International Journal of Engineering, Mathematical and Physical Sciences
ISSN: 2517-9934
Vol:2, No:10, 2008

Design Optimization for Efficient Erbium-Doped Fiber Amplifiers

Parekhan M. Aljaff, and Banaz O. Rasheed

***Abstract*—**The exact gain shape profile of erbium doped fiber amplifiers (EDFA`s) are depends on fiber length and Er^3 ion densities. This paper optimized several of erbium doped fiber parameters to obtain high performance characteristic at pump wavelengths of λ_p= 980 nm and λ_s= 1550 nm for three different pump powers. The maximum gain obtained for pump powers (10, 30 and 50mw) is nearly (19, 30 and 33 dB) at optimizations. The required numerical aperture NA to obtain maximum gain becomes less when pump power increased. The amplifier gain is increase when Er^{+3}doped near the center of the fiber core. The simulation has been done by using optisystem 5.0 software (CAD for Photonics, a license product of a Canadian based company) at 2.5 Gbps.

***Keywords*—**EDFA, Erbium Doped Fiber, optimization Optical Amplifiers.

I. Introduction

ERBIUM doped fiber amplifiers (EDFA) play an important role in light wave communication systems. In order to transmit signals over long distances (>100 km), 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 costs. 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 broadrangewithinthe1550nm window at which the attenuation of silica fiber is minimum and therefore its ideal for the optical fiber communication systems operating at this wavelength range.

Parekhan M. Aljaff She is with the University of Sulaimani, Physics department. She is now Dean of the College of Science, Iraq (e-mail:damed96@yahoo.com).
Banaz M. Rasheed .she is with the Department of Physics, Sulaimani University, Iraq (e-mail: banazrasheed@gmail.com).

For maximum signal gain, first the fiber length must be chosen to some optimized value L_{opt}. This optimal length actually depends on the input pump power, since a longer length of inverted medium can be achieved by a higher pump. The optimum length also depends on both pump and signal wavelengths, since the pump absorption coefficient and the signal gain coefficient are wavelength dependent.

For saturated EDFAs, the optimum length also depends on the signal power [2]. The first part of the paper considers the optimization of fiber length relative to erbium ion density at three different pump powers assuming fundamental LP01 mode excitation at the pump wavelength (λp =980nm). The study shows that the optimum fiber length decreases when erbium ion densities increase.

The second part of the study considers the optimization of numerical aperture for optimum fiber length and erbium ion density at two different pump powers. The last part considers the effect of concentrating the Er+3doping near the center of the fiber core on the signal gain.

II. The Configuration of EDFA

The main components of an EDFA should be at least consisting of:

1. The erbium-doped optical fiber
2. The pump laser
3. The wavelength-selective coupler.

The pump light is guided into the erbium-doped fiber by means of a wavelength division multiplexing (WDM), which is used to couple the pump signal into the doped fiber. Additionally, an isolator is generally placed at the output of an amplifier to prevent back reflection which can degrade amplifier performance or cripple the amplifier due to laser oscillation in the amplifier. Typically, the EDFA configuration can be categorized by pumping schemes into three particular arrangements. These schemes are:

1. Forward-pumped (co-pumped).
2. Backward-pumped (counter-pumped).
3. Dual-pumped.

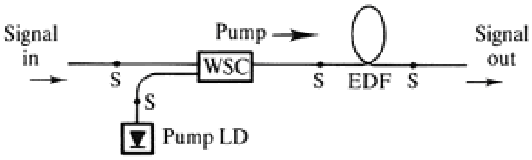

Fig. 1 Forward pumped EDFA structure

Efficient EDFA pumping is possible using semiconductor lasers operating near 980- and 1480-nm wavelengths. The required pump power can be reduced by silica fibers doped with aluminum and phosphorus or by using fluorophosphates fibers with the availability of visible semiconductor lasers, EDFAs can also be pumped in the wavelength range 0.6-0.7µm. Most EDFA us 980-nm pump lasers as such lasers are commercially providing more than 100mw of pump power, and it's used where low-noise s required. Pumping at 1480nm requires longer fibers and higher powers because it uses the tail of the absorption band, and it's used for higher power amplifiers [3].

