Erbium Doped Waveguide Amplifier Gain for Different Erbium Concentration Profiles: Effect of Chip Area and Pump Power

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Abstract _ **In this paper, the gain of the erbium doped waveguide amplifier (EDWA) is modelled and investigated. The model is derived from a model for straight EDWAs with constant erbium-doped phosphor silicate glass waveguide amplifiers. Different erbium concentration methods are used; namely: constant, step-like, diffusion and ion implantation. A comparative study of the optical signal gain, chip area and pump power is done. The optimal design parameters and the optimal doping method leading to maximum gain are then determined.**

Index Terms _ **Diffusion, erbium doped waveguide amplifier, ion implantation, phosphor silicate glass, step like concentration.**

I-INTRODUCTION

Erbium doped waveguide amplifiers (EDWAs) have their fiber advantages as no crosstalk between WDM channels, low noise figure and low power consumption. At the same time, the EDWA technology enables fabrication of amplifier arrays and integration of amplifiers with different functions, such as splitters, couplers etc., on a single chip. The high level of integration places a strong limit on the chip area assigned for an EDWA. It requires doping with very high erbium concentrations in order to compensate for the short length of the integrated devices [1].

The model in this paper is derived from an accurate and verified model for straight EDWAs [2] that fits experimental results for constant erbium-doped phosphor silicate glass waveguide amplifiers up to erbium concentrations of 6.10×10^{25} m^{-3}. The model is then applied to different Er profiles obtained by various doping methods, such as thermal diffusion, ion implantation and step-like profiles [3].

By the use of numerical algorithms, it was possible to simulate the electromagnetic field evolution along the propagation axis of the waveguides and calculate different performance parameters such as maximum obtainable gain, optimal waveguide length and pump power. Such algorithms are based on the solution of rate equations considering invariant field profiles. Simulation results are used for a comparative study of signal and pump evolution and of amplifier performances for the considered doping techniques. The optimal fabrication parameters for each doping method have been obtained.

II-NUMERICAL MODEL

The model uses a three level Er ion. The pump level is the $^4I_{11/2}$ state, which is pumped at 980 nm. It is assumed to remain unpopulated due to fast relaxation out of this level. The upper laser level is the metastable state $^4I_{13/2}$ and the lower laser level is the ground state $^4I_{15/2}$. From these three levels, we obtain our rate equations [4].

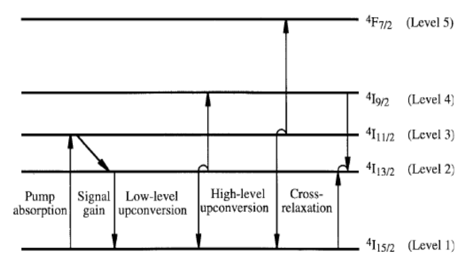

Fig. 1 Simplified energy level diagram of Er^{3+}.

$$\frac{dN_1}{dt} = -\sigma_{13} N_1 v_g N_p + \{\sigma_{21} N_2 - \sigma_{12} N_1\} v_g N_s + \frac{N_3}{\tau_{31}} + \frac{N_2}{\tau_2} + K_2 N_2^2 + K_3 N_3^2 - C_{14} N_1 N_4 \tag{1}$$

$$\frac{dN_2}{dt} = \{\sigma_{12} N_1 - \sigma_{21} N_2\} v_g N_s - \frac{N_2}{\tau_2} + \frac{N_3}{\tau_{32}} - 2K_2 N_2^2 + 2C_{14} N_1 N_4 \tag{2}$$

N_p and N_s are the pump and signal photon densities, σ_{13} is the cross section for pump absorption, while σ_{31} is considered the cross section for pump emission,τ_{32} is the non-radiative life time decay path from level 3, τ_{31} is the lifetime from level 3 to level 1 and both σ_{12} and σ_{21} are the cross sections for signal absorption and emission, τ_2 ,τ_4 ,τ_5 are the life times for level 2, 4 and 5, K_2 and K_3 are up-conversion coefficients, C_{14} is the cross relaxation coefficient, v_g is considered the group velocity $\{=c/(\varepsilon_r^{'})^{0.5}\}$, with $\varepsilon_r^{'}$ the relative dielectric constant of the host glass. Homogenous up-conversion is taken into account using the empirical formula that relates the upper level life time τ with the local population of this level N(x,y,z) [2 and 3].

