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A Comprehensive Study on EDFA Gain Flattening for WDM Transmission using Cascaded Fiber Bragg Gratings

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ABSTRACT

The gain flattening of optical amplifiers plays a crucial role in optical Wavelength Division Multiplexing (WDM) communication systems, ensuring uniform amplification across all channels. This study focuses on investigating the gain flattening characteristics of Erbium-Doped Fiber Amplifiers (EDFAs) using cascaded Fiber Bragg Gratings (FBGs) in the C-band wavelength range. A comparative analysis of various optical amplifiers revealed that EDFA exhibited the highest gain variation, making it an optimal choice for gain flattening. The key parameters to achieve optimal EDFA gain flattening include the wavelengths of the channels, EDFA length, noise figure (NF), and the number of cascaded FBGs. Simulation experiments are conducted using Optisystem software (ver. 14.2) and the obtained results reveal that EDFA gain flatness can be achieved within the wavelength range of 1531 to 1533 nm, utilizing an EDFA length of 6 m and 12 cascaded FBGs. These findings contribute to the advancement of gain flattening techniques in optical WDM systems, enhancing their performance and reliability.

1. Introduction

With the consistent progression of Wavelength Division Multiplexing (WDM) technology in long-distance optical communication systems in the past few years, signal attenuation has emerged to be a significant problem which can limit their performance. Consequently, optical amplifiers have been regarded as a crucial component in such systems owing to their high gain, low noise, and wide bandwidth [1]. Unfortunately, one of the difficulties in implementing a WDM system with the conventional Erbium-Doped Fiber Amplifier (EDFA) is that the EDFA gain spectrum is wavelength depending causing unequal amplification of the transmitted WDM channels which may lead to low signal-to-ratio (SNR) and severe signal distortion [1].

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Accordingly, there is a significant incentive to flatten the gain of EDFAs to ensure proper amplification of every channel in WDM optical communication systems for enhancing the systems' performance and improve the transmitted bandwidth.

To flatten the EDFA gain, several effective techniques have been used in the literature. These techniques can be categorized as intrinsic and extrinsic [2-5]. In the intrinsic method, various host materials, such as aluminosilicate and fluoride-based glasses, which can be utilized to change the spectrum characteristics of the erbium ions [6–8]. This technique can increase the gain's flatness over a narrow bandwidth. Extrinsic technique, on the other hand, enhance EDFAs' gain flattening over wider bandwidths. This can be accomplished by employing filters in the core of the fiber such as Chirped Fiber Bragg Gratings (CFBG), blazed FBG, and acousto-optic tunable filters [1]. The primary drawback of utilizing a CFBG filter is the difficulty of its fabrication, particularly when the equalization bandwidth is wide. Blazed FBG is susceptible to environmental circumstances since it depends on changing guided modes to non-guided modes. Also, acousto-optic filters use a lot of RF power [9].

Another applied extrinsic method for flattening EDFA gain is utilizing variable optical attenuator (VOA) to equalize various WDM channels coupled out of the optical fiber. Although this method can provide acceptable flattening in both C and L bands with little ripples, but unfortunately, its application is constrained by its high NF and insertion loss [10].

Another study reported EDFA gain flattening was achieved by connecting a series of cascaded short period Apodized FBGs (AFBGs) to an EDFA host made of germanosilicate. In WDM networks, just one channel must be flattened by each FBG. Low power usage and a small BER (less than 10^{-10}) are obtained [2].

In a recent study, it was shown how Artificial Neural Networks (ANNs) may be used to create an FBG array's filtering profile with fewer resonances than transmitted channels. The gain of an EDFA for the flattening amplification of eight optical WDM signals was to be equalized. With a frequency separation of 200 GHz between carriers, the center frequencies of these signals define a range of 1.4 THz between 195 and 196.4 THz. As their resonances must be assigned to the 1.4 THz band, these inputs have a direct relation to the technical requirements of the FBG design. However, the center frequency of an FBG resonance is not always the central frequency of an optical carrier. When compared to the system without equalization, the system based on three FBGs had an improvement factor of 18.51, while the system based on six FBGs had an improvement factor of 149 [11].

This paper optimized an Erbium-Doped Fiber Amplifier (EDFA) with 12 Fiber Bragg Gratings in the wavelength range 1526.44 nm to 1537.40 nm. The initial gain profile lacked ripples but had a 7.5966 dB discrepancy. Narrowing the focus to 1531 nm to 1533 nm, adjustments in pump power and FBG spacing reduced the difference between maximum and minimum gain. The optimized system demonstrated resilience to environmental changes.

This paper presents a comparative analysis of different optical amplifiers, namely Semiconductor Optical Amplifier (SOA), Raman amplifier, and EDFA, based on four key parameters: maximum gain, minimum gain, gain variation ratio, and NF. The focus is on identifying the amplifier with the highest gain variation ratio, indicating the lowest gain flattening, which is found to be EDFA. Subsequently, C-band EDFA configurations with varying numbers of cascaded FBGs (i.e., three, six, nine, and twelve) are investigated for 8 WDM channels after determining the optimal EDFA length.

