Optical channel waveguides by proton and carbon implantation in Nd:YAG crystals

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Abstract: In this work the formation of optical channel waveguides in Nd:YAG crystals by either proton or carbon implantation is reported. The channel waveguides were obtained by a single implantation process through an electroformed mask of nickel-cobalt alloy. Experimental measurements of the optical properties of these waveguides are presented.

OCIS codes: (230.7380) Waveguides, channeled; (140.3380) Laser materials.

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1. Introduction

Optical waveguides are essential blocks for the miniaturization of electro-optical elements, a primary objective in the development of integrated optics. Some of the advantages of optical waveguides are that their geometry offers high power densities confined in a small volume and they can be easily coupled to semiconductor lasers and fiber optic technology. Waveguides doped with rare-earth ions can be used for the development of miniaturized lasers and amplifiers providing high slope efficiency and low pump thresholds.

Waveguides have been fabricated in a variety of materials by means of several techniques. Among these, ion implantation has proved to be an effective technique to fabricate optical waveguides in more than 60 materials [1]. During ion implantation the damage caused by nuclear collisions reduces the physical density of the crystal in a thin buried layer. As a result this layer has a lower refractive index than the substrate and since it is produced at the end of the ion track it can act as an "optical barrier". The region between this barrier and the surface is then surrounded by regions of lower index and can act as a waveguide [2].

Depending on the material used as substrate and the manipulation of the different parameters of the implantation process (i.e. specific projectile ion, ion energy, total dose and the angle at which the implantation is done), it is possible to fabricate waveguides with different properties. One of the materials used as substrate to perform ion implantation is the neodymium doped YAG laser crystal (Nd:YAG). This material was one of the first used to form optical waveguides by helium implantation [3]. The first waveguide laser was obtained in a Nd:YAG crystal by He+ implantation too [4]. Some other works have reported the formation of planar waveguides in Nd:YAG by implantation of protons (H^+) or carbon ions (C^{2+}) [5-7]. In the case of helium ions the implantation is always performed at various energies and doses, namely multi-implant processes. For carbon ions the technique involves a single implant process, i.e. implant at fixed energy and incidence angle. In the case of protons planar waveguides have been obtained by both multiple and single implantation processes. In all cases laser oscillation has been shown at 1064 nm [4, 7, 8], and for proton implantation laser performance at 1338 nm has also been reported [9].

However, a currently real challenge for integrated optics is to miniaturize lasers. This issue stimulates research of single crystalline optical channel waveguides. Although channel waveguides [10] and channel waveguide lasers [11] formed by helium implantation in Nd:YAG crystals have been reported, this field is still under investigation [12] in order to solve the strong limitations reported when helium ions are used.

One method reported to obtain channel waveguides by ion implantation consist of adding vertical barriers in a planar waveguide. By homogeneous irradiation of the crystal surface with ions at a given energy, a bottom barrier is formed (the region between this barrier and the surface acts as a planar waveguide); then by varying the beam energy and by using appropriate doses, two vertical barriers, also by index decrease, are created laterally on both sides of a masked area of the crystal surface (the mask used is a photo-lithographically patterned gold film with a thickness of ~ 3 μm) [10, 11]. The channel is then limited by these three barriers and the surface. As it should be noted, all this process involves several implantation steps and the mask thickness must fully stop the ions; but in some cases it is clear that is very difficult to achieve this with photolithographic techniques.

Another method developed to obtain channel waveguides involves ion implantation at a fixed energy through a slit but by varying the incidence angle of the ion beam parallel to the slit direction [12]. The slit used is a few tenths of a millimeter in depth and a few centimeters in length, while its width can be adjusted in the 10-200 μm range. In this case the channel waveguides are formed by the index increase in the unmasked area of the crystal surface. Moreover, very recently by using this moving slit setup it was also demonstrated that a single implantation process was sufficient to obtain a positive index change and good lateral confinement in proton-implanted YAG channel waveguides [13].

The use of protons to fabricate waveguides has the advantage of producing fewer deleterious effects on the optical properties of the Nd:YAG crystal, even when high doses are

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employed [5]. On the other hand the implantation of carbon ions in Nd:YAG crystals causes a significant reduction of refractive index in the nuclear region when low doses are used and simultaneously induces an advantageous increase of refractive index in the electronic region [6].

