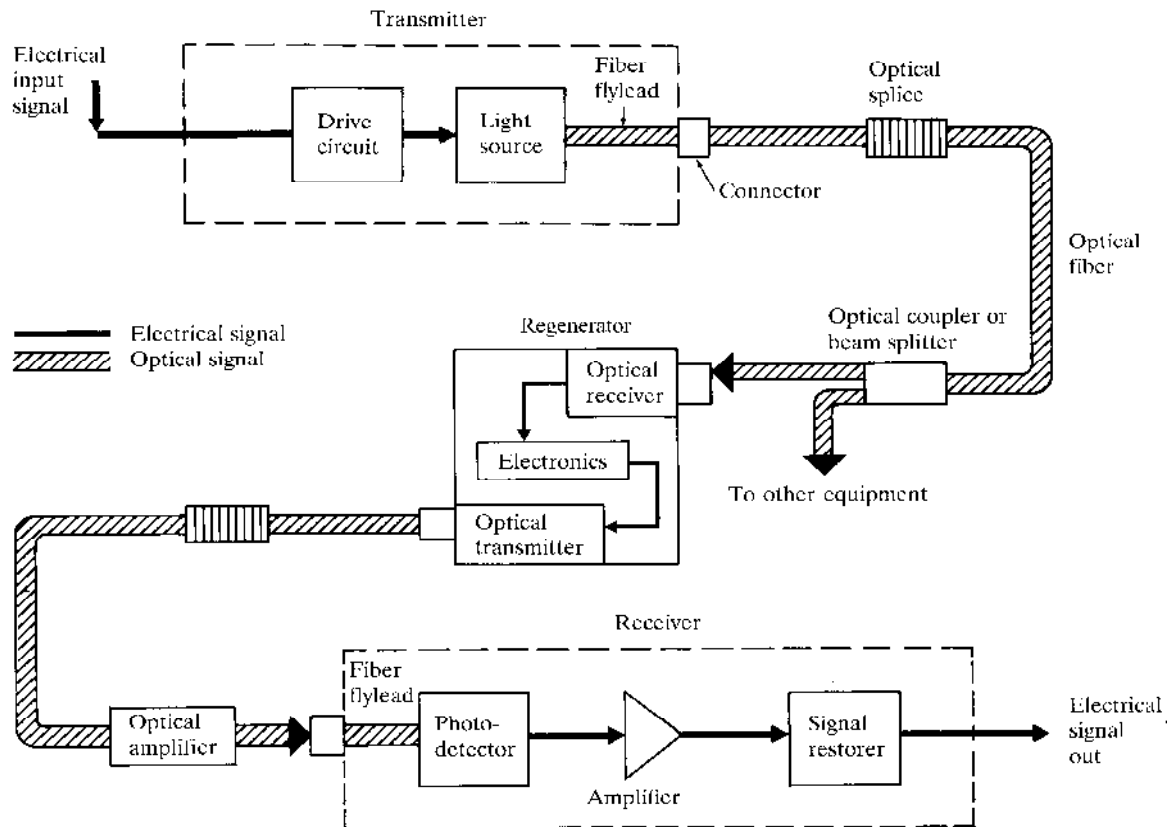
### 1.1 Introduction

Mankind has always throughout its history had the necessity for communication. Initially communication was done through signals, voice or primitive forms of writing. As time passed by there was a need to communicate through distances, to pass information from one place to another. Many different ways to exchange information over long distances have been used throughout history, some of them exotic such as the use of pigeons and smoke signals. All these methods were the evolutionary steps, which have led to today's modern technologies of long-distance communication. Today's long distance communications involve the transmission and reception of a large amount of information in a short period of time. This report investigates certain aspects of one of these technologies, wavelength-division multiplexing, a technique that involves the transmission of multiple signals over a single optical fiber using different wavelengths of light as the optical carriers.

Optical communications are not a privilege of the modern era. In fact, one could say that the Egyptians invented optical communications almost 5000 years ago when they discovered glass and experimented using it together with the sun to transmit signals. In the VI BC century, the Greeks used torches to transmit the fall of Troy. And in 1791 Claude Chapel invented the Semaphore, which is considered to be the first high-speed digital communications system [1]. The Semaphore was a system which consisted of mechanical arms that was installed on the top of a tower and operated manually. Using a chain of such devices it was possible to transmit messages over distances of around 150 miles in only 15 minutes [2]. All these inventions can be considered to be the ancestors of modern day optical fiber communications systems.

### 1.2 Optical Fiber Communication Systems

The most elementary type of communication system consists mainly of three components, the transmitter, the receiver and the channel [3]. The channel in this system is the medium, be it wire, coaxial cable, air, or an optical fiber. Figure 1.1 illustrates one such system where the fiber is used as the medium.



**Figure 1.1 Major elements of an optical fiber link are shown diagrammatically as:**

### 1.3 DEVELOPMENT

When the telephone was invented in 1876, there was a complete revolution in the world of communications and for many years' metallic cables consisting of twisted wire pairs was the media of choice. However, metallic cables had limitations and with the demand for telephone services increasing it was necessary to find an alternative medium for telephony to cope with the high demand [4]. In 1966 Kao and Hockham solved this problem by proposing the use of the optical fiber. The optical fiber was a perfect match for the laser, which had been invented in 1960 by Maiman and up to then, had no practical use in communications [5]. The light- guiding properties of optical fiber had been known for many years, but prior to the work of Kao and Hockham their attenuation was greater than 1000 dB/km. Kao and Hockham showed that these high attenuations were a result of impurities, and that low attenuation might be achieved if the impurities were controlled. This was first achieved in 1970 when Kapro fabricated the first low-loss optical fiber with attenuation around 20 dB/km at a wavelength of 0.63 mm. Eventually, this led to the first commercial deployments of practical fiber systems in 1977-78 . These operated at 0.85 mm, had a bit rate of 50-100 Mb/s and used electrical repeaters spaced 10 km apart to amplify and reshape the signals.

Current optical fiber communication systems operate at 1.3  $\mu\text{m}$  and 1.55  $\mu\text{m}$  where the attenuation is lower than at the shorter wavelengths [6]. These advances are due to not only better fibers but also because of the design of compatible light sources (transmitters) and photo detectors (receivers) at these wavelengths. The emergence of optical amplifier has also contributed to improvements in this field.

#### **1.4 Advantages of optical fiber communications (*light wave communications*) over electrical cables**

- The capacity of fibers for data transmission is huge: a single silica fiber can carry hundreds of thousands of telephone channels, utilizing only a small part of the theoretical capacity [7]. In the last 30 years, the progress concerning transmission capacities of fiber links has been significantly faster than e.g. the progress in the speed or storage capacity of computers.
- The losses for light propagating in fibers are amazingly small: 0.2 dB/km for modern single-mode silica fibers, so that many tens of kilometres can be bridged without amplifying the signals.
- A large number of channels can be re-amplified in a single fiber amplifier, if required for very large transmission distances [8].
- Due to the huge transmission rate achievable, the cost per transported bit can be extremely low.
- Compared with electrical cables, fiber-optic cables are very lightweight, so that the cost of laying a fiber-optic cable can be lower.
- Fiber-optic cables are immune to problems that arise with electrical cables, such as ground loops or electromagnetic interference (EMI).

However, fiber systems are more sophisticated to install and operate, so that they tend to be less economical if their full transmission capacity is not required. Therefore, the “last mile” (the connection to the homes and offices) and is usually still bridged with electrical cables, whereas fiber-based communications do the bulk of the long-haul transmission. Gradually, however, fiber communications are being used within metropolitan areas (*metro fiber links*), and even *fiber to the home* (FTTH) is being developed – particularly in Japan, where private Internet users can already obtain affordable Internet connections with data rates of 100 Mbit/s – well above the performance of current ADSL systems, which use electrical telephone lines.

#### **1.5 Telecom Windows**

**Optical fiber communications typically operate in a wavelength region corresponding to one of the following “telecom windows”:**

- The first window at 800–900 nm was originally used. GaAs/AlGaAs-based laser diodes and light-emitting diodes (LEDs) served as transmitters, and silicon photodiodes were suitable for the receivers [9]. However, the fiber losses are relatively high in this region, and fiber amplifiers are not well developed for this spectral region. Therefore, the first telecom window is suitable only for short-distance transmission.
- The second telecom window utilizes wavelengths around 1.3  $\mu\text{m}$ , where the loss of silica fibers is much lower and the fibers chromatic dispersion is very weak, so that dispersive broadening is minimized. This window was originally used for long-haul transmission. However, fiber amplifiers for 1.3  $\mu\text{m}$  (based on, e.g. on praseodymium-doped glass) are not as good as their 1.5- $\mu\text{m}$  counterparts based on erbium. Also, low dispersion is not necessarily ideal for long-haul transmission, as it can increase the effect of optical nonlinearities.
- The third telecom window, which is now very widely used, utilizes wavelengths around 1.5  $\mu\text{m}$ . The losses of silica fibers are lowest in this region, and erbium-doped fiber amplifiers are available which offer very high performance. Fiber dispersion is usually anomalous but can be tailored with great flexibility ( *dispersion-shifted fibers*).

**The second and third telecom windows are further subdivided into the following wavelength bands:**

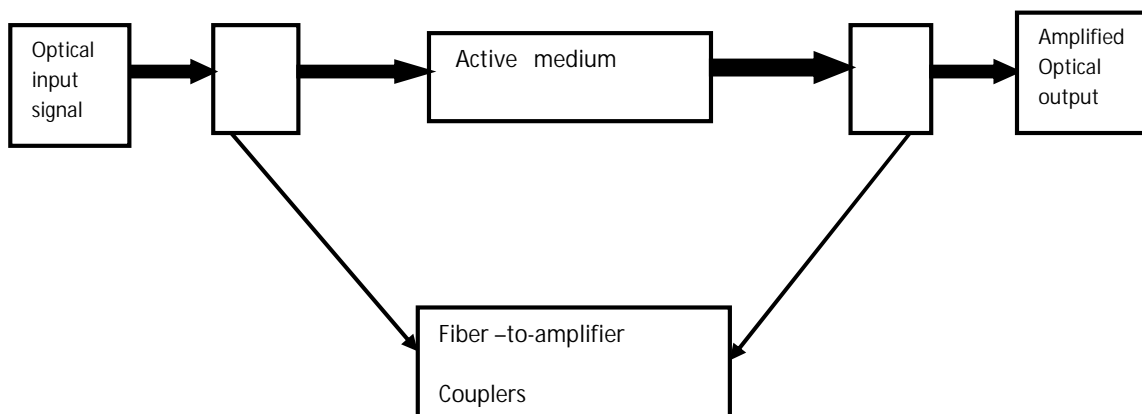
Band	Description	Wavelength range
O band	Original	1260–1360 nm
E band	Extended	1360–1460 nm
S band	short wavelengths	1460–1530 nm
C band	Conventional(“erbium window”)	1530–1565 nm
L band	long wavelengths	1565–1625 nm
U band	ultra long wavelengths	1625–1675 nm

**Table 1.1 Wavelength Bands**

## 2.1 OPTICAL AMPLIFIERS

Optical amplifiers have really revolutionized the field of fiber optics communication. Optical amplifiers are in general bit rate transparent and can amplify signals at different wavelength simultaneously. Optical amplifiers are mainly of two types i.e. Semiconductor optical amplifiers and Fiber amplifiers [13, 14]. These are further classified into travelling wave semiconductor optical amplifier, Fabry-perot semiconductor optical amplifier, Erbium doped fiber amplifier, Raman & Brillouin fiber amplifiers.

All optical amplifiers increase the power level of incident light through a stimulated emission to occur or an optical power transfer process. In SOAs and DFAs (doped fiber amplifiers), the mechanism for creating the population inversion that is needed for stimulated emission to occur is same as is used in laser diodes [13]. Although the structure of such an optical amplifier is similar to that of laser, it does not have the optical feedback mechanism that is necessary for lasing to take place. Thus, an optical amplifier can boost incoming signal levels, but it cannot generate a coherent output by itself [13]. The basic operation is shown in Figure 2.1 here the device absorbs energy supplied from an external source called the pump. The pump supplies the energy to electrons in an active medium, which raises them to higher energy levels to produce a population inversion. An incoming signal photon will trigger these excited electrons to drop to lower levels through a stimulated emission process. Since one incoming photon stimulates many excited electrons to emit photons of equal energy as they drop to the ground state, the result is an amplified optical signal.



**Figure 2.1 Generic optical amplifiers**

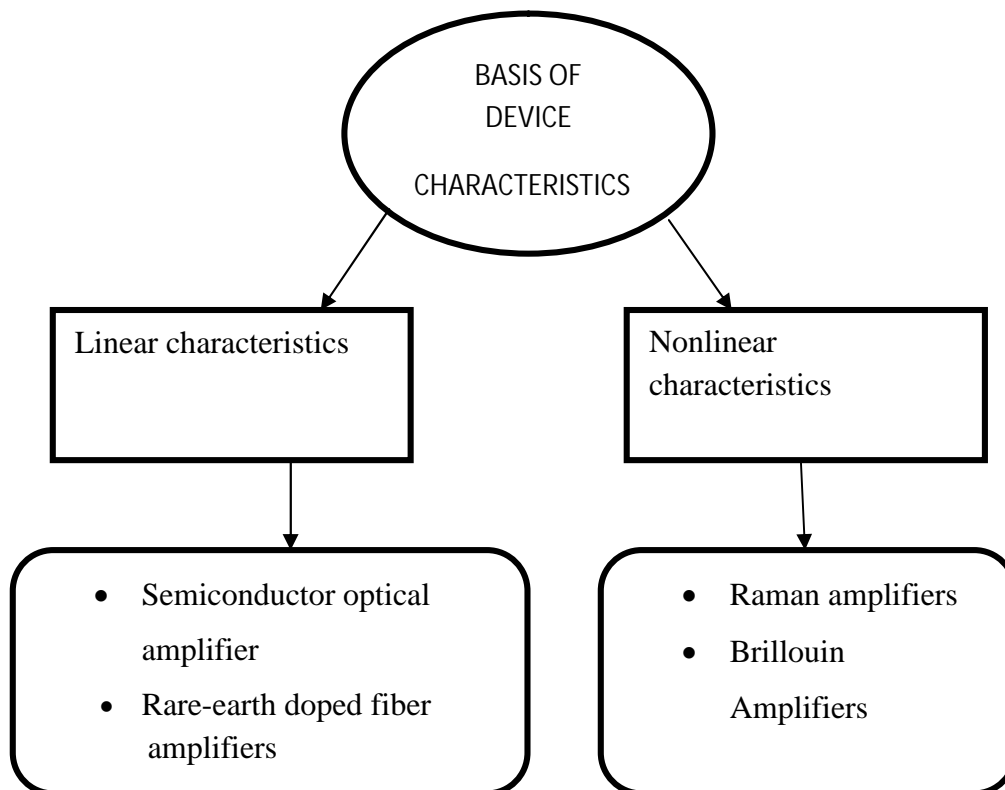
### 2.1.1 Principle & Theory

To achieve optical amplification, the population of upper energy level has to be greater than that of lower energy level, i.e.  $N_2 > N_1$ , where  $N_1$ ,  $N_2$  is population density of lower and upper state [14]. This condition is known as population inversion. This can be achieved by exciting electron into higher energy level by external source called pumping.

Stimulated emission occur, when incident photon having energy  $E = hc/\lambda$  interact with electron in upper energy state causing it return to lower state with creation of second photon, where  $h$  is Plank constant,  $c$  is velocity of light and  $\lambda$  is the wavelength of light . So light amplification occurs, when incident photon & emitted photon are in phase and release two more photon, continuation of this process effectively creates avalanche multiplication. Therefore amplified coherent emission is obtained.

### 2.1.2 Types of Optical Amplifiers

Optical amplifiers were classified on the basis of device characteristics i.e. whether it is based on:



**Figure 2.1.1 Types of Optical amplifiers**

### 2.1.3 General Applications

Figure shows general applications of the following three classes of optical amplifiers:

### **In-line Optical Amplifiers**

In a single-mode link, the effects of fiber dispersion may be small so that the main limitation to repeater spacing is fibre attenuation. Since such a link does not necessarily require a complete regeneration of the signal, simple amplification of the optical signal is sufficient [21, 22]. Thus, an in-line optical amplifier can be used to compensate for transmission loss and increase the distance between regenerative repeaters.

### **Preamplifier**

Figure shows an optical amplifier being used as a front-end preamplifier for an optical receiver. Thereby weak optical signal is amplified before photo detection so that the Signal-to-noise ratio degradation caused by thermal noise in the receiver electronics can be suppressed [12]. Compared with other front-end devices such as avalanche photodiodes or optical heterodyne detectors, an optical preamplifier provides a larger gain factor and a broader bandwidth.

### **Power Amplifier**

Power or booster amplifier applications include placing the device immediately after an optical transmitter to boost the transmitted power, as figure shows [11, 12]. This serves to increase the transmission distance by 10-100 km depending on the amplifier gain and fiber loss. As an example, using the boosting technique together with an optical pre-amplifier at the receiving end can enable repeater less undersea transmission distances of 200-250 km. One can also employ an optical amplifier in a local area network as a booster amplifier to compensate for coupler-insertion loss and power-splitting loss.

