In this paper, Gain Flatness and Noise Figure of Erbium Doped Fiber Amplifier (EDFA) have been investigated in 16-channels Wavelength Division Multiplexing (WDM). Fiber Bragg Grating (FBG) is used in C-band with the aim to achieve flat EDFA output gain. The proposed model has been studied in detail to evaluate and to enhance the performance of the transmission system in terms of gain, noise figure and eye diagram of the received signals. To that end, various design parameters have been investigated and optimized, such as frequency spacing, EDF length and temperature. To enhance the transmission system performance in terms of gain flatness, the Gain Flattening Filter (GFF) has been introduced in the design. To prove the efficiency of the new design, the optical transmission system with optimized design parameters has been compared with a previous works in the literature. The simulation results show satisfactory performance with quasi-equalized gain for each channel of the WDM transmission system.

1. INTRODUCTION

In the last decade, remarkable contributions have been made by researchers in using Erbium Doped Fibers Amplifiers (EDFA) for conventional C band optical communication (1530nm - 1565nm), since EDFAs offer high capacity, long-lifespan and multiple connection of optical communication network applications [12]. EDFAs also are designed to lessen the effects of dispersion and attenuation, which allows improved performance for long-haul optical systems [3]. However, the use of EDFA in WDM transmission systems and their related optical networks generates uneven output gain between optical channels [4], [5]. In long amplifier chains, even small spectral gain variations can give rise to large differences in the received signal power, causing large BER discrepancies between received signals [6]. For some optical channels, complete power extinction can occur at the system output, due to insufficient gain offset along the amplifier chain [7], [8]. The purpose of this paper is to treat this problem, caused by EDF Amplifiers in complexed WDM systems, by using Fiber Bragg Gratings (FBG) and Gain Flattening Filter (GFF). GFF are typically used to flatten and smooth out unequal signal intensities over a specified wavelength range [9]. GFF is used in conjunction with FBG to overcome the nonlinear effects generated by the use of EDFA in WDM systems and then to ensure that all the amplified channels have the same gain output [10], [11]. The paper is organized as follow, on one hand, we present the proposed model using FBG in sixteen channel wavelength division multiplexing.
division multiplexing system for C-Band frequencies. The developed method will be modeled and simulated to assess and to improve the transmission system performance in terms of EDF gain, gain flatness, noise figure and eye diagram of the received signals. For this purpose, various design parameters which include frequency spacing, EDF length and temperature have been investigated in order to optimize all settings. The optical transmission system under study with optimized design parameters has been compared with a previous model to prove the efficiency of the proposed method. On the other hand, the Gain flattening Filter (GFF) has been added to enhance the reliability of the whole model. To prove the efficiency of our design, the optical transmission system has been applied and compared with previous work proposed in the literature [12], [13]. All results are analyzed using Opti System simulator. The simulation results prove the high reliability of the developed gain flattening method.

2. WDM-EDFA SYSTEM USING UNIFORM FBG

2.1. System Design

In first part, we present a detailed study of the proposed model using Ideal FBG in C-Band frequency of sixteen channel wavelength division multiplexing system. As shown in Figure 1 the transmission system under study consists of 16 input signals (channels), an ideal multiplexer, two isolators, a pump laser, erbium doped fiber, demultiplexer, photo detector PIN, low pass Bessel filter, 3R regenerator and BER analyzer. The input of the system is 16 wavelength multiplexed signals with wavelengths varies from1546 nm to 1558 nm. The pumping at 980 nm is used to excite the erbium doped fiber atoms to a higher energy level. EDFA is combined with a dispersion compensator to overcome chromatic dispersion effects. Chromatic dispersion occurs when different wavelengths of light pulses are launched into the optical fiber. These pulses travel at different speeds due to the variation of refractive index exciting the erbium doped fiber atoms to a higher energy level. The optical fiber used is single mode fiber because it has higher data rate and long distance transmission. The fiber Bragg grating and the Photodetector Diode Positive Intrinsic Negative (PIN) are used as the dispersion compensator and optical signal translator respectively. For the operating optical transmission system, different parameters are adequately chosen, such as, Input power -25dB, reference wavelength 1550 nm, fiber length 50 km, and attenuation coefficient of cable 0.2dB/km. To achieve a high gain the frequency spacing, pump power, EDF length, and Temperature are considered as critical parameters for the study.