In this work, we report a method for the formation of channel waveguides by implantation of either proton or carbon ions in neodymium doped YAG single crystals. The optical characterization of the waveguides, that is microphotographs, optical transmission, luminescence analysis, launch efficiency and propagation loss is presented.

2. Experimental details

2.1 Ion implantation

In the methods described above the masking technique has some restraints in thickness and handling. For this reason we decided to explore the possibility of index increase in the crystal by a single implant process performed through an electroformed mask of a nickel-cobalt alloy. The mask consists of 3 sets of ten openings each one. All openings are 14 mm long, ten openings are 10 μm in width, the next ten are 15 μm and the last are 20 μm. The mask thickness in the opening regions is 25 μm which is sufficient to fully stop the ions at the energies used. The mask was fixed on the crystal surface and retained there during implantation by means of a mechanical device, this made very easy to fix and remove the mask from the substrate.

2.2 Optical characterization

Microphotographs were taken to the end-faces of the crystals to estimate the waveguide dimensions and compare it with predictions from TRIM calculations (*Transport of Ions in Matter* [14]) and mask opening dimensions.

To test the guiding properties of the waveguides, the light provided by a pigtailed fiber semiconductor laser (635 nm) was coupled into the waveguide, and the light of the waveguide end-face was collected through an optical microscope. A CCD camera was used to observe the intensity distribution of the propagation modes. Additionally, an optical power meter with an integrating sphere detector was used to measure the waveguide transmission. These values were used to estimate launch efficiency and propagation losses.

In order to obtain the luminescence spectra for each waveguide, the neodymium ions were excited using a Ti:Sapphire laser as a pumping source, the pumping beam was coupled into the waveguides with a 10X microscope objective by the end-fire coupling technique. The luminescence light was coupled out through a 20X microscope objective and directed to an Optical Spectrum Analyzer (HP 70951A) to record it. Luminescence analysis includes a comparison of the relative intensity between main peaks and broadening of these due to ion implantation.

3. Results and discussion

A total of 60 channel waveguides were obtained at room temperature on two Nd:YAG crystals (1% at.) by the ion implantation technique at the Instituto de Física (UNAM) 9SDH-2 Pelletron Accelerator. Each crystal has dimensions of 10x15x1 mm^3 and was covered with a different mask but with the same design. The implantation conditions are summarized in table 1. The incidence angle of the ion beam was taken relative to the surface normal in the opening direction.

Table 1. Implantation parameters used to fabricate channel waveguides.

Crystal	Ion	Energy (MeV)	Incidence Angle (°)	Dose (ions/cm^2)
Nd:YAG	Protons (H^+)	1.0	61	2.0 x10^{16}
Nd:YAG	Carbon (C^{2+})	7.0	8	5.0 x10^{14}

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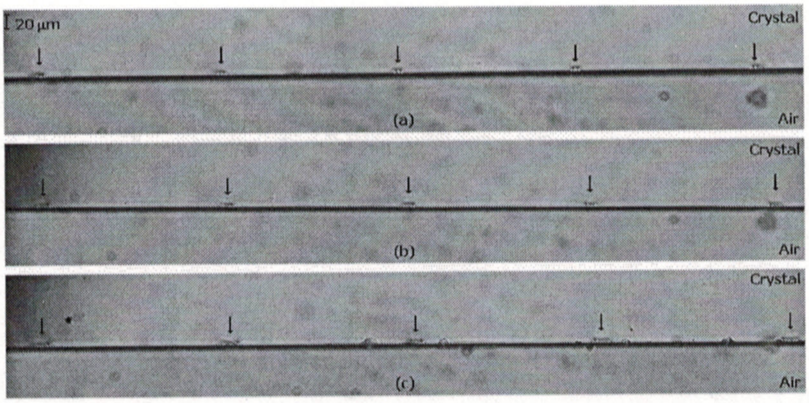

Fig. 1. Image constructed from waveguide end-face microphotographs of channels fabricated by carbon implantation, the arrows indicate the location of channels. (a) 10 micron waveguides, (b) 15 micron waveguides, (c) 20 micron waveguides.