Pumping at a suitable wavelength provides gain through population inversion the gain spectrum depends on the pumping scheme as well as on the presence of other dopants, such as germanium and alumina, within the fiber core [3].

III. Simulation Model

Giles algorithm 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. A simpler method of fiber characterization can be done by writing the amplifier equations in terms of Er3+ absorption coefficient (αk), gain coefficient (gk), 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 [4]:

$$\zeta = \pi \cdot b_{eff}^2 \cdot n_t / \tau \qquad (1)$$

where b_{eff} is the equivalent radius of the doped region, n_t is local erbium ion density, and τ is metastable life time parameter.

And the absorption and gain coefficients are expressed in terms of distributions of the ions and optical modes: [4]

$$\alpha_k(\lambda_k) = \sigma_a(\lambda_k) \cdot \int_0^{2\pi}\int_0^{\infty} i_k(r,\phi) \cdot n_t(r,\phi,z).rdrd\phi \qquad (2)$$

where $i_k(r,\varnothing)$ is defined as the normalized optical intensity.

$$g_k(\lambda_k) = \sigma_e(\lambda_k) \cdot \int_0^{2\pi}\int_0^{\infty} i_k(r,\phi) \cdot n_t(r,\phi,z).rdrd\phi \qquad (3)$$

For a uniform ion distribution the absorption and gain coefficients can be simplified as [4]:

$$\alpha_k(\lambda_k) = \Gamma(\lambda_k) \cdot \overline{n}_t \cdot \sigma_a(\lambda_k) \qquad (4)$$

$$g_k(\lambda_k) = \Gamma(\lambda_k) \cdot \overline{n}_t \cdot \sigma_e(\lambda_k) \qquad (5)$$

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

$$\frac{dp_k(z)}{dz} = u_k \cdot P_k(z) \cdot \left(g_k((\nu_k) + \alpha_k(\nu_k)) \cdot \frac{\overline{n}_2}{\overline{n}_t} - \alpha_k(\nu_k) - l_k \right) + u_k \cdot P_{ok} \cdot g_k(\nu_k).\frac{\overline{n}_2}{\overline{n}_t} \qquad (6)$$

Where each beam propagates in the forward (u_k =1) or backward (u_k = −1) direction and P_{ok} means the spontaneous emission contribution from the local metastable population n_2. P_{ok} = m.h.υ_k.$\Delta\upsilon_k$. 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: [4]

$$\frac{\overline{n}_2}{\overline{n}_1}(z) = \frac{\sum_{k=1}^{n} \frac{P_k(z) \cdot \alpha_k \nu_k}{h \cdot \nu_k \cdot \zeta}}{1 + \sum_{k=1}^{n} \frac{P_k(z) \cdot (\alpha_k(\nu_k) + g_k(\nu_k))}{h\nu_k}} \qquad (7)$$

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

IV. EDFA Simulation Program

After entering the required parameters for a desired amplifier in main menu and sub menus of the program, the optimization can be made for the EDFA`s. The main menu and some of the simulation program are shown in Fig. 2.

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

Name	Value	Units	Mode
Calculation algorithm	Giles		Normal
Relative error	0.0001		Normal
Max. number of iterations	50		Normal
Longitudinal steps	100		Normal
Overlap factor data	Calculate		Normal
Geometrical model	LP01		Normal
Overlap factor	Power independent		Normal

Fig. 3 Layout of Erbium Doped Fiber Amplifiers, 50m long, and pump power=10mw

V. Typical EDFA Characteristic Obtained with Simulation Program

Table I shows the typical EDFA parameters used in the simulation program.

