Continuous-wave laser action at λ=1064.3 nm in proton- and carbon-implanted Nd:YAG waveguides

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This work reports continuous laser oscillation at λ=1064.3 nm at room temperature in Nd:YAG planar waveguides fabricated by two different techniques: proton implantation with a multi-implant of energies around 1 MeV and carbon implantation with a single-implant at an energy of 7 MeV. Threshold powers of 11 and 22 mW and slope efficiencies of 7% and 9% were achieved in the proton- and carbon-implanted guides, respectively. The laser outputs show a very high stability operating in cw regime at room temperature.
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The field of waveguide lasers based on integrated-optics technology has created much interest during the last years and recently. The confinement of light in optical waveguides maintains a small spot size and hence a high intensity over lengths than would normally be forbidden by diffraction. If the waveguide is doped with an active ion, the enhancement of laser efficiency is allowed and, therefore, extremely low laser thresholds can be achieved. The excellent laser properties of Nd^{3+} ions combined with the characteristics of the YAG host allow the development of compact and efficient amplifiers and solid-state lasers, preserving the crystal quality and homogeneity. Several techniques, such as epitaxial growth of Nd:YAG layers on pure YAG substrates,[1] or helium implantation on Nd-doped YAG crystals,[2] have been proposed to fabricate optical waveguides, allowing high slope efficiency and low threshold laser operation at 1.06 μm. In fact, Nd:YAG was the first dielectric material that demonstrated the suitability of the ion implantation technique to fabricate waveguide lasers.[3]

The ion implantation process produces radiation damage at the end of the ion track (nuclear stopping region) 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. Typically, a 2.8 MeV He^+ ion energy produces an optical barrier situated at around 6 μm beneath the surface. An alternative way to fabricate wider waveguides using ion implantation is to use protons instead of He^+ ions, because, for a given energy, the ion range is much deeper in the case of lighter ions,[5] this fact being advantageous when infrared light propagates along the waveguide. Instead of using light ions, optical waveguides can also be produced implanting heavy ions,[6] such as carbon,[7] for which a greater index decrease in the nuclear region is produced for a given dose. This leads to the formation of a higher optical barrier, which implies a reduction of tunneling losses.

In this work, the characterization of Nd:YAG waveguide lasers operating at 1.06 μm fabricated by either proton or carbon implantation is reported. The characterization includes the laser excitation range, the pump powers needed to reach laser oscillation as well as the slope efficiencies for both implanted waveguides. The experimental results combined with the theoretical estimations for a four-level laser material have been used in order to determine the propagation losses in both waveguides.

A first 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 on a single substrate of Nd:YAG with energies of 1.0, 1.05, 1.1, and 1.25 MeV, with a total dose of 6×10^{16} ions/cm^2. A second waveguide was single-implanted with carbon ions at an energy of 7 MeV and a dose of 1×10^{16} ions/cm^2. In this case, a single implantation is enough because the created optical barrier is broader than that for the proton-implanted guide.[8] When a waveguide is formed by ion implantation, color centers are generated during the process, which would imply absorption losses in the waveguide.[9] Therefore, an annealing step is necessary in order to reduce these losses. In the present work, the Nd:YAG waveguides were introduced for half an hour in an open furnace operating at 400 °C in order to perform the annealing step and to recover the original transparency.

A cw Ti:sapphire laser, with a tuning range between 750 and 850 nm, was used as excitation source. The waveguide laser cavity was formed by butting mirrors to the polished end-faces of the planar waveguides, as is sketched in Fig. 1. *A*>99.9% reflectivity mirror at 1064 nm and transmission of 98% at 822 nm was placed in the front face as high reflector,

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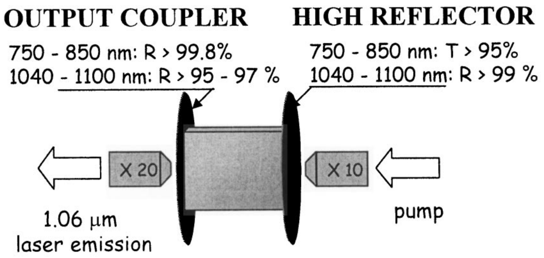

FIG. 1. Experimental setup used to obtain laser oscillation: the cavity is formed by butting mirrors to the polished end-faces of the implanted Nd:YAG planar waveguides.

while on the other face, a 97% at 1064 nm and >99.8% at 822 nm reflecting mirror was used as output coupler. The pump beam from the Ti:sapphire source was coupled into the waveguide with a 10× microscope objective by the end-fire coupling technique. The output light was collected through a 20× microscope objective and directed to the entrance slit of a monochromator (ARC SpectraPro 500-i), and was detected by using an InGaAs photodiode. The pump power as well as the laser output power from the waveguide were measured by a Spectra Physics Model 407A power meter and a Germanium photodiode (Thorlabs) respectively.

