Performance optimization of amplified spontaneous emission noise re-injection based L-band EDFA

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Abstract : Ever-increasing demands of internet services for high capacity puts a peer pressure on conventional (C-band) frequency band and there is need to use wavelengths of Long band (L-band) to meet the aforementioned requirement. However, amplification of L-band through EDFA suffered from various limitations. Therefore, in this work, L-band EDFA amplifier is proposed with and without amplified spontaneous noise reinjection. Different physical parameters such as core radius, EDF link lengths, launched powers are varied and results are analyzed in terms of Gain, noise figure. Moreover, amplified signals are transmitted over SMF-28 (single mode fiber) at varied link lengths using return to zero and non return to zero linecodings and results compared in terms of Q-factor and BER.

***IndexTerms* - Long-band (L-band), Erbium doped fiber amplifier (EDFA), Amplified spontaneous noise (ASE), Non-return to zero (NRZ), Return to zero (RZ), Fiber bragg grating (FBG)**

I. INTRODUCTION

With the evolvement of high capacity data communication systems, Long band erbium-doped fiber amplifiers (L-EDFAs) are getting more attention in recent times [1][2]. Major advantage of the L-band EDFA is that it provides the user to realize a system with wide bandwidth of 45 nm [3]. But, from the reported works, it is evident that the Long band EDFA has low pump conversion efficiency (PCE) and lies at the tail of the EDFA amplification window [4][5][6]. Efficiency of the pump and gain of the EDFA is enhanced in the L-band, either by using the long span of erbium fiber or by increasing the ion concentration of the amplifiers fiber [7]. Numerous works has been witnessed in the gain enhancement of aforementioned amplifiers. One of the best techniques was accomplished through seed signal injection of conventional band [8]. In Long band EDFA, prominent and premier technique of amplified spontaneous noise was used by utilizing forward and backward ASE to get the improved gain and less noise figure [9]. This process was done through the narrowband Fiber Bragg Gratings (FBG) or fiber reflectors mirrors [10]. The process such as feedback of undesired emergence of amplified spontaneous emission (ASE) power into erbium doped fiber to considered as the additional pump all the way through the employment fiber Bragg grating, C-band light assisted pumping, as well as using a double-pass technique [11]. From the above mentioned methods, technique based on double pass came out to be an ultimate cost effective solution that deploy circulators in order to recycle amplified spontaneous noise in the erbium fiber to augment the gain of L-band EDFA [12] [13]. From the extensive literature survey, it is perceived that either L-band Gain enhancement techniques were complex, costly or suffered from high noise figure.

In this work, two different scenarios are considered by presenting system with and without ASE and results are analyzed in terms of Gain and noise figure. A Long band erbium doped fiber amplifier is proposed with high gain and less noise figure by incorporating the two fiber bragg gratings (FBGs) for amplified spontaneous noise reinjection. Maximum ASE is emerged at 1565 nm for the 1570 nm input wavelength at -45 dBm carrier powers. Different physical parameters such as core radius, EDF link lengths, launched powers are varied and results are analyzed in terms of Gain, noise figure.

II. NEED OF AMPLIFIED SPONTANEOUS NOISE (ASE)

Amplification in EDFA amplifier is accomplished due to stimulated emission, but there is emergence of another type of emission termed as spontaneous noise in the amplifiers. Due to amplified spontaneous noise (ASE), Gain of the amplifiers decreases and noise figure increases. An prominent effect in the EDFA amplifier is that 980 nm pump light can generate a strengthened conventional band amplified spontaneous noise on the starting part as well as output of the EDF fiber because of the oscillation of ions between two energy levels such as $^4I_{13/2}$ and $^4I_{15/2}$. This ASE can be used as the secondary pump source in the EDFA amplifier and offer additional energy to the amplification stage. Therefore, main work of ASE injection into amplifier is to augment Gain and to suppress noise figure.

III. PROPOSED ARCHITECTURE FOR ASE RE-INJECTION L-BAND EDFA

In this work, a bi-directionally pumped long band erbium doped fiber amplifiers is proposed using two fiber bragg gratings with amplified spontaneous reinjection as depicted in Figure 1. Speed of the operation is fixed to 10 Gbps from binary data bits generator. A continuous wave laser at -45 dBm power and wavelength 1570 nm is incorporated in the system which is acting as L-band source. Laser signal is passed through optical isolator to prevent optical source from the back flowing optical intensity due to ASE. Laser signal fed to optical co-propagating pump coupler and a pump 1 at 974 nm wavelength is also coupled to this module. Here, FBG 1 is acting as the reflector of backscattered ASE signal at 1565 nm and combined with pump 1. The wavelength of 1565 nm is to be reflected because of maximum intensity of ASE at this point. Output of EDF fiber send to the counter propagating coupler and power of pump 2 at wavelength 976 nm is combined here. FBG 2 is employed to reflect the forward scattered amplified spontaneous noise and power is combined with pump 2. Finally signal passed through the isolator and gain of signal is accessed by dual port WDM analyzer.

