

## Analysis of Numerical Aperture Dependence in L-Band 16-Channel WDM Optical Communication System

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### Abstract

In this paper, the erbium doped fiber amplifier gain has been investigated in terms of varying numerical aperture, erbium doped fiber radius and pump power in sixteen channel wavelength division multiplexing system and the performance has been evaluated in terms of amplifier gain, noise figure and bit error rate. The simulation results show that erbium doped fiber amplifier gain is more at lower numerical aperture (i.e. up to 0.3) and at erbium doped fiber radius (3  $\mu\text{m}$ ) the maximum gain (i.e. 31 dB) is obtained for pump power 200 mW.

**Keywords** – Wavelength division mixing, erbium doped fiber amplifier, gain, numerical aperture, 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 [1].

Erbium doped fiber amplifier is an optical amplifier that uses a erbium doped optical fiber as a gain medium to amplify an optical signal. 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[6]. A single EDFA may be used for simultaneously amplifying many data channels at different wavelengths within the gain region[1].

For long distance communication, EDFAs with more pumping power and larger length are

available these days. Further 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 using advanced pumping techniques.

Y. Jin *et. al.* [3] proposed a dual stage L-band gain-clamped erbium doped fiber amplifier (GC-EDFA) by using backward C-band amplified spontaneous emission having higher and flatter clamped gain. M. Pal *et. al.* [4] investigated the gain and noise figure for multi-channel amplification in EDFA under optimized pump condition and observed bi-directional pumping manifests the best combination of low noise and high gain of EDFA. M. M. Ismail *et. al.* [5] discussed simulation of WDM optical network in terms of length and pump power and found gain flattened from 1546 nm to 1558 nm band of wavelength with noise figure less than 9 dB for 16-channels simultaneous amplification in a single stage EDFA. P. M. Aljaff *et. al.* [2] investigated the effect of increase in numerical aperture and erbium doped fiber radius on amplifier gain and noise figure at various pump powers (10 -50 mW) in C-band (1550 nm) in single optical channel but in this paper we have extended the setup for sixteen channels in L-band (1570-1610 nm) and also pump power is increased up to 200 mW. 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 is done in terms of amplifier gain, noise figure and BER by varying numerical aperture and erbium doped fiber radius 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 ( $\text{Er}^{3+}$ ) 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 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[1].

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:

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

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

Where  $\sigma_j^a$  and  $\sigma_j^e$  are the absorption and emission cross sections at the frequency  $\omega_j$  with  $j = p, s$ . Further,  $T_1$  is the spontaneous lifetime of the excited state (about 10 ms for EDFAs). The quantities  $\phi_p$  and  $\phi_s$  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:

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

$$s \frac{\partial P_p}{\partial z} = \Gamma_p (\sigma_p^e N_2 - \sigma_p^a N_1) P_p - \alpha' P_p \quad (4)$$

Where  $\alpha$  and  $\alpha'$  take into account fiber losses at the signal and pump wavelengths, respectively. These losses 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].

