

Study of an efficient longitudinal multimode pumping scheme for Si-nc sensitized EDWAs

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Abstract: We present an efficient multimode longitudinal pumping scheme which overcomes the main limitations of single-mode longitudinal pumping as well as top pumping in Si-nanoclusters sensitized Erbium-doped waveguide amplifiers. The proposed configuration is based on evanescent pump light coupling from a multimode waveguide to a Si-nanoclusters sensitized Er³⁺-doped active core. Theoretical predictions, based on propagation and population-rate equations for the coupled Er³⁺/Si-nanoclusters system, point out that the proposed pumping scheme can provide high pump intensity within the active core, also ensuring good uniformity of the population inversion along the waveguide amplifier. Although longitudinal multimode pumping by high power LEDs in the visible can potentially lead to low cost integrated amplifiers, further material optimization is required. In particular, we show that when dealing with high pump intensities, confined carrier absorption seriously affects the amplifier performance, and an optimization of both Si-nc and Er³⁺ concentrations is necessary.

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References and links

1. B. Jalali, S. Fathpour, "Silicon Photonics," *J. of Lightwave Technol.*, **24**, pp. 4600-4615 (2006).
2. H. Park, A. W. Fang, O. Cohen, R. Jones, M. J. Paniccia, J. E. Bowers, "A Hybrid AlGaInAs-Silicon Evanescent Amplifier," *IEEE Photon. Technol. Lett.*, **19**, 230-232 (2007).
3. A. W. Fang, H. Park, O. Cohen, R. Jones, M. J. Paniccia, and J. E. Bowers, "Electrically pumped hybrid AlGaInAs-silicon evanescent laser," *Opt. Express*, **14**, 9203-9210 (2006).
4. S. Ossicini, L. Pavesi, F. Priolo, "*Light Emitting Silicon For Microphotonics*," Springer Tracts in Modern Physics 194 (Springer-Verlag, Berlin) (2003).
5. J. H. Shin, J. Lee, H-S. Han, J-H. Jhe, J. S. Chang, S-Y. Seo, H. Lee, N. Park, "Si Nanocluster Sensitization of Er-Doped Silica for Optical Amplifier Using Top-Pumping Visible LEDs," *IEEE J. Sel. Top. Quantum Electron.* **12**, 783-796 (2006).
6. L. H. Slooff, P. G. Kik, A. Tip, A. Polman, "Pumping Planar Waveguide Amplifiers Using A coupled Waveguide System," *J. Lightwave Technol.* **19**, 1740-1744 (2001)
7. N. Daldosso, D. Navarro-Urrios, M. Melchiorri, C. Garcia, P. Pellegrino, B. Garrido, C. Sada, G. Battaglin, F. Gourbilleau, R. Rizk, L. Pavesi, "Er-Coupled Si Nanocluster Waveguide," *IEEE J. Sel. Top. Quantum Electron.* **12**, 1607-1617 (2006).
8. H.E. Hernandez-Figueroa, "Simple Nonparaxial Beam-propagation method for Integrated Optics," *J. Lightwave Technol.* **12**, 644-649 (1994).
9. G. Clauss and S. Valette, "Optics-integrated structure comprising in a substrate at least a non-buried guide portion and method for making same," US Patent No US 2004/0057690 A1 (2004).
10. D. Navarro-Urrios, M. Melchiorri, N. Daldosso, L. Pavesi, C. Garcia, P. Pellegrino, B. Garrido, G. Pucker, F. Gourbilleau, and R. Rizk, "Optical losses and gain in silicon-rich silica waveguides containing Er ions" *J. Lumin.* **121**, 249-255 (2006)

11. K.C. Reichmann, P.P Iannone, M. Birk, N.J. Frigo, D. Barbier, C. Cassagnettes, T. Garret, A. Verlucio, S. Perrier, J. Phlipsen, "A Eight-Wavelength 160-km Transparent Metro WDM Ring Network Featuring Cascaded Erbium-Doped Waveguide Amplifiers," *IEEE Photon. Technol. Lett.* **13**, 1130-1133 (2001).
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1. Introduction

