Low dose carbon implanted waveguides in Nd:YAG

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Abstract: For the first time to our knowledge, carbon implantation into YAG crystals doped with Nd has been used to produce optical waveguides. A considerable index decrease in the nuclear region (i.e., the region where the energetic ions stop) of ~ 2.5% was obtained with a low dose implant, while giving an index enhancement in the guiding region of ~ 0.35%. After an annealing step necessary to recover the transparency of the crystals, the layer of reduced refractive index produced by implantation is preserved. Spectroscopic studies carried out in a waveguiding configuration show that emission bands coming from the $^4F_{3/2}$ level present a slight broadening, while its associated lifetime is similar to that reported in bulk crystals (240 μs).

OCIS codes: (230.7390) Planar waveguides; (160.3380) Laser materials

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1. Introduction

A primary objective in the development of integrated optics is the miniaturization of electro-optic components. Optical waveguides are one of such structures which can be fabricated in a variety of materials. They offer high power densities which are confined in a small volume and can be used for nonlinear applications such as second harmonic generation, four wave mixing, etc. Some of the advantages of optical waveguides are that they can be easily coupled to semiconductor pump lasers and that modest powers are needed to achieve the nonlinear effects [1-3].

Earlier methods of forming optical waveguides include diffusion, ion exchange and layer deposition. However, these need a high temperature process and cannot be applied to some materials. Ion beam implantation has been an alternative technique to fabricate waveguides in more than 60 materials [1]. The damage caused by nuclear collisions during the implantation reduces the physical density of the crystal, which results in a reduction of the refractive index. The low density buried layer that is produced at the end of the ion track acts as an "optical barrier" which has a lower refractive index than the substrate [4]. Thus, the region between this barrier and the surface is surrounded by regions of lower refractive index and can act as a waveguide.

Nd:YAG is a well-known bulk laser material. As an optical waveguide it was the first such structure formed by ion implantation [5]. Previous work on ion implanted Nd:YAG waveguides has been done using helium ions and protons with energies of typically 1 to 2 MeV [6,7]. In this crystal as well as in other crystalline materials such as $LiNbO_3$ and $Bi_4Ge_3O_{12}$ [8,9] the refractive index in the guiding region increases by a small amount during ion implantation, producing a conventional waveguide profile with an enhanced index. In this case the optical barrier becomes superfluous for the lowest modes, as these can be confined without exhibiting tunneling loss, which normally will be caused by the presence of the optical barrier.

Instead of light ions it is possible to use heavier ions to produce waveguides that show a higher index decrease with a relatively low dose. An example of this approach was done by Townsend *et al*. [10] who used carbon ions to produce chemically stabilized waveguides in sapphire, in which He^+ implantation produces an acceptable index change with a dose in excess of 10^{17} ions/cm^2. Nevertheless, at such high implant levels the impurities create new compounds or generate stresses within the lattice. Recent results show that implantation of heavy ions such as Si^+ is an efficient method for waveguide formation using much lower doses [11].

In this Letter we report what is to our knowledge the first achievement of waveguide formation in Nd:YAG using carbon ion implantation. The planar waveguides have been characterized, and the spectroscopic properties of the Nd^{3+} ions in the guiding region have been investigated and compared with data obtained in bulk crystals.

2. Experimental methods

Nd:YAG commercial crystals (MolTech GmbH), doped with a 1% Nd^{3+}, were used to fabricate planar waveguides at room temperature by implanting 7 MeV carbon ions at a dose of 1×10^{16} ions/cm^2 using a 9SDH-2 Pelletron Accelerator. The propagation modes in the waveguide were measured by means of the m-line technique, where a rutile prism was used to couple light from a linearly polarized He-Ne laser (632.8 nm) into the waveguide. From the measured effective refractive indices of the modes, the related index profile of the planar waveguide was obtained using a multi-layer approximation, which not only gives the mode positions, but also takes into account the width of the resonant modes.