Figure 1. 16 channels WDM-EDFA system using FBG

3. DESIGN AND PERFORMANCE OPTIMIZATION OF WDM SYSTEM

3.1. Signal Quality for Different Frequency Spacing's

Frequency spacing is the spacing between two wavelengths or frequencies in a WDM system. It can be measured in units of wavelengths or frequencies. Four-wave mixing effect is critically dependent on the channel spacing and fiber chromatic dispersion. Decreasing the channel spacing increases the four-wave mixing effect, and so does decrease the chromatic dispersion effects. In general, scattering effects are characterized by a gain coefficient, measured in meters per watt. The gain coefficient is a measure of the strength of the nonlinear effect. The gain of different channel has to be equalized for identical performance of all the channels.

Gain Flatness and Noise Figure Optimization of C-Band EDFA in 16-channels WDM … (Chakour Mounia)
Figure 2. Eye Diagrams at different values of Frequency Spacing

Figure 2 shows the effect of nonlinearities on the eye diagrams of the received signals. By comparing the 5 eye diagrams, it can be seen that the eye opening is higher and the signal quality is better in 0.8nm and 1nm.

3.2. Gain and Noise Figure for Different EDF Lengths

Erbium Doped Fiber length impact on the performance of proposed system is also studied. The length of the EDF depends upon the input signal power, Er+3 ion density and the signal and pump wavelength. In Figure 3, we present the variation of gain and noise figure for different EDF length. It is clear that for 4m and 5m the gain are low and noise figure are high, by against, for 10m the Noise figure is high. For 6.7m and 7.1m, the gain is almost the same, however for a length of 6.7m the Noise figure is low, which means that 6.7m is the most proper EDF length.

Figure 3. Variation of Gain and Noise Figure at different values of EDF length
3.3. Gain and Noise Figure for Different Temperature Values

In this section we present the effect of temperature on gain and noise figure respectively. From Table 1 and Table 2 we can observe that 10°C and 20°C have achieved the best Gain Output, and 20°C and 50°C have obtained the lowest Noise Figure. So we can conclude that 20°C leads to the best optimized performance based on Gain and Noise Figure.

Table 1. Variation of gain with respect to channel wavelength at different values of temperature

| Wavelength (nm) | 5°C  | 10°C | 20°C | 50°C  |
|-----------------|------|------|------|-------|
| 1546            | 34.430 | 34.572 | 34.393 | 34.267 |
| 1548            | 34.667 | 34.637 | 34.549 | 34.352 |
| 1550            | 34.698 | 34.647 | 34.546 | 34.266 |
| 1552            | 34.629 | 34.572 | 34.461 | 34.173 |
| 1554            | 34.641 | 34.576 | 34.451 | 34.133 |
| 1556            | 34.392 | 34.326 | 34.201 | 33.895 |

Table 2. Variation of noise figure with respect to channel wavelength at different values of temperature

| Wavelength (nm) | 5°C | 10°C | 20°C | 50°C  |
|-----------------|-----|------|------|-------|
| 1546            | 7.359 | 7.239 | 7.016 | 6.453 |
| 1548            | 7.154 | 7.042 | 6.836 | 6.308 |
| 1550            | 7.054 | 6.933 | 6.742 | 6.078 |
| 1552            | 6.717 | 6.628 | 6.461 | 6.024 |
| 1554            | 6.510 | 6.431 | 6.284 | 5.893 |
| 1556            | 6.249 | 6.180 | 6.048 | 5.842 |

Figure 4 represents the behavior of the gain at different values of temperature in the wavelength of our interest. It can be observed for 1548 nm that when the temperature increases the gain value remains almost the same, which means that the gain flatness versus temperature can be considered as an added value for our work, since in a previous work, the gain at 1548 nm decreases as temperature increases [9].

![Gain variation for 1548nm wavelength at different temperatures](image)

Figure 4. Gain variation for 1548nm wavelength at different values of temperature

3.4. System Comparison

The proposed model under study with optimized values of FS, EDF length and Temperature at different pump powers has been compared with a previous model proposed by other authors [12]. Firstly, the eye diagrams at data receivers of both models have been introduced using the same initial setting as shown in Figure 5.
Figure 5. Eye diagram of the received signals, a: previous model [12], b: developed model.