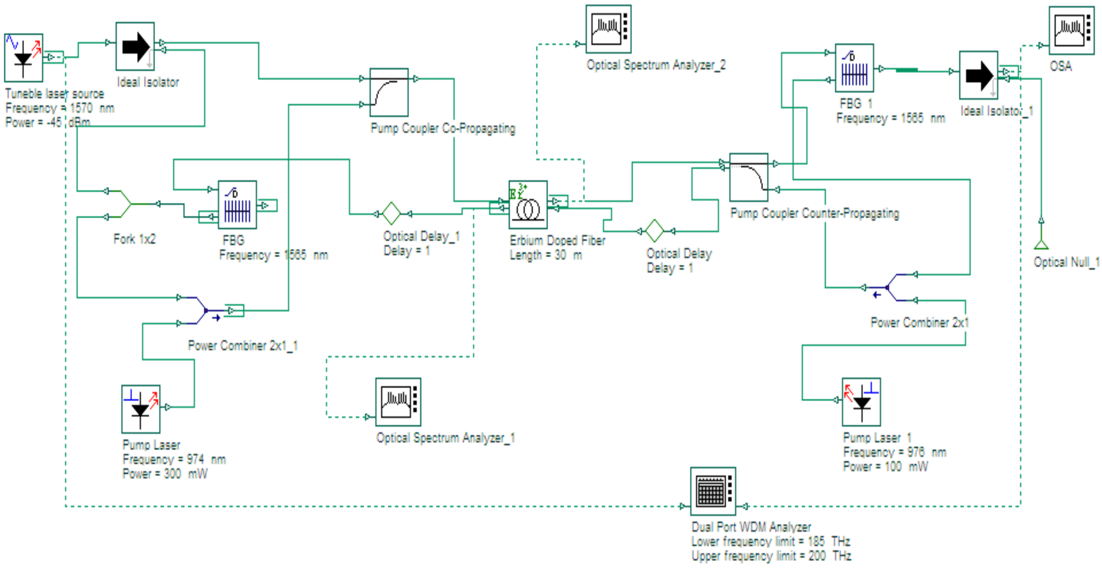


Figure 1: Simulation setup of proposed L-band EDFA

3.1 Analysis of different physical parameters of L-band EDFA

An erbium doped fiber with 200 ms metastable lifetime is taken. Various physical parameters are varied such as core radius, input power, doping radius and length of the EDF. Simulation parameters are shown in Table 1 to clear the factors that are considered for the proposed work. Moreover, to evaluate the performance of the system, an optical fiber standard SMF-28 is chosen for the design of L band single stage erbium doped fiber amplifier. Single mode fiber is considered with 0.2 dB per kilometer attenuation and pulse broadening of 17 ps per nm per kilometer. All the nonlinear effects are also kept on to get the close to practical results. Pseudo random bit sequence generator at 10 Gbps data rate is employed in the system for the generation of binary data bits. Non return to zero/ return to zero pulse shaping is done of the binary data. An intensity modulator for the electrical data to optical data conversion is incorporated in the system which gets derives from NRZ/RZ and laser signal.

Table 1: Simulation parameters of the demonstrated work

Parameters	Values
Laser	Tunable laser source
Wavelength and power	1570 nm and -45 dBm
Data speed	10 Gbps
Number of FBGs to reinject ASE	2
Length of EDF fiber	varied from 5m to 35 m
Core radius of EDF	varied from 0.7 um to 1.9 um
Input power	varied from -55 dBm to 5 dBm

IV RESULTS AND DISCUSSIONS

In this research work, a Gain enhancement of the long band erbium doped amplifier with and without the use of amplified spontaneous emission reinjection through FBGs is presented. To accomplish the work, Optiwave optisystem is considered. Effect of various physical parameters of erbium doped fiber such as radius of core, length of the EDF fiber, launched power, forward/backward ASE power emergence are investigated in terms of Gain, noise figure.