The spectroscopic characterization of the carbon implanted Nd:YAG waveguides has been performed under CW excitation by using an Ar-pumped Ti-Sapphire laser operating at the wavelength range of 790 to 830 nm, where the main absorption bands of Nd^{3+} ions are located. The excitation beam was coupled into the waveguide by using the end-fire coupling technique. The luminescence was collected at the other end, using a microscope objective, and then analyzed through an ARC monochromator, model SpectraPro 500-i. The fluorescence was detected by an InGaAs photodiode. In lifetime measurements, the signal was synchronously detected and averaged by a digital oscilloscope. It is important to note that in order to assess waveguide quality, it is necessary to compare the bulk and waveguide emissions. In particular, the lifetime is a very relevant parameter for amplification purposes. This parameter is very sensitive to structural changes that can be produced during the waveguide fabrication process.

After implantation, in order to recover transparency, the samples were annealed in a conventional oven at 400 ºC during 30 minutes in open atmosphere. In order to check reduction of waveguide losses after annealing, the transmission intensity from the planar waveguide was measured. For this purpose, two microscope objectives (20x and 10x) were used to couple light of a He-Ne laser (632.8 nm) into and out from the waveguide.

3. Results and discussion

The m-line spectrum shows at least six clear modes. The first five modes are quite narrow, indicating that these modes are well confined by the formation of an optical barrier. The sixth mode is also clearly seen, but it shows an appreciable broadening, which indicates that its effective refractive index is lower than the optical barrier and therefore is not totally confined. Taking into account the effective indices of the modes and their broadening, the refractive index profile of the planar waveguide can be obtained. The calculated index profile is shown in Fig. 1 (continuous line), plotted as an index decrease in order to emphasize the concept of the "well and barrier"; the effective index of the modes is also shown (triangles). One can see that an index decrease region is located at around 4 microns beneath the surface, acting as an optical barrier that can confine the optical radiation. The minimum refractive index is 2.5% with respect to the substrate index. The position of the optical barrier is in accordance with ion range calculations using the TRIM code (Transport of Ions in Matter). The ion implantation also produced an index increase in the region located between the barrier and the surface. This index enhancement in the guiding region represents a 0.35%, and allows the zero order mode to act as a non-tunneling mode, which can propagate along the waveguide without tunneling losses. The implantation of higher mass ions than that of He^+ or H^+ such as carbon on YAG produces a greater index reduction with a relatively low dose and at room temperature, leading to the formation of a higher and broader optical barrier and thus reducing tunneling losses. On the other hand, the refractive index increase in the guiding region is greater than that of He-implanted waveguides, where a multi-energy implant at low temperature was necessary to produce an index enhancement of ~0.25% (measured at 488 nm) [6].

After the carbon implantation process, the Nd:YAG substrate becomes grey due to the formation of color centers which induce extra losses via optical absorption. In order to recover the initial transparency, the carbon implanted waveguides were annealed as mentioned above. The temperature and exposition time were chosen to improve the waveguide quality, while taking care of preserving the induced optical barrier. We have found that the thermal treatment recovers the crystal transparency, increasing the transmitted intensity along the waveguide at least 10 times. After this step it was possible to perform the spectroscopic characterization of the active ions in the optical waveguides.

