A Novel Approach For Performance Improvement of DWDM Systems Using TDFA-EDFA Configuration

[1]Inderpreet Kaur, [2]Dr. Neena Gupta
[1]Electronics & Communication Engg. Deptt., R.B.I.E.B.T, Sahuran, Mohali, Punjab, India.
[2]Electrical & Electronics Communication Engg. Deptt., PEC, Univ. of Technology, Chandigarh, India
E-mail : [1]inder_preet74@yahoo.com, [2]neenagupta@ieee.org

Abstract

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. Hybrid amplifiers with different gain bandwidths are indensible for long haul wavelength multiplexed optical communication systems in C-band and L-band. In this paper, it is observed that when TDFA and EDFA are used in series configuration, then there is a noticeable reduction in the noise Fig. 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.

Keywords

Hybrid Amplifier, EDFA, TDFA, FRA, DRS, C-band, L-band and DWDM Systems.

I. 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. The invention of the 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. Higher bit rates are also possible using various dispersion compensation techniques. In general, EDFA has a narrow high gain peak at 1532 nm and a broad peak with a lower gain centered at 1550 nm. In order to take the advantage of the whole amplification band provided by EDFA gain spectrum, equalization techniques have to be applied. 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. The implementation of WDM network system requires a variety of passive as well as active devices to combine, distribute, isolate and amplify optical power at different wavelengths. Optical amplifiers, tunable optical filters and tunable sources constitute DWDM systems. Fig. 1 shows the implementation of active as well as passive components in a typical DWDM system having post amplifier, in-line amplifier and preamplifier [1-4].

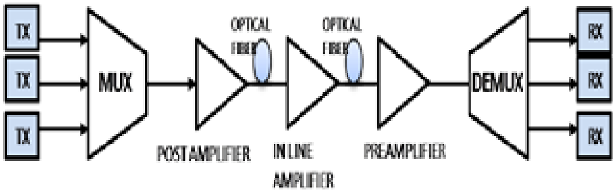

Fig 1: Implementation of a DWDM system having various types of optical amplifiers [1, 2]

II. 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) [1, 2].

$$\frac{\partial N(t)}{\partial t} = R_1(t) - R_2(t) - \frac{N(t)}{\tau_r} \qquad \text{...(1)}$$

where, $$R_1(t) = \frac{J(t)}{qd} \qquad \text{...(2)}$$

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

$$R_2(t) \cong g v_g N_p \qquad \text{...(3)}$$

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

This photon density Np is given by equation (4) as shown. below:

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

In equation (4), Ps is the signal power, vg 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 Fig. 2. [1, 2]

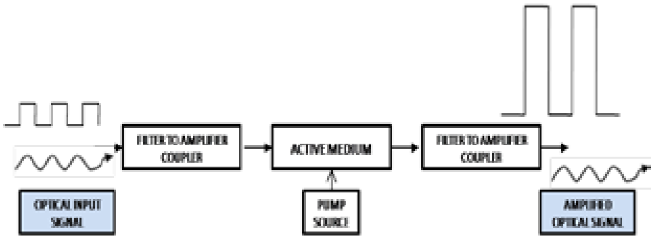

Fig. 2: The basic structure of an optical amplifier [1, 2]

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

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

where ,go is the peak value of the gain, ω is the optical frequency of the incident signal, ωo is the atomic transition frequency , P is the optical power of the signal being amplified,Psat is the saturation power andT is defined as the dipole relaxation time which is of the order 1 ps.In the unsaturated region, P /Ps«1. So, the gain coefficient becomes:-

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

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:-

$$G = \frac{P_{out}}{P_{in}} \qquad \text{...(7)}$$

Where Pin and Pout are the input and output powers of the continuous wave signal being amplified.

III. 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 FRA and 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. 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.

Table 1: Difference of materials and operating bandwidth of three 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

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.

A. 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 [5-7]. 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 Fig. (~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

IV. 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, Er3+. The gain is provided through stimulated emission, as in laser. The Er3+ ion acts mostly as a three level system, in which the main participants are the 4I15/2 ground state, the 4I13/2 first excited level and the 4I11/2second excited level. The energy level diagram of Er3+ is shown in Fig. 3 [1, 2].

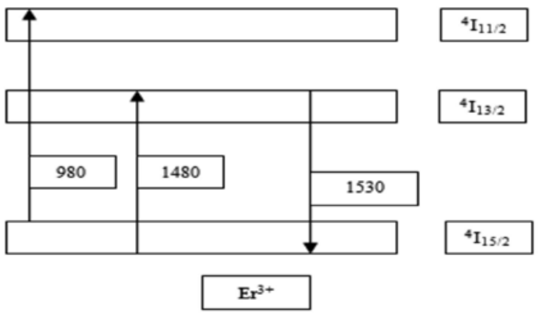

Fig. 3: Energy Level Diagram of Er3+ [1, 2]

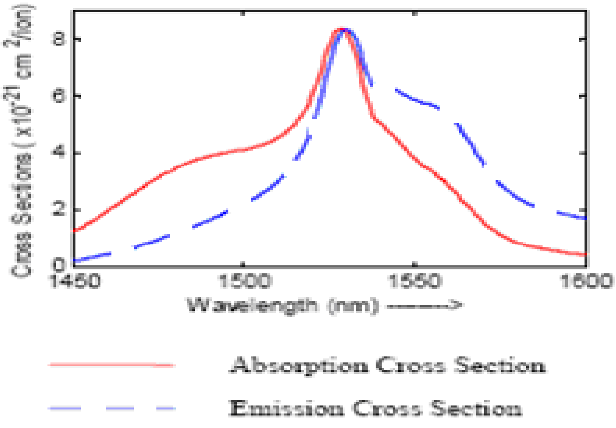

Fig. 4: Absorption and Emission Spectra of EDFA [1,2]S

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 from Fig. 4 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. 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.

