Gain Characteristics for *C*-Band Erbium Doped Fiber Amplifier Utilizing Single and Double-Pass Configurations: A Comparative Study

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Received on: 28/1/2013 & Accepted on: 5/6/2014

ABSTRACT

An erbium doped fiber amplifier in the conventional communication window utilizing single and double pump pass configurations were demonstrated and compared using OptiSystem 12 software.

Both of gain level and gain profile were improved in double-pass configuration utilizing broadband optical mirror. The maximum gain in both single and double-pass configurations are about 36.83dB and 50.1dB respectively, which represents a 37.13% improvement in gain level with double-pass configuration.

In addition, a 25mW pump power in double-pass configuration can provide the same gain level in a single-pass configuration at a pump power of 100mW and an input signal power of -20dBm at 1530nm. This represents a pump power conservation of about 25%.

The results show that the double-pass amplifier produces a higher noise figure than the single-pass configuration, but still in suitable level less than 6dB.

Keywords: Double-pass amplifiers, Gain profile, Gain saturation mechanisms, pump power conservation.

دراسة مقارنة لخصائص الربح للمضخمات ذات اشكال المرور المنفرد والمزدوج لليف البصري المطعم بايونات الاربيوم

الخلاصـــــة:

تم اجراء عرض ومقارنة للمضخمات ذات اشكال المرور المنفرد والمزدوج عند نافذة الاتصالات البصرئية التقليدية لليف البصري المطعم بايونات الاربيوم باستخدام برنامج (OptiSystem12) .

لقد تم تحسين كل من مستوى وشكل الربح للمضخمات ذات شكل المرور المزدوج باستخدام المرايا البصرية ذات النطاق الواسع. اقصى ربح للمضخمات ذات اشكال المرور المنفرد والمزدوج كانت بحدود 36.83 ديسبيل و 50.1 ديسبيل على التوالي والتي تمثل تحسيناً بمقدار 37.13% لمستوى الربح باستخدام المضخمات ذات شكل المرور المزدوج. كذلك يمكن للمضخمات ذات شكل المرور المزدوج عند قدرة ضخ 25 ملي واط تجهيز نفس مستوى الربح للمضخمات ذات شكل المرور المنفرد عند قدرة ضخ 100 ملي واط. النتائج اظهرت ان الضوضاء المتولدة في مضخمات المرور المزدوج هو اعلى من الضوضاء المتولدة في مضخمات المرور المنفرد ولكن عند حد مناسب واقل من 6 ديسبيل.

INTRODUCTION

The first generations of optical communication systems were made possible by development of low-loss single mode silica fiber in the 1970's. The current light-wave communication system, with widely improved capacity, speed and cost, is based in the development of the optical amplifiers [1]. The optical amplifiers play an important role in the long haul networks, prior to the advent of optical amplifiers, the standard way of coping with the attenuation of the optical signals along the fiber span was to periodically space electronic regenerators along the span. Such regenerators consist of a photodetector, electronic amplifiers, equalization system and a laser source with it's driver to lunch the signal along the next span [2].

Although, the optical communication systems have inherently large transmission capacity and bandwidth, due to their optical nature, they are limited by optoelectronic regenerators. On the other hand, the optical amplifiers are purely optically in nature and required no high speed circuit. The signal is not detected and regenerated; rather, it is very simply optically amplification. Thus, the shift from the optoelectronics regenerators to optical amplifiers produces a dramatic increase in both of the capacity and the speed of communication systems. The optical amplifiers were developed in 1980s and came partially into the use commercially in 1990s [3].

In improving the performance of the optical amplification, various gain medium materials such as such as Tellurite [4], multi-component Silicate [5], and Bismuth Oxide based glass [6] have been proposed. However, the gain spectrum of these amplifiers still remains non-uniform with the variation of wavelengths [7]. The optical amplifiers based on erbium doped fiber were the first successful optical amplifier and has revolutionized the optical communication industry in the early 1990s, due to high performance parameters, includes; high gain (30 - 50 dB), large bandwidth ($\geq$ 90 nm), high output power (10 - 20 dBm) and low noise figure (NF = 3 - 5 dB) within C-band communication window. On the other hand, researchers also proposed various configurations of EDF amplifiers such as single and double-pass propagation in co- and counter-pumped configurations [8-11].

