Investigating the Gain Characteristics of EDFA and its Application in WDM System

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Abstract. This paper presents the gain characteristics of Erbium Doped Fiber Amplifier (EDFA) by investigating the doped fiber length and pump power. It is seen that by varying doped fiber length up to 10 m, maximum gain of 41 dB can be achieved at pump power of 100 mW and also varying the pump power up to 300 mW, maximum gain of 46 dB can be achieved at doped fiber length of 10 m. Later on, we have implemented the EDFA in WDM system and analyzed the performance in terms of BER and Q-Factor by varying transmission distance. Due to the implementation of EDFA in WDM system improved BER and Q-Factor are achieved for the system. Maximum Q-Factor of 23.97 and 17.43 are achieved for the designed WDM system with and without EDFA respectively.

Keywords: EDFA, WDM, FBG, BER, Q-Factor, Optics.

1 INTRODUCTION

Optical fiber loss is one of the most important factors that limiting the transmission distance in optical communication systems (Çokrak *et al.* 2004). In order to transmit signals over long distances, it is necessary to compensate the attenuation losses within the fiber. The main advantage of optical amplifiers is that the optical signals to be directly amplified optically without any conversion. The fiber amplifiers can be made using different rare earth ions, the most used element is Er^{3+} , because EDFA operating in C band (1525-1565 nm) at which the attenuation of silica fiber is minimum and therefore it is ideal for the optical fiber communication systems operating at this wavelength range (Aljaff *et al.* 2008).

This paper aims to present the gain features of EDFA by varying the doped fiber length and pump power with a view to obtaining better performance. The gain characteristics of EDFA has been obtained through computation and simulation using MATLAB simulation tool. Our analysis provides an insight into the features of EDFA for improving the gain performance by varying different parameters. After that we have implemented the EDFA in WDM system and analyzed the performance in terms of BER and Q-Factor by varying transmission distance.

2 WDM: WAVELENGTH DIVISION MULTIPLEXING SYSTEM

Wavelength Division Multiplexing (WDM) is a technology which multiplexes a number of optical signals onto a single optical fiber by using different wavelengths of laser light. In WDM, several different wavelengths are transmitted over one single mode fiber at the same time. To increase the capacity of the system is to add additional channels by laying more fibers which is impractical because higher cost is responsible for such system. So, WDM systems are very popular for telecommunication companies because it permits them to extend the capacity of the system without laying more fibers. Capacity of a given system can be

expanded simply by upgrading the multiplexers and de-multiplexers at each end without having to overhaul the backbone network (Bischoff *et al.* 2009).

Generally a basic WDM system has been divided into three parts: (i) Transmitter section, (ii) Transmission link section and (iii) Receiver section.

2.1 Transmitter Section

In transmitter section, we have used externally modulated transmitter in order to achieve stability. This also helps to reduce the chirps and non-linear effects. Here, Pseudo Random Bit Sequence (PRBS) is used to generate digital data and Non-return zero (NRZ) pulse generator is used to convert digital signal into electrical signal. After that modulator mixes the electrical signal with the light source input signal and generate optical output signal which is then sent into the multiplexer.

In our design, equally spaced of 100 GHz frequency separation of eight transmitters are used starting from 193.1 THz. Transmitter power is set around -5 dBm for all the eight transmitters. Figure 1 shows the externally modulated transmitter section.



Fig. 1. Externally Modulated Transmitter

2.2 Transmission Link Section

In this transmission link design, single mode fiber (SMF) is used which has dispersion around 17 ps/nm.km and attenuation of 0.2 dB/km. Fiber Bragg Grating (FBG) is used to compensate the dispersion effect and EDFA is used as amplifier to compensate the fiber linear loss (attenuation).



Fig. 2. Transmission Link Section

When an optical signal such as 1550 nm wavelength signal enters the EDFA from input, the signal is combined with a 980 nm or 1480 nm pump laser through a coupler device. The input signal and pump laser signal pass through fiber doped with erbium ions. Here the 1550 nm signal is amplified through interaction with doped erbium ions.



