Full Length Research Paper

Modeling and characterization of all possible triple pass EDFA configurations

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The main purpose of designing multi-stage erbium-doped fiber amplifiers (EDFAs) is to achieve higher gain and lower noise figure for long haul optical communication. Among the multi-stage EDFAs, triple pass EDFAs were chosen in this research. This paper presents all possible triple pass EDFA configurations. The well-established one-stage mathematical models were modified to design two-stage and three-stage triple pass EDFAs. Performances of all the configurations were analyzed with pump power ratio and signal power. Optimum length and Optimum pump power ratio were also determined for each and every configuration. From the performance analysis, best triple pass EDFA was recommended for practical design.

Key word: Erbium-doped fiber amplifier (EDFA), triple pass, amplified spontaneous emission.

INTRODUCTION

Research interest on optical fiber communication system (OFCS) is increasing day by day because of its reliability in handling and transmitting data through hundreds of kilometers with an acceptable bit error rate. OFCS can meet the bandwidth requirement of a practical long-haul transmission. Signal passing through OFCS, experiences different types of attenuation such as fiber absorption and scattering losses. Optical amplifiers are used in long-haul OFCS to overcome the attenuation of signal experienced in the system. Among the optical amplifiers, doped optical amplifiers (DFA) are immune from interference effects such as crosstalk and inter-modulation distortion, between different optical channels within a broad spectrum of wavelengths that are injected simultaneously into the amplifier (Keiser, 2000). The most common dopant material used in DFAs is erbium, and such a fiber amplifier is known as erbium-doped fiber amplifier (EDFA). The founding of EDFA is a major breakthrough in communication technology since it has the ability to provide a broad and high optical gain within the optical communication bandwidth. It enhances the development of the long haul OFCS by increasing the capacity of data

transmission and extending the communication distance (Becker et al., 2002).

Multi-stage structures of the optical amplification block can have better gain and noise figure characteristics than one-stage structures (Becker et al., 2002; Desurvire, 1994; Desurvire, 2002). Recently, researchers are seeking interest to work on multi-stage EDFAs to achieve a practical long haul OFCS. Harun and Ahmed (2004) proposed an L-band EDFA with high flat-gain. It had achieved a flat gain output at 33.5 dB, which is 13.5 dB higher than that of the single pass system with only 84 mW of total pump power.

The gain variation was within 1 dB over 30 nm from the wavelength of 1570 to 1600 nm. The noise figure at flat gain region varied from 6.9 to 11.5 dB. The flat gain spectrum could be maintained even with the existence of 32 channels at -30 dBm in the system. However, the proposed configuration is not optimized and experimental setup of the proposed model is very costly.

Ali et al. (2009) proposed an architecture of two stage quadruple pass configuration. The performance of this proposed configuration had been analyzed with various pump powers and signal powers. However, the length of the first EDF is optimized, but not the second EDF that makes the whole EDFA un-optimized. This type of EDFA may give high performance but this will be very costly.

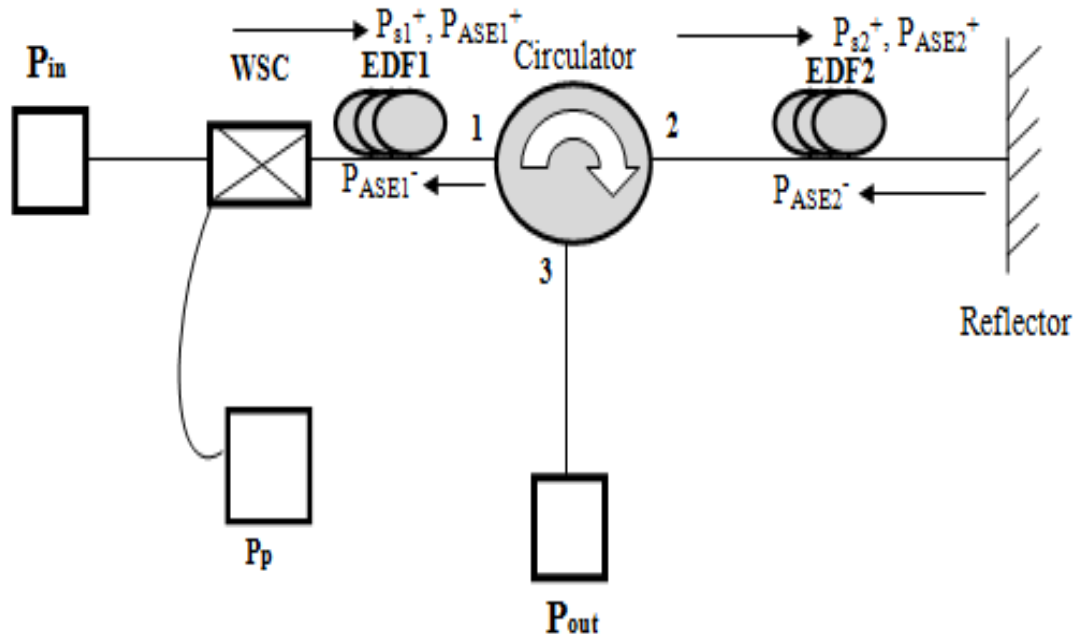*Corresponding author. E-mail: fowzia.2k3@gmail.com.