The paper is structured as follows: Section 1 is devoted for the introduction, background, and literature review. Section 2 provides model and analysis of gain and NF of different types of optical amplifiers and a brief description of FBG theory. Section 3 presents the obtained results and corresponding discussions. Finally, Section 4 concludes the paper by summarizing the key findings and implications followed by the references.

2. Model and Analysis

2.1 Optical Amplifiers' Gain and Noise Figure

2.1.1 EDFA gain and noise figure

The principle of amplification of EDFA depends on the concept of stimulated emission where the erbium ions are being excited by the pump laser, rising to a higher energy level. As the erbium ions decay to a lower energy level, photons are emitted increasing the intensity of the laser beams and amplification occurs [12].

The difference in population intensity (number of ions per unit volume) of erbium ions (n) is defined as the difference between the population density in the upper amplifier level (metastable level) with E_2 energy (N_2) and the population density in the ground level with E_1 energy (N_1). n can be expressed as follows [12]

$$\mathrm{n} = \frac{\mathrm{n_t} \,.\, (\mathrm{w_P} - \Gamma)}{2 \,.\, \sigma \,.\, \mathrm{c} \,.\, \mathrm{p} + \Gamma + \mathrm{w_P}} \tag{1}$$

where $\mathrm{n_t}$ is the total population density ($\mathrm{n_t} = N_2 + N_1$), $\mathrm{w_P}$ is the rate of the pump, Γ is the reciprocal of E_2 lifetime, σ is the cross-section of the induced emission, c is the velocity of light, and p is the photon density.

The gain of EDFA, $\mathrm{G_{EDFA}}$ can be defined as the product the difference in population density (n) between the energy states E_2 and E_1 and cross-section of the induced emission ($G_{EDFA} = \sigma.\mathrm{n}$). Consequently, amplification occurs when $G > 0$ and the life time is very large (τ_s) and this can only be achieved $\mathrm{w_P}$ is larger than the spontaneous emission rate [12]. Then the gain of EDFA can be expressed as [13]

$$\mathrm{G_{EDFA}} = \frac{\sigma \,.\, \mathrm{n_t} \,.\, (\mathrm{w_P} - \Gamma)}{2 \,.\, \sigma \,.\, \mathrm{c} \,.\, \mathrm{p} + \Gamma + \mathrm{w_P}} \tag{2}$$

The Amplified Spontaneous Emission (ASE) noise power ($\mathrm{P_{ASE}}$) exiting the fiber in a bandwidth ($\Delta\nu$) can de expressed as [13]

$$\mathrm{P_{ASE}} = \mathrm{n_{sp}} \,.\, \mathrm{h} \,.\, \nu \,.\, \Delta\nu \,.\, (\mathrm{G_{EDFA}} - 1) \tag{3}$$

where $\mathrm{n_{sp}}$ is the inversion factor, h is the Planck's constant, ν is the light frequency.

Single mode fiber amplifiers have two polarization modes and multimode fiber amplifiers can have a large number of spatial modes. In order to obtain the total ASE power for a single mode fiber, you have to multiply by a factor of 2. NF can be obtained in terms of total ASE power and can be expressed as [12]

$$NF = \frac{\mathrm{P_{ASE}}}{\mathrm{h} \,.\, \nu \,.\, \Delta\nu \,.\, \mathrm{G}} + \frac{1}{G} \tag{4}$$

2.1.2 Raman gain and noise figure

The principle of amplification of Raman amplifier is based on the non-linear Stimulated-Raman Scattering (SRS) effect between the pump and signal which arises when an input signal is fed into an optical fiber with a strong pump [14].

The Raman amplifier's gain is defined as the ratio between the output signal power to the input signal power and can be expressed as [14]

$$\mathrm{G(dB)} = 10\, log_{10}\left[\exp\{\frac{g_R\ P_p(0)}{\sigma_p} L_{eff} - \alpha_s\, L\}\right] \tag{5}$$

where, $P_p(0)$ is the power pumped at the start of the fiber, σ_p is the Raman cross section of the pump, L_{eff} is the effective length of the fiber, α_s is the loss of fiber, L is the length of the fiber, and g_R is the gain coefficient of Raman amplifier which can be expressed as [14]

$$g_R = \sigma_s(\mathrm{v})\ \frac{\lambda_s^s}{c^2 h(n(\mathrm{v}))^2} \tag{6}$$

where $\sigma_s(\mathrm{v})$ is the Raman cross section of the pump as a function of optical frequency (v), λ_s is the Stokes wavelength, c is the velocity of light, h is the Planck's constant, and $n(\mathrm{v})$ is the refractive index as a function of optical frequency (v).
While the NF of the Raman can be expressed as [14]

$$\mathrm{NF}_{Raman} = 10\, log_{10}\left[2\exp(-\alpha_s\, L) + \frac{1}{G}\right] \tag{7}$$

2.1.3 SOA gain and noise figure

Although SOA working principle depends on stimulated emission but it possess an advantage among other optical amplifiers that is the anti-reflection treatment which is being applied on both sides of the semiconductor laser eliminating the resonator's structure. The semiconductor carriers are converted into inverted particles by the driving current in the gain region causing electrons to lose energy in the form of photons, thus, amplifying the input optical signal [15].

