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Hybrid Fiber Amplifier

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1. Introduction

The advent of telecommunications in 1870s completely revolutionized the world of communications. Metallic cables consisting of twisted wire cables, co-axial cables were the media of choice for many years. These could be used efficiently up to frequencies of 10MHz but the system performance degraded beyond this range. However, with the increasing demand for telephone services, it was necessary to find an alternative medium for telephony to cope up with the high demand. The development of low loss optical fibers gave a solution to this problem and their use revolutionized the speed of telecommunication. Optical fibers have become an unavoidable part of any high speed communication system due to its high information carrying capacity, high bandwidth and extremely low loss. The transmission performance of the optical communication systems is limited by various effects such as attenuation, dispersion, non- linearity, scattering etc, which degrade the level of the signal. To compensate for all these limitations the signals have to be regenerated within the transmission link after some distance. While setting up the transmission link, it is to be ensured that the signal can be retrieved intelligibly at the receiving end. This can be done either by using optoelectronic repeaters or optical amplifiers. In optoelectronic repeaters the optical signal is first converted into an electric signal, then amplified in electric domain and finally converted back into optical signals. Regeneration by making use of repeater is a traditional way to compensate for loss and degradation along the transmission medium. Such regenerators become quite complex and expensive for dense wavelength division multiplexed (DWDM) lightwave systems. This process works well for moderate speed single wavelength operation but it can be fairly complex and expensive for high- speed multi- wavelength systems. Moreover these so called opto-electronic repeaters once installed into the system can not be upgraded to higher bit rates. Thus a great deal of effort has been spent to develop all optical amplifiers. These devices operate in the optical domain to boost the power level of the signals. In the history of optical fiber communication systems, the advent of optical amplifier was an important milestone. Optical amplifiers can amplify the optical signals directly without requiring its conversion to the electric domain. The development of optical amplifiers started in early eighties and their use for long haul communication systems became widespread during late nineties. Optical amplifiers provided flexibility while upgrading the installed transmission links to higher bit rates. This flexibility of the bit rates allows overcoming the electrical bottleneck of an electric repeater, which was unable to transmit at high bit rates. The opto-electronic repeaters provided with maximum of 40-80 Gbps bit rate.

1.1 DWDM systems

To increase the transmission capacity of a single fiber, DWDM is used. DWDM is a technology, which combines large number of independent information carrying wavelengths onto the same fiber. A characteristic of DWDM is that the discrete wavelengths form an orthogonal set of carriers, which can be separated, routed and switched without interfering with each other. This isolation between channels holds as long as the total optical power intensity is kept sufficiently low to prevent non linear effects e.g. Stimulated Brillouin Scattering (SBS) and Four Wave Mixing processes (FWM) from degrading the link performance. The implementation of DWDM system requires a variety of passive and active devices to combine, distribute, isolate and amplify optical power at different wavelengths. Passive devices require no external control for their operation, so they are less flexible. The wavelength dependent performance of active devices can be controlled electronically, so they provide more flexibility to the network system. Optical amplifiers, tunable filters and tunable sources are integral part of any DWDM system. The key component of DWDM system is optical amplifier. In DWDM system, it is desirable to set a very narrow grid of optical carriers in order to allow more channels in the same optical bandwidth. This not only demands an optical amplifier with high gain but also very broad and flat gain profile to ensure a nearly identical amplification factor in every channel. Figure 1 shows the implementation of active as well as passive components in a typical DWDM system having post amplifier, in-line amplifier and preamplifier [Keiser 2009; Mynbaev 2003].
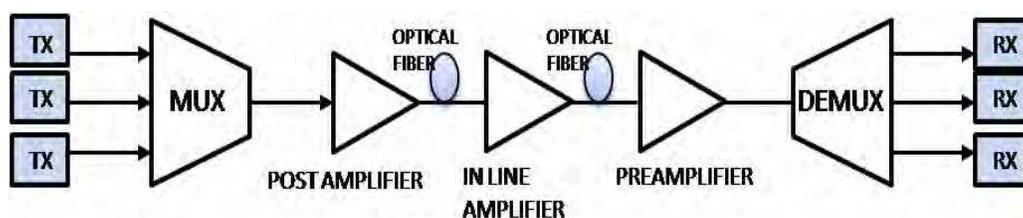

Fig. 1. Implementation of A DWDM System Having Various Types of Optical Amplifiers

2. Review of an optical amplifier

An optical amplifier works on the principle of stimulated emission. Optical amplifier increases the level of signal through this process. The mechanism for stimulated emission is same as that for lasers. The operation of laser diodes that are required for the fiber amplifier is similar to the external current injection method (which is used in semiconductor optical amplifiers, SOAs, discussed later). This method is the pumping method used to create population inversion needed for gain mechanism in fiber amplifiers. The sum of injection, stimulated emission and spontaneous recombination rates gives the rate equation that governs the carrier density N (t) in the excited state of both the amplifiers. This carrier density is given by equation (1) [Keiser 2009;Mynbaev 2003].

$$\frac{\partial N(t)}{\partial t} = R_1(t) - R_2(t) - \frac{N(t)}{\tau_r}$$

(1)

where,

$$R_1(t) = \frac{J(t)}{qd} \qquad (2)$$

is the external pumping rate from the injection current density J(t) into an active layer having thickness d, τ_r is the combined time constant coming from carrier-recombination mechanisms and spontaneous emission, and

$$R_2(t) \cong g v_g N_p \qquad (3)$$

is the net stimulated emission rate. Here, v_g is the group velocity of incident light, N_p is the photon density and g is the overall gain per unit length. The photon density N_p is dependent on optical signal power, energy of photons, group velocity and dimensions of active area of optical amplifier.

This photon density N_p is given by equation (4),

$$N_p = \frac{P_s}{(h\nu)(wd)v_g} \qquad (4)$$

In equation (4), P_s is the signal power, v_g is group velocity, w and d are the width and thickness of active area of optical amplifier respectively. The difference between the structure of optical amplifiers and laser diodes is that there is no feedback system in optical amplifiers. So, for boosting an incoming signal optical amplifier requires a pump. The pump supplies energy to the electrons in an active medium, which in turn causes population inversion. An incoming signal photon triggers these excited electrons to drop to lower levels through a stimulated emission process, thereby producing an amplified signal. The amplifier is connected with the optical fiber through a fiber- to- amplifier coupler. The basic components of an optical amplifier are shown in the figure 2) [Keiser 2009;Mynbaev 2003].
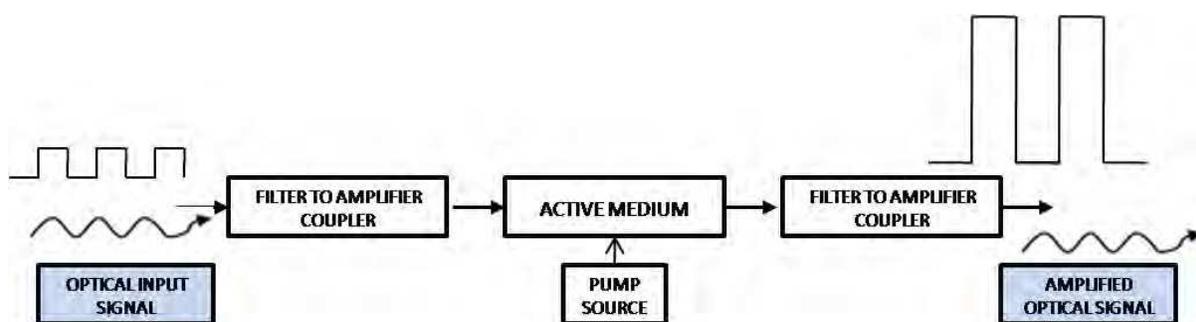

