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Performance analysis of 16-channel WDM system using Erbium Doped Fiber Amplifier

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Abstract— ***In this paper, the effect of pump power of erbium doped fiber amplifier gain and output power has been investigated in terms of varying erbium doped fiber length and wavelength in sixteen channel wavelength divison multiplexing system and the performance has been evaluated in terms of gain, output power, erbium ion density, noise figure and bit error rate. The simulations results show that, at higher pump power the output power as well as amplifier gain are maximum but noise figure also get increased. Gain and noise figure are also investigated in terms of erbium ion density. It is observed that bit error rate decreases as the pump power increases.***

Index Terms—**Wavelength division mixing, erbium doped fiber amplifier, gain, noise figure, output power, bit error rate.**

I. INTRODUCTION

Wavelength Division Multiplexing (WDM) is the basic technology of optical networking. It is a technique in which a fiber is used to carry many separate and independent optical channels. WDM is basically a fiber optical transmission technique, which multiplexes many signals of different wavelength and optically amplified by optical amplifier like erbium doped fiber amplifier, is capable of providing data capacity in excess of hundreds of gigabit per second over thousands of kilometers in a single mode fiber. Each Communication channel is allocated a different wavelength and then these channels are multiplexed by multiplexer onto a single fiber. At destination, different wavelengths are demultiplexed by using a demultiplexer and are spatially separated to different receiver channels [6]. Erbium doped fiber amplifier is an optical amplifier that uses a doped optical fiber as a gain medium to amplify an optical signal. In case of EDFA, the signal which is to be amplified and a pump laser are coupled into the doped fiber and the signal is amplified through stimulated emission. EDFA is the best known and most frequently used optical amplifier suited to low loss optical window of silica based fiber. A particular attraction of EDFAs is their large gain bandwidth, which is typically tens of nanometers and thus actually it is more than enough to amplify data channels with the highest data rates without introducing any effects of gain narrowing. A single EDFA may be used for simultaneously amplifying many data channels at different wavelengths within the gain region.[7] For long distance communication, EDFAs with more pumping power and larger length are available these days. So more and more research is being done to use EDFAs in WDM systems in order to improve their performance. In order to get data with minimum error, optical amplifiers namely EDFA with proper gain adjustment are used. By doing this we can achieve the greater distance transmission of data in WDM systems. EDFA is a workhouse of modern DWDM optical transmission system but still there is a need of improvement in its gain and noise figure and many researchers have investigated this problem but further improvement of its performance can be achieved by increasing the pumping techniques. M. Pal *et.al* [2] investigated optical gain and noise figure for multi-channel amplification in EDFA under optimized pump condition. M. R. Gangwar *et. al* [3] discussed gain optimization of an erbium-doped fiber amplifier and two-stage gain-flattened EDFA with 45 nm flat bandwidth in the L-band. R. Deepa *et. al*[4] investigated the influence of bidirectional pumping in high-power EDFA on single-channel, multichannel and pulsed signal amplification and it was concluded that bidirectional pumping was best way of achieving high power amplification with a moderate noise level.M. Ismail *et. al* [5] investigated the effect of erbium doped fiber amplifier length and pump power on output power ,gain and noise figure of EDFA, here amplifier length was taken up to 22 m and pump power was up to 500 mW but in this paper we have extended the system setup for amplifier length up to 50 m and pump power up to 800 mW and also effect of erbium ion density on gain and noise figure is investigated. This paper is organized as shown: In the first section, the introduction of erbium doped fiber amplifier is presented. In the second section, the theoretical model is proposed. The third section describes the simulation setup for an optical communication system. In the fourth section, the comparison of performance of erbium doped fiber amplifier based is done in terms of output power, gain and noise figure by varying wavelength at different pump powers. The fifth section gives the conclusion of this paper

II. THEORETICAL MODEL

Erbium has several important properties that make it an excellent choice for an optical amplifier. Erbium ions (Er^{3+}) have quantum levels that allows them to be stimulated to emit in the 1540 nm band, which is the band that has the least power loss in most silica-based fiber. Erbium's quantum levels also allow it to be excited by a signal at either 980 nm or 1480 nm, both of which silica-based fiber can carry without great losses. Erbium-doped fiber amplifiers are the most important fiber amplifiers in the context of long range optical

