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

Hak-Seung Han, Se-Young Seo, Jung H. Shin, and Namkyoo Park

Citation: Appl. Phys. Lett. **81**, 3720 (2002); doi: 10.1063/1.1520710
View online: http://dx.doi.org/10.1063/1.1520710
View Table of Contents: http://apl.aip.org/resource/1/APPLAB/v81/i20
Published by the American Institute of Physics.

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

Hak-Seung Han,[a] Se-Young Seo, and Jung H. Shin
Department of Physics, Korea Advanced Institute of Science and Technology (KAIST), 373-1 Kusung-dong, Yusung-gu, Taejon, Korea

Namkyoo Park
Optical Communication Systems Laboratory, School of EECS, Seoul National University, Seoul 151-744, Korea

(Received 20 August 2002; accepted 20 September 2002)

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:O_x ($x<2$) 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 $\geqslant10^{-17}$ cm^2 at 477 nm is obtained. © *2002 American Institute of Physics.*
[DOI: 10.1063/1.1520710]

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+} ($^4I_{13/2}\rightarrow{}^4I_{15/2}$) to amplify optical signals near 1.54 μm, the absorption minimum of silica-based optical fibers, EDFAs made the current wideband, all-optical networks possible.[2] However, because EDFAs 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.[4–7] Even without resonance, this excitation process can be very efficient, occurring within a few microseconds[8] with more than 60% efficiency[9] 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 flashlamps[11] 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,[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 SiO_x ($x<2$) 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 SiH_4 and O_2 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

[a]Electronic mail: hshan@mail.kaist.ac.kr

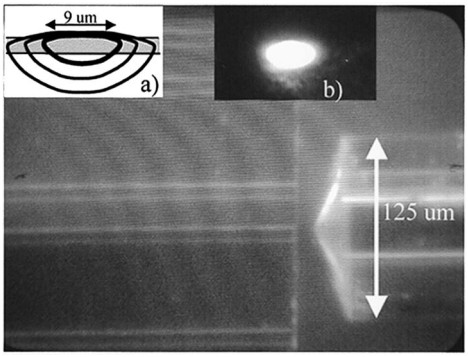

FIG. 1. CCD image of waveguide setup: (a) shows the mode profile at 1535 nm, calculated with effective index method, with lines indicating reduction in intensity by a factor of e and (b) shows the actual shape of the transmitted beam.

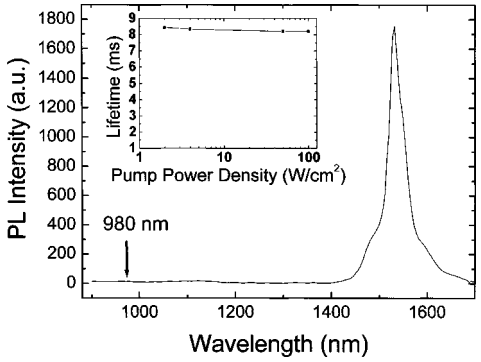

FIG. 2. Photoluminescence spectrum under the saturation condition. We observe the typical 1.54 μm Er^{3+} luminescence due to $^4I_{13/2}\rightarrow{}^4I_{15/2}$ transition, but virtually no 980 nm luminescence due to the $^4I_{11/2}\rightarrow{}^4I_{15/2}$ transition. The inset shows the Er^{3+} luminescence lifetime at 1.54 μm as a function of the pump power.

the output using an optical spectrum analyzer (OSA). The input signal power was kept low (<40 dBm) to measure the small signal gain. The waveguide was pumped using the 477 nm line of an Ar laser incident normally to the top surface of the waveguides. The 477 nm line was used because it does not coincide with any of the optical absorption bands of Er^{3+}, thus ensuring that all Er^{3+} are excited via Si nanoclusters and giving a good representation of a broadband excitation source. The pump beam was focused using a cylindrical lens to a size of $\sim 0.1\times 2$ mm. Photoluminescence measurements were performed by collecting the luminescence emitted normal to the film using lenses, a grating monochromator, a thermoelectrically cooled InGaAs detector, and employing the lock-in technique. All measurements were performed at room temperature, and the PL spectra were corrected for the system response.