$$\tau = \frac{\tau_0}{1 + \left(\frac{N(x,y,z)}{Q}\right)^2} ,$$

(3)

where τ_o is the upper level life time in the limit of zero Er concentration and is equal to 13.5 ms, while Q is the quenching parameter which is equal to $1.7x10^{25}$ m^{-3}. Then, by inserting the empirical equation in the rate equation, one gets the cubic equation for the local population N(x,y,z). Since a 3 level system is considered, then, the equations used in our system are the dN_2/dt and dN_1/dt equations in which we will equalize (i.e. $dN_2/dt = dN_1/dt$) and insert the empirical formula to get the local population cubic equation:

$$N(x,y,z)^3 + [(R(x,y,z) + w_a(x,y,z) + w_e(x,y,z)).\tau_0 + 1]. \left(\frac{Q}{\rho}\right)^2 .$$
$$N(x,y,z) - [R(x,y,z) + W_a(x,y,z)]. \left(\frac{Q}{\rho}\right)^2 .\tau_0 = 0$$

(4)

where R(x, y, z) is the pump absorption rate, $W_a(x,y,z)$ and $W_e(x,y,z)$ are considered the signal absorption and emission rates. The lower local population is obtained from $N^{'}(x,y,z) = \rho - N(x,y,z)$, with ρ the Er concentration.

The propagation equation is used to calculate the signal output power, P_{sout}. The propagation equations for pump channels (covering spectral region from 1450 to 1650 nm) have the form [1]

$$\frac{dp_s(z)}{dz} = \left[\iint_{S_{core}} \left(\sigma_{se}(\nu_s)\ N(x,y,z) - \sigma_{sa}(\nu_s)\ N^{'}(x,y,z)\right) .\ \psi_s(x,y)ds\right] .\ p_s(z)$$

(5)

with σ_{sa} and σ_{se} the absorption and emission cross-sections for the signal, S_{core} the waveguide core area, b the width of an ASE channel, z the coordinate along the waveguide and ψ_s the intensity profiles of the fundamental pump and signal modes.

The local loss coefficient is described by [1]

$$\alpha_s = \alpha_{bs} + \alpha_{rs}(z) , \qquad (6)$$

where α_s is the local loss coefficient, α_{bs} is the local background loss coefficient and α_r is the local radiation loss coefficient for signal mode [5].

To get the signal power out form this equation, the local population N(x,y,z) and the radiation losses α_{rs} are needed. The unknowns in this cubic equation {pump absorption rate, R_a, signal absorption rate, W_a, and signal emission rate, W_e} are, respectively, given by [6]

$$R_a \cong R(x,y,z) = \frac{\sigma_{pa}.I_p(x,y,z)}{h.\nu_p} , \qquad (7)$$

$$w_a \cong w_a(x,y,z) = \frac{\sigma_{sa} I_s(x,y,z)}{h\nu_p} + \sum_{i=1}^{N} \frac{\sigma_{sa}(\nu_i)}{h\nu_i}\left[I^+_{ASE} + I^-_{ASE}(x,y,z)\right],$$

(8)

and

$$w_e \cong w_e(x,y,z) = \frac{\sigma_{se} I_s(x,y,z)}{h\nu_s} + \sum_{i=1}^{N} \frac{\sigma_{se}(\nu_i)}{h\nu_i}\left[I^+_{ASE} + I^-_{ASE}(x,y,z)\right],$$

(9)

where h is Planck's constant and $\nu_p = c/\lambda$.

The second terms in W_e and W_a are equal to zero due to the application of the boundary conditions. The set of the rate-propagation equations must be solved numerically with the following boundary conditions:

$$p_p(0) = p_p^{in}$$
$$p_s(0) = p_s^{in}$$
$$p^+_{ASE}(0,\nu_i) = p^-_{ASE}(L,\nu_i)$$

(10)

We can ignore the ASE as the signal power in our model is 1 mw. When signal powers are stronger than 0.3 mW, the ASE can be neglected and the approximate solution is quite accurate. For weak signals, the ASE is too strong and cannot be neglected [7].

For light guided by the waveguide, the signal power coupled into a mode will have a finite spatial distribution over the waveguide plane. Defining the mode envelope as $\psi_s(x,y,z)$, where (x,y) represents the rectangular transverse coordinates, while z being the direction of propagation along the waveguide, the optical power, P_s, coupled into the mode results in a light intensity distribution, I(x,y,z), in the waveguide transverse plane, given by [8]

$$I(x,y,z) = p_s(0)\frac{\psi_s(x,y,z)}{\int_0^{2a}\int_0^{2b}\int_0^{L}\psi(x,y,z)dxdydz}$$

(11)

with

$$\psi_s(x,y,z) = \sin\left(\frac{\pi x}{2a}\right)\sin\left(\frac{\pi y}{2b}\right)\sin\left(\frac{\pi z}{L}\right)$$

(12)

where a is the half width of the core, b is the half thickness of the core and L is the optimum length for the waveguide [9].

