Journal of Applied Sciences

ISSN 1812-5654

ANSInet
an open access publisher
http://ansinet.com

Journal of Applied Science 6 (4): 789-794, 2006
ISSN 1812-5654

Simulation Based Analysis of Erbium Doped Fiber Amplifier (EDFA)

A. Temmar, H. Ould Saadi and A. Boutaleb
Laboratory of Optoelectronic, Institute of Telecommunications, Oran, Algeria

Abstract: The Erbium Doped Fiber Amplifier (EDFA) is an important factor in the improvement of the performance of optical fiber transmission systems. We study different features of this amplifier, which depend essentially on the optogeometric parameters of doped fiber amplifier, such as concentration of ions erbium, length of the fiber and the core diameter. The amplifier's gain G and power noise (Pase), which appear in the signal to noise ratio expression, are computed in terms of the internal parameters from simulations and are shown to contribute to its improvement.

Key words: Optical amplifier, gain, optical fiber, Erbium, optimization, optical telecommunications WDM

INTRODUCTION

Internet development, during the last decade, caused an increasing demand on fast optical components for information transmission. Nowadays, after twenty years of fruitful research and development, transmission using optical fiber media is the prime choice for designers of information technology systems (Fig.1). Due to their ability of handling high flux of data, Erbium Doped Fiber Amplifiers (EDFA) are regarded as a cost effective replacement of classical optoelectronic regenerative repeaters and remain the most important part of DWDM systems (Dense Wavelength Division Multiplexing) which extend the performance of MAN (Metropolitan Area Network) and WAN (Wide Area Network) networks. In this reserch we study the effect of opto geometric parameters on EDFA's maximal gain. Our work focuses mainly on amplifiers with monomode fiber, whose material is glass silica doped with Erbium and the results herein agree to some extent with some well known results in the literature of optical fiber amplifiers.

MATERIALS AND METHODS

EDFA's operation principle: The optical amplification, which takes place in doped fiber by Erbium active ions, is based on the mechanism of stimulated emission (Joundot, 1996; Desurvire, 1996, 2002). The Erbium is used as a doping agent, because it possesses an active transition at the 1550 nm wavelength which corresponds to the minimum of monomode fiber attenuation (0.2 dB km^{-1}) in glass silica. The electronic states associated with the Erbium ions are characterized by different levels of energy (Fig. 2). The excitation of the Er^{3+} ion is obtained with a laser pump at 980 nm wavelength, for which photon energy determines the transition energy between the fundamental ($l^{4I}15/2$) and upper ($^{4I}11/2$) states. The transfer mechanism speed is due to the short life cycle of ions in the upper state and causes population inversion between the meta stable

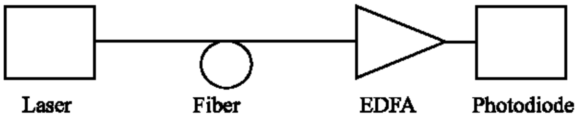

Fig. 1: Simple amplified optical link

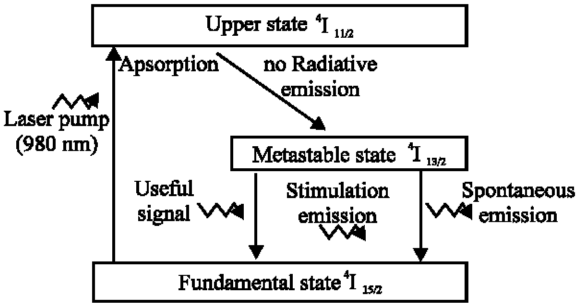

Fig. 2: Diagram showing the amplification mechanism

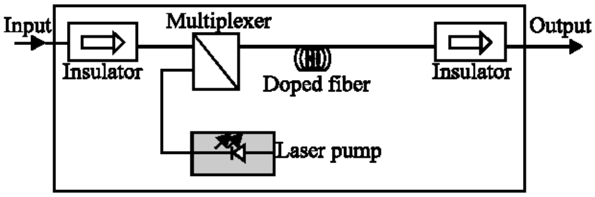

Fig. 3: Block diagram of Erbium Doper Fiber Amplifier

Corresponding Author: A.Temmar, Laboratory of Optoelectronic, Institute of Telecommunications, Route d'Es-Senia, BP 1518 M'Nouer, Oran 31000, Algeria, Tel: (213) 41594436-165 Fax: (213) 41594418

state and fundamental one. This phenomenon yields spontaneous and stimulated emissions under action of incidental photons (useful signal).

