Gain and Noise Figure Performance of Erbium-Doped Fiber Amplifiers at 10Gbps

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Abstract: Fiber loss is a fundamental limitation in realizing long haul point–to-point fiber optical communication links and optical networks. One of the advanced technologies achieved in recent years is the advent of erbium doped fiber amplifiers (EDFAs) that has enabled the optical signals in an optical fiber to be amplified directly in high bit rate systems beyond Tetra bits. In this paper, a simulation of an EDFA has been studied to characterize Gain, Noise Figure of a forward pumped EDFA operating in C band (1525-1565 nm) as functions of Er^{+3} fiber length, injected pump power, signal input power and Er^{+3} doping density. The simulation has been done by using Optisystem 5.0 software simulator (license product of a Canadian based company) at bit rate 10 Gbps.

Keywords: Optical Amplifiers, EDFA, Erbium Doped Fiber, Gain, Noise Figure...

1. Introduction

The erbium-doped fiber amplifier EDFA has made tremendous progress since its invention in 1986. It replaced the rather involved process of the fiber optic repeater station. It created a revolution in long distance optical communication systems. Simplicity and reliability of the repeater compartment are especially important when the optical fiber cable is used as a submarine cable [1].Erbium Doped Fiber Amplifiers (EDFA) made by doping the silica fiber with erbium ions can operate in a broad range within the 1550 nm window at which the attenuation of silica fiber is minimum and therefore it is ideal for the optical fiber communication systems operating at this wavelength range. According to the research performed in recent years, it is known that the pumping of erbium doped fiber at 980 nm or 1480nm is the most efficient way [2].High gain (30~50dB), large bandwidth (>90 nm), high output power (10~ 20 dBm)and low noise figure (NF=3~5 dB) can be obtained using an erbium doped fiber amplifier optimized for 1550 nm range [3].

2. The Structure of EDFA and its Pumping Requirements

The structure of a typical EDFA is shown in figure1. EDFAs consist of optical couplers to combine pump and signal lights injected to active fiber. The gain characteristics of EDFAs can be pumped at 980 nm or 1480 nm, and with different configurations: backward, forward or bidirectional. In forward pumping, both of the signal and pump lights propagate in the same direction through the fiber whereas in the backward pumping they propagate in the opposite direction.

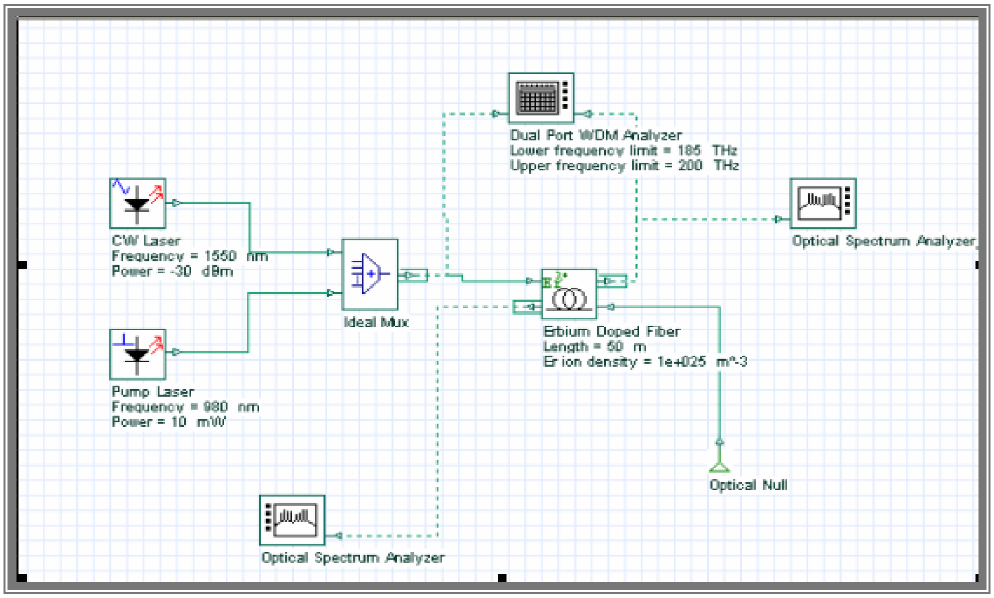


Figure1. Forward pumped EDFA structure [5]

3. Simulation Model

An EDFA model based on work by Giles is used to find the amplifier performance at a high bit rate. Additional loss mechnisem such us pump Excited State Absorption ESA, and the effects of background loss are only considered during the Giles algorithm calculation.