The following is the numerical investigation of the optical signal gain when the erbium concentration used. Erbium is considered as an active element instead of being constant. The gain is going to be evaluated as a function of erbium concentration profiles obtained by various doping methods. We have to consider changing the local population N_1 and the upper population N_2 [10 and 11]

$N_1 =$

$$\frac{A_{21}+R_{21}+W_{21}+W_{21}ASE}{A_{21}+R_{21}+W_{21}+W_{21}ASE+R_{12}+W_{12}+W_{12}ASE} * C_{Er} \tag{13}$$

In several cases, when the gain is lower than 20-25 dB, useful results can be obtained neglecting ASE, i.e.

$$N_2 = \frac{A_{21}+R_{21}+W_{21}}{A_{21}+R_{21}+W_{21}+R_{12}+W_{12}} * C_{Er} \tag{14}$$

$$N_2 = \frac{A_{21}+R_e+W_e}{A_{21}+R_e+W_e+R_a+W_a} * C_{Er} \tag{15}$$

where A_{21} is the spontaneous transition rate which is equal to τ^{-1}

$$W_{21} \quad N_1 \quad = \left(\left(W_{21}+A_{21}\right) * N_2\right) \tag{16}$$

where

$$R_a = \frac{\sigma_{pa} . I_p(x, y, z)}{h . \nu_p}, \tag{17}$$

$$R_e = \frac{\sigma_{pe} . I_p(x, y, z)}{h . \nu_p}, \tag{18}$$

$$W_a = \frac{\sigma_{sa} . I_s(x, y, z)}{h \nu_p}, \tag{19}$$

an

$$W_e = \frac{\sigma_{se} . I_s(x, y, z)}{h \nu_s}. \tag{20}$$

Different Er profiles are obtained by various doping methods such as, thermal diffusion, ion implantation and to step-like profiles [12].

a) Erbium diffused waveguide: the maximum obtainable gain is studied as a function of the initial erbium film width and diffusion depth; where w is the Er profile width, dy is the diffusion depth and C_o is the maximum concentration, The erbium concentration profile is given by the solution of the diffusion equation [13]

$$C(x, y) = \frac{C_0}{2} \exp\left[-\left(\frac{y}{dy}\right)^2\right] * \left\{erf\left(\frac{x+w}{dx}\right) - erf\left(\frac{x-w}{dx}\right)\right\} \tag{21}$$

b) Erbium ion implanted waveguides: An alternative approach to incorporate Er ions into $LiNbO_3$ given by MeV ion implementation. Due to the asymmetry of the implementation profile, the in-depth Er behavior is described by two semi-Gaussian functions as [14]

$$C(x, y) = \begin{cases} \frac{C_0}{2} \exp\left[-\left[\frac{y-d}{\alpha y_m}\right]^2\right]\left\{erf\left(\frac{x+w}{ax}\right) - erf\left(\frac{x+w}{ax}\right)\right\} & 0 \lhd y \lhd d \\ \frac{C_0}{2} \exp\left[-\left[\frac{y-d}{\alpha y_p}\right]^2\right]\left\{erf\left(\frac{x+w}{ax}\right) - erf\left(\frac{x+w}{ax}\right)\right\} & d \lhd y \end{cases} \tag{22}$$

where a_x is the spreading length of the lateral distribution and d is the implementation length, while ay_p is the tail width of the semi Gaussian depth distribution toward thin depth, and ay_m is the tail width of the semi Gaussian depth distribution toward the surface [15].

c) $LiNbo_3$ waveguides with step like erbium concentration profile:

Ion exchange is widely used in order to obtain doped waveguides in Lithium Niobate [16].

There are not published data about Er doping of $LiNbO_3$ by this method. So, it was decided to study the performance of Er in $LiNbO_3$ waveguides assuming a step like Er concentration profile, given by

$$C(x, y) = \begin{cases} \frac{C_0}{2}\left\{erf\left(\frac{x+w}{ax}\right) - erf\left(\frac{x+w}{ax}\right)\right\} 0 \le y \lhd d \\ \frac{C_0}{2} \exp\left[-\left(\frac{y-d}{ay}\right)^2\right]\left\{erf\left(\frac{x+w}{ax}\right) - erf\left(\frac{w+w}{ax}\right)\right\} d \lhd y \end{cases} \tag{23}$$

III- ANALYSIS and RESULTS

The following is the configuration which will be used in order to fit a waveguide into an available area. Configuration of this type with different number of coils is consisting of straight sections and curved sections of different radii [17].

