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An efficient, diode-pumped, ion-implanted Nd:GGG planar waveguide laser

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We report the first laser operation of an ion-implanted Nd:GGG planar waveguide laser at 1.062 μm. Diode array and dye laser pumping is described with threshold absorbed powers as low as 8 mW. Slope efficiencies of 30% with respect to absorbed power have been observed with output powers of up to 40 mW.

1. Introduction

The use of ion-implantation to form waveguides lasers in a range of crystals has recently been reported [1–5]. By creating single mode waveguide geometries within doped laser crystals it should be possible to obtain very high gain and very low laser thresholds, as has already been demonstrated very successfully in glass lasers in the form of doped optical fibers [6]. Crystal hosts can provide a number of advantages over glass such as large electro-optic and non-linear effects, and a large range of possible laser transitions with linewidths ranging from very narrow to very broad. In particular we are interested in the possibility of obtaining low threshold diode-pumped operation of broadly tunable lasers and for this reason GGG ($Gd_3Ga_5O_{12}$) is of particular interest as laser action has been observed in Cr^{3+} doped GGG [7]. As an initial step towards such a tunable laser we have investigated the properties of a planar Nd:GGG waveguide and have found that it gives the best ion-implanted waveguide laser performance yet reported.

2. Waveguide properties

Waveguides have been formed in GGG crystals by implantation of He^+ ions through a polished surface. The refractive index profile formed by the implant has been found to be similar to that obtained in YAG ($Y_3Al_5O_{12}$), [8], showing an increase in refractive index in the "electronic stopping" region (where the ions are slowed by electronic excitation) and a low index barrier at the end of the ion track (where the ions undergo nuclear collisions). Initial trials of waveguide fabrication were performed on undoped GGG samples. A guide with an ion dose of 4×10^{16} ions cm^{-2} at 2.5 MeV gave a 0.25% index increase in the electronic stopping region and a 2% index decrease at the end of the ion track. These figures are a theoretical fit to the dark mode pattern observed experimentally for the TM polarisation via prism coupling [9]. Similar measurements for the TE polarisation proved impossible as we could not obtain a dark mode pattern in this case. This guide showed a transmission of 50% (the combined effect of launch loss and propagation loss) at 1.064 μm over a 4 mm long guide for the TM polarisation, whereas the TE transmission was negligible. Thus it would appear that, as has previously been found in YAG, there are different index profiles for the TE and TM polarisations which leads to a lower cut-off wavelength in the TE case (we observed good transmissions for the TE polarisation in the visible region).

Guides fabricated with the same implant in Nd^{3+} doped GGG (3.35 at.%), while still showing good transmissions in the visible region, had no mode at 1.064 μm. To increase the cut-off wavelength and allow a 1.06 μm mode to propagate, a deeper guide was fabricated using 2.9 MeV energy ions at a dose of 2×10^{16} ions cm^{-2}. The resulting index profile is shown in fig. 1 for both 2.7 at.% and 3.35 at.% doped GGG. These results are the first in which we have observed a significant dependence of the refractive index profile on the doping level. The laser results described here were taken using the 3.35 at.% doped crystal. This guide allowed single mode propagation at the two main pump wavelengths (588 nm and 805 nm) and the signal wavelength (1.062 μm), with spot sizes calculated from measurements of the output divergence (the e^{-2} half width of the intensity profile) of 2.8 μm, 3.6 μm and 4.6 μm respectively. A second mode can propagate at 588 nm, but optimised launch conditions always resulted in propagation of just the lowest order mode. The waveguide shows 80% transmission (for the TM polarisation) over the 2.5 mm length crystal when a 1.064 μm beam is end-launched. As this figure includes the launch efficiency, which is typically found to be in the region of 80% under optimum focusing conditions, it appears that the guide losses must be small, probably ≤ 1 dB/cm. An accurate loss measurement has not yet been made. This would require a longer length of crystal so as to allow measurement, via prism coupling, of transmitted output versus propagation length.

