

## Analysis of the absorption coefficient by annealing in carbon implanted Nd: YVO<sub>4</sub>

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**Abstract.** Low loss in optical waveguides is very important in order to achieve high laser efficiency. Waveguide fabrication by ion implantation generates color centers, leading to absorption losses which can be reduced by annealing; however, this process may eliminate the waveguide and hence it is necessary to consider both the optimum annealing time and temperature. This work reports the behavior of the absorption coefficient by successive annealing steps in Nd:YVO<sub>4</sub> implanted with a dose of  $5 \times 10^{14}$  ions/cm<sup>2</sup>.

### 1. Introduction

Waveguides fabricated in crystals doped with rare earths are the very important for developed of the optics integrated, for example laser, amplification. Recently the implantation of heavy ions has been analysed with great interest since it usually requires smaller doses than those needed for light ions as it is the case of protons and helium ions [1]. Inside of the study of the waveguide is important the losses study to achieve good laser emission. When the principal effect in the crystal for the implantation of heavy ions is the change the refractive index, this effect is due the disorder produced by the processes of atomic displacement in the lattice. These displacements are in turn brought about by ion-atom and ion-ion interactions that modify the lattice structure. This causes a decrease in the physical density and therefore in the refractive index of the crystal at the end of the ion trajectory, generally producing an "optical barrier" of smaller index than that of the bulk [2]. For this method, one has control on the parameters for the formation of the guide and its realization can be at ambient temperature, which cannot be achieved for other methods, such as diffusion, ion exchange, or deposition [3].

When waveguides are formed by ion implantation, colour centres are generated during the process, which implies absorption losses in the waveguide. In the field of integrated optics and optical communications, a waveguide configuration is necessary because its size can be compatible with semiconductor laser and optical fiber technology [4].

## 2. Experimental Methods

$C^{2+}$  ions were implanted at room temperature on the surface of a Nd:YVO<sub>4</sub> crystal using the 9SDH-2 Pelletron accelerator at the Instituto de Física (UNAM) with a dose of  $5.0 \times 10^{14}$  ions/cm<sup>2</sup> and an energy of 7 MeV. The damage depth was calculated using ion implantation simulation software, SRIM (Stopping and Range for Ions in Matter) [5].

After the implantation, the sample was annealed using an electrical furnace in open atmosphere, either increasing the time at constant temperature or increasing the temperature for equal periods of time. The absorption spectrum was measured after each annealing step using a spectrophotometer. The measurement was made in the “a” axis (figure 1), in this way the absorption measured is due to the Nd ions in YVO<sub>4</sub> and the carbon ions.

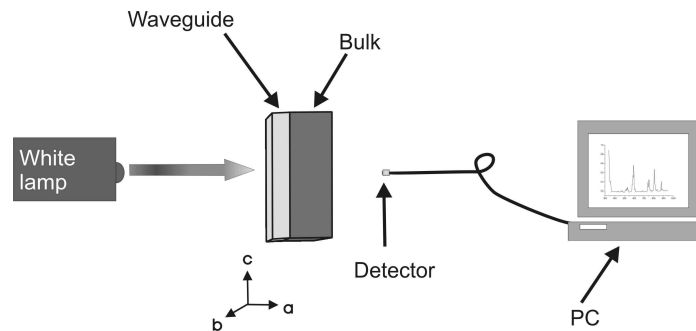


Figure 1. Scheme of the experimental setup for obtaining the absorption spectra.

## 3. Results and Discussion

The absorption coefficient was calculated according to the Lambert-Beer law,  $I = I_0 e^{-\alpha x}$  where  $I$  is the light intensity at a distance  $x$  into the medium and  $\alpha$  is called the absorption coefficient of the material, which is determined by [6]

$$\alpha = \frac{2.303(OD)}{x} \quad (1),$$

where the optical density is defined as  $OD = \log(I_0/I)$ .

According to the SRIM calculation, the damage depth is approximately 4.8  $\mu\text{m}$ . For the estimate of the absorption coefficient we used the depth obtained from the index profile, 4.6  $\mu\text{m}$  (ie. the parameter  $x$  in the equation) [7].

