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Review

Review of Erbium-doped fiber amplifier

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Data communication systems are increasingly employing optical fiber communication systems (OFCS) as the transmission paths for information. Various types of optical amplifiers have been developed in OFCS to amplify optical signals. In particular, the Erbium-doped fiber amplifier (EDFA) is one example of an optical fiber amplifier that is widely known for use in amplifying optical signals. The most significant points in any optical amplifier design are gain and noise figure (NF). They are closely related to each other. Low NF and high gain are the main features for optimum amplifier (Desurvire, 1987). On the other hand, the gain and NF have very strong impact with EDFA's configurations. Therefore, changes in EDFA's configuration play very important role during the designing of optical amplifier. The literature shows that there is no study that has been done to review the EDF configuration. Therefore, in this paper we are presenting an overview of most of the EDFA's configurations that have been proposed in order to provide the researchers with a clear view of what has been done in this field.

Key words: Communication system, optical amplifier, EDFA configurations, noise figure, gain amplifier, rare-earth doped fibers, atomic systems, EDFA's position.

INTRODUCTION

Optical fiber communication is seen as one of the most reliable telecommunication technologies to achieve consumers' needs for present and future applications. It is reliable in handling and transmitting data through hundreds of kilometers with an acceptable bit error rate. Today, optical fiber communication has been established as one of the most promising technologies within the area of medium and long distance data transmissions (Ji, 2005). Optical transmission systems are based on the principle that light can carry more information over longer distances in a glass medium, while the electrical signals can carry information over copper or coaxial cable. Light is electromagnetic waves and optical fiber is a wave-guide, in order to compensate the loss of the wave-guide, an optical amplifier is needed. Doped fiber amplifier (DFA) is an optical amplifier which uses rare-earth doping material which are: Erbium (Er3+), Praseodymium (Pr3+), Europium (Eu3+), Neodymium (Nd3+), Terbium (Te3+), Lutetium (Lu3+), Ytterbium (Yb3+), Holmium (Ho3+), Dysprosium (Dy3+), Gadolinium (Gd3+), Samarium (Sm3+), Promethium (Pm3+), Cerium (Ce3+), Lanthanum (La3+) and Thulium (Tm3+) inside the fiber. Essentially, within a transmission line the DFA is connected to a pump laser. It works on principle of stimulated emission and pump laser is used to provide energy and excite ions to an upper energy level (Mohammed et al., 2011a, 2011b). Then, the ions are stimulated by photons of the information signal and brought down to lower levels of energy. Subsequently, they emit photon energy exactly on the same wavelength of the input signal. The first rare

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earth doped material of Neodymium Nd3+ used in a single-mode fiber was demonstrated in 1960 (James, 1991).

The rare-earth doped fibers were fabricated in a wide variety of methods to suit different design of amplifiers. The DFAs are achieved though doping fluoride-based fibers (rather than silica fibers) with elements such as Praseodymium (Pr3+) with 1300 nm windows (Kunihiko, 1998), Europium (Eu3+) with 613 nm windows (Lihui, 2004) and Neodymium (Nd3+) with 740 nm windows (Jouin, 2002). In OFCS, the active medium of DFA which has less attenuation is operating in the 1550 nm window that is created by doping a silica fiber core with the Erbium (Er3+). To date, research works are concentrating more on the Erbium-doping, particularly in silica based fibers. This is due to the emission of Er3+ ions within a set of wavelength around 1550 nm where the silica fiber exhibits the minimum attenuation on information signal. Erbium doped fiber amplifiers (EDFA) could provide gains as high as 40 dB associated with low noise, as successfully demonstrated within a pumped power range of 50 to 100 MW (Mears, 1987). The important features of EDFAs include the ability to pump the devices at several different wavelengths, low coupling loss to the compatible fiber transmission medium and very low dependence of gain on light polarization due to the cylinder shape of EDF. In addition, EDFAs are highly transparent to signal format and bit rate, since they exhibit slow gain dynamics, with carrier lifetimes of 0.1 to 10 ms (Becke, 2002). The result is that the gain responses of EDFAs are basically constant for signal modulations greater than a few kilohertz. Consequently, they are immune from interference effects, such as crosstalk and inter- modulation distortion between different optical channels within a broad spectrum of wavelengths (a 30 nm spectral of the C-band ranging from 1530 to 1560 nm) that are injected simultaneously into the amplifier (Schawlow and Townes, 1958). By simply adding a broadband C-band fiber Bragg grating (FBG) in double-pass system a highly efficient gain-clamped can be achieved, L-band EDFA with improved NF characteristic (Sulaiman et al., 2004a; Naji et al., 2007a), or by incorporation of optical circulator between the two stages which prevents the backward amplifier spontaneous emission (ASE) from disrupting the population inversion at the first stage (Sulaiman et al., 2004b). Moreover, the temperature in C-band cause major problem to the EDFA. However, temperature co-efficients and gain variations increased when decreasing input signal is decreased (Yucel et al., 2008).

In addition, some numerical analysis of EDFA rate equation model is needed to design a practical C-band R-EDFA for the long haul OFCS. From the point of view of optimal design of R-EDFA their numerical plays an important effect on the C-band EDFA's design (Nadir et al., 2007a). On the other hand, the need for high gain EDFA can be obtained using several approaches including double-pass amplification (Lauridesen, 1991). The L-band for EDFA is given higher gain that flat is from 1574 nm to 1604 nm at gain variation and NF from 5.6 to 7.6 dB of which is better than the conventional band EDFA (Sulaiman et al., 2004c). L-band EDFAs usually adopt multi-stage and multi-pump architectures to obtain both high gain and low NF, especially when used as in-line power boosters for wavelength division multmalxing (WDM) systems. In addition, in multi-stage L-band EDFA with high-loss inter-stage element, some loss elements, such as dispersion compensation fiber (DCF) module or gain equalization filter (GEF), are commonly located within the stages in order to solve the tradeoff between NF degradation and output power decrease (Zhi et al., 2003). Many researches carried out extensive investigation for EDF (Desurvire, 1987; Bjarklev et al., 1989).

FUNDAMENTALS OF OPTICAL AMPLIFICATION IN EDFA

Effects of light amplification was first described theoretically (Schawlow and Townes, 1958), but an analysis of rare earth doped fiber characteristics was studied and demonstrated in 1962 (Becker et al., 2002). Then, an investigation on Erbium doped fiber was first done (Mears and Payne, 1987) from University of Southampton. Later on, many researches were extensively done by many scientists (Desurvire, 1987; Armitage, 1988; Bjarklev et al., 1989) and the first EDFA was commercialized in 1992. Each free ion of Erbium exhibits discrete energy level. The energy level refers to an amount of particular energy contained by the ion corresponding either to absorb or emitted energy. Amplification in Erbium doped fiber is closely related to the changes in energy level of Erbium ions. Absorbing energy will increase its energy level and vice versa for emitting energy. In amplification terms, emitting light is associated with emitting photons. Figure 1 shows the possible energy levels for Erbium ions as well as possible pumping bands. Absorption of pump photons excites Erbium ions to higher energy states.