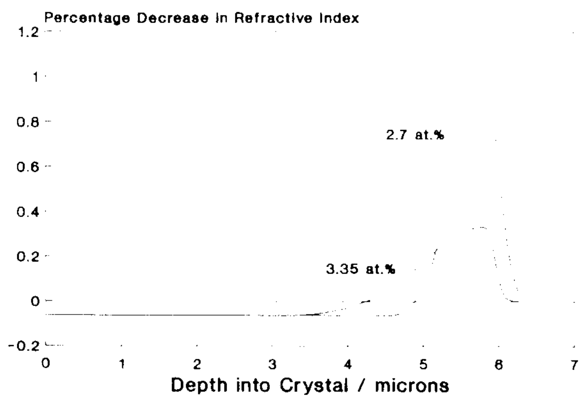

Fig. 1. TM refractive index profiles for 2.7 at.% and 3.5 at.% Nd^{3+} doped GGG waveguides (He^{+} implant of 2×10^{16} ions cm^{-2} at 2.9 MeV).

With guide losses in the region of ~1 dB/cm threshold powers for a planar waveguide laser are not expected to show any improvement over the performance of an ordinary bulk laser [5]. To achieve threshold reduction will require the use of a channel waveguide geometry. This can be readily achieved by ion-implantation [2,10], and the fact that GGG shows an index rise in the guide region is an advantage since this allows fabrication of channel waveguides with just a single implant through an appropriate ion-stopping mask [2].

3. Spectroscopy

Ion-implantation has been shown to cause a broadening of the narrow linewidth fluorescence spectra of Nd^{3+} ions in various crystal hosts [1–5]. The broadening appears to be dose dependent and so again the fact the GGG has an index enhancement type profile is an advantage, as the total ion dose can be kept to a relatively low level for this type of guide [2]. Fig. 2 shows the fluorescence spectra in the 1.06 μm region for the guide and bulk material. It can be seen that the broadening of the spectrum and consequent reduction in peak emission cross-section has been kept to a small level (a factor of 0.58). Measurements of the fluorescence lifetime (τ_{fl} = 180 μs) show no change between the bulk and the guide regions.

The 2.5 MeV waveguide described earlier which has no mode at 1.062 μm may be of interest for quasi-three level laser operation in the 940 nm region. For bulk operation at ~940 nm [11,12], it is necessary to use mirrors with a high degree of wavelength selectivity so as to suppress the normally dominant 1.06 μm line. In this case the guide could provide the selection. Fig. 3 shows the fluorescence spectra in the 900 nm region for this guide and for the bulk material. The waveguide spectrum is vertically displaced for ease of reading. In this case the peak emission cross-section is virtually unchanged, as has also

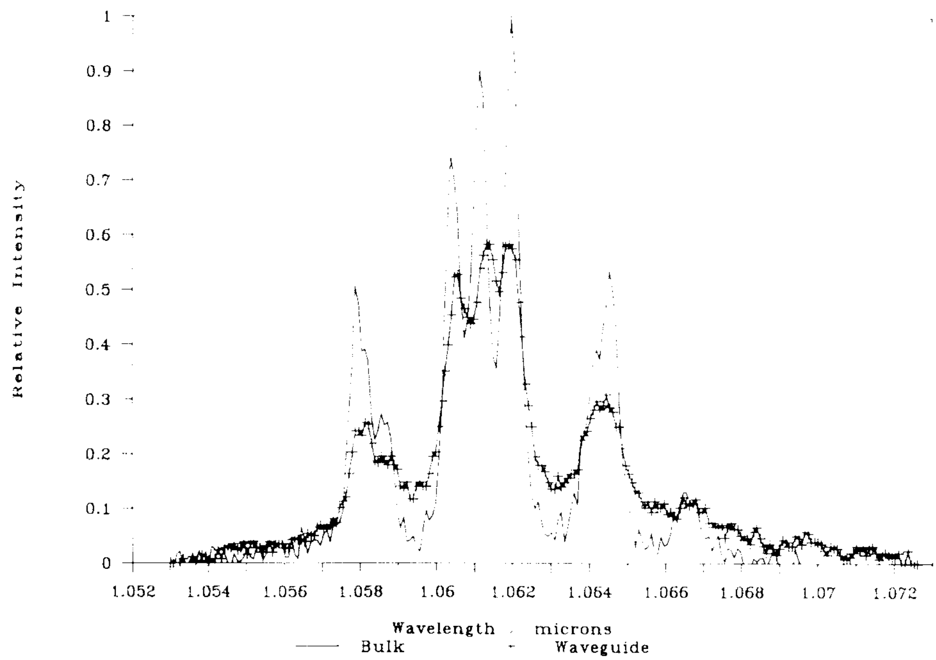

Fig. 2. Waveguide (TM polarised) and bulk crystal fluorescence spectra in the 1.06 μm region.

