Ion-implanted Nd:MgO:$LiNbO_3$ planar waveguide laser

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Laser oscillation in an ion-implanted planar Nd:MgO:$LiNbO_3$ waveguide is demonstrated for the first time to our knowledge. Details of the waveguide structure, spectroscopic properties, photorefractive effects, and laser performance are given. A simple calculation of the absorbed power threshold gives ~8 mW, in fair agreement with the experimental value of ~17 mW.

The combination of the excellent laser properties of the Nd^{3+} ion with the nonlinear and electro-optical properties of $LiNbO_3$ in Nd:MgO:$LiNbO_3$ permits the construction of many interesting systems where, for example, doubling and Q switching can be combined in a monolithic device.[1] Furthermore, combination of these features with existing integrated-optics technology to form planar and channel waveguide lasers should lead to efficient low-threshold devices. Lallier *et al.*[2–4] recently reported a proton-exchanged Nd:MgO:$LiNbO_3$ channel waveguide laser and amplifier with thresholds as low as ~1.5 mW. Brinkmann *et al.*[5] have also shown laser operation in a Ti-diffused channel waveguide based on Nd:MgO:$LiNbO_3$. Here we describe, for the first time to our knowledge, the use of ion implantation to form a planar Nd:MgO:$LiNbO_3$ waveguide laser. The calculated threshold is in fair agreement with experimental results, and similar calculations suggest that low thresholds would be obtained in a channel waveguide formed by ion implantation. This result also provides further demonstration of the versatility of the ion-implantation process, which can be used to form waveguides in a wide range of crystals[6] and has recently been used to form waveguide lasers based on Nd:YAG (Refs. 7 and 8) and Nd:YAP (Nd:$YAlO_3$).[9]

The material used in this experiment was grown by Crystal Technology[10] and is from the boule referred to in Ref. 1 as the low-doped sample. The boule contained 2.5 wt. % MgO and 0.15 wt. % Nd_2O_3. The crystal was cut to 2, 6, and 8 mm in the x, z, and y crystallographic directions, respectively.

The planar waveguide was formed by implanting He^+ ions through a flat polished surface, with the implant direction parallel to the x axis. A dose of 1.5 $\times 10^{16}$ ions per cm^2 at an ion energy of 1.8 MeV was used, with the crystal held at 77 K. The ions are initially slowed by electronic excitation (the electronic stopping region) and form defects that are subsequently removed by annealing at 200°C for 40 min. Near the end of their travel, where they have been slowed sufficiently, the ions undergo nuclear collisions that lead to the creation of a sharply defined layer of lowered refractive index. Thus light can be confined between this barrier and the crystal–air interface. Some crystals also exhibit an index rise in the electronic stopping region,[6] and this is the case with the extraordinary refractive index n_e in $LiNbO_3$.[11] This is the index of interest as it corresponds to the polarization direction for which the emission cross section is greatest.[1] Figure 1 shows the (extraordinary) refractive-index profile for this waveguide, which is calculated by a theoretical fit to the dark-mode characteristics observed by prism coupling.[12] The increase in n_e in the electronic stopping region is useful, as waveguide modes sitting within this index well do not need the low-index barrier to confine them. Thus, for extraordinary- (TE-) polarized modes there is no need to build up a thicker barrier with multiple ion doses of different energies to prevent leakage of light, as, for example, would be the case in YAP.[9] This means that the ion dose can be kept to a relatively low level, and any consequent disruption to the crystal spectroscopy can be kept to a minimum.

Ion implantation of undoped $LiNbO_3$ has been extensively studied with a view to creating active inte-

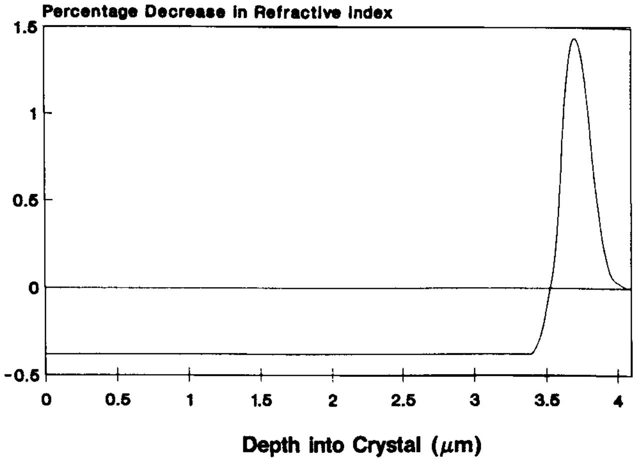

Fig. 1. Waveguide refractive-index profile measured at 633 nm.