One can get formulas connecting the amplifier length, L, with the chip area, S. The curvature radius is constant over the central–s shaped section and has there the minimal value R_{min}. Radii of other curved sections as shown in Fig. 2, radii of other curved sections increase with the coil number i , R_i= (i=1….n) .The waveguide length is described by [18]

$$L = 2.\left[\left(R_{min+n.\delta R}\right) + n.\sqrt{\left(2R_{min}\right)^2 + \left(\delta R\right)^2} + \pi\sum_{i=1}^{n} R_i + \frac{\pi}{2} R_{min}\right] \tag{24}$$

where The spacing between waveguide centres are δR. The value of S, a, b and L_{opt} are taken as in Table 1 at δR = 200 µm

$$R_i = R_{min} + \delta R.\,(i-1) \tag{25}$$

$$S = 4.\left[2R_{min} + \delta R.(n-1)\right].\left[R_{min} + \delta R.n\right] \tag{26}$$

Area (mm^2)	2a (mm)	2b (mm)	L_{opt} (cm)
20	4	5	5
60	5	6	25
100	10	10	40

Table 1 Waveguide dimensions table

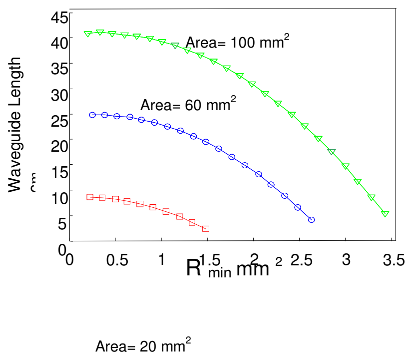

Fig.2. Waveguide length that can be arranged at a limited area as a function of minimal radius R_{min} for area values of 20, 60, 100, mm^2 and δR=200 μm.

I- Constant Concentration

The concentration in Eq. (15) is taken constant. To obtain the waveguide gain, we start with the wave function

$$\psi_s(x,y,z) = \sin\left(\frac{\pi x}{2a}\right)\sin\left(\frac{\pi y}{2b}\right)\sin\left(\frac{\pi z}{L}\right) = \psi_p(x,y,z). \quad (27)$$

The light intensity for pump and signal is obtained from Ref. [8], respectively, as

$$I_p(x,y,z) = p_p(0)\frac{\psi_s(x,y,z)}{\int_0^{2a}\int_0^{2b}\int_0^{L}\psi(x,y,z)dxdydz} \quad (28)$$

with the boundary condition: $P_p(0)=P_p^{in}=20$ mW.

$$I_s(x,y,z) = p_s(0)\frac{\psi_s(x,y,z)}{\int_0^{2a}\int_0^{2b}\int_0^{L}\psi(x,y,z)dxdydz} \quad (29)$$

with $P_s(0)=P_s^{in}=1$ μm

Both signal and pump light intensities are to substituted in the rate equations, that in turn be substituted in the local population equation to get the local population as

$$N(x,y,z)^3 + \left[\left(R(x,y,z)+W_a(x,y,z)+W_e(x,y,z)\right).\tau_0+1\right].\left(\frac{Q}{\rho}\right)^2 . N(x,y,z) - \left[R(x,y,z)+W_a(x,y,z)\right].\left(\frac{Q}{\rho}\right)^2 .\tau_0 = 0 \quad (30)$$

where $Q = 1.7\times10^{25}$ m^{-3}, τ_o=13.5 ms.

Based on [1], we consider:

$N(x, y, z) = N_2$ and $N'(x, y, z) = N_1$.

Therefore: $N_2 = \rho - N_1$

where, signal emission and absorption rates are, respectively, [6]

$$W_e \cong W_e(x,y,z) = \frac{\sigma_{se}.I_s(x,y,z)}{h\nu_s}, \quad (31)$$

where $\sigma_{se} = 6.05\times10^{-25}$ m^2 and $\nu_s = c/\lambda_s$ with λ_s =0.09 dB/cm [1].

$$W_a \cong W_a(x,y,z) = \frac{\sigma_{sa}.I_s(x,y,z)}{h\nu_p}, \quad (32)$$

where $\sigma_{sa} = 6.05\times10^{-2}$ m^2 and $\nu_p = c/\lambda_p$ with $\lambda_p = 0.08$ dB/cm [1].

and the pump emission and absorption rates are, respectively, [6]

$$R_a \cong R_a(x,y,z) = \frac{\sigma_{pa}.I_p(x,y,z)}{h.\nu_p}, \quad (33)$$

where $\sigma_{pa} = 2\times10^{-25}$ m^2 [1].

$$R_e \cong R_e(x,y,z) = \frac{\sigma_{pe}.I_p(x,y,z)}{h.\nu_p}, \quad (34)$$

with $\sigma_{pe} = 0.2\times10^{-24}$ m^2 [1].

