Miniature erbium doped planar optical amplifiers

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Abstract: Three new erbium-doped planar optical amplifier concepts are demonstrated: Eu and Yb co-doping to increase the gain; Si nanocrystals as sensitizers to replace the pump laser by a broad-band light source; and electrical pumping in a rare earth doped electroluminescent polymer.

1. Introduction

Erbium-doped optical amplifiers are of great importance in optical communications technology, to compensate for waveguide losses, coupling and splitting losses etc. Previously, we have demonstrated optical amplification in an erbium-doped Al_2O_3 photonic integrated circuit with a dimension of 4 mm^2, the smallest reported so far (see Fig. 1).[1] We have also demonstrated the highest net gain per unit length (4.1 dB/cm) in an erbium-doped phosphate glass waveguide amplifier, pumped at only 22 mW.[2]

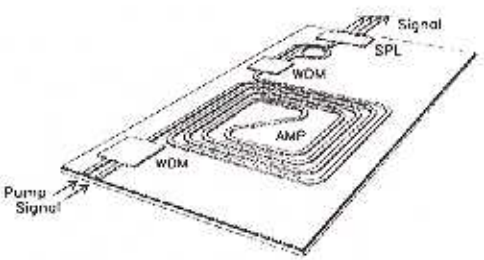

Fig. 1 Layout of a miniature planar optical amplifier: an amplifying loop section is integrated with a 1x4 splitter and wavelength division multiplexers for pump and signal beams.

In this paper, we will report a new concept to improve the performance of Er-doped amplifiers using Eu and Yb co-doping. We will also demonstrate that Si nanocrystals in silica glass are efficient sensitizers for Er, thereby removing the need for the pump laser. Finally, we will show how an Er-doped polymer waveguide amplifier can be made, and may be pumped using electrical excitation.

2. Eu and Yb co-doping to increase the gain

In order to achieve high gain in Er-doped planar optical amplifiers, high Er concentrations are required. However, at concentrations higher than typically 0.1 at.% strong co-operative upconversion interactions between excited Er ions take place,[3] that reduce the population of excited Er. As a result, high pump powers are required to achieve reasonable gain. High pump powers however, lead to excited state absorption that then further reduces the pump efficiency. To reduce these gain-deteriorating effects, Eu and Yb co-doping can be used.

The $^7F_0 \rightarrow {}^7F_4$ transition in europium is resonant with the $^4I_{11/2} \rightarrow {}^4I_{13/2}$ transition in Er. Therefore, energy transfer from Er to Eu can help to reduce the population of Er in the $^4I_{11/2}$ level, and to increase the population of the $^4I_{13/2}$ level that is used for amplification.[4] This is particularly useful in amplifiers that are pumped at 980 nm, and which have a long luminescence lifetime of the $^4I_{11/2}$ level. Figure 2 shows an optical micrograph of two Er-doped Y_2O_3 planar waveguides pumped at 980 nm, the top one doped with Er only (0.2 at.%), the bottom one co-doped with Eu (0.4 at.%). It can clearly be seen that Eu co-doping reduces the (green) emission that is a signature of second-order upconversion to the $^4S_{3/2}$ level of Er.

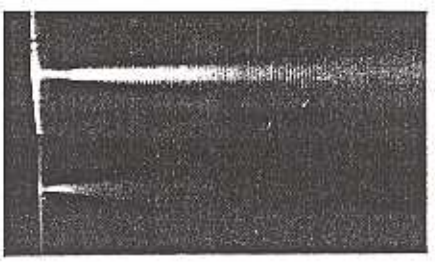

Fig. 2 Optical images of Er-doped Y_2O_3 planar waveguides without (top) and with (bottom) Eu co-doping. Eu co-doping reduces the green upconversion luminescence.

One well-known technique to enhance the effective excitation efficiency of Er is by co-doping with ytterbium. As the $^2F_{5/2}$ level of Yb is resonant with the Er $^4I_{11/2}$ level, Yb→Er energy transfer can take place. This is then followed by a rapid non-radiative relaxation to the $^4I_{13/2}$ level in Er. As the absorption cross section of the Yb $^2F_{5/2}$ level (at 975 nm) is roughly tenfold higher than that of Er, this may cause an increased Er excitation rate. We have performed experiments on Er-doped Al_2O_3 waveguides fabricated by co-sputtering (0.3 at.% Er) implanted with Yb (0.3 at.%), and measured the Yb→Er energy transfer rate to be 2500 s^{-1}.[5] The optimum Yb concentration depends strongly on the pump power used. If too high Yb concentrations are used, the pump power is not efficiently distributed over the waveguide length, and the presence of Yb can even reduce the gain, as shown in Fig. 3.[6]

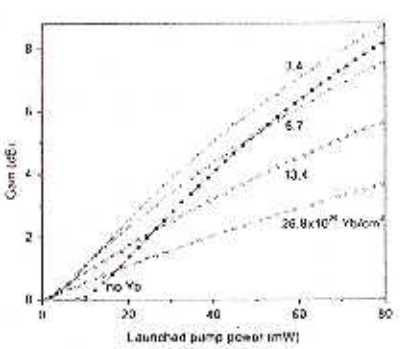

Fig. 3 Optical gain as a function of pump power in an Yb-sensitized Er-doped planar amplifier pumped at 980 nm, calculated for different Yb concentrations.