The optical amplifier is constituted of doped amplified fiber and laser pump coupled by an optical multiplexer. We often add optical insulators, at the input and output, in order to avoid ASE to propagate and prevent other signal reflections (Joindot, 2000), Fig (3).

Modelling the optical fiber amplifier: Several numerical models of optical fiber amplifier have been developed. These models solve the dynamics of different energy states of erbium ions and optical wave evolution that propagates in active medium. They give fairly precise results for 0.5 dB to 1.5 dB compared to analytical techniques (Giles and Desurivire, 1991). However, their computing time may be excessive for models which take into account substantial number parameters (Joindot, 2000).

Recently, Saleh *et al.* (1990) proposed an analytic model which computes the amplifier's gain according to different parameters: wavelength of the signal and pump, length of the fiber etc. This model is based on the following assumptions:

- The absorption by excited states doesn't exist.
- Homogeneous transitions of energy levels of Erbium atoms.
- Recovered signal mode on the excited ions is identical to the signal mode on ions at rest.
- No saturation of fiber amplifier by its own ASE.

More recently, Georges and Delevaque (1992) proposed an analytic model which takes into account the effect of the amplified spontaneous emission (ASE), improving the precedent model. The basic equation of the above models is the global photonic assessment of optical amplifier between incoming and retiring photons:

$$\mathrm{A.Ni.L}\frac{dx}{dt}=H(x)=\sum_{\nu_i}P_i^{so}-\sum_{\nu_i}P_i^{en}+P_{ase}(x)+P_{spont}(x) \qquad (1)$$

Where:

A: Dopage efficient surface (A = ð.r^2 where r is fiber core diameter)

Ni: Average Erbium ions concentration

L: Fiber amplifier length

x: Fraction of excited ions ($x \in [0,1]$)

ν_i: Spectral component of signal or pump

P_i^{so} and P_i^{en} : Number of photons per second in input and output (Pe is the signal power and Pp is the pump power) amplifier at the ν_i frequency.

P_{ase} and P_{spont} : Number of photons per second at output amplifier due, respectively to ASE and spontaneous emission.

The gain (or absorption) , at ν_i frequency, is given by the following expression:

$$\ln\left[\frac{P_i^{so}}{P_i^{en}}\right]=\left[\sigma_T(\nu_i)x-\sigma_a(\nu_i)\right]\Gamma(\nu_i)\cdot N\cdot L$$
$$=\ln\left(G(\nu_i)\right)=g(\nu_i) \qquad (2)$$

Where:

Γ_{ν_i} : Recovery factor between signal and excited ions to ν_i frequency

σ_T: sum of efficient sections emission σ_e and absorption σ_a, at ν_i frequency,

The contribution of the spontaneous emission, is given by:

$$P_{spont}(x)=\frac{A.N.L.x}{\tau} \qquad (3)$$

Where τ is life cycle of upper state.

The amplified spontaneous emission is computed by estimating the average factor of population inversion along the fiber. Its expression, integrated over the whole ASE spectrum, can be expressed as:

$$P_{ase}(x)=4.\int\frac{\sigma_e(\nu).x}{\sigma_T(\nu).x-\sigma_a(\nu)}(e^{g(\nu)}-1)d\nu \qquad (4)$$

The above model equations describe the evolution of the average fraction o f excited ions x according to the injected photons flux in the fiber and allow to find the fraction of excited ions at the equilibrium state. Which is obtained by solving the equation H(x) = 0, that expresses the conservation of incoming and retiring fluxes of photons in the amplifier.

