Cooperative emission in ion implanted Yb:YAG waveguides

G V Vázquez¹, H Desirena¹, E de la Rosa¹, E Flores-Romero², H Márquez³, J Rickards³ and R Trejo-Luna²

¹Centro de Investigaciones en Óptica, Loma del Bosque 115, Lomas del Campestre, 37150 León, Guanajuato, México
²Instituto de Física, UNAM, Apartado Postal 20364, 01000 México, D. F., México
³Departamento de Óptica, CICESE, Km 107 Carr. Tijuana-Ensenada, 22860 Ensenada, B. C., México

E-mail: gvvazquez@cio.mx

Abstract. In this work, we report the analysis of spectroscopic properties of waveguides fabricated by ion implantation in YAG doped with Yb³⁺ ions. Three emission bands were detected in the blue, green and red regions under 970-nm excitation. The strong blue-green emission can be explained by a cooperative process between ytterbium ion pairs, leading to emission centered at 514 nm. The additional blue bands as well as green and red emission bands are attributed to the presence of Tm³⁺ and Er³⁺ traces. The results include absorption and emission curves as well as decay time rates.

1. Introduction

Yb³⁺ has been used as an active dopant in a variety of host materials for high laser power lasers and wavelength tunable solid state lasers. It exhibits a very simple electronic level structure, with the ground state (2F⁷/₂) and one excited state manifold (2F⁵/₂), providing near infrared (NIR) and visible transitions. The combination of these properties with a waveguide configuration offers low pump power thresholds and high optical efficiencies. Also the small volume increases the probability of simultaneously exciting neighboring ions. Particularly, cooperative emission has been reported in epitaxial waveguides of Yb:YAG on YAG substrates, nanocrystals and the ion-ion interaction was studied for different Yb³⁺ content [1-3]. On one hand, upconversion could be detrimental for the NIR transition of Yb ions, by deviating part of the energy into different radiative transitions; and on the other hand, these energy transfer processes could be useful to purposely generate visible emission.

Among the waveguide fabrication techniques, ion implantation has been used successfully in a wide variety of materials. The principal optical effect of ion implantation is a decrease in refractive index at the end of the ion track. This index reduction is usually due to the disorder produced by atomic displacements in the lattice, which generates an optical barrier in the region where the ions are stopped [4]. The region between this barrier and the surface has a higher index and it can operate as a waveguide. Ion implanted waveguides have been reported in Yb:YAG and laser emission was obtained in the NIR region at 1.03 μm [5].

Here we report results on cooperative emission in a Yb:YAG planar waveguide fabricated by carbon implantation. The absorption and fluorescence curves including lifetime values are obtained.
2. Experiment

A planar waveguide was fabricated on a 5 at. % Yb:YAG sample by implanting 7 MeV carbon ions at a dose of $7 \times 10^{14}$ ions/cm$^2$. By optical microscopy, images of the implanted regions were obtained to estimate waveguide dimensions and compare them to calculations using the TRIM code (Transport of Ions in Matter) [6]. A pigtailed fiber semiconductor laser operating at 635 nm was used to couple light into the waveguide and with a CCD camera at the output, the intensity distribution of the propagating light was observed.

In order to obtain the spectroscopic properties of the Yb ions including cooperative emission, a diode laser operating at 970 nm was used as the pump source. Near infrared luminescence was collected using an end-coupling setup (objective lenses to couple light into and out of the waveguide end faces). The signal emitted was focused onto a SP-2357 monochromator (Acton Research) and detected by an InGaAs detector (Thorlabs DET10C) and a photomultiplier tube (Acton Research PD471). The decay profile corresponding to 514 and 1030 nm was recorded using a SR540 chopper (Stanford Research System), connecting the photodetector directly to an oscilloscope (Tektronix TDS 3025B). We found that the output visible intensity (i.e. cooperative emission) was very low and noisy when using this setup, thus the output signal was collected from the planar waveguide top surface. Absorption measurements were realized using a Perkin-Elmer spectrophotometer, in this case the spectrum was obtained from the whole crystal in the perpendicular direction of the waveguide, thus it includes both waveguide and bulk absorption. All the optical measurements were performed at room temperature.

3. Results and discussion

From the images obtained by optical microscopy the waveguide thickness was $\sim 4.6 \mu$m, in accordance with TRIM predictions. Figure 1 shows the microscope image of a section of the planar waveguide. Light confinement in the vertical direction is shown in figure 2, where the field pattern of the propagating modes in the waveguide can be seen.

![Figure 1. Microscope image of a section of the planar waveguide.](image)

![Figure 2. Intensity distribution of the propagating light at the waveguide output.](image)
According to the Dieke diagram of energy levels, single Yb$^{3+}$ ions have only two stark-split energy manifolds, the ground state $^2F_{7/2}$ and the excited state $^2F_{5/2}$ around 10 400 cm$^{-1}$ [7]. The absorption spectrum shows the characteristic broad band of 5 at. % Yb ions in YAG, from about 850 nm to 1050 nm, see figure 3, and is in agreement with the absorption band reported in bulk YAG crystals. In most of cases cooperative upconversion is accompanied by cooperative absorption, however contrary to other results reported recently [2], no absorption bands were observed in the visible region.

