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Full Length Research Paper

A novel theoretical analysis of quadruple pass Erbium-doped fiber amplifier

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A novel theoretical analysis model of dual stage quadruple pass (DSQP) Erbium-doped Fiber Amplifier (EDFA) is presented in this paper. This analysis is carried out by the broad input signal power starting from -50 to 0 dBm input signal with 10 to 220 mW pumping powers. The EDFA has been proposed and demonstrated by using an optical circulator and tunable band pass to reflect signal in each stage with a two level pump scheme through EDF length 10 and 15 m in the first and the second stage, respectively. The design parameters of EDFA are optimized using the numerical simulation of EDFA rate equations model in order to optimize the performance of EDFA. Finally, a comparative analysis is conducted to compare results of the theoretical modeling and the published experimental results. The comparative analysis showed that the proposed theoretical model has similar results compared to published experimental results.

Key words: Erbium-doped fiber amplifier (EDFA), dual stage quadruple pass (DSQP), TBF, double pass.

INTRODUCTION

In Erbium-doped fiber amplifier (EDFA), the active medium of DFA which is operating in the third window is created by doping a silica core with the Erbium (Er^{3+}). Up till date, researchers are concentrating on the EDFA, due to the emission of Er^{3+} excited ions within a set of wavelength in the C and L band where the silica fiber exhibits the minimum attenuation of information signal which about 0.2 db (Mears et al., 1987).

One of the important feature that EDFA provide is the high gain and low noise figure such 40 dB gain with low noise, as successfully reported within a pump power range from 50 to 100 mW (Xingyong et al., 2003; Desurvire and Simpson, 1989).

The other important features of EDFAs are the ability to be pumped by several different wavelengths, low coupling loss to the compatible fiber transmission medium and low dependence on light polarization (Urquhart, 1998).

Moreover, the EDFAs are constant for signal modulations greater than a few KHz and they are immune from interference effects (such as crosstalk and inter modulation distortion) between different optical wavelength within the C and L spectrum that propagating simultaneously inside the EDFA.

The development of high gain EDFAs has continued to form the backbone of high-capacity optical communications, despite the fact that, much progress since then has been made. However, fiber systems still suffer from losses resulted from different intrinsic characteristics of fiber materials. Therefore, much research effort is directed towards new materials and system optimization. Various configurations (Masuda and Takada, 1990) have been proposed to increase amplifier gain and reduce noise figure (NF). Osanai et al. (1976) was proposed a technique that reduces the effect of ASE self-saturation. However, this configuration suffers extra strenuous reflections resulted from imperfections of splices and other optical components (Lester et al., 1995). Besides, other reports have shown that filters can

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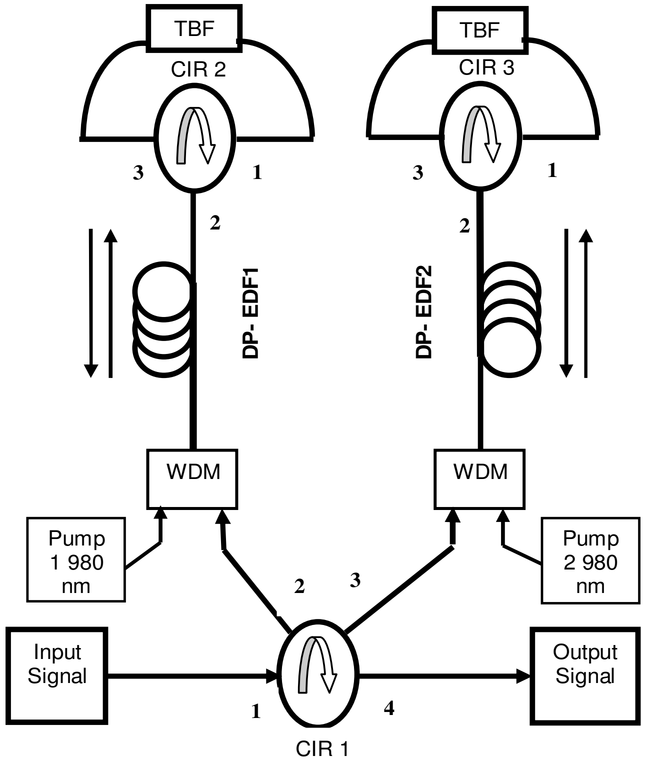

Figure 1. DSQP EDFA configuration incorporated with TBFs.

be used together with the midway isolator to suppress the forward ASE and improve the signal gain (Laming et al., 1992). An approach to obtain high gain incorporated a double-pass (DP) in the EDFAs was also proposed by Hossain et al. (2007). The proposed architecture in this paper, results in better gain enhancement and NF by using EDF. The configuration is formed by a circulator CIR1 with four parts: port 1 for input signal, port 4 for output and the other two are connected to circulators CIR2 and CIR3, each with three ports for the loop-back and two for TBFs.

