LOW THRESHOLD ION-IMPLANTED Nd : YAG CHANNEL WAVEGUIDE LASER

Indexing terms: Lasers, Waveguides, Integrated optics

The first channel waveguide laser in Nd : YAG showing a threshold reduction of 20 times compared to a planar waveguide is described. With diode pumping this ion-implanted waveguide laser has been operated with absorbed power thresholds as low as ~500μW in good agreement with theoretical expectation. Output slope efficiencies of ~29% have also been demonstrated.

Introduction: Ion implantation has been used to form waveguides in many different laser crystals,[1] and, to date, five different laser hosts (each Nd^{3+} doped) have shown planar waveguide laser operation.[2-6] The aim of this work is to produce lower laser thresholds (and higher gains per unit pump power) than could normally be achieved in the bulk crystal. An essential step toward this aim is the production of low loss channel waveguides, as has recently been reported in Nd^{3+} doped GGG crystals.* We report channel waveguide laser operation in Nd^{3+} doped YAG. The absorbed power threshold of ~500μW is the lowest yet reported for a laser based on integrated-optics technology (ion-implantation, ion-exchange,[7,8] Ti-indiffusion),[9] and is comparable to the best results achieved by crystal fibre growth.[10] From the results reported it is clear that there is considerable improvement still to come from the optimisation of the waveguide properties, bringing nearer the prospect of low threshold widely tunable laser devices.

Waveguide properties: The waveguide used in these experiments was created by a multiple energy implant of He^+ ions at 77 K. The implant dose and energies were 3×10^{16} ion/cm^2 at 2·8 MeV, $0{\cdot}75 \times 10^{16}$ ion/cm^2 at 2·4 MeV, $0{\cdot}75 \times 10^{16}$ ion/cm^2 at 2·2 MeV, 0·75 ion/cm^2 at 2·0 MeV and 0·75 ion/cm^2 at 1·8 MeV. Such an implant is known to cause ~0·2% index rise to a depth of ~6μm.[3,11] The YAG crystal was masked by photolithographically patterned gold of ~3μm thickness,* such that a range of channels from 4 to 20μm wide were created by this implant passing through the gaps in the mask. The gold was then removed and the end faces polished perpendicular to the channel direction.

To investigate the (TM) mode profile of each channel a × 10 microscope objective was used to focus the output light onto a CCD camera. The mode spot sizes ($1/e^2$ half width of intensity) for each channel at both the pump (807 nm) and signal (1064 nm) wavelengths could then be calculated from the measured waist spot sizes produced at the camera. As expected the vertical spot sizes were constant for each channel at 2·9μm (807 nm) and 3·6μm (1064 nm). The horizontal spot size varied from 7·3 to 6·0μm (807 nm) and 8·4 to 7·0μm (1064 nm) in the 20–4μm wide channels. Whereas the vertical spot sizes agree well with the theoretical expectation of 2·8μm (807 nm) and 3·1μm (1064 nm), the horizontal spot sizes are larger than expected in the smaller width channels. Using the effective index method,[12] the spot size would be expected to vary from 8·6 to 2·9μm (807 nm) and 9·2 to 4·1μm (1064 nm). On inspection of the end face under a microscope we observed that the gold mask appeared to have been of insufficient thickness to totally stop the He^+ ions, resulting in merely a 2 : 1 variation in the depth of the index enhancement region. This is the probable explanation for the larger than expected spot sizes in the smaller channels. For future work a thicker gold mask will be tried.

Using an R6G dye laser tuned off the strongest ~590 nm absorption we were able to observe ~60% transmission (accounting for the objective transmission and Fresnel losses) over the 5 mm length crystal for most of the channels. This is consistent with a launch efficiency of ~70%, as previously observed with other channels of similar dimensions,* and a propagation loss, similar to that found in planar YAG guides,[3,11] of ~1·5 dB/cm.

Laser performance: Fig. 1 shows the experimental arrangement used to test laser performance. The pump source was a singlemode 100 mW GaAlAs diode laser (SDL-5412-H1). The beam divergences from this laser in the vertical and horizontal planes are in the ratio of 2·5 to 1, and so can be well matched to the waveguide mode by collimating with a 6 mm focal length lens and focusing with a × 10 microscope objective. A $\lambda/2$ plate is used to rotate the polarisation of the pump beam so that it is TM polarised in the waveguide as the TE polarisation is near cutoff at this wavelength and has higher loss. A variable attenuator set at a ~70 times reduction in power was used in these threshold measurements to isolate the diode from back reflections from the waveguide mirror. Without the attenuator in place both the output power and wavelength of the diode were affected such that we could not accurately tune into the 807 nm absorption. This reduced the absorption from ~80 to ~30% in the guide which had now been cut and polished to a length of 2·5 mm.