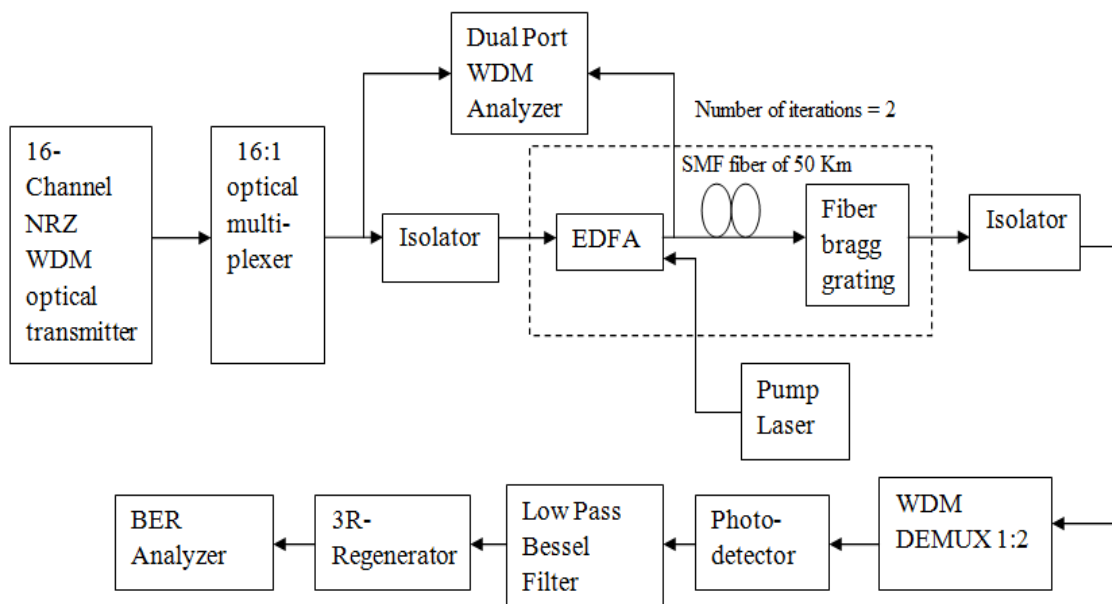
## III. SYSTEM SETUP

The system consists of 16 input signals (channels), an ideal multiplexer, two isolators, a pump laser, erbium doped fiber, fiber bragg grating, demultiplexer, photo detector PIN, low pass Bessel filter, 3R regenerator and BER analyzer as shown in Figure 1. There are sixteen wavelength division multiplexed signals in wavelength region 1570-1610 nm (i.e. L-band) having 2.5 nm channel spacing. The power of each channel is -30 dBm. The pumping at 980 nm is used to excite the erbium doped fiber atoms to a higher energy level. Implementation of two isolators are 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 nearly 20 dB and noise figure is less than 10 dB. The fiber length and wavelength are selected as parameters to be investigated to achieve the desired flat gain at varying temperature. Bit error rate analyzer is used to get the bit error rate of signal. A dual port WDM analyzer is also placed to measure Gain and Noise Figure. Typical parameter values of the simulation set up are as shown in Table 1.

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

| Parameter                        | Values (units)        |
|----------------------------------|-----------------------|
| Pump Laser Frequency             | 1480 (nm)             |
| Pump power                       | 200 (mW)              |
| Modulation Type                  | NRZ                   |
| Fiber Length                     | 50 (Km)               |
| Bessel filter cutoff frequency   | 0.75*Bit rate (Hz)    |
| Erbium core radius               | 2.2 ( $\mu\text{m}$ ) |
| PIN photo-detector responsivity  | 1 (A/W)               |
| Dark current of photo-detector   | 10 (nA)               |
| Bandwidth of fiber bragg grating | 150 (GHz)             |
| Frequency of fiber bragg grating | 193.1 (THz)           |
| Frequency of WDM transmitter     | 1570-1610 (nm)        |
| Frequency spacing                | 2.5 (nm)              |



