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The Effect of Erbium and Ytterbium Concentration on the Gain of the Er/Yb Co-Doped Waveguide Amplifiers

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ABSTRACT

This paper presents an analytical method for the dependence of the gain characteristics of the phosphate glass erbium-ytterbium (Er^{3+}-Yb^{3+}) co-doped waveguide amplifier (EYCDWA) on the concentration of both erbium and ytterbium, using a new fitting for the absorption and emission of the dopants on phosphate glass. The calculation are made from the rate equations and the light propagation equations and the steady-state condition, we have neglected the amplified spontaneous emission (ASE) and have introduced the initial energy transfer efficiency. The gain shows strong dependence on the concentration of both do-pants erbium and ytterbium and a different behavior with the ratio of each other.

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INTRODUCTION

Guided-wave amplifiers using Er_/Yb glass are now leading candidates for high-power applications such as common antenna television. (Maln *et al*., 2005), free-space communications, long wavelength L-band amplifiers, short-active-length integrated amplifiers (J. Nilsson *et al*., 2003), and super-fluorescent sources. While the first Er-Yb fiber amplifiers were pumped in the core at a wavelength of 1.06 µm, more recently, cladding pumping in the 920 to 980 nm absorption band of Yb has been used (Strohhofer C and Polman, 2001). Also erbium-ytterbium (Er^{3+}/Yb^{3+}) doped fiber lasers and amplifiers show a growing potential for many applications in different areas such as industry, medicine, communication, military and research. Cladding pumped fiber lasers based on Er^{3+}/Yb^{3+} doped silicate glass are an attractive technology for compact and efficient sources in the eye-safe spectral range (Jin GL *et al*., 2005), for both high power continuous wave (CW), as well as high repetition rate and high energy short pulse generation. The erbium doped waveguide amplifiers have recently attracted a great deal of attention because of the plausibility of introducing various active elements in integrated optical circuits. These integrated optics devices require a higher concentration of erbium ions than long fibers for comparable. However, high erbium concentration will increase the number of the erbium clusters, and hence reduce the spacing between the erbium ions. In this case the overlapping between the electrons clouds of erbium ions, increasing the excited state absorption (ESA). Therefore, the clustering enhances the ESA (Zhang XZ *et al*., 2006). The clustering greatly reduces the pump efficiency and degrades the gain performance. Fortunately, the rare-earth element ytterbium, exhibits a better overlapping between the Yb^{3+} emission spectrum and the Er^{3+} absorption spectrum and an intense broad absorption in the wavelength range from 800 to 1080 nm, and has a weak clustering effect and a large absorption cross-section compared to erbium, by which high ytterbium ion (Yb^{3+}) dopant level can realized in the waveguide (Shooshtari A *et al*., 1998, Yu-Hai Wang *et al*., 2009). This can noticeably reduce the quenching side-effect caused by high Er^{3+} dopant concentration (O. Mahran *et al*., 2014, Grubb SG *et al*., 1992), so the erbium-ytterbium (Er^{3+} - Yb^{3+}) co-dopant can efficiently improve the gain characteristics of the waveguide amplifiers (Jiang C and Zeng QJ, 2004).

We choose the phosphate glass Er^{3+} - Yb^{3+} - co-doped waveguide amplifier (EYCDWA) because has attracted much attention and nowadays plays an important role in optoelectronic integrated circuits (OEICs) ([De-Long Zhang *et al*., 2005, Husein AHM at al., 2011). In this paper, this paper presents an analytical method for the dependence of the gain characteristics of the phosphate glass erbium-

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ytterbium (Er3+-Yb3+) co-doped waveguide amplifier (EYCDWA) on the concentration of both erbium and ytterbium, using a new fitting for the absorption and emission of the dopants on phosphate glass. The calculation are made from the rate equations and the light propagation equations and the steady-state condition, we have neglected the amplified spontaneous emission (ASE) and have introduced the initial energy transfer efficiency. The gain shows different behavior with the concentration of both erbium and ytterbium and with the ratio of each other.

