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Formulized analytical technique for gain characteristics of phosphate glass Er^{3+}/Yb^{3+} co-doped waveguide amplifiers

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Novel formulas for analyzing the gain characteristics of the phosphate glass erbium-ytterbium (Er^{3+}-Yb^{3+}) co-doped waveguide amplifier (EYCDWA) are derived from the rate equations and the light propagation equations under the uniform dopant and steady-state conditions. In the derivation of these formulas, we have neglected the amplified spontaneous emission (ASE) and have introduced the initial energy transfer efficiency. By using these formulas, the effects of the pump power, signal power, dopant concentration and waveguide length on the gain characteristics of the EYCDWA are analyzed, the comparison is performed between the EYCDWA and the singly erbium-doped waveguide amplifier (EDWA), and some useful results are obtained.

Keywords: waveguide amplifier, erbium-ytterbium co-dopant, rate equations, propagation equations, gain characteristic.

1. Introduction

The erbium-doped waveguide amplifier (EDWA) has attracted more and more interest in optoelectronic integrated circuits (OEICs), because of its larger signal gain in a small device size compared with the singly erbium-doped fiber amplifier (EDFA) [1–6]. It has been reported that the EDWA has a shortage as follows. One excited erbium ion transfers energy to the other excited ion, causing the acceptor to be promoted to a higher energy state and the donor to be deexcited to the ground state nonradiatively, which would enhance processes of up-conversion by energy transfer [7]. In order to enhance the gain of unit length, an EDWA requires high erbium ion (Er^{3+}) concentration. However, high Er^{3+} concentration will increase the number of the Er^{3+} clusters, and hence reduce the spacing between the Er^{3+} ions. In this case, the overlapping between the electron clouds of Er^{3+} ions becomes severe, which causes the energy transfer between the Er^{3+} ions, increasing the excited state absorption

(ESA). Therefore, the clustering enhances the ESA [8]. The clustering greatly reduces the pump efficiency and degrades the gain performance [6, 9–12].

Fortunately, the rare-earth element ytterbium, as a sensitizer, exhibits a better overlapping between the Yb^{3+} emission spectrum ($^2F_{5/2}$–$^2F_{7/2}$) and the Er^{3+} absorption spectrum ($^4I_{13/2}$–$^4I_{15/2}$) 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 be realized in the waveguide. This can noticeably reduce the quenching side-effect caused by high Er^{3+} dopant concentration [13], so the erbium-ytterbium (Er^{3+}-Yb^{3+}) co-dopant can efficiently improve the gain characteristics of the waveguide amplifiers. The clustering would result in the process of the up-conversion of the energy transfer. The doping of Yb^{3+} ions can greatly separate the spacing of the Er^{3+} ions and prevent the interaction between the Er^{3+} ions, and hence efficiently reduce the number of the clusters [14]. Therefore, the phenomenon of up-conversion can be ignored when the high Yb^{3+} concentration is doped. This indicates that the Er^{3+}-Yb^{3+} co-doped waveguide amplifier (EYCDWA) has more potential applications than the EDWA.

Though some numerical methods, such as the finite difference beam propagation method (FD-BPM) [15] and Runge–Kutta (RK) method [16], can be used to analyze the gain characteristics of the EYCDWA, the simulation process is complicated, and requires much time spent on computing. In this paper, first in order to simplify the simulation process, novel formulas for analyzing the gain characteristics of the EYCDWA are derived from the rate equations and the light propagation equations based on the energy transfer process of Er^{3+} and Yb^{3+} ions. Then, by using these formulas, the effects of the pump power, signal power, dopant concentration and waveguide length on the gain characteristics are analyzed for the phosphate glass EYCDWA. Finally, some useful conclusions are reached on the basis of the analysis and discussion.

2. Theory

In this section, we propose an analytical technique for investigating the EYCDWA. Figure 1 shows the energy levels of an Er^{3+}-Yb^{3+} co-doped system [17, 18]. In terms of this figure, the transition and energy transfer of Er^{3+} and Yb^{3+} ions are described as follows.