Fig. 2. The Basic Structure of an Optical Amplifier

The optical gain depends on the frequency/ wavelength of the signal. Let us consider a medium of two level systems for demonstrating the dependence of gain on frequency. The gain coefficient of such a medium can be written as below [Agarwal 2003]:

$$g(\omega) = \frac{g_0}{1 + (\omega - \omega_0)^2 T^2 + \dfrac{P}{P_{sat}}} \qquad (5)$$

Where, g_o is the peak value of the gain, ω is the optical frequency of the incident signal, ω_o is the atomic transition frequency , P is the optical power of the signal being amplified, P_{sat} is the saturation power and T is the dipole relaxation time. In the unsaturated region, P /P_s«1. So, the gain coefficient becomes

$$g(\omega) = \frac{g_0}{1 + (\omega - \omega_0)^2 T^2} \tag{6}$$

This equation shows that the gain reaches its maximum when the incident frequency coincides with the atomic transition frequency. Another term associated with optical amplifiers is amplification factor or amplifier gain (G) defined as:-

$$G = \frac{P_{out}}{P_{in}} \tag{7}$$

Where P_{in} and P_{out} are the input and output powers of the continuous wave signal being amplified.

3. Applications of optical amplifiers

Optical amplifiers have found many applications ranging from ultra long undersea links to short links in access networks[Keiser 2009; Mynbaev 2003; Olsson1989 & Agarwal 2003].

• In-line amplifier
• Pre-amplifier
• Post -amplifier

In-line amplifier: This is used as a repeater along the link at intermediate points. It can be used to compensate for transmission loss and increase the distance between regenerative repeaters, as shown in figure 3a.
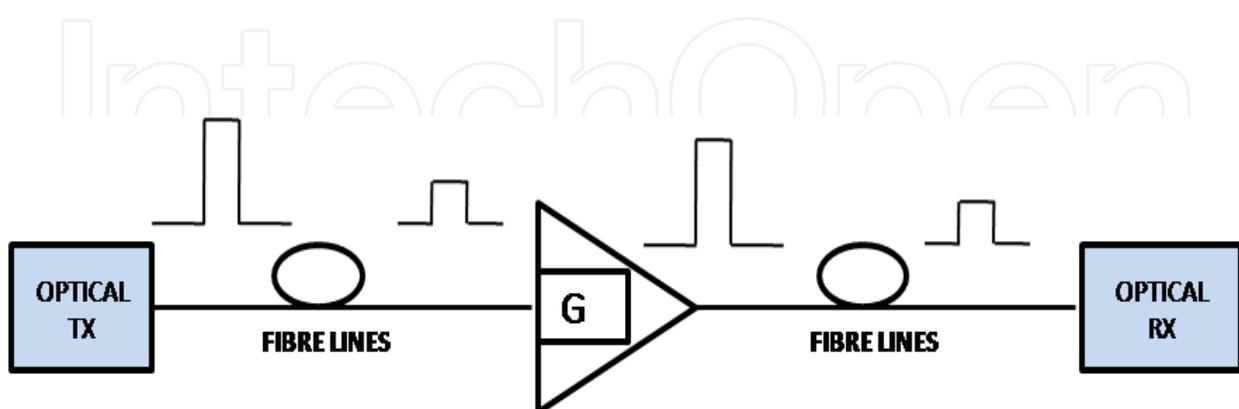

Fig. 3a. Optical Amplifier as In-Line Amplifier

Pre-amplifier: This is used before the photo detector at the receiver in order to strengthen the weak received signal. This increases the sensitivity of the detector effectively. This configuration is shown in figure 3b.
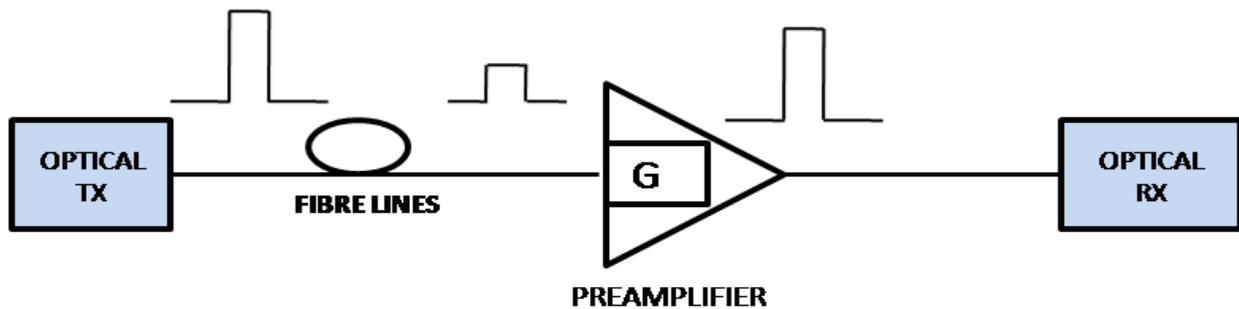

Fig. 3b. Optical Amplifier as Preamplifier

Post -amplifier: This is used at the transmitting end, after the source and operates near the saturation region. The power launched into the fiber is enhanced and so the repeater span can become large. This serves to increase the transmission distance by 10-100km depending on the amplifier gain and fiber loss. This configuration is shown in figure 3c.
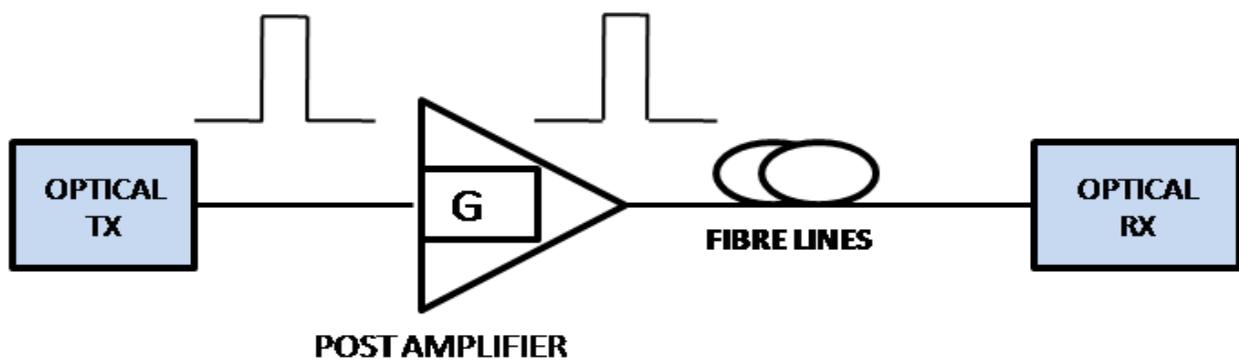

Fig. 3c. Optical Amplifier as Post Amplifier

4. Types of optical amplifiers

The optical amplifiers which find widespread use in communication systems can be classified into three categories:-

1. Fiber Raman Amplifier (FRA)
2. Erbium Doped Fiber Amplifier (EDFA)
3. Semiconductor Optical Amplifier (SOA)

The first two types, Fiber Raman Amplifier (FRA) and Erbium Doped Fiber Amplifier (EDFA) can be efficiently coupled to the transmission fiber by splicing with a minimum coupling loss. Of these two, EDFA requires lesser power for the pump source and the pump power requirements can be easily met by semiconductor laser diodes. Besides, the gain characteristics of EDFA are insensitive to polarization. Semiconductor Optical Amplifier (SOA) has the advantages of smaller size and lower power consumption. Its dimensional

compatibility with the transmission fiber is obviously not as good as the fiber amplifier. However, SOA is suitable for optoelectronic integrated circuits.Table1 shows the basic difference between the three optical amplifiers and Table 2 shows the comparison of optical amplifiers.