Figure 1. Two-stage triple pass 1 erbium doped fiber amplifier.

Naji et al. (2010) proposed two configurations of remotely pumped triple-pass EDFA which are named as A and B. The performance parameters (gain and noise figure) of these two configurations were compared with the variation of pump power and signal power. From the obtained results, configuration B was recommended for better optical signal amplification. However, the amplified spontaneous emission (ASE) effect is not included for the calculation in the second stage of EDF. The pump power and fiber length for the proposed design were not optimized.

Shan Qin et al. (2010) proposed a new three-stage L-band EDFA structure with ASE pumping. The characteristics of this L-band EDFA were studied on the basis of the Giles model with ASE. It showed that the present EDFA structure could provide 33.4 dB gain with only about 1 dB gain ripple and less than 4.5 dB noise figure (from 1570 to 1605 nm) when the input signal was fixed at -30 dBm. However, optimum EDF length and input pump power for practical implementation are not proposed.

Although, some researches have been done on multi-stage EDFAs including triple pass (TP) EDFAs, no mathematical model was developed till now. This paper presents complete mathematical models to design all possible triple pass EDFAs. There are three possible TP EDFAs. The performance of each and every configuration has been analyzed with pump power ratio and signal power. The effect on the number of erbium ions concentration in energy level 1 and 2 with the variation of fiber length was analyzed to determine the optimum fiber length. From the aforementioned analysis, optimum parameters (pump power ratio and fiber length)

were determined for practical design. The comparisons of all the configurations were also carried out to conclude the best TP design.

TRIPLE PASS EDFAS

TP EDFA is that configuration where signal passes thrice through the active material. Figure 1 shows the schematic diagram of the forward pumped TP1 EDFA configuration. In this configuration, there are two EDF connected in series through a circulator. The output signal power of the first stage EDF is the input signal power for the second stage EDF. The EDFs are connected in such way that signal passes once through the first EDF and twice through the second EDF. A mirror is used in the second EDF so that the amplified signal is reflected by the mirror and is passed again through that EDF.

There is one more two-stage EDFA configuration. Figure 2 shows the schematic diagram of forward pumped TP2 EDFA configuration. In this EDFA, there are two EDFs connected by a circulator in such a way that signal passes twice through the first EDF and once through the second EDF. Two different input pump powers are used to energize the active material. A mirror is used as a reflector with the first EDF to reflect the amplified signal back to that EDF. The output signal power of the first stage is the input signal power for the second stage EDF.