Figure 1 shows the CCD image of the waveguide setup, showing the fiber and the waveguides. We note that due to the experimental nature of the waveguide fabrication process, both the film and waveguides show significant scattering. Inset (a) shows the mode profile at 1535 nm, calculated with effective index method. Inset (b) shows the actual shape of the transmitted beam taken with an infrared camera, showing a good agreement with the calculated shape. As shown in Fig. 1, we estimate the core-mode overlap to be 53%.

Figure 2 shows the photoluminescence spectrum at a pump density of ~ 100 W/cm^2, at which the Er^{3+} luminescence intensity is completely saturated. We observe the typical $^4I_{13/2}\rightarrow{}^4I_{15/2}Er^{3+}$ luminescence peak near 1.54 μm, but virtually no peak near 0.98 μm due to the $^4I_{11/2}\rightarrow{}^4I_{15/2}$ transition. This is in contrast to previous reports on Er-doped silica-based materials that reported many high order transitions due to upconversion.[16,17] Similar results are obtained from the time-resolved Er^{3+} luminescence measurements. As shown in the inset, the Er^{3+} luminescence lifetime hardly changes as the pump power is increased by nearly 2 orders of magnitude to the saturation regime, in contrast to previous reports on Er-doped silica-based materials that reported strong lifetime quenching due to cooperative upconversion.[16,17] Taken together, Fig. 1 indicates that upconversion is nearly completely suppressed in our film.

Figure 3 shows OSA traces of the transmitted beam with the pump beam on and pump beam off. We observe a strong enhancement of the transmitted 1535 nm signal beam when the pump is turned on. On the other hand, we observe no effect of the pump beam on the intensity of the 1300 nm signal beam, demonstrating that the signal enhancement we observe is due to Er and not due to nc-Si alone or other spurious effects of the pump beam.

The intensity of the transmitted beam can be written as

$$\begin{aligned} I(0) &= cI_0\times e^{-(\alpha+\sigma_{\mathrm{abs}}N\Gamma)L} \quad \text{pump off,} \\ I(P) &= cI_0\times e^{-[\alpha+(\sigma_{\mathrm{abs}}N_1-\sigma_e N_2)\Gamma]L} \quad \text{pump on,} \end{aligned} \tag{1}$$

where c is the coupling efficiency, I_0 is the input signal intensity, α is the waveguide loss, σ_{abs} is the absorption cross section, σ_e is the emission cross section, N is total doping concentration, Γ is the core-mode overlap, and L is the illuminated length. N_1 and N_2 are the concentration of Er^{3+} 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, α 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

$$\mathrm{SE}\equiv I(P)/I(0)=e^{2(\sigma N_2\Gamma)L}. \tag{2}$$

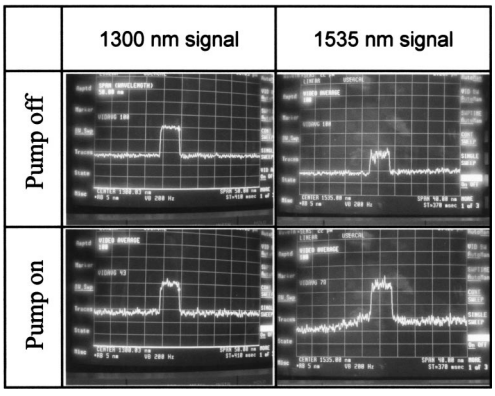

FIG. 3. OSA traces of the transmitted beam with the pump beam on and pump beam off. We observe a strong enhancement of the transmitted 1535 nm signal beam only, demonstrating that the signal enhancement we observe is due to Er.

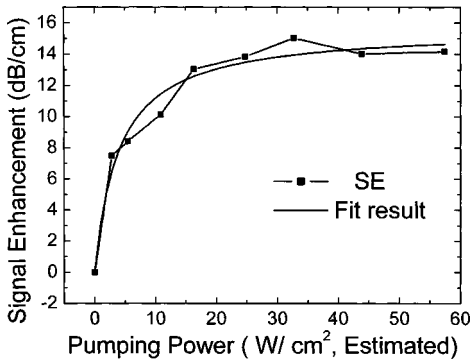

FIG. 4. Pump power dependence of SE and the fit using Eq. (4). We obtain a SE of up to 14 dB/cm, implying a possible net gain of up to 7 dB/cm. From the fit, we obtain emission cross section of 2×10^{-19} cm^2 and an effective excitation cross section of $\geqslant10^{-17}$ cm^2 at 477 nm.