Type of optical amplifier	Material required	Operating Working band
Semiconductor Optical Amplifier (SOA)	Semiconductor material from group III and V. *e.g.*phosphorous, gallium, indium and arsenic	O-Band and C-Band
Erbium Doped Fiber Amplifier (EDFA)	Lightly doping silica or tellurite with rare earth element *i.e.* erbium.	O-Band, S-Band, C-Band and L-Band
Fiber Raman Amplifier (FRA)	Raman Lasers	All Operating Bands

Table 1. Difference of materials and operating bandwidth of three optical amplifiers

S. No.	Parameter	Semiconductor Optical Amplifier (SOA)	Erbium Doped Fiber Amplifier (EDFA)	Fiber Raman Amplifier (FRA)
1	Gain(dB)	>30	>40	>25
2	Bandwidth (3dB)	60	30-60	Pump dependent
3	Max. Saturation (dBm)	18	22	0.75 X pump
4	Noise Figure (dB)	8	5	5
5	Pump Power	<400mA	25dBm	>30dBm
6	Wavelength(nm)	1260-1650	1530-1560	1260-1650
7	Time Constant	2×10^{-9} s	10^{-2} s	10^{-15} s
8	Size	Compact	Rack Mounted	Bulk Module
9	Cost factor	Low	Medium	High
10	Polarization Sensitivity	Yes	No	No

Table 2. Comparison of Optical Amplifiers

Although gain bandwidth of semiconductor laser amplifiers is ideally large, they have several drawbacks like polarization sensitivity, interchannel cross- talk and large coupling losses. Fiber amplifiers are preferable since the coupling loss due to fusion splice is negligible for them. Fiber amplifiers are also insensitive to polarization and have negligible noise for interchannel cross talk, which is one of the main noise sources in multichannel transmission or Dense Wavelength Division Multiplexing (DWDM). These reasons and available gain properties make the fiber amplifiers very suitable for modern optical transmission.

4.1 Advantages of EDFA

It is clear that EDFAs are the best choice for optical amplification in present lightwave systems. Erbium (Er: 68) is used as dopant into glass host (fiber) and the 'doped fiber' is

used as an amplifying medium. Er-doped fibers give an amplified output around 1550nm [Desurvire 2002; Becker, Olsson & Simpson 1999; Sun et.al.1997]. The EDFA is one of the key devices used for dense wavelength division multiplexed (DWDM) transmission systems. EDFAs are revolutionizing lightwave systems by reducing system costs and enhancing network performance. Some of the advantages offered by EDFAs are:

- High gain (~50dB)
- High output power (>100mW)
- Low noise figure (~4dB)
- Less gain variation
- Wide bandwidth of operating suiting DWDM
- Inherent compatibility to transmission fiber with low insertion loss
- Cross talk immunity in multichannel systems

5. Working principle of EDFA

The invention of the Erbium Doped Fiber Amplifier (EDFA) in the late eighties was one of the major events in the history of optical communication systems. It provided new life to the research of technologies that allow high bit rate transmission over long distances. EDFA has a narrow high gain peak at 1532nm and a broad peak with a lower centered at 1550nm. The use of an increasing number of channels in the present day DWDM optical networks requires a flat gain spectrum across the whole usable bandwidth. Owing to their versatility, useful gain bandwidth, high pumping efficiency and low intrinsic noise, EDFAs are the amplifier of choice for most of the network applications. They are based on single mode optical fibers with cores that have been doped, typically to a few hundred part per million, with the trivalent erbium ion, Er^{3+}. The gain is provided through stimulated emission, as in laser. The Er^{3+} ion acts mostly as a three level system, in which the main participants are the $^4I_{15/2}$ ground state, the $^4I_{13/2}$ first excited level and the $^4I_{11/2}$ second excited level. The energy level diagram of Er^{3+} is shown in figure 4) [Keiser 2009;Mynbaev 2003].
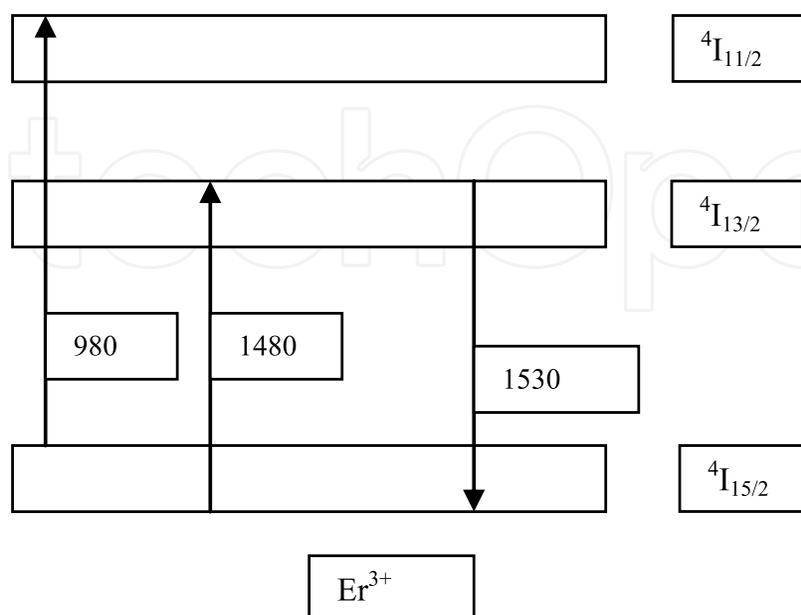