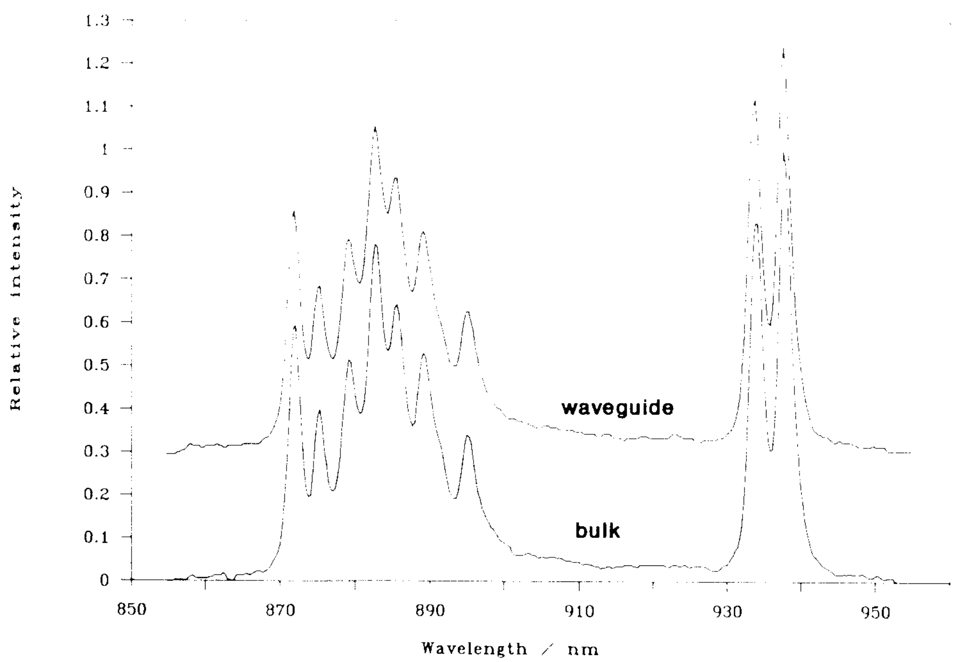

Fig. 3. Waveguide and bulk crystal fluorescence spectra in the 900 nm region.

been observed for some other relatively broad emission lines [5].

4. Laser performance

Fig. 4 shows a schematic diagram of the experimental apparatus used to investigate the 1.062 μm laser performance of the Nd:GGG planar waveguide. The crystal (supplied by Wacker Chemitronic) was oriented for propagation along the (111) direction. It was noticed that it exhibited striations perpendicular to this direction. The laser cavity is formed by butting mirrors directly to the end faces of the crystal. This is achieved by using thin mirrors held against the crystal by the surface tension of a small drop of fluorinated liquid [13]. Initially we used an R6G due laser tuned to the 588 nm absorption as the pump laser. With a pump waist spot size of ~3 μm incident on the waveguide end-face and using plane high reflectivity mirrors, a threshold of 20 mW power incident on the launch microscope objective was observed. This corresponds to a 12.5 mW absorbed power threshold (accounting for the objective and mirror transmissions and an assumed launch efficiency of 80%).