Using the obtained population, one can get EDWA gain

Gain= $P_{s\ output} / P_{s\ input}$,

where the input and output signal powers can be obtained from [1]

$$\frac{dP_s(z)}{dz} = \left[\iint_{S_{core}}\left(\sigma_{se}(\nu_s)N(x,y,z) - \sigma_{sa}(\nu_s)N'(x,y,z)\right)\psi_s(x,y)ds\right]P_s(z) \quad (35)$$

Gain as a function of waveguide length for constant Er concentration is displayed in Fig. 3.

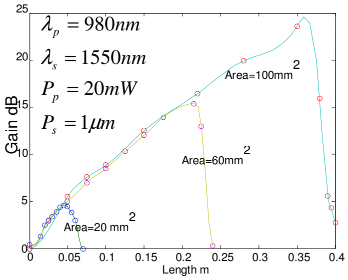

Fig. 3 Over all gain of limited area spiral EDWA as a function of waveguide length. S =20, 60 and 100 mm^2.for constant Er concentration method.

In Fig. 3, each curve represents a number of spirals with growing number of coils. In the curve where area is equal to 20 mm^2, one can see that the gain is relatively high as it has a small number of coils.

It is shown that as the length L increase the gain increases till it reaches the L_{opt} of 0.04 m, where the gain reaches its maximum of 4.5 dB. If the length exceeds 0.04 m, the gain will start to decrease more rapidly. It can be noticed that the gain difference between the different curves can reach 10 dB, which is considerably high.

II-Diffusion Method:

The described procedure is repeated and the concentration, in this case, has the form

$$C(x,y) = \frac{C_0}{2}\exp\left[-\left(\frac{y}{dy}\right)^2\right] * \left\{erf\left(\frac{x+w}{dx}\right) - erf\left(\frac{x-w}{dx}\right)\right\} \tag{36}$$

where $C_0 = 1.8\times10^{20}$ at/cm^3, dy = 8 µm, w = 0.1 µm and $d_x/d_y = 0.75$.

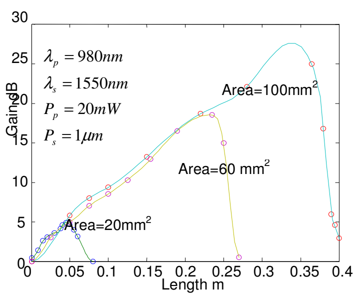

Fig. 4 Over all gain of limited area spiral EDWA as a function of waveguide length. S = 20, 60,100 mm^2 for diffusion method.

In Fig. 4, the maximal gain increases till it reaches its maximum value, where it starts to decline and decrease mor5e rapid;y when the length exceeds an optimum value, L_{opt} (e.g. L_{opt} = 0.27 m for an area of 60 mm^2). The highest gain difference is between the two curves of area 20 and 60 mm2 the gain difference is 13 dB which is considerably high.

III- Ion Implantation Method

The described procedure is repeated and the concentration, in this case, has the form

$$C(x,y) = \begin{cases} \frac{C_0}{2}\exp\left[-\left[\frac{y-d}{\alpha y_m}\right]^2\right]\left\{erf\left(\frac{x+w}{ax}\right) - erf\left(\frac{x+w}{ax}\right)\right\} 0 \lhd y \lhd d \\ \frac{C_0}{2}\exp\left[-\left[\frac{y-d}{\alpha y_p}\right]^2\right]\left\{erf\left(\frac{x+w}{ax}\right) - erf\left(\frac{x+w}{ax}\right)\right\} d \lhd y \end{cases} \tag{37}$$

where $C_o = 1.8\times10^{20}$ at/cm^3,d= 6µm,w=4 µm, a_x= 0.5 µm,a_{yp}= 0.3×6 µm and a_{ym}= 0.6×6 µm.

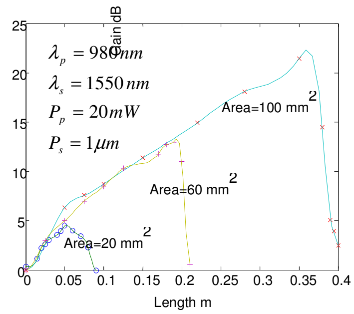

Fig. 5 Gain as a function of amplifier length ion implantation method.