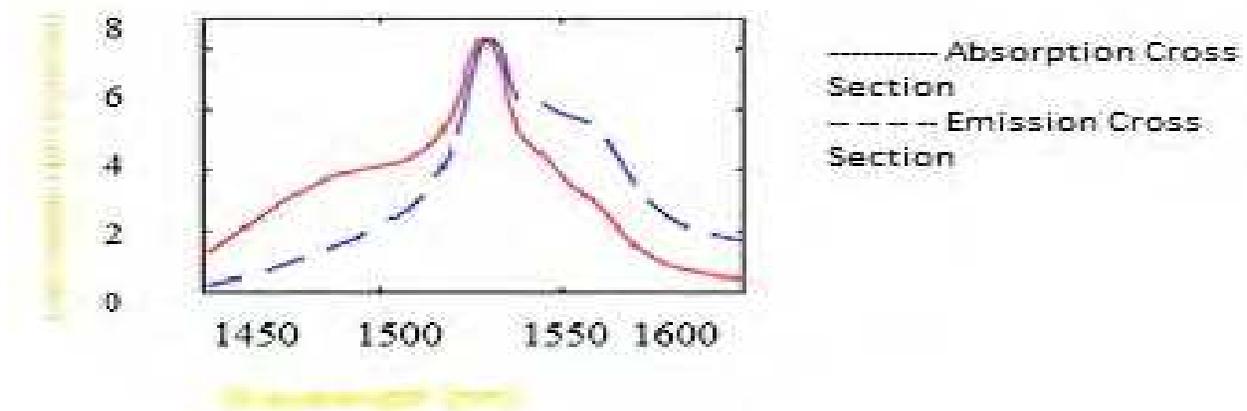Fig. 4. Energy Level Diagram of Er3+

Fig. 5. Absorption and Emission Spectra of EDFA

EDFAs are of particular interest in telecommunications, because their emission spectrum shows a gain of more than 20dB over the range of 1530-1560nm. This is also the third window used in optical communication. The absorption spectrum reveals that good absorption takes place around 380nm, 520nm, 800nm, 980nm, and 1480nm. The absorption bands at shorter wavelengths are not of interest owing to the non- availability of semiconductor laser diodes at these wavelengths. At 980nm and 1480nm, efficient laser diodes are available and therefore used as pump sources.

6. Limitations of EDFA

The main practical limitation of an EDFA stems from the spectral non-uniformity of the amplifier gain. As a result, different channels of a DWDM system are amplified by different amounts. These problems become quite severe in long-haul systems, employing cascaded chain of EDFAs. Secondly, for many EDFA deployments, automatic gain control (AGC) is used to ensure that the output signal power is proportional to the input power. However, there are times when a constant optical signal output, independent of input power, is more desirable, e.g., in an optical preamplifier at an optical receiver [Qiao & Vella 2007]. The figure 6) [Keiser 2009;Mynbaev 2003].Figure 6 shows the gain spectrum of EDFA, from which it is clear that EDFA has peak gain at 1530nm, beyond which the gain reduces slightly and remains flat almost until 1550nm. After that, the gain reduces sharply. Several gain flattening techniques of EDFA are available [Lee et,al 1996; Ono et.al.1997; Kim et.al.1998; Park et.al.1998; Kawai et.al.1999; Yun et al. 1999; Lu & Chu 2000; Pasquale & Federighi 1995; Kemtchou et. al.1996; Hwang et al.2000; .Bakshi et.al.2001; Sohn et.al.2002; Arbore et.al.2002; Kaur & Gupta 2009 and Lobo et.al. 2003]

So, EDFAs are widely used in the C-band (1530-1560nm) for optical communication networks. So, there is a necessity to improve the amplification bandwidth of EDFA (i.e. broadening as well as flattening of gain spectrum). This would help to cater the needs of present day communication systems. In order to overcome this limitation of EDFA, different doping elements are coming into existence. One of such doping material is thulium and the doped fiber amplifier is known as Thulium Doped Fiber Amplifier (TDFA). TDFAs are highly viable alternative to meet out the limitations of EDFAs and have bright future prospects to be used in optical communication systems.
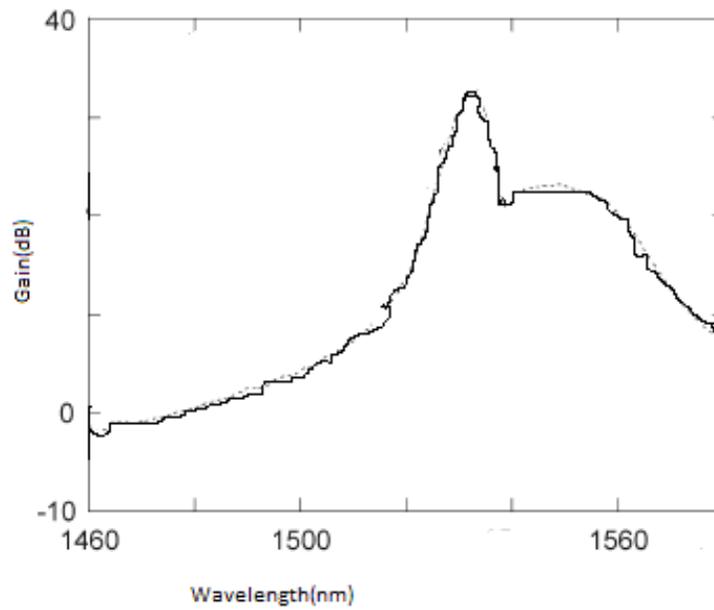
Fig. 6. Gain Spectrum of EDFA

7. Role of TDFA in communication systems

The optical fiber can be doped with any of the rare earth element, such as Erbium (Er), Ytterbium (Yb), Neodymium (Nd) or Praseodymium (Pr), Thulium (Tm). The host fiber material can be either standard silica, a fluoride based glass or a multicomponent glass. The operating regions of these devices depend on the host material and the doping elements. Fluorozirconate glasses doped with Pr or Nd are used for operation in the 1300nm window, since neither of the ions can amplify 1300nm signals when embedded in silica glass. The next popular material for long haul telecommunication applications is a silica fiber doped with Thulium, which is known as Thulium Doped Fiber Amplifier (TDFA). In some cases as Yb is added to increase the pumping efficiency and the amplifier gain. The TDFA are used in S-band (1460-1530nm). The energy state diagram of Tm^{3+} is shown in figure 7 [Aozasa et.al.2008].
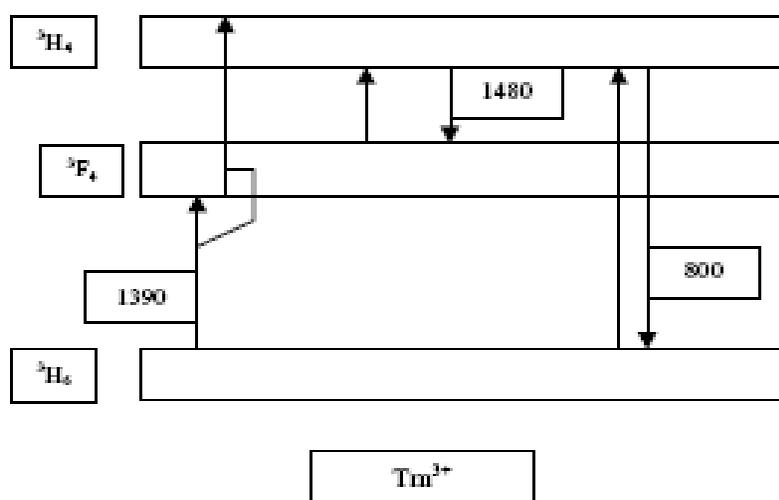