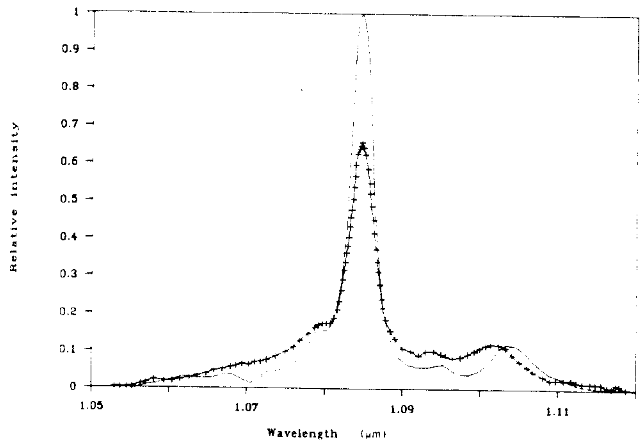

Fig. 2. Bulk (solid curve) and waveguide (crosses) fluorescence spectra (E parallel to c).

grated-optical devices, and waveguide losses of ~1.0 dB cm^{-1} can typically be expected from a planar guide.[13] This is consistent with observation of transmissions of ~63% for TE-polarized light (of a wavelength detuned from the Nd absorption, ~830 nm) when end launched into the 8-mm-long crystal. The contributions of launch loss and propagation loss have not been separately determined since the crystal is too short for an accurate loss measurement by the prism coupling method. The figure of 1.0 dB cm^{-1} looks feasible since this would imply a launch efficiency of ~76%, which is typical of previous results in YAG waveguides of similar depth with similar launch conditions.[8] The guide was found to have just one mode in the index well at both the pump (814 nm) and signal (1.085 μm) wavelengths.

The fluorescence spectra from the bulk and waveguide regions were measured with an argon-ion-pumped Ti:sapphire laser as the pump laser, tuned into the large absorption at 814 nm and polarized parallel to the c axis. Figure 2 shows the fluorescence spectra polarized parallel to the c axis (TE for the waveguide). As has previously been seen in Nd:YAG (Refs. 7 and 8) and Nd:YAP,[9] there is a broadening of the waveguide spectrum with respect to the bulk. By setting the area under the two spectra to be the same we can estimate that the peak emission cross section in the guide region is reduced by a factor of ~0.65. The fluorescence lifetime shows no change between the bulk and waveguide and was found to be ~120 μs, in agreement with Ref. 1. Thus we have found that a low-loss ion-implanted waveguide can be formed in Nd:MgO:$LiNbO_3$ with only minimal effect on the spectrum of the laser transition.

The Nd:MgO:$LiNbO_3$ crystal was end polished to ensure a good-quality surface right up to the edges, as the waveguide is actually contained in the top few micrometers of the crystal. The ~8-mm length had been chosen to approximately match the $1/e$ absorption length at ~814 nm for E parallel to c. There was no measurable difference, with similar focusing, between the absorption length in the guide and in the bulk. Figure 3 shows the experimental setup used to investigate laser performance. The laser cavity was formed by placing plane, high-reflectivity, dielectric mirrors directly onto the end faces of the waveguide by using a thin film of liquid to hold them in place by surface tension. Following the method of Ref. 14, we use fluorinated liquid (Fluorinert FC-70) because of its good thermal properties. This liquid was not chosen for index-matching purposes.

Using a beam chopper with a duty cycle of 50% and mean pump power of ~100 mW before the chopper, we were only able to obtain brief flashes of lasing with the crystal at room temperature. This was assumed to be due to photorefractive damage as has previously been observed in material from this boule at a pump wavelength of ~598 nm.[1] To overcome this problem we placed the crystal in thermal contact with a heated metal block. With the block held at ~90°C we obtained quasi-cw lasing, with the pump pulse duration typically at ~500 μs. No increase in threshold was observed at this elevated temperature. However, true cw operation could not be obtained at this temperature, and further temperature increase was prevented as a result of evaporation of the fluorinated liquid. This could be solved in the future by directly coating the end faces of the crystal. Pumping and/or lasing polarized along the ordinary refractive index axis may also help[1] but will give higher laser thresholds since the emission and absorption cross sections are smaller. It is interesting to note that other researchers have achieved cw operation while pumping in the 800–830-nm absorption band in both bulk[15] and proton-exchanged waveguide lasers.[3]

Laser action was obtained at a launched power threshold of ~28 mW, assuming ~76% launch efficiency. If we take into account the observed unabsorbed pump power and pump feedback off the output mirror, this corresponds to an absorbed power threshold of ~17 mW. A calculated threshold was obtained from the expression[16]

$$P_{th} = \left(\frac{\pi h\nu_p}{2\sigma_e\eta_p\tau_{fl}}\right)(W_{lx}^2 + W_{px}^2)^{1/2}(W_{ly}^2 + W_{py}^2)^{1/2}L, \tag{1}$$

where σ_e is the stimulated-emission cross section, η_p is the pump quantum efficiency (the number of ions