Photonic integration is rapidly progressing for realizing small form factor components which can potentially provide several functionalities for applications in optical interconnects as well as in optical communication systems. Among the several technologies, silicon photonics [1] provides a powerful platform for dense integration of several components. However, the difficulties in realizing silicon lasers and amplifiers have recently led to alternative approaches such as hybrid configurations, in which electrically pumped AlGaInAs Quantum Well materials are bonded on Silicon waveguide structures [2][3]. Although very attractive in terms of integration and cost effectiveness, waveguide amplifiers based on this hybrid approach would likely suffer from bit-pattern effect and cross-gain-modulation. On the other hand, Er³⁺ doped silica waveguide amplifiers (EDWA) can be easily integrated on silicon wafers but their practical applications are hindered by their high cost, mainly related to the requirement of expensive single mode pump lasers, and by their lower performance compared to standard EDFAs.

One way to overcome these limitations is the use of silicon nanoclusters (Si-nc) as efficient sensitizers for Er³⁺ ions [4]. Pump light from low-cost broadband excitation lamps can be efficiently absorbed by the Si-nc which then transfer their excitation to Er³⁺ ions. This feature results in an effective Er³⁺ excitation cross-section which is four-five orders of magnitude larger than for Er³⁺ in silica, opening the way to the use of low-cost broadband light sources, such as LEDs, instead of single mode pump laser.

Longitudinal single mode pumping is not practical in such waveguide amplifiers, due to the extremely high absorption cross-section of Si-nc in the visible, which would completely absorb the pump light over a very short longitudinal distance (few hundred microns). Top pumping schemes have then been proposed to overcome this limitation [5], in which arrays of low cost visible LEDs are butt-coupled to the active waveguide from the top. Although cost-effective, this top pumping configuration provides low pump power intensity over the active waveguide and quite poor pumping efficiency.

In this paper, we propose a highly efficient longitudinal multimode pumping scheme in which incoherent pump light in the visible, from high power LEDs, is longitudinally guided by a multimode waveguide structure, and gradually transferred to the active core by evanescent coupling. Due to the low multimode waveguide loss at pump wavelength and gradual transfer of pump energy to the active core, the proposed scheme overcomes the intrinsic limitation of longitudinal single mode pumping which would prevent the pump light from being gradually absorbed along the whole active waveguide length; it also performs better than top pumping due to higher pump light intensity achievable within the active core along its longitudinal extension. The proposed pumping configuration, previously suggested for Nd³⁺ doped waveguide amplifiers [6], can be optimized to ensure good uniformity of pump light distribution and Er³⁺ population inversion along the active core. Theoretical predictions, based on propagation and rate equations for the coupled Er³⁺ - Si-nc system, demonstrate the great potential of this multimode pumping scheme in terms of efficiency and flexibility. However, when dealing with high pump intensity values within the active core, confined carrier absorption (CCA) seriously affects the amplifier performance; further material optimization is then required to counteract this detrimental effect and an optimization of both Si-nc and Er³⁺ concentrations is necessary.

2. Theoretical model

The proposed model for analyzing multimode longitudinally pumped Si-nc sensitized EDWAs is directly derived from Maxwell's equations and describes the coupling between Si-

nc and Er³⁺ ions through population-rate equations. Considering for simplicity slab waveguides, and using the slowly varying amplitude approximation, the following equations are derived for the transverse electric polarized signal and pump fields:

$$-2j\beta_s k_{os} \frac{\partial \psi_s}{\partial z} = \frac{\partial^2 \psi_s}{\partial y^2} + k_{os}^2 (\epsilon_{xs} - \beta_s^2) \psi_s \quad (1)$$

$$-2j\beta_p k_{op} \frac{\partial \psi_p}{\partial z} = \frac{\partial^2 \psi_p}{\partial y^2} + k_{op}^2 (\epsilon_{xp} - \beta_p^2) \psi_p \quad (2)$$

where $\psi_{s,p}$ are the slowly varying amplitudes of the signal and pump electric fields $E_{xs,p}$, $k_{os,p}$ are the free-space wave numbers, $\beta_{s,p}$ the effective propagation constants and $\epsilon_{xs,p}$ the complex permittivities, whose imaginary parts are computed solving steady-state population rate-equations and conservation laws of the coupled Si-nc / Er³⁺ system [5]. The complex permittivities at the signal and pump wavelengths can be written as:

