

# Influencing Factors on Erbium-Doped Polymer Waveguide Amplifier

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We used fundamental rate equations and power propagation equations to simulate the gain factors of Er<sup>3+</sup>-doped polymer excited at 980 nm. The results of the calculations indicate close relationships between the gain and Er<sup>3+</sup> concentration, pump and signal absorption cross-sections, waveguide dimension, and metastable state lifetime of the states <sup>4</sup>I<sub>13/2</sub>. When the signal absorption cross section doubles, the gain will increase threefold. The radiative lifetime of Er<sup>3+</sup> in inorganic materials is much longer (milliseconds) than in the polymer (microseconds). If the lifetime of the states <sup>4</sup>I<sub>13/2</sub> decreases one level, there must be a corresponding increase in pump power so that the gain remains at the same level.

**Keywords:** Polymer Waveguide Amplifier, Er(DBM)<sub>3</sub>Phen-Doped PMMA-GMA, Gain.

## 1. INTRODUCTION

In recent years, much attention has been devoted to the development of erbium-doped optical waveguide amplifiers (EDWA) because of their potential applications for reducing various losses. The EDWA devices could provide a compact size, high Er<sup>3+</sup> concentration, and high gain per unit length. The materials for fabricating EDWA include inorganic (silicate, phosphate, Al<sub>2</sub>O<sub>3</sub>, LiNbO<sub>3</sub>) and polymer hosts. Erbium-doped inorganic materials have a typical gain value of 7 dB/cm,<sup>1</sup> and the pertinent technologies relatively mature. Compared with inorganic hosts, polymer materials have excellent properties such as: high bandwidth, simple processing steps, low cost, and compatibility with silicon substrates. Much attention is paid to synthesize erbium organic compounds to solve the problem that the inorganic erbium salts cannot be dispersed in polymer hosts; however, little work has been done on the gain of polymer EDWA. The only study of this type, reported by Wong in 2004<sup>2</sup> achieved a gain of 7.2 dB/cm. Therefore, theoretical studies on the performance of EDWA are necessary. The results may be used to improve the optical gain and pump efficiency as well as to optimize the parameters for polymer EDWA.

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In this article, we report a new kind of polymeric material, Er(DBM)<sub>3</sub>Phen-doped PMMA-GMA (poly-methylmethacrylate-glycidylmethacrylate) copolymer. The waveguide structure can be designed using the Marcatti theory. Using the Judd-Ofelt theory, we calculated the spontaneous transition probability, radiative lifetime, absorption cross-sections, and emission cross-sections of this polymer material. The fundamental rate equations and power propagation equations for erbium-doped waveguide amplifiers are introduced. With the cross-section parameters and radiative lifetime we calculated, the gain of EDWA can be simulated. The relationship between the gain and these parameters are being studied.

## 2. EDWA MODELING

We used a 980 nm laser to provide the pump power. The rare earth erbium ion is modeled as a four-energy level system in Figure 1.  $A_{ji}$  represents the spontaneous transition probability from level  $j$  to level  $i$ .  $W_{13}$ ,  $W_{31}$  represent the pump absorption and emission rates.  $R_{12}$ ,  $R_{21}$  represent signal absorption and emission rate.  $\sigma_{a12}$ ,  $\sigma_{e21}$  are the signal absorption cross section and emission cross section,  $\sigma_{e13}$ ,  $\sigma_{a31}$  represent pump absorption and emission cross section.  $C_{UP}$  is the upconversion coefficient.  $N_i$  is the concentrations of erbium in energy state  $i$ . Taking

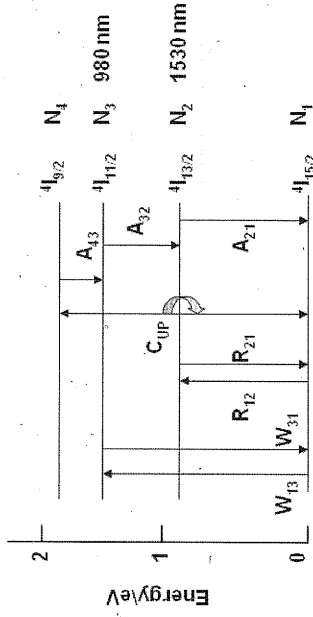


Fig. 1. Four energy levels system for Er<sup>3+</sup>.

