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EDFA gain flattening using fiber Bragg gratings employing different host materials

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Abstract

In this paper, erbium-doped fiber amplifier (EDFA) gain flatness is studied using cascaded fiber Bragg gratings (FBGs) with different numbers. The gain characteristics are investigated in reference to the wavelength, EDFA length, erbium ion density, and erbium radius. Three host materials are used: conventional silica, fluoride, and alumino-germanosilica, depending on their absorption and emission cross section areas. The convectional silica exhibits a high gain of 38.5 dB before flattening with an in-band gain of 6.5 dB. After flattening, the gain is dropped to 29 dB with a relative gain difference of 1.3% with 10 FBGs. The bandwidth of 28.42 nm is realized with 20 and 10 FBGs while the 30 FBGs configuration achieves a slightly lower value of 25 nm. The fluoride as host material depicts a lower gain after flattening of 12 dB, minimum relative gain difference of 10% with 30 FBGs and bandwidth of 28.42 nm. The alumino-germanosilicate depicts the highest gain of 30 dB with 28 nm bandwidth flattened with a relative gain difference of 1% at 30 FBGs configuration.

Keywords Erbium-doped fiber amplifier (EDFA) · Wavelength division multiplexing (WDM) · Fiber Bragg gratings (FBG) · Gain flattening

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1 Introduction

The overall transmission capability in communication systems depends on the spectral characteristics of the amplifying devices. These include the gain magnitude and bandwidth. For signals to be transmitted for long distances, it is important to compensate for attenuation losses within the fiber because the accrued effect of attenuation causes the signal to fade (Agrawal 2002). This can be achieved by the use of either an optical amplifier or a regenerator at an appropriate point along the fiber length. Before the invention of optical fiber amplifiers, electrical repeaters were used. The use of these repeaters in optical communication systems makes the systems more complicated and also increases installation cost. The optical amplifiers provide direct amplification of the optical signal.

The fiber amplifiers can be constructed using different rare-earth ions. The most commonly used element is erbium. EDFAs obtained by doping the silica fiber with erbium ions operate in a broad range within the1550 nm window where the loss of silica fiber is minimum (Aljaff and Rasheed 2008; Mears et al. 1987; Akaryia et al. 2004). EDFA has a number of advantages over the semiconductor laser amplifier. These include high gain, minimized noise and large bandwidth (Bayaki et al. 2012).

Erbium-doped fiber amplifiers (EDFAs) provide a key role in lightwave communication systems. The spectral gain of EDFA is not quite flat. This behavior affects the output signal gain levels which leads to some signal channels lost in some channels. This, therefore, demands gain flattening, especially when employed in wavelength division multiplexed (WDM) systems.

The conventional EDFA does not offer equalized gain spectrum, hence leading to high signal distortion and low signal-to-noise ratio (SNR) (Bebawi et al. 2018). The difference between the gain upper peak and the lower peak in the whole range of band in EDFA is termed in-band gain flatness. The smaller the difference is the better the gain flatness of the optical amplifier. Again, despite the fact that the power of the individual channel of the amplifier input terminal might be the same, enormous differences in the out channels will exist. This will lead to an increase in SNR and in effect reduce the gain of the output channels. Hence, EDFA gain flattening is an area of concern to achieve high performance within the transmission bandwidth of WDM optical systems.

Quite a number of approaches to attain EDFA gain evenness exist. These include; controlling the level of doping in EDFA length and pump power (Park et al. 1996), through appropriate selection of optical notch filter characteristics (Tachibana et al. 1991), by use of tunable acousto-optic notch filter (Su et al. 1993).

In this paper, we aim at EDFA gain flattening to avoid the mentioned problem and to amplify all signals equally. Here, gain flatness has been achieved through the use of cascaded uniform fiber Bragg gratings (FBGs). Three different host materials are investigated; namely, silica, fluoride, and alumino-germinosilicate. In the three host materials used, silica attains gain evenness at 29 dB level with a minimum relative gain difference of 1.3% and a broader bandwidth of 28.42 nm. The inversion realized in fluoride host material when the highest gain before flattening and after flattening are compared is very large, an approximate drop of 26 dB. While, best results are achieved with alumino-germinosilicate giving a flat gain output of 30 dB with in-band of ± 1 dB.

The paper is organized as follows. In Sect. 1, the introduction of the field of study, method used to obtain results and brief outcome of results is discussed. Section 2 considers the mathematical model used to achieve the results. The simulation of the mathematical model and the setup is discussed in Sect. 3. The achieved graphical results are analyzed in section four. Finally, Sect. 5 is devoted for the main conclusions of the obtained results.

2 System model

The design of the EDFA is based on a three-level atomic structure. The relevant characteristics of the EDFA can be attained through the model. To reduce the complication of EDFA model design, the basic three-level system is converted to a two-level system, with the assumption that the upper pump level and upper metastable level belongs to the same multiplet as shown Fig. 1 (Mears and Baker 1992).

EDFA is normally pumped at 980 nm or 1480 nm by semiconductor lasers (Kaler and Kaler 2011). The 980 nm pump is used in a three-level model, while the 1480 nm pump is used in a two-level model. Complete population inversion is attained with 980 nm pumping but not with a 1480 nm pump.