V. Role of TDFA in Communication Systems

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 Tm3+ is shown in Fig. 5 [4].

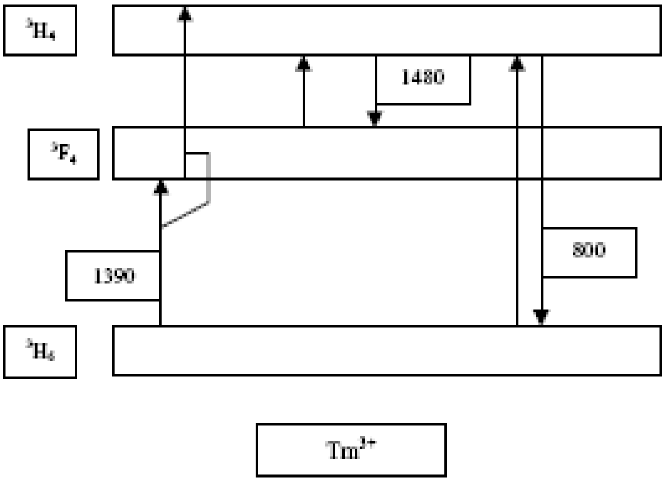

Fig. 5: Energy Level Diagram of Tm3+ [4]

VI. Hybrid Amplifier-A Review

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 Fig. degrades due to the loss of the coupler located in front of each amplifier[5-11]. 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.
- 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.

- 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.

Out of these, one of the-state-of-art hybrid amplifiers is TDFA -EDFA configuration. In this paper a novel technique is proposed to extend and flatten the gain bandwidth of a Hybrid amplifier. The gain bandwidth is extended by cascading EDFA with TDFA. This spectrum is then flattened by using a seven layer dielectric interference filter. When we cascaded EDFA 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

$$G_{T(\lambda)} = \exp\Big[\Big(\sigma_{T(1480)} NT_{2-\sigma T(1390)} NT_{1-\sigma T(800)} NT_0\Big)\Big]\big(\eta_T L_T\big) \qquad (8)$$

The gain of EDFA is given as:

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

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

$$G_{(\lambda)} = G_{T(\lambda)} \ X \ G_{E}(\lambda)$$

$$= \exp\left[(\sigma T(1480)NT2- \sigma T(1390)NT1- \sigma T(800)NT0)\right]X$$
$$\exp\left[(\sigma E(1530)NE2- \sigma E(1480)NE1) (\eta E\ LE) \qquad (10)\right.$$

In the above equations, σT(1480), σT(1390) and σE(980) denotes cross-sections of excited state absorption, stimulated emission and ground state emission of TDFA. Similarly, σE(1530), σE(1480) represents the respective cross sections of EDFA. ηT and ηE represents the confinement factors of TDFA and EDFA respectively. With this configuration we get a wide bandwidth spectrum of nearly 100nm i.e. from 1460nm to 1560nm wavelength range. This also includes the 1510nm-1520nm range where EDFA as well as TDFA has no large gain for themselves. This is also observes that this gain is unflattened mainly from 1520nm to 1540nm region.

VII. Methodology, Result and Analysis

One approach that is used in this paper is 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.

The objective of the proposed work/ open ended problems of research can be listed as below:

- Mathematical modeling of hybrid amplifier i.e. using TDFA and EDFA cascaded configuration along with either DGE (Dynamic Gain Equalizer) or TFF (Thin Film Filter). This model is proposed to increase the gain as well as broaden and flatten the gain spectrum i.e. from1460nm to 1580nm wavelength range.
- Analyzing different parameters e.g. gain, noise Fig. , amplified spontaneous emission of hybrid amplifier and its correction function, variation of length of TDFA and EDFA and variation of input power with pump power of proposed hybrid amplifier.
- Modeling of DWDM system for increased number of channels and implementation of proposed hybrid amplifier over the DWDM systems as well as to analyze the performance of DWDM system for larger number of channels i.e. upto 16 channels.
- Optimization of use of hybrid amplifiers, by way of using lesser number of fiber amplifiers as well as by increasing the number of DWDM channels for reasonable performance of the system.
- The mathematical model developed keeping into consideration all possible realistic parameters is simulated using some reliable software.

VIII. Conclusion

With this proposed design it has been found that when we cascaded TDFA with EDFA in series then gain spectrum is broadened. The gain variation is less than ± 1.5% in the wavelength region of 1460-1580 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 7dB.

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