There is only one three-stage TP EDFA. In TP3 EDFA, there are three active materials connected in series and signal passes once through each active material. Since
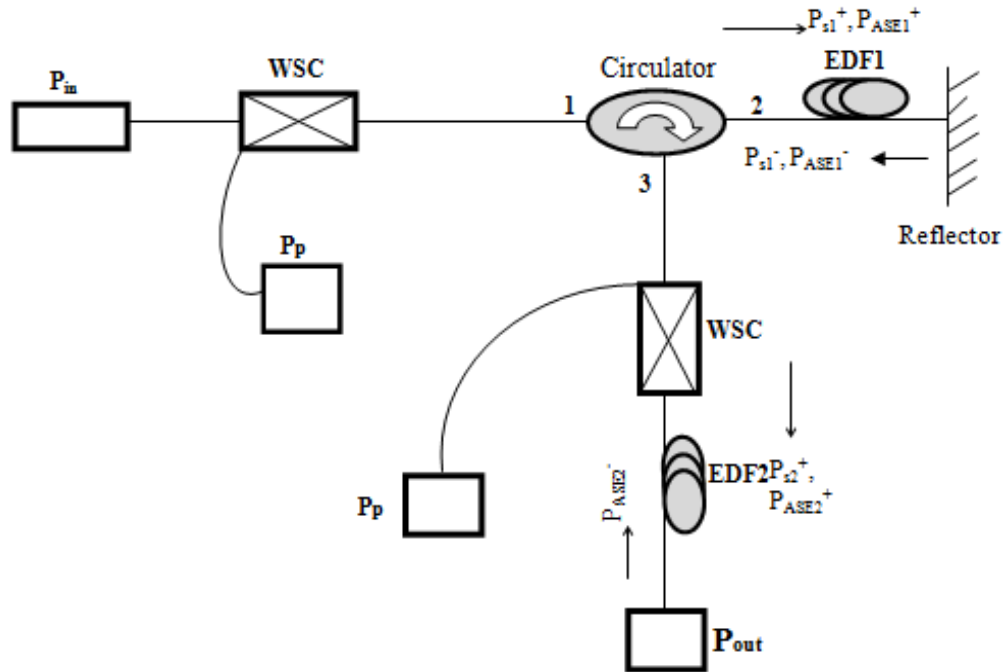
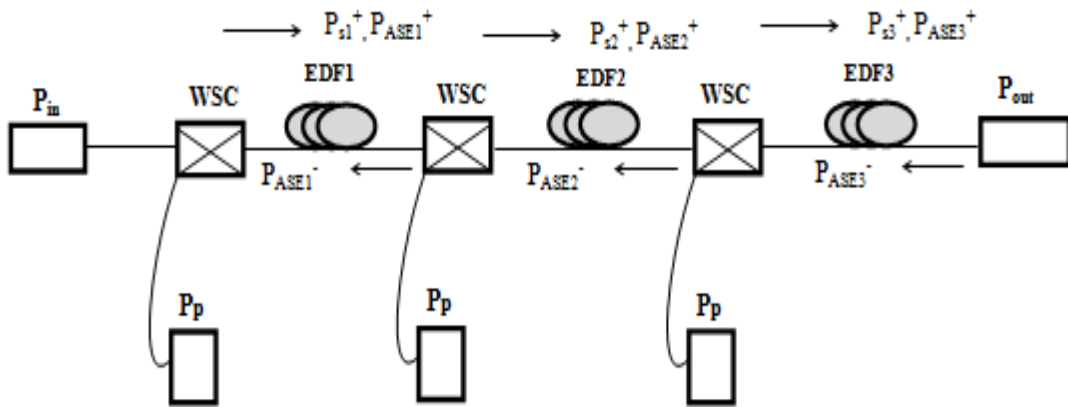**Figure 2.** Two-stage triple pass 2 erbium doped fiber amplifier.

Figure 3. Three stage triple pass 3 erbium doped fiber amplifier.

the total number of times that the signal can pass through EDF is three, it is called triple pass EDFA. The output signal power of the first stage is the input signal power for the second stage and the output signal power of the second stage is the input signal power for the third stage. Figure 3 shows the schematic diagram of forward pumped TP3 EDFA configuration.

MATHEMATICAL MODEL

It was assumed that it uses a pump wavelength of 1480 nm. The two energy levels system was considered and the Er^{3+} ions densities of upper state population (N_2) and ground state population (N_1) was calculated as follows (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 stimulated absorption rate and

stimulated emission rate respectively, R is the pumping rate, τ is the fluorescence lifetime and $\rho = N_1 + N_2$ is the Er^{3+} ions density per unit volume. The values of W_{12} and W_{21} are calculated as:

For the first SP EDF of TP1 EDFA (Giles and Desurvire, 1991),

$$W_{12} = \frac{\sigma_{SA}(\lambda_S)\Gamma_S}{hV_SA}\left(P_{S1}^+ + P_{ASE1}^+ + P_{ASE1}^-\right) \quad (3)$$

$$W_{21} = \frac{\sigma_{SE}(\lambda_S)\Gamma_S}{hV_SA}\left(P_{S1}^+ + P_{ASE1}^+ + P_{ASE1}^-\right) \quad (4)$$

While for second DP EDF of TP1 EDFA the equations were modified as:

$$W_{12} = \frac{\sigma_{SA}(\lambda_S)\Gamma_S}{hV_SA}\left(P_{S2}^+ + P_{S2}^- + P_{ASE2}^+ + P_{ASE2}^- + P_{ASE1}^+\right) \quad (5)$$

$$W_{21} = \frac{\sigma_{SE}(\lambda_S)\Gamma_S}{hV_SA}\left(P_{S2}^+ + P_{S2}^- + P_{ASE2}^+ + P_{ASE2}^- + P_{ASE1}^+\right) \quad (6)$$

For the first DPEDF of TP2 EDFA (Giles and Desurvire, 1991),

$$W_{12} = \frac{\sigma_{SA}(\lambda_S)\Gamma_S}{hV_SA}\left(P_{S1}^+ + P_{S1}^- + P_{ASE1}^+ + P_{ASE1}^-\right) \quad (7)$$

$$W_{21} = \frac{\sigma_{SE}(\lambda_S)\Gamma_S}{hV_SA}\left(P_{S1}^+ + P_{S1}^- + P_{ASE1}^+ + P_{ASE1}^-\right) \quad (8)$$

While for the second SP EDF of TP2 EDFA, the equations were modified as follows.