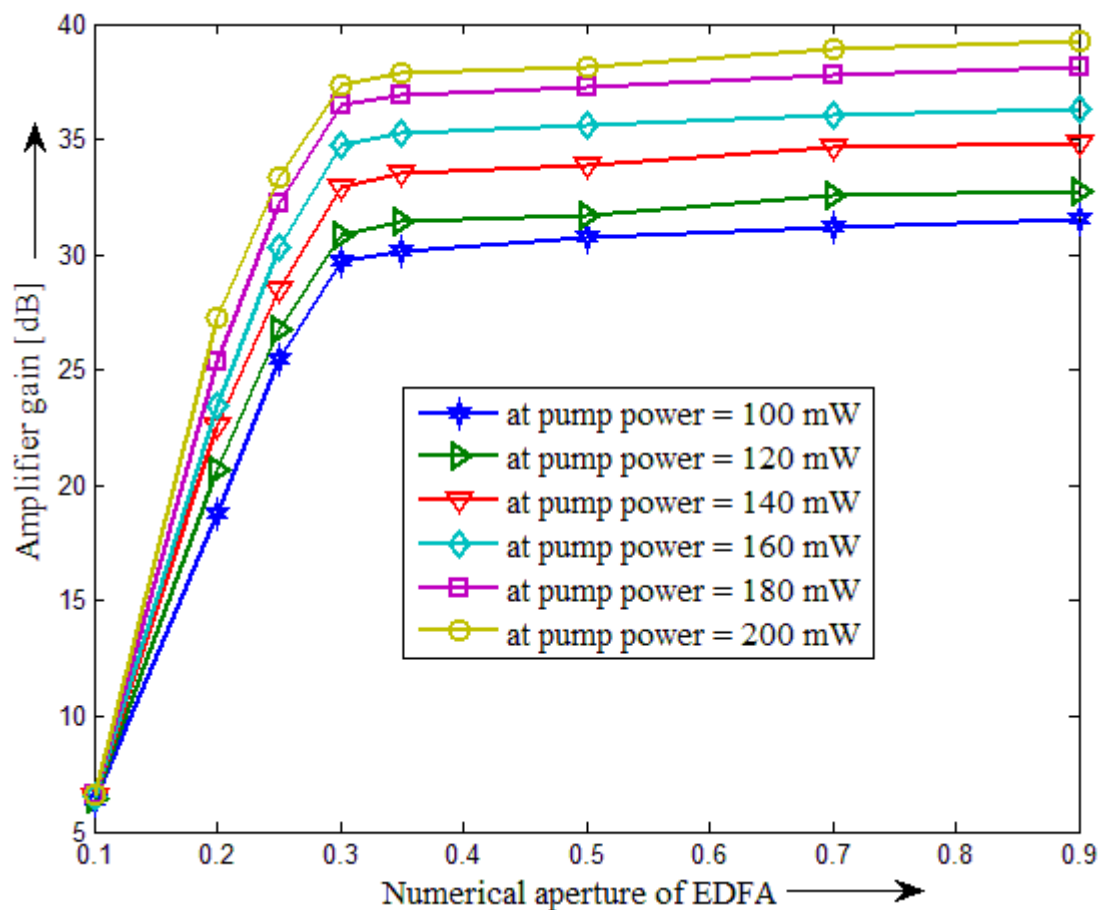
**Fig. 1: 16 channel WDM optical communication system using EDFA**

#### IV. Results and Discussion

The graphs showing amplifier gain, noise figure and BER variations with respect to numerical aperture and erbium doped fiber radius at different values of pump powers are given below:

Fig. 2 shows the amplifier gain as function of numerical aperture of erbium doped fiber amplifier. It is seen from observations that the amplifier gain increases with the increasing numerical aperture of erbium doped fiber amplifier and remains constant (saturate) after reaching at certain level for each pump power. The reason behind

