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Theoretical Analysis of Triple-pass Erbium-doped Fiber Amplifier

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***Abstract*— Many configurations of EDFA producing triple pass EDFAs have been used, however, only two configurations are commonly used in the optical fiber communication system due to their high performance. Those two configurations are configured in a double stage EDFA. The first configuration is (configuration A) consists of a single-pass EDFA as the first stage and a double-pass EDFA as the second stage. The second configuration is (Configuration B) which consists of a double-pass EDFA as the first stage and a single-pass EDFA as the second stage. The Literature shows the use of triple pass EDFA is either with configuration A or configuration B and literature also shows there is no theoretical analysis and comparison between the performance of two Triple-pass EDFA configurations A and B. This paper focus on the performance analysis of both configurations A and B. The importantance of this research is the theoretical analyses that analyze the performance of those two configurations and illustrate a comparison between them. This comparison is important to show which of the two configurations is more reliable in amplifying optical signal for the fiber optic communication systems.**

Keywords-component; Triple-Pass EDFA, double pass EDFA, NF, ASE, Gain.

1- Introduction

The objective of any communication system is the transfer of information from one point to another. Fiber optic communication system is one of the most common use and important communication systems related to the high bandwidth transmission [1]. It is a way of transmitting information from one place to another by sending pulses of light through an optical fiber. One of the most important devices in the optical fiber link is the Optical Amplifier. Since the transmission distance of the optical fiber communication system is limited by the signal attenuation, the optical amplifiers used to overcome this limitation [2]. Two main types of the optical amplifiers which can be classified as semiconductor optical amplifiers (SOAs) and active fiber or doped fiber amplifiers (DFAs). One of the important and most common use in the long haul optical fiber communication system is the Erbium-doped fiber amplifier (EDFA) due to the range of the amplification in the C-band and L-band.

There are two most common configurations related to the EDFA, single stage and double stages EDFA. Single stage EDFA is an optical amplifier that contains one EDFA and it can be single-pass or double-pass EDFA, while the double stages EDFA is also an optical amplifier that contains two EDFAs that can be both single-pass or both double-pass or could be mix, one single-pass and the other one is a double-pass.

In this paper the rate equations is used to calculate the Er^{+3} ions densities of upper state population N_2 and ground state population N_1, the pumping rate R, the stimulated absorption rate W_{12} and the stimulated emission rate W_{21}, the forward and backward amplified spontaneous emission , the Noise Figure (NF) and the amplifier Gain. Due to double-pass amplification relaxation method used in this paper to get the most approximate and satisfied results of the signal power values for both configurations A and B

2- EDFA Configurations:

Two configurations of the double stage triple-pass EDFA have been used in this paper, configuration A and B. For the purpose of the numerical simulation for both configurations that have been used two pumps were employed to pump the two stages of the EDFA with 1480nm wavelength and an input signal signal with 1550nm wavelength.

Configuration A is a double stage triple-pass EDFA that consists of a single-pass EDFA as the first stage and the double pass EDFA (with either a selective mirror or any other reflection optical device that can reflect the signal wavelength only without the ASE) as the second stage, a pump power 100 mw with 1480nm wavelength, and input signal power with 1550nm wavelength have been used for the two stages as shown in Figure-1 below.

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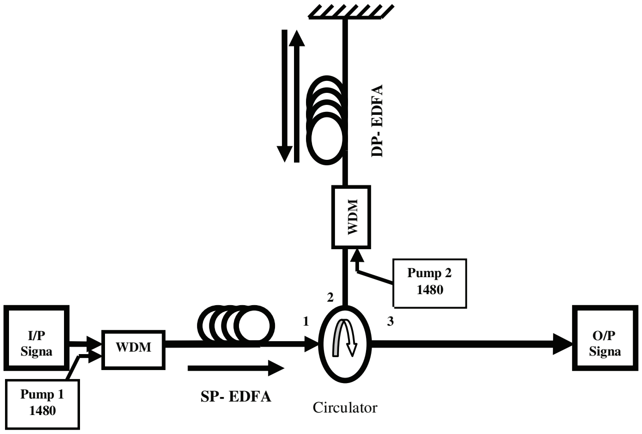

Figure-1 Configuration A Triple-Pass EDFA

Configuration B is also a double stage triple-pass EDFA but here the first stage is a double-pass EDFA (with either a selective mirror or any other reflection optical device that can reflect the signal wavelength only without the ASE) and the second stage is a single-pass EDFA, for both stages pump power of 100 mw with 1480nm wavelength, and input signal power with 1550nm have been used as shown in Figure2.