At higher energy levels, the ions may dissipate energy radiatively by releasing photons or converting the energy into heat. According to ion energy structure, each energy level has numbers of stark levels, as well as, each ion experiences a different field strength and orientation due to randomness in the glass molecular structure, resulting in different stark-splitting. The splitting causes a large gain bandwidth of rare-earth doped fiber amplifier. The number of stark split lines for each level are 7 and 8 for $^4I_{13/2}$ and $^4I_{15/2}$, respectively resulting in 56 possible transitions between those lines spreading across 1550 nm band at low temperature (Desurvire, 1994).

At 300 K temperature, the bands sufficiently overlap giving smooth and continuous transition. The increase of

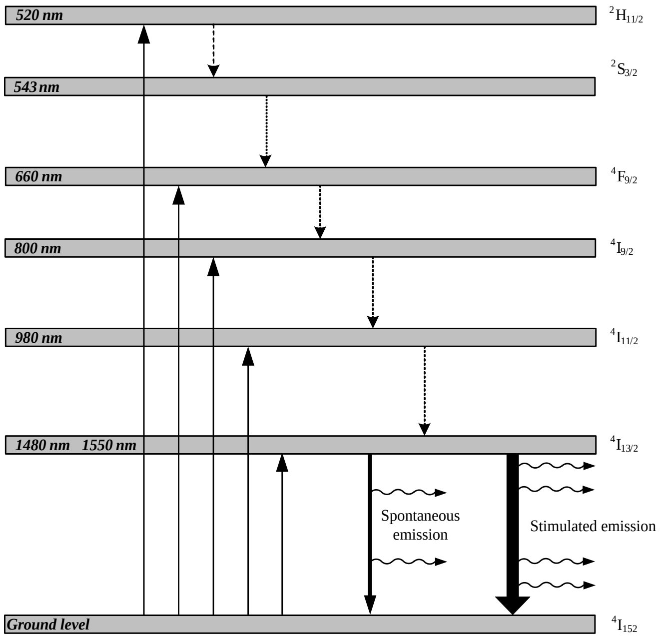

Figure 1. Energy levels of Erbium ions with the possible pump bands (Desurvire, 1994).

energy gap between levels will also increase the tendency of photon radiation when jumping to lower energy levels. Thus the transition between $^4I_{13/2}$ and $^4I_{15/2}$ is predominantly radiative resulting in 1550 nm wavelength region. Spectroscopy studies on Erbium glass showing pump wavelengths at 520 nm (Desurvire, 19870), 620 nm (Mears, 1987), 800 nm (Mears et al., 19880), 980 nm (Liaw et al., 1997; Haugen et al., 1992) and 1480 nm (Gabla et al., 1992) have been successfully demonstrated.

Availability and maturity of pump laser diodes for 980 and 1480 nm; these pump wavelengths are to be widely deployed (Franz and Jain, 2000). 980 nm pumps provides low noise amplifier output but it requires for wavelength accuracy due to the narrow absorption band while 1480 nm pump gives better power conversion efficiency as compared to 980 nm band (Desurvire, 1994).

According to Figure 1, discrete energy values are separated by energy gaps, which follow the laws of quantum physics. Ground level E_1 ($^4I_{15/2}$) indicates the lowest level and E_2 ($^4I_{13/2}$) indicates the first level. Any ion can jump to another level discretely, thus, changing its energy level. The difference of energy ΔE, when an atom moves from upper to lower level releases photon as a quantum of energy. The photon carries energy of Ep and is defined as (Desurvire, 1994):

$$Ep = hf = E_2 - E_1 \quad (1)$$

E_2 and E_1 refer to the atom's discrete energy during transition between levels, where h = 6.626 × 10^{-34} J.s is Planck's constant and photon frequency is denoted by f. Changes of atom energy level from a lower to a higher level require an external energy. The atom absorbs this energy and jumps to the higher level. As by nature, the atom tries to get itself to be at its lowest possible energy level. The drop in energy level to lower level radiates photons. The process of providing atoms with external energy, known as pumping, is depicted in Figure 2.

Initially the atom relaxes at E_1 which is the lowest energy level. Applied external energy is absorbed by the atom and causing it to jump to an upper level, E_2. This condition is known as light absorption. Light emission occurs when the atom from E_2 goes down to the lower energy level. Light emission either spontaneous or by stimulated processes. Spontaneous light emission occurs when atom returns to lower energy level randomly while stimulated emission takes place when photons having energy equal to the energy difference between E_2 and E_1. This causes the atom to return to E_1 and more photons are emitted that have similar frequency, phase and polarization with the ones that caused it. This is shown diagrammatically by Figure 3. Emission can occur in two ways:

1. Spontaneous emission where atoms return to the lower energy level in a random manner. According to quantum mechanics theory, spontaneous emission always involves transition from a higher energy state to a

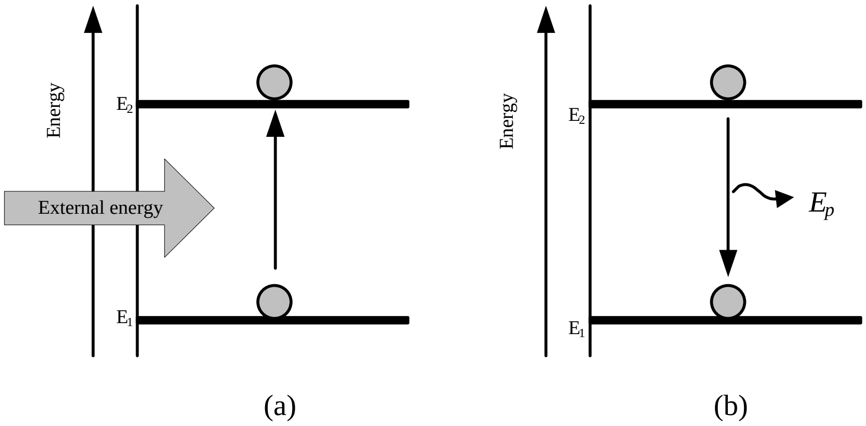

Figure 2. Atom with respective energy level: (a) light absorption and (b) light emission.

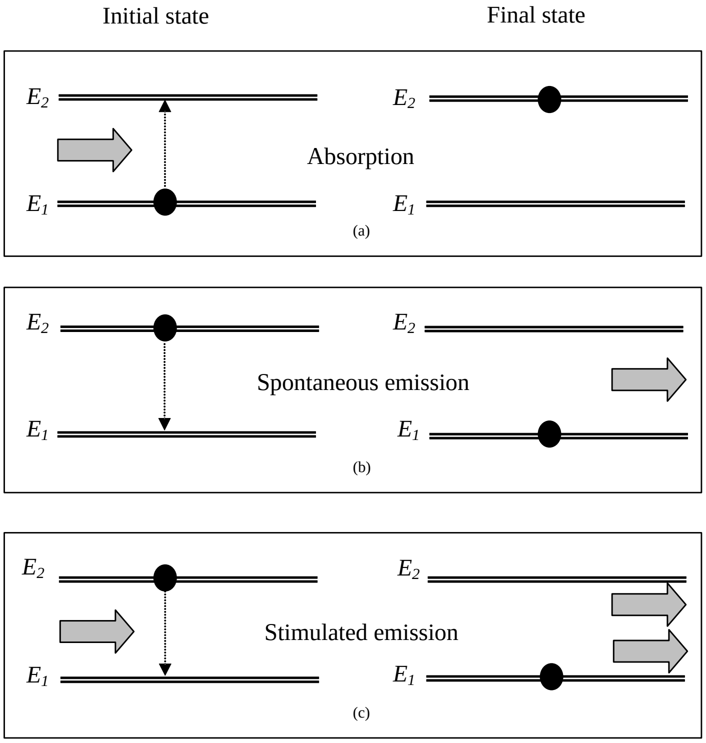

Figure 3. Schematic representations of absorption and emission between energy level 1 and 2: (a) absorption (b) spontaneous emission and (c) stimulated emission. The black dot indicates the state of the atom before and after transition takes place and the block arrow in: (a) represents pump light (b) represents ASE and (c) represents signal light (Nadir et al., 2007d).

lower energy state. The spontaneous emission produced would become the noise generated by the amplifier and is referred to as amplified spontaneous emission (ASE).