### **Diagrammatical representation of four possible applications of optical amplifiers:**

**(a) In-line amplifier**

**(b) Preamplifier**

**(c) Booster of transmitted power**

**(d) Booster of signal level in a local area network**

**Can be shown as:**

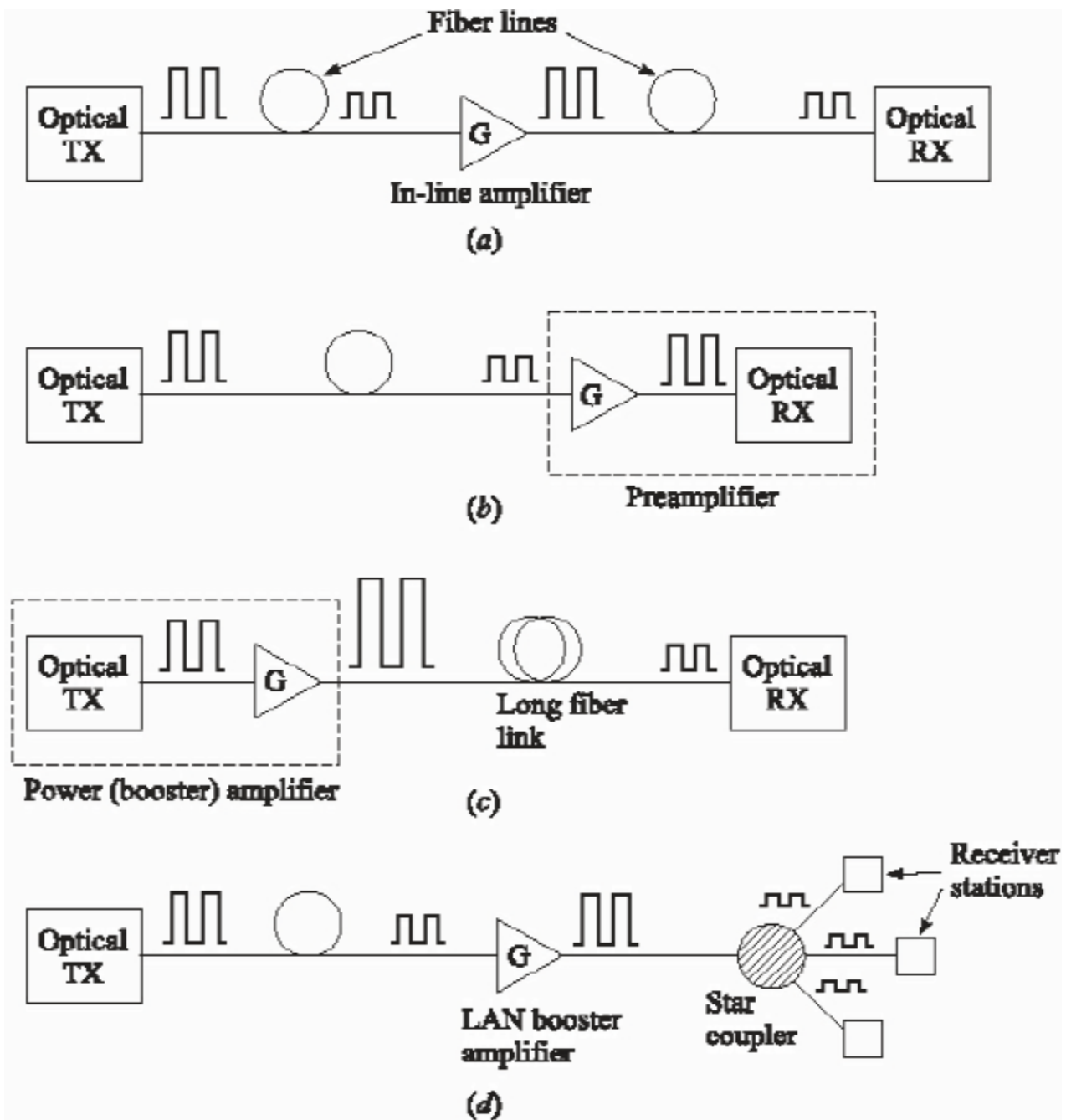
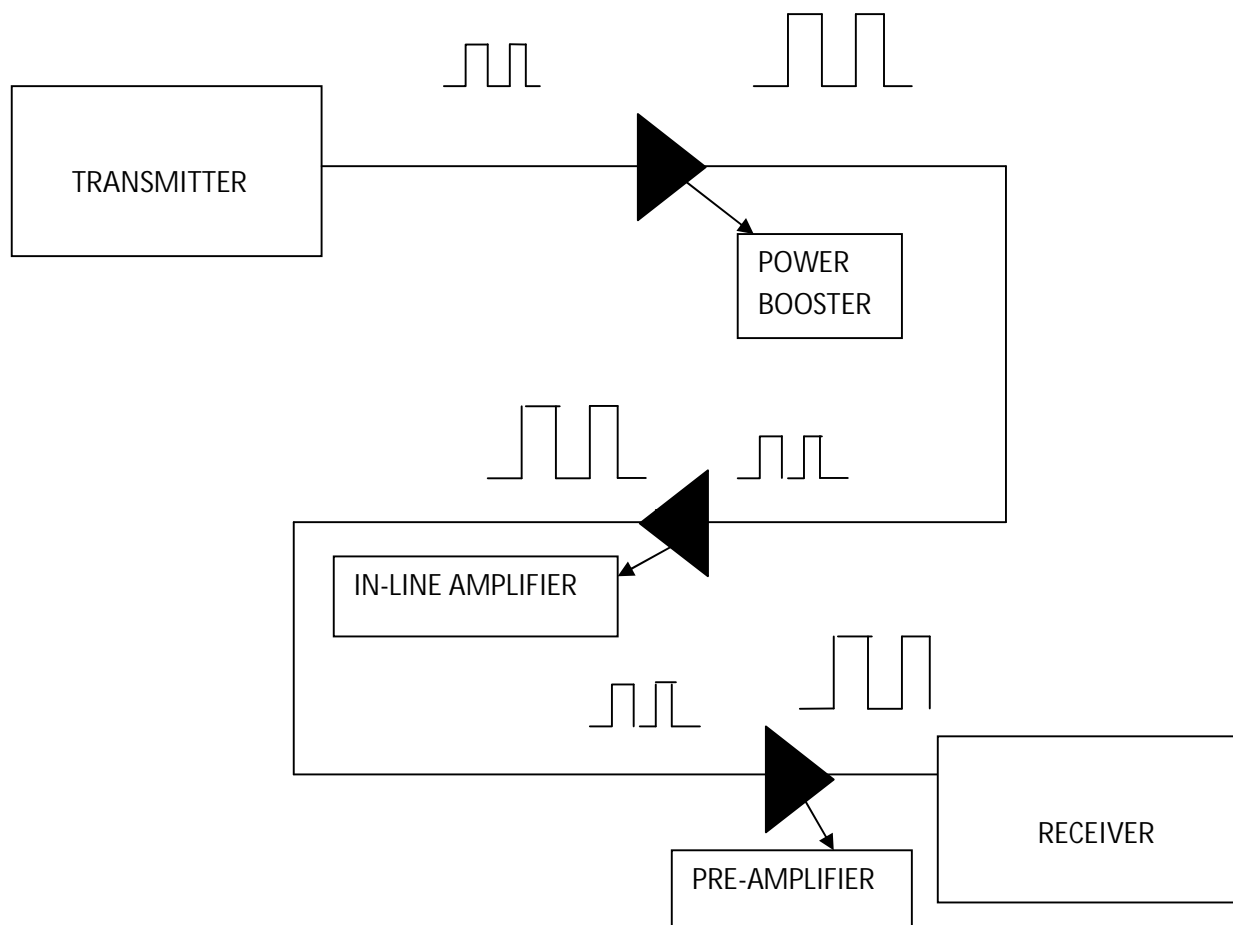


Figure 2.1.2 Diagrammatical representation of Four possible applications of optical amplifiers

**This can also be shown as:**



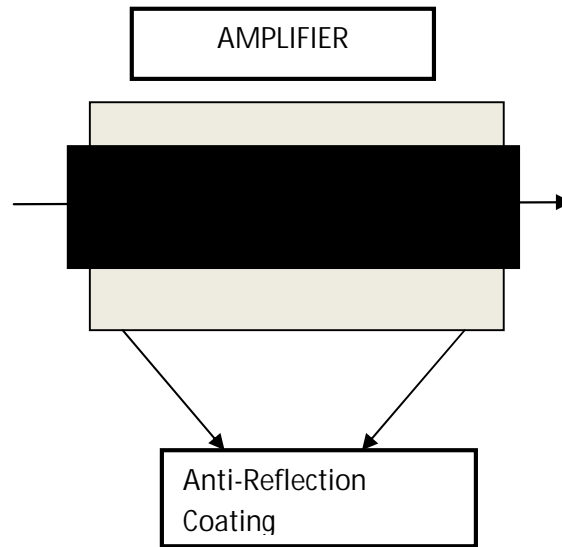
**Figure 2.1.3**

### **3.1 TYPES:**

#### **3.1.1 Semiconductor Optical Amplifiers**

Semiconductor Optical Amplifiers (SOAs) uses the principle of stimulated emission to amplify an optical information signal. Optical input signal carrying original data enters to semiconductor's active region through coupling. The coupling is required because the mode field diameter of single mode beam is 9.3 Mm, while size of active region is less. Injection current delivers the external energy to pump elements at conduction band [19]. The input signal stimulated the transition of electrons down to valence band & emission of photon with same energy & same wavelength as the input signal, so amplified optical signal is obtained [14]. SOA is of two types - Fabry -Perot Amplifier (FPA) & Travelling Wave Amplifier (TWA). Fabry-Perot Amplifier (FPA) is same as SOA. In this, light entering the active region is reflected

several times from cleaved face & amplified as it leaves the cavity. Travelling Wave Amplifier (TWA) is the SOA form.

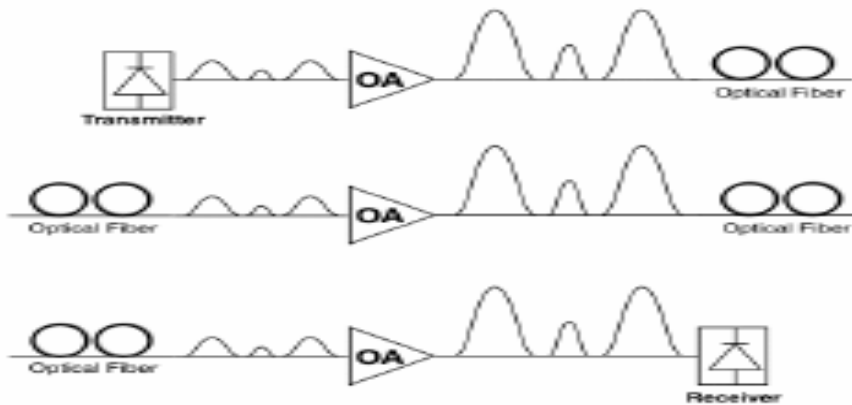


**Figure 3.1 Device Structure of SOA**

Simple SOA are almost the same as regular index-guided FP lasers. The back facet is pigtailed to allow the input of signal light [15]. The main problem is that it has been difficult to make SOAs longer than about 450  $\mu\text{m}$ . In this short distance there is not sufficient gain available on a single pass through the device for useful amplification to be obtained. One solution to this is to retain the reflective facets (mirrors) characteristic of laser operation. Typical SOAs have a mirror reflectivity of around 30%. Thus the signal has a chance to reflect a few times within the cavity and obtain useful amplification.

In TWA, there is an active medium without reflective facets, so that input signal is amplified by a single passage through active region. Practical active region without reflective facets was made by covering the facets of semiconductor material by antireflection coating, tilting the active region with respect to facet and using buffer material between active region & facet to also reduce reflectance R as small as  $10^{-4}$ . SOA's are typically used in the following ways as [15, 16] shown in the Figure 3.1.1.

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

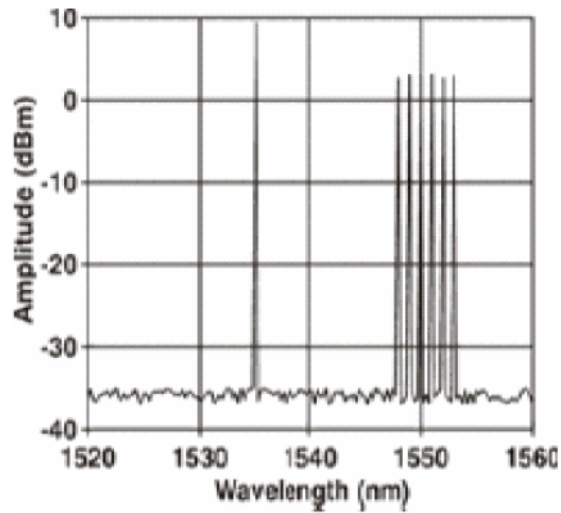


**Figure 3.1.1 Optical Amplifiers (SOAs)**

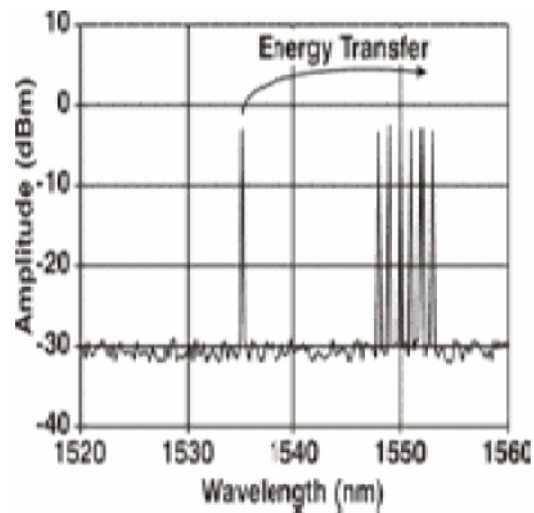
### 3.1.2 Raman Amplifiers

A Raman optical amplifier is based on a nonlinear effect called stimulated Raman scattering which occurs in fibers at high optical powers. The SRS effect is due to the interaction between an optical energy field and the vibration modes of the lattice structure in a material. A fiber based Raman amplifier uses stimulated Raman scattering (SRS) occurring in silica fibers when an intense pump beam propagates through it [16]. In SRS, incident pump photon gives up its energy to create another photon & remaining energy is absorbed by the medium in the form of molecular vibrations (optical phonon). In Raman amplifier, standard single-mode optical fiber can be used generally. The main features of the Raman amplification were that it realized as continuous amplification along the fiber, bidirectional in nature and offers more stability, insensitivity to reflections [17]. The saturation optical power level was very high as it depends on the pump power.

Whereas an EDFA requires a specially constructed optical fiber for its operation, a Raman amplifier makes use of the standard transmission fiber itself as the amplification medium. The Raman gain mechanism can be achieved through either a lumped amplifier or by a distributed amplifier



**Transmitted Spectrum**



**Received Spectrum**

In a lumped configuration spool of about 80 m of small core fiber along with appropriate pump lasers is inserted into the transmission path as a distinct package unit. For the distributed Raman amplifier, optical power from one or more Raman pump lasers is inserted into the end of the transmission fiber towards the transmitting end [17, 18].

The main disadvantage of this amplifiers that pump power requirement is relatively high in comparison with SOAs and EDFAs.

### 3.1.3 Brillouin Fiber Amplifier

The operating principle of this amplifier is same as Raman amplifiers except that optical gain is obtained by stimulated Brillouin scattering (SBS). Stimulated Brillouin scattering (SBS) arises when a strong optical signal generates an acoustic wave that produces variations in the refractive index. These index variations cause light waves to scatter in the backward direction towards the transmitter [15, 16]. This backward scattering light experiences gain from the forward propagating signals, which leads to the depletion of the signal power. In this, each pump photon creates signal photon and the remaining energy is used to excite an acoustic phonon. Amplification occurs only when the signal beam propagates in direction opposite to that of pump beam (backward pumping). Brillouin gain spectrum is extremely narrow with bandwidth  $< 100\text{MHz}$ . The narrow bandwidth of this amplifier makes them less suitable as power amplifier, preamplifier or in-line amplifier in light wave systems [16]. This amplifier used as channel selection by allowing amplification of a particular channel without boosting other nearby channels.

### **3.1.4 Fiber Amplifiers**

Fiber amplifiers act as power amplifier, repeater, and a preamplifier. The gain medium comprises a length of single-mode fibre connected to WDM coupler, which provides low insertion loss at both, signal & pump wavelength. Excitation occurs through optical pumping laser combined with optical input signal within the coupler [12]. Stimulated emission process occurred inside the fiber gain medium. The amplified optical signal is emitted from other end of fibre made from heavily doped ions depending upon type i.e. Rare-earth doped fibre amplifier, Raman fibre amplifier & Brillouin fibre amplifier [13].

### **3.1.5 Rare Earth Doped Fiber Amplifier**

Different rare-earth ions, such as erbium, holmium, neodymium, praseodymium, thulium and ytterbium can be used to realize fiber amplifiers operating at different wavelength covering visible to infrared region. In rare earth doped fiber amplifier, erbium's dopant in silica based single mode fiber used, so called erbium doped fiber amplifier (EDFA). A piece of fiber gain medium as an active medium is heavily doped with ions of Erbium [14, 15]. In this, population inversion is stronger due to large number of erbium ions that fall to level 2 from various upper levels. When optical information pass through such populated erbium doped fiber, it would stimulate transition of erbium ions from level 2 to level 1 & generating photons of same wavelength with direction & phase as input photon. EDFA consists of three basic components: length of erbium doped fiber, pump laser and wavelength selective coupler to combine the signal and pump wavelengths. Optimum fiber length used depends upon pump power, input signal power, amount of erbium doping and pumping wavelength. The 980 nm wavelength with semiconductor laser pumping source has proved to be best in terms of efficiency (more than 10 dB gain per mw pump

power) and better noise performance [14]. Typically noise figure lies between 4-5 dB and between 40-50% with forward pumping and equivalent figures for backward pumping are 6-7 dB and 60-70% assuming 1480 nm pumping light was used [15]. In praseodymium-doped fluoride fiber amplifier similar to EDFA, But operated at 1300 nm with noise figure 3-5dB for best performance. Thulium-doped fiber amplifiers had extended transmission bandwidth of optical fibers beyond the range available from EDFA.

## **4.1 EDFA AMPLIFIERS:**

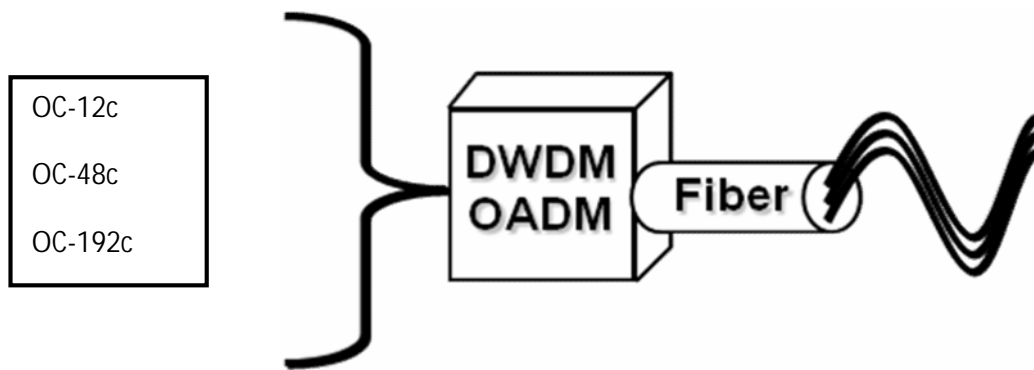
**Definition: (Erbium-Doped Fiber Amplifier)** A device that boosts the signal in an optical fiber. Introduced in the late 1980s, the EDFA was the first successful optical amplifier [29, 30]. It was a major factor in the rapid development of fiber-optic networks in the 1990s, because it extended the distance between costly regenerators [20, 21].

This EDFA is designed for the Dense Wavelength Division Multiplexing (DWDM) applications. The device features excellent gain flatness, low noise figure and wide operating wavelength range. It also has good network control interface.

### ***4.1.1 Dense WDM (Dense wavelength division multiplexing)***

#### **DWDM History:**

- Early WDM (late 80s) -  
Two widely separated wavelengths (1310, 1550nm)
- “Second generation” WDM (early 90s) -  
Two to eight channels in 1550 nm window and  
400+ GHz spacing
- DWDM systems (mid 90s) -  
16 to 40 channels in 1550 nm window and  
100 to 200 GHz spacing
- Next generation DWDM systems -  
64 to 160 channels in 1550 nm window and  
50 and 25 GHz spacing
- DWDM takes multiple optical signals and multiplexes them into a single fiber. There is no signal format conversion

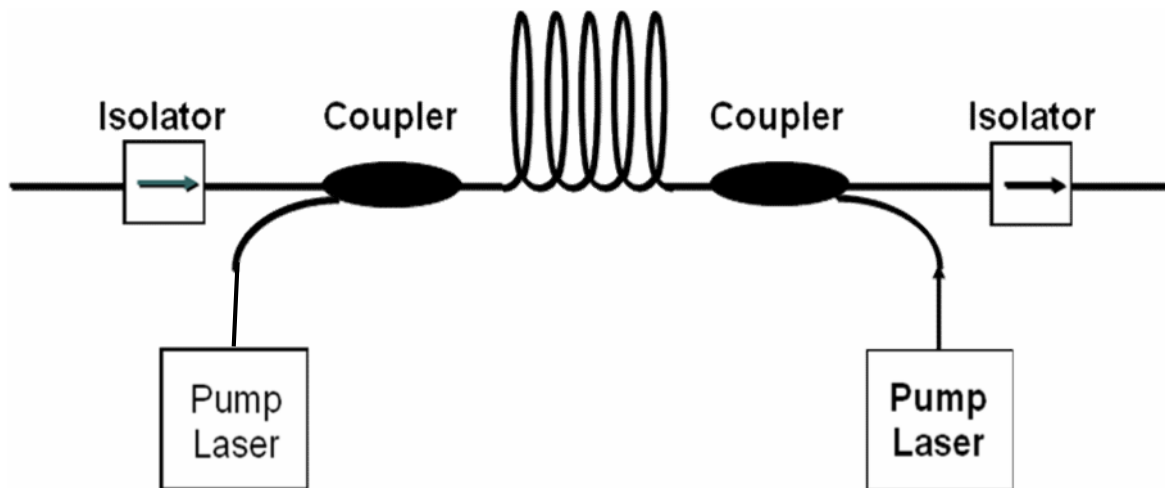


**Figure 4.1 DENSE WAVELENGTH DIVISION MULTIPLEXING**

WDM systems are divided in different wavelength patterns, *conventional* or *coarse* and *dense* WDM. Conventional WDM systems provide up to 16 channels in the 3rd transmission window (C-band) of silica fibers around 1550 nm [22].

#### **4.1.2 Setup and Operation Principle**

ERBIUM DOPED OPTICAL FIBER (10-50 m)
---



**Figure 5.1 Setup of an EDFA Amplifier**

A typical setup of a simple erbium-doped fiber amplifier (EDFA) is shown in Figure 5.1. Its core is the erbium-doped optical fiber, which is typically a single-mode fiber. In the shown case, the *active fiber* is “pumped” with light from two laser diodes (bidirectional pumping), although unidirectional pumping in the forward or backward direction (co-directional and counter-directional pumping) is also very common [23]. The pump light, which most often has a wavelength around 980 nm and sometimes around 1450 nm, excites the erbium ions ( $\text{Er}^{3+}$ ) into the  $^4\text{I}_{13/2}$  state (in the case of 980-nm pumping via  $^4\text{I}_{11/2}$ ), from where they can amplify light in the 1.5- $\mu\text{m}$  wavelength region via stimulated emission back to the ground-state manifold  $^4\text{I}_{15/2}$ . The setup shown also contains two “pig-tailed” (fiber-coupled) optical isolators. The isolator at the input prevents light originating from amplified spontaneous emission from disturbing any previous stages, whereas that at the output suppresses lasing (or possibly even destruction) if output light is reflected back to the amplifier [24]. Without isolators, fiber amplifiers can be sensitive to back-reflections. Very high signal gains, as used, e.g., for the amplification of ultra short pulses to high energies, are usually realized with amplifier chains, consisting of several amplifier stages with additional optical elements (e.g. isolators, filters, or modulators) in between [25].

