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Performance analysis of Erbium Doped Fiber Amplifier at different pumping configurations

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Abstract-The fiber amplifier is emerging as a major enabler in the development of worldwide fiber optics networks for high speed communication.Optical fiber is confined with different rare earth doped materials. One of those, are Erbium doped fiber amplifiers (EDFA) which are modeled using two level or three level rate equations. The performance parameters like Gain, Output power and BER are studied which depend on various parameters like Er3+ concentration, fiber length, pump and signal wavelength, pump and signal power etc. Amplifier performance is evaluated using simulation on MATLAB platform. By selecting suitable design parameters desired characteristics of amplifier can be obtained for the particular application.

Keywords- *EDFA, rate equations, pump power, signal power, gain characteristics,BER.*

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I. INTRODUCTION

Optical Fiber amplifier is key enabling technology for high speed optical communication.Generally, EDFA is suitable to operate in C-band from about 1530nm-1565nm.This amplifier enables simultaneous amplification of multiple wavelengths over 1.5µm wavelength region; these are interesting because they provide long haul communication over fiber networks. These optical amplifier is developed after the pioneering work on fiber laser and research on rare earth doped fiber[ ].The different types of rare earth doped material are Erbium(Er^{3+}),Ytterbium(Yb^{3+}),Thulium(Th^{3+}), Neodymium(Nd^{3+})etc. The erbium ions are mostly used because silica fibers with erbium ions can operate in the broad range with 1.5µm window [5] at which the attenuation is minimum and therefore ideal for optical fiber network communication.

The optical fiber amplifier allowed the signal amplification in optical domain, there is no need to convert the optical signal into electrical signal. Er3+ ions have the optical fluorescent properties that they are suitable for optical amplification. EDFA enables the optical signal to be amplified directly in the high bit rate systems.A major concern with using wavelength division multiplexed (WDM) systems is the non-uniform gain over the 1550nm window.Different wavelength signals experience different gain and therefore different signal to noise ratio. So it is important to compensate for this non-uniform gain spectrum over the 1.5µm window[7].

II. STRUCTURE OF EDFA

Basically the EDFA consists of optical coupler to combine the pump and signal light injected into the active optical fiber, pumping lasers, unidirectional optical isolators, polarization couplers to combine pump sources and optical band pass filters to reduce out of band noise. The pumping schemes are required to determine the gain and output power characteristics of amplifier[6]. The EDFA pumping is possible using operating range 980nm or 1480nm wavelength and with different configuration: forward, backward or bi-directional.

In the EDFA system, thepump light is transmit into the EDF by the use of wavelength division multiplexing, which is used to couple the pump signal into the doped fiber. The isolator is used at output of amplifier to prevent back reflection which can reduce the performance of amplifier which is shown in Fig.(1) Basic Structure of EDFA.

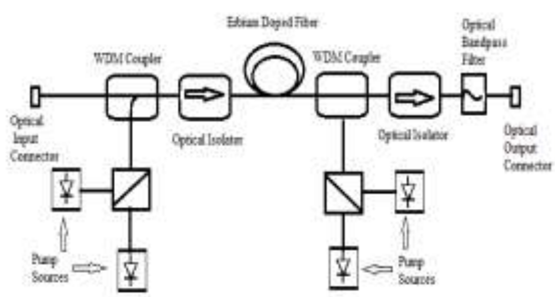

Fig.(1) Basic Structure of EDFA

III. PROBLEM FORMULATION

The simplest treatment of the erbium doped fiber amplifier is three level atomic system shown in Fig.(2). We consider a three level system with ground state denoted by1, an intermediate state denoted by 3 and metastable state denoted by 2, it has a long lifetime in the case of a good amplifier. This three level system is intended to represent that part of energy level structure of Er3+ that is relevant to the amplification process. To obtain amplification, we need a population inversion between state 1 and state 2, and since 1 is ground state, at least half of total population of erbium ions needs to be excited to level 2 to have population inversion. This increases the threshold pump power needed for amplification and is a known drawback of three level amplifier systems. In certain pumping configuration level 3 can be identical to level 2 in the sense that the upper pump level and upper amplification level belong to same multiplet, this is called two level systems shown in Fig.(2) Three level and Two level system of Amplifier for all practical purpose system[3].