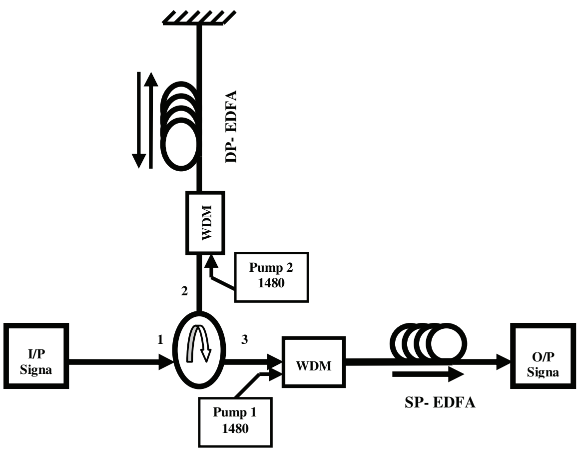

Figure-2 Configuration B Triple- Pass EDFA.

3- Numerical Analysis and optimization of the Triple pass EDFA:

Using the numerical simulation of the Triple pass EDFA for the two configurations A and B, the gain and the Noise Figure are calculated using the rate equation [3, 9, 10].

3.1- The rate equation model:

The pumping used in both of the configurations A and B is at 1480nm which populates the upper amplifier level of the Erbium ions directly, as the two energy levels transitions considered. The population densities N_1 and N_2 are calculated using the below equations [4]

$$N_{1}= \rho\,(1+ W_{21}\tau) / (1+ W_{12}\,\tau + W_{21}\,\tau + R_{12}\,\tau) \quad \text{-------}(1)$$

$$N_2 = \rho\,(W_{12}\tau + R_{12}\,\tau) / (1+ W_{12}\,\tau + W_{21}\,\tau + R_{12}\,\tau) \quad \text{----}\ (2)$$

Where N_1 and N_2 introduce as fractional densities of ions in the lower and upper energy levels respectively. $\rho = N_1 + N_2$ is the Erbium ion density per unit volume.

W_{12} and W_{21} are the stimulated absorption and emission rates between lower and upper energy levels respectively.

Where R_{12} is the pumping rate between lower and upper energy levels and $\boldsymbol{\tau}$ is the lifetime of the excited energy level.

$$W_{12} = ((\sigma_{SA}(\lambda_s)\,\Gamma_s) / hVs\,A)\,(Ps + P^{+}_{ASE} + P^{-}_{ASE}) \quad \text{--------}\ (3)$$

$$W21 = ((\sigma_{SE}(\lambda_s)\,\Gamma_s) / hVs\,A)\,(Ps + P^{+}_{ASE} + P^{-}_{ASE}) \quad \text{-------}\ (4)$$

$$R_{12} = (P_P^{+}\,\Gamma_P\,\sigma_{PA}(\lambda_P)) / hV_PA \quad \text{--------}\ (5)$$

$\sigma_{SE}(\lambda_s)$, $\sigma_{SA}(\lambda_s)$, $\sigma_{PE}(\lambda_P)$, $\sigma_{PA}(\lambda_P)$ are the emission and absorption cross sections at Signal (V_s) and Pump (V_p) frequencies, respectively .Γ_S and Γ_P are the overlap factor, representing the overlap between the Erbium ions and the mode of the signal light field and pump light field respectively. A is the effective cross- sectional area of the distribution of Erbium ions. h is the blank constant.