#### 4.1.3 AMPLIFICATION MECHANISM

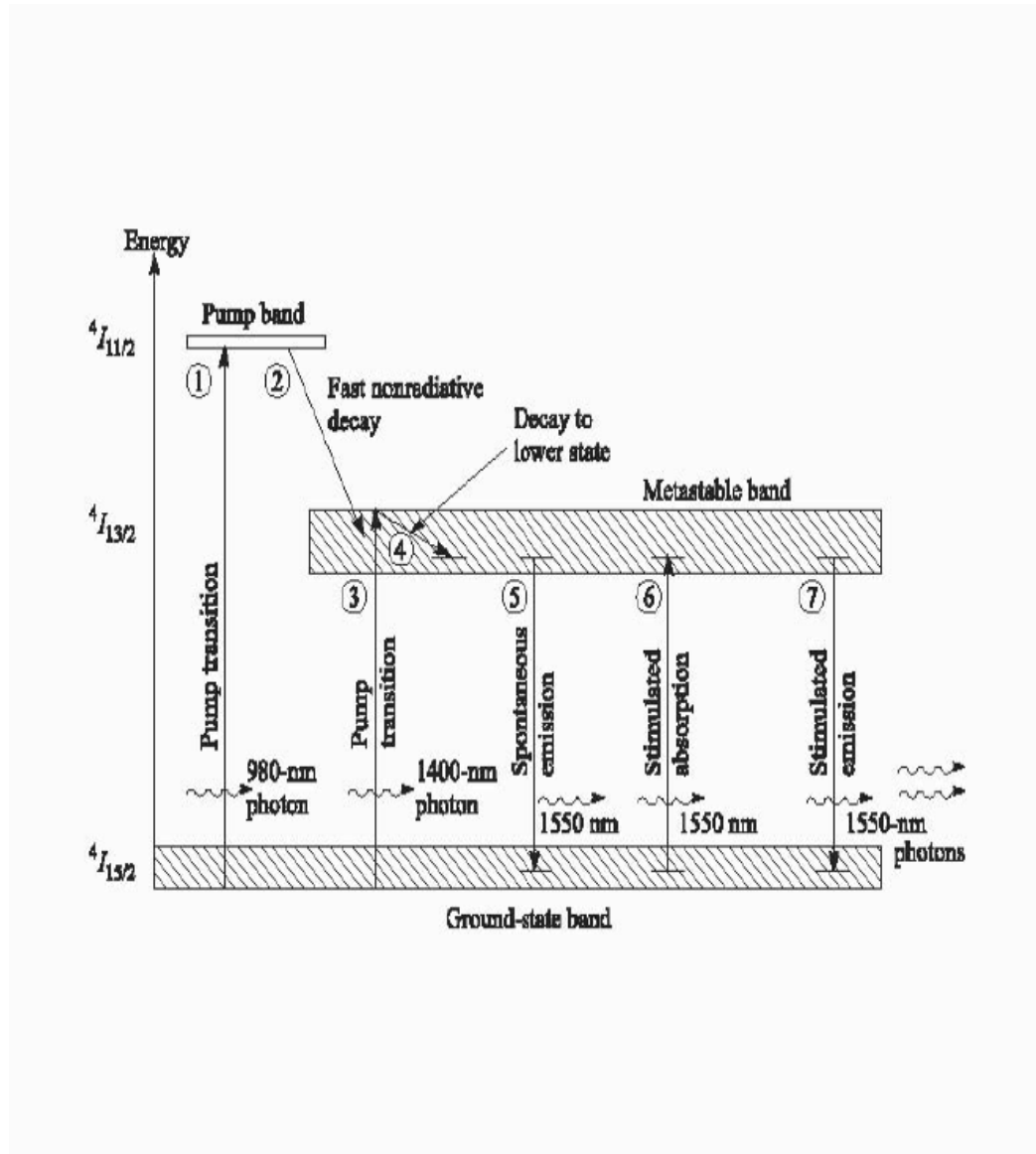
Whereas semiconductor optical amplifiers use external current injection to excite electrons to higher energy levels, optical fiber amplifiers use optical pumping. In this process, one use photons it directly raises electrons into excited states. The optical pumping process requires the use of three energy levels [25]. The top energy level to which the electron is elevated must lie energetically above the desired lasing level. After reaching its excited state, the electron must release some of its energy and drop to the desired lasing level. From this level, a single photon can than trigger the excited electron into stimulated

emission, whereby the electron releases its remaining energy in the form of a new photon with a wavelength identical to that of single photon .since the pump photon must have a higher energy than the signal photon, the pump wavelength is shorter than the signal wavelength.

To get a phenomenological understanding of how an EDFA works, we need to look at the energy level structure of erbium [26]. The erbium atoms in silica are  $\text{Er}^{3+}$  ions, which are erbium atoms that have lost three of their outer electrons.fig shows a simplified energy-level diagram and various energy-level transition process of these  $\text{Er}^{3+}$  ions in silica glass. The two principal levels for telecommunication applications are a metastable level (the so called  $^4\text{I}_{13/2}$  level) and the  $^4\text{I}_{11/2}$  pump level .the term “metastable” means that the lifetimes for transitions from this state to the ground state are very long compared with the lifetimes of the states that led to this level. The metastable, the pump and the ground state levels are actually bands of closely spaced energy levels that form a manifold due to the effect known as Starks splitting. Furthermost, each stark level is broadened by thermal effects into an almost continuous band.

**To understand the various energy transitions and photon emissions ranges, consider the following conditions:**

- The pump band shown in the top left of figure 5.1.1 exists at a 1.27 ev separation from the bottom of the  $^4\text{I}_{15/2}$  ground state. This energy corresponds to a 1980 nm wavelength.



**Figure 5.1.1** Energy-level diagrams and various transition processes of Er<sup>3+</sup> ions in silica

- The top of the  $4I_{13/2}$  metastable band is separated from the bottom of the  $4I_{15/2}$  ground state band by .841 eV. This energy corresponds to a 1480 nm wavelength.
- The bottom of the  $4I_{13/2}$  metastable band is separated from the bottom of the  $4I_{15/2}$  ground state band by about .775 eV. This energy corresponds to a 1600 nm wavelength [37, 38].
- This means that possible pump wavelengths are 980 and 1480 nm. The photons emitted during transitions of electrons between possible energy levels in the metastable and ground state bands can range from 1530 to 1600 nm.
- In normal operation, a pump laser emitting 980 nm photons is used to excite ions from the ground state to the pump level, as shown by transition process 1 in fig. these excited ions decay very quickly in about in 1  $\mu$ s. From the pump band to the metastable band, shown as transition process

2 [27].during this decay, the excess energy is released as phonons or, equivalently, mechanical vibrations in the fiber. Within the metastable band, the electrons of the excited ions tend to populate the lower end of the band. Here, they are characterised by a very long fluorescence time of about 10 ms.

- Another possible pump wavelength is 1480 nm. The energy of these pump photons is very similar to the signal photon energy but slightly higher. The absorption of a 1480 nm pump photon excites an electron from the ground state directly to the lightly populated top of the metastable level, as indicated by transition process 3 in fig. These electrons then tend to move down to the more populated lower end of metastable level (transition 4).
- Some of these ions sitting at the metastable level can decay back to the ground state in the absence of an externally stimulating photon flux, as shown by transition process 5[27,28].this decay phenomena is known as spontaneous emission and adds to the amplifier noise.

Two more types of transitions occur when a flux of signal photons that has energies corresponding to the band gap energy between the ground state and the metastable level passes through the device.

- First, a small portion of the external photons will be absorbed by ions in the ground state, which raises these ions to the metastable level, as shown by transition process 6).
- Second, in the stimulated emission process (transition process 7) a signal photon triggers an excited ion to drop to the ground state, thereby emitting a new photon of same energy, wave vector and polarisation as the incoming signal photon.
- The widths of the metastable and ground state levels allow high levels of stimulated emissions to occur in the 1530 to 1560 nm range. The absorption and emission responses of an EDFA depend on the composition of host glass and on the type of dopants such as Ge and Al in the glass.

#### **4.1.4 EDFA Architecture**

Optical fiber amplifier consists of a doped fiber ,one or more pump lasers, a passive wavelength coupler ,optical isolators , and tap couplers as shown in fig. the dichroic(two-wavelength) coupler handles either 980/1550 nm wavelength combinations to couple both the pump and signal optical powers efficiently into the fiber amplifier[26,29]. The tap couplers are wavelength – insensitive with typical splitting ratios ranging from 99:1 to 95:5.they is generally used on both sides of the amplifier to compare the incoming signal with the amplified output. The optical isolators prevent the amplified signal from reflecting back into the device, where it could increase the amplifier noise and decrease the amplifier efficiency.

**Three possible configurations of an EDFA:**

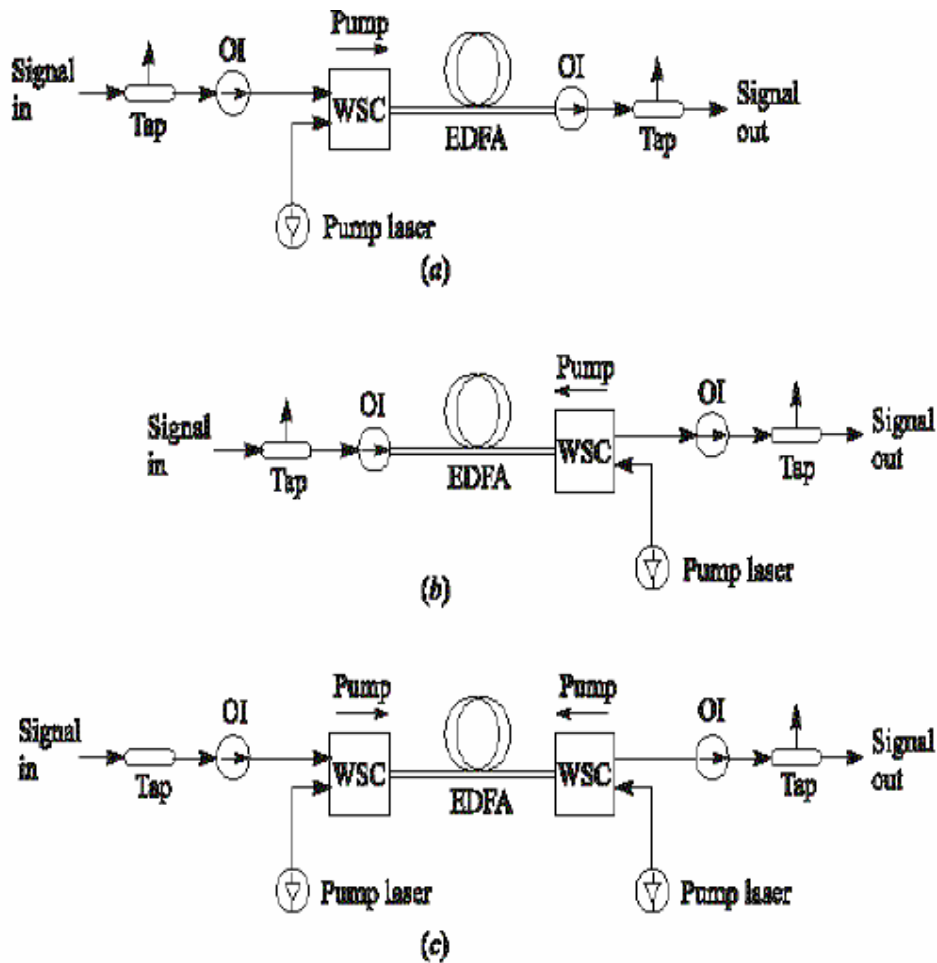
- (a) **Co-directional pumping**

**(b) Counter-directional pumping**

**(c) Dual-pump scheme**

The pump light is usually injected from the same direction as the signal flow. This is known as co-directional pumping [28]. It is also possible to inject the pump power in the opposite direction to the signal flow, which is known as counter-directional pumping.

As shown in Fig 5.1.2, one can employ either a single pump source or use dual pump schemes, the resultant gains typically being +17 dB and +35 dB, respectively.



OI: Optical isolator  
WSC: Wavelength-selective coupler

**Figure 5.1.2 Configurations of an EDFA**

**(a) Co-directional pumping**

**(b) Counter-directional pumping**

**(c) Dual pumping**

Counter-directional pumping allows higher gains but co-directional pumping gives better noise performance[28,29] .In addition, pumping at 980 nm is preferred, since it produces less noise and achieves larger population inversion than pumping at 1480 nm.

#### **4.1.5 APPLICATIONS**

##### ***Erbium-doped Amplifiers in Telecom Systems***

**EDFAs can serve various functions in systems for optical fiber communications; the most important applications are the following:**

- The power of a data transmitter may be boosted with a high-power EDFA before entering a long fiber span, or a device with large losses, such as a fiber-optic splitter [21]. Such splitters are widely used e.g. in cable-TV systems, where a single transmitter is used to deliver signals into many fibers.
- A fiber amplifier may also be used in front of a data receiver, if the arriving signal is weak. Despite the introduction of amplifier noise, this can improve the signal-to-noise ratio and thus the possible data transmission rate, since the amplifier noise may be weaker than the input noise of the receiver [25]. It is more common, however, to use avalanche photodiodes, which have some built-in signal amplification.
- In-line EDFAs are used between long spans of passive transmission fiber. Using multiple amplifiers in a long fiber-optic link has the advantage that large transmission losses can be compensated without (a) letting the optical power drop to too low levels, which would spoil the signal-to-noise ratio, and (b) without transmitting excessive optical powers at other locations, which would cause detrimental nonlinear effects due to the unavoidable fiber nonlinearities[28,29]. Many of these in-line EDFAs are operated even under difficult conditions, e.g. on the ocean floor, where maintenance would be hardly possible.
- Although data transmitters are normally not based on erbium-doped devices, EDFAs are often part of equipment for testing transmission hardware. They are also used in the context of optical signal processing.

#### 4.1.6 Comparison between different amplifiers:

<b>PROPERTY</b>	<b>SOA</b>	<b>EDFA</b>	<b>RAMAN AMPLIFIER</b>	<b>BRILLOUIN AMPLIFIER</b>
<b>UNSATURATED DEVICE GAIN</b>	>20 dB	>20 dB	5-15 Db	>25dB
<b>OPTICAL PUMP POWER</b>	NA	20-50 mW	100-200 mW	<10 mw
<b>OPTICAL PUMP WAVELENGTH</b>	NA	820 nm, 980 nm, 1400-1500 nm	Stokes shift below signal	
<b>ELECTRICAL BIAS CURRENT</b>	50mA	>100mA	>500mA	<50mA
<b>WAVELENGTH OF OPERATION</b>	any	1525 – 1565nm	Any, but subject to pump	
<b>BANDWIDTH</b>	20 – 50nm	10 – 40nm	20 – 40nm	0.001nm
<b>COUPLING LOSS</b>	5 – 6dB	<1dB	<1dB	<1dB
<b>POLARIZATION SENSITIVITY</b>	> few dB	0dB	0dB	0dB
<b>SATURATED OUTPUT</b>	> few mW	few mW	Limited only by pump power	
<b>DIRECTIONS</b>	bidirectional	bidirectional	bidirectional	unidirectional
<b>NOISE</b>	low	low	Very low	Very low

**Table 2.1 Comparison of Optical Amplifiers (NA: not applicable)**

## **CHAPTER 2**

### **LITERATURE SURVEY**

Different compensation methods were studied in the last decade and based on these methods efforts were made to increase the transmission distances and bandwidth of optical communication systems. B.P.Lathi et al. [3] demonstrated the design optimization for efficient erbium-doped fiber amplifiers. The gain and pumping efficiency of alumina silicate erbium-doped fiber amplifiers (EDFAs) are analyzed as a function of guiding parameters and Er-doping profile for two pump wavelengths of  $\lambda_p=980$  nm and  $\lambda_p=1.47$   $\mu$ m.

T.H.Maiman et al. [4] gave the idea about the three designs of fiber-amplifier waveguides: one with the same mode size as standard 1.5- $\mu$ m communication fibers (type 1); one with the same mode size as standard 1.5- $\mu$ m dispersion-shifted fibers (type 2); and one with mode size smaller than those of communication fibers (type 3).

G.P.Agrawal et al. [6] demonstrated the automatic gain control using an all-optical feedback loop in inline erbium-doped fiber amplifiers (EDFA's) used in hybrid analog/digital wavelength division multiplexing (WDM) systems was studied. It is found that the signal level variation for the digital channels can be maintained within a range  $\pm 3$ -dB between the presence and dropout of the analog channel when the narrowband feedback is entered at the amplified spontaneous emission (ASE) peak ( $\lambda = 1532$  nm) with loop loss ranging between 13-22 dB. Robust transmission at 2.5 Gb/s without measurable power penalty was obtained for the digital channels when the EDFA was saturated by either the analog or the control lasing signal.

J.P.Ryan and M.Steinberg et al. [10] described a comprehensive survey of photosensitivity in silica glasses and optical fiber is reviewed. Recent work on understanding the mechanisms contributing to germanium or aluminium doped fiber photosensitivity is discussed within the framework of photoelastic densification models.

S.Lee, Y.C.Chung, and D.J. DiGiovanni et al. [12] demonstrated that excitation of higher-order pump modes at 980 nm does not significantly affect the amplifier gain performance. The effect of concentrating the  $\text{Er}^{3+}$  doping near the center of the fiber core is shown to increase the amplifier gain coefficients by a factor of 1.5 to 2. Islam M.N et al. [18] demonstrated the effect of addition and/or

dropping of wavelength-multiplexed channels in a network comprising three concatenated lumped Raman fiber amplifiers (LRFAs) have been analyzed by numerical simulation and verified experimentally.

J.C. R. Giles and E. Desurvire et al. [19] described that Erbium-doped fiber amplifiers are modelled using the propagation and rate equations of a homogeneous two-level laser medium. Numerical methods are used to analyze the effects of optical modes and erbium confinement on amplifier performance, and to calculate both the gain and amplified spontaneous emission (ASE) spectra.

E. Desurvire, J. R. Simpson, and P. C. Becker et al. [23] demonstrated that Fibers with confined erbium doping are completely characterized from easily measured parameters: the ratio of the linear ion density to fluorescence lifetime, and the absorption of gain spectra. Analytical techniques then allow accurate evaluation of gain, saturation, and noise in low-gain amplifiers ( $\sim 20$  dB). R. J. Mears, L. Reekie, M. Jauncey, and D. N. Payne et al. [24] demonstrated the working principle theoretically and experimentally by coupling a selected wavelength of the ASE at the output of the EDFA back to the input. Such a feedback loop, which can be fabricated out of all-fibre passive components, could be easily implemented in any system using EDFAs.

P.C Becker, N.A. Olsson and J.R. Simpson et al. [27] gave the idea about a spectrum-resolved numerical model for the gain clamped EDFA is developed. Good agreement between the model and experimental results is achieved. The model results reveal the gain, clamped gain spectral distribution and noise figure characteristics of the amplifier. The model is used to optimize the selection of the clamped amplifier laser wavelength and laser output coupling to minimize the noise figure.

B. Pedersen et al. [29] demonstrated the basic operation and set up of an erbium doped amplifiers. Along with this the gain spectrum and the applications of the amplifiers in the telecom systems have been presented. Dwight H. Richards et al. [30] demonstrated a detailed theoretical analysis of the gain dynamics of erbium-doped fiber amplifiers (EDFA's) that have been gain-clamped using a ring laser structure and of gain-stabilized EDFA chains. In particular, the transient power excursions and relaxation oscillations experienced by surviving channels when the number of channels passing through an EDFA changes is described. J.L. Zyskind et al. [32] studied that Erbium-doped fiber amplifiers (EDFAs) are key enablers for WDM transmission systems and networks, but certain EDFA characteristics, notably amplifier noise, channel cross saturation and non-uniform gain spectra, give rise to critical limitations on the performance and capabilities of both transmission systems and optical networks.

A. Bononi et al. [35] demonstrated about the set of models for characterizing the gain, the input and output powers of single erbium-doped fiber amplifiers (EDFA's) and networks of EDFA's. They

described about the time dependent gain by a single ordinary differential equation for the average inversion level of an EDFA with arbitrary number of signal channels with arbitrary power levels and propagation directions. In steady state, this ordinary differential equation becomes a transcendental equation from which many important parameters are derived. Through perturbation analysis of the time dependent model, the output perturbation can be expressed explicitly in terms of the input perturbations, which is useful for tone calculations.

P. C. Becker et al. [37] described the effect of fast power transients in erbium-doped fiber amplifiers (EDFAs) on packetized traffic transmitted through a chain of five EDFAs is also presented. M. Menif et al. [38] studied that when the number of WDM channels transmitted through a circuit-switching network varies, channel addition/removal will tend to perturb signals at the surviving channels that share all or part of the route. It was shown that wavelength-division multiplexed (WDM) networks with fiber amplifier cascades face serious problem which is transient cross-gain saturation or gain dynamics of fiber amplifiers. Attention has been focused primarily on circuit-switched scenarios.

