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Full Length Research Paper

A novel wide-band dual function fiber amplifier

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The design of a novel wideband Dual-function Erbium-doped fiber amplifier (EDFA) with chirped fiber Bragg grating (CFBG) configured in two-stage double pass amplification scheme is demonstrated in this paper. The proposed architecture is designed to increase amplification bandwidth. The purpose of utilizing the CFBG is to reflect the amplified signal back to the Erbium-doped fiber and to compensate for the fiber dispersion. One of the most attractive features of this amplifier is the integration of both attenuation and dispersion compensation in a single black box. In this work, high gain and low noise figure (NF) for a long haul optical-fiber-communication system (OFCS) are considered as a main design objectives. Therefore, the effects of pump power, signal power, and wavelength on the gain and noise figure are analyzed from the numerical simulation of EDFA using rate equations model. The new proposed configuration is demonstrated using simulation and numerical modeling, and both results match with small differences. The configuration at low single power of -30 dBm is able to achieve gain up to 32.64 dB and noise figure of less than 5 dB.

Key words: Optical amplifier, Erbium-doped fiber amplifier (EDFA) configurations, chirped fiber Bragg grating, noise figure (NF), gain amplifier, optical fiber communication system.

INTRODUCTION

Optical fibre communication is seen as one of the most reliable telecommunication technologies to achieve consumers' needs for present and future applications. Today, optical fibre communication has been established as one of the most promising technologies within the area of medium and long distance data transmissions (Ji, 2005). The recent developments in Erbium-doped fiber amplifiers (EDFAs) have allowed a substantial increase in using repeaterless optical transmission systems, achieving spans of up to ranges of 357, 427, 529 km (Hansen, 1995a, b; Sian, 2002). EDFA has become an important component for long-haul transmission systems in 1550 nm wavelength region (Yamada, 1998). Traditionally, single-pass amplification realized in Remotely-pumped Erbium-doped fiber amplifier (R-EDFA) has been intensively investigated. A single-pass R-EDFA with a midway isolator is proposed to enhance noise figure (NF) and gain (Nuhauser, 2002). Furthermore, the filtration of amplified spontaneous emission (ASE) using midway isolator degrades the signal amplification at the input end of Erbium-doped fiber (EDF), hence reducing the effect of ASE self-saturation in the amplifier system (Matthew, 1998).

Another approach to obtain high gain is to use double-pass amplification in R-EDFA (Masuda, 2003). This approach is able to improve the signal gain due to double signal amplifications while propagating in the EDF. A practical comparative analysis has been carried-out between single and double pass amplification scheme (Naji, 2004), this comparative study shows that the single pass scheme suited for a booster or post-amplification purposes, while double pass scheme gives better performance for application as pre-amplifier stages. Recently chirped fiber Bragg grating (CFBG) utilized

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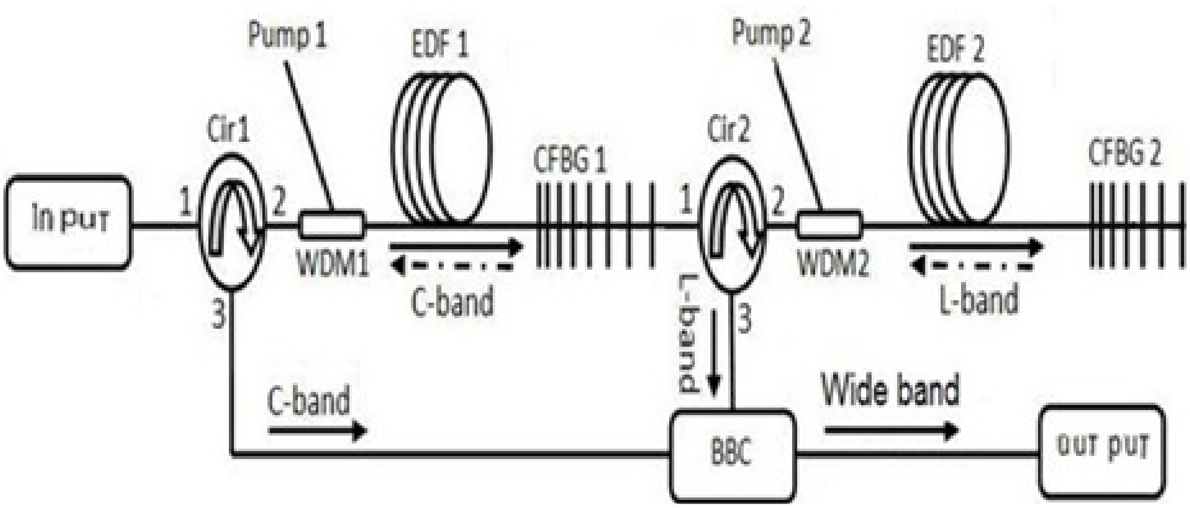