2. Stimulated emission where a photon (energy carrying atom) having energy equal to the energy difference between E$_2$ and E$_1$ interacts with the atoms in E$_2$, causing

them to return to E_1 along with the creation of more photons. This is also referred to as avalanche multiplication.

Photons produced by stimulated emission are generally of an identical energy to the ones that caused it and hence, the light associated with them is of the same frequency, phase and polarization. Furthermore, when an atom is stimulated to emit light energy by an incident wave, the liberated energy could add to the wave in a constructive manner, providing amplification.

Population inversion

In atomic systems with thermal equilibrium, the atom density in each energy level obeys the Boltzmann distribution (Senior, 1992):

$$N_2 / N_1 = e^{-[(E2 - E1)/KT]} = e^{-hf/KT} \tag{2}$$

N_1 and N_2 are atom densities for energy levels E_1 and E_2, respectively, K is the Boltzmann constant, T is the absolute temperature and h is Planck's constant. According to the aforementioned equation, N_2 is much smaller than N_1 in a normal atomic system at thermal equilibrium. Therefore, stimulated absorption is dominant as compared to stimulated emission. In conditions where the thermal equilibrium is achieved, the lower level energy contains more atoms than at the upper level at room temperature. A non-equilibrium distribution of atoms where a population of atoms at upper energy level is greater than the lower is necessary to have optical amplification. This condition is commonly known as population inversion, with $N_2 > N_1$ where both N_2 and N_1 represent the density of atoms in energy levels E_2 and E_1.

Through population inversion, N_2 will become much larger than N_1, resulting in a system with dominant stimulated emission. Population inversion is achieved by injecting power into the system through an external energy source, which is known as pumping. Pumping will excite atoms into the upper energy level E_2 and hence obtain a non-equilibrium distribution. Figure 4 shows the atom density curve for both normal and inverted system.

Two-level atomic system of EDFA

This work deals with the 1480 nm R-EDFA. For this reason, the following mainly discusses the theoretical concept for the two energy levels of EDFA. The well-separated spectral line in Erbium is called multiplet, which is composed of a certain number of broadened individual energy levels. In a two-level system, the population of ions and the rate equations involve Levels 1 and 2 of Erbium energy level system. The Level 2 involvements are only via the 1480 nm pump wavelength absorption cross section from Level 1 to Level 2 as depicted in Figure 5.

Consider the two energy levels system shown by Figure 5. Ground level is denoted by Level 1 and metastable level by Level 2. The metastable level is defined as a level where the lifetime of the system which is long as compared to 100 µs and it is a usual lifetime of a state which could be emptied by an allowed optical transition (Armitage, 1991). According to Figure 5, R_{12} is denoted as pumping rate between Level 1 to level 2. The spontaneous decay rate from Level 2 and 1 is $A_2 = RA_{21} + NRA_{21}$. It is assumed that spontaneous decay is dominated by the radiative decay rate, that is $RA_{21} >> NRA_{21}$. Thus the spontaneous decay rate between Level 2 to level 1 could be simplified to A_{21}. Generally, the transition rate of an erbium doped fiber can be defined as the following:

$$\text{Transition rate} = \sigma \frac{I}{hv} \tag{3}$$

where σ is the cross-section of the fiber, hv represents the band-gap energy with h being the Planck's constant and v being the frequency. I is the intensity and can further be defined as:

$$I = \frac{P}{A_{eff}} \tag{4}$$

Where P is the power and A_{eff} is the effective area of fiber. The stimulated absorption and emission rates between Level 1 and 2 are denoted by W_{12} and W_{21} respectively. From Equation 3 and 4, transition rates such as pumping rate (R_{12}), stimulated absorption rate (W_{12}) and stimulated emission rate (W_{21}) are defined as follow:

$$R_{12} = \frac{\sigma_{ap}\Gamma_p}{hv_p A_{eff}} P_p \tag{5}$$

$$W_{12} = \frac{\sigma_{as}\Gamma_s}{hv_s A_{eff}} \left[P_s + P_{ase} \right] \tag{6}$$

$$W_{21} = \frac{\sigma_{es}\Gamma_s}{hv_s A_{eff}} \left[P_s + P_{ase} \right] \tag{7}$$

where Γ_s = overlap factor, P_S = initial signal power and P_{ase} = forward spontaneous emission. However, spontaneous decay rate (A_{21}) depends on the fluorescence lifetime (τ) of the excited energy level, hence, it is defined as:

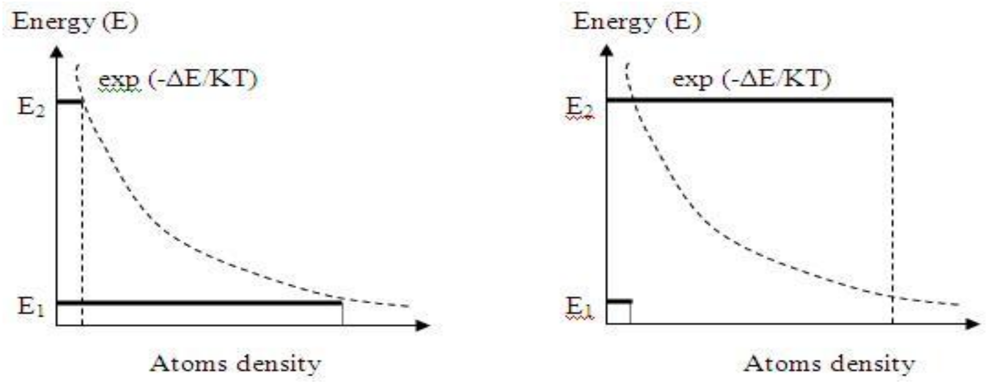

Figure 4. Population in a two energy levels system: (a) Boltzman distribution for a system in thermal equilibrium (b) a non-equilibrium (inverted) distribution showing population inversion. (Desurvire, 1994).