P_S is the signal power, P_P^{+} is the forward pump power as well as P^{+}_{ASE} and P^{-}_{ASE} are the forward and backward spontaneous emission spectrum. The equations describing the spatial development of Ps, P_P^{+}, P^{+}_{ASE} and P^{-}_{ASE} are written based on on the Becker, Giles, and Desurvire model [5,6,7,8] :

$$\frac{dP_P^{+}}{dz} = P_P^{+}\,\Gamma_P\,(\sigma_{PE}(\lambda_P)\,N_2 - \sigma_{PA}(\lambda_P)N_1) - \alpha_P\,P_P^{+} \quad \text{---------}(6)$$

$$\frac{dP_S}{dz} = P_S\,\Gamma_S\,(\sigma_{SE}(\lambda_S)\,N_2 - \sigma_{SA}(\lambda_S)N_1) - \alpha_S\,P_S \quad \text{----------}(7)$$

$$\frac{dP^{-}_{S}}{dz} = P^{-}_{S}\Gamma_{S}\,(-\sigma_{SE}(\lambda_S)\,N_2 + \sigma_{SA}(\lambda_S)N_1) + \alpha_S P^{-}_{S} \quad \text{----------} (8)$$

$$dP^{+}_{ASE} / dz = P^{+}_{ASE}\Gamma_S\,(\sigma_{SE}(\lambda_S)N_2 - \sigma_{SA}(\lambda_S)N_1) + 2\sigma_{SE}(\lambda_S)N_2\,\Gamma_S\,hV_S\Delta v - \alpha_S P^{+}_{ASE} \quad \text{--------} (9)$$

$$dP^{-}_{ASE} / dz = -P^{-}_{ASE}\Gamma_S\,(\sigma_{SE}(\lambda_S)N_2 - \sigma_{SA}(\lambda_S)N_1) + 2\,\sigma_{SE}(\lambda_S)N_2\,\Gamma_S\,hV_S\,\Delta v + \alpha_S P^{-}_{ASE} \quad \text{------} (10)$$

Where z is the coordinate along the EDFA. The second term of equation (9) and (10) is the spontaneous noise power produced per unit length of the EDFA within the EDFA homogeneous bandwidth (Δv), for both polarization states. α_P represents the internal Pump loss term of the EDFA.

Noise Figure (NF) is closely related to ASE, which is generated by spontaneous emission and the number of spontaneous photons is given by [6]:

$$\eta_{SP} = \eta\, N_2 / (\eta\, N_2 - N_1) \quad \text{-------------} (11)$$

Where $\eta = \sigma SE / \sigma_{SA}$. The NF of remotely pumped EDFA (NF (λ_S)) at the signal wavelength λ_S is calculated as:

$$NF(\lambda_S) = (1+2\eta_{SP}(G-1)) / G \quad \text{------------} (12)$$

G is the gain of the remotely pumped EDFA. For high gain condition (G>20dB) Noise Figure equation can be written as [4]:

$$NF(\lambda_S) \approx 2\eta_{SP} \quad \text{---------------} (12)$$

3.2- Results and Discussion:

A single pass EDFA and a double pass EDFA considered in two configurations. Gain and Noise figure of both single pass and the double pass EDFA are analyzed by using the two triple pass EDFA configurations A and B.

Various values of the EDFA length have been used (10 meters - 16 meters) and the results shows different value of the gain and the Noise figure for the triple pass EDFA configuration A and B as shown in Table-1.

Table-1 shows the best values of gain produced from configuration B which is higher than the values of the gain that produced from configuration A, although the noise figure values are approximately the same.

Table 1 shows the values of the Gain and noise figure related to different values of the EDFA length.

Length (m)	*Configuration A*		*Configuration B*	
	Gain	NF	Gain	NF
10	51	6.71	**55**	**6.69**
11	53	6.985	55	6.93
12	53	7. 38	55	7.26
14	54	9.061	55	8.4
16	53	13.99	56	10.5

From the results of Table-1, this paper focus on the values of the gain and the noise figure 10 meter EDFA length, 100 mw pump power at 1480nm wave length and 1550 nm signal power wavelength as the best values to get higher gain and lower noise figure.

Figure-3 below shows the increasing of the gain, the decreasing of the noise figure with the increasing of the pump power for both configurations A and B. From the results in figure-3, 4 and 5, the recommended configuration to be used is configuration B due to the high value of gain 55 dB, and the reasonable value of the noise figure dB.