4.1 Effect of Input power on Gain of L-band EDFA with and without ASE re-injection

First and foremost, effect of launched power is analysed on L-band EDFA. A tunable laser at wavelength 1570 nm is incorporated in the system with 10 MHz laser linewidth. Power is varied from -55 dBm to 5 dBm and iterated in the EDF fiber which connected with bidirectional pumping. Results are analyzed in terms of output power and readings are noted from wavelength division multiplexed analyzer. Figure 2 (a) (b) depicts the performance of the system at varied levels of input power levels in terms of Gain and noise figure with ASE and without ASE re-injection respectively. Results revealed that there is increase in output power from -55 dBm to -45 dBm and Gain starts decreasing beyond -45 dBm. In Figure 2 (a), Gain of the signal starts decreasing after -45 dBm and in Figure 1.2 (b) due to the less emergence of ASE on high power levels gain also reduces. It is evident that Gain is more in case of the system with ASE re-injection nd less in system without ASE re-injection. Highest Gain value of 38.21 dB is achieved at input power level of -45 dBm with noise figure of 4.67 dB in ASE re-injected system as shown in Table 2. Moreover, in case of noise figure, the power of the noise is approximately similar at all power levels except the -5 dBm. So, it is recommended to use ASE re-injection and -45 dBm input power due to highest Gain and acceptable level of noise figure.

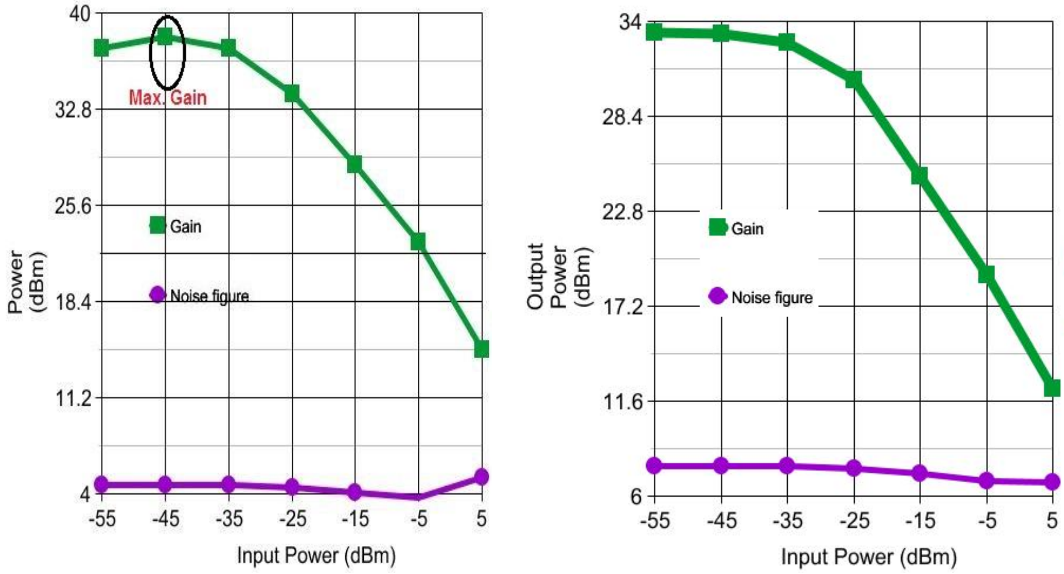


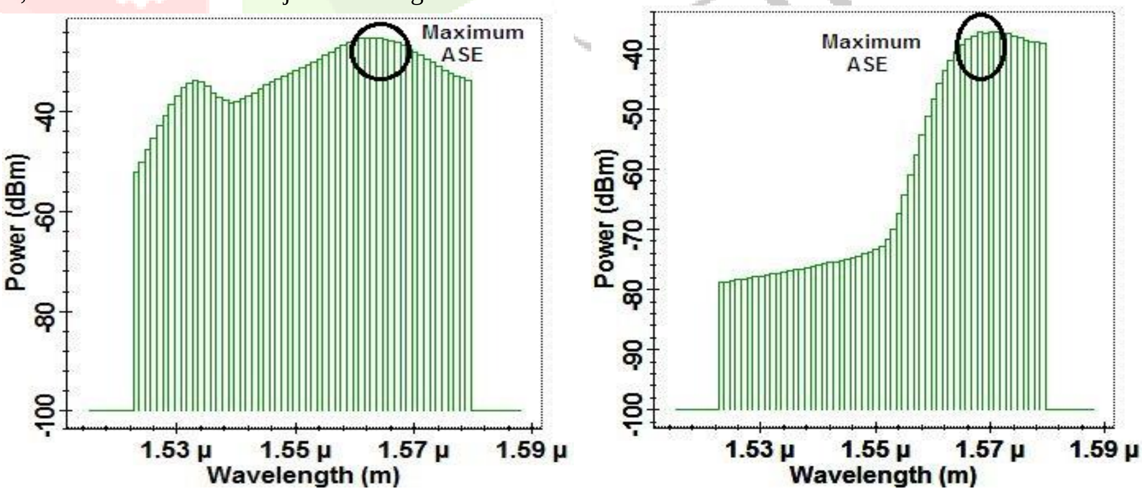
Figure 2: Variation of Gain and noise figure of proposed L-band EDFA with respect to input power (a) with ASE re-injection (b) w/o ASE re-injection

