EDFA gain flattening using cascaded fiber Bragg gratings

DALIA SALLAM, ISLAM ASHRY[a], ALI ELRASHIDI[a], ZIAD A. EL-SAHN[b], MOUSTAFA H. ALY[*]
Photonic Research Lab (PRL) Electronics and Communications Engineering Department, College of Engineering and Technology, Arab Academy for Science, Technology and Maritime Transport, Alexandria, Egypt
[a]*Mathematicaland Physical Engineering Department, Faculty of Engineering, Alexandria University, Alexandria, Egypt*
[b]*Photonics Group, Electrical Engineering Department, Faculty of Engineering, Alexandria University, Alexandria, Egypt*
[#] *Member of OSA*

Gain flattening of erbium-doped fiber amplifiers (EDFAs) is necessary for wavelength-division multiplexed (WDM) optical communication networks to offer equal amplifications for all channels. Such kind of amplifiers can be fabricated following two approaches: intrinsic modification of an amplifier host material and extrinsic incorporation of an optical filter. In this paper, we theoretically apply the two approaches simultaneously to design EDFA of flat gain spectrum. We use three different modified host materials and cascaded fiber Bragg gratings (FBGs) to get excellent EDFA flat gain. The designed structure in this paper could also be used to equalize any arbitrary gain profile.

(Received December 16, 2015; accepted June 9, 2016)

Keywords: Fiber Bragg grating, Erbium-doped fiber amplifier, Gain flattening

1. Introduction

Signal attenuation is a common problem in the long-haul optical wavelength-division multiplexed (WDM) communication networks. Therefore, erbium-doped fiber amplifiers (EDFAs) have been considered a pivotal device in such networks since they provide high gain, large bandwidth, and relatively low noise [1-3]. The conventional EDFA, unfortunately, offers non-equalized gain spectrum yielding to high signal distortion and low signal-to-noise ratio (SNR) [3]. Consequently, EDFA gain equalization has been considered as one of the hot photonic research topic to enhance the performance and transmission bandwidth of the WDM optical systems.

A lot of successful approaches have been deployed in the literature to flatten the EDFA gain, which can be divided into extrinsic and intrinsic techniques [4-7]. In the extrinsic methods, optical-fiber-based filters such as, blazed fiber Bragg gratings (FBGs) [8], chirped FBGs [9], and acousto-optic tunable filters [10] were used. The main drawback of using a blazed FBG is its high sensitivity to the environmental conditions since it basically converts the guided linearly-polarized (LP) modes to non-guided ones.

Also, fabricating chirped FBG encounters complexity especially when the equalization bandwidth is wide. Additionally, acousto-optic filters suffer from high radio frequency power consumption. However, extrinsic approach show stable and good performance to equalize EDFA gains over wide bandwidths. On the other hand, in the intrinsic techniques, the spectral behavior of the erbium ions is altered by adding different host materials such as, alumino-silicate and fluoride-based glasses [11,12]. This technique, however, is limited by improving the flatness of EDFA gain over only narrow bandwidths.

In this paper, we theoretically describe a new EDFA gain equalization method by combining both the intrinsic and extrinsic approaches. In this method, a modified host material EDFA is connected in series with cascaded apodized and short period FBGs. The advantages of the designed technique over those found in the literature are numerous; the used FBGs are short period which can easily be fabricated; any number of WDM channels can be equalized using this method; WDM channels can be flattened over any spectral band; and the properties of such design can be adaptive by tuning the Bragg wavelength of the FBGs using temperature or strain.

The remaining of this paper is arranged as follows; we report in Section 2 a theoretical background for calculating the reflection spectrum of the FBGs and the EDFA gain; Section 3 includes the obtained results and discussions; and finally we conclude the paper in Section 4.

2. Theoretical background

2.1 EDFA Gain calculation

The EDFA gain, G_{EDFA}, is defined as the ratio of the amplifier output power P_{out} to its input power P_{in}. In order to calculate the output power as a function of EDFA length L, the population inversion should first be calculated. The progress of the laser level population inversion at instant t and position z along the fiber is described by the following rate equations [13]

$$\frac{\partial N_2(z,t)}{\partial t} = [R_{13}(z,t) + W_a(z,t)]N_1(z,t) - [W_e(z,t) + \frac{1}{\tau_2}]N_2(z,t) \quad (1)$$

and

$$N_1(z,t) + N_2(z,t) = N \quad (2)$$

where N_1 (z,t) and N_2 (z,t) are the instantaneous population densities in level 1 (ground level) and level 2 (excited level), respectively, along the fiber. R_{13} represents the pumping rate. W_e and W_a are the emission and absorption rates of stimulated transition between the laser levels, respectively. τ_2 is the life time in the excited level, and N represents the total concentration of the ions. According to [13], these rates are given by