Figure 5 shows that maximum gains of 4.5, 13 and 22 dB are obtained at the areas indicated. The corresponding values of the optimum length are, respectively, 0.05, 0.19 and 0.36 m. For the 60 mm^2 area the optimum length is the shortest compared to the other used methods increasing this length will lead to very rapid decrease in the gain which acts more like a perpendicular line than a curve.

IV- Step-Like Method

The described procedure is repeated and the concentration, in this case, has the form

$$C(x,y) = \begin{cases} \frac{C_0}{2}\left\{erf\left(\frac{x+w}{ax}\right) - erf\left(\frac{x+w}{ax}\right)\right\} 0 \le y \lhd d \\ \frac{C_0}{2}\exp\left[-\left(\frac{y-d}{ay}\right)^2\right]\left\{erf\left(\frac{x+w}{ax}\right) - erf\left(\frac{w+w}{ax}\right)\right\} d \lhd y \end{cases} \tag{38}$$

where $C_o = 1.8\times10^{20}$ at/cm^3, $a_x = a_y$= 0.5µm, w = 4 µm and d= 5 µm.

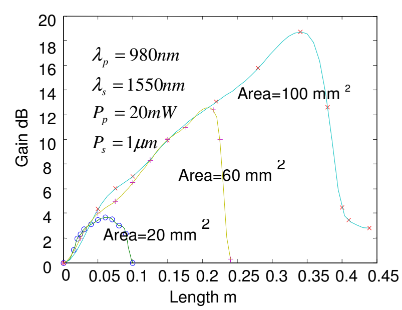

Fig. 6 Overall gain step-like concentration method.

In Fig. 6, the same behaviour is obtained with optimum lengths of 0.06, 0.21 and 0.34 m at maximum gain values of 3.5, 12.5 and 19 dB for areas 20, 60 and ,100 mm^2, respectively .

Amplifier Bandwidth

The amplifier bandwidth can be obtained through the study of the gain with the signal wavelength. A sample of results is displayed in Fig. 7, for the diffusion method.

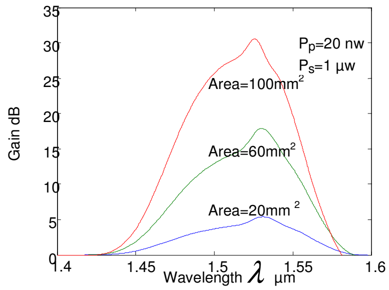

Fig. 7 Gain as a function of wavelength for Er concentration diffusion method

As expected, maximum gain wavelength is 1.53 µm. The bandwidth is easily 0.08, 0.022 and 0.03 µm, respectively, for 100, 60 and 20 mm^2. Therefore, the 100 mm^2 area is the best choice for the highest gain and broad bandwidth.

The same procedure is repeated for other concentration methods and a summary of the obtained results are given in Tables 2-4, where

A: Constant concentration method.

B: Diffusion method.

C: Ion implementation.

D: Step-like method.

Area	20 mm^2			
Methods used	A	B	C	D
G_{max} dB	2.55	5.5	4.52	4.9
λ_{max} µm	1.53	1.525	1.53	1.525
BW µm	___	0.08	0.095	0.09

Table 2 Bandwidth for different Erbium concentration methods for area 20 mm^2

Area	60 mm^2			
Methods used	A	B	C	D
G_{max} dB	15.5	18	12.5	12.5
λ_{max} µm	1.522	1.53	1.522	1.51
BW µm	0.035	0.022	0.05	0.05

Table 3 Bandwidth for different Erbium concentration methods for area 60 mm^2

Area	100 mm^2			
Methods Used	A	B	C	D
G_{max} dB	36	31	23	19
λ_{max} µm	1.521	1.53	1.53	1.5
BW µm	0.022	0.03	0.045	0.04

Table 4 Bandwidth for different Erbium concentration methods for area 60 mm^2

As for the other used methods, it is clear that for constant concentration for 20 mm^2 area, there is hardly any amplification and therefore, there is no bandwidth.

Gain as a function of EDWA length for different methods is illustrated in Figs. 8 and 9 at pumping powers 20 and 60 mW, respectively. A maximum gain is noticed with the broadest bandwidth diffusion method. This ensures the suitability of using this method for Er concentration.

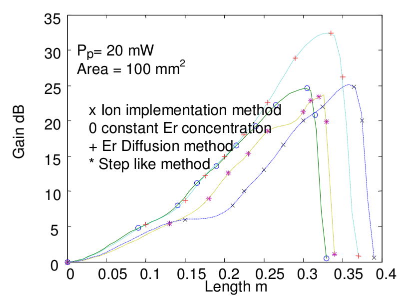

Fig. 8 Gain as a function of EDWA length at an area = 100 mm^2 and a pump power = 20 mW.