Fig. 7. Energy Level Diagram of Tm^{3+}

Tm^{+3} has three energy levels that are considered with respect to the Tm^{+3} populations. TDFA uses upconversion pumping method. The upconversion pumping consists of the two-step excitation of $^3H_6$ to $^3F_4$ and $^3F_4$ to $^3H_4$ with the same pump wavelength and this makes it possible to form a population inversion state between $^3F_4$ and $^3H_4$. The gain and loss of TDFA in the 1460-1530nm wavelength region are determined not only by the excited state absorption (ESA) ($^3F_4$ to $^3H_4$) and stimulated emission(SE) ($^3H_4$ to $^3F_4$) but also by the ground state absorption (GSA) ($^3H_6$ to $^3F_4$) The absorption, emission and ground state cross section emission of Tm^{3+} is shown in figure 8 [Aozasa et.al.2008,2002].
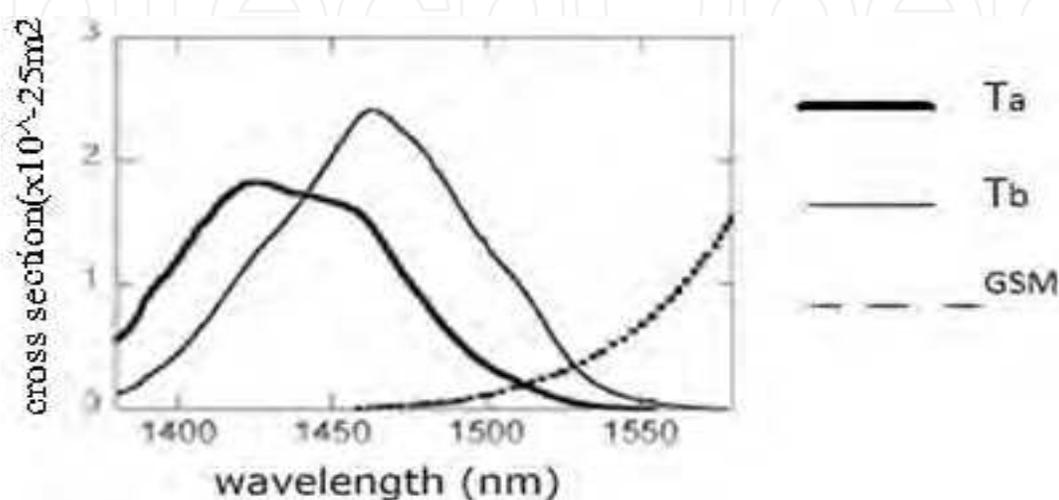

Fig. 8. Cross Sections of Tm^{3+}

The gain spectrum of TDFA is shown in figure 9 [Aozasa et.al.2008, 2002]. A gain of 22dB (approximate) is obtained from 1460-1485nm wavelength range. After this wavelength range the gain reduces sharply.
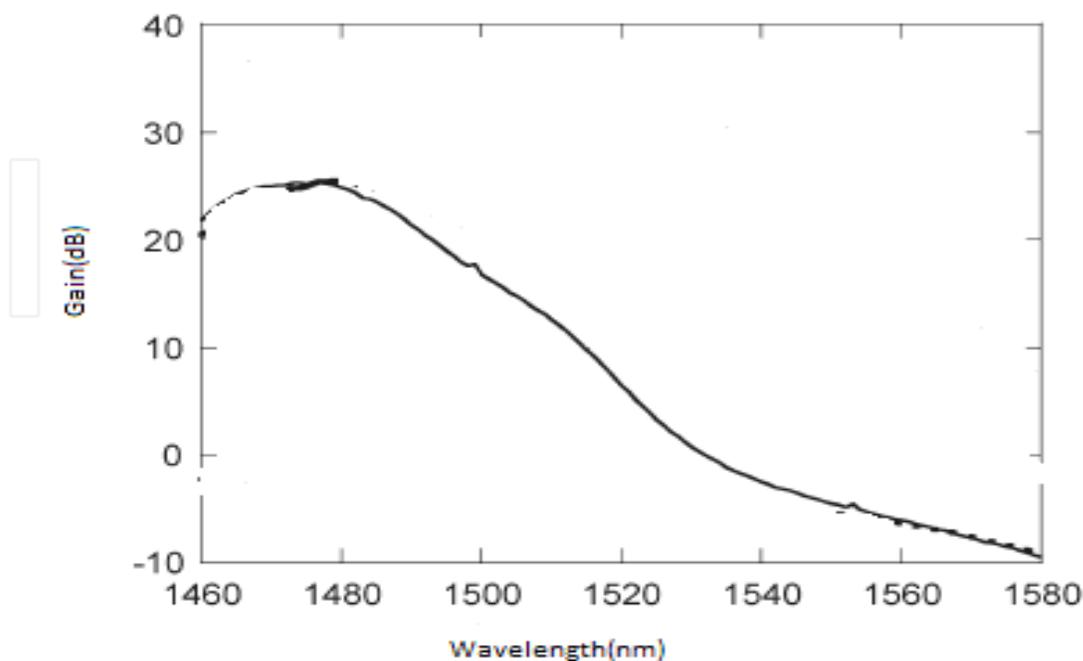

Fig. 9. Gain Spectrum of TDFA

So, to utilize the S-band, TDFA is proposed to be used by various authors. The S-band has attracted attentions because it has low fiber loss, low dispersion and also high gain and efficiency. The summary of the work done on EDFA, TDFA and TDFA-EDFA amplifiers is given in Table 3.

Type of Amplifier/ Parameters	EDFA in [Qiao & Vella2007]	TDFA [Aozasa et.al.2008]	TDFA-EDFA [Sakamoto et.al.2006]
Number of Stages	Two	Single	Four
ASE and its Correction Function	Considered with signal wavelength 1546nm	Considered	Not considered
Peak Gain /Range of Gain	0-37dB	22.6dB	20dB
Gain Excursion	0.35dB	0.35dB	2dB
Range of Input Power	-5 to 5 dBm	-32 to -2 dBm	-20 to -10dBm
Signal Gain Band	1525-1565nm	1479-1507nm	1460-1537nm
Noise Figure	Not considered	< 6.5dB	<7dB
No. of DWDM Channels Considered	8	8	4

Table 3. Summary of work done in [Qiao & Vella2007], [Aozasa et.al.2008], [Sakamoto et.al.2006]

8. Hybrid amplifiers

There is one more method of utilizing fiber amplifiers for optimum utilization of available fiber bandwidth i.e. by way of using various combinations of optical amplifiers in different wavelength ranges. The amplifiers can be connected either in parallel or in series. This configuration is termed as Hybrid Amplifier which is highly viable for the above discussed cause. In parallel configuration, the DWDM signals are first demultiplexed into several wavelength-band groups with a coupler, then they are amplified by amplifiers that have gains in the corresponding wavelength band and then they are multiplexed again with a coupler. The parallel configuration is very simple and applicable to all amplifiers. However, it has disadvantages also e.g. an unusable wavelength region exists between each gain band originated from the guard band of the coupler. Also, the noise figure degrades due to the loss of the coupler located in front of each amplifier. On the contrary, the amplifiers connected in series have relatively wide gain band, because they do not require couplers. Hybrid configurations can be made by combination of the following:

- **EDFAs and FRAs:** It has been observed that the gain spectrum of FRAs can be tailored by adjusting the pump powers and pump wavelengths. So this property is used to increase the amplification bandwidth of EDFA [Thyagarajan& Kakkar 2004; Oliveira et.al.2007, Kaur &Gupta 2008].