into account upconversion coefficients, the fundamental rate can be expressed as in Eqs. (1–5) (Ref. [3]):

$$\begin{aligned} \frac{\partial N_1}{\partial t} &= W_{31}N_3 + R_{21}N_2 + A_{21}N_2 + C_{UP}N_2^2 - R_{12}N_1 - W_{13}N_1 & (1) \\ \frac{\partial N_2}{\partial t} &= R_{12}N_1 + A_{32}N_3 - R_{21}N_2 - A_{21}N_2 - 2C_{UP}N_2^2 & (2) \\ \frac{\partial N_3}{\partial t} &= W_{13}N_1 + A_{43}N_4 - W_{31}N_3 - A_{32}N_3 & (3) \\ \frac{\partial N_4}{\partial t} &= C_{UP}N_2^2 - A_{43}N_4 & (4) \\ N_1 + N_2 + N_3 + N_4 &= N & (5) \end{aligned}$$

where the absorption and emission rates of pump and signal  $R_{12}$ ,  $R_{21}$ ,  $W_{13}$ ,  $W_{31}$  are given by Eqs. (6–9):

$$\begin{aligned} R_{12} &= \frac{\sigma_{a12}(v_s)I_s}{hv_s} & (6) \\ R_{21} &= \frac{\sigma_{e21}(v_s)I_s}{hv_s} & (7) \\ W_{13} &= \frac{\sigma_{a13}(v_p)I_p}{hv_p} & (8) \\ W_{31} &= \frac{\sigma_{e31}(v_p)I_p}{hv_p} & (9) \end{aligned}$$

The signal and pump power propagation equations can be expressed by Eqs. (10) and (11):

$$\begin{aligned} \frac{dP_p(z)}{dz} &= -\gamma_p(z, v_p)P_p(z) & (10) \\ \frac{dP_s(z)}{dz} &= [\gamma_{21}(z, v_s) - \gamma_{12}(z, v_s)]P_s(z, v_s) & (11) \end{aligned}$$

where the signal and pump absorption and emission coefficients  $\gamma_p(z, v_p)$ ,  $\gamma_{12}(z, v_s)$ ,  $\gamma_{21}(z, v_s)$  are given by Eqs. (12–14):

$$\begin{aligned} \gamma_p(z, v_p) &= \iint_A \Psi_p(x, y) [\sigma_{a13}(v_p)v_p N_1(x, y, z) - \sigma_{e31}(v_p)v_p N_3(x, y, z)] dx dy & (12) \end{aligned}$$

$$\gamma_{12}(z, v_s) = \iint_A \Psi_s(x, y) [\sigma_{a12}(v_s)N_1(x, y, z)] dx dy & (13)$$

$$\gamma_{21}(z, v_s) = \iint_A \Psi_s(x, y) [\sigma_{e21}(v_s)N_2(x, y, z)] dx dy & (14)$$

where  $A$  is the area of the waveguide cross section. We used the overlap integral between the pump and signal optical fields and the erbium ion distribution reported by Wang<sup>4</sup> to predigest these equations, and the gain was calculated using Eq. (15):

$$G(z) = 101g \left[ \frac{P_s(z)}{P_{s0}} \right] & (15)$$

### 3. NUMERICAL SIMULATION AND DISCUSSION

#### 3.1. Parameters

In order to obtain higher gain, Er<sup>3+</sup> was doped in both the core and the cladding layer.<sup>5</sup> In our experiment, Er(DBM)<sub>3</sub>Phen doped PMMA-GMA copolymer was prepared as the cladding layer and the core (adding epoxy to adjust the refractive index in the core). The lower glass transition temperature of linear MMA (78 °C) will lead to dissolve with each layer of waveguide devices and limit the fabrication of optical waveguide devices. However, the PMMA-GMA copolymer systems could solve this problem because its higher  $T_g$  (125 °C). Figures 2 and 3 are the absorption and photoluminescence spectra of the Er(DBM)<sub>3</sub>Phen-doped PMMA-GMA. The Judd-Ofelt theory<sup>6,7</sup> was used with the absorption spectrum to obtain the radiative lifetime and cross section. The transition probabilities for the electric-dipole  $A_{ed}$  and the magnetic-dipole  $A_{md}$  are 49.37 s<sup>-1</sup> and 31.27 s<sup>-1</sup>, respectively. The radiative lifetime of the states <sup>4</sup>I<sub>13/2</sub> is 12.4 ms. The calculated absorption and emission cross sections are  $\sigma_{a12} = 2.06 \times 10^{-25}$  m<sup>2</sup>,  $\sigma_{e21} = 2.11 \times 10^{-25}$  m<sup>2</sup>, and  $\sigma_{e13} = 2.047 \times 10^{-25}$  m<sup>2</sup>. The other parameters for the simulation are  $C_{UP} = 2.4 \times 10^{-24}$  m<sup>3</sup> s<sup>-1</sup>,  $\tau_{32} = 1$  us,  $\tau_{43} = 1$  ns.