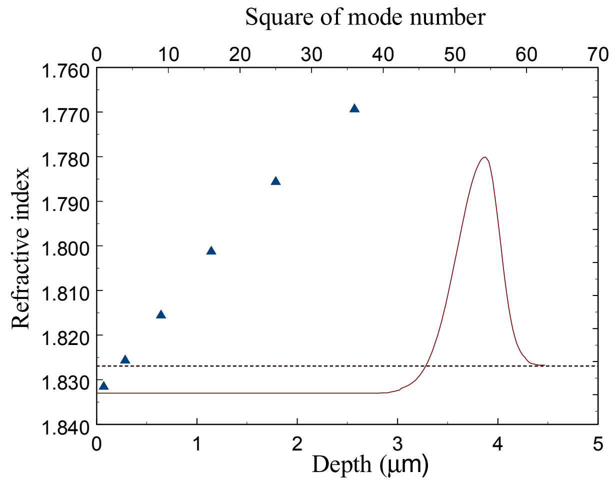


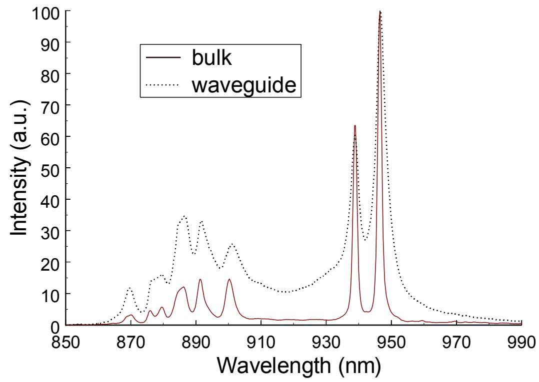
Fig. 1. Mode positions (triangles) and refractive index profile (solid line) for C^{3+} implanted Nd:YAG with 7 MeV at a dose of 1×10^{16} ions/cm^2. The dashed line represents the substrate refractive index.

When Nd^{3+} ions are excited around 810 nm ($^4I_{9/2} \rightarrow {}^2H_{9/2}{:}{}^4F_{5/2}$ absorption band) [12], a fast non-radiative transition to the $^4F_{3/2}$ metastable level takes place. From this level, the relaxation is partially radiative to the lower lying levels, giving luminescence at around 0.9 μm ($^4F_{3/2} \rightarrow {}^4I_{9/2}$), 1.0 μm ($^4F_{3/2} \rightarrow {}^4I_{11/2}$) and 1.3 μm ($^4F_{3/2} \rightarrow {}^4I_{13/2}$), and partially non-radiative to the $^4I_{13/2}$ manifold. Figure 2 shows the infrared emission spectra associated with these luminescent bands (Figs. 2(a), 2(b) and 2(c), corresponding to $^4F_{3/2} \rightarrow {}^4I_{9/2}$, $^4F_{3/2} \rightarrow {}^4I_{11/2}$ and $^4F_{3/2} \rightarrow {}^4I_{13/2}$ Nd^{3+} transitions respectively) measured in the planar waveguide (dotted line) and in the bulk (solid line). As it can be appreciated, although the emission bands in the waveguide exhibit a slight broadening, the peak positions are preserved indicating that the crystal quality is maintained during the implantation process.

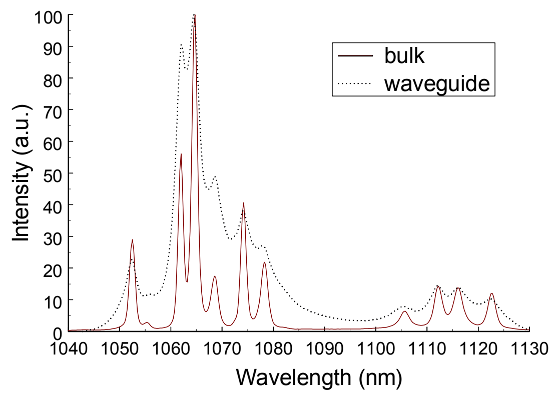
The dynamics of the $^4F_{3/2}$ Nd^{3+} metastable level in the planar waveguide was also explored. For this purpose, the excitation beam from the CW Ti:Sapphire laser was modulated by using a mechanical chopper. The temporal evolution of the $^4F_{3/2} \rightarrow {}^4I_{11/2}$ transition, recorded at 1064 nm (circles), is presented in Fig. 3. As it can be observed, the temporal decay exhibits a single exponential behavior which can be fitted with a lifetime value of 236 μs (continuous line), being in good accordance with that previously reported for bulk samples doped with a Nd^{3+} concentration of 1.0 % (240 μs) [12]. This fact, in combination with the spectra shown in Fig. 2, indicates that carbon implantation does not introduce important changes in the spectroscopic properties of neodymium ions.