RESULTS AND DISCUSSION

Optical fiber amplifier simulations: Our simulations are based on the scientific software simulator (Anonymous, 2001). We are mainly interested in the most important optical amplifier's features namely, gain and noise factor. The doped fiber parameters needed for gain calculation are its geometric structure, profile and ions active concentration of the host matrix. Some other factors such as the cut wavelength and the profile are introduced directly into the model. However, if the fiber diameter is exactly known, the exact profile doesn't affect the gain value because the majority of amplifier fibers have nearly a uniform dopage on the fiber core (Joindot, 2000). Therefore the gain depends essentially on the optogeometric parameters of the amplifier fiber.

Determination of Spectral response of the gain in terms of Ni concentration: The concentration represents the rate of dopage in erbium active ions of amplifier fiber

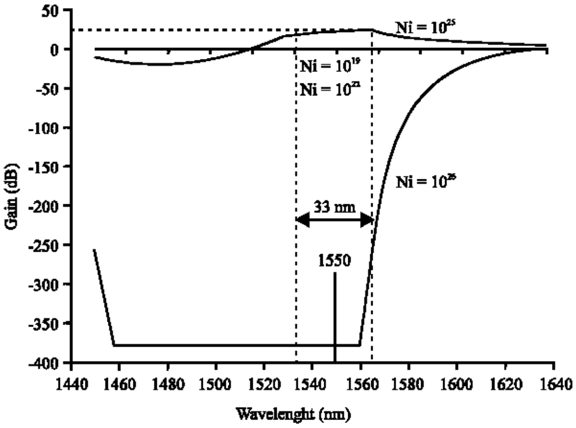

Fig. 4: Gain spectrum as a function of the Erbium ions concentration Ni

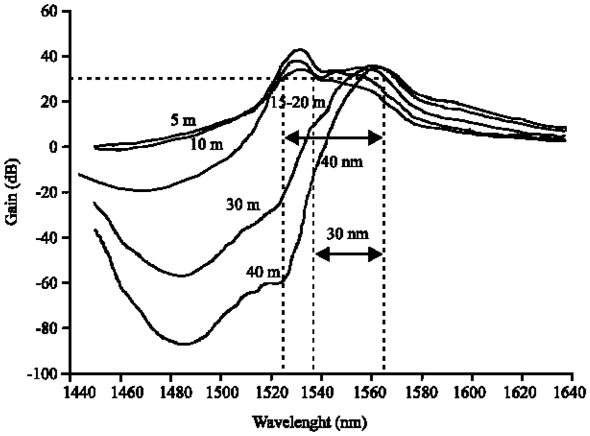

Fig. 5: Gain spectrum as a function of the fiber length

which is measured by the number of ions per cm^3. The rate value which gives the maximum gain (G = 30 dB), is maintained constant during the simulation. Figure 4 gives the spectral gain variation in terms of the concentration and shows that the best rate is around 10^{25} ions/cm^3. The gain decreases (toward 0 dB) and becomes even negative outside the above region in which the fiber is in an absorbing state. Let us notice that the losses of no resonance increase with the ions concentration.

Effect of the doped fiber length L on the amplifier gain: In order to study the effect of doped fiber length, the following parameter values were used:

Pp (power pump) = 10 mW
Ni (Erbium ions concentration) = 3,5 10^{25}/cm^{-3}
D (amplifier fiber diameter) = 2.2μm
Fiber type: glass silica (λ = 980 nm)
τ (high level time duration) = 10 ms
Pe (useful signal power) = -20 dBm