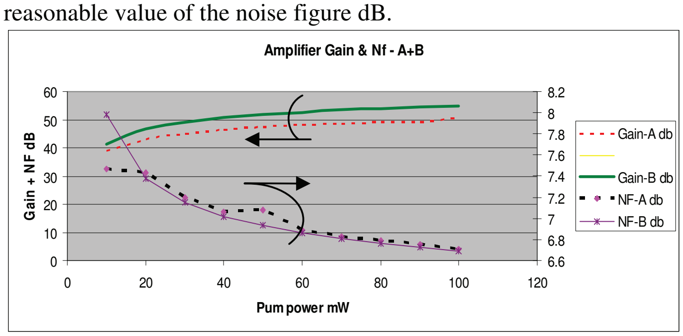

Figure-3 Gain and NF of configuration A and B – Pump Power -triple pass EDFA.

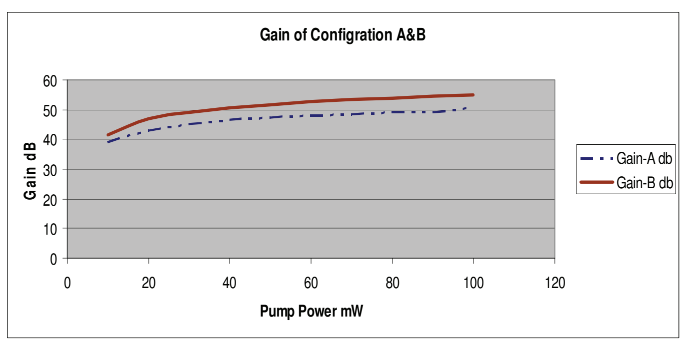

Figure-4 Gain of the two configurations A and B – Pump Power - triple pass EDFA.

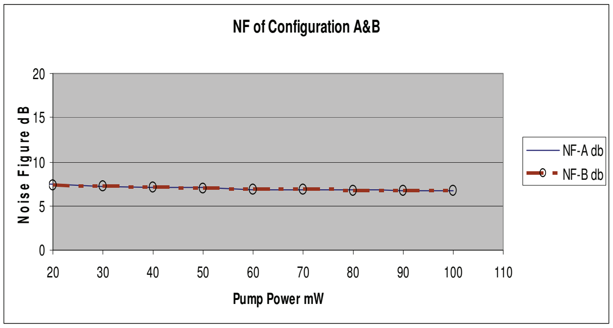

Figure-5 NF of the two configurations A and B – Pump Power - triple Pass EDFA.

Figure-6 below shows the increasing of the gain for both configurations A and B with decreasing of the signal power and the decreasing of the gain with the increasing of the signal power is also shown.

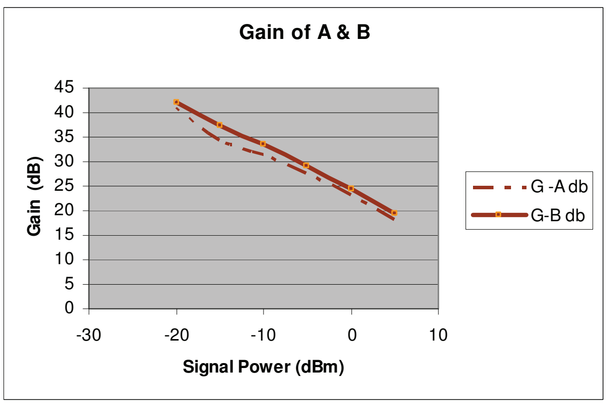

Figure-6 Gain of the two configurations A and B Signal Power-Triple pass EDFA.

4- Conclusion:

Two configurations of remotely pumped triple-pass EDFA have been discussed in this paper, configuration A and B. The parameters used are 100 mw Pump Power at 1480nm wavelength and input signal power at 1550nm at 10 meter EDF length and using the numerical simulation of EDFA rate equation model to get the best performance parameters of the two configurations of triple-pass EDFA.

The gain of configuration B is higher than the gain of configuration A. This paper shows results of gain and noise figure for both configuration A and B, although, the noise figure are approximately the same but the results of configuration B shows that it is more recommended to be used than configuration A due to the higher gain to perform better optical signal amplification.

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