The carrier density (N) in the active region is altered as light is injected into the SOA, and these changes is being represented using the rate equation and can be expressed as [16]

$$\frac{dN}{dt} = \frac{I}{q\,.V}\ (A.N + B.N^2 + C.N^3) - \frac{\Gamma.g(N,f).P_{av}\,.L}{V.h.f} - \frac{2\,\Gamma}{h\,H\,W} \sum_{j=0}^{N_m-1} \frac{g(N,v_j).k_j}{v_j}\ \mathrm{P_{ASE}} \tag{8}$$

where I is the DC current injected to the SOA, q is the charge of electron, V is the SOA's active volume, A is the nonradiative recombination coefficient due to the defects and traps, B is the radiative recombination coefficients, C is the Auger recombination coefficients, Γ is the confinement factor, $g(N,f)$ is the material gain coefficient as a function of carrier density (N) and light frequency (f), P_{av} is the average output power, L is the length of SOA, V is the active volume of SOA, h is the Planck's constant, H is the height of SOA, W is the width of SOA, N_m is a positive integer, $g(N,v_j)$ is the material gain coefficient as a function of carrier density (N) and noise photons frequencies (v_j), and $\mathrm{P_{ASE}}$ is the ASE noise power.
The overall gain of an optical wave experienced at a position z of an SOA can be expressed as [16]

$$G_{SOA} = e^{g_T\,.z} \tag{9}$$

where g_T is the net gain coefficient and can be defined as [16]

$$g_T = \Gamma . g(N, f) - \alpha_s \tag{10}$$

P_{ASE} coveys the traveling wave equation, and therefore, it can be expressed as [16]

$$\frac{dP_{ASE}}{dz} = (\Gamma . g(N, v_j) - \alpha_s)\, P_{ASE} + R_{sp} \tag{11}$$

where R_{sp} represents the local spontaneously generated noise.

2.2 Fiber Bragg Gratings (FBGs)

The discovery of the photosensitivity property of the optical fibers resulted in the development of FBGs. These devices can carry out filtering operations with low differential group delay and attenuation. An FBG features a periodic perturbation of the core refractive index along the fiber axis forming a periodic or quasi-periodic index modulation profile. Therefore, the gratings function as a selective mirror, reflecting only the light of a particular wavelength (the so-called Bragg wavelength λ_B) while transmitting the other wavelengths without losses [17]. A customized band-stop profile can be generated using cascaded FBGs operating at various Bragg wavelengths since the FBG is characterized by a band-reject filtering profile [18]. The Bragg wavelength can be defined as [17]

$$\lambda_B = 2\, n_{eff}\, \Lambda \tag{12}$$

where n_{eff} is the effective refraction index of the optical mode propagating along the fiber and Λ is the period of the grating structure.

Uniform FBG is the simplest and most widely used FBG type owing to its excellent WDM capability. It features a constant refractive index change (Δn) and grating period (Λ) along the whole length of the grating [17] (as shown in Figure 1).

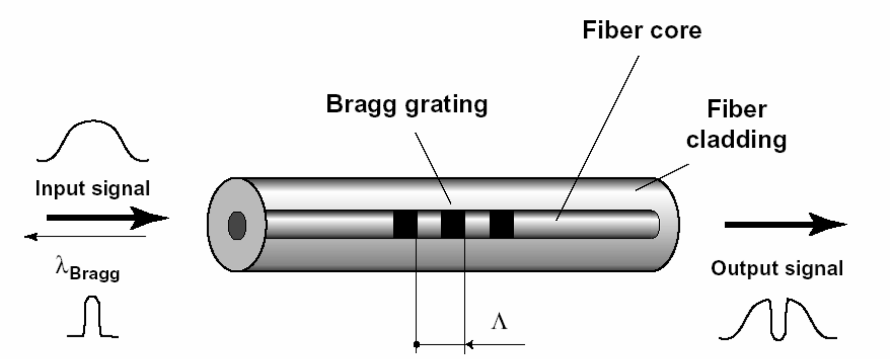


Fig. 1. Schematic diagram of uniform FBG [17]

The Coupled Mode Theory (CMT) is one of the most straightforward and precise techniques for analyzing the reflection characteristics of FBGs. The maximum reflectivity at the Bragg wavelength is given by [19]

$$R_{max}(l, \lambda) = tanh^2(\kappa l) \tag{13}$$

where l is the grating length, κ is the ac coupling coefficient and is defined as [17]

$$\kappa = \frac{\pi \Delta n}{\lambda} M_{power} \tag{14}$$

where λ is the wavelength, and $M_{power} = 1 - V^{-2}$ is the fraction of the fiber mode power contained by the fiber core, $V = \frac{2\pi}{\lambda} a\sqrt{n_{co}^2 - n_{cl}^2}$ is the fiber's normalized frequency, a is the core radius, n_{co} is the core refractive index, and n_{cl} is the cladding refractive index.