In this work, an erbium doped fiber amplifier in double-pass configuration (EDFA-DP) was investigated utilizing OptiSystem12 software to enhance the gain level in C-band communication window. In this design both of the forward amplified stimulated emission (F-ASE) and output signal power (P_{out}) are re-injected back into the gain medium employing a broadband optical mirror. The improvement in the amplifier performance was demonstrated by comparing both of the gain level and noise figure (NF) of the erbium doped fiber amplifier within single and double-pass configurations system.

The gain saturation mechanisms for both configurations in terms; of high pump power and large input signal are inspected in order to determine the optimum input design parameters.

Gain and Noise Figure in EDFA

This study focuses on the performance characteristics of the amplifier (gain and noise figure) assuming the fundamental mode exciting at the pump wavelength (λp= 1480 nm). Gain of an erbium-doped fiber with a length of L is the ratio of the signal power at the fiber output to the signal power injected at the fiber input as:

$$G = \frac{P_{s,out}}{P_{s,in}} \qquad \dots(1)$$

The noise figure NF is a measure of how much noise the amplifier adds to the signal. The definition is:

$$NF = \frac{(SNR)_{in}}{(SNR)_{out}} \qquad \dots(2)$$

Where:

SNR is the signal-to-noise ratio. Due to ASE, the SNRout at the amplifier output is less than that at the input, SNR in. If the signal is much stronger than the noise, the noise figure can be written as [1]:

$$NF = \left(1 + \frac{2P_{ASE}}{hu\Delta u_{sp}}\right)\frac{1}{G} \qquad \dots(3)$$

Where:

P_{ASE} is the ASE noise power, h is Planck's constant, ν is the frequency of the light and $\Delta\nu_{sp}$ is the bandwidth of the noise (i.e. the bandwidth of the EDFA).
After entering the required parameters for a desired amplifier in main menu and sub menus of the Opti System 12 software, gain and noise figure can be obtained as a function of fundamental fiber parameters namely: pump power and signal input power. Thus, the required fiber parameters and signal/pump power values can be optimized for a desired EDFA gain-NF performance. The main menu of the simulation programs is shown in Table-I.

Simulation setup

The simulation setup for both EDFA-SP and EDFA-DP is depicted in Fig.1-a and b. In the single-pass configuration the input signal power is obtained from a tunable laser source (TLS) with maximum power of 0 dBm at a wavelength range from 1525 nm to 1600 nm. The erbium amplification is acquired from 5 m erbium doped fiber co-pumped by laser diode with maximum power of 200 mW at 1480 nm. In this amplifier structure the input signal is injected through port 1 of optical circulator and through a wavelength division multiplexer (WDM) prior to propagate through the erbium gain medium as shown in fig(1-a). The output spectrum is deduced at the far end of the gain medium using an optical spectrum analyzer (OSA1)

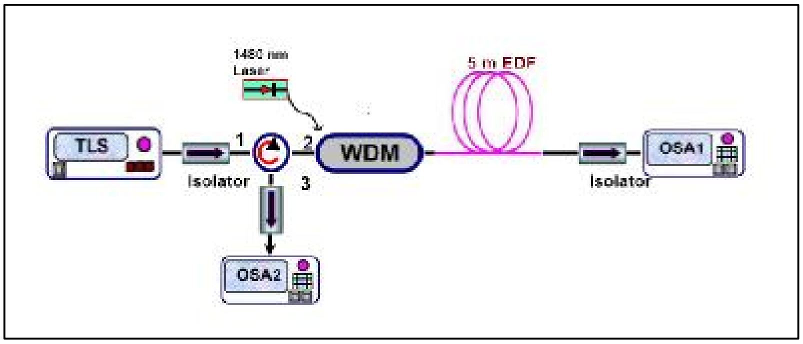


Figure (1)a. Simulation setup of Single pass EDFA.

In order to re-inject the output signal power in a double-pass configuration inside the gain medium a broadband mirror (M) was added to the design as shown in fig.1-b. The output spectrum is deduced at port 3 of the circulator using (OSA2).