Figure 2 shows the absorption spectra for Nd:YVO<sub>4</sub> without implantation (dashed line) and the implanted sample after the first annealing during 40 minutes at 250°C (solid line). Note that the absorption spectrum for the implanted sample behaves as a modulated exponential, but has all the absorption peaks of the original crystal, although less defined in the wavelength range between 400 and 500 nm. The absorption coefficient was calculated at 410 and 650 nm, because in these wavelengths there are no absorption peaks, thus having a good reference to calculate the absorption coefficient. According to figure 2, the absorption coefficient for implanted Nd:YVO<sub>4</sub> is 1870.7 and 101.5 cm<sup>-1</sup> for 410 and 650 nm respectively. These measurements are normalized according to the value of the sample without ion implantation. For 410 nm the absorption coefficient is high due to color centers, these are generated during the implantation process, where the sample acquired a green color (see figure 3).

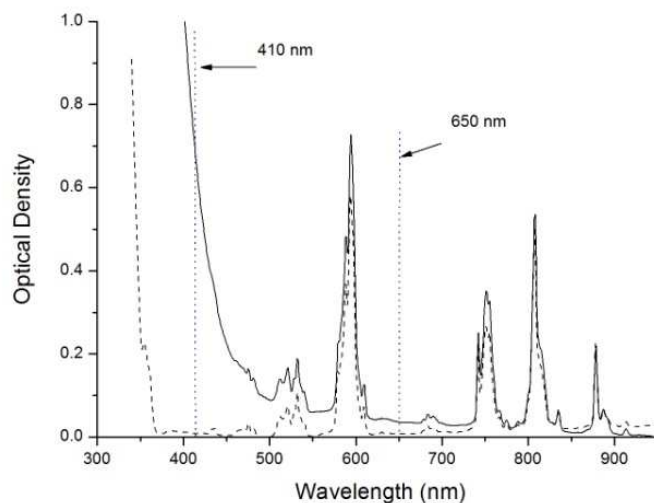


Figure 2. Absorption spectra of Nd:YVO<sub>4</sub> without implantation (dashed line) and the carbon implanted sample (solid line).

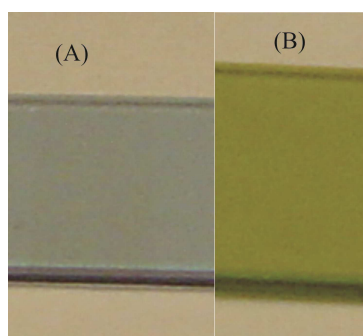


Figure 3. Pictures of the sample without implantation (A), and after the implantation with C<sup>2+</sup>(B) showing that the sample acquired a green color.

Figure 4 shows how the absorption spectrum varies with annealing at 300°C during 30 minutes (green dotted lines) and 120 minutes (red dotted lines) as well as 350°C for 30 and 240 minutes (blue dotted line and black continuous line respectively) where it is observed that the biggest decrease in the absorption coefficient is when the temperature was changed, whereas varying only the time and maintaining the temperature, the absorption coefficient change was very slow. For this reason, we decided to increase the temperature in steps of 50°C for each measurement with constant periods of time (30 minutes). Figure 5 shows the absorption spectra for temperatures of 400, 500, 600 and 700°C (green, red, blue dotted line and black continuous line respectively). Clearly, in the figure it is observed that already for an annealing at a temperature of 700°C the absorption coefficient is similar

to the sample without implantation. For an annealing at 800°C for 30 minutes the absorption spectrum is equal to that for sample without implantation.

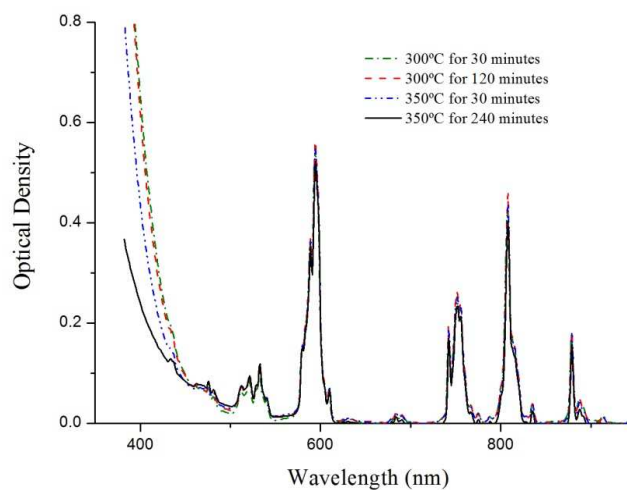


Figure 4. Comparison the absorption spectrum with a annealing for period time to 30 and 120 minutes at 300°C (green and red dotted line respectively) and for period time 30 and 240 minutes at 400°C (blue dotted line and black continuous line respectively).