- **TDFAs and FRAs**: Combining FRAs with TDFAs is very effective approach, because FRAs can provide any gain bandwidth by selecting the appropriate pump wavelengths. However, a drawback with FRAs is that double Rayleigh scattering (DRS) degrades the amplified signals [Percival & Williams 1994; Komukai et.al.1995,2001; Royet.al.2002and Aozasa et.al.2002].

- **TDFAs and EDFAs:** Hybrid amplifiers consisting of all rare –earth –doped- fiber amplifiers are easier to utilize than those incorporating FRAs, because these are free from DRS. These hybrid amplifiers are relatively simple in gain spectra control [Sakamoto et.al.2006 and Kaur & Gupta 2010]. Hybrid doped fiber amplifiers with different gain bandwidths have attracted a large interest for increasing the transmission capacity of long haul wavelength multiplexed optical communication systems in C-band and L-band.

Out of these, one of the-state-of-art hybrid amplifiers is TDFA -EDFA configuration. It is observed that for TDFA-EDFA configuration, the total gain of hybrid amplifier is given as product of gain of TDFA and gain of EDFA. The gain bandwidth is extended by cascading EDFA with TDFA. When EDFA is cascaded with TDFA in series, the total gain of hybrid amplifier is given by product of individual gains of each amplifier.The gain of TDFA is given as

$$G_{T(\lambda)} = \exp\left[\left(\sigma_{T(1480)}NT_{2-\sigma T(1390)}NT_{1-\sigma T(800)}NT_0\right)\right]\left(\eta_T\,L_T\right) \tag{8}$$

The gain of EDFA is given as:

$$G_{E(\lambda)} = \exp\left[\left(\sigma_{E(1530)}NE_{2-\sigma E(1480)}NE_1\right)\left(\eta_E\,L_E\right)\right. \tag{9}$$

This means the total gain of hybrid amplifier is given as:

$$G_{(\lambda)} = G_{T(\lambda)}\,X\,G_{E(\lambda)} =$$
$$= \exp\left[\left(\sigma_{T(1480)}NT_{2-\sigma T(1390)}NT_{1-\sigma T(800)}NT_0\right)\left(\eta_T\,L_T\right)\right]X\exp\left[\left(\sigma_{E(1530)}\,NE_{2-\sigma E(1480)}NE_1\left(\eta_E\,L_E\right)\right]\right. \tag{10}$$

In the above equations, $\sigma_{T(1480)}$, $\sigma_{T(1390)}$ and $\sigma_{E(980)}$ denotes cross-sections of excited state absorption, stimulated emission and ground state emission of TDFA. Similarly, $\sigma_{E(1530)}$, $\sigma_{E(1480)}$ represents the respective cross sections of EDFA. η_T and η_E represents the confinement factors of TDFA and EDFA respectively.

The above stated mathematical equations clearly illustrate the fact that the gain of hybrid amplifier broadens from 1460 nm to 1530 nm wavelength range. Further there is a noticeable reduction in the noise figure correspondingly in the hybrid amplifier. This affects in the gradual increase in the number of transmission channels of DWDM system, thereby increasing the overall transmission capacity of the optical communication system. The statistical analysis of TDFA-EDFA hybrid amplifier and EDFA-TDFA hybrid amplifier is done. The configuration TDFA-EDFA means the hybrid amplifier in which TDFA is in first stage and EDFA is in second stage, whereas configuration EDFA-TDFA means EDFA is in first stage and TDFA is in second stage. For this analysis, it is assumed that both fibers have step refractive index homogeneously broadened spectrum of thulium and erbium ions. We consider three levels of

TDFA i.e. $_3H^6$, $_3H^4$ and $_3F^4$, the other two levels of TDFA i.e. $_3H^5$ and $_3F^{2,\,3}$ are ignored as the rate of their non radiation (τ_{nr}) to the corresponding levels are very high. Similarly, in case of EDFA, two levels $_4I^{15/2}$, $_4I^{13/2}$ is considered and level $_4I^{11/2}$ is ignored for the same reasons. From the absorption and emission spectra, it is clear that the absorption and emission peaks of EDFA coincides at 1530nm, while the absorption peak of TDFA lies at 1430nm and emission peak of TDFA lies at 1460nm. Form the gain spectrum of EDFA, from which it is clear that EDFA has peak gain at 1530nm, beyond which the gain reduces slightly and remains flat almost until 1550nm. After that gain reduces sharply. This gain can be flattened by cascading TDFA with EDFA. Fig. 10 shows the flattened gain spectrum of Hybrid amplifier by cascading TDFA and EDFA. The thulium doped fiber (TDF) in first stage was forward pumped with a 1390nm pump laser diode (LD) and erbium doped fiber (EDF) in second stage is pumped with a 980nm LD. For efficient amplification the concentration of TDF $^{+3}$ ions was kept very high (approx. 7500 ppm) [Percival & Williams 1994; Komukai et.al.1995]. Table 4 shows the different characteristics of both configurations.

Feature	TDFA-EDFA	EDFA-TDFA
Gain	25 dB for 1456nm-1556nm range	20 dB for 1485nm-1550nm range
Noise Figure	<6Db	<7dB

Table 4. Features of TDFA-EDFA & EDFA-TDFA Amplifiers

F-ratio is calculated for the parameters mentioned in above Table 4. The calculated and tabulated value of F-ratio is shown in Table 5.

Source of variation	D.F	SS	MS	F-ratio	Tabulated F-ratio (1,2)
Between samples	1	1.5	1.5	.05	18.51
Within Samples	2	39.6	29.9		
Total	3	41.1			

Table 5. F-Measure Results

The table 5 shows that the F-ratio is significant of 5% level which means that both hybrid configurations work differently. F-ratio is used to judge whether the difference among several sample means is significant or just a matter of sampling fluctuations. MS residual is always due to fluctuations of sampling and so serves as the basis for the significance test. The F-ratio is compared with its corresponding table value for the given degree of freedom at a specified level of significance. The table 5 shows that both the F-ratios are significant of 5% level which means that TDFA-EDFA amplifier work differently as compared with EDFA-TDFA amplifier. The gain spectrum of TDFA-EDFA is more widened as compared to that of EDFA-TDFA configuration. Since there is a large difference between the calculated and the table value of F. So, the null hypothesis is rejected. For WDM systems, TDFA-EDFA has a great impact as a hybrid amplifier as compared with EDFA-TDFA amplifier[Kaur & Gupta 2009]. As studied from the existing schemes, the amplification of DWDM signals using TDFA-EDFA hybrid amplifiers have major problems and short comings which are as listed below:

- The use of increasing number of channels in the present day DWDM optical networks requires a flat gain spectrum across the whole usable bandwidth. The unflattened gain spectrum of hybrid amplifiers implies that different channels of a DWDM system are amplified by different amounts. Hence a need is felt to broaden as well as flatten the gain spectrum of hybrid amplifier.

- It is observed that amplified spontaneous emission and its correction function for hybrid amplifiers have not been carried out leading to lesser gain and more noise of the signal. So, there is a need to analyze different parameters e.g. gain, noise figure, amplified spontaneous emission of hybrid amplifier and its correction function.