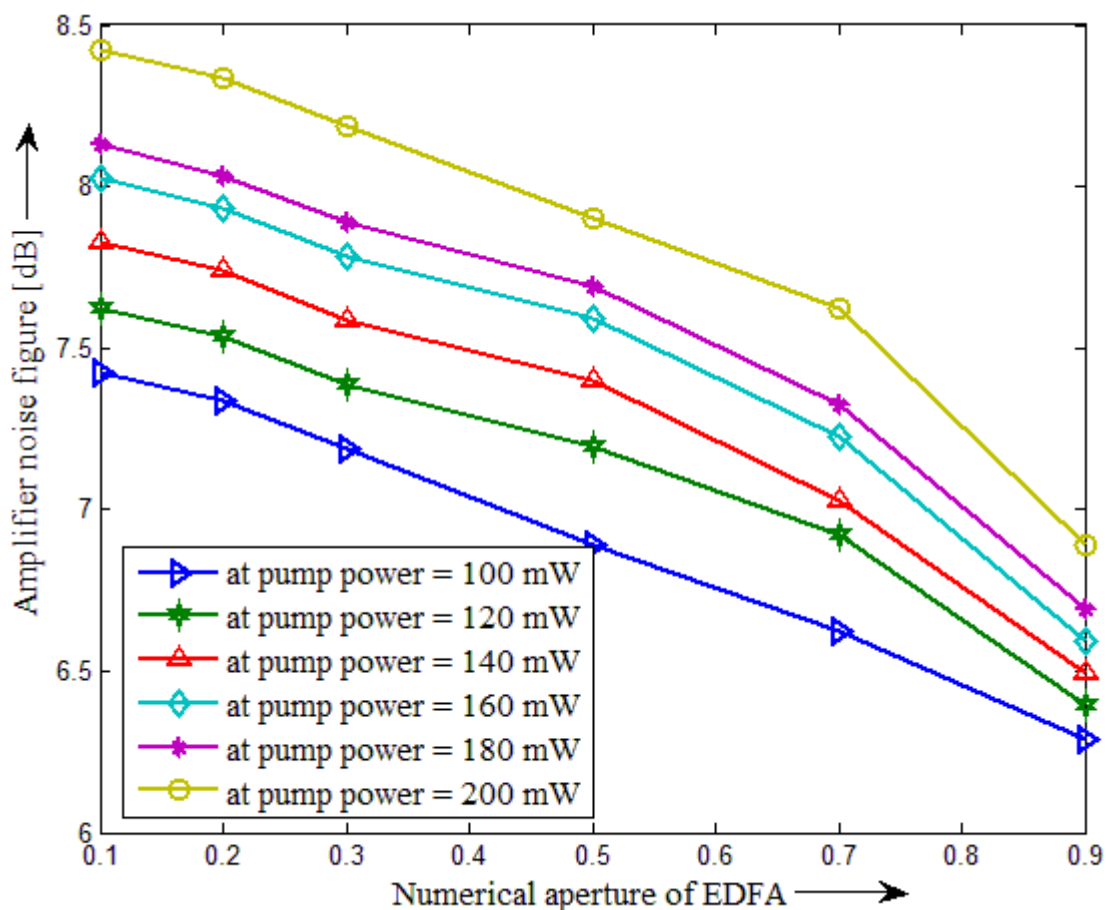
this is that at this stage the amplifier reaches at maximum level of population inversion. It is clear that the amplifier gain increases when numerical aperture proves the overlap between optical mode field and erbium ions. Therefore it is proved that by increasing pump power the required numerical aperture to obtain maximum gain becomes less. Therefore 0.3-0.4 numerical aperture is the best suitable range for best performance of erbium doped fiber amplifier to get maximum amplifier gain.



**Fig. 2: Variation in amplifier gain with respect to numerical aperture of erbium doped fiber amplifier at various pump powers**

Fig. 3 shows the amplifier noise figure variation of sixteen channel optical communication system for different pump powers with respect to the numerical aperture of erbium doped fiber amplifier. The input power is kept constant at -30 dBm. It is clear from figure as the numerical aperture of erbium doped fiber amplifier increases the amplifier noise figure decreases. This happens due to the reason that ASE noise generated during amplification process is added to the signal. When the numerical aperture of