Theory:

1. Er/Yb cross sections:

The absorption cross section of both erbium and ytterbium was obtained from Refs. (B.C. Hwang *et al*., 2000 , S. Honkanen *et al*., 1997) The new fitted absorption cross section of ytterbium as performed by us is given as

$$\sigma_a^{Yb}(\lambda) = 0.083f(\lambda,900,7.4,3) + 0.1f(\lambda,980,50,2.22) + 0.4f(\lambda,988,40,2.24) + 2.1f(\lambda,990,30,5) \quad (1)$$

where f is a generalized line shape function depending on wavelength λ, a center wavelength, λ_c , a width λ_w (all in nanometers) and an index n, and defined by

$$f(\lambda,\lambda_c,\lambda_w,n) = e^{-\left|\frac{\lambda-\lambda_c}{\lambda_w}\right|^n} \quad (2)$$

and the new fitted absorption cross section of ytterbium as performed by us is given as

$$\sigma_a^{Er}(\lambda) = 0.21f(\lambda,1420,18.4,2) + 0.44f(\lambda,1490,12,2.22) + 0.12f(\lambda,1513,4,1) + 0.66f(\lambda,1540,23,5) + 0.33f(\lambda,1550,4,0.5) \quad (3)$$

The emission profile of both is given by McCumber equation (E. Desurvire, 1994)

$$\sigma_e^{Yb,Er}(\lambda) = \sigma_a^{Yb,Er}(\lambda).\exp\left[\frac{hc(\frac{1}{\lambda_0}-\frac{1}{\lambda})}{KT}\right] \quad (4)$$

Where the emission profile for Yb is given by eq.4 with λ_o = 975nm and for the Er with λ_o = 1535 nm

2. Rate and light propagation equations:

Supposing N_1, N_2 and N_3 are the Er^{3+} ion concentrations on the $^4I_{15/2}$, $^4I_{13/2}$ and $^4I_{11/2}$ levels, respectively; N_{Er} is the total Er^{3+} ion concentration; N_4 and N_5 are the Yb^{3+} ion concentrations on the $^2F_{7/2}$ and $^2F_{5/2}$ levels, respectively; N_{Yb} is the total Yb^{3+} ion concentration (Shufeng LI *et al*., 2008). Under the conditions of the uniform dopant and the steady-state, the Er^{3+} ion and Yb^{3+} ion on the corresponding levels depend on the amplifier length z, i.e., $N_i = N_i(z)$. Therefore, the multilevel rate equations for the Er^{3+}-Yb^{3+} co-doped system are given by (Lu ZG *et al*., 2004, Berkdemir C and Özsoy, 2008).

$$\frac{dN_1}{dt} = -W_{12}N_1 - W_{13}N_1 + A_{21}N_2 + W_{21}N_2 + C_{up}N_2^2 + C_{up}N_3^2 - C_{cr}N_1N_5 \quad (5)$$

$$\frac{dN_2}{dt} = W_{12}N_1 - A_{21}N_2 - W_{21}N_2 + A_{32}N_3 - 2C_{up}N_2^2 \quad (6)$$

$$\frac{dN_3}{dt} = W_{13}N_1 - A_{32}N_3 - 2C_{up}N_3^2 + C_{cr}N_1N_5 \quad (7)$$

$$N_1 + N_2 + N_3 = N_{Er} \quad (8)$$

$$\frac{dN_4}{dt} = -W_{45}N_4 + A_{54}N_5 + W_{54}N_5 + C_{cr}N_1N_5 \quad (9)$$

$$\frac{dN_5}{dt} = W_{45}N_4 - A_{54}N_5 - W_{54}N_5 - C_{cr}N_1N_5 \quad (10)$$

$$N_4 + N_5 = N_{Yb} \quad (11)$$

Where $A_{ij} = 1/\tau_{ij}$, τ_{ij} is the lifetime between levels i and j, C_{up} is the cooperative up-conversion coefficients, C_{cr} is the Yb^{3+} to Er^{3+} cross-relaxation coefficients. W_{12}, W_{21} are the signal absorption and emission rates of erbium respectively.W_{45}, W_{54} are the pump absorption and emission rates of ytterbium respectively.W_{13} is the pump absorption rate of erbium. The stimulated emission and absorption transition rates of signal and pump wavelength, are given by

$$W_{12} = \frac{\sigma_{12}\Gamma_s P_s}{A_c h\nu_s} \quad W_{21} = \frac{\sigma_{21}\Gamma_s P_s}{A_c h\nu_s} \quad W_{13} = \frac{\sigma_{13}\Gamma_p P_p}{A_c h\nu_p} \quad W_{45} = \frac{\sigma_{45}\Gamma_p P_p}{A_c h\nu_p} \quad W_{54} = \frac{\sigma_{54}\Gamma_p P_p}{A_c h\nu_p} \quad (12)$$

Where Γ_p and Γ_s are the overlapping factors of the pump and the signal light, respectively, A_c is the area of the cross-section of the amplifier, $\sigma_{12}(\nu_s)$ and $\sigma_{21}(\nu_s)$ are the signal absorption and emission cross-section respectively, $\sigma_{13}(\nu_p)$ is the pump absorption cross-section, $\sigma_{45}(\nu_p)$ and $\sigma_{54}(\nu_p)$ are the pump absorption and emission cross-section, respectively, h is Planck's constant.

