Ion Implanted Nd:YAG Waveguide Lasers

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Abstract—**A detailed description of the use of ion implantation to create optical waveguides in laser crystals is given. Calculated mode profiles and lasing thresholds are shown to be in good agreement with experimental results in a monolithic planar waveguide Nd:YAG laser. The first fabrication and characterization of ion implanted channel waveguides in Nd:YAG is also reported.**

INTRODUCTION

THE use of ion implantation to create optical waveguides in various materials including ionic crystals has been studied extensively [1], [2], with losses of ≤ 1 dB/cm commonly reported in single-mode planar and channel waveguides [3], [4]. Much of the work carried out to date on ion implanted ionic crystals has concentrated on materials with high electro-optic coefficients, such as $LiNbO_3$ and $LiTaO_3$, with a view to creating active integrated optical devices. Recently we have reported the first laser action in an ion implanted crystal [5] using a single-mode planar waveguide in Nd:YAG [6]. A number of other methods have been used to fabricate optical waveguides in dielectric materials, including ion exchange and ion diffusion [7], [8]. However such techniques are not effective in a number of dielectric materials, Nd:YAG being such an example. So it is a particular attraction of ion implantation that the physical nature of the implantation process allows waveguides to be fabricated in a wide range of materials, thus opening the possibility for a number of waveguide laser devices.

In this paper we give a more detailed description of the waveguide properties than appeared in [5] and present new results on an improved Nd:YAG planar waveguide laser where high reflectivity coatings were applied directly to the ends of the waveguide. We also describe the first fabrication of channel waveguides in Nd:YAG using ion implantation. This is a necessary step towards the goal of low threshold operation. While these initial tests of the ion-implantation technique have been carried out in Nd:YAG, the longer term intention is to extend the technique to tunable laser materials. Here the goal is the achievement of widely tunable laser operation at thresholds low enough to allow pumping by laser diodes. Many applications can be anticipated for such devices.

CHARACTERISTICS OF ION IMPLANTED WAVEGUIDES

A general review of the principles of waveguide fabrication by ion implantation is given in [1]. For the work described in this paper, the ion implanted optical waveguides are formed using high energy (up to several MeV) He^+ ions. These ions are incident upon a polished surface of the crystal. Initially, they are slowed by electronic excitation, (the electronic stopping region), forming color centers which can be removed subsequently by annealing. When the ions have been slowed sufficiently at a depth which is usually several microns into the material, but depends on the initial ion energy, the ions suffer nuclear collisions. This creates a well-defined low index optical barrier, the depth and thickness of which can be controlled by varying the ion energy and dose. Thus light launched into the top few microns of the implanted crystal will be confined between the crystal-air interface and the low index barrier. However, it has been found [9] that for many materials, including YAG, $LiNbO_3$, $BeAl_2O_4$ (alexandrite), and $LiCaAlF_6$, there is also a small increase in the value of the refractive index in the electronic stopping region. This feature, discussed in detail in [6] for the case of Nd:YAG, makes an important contribution to the guiding behavior by providing an index well which prevents tunneling through the low index, as can otherwise occur for thin barriers. It also simplifies the fabrication of channel waveguides, as will be discussed later.

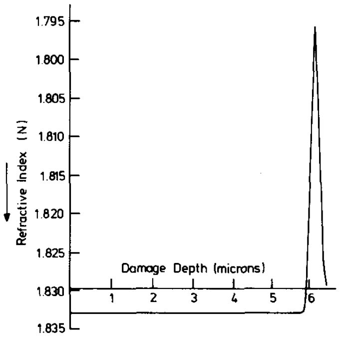

Fig. 1. Typical refractive index profile (at 633 nm) produced by ion implantation. The x axis represents the bulk refractive index.