$$\epsilon_{xs} = \epsilon_{Rxs} + j \left[\frac{n_r \lambda_s}{2\pi} (\alpha_s + \sigma_{CCA} N_b + \sigma_{12} N_1 - \sigma_{21} N_2) \right] \quad (3)$$

$$\epsilon_{xp} = \epsilon_{Rxp} + j \left[\frac{n_r \lambda_p}{2\pi} (\alpha_p + \sigma_{ab} N_a) \right] \quad (4)$$

where $\epsilon_{Rxs,p}$ are the real parts of the permittivities at the signal and pump wavelengths, N_1 and N_2 are the population densities of the ⁴I_{15/2} and ⁴I_{13/2} Er³⁺ levels respectively, N_a the population of the fundamental Si-nc level and $\alpha_{s,p}$ the background losses at signal and pump wavelengths. σ_{Er12} and σ_{Er21} are the Er³⁺ absorption and emission cross-sections at the signal wavelength (at around 1.55 μ m) and σ_{ab} the Si-nc absorption cross-section at the pump wavelength (477 nm, corresponding to large absorption of the Si-nc). CCA is described by its cross-section σ_{CCA} at λ_s , and is modelled as an additional loss in the dielectric permittivity at the signal wavelength; this process is clearly detrimental as it induces absorption of signal photons by the excited Si-nc in level b, which are promoted to a higher energy level and then decay back to level b.

Population densities N_1 , N_2 and N_a are obtained solving the steady-state rate-equations and conservation laws of the coupled Er³⁺ / Si-nc system, which are not reported here for compactness [5]. These equations describe the energy transfer from excited Si-nc to Er³⁺ ions in the fundamental level which promotes Er³⁺ ions to the metastable level ⁴I_{13/2}. Also up-conversion from the Er³⁺ metastable level is included as it can strongly degrade the amplifier performance at high concentration levels. Note that amplified spontaneous emission is not included in the model and also fast Auger processes [7] are neglected because they are outside the scope of this paper.

The solution of equations (1) and (2), which are indirectly coupled by the imaginary parts of the permittivities, is performed numerically using a 2-D split-step finite-element method [8]. A Galerkin based finite-element discretization is applied to the dependence on the transverse dimension y , and the approximate solutions $\psi_{s,p}$ at $z_2 = z_1 + \Delta z$ are obtained solving two linear systems (Crank-Nicolson scheme) in conjunction with the splitting operator technique [8]. At each step of the propagation algorithm, the complex permittivities are locally computed in each nodal point of the active region.

3. Waveguide structure and numerical results

In this section we show numerically how multimode pumping in the visible can be effectively performed by evanescent pump light coupling to the active core. The waveguide structure for multimode longitudinal pumping, which is discretized along the y direction by 3200 finite elements, is schematically shown in Fig. 1. The 4 μ m doped silica layer is characterized by a refractive index $n_3=1.464$ and is deposited on the top of a pure silica layer ($n_2=1.45$), grown

on a Si substrate for C-MOS compatibility; the active core, which can be realized by thermally annealing a thin Er^{3+} doped silicon rich oxide layer, has a width of $0.8 \mu\text{m}$ and refractive index $n_1=1.6$ with Si-nc content of $8 \times 10^{24} /\text{m}^3$ [6]. The active region is separated from the doped silica layer by another thin silica layer (width: $0.8 \mu\text{m}$, $n_2=1.45$). Note that the presence of Si-nc raises the refractive index of the Er^{3+} doped layer, allowing for easy waveguide formation on oxidized Si substrates. Both pump and signal lights propagate along the z direction in Fig. 1. Pump light at 477 nm is guided in multimode condition by the doped silica layer while the Er^{3+} doped thin layer provides a single mode waveguide for signals at around 1532 nm .

