Numerical analysis of amplification characteristics of Er$_x$Y$_2$–$_x$SiO$_5$

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**Abstract**

The gain characteristics of Er$_x$Y$_2$–$_x$SiO$_5$ waveguide amplifiers have been investigated by solving rate equations and propagation equations. The gain at 1.53 μm as a function of waveguide length, Er$^{3+}$ concentration and pump power is studied pumping at three different wavelengths of 654 nm, 980 nm and 1480 nm, respectively. The optimum Er$^{3+}$ concentrations of $1 \times 10^{21}$ cm$^{-3}$ have been found for all three pump wavelengths. Pumping at 654 nm wavelength is shown to be the most efficient one due to weak cooperative upconversion. A maximum 16 dB gain at 1 mm waveguide length under a 30 mW pump with Er$^{3+}$ concentration of $1 \times 10^{21}$ cm$^{-3}$ is demonstrated pumping at 654 nm wavelength.

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1. Introduction

Erbium Doped Waveguide Amplifiers (EDWA) have attracted a great deal of attention because of the plausibility of introducing various active elements in integrated optical circuits [1–5]. These integrated optics devices require a higher concentration of Er$^{3+}$ than Erbium Doped Fiber Amplifiers (EDFA) for comparable gain. Er$_2$SiO$_5$ has recently been studied as a material of great interest as Er based materials for small size and high optical gain waveguide amplifier in silicon photonics integration, since Er$_2$SiO$_5$ contains higher Er$^{3+}$ concentrations of around $1 \times 10^{21}$ cm$^{-3}$ by adding certain amount of Y is possible, which may reduce upconversion of Er$^{3+}$, and further increase Er$^{3+}$ luminescence efficiency. Our recent work on Er$_x$Y$_2$–$_x$SiO$_5$ material also demonstrated enhanced Er$^{3+}$ photoluminescence (PL) of Er$_2$SiO$_5$ through Y additions pumping at 654 nm wavelength [9]. Meanwhile, we also found that the pump wavelengths have a significant effect on optical properties of Er$_x$Y$_2$–$_x$SiO$_5$ material. In order to the convenience of further research, in the paper, we give an analysis of amplification characteristic of Er$_x$Y$_2$–$_x$SiO$_5$ by solving rate equations and propagation equations. The numerical results pumping at different wavelengths of 654 nm, 980 nm and 1480 nm are given, and corresponding mechanisms are discussed.

2. Theory models

Fig. 1 shows the simplified energy level diagrams pumping at three wavelengths of 654 nm, 980 nm and 1480 nm. It can be found that the electrons from ground state ($^4$I$_{15/2}$) absorb 654 nm photons to fourth excited state ($^4$F$_{5/2}$) for pumping at 654 nm (Fig. 1(a)). Electrons on each state, $^4$I$_{13/2}$, $^4$I$_{11/2}$, $^4$I$_{9/2}$ and $^4$F$_{5/2}$ have their own lifetime and could nonradioactively relapse to the states below by emission of photons. However, because first excited state ($^4$I$_{13/2}$) is in the middle of $^4$I$_{15/2}$ and third excited state ($^4$I$_{9/2}$), upconversion and cross-relaxation should be taken into consideration for given Er$^{3+}$ concentrations of $1 \times 10^{20}$ cm$^{-3}$–$1 \times 10^{22}$ cm$^{-3}$ [11]. Two Er$^{3+}$ ions in state $^4$I$_{13/2}$ interact, promoting one ion up to the $^4$I$_{9/2}$ state, leaving the other down to the state $^4$I$_{15/2}$. Cross-relaxation, on the other hand,
is the anti-effect of upconversion. Corresponding rate equations are written as:

\[
\begin{align*}
\frac{dN_{0}}{dt} &= -N_{0} + N_{1} + N_{2} + N_{3} + N_{4} \\
\frac{dN_{1}}{dt} &= N_{1} - N_{2} - N_{3} - N_{4} + W_{01}N_{0} - W_{10}N_{1} \\
\frac{dN_{2}}{dt} &= N_{2} - N_{3} - N_{4} + W_{10}N_{1} - W_{12}N_{2} \\
\frac{dN_{3}}{dt} &= N_{3} - N_{4} + W_{12}N_{2} - W_{32}N_{3} + 2C_{12}N_{2} - 2C_{11}N_{3} \\
\frac{dN_{4}}{dt} &= N_{4} - W_{04}N_{0} + 2W_{02}N_{2} + 2W_{20}N_{2} + 2C_{11}N_{3} - C_{03}N_{0}N_{4} \\
N_{f} &= N_{0} + N_{1} + N_{2} + N_{3} + N_{4}
\end{align*}
\]

(1)

(a) 654 nm model

![Energy level diagram for 654 nm](image)

(b) 980 nm model

![Energy level diagram for 980 nm](image)

(c) 1480 nm model

![Energy level diagram for 1480 nm](image)

Fig. 1. Simplified energy level diagrams pumping at three wavelengths: (a) 654 nm, (b) 980 nm, (c) 1480 nm.