Yb^{3+} ions on the fundamental level $^2F_{7/2}$ absorb the energy of the 980-nm pump light, and transit up to the excited level $^2F_{5/2}$, then quickly resonantly transfer their energy to nearby Er^{3+} ions on the fundamental level $^4I_{11/2}$, and then Er^{3+} ions transit up to the excited level $^4I_{11/2}$. Since this excited level $^4I_{11/2}$ is unsteady, Er^{3+} ions quickly decay to the metastable level $^4I_{13/2}$. In this process, the population inversion is realized on the metastable level $^4I_{13/2}$. The lifetime of Er^{3+} ions on the excited level $^4I_{11/2}$ is very short (~ns order) compared with that on the metastable level $^4I_{13/2}$ (about 8–10 ms), therefore, the number of Er^{3+} ions on the excited level $^4I_{11/2}$ is so small that it can be neglected. For the phosphate glass as a suitable host medium, large phonon

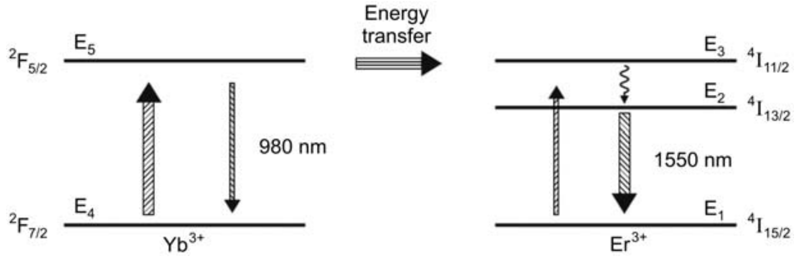

Fig. 1. Energy levels for the Er^{3+}-Yb^{3+} co-doped system.

energy can urge the transition probability of Er^{3+} ions transiting from the excited level $^4I_{11/2}$ to the metastable level $^4I_{13/2}$, which prevents the energy transfer from Er^{3+} ions back to Yb^{3+} ions [19].

Supposing N_1 and N_2 are the Er^{3+} ion concentrations on the $^4I_{15/2}$ and $^4I_{13/2}$ 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. 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 waveguide 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 [20–22]

$$\frac{\sigma_{12}(\nu_s)P_s(z)\Gamma_s}{A_c h\nu_s}N_1(z) + \frac{\sigma_{13}(\nu_p)P_p(z)\Gamma_p}{A_c h\nu_p}N_1(z) - \frac{\sigma_{21}(\nu_s)P_s(z)\Gamma_s}{A_c h\nu_s}N_2(z) - \frac{N_2(z)}{\tau_{21}}$$

$$+ \frac{\sigma_{45}(\nu_p)P_p(z)\Gamma_p}{A_c h\nu_p}N_4(z) - \frac{\sigma_{54}(\nu_p)P_p(z)\Gamma_p}{A_c h\nu_p}N_5(z) - \frac{N_5(z)}{\tau_{54}} = 0 \tag{1}$$

with

$$N_1(z) + N_2(z) = N_{\mathrm{Er}}, \qquad N_4(z) + N_5(z) = N_{\mathrm{Yb}} \tag{2}$$

where Γ_p and Γ_s are the overlapping factors of the pump and the signal, respectively; A_c is the area of the cross-section of the waveguide; $\sigma_{12}(\nu_s)$ 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, which satisfy the following transmission equations [22]

$$\frac{\mathrm{d}P_p(z)}{\mathrm{d}z} = -\Gamma_p\Big[\sigma_{13}(\nu_p)N_1(z) + \sigma_{45}(\nu_p)N_4(z) - \sigma_{54}(\nu_p)N_5(z)\Big]P_p(z) \tag{3}$$

$$\frac{\mathrm{d}P_s(z)}{\mathrm{d}z} = \Gamma_s\Big[\sigma_{21}(\nu_s)N_2(z) - \sigma_{12}(\nu_s)N_1(z)\Big]P_s(z) \tag{4}$$

2.1. Signal gain

From Equations (1)–(4) , we obtain

$$\frac{1}{A_c h \nu_p}\frac{dP_p(z)}{dz} + \frac{1}{A_c h \nu_s}\frac{dP_s(z)}{dz} + \frac{N_2(z)}{\tau_{21}} + \frac{N_5(z)}{\tau_{54}} = 0 \tag{5}$$