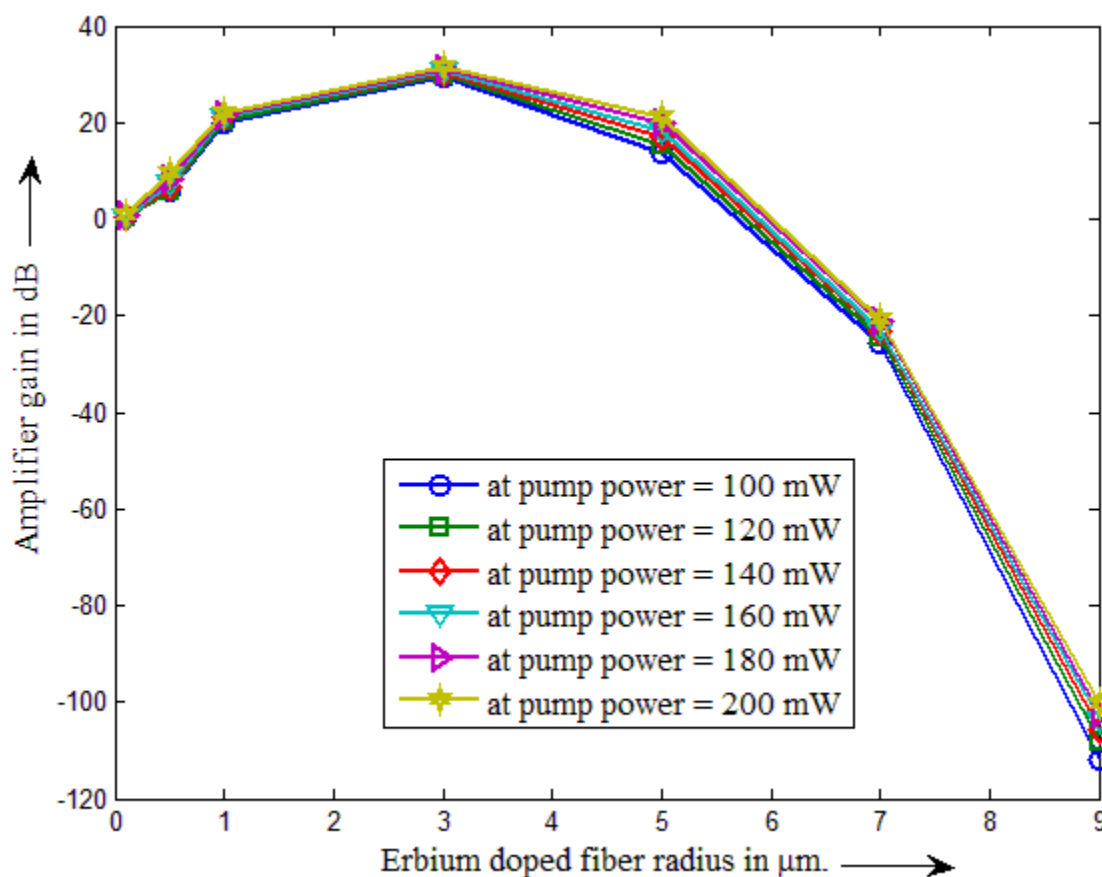
erbium doped fiber amplifier increases, this ASE noise get reduced due to reduction in backward propagation of erbium doped ions into erbium doped fiber amplifier and this reduction in ASE leads to increase in signal to noise ratio at amplifier output and hence the noise figure reduces. We have observed the minimum amplifier noise figure (6.2 dB) at 0.9 numerical aperture when the pump power is 100 mW.



**Fig. 3: Variation in amplifier noise figure with respect to numerical aperture of erbium doped fiber amplifier at various pump powers**

Fig. 4 shows the amplifier gain as function of erbium doped fiber radius. The erbium ion density is kept 1000 ppm-wt. The amplifier gain increases as doping radius decreases, because the signal light does not suffer from additional absorption. That means the erbium ions does not exist in the area where the pump power is small. It is shown that concentrating

the erbium doping near the fiber axis results at low pump power, improvement in the maximum amplifier gain. The maximum amplifier gain (31.5 dB) is obtained at 3 μm erbium doped fiber radius when the pump power is 200 mW. Therefore it is clear that up to 3 μm erbium doped fiber radius is suitable range of erbium doped fiber radius.