Bononi et al. [39] demonstrated that the Compact Transient EDFA model is based on a set of equations that deal with propagation along the length of the EDFA and a “reservoir” approach is used wherein the total EDFA upper-level population is used instead of the upper-level density as a function of length.

Sinkin et al. [45] studied the comparison of modulation formats CRZ, RZ and NRZ in generic undersea system using noise-free simulations has already been done by. First, an optimization procedure was performed over a wide range of parameters to achieve the best performance for each format in a given system and then the physical properties and limitations of the formats were studied. It was found that during transmission, rapid stretching and contractions, while in the receiver, concentration of the pulse energy in the centre of the bit slot, decrease inter-symbol interference.

Z.M. Liao et al. [46] demonstrated the technique to achieve higher spectral efficiency. To achieve this, it is necessary at some point to sacrifice these two properties of RZ formats in favour of formats like NRZ with smaller spectral bandwidth.

Santhanam et al. [47] presented the timing jitter expressions in dispersion-managed light-wave systems that are based on the moment method with the assumption of a chirped Gaussian pulse. A low-power light-wave system employing the RZ format finds that timing jitter can be minimized along the fiber link for an optimal choice of pre-compensation and post-compensation.

M. Jaworski et al. [48] demonstrated the performance analysis of non-return-to-zero (NRZ), return-to-zero (RZ), chirped return-to-zero (CRZ) and carrier suppressed return-to-zero (CSRZ) data formats in optical soliton transmission link under the impact of chirp and third-order dispersion (TOD).

The performance of these data formats has been analyzed on the basis of certain performance metric i.e. bit error rate (BER),  $Q^2$  (dB), OSNR, eye opening, etc. Neil barakat et al. [50] analysed the performance of optical burst switching networks with electronic header processing and found that the finite processing capacity of the electronic core-node header processors can have a significant impact on the maximum throughput and minimum burst length that can be supported.

Bononi et al. [53] demonstrated that the Compact Transient EDFA model is based on a set of equations which deal with propagation along the length of the EDFA. A “reservoir” approach was presented wherein the total EDFA upper-level population is used instead of the upper-level density as a function of length. This type of model can be derived from standard EDFA models. Deservire E. et al. [54] studied that high gain (30-50 dB), large bandwidth ( 90 nm), high output power (10 20 dBm) and low noise figure (NF=3-5 dB) can be obtained using an erbium doped fiber amplifier optimised for 1.55  $\mu\text{m}$  range. The amplification that could previously be made within C band (1525-1565 nm) has now extended to L band (1570-1620 nm) by co-doping the active fiber with Erbium ( $\text{Er}^{3+}$ ), and Ytterbium ( $\text{Yb}^{3+}$ ). On the other hand, Thulium ( $\text{Tm}^{3+}$ ) doped Raman fiber amplifiers have enabled to operate within the S band (1480-1520 nm). M. Monerie et al. [6] gave the idea that a high concentration of erbium ions may result in pair-induced quenching effects, which can potentially reduce the pump power conversion efficiency and degrades the noise figure for an EDFA.

S. J. Ahn et al. [57] presented a technique to reduce fiber length which involves the use of unpumped EDFA and double pass techniques. The effect of injecting conventional band amplified spontaneous emission (C-band ASE) on the performance of long wavelength band erbium-doped fiber amplifier (L-band EDFA) is demonstrated. A circulator and a broadband fiber Bragg grating (FBG) were used to route a C-band ASE into the amplifier system.

J. R. Simpson et al. [58] demonstrated a technique to calculate the maximum transmission distance, maximum number of wavelength channels, the number of amplifiers needed and the optimal distance between chains of EDFA amplifiers.

## **5.1 Motivation**

The optical amplifier is the key of optical transmission systems with Dense Wavelength Division Multiplexing (DWDM). Erbium Doped Fiber Amplifier (EDFA) is used in the optical communications technology at the standard telecommunication wavelength of 1550 nm. EDFA have a high gain, operating at low pump power and their performances are better in comparison with other similar amplifiers and optical devices. Using EDFA in optical networks is possible to extend transmission distances and the capacity in optical network. Also, the EDFA have a large bandwidth, a low noise figure and polarization

insensitivity.

But wavelength-division multiplexed (WDM) networks with fiber amplifier cascades face serious problem which is transient cross-gain saturation or gain dynamics of fiber amplifiers that are needed to be studied upon in different variations of the parameters. Also the OBS amplification with feedback loop was used to control transients and cause amplification. To precisely demonstrate the OBS (optical burst switching) networks, one should be properly aware about the burst length in OBS. But yet there are no predictions made with respect to the burst lengths. The burst length plays a vital role in the processing of data in the optical network. If the burst length is small, throughput is less, and if the burst length is very large delay will be very large. This is because higher wait times will be incurred when packets are formed into larger bursts causing additional overall delay. If burst lengths required in OBS networks are not well known, there may be loss of packets and the problem of contention may occur. Thus, main consideration is given towards burst length in OBS networks. Thus, the predictions should be made for the appropriate burst length, gain of EDFAs to be used for transient reductions and the relationship of burst length with other parameters of OBS.

Study of timing jitter dependence on data formats is also becoming important and controlling of timing jitter is a problem for developing long-distance optical communication systems. While designing high-capacity systems, it becomes very important to carefully model system performance before performing laboratory experiments and field trials, as these experiments are costly and time consuming. The huge design space can only be limited by analytical approximations and computer modelling using powerful simulation tools. As the complexity of the networks increases in DWDM networking, a major potential problem associated with the amplifier is the need for the control of the gain of EDFAs due to circumstances such as faults, adding and dropping of wavelength, and rerouting. In these cases, the total input signal power to the amplifier varies abruptly causing the dynamics of the population inversion to change accordingly. Therefore, the amplifier gain increases or reduces with the potential to cause receiver saturation or bit error rate increment. Thus, a gain-clamping mechanism is desired.

## **5.2 Objectives**

In this thesis, the research is carried out keeping in view the following main objectives:

1. To investigate the effect of channel adding/dropping on EDFA transients.
2. To investigate the possibilities of compensating spectral loss variations in EDFA amplifiers for different modulation formats.

3. To investigate the gain and noise figure performance of EDFAs and Compact EDFAs.

### **5.3 Organization of the Thesis**

The thesis has been organized into six chapters. Contents of each chapter are briefly described as under: Chapter 1 includes the brief introduction to the optical communication system with brief history. In this chapter, the various types of amplifiers and their applications are discussed in brief. Second chapter contains the literature survey and objectives. In the third chapter, EDFA modeling and analysis for its transient suppression has been presented. It is shown that in automatic optical-gain clamped EDFA; transients will decrease when the numbers of channels are added. The fourth chapter describes the method to compensate spectral loss variations in EDFA amplifiers for different modulation formats. The fifth chapter gives the comparison study of gain and noise figure performance of EDFAs and Compact EDFAs. Finally, the sixth chapter gives the conclusion of the thesis work.

### Effect of channel adding/dropping on EDFA Transients

In this chapter, we investigate the technique to control the transients by means of channel adding/dropping in cascades of erbium doped fiber amplifiers (EDFAs) in optical communication system. We demonstrate the transient reduction via simulation by employing the all-optical gain clamping (AOGC) in a chain of erbium doped fiber amplifiers (EDFAs). We show that as EDFAs are gradually added in the optical link, the transients are also reduced significantly. It is observed that when we use cascade of six EDFAs and note the transient reduction, it is not as much as in case of chain of ten EDFAs in which the transients are greatly suppressed. Using the same model we further compare the transient response of Compact EDFAs and Transient EDFAs. It is observed that suppression of transients is much in Compact EDFAs than Transient EDFAs.

#### 6.6 Introduction

The input powers to erbium-doped fibre amplifiers (EDFAs) may vary as slowly as their gain relaxation time in wavelength-division-multiplexed (WDM) networks because wavelength channels which pass through the EDFA can change as a result of network configurations or any other partial failures [30]. Due to this power transients or fluctuations are introduced in surviving channels which results in power transients or fluctuations. All-optical gain-control technique is used to prevent transients in which an EDFA is made to lase at a wavelength different from signal wavelengths, and thus regardless of input signal power level the gain is clamped [31]. Multi-wavelength optical networking (MONET) is a method for communicating digital information using lasers over optical fiber. It also uses EDFAs extensively to limit the effect of attenuation and power splitting in fibers. It provides the next level of communication networks after SONET optical networks with even greater bandwidth capacity. However as we move from the optical networking to the burst and packet switching the EDFAs aren't that steady in operation. Optical burst switching (OBS) is a technique proposed to overcome the shortcomings of deploying conventional wavelength-division-multiplexing (WDM) deployment which includes lack of fine bandwidth granularity in wavelength routing and electronic speed bottlenecks in SONET/SDH [32].

In burst and packet switching the data packets are transported to the destination in the form of the bursts. Due to this there is great possibility of the occurrence of long inter burst idle intervals which results in transients in erbium doped fiber amplifiers. These transients can to great extent deteriorate the overall network performance [32]. The transient speed in a cascade of EDFAs is proportional to the number of EDFAs in the cascade, making such effects more difficult to suppress, and the transients caused by channel dropping are more severe than those by channel adding [34].

Dwight H. Richards et al. [30] demonstrated a detailed theoretical analysis of the gain dynamics of erbium-doped fiber amplifiers (EDFA's) that have been gain-clamped using a ring laser structure and of gain-stabilized EDFA chains. In particular, the transient power excursions and relaxation oscillations experienced by surviving channels when the number of channels passing through an EDFA changes is described. J.L. Zyskind et al. [32] studied that Erbium-doped fiber amplifiers (EDFAs) are key enablers for WDM transmission systems and networks, but certain EDFA characteristics, notably amplifier noise, channel cross saturation and non-uniform gain spectra, give rise to critical limitations on the performance and capabilities of both transmission systems and optical networks. Y. Sun et al. [34] described the large signal dynamic response of chains of erbium-doped fiber amplifiers (EDFAs) and proved that it is much faster than that of the individual constituent EDFAs.

A. Bononi et al. [35] demonstrated about the set of models for characterizing the gain, the input and output powers of single erbium-doped fiber amplifiers (EDFA's) and networks of EDFA's. They described about the time dependent gain by a single ordinary differential equation for the average inversion level of an EDFA with arbitrary number of signal channels with arbitrary power levels and propagation directions. In steady state, this ordinary differential equation becomes a transcendental equation from which many important parameters are derived. Through perturbation analysis of the time dependent model, the output perturbation can be expressed explicitly in terms of the input perturbations, which is useful for tone calculations.

P. C. Becker et al. [37] described the effect of fast power transients in erbium-doped fiber amplifiers (EDFAs) on packetized traffic transmitted through a chain of five EDFAs is also presented. M. Menif et al. [38] studied that when the number of WDM channels transmitted through a circuit-switching network varies, channel addition/removal will tend to perturb signals at the surviving channels that share all or part of the route. It was shown that wavelength-division multiplexed (WDM) networks with fiber amplifier cascades face serious problem which is transient cross-gain saturation or gain dynamics of fiber amplifiers. Attention has been focused primarily on circuit-switched scenarios. Bononi et al. [39] demonstrated that the Compact Transient EDFA model is based on a set of equations that deal with propagation along the length of the EDFA and a "reservoir" approach is used wherein the total EDFA upper-level population is used instead of the upper-level density as a function of length.

However, these approaches require a high-power laser source, have slow response or suffer from relaxation oscillations. Also the OBS amplification with feedback loop was used to control transients and cause amplification. To precisely demonstrate the OBS networks, one should be properly aware about the burst length in OBS. But yet there are no predictions made with respect to the burst lengths. The burst length plays a vital role in the processing of data in the optical network. If the burst length is small, throughput is less, and if the burst length is very large delay will be very large. This is

because higher wait times will be incurred when packets are formed into larger bursts causing additional overall delay. If burst lengths required in OBS networks are not well known, there may be loss of packets and the problem of contention may occur. Thus, main consideration is given towards burst length in OBS networks. Thus, the predictions should be made for the appropriate burst length, gain of EDFAs to be used for transient reductions and the relationship of burst length with other parameters of OBS

In this chapter, we have observed that as we increase the number of EDFAs cascaded in the optical link employing the AOGC, the transients are significantly suppressed when using a chain of ten EDFAs as compared to chain of six EDFAs. In an AOGC EDFA, a lasing wavelength filtered from the ASE (i.e., amplified spontaneous emission) spectrum at the amplifier output is fed back into the EDFA. As we change the input power, the power of the lasing wavelength will change correspondingly. When a channel is dropped, the power of the lasing wavelength will increase and when a channel is added, its power will decrease. The total input power into the EDFA is kept almost constant. However, it is provided by simulation results that the AOGC EDFA can't completely eliminate transients. The power of the surviving channels stays constant in the steady state (when the transients have settled).

The amplitude and duration of such transients a complex function of several factors, including the power of the EDFA pump, the feedback loss used in the optical loop, the power of the adding/dropping channels, etc. The overshoots and undershoots shown can have detrimental effects. During the overshoots, noise will increase due to the enhanced nonlinear effects. During the undershoots, the power of signal channels will decrease. We have observed in our simulations of EDFA operation that both the amplitude and duration of EDFA transients will increase/decrease when we add/drop channel gradually, rather than abruptly. It is general and can be applied to amplifiers using different technologies, including EDFAs, solid state and Raman amplifiers.

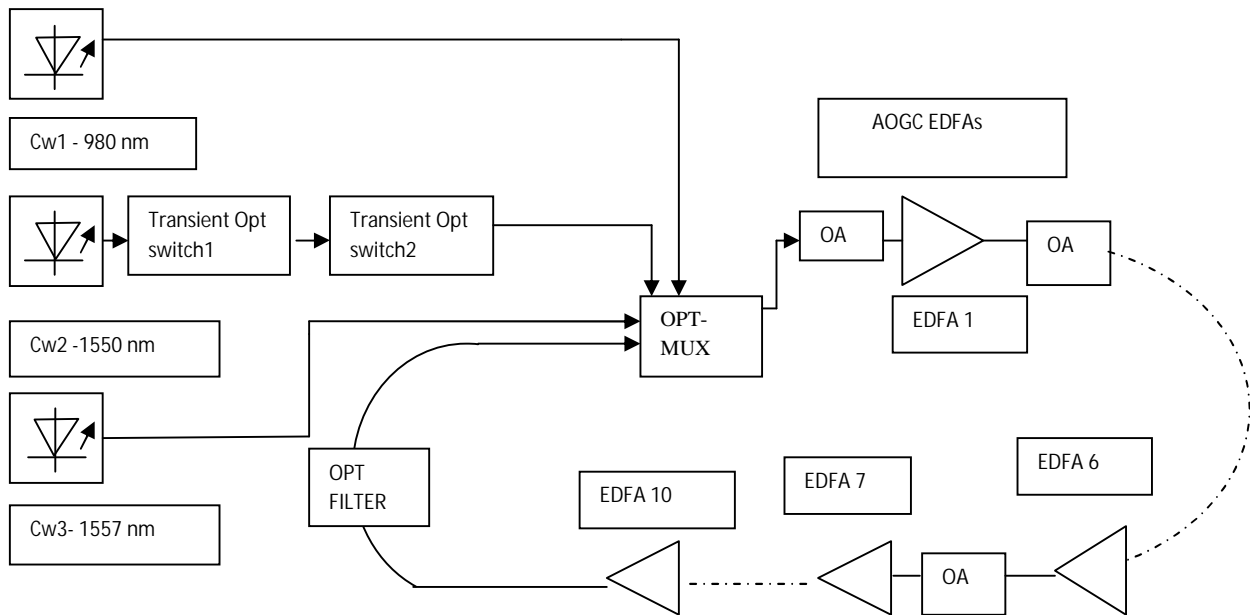
Further, a comparison between the transient response of Compact EDFA and Transient EDFA using the same simulation setup is also presented. It is shown that suppression of the transients is better in case of Compact EDFAs than Transient EDFAs.

This chapter is divided into five sections. Section 2 describes descriptive model and Section 3 describes the simulation set up for the new EDFA transient control technique. Section 4 includes the simulation results when the channels are added/ dropped along the link and also the transient response comparison of the Compact EDFA and Transient EDFA. Section 5 gives the conclusion related to the dependence of channel adding/dropping on the EDFA transients in optical communication system.

## **6.7 Descriptive model**

Figure 6.1 shows the block diagram of the proposed technique to control the EDFA transients in fiber based communication system. The set up contains a number of component models represented by block

icons. The Laser block shows simplified continuous wave lorentzian laser (1, 2, and 3) operating at 980nm, 1550 nm and 1557 nm wavelength.



**Figure 6.1 Block diagram of an optical system to suppress EDFA Transients**

Optical attenuators (OA) 1, 2, 3 attenuate the input optical signal. Then we have a chain of ten transient EDFA amplifiers connected end to end. Optical filter component implements a Gaussian transfer function filter having band pass filter synthesis. The EDFAs are connected in automatic optical gain clamped configuration (AOGC).

## 6.8 Simulation set up

Figure 6.2 shows the simulation set up to reduce the EDFA transients. In the model considered, CW Laser 1 operates at 980 nm wavelength,  $100.0 \text{ E-3}$  watts peak power operates in the single mode and no laser random phase. CW laser 2 operates at 1550 nm wavelength,  $20.0 \text{ E-3}$  peak powers, operates in the single mode and no laser random phase. CW laser 3 operates at 1557 nm wavelength,  $5.0\text{E-3}$  peak power, operates in the single mode and no laser random phase. The two CW lasers 2, 3 are transmitted along the EDFA chain. In this model we have used Transient optical switch 1(T\_OptSwitch1) and Transient optical switch 2(T\_OptSwitch2). The switch T1 simulates adding and dropping of the signal at wavelength 1550 nm .Both the switches has bar state as their initial state and it has parameters start\_first\_trans, end\_first\_trans, start\_second\_trans, and end\_second\_trans which occur at  $310 \mu\text{s}$ ,  $330 \mu\text{s}$ ,  $1400 \mu\text{s}$  and  $1450 \mu\text{s}$ . In this set up, we have used the Optical Multiplexer in the multiple-band mode which will put each optical signal band in its own signal representation, thereby decreasing the overall memory load of the simulation by not including the unused frequency bands between the bands. Optical attenuator 1, 2, 3 attenuates the input optical signal by 0 db. Each of the Transient EDFA has length 20 m, metastable lifetime of 10 ms, operates in the giles\_params simulation mode with 0 dB forward and

backward input and output loss. Optical filter component has 193.41 THz centre freq., 1537 nm centre wavelength and 19 dB feedback losses.