When an optical amplifier is pumped at 1480 nm, erbium ions doped in the fiber absorb the pump light energy and are excited to an excited state (E_2 in Fig. 1). When high enough pump power is launched to the fiber, population inversion between excited state E_2 and the ground state is created, and amplification through stimulated emissions occurs at around 1550 nm. When an optical amplifier is pumped at 980 nm, erbium ions absorb the pump light energy and hence excited to a higher excited state (E_3 in Fig. 1). The lifetime of the excited-state E_3 is too short (~ 10 μs), and consequently, the Er^{3+} ions are immediately decayed to the excited state E_2 by radiating heat energy. The relaxation process enables population inversion between excited state E_2 and the ground state to be achieved; hence amplification takes place at a wavelength of 1550 nm.

2.1 EDFA of gain (G_{EDFA})

The gain of EDFA, G_{EDFA} is defined as the product of the induced emission cross-section σ and the ion concentration difference between state E_2 and E_1. The difference in ion concentration between E_2 and E_1 is described by the equation below as (Padwal and Chattopadhyay 2012),

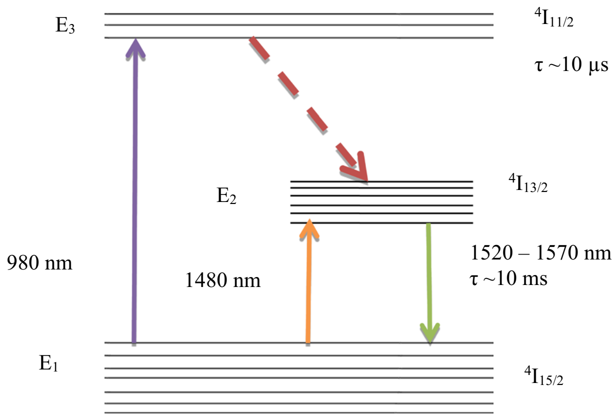


Fig. 1 Energy levels of erbium ions in EDFA (Mears and Baker 1992)

$$n = \frac{n_t \cdot (w_p - \Gamma)}{2\sigma c \cdot n \cdot p + \Gamma + w_p} \tag{1}$$

where $n = N_2 – N_1$, N_1 and N_2 is the ion concentration of ground state and E_2 respectively, n_t is the total ion concentration, w_p is the pump rate, Γ is the reciprocal of E_2 lifetime, σ is the induced emission cross-section, c is the velocity of light, and p is the photon density.

The absorption strength does not only present a material constant, but also depends on the difference in the density population density N_1–N_2 and therefore on the intensity, I = p.c., of the photon field. Amplification then takes place when (Padwal and Chattopadhyay 2012),

$$G = \sigma \cdot (N_2 - N_1) = \sigma \cdot n > 0$$

$$G_{EDFA} = \frac{\sigma \cdot n_t \cdot (w_p - \Gamma)}{2 \cdot \sigma c \cdot p + \Gamma + w_p} \tag{2}$$

For the amplification to be achieved, the pump rate has to be much higher than the rate of spontaneous emission. This is made possible by making the lifetime τ_s to be too large.

2.2 Noise figure of EDFA

Noise figure (NF) can be expressed in terms of both fiber bandwidth $\Delta\nu$ and ASE power as in (Becker et al. 2006)

$$P_{ASE} = n_{sp} \cdot h \cdot \nu \cdot \Delta v \cdot (G - 1) \tag{3}$$

where n_{sp} is the inversion factor, h is Planck's constant, G is the EDFA gain and ν is the frequency of light. Two polarization modes exist in single-mode fiber amplifiers, while large numbers of spatial modes are present in multimode fiber amplifier. A multiplying factor of 2 is used to get the total ASE power in a single-mode. The noise figure, therefore, is defined as (Becker et al. 2006)

$$NF = \frac{P_{ASE}}{h \cdot \nu \cdot \Delta V \cdot G} + \frac{1}{G} \tag{4}$$

2.3 Fiber Bragg grating (FBG) modeling

The FBG is a wavelength-dependent reflector/filter achieved by injecting a periodic refractive index into the core of a single-mode optical fiber. When light passes through the grating at a particular wavelength, called the Bragg wavelength (Kashyap et al. 2010; Othonos et al. 2006; Hill and Meltz 1997; Erdogan 1997), the light will be reflected. The specific wavelength, λ_B, is given by (Kashyap et al. 2010):

$$\lambda_B = 2\Lambda n_{eff} \tag{5}$$

where, Λ is the grating period and n_{eff} is the effective refractive index of the grating in the fiber core.

By considering a uniform fiber Bragg grating (UFBG) written in the fiber core and having a mean refractive index represented by n_{core}, the refractive profile index is hence expressed as

$$n(z) = n_{core} + \Delta n[1 + \cos(2\pi z/\Lambda)] \tag{6}$$

where Δn is the photoinduced change in the index. Using the coupled-mode theory (Lam and Garside 1981), and representing the peaks of the co-propagating and counter-propagating modes to be A(z) and B(z), hence,

$$\frac{dA}{dz} = kBe^{i\Gamma z} \quad \text{and} \quad \frac{dB}{dz} = kAe^{-i\Gamma z} \tag{7}$$

where $\Gamma = 2\beta - k$ is phase mismatch and $\beta = \frac{2\pi}{\lambda_0} n_{eff}$.

For a single-mode fiber with Gaussian approximation, the overlap integral is given by,

$$I \simeq 1 - \exp\left(-\frac{2a^2}{w^2}\right) \tag{8}$$

and

$$k \simeq \left(\frac{\pi \Delta n_o I}{\lambda_B}\right)$$

where w is the Gaussian spot size of the mode and a is the core radius.