Table 2: Values of Gain and NF at different input powers with ASE re-injection

Input power (dBm)	Gain (dB)	NF (dB)
-55	37.32	4.68
-45	38.21	4.67
-35	37.33	4.63
-25	33.89	4.45
-15	28.6	4.09
-5	22.81	3.72
5	14.74	5.25

4.2 ASE representation with optical spectrum analyzer

Amplified spontaneous emission noise is a prominent power degrading issue in the erbium doped fiber amplifiers. However, in this work, the use of ASE has been done to enhance the Gain through the FBGs. This is done by re-injecting the ASE in the EDF fiber with the combined power of pumps. It is seen that there are two type of ASEs in the system. One is forward ASE and second is backward ASE. Figure 3 (a) (b) represents the output of optical spectrum analyzer to depict the backward/forward ASE. It is percived from Figure 3 (a) that maximum backward ASE is emerged at the wavelength of 1565 nm and in Figure 3 (b), again the maximum forward noted ASE is near about 1565 nm. Thus, in proposed work, ASE at 1565 nm is reinjected through the two FBGs in the EDF fiber.



(a) (b)

Figure 3: Optical spectrum of amplified spontanwous noise for (a) Backward ASE (b) Forward ASE

4.3 Emergence of forward/backward ASE with input power

Figure 4 depictst the representation of forward ASE and backward ASE at different input powers. It is interesting to observe the launched power effects on the forward and backward ASEs. It is evident that increase in the launched power levels cause the suppression in the total output ASEs in both the cases. However, power level of backward ASE is greater than the forward ASE at every level of incident light.

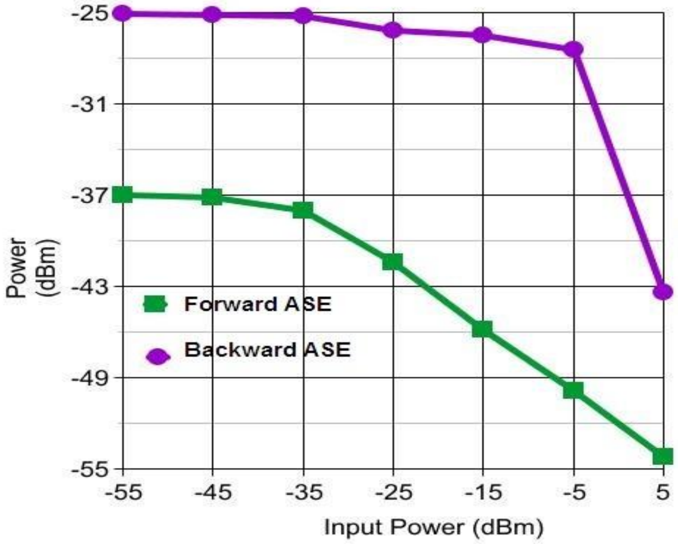


Figure 4: Graphical representation of forward ASE and backward ASE at different input powers

Backward and forward amplified spontaneous noises are similar for two power levels such as -55 dBm and -45 dBm and after this value it starts degrading. Lowest level of ASE is observed at power of 5 dBm as shown in Table 3. It is noteworthy that there is significant decrease in ASEs from -45 dBm to -5 dBm, but beyond this level, ASE reduces abruptly till 5 dBm.

Table 3: Forward/Backward ASE power variation with input power

Input power (dBm)	Forward ASE (dB)	Backward ASE (dB)
-55	-37.033	-25.1
-45	-37.15	-25.21
-35	-38.04	-25.25
-25	-41.43	-26.2
-15	-45.88	-26.5
-5	-49.91	-27.5
5	-54.25	-43.46

4.4 Effect of EDF length on Gain and noise figure with and without ASE re-injection

Figure 5 (a) (b) depicts the represents the effect of changing the length of the erbium doped fiber on the Gain and noise figure with ASE and without ASE re-injection respectively. EDF length has a significant effect on the overall gain of the system and it is reported that longer lengths cause more output power and inturn increase the Gain of the system. In proposed work, the length of the EDF tends to fluctuate between 5 m to 35 m and Gain is noted down on these values. In Figure 5 (a), It is observed that the highest Gain (38.26 dB) is seen at the length of 30 m annd value of noise figure at this point is 4.67 dB in system with ASE re-injection. However, in Figure 5 (b), it is percieved that lesser gain is acheived in the system without ASE re-injection. All the values of the Gains and noise figures acording to the different lengths of the erbium doped fiber are listed in Table 4. It is recommended to use 30 m length of EDF for maximum Gain.