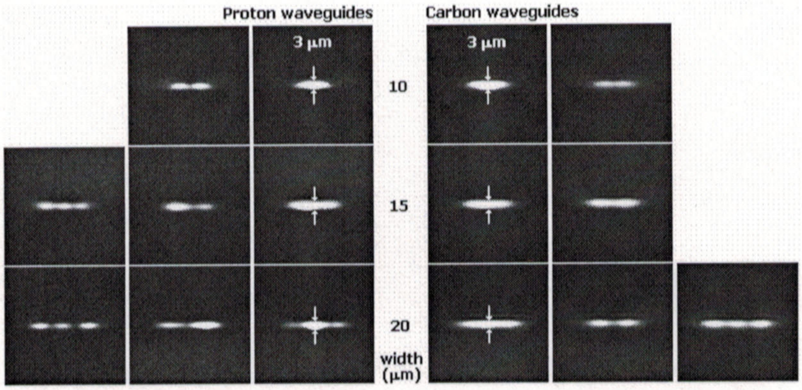

Fig. 2. Intensity distribution of the beam propagated along channel waveguides. The central numbers indicate the nominal waveguide widths.

According to the mask opening dimensions, the waveguides must be close to 10, 15 and 20 microns in width, and from TRIM calculations we expected optical barriers at depths of around 4.0 and 5.0 μm for carbon ions and protons, respectively. Microscopy measurements give us waveguide widths of ~11.0, 17.0 and 21.5 μm for carbon ions and of ~10.5, 15.0 and 20.5 μm for protons, in good accordance with mask opening dimensions. The optical barriers were located at depths of ~4.0 and 4.6 μm for carbon and protons respectively, in accordance with TRIM predictions. In Fig. 1 it is possible to observe an image of the waveguides formed by carbon implantation, note that one can differentiate waveguides of different width.

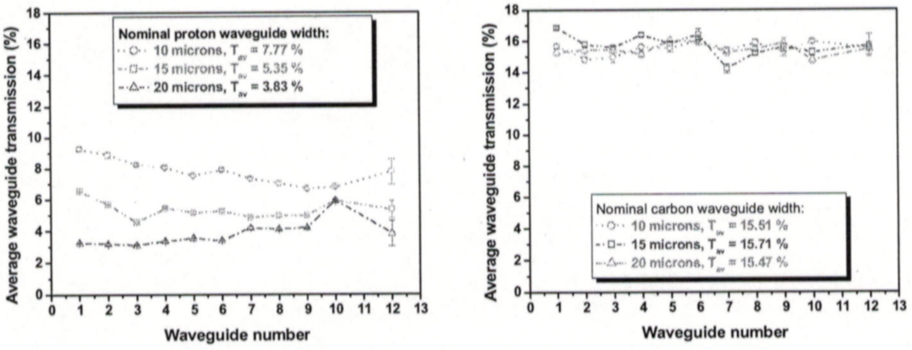

Fig. 3. Transmission measurements in channel waveguides by proton or carbon implantation. The waveguide number 12 represents the average transmission of the group.

Table 2. Optical transmission measurements and launch efficiency estimations in channel waveguides.

Implanted ion	Nominal Waveguide Width (μm)	Transmission (%)			Launch efficiency (%)
		Minimum	Maximum	Average	
Protons H^+	10	6.67411	9.26767	7.77300	61
	15	4.57988	6.56374	5.35163	53
	20	3.12429	5.91438	3.83531	48
Carbon C^{2+}	10	14.81832	16.05812	15.51853	63
	15	14.22669	16.84116	15.71569	50
	20	14.78378	16.04640	15.47814	43

Another estimation of the waveguide dimensions was provided by CCD images of the spot from the waveguide output light by means of end-fire coupling. In Fig. 2 we present typical images obtained, where it is possible to observe that: (a) 10 micron waveguides (proton and carbon) support TEM 00 and TEM 10 modes; (b) 15 micron carbon waveguides support two modes, TEM 00 and TEM 10; 15 micron proton waveguides support the three modes, TEM 00, TEM 10 and TEM 20; and (c) 20 micron waveguides (proton and carbon) support TEM 00, TEM 10 and TEM 20 modes. All the waveguides present light guiding and good lateral confinement which confirms the formation of channel waveguides due to index increase in the electronic region produced by implantation in both cases.