TABLE I
THE 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

A. Optimization of Length at Different Erbium Ion Densities

The optimization was done at three different pump powers (10, 30 and 50mw) for the fiber length equal to 50m and Erbium ion density swept from (1 to1000ppm-wt). Figs. 4 and 5 show the value of gain according to the Er^{+3} ion density relative to optimum fiber length, According to the result at optimization EDFA can be designed by inserting optimum length with the value of erbium ion density in which gain is maximum at each of three different pump powers.

It is shown that when Erbium ion density increases the optimum length decreases which is suitable for lumped amplifier, but we must take into account, that in practical applications, the value of Erbium ion density = 1000ppm-wt which correspond to (1×10^{25} m^{-3}) considered as an upper limit for the Erbium ion density in EDFAs, because high concentration of Er^{3+} deleterious gain due to clustering, this effect is known as cooperative energy transfer (CET) which reduces fluorescence lifetime.

It is seen from Fig. 5 that for 10mw pumping power the gain is low due to insufficient population inversion.

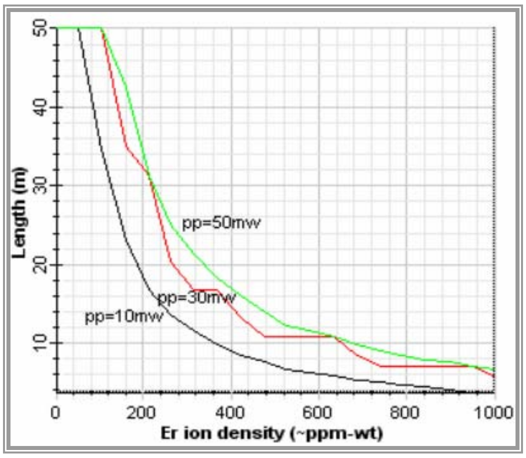

Fig. 4 Optimum length as a function of Er3+ ion density

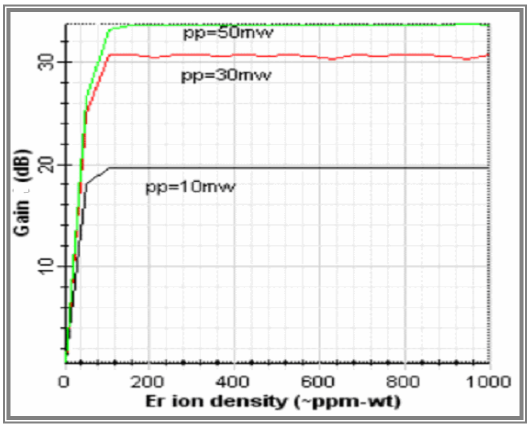

Fig. 5 Gain at different Er^{3+} ion density after optimization relative to each optimum length at pumping powers 10, 30 and 50mw

B. Change of Numerical Aperture (NA) at Optimum Fiber Length

Optimum fiber length with its relative Er^{+3} ion density at each of pumping powers (30 and 50 mw) is chooses. From Fig. 3 at 30mw, for optimum length (10.8m) the erbium ion density equal to(526ppm), and at pump power 50mw for the same density the optimum length is equal to (12.2m)is chooses. The NA is swept from (0.1 to 0.3).

The other parameters are the same as mentioned before. Fig. 6 shows the signal gain as function of numerical aperture. It is seen that the gain increases with increasing NA and remains constant (saturate) after certain level for each pump power, the reason for this is that the amplifier reaches the population inversion. It is clear that the gain increases when NA increases because increasing NA proves the overlap between optical mode field and erbium ions. Also with increasing pump power the required NA to obtain maximum gain becomes less.