- No scheme or algorithm has been designed to allow the hybrid amplifier to maintain a constant output signal power, independent of the optical wavelength and input power level. There are many occasions when constant optical signal power, independent of input power, is more desirable e.g. in an optical preamplifier in an optical receiver and automatic power control cannot guarantee constant signal output power.

- Hybrid amplifiers proposed till dates are using four or more than four amplifiers to achieve desirable gain, leading to higher complexity, noise. Hence there is a dire need to minimize number of amplifiers in hybrid configuration.

- DWDM system till date are upto thirty two (32) channels but with lesser gain and high noise figure. The systems having adequate gain have been designed only upto eight (8) channels. Hence, there is a drastic need to increase the number of channels in DWDM system.

Although there are many improvements in gain spectrum of EDFA, but still the improved configurations are unable to provide enough bandwidth for emerging high quality parameters like gain, noise figure, amplified spontaneous emission etc. Therefore, there is a need to search for a new and versatile approach that enables an effective system with adequate bandwidth to accommodate large number of DWDM channels. One approach that can do the job is use of hybrid amplifier consisting of TDFA and EDFA in cascaded series combination. This hybrid amplifier is proven effective in DWDM systems. Several challenging points of research are realization and development of hybrid amplifiers, which can increase the bandwidth for S-band, C-band and L-band. The biggest challenge with hybrid amplifier is to maintain and offer high bandwidth in case of higher number of channels.
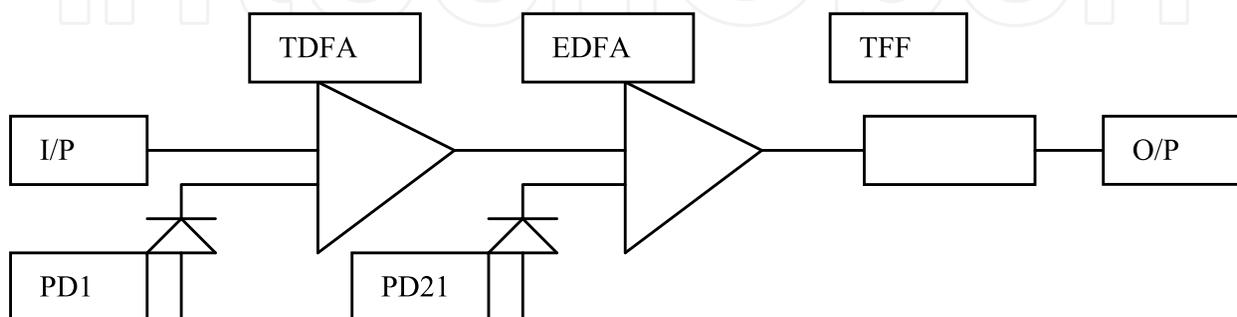

Fig. 10. Schematic Diagram of Cascaded TDFA-EDFA Hybrid amplifier using TFF

It is clear with the configuration as shown in figure 10 that a wide bandwidth spectrum of nearly 100nm i.e. from 1460nm to 1560nm wavelength range is obtained. This also includes the 1510nm-1520nm range where EDFA as well as TDFA has no large gain for themselves. This is also observed that this gain is unflattened mainly from 1520nm to 1540nm region. This whole wavelength range is flattened by using a seven layer interference filter (TFF).A seven layer optical thin film filters consists of a stack of seven dielectric thin a film is used along with a cascaded TDFA and EDFA [Kaur & Gupta 2010]. There are so many ways to flatten the gain bandwidth of EFDA such as gain equalizers based on Mach-Zehnder optical filters, interference filters or long period grating and fluoride or tellurite based EDFA. The figure (11) shows a schematic diagram of a seven layer dielectric interference filter for gain flattening of hybrid amplifier consisting of cascaded TDFA with EDFA. A seven layer dielectric film is proposed as a gain equalizer. In figure (11) the shaded layer as high index layer having refractive index 2.4. The unshaded layer is a low index layer having refractive index as 1.46. The refractive index of fiber is assumed as 1.46. The third and sixth layer of this filter is half wavelength thick and all other layers have one fourth wavelength thickness. The filter is so designed that transmission loss occurs around the maximum gain of hybrid amplifier i.e. at 1531nm. The transmission loss is about 9dB. The flattened gain bandwidth of hybrid amplifier with the help seven layer deictic filter is shown in figure (12). The gain variation is less than ± 2.5% in the wavelength region of 1460-1560 nm. A [2X2] square matrix of a dielectric filter for TM mode is given as

$$[\text{Matrix}] = [M] = \prod_{x=1} b \begin{bmatrix} \cos\beta x & \frac{j}{q}\sin\beta x \\ jq\sin\beta x & \cos\beta x \end{bmatrix} \tag{11}$$

The transmission of a TFF is given as

$$T = \left[1 + \frac{4R}{(1-R)2} \sin^2\left(\frac{\Phi}{2}\right) \right]^{-1} \tag{12}$$

From equations (11) & (12), we get following equation for transmission

$$T = \left[\frac{2\,n\,fiber}{\left(m_{11} + m_{12}n_{fiber}\right)n_{fiber} + \left(m_{21} + m_{22}n_{fiber}\right)} \right]^2 \tag{13}$$

Where m_{ij} are the components of the matrix [M]. Here we assume n_{fiber}=1.46.Since the gain peak of hybrid amplifier occurs at 1530nm. So here we designed TFF such that the maximum transmission loss occurs at around the gain peak at wavelength 1530nm, which is observed as 9dB. In case of TE mode all parameters remain same except q_x is replaced by p_x. It is clear from formula given in equation (13) that designing of interference filters with desired wavelength spectrum and transmittance is possible by selecting proper of layer of dielectric films, their thickness and refractive indices of core and cladding of the optical fiber.
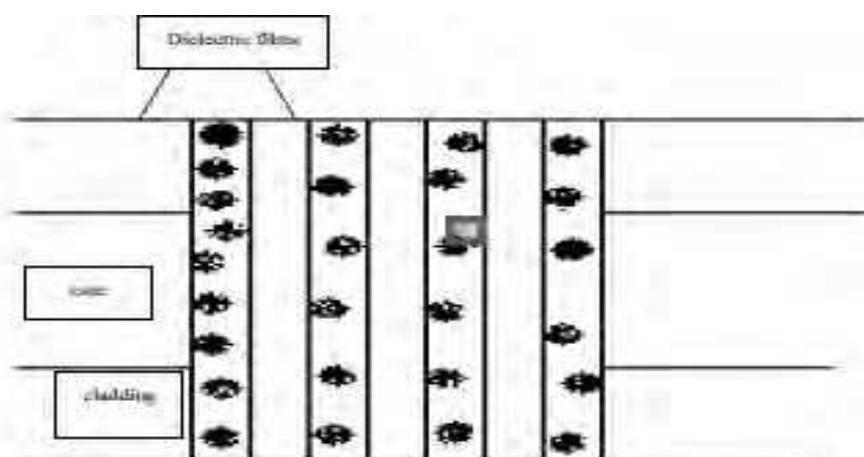
Fig. 11. Schematic Diagram of the dielectric multi-layer Interference Filter (TFF)
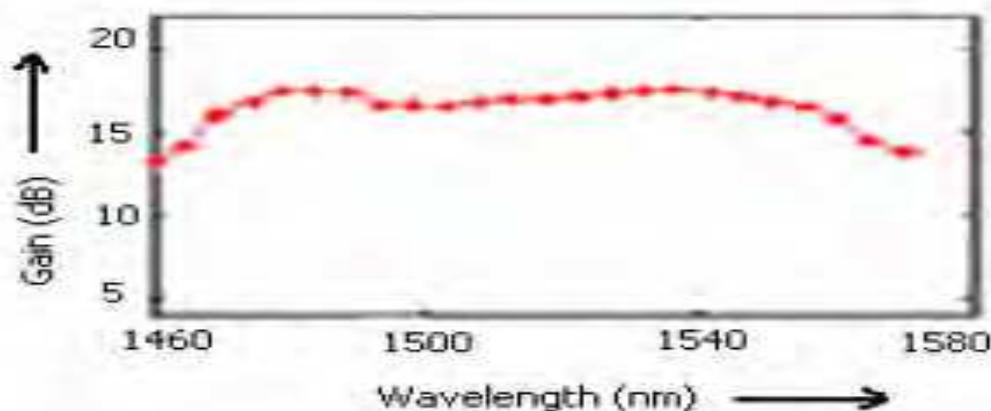