The propagation equations are given by:

\[
\begin{align*}
\frac{df_{p}}{dz} &= -X_{se}\phi_{p}\sigma_{abs}N_{0} \\
\frac{df_{0}}{dz} &= -X_{se}\phi_{p}\sigma_{abs}N_{0} + X_{se}\phi_{s}\sigma_{e}N_{1} \\
\frac{df_{se}}{dz} &= -X_{se}\phi_{p}\sigma_{abs}N_{0} + X_{se}\phi_{s}\sigma_{e}N_{1} + \frac{\sigma_{es}}{\sigma_{se}}N_{1}
\end{align*}
\]

(4)

\(N_{0}, N_{1}, N_{2}, N_{3}, \text{ and } N_{4}\) represent the \(\text{Er}^{3+}\) ions numbers in the energy levels \(^4I_{15/2}, ^4I_{13/2}, ^4I_{11/2}, ^4I_{9/2}\) and \(^4I_{11/2}\) respectively. \(N_{f}\) denotes the total \(\text{Er}^{3+}\) ions numbers. \(W_{ij}\) is the spontaneous emission photon flux, \(\phi_{p}\) is signal light photon flux, and \(\phi_{s}\) is pump light photon flux. \(X_{se}\) is the confinement factor between the pump and probe wavelengths for strip waveguide structure. A SiO\(_2\)/Erbium Silicate/SiO\(_2\) waveguide was adopted. Firstly the 400 nm × 400 nm Erbium Silicate waveguide was designed on the 10 μm thick thermally oxidized SiO\(_2\)/Si (100) substrate, then the 2 μm thick SiO\(_2\) film was clad on the top of Erbium Silicate strip waveguide. The confinement factors, based on my simulations (Gaussian Light Source into Erbium Silicate Material) are 0.635, 0.508, and 0.356, respectively, for three pump wavelengths of 654 nm, 980 nm and 1480 nm. C is upconversion coefficient. Hehlen et al. [13] reported that upconversion coefficient for \(\text{Er}^{3+}\) doped silicate glass increases approximately as the square root of concentration \(N^{0.5}\). Measurement value is about \(1 \times 10^{-18} \text{ cm}^3 \text{s}^{-1}\) for \(\text{Er}^{3+}\) concentration of \(1 \times 10^{20} \text{cm}^{-3}\), so \(C\) can be estimated as \(C = 1 \times 10^{-18} \times (N/10^{20})^{0.5}\). The parameters of \(\text{Er}_x\text{Y}_{2-x}\text{SiO}_5\) waveguide amplifiers are shown in Table 1.

3. Numerical results

Fig. 2 shows signal gain as a function of waveguide length and \(\text{Er}^{3+}\) concentration pumping at three wavelengths of 654 nm, 980 nm and 1480 nm with fixed pump power of 30 mW and signal power 30 μW. Fig. 2(a) shows the gain profile pumping at 654 nm wavelength. For
low Er³⁺ concentration of 1×10²⁰ cm⁻³, the gain is almost linear along the waveguide. With the increase of Er³⁺ concentrations to 1×10²¹ cm⁻³, gain is first linear, then flatten out, reaching its maximum gain of 16 dB for 1 mm waveguide length. When the Er³⁺ concentration was further increased to 1×10²² cm⁻³, the gain slopes downwards after reaching its maximum value within 1 mm waveguide length. It is suggested that strong pump light is able to thoroughly reverse the population between the ground and the first excited state for linear parts. The no linear parts, on the other hand, demonstrate that absorption has consumed the pump flux significantly, giving a flatter gain along waveguide. For higher Er³⁺ concentrations, the downward parts indicate that the pump power at that place along the waveguide is lower than the threshold, thus not being able to sustain the signal gain anymore. Upconversion should be another important reason that the gain curves drop so dramatically at the high Er³⁺ concentrations. As in our models, upconversion coefficient C is 1×10⁻¹⁸ cm³ s⁻¹ for Er³⁺ concentration of 1×10²⁰ cm⁻³, while C becomes 1×10⁻¹⁷ cm³ s⁻¹ with the increase of Er³⁺ concentration to 1×10²² cm⁻³, ten times higher than that of 1×10²⁰ cm⁻³, causing much lower Er³⁺ luminescence efficiency.