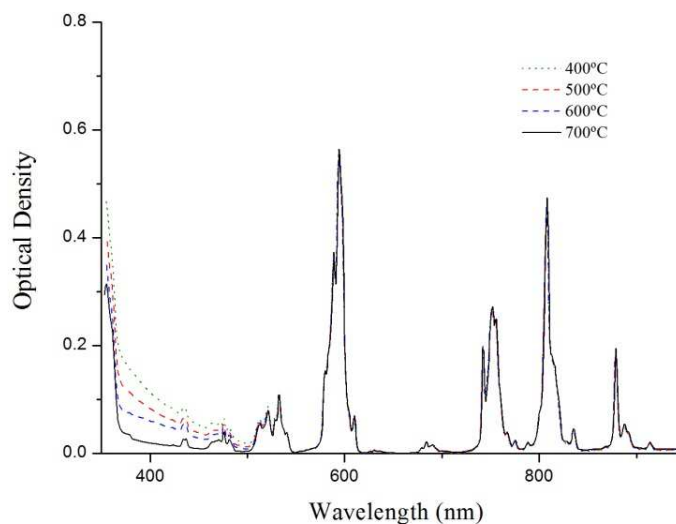


Figure 5. The absorption spectrum for the temperatures of 400°C (green dotted line), 500°C (red dotted line), 600°C (blue dotted line) and 700°C (black continuous line) for a period of 30 minutes for each measurement.

Making an analysis of the absorption coefficient variation for different temperatures with duration of 30 minutes, a dependence of a negative exponential was found, whose behavior approaches to the equation  $33000\exp(-x/87) + 22$  for the wavelength of 410 nm (see figure 6), and for the wavelength of 650 nm the approximation is  $12432\exp(-x/52) - 0.5$ . The difference in the equations for both wavelengths is explained by the fact that color centers are removed after each annealing, hence the absorption variation is greater at 410 nm.

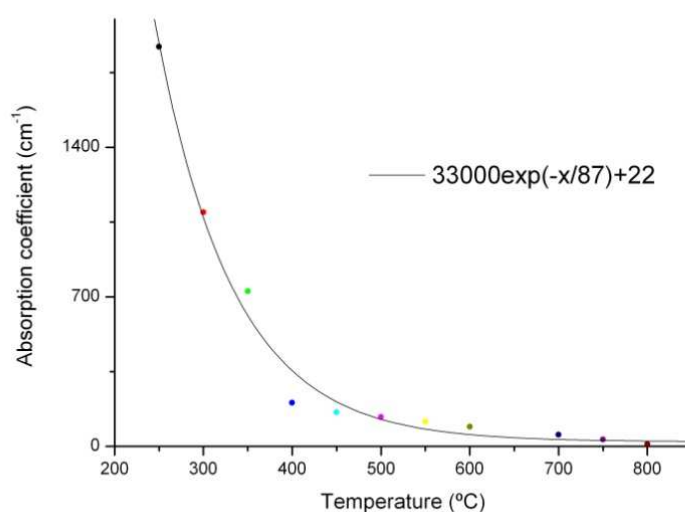


Figure 6. Absorption coefficient of Nd:YVO4 implanted with C2+ for different temperatures at a wavelength of 410 nm (dots). The function that represents the behavior of the dependence of the absorption coefficient is also shown (line).

#### 4. Conclusion

In this paper we discussed the behavior of the absorption coefficient as a function of the annealing in sample carbon-implanted, we observed that the coefficient was behavior decreasing exponential.

It was noted that there is a limit in reducing the coefficient for each temperature no matter how long lasted the annealing, the absorption coefficient variation was minimal, so if it was required that the ratio varied dramatically annealing was needed to higher temperature, caused the greatest variation in the absorption coefficient was in the first annealing at a given temperature, which in this case was analyzed with halves of 30 minutes after changes were minimal to annealing to 2 hours during.

#### References

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