$$R_{13}(z,t) = \frac{\sigma_{ap}(I_p^+(z,t) + I_p^-(z,t))}{hf_p} \quad (3)$$

$$W_a(z,t) = \frac{\sigma_a(I_s^+(z,t) + I_s^-(z,t))}{hf_s} \quad (4)$$

$$W_e(z,t) = \frac{\sigma_e(I_s^+(z,t) + I_s^-(z,t))}{hf_s} \quad (5)$$

where σ_{ap} and σ_a, are the absorption cross sections of the pump and signal, respectively and σ_e represents the emission cross sections of the signal. The pump intensity (signal) mode travelling in the positive and negative directions, respectively, are given by $I_p^+(I_s^+)$ and $I_p^-(I_s^-)$. f_p and f_s are the pump and signal frequencies, respectively, and h is the Planck's constant.

According to the perturbation theory in [13], the signal powers in both the positive and negative directions $P_s^{\pm}$ change over a small distance increment Δz as

$$P_s^{\pm}(z \pm \Delta z, t + \Delta z / v_s) = P_s^{\pm}(z,t)\exp(g_s(z,t)\Delta z), \quad (6)$$

and

$$g_s(z,t) = \int \sigma_e[N_2(r,z,t) - \gamma_s N_1(r,z,t)]s_o(r)d^2r. \quad (7)$$

Here, $g_s(z,t)$ is the power gain coefficient of the mode and v_s is the signal group velocity. The function $s_o(r)$ denotes the normalized intensity profile that connects the local intensity $I_s^{\pm}(r,z,t)$ of the signal mode to its power $P_s^{\pm}(z,t)$, where r denotes the position in a plane which is perpendicular to the fiber axis, and $\gamma_s = \sigma_a / \sigma_e$.

Approximating analytical expressions for both signal and pump powers and the excited level population, $N_2(z)$ can be derived using simplified practical assumptions as in [13]. By applying such assumptions, we get the EDFA gain, for the i^{th} channel, using the following equation

$$G_{EDFA} = 10\log(\frac{P_{\max}^i}{P_{input}^i}). \quad (8)$$

Using this model, the optimum length of EDFA that produces highest output power for the channel of minimum gain can be calculated. In other words, the signal power of the channel of minimum gain, $P_s^{\min}$, should satisfy the condition $\left(dP_s^{\min}(z)/dz\right)\Big|_{z=L_{opt}} = 0$.

2.2 Reflectivity and Transmissivity of FBGs

FBGs can be fabricated through creating a periodic perturbation of the core refractive index along the axis of an optical fiber, by subjecting the fiber to an ultraviolet interference pattern of high intensity. The profile of the refractive index $n(z)$ of a uniform FBG fabricated using an optical fiber of n_o core refractive index is defined as [14]

$$n(z) = n_o + \Delta n(z)\cos\left(\frac{2\pi}{\Lambda} z\right), \quad (9)$$

where $\Delta n(z)$ represents the amplitude of the perturbation of the refractive index, and Λ denotes the period of the grating. The reflected wavelength (Bragg wavelength), λ_B, is linked to the effective grating index n_{eff} as [14]

$$\lambda_B = 2\, n_{eff}\, \Lambda. \quad (10)$$

Using the coupled-mode theory, both of the reflectivity and transmissivity of a FBG can be represented as [14,15]

$$R(L_{FBG}, \lambda) = \frac{k^2 \sinh^2(sL_{FBG})}{s^2\cosh^2(sL_{FBG}) + \delta^2\sinh^2(sL_{FBG})} \quad (11)$$

$$T(L_{FBG}, \lambda) = 1 - R(L_{FBG}, \lambda) \quad (12)$$

where $R(L_{FBG}, \lambda)$ and $T(L_{FBG}, \lambda)$ respectively denote the reflectivity and transmissivity of a FBG that has length L_{FBG} and calculated at wavelength λ. δ (= $n_{eff}\ \omega / c - \pi / \Lambda$) represents the detuning from the Bragg wavelength, k is the coupling coefficient absolute value, and finally $s^2 = k^2 - \delta^2$. Considering that η is the fraction of the fiber mode power that propagated within the core and in case of a sinusoidal index perturbation variation along the fiber axis, the absolute value of the coupling coefficient is represented as

$$k(z) = \frac{\eta\ \pi\ \Delta n(z)}{\lambda_B} \quad (13)$$

A common problem of a uniform FBG is its reflection spectrum contains sidelobes which requires large spacing between the channels in WDM systems. This drawback is usually resolved by apodizing the FBG such that, $\Delta n(z)$ gradually changes at the both ends of the grating and the FBG reflectivity in such case can be modeled using the transfer matrix method [14]. Utilizing the Blackman apodization profile that was reported the best way to reduce the sidelobes level [15], $\Delta n(z)$ becomes

$$\Delta n(z) = \Delta n\left[\frac{1 + 1.19\cos(y) + 0.19\cos(2y)}{2.38}\right]$$

where

$$y = \frac{2\pi\left(z - \frac{B}{2}\right)}{B}, \quad 0 \le z \le B. \qquad (14)$$