Fig. 1 shows a typical calculated refractive index profile (for TM wave, i.e., E field perpendicular to the waveguide plane) that can be produced in YAG. The calculation of the profile is made by fitting to the observed waveguide mode characteristics [10] determined by using a prism coupling configuration. This particular profile was produced by a multienergy implant of He ions at 77 K with ion energies up to 2.8 MeV at a total ion dose of 7×10^{16} ions cm^{-2}. Fig. 2 shows calculated TM mode profiles at 0.59 and 1.06 μm, the pump and laser wavelengths, respectively, following the analysis of Wang [11] and assuming a square shaped index barrier of the same height and half width as the barrier in Fig. 1. At 0.59 μm, two modes are below cutoff, TM_0 [Fig. 2(a)] and TM_1 [Fig. 2(b)]. At 1.06 μm only the TM_0 mode, Fig. 2(c), is below cutoff. Measurements of the

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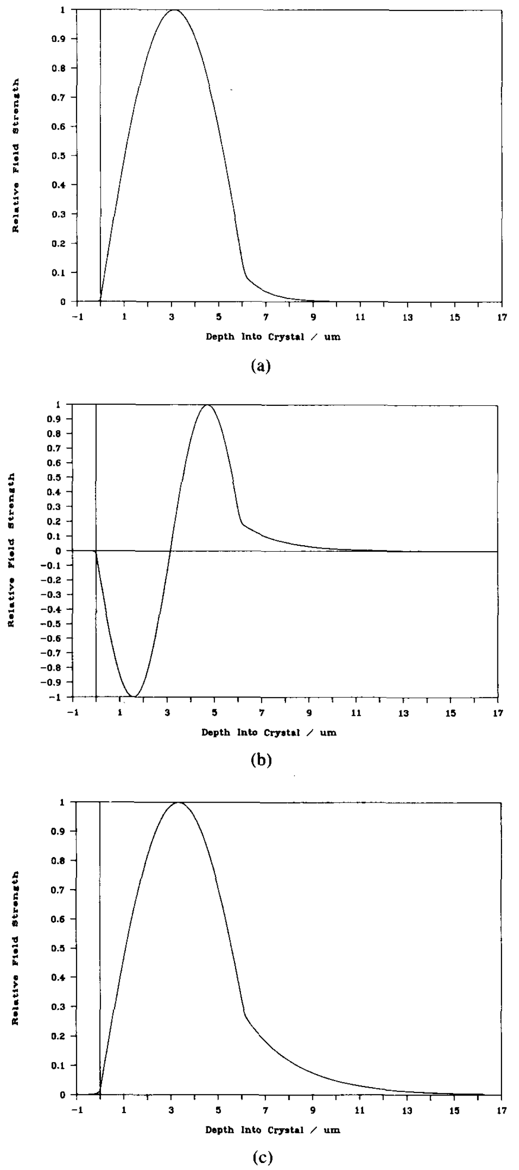


Fig. 2. Calculated TM mode profiles. (a) TM_0 at 0.59 μm, (b) TM_1 at 0.59 μm, and (c) TM_0 at 1.06 μm.

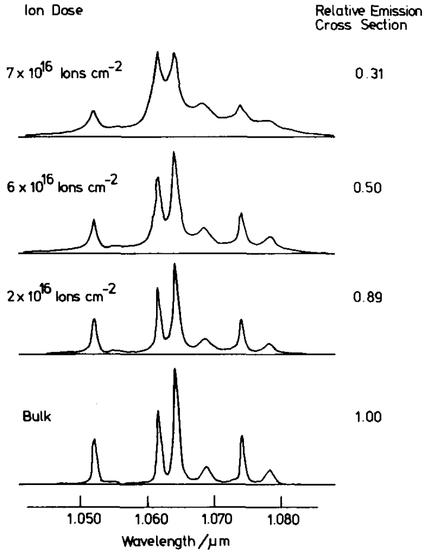


Fig. 3. Nd:YAG waveguide fluorescence spectra against ion dose.

index profile for TE waves indicate smaller index differences [6] than for TM, so that the TE_0 mode at 1.06 μm is cutoff. This is consistent with the experimental observation that lasing only occurs as a TM wave. Experimentally it was observed that two TM modes could be made to propagate at 0.59 μm and only one at 1.06 μm.

