

GAIN AND NOISE FIGURE OF EDFA AND HYBRID EDFA/FRA IN WDM SYSTEMS: A COMPARATIVE STUDY

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Multimedia optical networks are the demands of today to carry out large information. Presently, wavelength division multiplexing (WDM) technology transmission of multiple channels over the same fiber is adopted to achieve this demand. While light pulses propagate along the optical fiber, their energy dissipates. Beyond a certain distance, the number of photons in pulses becomes too small to be detected. Optical amplifiers like erbium doped fiber amplifier (EDFA) and fiber Raman amplifier (FRA) are considered as one of the most important elements in technology for optical communication networks. The present study investigates the importance of the use of an EDFA and a hybrid EDFA/FRA in the WDM transmission systems. A comparative study is carried out showing that the hybrid EDFA/FRA is one of the promising technologies to provide a widened and flattened gain-bandwidth over the C-band (1530-1565 nm) with high gain and low noise figure (NF).

Keywords: WDM, EDFA, FRA, Hybrid Fiber Amplifier, Gain, Noise Figure.

1. Introduction

A communication system transmits information from one place to another, whether separated by a few kilometers or by transoceanic distances. Information is often carried by an electromagnetic carrier wave whose frequency can vary from a few megahertz to several hundred terahertz. Optical communication systems use high carrier frequencies (~100 THz) in the visible or near-infrared region of the electromagnetic spectrum [1]. They are sometimes called lightwave systems to distinguish them from other. Fiber optic communication systems are lightwave systems that employ optical fibers for information transmission [2, 3]. Such systems have been deployed worldwide since 1985 and have indeed revolutionized the technology behind telecommunications. The lightwave technology, together with

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microelectronics, is believed to be a major factor in the advent of the “information age”.

Optical amplifiers have become essential components in high performance, long-haul, and multichannel fiber-optic communication systems [4, 5]. There are two main classes of optical amplifiers; namely, (i) semiconductor optical amplifiers (SOAs), which utilize stimulated emission from injected carriers, and (ii) fiber amplifiers, in which the gain is provided by either rare-earth dopants or stimulated Raman scattering [6]. Since the invention of optical amplifiers, like EDFA, the communication networks become all optical networks. In a previous work, different studies were carried out, including different types of amplifiers, pumping schemes and materials [7-14].

In all previous work, each type of amplifier was investigated individually without including hybrid systems. In this paper, EDFA with forward, backward and bidirectional pumping is investigated. FRA is also investigated. After that, a hybrid EDFA/FRA is investigated. A comparison of amplifier performance is carried out for these configurations. The best configuration is to be chosen that achieves the highest gain and lowest noise figure.

The remainder of paper is organized as follows. In Sec. 2, the mathematical model is explained in brief for EDFA FRA including the required equations to obtain gain and noise figure. Section 3 presents the proposed optical communication system including the optical amplifier within the fiber link. The obtained results are displayed and discussed in Sec. 4. It starts with EDFA only at different EDFA parameters and pumping configurations. This followed by the EDFA/FRA hybrid amplifier system. A comparison of different types is carried out. Section 5 is devoted to the main conclusions of this work.

2. System Modeling

In this section, the proposed mathematical models are discussed to achieve maximum gain and low NF by using EDFA. Different pumping configurations will be discussed: one stage EDFA with different pumping configurations and hybrid EDFA/FRA.

2.1 EDFA Gain

By applying such assumptions, one can get the EDFA gain, by definition, for the i^{th} channel as [15]

$$G_{\text{EDFA}} = 10 \log \left(\frac{P_{\text{max}}^i}{P_{\text{input}}^i} \right). \quad (1)$$