3. Results and discussion

In the EDFA design, we used three different host materials, germanosilicate (Type I), germane-aluminosilicate (Type II), and germane-aluminosilicate with high concentration of aluminum (Type III). These materials are common as host materials for silica-based EDFA. These materials are known to provide high gain, high saturation output power, low noise figure, minimum crosstalk, and negligible insertion loss. Applying the Mc-Cumber theory [13], the emission and absorption cross sections spectrum of the EDFAs doped with germanosilicate, germane-aluminosilicate, and germane-aluminosilicate with high concentration of aluminum are shown in Fig. 1.

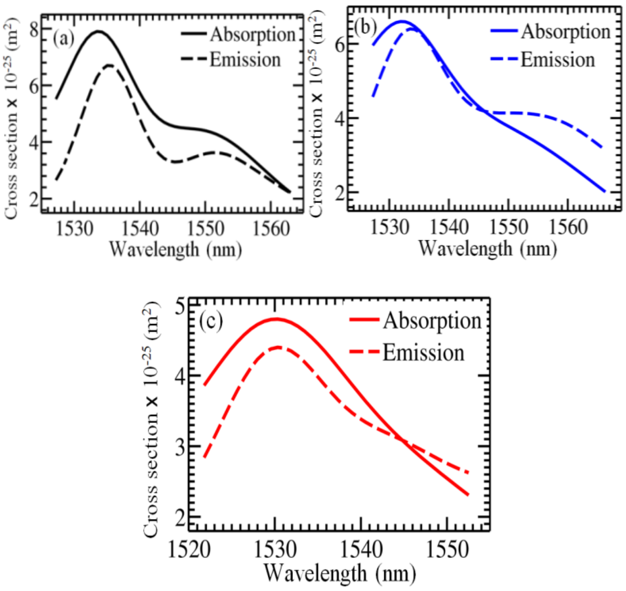

Fig. 1. Emission and absorption cross sections of different EDFAs doped with (a) germanosilicate, (b) germane - aluminosilicate, and (c) germane - aluminosilicate with high aluminum concentration

The used parameters, which are independent of the host material type, for EDFA gain calculation are listed in Table 1. λ_p and λ_s respectively denote the wavelengths of the pump and transmitted signal and σ_{ep} represents the cross section of the pump emission. The positive coefficient of the scattering loss at both the pump and signal power is denoted as $\alpha(\lambda)$, A is the cross sectional area of a fiber core, Γ_p and Γ_s are the filling factors of the pump and signal power, and NA is the numerical aperture of the fiber.

Table 1. Parameters used for the calculations of the EDFA gain

Three Level Parameters		Fiber Parameters	
λ_p	980 nm	A	1.96×10^{-11} m^2
λ_s	1550 nm	n_o	1.5
τ_2	10.8 ms	NA	0.18
σ_{ap}	2.0616×10^{-25} m^2	$\alpha(\lambda_p)$	6.45×10^{-3} m^{-1}
$\sigma_e(\lambda)$	depends on material	$\alpha(\lambda_s)$	3.22×10^{-3} m^{-1}
$\sigma_a(\lambda)$	depends on material	Γ_p	0.889
σ_{ep}	0	Γ_s	0.694

Substituting with the parameters of Table 1 in Eq. (8), one can illustrate the EDFA gains when using different doping materials such as, germanosilicate, germane-aluminosilicate, and germane-aluminosilicate with high concentration of aluminium as exhibited in Fig. 2 (a, b, c). These figures are calculated for the international telecommunication union (ITU) channels of 0.8 nm spacing.

