Ion-implanted Nd:GGG channel waveguide laser

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We report what is to our knowledge the first fabrication and laser operation of ion-implanted Nd:GGG channel waveguides. Diode-pumped operation has been achieved with absorbed power thresholds as low as ~2 mW and a slope efficiency of ~30% with respect to absorbed power.

The field of waveguide lasers based on integrated-optics technology is currently creating much interest. Low laser thresholds are possible owing to optical confinement, and compact integrated devices may be realized by exploiting electro-optic or nonlinear properties that may be present in the host crystal. $LiNbO_3$ has figured prominently as the host material, and by exploiting well-established techniques for fabricating channel waveguides in this material, low-threshold operation of $Nd:MgO:LiNbO_3$ (Refs. 1–4) and $Er:LiNbO_3$ (Ref. 5) lasers have been demonstrated. Our research[1,6-10] has concentrated on ion implantation as a technique for waveguide fabrication since it has the ability to form waveguides in a wide range of laser crystals in addition to $LiNbO_3$. A particular aim is the achievement of low thresholds in widely tunable laser materials. So far we have successfully operated ion-implanted waveguide lasers in five different laser hosts, although up to now these have all been planar waveguides, i.e., with guidance in one dimension only, rather than channel waveguides. However, to obtain low laser thresholds it is necessary to create channel waveguides in which small spot sizes can be maintained over lengths longer than diffraction would normally allow. Here we report what is to our knowledge the first laser operation of a channel waveguide formed by ion implantation, with the material being Nd:GGG. The choice of GGG as a host to investigate is based on the fact that laser action has been observed in Cr^{3+}:GGG,[11] thus pointing to the possibility of a low-threshold tunable laser in waveguide form.

Previous results on the fabrication of a planar waveguide in Nd-doped GGG (3.35 at.% Nd^{3+}), by He^+-ion implantation, showed (see Fig. 1 in Ref. 10) that with 2.9-MeV ions and a dose of 2×10^{16} ions cm^{-2}, a guide of ~5 μm depth could be produced. An important feature of the observed refractive-index profile is the presence of a refractive-index increase in the guide region. This index increase is small, ~0.06%, and in the planar guide the mode confinement resulted from the combined effect of the index increase and a low-index barrier formed where the ions are stopped. Despite the small size of the index increase, it was considered that it alone would be sufficient to allow guidance, and this suggested that it should be possible to fabricate channel guides simply by implantation through a suitable ion-stopping mask, as shown schematically in Fig. 1. In practice a mask of at least 3-μm thickness of gold is needed to stop He^+ ions of this energy. Since it proved impossible to achieve good adhesion for a mask of this thickness formed by evaporation, an electroplating procedure was adopted. The first step in the fabrication of the gold mask is the evaporation of an ~120-nm-thick nichrome layer (80% Ni, 20% Cr) onto the polished surface of the crystal to act as an electrode to allow electroplating of the gold mask. A 3-μm layer of photoresist is spun onto the nichrome layer, then soft baked and exposed through a suitable mask. Development leaves lines of photoresist where the channels are later to be implanted. A 3-μm layer of gold is then electroplated into the gaps between the lines of photoresist, which are then removed with acetone. The crystal is now implanted, after which the gold and nichrome are removed, as these would otherwise adversely affect the propagation loss of the waveguide.

For the experiments described here several sets of channels of widths 20, 16, 12, 10, 8, 6, and 4 μm were fabricated. The two end channels of each set (the 4- and 20-μm channels) were affected by some remaining nichrome on the surface, which resulted in poor transmissions and therefore could not be used. Of the others only the 6-μm channel failed to lase. Using a Rhodamine 6G dye laser tuned to ~610 nm, just off the 590-nm Nd absorbtion, we observed 57% transmission over the 9-mm-long guides. Similar transmissions were obtained for the 8–16-μm channels, but the 6-μm channel transmission was significantly lower. The launch efficiency was not measured directly; however, if we take the best launch efficiencies observed with planar guides of similar depths (i.e., ~80%) as an upper limit, this implies an upper limit on the propagation loss of ≤1.6 dB/cm. Optimum laser performance was obtained with 16–10-μm-width

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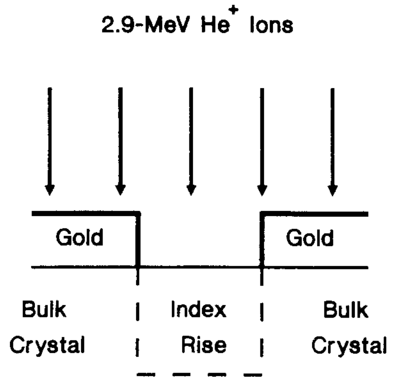

Fig. 1. Schematic diagram of the channel waveguide fabrication.

channels, which were all single mode at both the pump (805 nm) and signal (1.062 μm) wavelengths and had similar measured mode sizes, within experimental error ($\pm$5%). These were (for $1/e^2$ half-width of intensities) 3.7 and 6.4 μm for vertical and horizontal directions, respectively, at 805 nm, and 4.4 and 7.7 μm, respectively, at 1.062 μm. These relatively large spot sizes indicate that the 1.062-μm mode is rather poorly confined within the physical dimensions of the waveguide. This is in agreement with earlier results on planar GGG waveguides[10] and is consistent with the observation that the larger width channels show lower loss and therefore better laser performance. The percentage refractive-index increase in the guide region for GGG (0.06%) is relatively low compared with, for example, that of YAG (~0.2%) (Ref. 12) or $LiNbO_3$ (~1%).[13] As the laser threshold depends on the product of the vertical and horizontal spot sizes given above, further optimization of GGG guides will be directed at producing a greater degree of confinement, possibly by employing different implant conditions, and/or implanting low refractive-index side walls through multiple energy implants.[14] However, it should be noted that the confinement would in any case be better for the shorter wavelengths of interest for Cr:GGG.

