Erbium and Silicon nanocrystals for light amplification

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Integrated EDWAs (Erbium-Doped Waveguide Amplifiers) are fundamental elements in planar photonic circuits: many efforts are being focused in making them as compact and cheap as possible. The use of broadband efficient sensitizers for Er^{3+} ions relaxes the expensive conditions needed for the pump source and raises the performances of the optical amplifier. Within this context, Si nanoclusters (Si-nc) in silica matrices have showed many properties that make them optimum sensitizers. The effective excitation cross section of the Er^{3+} 1.54 μm luminescence (σ_{exc}) broadens and strengthens up to values of 10^{-16} cm^2, when visible light is used. These σ_{exc} values are orders of magnitude larger than those of Er^{3+} in SiO_2, where one measures absorption cross section values of 10^{-21} cm^2 at λ_{exc}=980 nm. Quantum efficiencies greater than 60% and Si-nc to Er^{3+} transfer rates higher than 1 μs^{-1} by pumping at 488 nm have been also measured. In addition to the increase of σ_{exc}, Si-nc increase the average refractive index of the dielectrics, allowing good light confinement, and conduct electrical current, which opens the route to electrically pumped optical amplifiers [1]. Encouraging results about Er coupled Si-nc silica waveguides have been reported by Shin et al. [2] and Daldosso et al. [3, 4]. However, the understanding of the material system is still far to be accomplished and strong detrimental processes, such as cooperative up-conversion and confined carrier absorption (CA) within the Si-nc, are to be figured out.

Our studies are focused on Er-doped Si-rich silica layers. The waveguides have been prepared by reactive magnetron co-sputtering. The incorporation of Si excess in the film was obtained by mixing the plasma with hydrogen, owing to its ability to reduce the oxygen provided by the silica target. More details on the process can be found elsewhere [5]. After the deposition of 1 μm thick Er/SRO (Silicon Rich Oxide) layer, a 1 μm thick SiO_2 cladding layer has been deposited by sputtering a SiO_2 target in pure argon plasma. Then the wafers have been annealed for different times at different temperatures under pure N_2 flux to activate Er^{3+} ions, to induce the precipitation of the Si excess into nanoclusters and to improve the energy transfer between the Si-nc and the Er^{3+} ions. About 7% of Si excess and $N_{Er}=4\times10^{20}$ at./cm^3, has been found by RBS measurements for the optimized series of samples.

In this work we present a systematic study on the insertion losses, photoluminescence, lifetime and pump/probe measurements, which have been carried out on rib-loaded waveguides.

- Optical transmission measurements both in the visible and at 1.55 μm have been performed to determine absorption losses and extract the absorption cross section of Si-nc and Er ions, respectevely. Propagation losses as low as 1 dB/cm have been found at 1.6 μm in such a waveguides.
- Confined carrier absorption (CA) plays an important role as it has revealed as an extra source of losses generated due to the signal photon absorption from the pump generated excitons within the Si-nc. The carrier absorption mechanism at 1.55 μm has been investigated by pumping at different wavelengths (i.e. 476, 488, 532 nm). At the highest photon flux, the measured losses were about 6 dB/cm. We demonstrate that the dynamics of the CA is the same of the luminescence. The measured risetime for the CA is 20 μs and the decay time 60 μs, while the β factor of the stretched exponential is 0.5. The time resolved photoluminescence stretched exponential best fit gives a decay time of 20 μs and a β factor of 0.5, in agreement with the CA analysis.
- We demonstrate that the low excitable erbium fraction through the Si-nc is the main limiting factor to achieve optical gain as it is evidenced from the pump flux dependence of the effective average excitation cross section and from photoluminescence measurements at non resonant pumping wavelengths. A short range (0.5 nm) distance dependent interaction model [6] is developed that accounts for this low Er population inversion. The model points to the low density of Si-nc ($3–5\times10^{17}$ cm^{-3}) as the ultimate limiting step for indirect Er excitation in this system.
- The role of cooperative up-conversion in shifting towards higher fluxes the conditions for population inversion is also discussed through lifetime measurements.

Finally, in the optimized samples, we present amplification measurements, where optical gain and partial inversion of the Er^{3+} ions excited via Si-nc are presented and discussed.

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