Letting P_p and P_s be the pump and signal powers in the steady state, respectively, along the EYDFA are described by the power propagation equations which are given by the following equations.

$$\frac{dP_p(z)}{dz} = -\Gamma_p[\,\sigma_{13}(\nu_p)N_1(z) + \sigma_{45}(\nu_p)N_4(z) - \sigma_{54}(\nu_p)N_5(z)\,]P_p(z) \quad (13)$$

$$\frac{dP_s(z)}{dz} = \Gamma_s[\,\sigma_{21}(\nu_s)N_2(z) - \sigma_{12}(\nu_s)N_1(z)\,]P_s(z) \quad (14)$$

Australian Journal of Basic and Applied Sciences, 9(11) May 2015, Pages: 84-92

3. Analytical Solutions to the Rate Equations:

The multilevel rate equations (Eqs.(5)-(11)) for the EYCDFA system is obtained under steady-state conditions, i.e., $dN_i/dt=0$ and are simplified to

$$\frac{\sigma_{12}(\nu_s)P_s(z)\Gamma_s N_1(z)}{A_c h\nu_s} + \frac{\sigma_{13}(\nu_p)P_p(z)\Gamma_p N_1(z)}{A_c h\nu_p} - \frac{\sigma_{21}(\nu_s)P_s(z)\Gamma_s N_2(z)}{A_c h\nu_s} - \frac{N_2(z)}{t_{21}} + \frac{\sigma_{45}(\nu_p)P_p(z)\Gamma_p N_4(z)}{A_c h\nu_p} - \frac{\sigma_{54}(\nu_p)P_p(z)\Gamma_p N_5(z)}{A_c h\nu_p} - \frac{N_5(z)}{t_{54}} = 0 \quad (15)$$

3.1 Signal gain:

From Equations (8), (11), (13), (14) and (15) we obtain

$$\frac{1}{A_c h\nu_p}\frac{dP_p(z)}{dz} + \frac{1}{A_c h\nu_s}\frac{dP_s(z)}{dz} + \frac{N_2(z)}{t_{21}} + \frac{N_5(z)}{t_{54}} = 0 \quad (16)$$

By defining $\eta_0 = N_2/(N_2+N_5)$ as the initial energy transfer efficiency (Shufeng LI *et al*., 2008), that is, $N_5 = ((1-\eta_0)/\eta_0)N_2$, and letting $B = (\tau_{21}\,\tau_{54})/(\tau_{54}+\tau_{21}(1-\eta_0)/\eta_0)$, Eq.(16) can be rewritten as

$$N_2(z) = -B\frac{1}{A_c h\nu_p}\frac{dP_p(z)}{dz} - B\frac{1}{A_c h\nu_s}\frac{dP_s(z)}{dz} \quad (17)$$

Setting $S = \int_0^z N_2(z)dz$, and then integrating Eqs. (13), (14) and (17), we get

$$S = \frac{\frac{1}{\Gamma_p}\ln\frac{P_p(z)}{P_p(0)} + \sigma_{13}N_{Er}z + \sigma_{45}N_{Yb}z}{\sigma_{13}+(1-\eta_0/\eta_0)(\sigma_{45}+\sigma_{54})} \quad (18)$$

$$S = \frac{\frac{1}{\Gamma_s}\ln\frac{P_s(z)}{P_s(0)} + \sigma_{12}N_{Er}z}{(\sigma_{12}+\sigma_{21})} \quad (19)$$

$$S = -B\frac{1}{A_c h\nu_p}[P_p(z)-P_p(0)] - B\frac{1}{A_c h\nu_s}[P_s(z)-P_s(0)] \quad (20)$$

From Equations (18) and (19), we get

$$P_p(z) = P_p(0)\left[\frac{P_s(z)}{P_s(0)}\right]^{\alpha} \times \exp\left[\alpha\Gamma_s\sigma_{12}N_{Er}z - \Gamma_p z(\sigma_{13}N_{Er}+\sigma_{45}N_{Yb})\right] \quad (21)$$

Where

$$\alpha = \frac{\Gamma_p\sigma_{13}+\Gamma_p(\sigma_{45}+\sigma_{54})(1-\eta_0)/\eta_0}{\Gamma_s(\sigma_{12}+\sigma_{21})} \quad (22)$$