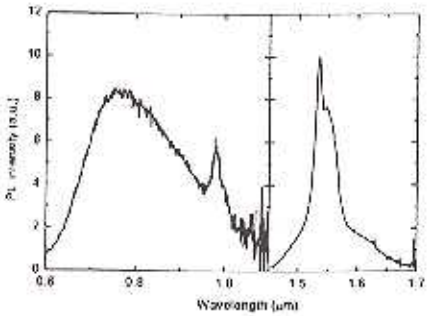

Fig. 4 Photoluminescence spectrum of Er and Si nanocrystal doped SiO_2, pumped at 458 nm.

3. Si quantum dots to remove the pump laser

Silicon quantum dots are known to absorb and emit light at wavelengths that are dependent on their size, due to a quantum confinement effect. We have fabricated Si nanocrystals in SiO_2 by Si ion implantation, followed by thermal annealing at 1100 °C. The quantum dot diameter ranges between 2-5 nm. Such quantum dots have absorption cross-sections as high as 10^{-14} cm^2 depending on the excitation energy and size. Next, we have doped these layers with Er by ion implantation with the aim to study the energy transfer between quantum dots and Er. The nanocrystal bandgap is well above that of bulk Si (1.1 eV), while the Er $^4I_{15/2} \rightarrow {}^4I_{13/2}$ transition occurs at 0.8 eV.

Figure 4 shows a PL spectrum of a Si nanocrystal-doped layer implanted with a peak concentration of 1.8 at.% Er, measured at 300 K. The broad feature between 0.6 and 1.1 μm is due to the radiative recombination of quantum-confined excitons in nanocrystals that do not couple to Er. Two Er-related luminescence lines at 980 nm ($^4I_{11/2} \rightarrow {}^4I_{15/2}$ transition) and 1.53 μm ($^4I_{13/2} \rightarrow {}^4I_{15/2}$ transition) are also clearly distinguished. These PL spectra are measured under 458-nm excitation, a wavelength at which direct excitation of Er does not occur. In fact, PL excitation spectra clearly indicate that the Er is not excited directly into a 4f manifold, but rather indirectly, through the recombination of optically generated excitons in the nanocrystals. In this way the quantum dots act as efficient sensitizers for Er. From measurements as a function of temperature and Er concentration we conclude that (1) the Er is excited through a strong coupling mechanism (i.e. a nanocrystal nearby an Er ion is optically dead), (2) the excitation rate at room temperature is >10^6 s^{-1}, and (3) one nanocrystal can excite only 1-10 Er ions at a time.[7]

As the nanocrystals have a very broad absorption spectrum and high cross-section, this sensitization scheme can be employed to design Er-doped optical amplifiers that can be pumped with a broad-band light source, rather than an (expensive) pump laser.

4. Polymer waveguide amplifiers

The importance of polymer optical waveguide technology is growing rapidly. First of all, polymer fibers are used more and more in short-distance optical links. Also, thin film integrated optical devices based on polymers become important. It would be of great interest to dope a polymer waveguide with Er in order to fabricate a polymer-based optical amplifier. Unfortunately, the erbium salts typically used in wet chemical processing are insoluble in the polymer precursors. To overcome this problem, we have developed a nanocomposite material composed of Er-doped SiO_2 colloids embedded in a polymer. In this way the excellent properties of both materials: SiO_2 as a good host for Er, and the easy polymer processing, are combined. We have fabricated 360-nm diameter SiO_2 colloids by wet chemical processing using tetraethoxysilane, and implanted them with Er to concentrations in the range 0.2–1.1 at.%. Clear photoluminescence at 1.5 μm is observed with lifetimes as high as 17 ms are observed, corresponding to a luminescence quantum efficiency as high as 80 %, indicating the colloid material is a good host for Er.[8] Optical gain calculations show that if these colloids could be embedded in a high-index-contrast waveguide with well-confined modes, an optical gain of 4 dB could be achieved for a 3-cm long waveguide at a pump power of only 10 mW.

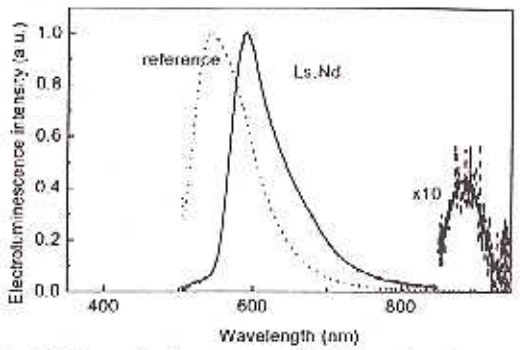

Fig. 5 Electroluminescence of Nd-doped polymer light emitting diode based on a ITO/PEDOT/F8BT:Ls.Nd^{3+}/Ca /Al structure, biased at 31 V (~100 mA/cm^2) (solid line).

We have also fabricated a polymer LED doped with a lissamine-sensitized Nd-doped organic cage complex. Room-temperature emission from Nd at 890 nm is observed under electrical excitation (Fig. 5).[9] This material may be used for the fabrication of an electrically pumped rare earth doped polymer amplifier.

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