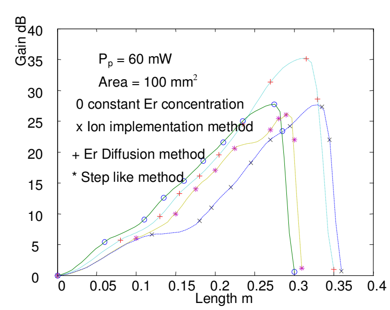

Fig. 9 Gain as a function of EDWA length at an area = 100 mm^2 and a pump power = 60 mW.

It was noticed that, for the four methods used, the gain increases with the pump power and the EDWA optimum length decreases. This exactly is also obtained at an area of 20 mm^2. Repeating at an area of 60 mm^2, in the ion implantation method, the gain is obtained the same when the pump power is increased, while the EDWA optimum length increases. In the step-like method, both gain and EDWA optimum length decrease. In the constant Er concentration method, gain increases and the length remains the same when pump power increases. Therefore, one can get the maximum gain and optimum length by increasing the pump power to 40 mw for 100 mm^2 area of the waveguide applied to the diffused method.

EDWA optimum length as a function of area

The EDWA optimum length, L_{opt}, is investigated with the area for the different concentration methods. The obtained results are shown in Fig. 10.

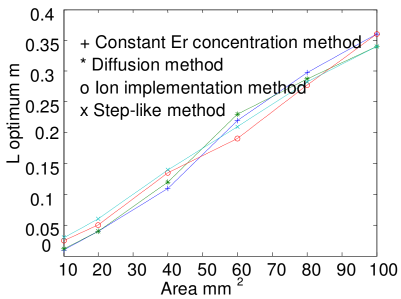

Fig. 10 EDWA optimum length as a function of area for different Er concentration methods

It is clear that, the length increases with area for area 20 mm^2 and the step-like method has the highest optimum length while the constant Er concentration and the diffusion method are alike. For the 60 mm^2, the diffusion method has the highest length and the ion implantation method has the least length. But, at 100 mm^2, both constant Er concentration and ion implantation are the highest with the same length while the other two are the lowest with the same length. A summary of the obtained optimum EDWA length is given in Table 5.

	L_{opt} m					
Area mm^2	10	20	40	60	80	100
A	0.01	0.04	0.01	0.22	0.29	0.36
B	0.01	0.04	0.01	0.23	0.28	0.34
C	0.02	0.05	0.13	0.19	0.28	0.36
D	0.03	0.06	0.14	0.21	0.29	0.34

A Constant Er concentration method
B Diffusion method
C Ion implementation
D Step-like method
Table 5 Optimum EDWA length for different Erbium concentration methods

EDWA gain as a function of area

The EDWA gain is studied with the area for the different concentration methods. The obtained results are shown in Fig. 11.

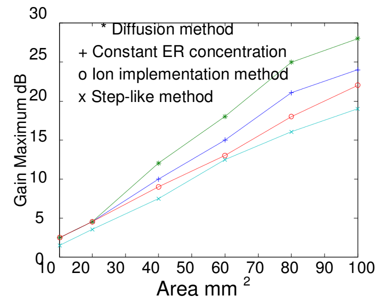

Fig. 11 Maximum EDWA gain versus area for different concentration methods.

In Fig. 11, it is obvious that, the maximum gain increases with area, in general. The main differences between different concentration methods are summarized in Table 6.

	G_{max} dB					
Area mm^2	10	20	40	60	80	100
A	2.5	4.5	10	15	20	24
B	2.5	4.5	12	18	25	28
C	2.5	4.5	9d	13	18	22
D	1.5	3.5	7.5	12.5	16	19

A Constant Er concentration method
B Diffusion method
C Ion implementation
D Step-like method
Table 6 Maximum EDWA gain for different Er concentration methods

The maximum gain and optimum EDWA length for the diffusion method are is studied with the waveguide parameters w, dx and dy. The obtained results are displayed in Figs. 12-14.

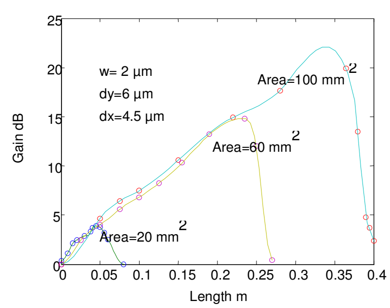

Fig. 12 EDWA gain as a function of length for Er diffusion method w = 2 µm, dx = 4.5 µm and dy = 6 µm.