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fiber communications; they can efficiently amplify light in the 1500 nm wavelength region, which coincides with the third transmission window of silica based optical fiber.[8] Consider a simple two-level model that is valid when ASE and excited-state absorption are negligible. The model assumes that the top level of three-level system remains nearly empty because of a rapid transfer of the pumped population to the excited state. The population densities of the two states, N_1 and N_2 , satisfy the following two rate equations:

$$\frac{\partial N_2}{\partial t} = (\sigma_p^a N_1 - \sigma_p^e N_2)\,\emptyset_p + (\sigma_s^a N_1 - \sigma_s^e N_2)\emptyset_s - N_2/T_1 \quad (1)$$

$$\frac{\partial N_1}{\partial t} = (\sigma_p^e N_2 - \sigma_p^a N_1)\emptyset_p + (\sigma_s^e N_2 - \sigma_s^a N_1)\emptyset_s + N_2/T_1 \quad (2)$$

Where σ_j^a and σ_j^e are the absorption and emission cross sections at the frequency ω_j with $j = p, s$. Further, T_1 is the spontaneous lifetime of the excited state (about 10 ms for EDFAs).the quantities $\emptyset_p$ and $\emptyset_s$ represent the photon flux for the pump signal waves. The pump and signal powers vary along the amplifier length because of absorption, stimulated emission and spontaneous emission. If the contribution of spontaneous is neglected, P_s and P_p satisfy the simple equations:

$$\frac{\partial P_s}{\partial_z} = \Gamma_s(\sigma_s^e N_2 - \sigma_s^a N_1)P_s - \alpha P_s \quad (3)$$

$$s\frac{\partial P_s}{\partial_z} = \Gamma_p(\sigma_p^e N_2 - \sigma_p^a N_2)P_p - \alpha' P_p \quad (4)$$

Where α and α' take into account fiber loses at the signal and pump wavelengths, respectively. These loses can be neglected for typical amplifier lengths 10-20 m. EDFAs are pumped by using CW lasers, but the signal is in the form of pulse train and duration of individual pulses is inversely related to the bit rate.[1]

III. SYSTEM SETUP

The system consists of 16 input signals (channels), an ideal multiplexer, two isolators, a pump laser, erbium doped fiber, demultiplexer, photo detector PIN, low pass Bessel filter, 3R regenerator and BER analyzer as shown in Figure 3. The input of the system is 16 wavelength multiplexed signals in the wavelength region (1546 nm-1558 nm) with 0.8 nm channels spacing. The power of each channel is –26 dBm. The pumping at 980 nm is used to excite the erbium doped fiber atoms to a higher energy level. Implementation of two isolators is to prevent Amplified Spontaneous Emission (ASE) and signals from propagating in backward direction. Otherwise, reflected ASE would reduce the population inversion, hence reducing the gain and increasing the noise figure. The desired gain is more than 40 dB and output power is more than 5 dBm but less than 30 dBm. The fiber length and pump power are selected as parameters to be investigated to achieve the desired gain under output power and gain flatness constraints. Bit error rate analyzer is used to get the bit error rate of signal. An optical power meter is placed to measure the output power. A dual port WDM analyzer is also placed to measure Gain and Noise Figure.

Table no. 1.Parameter values of system set up in fig. 1

Parameter	Values (units)
Pump Laser Frequency	980 (nm)
Power of each channel	-26 (dBm)
Modulation Type	NRZ
Fiber Length	50 (Km)
Bessel filter cutoff frequency	0.75*Bitrate (Hz)
Erbium core radius	2.2 (µm)
PIN photodiode responsibity	1 (A/W)
Dark current of photodiode	10 (nA)
Numerical aperture of EDF	0.24

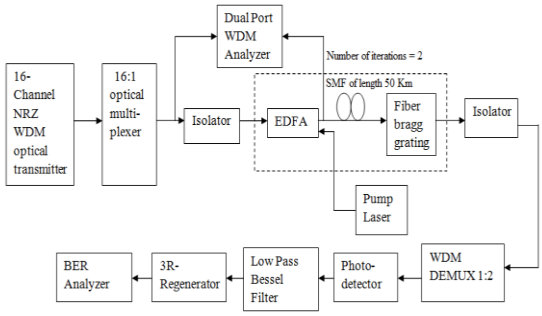

Fig. 1: 16 channel WDM optical system using EDFA optical amplifier

III. RESULT AND DISCUSSION

The system set up as shown in Fig. 3 has sixteen channels ranging from 1546 nm to 1558 nm wavelength of the transmitter when frequency spacing is 0.8. The length of erbium doped fiber is varied from 2 to 50 m. The output power is measured by varying the length of erbium doped fiber for pump power ranging 100-800 mW at a constant input power which is set at -26 dBm. Fig. 2 shows the effect of increasing pump power on the output power at varying length of erbium doped fiber amplifier. Output power increases as the pump power increases. By increasing pump power, the output power increases due to increase in power of transmitted signal. As the fiber length increases, the erbium ions will excite to higher level but after reaching at certain length, pump power is exhausted and the unexcited ions will cause decrease in output power. The maximum output power is attained at 10 m length of amplifier. So this is the length of erbium doped fiber amplifier where maximum output is achieved. After this length, optical output power starts decreasing as shown in graph. Due to excessive pump depletion in longer length, the output power decreases. Hence it is clear from observations that the output power of erbium doped fiber starts decreasing after attaining maximum value.