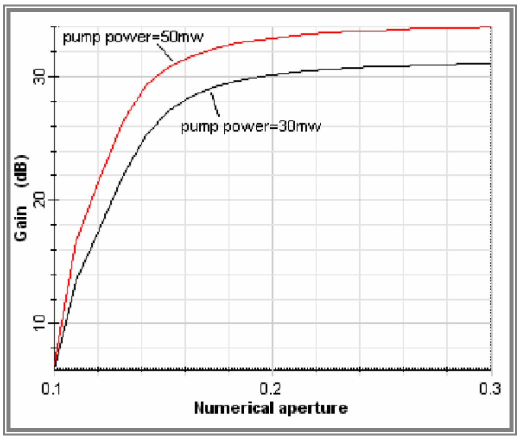

Fig. 6 Signal gain as a function of NA

C. Change of Er- Doped Radius for Optimum Fiber Length

The erbium doping radius was ranged from (1 to 15 µm), and fiber core radius equal to 2.2µm. Fig. 7 shows the signal gain as function of Er^{3+}-doped radius (a_0), The Er^{3+} ion density was assumed to be 526ppm-wt.The pump wavelength is 980nm and the pump power is 30 and 50 mw. The signal wavelength is 1550nm and the signal power is -30dBm. The signal gain increases as doping radius decreases, because the signal light does not suffer from additional absorption. That is, the Er^{3+} - ions does not exist in the area where the pump power is small. It is shown that concentrating the erbium doping near the fiber –axis results, at low pump power, in improvement maximum gain, because the inner region of the core is inverted and has gain the outer region that is not inverted is absorbing.

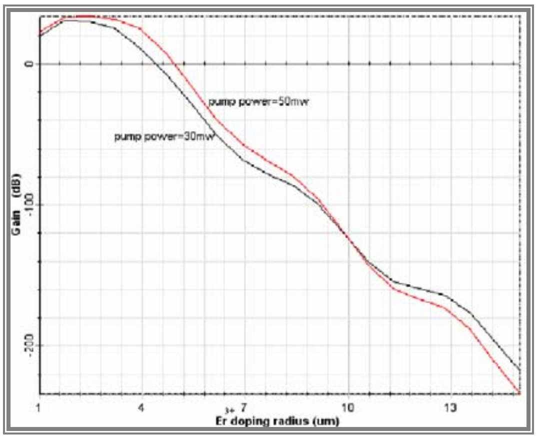

Fig. 7 Signal gain as a function of Er^{3+} doping radius

VI. Conclusion

1) The optimum fiber length decreases when erbium ion densities increase. According to the result, it is possible to design amplifiers with high gain for amplifier length as short as few meters by increasing erbium ion density and vise versa. The maximum gain obtained for pump powers (10, 30 and 50mw) is nearly (19, 30 and 33 dB) at optimizations.

2) The required numerical aperture NA to obtain maximum gain becomes less when pump power increased.

3) The maximum gain is obtained when erbium doping radius is less than the fiber core radius and concentrating the erbium doping near the fiber –axis results, at low pump power, in improvement maximum gain. The optimum erbium doped radius for the two different pump powers (30 and 50mw) are 1.96 and 2.06µm respectively.

Acknowledgment

The authors would like to thank Dr. S. Abalkerim for her helpful advice.

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Parekhan M. Aljaff was born in Kirkuk,Iraq, on July 1954 .she received Bachelor Degree in physics from Sulaimany University.Sulaimany,Iraq,1976,and the MS.C , and PH.D. Degrees in University of Babes- Bolyai Culi-Napoca, Romania.1984.

She became Assistant professor in 2004. She is now Dean of the College of Science. She has many researches, one of them published in Trieste, Italy, on lasers in Chemistry, 1991, also researches published in journals in Iraq, Sulaimani, Journal of Zancoy Sulaimani, Part A,Vol.6 (1)2003.and in Iraq, Duhok, Journal of Duhok University,v1.2,no. 1,1999.

Banaz M. Rasheed was born in Sulaimani, Iraq, on Febreuary1968.After graduating from Baghdad University with Bachelor of Science degree in physics 1990, she attended Sulaimani university in1995, and she worked in physics laboratories. In 2007, she earned MS.C degree in optical amplifiers. She is now Lecturer in Sulaiimani University.