They are related as (Andrew 2005)

$$\frac{w}{a} = 0.65 + \frac{1.619}{V^{3/2}} + \frac{2.879}{V^6} \tag{9}$$

V lies in the range of $0.8 < V < 2.5$

Hence, the reflectivity of the grating is given by,

$$R(l, \lambda) = \frac{k^2 sinh^2(\gamma L)}{\frac{\Gamma^2}{4} sinh^2(\gamma L) + \gamma^2 cosh^2(\gamma L)} \tag{10}$$

where $\gamma^2 = k^2 - \frac{\Gamma^2}{4}$ with the conditions $A(z=0)=1$ and $B(z=L)=0$.

At Bragg wavelength, λ_B, $2\beta = k = \Gamma = 0$ *and* $\gamma = k$, therefore

$$R = tanh^2(kL) \tag{11}$$

2.4 Emission and absorption cross-sections for the host materials

The emission σ_e and the absorption σ_a cross-section areas in reference to the wavelength λ_s of the signal were obtained by implementing the fitting expressions using Matlab.

3 Simulation setup

The simulation was carried out with and without fiber Bragg gratings to flatten the gain using the Optiwave version 16.0 software. Figure 2 shows the complete system of EDFA without gain flattening. The wavelength range covers the C-band 1530 to 1560 nm and is generated at the transmitter. The NRZ scheme is used with input power − 10 dBm. After modulation, the signal is multiplexed with pump signal through a coupler and transmitted to the input isolator which blocks backward direction propagation of the amplified spontaneous emission (ASE) and signals. If the reflected ASE is not eliminated, a reduction in the population inversion will be encountered, which will lead to a reduction in the gain and an increase in the noise figure. The signal is passed to the EDFA that amplifies the signal with unequal gains at different wavelengths. The output isolator blocks light from output reflections re-entering the EDFA (Husein and El-Nahal 2012). The pump is used to excite the erbium-doped ions to a higher energy level (Mounia et al. 2017).

An EDFA of 5 m long is used with forward pump wavelength 980 nm and forward pump power 100 mW. After passing through the second isolator, the signal is delivered to the receiver which consists of pin photodiode which converts the optical signal to an electrical signal.

To be able to flatten the EDFA gain output, cascaded FBGs are used as presented in Fig. 3. To equalize the gain of EDFA, the reflectivities of cascaded FBGs are to be considered and they are adjusted based on the EDFA gain profile. The condition for gain flattening for the WDM channels is

$$\mathrm{G}_{\mathrm{EDFA}}\left(\lambda_{\mathrm{n}}\right)\left[1-\mathrm{R}\left(\lambda_{\mathrm{n}}\right)\right]=\mathrm{G}_{\mathrm{EDFA(min)}} \tag{13}$$

where $\mathrm{R}\left(\lambda_{\mathrm{n}}\right)$ denotes the peak reflectivity of the FBG having a Bragg wavelength λ_{n}, n taking numerical values 1, 2,…., m−1. $\mathrm{G}_{\mathrm{EDFA}}\left(\lambda_{\mathrm{n}}\right)$ represents the gain of a channel with a wavelength λ_{n} and $\mathrm{G}_{\mathrm{EDFA(min)}}$ denotes the minimum EDFA gain of the channels.

