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Performance Characteristic of Distributed Erbium Doped Fiber Amplifier (D-EDFA)

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Abstract

D-EDFA have their signal gain distributed over long fiber lengths. This paper deals with gain and noise figure characteristics at 150dB/km Rayleigh constant of a forward, and bidirectional pumped distributed EDFAs, operating in 1550 nm as a function of fiber length, Erbium ion density, injected pump power and signal input power. These studies are done by using optiystem 6.0 software simulation (optical amplifier and communication system design software) at bit rate of 2.5 Gbps.

Keywords: distributed erbium doped fiber amplifier (D-EDFA), Gain, Noise figure.

خصائص الاداء لمكبرات الالياف الضوئية المطعمة بالأربيوم الموزع

الخلاصة

احد اساسيات تقيد في نقل الاشارة من نقطة الى اخرىوللمسافات البعيدة بواسطة الالياف البصرية هي خسارة في الياف. المكبر الضوئي المطعم بالأربيوم(D-EDFA) واحد من اهم التكنولوجيا المتقدمة التي تعوض عن الخسارة و تكبرالأشارة الضوئيةبطريقة مباشرة و من غير تحويلها الى اشارة كهربائية.

في هذا البحث تم دراسة خواص الربح والضوضاء لمضخم المطعم بالأربيوم (D-EDFA) عند ثابت رايلي (150 dB/km) ، وتم ضخ المضخم باتجاه امامي و كلا اتجاهين لنقل الاشارة لطول الموجي (1550nm).وتم دراسة خواص الربح والضوضاء بدلالة كل من طول الليف الضوئي ، كثافة ايون Er3+ في الليف، قدرة الموجة الضاخةو الاشارة الداخلة.و قد وجدنا ان قيمة الربح للأشارة احسن في حالة الضخ المكبر بكلا اتجاهين.و عند قدرة الأشارة (40 dBm-) قيمة الضوضاء اقل في حالة الضخ امامي مقارنة بضخ اتجاهين تم انجاز الدراسة باستخدام برمجيات خاصة من نوع (Optsystm6.0) بسرعة نقل المعلومات مقدارها 2.5 كيكا بايت /ثانية و هذا البرنامج الحاسوبي مخصص لتصميم المكبرات و المنظومات الخاصة بالاتصالات الضوئية.

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I. Introduction

ERBIUM doped fiber amplifiers (EDFA) play an important role in light wave communication systems. In order to transmit signals it is necessary to compensate for attenuation losses within the fiber because the cumulative effect of attenuation and dispersion make the signals to become weaker, indistinguishable and to be detected reliably [1]. Before this happens, the strength and shape of the signals must be restored. This can be done by using either a regenerator or an optical amplifier at an appropriate point along the length of the fiber. Electrical repeaters, which require optical-electrical signal conversion, have previously been used to compensate the power losses increasing with distance. The use of such repeaters in optical communication systems have made the systems more complex and increased their installation cost. The optical amplifiers enable the optical signals to be directly amplified optically. The fiber amplifiers can be made using different rare ions, the most interesting element is Erbium, because erbium doped fiber amplifiers (EDFA) made by doping the silica fiber with erbium ions can operate in a broad range within the 1550nm window at which the attenuation of silica fiber is minimum and therefore it's ideal for the optical fiber communication systems operating at this wavelength range.[2]

Distributed EDFAs have their signal gain distributed over long fiber lengths (L=1-100 km) of weakly doped fibers. The pump wavelength is usually chosen near 1480nm, the closest possible to minimum absorption.[3] the back ground loss from impurities must be considered for distributed amplifiers. According to the research performed in recent years, on D-EDFA showing that 10 km of an active span could be made lossless for low signal levels and 20mW of 1480nm pump power. [4, 5, 6] signal excursions along the length as small as 0.2 dB were demonstrated. Longer lengths (54km) were used with launched signal power of -2 dBm and total bidirectional pump power of 110Mw.[7] The parameter determining the amplified system noise performance is the amplifier input power [8].