Fig. 2(b) and (c) shows the gain profile pumping at 980 nm and 1480 nm, respectively. Similar gain change trend is depicted compared with that of pump at 654 nm. However, the gain value is lower than that of pump at 654 nm. It is suggested that in 980 nm's 4 level model, electrons at the ground state ⁴I₁₃/₂ are pumped to the second excited state ⁴F₉/₂, the state between two upconversion related states, the first excited state ⁴I₁₁/₂ and the third excited state ⁴F₇/₂. Because of the fast nonradioactive relapse between these three levels, numerical results indicated that under a 30 mW pump power with Er³⁺ concentration of 1×10²¹ cm⁻³, the distribution of electrons would be more than 13% on ground state ⁴I₁₅/₂, 70% on first excited state ⁴I₁₁/₂ and almost 10% on ⁴F₇/₂. However, for the 654 nm's results, because electrons are first pumped to ⁴F₅/₂, an energy state that is above all upconversion related states, the distribution of electrons at the same condition would be less than 10% on ⁴I₁₅/₂, almost 80% on ⁴I₁₁/₂ and almost 6% on ⁴F₇/₂. It can be concluded that the population inversion results for 654 nm model are better and almost 90% of electrons are on the ground and first excited states, while in 980 nm, only around 80% electrons are confined in these two states. In 1480 nm pump, no more than 10 dB gain within 1 mm waveguide length is available, comparing with the results of previous two wavelengths. It is the reason that the high ESA (⁴I₁₁/₂ to ⁴F₇/₂) reduced the population of ⁴I₁₁/₂ significantly and the pump efficiency should be much lower than the 654 nm and 980 nm ones. Fig. 3 shows the signal gain as a function of pump power and Er³⁺ concentration pumping at three wavelengths of 654 nm, 980 nm and 1480 nm. Each point in the figures indicates an optimized maximum gain achieved somewhere along a 1 mm waveguide length under the given Er³⁺ concentration and pump power. Fig. 3(a) shows the gain profile pumping at 654 nm wavelength. For low Er³⁺ concentration of 1×10²⁰ cm⁻³, the gain raises very fast first, almost converges with the y-axis, and then flattens out to be horizontal finally. With the
When the Er\(^{3+}\) concentrations were further increased to enough to reverse the population for the initial almost linear region, the gain curve would finally slope downwards after reaching its maximum gain within 1 mm waveguide length, instead of 654 nm of 980 nm’s horizontal ones. For more than Er\(^{3+}\) concentrations of 2 \times 10^{21} \text{ cm}^{-3}, because their maximum gain couldn’t be reached within 100 mW, only uprising parts of their curves are depicted. However, it is suggested that with larger pump power, their gain curves should slope downwards finally just as the lower concentration ones. This is due to the ESA effect. Because the energy gap between \(4I_{15/2}\) and \(4I_{13/2}\) is almost the same as the energy gap between \(4I_{13/2}\) and \(4I_{13/2}\), significant absorption from \(4I_{13/2}\) should happen if pump power is high. Thus higher pump actually could even decrease the gain. By comparing results of different pump wavelengths, we find that 654 nm pump has the highest optical gain per unit waveguide length. However, some parameters are needed for further discussion, especially the exact value of absorption cross section, emission cross section of the material and passive loss of the waveguide, which could support simulation estimation with more solid evidence.

4. Conclusions

The gain within 1 mm Er\(_x\)Y\(_{2-x}\)SiO\(_5\) waveguide length was numerically analyzed pumping at three wavelengths of 654 nm, 980 nm and 1480 nm. From which comparison shows that the pumping at 654 nm wavelength has the best gain properties. By adjusting parameters, 1 \times 10^{21} \text{ cm}^{-3} \sim 2 \times 10^{21} \text{ cm}^{-3} is known to be the optimum Er\(^{3+}\) concentration. Above 16 dB gain for pump power of 30 mW and 20 dB gain for 100 mW within 1 mm waveguide length pumping at 654 nm were demonstrated when Er\(^{3+}\) concentration is 1 \times 10^{21} \text{ cm}^{-3}. Such a high gain in a short waveguide presents an excellent property for silicon photonics integration.

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