Note that in Eq. (2), we have approximated that $\sigma_{\mathrm{abs}}=\sigma_e=\sigma$, 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.

$$\frac{dN_2}{dt}=\Sigma\Phi(N-N_2)-wN_2, \tag{3}$$

where Σ is the effective absorption cross section of Si nanocrystal sensitized Er, Φ 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 power was used. Using this model, the pump power dependence of SE is simply

$$\mathrm{SE}(P)=e^{2[\sigma N\Sigma\Phi/(\Sigma\Phi+w)\Gamma]L}. \tag{4}$$

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 $2\pm0.5\times10^{-19}$ cm^2 for the emission cross section of Er^{3+} at 1535 nm. An accurate value of the effective excitation cross section Σ 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 $2\pm1\times10^{-17}$ cm^2 at 477 nm.

These values are much larger than those commonly accepted for Er^{3+} in pure silica ($\sim10^{-21}$ 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 7×10^{-17} and 2×10^{-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 8×10^{-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 σ 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. %.

This work was supported in part by Advanced Photonics Project and National Research Laboratory Project from MOST and by Fifth Leader Technology Development Project from MIC in Korea.

[1] C. R. Giles, D. Bishop, and V. Aksyuk, MRS Bull. **26**, 328 (2001).
[2] *Condensed Matter and Materials Physics*, National Research Council (National Academic, Washington, DC, 1999).
[3] E. Delevaque, T. Georges, M. Monerie, P. Lamouler, and J. F. Bayon, IEEE Photonics Technol. Lett. **5**, 73 (1993).
[4] J. H. Shin, M. Kim, S. Seo, and C. Lee, Appl. Phys. Lett. **72**, 1092 (1998).
[5] M. Fujii, M. Yoshida, Y. Kanazawa, S. Hayashi, and K. Yamamoto, Appl. Phys. Lett. **71**, 1198 (1997).
[6] P. G. Kik and A. Polman, J. Appl. Phys. **88**, 1992 (2000).
[7] A. J. Kenyon, P. F. Trwoga, M. Federighi, and C. W. Pitt, J. Phys.: Condens. Matter **6**, L319 (1994).
[8] M. Fujii, M. Yoshida, S. Hayashi, and K. Yamamoto, J. Appl. Phys. **84**, 4525 (1998).
[9] P. G. Kik, M. L. Brongersma, and A. Polman, Appl. Phys. Lett. **76**, 2325 (2000).
[10] S.-Y. Seo and J. H. Shin, Appl. Phys. Lett. **78**, 2709 (2001).
[11] A. J. Kenyon, C. E. Chryssou, and C. W. Pitt, Appl. Phys. (N.Y.) **76**, 688 (2000).
[12] D. Kovalev, J. Diener, H. Heckler, G. Polisski, N. Kunzner, and F. Koch, Phys. Rev. B **61**, 4485 (2000).
[13] H.-S. Han, S.-Y. Seo, and J. H. Shin, J. Appl. Phys. **27**, 4568 (2001).
[14] H.-S. Han, S.-Y. Seo, J. H. Shin, and D.-S. Kim, J. Appl. Phys. **88**, 2160 (2000).
[15] S.-Y. Seo and J. H. Shin, Appl. Phys. Lett. **75**, 4070 (1999).
[16] E. Snoeks, G. N. van den Hoven, A. Polman, B. Hendriksen, M. B. J. Diemeer, and F. Priolo, J. Opt. Soc. Am. B **12**, 1468 (1995).
[17] G. Nykolak, P. C. Becker, J. Shmulovich, Y. H. Wong, D. J. Digiovanni, and A. Bruce, IEEE Photonics Technol. Lett. **5**, 1014 (1993).
[18] W. J. Miniscalco, J. Lightwave Technol. **9**, 234 (1991).
[19] P. Blixt, J. Nilsson, T. Carlnas, and B. Jaskorzynska, IEEE Photonics Technol. Lett. **3**, 996 (1991).
[20] A. J. Kenyon, C. E. Chryssou, C. W. Pitt, T. Shimizu-Lwayama, D. E. Hole, N. Sharme, and C. J. Humphreys, J. Appl. Phys. **91**, 367 (2002).
[21] G. Franzo, V. Vinciguerra, and F. Priolo, Appl. Phys. A: Mater. Sci. Process. **69**, 3 (1999).
[22] P. G. Kik and A. Polman, J. Appl. Phys. **91**, 534 (2002).