By comparing the 2 eye diagrams, it is clear that the eye opening is higher and the signal quality is better. The comparison has then been carried out based on Gain and Noise Figure at different pump powers as shown in Table 3 and Table 4.

### Table 3. Gain with different Channel Wavelength

| Wavelength (nm) | 100 (dB) | 200 (dB) | 300 (dB) | 400 (dB) |
|----------------|---------|---------|---------|---------|
| 1546           | 33.474  | 34.393  | 36.917  | 38.371  |
| 1548           | 33.167  | 34.549  | 36.736  | 38.607  |
| 1550           | 33.036  | 34.546  | 36.675  | 38.578  |
| 1552           | 33.092  | 34.461  | 36.860  | 38.828  |
| 1554           | 33.344  | 34.451  | 36.177  | 37.283  |
| 1556           | 32.786  | 34.201  | 35.788  | 36.906  |

### Table 4. Noise Figure with different Channel Wavelength

| Wavelength (nm) | 100 (dB) | 200 (dB) | 300 (dB) | 400 (dB) |
|----------------|---------|---------|---------|---------|
| 1546           | 12.806  | 7.016   | 10.768  | 6.616   |
| 1548           | 12.314  | 6.836   | 10.350  | 6.450   |
| 1550           | 11.749  | 6.742   | 9.883   | 6.404   |
| 1552           | 11.099  | 6.461   | 9.355   | 6.126   |
| 1554           | 10.543  | 6.284   | 8.960   | 5.981   |
| 1556           | 9.884   | 6.048   | 8.482   | 5.750   |

The obtained gain in the previous work at pump power of 100mW is 33.474dB with noise figure of 12.806dB. While the gain of the model developed in this work at same pump power of 100mW is 34.393dB with noise figure of 7.016dB, which means that a better gain power & less Noise Figure have been achieved. The simulation results demonstrate the high reliability of the proposed model in comparison with other models.

### 4. EDFA-WDM SYSTEM USING UNIFORM FBG AND GFF

#### 4.1. Proposed Model with GFF

To enhance more and more the reliability of the new model, we introduce the Gain flattening Filter (GFF) in our system as can be shown in Figure 6. The GFF is placed after the FBG before the demultiplexing process, so the multiplexed signals can be filtered automatically from unequal gain values.
4.2. Performance Analysis

The gain flatness of the developed model with and without GFF is analyzed for different frequency spacing’s. Table 5 shows that, the Gain flatness has increased by the use of GFF, especially for the optimized value of frequency spacing 0.8 nm, which went down from 0.647 dB to 0.303 dB.

Table 5. Gain flatness at different values of frequency spacing

| Frequency spacing (nm) | Gain Flatness (dB) Without GFF | Gain Flatness (dB) With GFF |
|------------------------|--------------------------------|-----------------------------|
| 0.2                    | 0.254                          | 0.153                       |
| 0.4                    | 0.207                          | 0.202                       |
| 0.6                    | 0.261                          | 0.242                       |
| 0.8                    | 0.647                          | 0.303                       |
| 1                      | 2.281                          | 1.555                       |

Figure 7 shows the gain flatness of the developed model with GFF and without GFF based on different EDF lengths. Results prove that with GFF we obtain better Gain flatness as compared to the developed model without GFF. It can also be noticed that 6.7m is the most proper EDF length since we obtain a minimum value of gain flatness 0.303dB.

The Gain Flatness of the proposed method with and without GFF for different Temperature values is depicted in Figure 8. It can be seen that the use of GFF offers better Gain Flatness for all temperature values.
Table 6 shows the comparison results of Gain Flatness based on pump power for the proposed method with GFF and without GFF. One can see that the proposed model with GFF has provided the lowest gain flatness which results in all over better performance.

| Pump Power (mW) | Gain Flatness (dB) Without GFF | Gain Flatness (dB) With GFF |
|-----------------|-------------------------------|----------------------------|
| 100             | 0.647                         | 0.303                      |
| 200             | 1.221                         | 0.361                      |
| 300             | 1.547                         | 0.692                      |
| 400             | 1.768                         | 0.768                      |