The excess loss for any pigtailed fiber waveguide is the sum of four terms: propagation loss in the structure, the Fresnel reflection, the mode-size mismatch between the fiber and the waveguide and their misalignment [15]. In general the last three terms affect the quantity of light coupled into the waveguide, i.e. launch efficiency; and the first one depends on the waveguide fabrication parameters and the structure design. The interest is focused in obtaining channel waveguides with high launch efficiency and low propagation losses. In order to make an estimation of the waveguide losses, we first estimated theoretically the launch efficiency and performed measurements of optical transmission in the waveguides.

Figure 3 and table 2 show the results of channel waveguide transmission. From these values we observe that transmission depends on the implanted ion, that is, carbon waveguides present better transmission (~15%) than proton waveguides (3.8-7.7%). Besides, there is a different behavior with respect to waveguide width, proton waveguide transmission clearly depends on waveguide width (wider waveguides present less transmission); while it is not so for carbon waveguides, where transmission remains almost constant independently of

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waveguide width. It is also evident that channel waveguides present better transmission than planar waveguides obtained with similar parameters [16].

Considering a fiber mode described by a circular gaussian (waist w_0=3.5 μm) and the waveguide mode as the TEM 00 showed in Fig. 2; the mode coupling, misalignment, and Fresnel reflections give a fiber launch efficiency as presented in table 2. It can be seen that the different spot sizes give different launch efficiencies, as expected. It is useful to note that the main source of insertion losses is the mismatch between fiber and waveguide modes (mode mismatch). With launch efficiency values, and from waveguide transmissions, we estimate the waveguide propagation losses to be between 8.7-10.7 dB/cm for proton waveguides, and between 4.1 and 5.8 dB/cm for carbon waveguides. At this point we must note that the waveguides were analyzed as implanted, i.e. without any post processing.

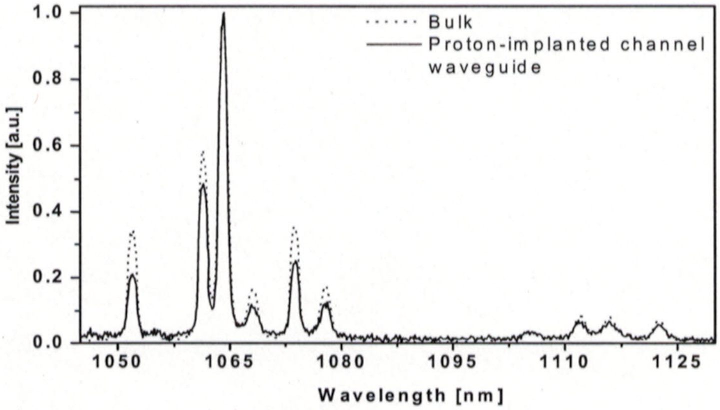

Fig. 4. Typical emission spectrum from proton-implanted channel waveguides for transition $^4F_{3/2} \rightarrow {^4I_{11/2}}$.

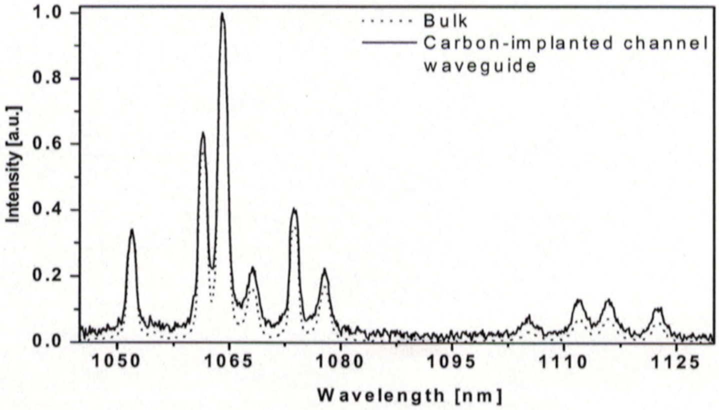

Fig. 5. Typical emission spectrum from carbon-implanted channel waveguides for transition $^4F_{3/2} \rightarrow {^4I_{11/2}}$.