As explained by Townsend *et al.* [10], the use of group IV elements such as carbon leads to distortions which are not localized at a single site but influence some tens of nearby lattice atoms. Defect retention is induced via defect trapping at the perturbed sites. As carbon is chemically active, there could be a series of defect models such as carbide bonds, carbonate groups, etc. An appraisal of the luminescence data and the broadening of Nd bands in the waveguide could be explained by considering that not all the light that propagates through the waveguide is restricted to the guiding region, but a fraction of the intensity penetrates into the barrier. This fraction varies depending on the parameters of the barrier (i.e., height and width). Another factor that could increase the linewidth is a loss of crystallinity in the guiding region caused by ion implantation. Field *et al*. [13] investigated the dependence of band broadening on ion dose in Nd:YAG and they found that the 1.06 μm spectral region deteriorates for He doses up to 7×10^{16} ions/cm^2.

(a)



(b)



(c)

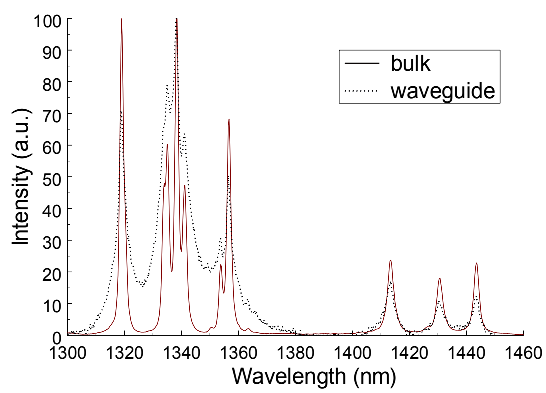


Fig. 2. Emission spectra of Nd^{3+} ions in YAG crystal, measured in bulk (solid lines) and in waveguide (dotted lines), after excitation to the $^2H_{9/2}$:$^4F_{5/2}$ at room temperature.

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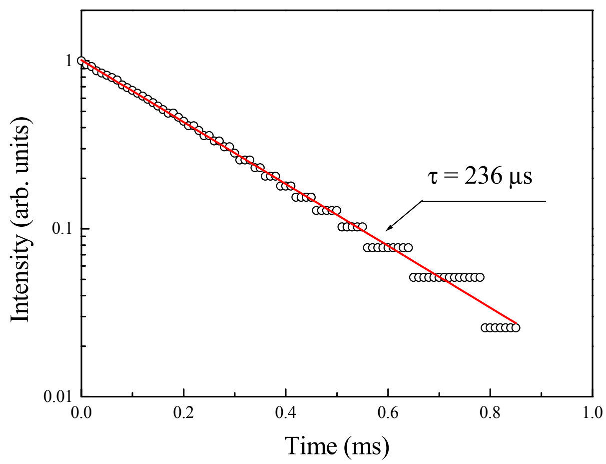

Fig. 3. Temporal evolution associated to the $^4F_{3/2} \rightarrow {}^4I_{11/2}$ Nd^{3+} transition measured at 1.064 μm, where a lifetime of 236 μs is calculated

4. Conclusions

Carbon implantation at energies of 7 MeV offers an effective technique to fabricate planar waveguides in Nd:YAG crystals, using doses as low as $1x10^{16}$ ions/cm^2. The use of carbon ions in this material causes a significant reduction of refractive index in the nuclear region (optical barrier), while simultaneously inducing an advantageous increase of refractive index in the electronic region (guiding region). This refractive index profile supports a non-tunneling guiding regime able to confine the first propagation mode. Spectroscopic results indicate, on the other hand, that carbon implantation does not introduce notable changes in the emission spectra nor in the temporal decay associated with the $^4F_{3/2}$ Nd^{3+} manifold. These facts indicate that this waveguide fabrication technique could be of particular interest for developing integrated lasers and optical amplifiers on YAG crystals in a guiding configuration.

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