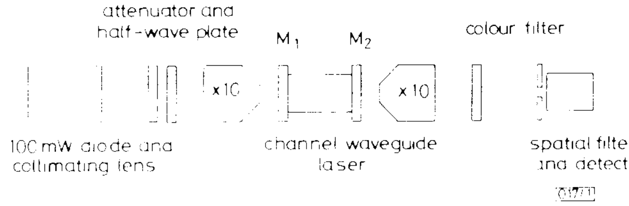

Fig. 1 *Experimental arrangement used to test waveguide laser performance*

Mirrors M_1 and M_2 form the laser cavity

The cavity was formed by butting two thin high reflectivity dielectric mirrors against the polished waveguide end faces. These mirrors were held in place by the surface tension of a drop of fluorinated liquid. The output beam is collected by a × 10 objective and focused onto a detector through a spatial filter, which ensures that only light from the waveguide region is detected, and a colour filter to block any left over pump light.

Laser action was observed in all the different sized channels, however the best threshold was obtained for the 20μm wide channel. This must be due to lower propagation loss, possibly due to most of the mode being contained within the physical dimensions of the channel. Laser action occurred at a pump power of 1·3 mW incident on the launch objective. This corresponds to a 660μW launched power accounting for the objective and mirror transmissions, and a 70% launch efficiency. The transmitted unabsorbed power was measured to be 120μW giving an absorbed power threshold of 540μW. A simple calculation,[4] based on the measured mode spot sizes, a propagation loss of 1·5 dB/cm, and a reduction in the emission cross-section of a factor of 2 (as found earlier for Nd : YAG crystals with this implant),[3] gives an answer of ~400μW, in good agreement with our results. The difference between figures may well be due to extra loss associated with the butting of the mirrors. This could be avoided by directly coating the end faces. A factor of two improvement could also be expected from improving the mode confinement in the horizontal plane by refining our implant/masking techniques.

The output efficiency of this laser was tested by butting a nominally 17% output coupler to one end. Fig. 2 shows the results obtained. The best fit to the experimental points gives a slope efficiency of 29 ± 2%. This is similar to that found with an Nd : GGG waveguide under the same experimental conditions.* The threshold of ~1·6 mW is slightly higher than theory predicts (~0·9 mW) and the slope is smaller than the expected value of ~40% calculated using the known losses, due to propagation loss and mirror transmission. This may again be due to mirror butting losses. As it was necessary to remove the attenuator to carry out this part of the experiment, adverse effects of feedback were encountered leading to a reduced absorption as previously stated, and limiting the absorbed power to only ~20 mW.

Conclusion: We have demonstrated the first laser action in an ion-implanted Nd : YAG channel waveguide. Compared with planar waveguides,[3] significantly lower thresholds (~ × 20) have been observed, in good agreement with theoretical expectation, and output slope efficiencies of ~29% have been

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* FIELD, S. J., HANNA, D. C., LARGE, A. C., SHEPHERD, D. P., TROPPER, A. C., CHANDLER, P. J., TOWNSEND, P. D., and ZHANG, L.: 'An ion-implanted Nd : GGG channel waveguide laser', submitted to *Opt. Lett.*

demonstrated. Optimisation of the implant/masking conditions could lead to significant further reductions in threshold. It is interesting to note that the calculated thresholds for similar guides in a number of broadly tunable systems indicate powers around the 10mW level. This should readily allow diode pumped operation of such lasers in the future.