In terms of optical characterization and by using the standard m-line technique, it was found that the Nd:YAG proton-implanted waveguide presents an optical barrier height (decrease in refractive index relative to the substrate) of approximately 0.98% with a depth of 9.5 μm; on the other hand, the barrier height induced by the carbon implantation process is ~2.5% and is situated at 4 μm beneath the surface. With the refractive index profile measured at 633 nm and by using a multilayer approximation assuming that the index refractive increase is independent of the wavelength, it was found that the fundamental mode (nontunneling mode) is confined at 1.06 μm for both waveguides. The spectroscopic characterization showed that the luminescence from the waveguides is coincident with the luminescence of the bulk-doped Nd:YAG and both waveguides exhibit a single exponential decay with a value of 240 μs which is close to that previously reported in bulk.[5,8]

It is well known that when the Nd^{3+}-doped waveguides are coupled to a resonant cavity, they can operate as a four-level scheme to lead laser action.[10] The inset of Fig. 2 shows a photograph, taken by a digital camera through an infrared viewer, of the output waveguide laser focused on a screen when the proton-implanted Nd:YAG waveguide was coupled to the resonant cavity (see Fig. 1), were a laser spot size of 1500 μm^2 was measured.

When Nd^{3+} ions are excited to the $^2H_{9/2}$:$^4F_{5/2}$ manifold they relax mainly via a nonradiative decay to the $^4F_{3/2}$ metastable level. If stimulated emission occurs, the $^4F_{3/2} \rightarrow {}^4I_{11/2}$ transition dominates over all other relaxation channels and an intense infrared beam is observed. Figure 2 shows the recorded spectra of the laser emission for the proton-implanted planar waveguide after pumping at 822 nm. A narrow band centred at 1064.3 nm with a full width at half-maximum of around 0.14 nm obtained by using a 0.1 nm resolution monochromator can be appreciated, which corresponds to the maximum gain transition of the neodymium ions in YAG crystals.

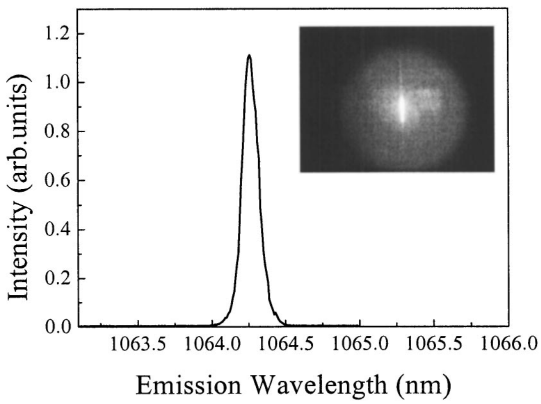

FIG. 2. Recorded laser output spectra of the proton implanted Nd:YAG waveguide after pumping at 822 nm at room temperature showing a narrow band centered at $\lambda = 1064.4$ nm. The inset shows a photograph of the waveguide laser output.

Taking advantage of the wide tuning range supplied by the Ti:sapphire laser and the high transmission (95% ± 5%) of the output coupler in this region (700–900 nm) it was possible to obtain the excitation range for the waveguide lasers at 1064.3 nm (Fig. 3). As it can be observed, the laser can be optically pumped by tuning the excitation in two different bands corresponding to the $^4I_{9/2} \rightarrow {}^4F_{7/2}$ and $^4I_{9/2} \rightarrow {}^4F_{5/2}$ transitions of the neodymium ions.

In order to measure the main laser features in cw regime, the Ti:sapphire was tuned at 822 nm which minimize the heat released to the host (see Fig. 3). The output laser characteristics of the implanted Nd:YAG waveguides are given in Fig. 4, where laser output power versus launched pump power is presented. For the proton-implanted guide [Fig. 4(a)] the launched pump power needed to reach laser oscillation is 11 mW, the slope efficiency being approximately 7%. On the other hand, the carbon-implanted waveguide [Fig. 4(b)] shows a power threshold of 22 mW and a slope efficiency of around 9%. The observed differences in the laser power thresholds can be attributed to the fact that the proton-multi-implanted waveguide has lower propagation losses than the carbon one.