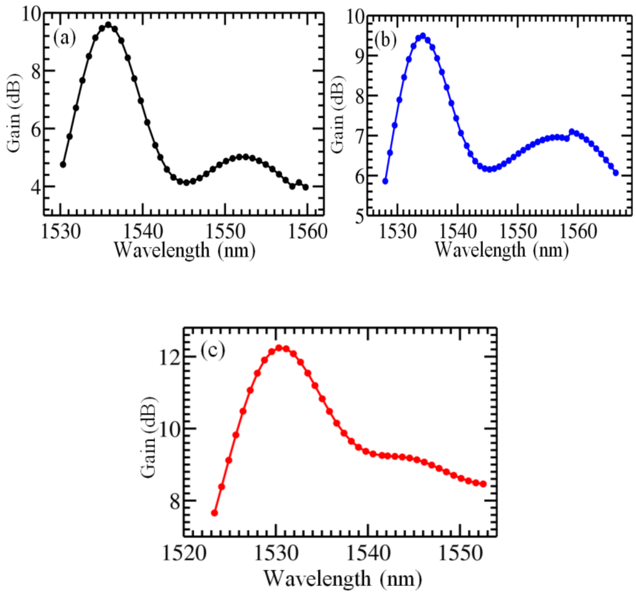

Fig. 2. Gain spectrum for EDFAs doped with (a) germanosilicate, (b) germane-aluminosilicate, and (c) germane - aluminosilicate with high aluminum concentration

Fig. 3 shows the schematic diagram of the designed architecture to equalize the gain of EDFA. The WDM channels of wavelengths λ_1, λ_2, …., λ_m, where m is the maximum number of wavelengths used in the network, are first directed to the used EDFA. Based on the type of the used EDFA, these channels are amplified with different gains, as shown in Fig. 2. In order to flatten the gain of these channels, we use cascaded and apodized FBGs of Bragg wavelengths that are identical to the wavelengths of the used WDM channels.

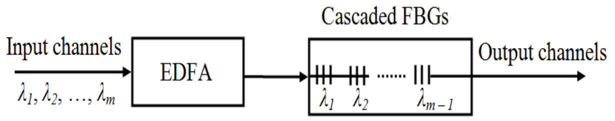

Fig. 3. Schematic diagram of the reported EDFA with gain flattening

The condition for gain equalization of the used WDM channels is

$$G_{EDFA}(\lambda_n)[1-R(\lambda_n)] = G_{EDFA,\min}, \qquad (15)$$

where $G_{EDFA}(\lambda_n)$ represents the gain of the EDFA for a channel of λ_n wavelength such that, n = 1, 2, …, m – 1. $R(\lambda_n)$ denotes the peak reflectivity of the FBG, and $G_{EDFA,\min}$ is the minimum EDFA gain value of the channels. As a result, it is necessary to change the reflectivity of each FBG to flatten the gain of all channels at the minimum one. Using Eq. (14) and the transfer matrix method to find the change of $R(\lambda_n)$ of the used apodized FBGs with $\int_0^L k(z)dz$, as in Fig. 4.

This figure is used as a lookup window to determine the proper value of the integration that corresponds to $R(\lambda_n)$ satisfying Eq. (15).

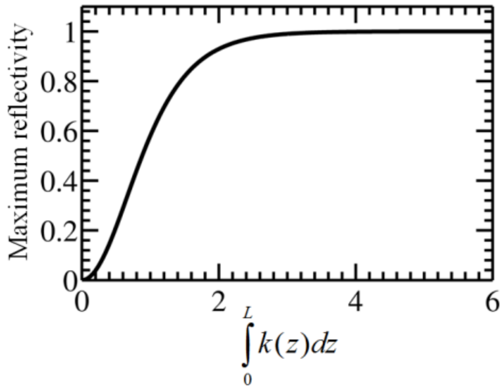

Fig. 4. Change of the maximum reflectivity of the apodized FBG

Fig. 5 shows the reflectivity of the cascaded FBGs used to flatten the gain of EDFAs doped with the different materials under test.

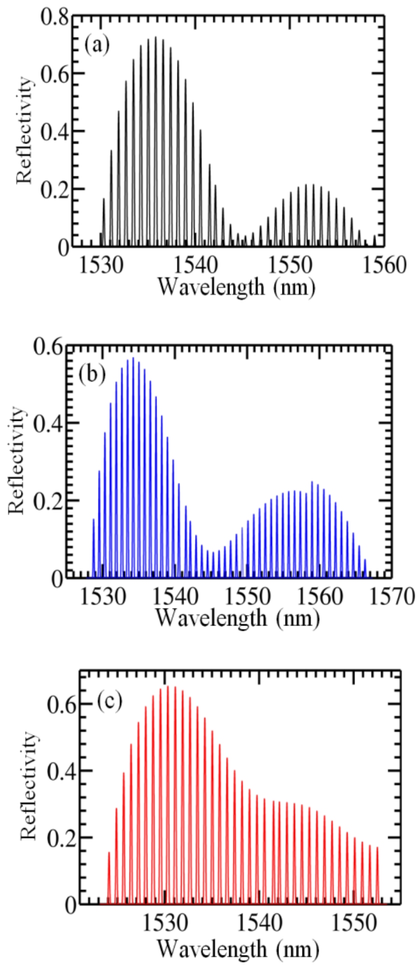

Fig. 5. Reflectivity of the cascaded apodized FBGs used for equalizing the gain of EDFAs doped with (a) germanosilicate, (b) germane-aluminosilicate, and (c) germane - aluminosilicate with high aluminum concentration.