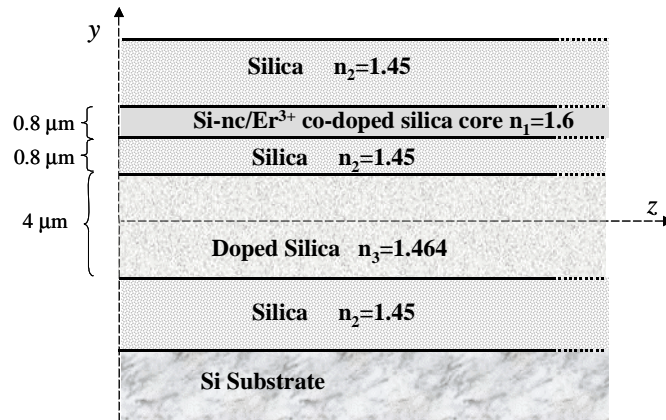


Fig. 1. Waveguide structure and refractive indices

The material parameters used in the simulations are reported in Table I and are taken from literature [5][7].

Table 1. Si-nc Er^{3+} doped layer parameters

Parameter used in the waveguide design	Parameter value
Si-nc to Er^{3+} energy transfer coefficient	$2 \times 10^{-20} \text{ m}^3/\text{s}$
Er^{3+} absorption cross section at 1532 nm	$6.6 \times 10^{-25} \text{ m}^2$
Er^{3+} emission cross section at 1532 nm	$5.7 \times 10^{-25} \text{ m}^2$
Si-nc absorption cross-section at 477 nm	$2 \times 10^{-20} \text{ m}^2$
Erbium concentration	$1 \times 10^{26} - 3 \times 10^{26} \text{ ions}/\text{m}^3$
Si-nc content	$5 \times 10^{23} - 8 \times 10^{24} /\text{m}^3$
Si-nc recombination lifetime	$25 \mu\text{s}$
Er^{3+} metastable level lifetime	8.5 ms
Pump power density range	$4 - 8 \times 10^4 \text{ W}/\text{m}$
Signal power density	$1 \text{ W}/\text{m}$
Er^{3+} metastable up-conversion coefficient (with $N_{\text{Er}}=3 \times 10^{26} \text{ ions}/\text{m}^3$)	$5.95 \times 10^{-23} \text{ m}^3/\text{s}$
Background losses $\alpha_{p,s}$	$0.5 \text{ dB}/\text{cm}$

The pump coupling properties from multimode waveguide to the active core has been optimized by carefully designing the slab structures in Fig. 1. The $4 \mu\text{m}$ width silica doped core is excited with a Gaussian beam along the y direction at 477 nm , defined as $\psi(y, z=0) = \psi_0 \exp(-y^2/w^2)$, with $w=1.75 \mu\text{m}$ and characterized by a pump power density of $6 \times 10^4 \text{ W}/\text{m}$, which well describes coupling from a LED by a tapered waveguide. Note that as the active

waveguide is narrow and closely spaced to the passive multimode waveguide, coupling pump and signal beams simultaneously could be an issue. However the problem can be effectively overcome by using a structure in which the signal light is coupled to the active core through a partially buried waveguide structure, possibly realized through an ion-exchange and bonding technique as described in reference [9].

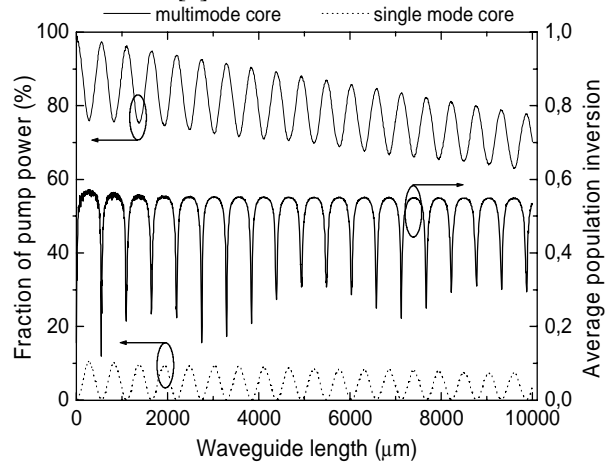


Fig. 2. Pump power transfer and average inversion characteristics

Figure 2 reports the normalized pump power transfer characteristic of the waveguide structure shown in Fig. 1; a beat length of approximately 550 μm can be noted, with a maximum coupled pump power into the active core which is approximately 10% of the total pump power at the waveguide input. Coupling from the multimode core to the active region takes place gradually along the waveguide length, ensuring effective pumping along the amplifier. Figure 2 also reports the average population inversion along the waveguide, computed as the average value of $(N_2 - N_1)/N_{\text{Er}}$ across the active region (N_{Er} is the total Er^{3+} concentration); although the average population inversion decreases at the pump power minima along the active core, it is always positive, ensuring a monotonic increase of the signal power along the amplifier.

