values greater than 10dB are achieved over a bandwidth of ≈ 4 nm, or the bias range 8–12 V. In many applications, when AC coupling for example, the reflection change is a more appropriate parameter to use to characterise the device. For the AFPM a reflection change of 42·6% is observed at the resonant wavelength. It is worth noting that this large change is maintained over an optical bandwidth of 7 nm for 8–10 V bias. The maximum change in reflectivity (from 66·8 to 13·1%) occurs at a wavelength of 863·3 nm. On the same device, measurement of photocurrent spectra showed a strong voltage-dependent increase in photocurrent at the resonant wavelength. The increase was well in excess of that due simply to the bias dependence of the internal quantum efficiency of the *pin* structure, which could be observed at wavelengths off resonance, and confirmed the proposal[2] that the AFPM structure could be used as an extremely efficient photodetector, permitting complete absorption at resonance even for thin absorbing layers.

In summary we have demonstrated a significant improvement in the performance of GaAs–AlGaAs MQW electro-absorption modulators. The results are encouraging for applications in optical interconnection of VLSI or WSI circuits. In that context the modulators would act as interface elements between optics and electronics.[10] We are optimistic that with small modifications (outlined in Reference 2) to the structure demonstrated here, operating voltages of ≈ 5 V will be achievable and insertion loss reduced.

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ION-IMPLANTED Nd:YAG PLANAR WAVEGUIDE LASER

Indexing terms: Lasers and laser applications, Waveguides, Dielectrics and dielectric devices, Ion implantation

We report the first operation of an ion-implanted dielectric waveguide laser. Details of the Nd:YAG waveguide structure, spectroscopic properties, and laser performance are given.

Introduction: By applying ion implantation techniques,[1,2] to a standard laser crystal, a planar optical waveguide can be formed which is capable of supporting laser oscillation. The waveguide confinement can in principle enable high values of gain to be achieved for low pump powers. Thus if low waveguide losses can be achieved, very low threshold laser operation could be possible. The fact that ion implantation can be used to form waveguides in a wide range of laser crystals (and glasses) suggests very many potential applications, for example in the very low threshold operation of CW widely tunable lasers. These possibilities are enhanced by the fact that 'stripe' waveguides (guided in two dimensions) may also be formed by ion implantation. For an initial demonstration of such a waveguide laser we chose to investigate Nd-doped YAG.

Waveguide properties: Waveguide fabrication involves the use of high-energy He^+ ions which travel a short way into the crystal through a polished surface. At the end of the ion track displacement damage lowers the refractive index, creating an optical barrier which can confine light travelling along the top of the crystal between itself and the crystal surface. It has been experimentally found that for many materials, including YAG, there is also a slight index rise in the guiding region itself.[2] This can be very useful as modes sitting within this 'index well' cannot tunnel through the index barrier. The waveguide was created by a multienergy implant of He^+ ions at 77 K, with ion energies up to 2·8 MeV at a total dose of 7×10^{16} ions cm^{-2}. The refractive index profile of the waveguide, calculated by fitting to the observed mode characteristics,[3] is shown in Fig. 1. The waveguide supports two confined spatial

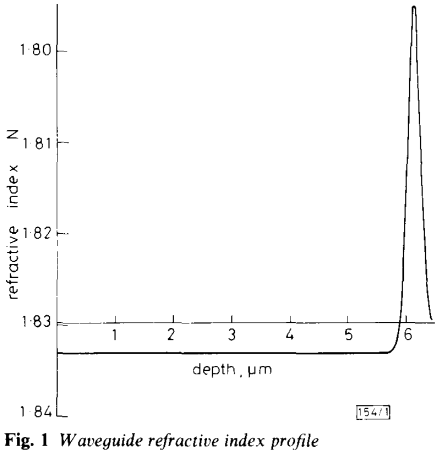

Fig. 1 *Waveguide refractive index profile*
Note that refractive index increases downwards

modes at the pump wavelength (~590 nm), with the mode indices having values larger than the substrate index, and just one mode at the signal wavelength (~1·06 µm).

By end-launching the output of a monolithic Nd:YAG laser and measuring the transmission, the waveguide losses at 1·064 µm were shown to be < ~4 dB cm^{-1}. However this was an unannealed sample, whereas for an annealed sample waveguide losses as low as 1·5 dB cm^{-1} were measured at 632 nm via prism coupling.

Spectroscopic properties: Fig. 2 shows the fluorescence spectrum of Nd:YAG around 1·06 µm in (*a*) the implanted region and (*b*) the bulk, untreated region. Clearly the fluorescence spectrum has been significantly broadened although there is no observable shift in any of the lines. The lifetime of the 1·064 µm line also shows no observable change. However there is a significant change in relative peak intensities, with the 1·062 µm intensity becoming essentially equal to that of the normally dominant 1·064 µm. Studies of the absorption spectrum again show broadening but no overall shifting of the absorption peaks in the 590 nm spectral region.