We have also demonstrated diode pumping using a 500 mW, 10 stripe diode array (SDL 2432). The set up, as shown in fig. 4, is the same as for dye laser pumping except for the collimating optics which consisted of a 6.5 mm focal length diode collimating lens and a 15 cm focal length cylindrical lens which gives extra collimation in the plane of the array. The launching ×10 microscope objective produces a 3 μm by 65 μm waist spot size in the vertical (diffraction-limited) and horizontal planes respectively, which allows efficient coupling to the planar waveguide. A half-wave plate is used to ensure TM polarisation for the pump light. The diode was temperature tuned to the 805 nm absorption which, proved to be the optimum wavelength for diode pumping. Fig. 5 shows the bulk absorption spectrum around the 800 nm region (obtained using a Perkin Elmer lambda 9 spectrophotometer) showing that the 805 nm and 807 nm absorptions are of similar strength but the 805 absorption is slightly broader.

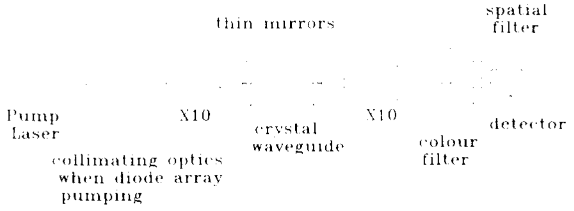

Fig. 4. Experimental arrangement for assessing laser performance.

With the diode set at full output power and using a variable neutral density filter to adjust the power reaching the waveguide we found a threshold of 30 mW incident upon the launch objective. This corresponds to an absorbed power threshold of 17 mW (again assuming an 80% launch efficiency). This higher threshold compared to the dye laser result is probably due to the different pumping geometry. If the diode power itself was adjusted to find the threshold then a figure of just 8 mW absorbed power was observed (taking care to account for any increase of diode output due to feedback). Again this difference in threshold is probably due to the changed diode output profile, and hence pumping geometry, at this very low output power. A rough estimate of the absorbed threshold power [2,4], based on the observed pump and laser spot sizes and assuming that the losses are dominated by a waveguide loss of 1 dB/cm, gives an answer of 4.5 mW for diode laser pumping. In this calculation we have used an emission cross-section of 1.7×10^{-23} m^2 which is the figure found by Kaminskii et al. [14], multiplied by 0.58 to account for the fluorescence broadening in the waveguide. Given the uncertainty in many of the figures used in this calculation (especially the assumption of loss-less mirror butting) the estimate provides a useful, if rough, guide to actual threshold.

The waveguide laser output profile was monitored on a beam profile analyzer (Big Sky Software Corporation beamview analyzer). The output was single mode with approximate gaussian profiles in both planes. Spot sizes of 4.6 μm and 72 μm respectively in the guided and unguided planes were calculated from the measured output divergences. The output was TM polarised due to the guide's polarisation selection.

To test the efficiency of the waveguide laser were replaced one of the high reflectivity mirrors with a an output coupler of nominally 17% transmission. With the diode running at full power and using the variable neutral density filter to vary the power in-