This EDFA model assumes radially symmetric optical mode and dopant distribution, and that erbium radial distribution is well approximated by an overlap factor. Measured Giles parameters, (α_k)-absorption per unit length and (g_k)-small signal gain per unit length are used for basic modeling parameters. Giles parameters can be related to absorption and emission cross-sections, overlap factor, and erbium concentration by following overlap integral.

$$\alpha_k(\lambda_k) = \Gamma(\lambda_k)\cdot \bar{n}_t \cdot \sigma_a(\lambda_k) \qquad (1)$$

$$g_k(\lambda_k) = \Gamma(\lambda_k)\cdot \bar{n}_t \cdot \sigma_e(\lambda_k) \qquad (2)$$

Where σ_a (λ) and σ_e (λ) are radially averaged absorption and emission cross sections of erbium ions, n_t is the averaged erbium ion concentration, and Γ (λ) is the overlap factor between the optical mode field and erbium ions, which can be determined from optical mode field and erbium ion distribution via the following equation.

$$\Gamma(\lambda) = \int_0^{2\pi}\int_0^{+\infty} \psi(r,\phi) n_o(r,\phi) r dr d\phi \qquad (3)$$

Where $\psi(r,\phi)$ is the normalized mode intensity distribution of the fundamental mode, and $n_o(r,\phi)$ is the normalized erbium ion density. If we assume that the fiber has a step index core with a radius of "a", the radially symmetric mode intensity field then is [4]

$$\psi(r) = \left\{ \frac{1}{\pi}\left[\frac{y}{aV} \cdot \frac{J_O\left({r \over a} \cdot x \right)}{J_1(x)} \right]^2 \right\} \text{ for } \quad r \langle a \qquad (4)$$

$$\psi(r) = \left\{ \frac{1}{\pi}\left[\frac{x}{aV} \cdot \frac{K_O\left({r \over a} \cdot y \right)}{K_1(y)} \right]^2 \right\} \text{for} \quad r \geq a \quad (5)$$

Where V equals $2\pi aNA \big/ \lambda J_{0,1}$ and $K_{O,1}$ is Bessel and modified Bessel functions, respectively. Parameters x and y are determined by the characteristics equation that satisfies the boundary conditions at fiber core/cladding $_{\text{interface}}$.

4. 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:

$$G = P_s(L) / P_s(0) \qquad (6)$$

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:

$$NF = (SNR)_{in} / (SNR)_{out} \qquad (7)$$

Noise Figure can also be expressed in terms of gain and spontaneous emission factor (n_{sp}) [2]:

$$NF = 2n_{sp}\,(G-1)/G \approx 2n_{sp} \qquad (8)$$

$$n_{sp} = n_2 / n_2 - n_1 \qquad (9)$$

n_1 and n_2 are ionic population in two energy levels .

5. EDFA Simulation Program

This study focuses on the performance characteristics of the amplifier (gain and noise figure) assuming the fundamental LP_{01} mode exciting at the pump wavelength (λ_p= 980 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. Thus, the required fiber parameters and signal/pump power values can be optimized for a desired EDFA gain-NF performance at 10Gbps.The main menu of the simulation programs are shown in table (1).

Table 1: EDFA properties

Name	Value	Units	Mode
Length	50	m	Normal
Er metastable lifetime	10	ms	Normal
Input data	Fiber specification		Normal
Saturation parameter	4.4e+015	1/(s.m)	Normal
Core radius	2.2	um	Normal
Er doping radius	2.2	um	Normal
Er ion density	1e+025	m^-3	Normal
Numerical aperture	0.24		Normal

6. Typical EDFA Characteristic Obtained With Simulation Program

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 [6].