II. Simulation Model

This paper focuses on the performance characteristics of the distributed amplifier assuming the fundamental LP_{01} mode exciting at the pump wavelength 1480nm with background loss of 150dB/km Rayleigh constant.

Giles logarithm calculation was used which provides a full spectral solution and the propagation equation is integrated back and forth along the fiber in an iterative numerical process until the solution converges, or the maximum number of iterations is reached and additional loss mechanism such us pump excited state absorption ESA, and the effects of background loss are only considered during the Giles algorithm calculation.[9]

A simpler method of fiber characterization can be done by writing the amplifier equations in terms of Er^{3+} absorption coefficient (αk), gain coefficient (gk) for the kth beam, and a fiber saturation parameter (ζ). These parameters can be obtained by conventional fiber measurement techniques.

The saturation parameter (ζ) can be defined theoretically as [9]:

$$z = p \cdot b_{eff}^{2} \cdot n_t / t \quad \ldots \quad (1)$$

Where b_{eff} is the equivalent radius of the doped region, η_t is local erbium ion density, and τ is metastable lifetime parameter.

The absorption and gain coefficients are expressed in terms of distributions of the ions and optical modes [9]:

$$a_k(l_k) = s_a(l_k) \cdot \int_0^{2p}\int_0^{\infty} i_k(r,f) \cdot n_t(r,f,z)\, r\,dr\,df \quad \ldots \quad (2)$$

Where i_k (r , Ø) is defined as the normalized optical intensity.

$$g_k(l_k) = s_e(l_k) \cdot \int_0^{2p}\int_0^{\infty} i_k(r,f) \cdot n_t(r,f,z)\, r\,dr\,df \quad \ldots \quad (3)$$

For a uniform ion distribution the absorption and gain coefficients can be simplified as [9]:

$$a_k(l_k) = \Gamma(l_k) \cdot \bar{n}_t \cdot s_a(l_k) \quad \ldots (4)$$

$$g_k(l_k) = \Gamma(l_k) \cdot \bar{n}_t \cdot s_e(l_k) \quad \ldots (5)$$

The confinement factors Γ is taken into account for the fact that the doped region within the core provides the gain for the entire fiber mode, σ_a and σ_e are absorption and emission cross-section of the k_{th} beam.

Giles and Desurvire wrote the propagation equation in terms of saturation parameter, with absorption and emission coefficients:

$$\frac{dp_k(z)}{dz} = u_k \cdot P_k(z) \cdot \left((g_k(l_k) + a_k(n_k)) \frac{\bar{n}_2}{\bar{n}_t} - a_k(n_k) - l_k \right) + u_k \cdot P_{ok} \cdot g_k(n_k) \frac{\bar{n}_2}{\bar{n}_t} \quad \ldots \quad (6)$$

Where each beam propagates in the forward (u_k =1) or backward (u = -1) direction and P_{ok} means the spontaneous emission contribution from the local metastable population η_2.

P_{ok}= m.h.υk.Δυk. Where m is normalized number of modes, and $\Delta\nu$ is the noise band width, and l_k is the background loss.

In the same way, the steady-state solution of rate equation may be written as: [10]

$$\frac{\bar{n}_2}{\bar{n}_1}(z) = \frac{\sum_{k=1}^{n} \frac{P_k(z) \cdot a_k n_k}{h \cdot n_k \cdot z}}{1 + \sum_{k=1}^{n} \frac{P_k(z) \cdot (a_k(n_k) + g_k(n_k))}{h n_k}} \quad \ldots (7)$$

The above two equations (6) and (7) are referenced further as a Giles model. These equations are solved in the homogeneous line broadening case.

