Laser oscillation in proton implanted Nd:YAG waveguides

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This work reports continuous laser oscillation at λ=1064.4 nm at room temperature in Nd:YAG waveguides fabricated by proton implantation technique. The resulting index profiles after the multi-implant, the spectroscopic characteristics of the Nd^{3+} ions in the waveguide, as well as the laser characteristics of the proton implanted Nd:YAG waveguide laser are reported.

Keywords: laser, waveguide, rare earths, ion implantation.

Introduction

Nd doped YAG is one of the most attractive dielectric materials for solid state lasers. The efficiency of laser operation is enhanced by using waveguide geometries, because the optical modes propagate well confined in the waveguide structure, avoiding thus diffraction effects. Several techniques have been proposed to fabricate optical waveguides in Nd:YAG, including epitaxially grown Nd:YAG layers on pure YAG substrates [1], or helium implantation on Nd doped YAG crystals [2], allowing high slope efficiency and low threshold laser operation at 1.06 μm. In fact, Nd:YAG was the first material that demonstrated the suitability of the ion implantation technique to fabricate waveguide lasers [3].

The ion implantation process produces at the end of the ion track an amorphization of the crystal, giving rise to a decrease of the refractive index in many dielectric materials [4]. This low-density region generates an optical barrier that confines the radiation, producing an optical waveguide. One of the problems faced when He^+ is used to produce optical waveguides is the short range of the implanted ions. Typically, a 2.8 MeV ion energy produces an optical barrier situated at around 6 μm beneath the surface. As higher energies is difficult to achieve in practice, a different approach becomes necessary. An alternative to fabricate wider waveguides using ion implantation technique is to use proton instead of He^+ ions, as for a given energy the ion range is much deeper in the case of lighter ions [5].

In this work the characterization of a Nd:YAG waveguide laser operating at 1.06 μm fabricated by proton implantation is reported. The characterization includes the waveguide index profile induced by the ion implantation, the main spectroscopic features of the Neodymium ions inside the waveguide, as well as the laser characteristics such as slope efficiency and threshold obtained using a Ti:Sapphire as the pump source.

Experimental Procedure

A planar waveguide was fabricated at room temperature on Nd:YAG by the technique of ion implantation using protons of energy around 1 MeV. In order to produce a broad barrier to avoid tunneling losses, a multi-implant was performed in the Nd:YAG substrate. Four different implants, with energies of 1.0, 1.05, 1.1 and 1.25 MeV, were performed on a single substrate, with a total dose of $6x10^{16}$ ions/cm^2.

To obtain the waveguide refractive index profile, the propagation constants of the modes were measured by the standard m-line method, using a rutile prism to couple the light into the waveguide coming from a polarized He-Ne laser (λ=633nm).

A CW Ti:sapphire laser, with a tuning range between 750-850 nm, was used as the excitation source. The pump beam was coupled into the waveguide with a x10 microscope objective by the end-fire coupling technique. The output light was collected through a x20 microscope objective and directed to the entrance slit of a monochromator (ARC SpectraPro 500-i) being detected by using an InGaAs photodiode.

A laser cavity was formed by butting mirrors to the polished end-faces of the waveguide. A >99.9 % reflectivity mirror at 1064 nm and transmission of 98% at 816 nm was placed in the front face, while on the other face a 97% at 1064 nm and >99.8% at 816 nm reflecting mirror was used. The pump power as well as the laser output power from the waveguide were measured by a silicon detector (Newport Model 1815-C and Spectra Physics Model 407A power meters).

Results and discussion

Figure 1 shows the calculated refractive index profile of the resulting waveguide after the multi-implant, using the experimental dark mode set measured at 633 nm. The profile exhibits an optical barrier height of approximately 0.98 % (decrease in refractive index relative to the substrate) located at a depth of 9.5 μm induced by the ion implantation process. Note that the profile in the figure is plotted as an index decrease in order to emphasize the concept of "optical well" and "optical barrier". It is also important to remark that the effective index in the surface region is slightly higher than that of the substrate by a 0.03%.

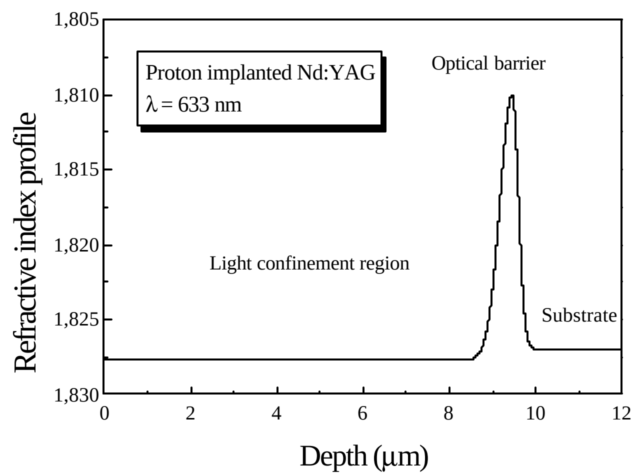

Figure 1: Refractive index profile corresponding to a proton implanted waveguide, measured at λ = 633 nm.