Manipulating Eqs. (19), (20) and (21), we can arrive at the following equation

$$\left[\frac{P_p(z)}{P_p(0)}\right]^{\frac{1}{\alpha}}\exp[\Gamma_s\sigma N_{Er}z] = 1 - \frac{\nu_s P_p(0)}{\nu_p P_s(0)}\left[\frac{P_p(z)}{P_p(0)}-1\right] - \frac{\ln[P_p(z)/P_p(0)]+\alpha\Gamma_s N_{Er}z(\sigma+\sigma_{12})}{\alpha B\Gamma_s(\sigma_{12}+\sigma_{21})}\frac{A_c h\nu_s}{P_s(0)} \quad (23)$$

$$[G(z)]^{\alpha}\exp[-\alpha\Gamma_s\sigma N_{Er}z] = 1 - \frac{\nu_p P_s(0)[G(z)-1]}{\nu_s P_p(0)} - \frac{\ln G(z)+\Gamma_s\sigma_{12}N_{Er}z}{B\Gamma_s(\sigma_{12}+\sigma_{21})}\frac{A_c h\nu_p}{P_p(0)} \quad (24)$$

With $G(z) = P_s(z)/P_s(0)$

$$\sigma = \frac{\sigma_{12}+\sigma_{21}}{\sigma_{13}+\frac{(\sigma_{45}+\sigma_{54})(1-\eta_0)}{\eta_0}} \times \left(\sigma_{13}+\sigma_{45}\frac{N_{Yb}}{N_{Er}}\right) - \sigma_{12} \quad (25)$$

Where G(z) is the gain of the amplifier.

RESULTS AND DISCUSSION

Table 1: Summarizes the parameters of the Er_Yb.

Parameter	Symbol	Value	Unit
Pump wavelength	λ_p	980	nm
Signal wavelength	λ_s	1550	nm
Er concentration	N_{Er}	1.0×10^{26}	m^{-3}
Yb concentration	N_{Yb}	2.0×10^{27}	m^{-3}
Er^{3+} absorption cross-section	σ_{13}	2.58×10^{-25}	m^2
Yb^{3+} absorption cross-section	σ_{45}	1.0×10^{-24}	m^2
Yb^{3+} emission cross-section	σ_{54}	1.0×10^{-24}	m^2
Er^{3+} absorption cross-section	σ_{12}	6.5×10^{-25}	m^2
Er^{3+} emission cross-section	σ_{21}	9.0×10^{-25}	m^2
Er^{3+} emission lifetime	τ_{21}	10	ms
Yb^{3+} emission lifetime	τ_{54}	2	ms
Initial energy transfer efficiency	η_0	0.115	-
Core refractive index	n_1	1.52812	-
Cladding refractive index	n_2	1.51	-
Amplifier cross-section	A_c	16	μm^2
Pump overlap factor	Γ_p	0.921	-
Signal overlap factor	Γ_s	0.795	-

Australian Journal of Basic and Applied Sciences, 9(11) May 2015, Pages: 84-92

Effect of the ratio of Er^{3+}-Yb^{3+} concentration on gain:

Figure 1 shows the curves of the gain G versus the Yb^{3+}/Er^{3+} ion concentration ratio N_{Yb}/N_{Er}, where we take the signal power P_{s0} = 1 μW, pump power P_{p0} = 50 mW, Er^{3+} ion concentration $N_{Er} = 0.5\times10^{26}$, m^{-3} , and length z = 2, 3,4 cm.

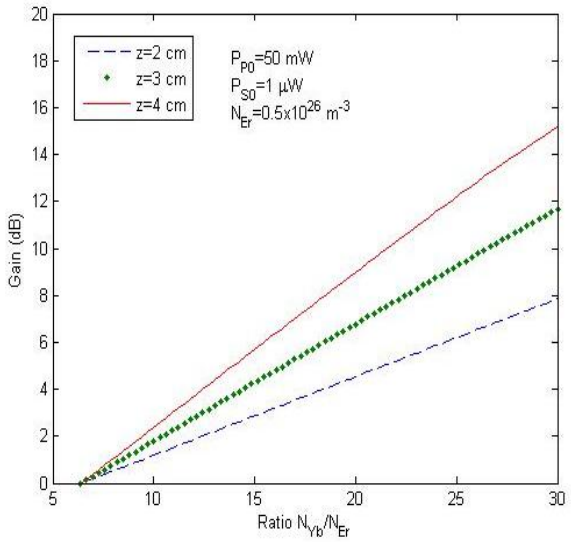

Fig. 1: Curve of gain G versus Yb^{3+}/Er^{3+} ion concentration ratio N_{Yb}/N_{Er} at $N_{Er}=0.5\times10^{26}$ m^{-3}

We can see that the gain is negative when the ratio $N_{Yb}/N_{Er} < 6.5$. In this case, the negative gain is due to the small ratio N_{Yb}/N_{Er}, Yb^{3+} ions absorb the pump energy insufficiently, Er^{3+} ion clusters may occur, which leads to concentration quenching, so the energy transfer from Yb^{3+} ions to Er^{3+} ions is not very efficient. Beyond this value of the ratio N_{Yb}/N_{Er}, the gain becomes positive; the gain increases nearly linearly, and then becomes saturate with further increasing of the ratio N_{Yb}/N_{Er}.