Fig. 3. Schematic diagram of Er³⁺ energy levels (Ivanovs et al. 2014)

The population of erbium ions in the three levels are denoted by N_1 , N_2 , N_3 respectively. Two pump wavelengths of 980 nm and 1480 nm can be used for EDFA. With 980 nm pumping wavelength the Er^{3+} ions in the ground state are excited to the higher state. The ions in the excited state are not going to stay there for a long time and decays back to the meta-stable state and then fall back to the ground state after approximately 10 ms and emits photon. This is called spontaneous emission which is responsible for the Amplified Spontaneous Emission (ASE) noise of EDFA. But when the ions or photons that are in the metastable state incident with light photons of suitable wavelength, they fall back to the ground state emitting photons having same phase, frequency and travel in the same direction as the photons of the incident wave. This is called stimulated emission. In this process one photon gives two photons at the output and it amplifies the input signal. When the number of ions in the excited state or metastable state is greater than the ions in the ground state then the population inversion mechanism occurs (Balani *et al.* 2013).

2.3 Receiver Section

In receiver section, PIN photo-detector is connected to the output to detect the optical signal and convert it to electrical signal and send it to low pass Bessel filter which pass the low frequency signal and discard high frequency carrier signal. Then BER Analyzer is used to analyze the bit error rate and quality factor of the designed system.



Fig. 4. Receiver Section.

3 GAIN CALCULATION OF EDFA

Erbium Doped Fiber (EDF) is divided into many individual small gain slices with the length of Δz . In each slice, the population density at metastable state $N_2(z)$ and the population density at ground state $N_1(z)$ are assumed to be unchanged. As a result, an EDFA is considered as a series of many amplifiers of the incremental length Δz (Suong *et al.*).



Fig. 5. Individual gain slices of Erbium Doped Fiber.

The gain of EDFA with length L is composed of the contributions of all the gain elements of n slices along the amplifier fiber (Suong *et al.*).

$$G = \lim_{\Delta z \to 0} \{ e^{g(z_1)\Delta z} \times e^{g(z_2)\Delta z} \times \dots \times e^{g(z_n = L)\Delta z} \}$$

= $\exp\left(\int_0^L g(z)dz\right)$ (1)

The gain g(z) in a slice of fiber can be determined by (Suong *et al.*)

$$g(z) = \Gamma_s[\sigma_{e,s}N_2(z) - \sigma_{a,s}N_1(z)]$$
⁽²⁾

Where Γ is the overlap factor between field and erbium ion population, $\sigma_{e,s}$ and $\sigma_{a,s}$ are emission and absorption cross-section of the signal respectively. $N_1(z)$ and $N_2(z)$ are the population density at ground and metastable state.

The energy levels of rare earth ions are composed of relatively well-separated multiplets. The pumping level 3 belongs to a multiplet different than that of level 2 and we assume that there is rapid relaxation from level 3 to level 2. For all practical purposes, the population in level 3 is then effectively zero and the rate equations involve only the levels 1 and 2, with level 3 being involved only via the value of the pump absorption cross section from level 1 to level 3. By reducing the three-level system to an effective two-level system, we can write the rate equations so as to involve only the total population densities of multiplets 1 and 2 as (Becker *et al.* 1999),

$$\frac{dN_2}{dt} = -\Gamma_{21}N_2 + (N_1\sigma_{a,s} - N_2\sigma_{e,s})\Phi_s - (N_2\sigma_{e,p} - N_1\sigma_{a,p})\Phi_p$$

$$\frac{dN_1}{dt} = \Gamma_{21}N_2 + (N_2\sigma_{e,s} - N_1\sigma_{a,s})\Phi_s - (N_1\sigma_{a,p} - N_2\sigma_{e,p})\Phi_p$$
(3)

Where, $\sigma_{a,s}$, $\sigma_{e,s}$, $\sigma_{a,p}$, $\sigma_{e,p}$ represent the signal and pump absorption and emission

cross sections respectively, Φ_s and Φ_p are the signal and pump flux respectively. The total population density, N=N₁ + N₂

Now replacing the value of $\Phi_s = I_s / h\upsilon_s$ and $\Phi_p = I_p / h\upsilon_p$ also solving the rate equation under steady state condition we can get (Becker *et al.* 1999), (Hapanowicz, Rick 2001),

$$N_2(z) = \frac{\frac{\tau\sigma_{a,s}}{h\upsilon_s}I_s(z) + \frac{\tau\sigma_{a,p}}{h\upsilon_p}I_p(z)}{\frac{\tau(\sigma_{a,s} + \sigma_{e,s})}{h\upsilon_s}I_s(z) + \frac{\tau(\sigma_{a,p} + \sigma_{e,p})}{h\upsilon_p}I_p(z) + 1}N$$
(4)