Table 2. Typical EDFA parameters used in the simulation program

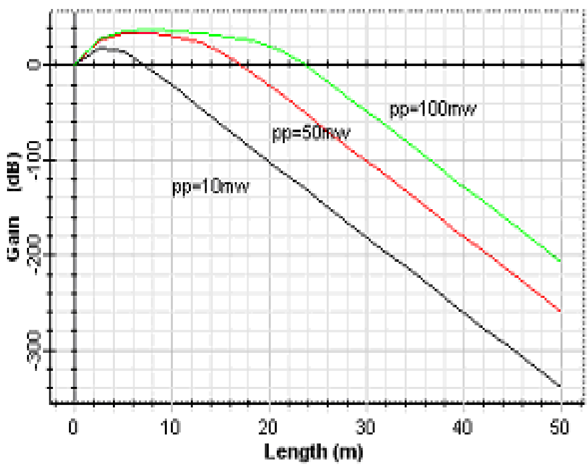
Parameter	Symbol	Value	Unit
Pump absorption cross section	σ_{pa}	1.8×10^{-25}	m^2
signal absorption cross section	σ_{sa}	2.14×10^{-25}	m^2
Pump emission cross section	σ_{se}	3.15×10^{-25}	m^2
signal input power	P_S	-30	dBm
Signal wavelength	λ_s	980	nm
Pump wavelength	λ_p	1550	nm

6.1 Gain Characteristics

The variation of gain with fiber length is shown in figure (2.a) for different pump powers having a constant signal input power and erbium doping density. 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+ Er absorption loss).

Figure (2.b) shows the variation of gain with pump Power for different fiber lengths (10, 30, 50) m, pumping power is swept from (0 to 100) mw, and erbium ion density=1×10^{24} m^{-3} (100 ppm-wt).

It is seen that the gain of 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 longer erbium doped fiber is used with sufficient pumping.



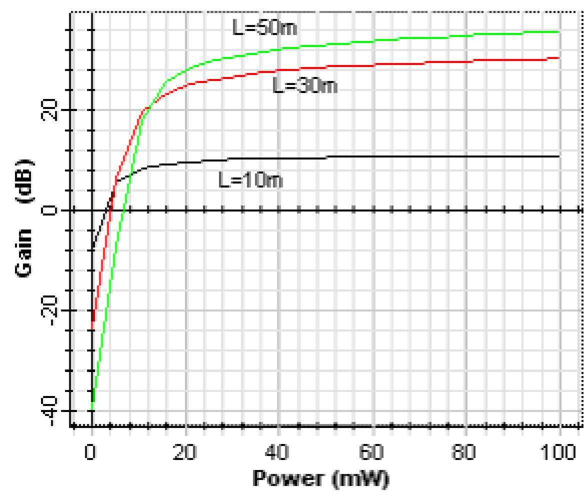


Figure 2.the variation of gain with a) fiber length and b) pump power

Figure (3.a) shows how the gain varies as a function of signal input power for different pumping powers (10, 50and100 mw), constant fiber length (50m) and erbium doping density (100ppm-wt), signals power was swept from (-40dBm to 5dBm).

It is seen that EDFA 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. When the amplifier reaches the saturation the maximum gain dropped by 3 dB below its unsaturated value G_{max}.

The physical meaning of this is the easier saturation of the EDFA at higher signal powers for a constant pump power.