1. Gain and Noise Figure

Gain of an erbium-doped fiber with a length of L is the ratio of signal power at the fiber output to the signal power injected at the fiber input as:

$$G = P_s(L) / P_s(0) \quad \ldots(8)$$

Amplified Spontaneous Emission (ASE) noise generates during amplification process is added to the signal leading to decrease in signal to noise ratio(SNR) at the amplifier output.SNR reduction ratio from input to output of the amplifier is defined as Noise Figure(NF),which is also used for electronic amplifier:

$$NF = (SNR)_{in} / (SNR)_{out} \quad \ldots(9)$$

Noise Figure can also be expressed in terms of gain and spontaneous emission factor (n_{sp}) [3]:

$$NF = 2n_{sp}(G-1)/G \approx 2n_{sp} \quad \ldots(10)$$

$$n_{sp} = n_2 / n_2 - n_1 \quad \ldots(11)$$

n_1 and n_2 are ionic population in two energy levels .

Iii.D- Edfa Simulation Program

This study also focuses on the performance characteristics of the D-EDFAs (gain and noise figure) assuming the fundamental LP_{01} mode exciting at the pump wavelength (λp= 1480 nm).After entering the required parameters for a desired amplifier in main menu and sub menus of the program gain and noise figure can be obtained as a function of four fundamental fiber parameters namely: fiber length, pump power, signal input power and erbium doping density. The main menu of the simulation programs is shown in table (1). Figure 1 shows the D-EDFAs layout for forward pump power.

Table (2) represents the typical EDFA parameters used in the simulation program. Cross sections parameters obtained form the shape of absorption and emission cross-section as a function of wavelength in the program [8].

A. Gain Characteristics

1. The variation of gain with fiber length for Forward and Bidirectional Pump Power:

As shown in figure (2-a) the gain varies along the fiber length because of pump power variations. For a given amplifier length, the amplifier gain initially increases exponentially with the pump power and then goes to saturation after a certain level of pump power. For a given pump power the amplifier gain increases up to a certain length of fiber, and then begins to decrease after a maximum point. The physical considerations for the decrease in gain is insufficient population inversion due to excessive pump depletion and getting higher losses than the provided gain at the signal wavelength due to high total loss of Erbium doped fiber (fiber background loss and Er^{+3} absorption loss).

Figure (2-b) illustrates that bidirectional pump powers are better than the forward pump power, because the gain in the bidirectional pump power higher than the gain in forward pump powers, the required pump power to obtain high gain is decreases in Bidirectional pump power (30 mW) in bidirectional pumping power is better than the (150 mW) in forward pumping. Also the gain is present for a much more range of fiber length in Bidirectional pumping

2- The variation of gain with Erbium ion density for Forward and Bidirectional Pump Power:

The gain variation as a function of erbium doping density is shown in Figure (3-a) for a 1000m long fiber and a constant signal input power for three different forward pump powers (30mW, 50mW and 150mW). It can be seen that for sufficiently large pump power, the gain linearly increases with increasing erbium ion density and remains constant after a certain level. Since the amplifier reaches the population inversion, the variation in maximum gain is small despite occurring a high increase in pump power. In the trace obtained for 30mW pump power the gain reduces sharply in highly doped fiber due to insufficient pumping.

The comparison between forward and bidirectional pump power is illustrated in figure (3-a) and (3-b), it is shown that for a given fiber length and in suitable pump power the amplifier gain is maximum in much more range of Erbium ion density, and then begins to decrease. The physical meaning for that is where amplifier pumped Bidirectional a large number of Erbium ions reaches the population inversion.

3-The variation of gain with pump power for forward and bidirectional pump power:

The simulation was made for three different fiber lengths (1000, 2000, 2500) m, pumping power was swept from (1 to 200) mW, and erbium ion density chosen to be (11.4 ppm-wt) in which the gain is maximum in that ranges of fiber length. For bidirectional pump power the value of backward pump power was chosen to be (30 mW) since the gain nearly maximum at this value.

As shown in figure (4-a) the gain of distributed EDFA sharply increases with the increasing pump power. After a certain level of gain, the increase in gain becomes smaller when the population inversion is provided for all the erbium ions in the fiber and therefore amplifier goes to saturation ,in addition, a higher gain can be obtained if a shorter erbium doped fiber is used with sufficient pumping. When the amplifier have Bidirectional pumped the variation of gain with the forward pumping power is better than the amplifier when pumped. For 1000 m fiber length the gain is better, for (32.42 mW) the gain equal (37.4 dB) since in forward pumped amplifier the gain equal to (31.5 dB) at (31.57 mW) pump power. The zigzag change of the lines refers the nonlinearities.