Where $I_s(z)$ and $I_p(z)$ are the field intensity of signal and pump respectively, τ is the spontaneous decay time, v_s and v_p are optical signal and pump frequencies respectively. The signal and pump intensity equation can be written in terms of power at the position z of the fiber (Becker *et al.* 1999),

$$I(z) = \frac{P(z)\Gamma}{A_{\text{eff.}}}$$
(5)

Where, $A_{eff.}$ is the effective cross-sectional area, Γ is the overlap factor between field and erbium ion population.

4 SIMULATION & RESULTS

Equations from (1) to (5) show that EDFA gain is changed along the fiber. Gain characteristics also depend on material and structural parameters of EDF i.e. absorption and emission cross-sections, effective cross-sectional area, Er^{3+} distribution radius, fiber length, pump wavelength, signal wavelength, signal power and pump power. By changing the values of these parameters, the performance of EDFA gain at different operation conditions can be simulated.

Table 1. Key parameters used in the simulation (Becker et al. 1999), (Pask et al. 1995)

Parameters	Symbol	Value	Unit
Doped fiber core diameter	а	5.5	μm
Doping Concentration	Ν	$2.5 imes 10^{24}$	m ⁻³
Signal Power	Ps	0.03	mW
Absorption Cross-section of Signal	$\sigma_{a,s}$	$2.70\times10^{\text{-}25}$	m ²
Absorption Cross-section of Pump	$\sigma_{a,p}$	$2.80\times10^{\text{-}25}$	m ²
Emission Cross-section of Signal	$\sigma_{e,s}$	3.96×10^{-25}	m ²
Emission Cross-section of Pump	$\sigma_{e,p}$	0	m ²
Pump Wavelength	$\lambda_{ m p}$	980	nm
Signal Wavelength	λ_{s}	1550	nm
Spontaneous Decay Rate	τ	10	ms
Overlap Factor	Г	0.72	-

4.1 Simulation of the Gain Characteristics of EDFA

The gain characteristics of the simulation are shown in figure 6 to figure 8. For the simulation we have used the above Table 1 parameters value.



Fig. 6. Gain vs. Wavelength curve for different doped fiber length at pump power of 100 mW.

In figure 6, the characteristics of EDFA gain versus signal wavelength is presented for different value of doped fiber length at particular pump power of 100 mW. It is seen that for the doped fiber length of 5m, 7.5m and 10m the maximum peak gain is obtained around 21dB, 31.5dB and 41dB respectively at 1530nm signal wavelength. Obtaining relatively flat gain spectrum over a wide wavelength band is very difficult. However, from our simulation it is seen that the gain is almost flat at the 1540 nm to 1560 nm wavelength region, which makes the EDFA to perform best if we set the transmitters of WDM system in that wavelength range.



Fig. 7. Gain vs. Wavelength curve for different pump power at doped fiber length of 10 m.

The characteristics of EDFA gain versus signal wavelength is shown in figure 7 for different pump power at particular doped fiber length of 10 m. It is seen that for the pump power of 50 mW, 100 mW, 200 mW and 300 mW the maximum peak gain is obtained around 38dB, 41dB, 45dB and 46dB respectively at 1530 nm signal wavelength. It is also seen that gain



reaches to the saturation point at around 200 mW of pump power i.e. after the increasing of the pump power there is no significance change of the gain characteristics.

Fig. 8. Gain vs. Pump power simulation curve for different doped fiber length.

In figure 8, the characteristics of EDFA gain versus pump power is presented for different value of doped fiber length. It is seen that for the doped fiber length of 5m, 7.5m and 10m the gain reaches to the saturation level at around 150 mW of pump power. So, after the increase of the pump power there is very small change of gain characteristics.