By defining $\eta_0 = \frac{N_2}{N_2 + N_5}$ as the initial energy transfer efficiency [23], that is, $N_5 = \frac{1-\eta_0}{\eta_0} N_2$, and letting $B = \frac{\tau_{21}\tau_{54}}{\tau_{54} + \tau_{21}(1-\eta_0)/\eta_0}$, Eq. (5) can be rewritten as

$$N_2(z) = -B\frac{1}{A_c h \nu_p}\frac{dP_p(z)}{dz} - B\frac{1}{A_c h \nu_s}\frac{dP_s(z)}{dz} \tag{6}$$

Setting $S = \int_0^z N_2(z)dz$ and integrating Eqs. (3), (4) and (6), we get

$$S = \frac{\frac{1}{\Gamma_p}\ln\frac{P_p(z)}{P_p(0)} + \sigma_{13} N_{Er} z + \sigma_{45} N_{Yb} z}{\sigma_{13} + \frac{1-\eta_0}{\eta_0}(\sigma_{45} + \sigma_{54})} \tag{7}$$

$$S = \frac{\frac{1}{\Gamma_s}\ln\frac{P_s(z)}{P_s(0)} + \sigma_{12} N_{Er} z}{\sigma_{12} + \sigma_{21}} \tag{8}$$

$$S = -B\frac{1}{A_c h \nu_p}\left[P_p(z) - P_p(0)\right] - B\frac{1}{A_c h \nu_s}\left[P_s(z) - P_s(0)\right] \tag{9}$$

From Equations (7) and (8), we get

$$P_p(z) = P_p(0)\left[\frac{P_s(z)}{P_s(0)}\right]^{\alpha}\exp\left[\alpha\Gamma_s\sigma_{12}N_{Er}z - \Gamma_p z(\sigma_{13}N_{Er} + \sigma_{45}N_{Yb})\right] \tag{10}$$

where

$$\alpha = \frac{\Gamma_p\sigma_{13} + \Gamma_p(\sigma_{45} + \sigma_{54})(1-\eta_0)/\eta_0}{\Gamma_s(\sigma_{12} + \sigma_{21})} \tag{11}$$

Manipulating Eqs. (8), (9) and (10), we can arrive at the following equation

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

with

$$G(z) = \frac{P_s(z)}{P_s(0)}, \qquad \sigma = \frac{\sigma_{12}+\sigma_{21}}{\sigma_{13}+(\sigma_{45}+\sigma_{54})(1-\eta_0)/\eta_0}\left(\sigma_{13}+\sigma_{45}\frac{N_{\text{Yb}}}{N_{\text{Er}}}\right)-\sigma_{12} \tag{13}$$

where $G(z)$ is the gain of the amplifier.

2.2. Pump threshold

Letting $G(L) = 1$, from Eq. (12), we can express the pump threshold P_{th} as

$$P_{\text{th}} = P_p(0) = \frac{A_c h\nu_p\sigma_{12}N_{\text{Er}}L}{B(\sigma_{12}+\sigma_{21})\left[1-\exp(-\alpha\Gamma_s\sigma N_{\text{Er}}L)\right]} \tag{14}$$

2.3. Optimum waveguide length

When $\left.\frac{\partial G(z)}{\partial z}\right|_{z=L_0} = 0$, from Eq. (12), we can express the maximum gain G_0 and the optimum waveguide length L_0 as follows, respectively

$$G_0(L_0) = \gamma^{1/\alpha}\exp(\Gamma_s\sigma N_{\text{Er}}L_0) \tag{15}$$

$$L_0(G_0) = \frac{\ln G_0-\frac{1}{\alpha}\ln\gamma}{\Gamma_s\sigma N_{\text{Er}}} \tag{16}$$

where

$$\gamma = \frac{A_c h\nu_p\sigma_{12}}{\alpha B\Gamma_s(\sigma_{12}+\sigma_{21})P_p(0)\sigma} \tag{17}$$

Specially, when $N_{\text{Yb}} = 0$, then $N_4 = N_5 = 0$, in this case, the EYCDWA degenerates as an EDWA.