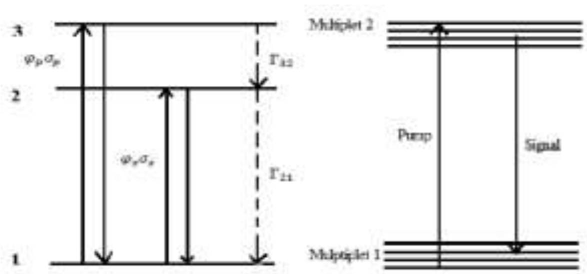

Fig.(2) Three level and Two level system of Amplifier

A. RATE EQUATIONS

The rate equations for population change are written as,

$$\frac{dN_3}{dt} = -\Gamma_{32}N_3 + (N_1 - N_3)\varphi_p\sigma_p \quad \ldots (1)$$

$$\frac{dN_2}{dt} = -\Gamma_{21}N_2 + \Gamma_{32}N_3 - (N_2 - N_1)\varphi_s\sigma_s \ldots (2)$$

$$\frac{dN_1}{dt} = \Gamma_{21}N_2 - (N_1 - N_3)\varphi_p\sigma_p + (N_2 - N_1)\varphi_s\sigma_s \quad \ldots (3)$$

In the steady state situation the time derivatives will be zero,

$$\frac{dN_1}{dt} = \frac{dN_2}{dt} = \frac{dN_3}{dt} = 0 \quad \ldots (4)$$

And the total population N is given by,

$$N = N_1 + N_2 + N_3 \quad \ldots (5)$$

We can write the population of level 3 as,

$$N_3 = \frac{1}{1 + \Gamma_{32}/\varphi_p\sigma_p}N_1 \quad \ldots (6)$$

When Γ_{32} is large (fast decay from level 3 to level 2) compared to the effective pump rate into level 3 $\varphi_p\sigma_p$, N_3 is very close to zero, so that the population is mostly in levels 1 and 2.

$$N_2 = \frac{(\varphi_p\sigma_p/\Gamma_{32}) + \varphi_s\sigma_s}{\Gamma_{21} + \varphi_s\sigma_s} \quad \ldots (7)$$

$$N_2 - N_1 = \frac{\varphi_p\sigma_p - \Gamma_{21}}{\Gamma_{21} + 2\varphi_s\sigma_s + \varphi_p\sigma_p} \quad \ldots (8)$$

The condition for population inversion and thus for gain on the 2 to 1 transition is that $N_2 \geq N_1$. The threshold correspond to $N_1 = N_2$ andresults in following expression for the pump flus required,

$$\varphi_{th} = \frac{\Gamma_{21}}{\sigma_p} = \frac{1}{\tau_2\sigma_p} \quad \ldots (9)$$

The condition for low pump threshold are thus easily summarized as,

(a) High absorption cross section

(b) Long lifetime of metastable level

We know consider that N, N_1, N_2, N_3 are density of populations. Two lights fields through the medium, interacting with the ions and have intensity I_s (Signal field) and I_p (pump field). The photon fluxes are given by,

$$\varphi_s = \frac{I_s}{h\nu_s} , \qquad \varphi_p = \frac{I_p}{h\nu_p} \quad \ldots (10)$$

In the one dimensional case, the length field intensities are derived from light field powers by the simplified relationship,

$$I(z) = \frac{P(z)\Gamma}{A_{eff}} \quad \ldots (11)$$

Where, Γ is the overlap factor representing the overlap between the erbium ions and the mode of light field and A_{eff} is the effective cross-sectional area of distribution of erbium ions.

The fields will be attenuated or amplified after an infinitesimal length dz by combined effects of absorption arising from ions in their ground state N_1 and stimulated emission from ions in excited state N_2 and N_3.

$$\frac{d\varphi_s}{dz} = (N_2 - N_1)\varphi_s\sigma_s \quad \dots(12)$$

$$\frac{d\varphi_p}{dz} = (N_3 - N_1)\varphi_p\sigma_p \quad \dots(13)$$

This leads,

$$\frac{dI_s}{dz} = \frac{\left(\frac{\varphi_p\sigma_p}{h\nu_p}\right) - \Gamma_{21}}{\Gamma_{21} + 2\frac{\sigma_s I_s}{h\nu_s} + \frac{\sigma_p I_p}{h\nu_p}}\sigma_s I_s N \quad \dots(14)$$

We can write equation for attenuation of the pump intensity as,

$$\frac{dI_p}{dz} = -\frac{\Gamma_{21} + \left(\frac{\varphi_s\sigma_s}{h\nu_s}\right)}{\Gamma_{21} + 2\frac{\sigma_s I_s}{h\nu_s} + \frac{\sigma_p I_p}{h\nu_p}}\sigma_p I_p N \quad \dots(15)$$

The gain in dB of the signal after a length L of fiber is defined as,

$$G = 10\log\frac{I_s(z = L)}{I_s(z = 0)} \quad \dots(16)$$

For a given pump power to obtain the maximum amount of gain for given erbium concentration in the fiber core, the fiber length should be increased to that point at which the pump power becomes equal to the intrinsic pump threshold.