4-The variation of gain with signal power for Forward and Bidirectional Pump Power:

The variation of gain with signal power is shown in figure (5-a), for three different forward pumping powers (30, 50 and 150 mW), constant fiber length

(1000m) and erbium doping density (11.4 ppm-wt), signals power was swept from (-40dBm to 0 dBm) for bidirectional amplifier the backward pump power was (30 mW).

From the figure, it is seen that amplifier gain decreases with the increasing signal input power. When signal power less than -30 dBm the amplifier works in small – signal regime where the signal gain is independent of the input signal power indeed the signal power is very weak and the amplifier works in unsaturated gain regime.

As shown in figure (5-b), amplifier gain is higher than that obtained for forward pump amplifier and the gain decreases with increasing signal power.

B.Noise Figure Characteristics

The variation of noise figure as a function of fiber length is shown in figure (6-a and 6- b) for three different Forward pumping powers at a constant signal input power and erbium ion density of 15 ppm-wt .

As seen in the figure for less pump power, the increase in noise figure can be clearly noticed. The reason for this increase is the decreasing gain with sharp pump depletion.

In bidirectional pumping powers the noise figure is nearly the same and differs a bit from unidirectional forward pumping. The noise figure increased by pump decay along the fiber, pumps decay results in lower medium inversion and causes the ending portion of the fiber to be loosely.

The variation of noise figure with Erbium ion density for different pump configuration are seen in figure (7-a and 7-b); Erbium ion density was taken from (0 to 100 ppm). It is seen that the noise figure remains constant in a certain value of erbium ion density even if the pumping power is increased. Beyond 16 ppm and for a 30mW pumping power, insufficient pumping occurs and the noise figure sharply increases and for 50mw pumping power beyond 24 ppm the noise figure sharply increases due to insufficient population inversion.

For bidirectional pumping ,It is seen that the much more range of noise figure remains constant in a much more range of erbium ion density because in Bidirectional pumping much more ions reach the population inversion.

The variation of noise figure with pump power for the three different fiber lengths (1000, 2000 and 2500m) are shown in figure (8-a) for the same parameters mentioned before. In an amplifier having those parameters, it can be seen that the noise figure decreases with increasing the pump power, at low pump power the noise figure is large for longer fiber length than short fiber; this is due to the insufficient pump power needed to obtain high gain in an active fiber, and because high gain in an active fiber with the total population inversion causes the spontaneous emission to stay in low levels. The noise figure of a distributed EDFA varies linearly with ASE power and inversely with the amplifier gain; therefore, the NF of a

distributed EDFA can be reduced to a minimum level by increasing the gain.
The variation of noise figure with forward pumping power in bidirectional amplifier is shown in figure (8-b), where the background pump power was chosen to be 30 mW.

As shown in the figure the noise figure decrease with increasing pump power, the noise figure is maximum in bidirectional pumping amplifier than in unidirectional forward pumping amplifier.

The variation of noise figure as a function of input signal power is shown in the figure (9-a) for a constant fiber length and erbium ion density. The graph shows that the NF noise figure of a Distributed EDFA decreases with increasing signal input power. When signal power equal to -9.93 dBm the noise figure has minimum point equal to 4.82 dB for the pump powers 30 mW and 150mW.

The variation of noise figure as a function of input signal power for bidirectional pump power is shown in the figure (9-b) for a constant fiber length and erbium ion density. The graph shows that the NF of a distributed EDFA decreases with increasing signal input power. When signal power equal to -8.01 dBm, the noise figure is constant for the two different powers (30 mW and 50mW) and equal to 4.96 dB.