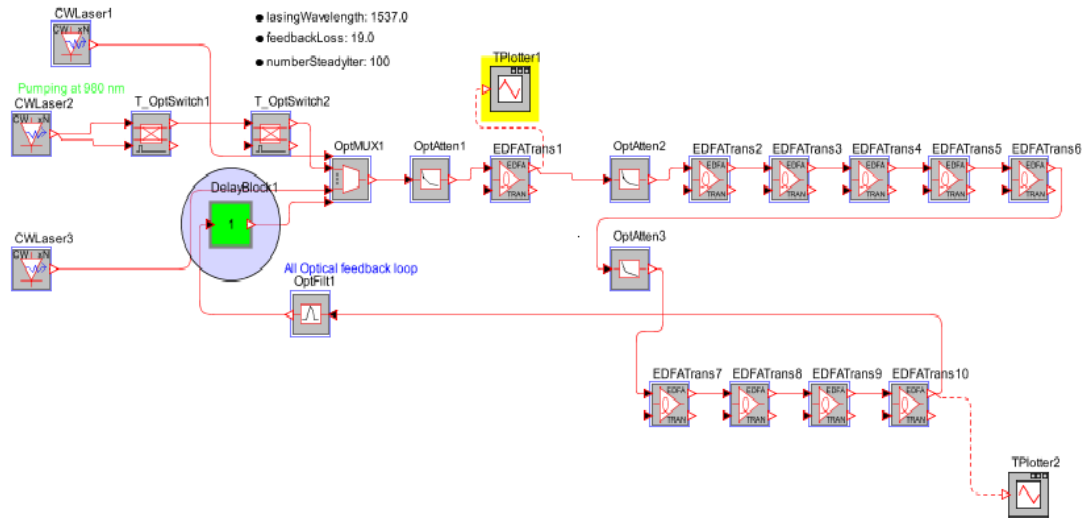
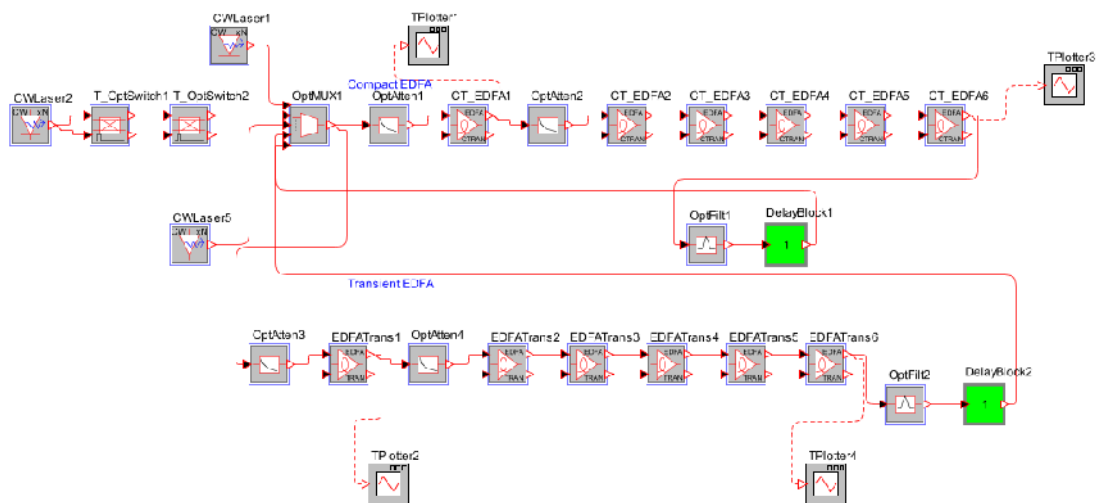


Figure 6.2

**Simulation setup consisting of cascade of 10 AOGC EDFAs**



**Figure 6.3 Simulation setup to compare transients of Compact and Transient EDFA**

The schematic also uses a feedback loop to create a ring laser configuration. The EDFA provides the necessary gain. The signal at wavelength 1550 nm is turned on and off by the switch model shown in

the Figure 6.2, 6.3. The lasing signal at 1537 nm clamps the gain of the surviving channel when the signal at 1550 is dropped. As shown in Figure 6.2 and 6.3, the relaxation oscillations of the lasing signal at 1537 nm causing some relatively minor oscillations to be transformed to the surviving channel. However, these small power excursions are much smaller than those that would be realized without the gain control mechanism. The lasing signal evolves from the ASE noise of the EDFA. The lasing wavelength is selected by the filter in the feedback path. By controlling the amount of loss in the feedback path, we can trade gain stability for EDFA gain. It is observed that lowering the loss in the loop leads to a stronger lasing signal and consequently greater stability of the surviving signal. However, this is achieved at the expense of the overall gain of the EDFA. The Delay Block must be part of all feedback loops in OptSim. It provides an initial signal for the multiplexer to satisfy the requirements of the simulation scheduler. It does not affect the physical properties of the signals passing through it. The measurement components used are Transient analyzers.

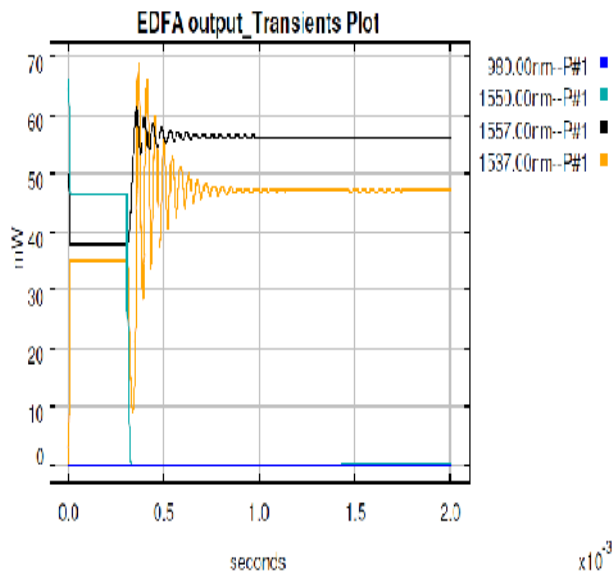
## 6.4 Simulation results and Discussions

In this chapter, an EDFA Transient control technique for fiber based communication system based on the channel adding/dropping principle has been investigated. The technique is demonstrated using a laser ring configuration and is used to control gain transients at the output section. By using simulation, it is also shown that the technique can be used at the first EDFA in a link to provide excellent transient control for the whole link.

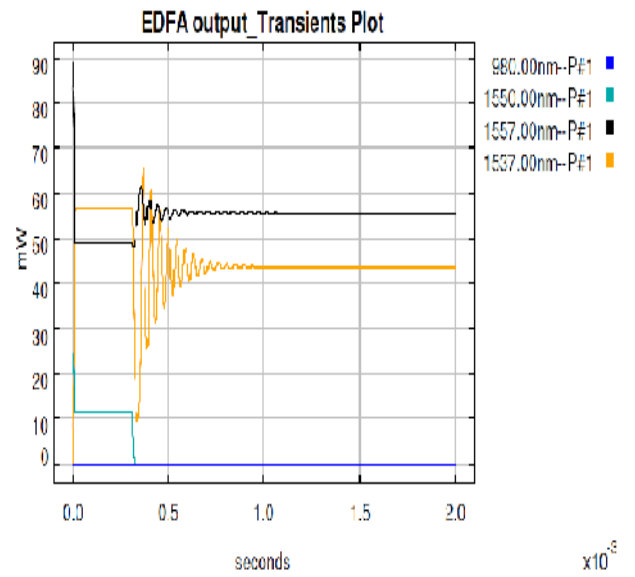
The predictions are done from the transient analyzers connected at various points in the link. The figures 6.1(a - f) shows the results obtained at the output of six Transient EDFA s connected in the link. Firstly, we consider the channel consisting up to six EDFAs and check the transient variations as we increase the EDFA s from one to six. It is observed that after the simulation run, the result shows the impacts of increasing the number of channels on the transient variation of the system. The results are obtained in the form of transient plots for different wavelengths i.e. 1537 nm, 1550 nm and 1557 nm.

The figure 6.1(a) shows the transient plot at the output of the 1<sup>st</sup> EDFA. The induced power transients are maximum in this case. Then transients are plotted by increasing the number of the EDFA amplifiers in the link from 1 to 6. After taking a look on the results it is observed that the transient induced at the output of the 2<sup>nd</sup> EDFA in Figure 6.1(b) are less as compared to the 1<sup>st</sup> EDFA. The transients are significantly reduced for the 1550 nm wavelength. Then at the output of the 3<sup>rd</sup> EDFA in the link ,it is observed that least amount of transients are present for 1550 nm wavelength and suppression of the transients is also visible for 1537 nm and 1557 nm wavelengths. Further, it is shown that upon increasing the EDFA amplifiers from 4 to 6, no transients are present for 1550 nm wavelength.

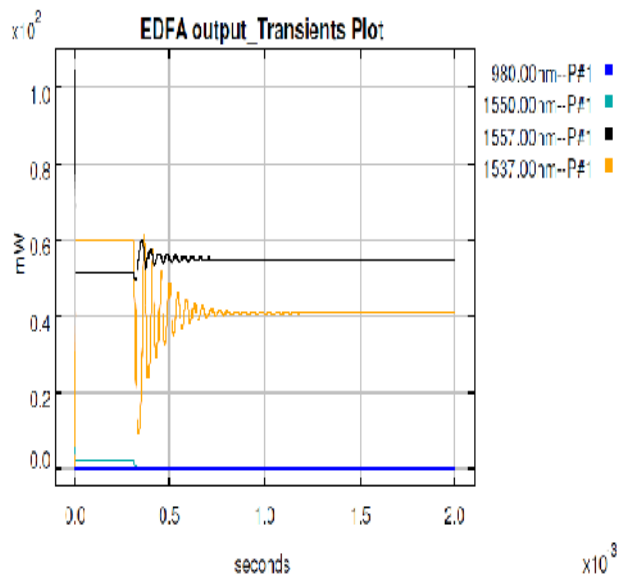
But still significant transients can be seen at the output of the 6th EDFA for 1537 nm and 1557 nm wavelengths.



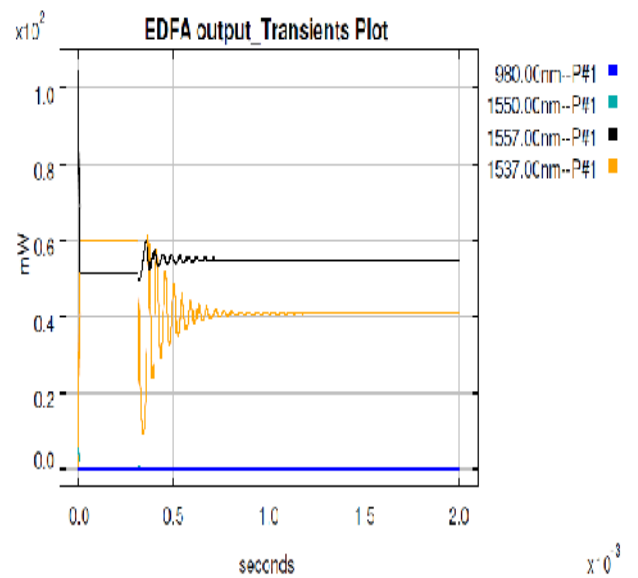
**Fig. 6.1(a) Output of 1<sup>st</sup> EDFA**



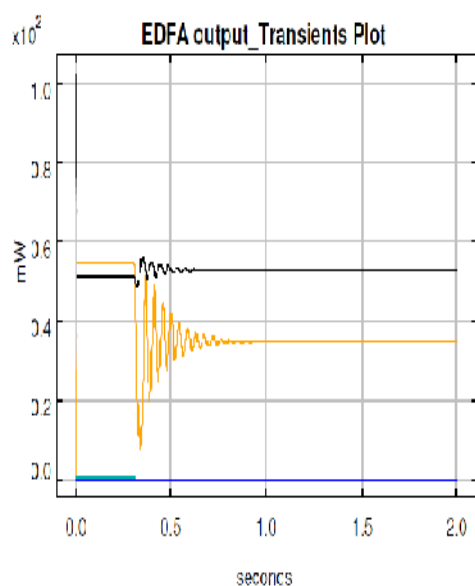
**Fig. 6.1(b) Output of 2<sup>nd</sup> EDFA**



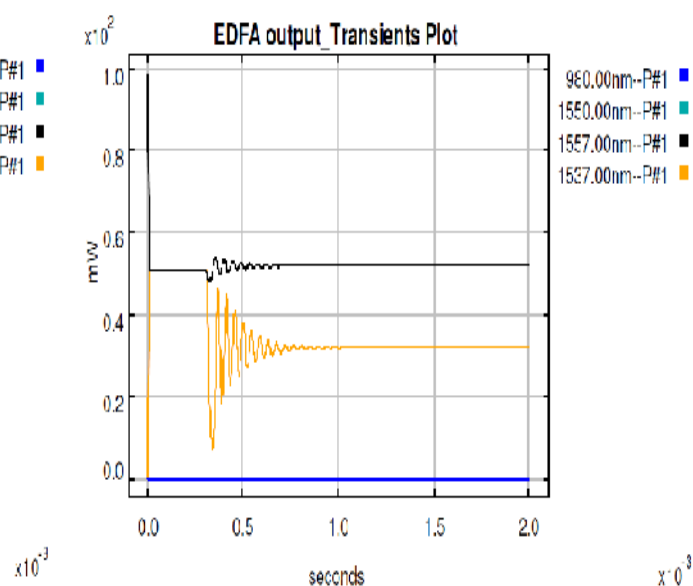
**Fig. 6.1(c) Output of 3<sup>rd</sup> EDFA**



**Fig. 6.1(d) Output of 4<sup>th</sup> EDFA**



**Fig. 6.1(e) Output of 5<sup>th</sup> EDFA**

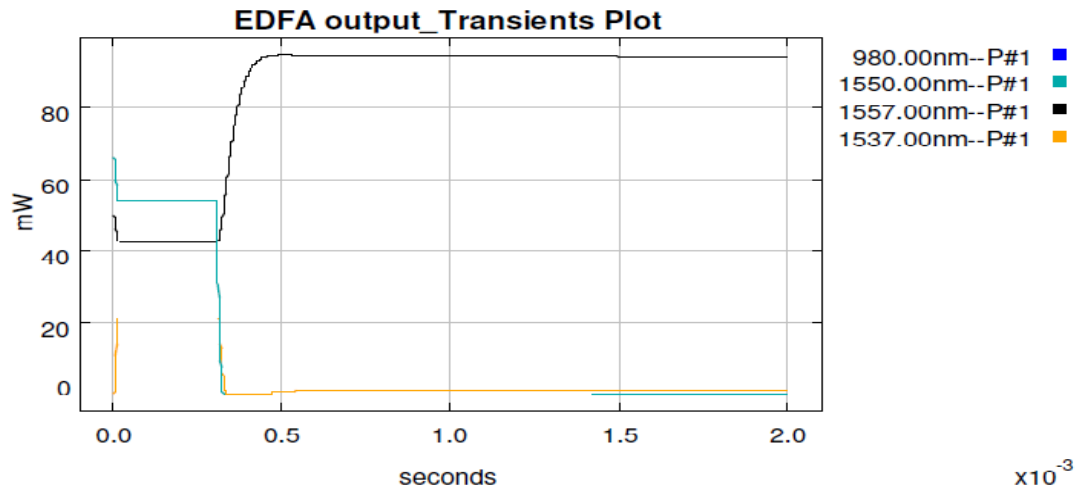


**Fig 6.1(f) Output of 6<sup>TH</sup> EDFA**

In the plots shown above; we have taken a point-to-point multiwavelength optical link consisting of a cascade of 6 AOGC EDFAs (automatic optical gain-clamped EDFA) and variation of transients is shown. It is shown that no transients are present for 1550 nm wavelength but suppression is not much for 1537 nm and 1557 nm wavelengths even when we take chain of 6 EDFAs.

Then we increase the number of channels up to 10 on the link as shown in the Fig 6.2(a) and then the channels each of which simulates a packet-switched connection are dynamically added and dropped. The induced power transients on each of the channel are than measured. It is observed that the significant transients are present at the output of the 1<sup>st</sup> EDFA. Then we note the transients at the output of the 2<sup>nd</sup> EDFA, it is shown that transients are greatly suppressed for 1550 nm and 1557 nm wavelengths. Also at the output of the 3<sup>rd</sup> EDFA least transient variations are present for 1550 nm wavelength and are reduced to a great amount for 1557 nm wavelength. It is shown that no transients are present at the output of the 4<sup>th</sup> EDFA for 1550 nm wavelength and are further reduced for 1557 nm wavelength. Also transients are suppressed to a little amount for 1537 nm wavelength. Further upon increasing the EDFA amplifiers in the link, significant change is observed when the number of EDFA amplifiers is increased up to 8. At the output of the 8<sup>th</sup> EDFA, fewer transients are observed for 1537 nm and 1557 nm wavelengths. Then upon increasing the number of EDFA amplifiers upto 10, transients are reduced to large amount for 1537 nm ,1557 nm wavelengths and no transients are present for 1550 nm

wavelength. It is observed that suppression of transients is much better when we take chain of ten EDFAs than in case of six EDFAs connected in AOGC configuration.