3. Analysis and discussions

In this section, we analyze the gain characteristics of the phosphate glass EYCDWA. The values of parameters used in the calculation are selected as [2, 22]: the pump wavelength λ_p = 980 nm, signal wavelength λ_s = 1550 nm, Er^{3+} absorption cross-section $\sigma_{13}(\lambda_p) = 2.58\times10^{-25}$ m^2, Yb^{3+} absorption cross-section $\sigma_{45}(\lambda_p) = 1.0\times10^{-24}$ m^2, Yb^{3+} emission cross-section $\sigma_{54}(\lambda_p) = 1.0\times10^{-24}$ m^2; Er^{3+} absorption cross-section $\sigma_{12}(\lambda_s) = 6.5\times10^{-25}$ m^2, Er^{3+} emission cross-section $\sigma_{21}(\lambda_s) = 9.0\times10^{-25}$ m^2; Er^{3+} emission lifetime τ_{21} = 10 ms; Yb^{3+} emission lifetime τ_{54} = 2 ms; the initial energy transfer efficiency η_0 = 11.5%; the core refractive index n_1 = 1.52812, the cladding refractive index n_2 = 1.51, waveguide cross-section A_c = 4×4 μm^2, the calculated overlapping factors $\mathit{\Gamma}_p$ = 0.921 and $\mathit{\Gamma}_p$ = 0.795.

Figure 2 shows the curves of the gain G versus the pump power P_{p0}, where we take the signal power P_{s0} = 1 μW, Er^{3+} ion concentration $N_{\rm Er} = 1.0\times10^{26}$ m^{-3}, Yb^{3+} ion concentration $N_{\rm Yb}$ = 0, 2.0×10^{27} m^{-3}, and waveguide length z = 1, 2, 3 cm. We find that the gain increases as the pump power increases. Under the condition of the EYCDWA and the EDWA having the same size, when the pump power is larger than a certain value, the gain of the EYCDWA is larger than that of the EDWA. This

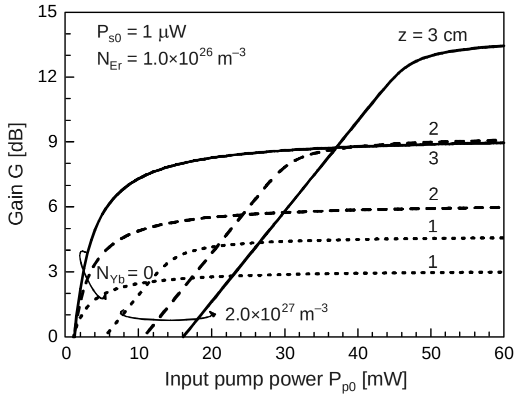

Fig. 2. Curves of gain G versus pump power P_{p0}.

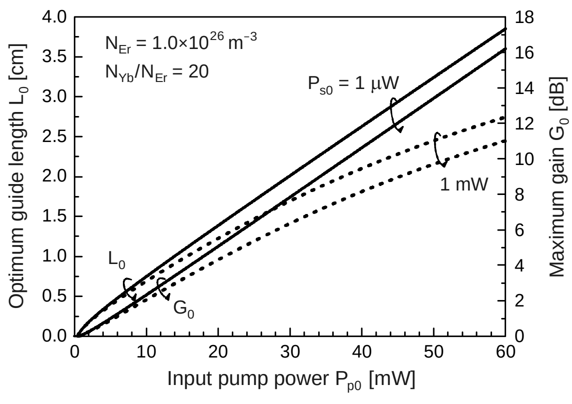

Fig. 3. Curves of optimum waveguide length L_0 and maximum gain G_0 versus pump power P_{p0}.

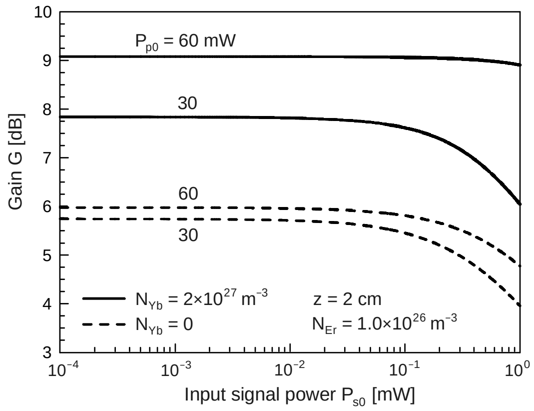

Fig. 4. Curves of gain G versus signal power P_{s0}.

is because the doped Yb^{3+} ions surround Er^{3+} ions and form Er^{3+}-Yb^{3+} ion-ion pairs, by which the Yb^{3+} ion absorbed photon energy transited phonon energy, which can sufficiently transferred to Er^{3+} ions to make more population reversion. This means that Yb^{3+} ions can provide an indirect exciting way to Er^{3+} ions. As the pump power increases to sufficiently large, almost all the Er^{3+} ions have realized the population reversion, then the gain becomes saturate. At the same condition, because the doped Yb^{3+} ions absorb some pump energy, the pump threshold power of the EYCDWA is larger than that of the EDWA.