2.2 EDFA Noise Figure

The SNR can be calculated in terms of the received signal photocurrent, i_{sig} , and the variance of the received photocurrent noise, $\Delta^2 i_n$, as [16]

$$\text{SNR} = \frac{(i_{\text{sig}})^2}{(\Delta^2 i_n)} \quad (2)$$

Most, if not all, applications of photons and lightwave signals in communications, sensors, signal processing, require the detection and subsequent conversion of an electrical signal. In this process, the useful signal will be corrupted by noise and the ultimate sensitivity and performance of the system is limited by the noise characteristics [17]. The noise figure, NF, reflects the impact of the diversity of noise sources that impact the overall noise performance of the amplifier or component. The noise factor F is defined by [18]

$$F(v, f) = \frac{\text{SNR}_{\text{in}}}{\text{SNR}_{\text{out}}(v, f)} \quad (3)$$

where SNR_{in} and SNR_{out} are, respectively, the SNR at the amplifier input and output. In general, the noise factor is a function of both the optical frequency, v, and the baseband frequency, f, [19].

The NF in terms of noise factor is expressed as

$$\text{NF} = 10 \log_{10}(F) \quad (4)$$

2.3 Raman Gain and Noise Figure

When an input signal is introduced to an optical fiber with strong pump, it will be amplified due to Raman interaction between the pump and signal.

The gain of Raman amplifier is the ratio of output signal to input signal power and is expressed in terms of its gain coefficient, g_R , as [15]

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

where

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

σ_s and σ_p are, respectively, the Raman cross sections of the signal and pump, λ_s is the Stokes wavelength, h is Planck's constant, $n(v)$ is the frequency dependent refractive index, L and L_{eff} are the fiber length and effective length, respectively, $P_p(0)$ is the pump power at the beginning of the fiber and α_s is the fiber loss.

For Raman amplifier noise figure, NF_{Raman} , is given as [20]

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

3. Proposed System

The proposed system is shown in Fig.1. According to proposed system the simulation is conducted using OptiSystem software (ver. 7.0). This simulation tool efficiently simulates a real optical system, which is very useful in analyzing optical performance in optical systems.

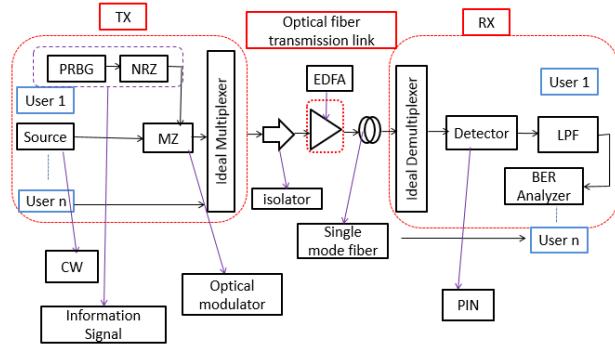


Fig.1 WDM system using one stage EDFA.

3.1 Transmitter Section

This system consists 16 channels in the range of C band multiplexed in the wavelength range 1546.52 to 1552.52 nm. The wavelength spacing is kept to 0.4 nm (50 GHz). The transmitter consists of a pseudo random bit sequence generator (PRBS), which generates bit sequences at the rate of 10 Gbps. This bit sequence is fed to the non-return-to zero (NRZ) coder that produces an electrical NRZ coded signal. The pulses are then modulated with a continuous wave (CW) laser. The modulator used here is the Mach-Zehnder modulator. It has two inputs, one for the laser diode and the other for the data from the channels. It converts the electrical signal into an optical signal form.

3.2 Receiver Section

At the output, a photodiode converts the optical signal into an electrical signal. An electrical low pass Bessel filter follows the photodiode, followed by a BER analyzer.

3.3 Fiber Optical Transmission Link

The optical signal is fed into the isolator, and then passes through the optical fiber. The optical fiber link comprises of an EDFA, at least one pump laser, a passive wavelength coupler, and an optical isolators. The wavelength selective coupler couples both the pump and signal optical power effectively into the fiber amplifier. The optical isolators keep the amplified signal from reflecting once again into the device, where it increases the amplifier noise and decreases its efficiency [21].