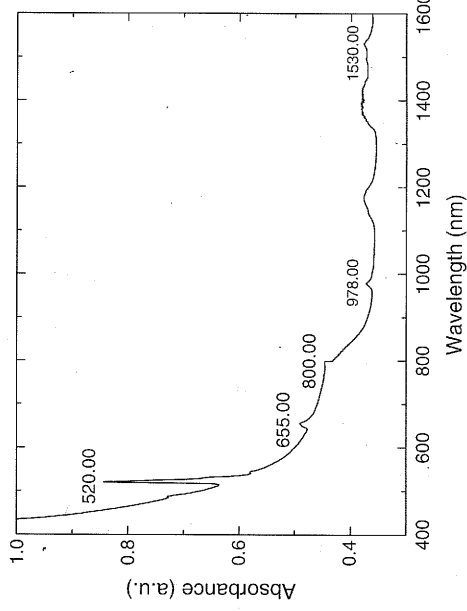


Fig. 2. The absorption spectrum of Er(DBM)<sub>3</sub>Phen doped PMMA-GMA at room temperature.

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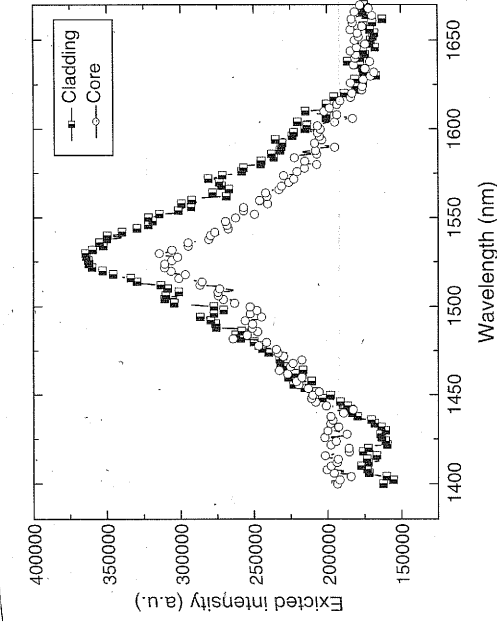


Fig. 3. The photoluminescence spectrum of Er(DBM)<sub>3</sub>:Phen-doped PMMA-GMA, at room temperature when pumped by a 980 nm laser.

Figure 4 shows the cross section of the polymer waveguide structure for optical gain calculations. The refractive index of the cladding is 1.553 and the refractive index of the core is 1.545 as measured with WVASE32 at 1,530 nm. Based on the refractive indexes, we calculated the thickness for single mode square channel waveguides at 980 nm and 1535 nm wavelengths. We chose  $3.5 \times 3.5 \mu\text{m}^2$  as the waveguide core dimension. The corresponding Er<sup>3+</sup> concentrations were 0.3 wt% in the cladding 0.5 wt% in the core. Assuming the Er<sup>3+</sup> doped in the polymer is uniform, the overlapping factors can be expressed as  $\Gamma_{p,s} = \int \int_A \Psi_{p,s}(x,y) dx dy^2$ . The overlapping factors depend on the optical field distribution of the pump and signal lasers and can be calculated according to the Marcattili theory. The calculated overlapping factors of the pump and signal lasers are 0.543 and 0.403, respectively. The waveguide length is 10 cm. These parameters used for optical gain simulation were all obtained in our experimental spectra and calculations.

### 3.2. Dependence of the Gain on Concentration of Er<sup>3+</sup>

Inorganic erbium salts cannot be dispersed directly into an organic matrix. Although this problem can be solved by

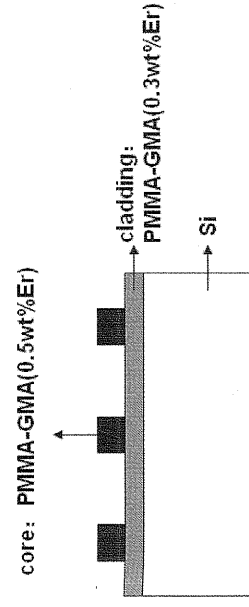


Fig. 4. The cross section view of the polymer waveguide structure for optical gain calculations.

