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Coefficient determination related to optical gain in erbium-doped silicon-rich silicon oxide waveguide amplifier

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Gain-determining coefficients in Er-doped, nanocrystal-Si (nc-Si) sensitized silica waveguide amplifiers are investigated. Single-mode, Er-doped silica waveguides with nc-Si embedded in them were prepared by electron cyclotron resonance plasma-enhanced chemical vapor deposition of Er-doped a-Si:Ox (x<2) followed by a high-temperature anneal to precipitate nc-Si. Exciting the Er ions via nc-Si by pumping the waveguide from the top with the 477 nm line of an Ar laser resulted in an enhancement of the transmitted 1535 nm signal of up to 14 dB/cm, indicating a possible net gain of up to 7 dB/cm. From the dependence of the signal enhancement upon the pump power, an emission cross section of 2×10^-19 cm^2 at 1535 nm and an effective excitation cross section of ≥ 10^-17 cm^2 at 477 nm is obtained. © 2002 American Institute of Physics.

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The amount of information being transmitted via optical fibers has been increasing exponentially at a rate exceeding even the vaunted “Moore’s Law” of silicon integrated circuits.1 One key technology that enabled such rapid growth is erbium-doped fiber amplifiers (EDFA). By using the intra-4f transition of Er^3+ (4I_{13/2}→4I_{15/2}) to amplify optical signals near 1.54 μm, the absorption minimum of silica-based optical fibers, EDFA made the current wideband, all-optical networks possible.2 However, because EDFA require expensive lasers tuned to one of the absorption bands of Er^3+ for excitation of Er, they remain too expensive to be used widely, thereby hindering the extension of the all-optical network all the way to the individual end users. Yet neither substituting the fiber for a waveguide nor sensitizing Er^3+ with other rare earth ion such as Yb^3+ can fundamentally solve this problem. In fact, the high Er^3+ concentrations required for waveguide-based amplifiers due to the need to compress long fibers into short waveguides leads to pair-induced quenching,3 necessitating the use of even more powerful and expensive lasers.

Recently, it was demonstrated by using nanocrystal Si (nc-Si) as sensitizers, Er^3+ ions can be excited through Auger-type interaction with carriers generated inside nc-Si.4-15 Even without resonance, this excitation process can be very efficient, occurring within a few microseconds4 with more than 60% efficiency8 and total internal quantum efficiency of greater than 15%.10 As only photocarriers need to be generated in this excitation process, any inexpensive broadband light source such as flashlamps11 or light emitting diodes (LEDs) can be used to excite Er^3+, significantly reducing the cost. Furthermore, because the Si nanocrystals have absorption cross section in the range of 10^-18–10^-16 cm^2,2,12 Er^3+ ions can, in fact, need to be pumped from the top, obviating the need to couple the pump beam in and out of the path of the signal beam.

Given such promises, it is important to find out the values of the coefficients that determine gain, and ascertain whether practical devices may be fabricated using nc-Si sensitization. Recently, we demonstrated that optical gain is possible in an nc-Si sensitized, Er doped silica waveguide.13 In this letter, we determine the effective Er^3+ excitation and emission cross sections in such a waveguide. We find that they are both greatly enhanced by nc-Si sensitization, and that up to 7 dB/cm gain should be possible in a top-pumped waveguide even with a very low (0.03 at.%) concentration of Er.

A 2.5 μm thick Er-doped SiOx (x<2) film was deposited on a Si wafer with a 10 μm thick thermal oxide by electron-cyclotron resonance plasma enhanced chemical vapor deposition with concurrent sputtering of Er using SiH4 and O2 as source gases. Details of the deposition process can be found in Ref. 4. The Si and Er content of the film was determined by Rutherford backscattering spectroscopy to be 34 and 0.03 at.%, respectively (not shown). After deposition, the film was rapid thermal annealed at 1000 °C for 5 min both to activate Er and to precipitate nc-Si. The presence of nc-Si also raises the refractive index of the film to 1.46, thereby providing the index contrast necessary for waveguiding. This particular composition and processing parameters were chosen to induce the optimum Er^3+ luminescence properties.14,15

Following film deposition, 1 cm long ridge-type waveguides were fabricated by photolithography and wet chemical etching. The ridges were 9 μm wide and 0.5 μm high, and their facets were polished mechanically. No top cladding layer was deposited, however. Optical gain was measured by coupling an external signal from a DFB laser diode into the waveguide using a lensed fiber, and measuring.

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rations due to upconversion. Similar results are obtained for silica-based materials that reported many high order transitions. This is in contrast to previous reports on Er-doped silica-based materials that reported virtually no peak near 0.98 μm due to cooperative upconversion. Taken together, Fig. 1 indicates that upconversion strongly lifetime quenching due to cooperative upconversion.

