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Waveguide Lasers Operating at 1084 nm in Neodymium-Diffused Lithium Niobate

Martin Hempstead, James S. Wilkinson and Laurence Reekie

Optoelectronics Research Centre, University of Southampton,
Southampton, SO9 5NH, England.
Tel: 44 703 592825

Abstract

We report the demonstration of waveguide lasers in lithium niobate into which the active element neodymium has been introduced by thermal diffusion. The waveguides were fabricated using conventional Ti indiffusion, and optical feedback was provided by the polished endfaces alone. The absorbed power threshold of one waveguide laser was estimated at 13±3 mW for pumping at 814 nm, and its slope efficiency in terms of total lasing output as a function of absorbed pump power was estimated to be 55±8%. Laser output powers in excess of 100 mW were observed.

Introduction: Lasers in lithium niobate grown from the melt already doped with neodymium have a long pedigree, with the first Nd:$LiNbO_3$ laser being reported in 1967[1]. Recently, channel waveguide lasers have been fabricated in neodymium-doped lithium niobate by titanium- and proton-diffusion [2,3], and erbium-doped waveguide lasers have been made using thermal diffusion of the rare-earth into lithium niobate [4].

The diffusion of the active dopant into the crystal affords the possibilities, on a microscopic scale, of tailoring the gain distribution to a specific device and, on a macroscopic scale, of avoiding the fabrication compromises that would be imposed on integrated configurations by the presence of dopant throughout the bulk of the substrate.

We report here on what is, to our knowledge, the first demonstration of a Nd:Ti:$LiNbO_3$ waveguide laser by thermal diffusion of both the neodymium and titanium.

Fabrication: a square slice of x-cut undoped lithium niobate of dimensions 50mmx50mmx1mm supplied by Fujian Castech (China) was used. The substrate was cleaned and a layer of neodymium of density approximately 2 $\mu g\ cm^{-2}$ was deposited by evaporation from a tungsten boat. The thickness was chosen, according to published diffusion parameters [5], so as to avoid saturating the solubility of neodymium in the crystal after the intended diffusion time. It was anticipated that this would mitigate the problem of excessive surface roughness previously encountered in neodymium diffusion into lithium niobate [5]. A region of the surface was left uncoated for purposes of comparison.

The sample was put in a tube furnace at approximately 1015° C for 203 hours in an atmosphere of dry oxygen at slightly above 1 bar pressure and with a flow rate of approximately 0.5 l min^{-1}. After this treatment the sample was removed and examined. Where coated with neodymium, the surface was found to be rough, with peak-to-peak height fluctuations of the order of 10 nm over distances of a few μm.

The sample was replaced in the furnace and diffused in the same atmosphere at 1070° C for a further 210 hours. It was again inspected, and the surface found to have become uniformly smooth so that no difference could be seen between the doped and undoped regions.

Stripes of titanium 76 nm thick were defined by photolithographic lift-off of a layer evaporated from a tungsten helix. The stripes were oriented parallel to the crystallographic y-axis, and had widths ranging from 2.5 to 9 μm in steps of approximately 0.2 μm. Several identical sets of stripes were deposited, one of which was confined to the region undoped with neodymium, to provide undoped waveguides for comparison. The titanium was diffused into the sample at 1005° C for 9 hours in a dry oxygen atmosphere at slightly over 1 bar pressure and at 0.5 l min^{-1} flow rate.

After this second diffusion the endfaces were cut and polished, to yield sets of waveguides 38 mm long.

Results: Bulk measurements of the optical transmission spectrum of the sample normal to the diffusion surface and avoiding the titanium-doped stripes, using a spectrophotometer, showed it to be identical, within 1%, to that of a fresh sample.

Light from a laser diode at 809 nm was coupled into the waveguides with a microscope objective lens; the near-field mode profiles of the endfaces of the waveguides showed those formed from titanium stripes wider than approximately 4 μm to be multimoded in the crystal z-direction, and single-moded in the x-direction. Fluorescence was observed from the endfaces, with an intensity distribution single-moded in both directions. Fluorescence spectra generated by pumping with a Ti:sapphire laser at 814 nm are shown in fig. 1. The positions of the peaks in these spectra are closely similar to those for bulk-doped Nd:$LiNbO_3$ [3]. The relative magnitudes are not significant since the spontaneous emission was subject to amplification.