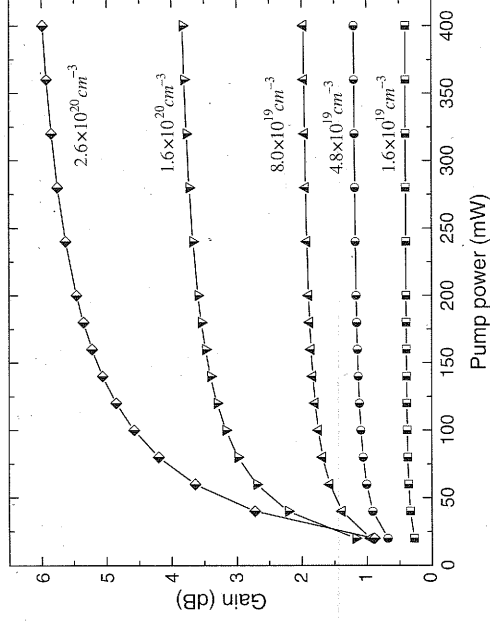


Fig. 5. The gain as a function of pump power at 980 nm for different concentrations of Er<sup>3+</sup>.

synthesis of an erbium organic complex, the lower solubility in polymer is still an intractable question. The highest concentration of Er<sup>3+</sup> in polymer reported by Slooff in 2002 is  $9.0 \times 10^{19} \text{ cm}^{-3}$  (Ref. [8]). However, this value is still too low if compared with the concentration in inorganic materials, which can reach  $10^{20} \text{ cm}^{-3}$ .

Figure 5 shows the gain as a function of pump power at 980 nm for different concentrations of Er<sup>3+</sup>. With pump power increasing, the gain increases and then remains nearly constant. It is shown that the gain and the threshold pump power increase with increasing concentration of Er<sup>3+</sup>. When the pump power is 400 mW, the gain increases from 0.403 to 5.985 dB as the concentration of Er<sup>3+</sup> varies from  $1.6 \times 10^{19} \text{ cm}^{-3}$  to  $2.6 \times 10^{19} \text{ cm}^{-3}$ . Taking into account the real solubility of Er<sup>3+</sup> in polymer, we use  $8 \times 10^{19} \text{ cm}^{-3}$  as the following simulant concentration on a 10 cm long waveguide.

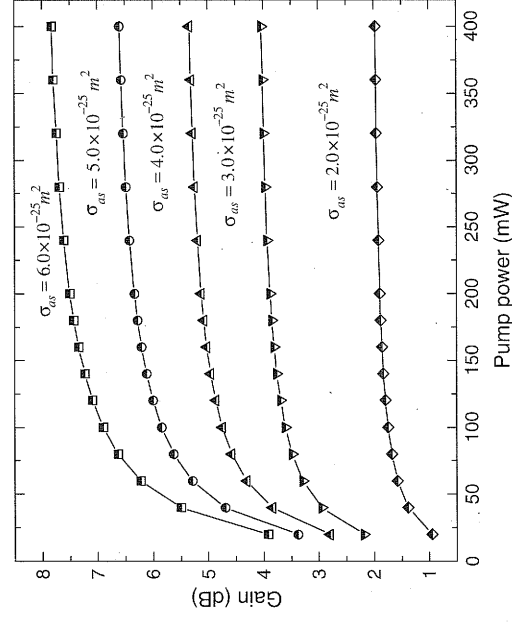


Fig. 6. The gain as a function of pump power at 980 nm for different signal absorption cross sections ( $\sigma_{a13} = 2.047 \times 10^{-25} \text{ m}^2$ ).

### 3.3. Dependence of the Gain on Absorption Cross Section

Figures 6 and 7 show the gain as a function of pump power at 980 nm for different signal and pump absorption cross sections. Figure 6 shows that the gain increases from 1.97 to 7.83 dB as the signal absorption cross section varies from  $2.0 \times 10^{-25} \text{ m}^2$  to  $6.0 \times 10^{-25} \text{ m}^2$  with pump power of 400 mW. When the pump power is 20 mW, the gain increases from 0.94 to 1.37 dB as the pump absorption cross section increases as shown in Figure 7. The variety is 0.43 dB when the pump power reaches the threshold value. It is shown that a bigger absorption cross section could increase  $\text{Er}^{3+}$  absorptency of the pump and signal laser, producing a higher gain.