$$W_{12} = \frac{\sigma_{SA}(\lambda_S)\Gamma_S}{hV_SA}\left(P_{S2}^+ + P_{ASE2}^+ + P_{ASE2}^- + P_{ASE1}^-\right) \quad (9)$$

$$W_{21} = \frac{\sigma_{SE}(\lambda_S)\Gamma_S}{hV_SA}\left(P_{S2}^+ + P_{ASE2}^+ + P_{ASE2}^- + P_{ASE1}^-\right) \quad (10)$$

For TP3 EDFA, calculation of W_{12} and W_{21} were followed by equations 3 and 4 while for the second and third EDF, the equations of W_{12} and W_{21} were modified as:

For second stage,

$$W_{12} = \frac{\sigma_{SA}(\lambda_S)\Gamma_S}{hV_SA}\left(P_{S2}^+ + P_{ASE2}^+ + P_{ASE2}^- + P_{ASE1}^+\right) \quad (11)$$

$$W_{21} = \frac{\sigma_{SE}(\lambda_S)\Gamma_S}{hV_SA}\left(P_{S2}^+ + P_{ASE2}^+ + P_{ASE2}^- + P_{ASE1}^+\right) \quad (12)$$

For third stage,

$$W_{12} = \frac{\sigma_{SA}(\lambda_S)\Gamma_S}{hV_SA}\left(P_{S3}^+ + P_{ASE3}^+ + P_{ASE3}^- + P_{ASE2}^+\right) \quad (13)$$

$$W_{21} = \frac{\sigma_{SE}(\lambda_S)\Gamma_S}{hV_SA}\left(P_{S3}^+ + P_{ASE3}^+ + P_{ASE3}^- + P_{ASE2}^+\right) \quad (14)$$

The value of R can be calculated as (Giles and Desurvire, 1991):

$$R = \frac{P_p^+\Gamma_p\sigma_p}{hV_pA} \quad (15)$$

Where, σ_{SE} and σ_{SA} are the emission and absorption cross-sections of the signal, while σ_{PE} and σ_{PA} are the emission and absorption cross-sections of the pump. V_S and V_P are the signal and pump frequencies respectively, Γ_S and Γ_P are the overlap factors of the signal and the pump respectively. It represents the overlap of the erbium ions with 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 Planck constant, P_S^+ is the forward signal power and P_P is the pump power of the EDFA. P_{ASE}^+ and P_{ASE}^- are the forward and backward spontaneous emission powers of the EDFA, respectively (Giles and Desurvire, 1991; Qinghe et al., 1999).

$$\frac{dP_P^+}{dz} = P_p^+\Gamma_p\left(\sigma_{PE}N_2 - \sigma_{PA}N_1\right) - \alpha_pP_p^+ \quad (16)$$

$$\frac{dP_S^+}{dz} = P_S^+\Gamma_S\left(\sigma_{SE}N_2 - \sigma_{SA}N_1\right) - \alpha_SP_S^+ \quad (17)$$

$$\frac{dP_S^-}{dz} = -P_S^-\Gamma_S\left(\sigma_{SE}N_2 - \sigma_{SA}N_1\right) + \alpha_SP_S^+ \quad (18)$$

$$\frac{dP_{ASE}^+}{dz} = P_{ASE}^+\Gamma_S\left(\sigma_{SE}N_2 - \sigma_{SA}N_1\right) + 2\sigma_{SE}N_2\Gamma_ShV_S\Delta V - \alpha_SP_{ASE}^+ \quad (19)$$

$$\frac{dP_{ASE}^-}{dz} = -P_{ASE}^-\Gamma_S\left(\sigma_{SE}N_2 - \sigma_{SA}N_1\right) - 2\sigma_{SE}N_2\Gamma_ShV_S\Delta V + \alpha_SP_{ASE}^- \quad (20)$$

Where Δv is the bandwidth of the ASE, z is the co-ordinate along the EDF, α_S and α_p represents the internal signal and pump loss term of the amplifier respectively.

During the reflection by the fiber loop mirror, a reflection loss (R_{LOSS}) to the amplified P_S^+ was considered. (R_{LOSS}) was calculated as (Qinghe et al., 1999):

$$R_{LOSS} = 4K(1-K)(1-\Gamma)^2 e^{\alpha L} \quad (21)$$

Where K, Γ and αL are coupling ratio, the coupling loss and the attenuation induced by the fiber loop respectively. Noise figure is closely related to ASE which is generated by spontaneous emission and the number of spontaneous photons is given by (Qinghe et al., 1999):