B. BIT ERROR RATE (BER)

BER is a best measurement of the system performance, because it quantifies the probability in which an error is made in the decision system. BER typically depends on the Signal to Noise Ratio(SNR) of the signal received[9]. Mathematically it is expressed as,

$$BER = p(1)P\left(\frac{0}{1}\right) + p(0)P\left(\frac{1}{0}\right) \quad \dots(17)$$

The equation for BER as follows,

$$BER = \frac{1}{2}erfc\left(\frac{Q}{\sqrt{2}}\right) \approx \frac{exp\left(-\frac{Q^2}{2}\right)}{Q\sqrt{2\pi}} \quad \dots(18)$$

Where, $Q = \frac{I_1 - I_0}{\sigma_1 + \sigma_0}$,$I_1$ and I_0 are average photo currents generated by bit 1 and bit 0 respectively; and σ_1^2 and σ_0^2 are the noise variance for bit 1 and bit 0 respectively[3].

IV. SIMULATION AND RESULTS

An EDFA model based on work by Giles is used to find the amplifier performance at high bit rate. The simulation setup consist of the continuous wave laser, pump laser, polarization coupler, erbium doped fiber, optical isolator, optical band-pass filter. This paper focus on the performance characteristics of amplifier like gain, output power and BER . The gain and output power can be obtained for forward pumping configuring as function of fundamental parameters namely; fiber length, pump power and signal power etc. The fundamental parameters of the simulation are shown in Table (A).

Table (A).Fundamental parameters of simulation

Parameters	Value	Unit
Diameter of core	5.5	µm
Length of fiber	5, 10, 15	m
Pumping power	40,60,80,100	mW
Signal power	1	mW
Pump wavelength	1530	nm
Signal wavelength	980, 1480	nm
Er^{3+} ion density	$1.6\times 10^{+24}$, $10\times 10^{+24}$	$/m^3$
Fiber absorption Parameter	2.5	dB/m
Pump Direction	Forward	

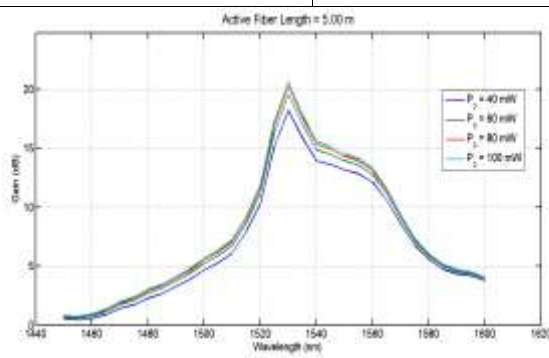

Fig.(3) Gain vs Wavelength when the length of fiber is 5m and the pump power is respectively, 40,60,80,100mW at 980nm pump wavelength.

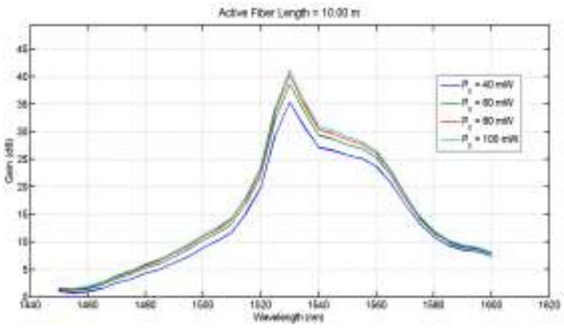

Fig.(4) Gain vs Wavelength when the length of fiber is 10m and the pump power is respectively, 40,60,80,100mW at 980nm pump wavelength.

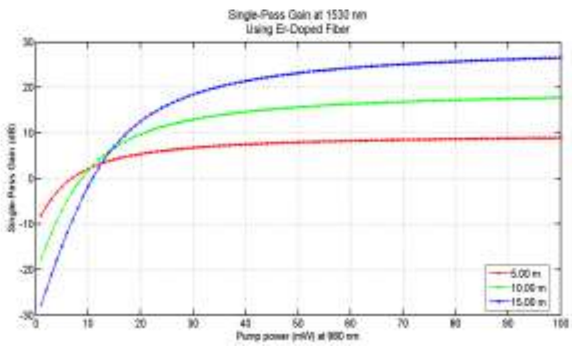

Fig.(5) Single-pass Gain vs Pump power with length 5,10,15m of fiber at 980nm pump wavelength.

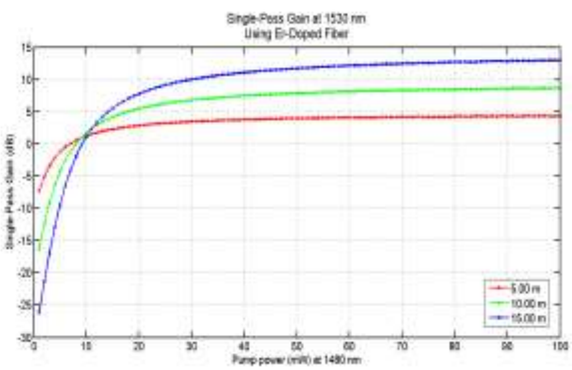

Fig.(6) Single-pass Gain vs Pump power with length 5,10,15m of fiber at 1480nm pump wavelength.