### 3.4. Dependence of the Gain on Overlapping Factors of Pump and Signal

Figure 8 shows the gain as a function of pump power for different overlapping factors. When the pump power is 400 mW, the gain increases from 1.97 to 4.44 dB as the overlapping factor varies from about 0.5 to 0.9. With the overlapping factors increased, the waveguide absorptency of the pump and signal lasers is enhanced. The overlapping factors can be adjusted by controlling the refractive index of the material, the waveguide dimensions, and so on.

### 3.5. Dependence of the Gain on the Radiative Lifetime

The  ${}^4I_{13/2}$  states radiative lifetime of  $\text{Er}^{3+}$  in the  $\text{Er}(\text{DBM})_3\text{Phen}$  in PMMA-GMA copolymer is 12.4 ms calculated from Judd-Ofelt theory, while the measured fluorescence lifetime is  $15.8 \mu\text{s}$ , much shorter than the calculated value. Sun reported that the calculated lifetime of erbium complex in ErDP gel was 9.006 ms while the

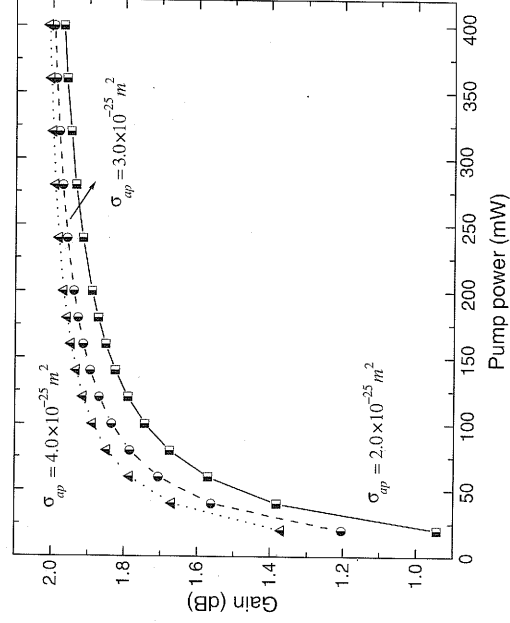


Fig. 7. The gain as a function of pump power at 980 nm for different pump absorption cross sections ( $\sigma_{a12} = 2.06 \times 10^{-25} \text{ m}^2$ ).

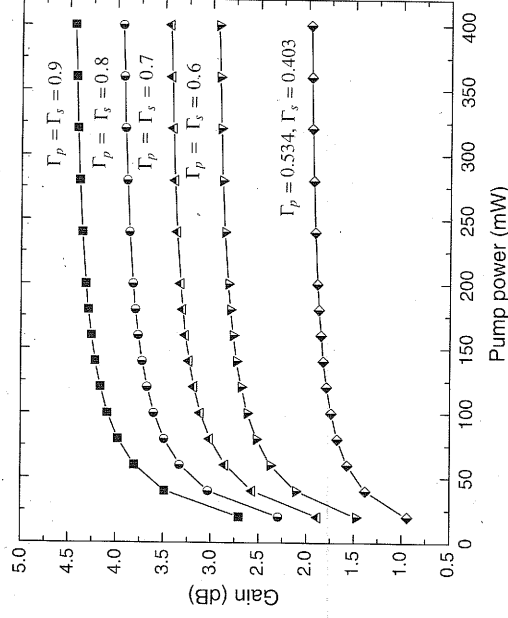


Fig. 8. The gain as a function of pump power for different overlapping factors.

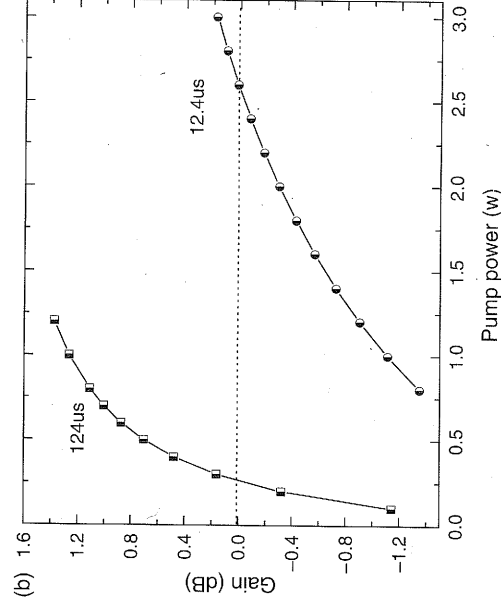
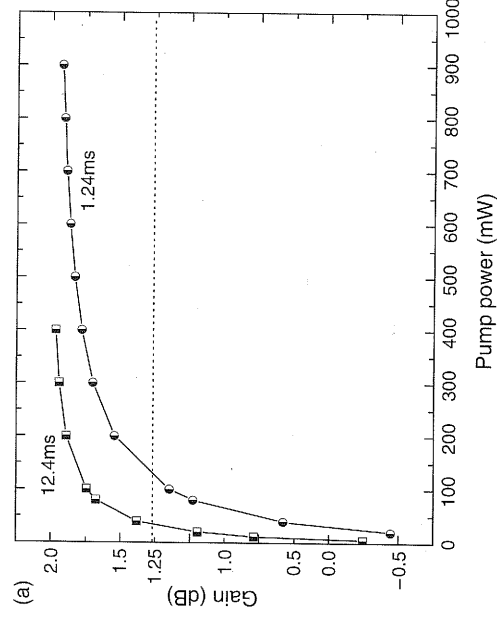


