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ERBIUM-DOPED PLANAR OPTICAL AMPLIFIERS

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Four new miniature erbium-doped planar optical amplifier concepts are demonstrated. They are based on: Eu and Yb co-doped Al_2O_3:Er; Si nanocrystal-sensitized SiO_2:Er; a rare-earth doped electroluminescent polymer; and a Si-based photonic crystal.

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]

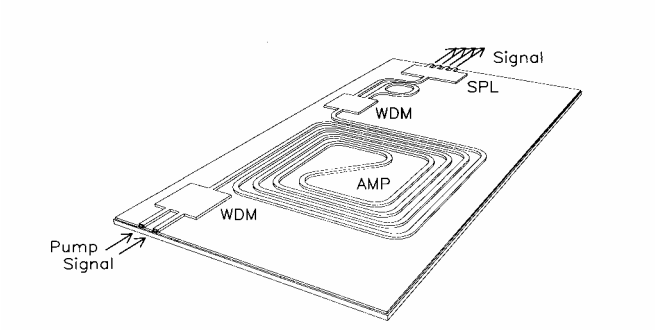

Fig. 1 Layout of a miniature planar optical amplifier: an amplifying loop section is integrated with a 1x4 splitter and wavelength division multiplexers for pump and signal beams.

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. Next, we will show how an Er-doped polymer waveguide amplifier can be made, and may be pumped using electrical excitation. Finally, we will illustrate the use of Si photonic crystals for further device miniaturization of erbium-doped photonic integrated circuits.

2. Europium and ytterbium co-doping to increase the gain in miniature Er-doped amplifiers

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.

As can be seen in the level diagram in Fig. 2(a), 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(b) 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

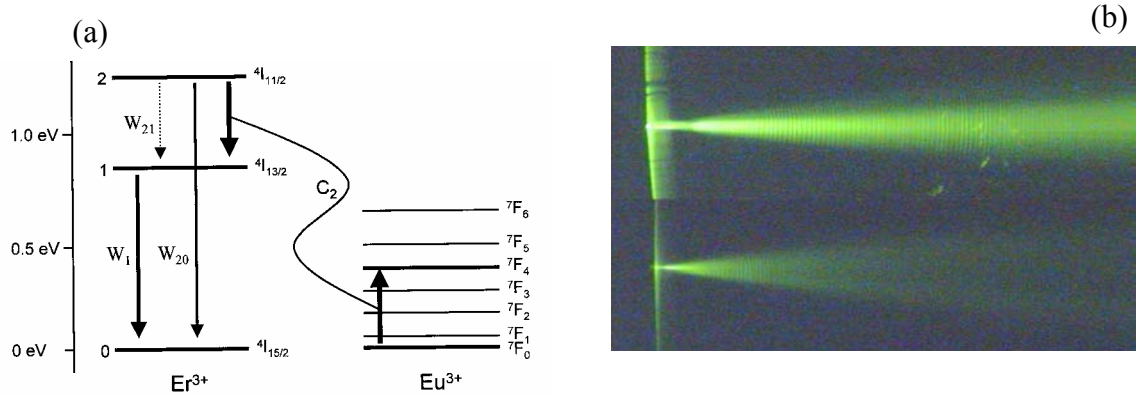

Fig. 2 (a) Schematic energy level diagram for energy transfer between Er and Eu. (b) Optical micrograph showing the green upconversion luminescence intensity for Er-doped planar Y_2O_3 waveguides with (bottom) and without (top) Eu codoping.

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.

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.[6]

3. Si quantum dots as sensitizers for Er

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. Figure 3(a) shows a schematic of the energy bands involved. The nanocrystal bandgap is well above that of bulk Si (1.1 eV), while the Er $^4I_{15/2}$→$^4I_{13/2}$ transition occurs at 0.8 eV.