Measurements of the beam divergence, perpendicular to the waveguide plane, were made for TM_0 modes both at 0.59 and 1.06 μm. Assuming Gaussian profiles, these measured divergences implied spot sizes (W_0, $1/e$ field radius) of 3 and 4 μm, respectively, which are in reasonable agreement with the spot sizes deduced from Fig. 2, viz. 2.4 and 2.6 μm. Guide propagation losses for the guide shown in Fig. 1 were measured by a standard prism-coupling technique. One prism is used to launch through the guide surface, another to extract light from the guide surface, and by monitoring extracted light power versus separation, a loss figure of 1.5 dB/cm at 633 nm was obtained. More recent results on another guide have yielded 1.2 dB/cm. On the other hand, with end launching into guides, a typical transmission is ~65% for a 5 mm long guide, indicating, in view of the above propagation losses, that launch efficiencies of ~80% have been obtained.

If ion implanted crystal waveguides are to provide an effective route to low threshold laser systems, it is important that their spectroscopic properties should not be significantly degraded by the ion implantation process. Fig. 3 shows how the Nd:YAG fluorescence spectrum around 1.06 μm changes with increasing ion dose, the lowest trace corresponding to the bulk material which has received no dose. It is seen that there is a broadening of the fluorescence linewidth which increases with dose, which in the most extreme case for the three guides shown here reduces the peak emission cross section by a factor of ~3. There is, however, no observable change in the fluorescence lifetime. All three guides have been operated as lasers, and in the case of the highest dose, the spectral shape had changed to the extent that lasing occurred at both 1.062 and 1.064 μm, with the normally dominant 1.064 μm line having the higher threshold. The lowest threshold for lasing was obtained with the guide having the lowest dose, 2×10^{16} ions/cm^2, and for this guide the reduction in the peak-emission cross section is only ~10% relative to the bulk crystal. Thus although it is apparent that the ion-implantation process can significantly degrade the spectral characteristics it is also clear that the spectral change can be kept to an insignificant level for a dose which is sufficient to produce a good quality guide.

CHANNEL WAVEGUIDE FABRICATION

While initial efforts have been directed at the formation of planar waveguides, it is clear that, for low threshold operation it is necessary to use a channel waveguide, where confinement is in two dimensions. Our initial investigations in this direction have again been concentrated on Nd:YAG, on account of its ready availability. The first step in the fabrication procedure is to polish the YAG surface to be implanted. A thin (~100 nm) layer of chromium is then evaporated onto this surface to aid adhesion of a subsequent, much thicker gold film which acts as the ion stopping mask. A sputtering technique was used for deposition of the gold. A layer of photoresist is then deposited and patterned via standard photolithographic techniques such that various sized channels, from 2 to 40 μm in width, are created. The gold beneath these channels is then chemically etched away leaving an ion stopping mask as shown in Fig. 4, which can then be implanted with the same ion dose used to create the planar guide. Finally, the remaining gold and chromium are removed and the end faces polished to allow end coupling. Channel guides formed in this way rely on the increase in index within the guide region to provide lateral confinement. If the implantation process had led only to an index decrease in the barrier, without an index increase in the guide region, then it would have been necessary to build up low index side walls to the channel, by multienergy implants, as has been demonstrated for $LiNbO_3$ [4]. So far the gold films produced by sputtering have been no thicker than ~1 μm and this is insufficient to completely stop the high energy ions needed for waveguide fabrication in YAG. Thus the ion stopping mask has so far only resulted in a small variation in the depth of the low index barrier. This is shown schematically in Fig. 4 and can be seen quite easily under a microscope. Despite the shallowness of this laterally confining structure, we have been able to observe channel waveguide propagation with overall transmission figures, including launch and propagation loss, of nearly 50% at ~620 nm in the 7 mm long crystal. As the launch efficiency is probably reduced from that obtained with the planar guide (~80%), the propagation loss should be within the range of 1.5-3.0 dB/cm. Transmissions of over 40% have also been obtained at 1.064 μm.

Fig. 5 shows a magnified picture of one end face of the YAG sample seen in transmitted light. A selection of channels, from 40 to 14 μm wide, are visible. The picture also shows the planar waveguide regions between the channels. The spatial mode profiles were measured in the vertical and horizontal planes using a scanning photodiode array. The guides become purely single mode for widths of 10 μm or less, but propagation of just one mode was possible for all widths of guide by careful adjustment of the launch conditions. The vertical spot sizes W_y ($1/e$ radius for the field) were constant for all the guides, at 2.2 and 3.5 μm for the 0.59 and 1.064 μm wavelengths, respectively. The horizontal spot sizes varied from 4 to 10 μm at 0.59 μm and from 7 to 10 μm at 1.064 μm, as the channel width increased from 4 to 20 μm.