Pumping at a reasonable wavelength gives gain through population inversion and the gain spectrum relies on the pumping scheme [22]. Ordinarily, the EDFA setup can be ordered by pumping schemes into three specific arrangements; forward pumped or co-pumped (FWD), Fig. 2, backward-pumped or counter pumped (BWD), Fig. 3, and bidirectional-pumped (dual-pumped), Fig. 4.

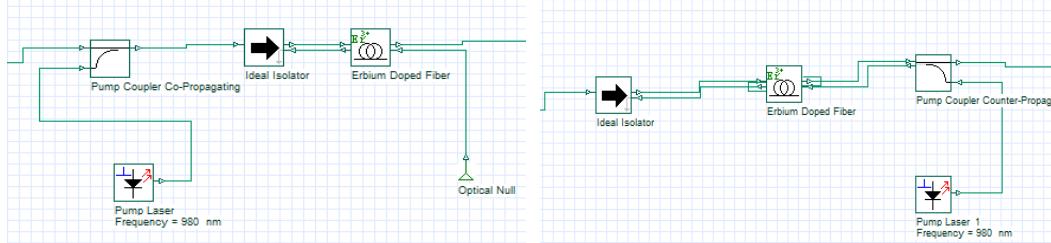


Fig. 2 Forward pumped EDFA structure.

Fig. 3 Backward pumped EDFA structure.

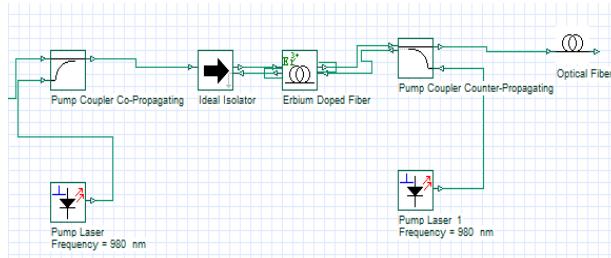


Fig. 4 Bidirectional pumped EDFA structure.

3.4 Hybrid EDFA/FRA

The transmission fiber link changes to include the hybrid system: EDFA/FRA for 16 WDM system, as shown in Fig. 5 using EDFA with forward pumping and multiple forward pumping FRA.

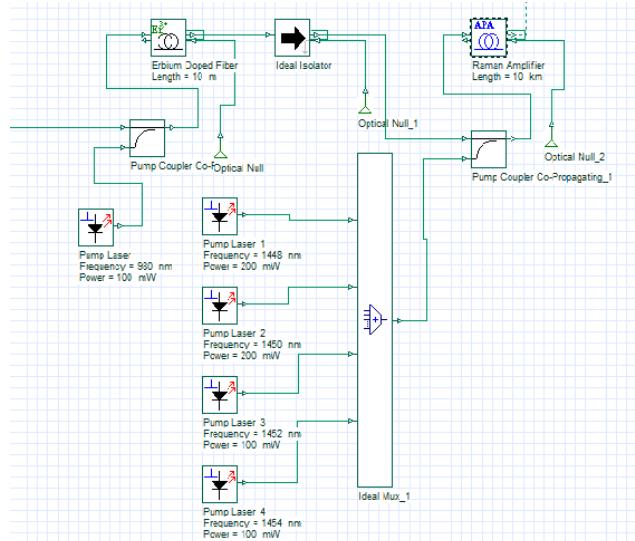


Fig. 5 Hybrid EDFA/FRA.

4. Results and Discussion

This section presents the simulation results and discussion according to proposed systems discussed in previous section. First, EDFA with different pumping configurations is investigated. After that, the hybrid EDFA/FRA system is studied to achieve maximum gain and low NF.

4.1 EDFA Gain and Noise Figure

We start with the simple system shown in Fig. 5(a) to analyze the gain and NF for EDFA with forward pumping. The parameters are adjusted according to the simulation environment and are given in Table 1.

Table 1

System parameters [23].