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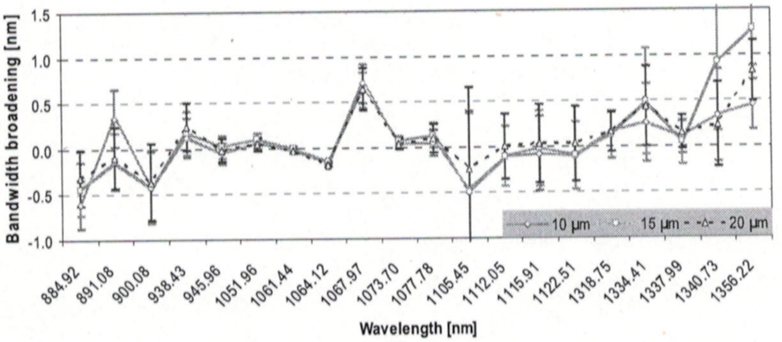

Fig. 6. Average induced broadening in waveguide spectra due to proton implantation in Nd:YAG crystals.

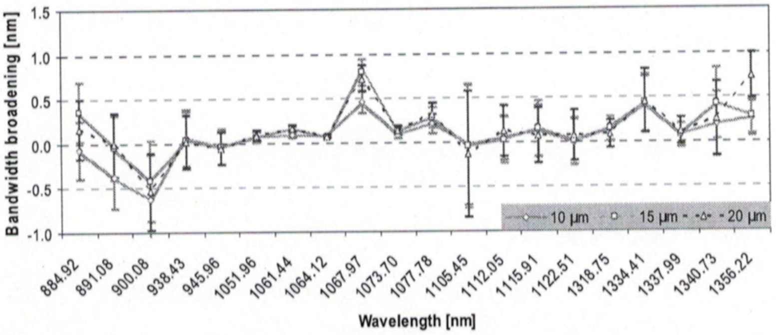

Fig. 7. Average induced broadening in waveguide spectra due to carbon implantation in Nd:YAG crystals.

To determine any broadening in the neodymium spectrum bands we analyzed the three main level transitions: ${}^4F_{3/2} \rightarrow {}^4I_{9/2}$, ${}^4F_{3/2} \rightarrow {}^4I_{11/2}$ and ${}^4F_{3/2} \rightarrow {}^4I_{13/2}$ whose main peaks are located approximately at 946, 1064 and 1318 nm, respectively. Figures 4 and 5 show recorded typical spectra from the bulk and channel waveguides. Analysis was performed by fitting gaussian functions to each peak of the bulk and waveguide spectra, then we obtained the full width at half maximum (FWHM) for each function. Finally we quantified the broadening by comparing the FWHM for each peak in each waveguide spectrum with the FWHM of the corresponding peak in the bulk spectrum. The results can be visualized in Figs. 6 and 7, these show that there is a broadening of less than 0.5 nm in the luminescence spectra main peaks which implies that neodymium ions properties in YAG are almost preserved.

Some comments must be done to clarify the broadening results presented. In Figs. 6 and 7 the average broadening is near to zero for about 60 percent of the data. Although some values are located above 0.5 nm and others are below 0 nm, this issue does not affect our conclusion since we can explain the discrepancy considering that the Gaussian approximation used to obtain the FWHM is not perfect in those points because of noise or due to very close peaks in the spectrum. Taking into account these facts we consider a broadening of less than 0.5 nm a good approach to the behavior observed.

4. Conclusion

A method for forming optical channel waveguides by means of ion implantation through an electroformed mask was achieved. The mask used was enough to fully stop the ions in the

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regions desired to be without implantation. Numerous sets of various width waveguides were formed together with the same implantation conditions, and this opens a large-scale production opportunity for industrial applications.

The waveguides were obtained by either proton or carbon single implantation processes in Nd:YAG crystals. All the expected waveguides were obtained and the dimensions are in agreement with theoretical predictions. It is noteworthy that a single carbon implant produced a refractive index increase in the guiding region which is enough to laterally confine the light. In addition the channel waveguides present better light confinement and greater transmission than planar waveguides obtained with similar parameters, and the carbon waveguides have better transmission than proton waveguides.

The luminescence of neodymium ions was investigated in both kinds of waveguides. Analysis of broadening in each peak of the emission spectra indicates that the waveguide structure preserves the spectroscopic properties of the Nd^{3+} ions. In particular, an average broadening less than 0.5 nm in the emission spectra was observed. This is especially remarkable for the carbon implanted waveguides and suggest that carbon implantation is promising for the formation of channel waveguide lasers.

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