Figure 3 shows the curves of the optimum waveguide length L_0 and the maximum gain G_0 versus the pump power P_{p0}, where we take the signal power P_{s0} = 1 μW, 1 mW, Er^{3+} ion concentration $N_{Er} = 1.0\times10^{26}$ m^{-3}, Yb^{3+} ion concentration $N_{Yb} = 2.0\times10^{27}$ m^{-3}, that is $N_{Yb}/N_{Er} = 20$. We can see that as the pump power increases, both the optimum waveguide length and the maximum gain increase. The optimum waveguide length for a large signal power is shorter than that for a small signal power. Moreover, the maximum gain of the former is less than that of the latter.

Figure 4 shows the curves of the gain G versus the signal power P_{s0}, where we take the waveguide length z = 2 cm, Er^{3+} ion concentration $N_{Er} = 1.0\times10^{26}$ m^{-3}, Yb^{3+} ion concentration $N_{Yb} = 0$, 2.0×10^{27} m^{-3}, and pump power P_{p0} = 30, 60 mW. We can observe that within the range of the input signal power $P_{s0} < 2\times10^{-2}$ mW, the gain nearly keeps a constant for every curve. Beyond this, the gain decreases obviously with an increase in the input signal power. This is because stronger signal power can decrease Er^{3+} ion population reversion, and so the gain becomes weak.

Figure 5 shows the curves of the gain G versus the waveguide length z, where we take the signal power P_{s0} = 1 μW, Er^{3+} ion concentration $N_{Er} = 1.0\times10^{26}$ m^{-3}, Yb^{3+} ion concentration $N_{Yb} = 0$, 2.0×10^{27} m^{-3}, and pump power P_{p0} = 30, 40, 50, 60 mW. We find that as the waveguide length increases, first the gain increases to a maximum, and then decreases. The maximum gain is corresponding to the optimum waveguide length. As an example, for the pump power P_{p0} = 30 mW, the optimum waveguide length is about 2 cm and the maximum gain is about 7.8 dB. The larger the pump power, the larger the optimum waveguide length becomes. If the waveguide length is too large so as to the gain less than zero, in this case, the Er^{3+} ion population reversion cannot be realized in the waveguide, moreover, Er^{3+} ions absorb the signal energy, and then the gain turns to the absorption. The introduction of Yb^{3+} ions can shorten the optimum waveguide length greatly, compared with the case of $N_{Yb} = 0$ (EDWA); this is of benefit to the miniaturization and the integration of the EYCDWA device.

Figure 6 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 $P_{p0} = 40$ mW, Er^{3+} ion concentration $N_{Er} = 1.0\times10^{26}$, 1.6×10^{26} m^{-3}, and waveguide length $z = 2$, 3, 4 cm. 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}.

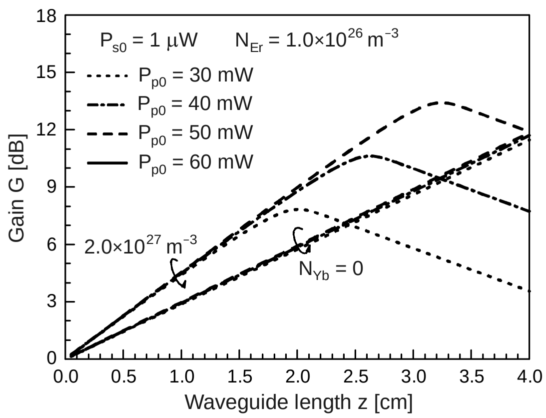

Fig. 5. Curves of gain G versus waveguide length z.