Parameter	Value
Power per channel	-7 dBm
Input wavelength	1520 to 1580 nm
Pump wavelength	980 nm
Core radius	2.2 μ m
Er doping radius	2.2 μ m
Er ion density	10^{-25} m ⁻³
Fiber numerical aperture	0.24

For a given pump power, both gain and NF depend on signal wavelength and the length of the EDFA section in the fiber. Figures 6 and 7 show, respectively, gain and NF spectra for a single EDFA at different EDFA lengths. The input signal and 980 nm pump powers are set at a steady input power of -7 dBm and pump power =100 mW.

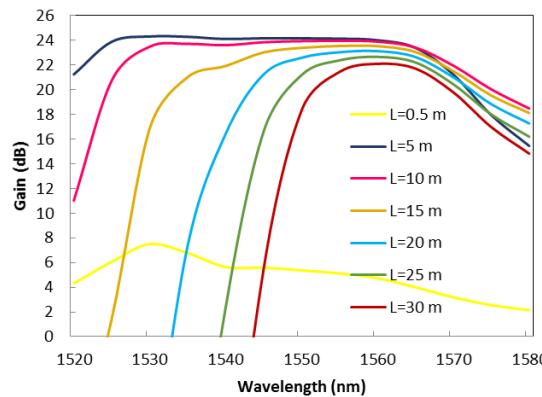


Fig. 6 Variation of gain with wavelength at different EDFA lengths.

Clearly, gain starts at low values and then increases with wavelength reaching its maximum and then falls down. A better flat gain is noticed at 10 m EDFA, allowing more WDM channels. This is matched with Ref. [24]. In general, it is observed that the best fiber length lies between 5 m to 10 m because of the minimum loss and flattened gain. Different pump powers are investigated and 100 mW was the best choice.

For a given pump power, it is found that when the EDFA length increases, the gain increases too to the maximum at a specific value of L and after that it drops sharply with the increase in L . For a given amplifier length L , it is found that the amplifier gain initially increases with the pump power and the increase becomes smaller in case when the pump power exceeds a certain value. This can be explained as follows. The pump does not have enough energy to create complete population inversion in the lower portion of the doped fiber. The un-pumped section of this fiber, therefore, absorbs the signal, resulting in signal loss rather than gain. As the optimum value of L depends on the pump power P_p , it is essential to choose both L and P_p appropriately [25].

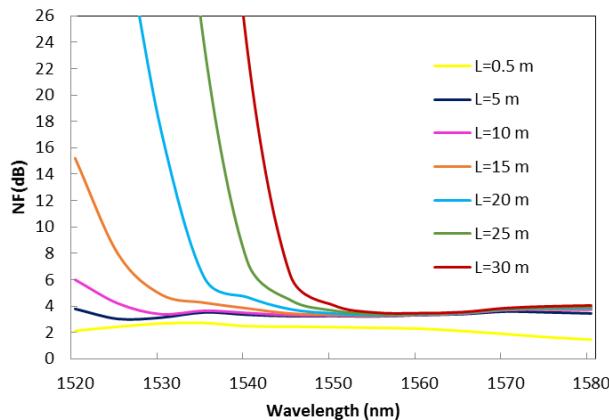


Fig. 7 Variation of noise figure with wavelength at different EDFA lengths.

Fig. 7 shows that with the increase of fiber length, the system provides observably high NF and inclines to decrease after the fiber length was optimized. For 5 m and 10 m long fiber, NF has mostly a fixed value of 4 dB and it does match theoretical data for EDFA with FWD pumping configuration [26].

It is clear that the NF diminishes with increasing pump power. The gain in a fiber with the total population inversion provided causes the spontaneous emission to remain at low levels. The NF of the EDFA fluctuates directly with ASE power and conversely with the amplifier gain, the NF of an EDFA can be reduced to a minimum level by increasing the gain [24]. Thus, NF depends both on the L and P_p .

4.2 Effect of Pumping Wavelength

The amplifier performance characterized by its gain and NF depend on the pump wavelength as shown in Figs. 8 and 9. The pumping requirements are shown in two different options; 980 nm and 1480 nm. Both are the most important ones used in EDFA [22].