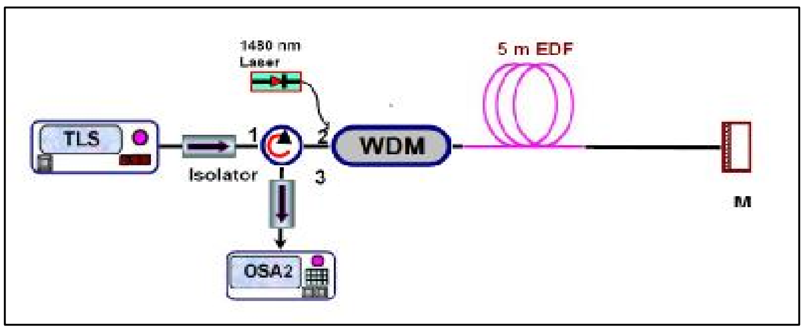


Figure (1) b. Simulation setup of Double pass EDFA.

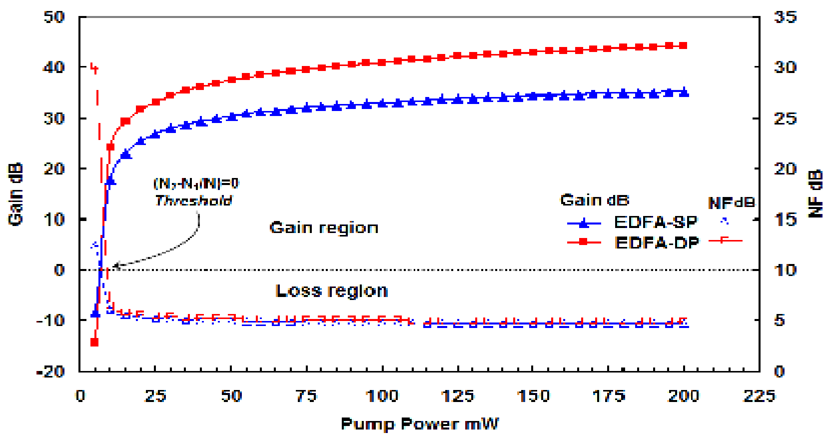
Results and Discussion

The gain and noise figure (NF) characteristics for the two pump configurations at a pump power range from 5mW to 200mW was depicted in fig.2.

It can be seen that, at a pump power (P_p) ≤ 5mW the gain level is actually less than 0dB. i.e. the amplifier system work within the loss region and the population difference (N_2-N_1)/N < 0, so, a finite pump power is required to generate population inversion and achieve transparency.

At a Pump power of 7.5 mW, both amplifiers work within the transparency region and the population difference = 0, in other word the gain is about 0 dB and 7.5 mW pump power represents a threshold for both amplifiers. Beyond 7.5 mW, the population difference becomes > 0 and the system work within the gain region. Through this region,

the gain increases quickly as the pump power increased, and begins to saturate as the pump power starts to fully invert the population in the EDF.
According to the obtained results, the maximum gain is about 35.21 dB and 44.4 dB at 200 mW pump power for EDFA-SP and EDFA-DP respectively. This can be attributed to the double pass propagation of F-ASE and signal power in the gain medium. In addition, in double-pass configuration a 25 mW pump power can provide the same gain level in a single-pass configuration at a pump power of 100 mW and an input signal power of -20 dBm at 1530 nm, which gives a 25% improvement in pump power needed in EDFA-DP to achieve the same gain as compared to the EDFA-SP.
From Fig.2 the highest value of NF are 30.15 dB and 12.49 dB for EDFA-DP and SP respectively which was recorded within the loss region. For the gain region, the double-pass amplifier produces a higher noise figure because the signal propagates twice inside the gain medium, but still in suitable level of less than 6 dB.