Figures 2, 3 and 4 show the curves of the gain G versus the Yb^{3+}/Er^{3+} ion concentration ratio N_{Yb}/N_{Er}, where we take the signal power P_{s0} = 1 μW, pump power P_{p0} = 50 mW, Er^{3+} ion concentration $N_{Er} = 1.0\times10^{26}$, 1.5×10^{26} and 2.0×10^{26} m^{-3} , and length z = 2, 3,4 cm.

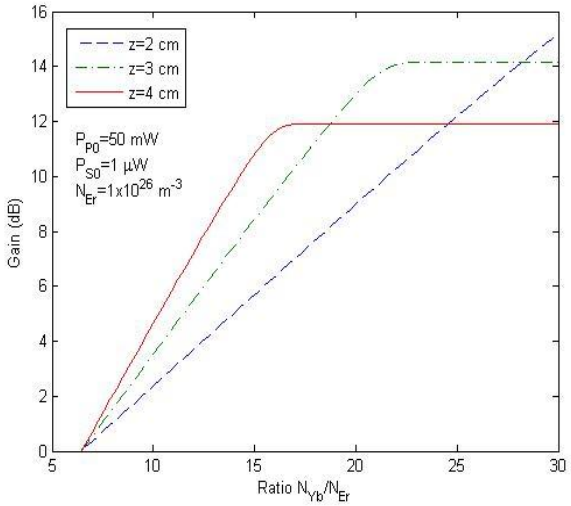

Fig. 2: Curve of gain G versus Yb^{3+}/Er^{3+} ion concentration ratio N_{Yb}/N_{Er} at $N_{Er}=1.0\times10^{26}$ m^{-3}

We can see from the figures that the larger the Er^{3+} ion concentration, the faster the saturate gain is reached. The reason of the gain saturation is that, for a certain Er^{3+} ion concentration, when the ratio N_{Yb}/N_{Er} increases to a certain value, these Er^{3+} ions have all realized population reversion, therefore, the gain becomes constant, the gain saturation appears, and further increasing of the ratio N_{Yb}/N_{Er} no longer affects the gain characteristics.

Therefore, it is important to select an appropriate ratio N_{Yb}/N_{Eb}. There is a definite optimal ratio N_{Yb}/N_{Er} for a certain length and a certain Er^{3+} ion concentration. For example, in the case of the length z = 3 cm, pump power P_{P0} = 50 mW, and signal power P_{S0} = 1 μW: when Er^{3+} ion concentration is 1.0×10^{26} m^{-3}, the optimal ratio N_{Yb}/N_{Er} is about 23.33 and the corresponding gain is about 14.16 dB; while Er^{3+} ion concentration is 1.5×10^{26} m^{-3}, the optimal

ratio N_{Yb}/N_{Er} is about 15.45 and the corresponding gain is about 10.79 dB; while Er^{3+} ion concentration is 2.0×10^{26} m^{-3}, the optimal ratio N_{Yb}/N_{Er} is about 11.82 and the corresponding gain is about 7.42 dB.

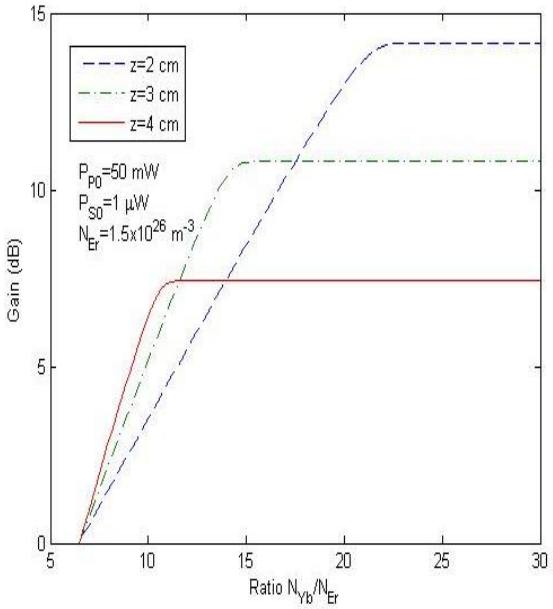

Fig. 3: Curve of gain G versus Yb^{3+}/Er^{3+} ion concentration ratio N_{Yb}/N_{Er} at $N_{Er}=1.5\times10^{26}$ m^{-3}