3. Results and Discussions

3.1 Analyzing the Gain Flattening of EDFA, Raman Amplifier and SOA

For a fair and realistic comparison, while modelling several types of optical amplifiers on OptiSystem software (version 14.2), specific parameters for each type must be maintained constant which includes that all the fibers are single-mode step-index with core, r_{co}, and cladding, r_{cl}, radii of values 2 and 62.5 µm, respectively. n_{co} is 1.46, while n_{cl} is 1.45 [19].

The WDM transmitter consists of eight channels with a combined power of -20 dBm, Non-Return to Zero (NRZ) modulation, and a frequency separation of 200 GHz, covering a band of 1.4 THz between 195 and 196.4 THz (wavelengths ranging from 1526.44 to 1537.4 nm). The frequency range of WDM Mux was chosen to be the same as that of the WDM transmitter, with a bandwidth of 10 GHz.

For SOA, the injection current was maintained at 50 mA. For Raman amplifier, the length was chosen to be 10 km, while the wavelength of its pumping laser wavelength is kept at 1450 nm with a power of 800 mW. As for EDFA, its length was chosen to be 5 m, with a core radius of 2.2 μm, and Numerical Aperture (NA) of 0.24. It was doped by erbium of radius 2.2 μm and density of $1 \times 10^{25}\ m^{-3}$.

For a comparative study between the different types of optical amplifiers, the first simulation (shown in Figure 2) is carried out for EDFA to indicate the four measuring parameters: maximum gain, minimum gain, gain variation ratio, and NF (in dB). The same configuration was repeated for SOA and Raman amplifier with the previously mentioned specifications for each amplifier.

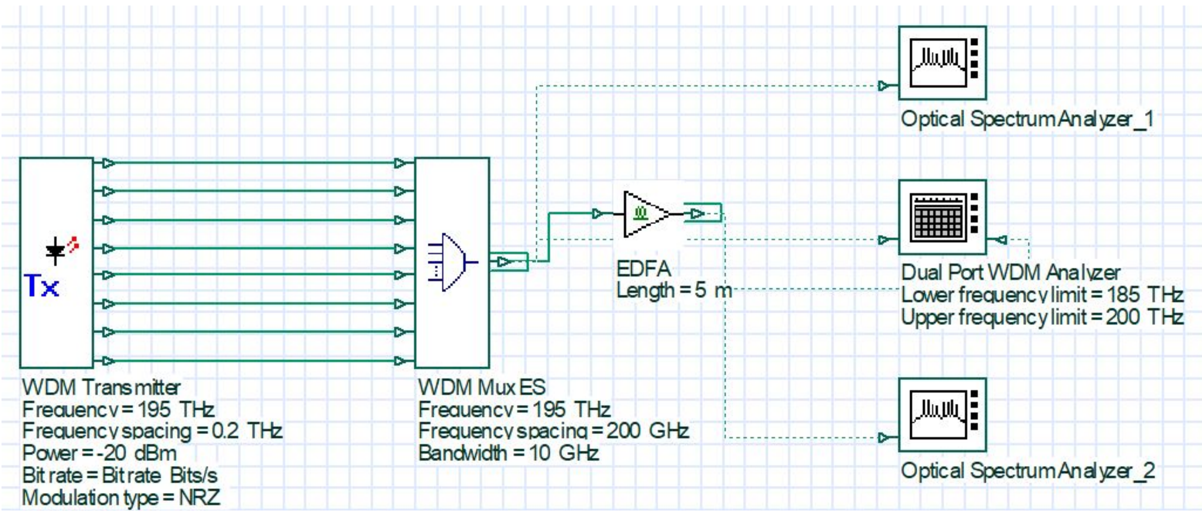
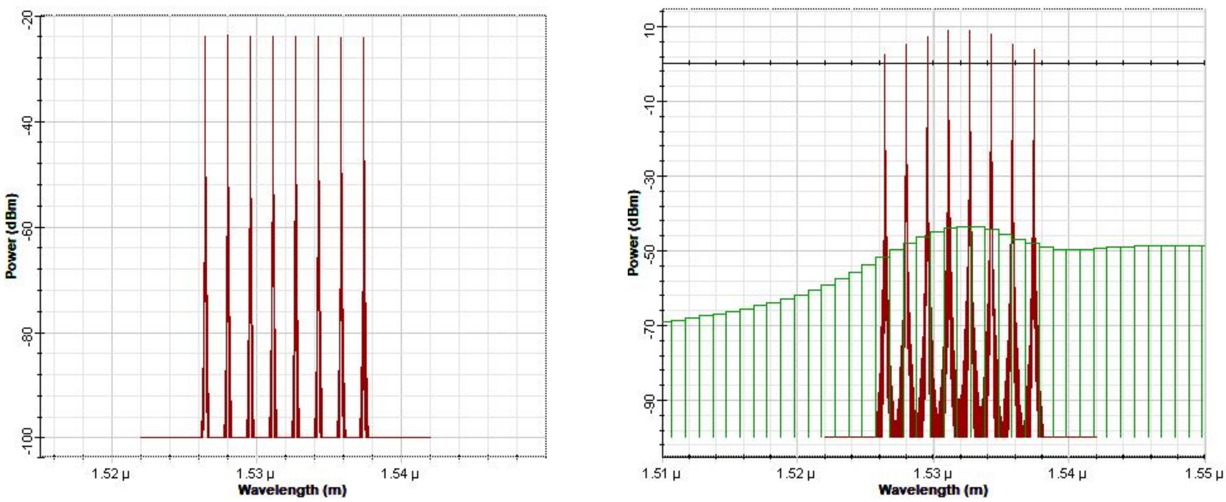


Fig. 2. WDM Transmission system with EDFA

By examining the optical spectrum analyzers before EDFA (shown in Figure 3(a)) and after EDFA (shown in Figure 3(b)), it can be observed that the EDFA has high NF and also the gain achieved for the different wavelengths is varying.