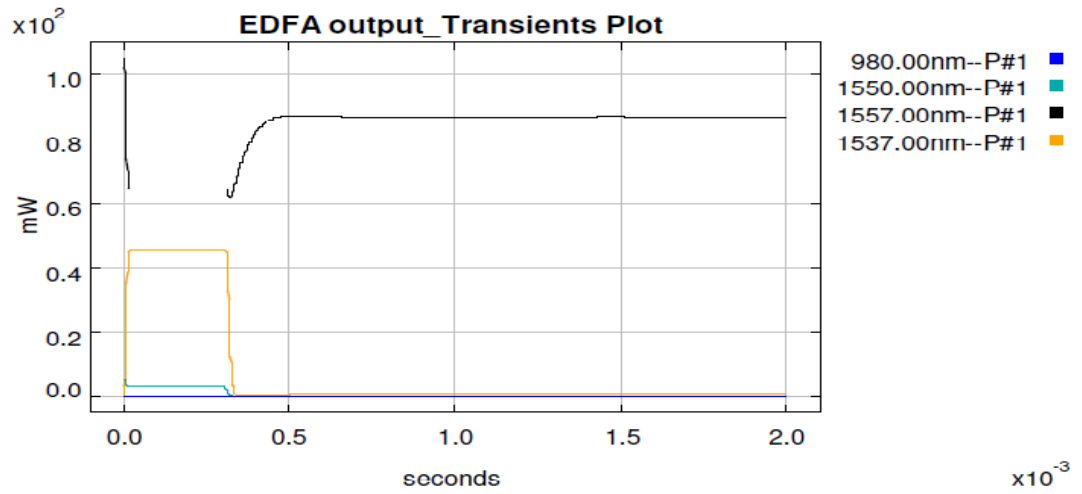


Output of 1<sup>st</sup>

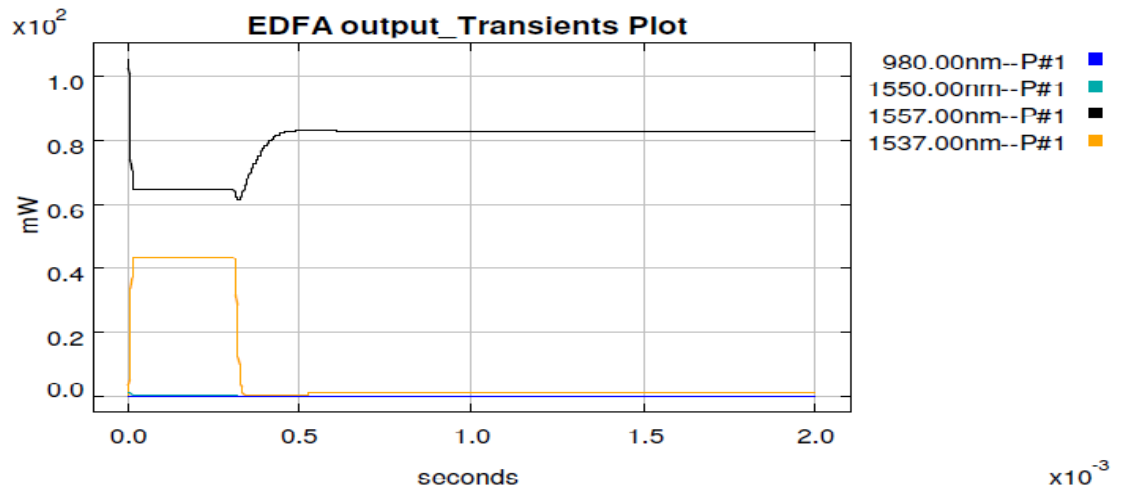
EDFA

Output of 2<sup>nd</sup>

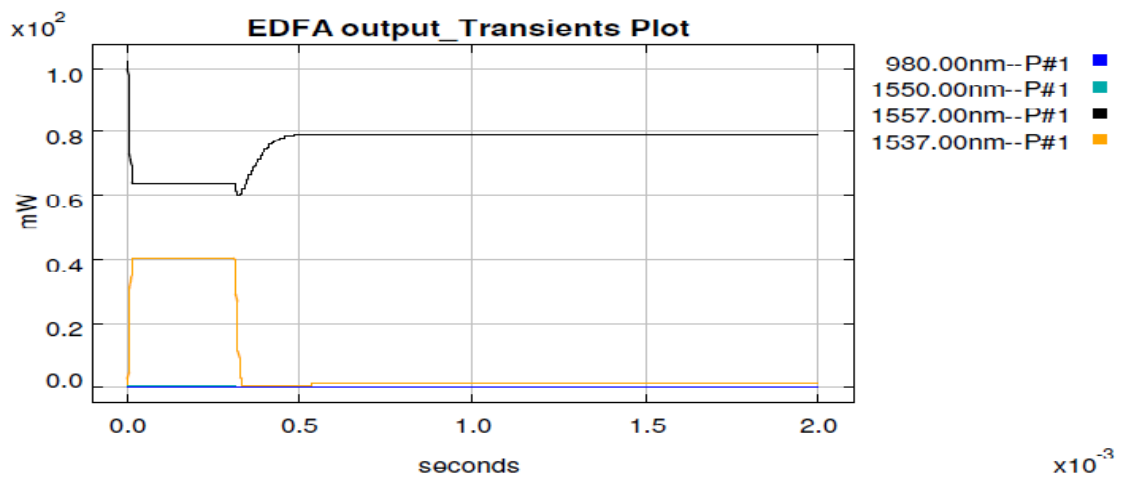
EDFA



**Output of 3<sup>rd</sup> EDFA**

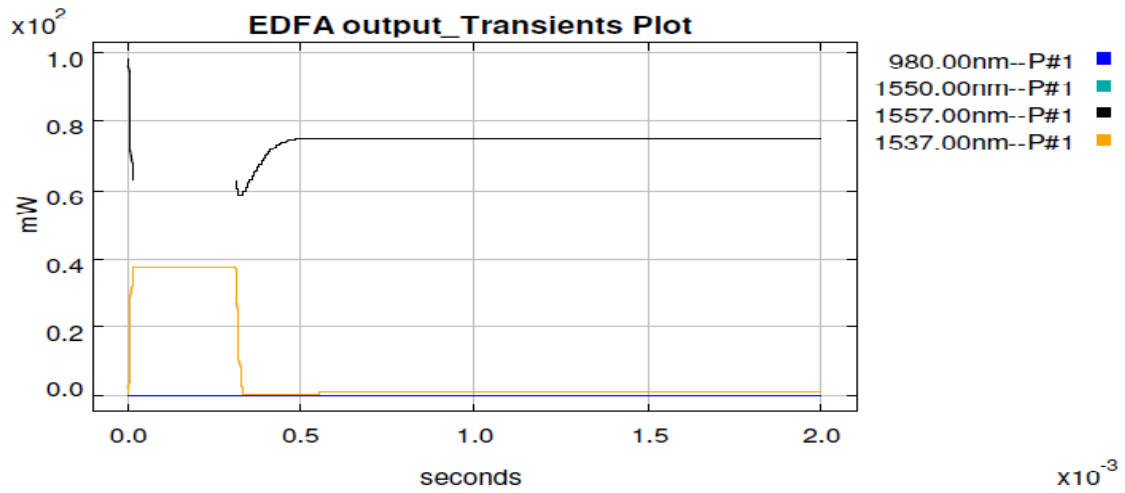


**Output of 4<sup>th</sup> EDFA**

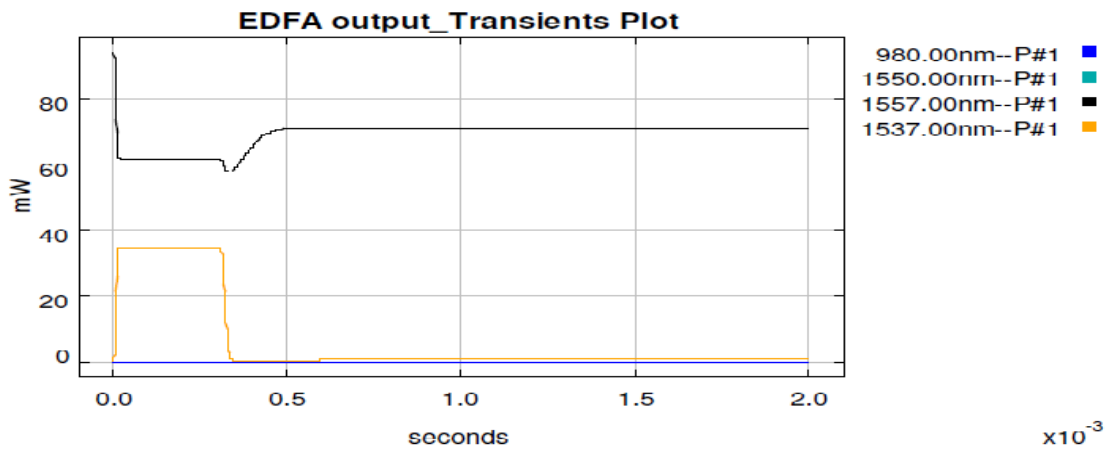


**EDFA**

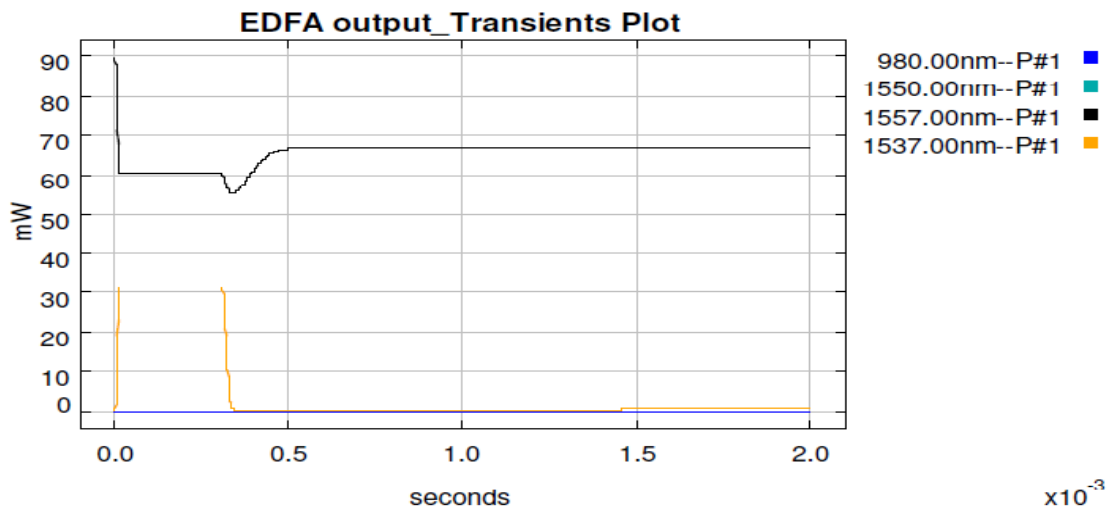
**Output of 5<sup>th</sup>**



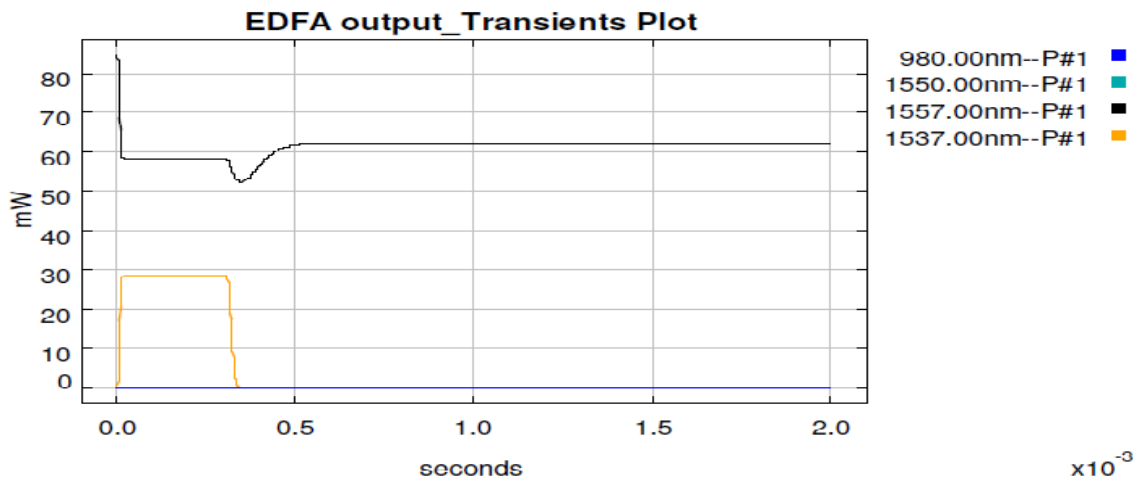
**Output of 6<sup>th</sup> EDFA**



**Output of 7<sup>th</sup> EDFA**



**Output of 8<sup>th</sup> EDFA**

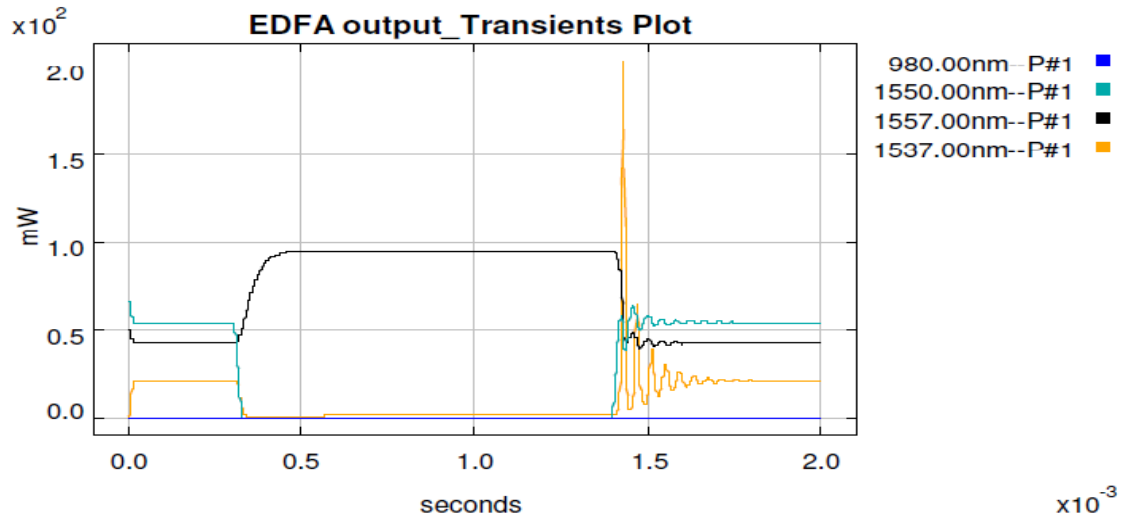


**Output of 9<sup>th</sup> EDFA**

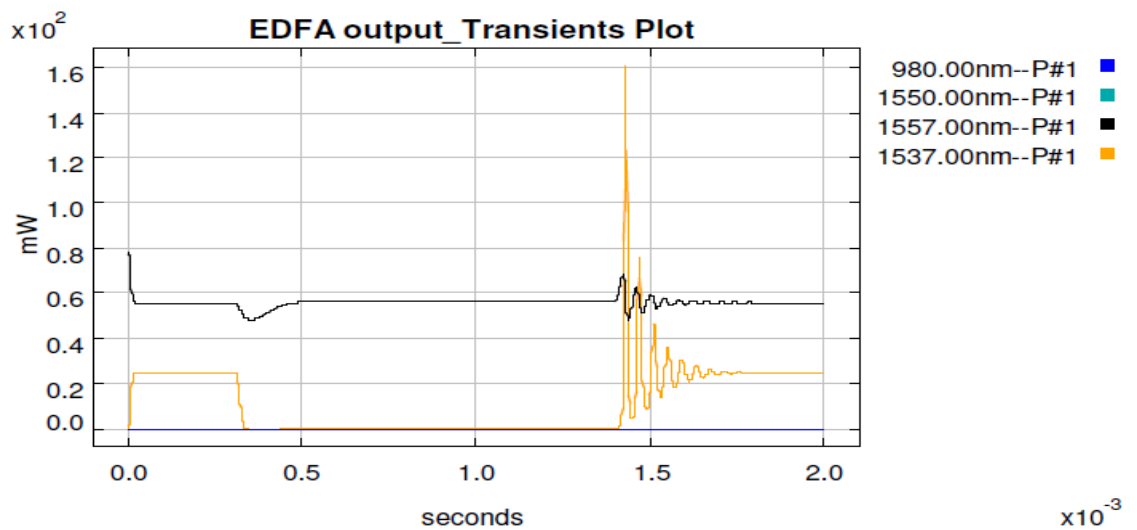
**Output of 10<sup>th</sup> EDFA**

**Figure 6.2(a) Transient's variations as number of channels are increased up to 10**

Further we also demonstrate the effect of optical switching on transients. It is demonstrated by using only the transient optical switch T1 and noting the transients at the input and output.



**Fig 6.2(b) Output of 1<sup>st</sup> EDFA using only T1**

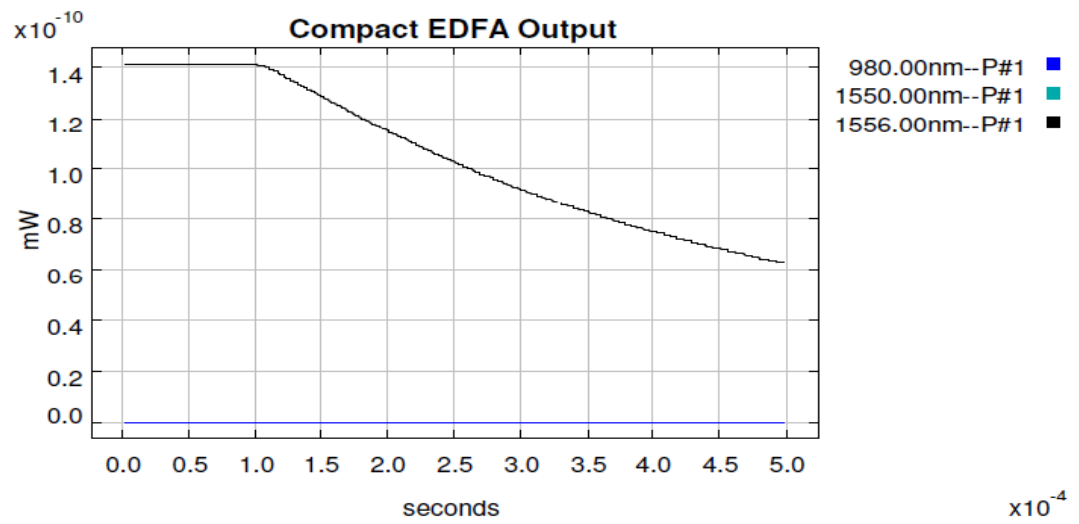


**Fig 6.2(c) Output of 10<sup>th</sup> EDFA using T1**

As clear from the above figures 6.2(b, c), it is observed that the switching is also having adverse effect on the transients produced at the output. The figures above show the impact of adding/dropping channels and optical switching on the induced transients. It is observed that with the increase in number of the EDFA channels and using the switching at the proper instants, the transients are significantly suppressed.

This means that the performance of the system is getting weakened as the number of channels decreases. The plots obtained to compare transient characteristics of Compact EDFAs and Transient EDFAs are shown in Figure 6.3(a, b).

**Figure 6.3(a) Input transient response of Compact EDFA and Physical EDFA**



**Figure 6.3(b) Output transient response of Compact EDFA and Physical EDFA**

It is observed that Compact EDFAs reduces transients to a greater extent than Transient EDFAs.

## **6.5 Conclusions**

In this chapter, we investigate the effect of increasing/decreasing the number of channels and switching on transients induced in fiber based communication system. This effect is seen from the variations of power characteristics depicting transients. It is observed that the behaviour of transients produced becomes predictable with increase of number of channels.

It is also shown that up to 6 channels the transients are not significantly reduced as compared to increasing the number of channels up to 10. It is studied that any further increase in channels causes the great fluctuations in the characteristics of the measured parameters. We further show that by using the same simulation set up, suppression of transients is much better in case of compact EDFAs than Transient EDFAs.

# Compensating spectral loss variations in EDFA Amplifiers for different modulation formats

In this chapter, we investigate the performance of the optical system consisting of chain of EDFA amplifiers for different data formats such as non return to zero (NRZ), return to zero (RZ) and Manchester. Their effect on the spectral loss variations produced in fiber output is analysed. We show that when the RZ raised cosine and Manchester raised cosine modulation formats are used, the non linear ties are produced in power spectrum plots which severely distort the signals obtained at the output of the chain of the EDFA amplifiers. On the other hand, the NRZ raised cosine modulation format best compensates the spectral loss variations in the power spectrum plots obtained at the output. We further show that NRZ raised cosine has good eye opening as compared to other modulation formats.

## 7.6 Introduction

The fourth generation today represents the long-haul transmission system the utilizing multiple carrier wavelengths, which has led to an explosion of channel capacity. At the same time, deregulation of telecommunication markets and global success of the internet has driven the demand for higher and higher system capacity. In 1998, existing systems were upgraded to carry up to four coarsely spaced wavelengths. Today, new dense wavelength-division multiplexing (DWDM) systems that will soon deliver up to 1 Tbit/s of data per fiber over transoceanic distances are under construction. Conventionally, the Non-Return-to-Zero (NRZ) modulation format has been used in long-haul transmission systems [41]. These systems are based on the fact that fiber dispersion and non-linear ties are detrimental effects. NRZ is used advantageously as it provides minimum optical bandwidth and minimum optical peak power per bit interval for a given average power. A RZ-modulated signal stream consists of a sequence of similar pulse shapes, whereas a NRZ-modulated stream does not. Manchester encoding is a special case of binary phase-shift keying (BPSK), where the data controls the phase of a square wave carrier whose frequency is the data rate. Such a signal is easy to generate [42]. Manchester code always has a transition at the middle of each bit period and may (depending on the information to be transmitted) have a transition at the start of the period also. The direction of the mid-bit transition indicates the data [43]. Transitions at the period boundaries do not carry information. They exist only to place the signal in the correct state to allow the mid-bit transition [44]. Although this allows the signal to be self-clocking, it doubles the bandwidth requirement compared to NRZ coding schemes. From the point of view of designing a system,

impairments from optical transmission need to be understood. Also we have to understand what the ways to reduce them are, how the receiver affects the signal and whether it can improve the performance.

Sinkin et al. [45] studied the comparison of modulation formats CRZ, RZ and NRZ in generic undersea system using noise-free simulations has already been done by. First, an optimization procedure was performed over a wide range of parameters to achieve the best performance for each format in a given system and then the physical properties and limitations of the formats were studied. It was found that during transmission, rapid stretching and contractions, while in the receiver, concentration of the pulse energy in the centre of the bit slot, decrease inter-symbol interference. Z.M. Liao et al. [46] demonstrated the technique to achieve higher spectral efficiency. To achieve this, it is necessary at some point to sacrifice these two properties of RZ formats in favour of formats like NRZ with smaller spectral bandwidth.

Santhanam et al. [47] presented the timing jitter expressions in dispersion-managed light-wave systems that are based on the moment method with the assumption of a chirped Gaussian pulse. A low-power light-wave system employing the RZ format finds that timing jitter can be minimized along the fiber link for an optimal choice of pre-compensation and post-compensation.

M. Jaworski et al. [48] demonstrated the performance analysis of non-return-to-zero (NRZ), return-to-zero (RZ), chirped return-to-zero (CRZ) and carrier suppressed return-to-zero (CSRZ) data formats in optical soliton transmission link under the impact of chirp and third-order dispersion (TOD). The performance of these data formats has been analyzed on the basis of certain performance metric i.e. bit error rate (BER),  $Q^2$  (dB), OSNR, eye opening, etc. Neil barakat et al. [50] analysed the performance of optical burst switching networks with electronic header processing and found that the finite processing capacity of the electronic core-node header processors can have a significant impact on the maximum throughput and minimum burst length that can be supported.

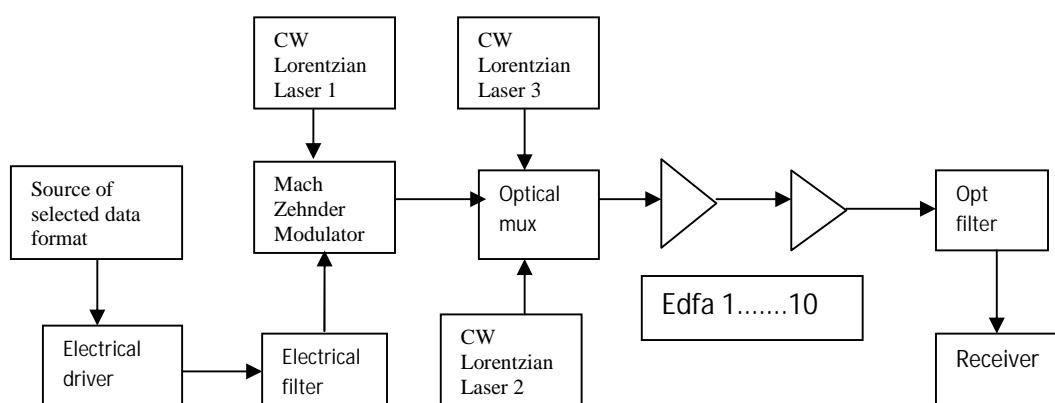
Thus, study of timing jitter dependence on data formats is becoming important and controlling of timing jitter is a problem for developing long-distance optical communication systems. While designing high-capacity systems, it becomes very important to carefully model system performance before performing laboratory experiments and field trials, as these experiments are costly and time consuming. The huge design space can only be limited by analytical approximations and computer modelling using powerful simulation tools.

In this chapter, we focus on the characteristics of optical pulse propagation over modern long-haul fiber-optic transmission systems. Major distortions of optical systems arise from pulse timing jitter, which are introduced by various sources along the propagation path. The subject of this work is to investigate by simulation the timing jitter.

This chapter is divided into five sections. Section 2 describes the descriptive model and Section 3 describes the simulation set up for the reduction of spectral loss variations in chain of EDFA amplifiers. Section 4 includes the simulation results showing the power spectrum plots and eye diagrams for RZ raised cosine, NRZ raised cosine and Manchester raised modulation formats. Section 5 gives the conclusion related to the dependence of the reduction of the spectral losses of the fiber based system on the type of the modulation format used.

## 7.7 Descriptive model

Figure 7.1 shows the block diagram of the proposed technique to control the spectral losses in system consisting of chain of EDFA amplifiers. The set up contains a number of components models represented by block icons which can be categorized into four categories: transmitter, channel and receiver. The transmitter section consists of pseudorandom binary sequence generator (PRBS generator) or a deterministic logical signal generator which is the source of the selected data format. The Electrical driver block simulates an electrical driver which converts the logical input signal to a binary sequence of zeros and ones into an electrical signal. This component acts as RZ raised cosine, NRZ raised cosine and Manchester raised cosine rectangular driver. The electrical filter used in this set up is Bessel filter in low pass (LP) configuration. External modulator models an electro-optic modulator. In this set up we have used Mach-Zehnder type modulator in which the sine function is used instead of the cosine function so that the modulated signal will have the same polarity as the original binary sequence.