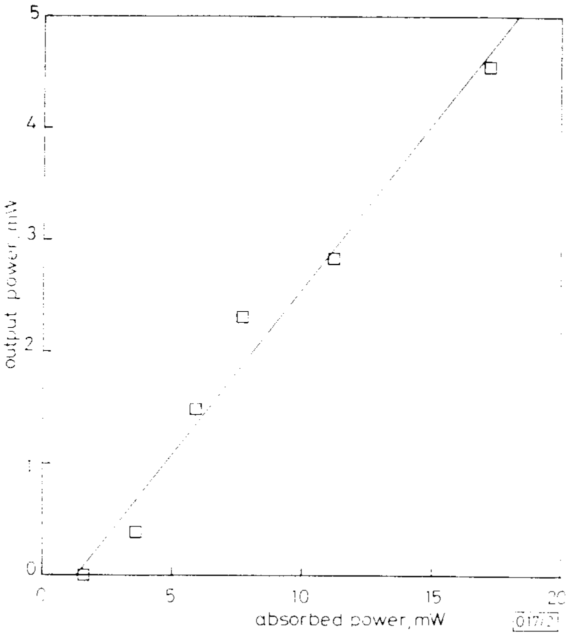

Fig. 2 *Output power against absorbed pump power with ~17% transmission output coupler*

Slope efficiency = 29%

Acknowledgments: This work has been supported by the SERC and S. J. Field and A. C. Large acknowledge SERC for the provision of research studentships. We thank M. Milton of NPL for the loan of the 100mW single stripe diode used in these experiments.

S. J. FIELD
D. C. HANNA
A. C. LARGE
D. P. SHEPHERD
A. C. TROPPER

Department of Physics and Optoelectronics Research Centre
University of Southampton
Highfield, Southampton SO9 5NH, United Kingdom

P. J. CHANDLER
P. D. TOWNSEND
L. ZHANG

School of Mathematical and Physical Sciences
University of Sussex
Falmer, Brighton BN1 9QH, United Kingdom

9th October 1991

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20Gbit/s AlGaAs/GaAs HBT DECISION CIRCUIT IC

Indexing terms: Integrated circuits, Optical communication, Decision circuits

An experimental 20Gbit/s decision circuit IC based on AlGaAs/GaAs HBTs has been implemented, which features a differential input sensitivity of 80mV peak to peak and a phase margin of 292° at the SONET STS-192 rate of 9·95Gbit/s. The IC nominally dissipates 870mW of power, but may be operated up to 10Gbit/s with a power dissipation of 450mW. The circuit was fabricated in a high current gain baseline HBT technology, and occupies an area of $1{\cdot}15 \times 1\,mm^2$.

Introduction: Optical fibre transmission systems operating at multigigabit data rates are of increasing practical importance, for example for future interoffice selfhealing SONET ring networks.[1] For such networks, transmission rates at the next generation SONET rate of 9·95Gbit/s (STS-192), or higher are desirable. To achieve such high bit rates, the speed of the electronic and optoelectronic interface circuits must be optimised. High-speed decision circuits are one of the key elements in these systems. At present, a number of decision circuits have been published based on various technologies,[2–4] with performances ranging from several Gbit/s up to 20Gbit/s for a selfaligned HBT technology. We report on the design, fabrication, and measured performance of a experimental 20Gbit/s AlGaAs/GaAs HBT decision circuit fabricated in a high current gain baseline HBT technology.

Design: Fig. 1 shows a schematic diagram of the decision circuit IC. Differential operation is used throughout the design. The decision circuit consists of an input buffer, master-slave D-type flipflop, and an output buffer. The data, and clock paths, feature on-chip terminating resistors which can provide low input return loss to 30GHz.[5] The input buffers consist of two emitter followers in the data path, and three emitter followers in the clock path. The master and slave

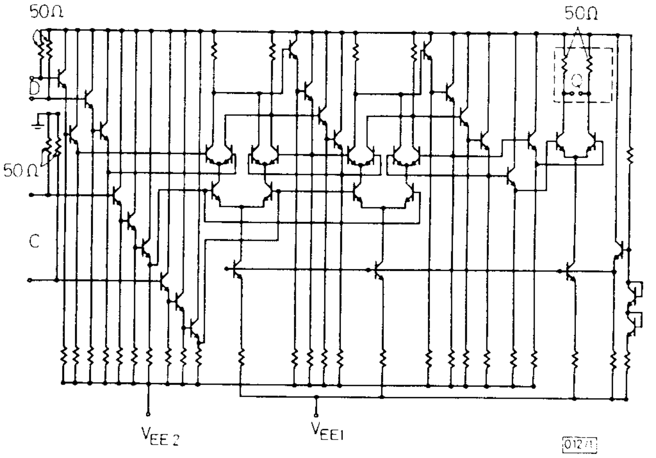

Fig. 1 *Schematic diagram of decision circuit IC*