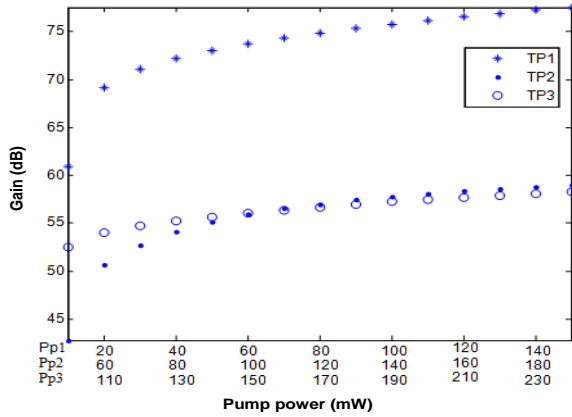$$\eta_{SP} = \frac{\eta N_2}{\eta N_2 - N_1} \quad (22)$$

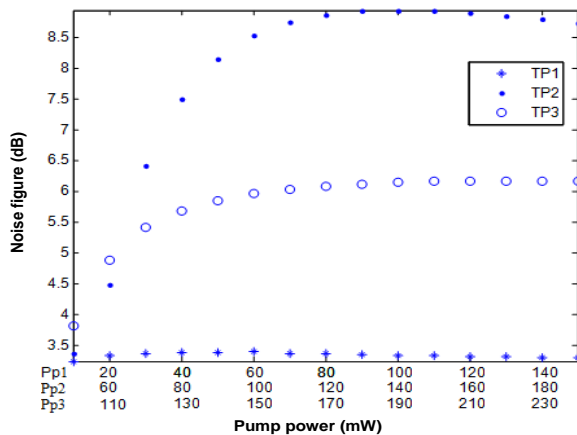**Figure 4.** Gain performance of all TP EDFAs with the variation of pump power at signal power -33 dBm and λ=1550 nm.

Figure 5. Noise figure performance of all TP EDFAs with the variation of pump power at signal power -33 dBm and λ=1550 nm.
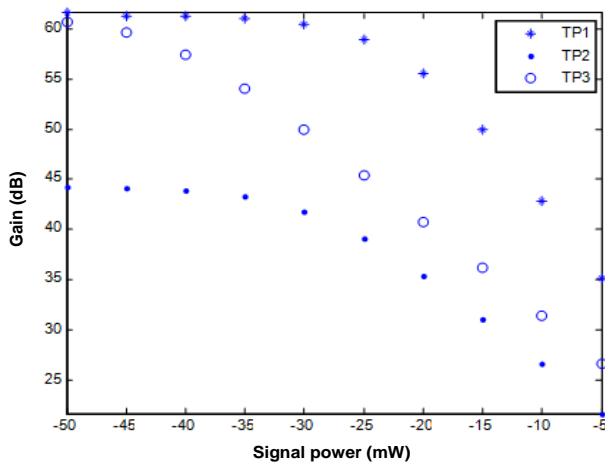

Figure 6. Gain performance of all TP EDFAs with the variation of signal power for Pp1=10 mW, Pp2=50 mW, Pp3=100 mW and λ=1550 nm.

Where η_{SP} is known as the spontaneous emission factor and η=σ$_{SE}$/σ$_{SA.}$ The noise figure of the R-EDFA (NF^{Er}(λ$_S$)) at the signal wavelength λ_S can be calculated as (Qinghe et al., 1999):

$$\mathrm{NF}^{\mathrm{Er}}\left(\lambda_{\mathrm{S}}\right) = \frac{1 + 2\eta_{\mathrm{SP}}\left[G_{\mathrm{EDFA}} - 1\right]}{G_{\mathrm{EDFA}}}$$

(23)

For high gain condition (G$_{EDFA}$>20 dB) equation can be written as (Naji et al., 2006):

$$\mathrm{NF}^{\mathrm{Er}}\left(\lambda_{\mathrm{S}}\right) \approx 2\eta_{\mathrm{SP}}$$

(24)

RESULTS AND DISCUSSION

The performance analysis of all the TP EDFAs were carried out with the variation of pump power, signal power. The effect on the number of erbium ions concentration in energy level 1 and 2 with the variation of fiber length was also analyzed to determine the optimum fiber length.

Figure 4 shows the gain performance of TP1 EDFA, TP2 EDFA and TP3 EDFA with the variation of pump power. Performance analyses were carried out for the variation of Pp1 from 10 to 150 mW, Pp2 from 50 to 190 mW and Pp3 from 100 to 240 mW. From this figure, it is seen that the performance of TP1 EDFA is better than TP2 EDFA and TP3 EDFA. The maximum obtained gain of TP1 was 77.54 dB, whereas for TP2 and TP3, 58.99 and 58.29 dB was obtained respectively. For a low input pump power (10:50 mW), it was possible to achieve a very high gain of 60.93 dB in TP1 EDFA. Observing the gain (Figure 4) and noise figure (Figure 5) values, the determined optimum pump power ratio for TP1 EDFA was 80:120 mw and for TP2 EDFA, it was 10:50 mW. For TP3 EDFA, the optimum pump power ratio was 70:110:160 mW.