Variables		Peak Gain at 1530 nm (dB)	Approximate Flat Gain at 1540 nm to 1560 nm region (dB)	
Doped Fiber Length (L)	5 m	21	14 to 15	
	7.5 m	31.5	21 to 23	
	10 m	41	28 to 31	
Pump Power (P _p)	50 mW	38	25 to 29	
	100 mW	41	28 to 31	
	200 mW	45	29 to 32	
	300 mW	46	29.5 to 32.5	

Table 2. Key results obtained from the simulation

4.2 Performance Analysis of the WDM System

For the analysis of the WDM system designed in Section 2 of this paper we have studied the performance in terms of BER and Q-Factor by varying transmission distance. A comparative analysis of WDM system with and without EDFA is showed in this section of the paper. In that case, we have used OptiSystem 7.0 software for the simulation and performance analysis of the system.

4.2.1 BER Analysis

One of the key performance indicators in WDM system is the bit error rate analysis of the system. Bit error rate is defined as-

$$BER = \frac{Number of \ error \ bits \ at \ receiver \ end}{Number \ of \ transmitted \ bits}$$
(6)

There is a relation between BER and Q-Factor of the system, which is (Sharma et al. 2013)

$$BER = \frac{1}{2} erfc\left(\frac{Q}{\sqrt{2}}\right) \approx \frac{exp\left(\frac{-Q^2}{2}\right)}{Q\sqrt{2\pi}}$$
(7)

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Where, erfc is the complementary error function. From Eq. 7 it is seen that BER improves with the increasing of Q-Factor as they are proportionally co-related.



Fig. 9. Bit Error Rate analysis of the designed system by varying transmission distance up to 100 Km considering (a) with EDFA, (b) without EDFA

Figure 9 shows the Bit Error Rate analysis of the designed system with and without EDFA by varying transmission distance up to 100 Km and Figure 10 illustrates the comparative analysis between them. It is seen that due to the implementation of EDFA in WDM system improved BER is achieved for the system which makes the system capable for long haul operation. A minimum BER of 1.84×10^{-127} and 2.54×10^{-68} are found at the distance of 40 Km of the system with and without EDFA respectively.



Fig. 10. Comparison of BER analysis of the system with or without EDFA.

4.2.2 Q-Factor Analysis

Another important key performance indicator in WDM system is Quality Factor analysis. Q Factor is given as (Sharma *et al.* 2013),

$$Q = \frac{I_1 - I_0}{\sigma_1 + \sigma_0} \tag{8}$$

Where, I₀ and I₁ are the average photocurrent generated by a 0 bit and 1 bit respectively. σ_0^2 and σ_1^2 are the noise variances for 0 bit and 1 bit respectively.



Fig. 11. Q-Factor analysis of the designed system by varying transmission distance up to 100 Km considering (a) with EDFA, (b) without EDFA

Figure 11 shows the Q Factor analysis of the designed system with and without EDFA by varying transmission distance up to 100 Km and Figure 12 illustrates the comparative analysis between them. Maximum Q Factor of 23.97 and 17.43 are found at the distance of 40 Km of the system with and without EDFA respectively.



Fig. 12. Comparison of BER analysis of the system with or without EDFA.

It is seen that due to the implementation of EDFA in WDM system, improved Bit Error Rate and Q Factor can be achieved for the system which makes the system capable for long haul operation. Based on the position, EDFA can be used as power amplifier or inline amplifier or pre-amplifier. In our designed system we have used EDFA as power amplifier to reduce the fiber linear losses. With a view to obtaining good Q Factor and Bit Error Rate it is recommended to use amplifier after each 100 Km. In table 3, we have showed the key results obtained from the simulation.

Distance	Minim	Minimum BER		Maximum Q-Factor	
(Km)	With EDFA	Without EDFA	With EDFA	Without EDFA	
40	$1.84 imes 10^{-127}$	$2.54 imes 10^{-68}$	23.97	17.43	
60	$1.08 imes 10^{-114}$	1.03×10^{-11}	22.72	6.70	
80	$4.51\times10^{\text{-}94}$	$9.18 imes 10^{-4}$	20.53	3.11	
100	$7.30\times10^{\text{-}74}$	1	18.13	0	

Table 3. Key results obtained from the performance analysis of the designed system

5 CONCLUSIONS

The main reason of the performance degradation in optical fiber communication system is nonlinear effects in fiber. Also EDFA adds noise caused by amplified spontaneous emission (ASE) that propagates along with the signal. EDFA amplifies the incoming signal by stimulated emission but spontaneous emission also takes place there. This emission adds noise in the signal. Combination of nonlinear effects and EDFA's ASE noise increase the BER at the receiver. Such of these should be studied further.

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