The gain characteristics of EDFA at forward pumping configuration are varied along with the length is shown in Fig.(3)&Fig.(4) having constant radius, signal power,Er^{3+}doping density. By the comparing the graph, we can give conclusion that whenwe increased the length of fiber and the pump power, the gain also increased. At different length of fiber, the single pass gain characteristics gave the flatness response with increasing pump power shown in Fig.(5)&Fig.(6).

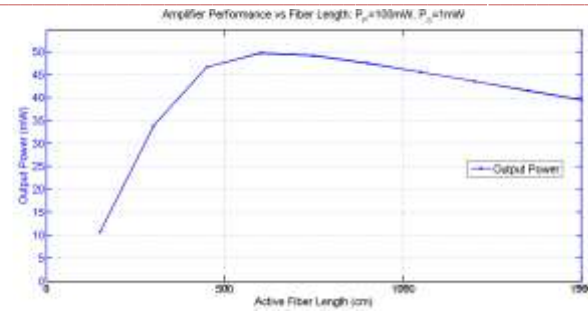

Fig.(7) Output power vs Fiber length with length 5m,10m,and 15m respectively at 980nm pump wavelength.

The output power characteristic of EDFA is varied with the length of fiber shown in Fig.(7) with high Er^{3+} doping density. The output power decreases along the length of fiber at constant pump and signal power. At 1530 nm signals, 1480nm provides higher output power compared to 980nm shown in Fig.(8) and Fig.(9).

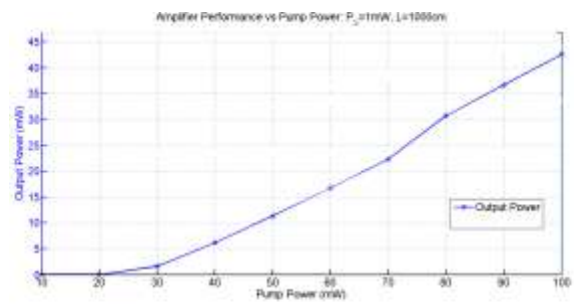

Fig.(8) Output power vs Pump power with 10m fiber length at 980nm pump wavelength

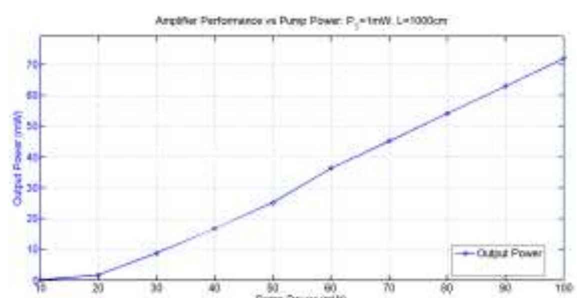

Fig.(9)Output power vs Pump power with 10m fiber length at 1480nm pump wavelength

The BER vs SNR is shown in Fig.(10), where the on-off signaling using root-raised cosine pulse is used. The SNR represent the power level of 1 bit (as opposed to an average power level of 1bits and 0 bits).

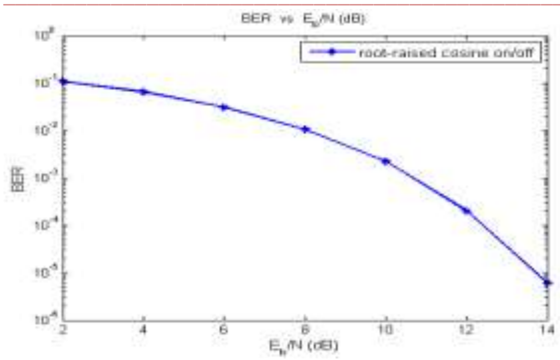

Fig.(10) BER vs SNR

V. CONCLUSION

The discussion presented in this article is based on the simulation analysis of EDFA for its suitability as an optical amplifier. This article shows the relationship between the pump power, signal power, gain and output power at 980nm and 1480nm pump wavelength. By selecting suitable design parameters desired characteristics of amplifier can be obtained for the particular application.

According to results the too short length gives the lowest gain, but gives the highest output power at fixed pump wavelength. Whereas, the long length of fiber gives high gain but decreases the output power with fiber length increase. So we found that, at 5m, 10m, 15m length of fiber, the optimum length is 10m as at 10m length of fiber the gain response and output power response is maximum. In this study, we found that the gain is maximum at 980nm pump wavelength whereas, the maximum response of output power at 1480nm than 980nm pump wavelength with fixed length of fiber. So 1480nm is the preferred pump choice for power amplifier, when the high output power is desired.

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