The profile measurements show that the single-mode waveguide spatial modes are somewhat larger in the horizontal dimension (approximately twice) than the physical size of the channels. It was also noted that the transmission figure was very sensitive to the angle between the channel and the input beam, indicating weak confinement in the horizontal plane. This point is clearly demonstrated in Fig. 6 which shows the channel waveguide transmission versus angle of incidence for an end launched beam. As yet this guide has failed to operate as a laser despite having coated ends. This is almost certainly because the channels are not accurately perpendicular to the coated end faces of the YAG crystal, thus causing the reflected mode to be di-

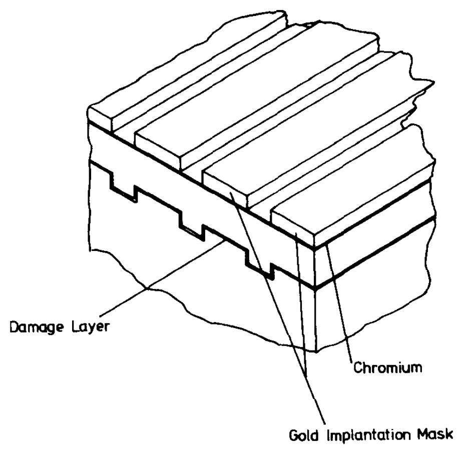


Fig. 4. Schematic diagram of channel waveguide fabrication.

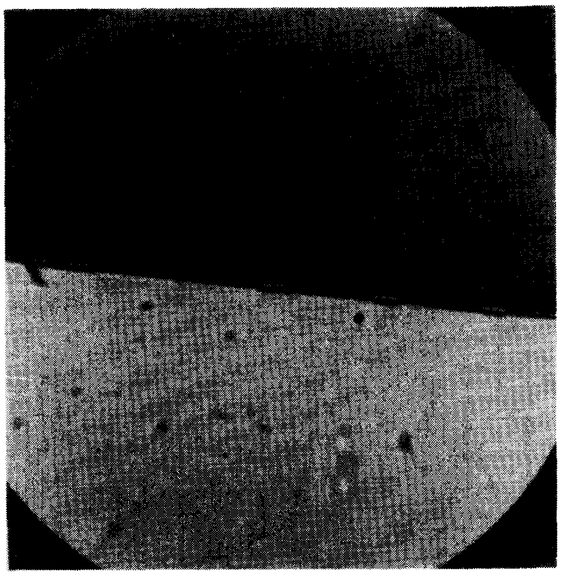


Fig. 5. Channel waveguide end face.

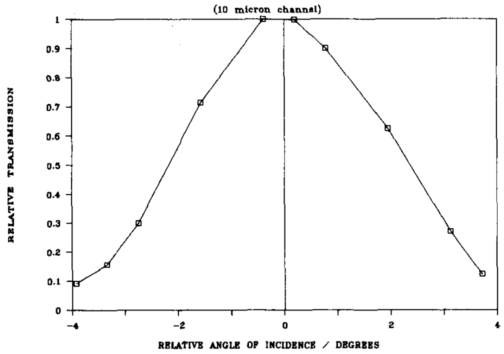


Fig. 6. Channel waveguide transmission versus angle of incidence of end launched beam.

rected out of the channel. Future work is aimed at improving the confinement using electroplating, rather than sputtering, to produce thicker gold masks that can completely stop the high-energy ions, and perpendicularity of the channels will be ensured by using an accurate mask alignment procedure.

PLANAR WAVEGUIDE: LASER PERFORMANCE

The first reported result of lasing in the planar ion-implanted waveguide Nd:YAG device, involved a high threshold, ~50 mW of launched pump power [5]. The laser cavity was formed by butting two mirrors directly to the end faces of the crystal. However this arrangement was difficult to adjust satisfactorily and carried the constant risk of damage by contact with the waveguide ends. To avoid these problems the guide used in these experiments was coated at each end with high-reflectivity dielectric multilayers. To ensure good quality coatings over the top few microns they were allowed to "spill over" onto the top surface for ~1 mm. This did not seem to have any adverse effect on the loss of the guide as similar transmissions were obtained to those observed with no coatings present. In scanning a 590 nm beam over the coated crystal end face no significant change was found in the reflectivity between the bulk of the crystal and the guide region, suggesting that we do indeed maintain good quality right to the edge of the crystal face.