Table 4: Gain and NF values at varied EDFA lengths with ASE re-injection

Length EDFA (m)	Gain (dB)	NF (dB)
5	27.59	4.55
10	33.33	4.85
15	35.96	4.9
20	37.54	4.87
25	38.25	4.79
30	38.26	4.67
35	37.54	4.54

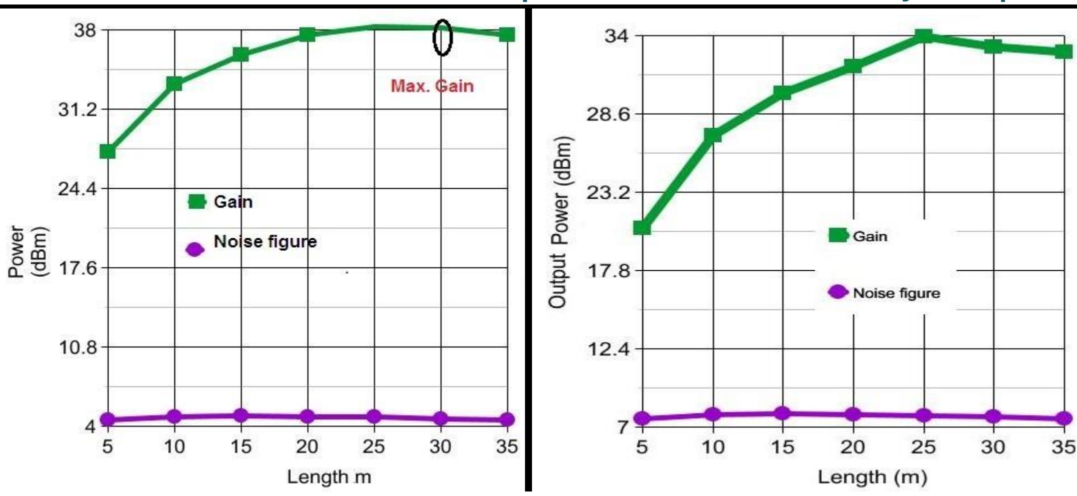


Figure 5: Effect of EDF length on Gain and noise figure of proposed L-band EDFA (a) with ASE re-injection (b) without ASE re-injection

4.5 Effect of core radius of EDFA on Gain and noise figure with and without ASE re-injection

Further, a performance comparison has been carried out for different values of core radius. Core radius is varied from 0.7 micron meter to 1.9 micron meter of erbium doped fiber to check the gain and noise figure. From the Figure 6 (a) (b), it is perceived that the at the initial small core radius values (0.7 – 1.1 µm), Gain tends to increase and after 1.1 µm it starts decreasing. Highest Gain is found at the core radius value of 1.1 µm in case of ASE re-injection system as depicted in Figure 6 (a). However, in Figure 6 (b), maximum Gain is observed at core radius of 1.3 um but Gain is lesser in the system without ASE re-injection.