Before the laser experiments, the main spectroscopic characteristics of the Nd^{3+} ions in the waveguide were studied, using a Ti:sapphire as excitation source. After excitation to the $^2H_{9/2}$:$^4F_{3/5}$ manifold (λ= 816 nm) the neodymium ions relax non-radiatively to the $^4F_{3/2}$ level. From this level the relaxation is mainly radiative to the lower levels, giving rise to the apparition of three near-infrared emission bands at around 940, 1064 and 1340 nm corresponding to $^4F_{3/2} \rightarrow {}^4I_{9/2}$, $^4F_{3/2} \rightarrow {}^4I_{11/2}$, $^4F_{3/2} \rightarrow {}^4I_{15/2}$ transitions, respectively. The spontaneous spectrum associated to the radiative relaxation from the $^4F_{3/2}$ level, measured in the waveguide, which exhibits the highest emission cross section, is presented in figure 2. The luminescence from the waveguide shown in this figure is coincident with that previously reported from bulk in Nd:YAG [5] having the same structure. Also, the lifetime measured in waveguide configuration is coincident to that measured in bulk crystal, around 240 μs.

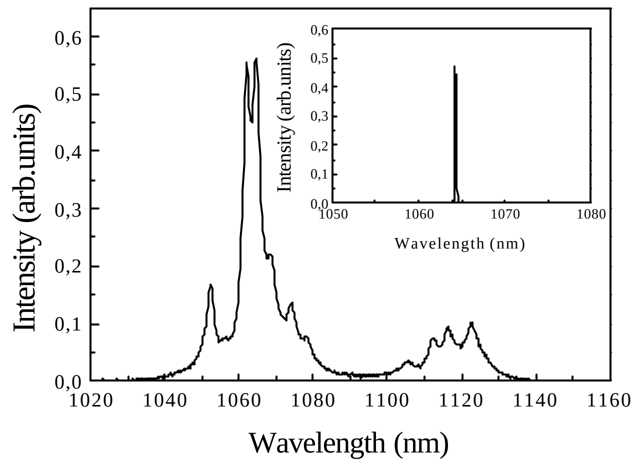

Figure 2: Spontaneous emission of the Nd3+ ions in waveguide configuration after pumping at 816 nm. The inset shows the laser output spectrum using 120 mW pump power.

It is well known that when neodymium is coupled to a resonant cavity it can operated as a four level scheme leading to laser action [6]. By fabricating a laser cavity with two mirrors attached directly to the proton implanted Nd:YAG waveguide, an intense infrared beam is observed. If stimulated emission occurs, the $^4F_{3/2} \rightarrow {}^4I_{11/2}$ transition dominates over all other de-excitation processes. The inset of figure 2 shows the recorded spectrum of the laser emission after pumping at 816 nm, where a narrow band centered at 1064.4 nm with a full width at half maximum (FWHM) of 3 nm, is observed. This laser emission corresponds in fact to the maximum gain transition of the Nd^{3+} ions in YAG crystals.

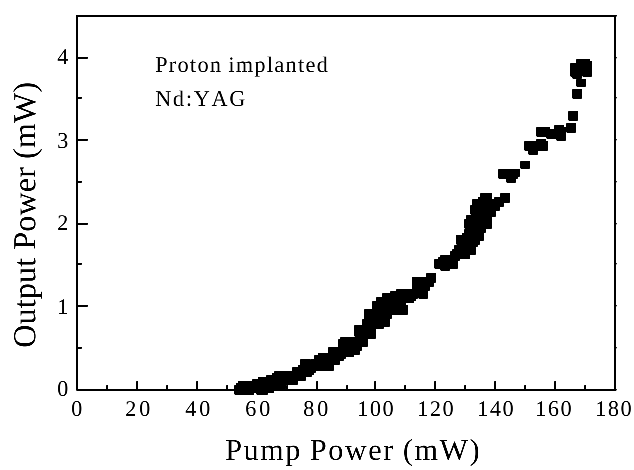

Figure 3: Output characteristics of the proton implanted waveguide Nd:YAG laser, showing a threshold of around 54 mW pumping at 816 nm.

The output characteristics of the proton implanted Nd:YAG waveguide operating in CW mode are given in figure 3, where the laser output power versus the pump power is presented. The pump power needed to reach laser oscillation gives a threshold of P_{th}= 54 mW, being the slope efficiency (the ratio of the output power to pump power above threshold) around 5%. The laser output showed a very high stability, even under continuous wave pump operation at room temperature, which clearly confirms the excellent mechanical, thermal and optical properties of the YAG matrix, besides the suitability of the ion implantation to construct miniaturized integrated devices.

Acknowledgements

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