The (TM) refractive index profile for the coated waveguide is shown in Fig. 7 and the fluorescence spectrum is shown in Fig. 3 (ion dose 2×10^{16} ions cm^{-2}). The unusual profile for this guide is discussed in [6], but the main guidance is again due to index enhancement in the electronic stopping region. The crystal end faces had previously been polished taking great care to produce high-quality edges as the guide forms the top ~4 μm of the 4 mm long crystal. It was noted however that the end faces were not perfectly parallel, being misaligned by ~2 minutes in both the horizontal plane (the plane of the guide) and the vertical.

The experimental arrangement consisted of an argon-ion pumped R6*G* dye laser as the pump source, a focusing microscope objective, and the guide held on a 4-axis micropositioner that allows alignment of the waveguide such that the coated end faces are perpendicular to the pump beam. With the dye laser tuned into the main Nd:YAG absorption line at ~590 nm, we observed an absorbed (launched) pump power threshold of 10.5 (12.1) mW. The predicted threshold absorbed power was calculated from the equation [12]:

$$P_{a,\mathrm{th}} = [(\pi h\nu_p)/(2\sigma_e\eta_p\tau_{\mathrm{fl}})] \cdot (W_{lx}^2 + W_{px}^2)^{1/2} \cdot (W_{ly}^2 + W_{py}^2)^{1/2} \cdot L$$

where σ_e is the stimulated emission cross section, η_p is the pump quantum efficiency (the number of ions excited to the upper laser level per absorbed pump photon), and τ_{fl} is the fluorescence lifetime. The quantities W_{lx} and W_{ly}, are the laser beam spot sizes in and out of the plane of the guide, respectively, (all spot sizes are half-widths to $1/e^2$ intensity). W_{px} and W_{py} are the corresponding quantities for the pump beam. This equation assumes constant spot sizes along the length of the guide. While this is clearly valid for W_{ly} and W_{py}, since guidance occurs in the y direction, for the x direction the pump spot size W_{px} varied considerably along the guide and therefore a value, averaged over the pump extinction length (~1 mm) was used. A rough estimated was made of the expected spot size for the laser beam in the horizontal (unguided) plane by considering the spot size which would give maximum overlap after one round-trip, taking into account both the diffraction and nonparallelism of the waveguide ends. The predicted value, 53 μm, is reasonably close to the actually observed value ~60 μm, taken from a series of readings of beam profile versus distance from the guide. A typical near field profile is shown in Fig. 8(a). The observed profile shows significant asymmetry due to the nonparallelism of the ends. The analysis, following Wang [11] for the mode profile in the guided y direction predicts a profile with spot size of ~4 μm and similar envelope to that observed in practice [Fig. 8(b)]. The predicted spot size is relatively large compared to the guide width since operation is close to cutoff. In practice, the observed spot size, taken from a series of profile measurements as in Fig. 8(b), is even larger at ~7 μm. The origin of this discrepancy is not clear since the measured pump spot size of 2.4 μm is in fair agreement with the calculated value (1.8 μm).