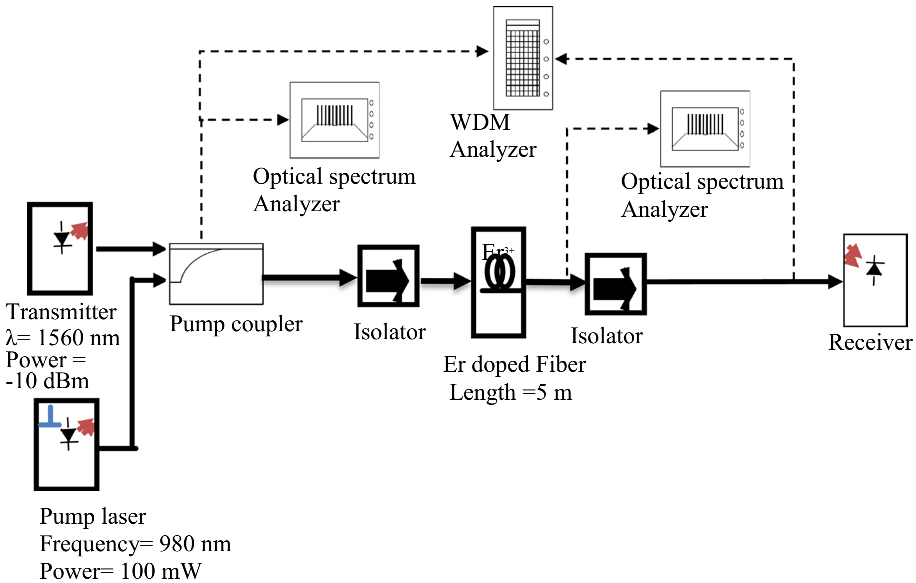


Fig. 2 EDFA system without FBGs

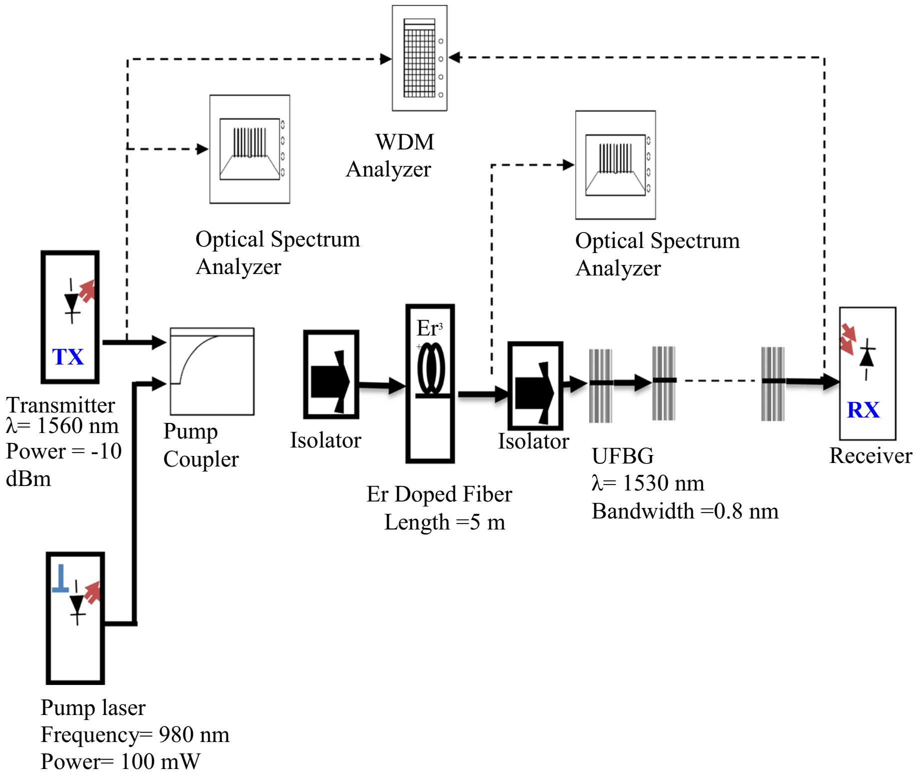


Fig. 3 Uniform FBGs cascaded to flatten the EDFA gain

4 Results and discussion

First, Matlab R2018b is used to simulate the emission and absorption cross-section areas of the three host materials experimentally obtained [22, 23, 24]. This enables the generation of emission and absorption versus wavelength. Thereafter, data is loaded to Optisystem software. In the design, three host materials are used: conventional silica, fluoride, and alumino-germanosilicate (Fig. 4).

Following the described model, the EDFA gain is then obtained using the three host materials. The EDFA gain is displayed against the wavelength in Fig. 5, for the silica, fluoride, and alumino-germanosilicate.

From Fig. 5, it is seen that the gain variation between highest and lowest values is approximately 2 dB for silica, 9 dB for fluoride and 5 dB for alumino-germanosilicate in the C band (1530–1560 nm). These values are quite high, especially for fluoride and alumino-germanosilicate host materials. This leads to unequally amplification for all signals simultaneously. To avoid this problem, this implies the use of flattening techniques to smooth the flatten the gain. One of these techniques is the use of cascaded FBGs (Kashyap et al. 2010; Othonos et al. 2006; Hill and Meltz 1997; Erdogan 1997), as shown in Fig. 3.

Now, we use the set up with FBGs to flatten the gain. Figures 6, 7, 8 and 9 show the gain characteristics of silica-based EDFA with wavelength, length, erbium ion concentration, and erbium-doping radius.

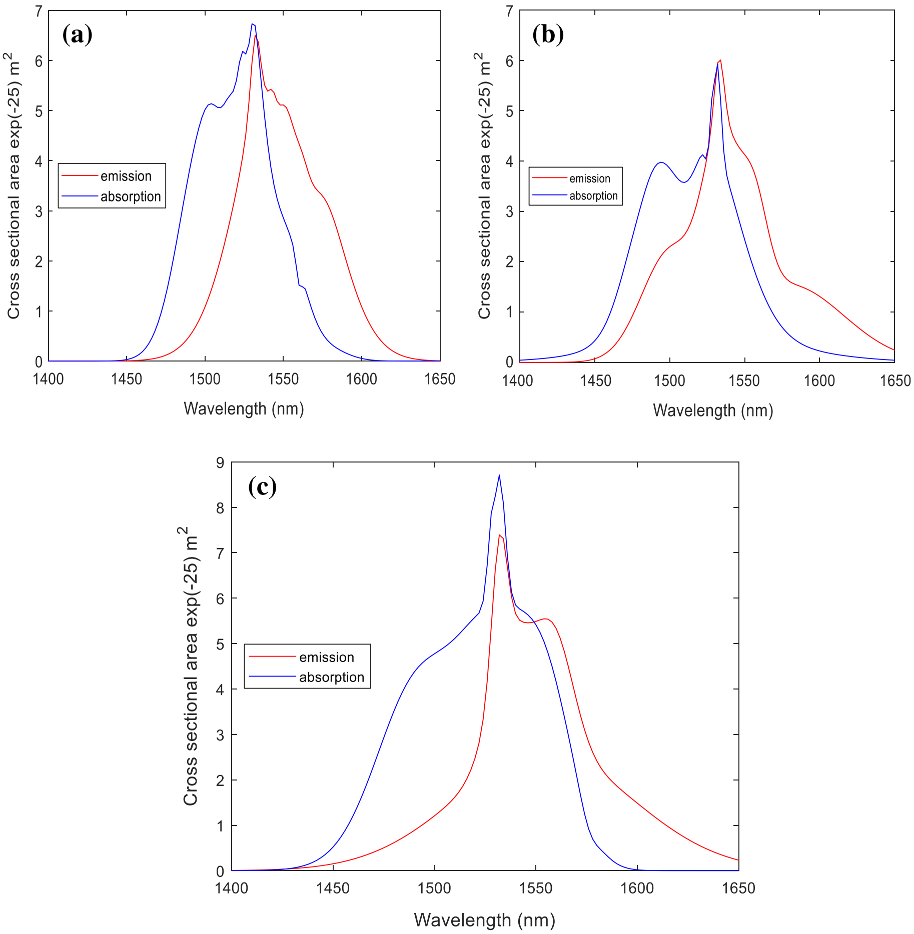


Fig. 4 Emission and absorption cross-section areas of the host materials **a** Silica (Digonnet et al. 2002). **b** Fluoride (Ohishi et al. 1998). **c** Alumino-germanosilicate (Tarbox et al. 1991)