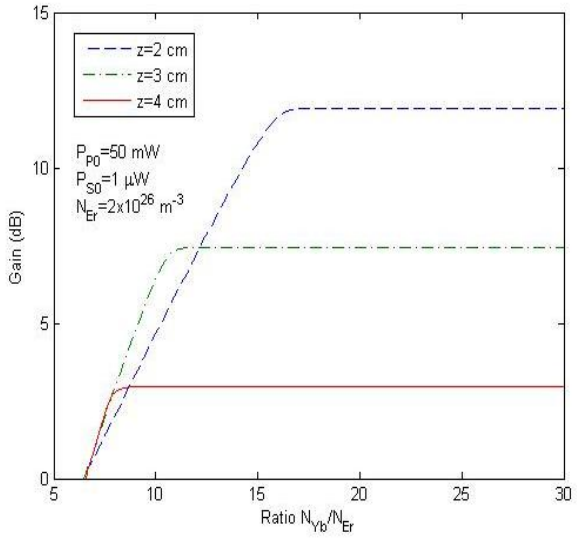

Fig. 4: Curve of gain G versus Yb^{3+}/Er^{3+} ion concentration ratio N_{Yb}/N_{Er} at $N_{Er}=2.0\times10^{26}$ m^{-3}

Effects of the Erbium concentration on gain:

Figures 5, 6, 7 and 8 show the signal gain as a function of Er^{3+} concentration for EYCDFAs, where we take the signal power P_{s0} = 1 μW, pump power P_{p0} = 50 mW, Yb^{3+} ion concentration N_{Yb} = 15×10^{26}, 20×10^{26}, 25×10^{26} m^{-3} and 30×10^{26} m^{-3} and for different amplifier length z = 2, 3,4 cm.

From all these figures we can see that the gain of the amplifier increases as the erbium ion concentration reaches the peak value (11, 13.42, 14.88, 15.85 dB) near ($1.42x10^{26}$, $1.09x10^{26}$, $8.78x10^{25}$, $7.27x10^{25}$) at amplifier length 3 cm, respectively and then decreases as the concentration further increases and the increase in the gain due to increasing ytterbium concentration.

For different amplifier lengths, it is shown that the gain increase and reaches the peak value and reduces beyond the concentration and as the amplifier lengths increase the erbium ion concentrations decrease and the result is agree with.

Effects of the ytterbium concentration on gain:

Figure 9 shows the dependence of gain on ytterbium ion concentration and amplifier length. Erbium ion concentrations are $0.5x10^{26}$,pump power is 50 mW and signal power P_{s0} = 1 μW.

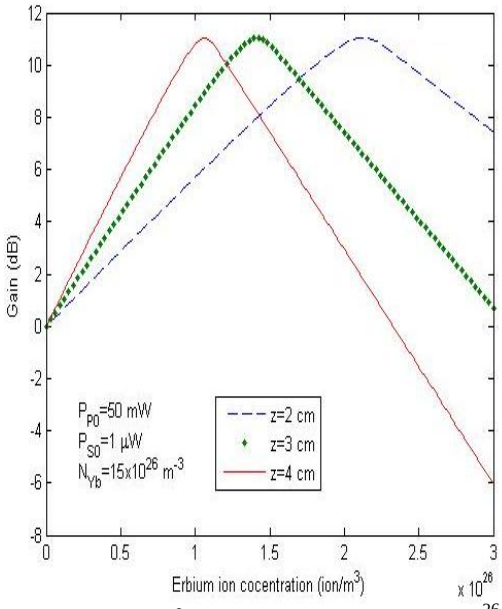

Fig. 5: Signal gain versus erbium concentration for EYCDFAs at $N_{Yb}=15x10^{26}$

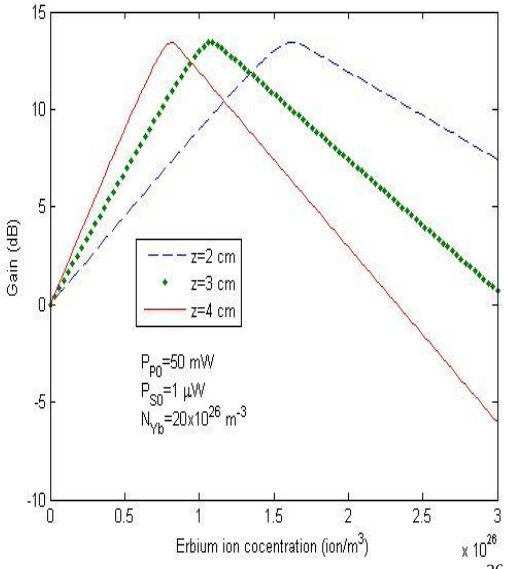

Fig. 6: Signal gain versus erbium concentration for EYCDFAs at $N_{Yb}=20x10^{26}$