Figure 3(b) 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 ($^4I_{11/2}$→ $^4I_{15/2}$ transition) and 1.53 μm ($^4I_{13/2}$→$^4I_{15/2}$ 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]

An added advantage of the use of Si nanocrystals as sensitizers for Er is that they locally raise the refractive index and thereby create a waveguide. Figure 3(c) shows an intensity map of a 1.5 μm mode that was guided along a Si nanocrystal doped channel waveguide in SiO_2. Excellent mode confinement is observed. Optical gain measurements in these waveguides are underway and a maximum gain of 1 dB/cm is predicted. As the nanocrystals have a very broad absorption spectrum

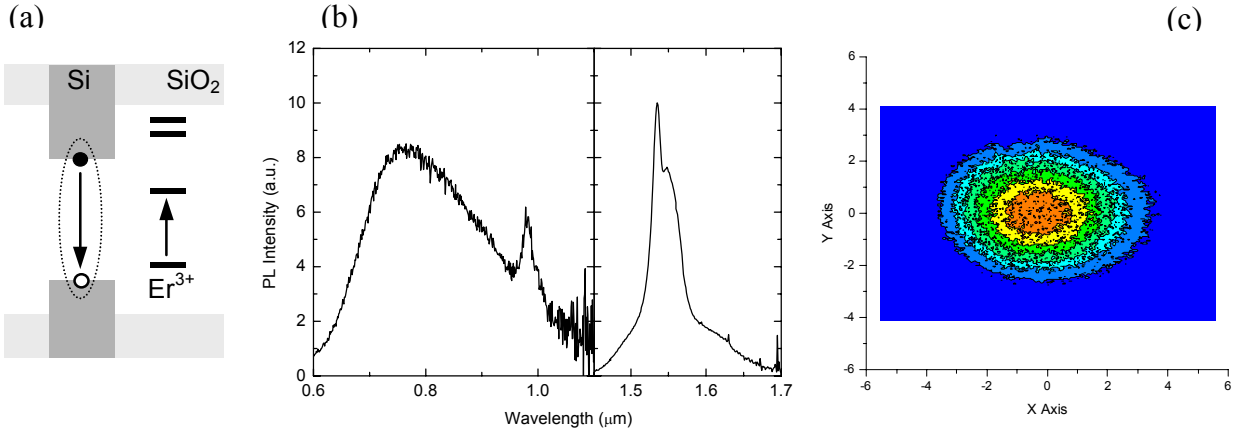

Fig. 3 (a) Schematic of energy levels involved in energy transfer between Si quantum dots and Er. (b) PL spectrum of Er-doped Si nanocrystal-doped SiO_2 measured at room temperature. Pump wavelength 458 nm. (c) Optical mode profile at 1.5 μm of a Si nanocrystal-doped channel waveguide in SiO_2.

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. Rare-earth doped 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.

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.[9] This material may be used for the fabrication of an electrically pumped rare earth doped polymer amplifier.

5. The ultimate miniaturization: photonic crystal waveguides

The size of a photonic integrated circuit is often determined by the smallest waveguide bending radius that can be made. For example, in the device layout of Fig. 1 for Al_2O_3, the minimum radius is 50 μm. Thus, the total area of the amplifier spirals in Fig. 1 is 1 mm^2. The radius could be further reduced by using a higher-index core material. Alternatively, a photonic bandgap effect may be used. As an example, we show our work on two-dimensional photonic crystals made of Si pillars. Figure 4(a) shows an array of 5 μm tall Si pillars, 205 nm in diameter, arranged in a square lattice with 570 nm pitch, made by deep anisotropic etching using an SF_6/O_2 electron cyclotron resonance

(a) (b)