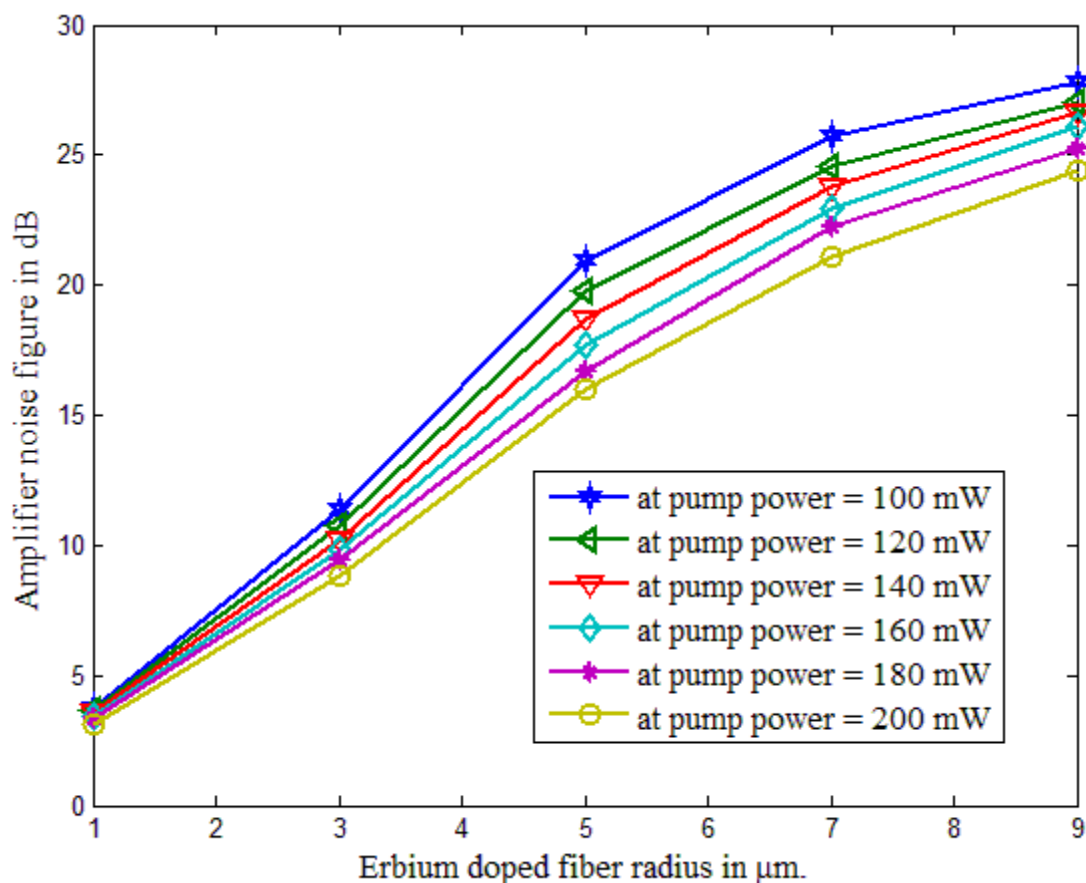


**Fig. 4: Variation in amplifier gain with respect to erbium doped fiber radius at various pump powers**

Fig. 5 shows the variation in amplifier noise figure with respect to erbium doped fiber radius. It is found from the observations that as the erbium doped fiber radius increases, the amplifier noise figure also increases. This happens due to the reason that there is overlap between the mode field intensity at the pump and signal wavelengths and hence pump efficiency decreases with increasing erbium doped fiber radius as the field intensity at both the pump

and signal wavelengths decreases with erbium doped fiber radius. Where pump efficiency is the ratio between gain in decibels and launched pump power in milliwatts. The minimum amplifier noise figure is obtained up to 3 μm erbium doped fiber radius is 3.1 dB when pump power is 200 mW.

Therefore it can be concluded that from 1 μm-3 μm is the best suitable range of erbium doped fiber radius.



**Fig. 5: Variation in amplifier noise figure with respect to erbium doped fiber radius at various pump powers**

Fig. 6 shows the variations in BER with respect to numerical aperture of erbium doped fiber amplifier. It is observed from the figure that bit error rate of erbium doped fiber amplifier decreases as the numerical aperture of erbium doped fiber amplifier increases. This happens due to the reason that ASE noise generated in an erbium doped fiber amplifier gets reduced, so it will not degrade the signal to noise ratio as much at the optoelectronic receiver thus decreasing the bit error rate of the communication

system. The bit error rate of erbium doped fiber amplifier is minimum at 0.9 value of numerical aperture with value  $1.00057 \times 10^{-10}$  at 200 mW pump power. But at lower values of numerical aperture i.e. up to 0.3, bit error rate also remains low ( $1.263111 \times 10^{-9}$ ). Therefore we can conclude that from 0.1 to 0.3 numerical aperture is the best suitable for erbium doped fiber amplifier.