Figure 1. Wideband dual-function two-stage double-pass EDFA with CFBG configuration.

inside EDFA to perform the double pass amplification and to compensate the fiber dispersion at the same time [10]. Theoretically, the rate equations model of Double-pass Erbium-doped fiber amplifier (DP EDFA) (with Mirror) is first time reported in (Hossain, 2007) based on E. Desurvire SP rate equation model. Then, the rate equation model for DP EDFA together with the experimental evaluation (with CFBG to compensate dispersion) is reported by (Nadir, 2007). In this paper, a novel wideband Dual-function Erbium-doped fiber amplifier is demonstrated. The proposed architecture is especially designed to be use for Pre-Amplification application in any long-haul optical communication system.

AMPLIFIER ARCHITECTURE

The proposed wide-band dual-function two-stage double-pass EDFA with CFBG is shown in Figure 1. The gain and noise figure are chosen to be the performance parameters of this design, while the signal power, pump power, EDF length considered as a design parameters. The forward pumping scheme in considered in this design, as the earlier work (Khairi, 2005) investigated the impact of the pumping direction scheme on the performance of DP EDFA, and shows that the there is very minimal impact from using forward or backward pumping scheme.

The amplifier consists of two sections: Sections 1 and 2, with each section comprising of a circulator, pump power, wavelength division multiplexer (WDM), EDF and a CFBG. The 1480 nm pump power is used to provide optical energy in a forward pumping direction for each EDF. The circulator1 and 2 are mainly used to control the directions of the signal and are also utilized to minimize the effect of multipath interference noise in the transmission line. The length of EDF and specification of CFBG are different between the sections 1 and 2. The 7 m of EDF1 with CFBG1 reflect only on C-band wavelengths, while the 17 m of EDF2 with CFBG2 reflect only on L-band wavelengths. Both CFBG1 and CFBG2 have a 90% reflectivity. WDM is used to combine signal and pump light. Broad Band Coupler (BBC) is used to collect the C-band and L-band wavelengths. Normally, the reflector can be built either from a mirror, sagnac loop fibre, FBG or fibre loop mirror or CFBG. However, CFBG used in this work can be utilized as bandwidth reflector. The main advantage of having CFBG in double-pass amplifier structure is to have the capability of compensating the fiber dispersion. The input signal enter from port1 of Circulator 1, this circulator will forward the input signal to port 2. The first active material (EDF1) receives the signal from port 2 and amplifies any frequency within the C-band, then it will get reflected back to EDF1 by CFBG1 for second round of amplification and then the amplified output signal of C-band collected at port 3 of circulator 1. Since the CFBG1 will reflect back only the signals in C-band, the other signals in L-band will propagate through the CFBG1 to reach the second active material (EDF2). Then the signal will get reflected back to EDF2 by CFBG2 for second round of amplification and then the amplified output signal of L-band collected at port 3 of circulator 2. Finally, the whole signals in of C and L band can be collected from the output port of the BBC.

SIMULATION WORK

This work used standard Single Mode Fiber (SMF) with mean dispersion of 17 ps/nm*km. The CFBG has an internal reflection loss of 10 % of the input signal in CFBG and to compensate the total dispersion of 1340 ps/nm.