CONFIGURATION

The EDFA has been achieved by the use of dual stage double pass configuration as shown in Figure 1. The two TBFs were incorporated into the device between input port 3 and 1 for each of the two circulators CIR2 and CIR3. The 980 nm semiconductor lasers were used as pumps with maximum power of 300 mW. The EDFA stages are formed by an 11 m length EDF1 in first stage and a 15 m EDF2 in second stage. Both EDF1 and EDF2 are have NA of 0.27, peak absorption of 6 dBm^{-1} and cutoff wavelength of 840 nm at a signal wavelength of 1550 nm, where the Erbium concentration has been estimated to be 440 ppm. Calibration model showed that each turn consistently gave a signal attenuation of 12 dB (three CIRs and two TBFs). Thus first, the amplified signal propagates through CIR1 port 1 to port 2, then through EDF1. As it propagates, it is amplified first by EDF1, next through port 2 into port 3 of CIR2 it passes through the first TBF into port 1 and back to port 2 where it gets amplified again during the second pass through EDF1 into port 2 of CIR1. It goes on then to the second stage passing through EDF2 and CIR3.

The output terminal is connected to port 4 of CIR1 (Figure 1). This technique allows amplifying of the signal by undergoing a quadruple pass through the dual amplifier stages.

THEORETICAL MODELING

The gain of the EDF (G-EDF) is calculated by the numerical simulation of the EDFA rate equations model as reported. Here, we describe the rate equation model of EDFA.

Since the pumping at 980 nm, populates the upper Er^{3+} energy level $^4I_{13/2}$ of the Erbium ions directly, a two level transition between $^4I_{15/2}$ - $^4I_{13/2}$ is considered. The population densities N_1 and N_2 of the $^4I_{15/2}$ and $^4I_{13/2}$ are calculated as (Giles and Desurvire, 1991):

$$N_1 = \rho \frac{1+W_{21}\tau}{1+(W_{12}+W_{21})\tau+R\tau} \tag{1}$$

$$N_2 = \rho \frac{1+W_{12}\tau}{1+(W_{12}+W_{21})\tau+R\tau} \tag{2}$$

Where W_{12} and W_{21} are the absorption and emission stimulated transition rates respectively, R is the pumping rate, τ is the fluorescence lifetime and by definition, $\rho = N_1 + N_2$ is the Erbium ion density per unit volume. $\sigma_{SE}(\lambda_S)$, $\sigma_{SA}(\lambda_S)$, $\sigma_{PE}(\lambda_P)$, $\sigma_{PA}(\lambda_P)$ are the cross sections emission and absorption at signal (V_s) and pump (V_p) frequencies, respectively. Γ_P and Γ_S are the overlap factor between the Erbium ions and the mode of pump light field and the signal light field respectively. The effective cross-sectional area of the distribution of Erbium ions is A. The value of W_{12}, W_{21} and R are computed as:

$$W_{12} = \frac{\sigma_{SA}\Gamma_S}{h\nu_S A}[P_S^+ + P_S^- + P_a^+ + P_a^-] \tag{3}$$

$$W_{21} = \frac{\sigma_{SE}\Gamma_S}{h\nu_S A}[P_S^+ + P_S^- + P_a^+ + P_a^-] \tag{4}$$

$$R = \frac{P_P\Gamma_P\sigma_P}{hV_P A} \tag{5}$$

Where h is Plank's constant, Pp 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 P_S^+ , P_S^-, P_P^+ , P_{ASE}^+ and P_{ASE}^- are based on the Becker, Giles and Desurvire model (Giles and Desurvire, 1991; Qinghe et al., 1999):

$$\frac{dP_P^+}{dz} = P_P^+\Gamma_P(\sigma_{PE}N2 - \sigma_{PA}N1) - \alpha_P P_P^+ \tag{6}$$

$$\frac{dP_S^+}{dz} = P_s^+\Gamma_s\,(\sigma_{SE}(\lambda_S)N_2 - \sigma_{SA}(\lambda_s)N_1) - \alpha_s P_s^+ \tag{7}$$

$$\frac{dP_S^-}{dz} = P_s^-\Gamma_s\,(-\sigma_{SE}(\lambda_S)N_2 + \sigma_{SA}(\lambda_s)N_1) + \alpha_s P_S^- \tag{8}$$