The absorption spectrum of the widest waveguide for π-polarised light (i.e. with the E-field along the crystal z-axis) in the region 785-845 nm is shown in fig. 2. The spectrum was obtained by dividing the transmission of a neodymium-doped guide by that of an undoped one on the same substrate. The absorption spectrum is not significantly different from that for bulk-doped lithium niobate [3]. Total losses of 1.0 dB cm^{-1} were estimated at a wavelength of 809 nm from the intensity of light scattered from the waveguide as measured using a video camera [6]. Subtracting an estimated resonant contribution of 0.6 dB cm^{-1}, waveguide baseline losses were estimated at 0.4 dB cm^{-1}.

To measure laser characteristics, light was launched into the waveguides using a microscope objective lens, from an argon-ion-laser-pumped Ti:sapphire laser with a tuning range 790-840 nm and maximum output power of approximately 2 W at 810 nm. The sample was placed on a plate heated to 225° C to provide continuous annealing of photorefractive damage [7].

With pump light at 814 nm in the π-polarisation and with feedback provided only by the intrinsic Fresnel reflections at the end faces, lasing was observed in channels greater than approximately 5 μm wide. Laser emission was at the Nd:$LiNbO_3$ maser line, 1084 nm, with a FWHM linewidth of approximately 0.3 nm, as measured on an ANDO AQ-6310B optical spectrum analyzer. The endface reflectivity is approximately 14%, which implies a gain of at least 2 dB cm^{-1}. The lasing characteristic of the widest channel, diffused from a 9 μm titanium stripe, is shown in fig. 3. Total laser power is estimated by doubling the measured power emitted from the non-pumped end of the waveguide, to include that power emitted from the pumped end. Total powers in excess of 100 mW were observed. Absorbed pump power (which we define to include non-resonant losses) was computed from transmitted pump power, using the baseline waveguide losses of 0.4 dB cm^{-1} and the pump absorption of 51% at 814 nm when above lasing threshold.

The pump absorption was deduced by comparison of transmitted power at 814 nm and 840 nm, at which latter wavelength absorption due to neodymium is negligible. We estimate the uncertainty in absorbed pump power - which leads to an uncertainty in slope efficiency -to be 15%. It can be seen from fig. 3 that the efficiency drops as the power rises: this effect is not presently understood, although residual photorefractive damage may contribute. The laser emission also showed increasingly large fluctuations as the pump power increased, which may be partly attributable to the absence of an isolator between the waveguide and the Ti:sapphire laser, resulting in feedback instabilities, and partly to fluctuations caused by convection currents between the unheated input objective lens and the waveguide, changing the launching conditions. A linear fit, to the points in fig. 3 with absorbed pump power below 100 mW, yields a threshold of 13±3 mW absorbed pump power and a slope efficiency of 55±8% (the uncertainties incorporate the 15% uncertainty in absorbed pump power). This slope represents, in terms of the power absorbed in the neodymium resonance, a quantum efficiency of 109±16%, consistent with reference 3.

Lasing at the same wavelength was also observed with a σ-polarised pump (i.e. E-field perpendicular to the crystal z-axis), but this has not yet been investigated in detail.

Conclusion: We have successfully demonstrated Nd-doped Ti:$LiNbO_3$ waveguide lasers by thermal diffusion of the neodymium. A threshold of 13 mW absorbed pump power at 814 nm, a low-power slope efficiency of 55% and a maximum output power in excess of 100 mW have been measured. Baseline losses in the doped waveguides are as low as 0.4 dB cm^{-1} at the pump wavelength. We conclude that diffusion of neodymium into lithium niobate is an effective technique for the fabrication of low loss waveguide lasers, affording the potential for flexible design of active devices in standard lithium niobate substrates.

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FIGURES

Figure 1. Fluorescence emitted by Nd-doped waveguide pumped at 814 nm. Solid line: π-polarised pump; broken line: σ-polarised pump.