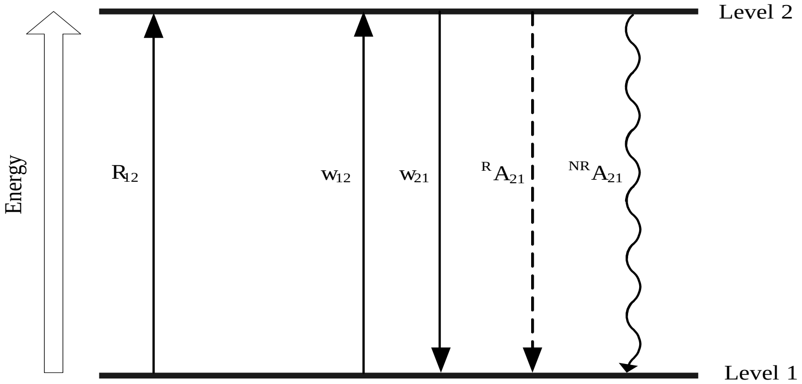

Figure 5. Energy level of two-level system (Becker et al., 2002).

$$A_{21} = \frac{1}{\tau} \qquad (8)$$

The total ion density (ρ) is equal to $N_1 + N_2$. N_1 and N_2 are introduced as fractional densities of ions in the energy levels 1 and 2, respectively. In the initial condition where there is no pump, $N_2 = 0$ and $\rho = N_1$. During excitation through optical pumping, ions from level 1 will be excited to level 2 depending on the R_{12}. The following equations show the atomic rate transition for these ion populations (Desurvire, 1994):

$$\frac{dN_1}{dt} = -W_{12}N_1 + W_{21}N_2 + A_{21}N_2 - R_{12}N_1 \qquad (9)$$

$$\frac{dN_2}{dt} = W_{12}N_1 - W_{21}N_2 - A_{21}N_2 + R_{12}N_1 \qquad (10)$$

At steady state,

$$\frac{dNi}{dt} = 0 \qquad (11)$$

Substituting Equation 11 into Equation 9 for N1 yields,

$$-W_{12}N_1 + W_{12}N_2 + A_{21}N_2 - R_{12}N_1 = 0 \qquad (12)$$

Further rearranging Equation 12 produces the following equation:

$$N_1 (W_{12} + R_{12}) = N_2 (W_{21} + A_{21}) \qquad (13)$$

Since $\rho = N_1 + N_2$, where ρ is the total atom density, Equation 13 reduces to 14:

$$N_1 = \frac{\rho\left(1 + \frac{W_{21}}{A_{21}}\right)}{1 + \frac{W_{12}}{A_{21}} + \frac{R_{12}}{A_{21}} + \frac{W_{21}}{A_{21}}} \qquad (14)$$

Substituting Equation 8 into Equation 14 yields:

$$N_1 = \frac{\rho\left(+W_{21}\tau\right)}{1+W_{12}\tau+W_{21}\tau+R_{12}\tau} \quad (15)$$

Substituting Equation 11 into Equation 10 yields:

$$W_{12}N_1 - W_{21}N_2 - A_{21}N_2 + R_{12}N_1 = 0 \quad (16)$$

Further rearranging Equation 16 produces the following equation:

$$N_2\left(W_{21}+A_{21}\right) = N_1\left(W_{12}+R_{12}\right) \quad (17)$$

Substituting ρ = N_1 + N_2, where ρ is the total atom density, Equation 17 reduces to Equation 18 as follows:

$$N_2 = \frac{\rho\left(\frac{W_{12}}{A_{21}}+\frac{R_{12}}{A_{21}}\right)}{1+\frac{W_{21}}{A_{21}}+\frac{W_{12}}{A_{21}}+\frac{R_{12}}{A_{21}}} \quad (18)$$

Substituting Equation 8 into Equation 18 yields:

$$N_2 = \frac{\rho\left(W_{12}\tau+R_{12}\tau\right)}{1+W_{21}\tau+W_{12}\tau+R_{12}\tau} \quad (19)$$

CONFIGURATIONS OF EDFA

This part of the work explores the research and the previous studies that are relevant to the proposed topic. In addition, it discusses the different configurations of the EDFA and its effect on the NF and gain amplifier. There are varieties of configurations of EDFA which are dependent on the kind of application. Generally, from the pass until present, studies on the EDFA can be divided according to configuration into stages and passes as follows:

One- stage EDFA

The one-stage EDFA configuration which means only one EDF that works as an active area. The one-stage can be a single-pass or double-pass configuration as shown in Figure 6.

Single- pass

The basic single pass (SP-EDFA) module or configuration comprises one or two pump laser diode (LD) modules with fiber output, and also one or two wavelength division multmalxing (WDM) to collect the light with pump power. Furthermore, input and output isolators, and the active medium (EDF). All the optical components have single mode fiber (SMF) pigtails and are spliced together to form an EDFA module as shown in Figure 1a. Chun et al. (2003) proposed configuration for automatic gain control of optical EDFA that uses novel dual control lasers optical. The output power change of the surviving signal reduces to 5.7% when 1546 nm signal are added/dropped at 1 kHz. Meanwhile, the configuration is flexible and the clamped-gains can be tuned in the range of 13.5 to 31.5 dB. This method has some advantages such as, the grating resonance wavelengths can be tuned by bending the fiber section that contains the grating. Mrinmay et al. (2007) investigated the optical gain and NF for multichannel amplification in EDF under optimized pump condition. They experimentally studied the optical gain and NF for simultaneous multi-channel amplifications in EDFA under optimized pump condition for different input signal levels of optimized fiber lengths. It was observed that the gain and NF values primarily depend on the pumping configurations and produced optimum result at bi-directional pumping, whereas the gain-spectra and noise characteristics depend mainly on the population inversion level along the fiber length. Moreover, EDFA which is the population inversion along the fiber length was controlled by varying the injected pump power. However, Bi-directional pumping results the best combination of gain and NF of EDFA. While co-propagation of pump and signal produces the best noise performance. Moreover, at higher input signal power levels, the signal significantly depletes the inversion beyond the pump’s ability to replenish it and the NFs increase rapidly with signal power. The authors have taken another direction which integrated (SP-EDFA) with a chirped fiber Bragg grating (CFBG) to compensate both the attenuation and dispersion as well as considering the high gain and low NF by very low remote pump power .Therefore, the numerical results play an important role in designing an optimized remotely pumped SP-EDFA for the repeater-less long haul OFCS from the point of view of economic usage of pump power (Nadir et al., 2007b).