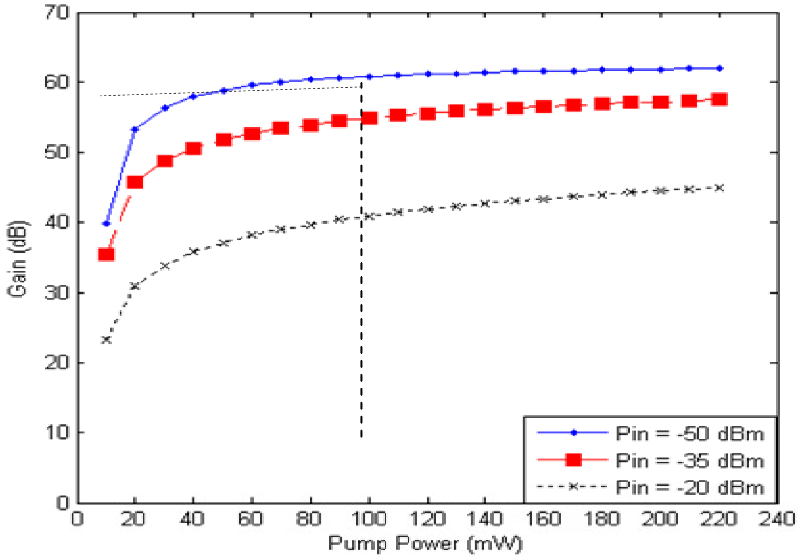

Figure 2. Model gain against pumping power at λ = 1550 nm obtained using DSQP EDFA.

$$\frac{dP_{ASE}^{+}}{dz} = P_{ASE}^{+}\Gamma_S(\sigma_{SE}N2 - \sigma_{SA}N1) + 2\sigma_{SE}N2\Gamma_S hV_S\Delta v - \alpha_P P_{ASE}^{+} \qquad (9)$$

$$\frac{dP_{ASE}^{-}}{dz} = -P_{ASE}^{-}\Gamma_S(\sigma_{SE}N2 - \sigma_{SA}N1) + 2\sigma_{SE}N2\Gamma_S hV_S\Delta v + \alpha_P P_{ASE}^{-} \qquad (10)$$

the co-ordinate along the EDFA is z. The second end on the right hand side of Equation (9) and (10) is the spontaneous noise power produced in per unit length of the EDFA within the EDFA homogeneous bandwidth (Δv), for both polarization states. α_P represents the internal pump loss part of the EDFA. NF is closely related to ASE, which has been generated by spontaneous emission and the number of spontaneous photons is given by Qinghe et al. (1999):

$$\eta_{SP} = \frac{\eta N2}{\eta N2 - N1} \qquad (11)$$

Where $\eta = {}^{\sigma_{SE}}/_{\sigma_{SA}}$ The NF of pumped EDFA (NF (λS)) at the signal wavelength λS is calculated as:

$$NF(\lambda_S) = \frac{1 + 2\eta_{SP}[G-1]}{G} \qquad (12)$$

G is the gain of EDFA. For G>20 dB ,the NF equation is calculated as following [16]:

$$NF(\lambda_S) \approx 2\eta_{SP} \qquad (13)$$

Here, the first stage has been explained. However, the second stage is similar to first stage, but the backward ASE of the first stage must be counted in the second stage. Therefore, the equations that differ are shown subsequently:

$$W_{12} = \frac{\sigma_{SA}\Gamma_S}{hV_S A}[P_{S(2nd\ stage)}^{+} + P_{S(2nd\ stage)}^{-} + P_{a(2nd\ stage)}^{+} + P_{a(2nd\ stage)}^{-} + P_{a(1st\ stage)}^{-}] \qquad (14)$$

$$W_{21} = \frac{\sigma_{SE}\Gamma_S}{hV_S A}[P_{S(2nd\ stage)}^{+} + P_{S(2nd\ stage)}^{-} + P_{a(2nd\ stage)}^{+} + P_{a(2nd\ stage)}^{-} + P_{a(1st\ stage)}^{-}] \qquad (15)$$

where P_S^{+} is the forward signal power, P_S^{-} is the backward signal power which is equal to the final signal output power of DP EDFA for second stage. $P_{a(2nd\ stage)}^{+}$ and $P_{a(2nd\ stage)}^{-}$ are the forward and backward spontaneous emission powers of EDFA of second stage respectively. $P_{a(1st\ stage)}^{-}$ is the backward spontaneous emission powers of EDFA of first stage.