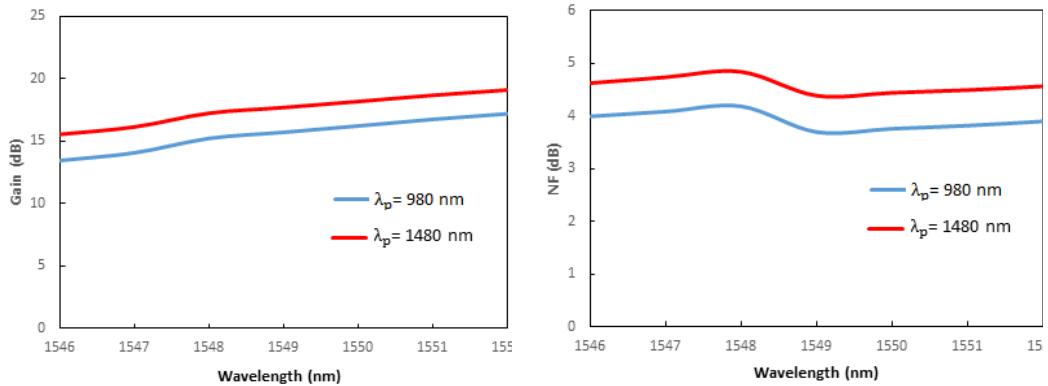


Fig. 8 Variation of gain with wavelength at different pumping wavelengths.

Fig. 9 Variation of noise figure with wavelength at different pumping wavelengths.

Fig. 8 displays the gain at 16 channels, for both 980 nm and 1480 nm pumping wavelengths. The 1480 nm pump provides a higher gain than that of the 980 nm pump at the same pump power. This is in a fair agreement with that obtained in Ref. [27]. At the same time, the 980 nm pump provides a lower, which is matched with that obtained in [28]. Values of NF are generally larger for EDFA pumped at 1480 nm because the pump level and the excited level lie within the same band for 1480 pumping. It is difficult to achieve complete population inversion under such conditions [29]. So, the 980 nm pumping is the more convenient choice.

4.3 Gain and NF for Different Pumping Techniques

At 980 nm pumping, the procedure is repeated for the other pumping schemes and the obtained gain and NF are compared in Figs. 10 and 11, respectively.

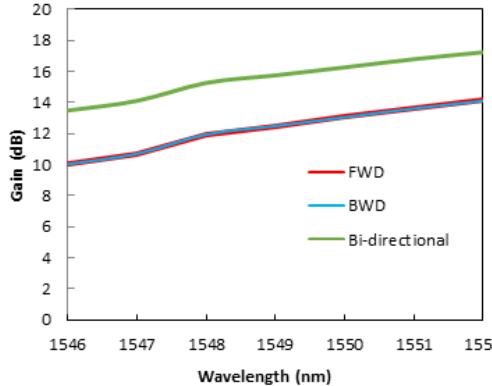


Fig. 10 Variation of gain with wavelength for different pumping configurations.

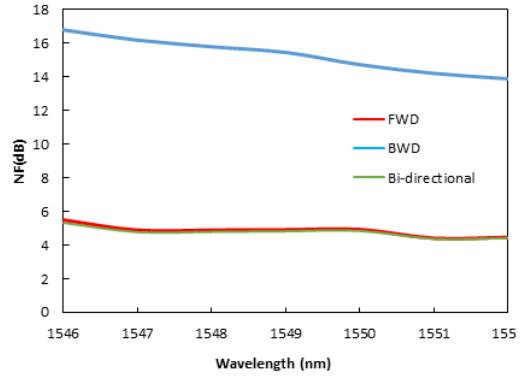


Fig. 11 Variation of noise figure with wavelength at different pumping configurations.

It is found that, the minimum NF occurs for both FWD and bidirectional pumping configurations whereas maximum gain is obtained by using bidirectional pumping configuration, while the gain for FWD and BWD pumping configurations is almost same. Thus, bidirectional pumping configuration can be considered the best configuration, achieving higher gain and lower NF, but it is complex to design and is more expensive.