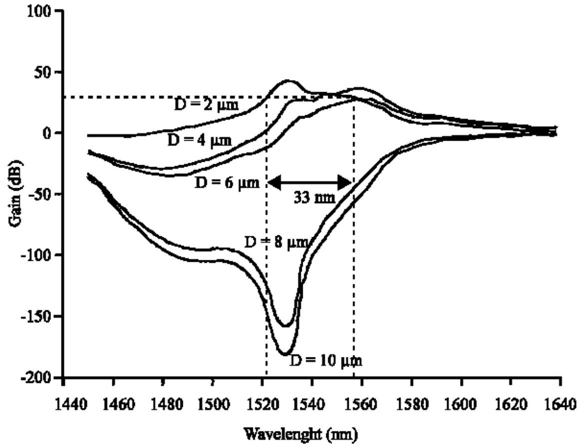

Fig. 6: Gain spectrum as a function of the core diameter D of the doped fiber

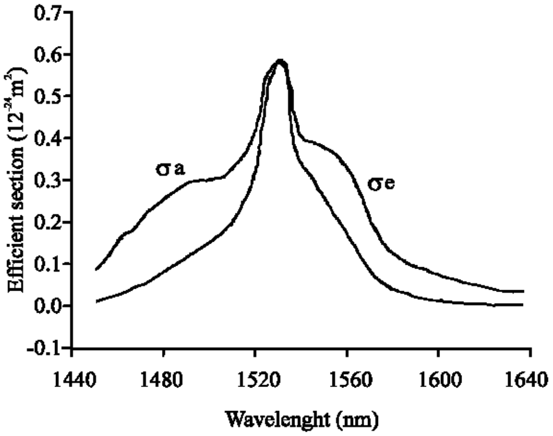

Fig. 7: The efficient sections spectrum of Erbium in glass silica matrix

Simulation results Fig.5 show that the optimal value for which the gain is maximum (over 30 dB) is included between 10 and 20 m and that stability of gain is also verified (G>30 dB and $\Delta\lambda$>30 nm). If L is outside of this optimal strip, the gain G decreases with deterioration of the bandwidth and stability. This phenomenon is explained by the profile of concentration that losses its regularity along core, with increasing of L; the population inversion doesn't made more completely, the absorption is over the emission and the fiber becomes absorbing (negative gain). We notice that our results are nearly the same one (about 15 m) that those found in reference by Lecoy (1997).

Variation of gain spectrum as fuction of the core diameter fiber D: Although theoretically, the gain is maximum for a dopage concentrated in the center of core, we find a maximum gain for a diameter lower than 4 μm as

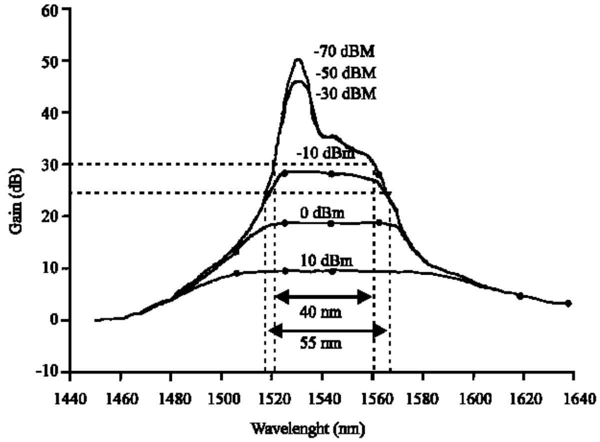

Fig. 8: Gain spectrum as a function of input power Pe (dBm)