RESULTS AND DISCUSSION

In any amplifier design, gain and noise figure are the two main concerns. Gain and noise figure are closely related to each other. Low noise figure and high gain are the main feature for optimum amplifiers. Pump light is injected into the active material to excite the Er^{3+} ions to higher energy level for signal amplification. Here, its effect on gain and noise figure is investigated.

Figure 2 shows gain against pump power at 1550 nm signal wavelength for signal powers of -20, -35 and -50 dBm in model and experiment. The pump power has been optimized in this model is similar to the experiment, the first stage was fixed at 10 mW and the pump power in the second stage was varied from 10 to 220 mW in 10 mW steps. The gain value was 41 dB with only 10 mW pump power for both stages, recording a 4.1 dB/mW gain coefficient with -50 dBm input signal power. The gain increased gradually for three signal powers until pump powers reach 80 mW in the second stage. Above 80 mW pump powers, the gain increased slightly for three signal powers. The highest gain of 61 dB was obtained at 220 mW pump power for -50 dBm signal. As shown in Figure 2, both the model and the experiment (Ali et al., 2009) have the similar gain signal characterization against pump power at 1550 nm signal wavelength. However,

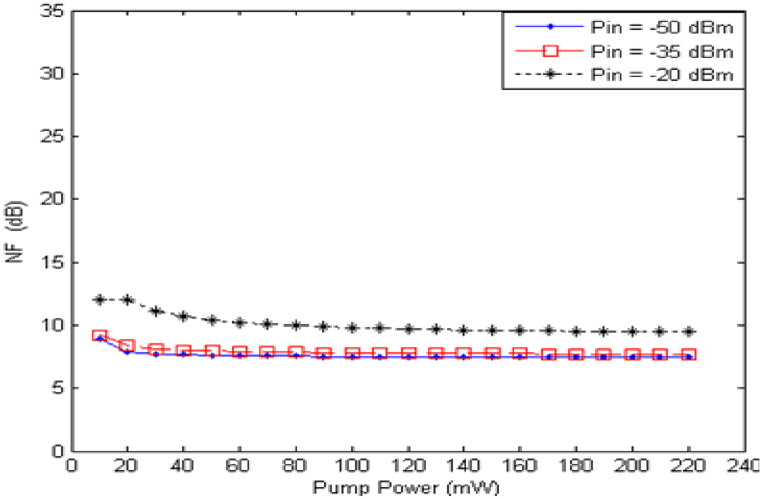

Figure 3. Model noise figure against pumping power at A = 1550 nm obtained using DSQP EDFA.

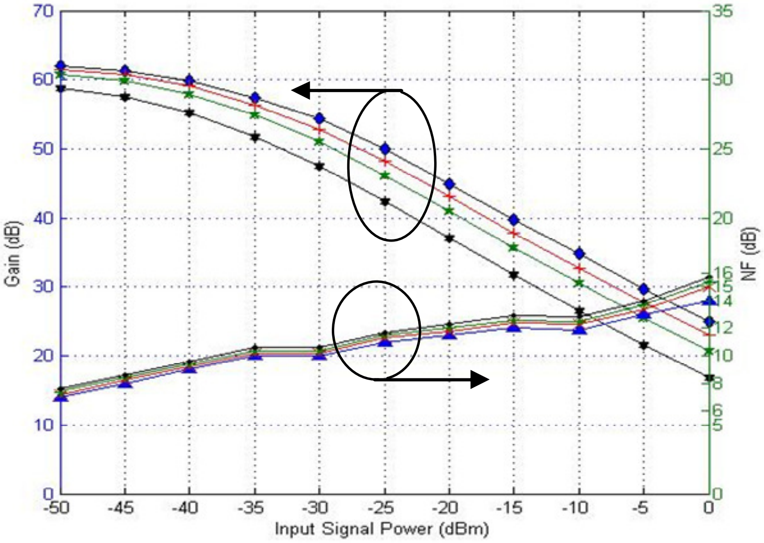

Figure 4. Model gain and noise figure against input signal power at λ = 1550 nm obtained using DSQP EDFA.

there is a 3 dB differrent between the model and the experiment result in the range of pump power from 100 to 140 mW.

Figure 3 depicts NF against the pumping power, it shows a constant behaviour of NF during the increase of pumping power. This can be demonstrated based on the relation between NF and the pump power, and may be the influence of the filter that is remarked it has the role to eliminate forward ASE; therefore, it locks the NF at a fixed value. The NF records the lowest value for -50 dBm about 7 dB, and the highest value for -20 dB.