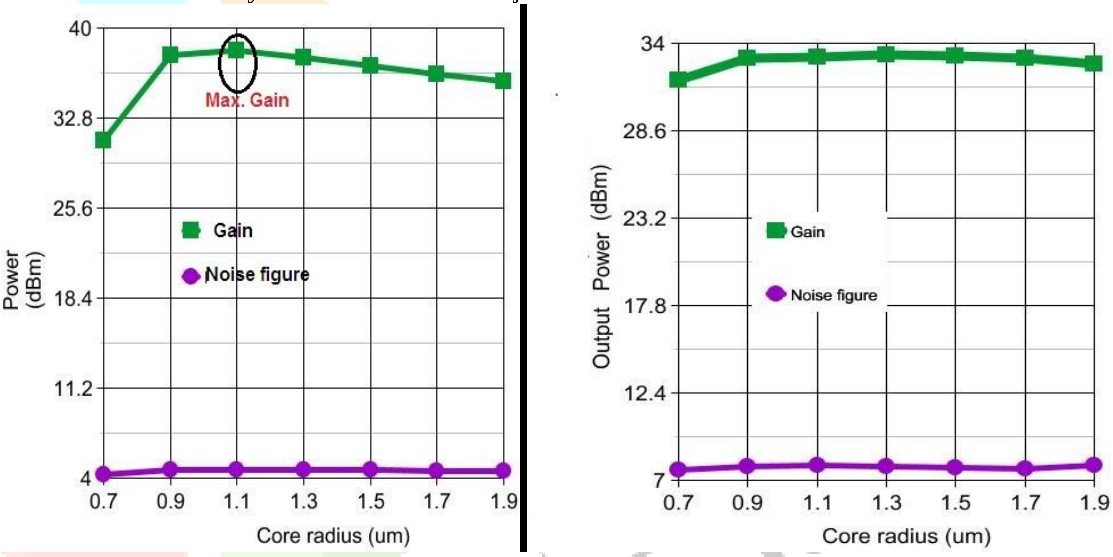


Figure 6: EDF's core radius effects on (a) ASE re-injected (b) without ASE re-injected L-band EDFA in terms of Gain and noise figure

Table 5 shows the values of the Gain and noise figure at varied radius of the EDF's core. Numerical aperture of the fiber also varies with the change in the core radius. Enhanced value of Gain with acceptable noise figure is reported at the 1.1 µm and thus recommended to use this core radius.

Table 5: Power values to represents Gain and NF at different core radiuses of ASE re-injected system

Core radius (um)	Gain (dB)	NF (dB)
0.7	31	4.31
0.9	37.81	4.66
1.1	38.21	4.67
1.3	37.64	4.65
1.5	36.94	4.62
1.7	36.3	4.56
1.9	35.73	4.57

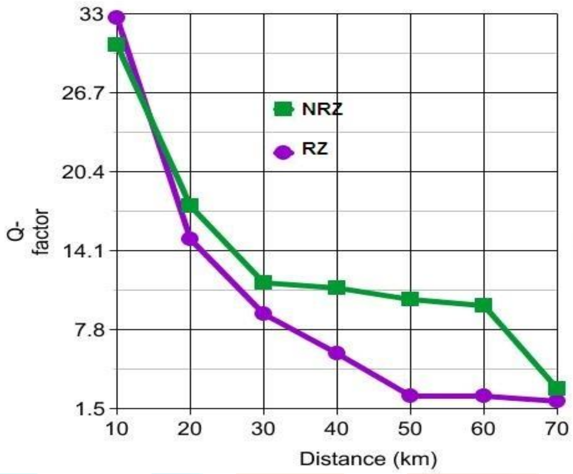
From the aforementioned performed evaluations and results, it is observed that the optimal length of erbium doped fiber is 30 m with the launched power of -45 dBm. Also the core radius should be considered 1.1 micron meter.

4.6 Performance of NRZ/RZ in proposed system

In order to validate the performance of proposed L-band EDFA over single mode fiber, distance is varied from 10 km to 70 km and results are examined in terms of Q factor and bit error rate (BER). Performance of two different line coding such as Non-return to zero and return to zero has been compared. Figure 7 depicts the performance of NRZ and RZ modulation formats over different lengths of single mode fiber in terms of Q-factor. Results revealed that as the link length increases from 10 km to 70 km, Q of the received signal in both cases decreases. This is due the effects of attenuation, dispersion and nonlinear effects. It is evident that due to the bandwidth efficiency of NRZ modulation format, it surpasses the performance of RZ modulation format. Table 6 shows the values of Q-factor at the different link lengths of the optical fiber. It is clearly observed that system works for 65 kms in case of NRZ within acceptable range of Q-factor and in case of RZ, It works for only 40 kms.

Table 6: Distance versus Q-factor values in case of NRZ and RZ

Distance (km)	NRZ	RZ
10	30.5	32.62
20	17.66	14.99
30	11.5	9.03
40	11.14	5.9
50	10.21	2.52
60	9.72	2.45
70	3.07	2.1



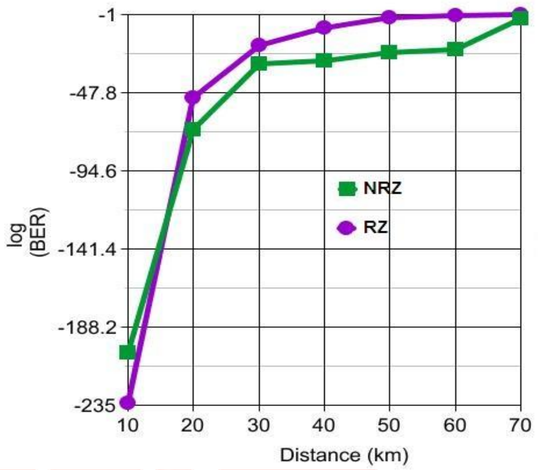


Figure 7: Q-factor versus distances for NRZ/RZ   Figure 1.8: log (BER) Vs Distance