Double pass

The basic double pass (DP-EDFA) is a state in which signal will pass two times through active medium, the Erbium doped fiber (EDF) as shown in Figure 6b. Theoretically it is proven that the double pass method will enhance the gain twice as compared to the single pass (Desurvire, 1994). Rosolem et al. (2008) investigated simple double pass configuration by using a single commercial EDFA for S-band application as well as amplifier spontaneous emission (ASE). The design shows excellent gain performance when compared with

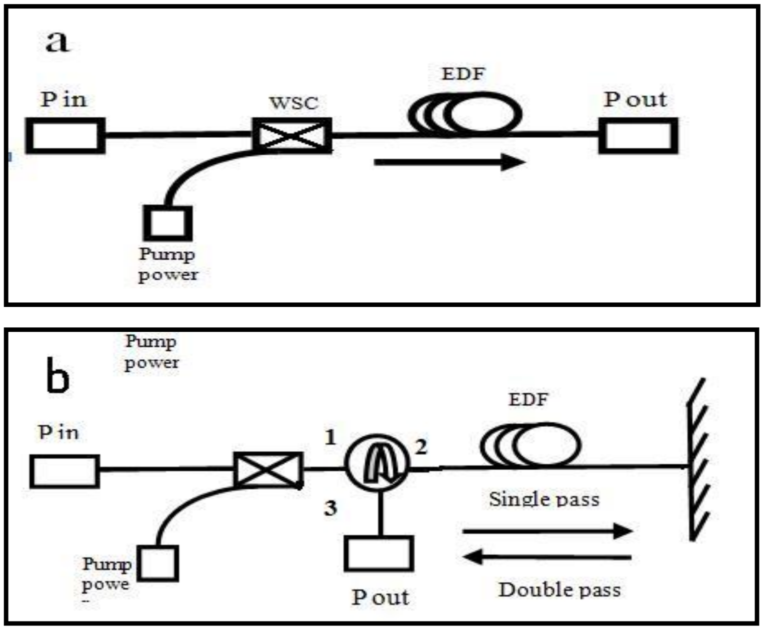

Figure 6. (a) One -stage single pass (b) one- stage double pass.

the previous works. However, it is recognized that the gain is not flat which may require a gain-flattening device for gain equalization. Zhang et al (Hao et al., 2005) improved the NF of an EDFA with double-pass configuration. However, the gain of new double-pass EDFA is averagely 1.3 dB lower than that of the conventional one. Moreover, the ASE wavelengths will be amplified simultaneously with the signal ones, leading to higher NF, because output spectrum is not modulated by the HiBi fiber loop mirror. (Naji et al., 2006a) proposed an amplifier which is able to maintain gain of higher than 20 dB for small signals less than -23 dBm with pump power 10 MW. Authors have chosen double pass with chirped fiber Bragg grating (CFBG) to compensate the fiber dispersion as well as to amplify the weak signal, (Naji et al., 2006b). In Nadir et al. (2007c) the main design objectives of the remotely pumped DP-EDFA are higher gain and low NF. However, the higher remote pump power conflicts with the main design objective of remotely pump power, where increased pump power will increase the NF. While the result (Naji et al., 2004) shows that the double-pass EDFA gives a better performance for small signal powers of less than -25 dBm and the single-pass EDFA performs better for higher signal powers of greater than -25 dBm. BER is used as the benchmark to indicate the performance of the repeaterless transmission systems (Naji et al., 2007b).

Two stages of EDFA

The two-stage EDFA configuration can be double-pass, Triple-pass or quadruple-pass as shown in Figure 7.

Double passes

In Juhan (1999) a novel highly efficient EDFA structure for long bandwidth from 1570-1610 nm band signal amplification is proposed. Four types of L-band silica-based EDFA are experimented; 1. Type I: conventional forward pump. 2. Type II: conventional backward pump. 3. Type III: unpumped EDF section before forward pump. 4. Type IV: unpumped EDF section after backward pump. The result shows that the type III got the higher gain and the lower NF 22 and 5 dB, respectively as compared to the other types. It is to compare the rest according to the gain and NF which are dramatic increase in power conversion efficiency (maximum from 11.7 to 25.7%) and small-signal gain (4 dB maximum) that had been shown when compared with other EDFA structures with the same pump power and EDF length. However, the configuration is relatively suffering from a small penalty on NFs. In Belal et al. (2011) authors proposed a novel wide-band dual function fiber amplifier. This novel configuration at low single power of -30 dBm is able to achieve gain up to 32.64 dB and noise figure of less than 5 dB.

Triple pass

In Khairil (2004) authors have proposed new high gain Erbium-doped fiber amplifier configured in dual-stage triple-pass amplification where the first stage amplifier provides high gains, while the second stage amplifier provides single-pass amplification. The gain value achieved

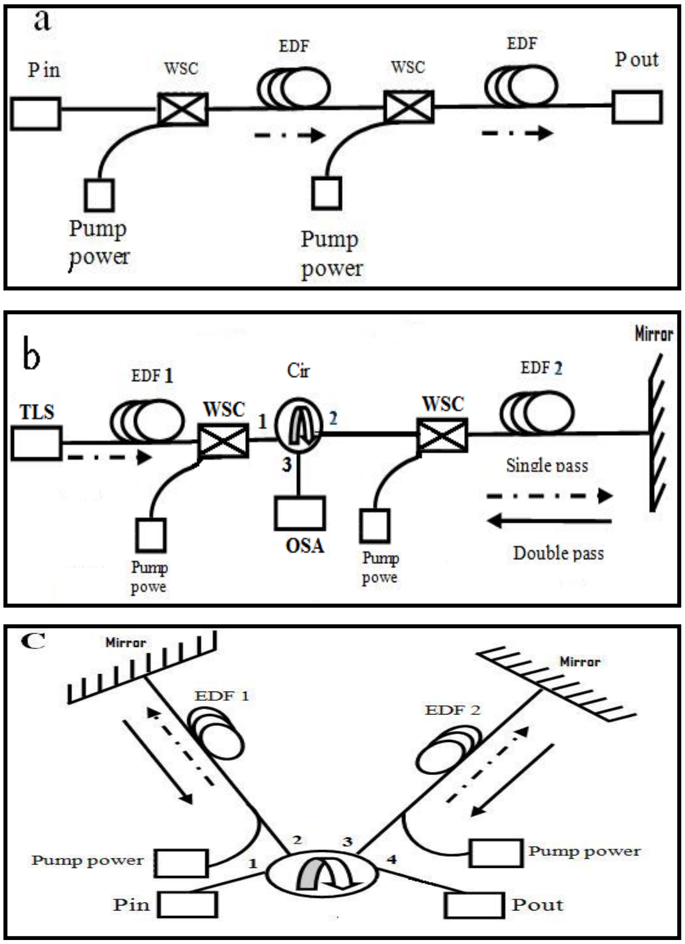

Figure 7. (a) Two-stage double pass (b) two-stage triple pass (c) two-stage quadruple pass EDFA configuration.