Figure 2 shows the photoluminescence spectrum under the saturation condition. We observe the typical 1.54 μm Er³⁺ luminescence due to ⁴I_{13/2}→⁴I_{15/2} transition, but virtually no 980 nm luminescence due to the ⁴I_{11/2}→⁴I_{15/2} transition. The inset shows the Er³⁺ luminescence lifetime at 1.54 μm as a function of the pump power.

The intensity of the transmitted beam can be written as

\[ I(P) = c I_0 e^{-\alpha + \sigma_{ab} N_1} I \] pump on,

\[ I(0) = c I_0 e^{-\alpha + \sigma_{ab} N_2} I \] pump off,

where \( c \) is the coupling efficiency, \( I_0 \) is the input signal intensity, \( \alpha \) is the waveguide loss, \( \sigma_{ab} \) is the absorption cross section, \( \sigma_e \) is the emission cross section, \( N \) is total doping concentration, \( \Gamma \) is the core-mode overlap, and \( L \) is the illuminated length. \( N_1 \) and \( N_2 \) are the concentration of Er³⁺ ions in the ground and excited state, respectively, such that \( N_1 + N_2 = N \). The coupling efficiency is difficult to estimate, but is expected to be low due to poor mode matching, as can be seen in Fig. 1. Furthermore, due to the experimental nature of the fabrication process, \( \alpha \) is also expected to be high. These coefficients, however, are process-related and thus do not pose fundamental limitations. Therefore, we concentrate on signal enhancement (SE), defined as

\[ SE = I(P) / I(0) = e^{2 \sigma_{ab} N_2 \Gamma L} \]
Note that in Eq. (2), we have approximated that $\sigma_{abs} = \sigma_{em} = \sigma$, which is quite accurate for 1535 nm.18

In general, the rate equations governing the transitions between different excited levels of Er$^{3+}$ are coupled, and quite complex.19 However, as can be seen from Fig. 2, there is very little upconversion in our film, which we attribute to the low Er concentration used. Thus, we model the Er$^{3+}$ as a simple 2 level system.

$$\frac{dN_2}{dt} = \Sigma \Phi(N - N_2) - wN_2,$$

(3)

where $\Sigma$ is the effective absorption cross section of Si nanocrystal sensitized Er, $\Phi$ is the pump flux, and $w$ is the decay rate of excited Er$^{3+}$. Note that we neglect the stimulated emission due to the signal beam since a very low signal value reported by Kenyon et al.20

Figure 4 shows the pump power dependence of SE and the fit using Eq. (4). We find that we can obtain a SE of up to 14 dB/cm, implying a possible net gain of up to 7 dB/cm. From the known concentration of Er and the length of the pump beam, we obtain a value of $2 \pm 0.5 \times 10^{-19}$ cm$^2$ for the emission cross section of Er$^{3+}$ at 1535 nm. An accurate value of the effective excitation cross section $\Sigma$ is difficult to obtain due to the uncertainty of aligning a long, narrow pump beam on a long, narrow waveguide. Assuming a uniform pump intensity and optimum alignment, we obtain a value of $2 \pm 1 \times 10^{-17}$ cm$^2$ at 477 nm.

These values are much larger than those commonly accepted for Er$^{3+}$ in pure silica ($\sim 10^{-21}$ cm$^2$ and optical gain of only about 1 dB/cm or less). The large effective excitation cross section is easily attributed to the large absorption cross section of Si nanocrystals, and is in good agreement with the value reported by Kenyon et al. and Priolo et al., who suggested a value of $7 \times 10^{-17}$ and $2 \times 10^{-17}$ cm$^2$, respectively.20,21 The near-hundred-fold increase in the Er$^{3+}$ emission cross section, on the other hand, is so far unexplainable, since it is that of an innershell transition and should be only weakly dependent upon the host material. We note, however, that our value for emission cross section is in good agreement with that reported by Kik et al., who, on the basis of absorption measurement, have suggested a value of $8 \times 10^{-20}$ cm$^2$ as the lower limit for the emission cross section of Er$^{3+}$ in nc-Si sensitized silica,22 indicating that such enhancement in Er$^{3+}$ emission cross section is a real effect.

It should be pointed out that such an enhancement of emission cross section is critical if nc-Si sensitized, Er doped silica is to be used for practical applications. As can be seen in Eq. (4), the maximum gain achievable in a given length is completely determined by $\sigma$ and $N$ only. Thus, without an increase in the emission cross section, we would still need a waveguide that is several tens of cm long to achieve practical gain. Such a long waveguide, however, is impractical to pump from the top, thus negating the beneficial effect of nc-Si sensitization. However, because of the enhanced emission cross section, a waveguide that is only several cm long is sufficient, opening the possibility of a waveguide amplifier pumped from the top with a linear array of inexpensive LEDs.

In conclusion, we investigated optical gain determining coefficients of nc-Si sensitized, Er-doped silica waveguide. We find that nc-Si sensitization results in great increases in both excitation and emission cross sections of Er$^{3+}$, resulting in a theoretical maximum possible gain of 7 dB/cm at 1535 nm for an Er concentration of 0.03 at. %.

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