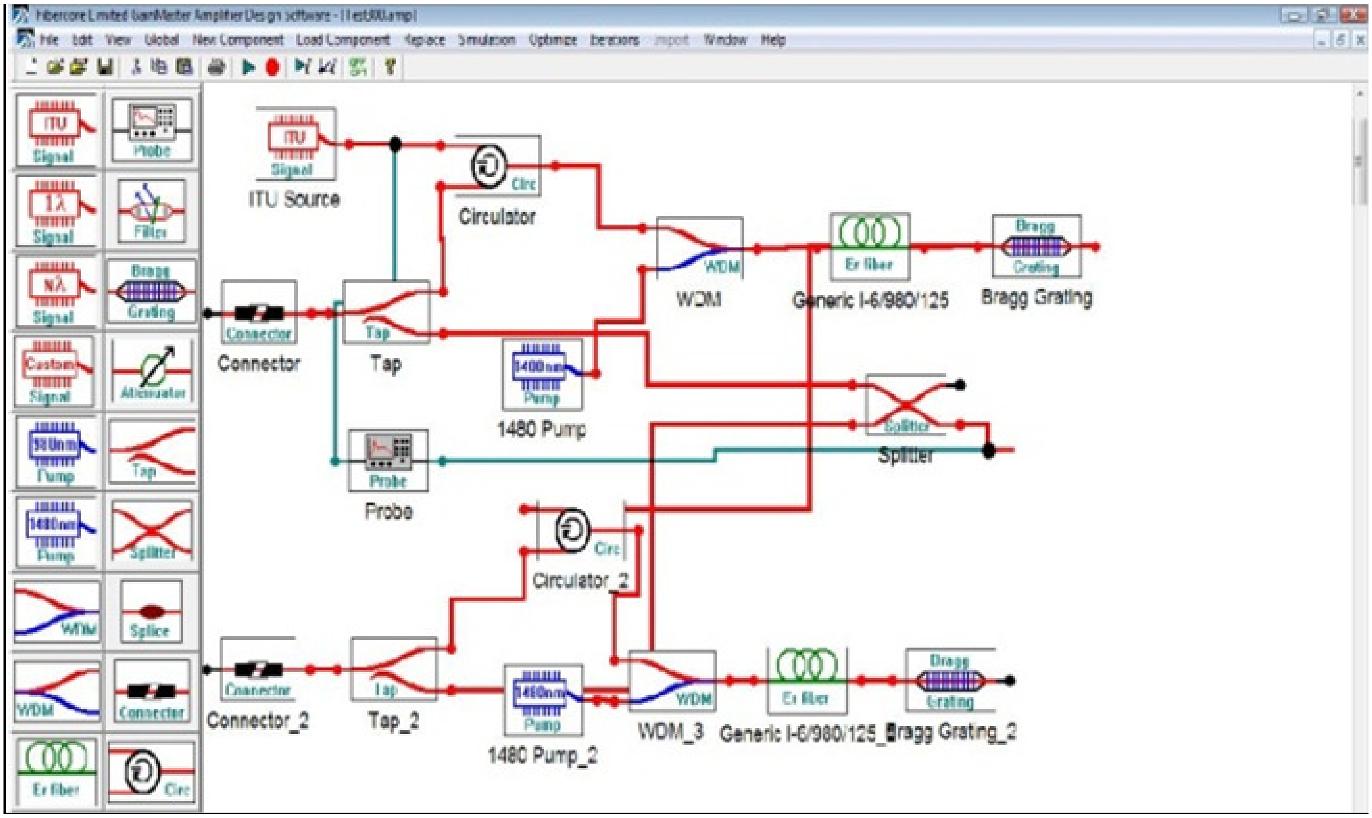

Figure 2. The design of the proposed amplifier using GainMaster simulation.

During the transmission of signal power through the span length from transmitter to EDFA, the fiber suffers from attenuation and distortion effects; hence P (input signal) = -30 dBm. The configuration included the C-band (1520-1565 nm) and L-band (1565-1615 nm) and both compensate for the attenuation and dispersion. The results from this work are obtained by two ways, namely, GainMaster simulation and numerical modeling. Finally a comparison between these two results is conducted.

SIMULATION RESULT OF GAINMASTER

The GainMaster simulator used to simulate the proposed (As shown in Figure 2). The GainMaster simulator is a produced by the very well known company (Fibercore LT. UK. The Fibercore Company shows that the GainMaster is designed to provide customer with a very accurate simulations of any EDFA designs, therefore it has been consider in this project.

The design parameters in this simulation are: Section 1, EDF1 length is 7 m and the pump power is 80 mW. While in section 2, the EDF2 length is 17 m and pump power is 120 mW.

The results obtained from this simulation are: Highest gain obtained at 1530 nm is 32.22 dB and minimum gain at 1614 nm is 9 dB as shown in Figure 3. However, the maximum NF is 7.2 dB at 1530 nm and minimum NF 5dB at 1614 nm as shown in Figure 4.

SIMULATION RESULT OF NUMERICAL MODELING

The second result is obtained from the rate equations model of EDFA using the Matlab version 2010a software. Figure 5 shows the result of the gain and NF. Since pump at 1480 nm populates the upper amplifier level 4I13/2 of the Erbium ions directly, the transition between 4I15/2 to 4I13/2 level is considered. N1 and N2 (population densities) of the 4I13/2 and 4I15/2 and are calculated as follows (Naji, 2007):

$$\frac{dP_P^+}{dz} = P_P^+ \Gamma_P \left[\sigma_{PE}(\lambda_P) N_2 - \sigma_{PA}(\lambda_P) N_1 \right] - \alpha_P P_P^+ \qquad (1$$

$$\frac{dP_S^+}{dz} = P_S^+ \Gamma_S \left[\sigma_{SE}(\lambda_S) N_2 - \sigma_{SA}(\lambda_S) N_1 \right] - \alpha_S P_S^+ \qquad (2)$$

$$\frac{dP_S^-}{dz} = -P_S^- \Gamma_S \left[\sigma_{SE}(\lambda_S) N_2 - \sigma_{SA}(\lambda_S) N_1 \right] + \alpha_S P_S^+ \qquad (3)$$