sis higher than 37dB at NF 6.5 dB when signal power is set at -40 dBm. In addition the design can be cost-effective to increase the receiver sensitivity in optical fiber communication systems. However, the NF value 6.5 dB is quite high from the acceptable value of 980 nm. According to Khairil et al. (2006), a maximum is gain 51.72 dB with NF of 6.1 dB in their experiment at achieved 30% pump ratio. Although, 6.1 dB is high as compared to the acceptable NF value from 3 to 5 dB (Bouzid et al., 2003). The gain and NF have been enhanced in this article by optimization of pump power distribution for dual-stage double-pass amplifier. The highest gain recorded is 51.72 dB with NF of 4.86 dB which is considered a good result. The optimum pump power for gain occurs when the pump ratio of the first pump laser to the total pump power is 30%. On the other hand, in Chien et al. (2004) new S-plus C-band EDFA module with coupled where 30 and 36.2 dB peak gains are observed at 1506 and 1532 nm, when input signal power is -25 dBm. Moreover, it provides a broadband ASE light source from 1480 to 1578 nm while the optical output level is above -40 dBm. However, the results from the experiments showed higher gain for the S and C-band, but the NF quite high at 8.2 and 7.2 dBm, respectively. In addition, bandwidth is still low whereas the demand today is for high capacity long haul telecommunication systems (Rolland et al., 1992). Therefore, broad-band EDFA with double-pass configuration is proposed in (Seongtaek et al., 2001) where the first stage of the EDFA combines C and L-band amplification, and the second-stage only amplifies L-band signals. The signal gain and NF obtained more than 24 dB and less than 6 dB. While in Sulaiman et al. (2004d, 2006) the clamed gain about 22 dB with low NF within the gain clamped region is maintained below 5 and 6 dB, respectively which is achieved by reflecting a portion of backward ASE back into the system with gain variation of less than 0.5 dB and input signal power increment up to -12 and -8 dBm, respectively. In Tsair et al. (2008) a total of five different configurations of L-band Erbium-doped fiber amplifier EDFAs of low NF and high clamped-gain are examined and compared. Among these

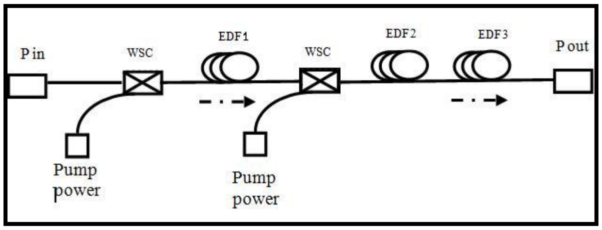

Figure 8. Three-stage with three-pass.

configurations minimum gain variation of 2.9 dB and moderate low NF of 4.8 dB can be achieved by using fiber Bragg grating (FBG) and double-pass. This work provides the optimum gain-clamped EDFA configuration for multi-wavelength WDM L-band light wave systems (Naji et al., 2011).

Quadruple pass

In Sulaiman et al. (2004f), authors have proposed amplifier which achieve flat-gain output at 33.5 dB. The gain is 13.5 dB higher than that of the single pass system with only 84 MW 980 nm pumping power and the NF at flat gain region varies from 6.9 to 11.5 dB. Although, the new configuration is demonstrated, L-band EDFA with high flat-gain, the NF is higher with respect to the pump power 980 nm. While in Chang et al. (2006), three dual pumped double-pass EDFA systems are considered and compared the performances in terms of NF, gain and pump conversion efficiency. Double-pass amplifier with narrow-band reflectors is definitely better than its counterpart, because not much ASE is reflected back when using only a few narrow-band reflectors. Moreover, this new double-pass configuration provides a lower NF 4.4 dB and a higher gain 34.4 dB. The reason for the performance improvement by using FBGs as reflectors is that a great deal of ASE noise is filtered out and does not re-enter the EDFA to deplete the population inversion.

However, when the number of coexisting channels increases, that leads to lower gains as well as higher NF as compared to the situation in which only fewer channels coexist. On the other hand, higher gain of 61 dB and NF 7 dB is achieved for -50 dBm signal power at 1550 nm by using a fiber loop-back incorporated with tunable band pass filter (Ali et al., 2009).

Three stages of EDFA

The three-stage EDFA configuration means three EDFs that are working as active areas. The three-stage can be represented as follows; triple-pass with signal passes three times on EDFs configuration as shown in Figure 8. Theoretical investigation has been done (Zhi et al., 2003) where optimization of a two-pump, three-stage L-band EDFA with high-loss inter-stage element was based on a reliable numerical model. By optimizing the EDF length of each stage properly, both high-output gain and uniform NF profile can be derived even with high-loss inter-stage devices which are about 20.7 and 5.5 dB, respectively. In addition, in a WDM channel add/drop scenario, the former pump power and population inversion should be kept high to avoid NF degradation. While in Qiang et al. (2004) authors proposed novel three-stage L-band EDFA structure with ASE pumping. The three configurations with three designs which are the first is conventional signal-stage EDFA, the second one is structure introduced and the third is the new proposed. The numerical results under pump power 980 nm for various structures showed that gain and NF are 11, 19, 28.9 dB and 5.3, 9, 3.6 dB, respectively. As a result, the new proposal performed excellent with respect to other structures where 28.9 dB gain with only about 1 dB gain ripple and less than 3.6 dB NF (from 1570 nm to 1605 nm) is provided when the input signal is fixed at -30 dBm.

Chin-Feng and Likarn (2007) presented an idea of using residual pump power for implementation of low-noise and high-gain L-band EDFAs by using a single 1480 nm pump laser and -30 dBm signal power for all experiments (Chin et al., 2007). In addition, reviews of two conventional L-bands EDFA systems have been reported to be able to enhance pump conversion efficiency (Juhan, 1999). The result at wavelengths (1570 and 1590 nm) showed that the first conventional L-band EDFA system got a gain of about 29 dB and NF of about 6 to 7 dB. The second conventional L-band EDFA system got a gain about 27 dB and NF about 6 to 7 dB. The new configuration comes from modifying the second conventional L-band EDFA system to get higher gain with acceptable NF where a new EDF is added between the two EDFAs, second conventional would definitely deteriorate NF. The gain and the NF for the proposed three-stage EDFA are 36 dB and 4.3 to 4.8 dB, respectively which clearly shows the difference as compared to the first and second conventional L-band EDFA system. However, adding new EDF that help to reduce the NF produce little positive gain for signals which increased the cost.

From the previous work it is clear that pump power plays very important role which have effect on gain and noise figure. Therefore optimsing the pump power is important in order to get higher gain and low noise figure. For example Nadir et al. (2007b) characterize the gain and NF at 1550 nm as a function of pump power using a 10 m long EDF as shown in Figure 9.

Referring to Figure 9, for the increment of pump power from 5 to 14 MW, signal gain increases from 8.73 to 12.02 dB and NF decreases from 5.49 to 4.65 dB. On the other hand, for the increment of pump power from 14 to 60 MW, signal gain increases from 12.02 to 13.54 dB and NF decreases from 4.65 to 4.35 dB. These results clearly

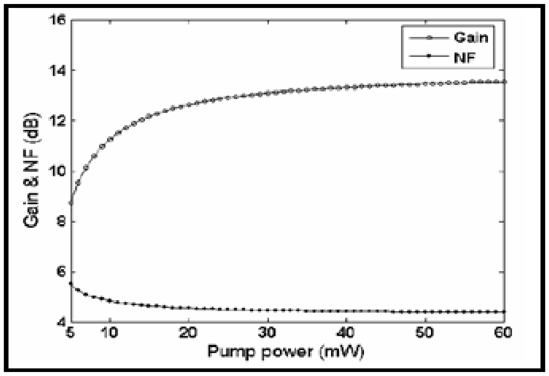

Figure 9. Gain and NF in dB as a function of pump power in MW using a 10 m long reference EDF at 1550 nm signal wavelength and injected signal power of -35.46 dBm.