In a four-level laser, the threshold (P_{th}) and the slope efficiency (ϕ) can be theoretically estimated by:[11,12]

$$P_{th} = \frac{h\nu_P}{\eta\sigma_e\tau}\frac{\delta}{2}A_{eff}, \tag{1}$$

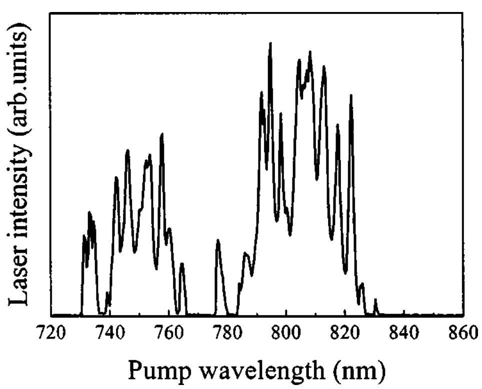

FIG. 3. Laser excitation range at 1064.3 nm of the Nd:YAG waveguides where two different bands corresponding to the $^4I_{9/2} \rightarrow {}^4F_{5/2}$ and $^4I_{9/2} \rightarrow {}^4F_{7/2}$ transitions can be clearly observed.

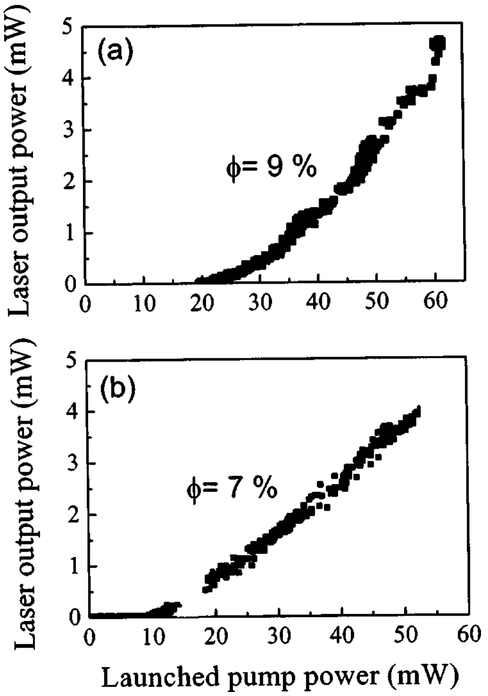

FIG. 4. Cw laser output power at λ = 1064.3 nm as function of the launched pump power at λ = 822 nm. A slope efficiency of 7% and a threshold of 11 mW for the proton-implanted waveguide (a) and a slope efficiency of 9% and a threshold of 22 mW for the carbon-implanted waveguide (b) are obtained.

$$\phi = \eta \frac{1-R_2}{\delta} \frac{\nu_S}{\nu_P}, \tag{2}$$

where ν_S and ν_P are the signal and pump frequencies, respectively, σ_e is the stimulated emission cross section with a value of 3.1×10^{-19} cm^2,[12] τ is the fluorescence lifetime, η is the fraction of absorbed photons that contribute to the population of the $^4F_{3/2}$ metastable state ($\eta=1$), A_{eff} is the effective pump area, and R_2 is the output reflectivity mirror at the signal wavelength. Finally, the round-trip cavity exponential factor δ, which depends on the scattering losses (α), the cavity length (l), and the input (R_1) and output (R_2) mirrors, reflectivity is defined as

$$\delta = 2\alpha l - \ln(R_1 R_2). \tag{3}$$

Therefore, the product of P_{th} and ϕ is

$$P_{\mathrm{th}}\phi = \frac{h\nu_S}{\sigma_e \tau} \frac{1-R_2}{2} A_{\mathrm{eff}}, \tag{4}$$

from where the value of the effective area can be readily obtained.

In the case of proton-implanted waveguide, the A_{eff} value was calculated to be 1980 μm^2, in good accordance with the measured spot size (see inset Fig. 2). Taking into account these values, a scattering losses of 0.6 dB/cm were estimated, which compare favorably with previously reported losses in YAG waveguides.[12] Similar calculations have been carried out for the carbon-implanted waveguide. Using the measured parameters for this waveguide laser, the overall data are consistent with scattering losses around 1 dB/cm. With our available pump power the proton waveguide laser could emit up to 4 mW and the carbon waveguide emits up to 4.6 mW in cw, being the laser emissions quite stable, without any reduction in the output power even under continuos pump operation at room temperature.

In conclusion, both proton- and carbon-implanted waveguide lasers on Nd:YAG crystals have been demonstrated, showing thresholds of 11 and 22 mW, respectively, after pumping at 822 nm, and slope efficiencies of around 8% for both waveguides. The laser outputs show a very high stability operating in cw regime at room temperature, which clearly confirms the excellent mechanical, thermal, and optical properties of the YAG host, besides the suitability of the ion implantation technique to construct miniaturized devices.

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