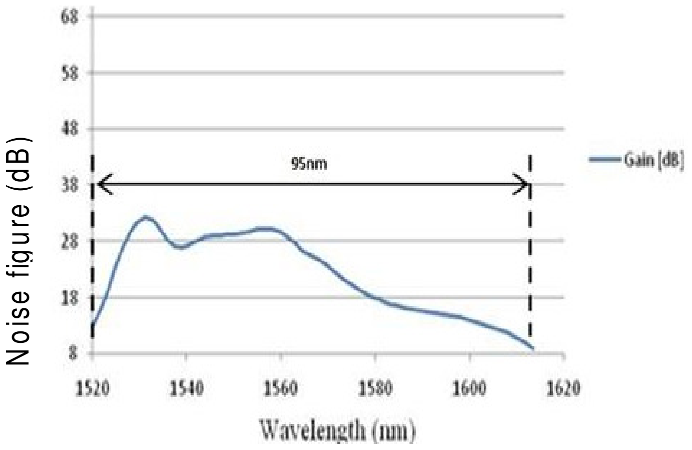

Figure 3. Gain Vs signal wavelength at signal power of -30 dBm, pump power 80 mW and EDF1 length 7 m at C-band, 120 mW and EDF2 length of 17 m at L- band.

$$\frac{dP^{+}_{ASE}}{dz} = P^{+}_{ASE}\Gamma_S\left[\sigma_{SE}(\lambda_S)N_2 - \sigma_{SA}(\lambda_S)N_1\right] + 2\sigma_{SE}(\lambda_S)N_2\Gamma_S hV_S\Delta v - \alpha_S P^{+}_{ASE} \qquad (4)$$

$$\frac{dP^{-}_{ASE}}{dz} = -P^{+}_{ASE}\Gamma_S\left[\sigma_{SE}(\lambda_S)N_2 - \sigma_{SA}(\lambda_S)N_1\right] + 2\sigma_{SE}(\lambda_S)N_2\Gamma_S hV_S\Delta v - \alpha_S P^{-}_{ASE} \qquad (5)$$

where σ is the cross-section of the fiber, hv represents the band-gap energy with h being the Planck's constant , v being the frequency, P_P^{+} is the forward pump power as well as P^{+}_{ASE} and P^{-}_{ASE} are the forward and backward spontaneous emission spectrum.

The ρ = N1 + N2 is the Erbium ions density per unit volume τ is the fluorescence lifetime and by definition. 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 $\sigma_{SE}(\lambda_S)$, $\sigma_{SA}(\lambda_S)$, $\sigma_{PE}(\lambda_P)$, $\sigma_{PA}(\lambda_P)$ are the emission and absorption cross sections at signal (VS) and pump (VP) frequencies, respectively. A is the effective area of the distribution of Erbium ions. The equations describing the spatial development of P^{+}_{ASE}, P^{-}_{ASE}, P_P^{+} and P_S are written based on the (Desurvire ,1991).

The following three equations are represented the spontaneous noise power produced a long the DP-EDFA within the DP EDFA homogeneous bandwidth Δv for both states, while α_S and α_P represent the internal-signal and pump-loss terms of DP EDFA. The NF is generated by the spontaneous-emission and the number of spontaneous photons is calculated by (Becker, 1999):

$$\eta_{SP} = \frac{\eta N_2}{\eta N_2 - N_1} \qquad (6)$$

where the (z) is the coordinate along the EDFA fiber and η defined as following;

$$\eta = \frac{\sigma_{SE}}{\sigma_{SA}} \qquad (7)$$

As a result, NF of the high gain DP-EDFA at signal wavelengths (λ_S) is calculated as following:

$$NF(\lambda_S) \approx \eta_{SP} \qquad (8)$$

Figure 5 shows the highest gain (32.64 dB) at 1530 nm and around 7 dB as NF in section1 (C-band).The minimum gain is 9 dB at 1614 nm and around 5 dB as NF in section 2 (L-band). The gain starts from 20 dB at 1520 nm and sharply increases up to reach the maximum at 1530 nm due to its higher absorption and emission. The phase starts decreasing until 1540 nm and begins approximately stable until 1570 nm and then drops again.