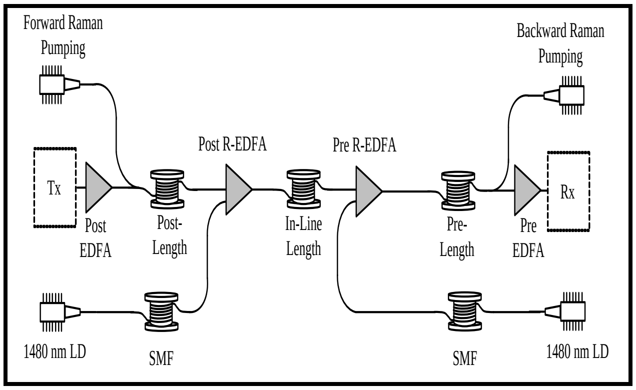

Figure 10. Configuration of optical transmission system.

show that the increment of gain and the decrement of NF are very low with respect to the increment of pump power exceeding 14 MW. Therefore, the pump power of 14 MW is chosen as the optimum pump power, because pump power exceeding 14 MW has no high impact on the gain and NF of 10 m long EDFA.

IMPACT OF EDFA POSITION ON THE OFCS DISTANCE PROGRESSION

One of the goals to be achieved in any communication links is to have the longest distance between transmission ends. This can be realized by today's technology concerning optical transmission systems such as undersea, intercontinental and terrestrial links. Commonly, the hardware used between transmission ends is desirable to be reduced to maintain cost effectiveness. Optical transmission systems in optical communication become significant as there is no costly repeater.

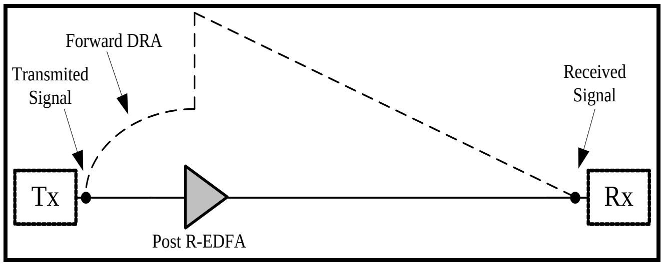

Figure 11. Signal power evolution experienced by forward DRA and post R-EDFA.

Numerous systems demonstrations have been reported with huge span distances and high bit rates (Park et al., 1993; Miyamoto et al., 1994). The control of span dispersion and nonlinear effect as well as advances in achievable transmitted power and receiver sensitivity resulted in a progress in optical transmission systems since 1989 (Grosz et al., 1999). A good dispersion management results in a high data rate of transmission along with receiver and transmitter signal improvement. The data rate can be upgraded from 10 to 40 Gbps by upgrading the existing dispersion shifted fiber at the receiver end (Senior, 1992; Sano et al., 1996).

Optical transmission systems are capable of covering a range of network applications. Typically, unrepeated optical system connects an island to the mainland via undersea cables as well as a group of islands. Transmission links along coasts of a mainland is more favorable as most of the population around the globe is located near the ocean. Unrepeated systems significantly complete the repeated system. Furthermore, mixing it with other type of connections within a terrestrial network can be realized where the optical transmission systems allow a transmission crossing the wet area.

Therefore, determining the position of the amplifier is one of the most important steps to get best results. A schematic drawing of the optical transmission system configuration is show in Figure 10. This configuration includes most of the technologies that have enabled the recently reported rapid increase in transmission distance. The transmitter usually includes a DFB (distributed feedback) laser. Data of pseudo-random bit sequence is encoded by a Mach-Zehnder modulator. Stimulated Brillouin scattering is suppressed by passing the signal through a phase modulator driven by a comb of low-power frequencies to broaden the spectrum (Korothy et al., 1995).

A locally-pumped post EDFA (booster) boosts the signal level before launching it into transmission fiber. The boosted signal can be further amplified using forward distributed Raman amplification (DRA). A post R-EDFA is located a few tenths of kilometers from the transmitter to amplify the weak signal. This EDFA pumped via a dedicated pump fiber. Figure 11 shows the signal power evolution, represented by a dashed line along

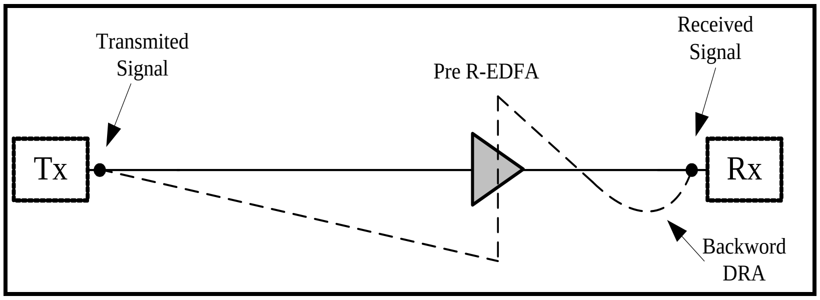

Figure 12. Signal power evolution experienced by backward DRA and pre R-EDFA.

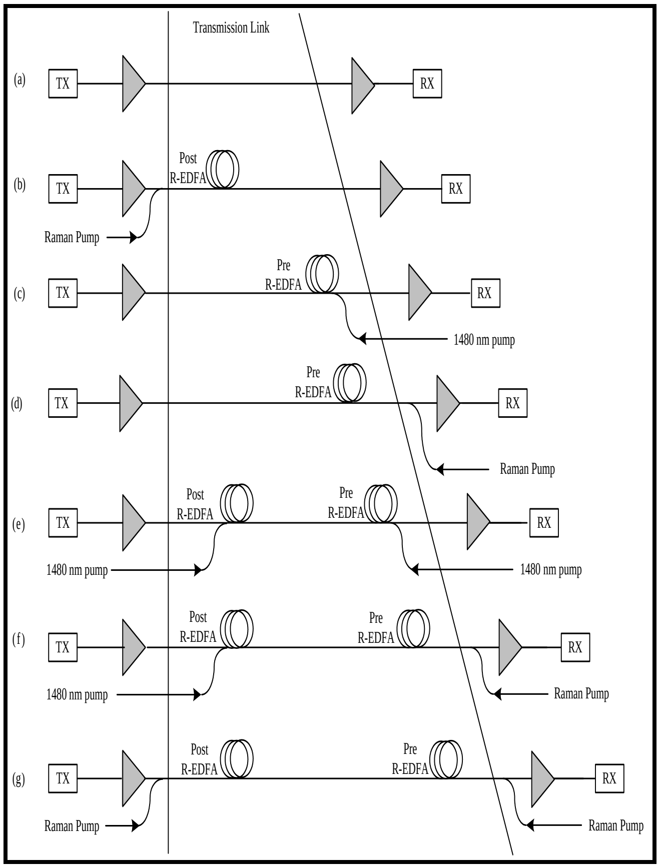

Figure 13. Various configurations of optical transmission systems.

transmission distance using forward DRA and post R-EDFA (Hansen and Eskildsen, 1997).

On the other hand, Figure 12 shows signal power evolution with respect to backward DRA and pre R-EDFA. At the receiver terminal, a discrete pre EDFA is used to amplify the received signal, this local-pumped EDFA followed by optical filter and a pin detector (optical-to-electrical converter).