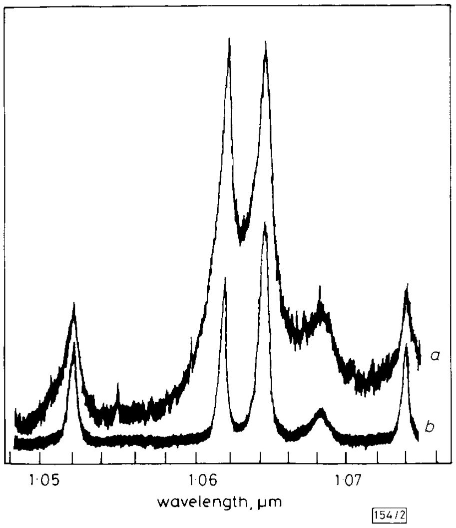

Fig. 2 *Waveguide (a) and bulk (b) fluorescence spectra*

Laser performance: Fig. 3 shows the experimental apparatus used to assess laser performance. The Nd:YAG crystal has dimensions of 10 × 5 × 1 mm, with the two 5 × 1 mm end faces and the 10 × 5 mm top face having polished surfaces. The 6 µm-deep waveguide is formed at this upper surface with consequent stringent requirements for end-face polishing.

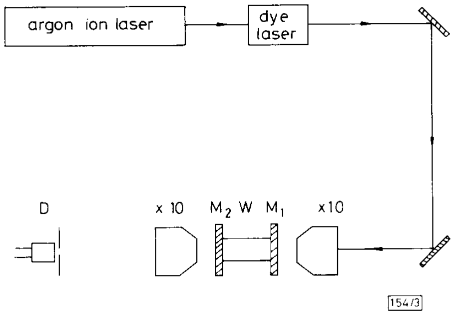

Fig. 3 *Waveguide laser cavity*

M$_1$ = plane mirror (HR at 1·06 µm, HT at 590 nm), M$_2$ = plane mirror (97·5% *R* at 1·06 µm), *W* = Nd:YAG waveguide, D = aperture and detector

The waveguide is pumped on the main absorption line around ~590 nm by an R6G dye laser. A ×10 microscope objective couples the light into the waveguide, producing a ~3 µm waist spot size at the front face. When the dye laser is detuned from the Nd absorption, transmissions of around 50% are typically observed. This figure includes launch efficiency and waveguide attenuation. The output of the waveguide is imaged by another ×10 objective and a slit aperture then used to separate light from the waveguide region from any light emerging from the bulk of the crystal.

The laser cavity is formed by butting two plane mirrors M$_1$ (HR at 1·06 µm) and M$_2$ (97·5% *R* at 1·06 µm) against the crystal end faces. Laser threshold was reached with ~120 mW of pump incident on the first objective, corresponding to a launched power of approximately ~50 mW. The high threshold for this initial demonstration is due to the large losses in the present cavity, most of which can be eliminated or greatly reduced. Firstly the optical quality of the end-face surfaces is only moderate. The end faces are also slightly curved, preventing perfect butting of the mirrors to the crystal surface. The mirror alignment was also imperfect since the crystal end faces are ~5′ out of parallel. The waveguide loss could be greatly reduced by simply using a shorter length of crystal. This would not reduce the available gain as most of the pump radiation is absorbed in the first few millimetres of the waveguide. A shorter crystal length would also reduce the diffraction losses in the unguided plane. Finally it should be noted that annealing the waveguide may improve the waveguide losses. All these possible improvements are currently under investigation.

The laser output consists of random spiking. For incident pump powers of ~270 mW output powers of ~1·0 mW are observed, indicating a slope efficiency of ~1·7% with respect to absorbed power. The output beam divergence is consistent with a ~4 µm waist spot size in the plane perpendicular to the guide, and a ~75 µm waist in the plane parallel to the guide. Thus the signal mode within the laser is such that most of the available gain is contained within its volume.

Observation of the signal wavelength shows the waveguide laser to be oscillating at 1·062 µm and 1·064 µm simultaneously, with the shorter wavelength line having a slightly lower threshold. This change from the bulk performance, which lases only on the 1·064 µm line, is related to the change in the fluorescence spectrum shown in Fig. 2. The output is also observed to be vertically polarised (TM).

Summary: We have demonstrated the first laser action in an ion-implanted dielectric waveguide structure. The present laser performance is clearly far from optimised and considerable reductions in threshold should be possible. Ion implantation could also be used to form stripe waveguides, with a consequent major reduction in the laser threshold. The physical nature of the ion implantation process means it can be applied to a great range of laser crystals and glasses, producing waveguides compatible with integrated planar technology.

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