Figure 6 shows the gain and NF in dB as a function of pump power in mW at 1550 and 1590 nm utilized in sections 1 and 2, respectively. The lengths EDF1 used at (C-band) are from 5 to 15 m and, while fro EDF2 are from

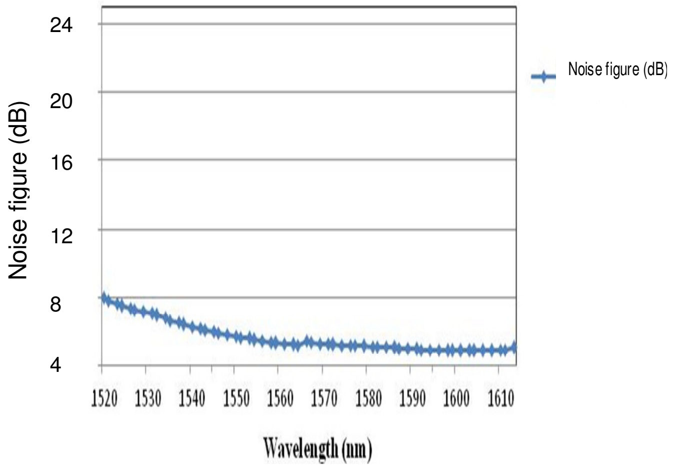

Figure 4. Noise figure Vs information signal wavelangth.

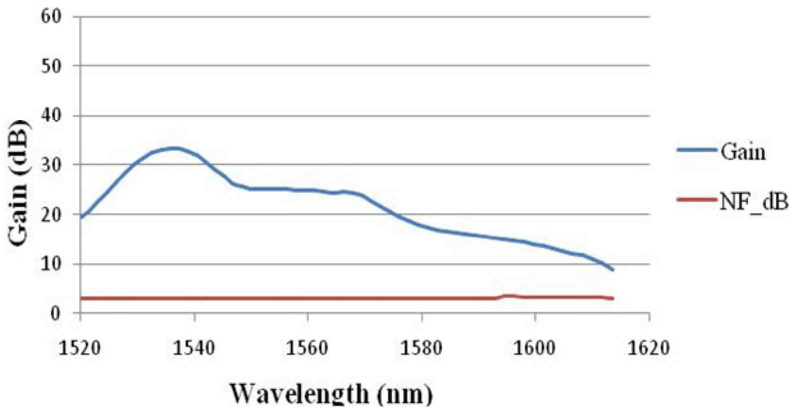

Figure 5. The gain and NF Vs signl wavelength at 153 nm with NF at (1530 nm) = 7.2 dB and minimum gain at (1614 nm) = and NF at (1614 nm) = 5 dB.

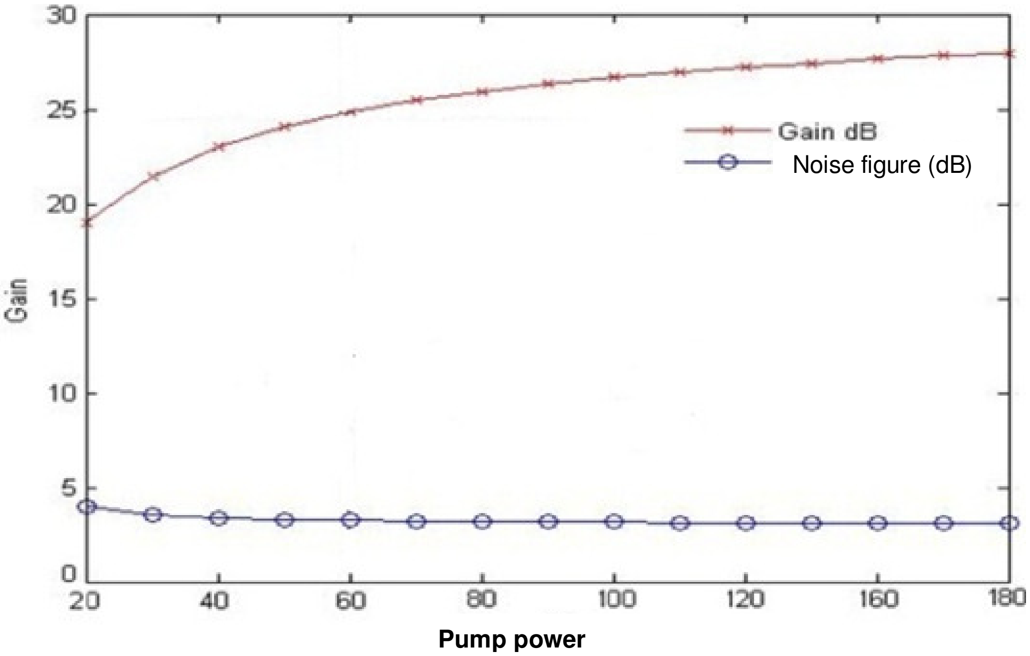

Figure 6. Gain and NF in dB as a function of pump power in mW using a 10 m long EDF at 1550 nm signal wavelength.

15 to 25 m for (L-band). As well as, from the literature review the 1550 nm and 1590 nm have been chosen as example from the C-band and L-band respectively. The operating pump power of DP EDFA architecture for EDF1 and EDF2 is specified by varying the pump power against the operating signal power.