Fig. 12. Broadened and Flattened Gain Spectrum of Hybrid Amplifier

9. Conclusion

Wavelength multiplexing (WDM) technology along with optical amplifiers is used for optical communication systems in S-band, C-band and L-band. To improve the overall system performance Hybrid amplifiers consisting of cascaded TDFA and EDFA with different gain bandwidths are preferred for long haul wavelength multiplexed optical communication systems. It has found that calculated value of F ratio is very much different from the tabulated value, so the difference between parameters is considered as significant and we reject the null hypothesis. Here, we are able to conclude that for WDM systems, TDFA-EDFA hybrid fiber doped amplifier has higher gain and lower noise figure. So, this configuration gives better performance in WDM systems as compared with the EDFA-TDFA hybrid configuration. With this design it has also been found that when TDFA with EDFA are cascaded in series then gain spectrum is broadened. The gain variation is less than ± 2.5% in the wavelength region of 1460-1560 nm. The TF filter is so designed that transmission loss occurs around the maximum gain of hybrid amplifier i.e. at 1531nm. The transmission loss is about 9dB.The simulation process can be represented by a flowchart as shown in figure 13.
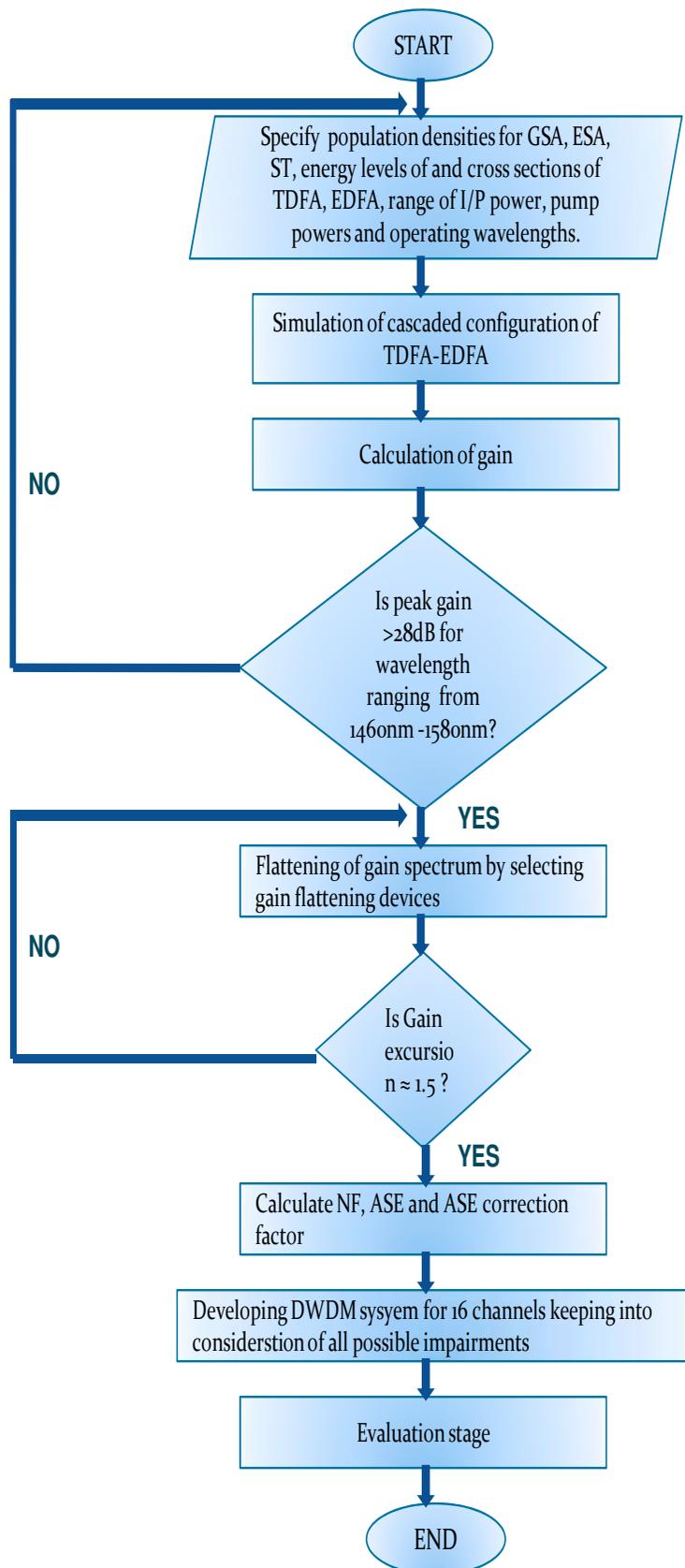
Fig. 13. Flowchart Showing Simulation Process

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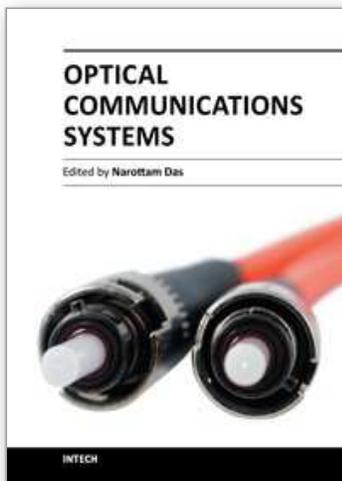
Optical Communications Systems

Edited by Dr. Narottam Das

Optical communications systems are very important for all types of telecommunications and networks. They consists of a transmitter that encodes a message into an optical signal, a channel that carries the signal to its destination, and a receiver that reproduces the message from the received optical signal.This book presents up to date results on communication systems, along with the explanations of their relevance, from leading researchers in this field. Its chapters cover general concepts of optical and wireless optical communication systems, optical amplifiers and networks, optical multiplexing and demultiplexing for optical communication systems, and network traffic engineering. Recently, wavelength conversion and other enhanced signal processing functions are also considered in depth for optical communications systems. The researcher has also concentrated on wavelength conversion, switching, demultiplexing in the time domain and other enhanced functions for optical communications systems. This book is targeted at research, development and design engineers from the teams in manufacturing industry; academia and telecommunications service operators/ providers.

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