Figure 2. Absorption spectrum of the widest Nd-doped waveguide with respect to the widest undoped waveguide. Arbitrary baseline.

Figure 3. Lasing characteristic of widest Nd-doped waveguide. The line shows the fit discussed in the text, with the solid portion covering that part of the data used in the fit.

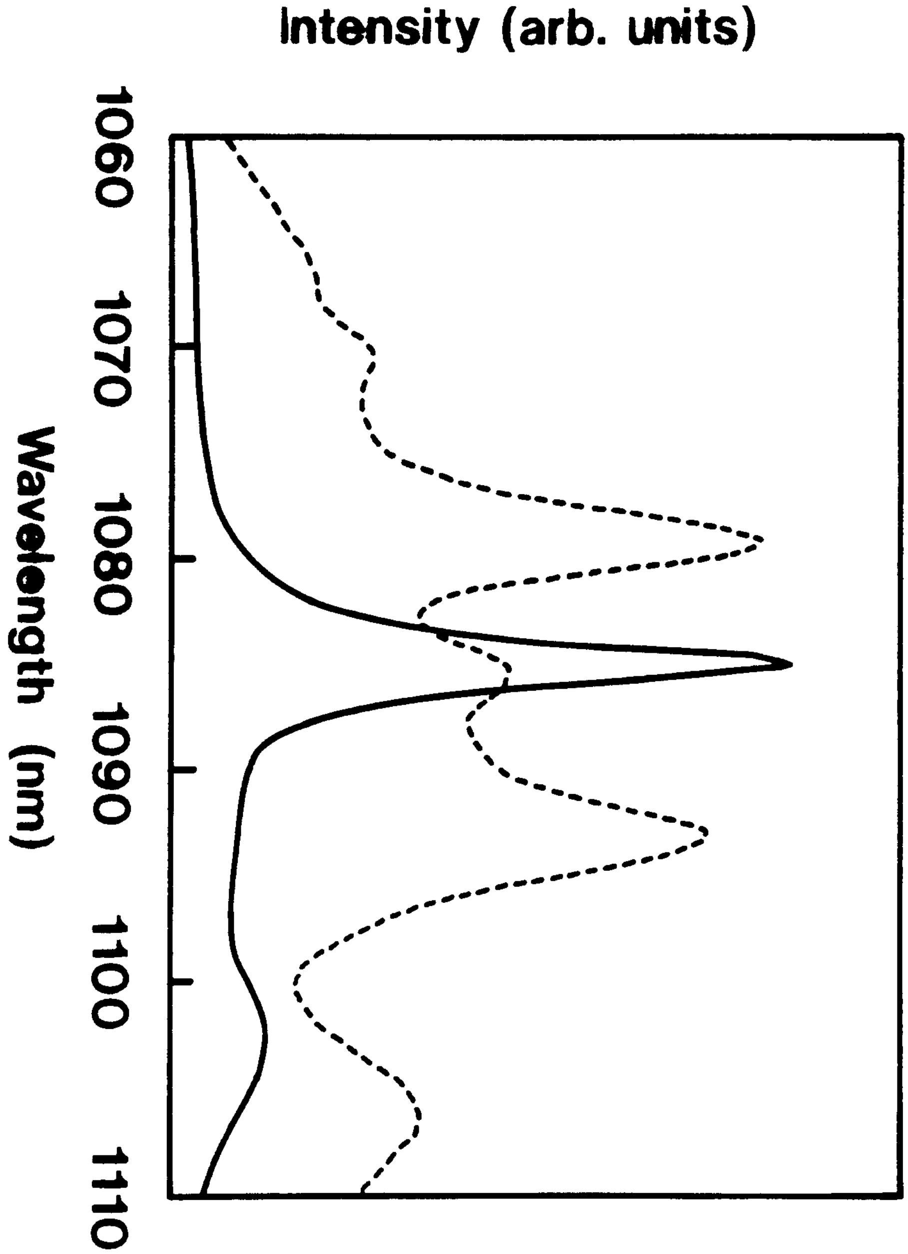
Intensity (arb. units)
1060
1070
1080
1090
1100
1110
Wavelength (nm)