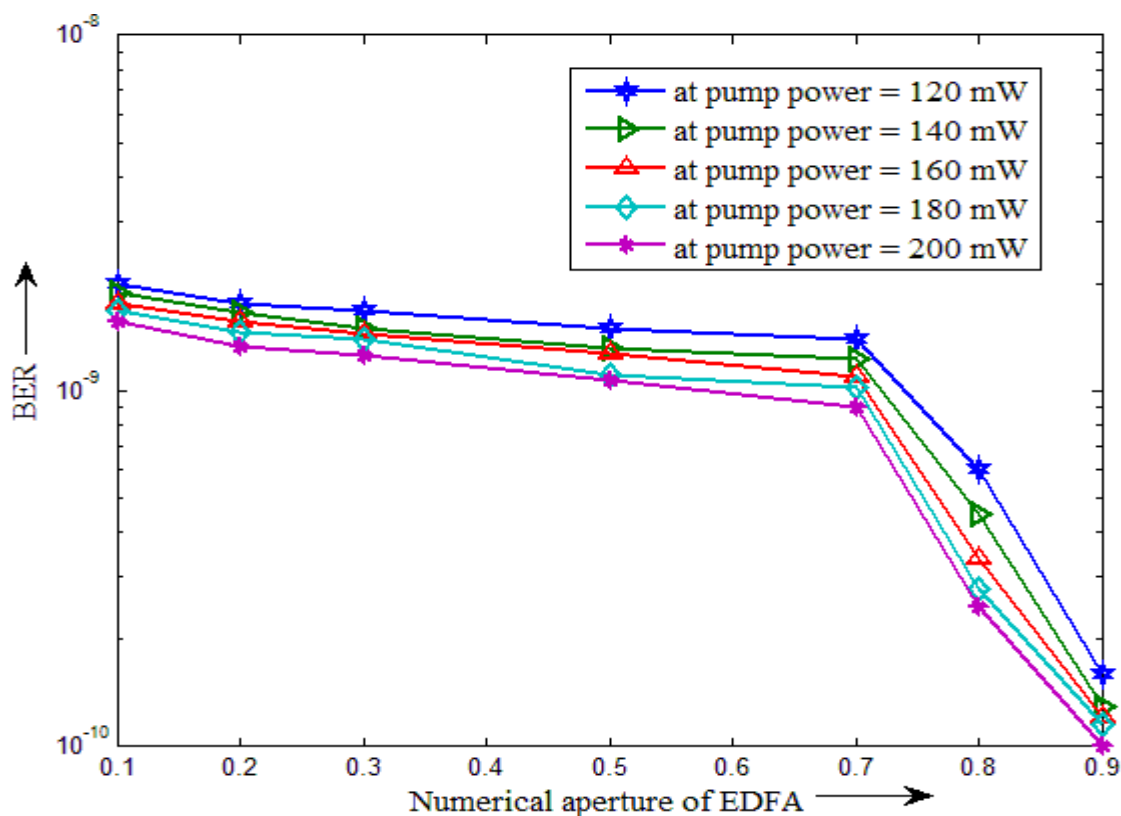


Fig. 6: Variation in BER with respect to numerical aperture of erbium doped fiber amplifier at various pump powers

### V. Conclusion

In this paper the effect of the erbium doped fiber radius and numerical aperture on amplifier gain, amplifier noise figure and bit error rate 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, amplifier gain of EDFA increases and bit error rate decreases. The maximum amplifier gain (31.5 dB) is obtained at 4 μm erbium doped fiber radius and also maximum amplifier gain is obtained at 0.3 numerical aperture. Therefore it is concluded that the maximum amplifier gain is obtained when erbium doping radius is less. The optimum erbium doped fiber radius 3.06 μm.

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