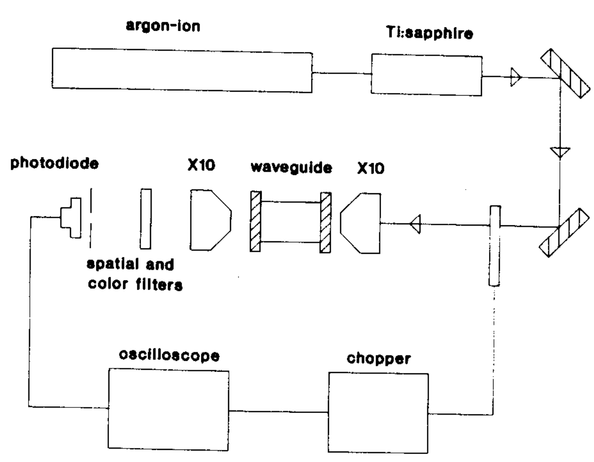

Fig. 3. Waveguide laser cavity and pumping arrangement.

excited to the upper laser level per absorbed pump photon), and τ_{fl} is the fluorescence lifetime. The quantities W_{py} and W_{ly} are the pump and laser spot sizes (half-width of the $1/e^2$ intensity points) perpendicular to the plane of the guide. These were measured to be ~1.2 μm and ~1.7 μm, respectively, with the latter figure actually being measured from a 1.064-μm end-launched laser beam. The quantities W_{px} and W_{lx} are the corresponding spot sizes in the plane of the guide. Equation (1) assumes constant spot sizes along the length of the guide. Clearly this is not valid for the unguided spot sizes W_{px} and W_{lx}. Therefore we use a value averaged over the crystal length.[1] The output power through the high-reflectivity mirror was too low to measure accurately the laser spot size in the plane of the guide. However, a lower limit for the threshold can be obtained by assuming that the average pump spot size (W_{px} = 272 μm) dominates this part of the expression. We also assume that the single-pass loss L is dominated by a propagation loss of ~0.8 dB (typically 1 dB cm^{-1}, 8-mm crystal length). Thus taking $\eta_p = 1$, $\tau_{fl} = 120$ μs, and $\sigma_e = 4 \times 10^{-23}$ m^2, calculated by multiplying the figure found in Ref. 1 by 0.65 to account for the spectroscopic changes, we arrive at P_{th} = 8.3 mW. This is in satisfactory agreement with experiment in view of the various uncertainties, particularly with regard to loss and with regard to the uncertainty over the value of σ_e, for which we have assumed the largest published value. No output power or slope efficiency measurements have been made, as to date only high-reflectivity mirrors have been used.

The implication of the above calculation for channel waveguides, where the spot sizes W_{lx} and W_{px} could be reduced to just a few micrometers, are that submilliwatt thresholds should be achievable if propagation losses can be kept to near ~1 dB cm^{-1}. Such low-loss channel waveguides formed by ion implantation have already been demonstrated in undoped $LiNbO_3$.[17] Considerably improved planar waveguide thresholds may also be obtained through line focusing by use of cylindrical lenses rather than microscope objectives.

As stated above, one of the interesting features of Nd:MgO:$LiNbO_3$ is that it should allow the construction of self-frequency-doubled lasers. The use of temperature-tuned, 90° phase matching in a waveguide would lead to a simple and efficient device. However, this would require guidance for both the ordinary and the extraordinary polarizations. In this case ion-implanted waveguides may offer a particular advantage for such a device, as proton-exchanged waveguides are reported not to guide the ordinary polarization,[2–4] and Ti-diffused waveguides are reported to suffer from a greatly reduced resistance to photorefractive damage,[18] although this may not be important at the phase-matching temperature. To make such a device it may be necessary to force lasing on the ordinary polarization. This should be possible by using dichroic mirrors that strongly favor operation at 1.093 μm (the peak of the ordinary polarization fluorescence spectrum) rather than at 1.085 μm. It is possible to fabricate low-loss guides for the ordinary polarization with a relatively low implanted ion dose (and therefore minimal disruption to the spectroscopy), despite the profile's being of the barrier type, because of the relatively high percentage change in refractive index.

In conclusion, we have demonstrated what is to our knowledge the first laser oscillation in an ion-implanted Nd:MgO:$LiNbO_3$ planar waveguide. Calculated and experimental thresholds have been shown to be in good agreement and suggest that submilliwatt thresholds should be obtained in a low-loss (~1.0-dB/cm) channel waveguide. Ion-implanted Nd:MgO:$LiNbO_3$ waveguides now offer the possibility of many interesting devices such as efficient self-frequency-doubled and monolithic modulated lasers.

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