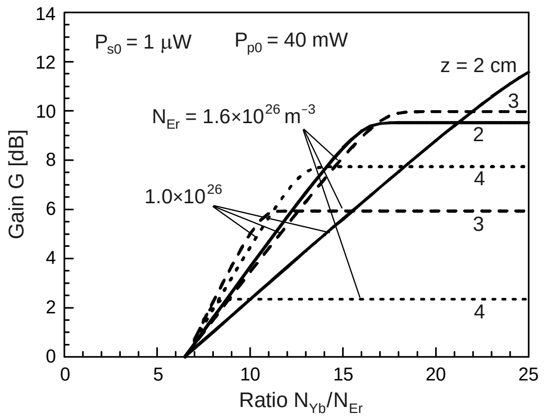

Fig. 6. Curves of gain G versus Yb^{3+}/Er^{3+} ion concentration ratio N_{Yb}/N_{Er}.

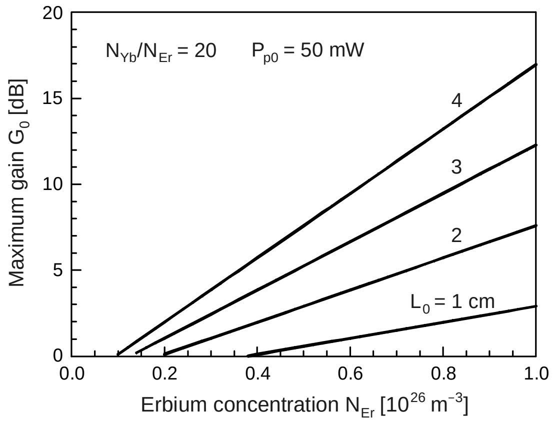

Fig. 7. Curves of maximum gain G_0 versus Er^{3+} ion concentration N_{Er}.

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 waveguide length and a certain Er^{3+} ion concentration. For example, in the case of the waveguide length $z = 3$ cm, pump power $P_{p0} = 40$ 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 18 and the corresponding gain is about 9.9 dB; while Er^{3+} ion concentration is 1.6×10^{26} m^{-3}, the optimal ratio N_{Yb}/N_{Er} is about 11 and the corresponding gain is about 5.8 dB.

Figure 7 shows the curves of the maximum gain G_0 versus the Er^{3+} ion concentration N_{Er}, where we take the pump power $P_{p0} = 50$ mW, ratio $N_{Yb}/N_{Er} = 20$, waveguide length $z = 1, 2, 3, 4$ cm. We can observe that the maximum gain increases as the Er^{3+} ion concentration increases. For a certain maximum gain, the shorter the optimum waveguide, the larger the Er^{3+} ion concentration required. Moreover, only as the Er^{3+} ion concentration increases to a certain value, the gain becomes positive, the device begins to have the amplification function. For instance, when the waveguide length $z = 2$ cm, the Er^{3+} ion concentration must be lager than 2×10^{25} m^{-3}.

4. Conclusions

On the basis of preceding analysis and discussion for the gain characteristics of the phosphate glass EYCDWA, some conclusions are reached as follows.

The sensibilization of Yb^{3+} ions can effectively restrain the Er^{3+} ion clusters, and reduce up-conversion nonlinear side effect. This can increase the total gain and the unit length gain greatly; therefore, the performance of the EYCDWA is better than that of the EDWA. Furthermore, the introduction of Yb^{3+} ions can shorten the optimum waveguide length; this is propitious to the miniaturization and the integration of the EYCDWA device.

The device has the maximum gain under the optimum waveguide length. When the pump power and the optimal Er^{3+}-Yb^{3+} co-dopant ratio are sufficiently large, the gain tends to saturation. For different Er^{3+} ion concentration and waveguide length, there are different optimal Yb^{3+}/Er^{3+} ion concentration ratio. Therefore, it is important to select a proper value of this ratio to either increase the gain of the device, or avoid the co-dopant over large.

By using this proposed analytical technique for the EYCDWA, satisfactory results can be obtained conveniently, which are in agreement with those of the numerical simulation reported in a previously published paper [22], and the relative error is within 3%. So we think that the EYCDWA model considered is reasonable, and the technique presented is useful and valuable for the characteristic analysis, parameter optimization and structural design of this kind of waveguide amplifiers.

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