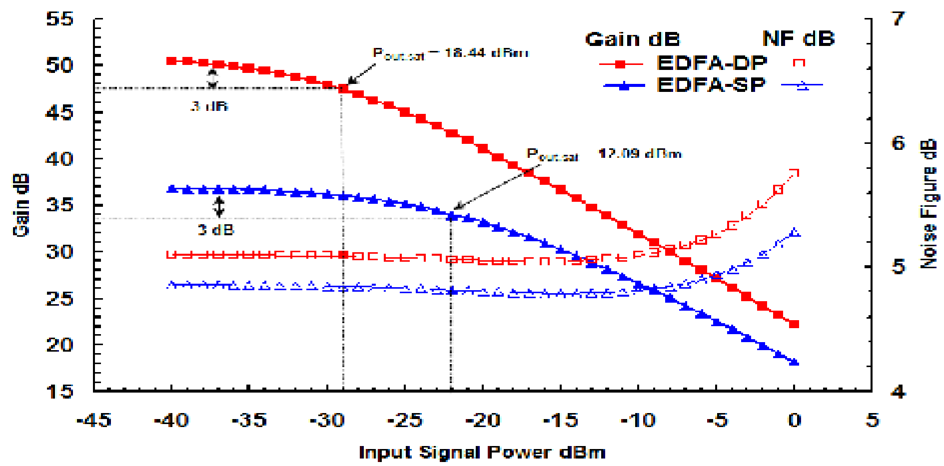


Figure(2). Gain and noise figure vs 1480 nm pump power at 1530 nm signal wavelength and -20 dBm input signal power.

Figure 3 shows the gain and NF characteristics as function of the signal power for the two configurations at a pump power of 100mW and 1530nm signal wavelength. It can be seen that at an input signal power of -40dBm, the maximum gain is about 36.83 dB with a NF of 4.85 dB and 50.51 dB with a NF 5.1 dB for the EDFA-SP and EDFA-DP respectively, which represents an enhancement in the gain level of about 37.13%.
As the gain saturation due to large input signal is defined as the 3-dB gain compression from its maximum unsaturated value, it is clearly shown that the gain for EDFA-DP saturates earlier as compared to EDFA-SP with a higher gain level and higher output saturation power ($P_{out,\ sat.}$). The output saturation powers are 18.44 dBm and 12.09 dBm for EDFA-DP and EDFA-SP respectively.

This is can be attributed as follows; in double pass amplifier pumped, the input signal of -29 dBm represents a small signal power for the first pass and the system work within the forward pump direction. Whereas, the output signal of 7.08 dBm represents a large input signal for the second pass and the system work within backward direction. Thus, the double-pass system introduces a higher gain level and earlier saturation level than the single-pass amplifier. Furthermore, the variation of the noise figure as function of the input signal power is also depicted in Fig.3. The results show that the NF is approximately constant as the input signal power increased, and start to increase beyond -4 dBm to reach the highest value of 5.28 dB and 5.75 dB for EDFA-SP and EDFA-DP respectively at an input signal power of 0 dBm.

Although, the EDFA-DP results show a higher NF level than the EDFA-SP but still suitable and less than 6 dB.



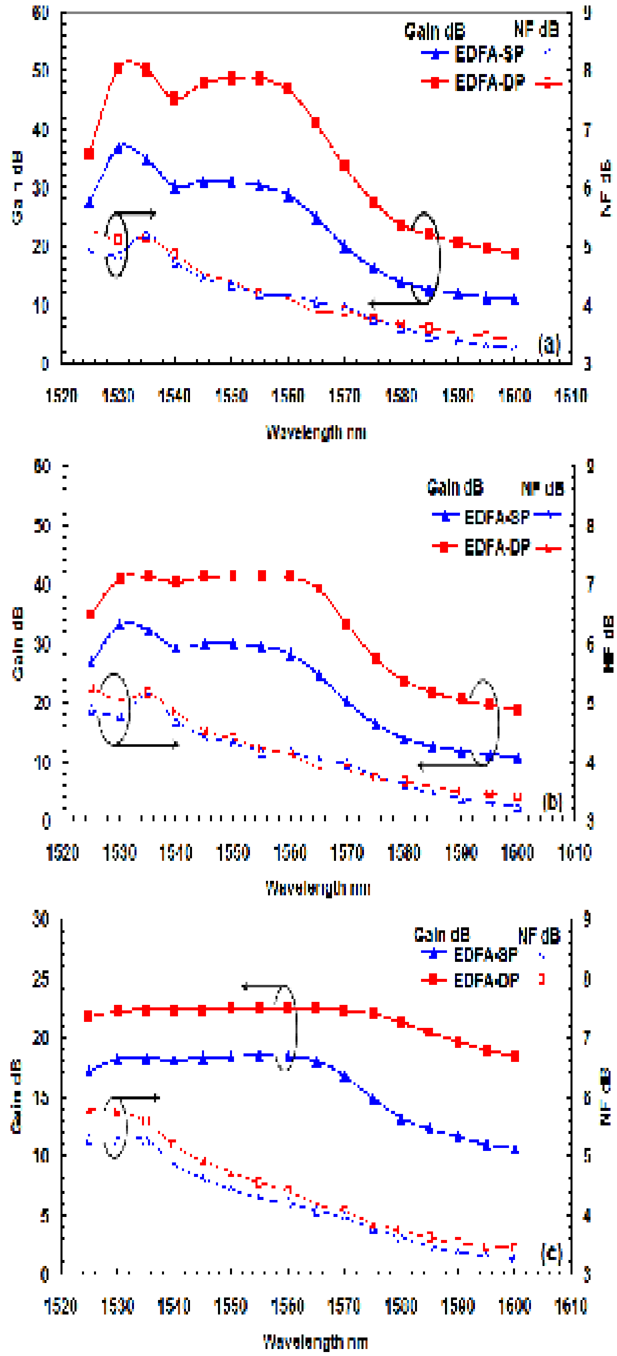
Figure(3). Gain and noise figure vs input signal power at 1530 nm signal wavelength and 100 mW pump power.