To evaluate the gain flatness, we define the following parameters

$$\text{Relative gain difference} = \frac{G_{max} - G_{min}}{G_{max}} \% \tag{14}$$

G_{max} and G_{min} represent maximum and minimum gain respectively.

$$Bw = \left(\lambda_{upper} - \lambda_{lower}\right) nm \tag{15}$$

where λ_{upper} and λ_{lower} represent upper and lower wavelength within the gain even range, respectively.

Figure 6 shows the flattened gain profile. The configuration with 30 FBGs achieves a flat gain profile with a relative difference of 10.9% and the bandwidth of 25 nm. The maximum gain in the configuration without FBGs is 38.28 dB and after in-cooperating gain flattening devices; the gain is dropped to approximately 29 dB. Hence, the gain of

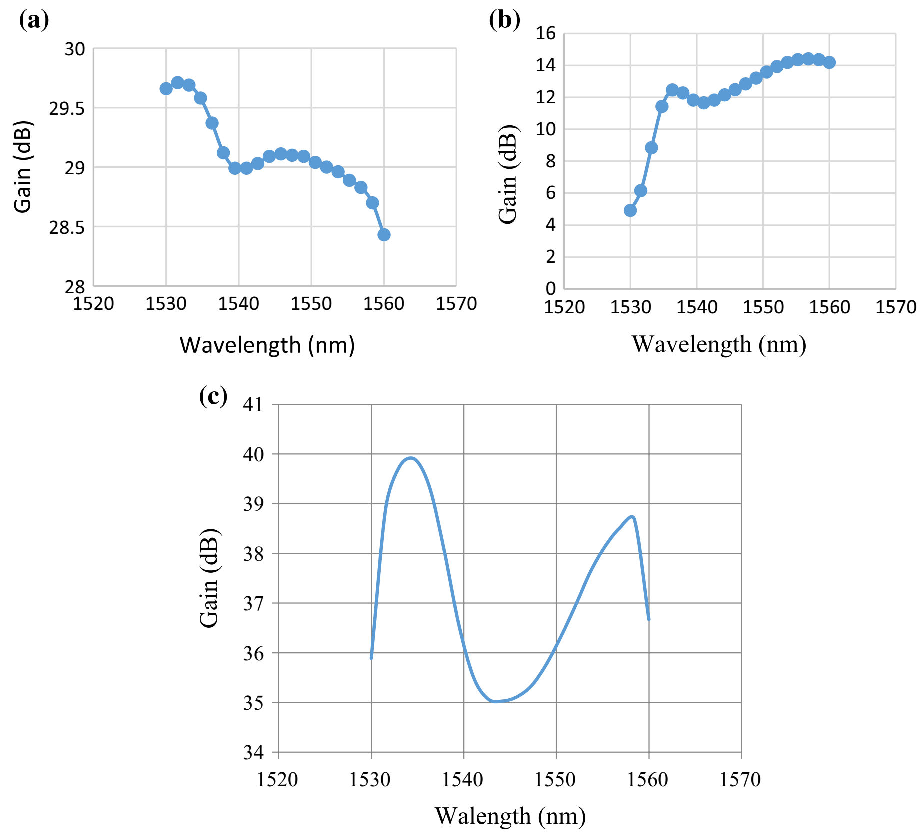


Fig. 5 Gain spectrum for EDFA doped with **a** silica **b** fluoride **c** alumino-germanosilicate