Fig. 9. (a) The gain as a function of pump power at 980 nm for different radiative lifetimes. The metastable state lifetime are 12.4 ms and 1.24 ms. (b) The gain as a function of pump power at 980 nm for different radiative lifetimes. The metastable state lifetime are 124  $\mu\text{s}$  and 12.4  $\mu\text{s}$ .

experimental value was 90  $\mu\text{s}$ .<sup>9</sup> In Slooff's paper, the lifetime for Er-doped organic cage complex was 0.8  $\mu\text{s}$ , but the calculated value was 4 ms.<sup>10</sup> The calculated radiative lifetime using the Judd-Ofelt theory agrees with the measured value in erbium-doped inorganic materials.<sup>11,12</sup> However, this is not the case for polymers because of the significant quenching due to O—H and C—H groups. Figure 9 shows the gain as a function of pump power at 980 nm for different radiative lifetimes. In Figure 9(a), when the gain reaches 1.25 dB, the required pump powers are 32 mW and 115 mW corresponding to the lifetimes of 12.4 ms and 1.24 ms. To achieve the same gains for the lifetimes of 124  $\mu\text{s}$  and 12.4  $\mu\text{s}$ , the pump power must reach 0.265 W and 2.56 W, respectively (Fig. 9(b)). The two figures show that if the lifetime of the states  $^4I_{13/2}$  decreases one level, there is a corresponding increase in pump power so that the gain remains at the same level. That is because the radiative lifetime of the energy state represents the storage capacity of the state. The longer the lifetime, the higher the stored ion concentration. One of the necessary conditions for gain is the particle reversal, which requires that the ion concentrations in the metastable state be comparable with ion concentrations in the ground state. Therefore, larger pump power is needed to excite large numbers of ions from the ground state to the metastable state if the lifetime is shorter. However, such a large pump power is difficult to achieve experimentally; so, it is essential to improve the metastable state lifetime of  $\text{Er}^{3+}$  in polymer.

#### 4. CONCLUSIONS

The single mode square channel waveguide dimension of  $\text{Er}(\text{DBM})_3$ -Phen-doped PMMA-GMA copolymer has been designed using the Marcattili theory. With the radiative lifetime, the absorption cross-sections, and the emission cross-sections of this polymer material calculated using the Judd-Ofelt theory, we simulated the gain from  $\text{Er}(\text{DBM})_3$ -Phen-doped PMMA-GMA copolymer using a rate equation propagation model. We studied the relationship between the gain and  $\text{Er}^{3+}$  concentration, the absorption cross section, the overlapping factors of pump and signal, and the radiative lifetime. The behavior of the gain at 1535 nm in a 10 cm length waveguide was studied for an  $\text{Er}^{3+}$  concentration of  $8 \times 10^{19} \text{ cm}^{-3}$ , which is realistic for polymer materials.

When the signal absorption cross-section doubles, the gain will increase threefold. The gain also increases with the increase in overlapping factors. The radiative lifetime of  $\text{Er}^{3+}$  in inorganic materials is much longer (milliseconds) than in polymer (microseconds). Our analyses show that if the lifetime of the state  $^4I_{13/2}$  decreased one level, there was a corresponding increase in pump power so that the gain remains at the same level. In conclusion, lower solubility of  $\text{Er}^{3+}$  in polymer and short metastable state lifetime are significant factors for polymer waveguide amplifiers. Therefore, it is essential to improve the absorption cross section and concentration of  $\text{Er}^{3+}$  in the polymer, optimize the waveguide dimension and decrease the quenching due to O—H and C—H groups to obtain the same level of radiative lifetime with  $\text{Er}^{3+}$  in inorganic hosts.

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