IV. Conclusion

The gain and noise figure are strongly depended on the fiber length, pumping power, signal input power and erbium ion density. The gain characteristic of the D-EDFA is better in bidirectional pumping. Bidirectional pumping offers the advantage of a more uniform medium inversion along the fiber, along with the possibility to reduce the required input pump power at both fiber ends.
For maximum signal gain, in D-EDFA the required Erbium ion density is decreases for (1000 m) fiber length , it's value is (11.4 ppm-wt. For distributed amplifier with unidirectional forward and Bidirectional pumping, the value of noise figure at (-40 dBm) signal power is lowest with forward pumping.

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Table (1) D- EDFA properties

Length	10000	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	15	~ppm-wt
Numerical aperture	0.24	
Background loss data type	Constant	
Loss at 1310 nm	0.1	dB/km
Background loss file name	Loss.dat	
Include Rayleigh scattering	☑	
Rayleigh constant	150	dB/Km

Table (2) other D-EDFA properties

Parameter	Symbol	Value	Unit
Pump absorption cross section	σ_{pa}	2×10^{-25}	m^2
signal absorption cross section	σ_{sa}	2.54×10^{-25}	m^2
Pump emission cross section	σ_{se}	3×10^{-25}	m^2
signal input power	P_S	-40	dBm
Signal wavelength	λ_s	1480	nm
Pump wavelength	λ_p	1550	nm

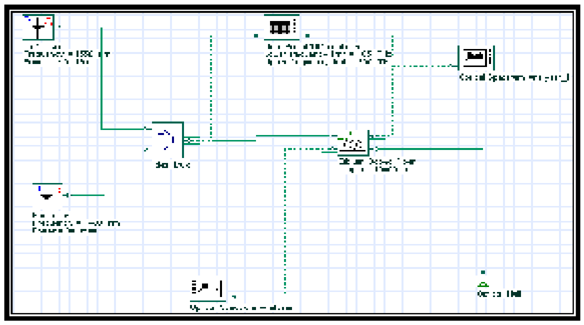

Figure (1) Layout of Distributed Erbium Doped Fiber Amplifiers, 10000m long, and 30mW pump power for Forward Pump Power

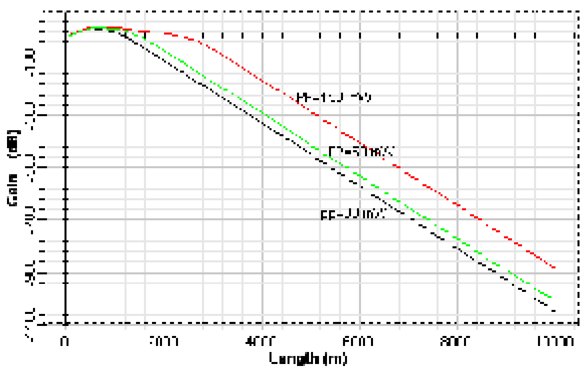

Figure (2-a) The variation of gain with fiber length for three different Forward Pump powers

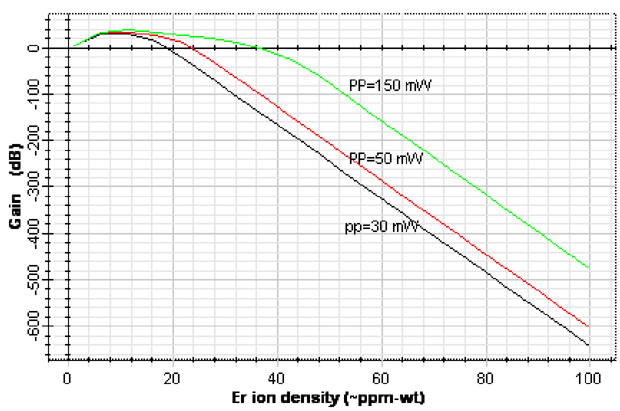

Figure (3-a) The variation of gain with Erbium ion densities for three different Forward