(a) (b)

Fig. 3. Optical spectrum analyzers output (a) before EFDA, (b) after EDFA

After simulating the WDM system using the same configuration of Figure 2 for SOA and Raman amplifier, the three systems were evaluated in terms of the four measuring parameters (as shown in Table 1). Based on Table 1, one can conclude that the SOA can achieve the best gain flattening since it has the minimum ratio between the maximum and minimum gain values of 0.0664 dB and a minimum NF of 0.0664 dB as well. Meanwhile, the EDFA has the highest ratio value of 6.6912 dB with a high NF of 1.9542 dB. Accordingly, we work on EDFA to improve its gain flattening.

Table 1
Comparison between the WDM systems using EDFA, Raman Amplifier, and SOA

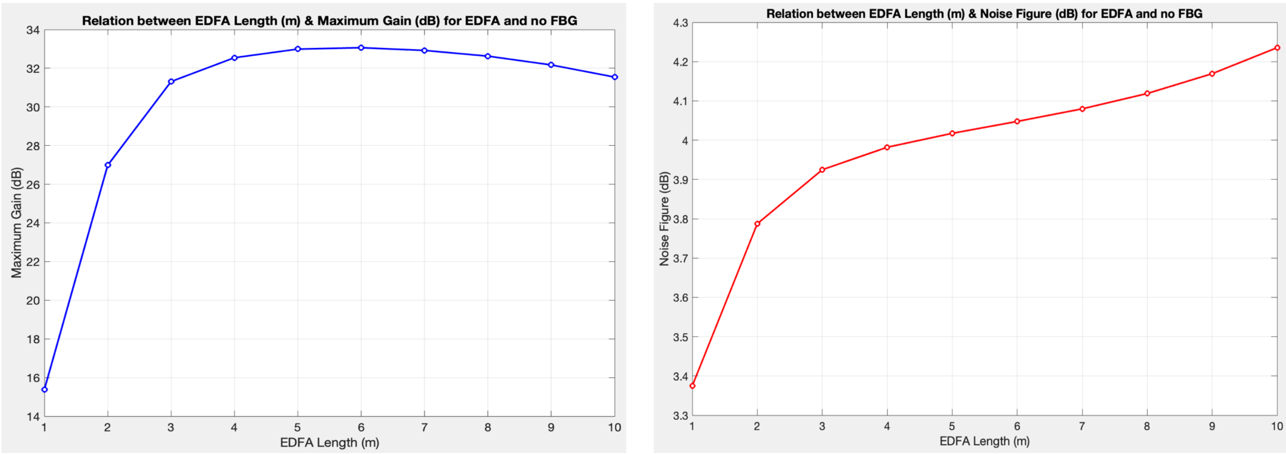
	EDFA	Raman Amplifier	SOA
Gain Max Value (dB)	32.9900	9.8940	21.7889
Gain Min Value (dB)	26.2988	8.0283	21.7225
Ratio max/min (dB)	6.6912	1.8657	0.0664
NF (dB)	1.9542	0.1877	0.0664

3.2 Indicating EDFA Length for Maximum Amplifier Gain

With the approach of varying EDFA length, we can determine the best length of EDFA which corresponds to the maximum gain achieved by the amplifier. Once indicated, this value can be introduced to the cascaded FBGs for further improvement of gain flattening. Table 2 shows the different EDFA lengths (ranging from 1 to 10 m) and the corresponding maximum gain and the maximum NF (in dB). The relation between EDFA length and the corresponding maximum gain is illustrated in Figure 4(a). While the relation between EDFA length and the corresponding maximum NF is illustrated in Figure 4(b).

Table 2
Maximum gains and maximum NF for different values of EDFA length

EDFA Length (m)	Max. Gain (dB)	Max. NF(dB)
1	15.3846	3.3750
2	26.9841	3.7874
3	31.3110	3.9249
4	32.5448	3.9821
5	32.9900	4.0175
6	33.0599	4.0478
7	32.9210	4.0798
8	32.6255	4.1188
9	32.1707	4.1693
10	31.5418	4.2355



(a) (b)

Fig. 4. Relation between EDFA length and (a) maximum gain, (b) maximum NF

From Table 2 and Figure 4, it can be concluded that the 6 m EDFA length has recorded the highest maximum gain of 33.0599 dB and a reasonable NF too of value 4.0478 dB.