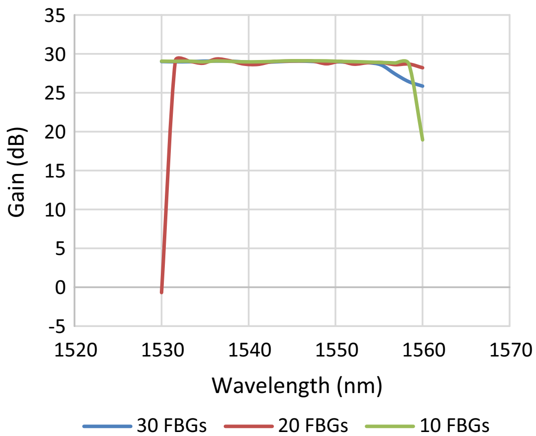


Fig. 6 Silica EDFA with gain flattening using various numbers of FBGs

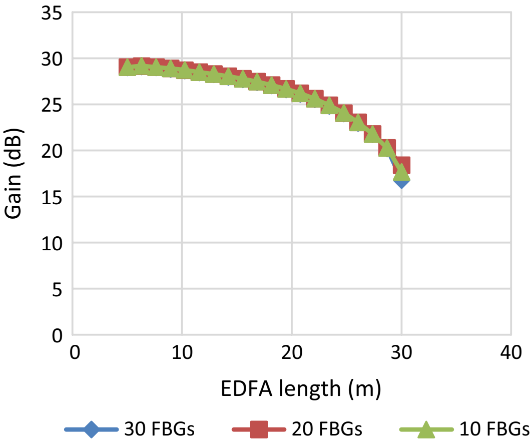


Fig. 7 Silica EDFA gain against EDFA length

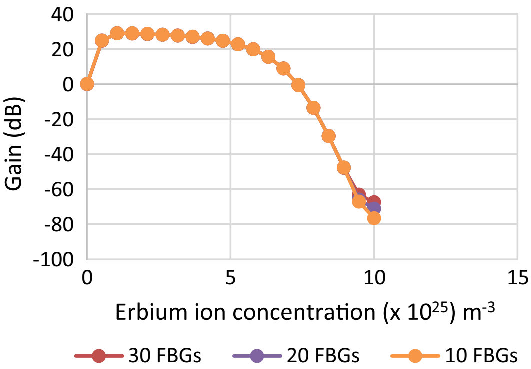


Fig. 8 Silica EDFA gain against Er^{3+} ion concentration

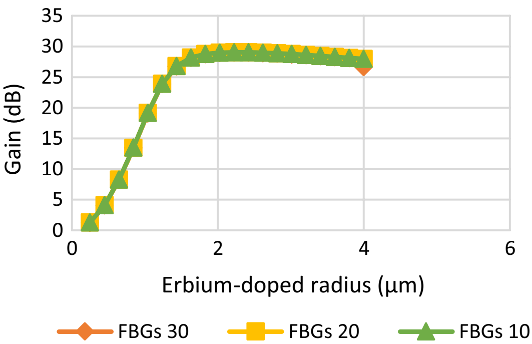


Fig. 9 Silica EDFA gain against Er-doping radius

the amplifier is compromised if flattening is to be achieved. However, a gain with very small variation is achieved. When the number of FBGs is reduced to 20, the relative gain difference is improved to 3% and the bandwidth is widened to 28.2 nm. By further reduction of FBGs to 10, the relative gain difference is greatly improved to 1.3%. The relative gain difference measures the difference between the highest gain and the lowest gain. The smaller the relative gain difference, the better the gain flatness of the EDFA.

To obtain EDFA gain optimization, parameters of the EDFA must be set to optimum values. A 5 m doped length of the fiber amplifier in Fig. 7 achieves maximum gain. Figure 7 shows that increasing length greater than 5 m, the gain is reduced in effect. The number of FBGs has no weighty effect on the relation between the gain of the EDFA and the length of the doped fiber amplifier.

When erbium ion concentration is varied from a minimum value, maximum gain is attained at 1.0535×10^{25} m^{-3}. At a given pump power, as ion concentration increases, the gain first increases to a peak value of approximately 30 dB and then begins to drop with increasing erbium ions concentration. This is because the pump power is exhausted, therefore no more erbium ions excited and the gain drops as shown in Fig. 8. Again, it is noted from Fig. 8 that the number of FBGs has no effect on the output behavior of the gain against erbium ion density.

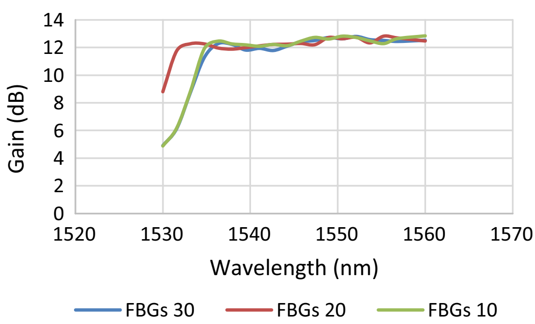
Figure 9 displays the characteristic behavior of EDFA gain in relation to the erbium-doping radius. The gain increases with the doping radius up to a maximum of 1.5 µm. Thereafter, it remains constant with the change of radius up to 4 µm, where it starts to decrease gently. By increasing the doped radius from the best value (1.5 µm), the gain decreases because of the expanded absorption area created by the dopant ions residing in the core-cladding boundary region (Amin et al. 2019). On the other side, the gain decreases because of ion-ion interaction effects when the doped radius is decreased from the optimum value.

However, the pump conversion efficiency in an EDFA can be improved by controlling the doping radius of an EDFA to lower values (Armitage 1988). A small EDFA doped radius eliminates ions from the sections of the EDFA core where pump absorption is completely weak. Y. Ohashi showed that decreasing the doping radius theoretically leads to an increase in the signal gain (Amin et al. 2019; Ohashi 1991). From Fig. 9, it is noted that the number of FBGS used to obtain the gain evenness has no effect on the characteristics of gain in relation to the erbium-doping radius.

In this section, the procedure is repeated for fluoride host material. The obtained results are displayed in Figs. 10, 11, 12 and 13 with different numbers of cascaded FBGs.

The gain flattening of fluoride based EDFA under the same condition applied to silica based EDFA yields unsatisfactory results as compared to silica based. The relative gain difference calculated when the number of FBGs is varied is 10%, 13.57% and 14% for 30 FBGs, 20 FBGs, and 10 FBGs, respectively. The values are significantly high as compared with what was calculated for silica based EDFA.