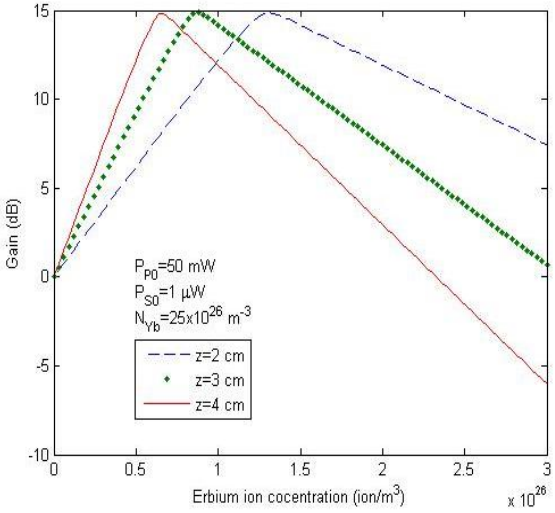

Fig. 7: Signal gain versus erbium concentration for EYCDFAs at $N_{Yb}=25x10^{26}$

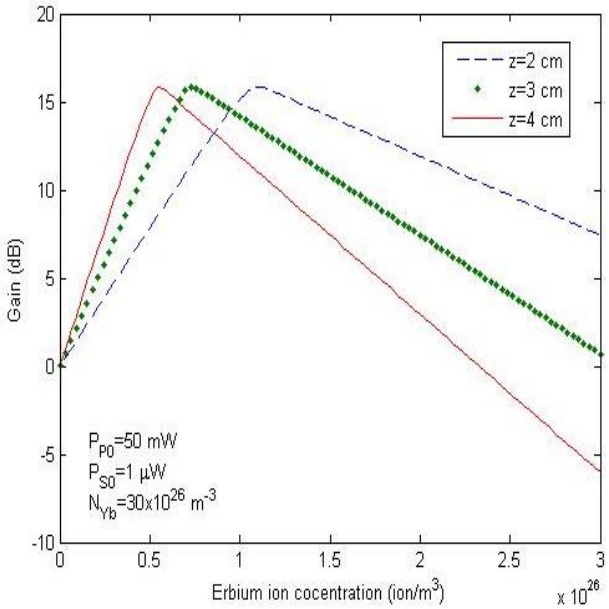

Fig. 8: Signal gain versus erbium concentration for EYCDFAs at $N_{Yb}=30x10^{26}$

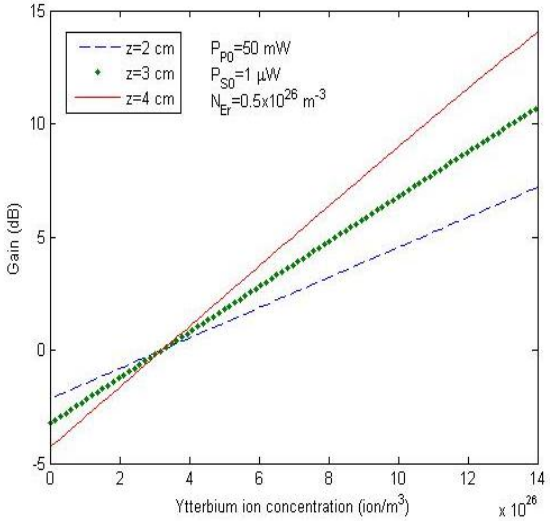

Fig. 9: Signal gain versus ytterbium concentration for EYCDFAs at $N_{Er}=0.5x10^{26}$

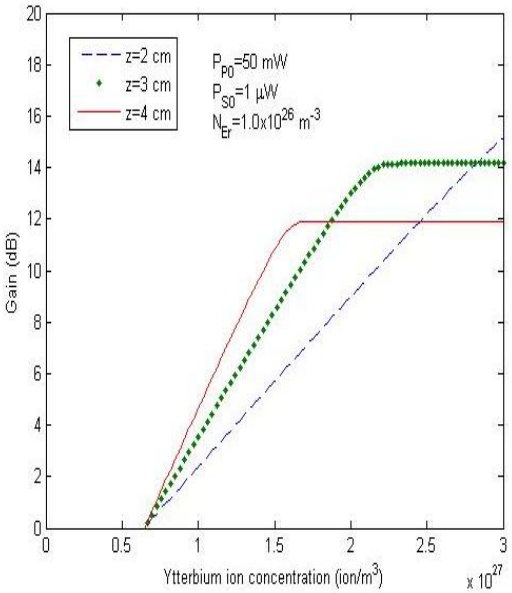

Fig. 10: Signal gain versus ytterbium concentration for EYCDFAs at $N_{Er}=1.0x10^{26}$