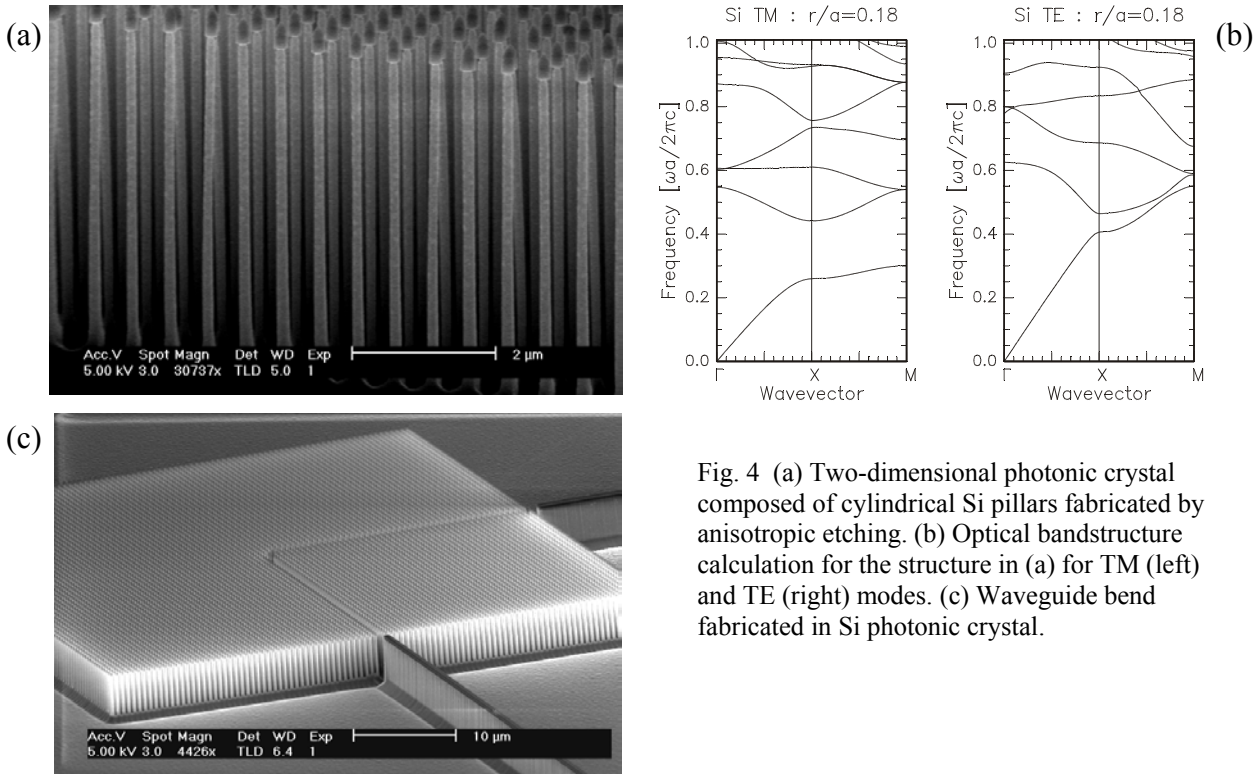

Fig. 4 (a) Two-dimensional photonic crystal composed of cylindrical Si pillars fabricated by anisotropic etching. (b) Optical bandstructure calculation for the structure in (a) for TM (left) and TE (right) modes. (c) Waveguide bend fabricated in Si photonic crystal.

driven plasma.[10] Optical bandstructure calculations for this structure are shown in Fig. 4(b) for TM and TE modes. A large bandgap (37 % of the central frequency) is observed for TM modes for our (pillar radius)/pitch ratio of 0.18. No bandgap is found for TE modes. For a pitch of 570 nm (as in Fig. 4(a)) the center gap for TM modes lies exactly at 1.53 μm. Figure 4(c) shows a waveguide bend that can be made using this material: an array of Si pillars is removed to define a waveguide in the pillar structure, in which otherwise no modes at 1.5 μm exist. In order to achieve confinement in the third dimension, a 2 μm thick region of the Si structure was amorphized before processing, using 4 MeV Xe irradiation. Input and output waveguides are integrated with the structure as can be seen in Fig. 4(c). Calculations predict an optical throughput as high as 98 % for the bend, which has an effective radius of only 1.5 μm. Measurements on this device are underway. Photonic crystals can also be used to tailor optical transition rates, e.g. of unwanted optical transitions, as occurring in upconversion processes that limit the gain performance in miniature optical amplifiers.

6. Conclusion

We demonstrate several novel concepts that will enhance the gain, reduce the pump power, reduce the size and enhance the efficiency of miniature planar Er-doped optical amplifiers.

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