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A study of green wavelength-division multiplexed optical communication systems using cascaded fiber bragg grating

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ABSTRACT

This paper studies the performance analysis of wavelength-division multiplexed optical communication systems (WDM). First, flat-gain erbium doped fiber amplifiers (EDFAs) are seriously needed to obtain proper and equal amplification of all channels. Such amplifiers can be designed by intrinsically modifying the host material or extrinsically using proper filters. In this research, we benefit from both the intrinsic and extrinsic methods to achieve sharp flat EDFA output gain using cascaded fiber Bragg gratings (FBGs). Second, the performance of our technique has been evaluated through calculating the bit error rate (BER) and signal-to-noise ratio (SNR) of a WDM system embedded with the reported EDFA flattening system. The parametric simulations of the FWHM of FBGs, SNR, optical power and the transmission distance have shown a noticeable improved performance. Sending data via an optical WDM system will be proven from comprehensive simulations to achieve high quality signal transmission spectrums, increased transmission distances and low power consumption. By extension, the reported design using cascaded FBGs can also be generalized to equalize the gain of any arbitrary profile.

1. Introduction

Erbium doped fiber amplifier (EDFA) has been considered as one of the key devices in long-haul wavelength-division multiplexed (WDM) optical communication systems [1–3]. These types of amplifiers have several advantages such as, high gain, low noise, and large bandwidth [2]. Unfortunately, the typical EDFA provides nonequalized gain for the transmitted channels in WDM systems [3]. This drawback results in low signal-to-noise ratio (SNR) and signal distortion. As a result, there is a strong motivation to equalize the gain of EDFAs to improve the transmission bandwidth and performance of WDM systems. The performance enhancement of EDFAs will meet the ever increasing demand for effective delivery of baseband signals using minimum energy consumption. This will help to construct the green communications systems which are environment-friendly and cost-effective.

Several successful techniques have been developed in the literature to equalize the gain of EDFAs which can be classified as intrinsic or extrinsic methods [4–6]. In intrinsic methods, the spectral properties of the erbium ions can be modified by using different host materials such as, fluoride-based and aluminosilicate glasses [7–9]. This method, however, can improve the flatness of EDFAs gain over a small bandwidth. On the other hand, extrinsic methods are characterized by the ability to improve the flatness of EDFAs gain over wider bandwidths. This can be achieved by using in-fiber filters such as, chirped fiber Bragg grating (FBG) [10], blazed FBG [11], and acoustooptic tunable filters [12]. The main limitation of using chirped FBG filter is the complexity of its fabrication, especially, when the equalization bandwidth is large. Blazed FBG depends on converting the guided modes to nonguided and, therefore, it is sensitive to environmental conditions. Also, acoustooptic filters consume high RF power.

Another successful extrinsic technique used for flattening EDFA gain is designed by coupling different WDM channels out of the optical fiber to be equalized using variable optical attenuator (VOA) [13,14]. This technique can offer good flattening in the C and L bands with low ripples, however, its usage is limited by the high insertion loss and noise figure.

In this paper, we report EDFA gain flattening using a new and simple configuration in which cascaded short period apodized FBGs connected in series with a modified host material EDFA. Each FBG is responsible for flattening only one channel in the WDM networks. The main advantages of the reported configuration over those found in the literature are numerous: The fabrication

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simplicity of the short period FBGs; There are no limitations on the number of WDM channels required to be equalized; The WDM channels can be equalized over any wavelength band; And the Bragg wavelength of the short period FBG can be easily tuned using temperature or strain. Furthermore, the performance of the reported architecture is evaluated through embedding it in a WDM system and calculating the bit error rate (BER) and SNR using OptiSystem 11.0 software from Optiwave Inc.

This paper is organized as follows: Section 2 briefly describes the theory of FBG. Section 3 represents the results and discussions for EDFA gain flattening using cascaded apodized FBGs. Section 4 includes the simulation part of a WDM system embedded with the reported EDFA gain flattening architecture. The performance improvement of the WDM system which uses the reported EDFA flattening method is shown in Section 5. Finally, Section 6 concludes the obtained results.

2. Theory of FBG

FBG filter can be fabricated by creating a periodic perturbation of the core refractive index along the optical fiber. This can be achieved by subjecting the fiber to an intense ultraviolet (UV) interference pattern. The refractive index profile $n(z)$ of a uniform FBG fabricated within an optical fiber of n_o core refractive index can be expressed as: [15]

$$n(z) = n_o + \Delta n(z)\cos\left(\frac{2\pi}{\Lambda}z\right) \tag{1}$$

where $\Delta n(z)$ denotes the amplitude of refractive index perturbation, and Λ represents the period of the grating. The Bragg reflected wavelength, λ_B, is related to the effective grating index n_{eff} by $\lambda_B = 2\, n_{eff}\, \Lambda$.