Figure (4(a), (b) and (c)) show the gain profile and the NF penalty profile for the two pump configurations at an input signal power of -40 dBm, -20 dBm and 0 dBm respectively. In this simulation the pump power was fixed at 100mW and the input signal wavelength was tuned from 1225nm to 1600 nm step 5nm.

At an input signal power of -40dBm, the highest gain level of about 50.51dB and 36.83dB for single and double-pass amplifier was observed at an input signal wavelength of 1530nm as shown in fig(4.a).

For a signal power of -20dBm, a peak gain of 33.18dB was observed at 1530nm signal wavelength for EDFA-SP, while a peak gain of 41.56dB was observed at 1550nm signal wavelength for EDFA-SP as shown in fig(4.b). A shift of 25nm can be observed between the two pump configurations, due to the gain saturation appears early in EDFA-DP configuration, i.e. the input signal power of -20 dBm represents a large signal power for EDFA-DP, while it represents a moderate input signal for EDFA-SP. In addition, the gain profile is improved as the signal power increased, due to the difference in saturation level for different input signal wavelengths. For a large input signal power of 0dBm, the peak gain level was 18.49 dB shifted from 1530 nm to 1555 nm for a single-pass amplifier, and about 22.44 dB shifted to 1650 nm for a double - pass amplifier as shown in fig(4.c).

The EDFA with a double - pass configuration shows a better flatted gain profile than a single-pass configuration as depicted in the Table(2).



Figure(4). **Gain and noise figure vs. input signal wavelength at pump power of 100 mW for: (a) Input signal power of -40 dBm. (b) -20 dBm. (c) 0 dBm.**

Table(1). List Of Edf Parameters Used In The Simulation

Name	Value	Units
Length	5	m
Er metastable lifetime	10	ms
Input data	Fiber specification	
Saturation parameter	4.4e+015	1/(s.m)
Core radius	2.2	um
Er doping radius	2.2	um
Er ion density	10e+024	m^-3
Numerical aperture	0.24	

Table(2).Gain Flatted Within 3-Db Vs. Different Input Signal Power For Edfa-Sp & Edfa-Dp

Input signal Power dBm	Gain Flatted within 3-dB		Flatted borders		Average gain dB		Average NF dB	
	SP	DP	SP	DP	SP	DP	SP	DP
-40	5 nm	25 nm	1530-1535	1530-1555	35.87	48.45	5.04	4.7
-20	5 nm	35 nm	1530-1565	1530-1555	32.78	40.95	4.97	4.53
0	45 nm	60 nm	1525-1570	1525-1585	18.04	22.05	4.63	4.65

CONCLUSIONS:

The performance of C-band EDFA under two different amplifier configurations was investigated and compared utilizing OptiSystem12 software. The double- pass of F-ASE and input signal improved the gain level by 37.13 % and conserved the pump power to 25 %. The gain saturation due to large signal mechanism appears early in the EDFA-DP, with a higher gain level than EDFA-SP. The flat gain bandwidth within 3-dB variation is better in EDFA-DP and about 35 nm with an average gain of 40.95 dB.

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