Fig. 10 Fluoride EDFA gain flattening using different numbers of FBGs



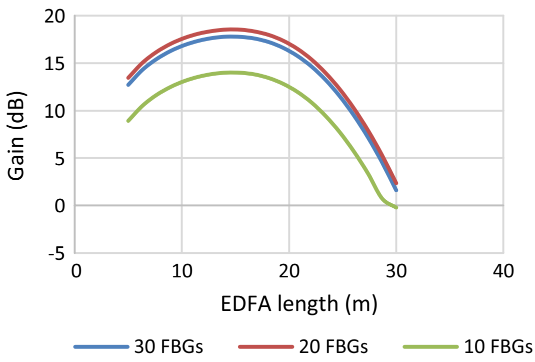


Fig. 11 Fluoride EDFA gain against length using different numbers of FBGs

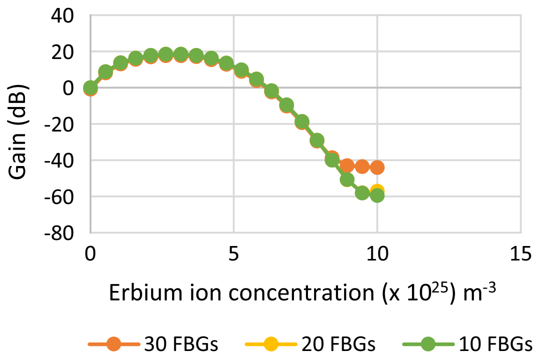


Fig. 12 Fluoride EDFA gain against Er^{3+} concentration

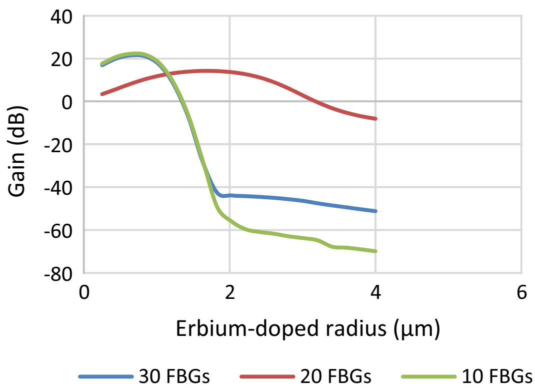


Fig. 13 Fluoride EDFA gain against Er-doping radius

The calculated bandwidth is 25.26 nm for 30 FBGs, 28.42 nm for 20 FBGs and 25.26 nm for 10 FBGs. The configuration with 20 FBGs gives the same bandwidth as what was obtained in silica based. The gain evenness obtained was far below the value of the silica based, i.e., at around 12 dB, Fig. 10 compared to 29 dB for silica. However, by using different configuration from the one used, fluoride based gives best results (Bayart et al. 1994; Yamada et al. 1996). Fluoride-based host material when used in EDFA has practical merits as compared to silica based EDFA (Yamada et al. 1996; Clesca et al. 1994; Ronarc'h et al. 1994).

Figure 11 shows that when the length is increased from a minimum point, the gain increases to a peak value at an EDFA length of 15 m. The gain remains constant with length up to approximately 18 m, where it starts to drop. The drop in gain is due to the pump power weakening as the length is increased hence, leading to a reduction in population inversion. All three configurations, i.e., using different number of FBGs show the same behavior.

From Fig. 12, the erbium ion concentration has an important effect on the EDFA gain. When the doping concentration is too low, excited-state (Zhang et al. 2008) depletion will be experienced. Hence, amplification of the optical signal will be limited to the smaller ion number. However, heavy doping can lead to a quenching mechanism brought about by cross-relaxation and ion-pairing up conversions. These processes reduce the pumping efficiency and therefore the signal gain (Kir'Yanor et al. 2013; Carlnäs et al. 1991; Myslinski et al. 1997).

As shown in Fig. 13, and unlike silica based EDFA, fluoride EDFA shows a gain abrupt change as the radius of the Er^{3+} is increased especially for 30 FBGs and 10 FBGs configurations after 1 μm. The 20 FBGs configuration shows a slight change up to a radius of 3 μm, where it slowly drops.

The gain characteristics of alumino-germanosilicate are shown in Figs. 14, 15, 16 and 17, where the same configuration used in the silica based is applied except the pump wavelength. The 980 nm pumping could not give any results. When the pump wavelength is changed to 1480 nm, better results are achieved.

As compared to the silica and fluoride based, Fig. 14 shows that the evenness is attained at a higher gain value of around 30 dB. The calculated relative gain difference is found to be 1% at 30 FBGs, 4.8% at 20 FBGs and 7% at 10 FBGs. The 1% realized at 30 FBGS gives the best value in all the host materials used. A bandwidth of 28 nm is achieved, which still stands good as compared to the other host materials.

The gain decreases at a length beyond 15 m, Fig. 15. This arises due to weakening of the pump power as the length grows longer hence reducing the population inversion. Figure 16 displays the gain with respect to Er^{3+} ion density. As per the result, the best Er^{3+} ion density is noted at 1×10^{25} m^{-3}. Further increase in Er^{3+} ion density leads to clustering which reduces the fluorescence lifetime and hence, lowering the gain. In Fig. 17, it is noted that the gain increases with an increase in radius until a saturation point, where it starts to drop gently. The peak gain is attained at a doping radius slightly less than the core radius.