Figure 5 shows noise figure performance of TP1 EDFA, TP2 EDFA and TP3 EDFA with the variation of pump power. From this figure, it is seen that the performance of TP1 EDFA was better than that of TP2 EDFA and TP3 EDFA. At pump power ratio 10:50 mW, the lowest Noise figure obtained by TP1 was 3.24 dB and TP2, was 3.37 dB. Whereas, the lowest value of the noise figure for TP3, was 3.81 dB at pump power ratio is 10:50:100 mW. By observing the noise figure performance of all triple pass EDFAs with the variation of pump power, it can be said that TP1 EDFA will be best one.

The impact of changing signal power on the gain performance of TP1 EDFA, TP2 EDFA and TP3 EDFA are demonstrated in Figure 6. From this figure, it can be said that as the signal power increases, the gain decreases for all TP EDFAs. Values of lowest gain at -5 dBm signal power obtained by TP1, TP2 and TP3 EDFA
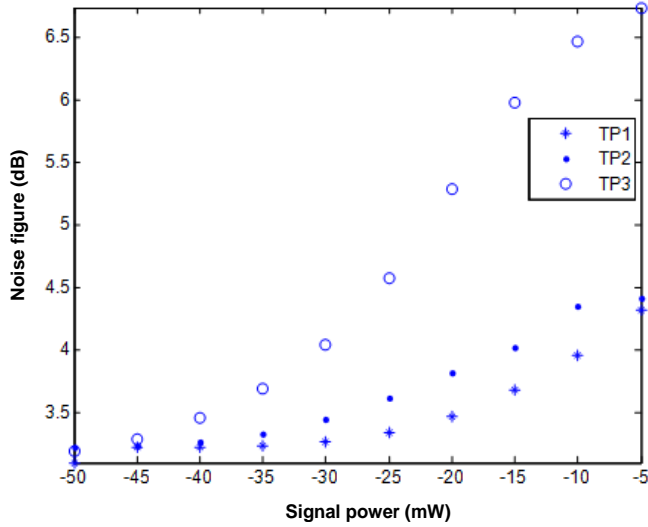
Figure 7. Noise figure performance of all TPEDFAs with the variation of signal power for pp1=10 mw, pp2=50 mw, pp3=100 mw and λ=1550 nm.

Figure 9. Upper state population and ground state population as a function of fiber length for the second EDF of TP1 at 10 mW pump powerand λ=1550 nm.
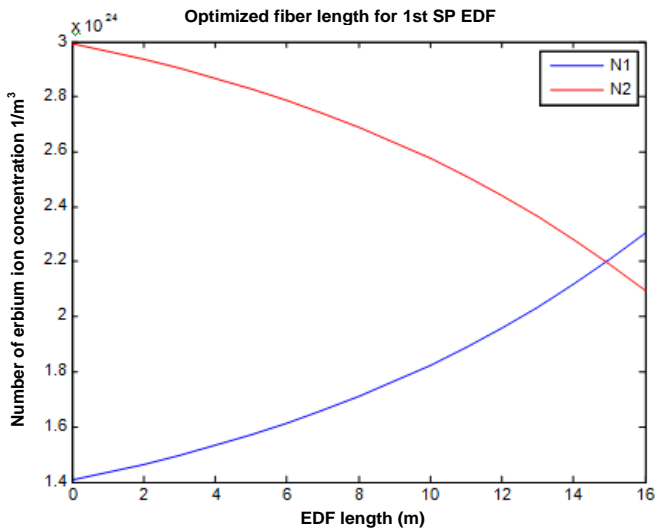

Figure 8. Upper state population and ground state population as a function of fiber length for the first EDF of TP1 EDFA at 10 mW pump power and λ=1550 nm.

Figure 10. Upper state population and ground state population as a function of fiber length for the first EDF of TP2 EDFA at 10 mW pump power and λ=1550 nm.

were 35.148, 21.639 and 26.624 dBm respectively. In this case, TP1 EDFA performs best and between TP2 and TP3 EDFA, TP3 performs better.