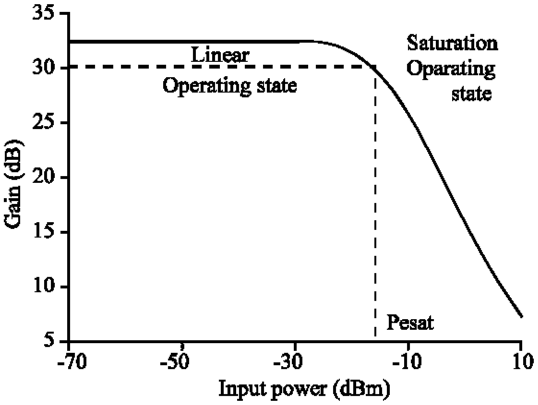

Fig. 9a: Gain as a function of the input power Pe

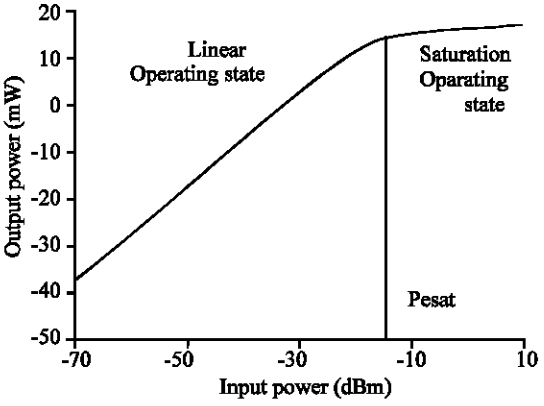

Fig. 9b: Output power Po as a function of the input power Pe : Saturation

it is shown in Fig. 6, beyond this value the fiber becomes absorbing because the dopage is not uniform and no extract on the core, so the gain degenerates and becomes negative. For the optimal values of D (2.2 μm), the 'standard gain' well is found (about 30 dB with a bandwidth over than 30 nm around 1550 nm wavelength). The parameters used in this case are:

Pp (power pump) = 10 mW
Ni (Erbium ions concentration) = 3,5 $10^{25}/cm^{-3}$
L (fiber amplifier length) = 20 m
Fiber type: monomode glass silica (λ = 980 nm)
τ (high level time duration) = 10 ms
Pe (signal useful power) = -20 dBm

Effect of input power Pe on gain spectrum: The efficiency of an ion to emit (or to absorb) a radiance is characterized by the spectral emission's σe (or absorption σa) efficient sections of active ion transitions (Joindot, 2000).

The spectral shape of the gain depends on the composition of the host matrix of the amplifier fiber, its optogeometric parameters and its efficient sections σe and σa. These factors contribute, to a large extent, to the level of amplification and gain G as expressed in formula 2. Fig. 7 shows the erbium emission and absorption spectrum. Notice that the maximum of efficiency is attained around the 1550 nm wavelength (which corresponds to the minimum value of attenuation fiber).

Figure 8 illustrates gain variation according to wavelength for various input powers Pe. For lower input powers, the gain remains at its maximum and constant in the C classical band of optical fiber amplifier (1520 nm to 1560 nm) and it is inversely proportional to Pe. Gains more than 30 dB and bandwidth over 30 nm (>4000 GHz) can be attained.

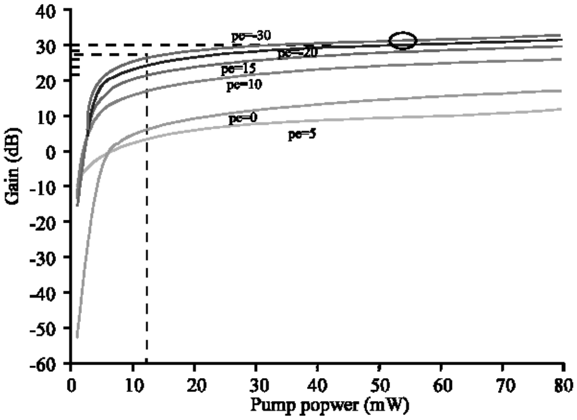

Fig. 10: Gain variation as a function of pump power Pp for various values of Pe

Two important features can be extracted from this curve:

Bandwidth feature : From the simulation results, shown in Fig. 8, we conclude that bandwidth's gain depends on active ions of the host matrix and it is influenced by the input power which is inversely proportional to the gain. At the optimal point region (G = 30 ± 3dB), the excursion strip is about 40 nm .The strip can reach 55 nm but with a decreasing gain (25 dB). This strip's increase is highly advantageous in WDM systems.