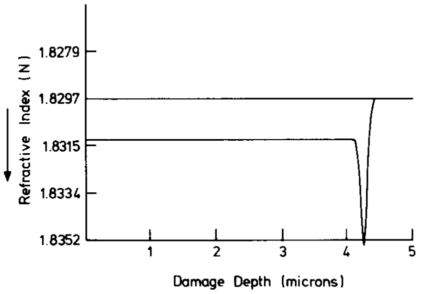


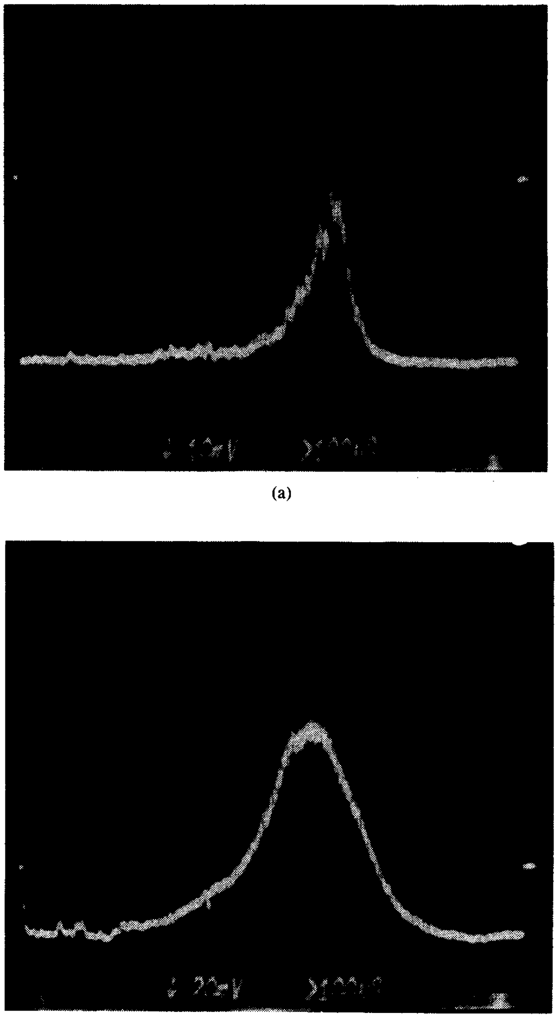
Fig. 7. TM refractive index profile (at 633 nm) for the monolithic Nd:YAG planar waveguide. The bulk refractive index is represented by the solid line at 1.8297.

A threshold prediction using (1) was made, with $\eta_p = 1$, $W_{lx} = 60$ μm, $W_{ly} = 7$ μm, $W_{px} = 20$ μm, $W_{py} = 2.4$ μm, and $\sigma_e = 3.1 \times 10^{-23}$ m^2. The latter value is reduced by 0.89 relative to the published value of 3.5×10^{-23} m^2 [13] to account for the spectral broadening in Fig. 3. The loss was calculated from the measured propagation loss together with an estimated contribution from the end face misalignment. The latter was in fact a small correction compared with the propagation loss. The resulting predicted threshold of 6.4 mW absorbed is in reasonable agreement with the observed 10.5 mW. Output powers were low (up to a maximum of ~1 mW observed) since the mirror coatings were chosen for maximum reflectivity and, hence, minimum threshold. Based on the observed guide losses, it is expected that with an output transmission of around 20% a slope efficiency of 20 to 30% would be obtained.

Laser action was also observed with Styryl 9 pumping at ~807 nm. Despite the higher quantum efficiency for this pump wavelength the threshold absorbed power was actually slightly higher, at 14.9 mW. The reason for this increase is not clear at present.

SUMMARY

We have demonstrated the use of ion implantation to fabricate crystal waveguide lasers in Nd:YAG. Experimental laser performance in a monolithic Nd:YAG planar waveguide was close to theoretical predictions. Similar predictions for channel waveguides suggest that it should be possible to obtain over an order of magnitude reduction in threshold compared to bulk crystals for typical guide losses of ~1 dB/cm. If guide losses of this order could be achieved in widely tunable laser materials


(a)

(b)

Fig. 8. (a) Laser output mode profiles in the horizontal (unguided) plane and (b) the vertical plane. The vertical axis represents relative intensity and the horizontal axis is relative position across the beam profile (the scales are different in the two pictures).

such as Ti : Al_2O_3, Cr : $BeAl_2O_4$ or various Cr doped garnets then threshold levels compatible with diode pumping will be possible. The first fabrication of such channel waveguides in Nd : YAG has been demonstrated with measured losses in the region of 1.5–3.0 dB/cm. Work is continuing on improving channel waveguide fabrication and investigating ion implantation effects in a wide range of laser crystals, with promising results already obtained in $LiNbO_3$, alexandrite, YAP, and YLF.

ACKNOWLEDGMENT

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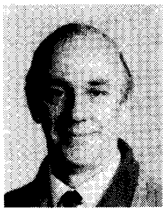

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