This work applied 10 /m FED1 length and 20 m for EDF2 to get the optimum pump power. The gain and NF characteristics at 1550 nm as a function of pump power and 10 m is selected as reference for the current work (C-band) and injected signal power of -30 dBm is shown in Figure 6.

To obtain the optimum pump power for the DP EDFA of the section 1, different values of pump powers from 20 to 180 mW were varied. Figure 6 shows that the pump power from 20 mW up to 80 mW can give gain from around 19.1 /dB until 25 dB. While the NF is around 5 dB and becomes almost constant when the pump power exceeds 25 mW. This is due to the Erbium ions concentration in upper state population reaches the saturation after certain amount of pump power.

On the other hand, increasing the pump power from 80 to 100 mW increases the gain slightly from 25 to 25.45 dB with almost a constant NF. Therefore, the pump power of

Table 1. EDF parameters used in simulation.

λ_S = 1550 nm	$\sigma_{SA}(\lambda_S)$ = 2.85 × 10^{-25} m^2
λ_p = 1480 nm	$\sigma_{SE}(\lambda_S)$ = 4.03 × 10^{-25} m^2
Γ_S = 0.43	$\sigma_{PA}(\lambda_P)$ = 2.86 × 10^{-25} m^2
Γ_P = 0.40	$\sigma_{PE}(\lambda_P)$ = 0.32 × 10^{-25} m^2
A = 19.8 × 10^{-8} m^2	Δv =3100 GHz (25 nm)
ρ = 440 ppm	τ = 0.011 s
α_S = 0.20 dB/Km	α_P = 0.24 dB/Km

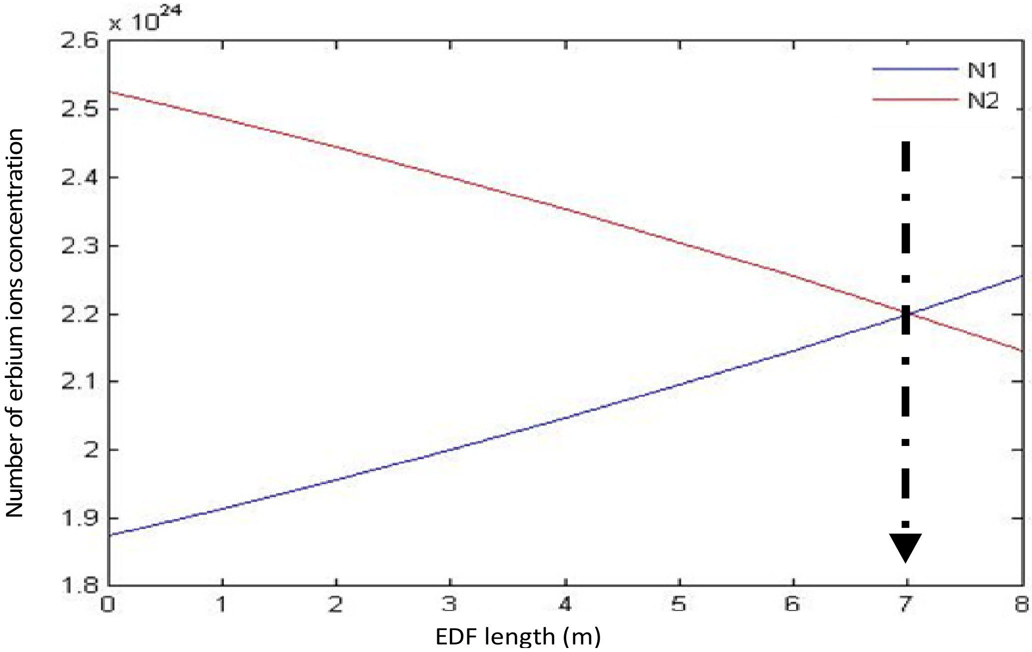

Figure 7. Populations in upper stat N_2 and ground state N_1 as function of position along a 7 m long EDF at 1550 nm using 80 mW.

80 mW is chosen as the optimum pump power for the DP EDFA configuration using the EDF1. The EDF1 parameters used to simulate the model are tabulated in Table 1.

Figure 7 shows how to calculate optimum length of EDF1. The length of the EDF is calculate by using the optimum pump power 80 mW and using N1 and N2 as function of position along the length of EDFA.

When N1 and N2 intersect together, the optimum length for 1550 nm during the C-band is obtained. As a result, the optimum length for C-band is 7 m as shown in Figure 7.

Referring to Figure 7, N2 increases up to the length of 7 m and after that it begins to decrease. This is because the pump power is absorbed inside the EDF due to the population inversion. If the length of EDF1 is more than 7 m, the portion of the EDF1 that exceeds 7 m remains unpumped. This unpumped portion of the EDF will absorb the signal and degrades the EDFA performance.