Fig. 14 Alumino-germanosilicate EDFA gain spectrum

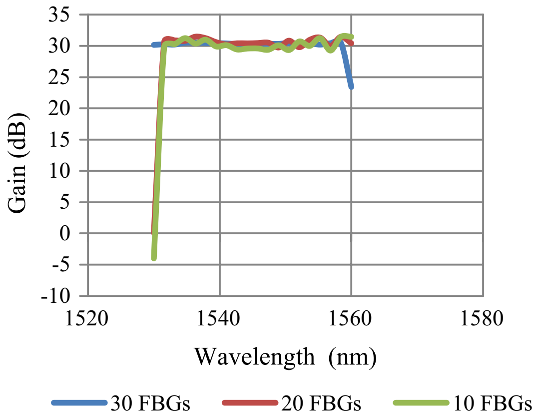


Fig. 15 Alumino-germanosilicate EDFA gain against the length

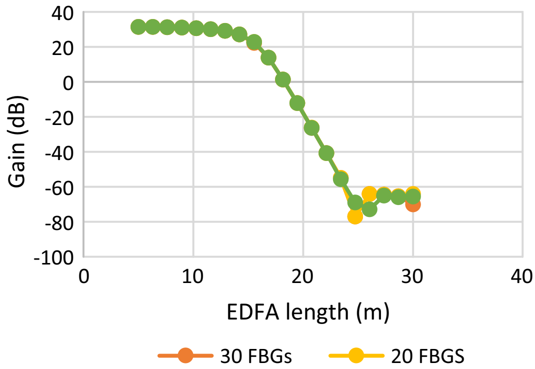


Fig. 16 Alumino-germanosilicate EDFA gain as a function of erbium ion concentration

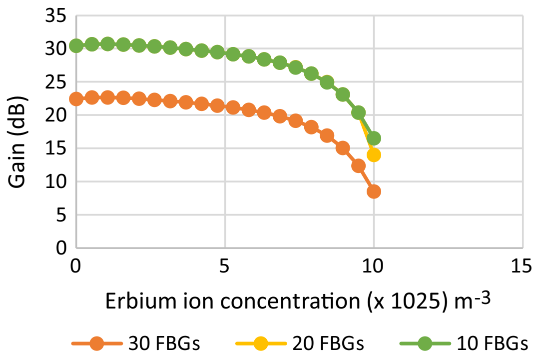
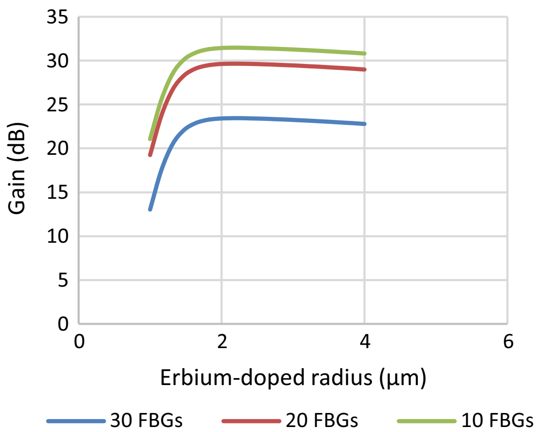


Fig. 17 Alumino-germanosilicate EDFA gain versus the Er-doping radius



Usually, the doping is concentrated in the core of the erbium-doped fiber. Hence, a radius greater than the core radius will yield a lower gain.

The obtained results for the different host materials are summarized in Table 1.

To show the superiority of our work, a comparison is performed with a previous work (Sallam et al. 2016). In the previous work and before flattening, the germanosilicate

Table 1 Comparison of relative gain difference and bandwidth of EDFA host materials

Host parameter	Silica			Fluoride			Alumino-Germanosilicate		
	30 FBGs	20 FBGs	10 FBGs	30 FBGs	20 FBGs	10 FBGs	30 FBGs	20 FBGs	10 FBGs
Relative gain difference (%)	10.9	3	1.3	10	13.53	14	1	4.8	7
Bandwidth (nm)	25	28.42	28.42	25.26	28.42	25.26	28	28	28

germano-aluminosilicate achieved a maximum gain of 9.5 and 9.8 dB, respectively. After flattening, both achieved a good gain flattening on the expense of reducing the maximum gain to 4 and 6 dB, respectively, in the C-band. On the other hand, our technique achieved a good flattening but with high gain at the same time, reaching 29 dB for silica, 12 dB for fluoride, and 30 dB for aluminosilicat, respectively.

5 Conclusion

In this paper, EDFA gain flattening using cascaded FBGs is investigated. Three configurations of FBGs are employed where the relative gain difference and bandwidth are compared. The lower values of this relative difference indicate a better gain flattening. Silica based EDFA achieved gain evenness and broadband gain a level of 29 dB with fewer number of cascaded FBGs. In fluoride host material, a gain evenness is achieved at a lower level of 12 dB, with a quite high relative gain differences in all the FBGs configurations. However, a bandwidth of 28.42 nm is noted at 20 FBGs configuration. The alumino-germanosilicate achieves the best relative gain difference of 1% among all the materials, with a high gain level of evenness approximately 30 dB and bandwidth of 28 nm. So, the alumino-germanosilicate is recommended because it achieves the best flatness and maximum bandwidth which can be used in wavelength division multiplexing (WDM).

In silica host material, the Er^{3+} ions concentration of 1.0535×10^{25} m^{-3} achieves the maximum gain. The fluoride host material showed the same behavior as silica; though the maximum gain attained is lower. The alumino-germanosilicate, despite indicating the same behavior as the preceding two host materials, with 20 FBGs configuration achieves the highest gain at lower Er^{3+} ions concentration. The gain as a function of erbium-doped radius in silica and alumino-germanosilicate indicated the same behavior, showing a gain increase with the radius. However, fluoride gain characteristics with respect to radius attained a maximum peak and immediately drop with 30 and 10 FBGs configuration. The 20 FBGs configuration maintains a gentle increase up to 2 μm then started dropping.

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