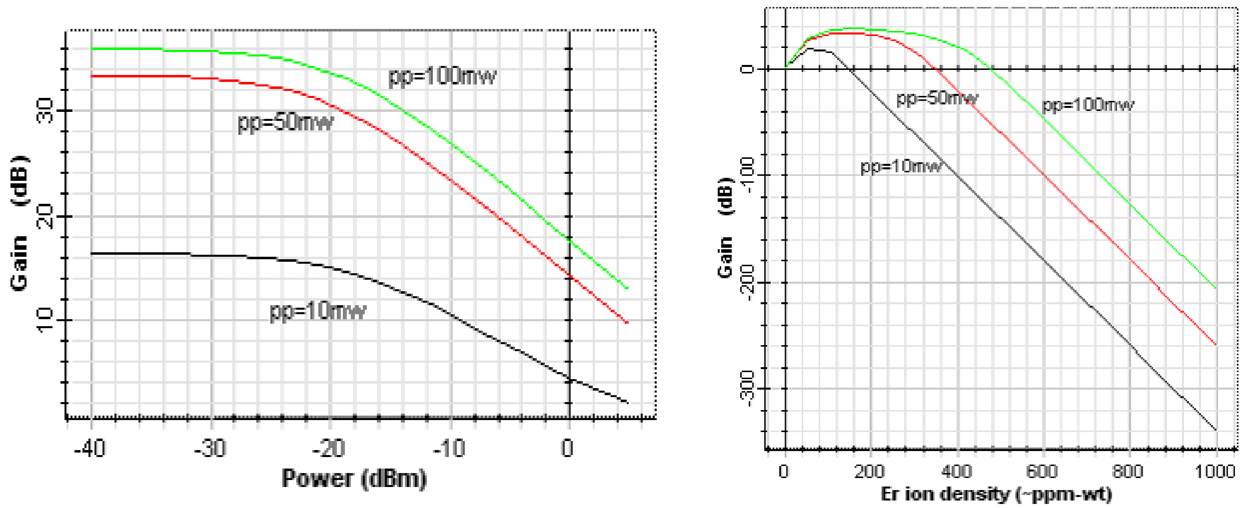


Figure 3.The variation of gain with a)signal input power and b) Erbium ion density

The gain variation as a function of erbium doping density is shown in figure 3.b for a 50m long fiber and a constant signal input power for three different pump powers (10mw, 50mw and 100mw). 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 then decreases. Once the amplifier reaches the population inversion, the variation in maximum gain is small despite a high increase in pump power. In the trace obtained for10mw pump power the gain reduces sharply in highly doped fiber due to insufficient pump.

5.2 Noise Figure (NF) Characteristics

The variation of noise figure as a function of fiber length is shown in figure (4.a) for different pumping powers at a constant signal input power and erbium ion density(1000ppm-wt) . For a pump power of 10mw the increase in noise figure from 8 m can b e clearly noticed. The reason for this increase is the decreasing gain with sharp pump depletion.

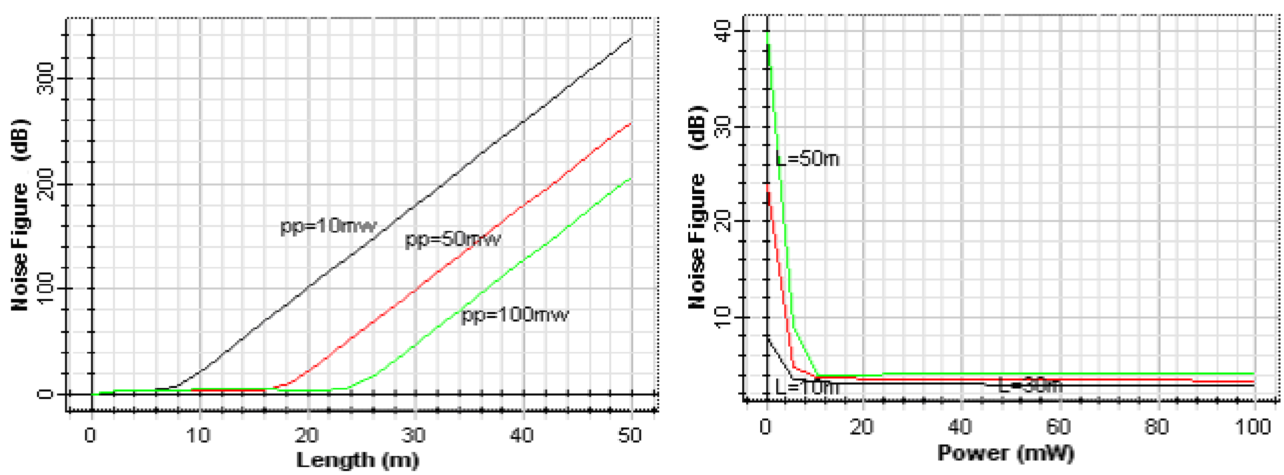


Figure 4. The variation of noise figure with a) fiber length and b) pump power

Figure (4.b) shows the noise figure variations as function of pump power for different fiber lengths (10,30and50m) at a constant signal input power and doping density as 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 shorter fiber, this is due to the insufficient pump power needed to obtain high gain in an active fiber, 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 an EDFA varies linearly with Amplified Spontaneous Emission (ASE) power and inversely with the amplifier gain; therefore, the NF of an EDFA can be reduced to a minimum level by increasing the gain.