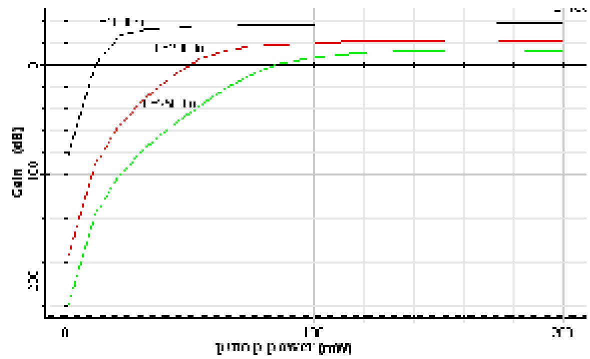

Figure (4-a) The variation of gain with pump power for three different fiber lengths when forward pumped

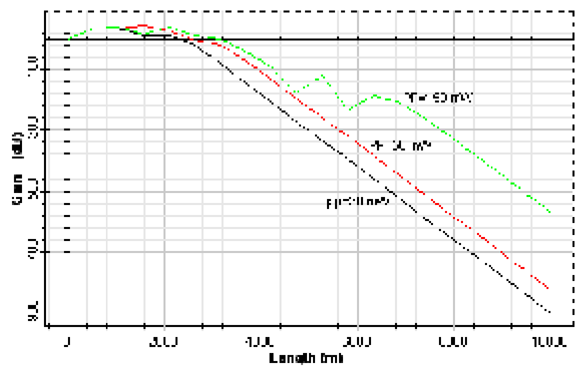

Figure (2-b): The variation of gain with fiber length for three different Bidirectional Pump

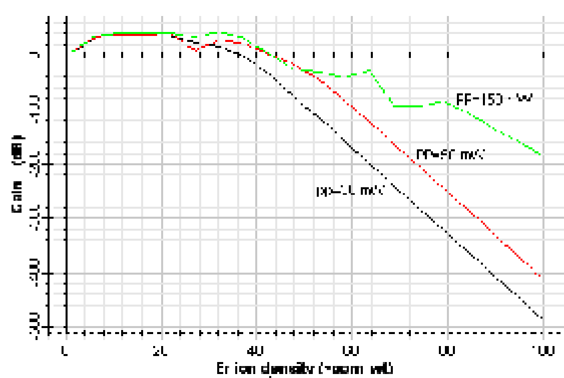

Figure (3-b): The variation of gain with Erbium ion densities,

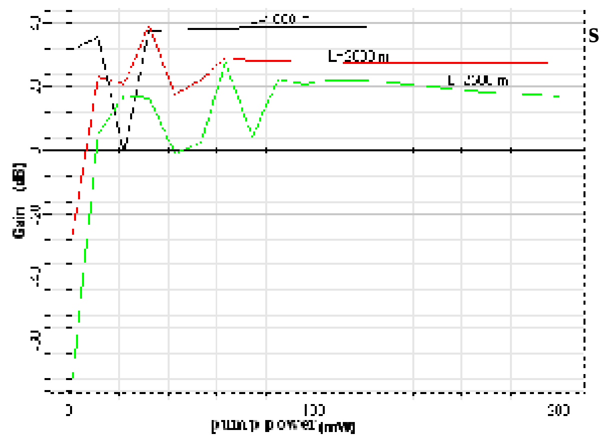

Figure (4-b) : The variation of gain with pump power for three different fiber lengths when Bidirectional pumped

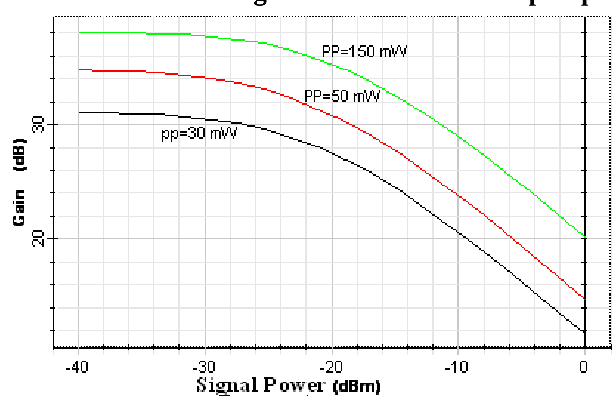

Figure (5-a): The variation of gain with Signal power for three different Forward pump powers