On the other hand, the gain and NF characteristics at 1590 nm as a function of pump power and 20 m is selected as reference for (L-band) is shows in Figure 8.

By applying different values of pump powers from 30 to 230 mW, Figure 8 shows that that gain increases from 15.5 dB at 30 mW until 18.5 dB at 120 mW pump power. However, after 120 mW, the gain is slightly increased with a little bit different from 120 until 230 mW. This is due to the erbium ions concentration at the upper population reaches almost to constant level and hence the increment of the gain is tend to be constant.

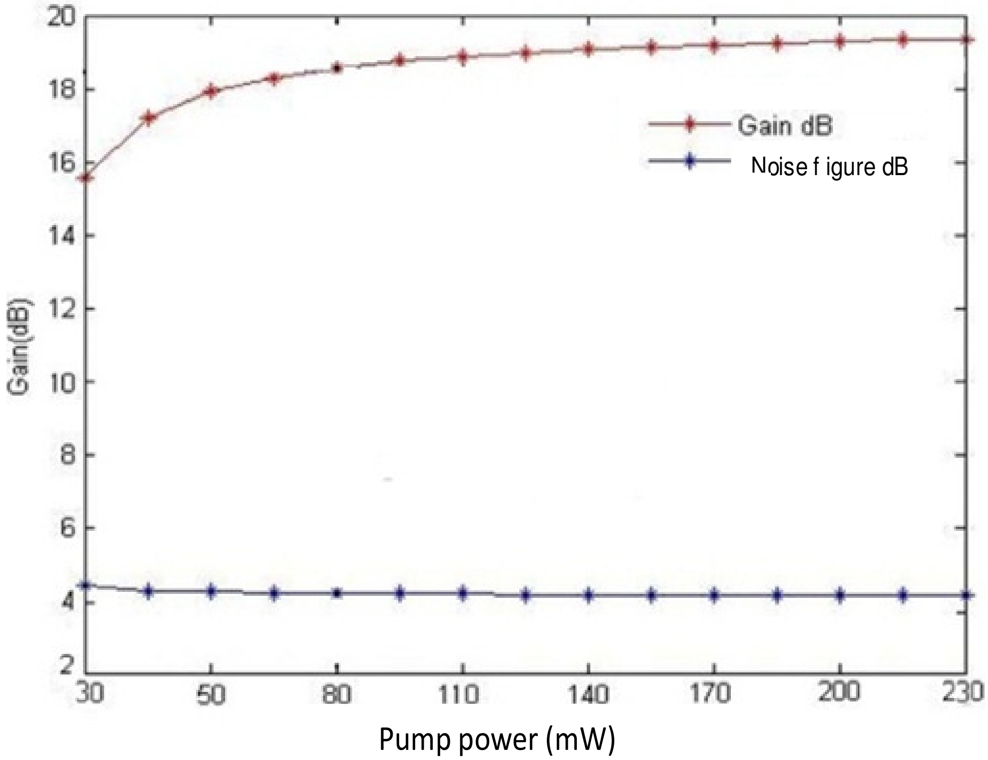

Figure 8. Gain and NF in dB as a function of pump power in mW using a 20 m long EDF at 1590 nm signal wavelength.

Table 2. EDF parameters used in simulation.

λ_S = 1590 nm	$\sigma_{SA}(\lambda_S)$ = 421 × 10^{-25} m^2
λ_p = 1480 nm	$\sigma_{SE}(\lambda_S)$ =1.297 × 10^{-25} m^2
Γ_S = 0.43	$\sigma_{PA}(\lambda_P)$= 2.86 × 10^{-25} m^2
Γ_P = 0.40	$\sigma_{PE}(\lambda_P)$ = 0.32 × 10^{-25} m^2
A = 19.8 × 10^{-8} m^2	Δv =3100 GHz (25 nm)
ρ = 440 ppm	τ =0.011 s
α_S = 0.20 dB/Km	α_P = 0.24 dB/Km

The NF reaches a constant value 4.5 /dB for the pump power exceeds 120 mW. This is because the Erbium ions concentration at upper state population reaches a constant level and hence is tends to be constant.

Therefore, the pump power of 120 mW is chosen as the optimum pump power for the EDF2. All the EDF2 parameters used to simulate the model 1590 nm are shown in Table 2 are also collected from the Fibercore Ltd.

In addition, all the design parameters used in wavelength 1590 nm are same as the parameters that used in previous wavelength 1550 /nm at the C-band, except the values of absorption of cross section of signal $\sigma_{SA}(\lambda_S)$ = 0.421 × 10 - 25 m^2 and emission of cross section of signal $\sigma_{SE}(\lambda_S)$ = 1.297 × 10 to 25 m^2.