The output channels gain of the three EDFA types are shown in Fig. 6 indicating a good gain flattening, but at the expense of the value of the gain.

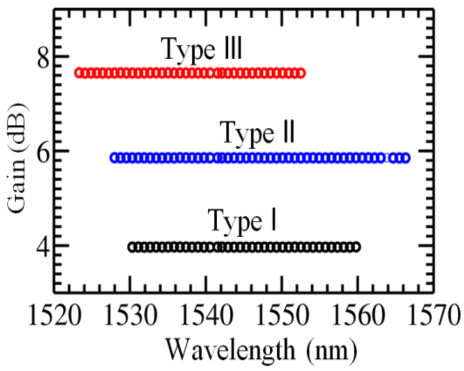

Fig. 6. The gain of output channels after flattening

The reported design has several advantages such as, the ability to equalize any number of WDM channels, simplicity to design and fabricate short period FBGs, capability to be adaptive structure by tuning the Bragg wavelength of the used FBGs, and this design would be able to flatten the gain of any arbitrary profile. However, the main disadvantage of this technique is its flattening occurs at the position of the lowest EDFA gain value for the channels.

4. Conclusion

In this paper, we reported a new method to get a flat EDFA gain using short period and cascaded apodized FBGs. This technique is used to efficiently flatten the gain of EDFAs doped with germanosilicate, germane-aluminosilicate, and germane-aluminosilicate with high aluminum concentration. The reported method has the advantages of simple fabrication, capability to flatten any number of channels, tunability of Bragg wavelengths, and ability to equalize the gain of any arbitrary profile.

References

[1] X. Li, J. Yu, Z. Dong, H.C. Chien, Z. Jia, N. Chi, Opt. Express, **20**, B217-B222 (2012).

[2] E. Bayaki, D. S. Michalopoulos, R. P. Schober, IEEE Trans. on Commun., **60**, 3797 (2012).

[3] S. Singh, R. S. Kaler, IEEE Photonics Technol. Lett., **25**, 250 (2013).

[4] C. A. F. Marques, R. A. Oliveira, A. A. P. Pohi, R. N. Nogueira, Opt. Commun., **285**, 3770 (2012).

[5] K. Zhou, S. Pan, N. Q. Ngo, X. Zhang, Opt. Lett., **10**, 70604 (2012).

[6] A. Malekmohammadi, M. A. Malek, Int. J. Light and Electron Opt., **123**, 2059 (2012).

[7] I. Ashry, H. M. H. Shalaby, in *Proc.* IEEE Conference on Transparent Optical Network, (Munich, 2010), pp. 1–3.

[8] R. Kashyap, R. Wyatt, P. F. McKee, Electron. Lett., **29**, 1025 (1993).

[9] L. Kaixian, D. Juan, in Proc. IEEE Conference on Broadband Network & Multimedia Technology, Beijing, 2009, pp. 418-421.

[10] H. S. Kim, S. H. Yun, H. K. Kim, N. Park, B. Y. Kim, IEEE Photon. Technol. Lett., **10**, 790 (1998).

[11] Z. Jia, H. Li, X. Meng, L. Liu, G. Qin, We. Qin, Opt. Lett., **38**, 1049 (2013).

[12] M. C. Paul, S. W. Harun, N. A. D. Huri, A. Hamzah, S. Das, M. Pal, S. K. Bhadra, H. Ahmad, S. Yoo, M. P. Kalita, A. J. Boyland, J. K. Sahu, J. Lightw. Technol., **28**, 2919 (2010).

[13] M. J. F. Digonnel, Rare Earth Doped Fiber Lasers and Amplifiers, Marcel Dekker, 2001.

[14] A. Othonos, K. Kalli, Fiber Bragg Gratings: Fundamentals and Applications in Telecommunications and Sensing, Artech House, 1999.

[15] M. M. Keshk, I. A. Ashry, M. H. Aly, A. M. Okaz, in Proc. 24th National Radio Science Conference, Cairo, Egypt, 2007, paper D7, pp. 1-13.

*Corresponding author: drmosaly@gmail.com