Also note that this multimode coupling overcomes the main limitation of single mode longitudinal pumping, in which pump light in the visible would be completely absorbed by the Si-nc within a very short longitudinal section of the waveguide amplifier. We have then investigated the amplification properties of the Si-nc sensitized EDWA by exciting the active waveguide with its fundamental mode at 1532 nm, and the doped silica layer with a Gaussian beam at 477 nm. Note that the pump coupling mechanism is slightly dependent on the pump beam excitation characteristics; we have verified that changing the spot size of the Gaussian beam and also exciting the multimode waveguide by its fundamental mode at 477 nm, does not substantially affect the coupling characteristics reported in Fig. 2.

The amplifier gain characteristics at constant pump power density of 6×10^4 W/m, have been investigated by changing the Si-nc and Er^{3+} concentrations, considering a 3 cm long waveguide (for slab waveguides, which are invariant along one transverse dimension, the pump and signal powers are well described by linear power densities in W/m; assuming for example a 4 μm transverse dimension along x in Fig. 1, a pump power density of 6×10^4 W/m would correspond to 240 mW, easily achievable with commercial LEDs).

The fraction of pump power coupled into the active core can be flexibly controlled by optimizing the waveguide geometry and refractive index profile. Figure 3 shows the pump and signal electric field distributions along the transverse coordinate y , at the input and output of a 3 cm long waveguide amplifier; input pump and signal power densities are 6×10^4 W/m and 1 W/m respectively. It is evident from Fig. 3 that the pump light is transferred to the active layer and then gradually absorbed along the waveguide; on the other hand the signal at

1532 nm propagates in single mode condition and is effectively amplified within the active core along the waveguide amplifier. Due to the higher refractive index of the active waveguide, there is no signal coupling to the multimode waveguide.

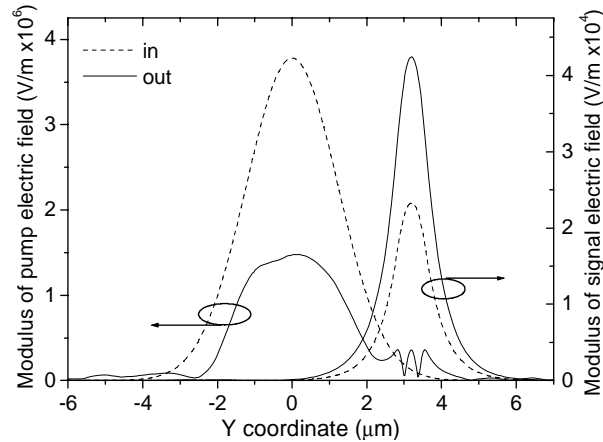


Fig. 3. Pump and signal light distributions at waveguide input/output

The maximum pump power intensity achievable within the active core by this multimode pumping scheme can be up to two-three order of magnitude greater than in case of top pumping [5], providing much higher gain (typical pump intensity achievable in top pumping schemes with commercially available LEDs is limited to $3 \times 10^5 \text{ W/m}^2$). Assuming a constant pump intensity inside the active core in order to simulate a top-pumping scheme, well justified by the fact that only a few percentages of pump power would be absorbed by a layer of only $0.8 \mu\text{m}$ thickness, we obtained a maximum gain of 0.25 dB/cm for optimized Er^{3+} and Si-nc concentrations, much lower compared to the values achieved with the proposed longitudinal pumping scheme which are reported next.