Initial results were taken with a 9-mm-long crystal, although this was considerably longer than required to absorb all the pump light. The end faces were polished perpendicular to the channel guides, and the laser cavity was then formed as described in Ref. 7 by butting thin, light-weight dielectric mirrors against these faces using the surface tension of a drop of fluorinated liquid. A 50-mW single-stripe diode laser was used as the pump source. The output of the diode was collimated with a 6.5-mm focal-length lens, resulting in an elliptical beam profile that was a reasonable match to the mode profile of the channel guides. A half-wave plate is used to select TM-polarization pumping. All the results quoted in this section are for 16- and 12-μm-width channels, which were found to give the best results and have similar laser performances. With butted high-reflectivity mirrors channel waveguide laser operation was achieved at a power of 8.4 mW incident upon the launch microscope objective. The launch efficiency must lie between the observed channel transmission of ~60% (i.e., assuming zero propagation loss) and that found for planar guides of similar dimensions, ~80%. Therefore assuming a launch efficiency of 70 ± 10% and taking into account the objective and mirror transmissions at the pump wavelength, we find a threshold absorbed pump power of 4.3 ± 0.6 mW. A simple calculation of the expected threshold[1] gives a value of 1.5 mW. Here we have accounted for the small change in emission cross section caused by ion implantation[10] and the measured mode spot sizes and assumed a propagation loss of ~1 dB cm^{-1} (corresponding to the observed channel transmissions and a 70% launch efficiency). The difference between calculation and observation is probably due to additional losses involved in the arrangement for butting the mirrors. We have also operated this laser with an extended cavity configuration, as shown in Fig. 2, in which the output of the waveguide is collimated by a microscope objective before it propagates to the feedback mirror. This arrangement would allow the introduction of intracavity elements for modulation or tuning. In this case the absorbed power threshold was 8 ± 1 mW.

The crystal was then cut and polished to a length of 2.5 mm to reduce the total propagation loss while most of the pump power was still absorbed. Experimentally we observed ~76% absorption of the diode pump light in guides of this length. With butted high-reflectivity mirrors we observed an absorbed

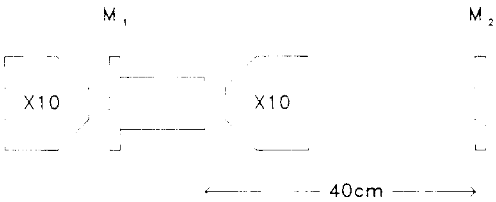

Fig. 2. Extended cavity configuration. The laser cavity is formed by mirrors M_1 and M_2.

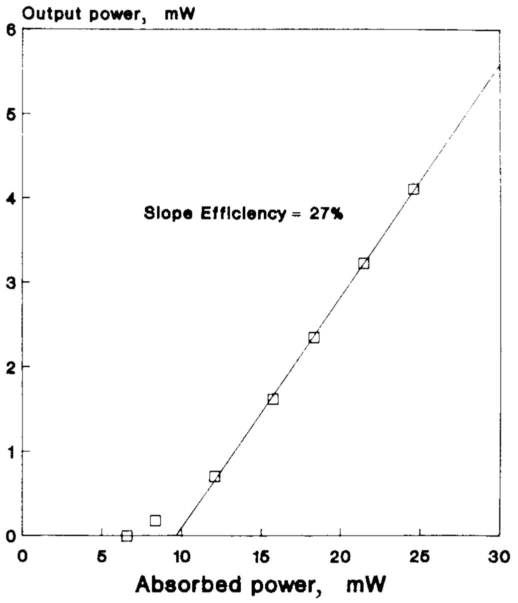

Fig. 3. Output efficiency of the diode-pumped Nd:GGG channel waveguide laser.

power threshold of just 1.9 ± 0.3 mW. The reduction in threshold by a factor of 2.3 produced by reducing the length by a factor of 3.6 suggests that the butting losses are becoming significant compared with the propagation losses, which are now ~0.25 dB (~6%) per pass. If these were eliminated by using directly coated crystals, submilliwatt thresholds should be possible.

The output efficiency of the waveguide laser was investigated by using a butted output coupler of nominally ~17% transmission. In measuring this output power a spatial filter was used to select only the power in the fundamental mode of the guide. The results shown in Fig. 3 indicate an absorbed power threshold of 6.6 ± 0.9 mW and a slope efficiency of 27 ± 4%. This is similar to the slope efficiency found in the planar version of this waveguide laser,[10] but the threshold is now an order of magnitude lower. If the output is not spatially filtered it is found that there is an ~36% increase in the observed output power that appears to originate from below the waveguide. A similar observation has been made by Lallier *et al.*[15] The origin of this emission is thought to be scattering from the channel guide, thus possibly indicating one of the causes of propagation loss.

In conclusion, we have demonstrated what is to our knowledge the first laser operation in a channel waveguide fabricated by ion implantation. Thresholds as low as ~2 mW have been achieved with diode pumping. A further reduction in threshold can be expected by using directly coated reflectors at the ends of the waveguide and by further optimization of the implant conditions to give a more strongly confined mode. This waveguide laser has also been operated with an extended cavity. The results presented here are an important step toward the achievement of low-threshold operation of broadly tunable lasers such as Cr:GGG.

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