4.4 Hybrid EDFA/FRA

The proposed system shown in Fig. 1 is now studied first by replacing the EDFA with a FRA and then by adding a FRA to EDFA, forming the hybrid EDFA/FRA in the fiber optical transmission link. The EDFA is with FWD pumping at length =10 m, input signal of -7 dBm, EDFA pump power is 100 mW and FRA parameters are summarized in Table 2.

Table 2

FRA parameters [11].

Parameter	Value
Length	10 km
First pump wavelength	1448 nm
Second pump wavelength	1450 nm
Third pump wavelength	1452 nm
Fourth pump wavelength	1454 nm
First and second pump power	200 mW
Third and fourth pump power	100 mW

Gain and NF of the hybrid system are investigated and are compared with those of EDFA only and FRA only. This comparison is illustrated in Figs. 12 and 13. Fig.

12 displays the gain of the three amplifiers as a function of signal wavelength. The RA length is 10 km, with multiple forward pumping wavelengths. Figure 12 shows that, in case of using hybrid EDFA/FRA, the gain is enhanced by 16 dB at input wavelength =1552.52 nm as compared with FRA only and is improved by 9 dB while using EDFA only. The lower gain was obtained for Raman amplifier only over the signal wavelength. Using the same parameters in Fig. 13, the lower values of NF are obtained for EDFA/Raman and EDFA only and the higher values of NF were obtained for Raman amplifier only. So, the combination of fiber Raman amplifier and EDFA presents a better performance than conventional EDFA only systems, in a fair agreement with that obtained in Ref. [11]. The hybrid EDFA/FRA has the benefits of both EDFA and FRAs, hence some efforts have been carried out to offer efficient construction for hybrid EDFA/FRA.

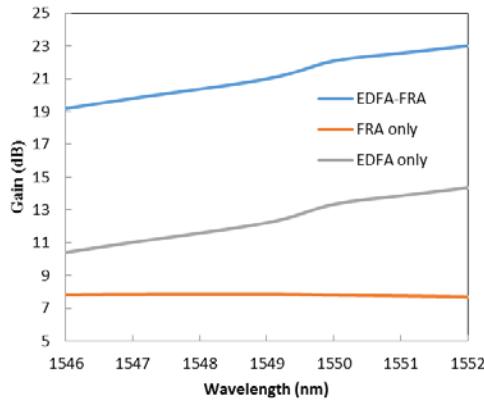


Fig. 12 Variation of gain with wavelength for three amplifiers.

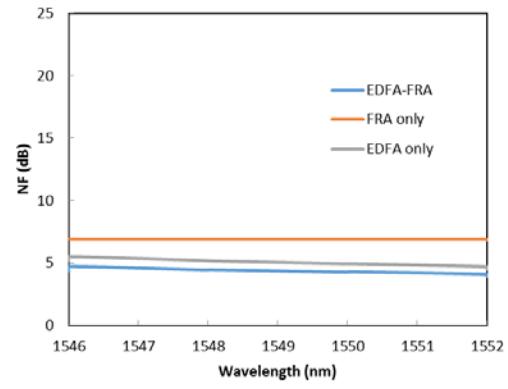


Fig. 13 Variation of NF with wavelength for three amplifiers.

5. Conclusion

In this paper, amplifier performance is investigated. Different amplifier types and pumping schemes are considered. The amplifier performance is evaluated aiming to higher gain and lower noise figure. The simulation results show that for 16 WDM channels, the best EDFA length of 10 m and pump power =100 mW. Different pump powers and pump wavelengths are investigated and 100 mW and the 980 nm are the most convenient choice. The bidirectional pumping configuration is considered the best configuration, achieving at least 4 dB higher gain and 10 dB lower NF, but it is complex to design and is more expensive. The use of hybrid EDFA/FRA enhances the system performance, achieving 8 dB higher gain and 3 dB lower NF, as compared with EDFA only, at any input signal wavelength.

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