3.3 Improving the Gain Flattening of EDFA through Cascaded FBGs

To improve the gain flattening of EDFA, four tests were performed on the WDM transmission system with EDFA by adding three, then six, then nine and finally twelve cascaded uniform FBGs. The length of each FBG was chosen to be 10 mm and based on the obtained results of Section 3.2; the EDFA length was fixed at 6 m for maximum gain achievement. The first test was performed using the simulation illustrated in Figure 5 which has the same connection as the one shown before in Figure 2, with the same parameters indicated above but with the addition of three FBGs. The centered wavelengths of the first, second and third FBG were chosen to be 1529.15 nm, 1531.92 nm, and 1534.65 respectively.

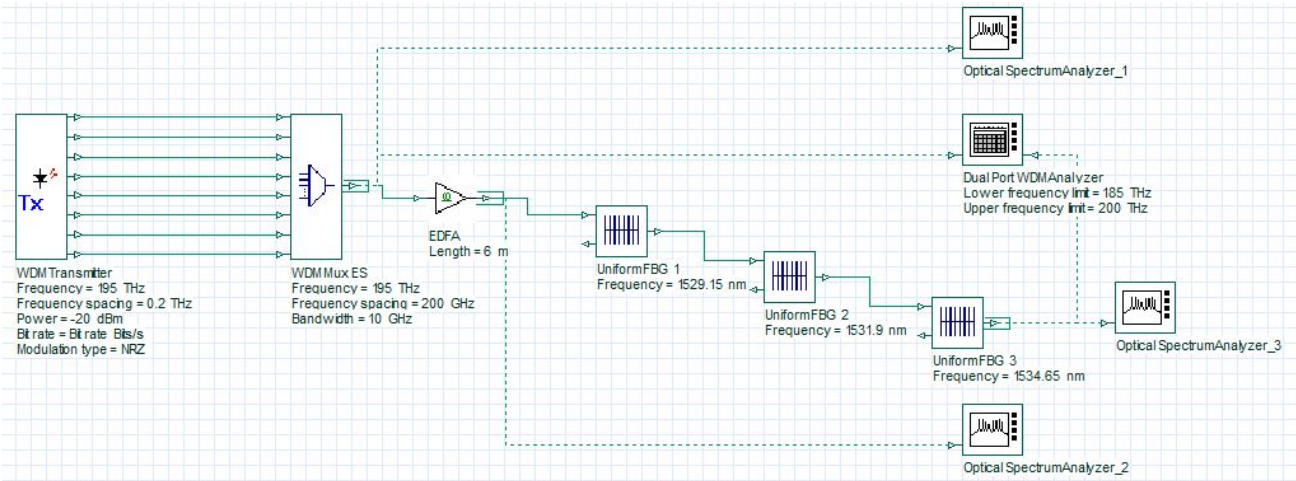


Fig. 5. WDM Transmission system with EDFA and three cascaded FBGs

For the second performed test with the addition of six cascaded FBGs, the simulation illustrated in Figure 5 is then repeated but by adding six FBGs instead of three. The centered wavelengths of the first FBG is 1528.11 nm, second is 1529.55 nm, third is 1531.12 nm, fourth is 1532.68 nm, fifth is 1534.25 nm, and sixth is 1535.82 nm. The same idea is repeated for the third test with the addition of nine cascaded FBGs. The centered wavelength of the first FBG is 1527.54 nm with a spacing of 1.096 nm between the centered wavelengths of the successive FBGs. The last test performed by adding twelve cascaded FBGs. The centered wavelength of the first FBG is 1527.28 nm with a spacing of 0.843 nm between the centered wavelengths of the successive FBGs. In all cases mentioned in this section, the centered wavelengths of the FBGs were chosen to cover the range of the input carriers' wavelengths and consider their resonance with the FBGs added.

The results of adding cascaded FBGs (none, 3, 6, 9, and 12 FBGs) to the EDFA (of length 6 m) over a range of wavelengths from 1526.44 to 1537.40 nm are illustrated in Table 3 and Figure 6.

Table 3
Comparison between the EDFA system gain without FBG and with cascaded FBGs in terms of the eight wavelengths of WDM channels

Wavelength (nm)	Gain (dB)				
	No FBG	3 FBGs	6 FBGs	9 FBGs	12 FBGs
1526.44	28.0867	25.3771	25.3545	25.3254	25.2953
1527.99	29.7980	28.3687	27.9597	28.2728	27.6680
1529.55	32.1210	30.7715	30.7584	30.6329	30.6291
1531.12	33.9224	32.5312	32.4981	32.3607	32.3609
1532.68	33.5196	33.0166	32.9574	32.9366	32.8919
1534.25	32.5418	31.9723	31.6807	31.3418	31.7098
1535.82	30.3486	29.8981	29.8331	29.8138	29.4420
1537.40	28.6480	28.4702	28.4447	28.4171	28.3896