The reported configurations of optical transmission systems are categorized based on the progression of systems from a distance point of view as shown in Figure 13, which is discuss in this part of the work. This study is carried out mainly to illustrate the impact of system configuration on total transmission distance, while the subsequent part of the work discusses the reported optical transmission systems from year of publication point of view.

The first configuration is an optical transmission system without incorporating any in-line R-EDFAs along its transmission link as depicted by Figure 13a. Post and pre

EDFAs typically are used after a transmitter and before a receiver, respectively in a conventional transmission system. Normally, post and pre EDFAs are treated as part of the transmitter and receiver, respectively. The transmission distance for this configuration is limited by the launched signal power from the transmitter and receiver sensitivity.

Many researchers have worked on this configuration to increase the total transmission distance, where Hagimoto et al. (1989) demonstrated a 250 km at 1.8 Gb/s optical transmission system using EDFA as pre and post amplifiers. A high gain of post and pre EDFA with the low-loss dispersion shifted fiber are used to achieve this distance. On the other hand, increasing the gain of post EDFA has a significant drawback on the quality of the transmitted information signal due to the non-linear effects of the transmission fiber. This fact had not been taken into account also in the 2.5 Gb/s optical experiment for the same configuration (Figure 12a), where two post-EDFAs (boosters) have been used to push the signal up to +16 dBm (Park et al., 1993). In fact, the nonlinearity of fiber like self phase modulation (SPM) has a high effect on the performance of the transmission system that uses a data rate of more than 2.5 Gb/s. By neglecting this fact, Grandpierre et al. (1993) have achieved a 252 km optical transmission distance at 10 Gb/s.

Later on, Wedding et al. (1993) has considered and investigated the nonlinear effects of the transmission fiber especially SPM and stimulated Brillouin scattering (SBS) on the transmission distance through a 182 km at 10 Gb/s optical transmission system. In addition to that, Blondel (1995) has taken into account the effect of SPM during development of optical configuration for a 2.5 Gb/s optical transmission experiment, where distributed Raman amplification (DRA) and post R-EDFA have been utilized to improve the optical configuration as shown in Figure 13b. This type of configuration, also known as a hybrid amplifier transmission system. A 1000 MW co-pumping (forward) power was used in this experiment to generate Raman scattering from the transmitter side. Although this experiment employed a very high Raman pump to improve the power budget, the SBS has not been considered in this experiment. The SBS could potentially degrade the transmission performance. Furthermore, Gabla et al. (1992) has used a similar configuration but with counter-pumped pre R-EDFA to achieve a 357 km at 2.488 Gb/s optical transmission experiment, as shown in Figure 12c. A forward error correction (FEC) code scheme was implemented in this experiment which increased the power budget by about 5 dB. Although the system has used the counter-pumping scheme for remote amplification from the receiver side but it has not considered the matter of DRA. DRA that is pumped from the receiver can extend the transmission distance by several tens of kilometers. Chaudhry et al. (1994) has demonstrated this fact in his experiment as shown in Figure 13d. In this experiment a 410 km at 2.488 Gb/s optical transmission distance was achieved by using hybrid pre R-EDFA and DRA. The pre R-EDFA was pumped over the transmission fiber from the receiver end using a 300 MW pump power at 1480 nm pump wavelength, which ensures the Raman gain over the pre-length.

Identical configuration has been demonstrated (Hansen et al., 1995a; Esklidsen et al., 1996; Koga et al., 1998; Neuhauser et al., 2002; Karasek et al., 2004) in a 374, 490, 340, 200 and 202 km optical transmission experiments, respectively. Moreover, Brandon et al. (1998) has modified the configuration of Figure 13d by using a dedicated fiber line from the receiver end to pump the pre R-EDFA in a 461 km at 2.5 Gb/s × 8 optical transmission experiment. In this experiment two 1480 nm pumps with a total of 700 MW pump power were employed to pump the pre R-EDFA. In order to increase the total optical transmission distance, Cremer et al. (1996) has combined both configuration of Figure 13c and d in a 254 km at 4 × 10 Gb/s optical transmission experiment.

This new configuration, which is shown in Figure 13e, has utilized both post R-EDFA and pre R-EDFA at the same time. A similar configuration was demonstrated over 250 km at 10 Gb/s (Mahgerefteh et al., 2005). In both of these experiments, the DRA have not been implemented which is expected to increase the overall system performance. Hansen et al. (1995) has implemented a backward DRA from the receiver side in a more improved configuration which is illustrated in Figure 13f. In this configuration, post R-EDFA was pumped using dedicated fiber line, while pre R-EDFAs was pumped using the transmission fiber from the receiver side. A backward DRA was employed also to achieve a 423 km at 2.488 Gb/s optical transmission distance. Many similar experiments have been demonstrated using the same configuration of Figure 13f (Ma, 1998; Hansen et al., 1995, 1995b) have achieved 240, 442 and 529 km optical transmission systems, respectively.

In all these experiments the post R-EDFAs were pumped using dedicated fiber without considering the forward DRA from the transmitter side. Gautheron et al. (1994) has used forward DRA from the transmitter side in additional to the backward DRA to produce a new configuration which is shown in Figure 13g. Using this configuration, a 407 km at 2.488 Gb/s optical transmission distance was achieved. Moreover, a 427 and 481 km optical transmission distance have been achieved by using additional numbers of 1480 nm laser pumps (Sian et al., 1996; Gautheron et al., 1995). Finally, the same configuration was used by Miyakawa et al. (2002) to achieve optical transmission distance of 362 km through 8000 MW total pump power.

CONCLUSION

Data communication systems are increasingly employing optical fiber communication systems (OFCS) as the transmission paths for information. The use of OFCS generally allows for the transmission of large amounts of data at high speeds for long distance transmission. The amplifier is an essential component in any optical fiber communication systems, because it has an advantage that can compensate the transmission loss during the propagation of the transmitted signal from one place to another and the common optical amplifier today is the EDFA. The EDFA configuration plays very important role in the design of EDFA due to the fact that the differences in configuration need different parameters and requirements as well. These parameters need to be controlled to get higher gain and lowest NF. These parameters still cannot be completely controlled to get higher gain and lowest NF. A basic understanding on OFCS and light amplification is highlighted throughout this paper as well as optical transmission systems. For the optical transmission system, the elaborated technologies reveal its importance relating to the cost of the overall system. Optical amplifiers can extend the transmission distance to a point where the dispersion of the span, limits the system performance. Dispersion compensating fiber, fiber Bragg gratings, higher-order spatial mode compensators and a bulk optic phased array are used as dispersion compensating components in optical transmission system. System configurations show a practical implementation and typical positions of the R-EDFA and DRA in order to enhance the transmission performance. Furthermore, two important factors affect the optical transmission performance. The first factor is the system configuration, where many system configurations were reviewed and criticized. It shows that the configuration has a direct effect on the performance. The second factor is the total pump power injected into the system. By increasing the total pump power, the transmission distance can be increased. On the other hand, increasing the total injected pump power increases the non-linear effects of the transmission fiber, which degrades the system performance. Until now, there are no clear and structured design rules for optical transmission systems. Therefore, design rules for optical transmission systems have become essential in this field. Finally, Future researches are expected to focus on reducing the noise figure at high pump powers.

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