For pump powers from 20 to 220 mW, the noise figure is maintained because the effect of ASE on reducing the population inversion is being counter acted by an increase in the pump power. The amplified signal after propagation twice in each EDF is more dominant than the initial input signal. Therefore, the gain of this input signal is reduced and hence, the overall noise figure is also degraded as depicted in Figure 3.

As demonstrated previously, the model has the same NF characterization against pump power as the experiment (Ali et al., 2009) (Figure 3).

Figure 4 plots gain and NF against input signal power at 1550 nm signal wavelength. The first stage is fixed with 10 mW value, while the second stage pump power was set at 220, 150, 100 and 50 mW. The gain value

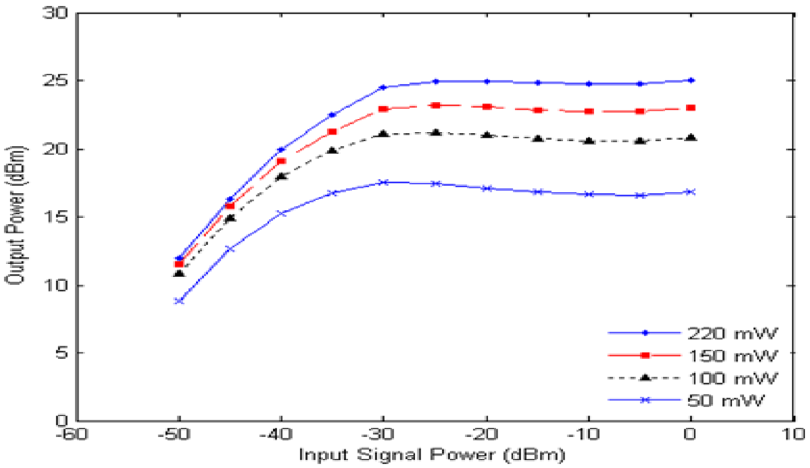

Figure 5. Model output signal power against input signal power at λ = 1550 nm obtained using DSQP EDFA.

Table 1. Model and experimental results.

Results	Signal	Values	Noise figure (dB)	Gain (dB)
Model	Pump power	220 mW	6.39	61
		100 mW	7.05	57.47
		50 mW	7.72	44.69
	Input signal power	-50 dB	6.39	61.68
		-35 dB	9.22	58
		-20 dB	11.17	53
Experiment	Pump power	220 mW	6.01	61
		100 mW	7	55
		50 mW	8	51
	Input signal power	-50 dB	6.01	61
		-35 dB	9	50
		-20 dB	11	38

passes the 40 dB at -30 dBm signal power with 50 mW minimum pumping power, so the highest gain region is recorded above 50 mW and less than -30 dBm input signal power. There is no significant sign of gain saturation in the small signal regime (< -40 dBm). It is expected that the gain value can exceed 70 dB if lower signal powers (-60 dBm) are used. The NF of the amplifier is recorded against the input signal power. By increasing the input signal power, the NF is also increased, when the signal power is less than -30 dBm the NF reaches its lowest value between 7 and 10 dB.

Figure 5 illustrates the output signal power characteristics against input signal power at different pump powers 50, 100, 150, and 200 mW. The plotted graph shows that the output signal power increases with the increase in the input power.

From the plotted graphs they are found that the dependence of the output power on the input signal power using the DSQP EDFA system shows a high output power of less than 18 dBm for the higher input signal power of more than -30 dBm while decreasing the input signal power will reduce the output signal power of less than 10 dBm for the input signal power between -47 and -50 dBm.

The comparison between the model and experimental results, it has been found that gain increases by increasing in pump power and by increasing in input power for the model and experimental results. However, a good agreement between model and experiment has been shown for DSQP EDFA. The comparison between model and experimental study is summarized in Table 1.

The usage of A 1480 nm pump gave higher gain compared to the usage of 980 nm. On the other hand the 1480 nm increase the NF while the usage of 980 gives less NF values.

CONCLUSION

This paper explains the model setup and its results of DSQP EDFA and compares them with experimental results. The gain and noise characteristics of the DSQP EDFA are derived based on design parameters. The launched signal power of the input port and pump power of EDFA have been set in the model based on the experimental work. The comparison between the theoretical and experimental study has been demonstrated in this paper. Finally, the theoretical results have a similar pattern to the experimental results.

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