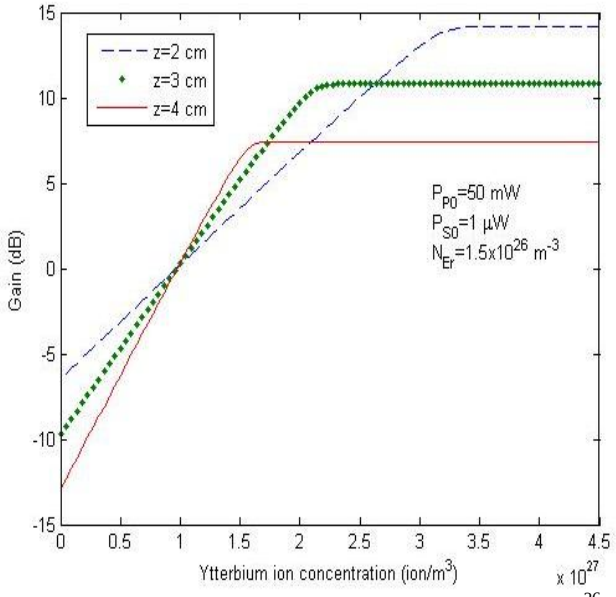

Fig. 11: Signal gain versus ytterbium concentration for EYCDFAs at N_{Er}=1.5x10^{26}

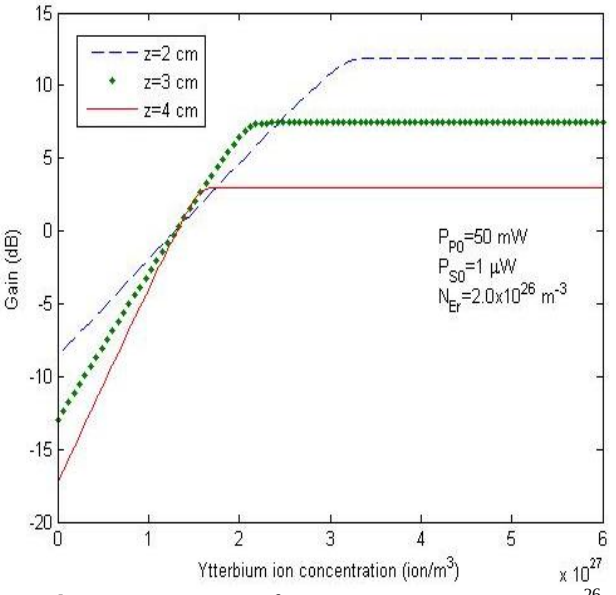

Fig. 12: Signal gain versus ytterbium concentration for EYCDFAs at N_{Er}=2.0x10^{26}

Figures 10, 11 and 12 show the curves of the gain *G* versus ytterbium ion concentration and amplifier length. Erbium ion concentrations are 1.0x10^{26}, 1.5x10^{26}, 2.0x10^{26} m^{-3}, pump power is 50 mW and signal power P_{s0} = 1 μW.

The results demonstrate that the gain increases as the ytterbium ion concentration increases. Figure 9 at z=3 cm shows that the gain increases almost linearly as ytterbium ion concentration is below 2.19x10^{27} and then increases slightly and reaches saturation. With fixed ytterbium concentration, the gain increase at z=2 cm and decreases as fiber length increases from 2 to 4 cm. The higher value of gain at z=3 cm and erbium concentration 1.0x10^{26} is 14.15 dB and this discussed why we choose this erbium concentration along our calculation. And in general, at a certain value, the gain decrease after it and the gain increase below it.

Conclusion:

We have demonstrated a computational method for calculating the properties of phosphate glass Er^{3+}-Yb^{3+}-co-doped waveguide amplifiers (EYCDFA). Several parameters have important effects on gain of EYCDFA, like the concentration of both dopants(Er and Yb). The calculations of the gain characteristics of the phosphate glass erbium-ytterbium (Er^{3+}-Yb^{3+}) co-doped waveguide amplifier (EYCDWA) using the parameters of the concentration of both erbium and ytterbium are performed using a new fitting for the absorption and emission of the dopants on phosphate glass. The calculation are made from the rate equations and the light propagation equations and the steady-state condition, we have neglected the amplified spontaneous emission (ASE) and have introduced the initial energy transfer efficiency. The gain shows different behavior with the concentration

of both erbium and ytterbium and with the ratio of each other. When the Er^{3+}-Yb^{3+}-co-dopant ratio are sufficiently large, the gain tends to saturation, as Er or Yb concentration decreases the gain tends to negative value, so the concentration of both dopant must exceed defined value(optimum value) to give suitable value of the gain.

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