Furthermore, after calculatingthe optimum pump power of 1590 nm, the optimum length of EDF1 can be calculated by fixing the optimum pump power 120 mW and using N1and N2 as function of the position along the length of EDFA to find the optimum length of EDF2.

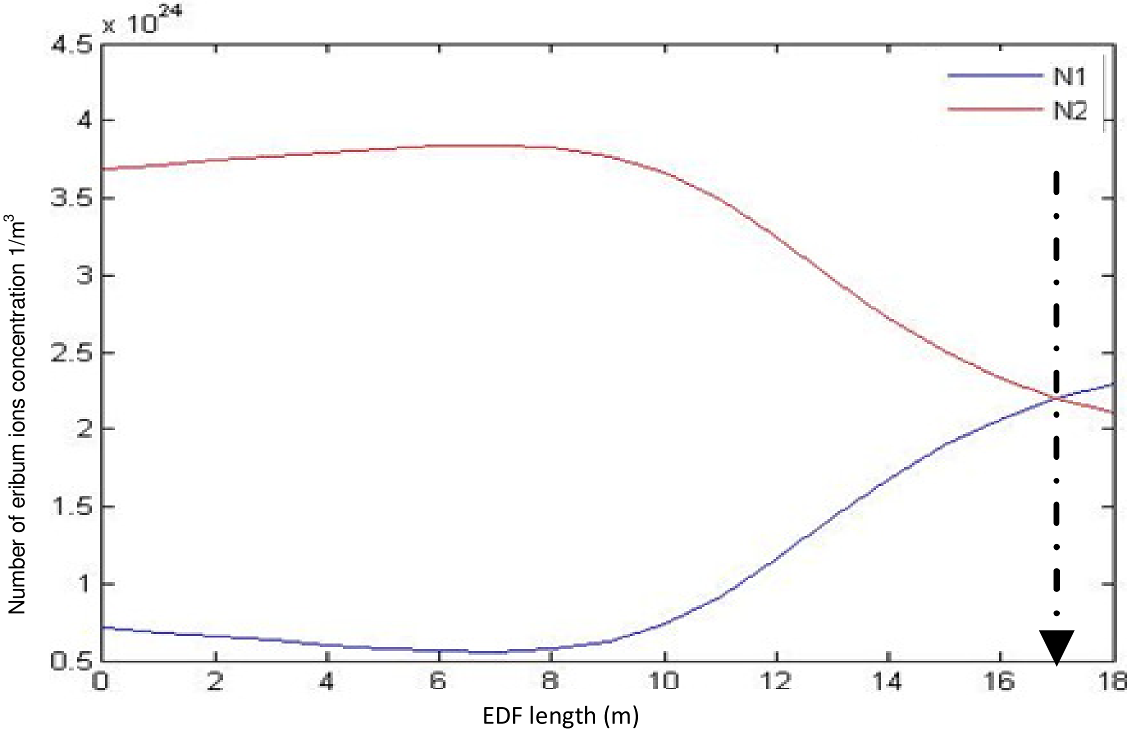

Figure 9. Populations in upper state N2 and ground state N1 as function of position along a 17 m long EDF at 1590 nm using 120 mW.

When N1 and N2 intersect together then the optimum length is obtained for 1590 nm during the L-band. As a result, the optimum length for EDF2 is 17 m as shown in Figure 9.

The comparison between the results from Matlab simulation and GainMaster simulation shows that the gain in Matlab simulation (32.64 dB) is slightly higher than gain of GainMaster (32.22 dB). This shows that the difference is very minimal and both simulations give close results. Furthermore, the NFs from both simulations were also closed, where less than 5 dB and less than 6.7 dB for Matlab and GainMaster respectively.

CONCLUSION

A new wideband dual-function EDFA integrated with a CFBG has been successfully demonstrated to compensate fiber dispersion as well as to amplify the optical signal. Optimization of the pump power and EDF length were discussed and demonstrated using the mathematical model of N1 and N2. The effects of pump and signal power, signal wavelength, EDF length on the gain and NF of the EDFA were analyzed using the numerical simulation of the rate equations model. The new EDFA is designed to cover wideband (C-band and L-band). For the optimized design, a signal gain of higher than 32 dB is obtained for small input signal -30 dBml. Furthermore, the optimum pump power and EDF length are 30 m and 7 m in section 1 and 80 mW, 17 m in section 2. Hence, the theoretical results have a similar pattern to the experimental results. This work does not apply any gain flatting technique. Therefore, as future work, we recommend using suitable technique of gain flatting technique to enhance the performance of the current work. This proposed amplifier can be used in modern long haul OFCS. Finally, it is hope that these findings will spark the thoughts of other researchers to integrate dispersion compensating modules with optical amplifiers in a single black box.

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