In figure 5.a the variation of noise figure is given as a function of signal input power for a constant fiber length and erbium ion density. In this simulation a 50m long EDFA with an erbium ion density of 100ppm was used. The graph shows that the NF of an EDFA increases with increasing signal input power. The variation of noise figure with Er^{+3} ion density is given in figure (5.b) for a constant fiber length and signal input power. Erbium ion density was taken from (1 to 1000 ppm-wt). It is seen that the noise figure remains constant nearly (3 dB) in a certain value of erbium ion density even if the pumping power is increased. Beyond 120ppm and for a 10mw pumping power, insufficient pumping occurs and the noise figure sharply increases and for 50mw pumping power beyond 315ppm the noise figure sharply increases due to insufficient population inversion.

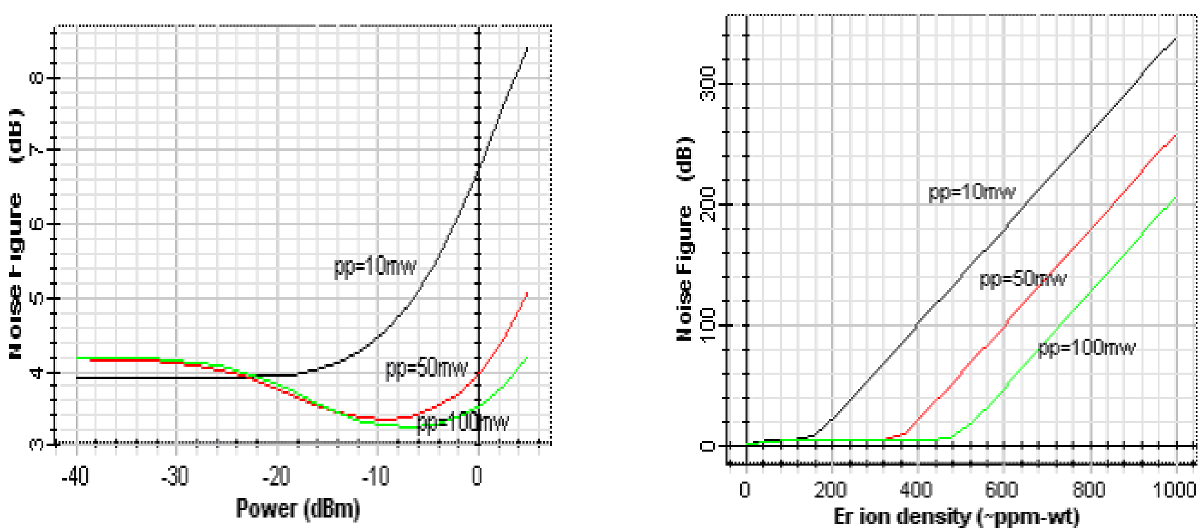


Figure5. The variation of noise figure with a) signal input power and b) Erbium ion density

7. Conclusion

In this study, the performance characteristic of EDFA operating in C band and pumped at 980nm simulated: Gain and noise figure variations were obtained as functions of fiber length, pump power, signal input power and erbium doping density in high bit rate 10Gbps.

According to our results, it was seen that the pump power applied to EDFA sharply reduces due to absorption in erbium doped fiber; in addition gain and NF is strongly dependent on the fiber length, pumping power, signal input power and erbium ion density. The gain varies along the fiber length because of pump power variations .When the EDFA is supplied with sufficient pump power, it was shown that EDFA could be operated in saturation regimes leading to maximum gain and minimum NF.

It was seen that the variation of gain and noise figure as functions of fiber length, pump power, signal input power and erbium doping density do not change when bit rate is increased from (2.5 to 10 Gbps).

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الملخص

اان الخسائر التي تعاني منها الآشارة المنقولة بين نقطتين بعيدتين عن بعضهما تعمل على التحديد من استخدام الآلياف الضوئية لهذا الغرض بين تلك النقاط البعيدة. تعتبر مكبرات الآلياف الضوئية المطعمة بالآربيومEDFA احدى الوسائل المتطورة القادرة على تكبير الموجات الضوئية بشكل مباشر وبسرع اعلى من تيترابايت .

في هذا البحث تم دراسة عمل الآلياف الضوئية المطعمة بالآربيوم مضخة باتجاه امامي و تعمل عند الحزمةC (1525-1565 nm) بواسطة نظام محاكاة برمجية لدراسةخا صيتي الربح و الضوضاء بدلالة طول الليف،كثافة ايون الآربيوم،قدرةالضخ و قدرة الآشارة الحاملة للموجة.
تم انجاز البحث باستخدام برنا مج Optisystem 5.0 بسرعة 10Gbps.