Further, analysis of the performance of NRZ and RZ modulation formats over different lengths of single mode fiber in terms of log (BER) has been done. Results revealed that as the link length increases from 10 km to 70 km, log (BER) of the received signal in both cases increases. This is due the effects of attenuation, dispersion and nonlinear effects. It is evident that due to the bandwidth efficiency of NRZ modulation format, it surpasses the performance of RZ modulation format. Table 7 shows the values of BER at the different link lengths of the optical fiber. It is clearly observed that system works for 65 kms in case of NRZ with BER $3.1*10^{-19}$ and in case of RZ, It works for only 40 kms with BER value $1.4*10^{-9}$.

Table 7: Values of BER of NRZ and RZ at varied distances

Distance (km)	NRZ	RZ
10	$2.3*10^{-204}$	$4.1*10^{-234}$
20	$4.7*10^{-70}$	$6.2*10^{-51}$
30	$7.4*10^{-31}$	$8.3*10^{-20}$
40	$3.3*10^{-29}$	$1.4*10^{-9}$
50	$1.2*10^{-24}$	$4.5*10^{-3}$
60	$2.6*10^{-22}$	$9.1*10^{-2}$
70	$7.2*10^{-4}$	$1.2*10^{-1}$

4.7 Eye diagrams for NRZ/RZ

`Eye diagram is an important depiction to decide the performance of the system. If eye opening is more of the received signal then the Q-factor automatically increases with the low BER. Q-factor degrades if the received eye diagram has more eye closer. At the distance of 10 km, observed eye diagram is open to the maximum height due to less attenuation and dispersion effects. As the distance prolongs, attenuation also increases and ultimately eye opening becomes less. Maximum eye closer penalty is found at the 70 km link distance in the both cases such as NRZ and RZ. However, the extent of eye opening is more in case of NRZ at all the distances as compared to the return to zero modulation format. This is because of the bandwidth efficiency of the on-return to zero modulation format. Figure 9 (a) (b) depicts the eye diagram of NRZ signal at 10 km and 70 km respectively. Also, Figure 9 (c) (d) represents the eye of RZ at 10 km and 70 km respectively.