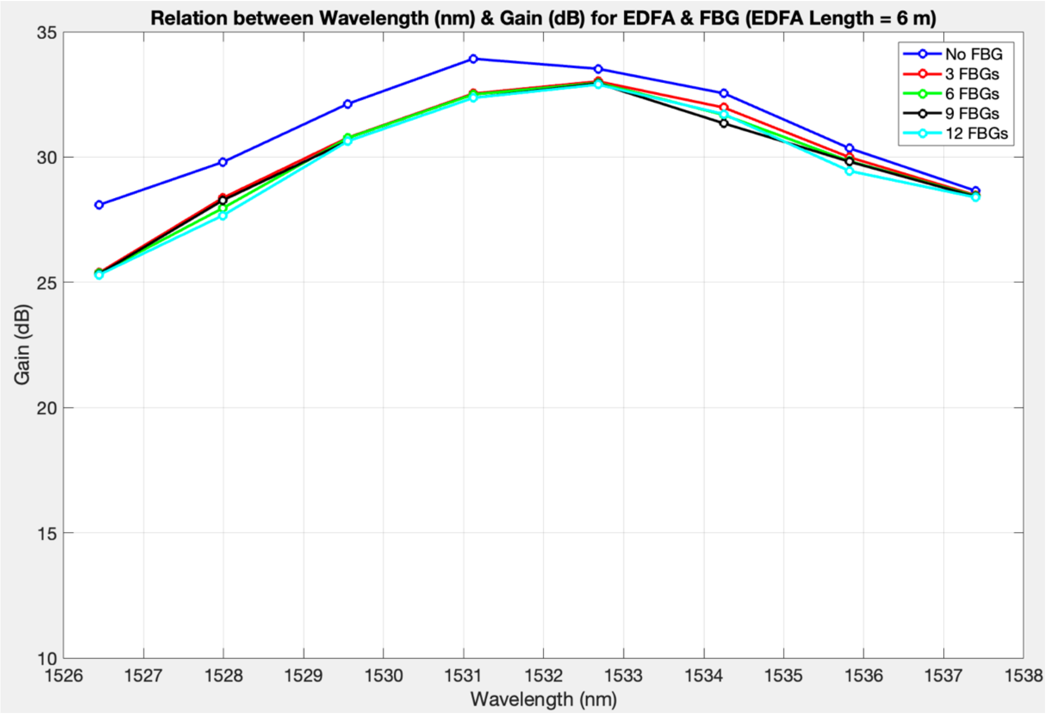


Fig. 6. Gain as a function of wavelength (ranging from 1526.44 to 1537.4 nm) for WDM system with EDFA without FBG, and with three, six, nine and twelve cascaded FBGs

From Table 3 and Figure 6, we can conclude that increasing the number of cascaded FBGs improves the gain flattening of the EDFA with the indicated wavelengths range. Moreover, by focusing on the range of wavelength from 1531 nm to 1533 nm, further flattening of EDFA gain is achieved as shown in Figure 7.

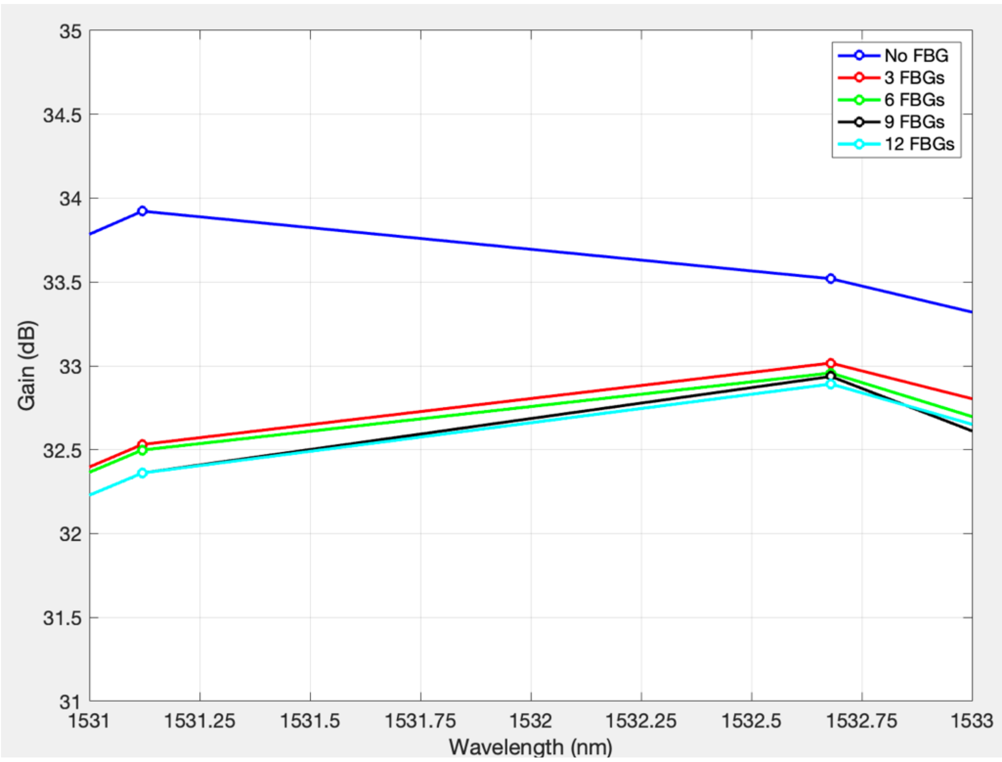


Fig. 7. Gain as a function of wavelength (ranging from 1531 to 1533 nm) for WDM system with EDFA without FBG, and with three, six, nine and twelve cascaded FBGs.