Gain stability feature: Low variability of gain is an important factor of the bandwidth where gain excursion is under -3 dB. We generally seek a gain spectrally flat and constant (in the C band). In WDM systems, for which a weak variation of gain on the amplification band is sufficient to decrease power differences, stability of gain is a design constraint that must be satisfied. These differences result in gaps of signal to noise ratio which in turn induce a variation of the quality between channels of multiplex. Present results show that we can multiplex more than eight channels separated by 0.8 nm within 40 nm bandwidth. It is worth mentioning that gain equalization methods can be used but at the expense of using passive filters. Some more complex active solutions (with acoustic optical filters) may also be used in the equalization process (Desurvire, 2002). Another type of promising solutions using intelligent optical amplifiers for automatically equalizing gain spectrum are under development and have not been fully tested in practice.

Effect of input power on gain: Figure 9a shows gain variation as a function of the input power Pe. With low values of power (Pe < Pesat) the gain is nearly constant (Pesat represents the input power for which the amplifier begin to saturate). The amplifier is in its linear operating state.

For higher powers (Pe>Pesat), however, the gain drop and saturation are caused by the decrease of population inversion because there is less excited ions.

Gain variation as function of pump power and input power: Laser pump power is predominant in gain calculation (formula 1); it causes population inversion and influences optical amplifier yield. Fig. 10 shows the fast increase of gain with the pump power, a slow variation around the value of Pp = 10 mW and a decrease with increasing input power. Beyond 10mW the gain becomes indeed constant around -3 dB and stabilizes at an optimal value of 30 dB which can be explained by the fact that reduction of population inversion causes gain saturation. For weak values of the input power (Pe <Pesat and Pesat = -15 dBm) gain does not vary too much and remains at the optimal value of 30 dB. In conclusion, an increase of Pe, causes a decrease in gain G which may drop below 5 dB.

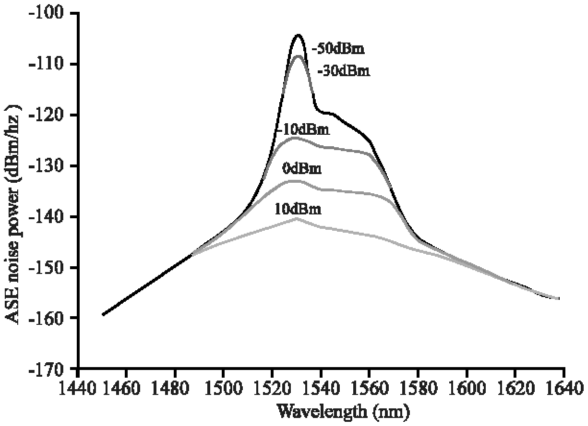

Fig. 11: ASE's Spectral power according to input power Pe

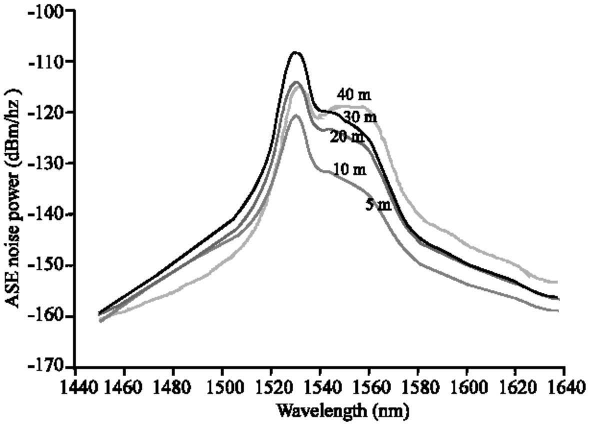

Fig. 12: ASE's spectral power according to fiber length L

Effect of input power Pe on noise spectrum: Some randomly emitted ions, amplified by the signal, are considered as the amplifier noise source and called Amplified Spontaneous Emission (ASE). This phenomenon reduces the population inversion and consequently causes a gain drop.