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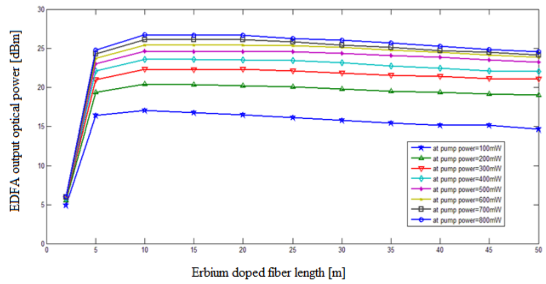

Fig. 2: Variation of EDFA output optical power with respect to EDF length at various values of pump power

Table no. 2: EDFA gain with different channel wavelength

Wavelength (nm)	Gain (dB) at Pump Power (mW)			
	100	200	300	400
1546	33.474	36.917	38.371	39.945
1548	33.167	36.736	38.607	39.876
1550	33.036	36.675	38.578	39.867
1552	33.092	36.860	38.828	40.157
1554	33.344	36.177	39.168	40.507
1556	32.786	35.788	38.829	39.990

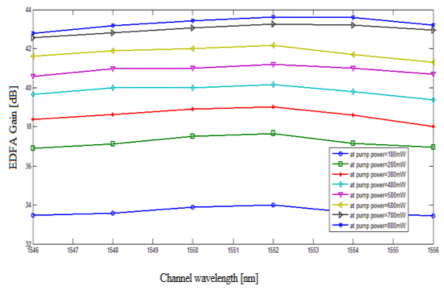

Fig. 3: Variation of amplifier gain with respect to channel wavelength at different values of pump power

Fig. 3 shows the graph between Gain and wavelength at various values of pump power. As the wavelength increases, the gain also increases but after reaching at the saturation point, it starts decreasing as shown in the above graph. Gain starts decreasing after a certain point because despite of increase in pump power, the population inversion decreases due to exhausted pump power. Due to excessive pump depletion, the gain obtained from an amplifier begins to decrease after a maximum level. Gain saturation is defined as - the signal level decreases, the amplifier saturates and cannot produce any more output power and therefore the gain reduces.

Table no. 3: EDFA noise figure with channel wavelength at various pump powers

Wavelength (nm)	NF (dB) at Pump Power (mW)			
	100	200	300	400
1546	12.806	10.768	10.030	9.630
1548	12.314	10.350	9.646	9.269
1550	11.749	9.883	9.224	8.875
1552	11.099	9.355	8.875	8.430
1554	10.543	8.960	8.425	8.145
1556	9.884	8.482	8.019	7.797

Fig. 4 shows the NF variation of each channel for different pump powers at a constant input power of -26 dBm. ASE noise generated during amplification process is added to the signal. When the wavelength increases, this ASE noise get reduced due to reduction in backward propagation of erbium doped ions into EDFA. this reduction in ASE leads to increase in signal to noise ratio (SNR) at the amplifier output and hence the noise figure decreases. We get minimum amplifier noise figure (8dB) at 1554 nm wavelength when the pump power is 800 mW.

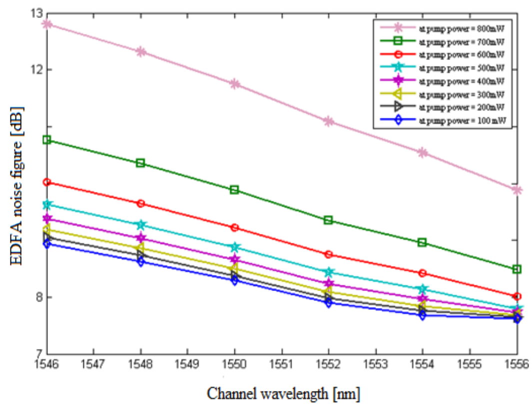

Fig. 4: Variation of amplifier noise figure with respect to channel wavelength at different values of pump power