Figure 4 shows the small signal gain at 1532 nm versus Si-nc content for different Er^{3+} concentrations, with and without CCA (we have assumed $\sigma_{\text{CCA}} = 10^{-23} \text{ m}^2$, 1-2 orders of magnitude lower than in bulk Si as recently suggested in [10]).

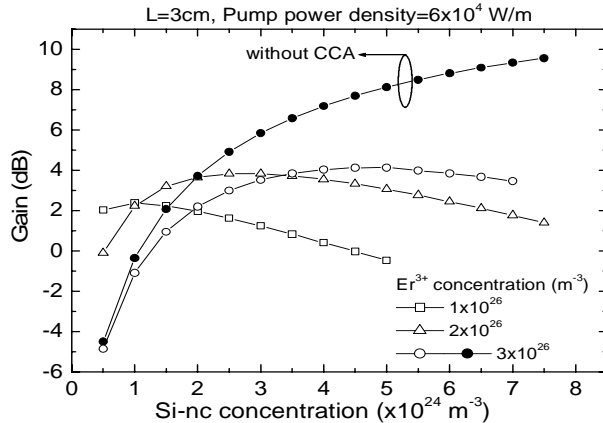


Fig. 4. Gain versus Si-nc content at different Er concentrations

The graph clearly shows that CCA seriously affects the amplifier performance; an optimum range of Si-nc concentrations must be identified, for each Er^{3+} concentration, above and below which the signal gain decreases (for $N_{\text{Er}} = 3 \times 10^{26} \text{ ions/m}^3$ the Si-nc content should be within the range $3.5 \times 10^{24} \text{ m}^{-3} - 7 \times 10^{24} \text{ m}^{-3}$). It is also evident that due to low available gain,

the material properties should be improved in order to make the device attractive for practical applications.

We have then investigated the amplifier small signal gain characteristics versus waveguide length at different pump power densities (Fig. 5) for optimized Er^{3+} and Si-nc concentrations, respectively $N_{\text{Er}}=3 \times 10^{26}$ ions/ m^3 and $N_{\text{Si-nc}}=6 \times 10^{24}$ m^{-3} . A significant net gain (greater than 8 dB) requires long waveguides (longer than 6 cm) and high power densities, making integration and pump light coupling more difficult.

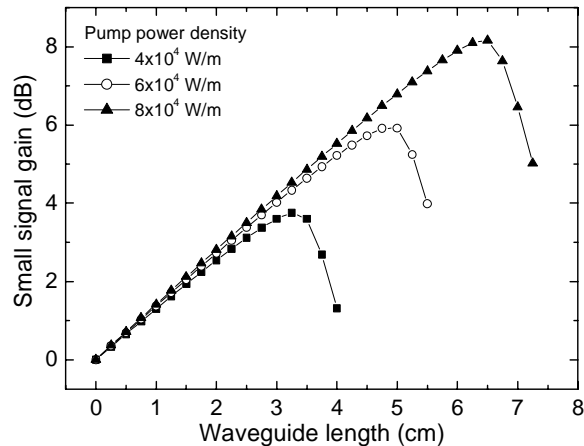


Fig. 5. Gain versus waveguide length at different pump power densities

We have finally studied the amplifier gain saturation for $N_{\text{Er}}=3 \times 10^{26}$ ions/ m^3 , and $N_{\text{Si-nc}}=6 \times 10^{24}$ m^{-3} , with pump power density of 1.5×10^5 W/m. For an 8 cm long waveguide, and assuming an active core dimensions of $0.8 \mu\text{m} \times 1.5 \mu\text{m}$, we obtain a 3-dB gain compression saturated output power of 8.4 dBm, which is slightly lower compared to standard EDWAs [11] as could be expected due to the fact that CCA is affecting the amplifier performance.

4. Conclusions

We have presented and investigated a multimode longitudinal pumping scheme for Si-nc sensitized EDWAs which overcomes the main limitation of top and longitudinal single-mode pumping configurations; it provides great flexibility in controlling the pump intensity within the active core, along its complete longitudinal extension. Although these features can potentially lead to more efficient and cost effective integrated amplifiers, further optimization of the material properties are required to counteract detrimental effects arising at high pump intensity, such as confined carrier absorption.

Acknowledgments

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