3.4 Gain Flattening Proposed Model

Based on the results of sections 3.1, 3.2 and 3.3. We proposed a model to improve the gain flattening of EDFA through maintaining the EDFA length at 6 m, adding 12 cascaded FBGs and working in the wavelengths ranging from 1551 to 1533 nm. Table 4 and Figure 8 show the gain flattening of the proposed model over the indicated wavelengths range.

Table 4
The gain corresponding to each WDM channel in the gain flattening proposed model

Wavelength (nm)	Gain (dB)
1531	32.2251
1531.29	32.3349
1531.57	32.4575
1531.86	32.5590
1532.14	32.6437
1532.43	32.7521
1532.71	32.8976
1533	32.9543

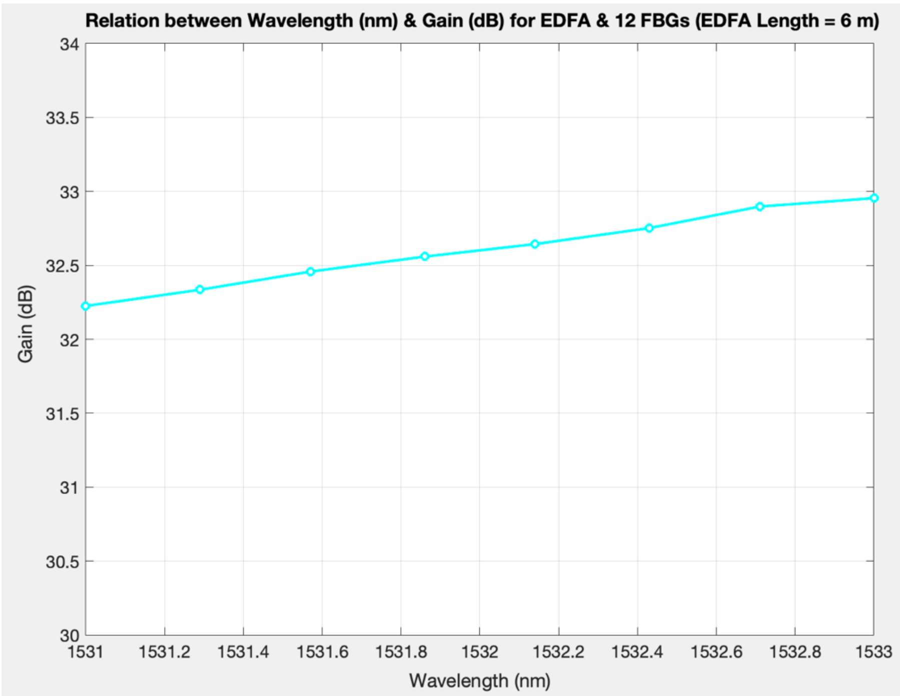


Fig. 8. Gain as a function of wavelength for gain flattening proposed model

From Table 4 and Figure 8, one can conclude that the proposed model achieved an optimum gain flattening with a difference of 0.7292 dB between the first and last gains in the wavelength range from 1531 to 1533 nm. In this proposed model, we delineated a wavelength range spanning from 1526.44 nm to 1537.40 nm utilizing an Erbium-Doped Fiber Amplifier (EDFA) system featuring a cascade of 12 Fiber Bragg Gratings (FBGs), as illustrated in Figure 6. Remarkably, we observed a gain profile that exhibited a near-linear trend, devoid of the typical ripples reported in the literature, particularly in the wavelength range of 1530 nm to 1565 nm where a 0.1 dB ripple had been previously noted.

While the issue of ripples was effectively addressed within our chosen range of 1526.44 nm to 1537.40 nm, a new concern arose with a discernible discrepancy between the maximum and minimum gain, measuring at 7.5966 dB. Our objective was to mitigate this discrepancy through further optimization. Consequently, we directed our focus specifically on the narrower wavelength range from 1531 nm to 1533 nm.

This meticulous narrowing of our investigation allowed us to scrutinize the gain characteristics within the specified wavelength band. By concentrating on this refined range, we aimed to achieve a more pronounced flattening of the gain profile and, thereby, effectively reduce the observed difference between the maximum and minimum gain values. Our findings in this targeted range contribute valuable insights toward advancing the performance and uniformity of EDFA systems in optical communication networks.

4. Conclusions

This study investigates EDFA gain flattening using cascaded FBGs. Three, six, nine, and twelve cascaded FBGs configurations are employed in the EDFA system to compare the relative gain differences between them. Lower relative differences indicate better gain flattening. EDFA demonstrates improved gain flattening performance with a 6-meter length and a configuration of twelve cascaded FBGs, achieving a difference of 0.7292 dB between the first and last gains within the wavelength range of 1531 to 1533 nm. The 2 nm nominal bandwidth, though seemingly modest, proves strategically effective for long-haul and metro optical communication applications. Its choice is especially advantageous, particularly within the C-band, making it highly practical for telecommunication networks due to seamless compatibility with established fiber infrastructure. These findings contribute to enhancing gain flattening techniques in EDFA systems, ensuring improved signal quality and stability in the targeted wavelength range.

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