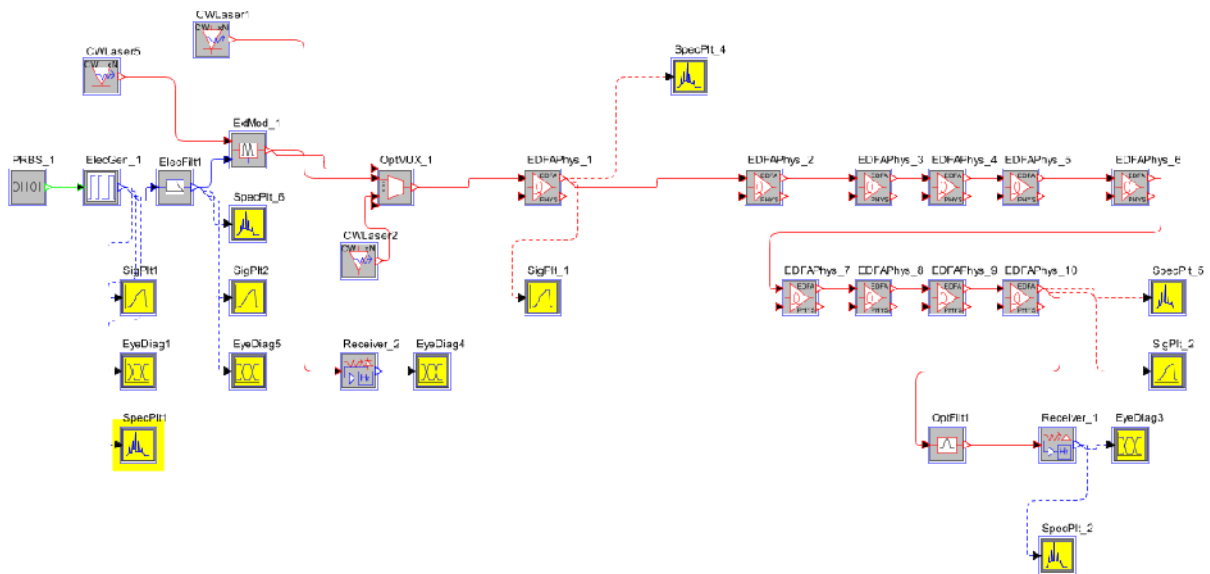


**Figure 7.1 Block diagram of the system to reduce losses for different modulation formats**

The Optical WDM Multiplexer accepts multiple optical signals at its input ports and produces a WDM optical signal at its output port which includes all the input WDM optical signals. Laser block shows simplified Continuous wave Lorentzian laser (1, 2, and 3). Then we have a chain of ten physical EDFA amplifiers connected end to end. In the receiver section we have the Optical filter which implements a Gaussian transfer function filter having band pass filter synthesis. Then we have Compound Optical Receiver which receives the optical input and generates the electrical output signal.

## 7.8 Simulation set up

Figure 7.2 shows the simulation set up consisting of a cascade of ten EDFAs. Data source block simulates a pseudo-random or a deterministic logical signal generator. Besides the logical signal, this component generates an electrical signal synchronized to the baud rate. The bit-time in simulation, i.e. the time-duration of the bit, must be an integer number of time-samples  $NS$  (Samples per bit value). Parameters of basic attribute section taken are 10Gb/s bit rate, 10Gb/s baud rate, 474 samples per bit, one bit/symbol and 7 degree pseudorandom sequence. Driver block simulates an electrical driver which converts the logical input signal to a binary sequence of zeros and ones into an electrical signal. In case of NRZ, non-return-to-zero (NRZ) line code is a binary code in which "1s" are represented by one significant condition (usually a positive voltage) and "0s" are represented by some other significant condition (usually a negative voltage), with no other neutral or rest condition. Return-to-zero (RZ) describes a line code used in telecommunications signals in which the signal drops (returns) to zero between each pulse. This takes place even if a number of consecutive 0's or 1's occur in the signal. In Manchester encoding (also known as Phase Encoding or PE) is a line code in which the encoding of each data bit has at least one transition and occupies the same time. A '0' is expressed by a low-to-high transition, a '1' by high-to-low transition and the transitions which signify '0' or '1' occurs at the midpoint of a period. Raised Cosine implies that signal includes the timing jitter, but does not include the user-specified rise and fall times because the signal shape is specified as a raised cosine. This signal type is not passed through the ringing generation filter. The duty cycle of the pulse may be varied from nearly 0% to 50% using the alpha parameter. The electrical filter used in this set up is in low pass (LP) configuration with the bandwidth 1.0 E10 of the 4<sup>th</sup> order. External modulator used is Mach-Zehnder type modulator which has 5db insertion loss, 30db extinction ratio and 0.5 chirp factor. In this we have used the Optical Multiplexer in the multiple-band mode which will put each optical signal band in its own signal representation, thereby decreasing the overall memory load of the simulation by not including the unused frequency bands between the bands.



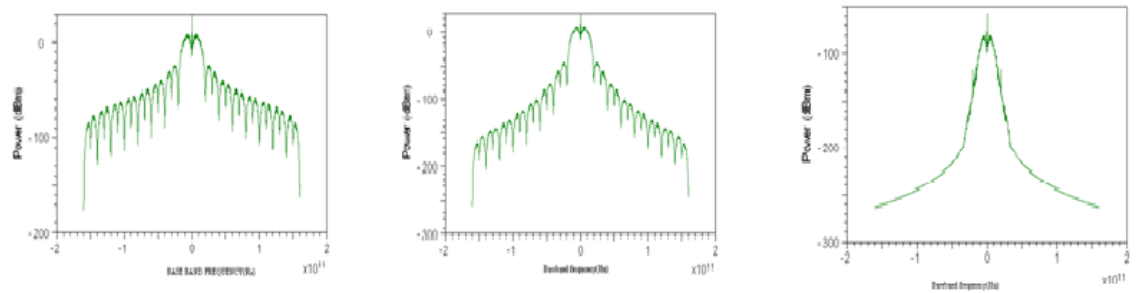
**Figure 7.2 Simulation setup consisting of cascade of 10 EDFAs**

CW lorentzian laser 1 is used in conjunction with the external modulator model to encode a binary signal upon the CW source. In the model considered, it has 1550 nm wavelength, 20.0E-3 watts peak power, operates in single mode and no laser random phase. CW lorentzian laser 2 has 1557 nm wavelength, 5.0 E-3 watts peak power, operates in single mode and no laser random phase. CW lorentzian laser 3 operates at 980 nm wavelength, 100.0E-3 watts peak power and in single mode with no laser random phase. Each of the EDFA has length 10 m, metastable lifetime of 10 ms with calculated overlap simulation mode and no up-conversion coefficient. Optical Filter used in the set up has 193.41 THz centre frequency and 1550 nm centre wavelength. Compound optical receiver is composed of several individual building blocks: the photo detector, the preamplifier, and the post amplifier/filter and the outputs are electrical in nature. At the receiver after the signal passes through the optical filter, we get electrical signal at the output of the compound optical receiver. The measurement components used are signal spectrum analyzers and eye diagram analyzers.

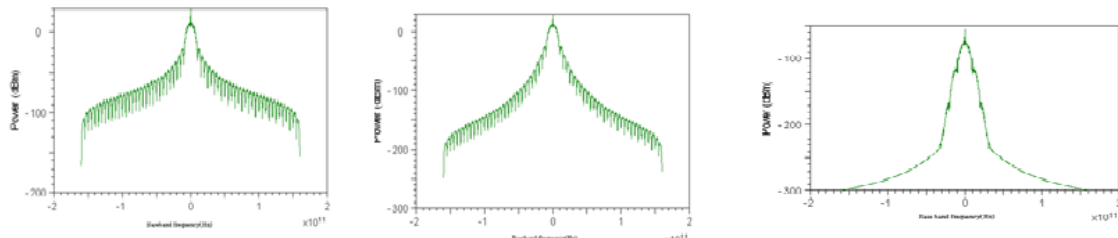
## 7.9 Simulation results and Discussions

In this chapter, the robustness of NRZ raised cosine, RZ raised cosine and Manchester raised cosine modulation formats in the fiber based communication system has been investigated. The technique is demonstrated using a 10 Gbps and it is used to control the non-linear ties in long haul link at the output section. By using simulation, it is shown that the technique can be used in the link consisting of chain of the EDFA amplifiers to provide excellent loss control of fiber nonlinearities.

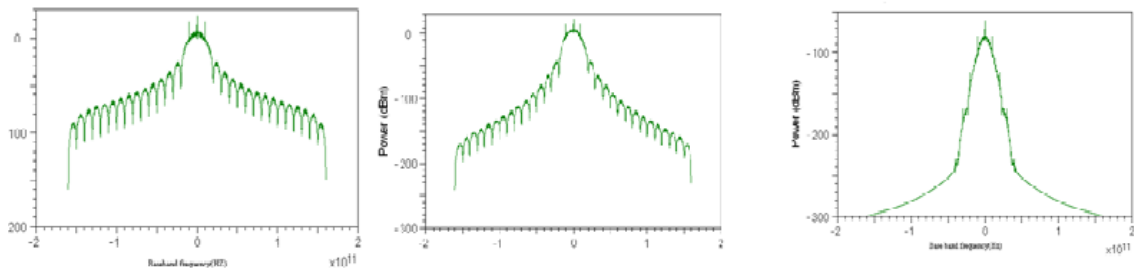
The investigations reveal that the highest power level produced at the output with the minimum noise is in case of NRZ raised cosine data format. For our topology, if we examine the curves corresponding to the cases with and without amplifier noise; we see that until the launched power is low enough, the link noise plays a dominant role. However, at higher launched powers, the nonlinearities dominate the performance impairments as compared to the influence of link noise. The predictions are done from the eye diagrams and the power spectrum plots. The comparison of noise produced at the output of the receiver for above mentioned modulation formats is shown in Figure 7.2(a, b, c).



**Figure 7.2(a) Power spectrum plots for Manchester raised cosine signals in link**



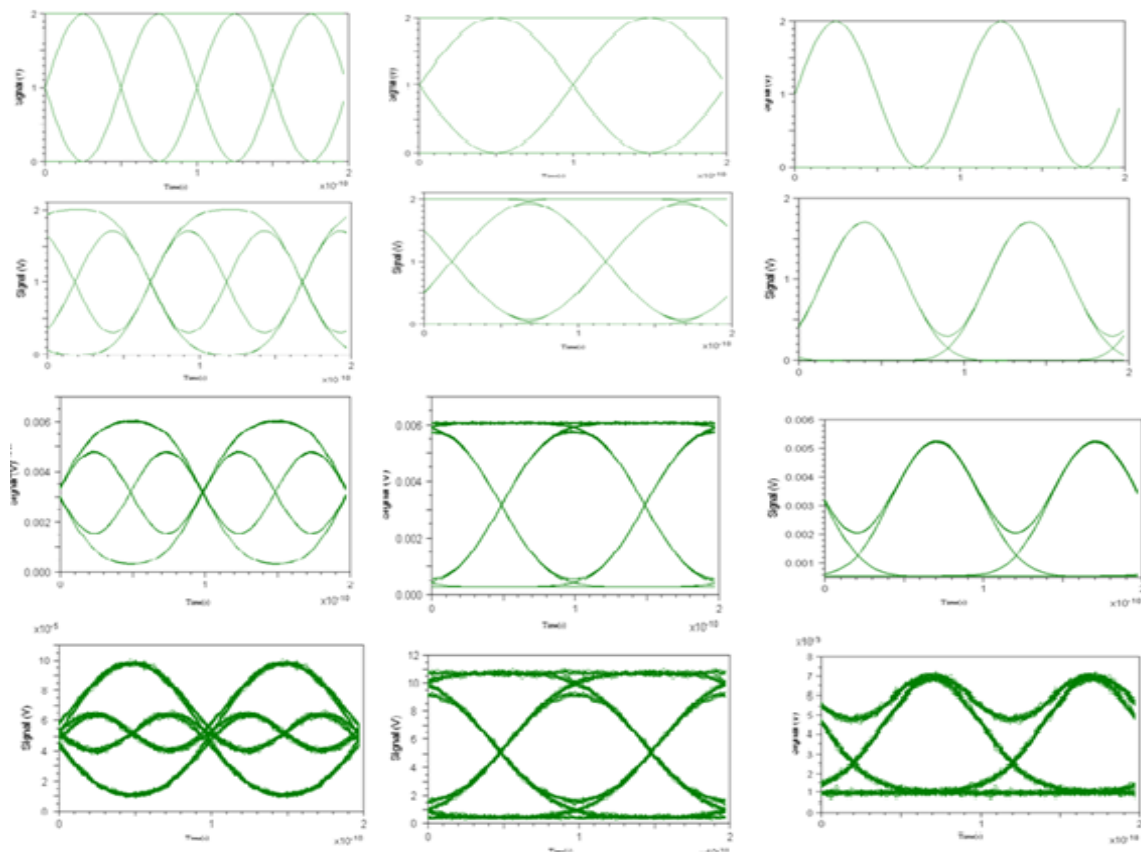
**Figure 7.2(b) Power spectrum plots for NRZ raised cosine signals in link**



**Figure 7.2(c) Power spectrum plots for RZ raised cosine signals in link**

The power spectrum plots shown in the Figure 7.2(a, b, c) are taken at the output of the electrical generator, at the output of the electrical filter and then at the output the receiver for all the three modulation formats. Figure 7.2(a) shows the power spectrum plots for Manchester raised cosine modulation format, Figure 7.2(b) shows the power spectrum plots for NRZ raised cosine modulation format and Figure 7.2(c) shows the power spectrum plots for NRZ raised cosine modulation. It is observed that at the output of the electrical filter the noisy variations are produced least in case NRZ raised cosine format. Then at the output of chain of EDFA amplifiers, it is shown that the noisy spikes produced in the power spectrum are more in case of Manchester raised cosine than in RZ raised cosine. As shown in the Figure 7.2(b), it's clearly visible that that the variations produced in the power spectrum plots are minimum in case of the NRZ raised cosine modulation format. The plots show that received signal quality with the minimum non-linear ties and least spectral loss variations is best with NRZ raised cosine than in case of Manchester raised cosine and RZ raised cosine modulation formats.

Now for different modulation formats, the eye diagrams are shown in Figure 7.3(a, b, c).The eye diagrams are plotted at the output of the electrical driver, electrical filter, external modulator and then at the output of the receiver.



**Figure 7.3(a,b,c) Eye diagrams for Manchester raised cosine (left column) and NRZ raised cosine (center column) and RZ raised cosine (left column) signals in link**

The eye diagram within the span of the cascaded EDFAs is shown in the figure 7.3(a, b, c). It is observed that the eye diagram distortion is found for RZ, raised cosine and Manchester raised cosine formats in Figure 7.3(a, c). However, there was nearly no distortion for the eye diagrams of RZ raised cosine signals, as shown in Figure 7.3(c). It is shown that by using the NRZ raised cosine modulation format, the eye opening increases. Also, if we use RZ raised cosine and Manchester raised cosine modulation formats, and then there will be more eye closure. Here, the wider eye opening in case of NRZ raised cosine in comparison of RZ and Manchester raised cosine demonstrate its robustness on noise and higher-order nonlinear effects.

## **7.10 Conclusions**

In this chapter, the robustness of NRZ, RZ and Manchester raised cosine modulation formats at 10 Gbps for optical long haul link on the amplifier noise variations has been investigated. It has been noticed that in link consisting of the chain of EDFA amplifiers, the NRZ 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. The RZ raised cosine also provides the better results than the Manchester raised cosine format. But NRZ raised cosine modulations are robust and indicate the better link performance. Further, the robustness on dispersive noisy link for NRZ modulation has been justified by wide eye opening in comparison with RZ, and Manchester raised cosine modulation formats.

**Gain and Noise Figure Performance of Erbium doped fiber amplifiers (EDFAs) and Compact EDFAs**

In this chapter, we compare the gain and noise figure characteristics of Physical EDFAs and Compact EDFAs in an optical system consisting of cascade of both the amplifiers. We demonstrate the Gain, Noise Figure variations of a forward pumped EDFA and Compact EDFA as functions of  $\text{Er}^{3+}$  fiber length, injected pump power and up-conversion coefficient. It is observed that the gain becomes constant when the length of both the amplifiers reaches above 20m. The comparison shows that the higher gain with flatter output is obtained in case of Compact EDFAs than Physical EDFAs in a system consisting of chain of both the amplifiers. It is further investigated that the agreement between the Compact and Physical EDFA models is good up to 10 m with the no up-conversion co-efficient. Also, the noise figure obtained in case of Physical EDFA is higher than Compact EDFA when same amplifier length is more than 20 m and then becomes constant for both the amplifiers.

**8.1 Introduction**

Fiber loss is a fundamental limitation in realising long haul point-to-point fiber optical communication links and optical networks. One of the advanced technologies achieved in recent years is the advent of erbium doped fiber amplifiers (EDFAs) that has enabled the optical signals in an optical fiber to be amplified directly in high bit rate systems beyond Terabits. One of the most important factors limiting the transmission distance in fiber optical communication systems is the optical power loss caused by scattering and absorption mechanisms in optical fiber [51]. Electrical repeaters, which require optical-electrical signal conversion, have previously been used to compensate the power losses increasing with distance. The use of such repeaters in optical communication systems have made the systems more complex and increased their installation costs. The optical amplifiers, that were developed in 1980s and came partially into the use commercially in 1990s, enable the optical signals to be directly amplified optically [52]. The most significant types of optical amplifiers are semiconductor laser amplifiers, Raman and Brillouin amplifiers, and rare-earth doped fiber amplifiers. The fiber amplifiers operating at specific wavelengths from visible to infrared light region (up to 3  $\mu\text{m}$ ) can be made using different rare earth ions such as Erbium ( $\text{Er}^{3+}$ ), Holmium ( $\text{Ho}^{3+}$ ), Neodmium ( $\text{Nd}^{3+}$ ), Prasedmium ( $\text{Pr}^{3+}$ ), Samarium ( $\text{Sa}^{3+}$ ), Thulium ( $\text{Tm}^{3+}$ ) and Ytterbium( $\text{Yb}^{3+}$ ). However, the most interesting element listed above is erbium. Because, Erbium Doped Fiber Amplifiers (EDFA) made by doping the silica fiber with erbium ions can operate in a broad range within the 1550 nm window at which the attenuation of silica fiber is minimum and therefore it is ideal for the optical fiber communication systems operating at this wavelength range

[55]. Compact EDFA models the dynamic operation of an erbium-doped fiber amplifier (EDFA) via a “reservoir”-based model. It supports a variety of pump and signal configurations, as well as both fiber and waveguide amplifier geometries.

Bononi et al. [53] demonstrated that the Compact Transient EDFA model is based on a set of equations which deal with propagation along the length of the EDFA. A “reservoir” approach was presented wherein the total EDFA upper-level population is used instead of the upper-level density as a function of length. This type of model can be derived from standard EDFA models. Deservire E. et al. [54] studied that high gain (30-50 dB), large bandwidth (90 nm), high output power (10–20 dBm) and low noise figure (NF=3-5 dB) can be obtained using an erbium doped fiber amplifier optimised for 1.55  $\mu\text{m}$  range. The amplification that could previously be made within C band (1525-1565 nm) has now extended to L band (1570-1620 nm) by co-doping the active fiber with Erbium ( $\text{Er}^{3+}$ ), and Ytterbium ( $\text{Yb}^{3+}$ ). On the other hand, Thulium ( $\text{Tm}^{3+}$ ) doped Raman fiber amplifiers have enabled to operate within the S band (1480-1520 nm). M. Monerie et al. [6] gave the idea that a high concentration of erbium ions may result in pair-induced quenching effects, which can potentially reduce the pump power conversion efficiency and degrades the noise figure for an EDFA.

S. J. Ahn et al. [57] presented a technique to reduce fiber length which involves the use of unpumped EDFA and double pass techniques. The effect of injecting conventional band amplified spontaneous emission (C-band ASE) on the performance of long wavelength band erbium-doped fiber amplifier (L-band EDFA) is demonstrated. A circulator and a broadband fiber Bragg grating (FBG) were used to route a C-band ASE into the amplifier system.

J. R. Simpson et al. [58] demonstrated a technique to calculate the maximum transmission distance, maximum number of wavelength channels, the number of amplifiers needed and the optimal distance between chains of EDFA amplifiers.