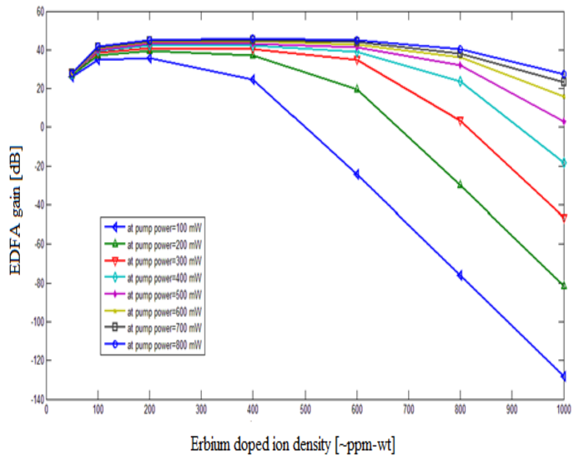

Fig. 5: Variation of amplifier gain with respect to erbium ion density at different values pump power

The amplifier gain variation as a function of Erbium Ion Density is shown in Fig. 5 for varying pump power from 100 to 800 mW. It can be seen that for sufficiently large pump power, gain linearly increases with increasing erbium ion density and remains constant after a certain level then decreases. This is because once the amplifier reaches the maximum population inversion, after that the gain is decreases due to exhausted ions. The gain reduces sharply in highly doped fiber due to insufficient ions. It is found from our observations that the EDFA gain increases upto 400 (~ppm-wt) erbium ion density and after that it starts decreasing. Hence erbium ion density up to 400 (~ppm-wt) is best suitable.

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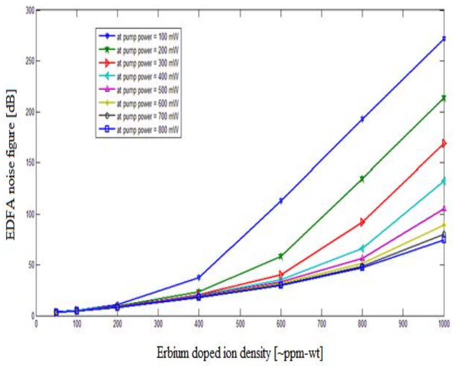

Fig. 6: Variation of EDFA noise figure with respect to erbium ion density at different values pump power

In figure 6 the variation of noise figure is given as a function of Erbium Ion Density for a constant fiber length and signal input power for different values of pump power. It is seen that the noise figure remains constant nearly (3 dB) in a certain value of erbium ion density even if the pumping power is increased. Beyond 120 ppm, insufficient pumping occurs and the noise figure sharply increases. So after 120 ppm, the noise figure continues to increase due to insufficient population inversion. It is found that the noise figure remains low in range of 100 to 500 (~ppm-wt) erbium ion density and after this range increases sharply. So erbium ion density range from 100-500 (~ppm-wt) is more reliable range. Figure 7 shows that the variation in BER with respect to channel wavelength at different pump powers. BER at first increases as the wavelength increases and after reaching the maximum value, it starts to decrease. Bit error rate is less at more pump power. The value of bit error rate is minimum at 1546 nm wavelength and maximum at 1552 nm. Bit error Rate increases due to inter-symbol interference as the wavelength increases. Bit error rate depends on decision threshold and this decision threshold influences the Q-factor. Due to addition of shot and thermal noises, Q-factor decreases and hence bit error rate decreases because bit error rate is inversely proportional to Q-factor.

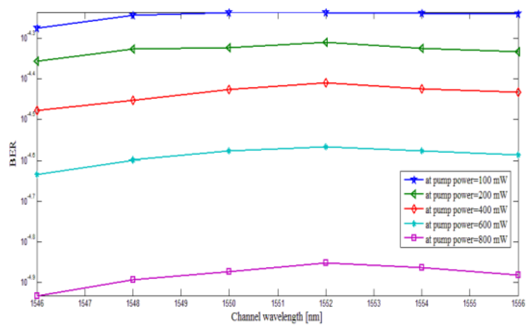

Fig. 7: Variation of bit error rate with respect to channel wavelength at different pump powers

IV. CONCLUSION

In this paper the effect of the erbium doped fiber length, pump power and erbium doped ion density on EDFA output power, amplifier gain and noise figure has been investigated in sixteen channel WDM system by varying values of pump power. The comparison of various pump powers shows that as the pump power increases, the output power as well as gain of EDFA increases. At 800mW pump power the output power is 26 dBm but at 100 mW pump power reduces by 11 dBm. Also at pump power 800 mW the Gain of EDFA is about 44 dB which is very high but at the same time noise figure is high for this pump power. So the best value of pump power is 500 mW where high gain and low noise figure are achieved.. The effect of erbium ion density on gain of EDFA is also investigated. As ion density increases, the gain at first increases than starts to decrease due to unexcited ions. The suitable value of erbium doped ions is 500 (~ppm-wt) where gain is high and noise figure is low It is also observed from simulations that the BER increases as the pump power increases. Hence, it is concluded that higher pump power is best suitable to be employed in practical communication systems for obtaining maximum output power and lower noise figure of EDFA within WDM systems.

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