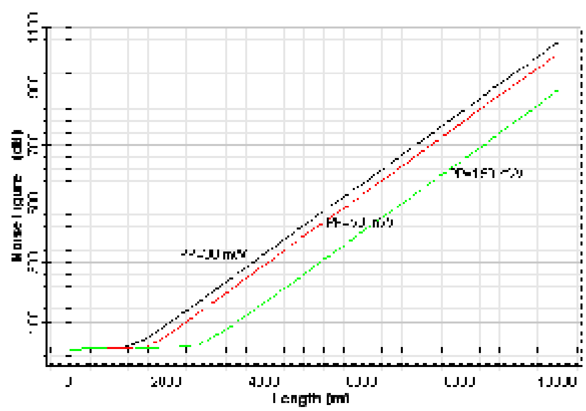

Figure (6-a): The variation of noise figure with Fiber length

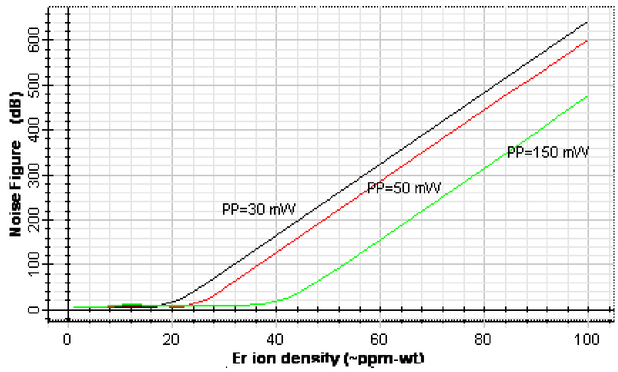

Figure (7-a): The variation of noise figure with Erbium ion density for three different Forward pump Powers

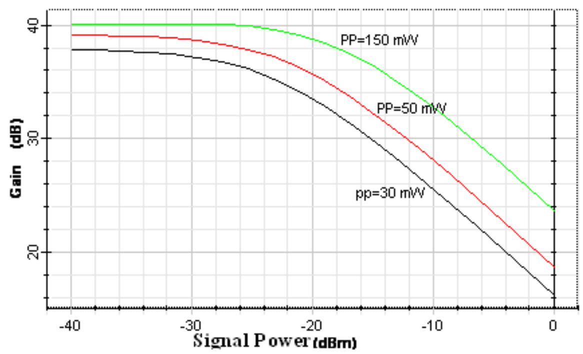

Figure (5-b): The variation of gain with Signal power, for three different Bidirectional pump powers

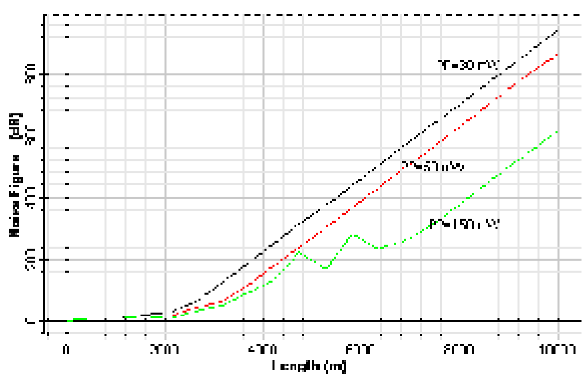

Figure (6-b): The variation of noise figure with Fiber length, for three different Bidirectional pump powers

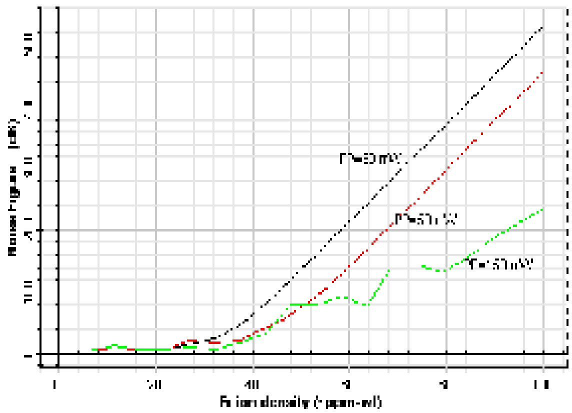

Figure (7-b): Variation of noise figure with rbium ion density, for three different Bidirectional pumps Powers