Figure 7 shows the signal power versus noise figure performance of TP1 EDFA, TP2 EDFA and TP3 EDFA. From this figure, it can be said that as the signal power increases, the noise figure increases for all TP EDFAs. Values of lowest noise figure at -50 dBm signal power obtained by TP1, TP2 and TP3 EDFA are 3.102, 3.229 and 3.194 dBm respectively. In this case, TP1 EDFA performs best and between TP2 and TP3 EDFA, TP2
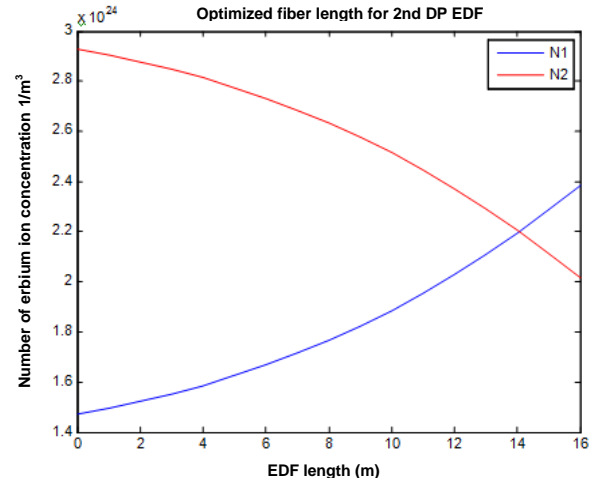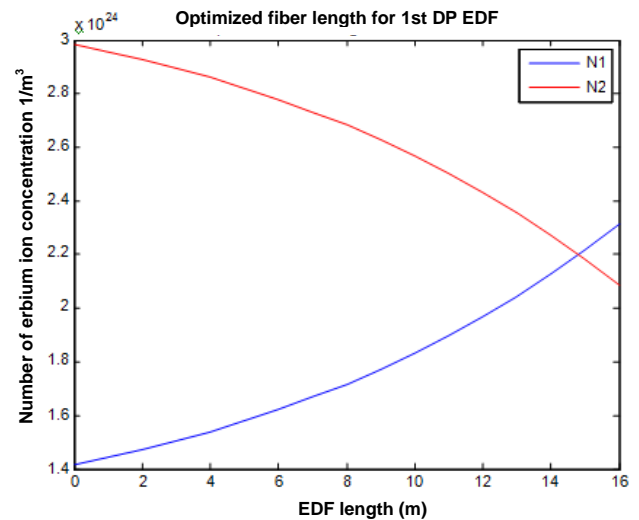
performs better. The optimum signal power of TP1, TP2 and TP3 EDFAs are in between -50 and -35 dBm.

Figure 8 shows the erbium ions concentration versus fiber length curve for the first SP EDF of TP1 EDFA. Here, N1 and N2 intersect each other at fiber length 15 m due to insufficient pump power. This means the optimum length of the first SP EDF of TP1 EDFA is 15 m.

Figure 9 shows the erbium ions concentration versus fiber length curve for the second DP EDF of TP1 EDFA. Here, N1 and N2 intersect each other at fiber length 14 m. This means the optimum length of the second DP EDF of TP1 EDFA is 14 m.

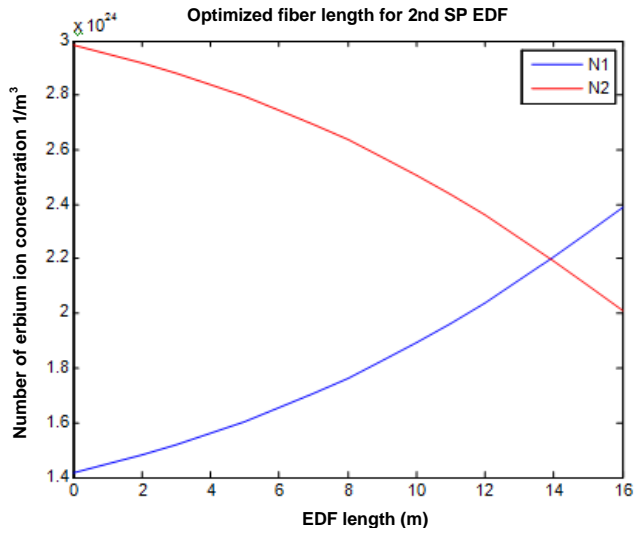Figure 10 shows the erbium ions concentration versus

Figure 11. Upper state population and ground state population as a function of fiber length for the second EDF of TP2 EDFA at 10 mW pump power and λ=1550 nm.
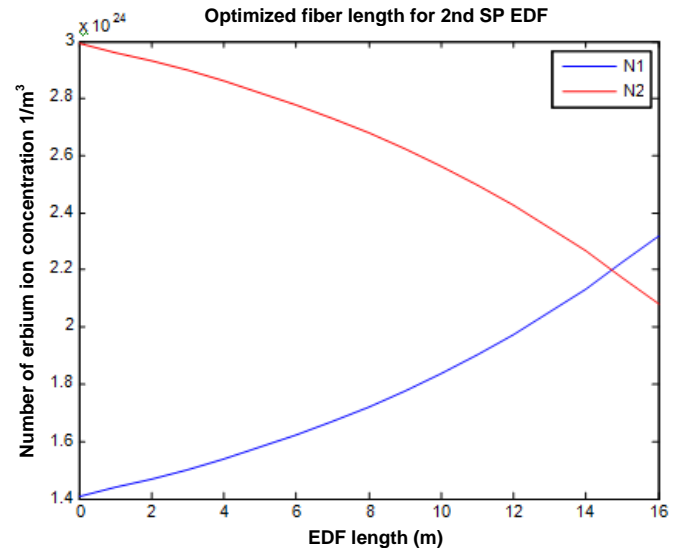