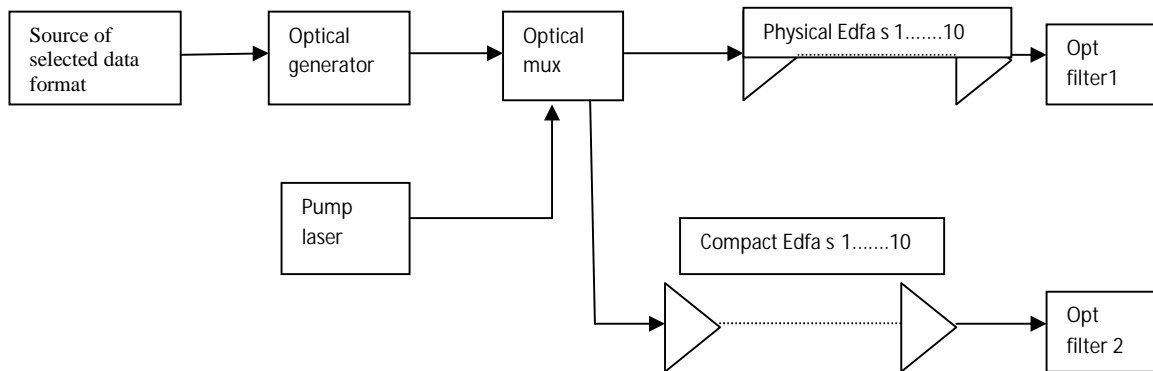
As the complexity of the networks increases in DWDM networking, a major potential problem associated with the amplifier is the need for the control of the gain of EDFAs due to circumstances such as faults, adding and dropping of wavelength, and rerouting. In these cases, the total input signal power to the amplifier varies abruptly causing the dynamics of the population inversion to change accordingly. Therefore, the amplifier gain increases or reduces with the potential to cause receiver saturation or bit error rate increment. Thus, a gain-clamping mechanism is desired.

In this chapter, we focus on the gain and noise figure characteristics of Physical EDFAs and Compact EDFAs in a fiber-optic transmission system consisting of cascade of Physical EDFAs and Compact EDFAs. It is shown that the performance of the system is better in case of the Compact EDFAs than that of the Physical EDFAs.

This chapter is divided into four sections. Section 2 describes the descriptive model and Section 3 describes the simulation set up for the comparing the Gain and Noise Figure characteristics of Physical EDFAs transient and Compact EDFAs. Section 3 includes the simulation results when we vary the Gain, Noise Figure of forward pumped EDFA and Compact EDFA as functions of Er<sup>3+</sup> fiber length, injected pump power and up conversion coefficient. Section 4 gives the conclusion related to performance characteristics obtained in both the cases.

## 8.2 Descriptive model

Figure 8.1 shows the block diagram of the proposed technique to compare the Gain and Noise figure characteristics of Physical EDFAs and Compact EDFAs in a system consisting of cascade of both the amplifiers. The set up contains a number of component models represented by block icons. The transmitter section consists of pseudorandom binary sequence generator (PRBS generator) or a deterministic logical signal generator which is the source of the selected data format.



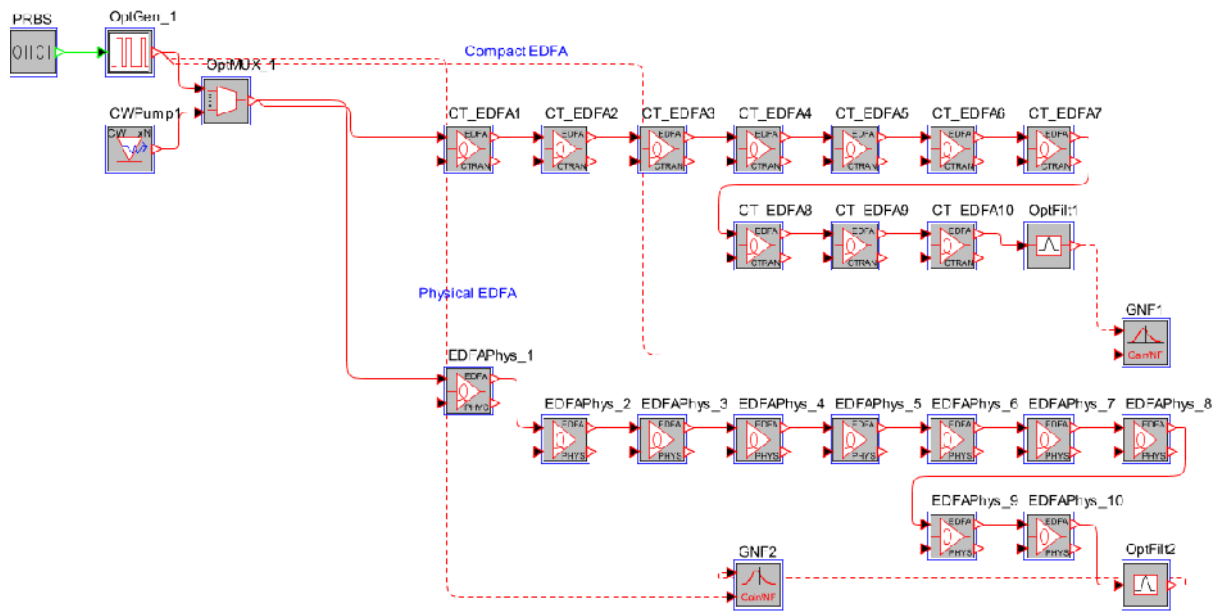
**Figure 8.1 Block diagram of the system to compare the gain and noise figure characteristics**

Optical signal generator converts an input binary signal into an output optical signal. The Laser block shows simplified continuous wave lorentzian laser 1 which is used for pumping. The Optical WDM Multiplexer accepts multiple optical signals at its input ports and produces a WDM optical signal at its output port which includes all the input WDM optical signals. Then we have a chain of ten Physical EDFA and Compact EDFA amplifiers connected end to end. Optical filter component implements a Gaussian transfer function filter having band pass filter synthesis.

## 8.3 Simulation set up

Figure 8.2 shows the simulation set up to compare the gain and noise figure characteristics of Physical EDFAs and Compact EDFAs in a system consisting of cascade of both the amplifiers. Data source block simulates a pseudo-random or a deterministic logical signal generator(PRBS generator) .Besides the logical signal, this component generates an electrical signal synchronized to the baud rate .The bit-time in simulation, i.e. the time-duration of the bit, must be an integer number of time-samples NS (Samples per

bit value). Parameters of basic attribute section taken are 10Gb/s bit rate, 10Gb/s baud rate, 474 samples per bit, one bits/symbol and 7 degree pseudorandom sequence.



**Figure 8.2 Simulation set up for comparing the characteristics of Compact and Physical EDFAs**

Optical generator (OptGen\_1) has on-off-ramp drive type with signal rise and falls time of  $4 \times 10^{-12}$  seconds, NRZ modulation, 1535 nm wavelength, ring filter and random initial phase of -150 dB/Hz. In the model considered, the continuous wave laser (CWpump1) has 1480 nm pump wavelength, .04 watts peak power, operates in single mode and no laser random phase. The Optical Multiplexer (Opt\_Mux1) is used to combine the signals obtained from the output of optical generator and CW Laser. It operates in the multiple-band mode with 0 dB loss which will put each optical signal band in its own signal representation, thereby decreasing the overall memory load of the simulation by not including the unused frequency bands between the bands. Each of the Compact EDFA and Physical EDFA has 1550 nm wavelength, length 10 m, metastable lifetime of 10 ms with calculated overlap simulation mode and no up-conversion coefficient. Optical Filters 1, 2 are used in the set up with 193.41 THz centre frequency, bandwidth  $100 \times 10^{-9}$  and 1550 nm centre wavelength. The measurement components used are Gain and Noise figure analyzers.

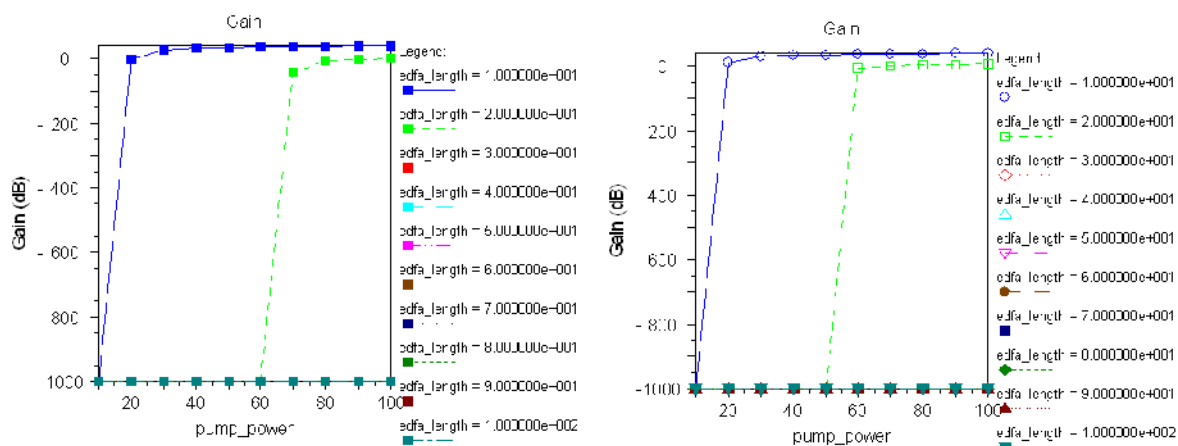
## 8.4 Simulation results and Discussions

In this chapter, the comparison of gain and noise figure characteristics of Physical EDFAs and Compact EDFAs in a system consisting of cascade of both the amplifiers has been investigated.

## Gain Characteristics

The variation of EDFA and Compact EDFA gain with Pump power is shown in Figure 8.2(a, b) for different fiber lengths having a constant signal input power and erbium doping density. In Figure 8.2(a, b), the gain obtained at the output of cascade of Physical EDFAs and Compact EDFAs for ten different fiber lengths which are varied from 10 to 100m with the pump power supplied increased from 10 mW to 100 mW and  $.7e-19$  erbium ion doping density .

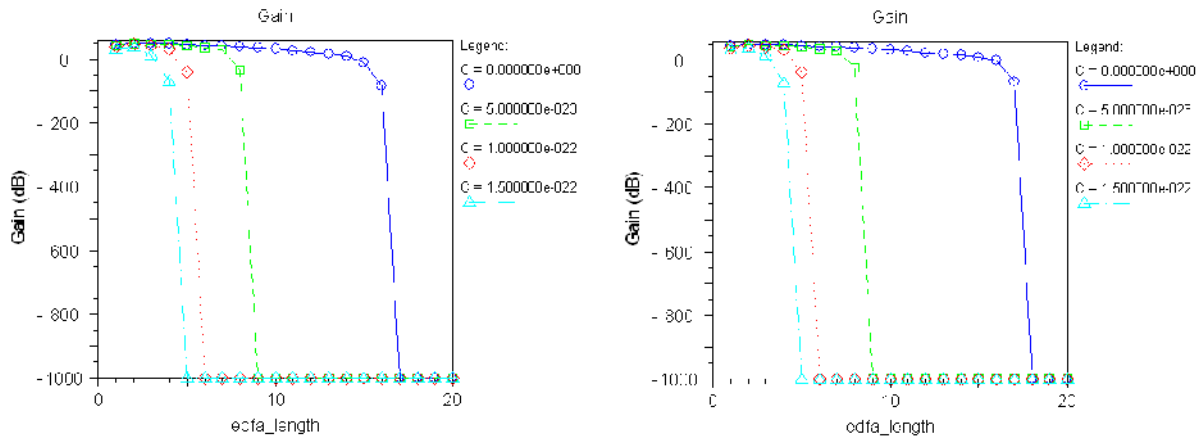
It is shown that when the EDFA and Compact EDFA length is 20 m, the gain increases linearly with the pump power for both the amplifiers.



**Figure 8.2 Gain variation of a) EDFA b) compact EDFA with Pump power**

It is observed that when a signal input power of  $-40\text{dBm}$  is applied to the system, the gain increases linearly with the increasing pump power up to length of 20 m and then becomes constant when further the EDFA length is increased up to 100m in both the cases. It is shown that the gain then goes to saturation level after a certain level of pump power. The comparison thus shows that the higher gain with flatter output is obtained in case of Compact EDFA than Physical EDFA in a system consisting of cascade of both the amplifiers. It is shown that the Compact EDFA has better gain performance characteristics than the Physical EDFA when the length of both the amplifiers is varied from 10 to 100m in the system.

Figure 8.2(c, d) shows the variation of gain with EDFA length when the up-conversion co-efficient is varied for Physical EDFA and Compact EDFA.



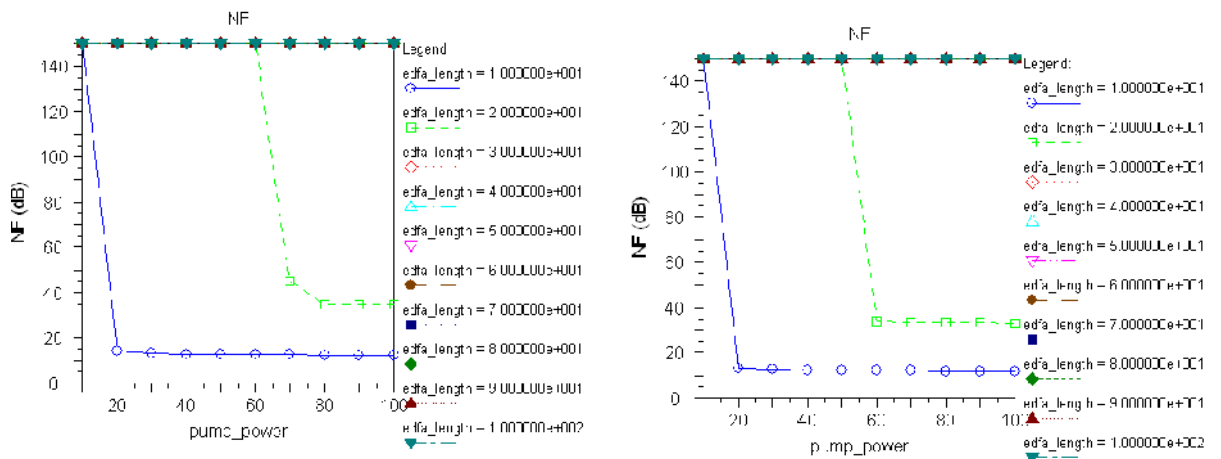
**Figure 8.2 Gain variation c) Physical EDFA d) Compact EDFA with amplifier length**

The up-conversion co-efficient value is varied from 0 to  $1.5 \times 10^{-22}$  with an increment of  $.5 \times 10^{-22}$ . It is observed that agreement between the Compact and Physical models is good up to roughly 10 m, with the no up-conversion case showing the best results for longer devices. However, clearly for moderate device lengths up-conversion can be accurately accounted for.

Gain output is also higher in case of the Compact EDFA when the value of up-conversion co-efficient is zero.

### Noise Figure Characteristics

Figure 8.3(a, b) shows the variation of noise figure as a function of the pump power in case of Physical EDFA and Compact EDFA. It is obtained for different lengths of both the amplifiers at a constant signal input power and erbium ion density. The noise figure is obtained for ten different fiber lengths, a -40 dBm signal input power with an erbium doping rate of  $.7 \times 10^{-19}$  and the pump power is increased from 10 mW to 100 mW. It can be seen from the figure that the noise figure decreases with increasing pump

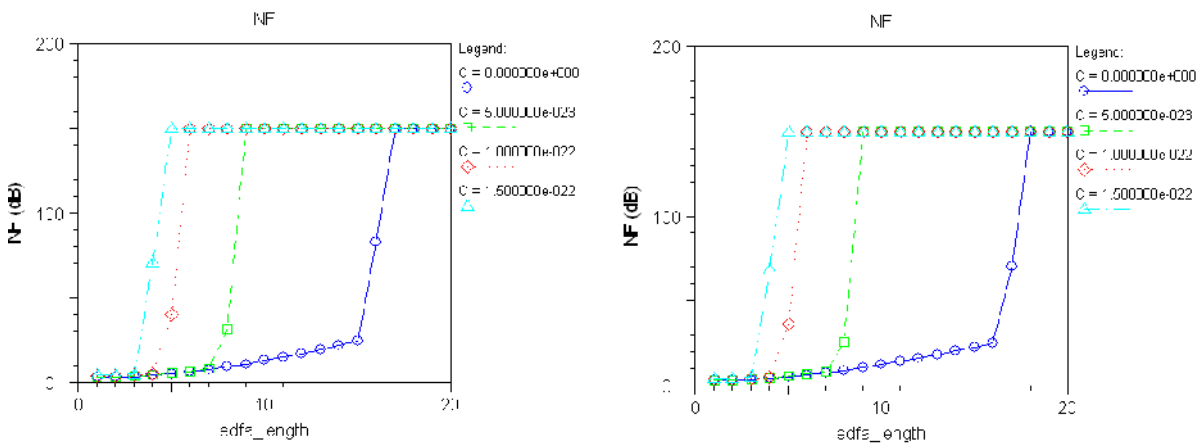


power.

**Figure 8.3 Noise Figure variation of a) EDFA b) compact EDFA with pump power**

The high gain in an active fiber with the total population inversion provided causes the spontaneous emission to stay in low levels. It is observed that when length of both amplifiers is 20 m, the noise figure obtained is more than 40 dB in case of the Physical EDFA which is higher than that of the Compact EDFA.

Figure 8.3(c, d) shows the variation of gain with EDFA length when the up-conversion co-efficient is varied for Physical EDFA and Compact EDFA.



**Figure 8.3 Noise Figure variation of c) EDFA d) compact EDFA with EDFA length**

It is observed that no up-conversion case shows the best results for both the devices. The agreement between the Compact and Physical models is good up to roughly 10 m. It is shown that when length of the amplifier taken in both the cases is 15 m, noise figure obtained in case of Physical EDFA is 30 dB which is higher than Compact EDFA for the same amplifier length. There is a sharp increase of the noise figure when the length of the amplifiers is increased above 15 m in case of the Physical EDFAs than the Compact EDFAs.

It is observed that Compact EDFA exhibits better gain and noise figure characteristics when we vary the gain and noise figure with respect to the amplifier length and pump power values.

### 8.5 Conclusions

In this chapter, the Gain and Noise Figure performance comparison of Physical EDFA and Compact EDFA at 10 Gbps for optical long haul link has been investigated. 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 we vary the pump power 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. For no up-conversion coefficient values, Compact EDFAs exhibits the best results by varying the amplifier lengths and pump power values.

## CHAPTER 5

### Conclusions and Future work

In this final chapter, we summarize the conclusions that can be drawn from the research performed for this thesis, and then provide suggestions for future research.

#### 9.1 Summary

The main motivation of this work was to study simulation studies of EDFA amplifier based communication systems. The effect of increasing/decreasing the number of channels and switching on transients induced in cascade of EDFA amplifier based communication system is discussed. This effect is seen from the variations of power characteristics depicting transients. It is observed that the behaviour of transients produced becomes predictable with increase of number of channels. It is seen that up to 6 channels the transients are not significantly reduced as compared to increasing the number of channels up to 10. It is also studied that any further increase in channels causes the great fluctuations in the characteristics of the measured parameters. Further, it is also seen that by using the same simulation set up, suppression of transients is much better in case of compact EDFAs than Transient EDFAs.

The robustness of NRZ, RZ and Manchester raised cosine modulation formats at 10 Gbps for optical long haul link on the amplifier noise variations has also been investigated. It has been noticed that in link consisting of the chain of EDFA amplifiers, the NRZ 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. The RZ raised cosine also provides the better results than the Manchester raised cosine format. But NRZ raised cosine modulations are robust and indicate the better link performance. Further, the robustness on dispersive noisy link for NRZ modulation has been justified by wide eye opening in comparison with RZ, and Manchester raised cosine modulation formats.

We further investigate the Gain and Noise Figure performance comparison of Physical EDFA and Compact EDFA at 10 Gbps 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 we vary the pump power 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. For no up-conversion coefficient values, Compact EDFAs exhibits the best results by varying the amplifier lengths and pump power values.

Therefore, this study establishes simulation of EDFA amplifier based optical communication systems with the induced transients and its performance comparisons with the Compact EDFAs.

## **9.2 Suggestions for Future Research**

During the course of this thesis, several avenues for the continuation of this study became evident. The topics that were considered worthwhile are summarized as under:

The effects of channel adding and dropping on the induced transients in EDFA amplifier based communication system have been studied. The work can also be extended to use the concept of power shaping to suppress the EDFA transients; this can also be studied for different amplifiers using different technologies, including solid state and Raman amplifiers.

The structural parameter optimization of EDFA to reduce the spectral loss variations and nonlinearities in doped fiber amplifiers can be extended for long haul WDM transmission link at higher bit rate. The work also needs to study of self phase modulation of all optical amplifiers. The comparison results of EDFA and Compact EDFA can be enhanced further for other parameters such as erbium ion doping density and signal input power.

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