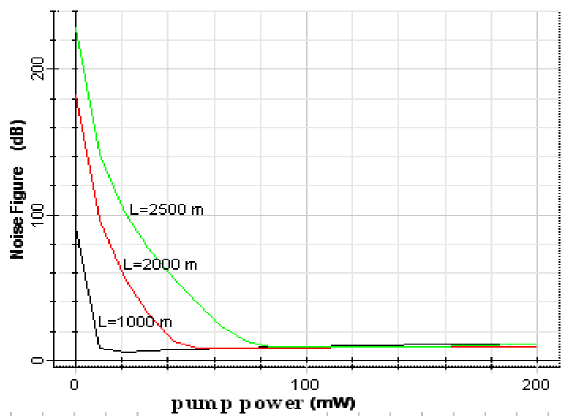

Figure (8-a): The variation of noise figure with pump power for three different fiber lengths when forward pumped

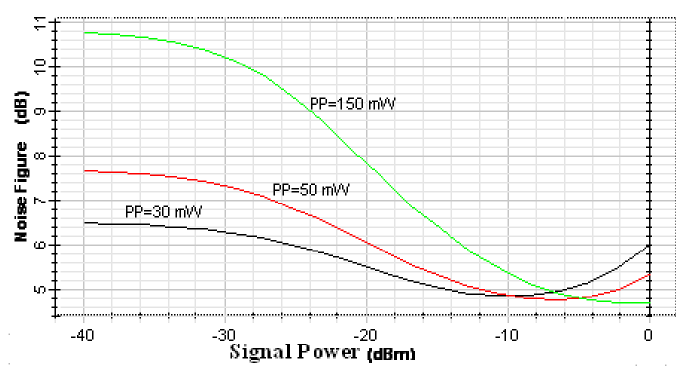

Figure (9-a): The variation of noise figure with Signal power for three different Forward pumping powers

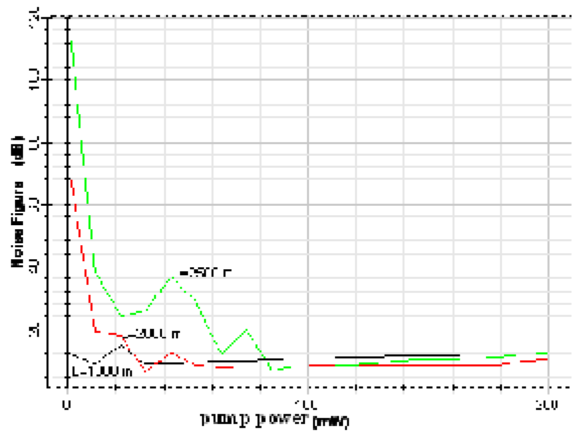

Figure (8-b): The variation of noise figure with pump power, for three different fiber lengths when forward pumped

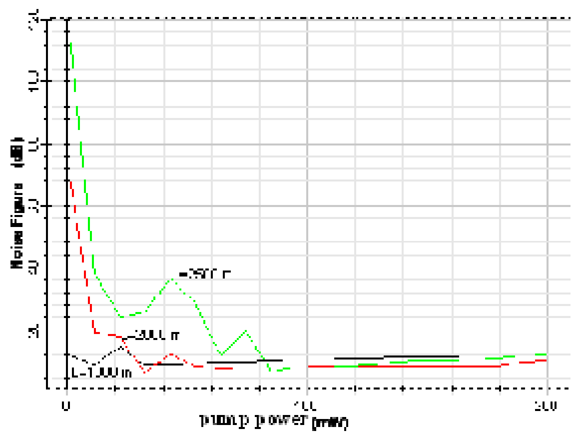

Figure (9-b): The variation of noise figure with Signal power, for three different Bidirectional poewrs