The population inversion parameter or noise parameter, called n_{sp}, characterizes the noise power spectral density. After simplification of the expression (4), the noise power spectral density can be written as:

$$P_{ESA}(\lambda) = n_{sp}(G-1)\,h\nu \qquad (5)$$

where:

G is static gain
h Planck constant
ν optical frequency

Figure 11 shows ASE noise power spectrum. This curve has the same form that gain curve (Fig. 8) and has a peak around λ =1530 nm. The noise level is very weak (-100dBm/Hz) compared to the useful signal. It is however eliminated by the optical detector at reception (Desurvire, 2002). We often add other filters at reception for further noise reduction.

Influence of fiber length on the noise spectrum: Given that noise is generated by amplified spontaneous emission of Erbium doped fiber, we analyzed the effect of fiber length L on noise spectrum. Our results are illustrated in Fig. 12, which has the same as form as that in Fig. 8.

CONCLUSIONS

In this study simulation is used as an efficient technique for the design of optogeometric parameters, (L, D, Pp, Pe….), of doped fiber that optimize the gain G and ASE's power Pase. , which are the main factors in the calculation of signal to noise ratio of an optical fiber transmission system. As a matter of fact, our analysis shows that if L = 20 m and D = 2 μm, the gain is maximum (>46 dB), with a bandwidth near 40 nm. This optimized gain value is close to the real values of the commercially available amplifiers in the range 25 to 50 dB (illustrated in Fig. 8). Furthermore, the knowledge of optimal values of the erbium doped fiber amplifier parameters (EDFA) is necessary to estimate the value of the maximal gain and its bandwidth. Those parameters affect the transmission system performances. Depending on the position of EDFA within an optical fiber system, EDFA's gain was estimated according to the following scenarios:

- In emission (EDFA used as a booster amplifier): we look for a maximal gain (without diminishing the bandwidth and its stability).
- On line (as a line amplifier to increase the range of the system): we seek a flat gain and a larger bandwidth
- In reception (as a preamplifier to increase detector sensitivity): we look for an average and flat gain.

Moreover our simulation results show that:

- The optimum diameter of doped fiber must be lower than 4 μm, which is approximately equal at theoretical value (Boreius, 2002)
- The optimal fiber length must be between 10 and 20 m, which is nearly identical to that found in reference (Lecoy, 1997).
- The concentration of erbium active ions is about 10^{25} ions/cm^3, which somehow different than the theoretical value 3.5 x 10^{19} ions/cm^3 (Joindot, 1996).
- The input power values depend of the application system, for example; big gain, large strip, important flat gain (WDM systems), high detector sensitivity etc…

REFERENCES

Anonymous, 2001. Software COMSIS IPSIS, France.

Bordais, S., 2002. Amplifiers and lasers 1 μm high power on Ytterbium doubled doped clad fiber. Ph.D Thesis, University of Rennes I, France.

Desurvire, E., 1996. Erbium Doped Fiber Amplifier: Principles and Applications. Wiley and Sons, NewYork.

Desurvire, E., 2002. Erbium Doped Fiber Amplifier, Device and System Developments, Wiley-Interscience.

Giles, C.R. and E, Desurvire, 1991. Modeling erbium-doped fiber amplifiers: J. Lightwave Technol., V.LT-9, pp: 271.

Georges, T. and E, Delevaque, 1992. Analytic modeling of high-gain erbium-doped fiber amplifier. Optics Lett., 17: 1113-1115.

Joindot, I., 1996. Telecommunications via optical fiber: CENT-ENST, Paris, Dunod .

Joindot, M., 2000. Transmission systems on optical fiber. Treatise of Telecommunications: TE 7115, pp: 6-9.

Lecoy, P., 1997. Telecommunications on Optical Fiber. Networks and Telecommunications. Hermes 2d Edn.

Saleh, A.A.M., R.M. Jopson, J.D. Evankow and J. Aspell, 1990. Modeling of Gain in Erbium Doped Fiber Amplifiers. IEEE Photonics Technol. Lett., V2: 714.