5. PERFORMANCE COMPARISON

In this part, we compare the proposed method performance to prove the efficiency of our method. So we have applied the proposed method with EDF and GFF in the same communication system [13], using the same initial setting: 20°C temperature, 7m fiber length and the signal wavelength of 1546.8 nm as shown in Figure 9.
Table 7 shows the comparison results in terms of gain and the gain flatness. It can be clearly seen that better gain value and improved gain flatness have achieved.

| Parameters | Previous Model | The New Model Without GFF | With GFF |
|------------|----------------|---------------------------|----------|
| Gain       | 28             | 36.28                     | 37.12    |
| Gain Flatness | 1.14           | 0.85                      | 0.10     |

6. CONCLUSION

In this paper, the Gain Flatness and the Noise Figure of EDF Amplifier in 16-channels WDM system have been studied. The gain non-uniformity for each channel using FBG and GFF has been corrected in order to equalize the amplitude gain in the WDM system. The most convenient design parameters are optimized to be used in the new method. Useful results show that 0.8nm, 6.7m and 20°C are the most proper values of Frequency spacing, EDF length and Temperature respectively. Results have been compared with previous works in terms of the output Gain and Noise Figure. The simulation results prove that the proposed method offers improved values of performance all parameters.

REFERENCES

[1] R. Ramaswami, K.N. Sivarajan, G.H. Sasaki, "Optical Networks: A Practical Perspective", Third Edition. ELSEVIER, 2010.
[2] B.R Mhdi*, N. Aljaber, S.M. Aljwas, A.H., "Khalid, Design and Construction of Optical Fiber Sensor System for Detection of the Stress and Fine Motion", International Journal of Nano Devices, Sensors and Systems (IJ-Nano), Volume 1, No. 1, May 2012.
[3] P. Shukla, K. Kaur, "Performance Analysis of EDFA for Different Pumping Configurations at High Data Rate", Global Journal of Researches in Engineering Electrical and Electronics Engineering, Volume 13 Issue 9 Version 1.0, 2013.
[4] M. Chakkour, A. Hajaji and O. Aghzout, "Design and Study of EDFA-WDM Optical Transmission System using FBG at 10 Gbits/s Chromatic Dispersion Compensation Effects", Mediterranean Conference on Information & Communication technologies, May 2015.
[5] M.M. Ismail, M.A. Othman, "EDFA-WDM Optical Network Design System", International Journal for Light and Electron Optics, optic (Elsevier), vol. 53, pp. 294-302, 2013.
[6] B. Rindhe, J. Digge, S. Narayankhedkar, "Implementation of Optical OFDM Based System for Optical Networks", International Journal of Electrical and Computer Engineering (IJECE), Vol. 4, No. 5, October 2014.
[7] R. Kaler and R S Kaler, "Gain and Noise Figure Performance of ErbiumDoped Fiber Amplifiers (EDFA) and Compact EDFAs", pp. 440-443, Elsevier, 2011.
[8] J. Usman Sindhi, Rohit B Patel, injaal A Mehta and Vivekananda Mishra, "performance analysis of 32-channel WDM system using erbium doped fiber amplifier", International Journal of Electrical and Electronic Engineering & Telecommunications, Vol. 2, No. 2, April 2013.
[9] R. Anthony, S. Biswas "Temperature Dependent Gain Analysis of a Cascaded C-Band EDFA DWDM Network", International Journal for Light and Electron Optics, optic (Elsevier), Procedia Technology, 2012.
[10] F. Chaoui, A. Hajaji, O. Aghzout, M. Chakkour, M. El Yakhlefoui, "Chirped Bragg Grating Dispersion Compensation in Dense Wavelength Division Multiplexing Optical Long-Haul Networks", International Journal of Microwave and Optical Technology (IJMOT), Volume. 10, No. 5, September 2015.
[11] B. ALTINER, N. Özlem ÜNVERDİ, "Modelling - Simulation and Gain Flattening Improvements for an Erbium Doped FiberAmplifier", IEEE, 2009.
[12] K. Kaur, K. Singh, "Performance analysis of 16-channel WDM system using Erbium Doped Fiber Amplifier", International Journal of Engineering and Innovative Technology (IJEIT), Volume 3, Issue 6, December 2013.
[13] A.H.M. Huseina, F.I. El-Nahal, "Optimizing the EDFA gain for WDM lightwave system with temperature dependency", International Journal for Light and Electron Optics, optic (Elsevier), Procedia Technology, 2011.
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