The reflectivity and transmissivity of FBG can be obtained by using the coupled-mode theory: [15,16]

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

$$T(L_{FBG},\lambda) = 1 - \mathrm{R}(L_{FBG},\lambda) \tag{3}$$

where $R(L_{FBG}, \lambda)$ and $T(L_{FBG}, \lambda)$ are the reflectivity and transmissivity functions of a FBG of length L_{FBG} and at wavelength λ, respectively. δ ($= n_{eff}\,\omega/c - \pi/\Lambda$) is the detuning from the Bragg wavelength, k represents the absolute value of the coupling coefficient, and $s^2 = k^2 - \delta^2$. For sinusoidal variation of index perturbation along the fiber axis, the absolute value of the coupling coefficient is given by:

$$k(z) = \frac{\eta\pi\Delta n(z)}{\lambda_B} \tag{4}$$

where η represents the fraction of the fiber mode power inside the core.

One of the main problems of the uniform FBG is its reflectivity includes sidelobes which limits the spacing between the channels in WDM networks. This problem can be resolved by apodizing the grating such that, $\Delta n(z)$ changes gradually at either end of the grating and the reflectivity in this case can be calculated using the transfer matrix method [15]. Using the Blackman apodization profile which was found the best to eliminate the sidelobes [16,17], $\Delta n(z)$ becomes:

$$\Delta n(z) = \Delta n\left[\frac{1 + 1.19\cos(x) + 0.19\cos(2x)}{2.38}\right] \tag{5}$$

where

$$x = \frac{2\pi(z - \frac{H}{2})}{H}, \; 0 \leqslant z \leqslant H.$$

3. Results and discussions

In this section, we used germanosilicate as host material for silica-based EDFA. It provides high gain, high saturation output power, no crosstalk, low noise figure, and low insertion loss. Using Mc-Cumber theory [18], the absorption and emission cross sections spectra of the EDFAs doped with germanosilicate are calculated.

Optimum amplifier length and pump power are two key parameters that affect the EDFA gain. The optimum EDFA length offers maximum output power for the channel of minimum gain. The value of the optimum EDFA length increases with the increase of both the pump and signal powers [15].

Some of the numerical constants, listed in Table 1, are required for the convergence of the EDFA gain calculation which is independent on the host materials. λ_p and λ_s are the pump and transmitted signal wavelengths, σ_{ep} is the pump emission cross section, $\alpha(\lambda)$ is a positive coefficient represents the scattering loss at the pump and signal power, Γ_p and Γ_s are pump and signal power filling factors, A is a fiber core cross sectional area, and NA is a numerical aperture of the fiber. Using these parameters and Mc-Cumber theory, we can illustrate the gain of EDFA for the international telecommunication union (ITU) channels of 0.8 nm spacing, as shown in Fig. 1.

In order to equalize the gain of these channels, we use cascaded apodized FBGs, as shown in Fig. 2, of Bragg wavelengths identical to the wavelengths of the WDM channels. The condition for flattening the gain of the used WDM channels is:

$$G_{EDFA}(\lambda_n)[1 - \mathrm{R}(\lambda_n)] = G_{EDFA,\min}, \tag{6}$$

where, $G_{EDFA}(\lambda_n)$ is the EDFA gain of a channel of λ_n wavelength such that, $n = 1, 2, \ldots, m - 1$. $R(\lambda_n)$ represents the maximum reflectivity of the FBG of Bragg wavelength λ_n, and $G_{EDFA,\min}$ is the minimum EDFA gain of the channels. Therefore, it is required to modify the reflectivity of each FBG to equalize the gain of all channels to the minimum one. The transfer matrix method and Eq. (5) are used to find the proper value of $R(\lambda_n)$ which satisfies Eq. (6).

The reflectivities of the cascaded FBGs used to equalize the gain of EDFA doped with germanosilicate are shown in Fig. 3(a). The output channels gain, Fig. 3(b), shows excellent gain flattening.

This technique has several advantages such as, simplicity of fabricating short period FBGs, ability to equalize the gain of any arbitrary profile, any number of WDM channels can be equalized, and the Bragg wavelengths of the used FBGs can be tuned. However, the main drawback of this method is its equalization occurs at the level of minimum EDFA gain of the channels.

It is also worth to discuss the issue of using the reported EDFA gain equalizer in dynamic optical networks. For example, channels add/drop yields to significant modifications in EDFA gain profile [19,20]. In particular, tilting in EDFA gain may be introduced when WDM channels are dropped. This behavior can be accumulated in case of using cascaded amplifiers to produce excessive power at one side of the spectrum. Unfortunately, the passive designed architecture in this paper can only equalize the EDFA gain at

Table 1
Constant parameters used for the EDFA gain calculations.

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}
$\sigma_e(\lambda)$	Depend on material	$\alpha(\lambda_s)$	3.22×10^{-3} m^{-1}
$\sigma_a(\lambda)$	Depend on material	Γ_p	0.889
σ_{ep}	0	Γ_s	0.694