![Absorption spectrum of 5 at.% Yb ions in YAG.](image)

Figure 3. Absorption spectrum of 5 at.% Yb ions in YAG.

The well-known NIR emission of Yb$^{3+}$ ($^2F_{5/2} \rightarrow ^2F_{7/2}$) in the Yb$^{3+}$ doped YAG crystal was observed at 1030 nm with the band ranging from 850 to 1100 nm, see figure 4. This means, 175 nm of emission bandwidth. This broad band is useful for tuneable lasing design and is in agreement with the emission reported in bulk crystal. In addition to the NIR signal emitted, several visible bands were observed at the naked eyes. Such bands are blue, green and red centered at 499, 524+542 and 668 nm respectively, see figure 5. According to the Dieke diagram, these bands correspond to $^4F_{5/2} \rightarrow ^4I_{15/2}$, $^2H_{11/2} + ^4S_{3/2} \rightarrow ^4I_{15/2}$ and $^4F_{9/2} \rightarrow ^4I_{15/2}$ classical transitions of Er$^{3+}$ [7]. It should be noted that this sample was not consciously doped with Er$^{3+}$, however four emission bands corresponding to transitions of Er appear when the sample is excited at 970 nm. This may be due to the Yb concentration used to fabricate the crystal which was not completely pure and some traces of Er$^{3+}$ were included in the sample. From this deduction, it is clear that the Yb concentration is much higher than that of Er, giving as result several Yb ions surrounding one Er ion. This fact is favorable to obtain efficient energy transfer (ET) from Yb to Er. The overall result is a strong emission of blue-green light. In addition to this, three blue bands centered at 460, 472 and 477 and 486 nm are observed in Figure 5. These band emissions correspond to Tm$^{3+}$ ions and are attributed to the transition $^1G_4 \rightarrow ^3H_6$ of Tm$^{3+}$. 
Figure 4. NIR luminescence spectrum of Yb ions in YAG.

Figure 5. Visible emission spectrum from the Yb:YAG waveguide.
An emission band centered at 514 nm was also observed; this band does not match any transition of Er and is attributed to cooperative upconversion of Yb$^{3+}$. In this phenomenon two excited Yb$^{3+}$ ions transfer their energy simultaneously to a nearby Yb ion, which subsequently emits a photon with the sum of energies, leading to blue-green emission. Cooperative upconversion is more pronounced when the Yb concentration increases, however this also increases the traces of Er. This fact, partly enhances the upconversion process of Er ions by energy transfer, and partly promotes migration of energy among Yb$^{3+}$-Yb$^{3+}$ ions. When considering the applications of active materials such as lasers at 1.03 μm, the important requirement for high quantum yield is that all the losses by upconversion should be minimized. All these phenomena are a drawback for high efficiency for the 1.03 μm emitted signal. In order to find the best evidence that the observed visible band at 514 nm corresponds to cooperative upconversion of Yb$^{3+}$, fluorescence lifetimes were measured. Such lifetime of cooperative upconversion should be half the lifetime of the infrared transition, this fact has been reported previously [8]. The fluorescence lifetime plot of the $^{4}F_{5/2} \rightarrow ^{4}F_{7/2}$ transition in Yb$^{3+}$ is shown in figure 6, the lifetime being ~ 1.28 ms, in accordance with previous reports where a similar Yb concentration was used in Yb doped YAG. No significant difference was found between the waveguide and bulk crystal which means that the implantation process did not affect the emission properties of Yb$^{3+}$. Figure 7 shows the decay time of the visible emission, from which a lifetime value of ~ 600 μs was calculated, approximately half of that obtained for the IR luminescence which confirms that this is a cooperative emission of Yb.

![Figure 6. Temporal evolution of 5 at.% Yb$^{3+}$ ions in the YAG waveguide.](image)

1.28 ms
4. Conclusions
Blue luminescence was observed in an ion implanted Yb:YAG planar waveguide, this phenomenon is related to a cooperative process between ytterbium ion pairs. An additional blue band as well as a green and a red emission band were also observed which are attributed to traces of other rare earth ions such as erbium and thulium. Additional work is in progress to evaluate a negative effect of visible emission on NIR laser emission versus the possibility of tailoring parameters such as dopant concentration and waveguide properties to design a blue compact laser using upconversion processes.

References
[1] Malinowski M, Nakielska M, Piramidowicz R and Sarnecki J 2007 Spectr. Lett. 40 271
[2] Malinowski M, Kaczkan M, Piramidowicz R, Frukacz and Sarnecki J 2001 J. Lumin. 94-95 29
[3] Townsend P D, Chandler P J and Zhang L 1994 Optical Effects of Ion Implantation (Cambridge: Cambrigde University Press)
[4] L.A. Diaz-Torres, E. De la Rosa, P. Salas, H. Desirena, 2005, Opt. Mat. 27 1305
[5] Hanna D C, Jones J K, Large A C, Shepherd D P, Tropper A C, et al 1993 Opt. Comm. 99 211
[6] http://www.srim.org/SRIM/SRIM2003.htm
[7] Dieke G H 1968 Spectra and Energy Levels of Rare Earth Ions in Crystals (New York: Wiley Interscience)
[8] Goldner P, Pellé F, Meichenin D and Auzel F 1997 J. Lumin. 71 137