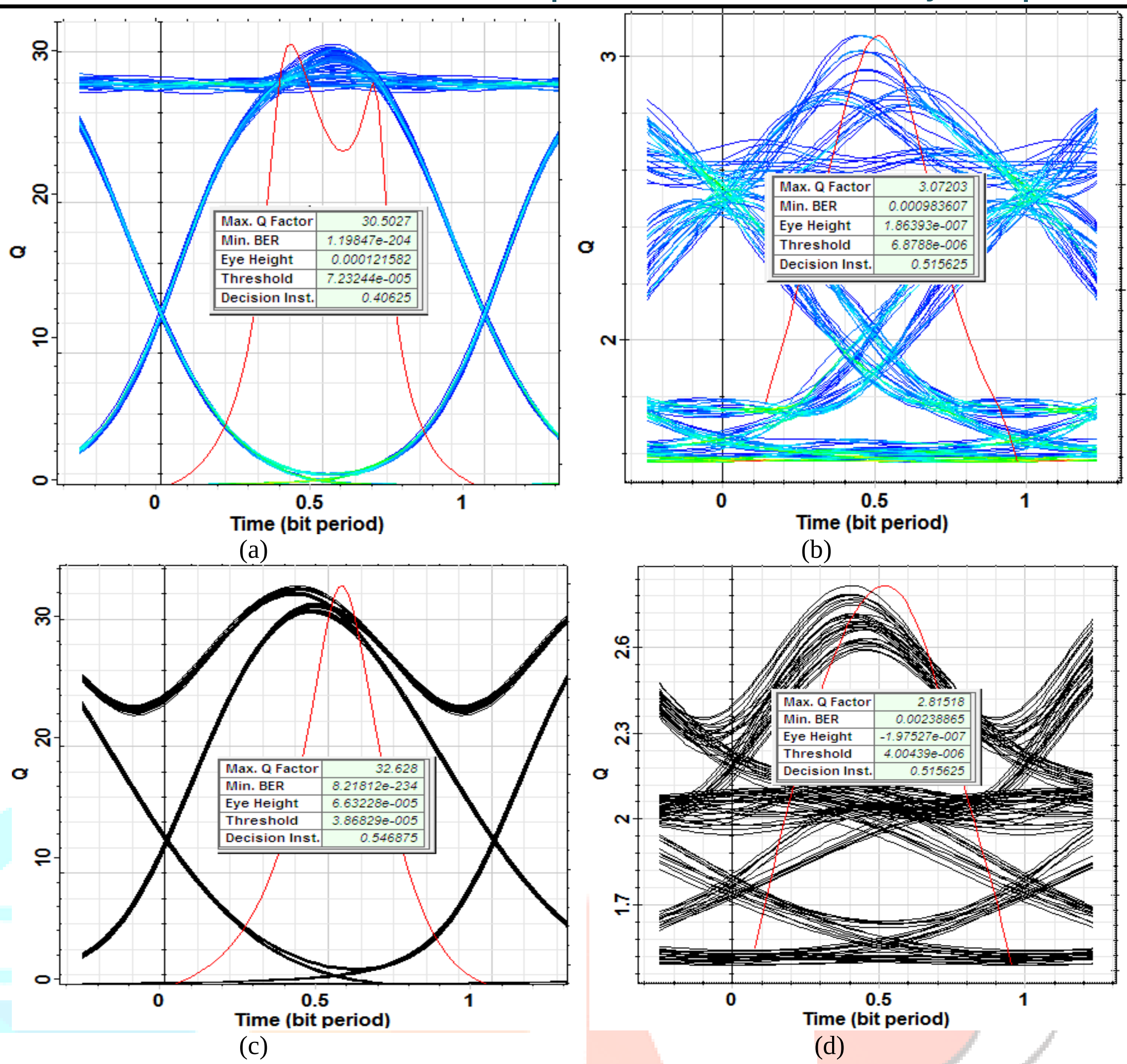


Figure 9: Eye diagram of NRZ after (a) 10 km (b) 70 km and of RZ after (c) 10 km (d) 70 km

Table 8 Concluding remarks and comparison of system with ASE and without ASE re-injection

Parameter	**Recommendations/Conclusions with ASE re-injection**	**Recommendations/Conclusions without ASE re-injection**
Input power varied from -55 dBm to 5 dBm	• Low input power provide (-45 dBm) • Maximum Gain (38.21 dB)	• Low input power provide (-55 dBm) • Maximum Gain (33.29 dB)
EDF length varied from 5 m to 35 m	• Gain of 38.26 (maximum) is achieved at 30 m EDF length. • Gain increases with EDF length	• Gain of 33.95 (maximum) is achieved at 25 m EDF length. • Gain increases with EDF length
EDF core radium varied 0.7 um -1.9 um	• Best Gain (38.21 dB) is obtained at 1.1 um core radius. • Gain increases till 1.1um and then stats decreasing due to more coupling of random noises	• Best Gain (33.29 dB) is obtained at 1.3 um core radius. • Gain increases till 1.3 um and then stats decreasing due to more coupling of random noises
ASE forward and backward	• Maximum ASE is obtained for forward ASE and backward ASE at -45 dBm.	• Not considered
Modulation formats varied such as NRZ and RZ	• NRZ found out be best modulation format in this work due to enhanced performance in terms of Q factor and BER. • Major cause of better performance is the bandwidth efficiency of the NRZ format.	• Not considered

V CONCLUSION

In this work, the effect of different physical parameters of the erbium doped fiber amplifier on the L- band wavelengths has been studied in the system by including and excluding amplified spontaneous emission noise re-injection. With the incorporation of the two FBGs in the system, there is significant increase in the values of the Gain. Maximum Gain is achieved at the input power level of -45 dBm and the maximum ASE is emerged (both forward and backward) at 1565 nm. Further, core radius, erbium doped fiber length is varied along with the input power to examine their effects on the Gain of the system. It is perceived that for the system with ASE re-injection, the input power of -45 dBm, core radius of 1.1 um and EDF length of 30 m provides the maximum Gain of 38.21 dB with the noise figure of 4.47 dB and is found out to be the optimal parameters. Gain of the system without ASE re-injection is less and noise figure is more than system which uses ASE re-injection. In order to validate the performance of proposed L-band EDFA over single mode fiber, distance is varied from 10 km to 70 km with the incorporation of two different modulation formats such as non-return to zero (NRZ), return to zero (RZ) and results are examined in terms of Q factor and bit error rate (BER). It is observed that due to the greater bandwidth efficiency, NRZ performs better than RZ in terms of Q-factor and BER.

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