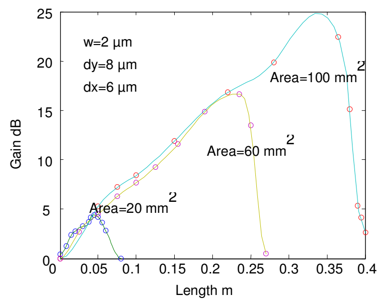

Fig. 13 EDWA gain as a function of length for Er diffusion method w = 2 µm, dx = 6 µm and dy = 8 µm.

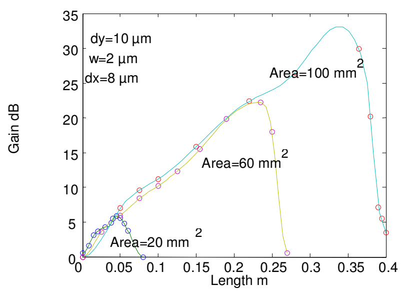

Fig. 14 EDWA gain as a function of length for Er diffusion method w = 2 µm, dx = 8 µm and dy = 10 µm.

The procedure is repeated at different values of the diffusion length, w. The obtained results are given in Tables 7 and 8 for the diffusion method, in Tables 9 and 10 for the step-like method, and in Tables 11 and 12 for the ion implantation method.

D	L_{opt} µm	W=2 µm		
		A	B	C
		G_{max}	G_{max}	G_{max}
20	0.04	3.88	4.376	5.834
60	0.23	14.81	16.65	22.2
100	0.34	22.06	24.5	33.09

A dy=6 µm dx=4.5 µm
B dy= 8 µm dx=6 µm
C dy=10 µm dx=8 µm
D Area mm^2
Table 7 EDWA gain at different areas at w = 2 µm, for the diffusion method.

D	L_{opt} µm	W=4 µm		
		A	B	C
		G_{max}	G_{max}	G_{max}
20	0.04	3.403	5.348	6.32
60	0.23	12.90	20.35	24.05
100	0.34	19.3	30.33	35.84

A dy=6 µm dx=4.5 µm
B dy= 8 µm dx=6 µm
C dy=10µm dx=8 µm
D Area mm^2
Table 8 EDWA gain at different areas at w = 4 µm, for the diffusion method.

D	L_{opt} µm	W=3 µm		
		A	B	C
		G_{max}	G_{max}	G_{max}
20	0.06	3.293	3.842	4.135
60	0.22	11.29	13.18	14.18
100	0.345	16.85	19.65	21.15

A d=4 µm
B d=6 µm
C d=7 µm
D Area mm^2
Table 9 EDWA gain at different areas at w = 3 µm, for the step-like method.

D	L_{opt} µm	W=5 µm		
		A	B	C
		G_{max}	G_{max}	G_{max}
20	0.06	3.842	4.244	4.427
60	0.22	13.18	14.56	15.18
100	0.345	19.65	21.71	22.65

A d=22 µm
B d=23 µm
C d=24 µm
D Area mm^2
Table 10 EDWA gain at different areas at w = 5 µm, for the step-like method.

D	L_{opt} µm	W=6 µm		
		A	B	C
		G_{max}	G_{max}	G_{max}
20	0.05	3.867	4.095	5.005
60	0.22	11.31	11.98	14.64
100	0.36	18.98	20.1	24.56

A d=3 µm
B d=4 µm
C d=5 µm
D Area mm^2
Table 11 EDWA gain at different areas at w = 6 µm, for the ion implantation method.

D	L_{opt} µm	W= 8 µm		
		A	B	C
		G_{max}	G_{max}	G_{max}
20	0.05	5.232	5.40	5.551
60	0.22	15.3	15.96	16.24
100	0.36	25.68	26.8	27.24

A d=3 µm
B d=4 µm
C d=5 µm
D Area mm^2
Table 12 EDWA gain at different areas at w = 8 µm, for the ion implantation method.

IV- CONCLUSION

The EDWA gain is studied at different affecting parameters for different erbium concentration methods. For a chip area 60 and 100 mm^2, the maximum gain of 18 and 28 dB respectively is reached which is the highest of all methods used.

Among different methods, the step-like method has the least performance: lowest gain and maximum optimum EDWA length. As expected, wavelength corresponding to maximum gain is 1.53 µm. The best (maximum) bandwidth is obtained using the diffusion method with values: 0.08, 0.022 and 0.03 µm, respectively, for 100, 60 and 20 mm^2. Therefore, the 100 mm^2 area is the best choice for the highest gain and broad bandwidth. At the same time, a maximum gain is also obtained using the diffusion method. This ensures the suitability of using this method for Er concentration. The maximum gain and optimum length obtained at a pump power to 40 mw for 100 mm^2 area of the waveguide.

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