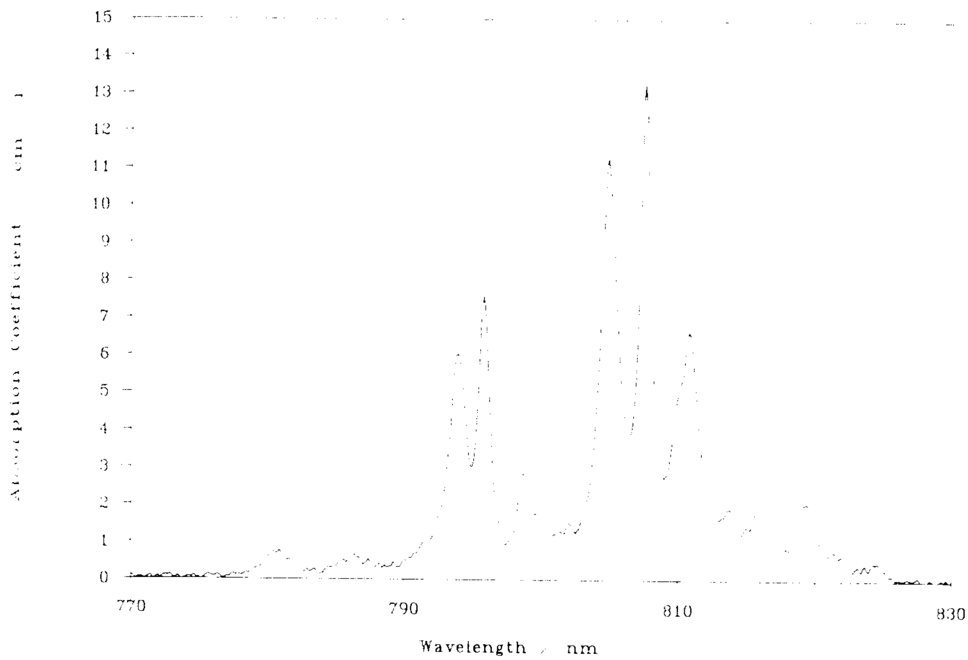

Fig. 5. Bulk crystal absorption spectrum in the 800 nm region.

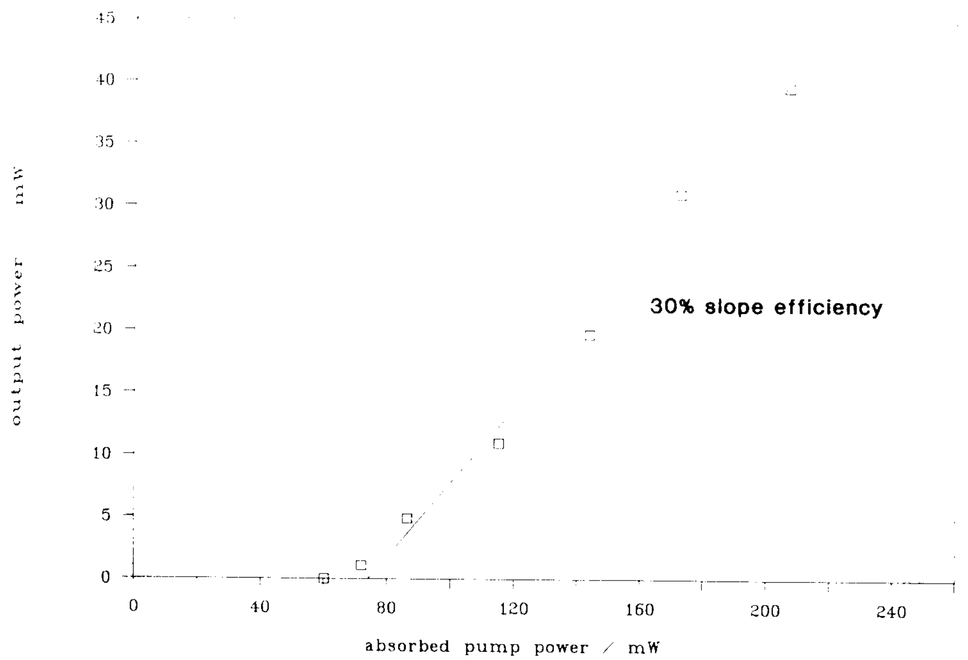

Fig. 6. Output power versus absorbed pump power for the Nd:GGG planar waveguide laser (using a 17% output coupler).

cident on the waveguide the results shown in fig. 6 were obtained. These results show a 30% slope efficiency with respect to absorbed power and output powers of up to 40 mW (with 360 mW of power incident on the launch objective) with no indication of any falling off of the efficiency. Improvements in both threshold and slope efficiency may be obtained by using mirror coatings directly deposited onto the end faces rather than the butting technique described here. These results suggest that if a similar loss can be achieved for a channel guide, where the laser and pump spot sizes could be kept to just a few microns in both dimensions, then sub-milliwatt thresholds for Nd^{3+} doped GGG should be available.

5. Summary

We have demonstrated the first operation of an ion-implanted Nd:GGG waveguide laser. Diode pumped thresholds as low as 8 mW have been achieved in a planar waveguide geometry, suggesting that sub-milliwatt thresholds should be obtainable in a channel waveguide version. Slope efficiencies of 30% have been observed with output powers of up to 40 mW. These results provide encouragement that it should ultimately be possible to obtain low threshold operation for a broadly tunable channel waveguide laser based on Cr^{3+} doped GGG.

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