Figure 13. Upper state population and ground state population as a function of fiber length for the second EDF of TP3 EDFA at 10 mW pump power and λ=1550 nm.
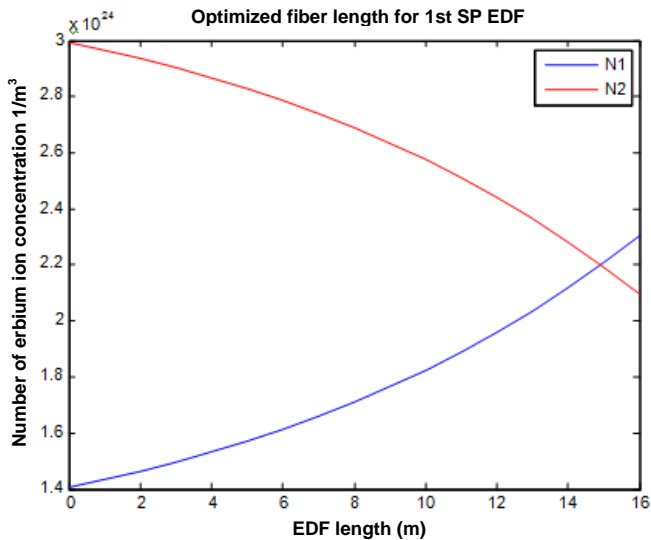

Figure 12. Upper state population and ground state population as a function of fiber length for the first EDF of TP3 EDFA at 10 mW pump power and λ=1550 nm.
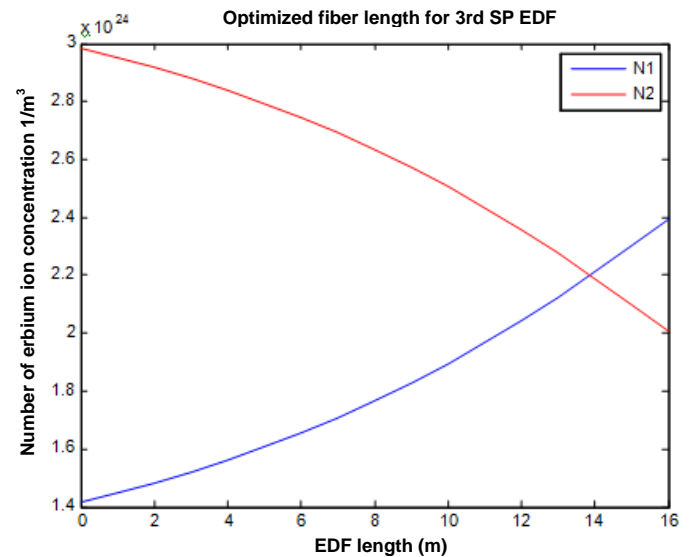

Figure 14. Upper state population and ground state population as a function of fiber length for the third EDF of TP3 EDFA at 10 mW pump power and λ=1550 nm.

fiber length curve for the first DP EDF of TP2 EDFA. Here, N1 and N2 intersect each other at fiber length 15 m. This means the optimum length of the first DP EDF of TP2 EDFA is 15 m.

Figure 11 shows the erbium ions concentration versus fiber length curve for the second SP EDF of TP2 EDFA. Here, N1 and N2 intersect each other at fiber length 14 m. This means the optimum length of the second SP EDF of TP2 EDFA is 14 m.

Figure 12 shows the erbium ions concentration versus

fiber length curve for the first SPEDF of TP3 EDFA. Here, N1 and N2 intersect each other at fiber length 15 m. This means the optimum length of the first SPEDF of TP2 EDFA is 15 m.

Figure 13 shows the erbium ions concentration versus fiber length curve for the second SP EDF of TP3 EDFA. Here, N1 and N2 intersect each other at fiber length 15 m. This means the optimum length of the second SP EDF of TP2 EDFA is 15 m.

Figure 14 shows the erbium ions concentration versus

fiber length curve for the third SP EDF of TP3 EDFA. Here, N1 and N2 intersect each other at fiber length 14 m. This means the optimum length of the third SP EDF of TP2 EDFA is 14 m.

Conclusion

All possible triple pass EDFAs were presented and the performances were compared with each other. Comparing the gain and noise figure values, optimum pump power ratio and signal power are determined for all TP EDFAs. Optimum fiber lengths for specific values of signal power and pump power are also determined. The performance analyses of TP EDFAs were carried out successfully and it was obtained that TP1 performs best than any other TP EDFAs at any input pump power and signal power. With a very small input pump power and signal power, a very high gain and low noise figure can be obtained by using TP1 EDFA configuration. From the obtained results, it can be said that TP1 EDFA will be the best for practical design.

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