FIG. 1

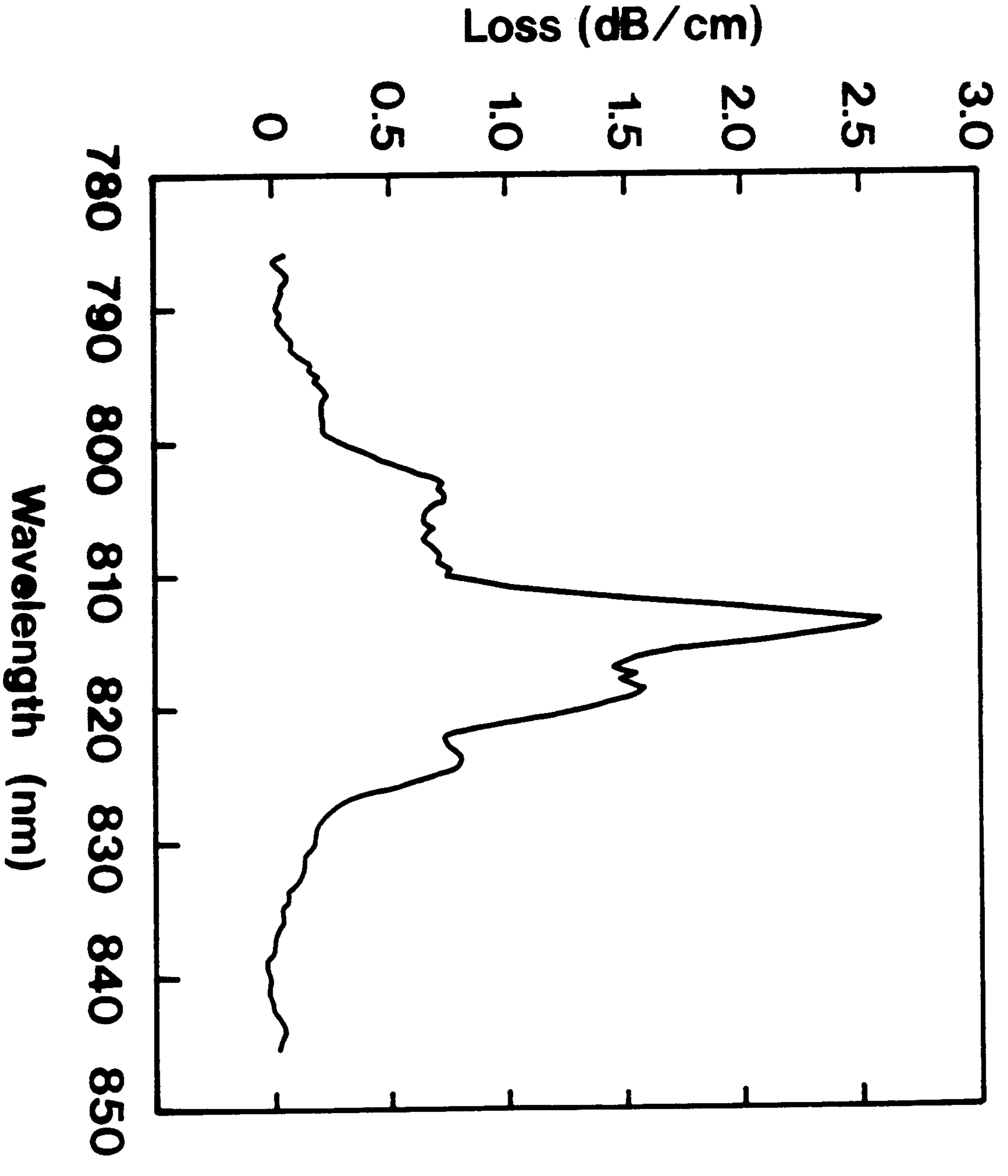
Loss (dB/cm)
0
0.5
1.0
1.5
2.0
2.5
3.0
780
790
800
810
820
830
840
850
Wavelength (nm)

FIG. 2

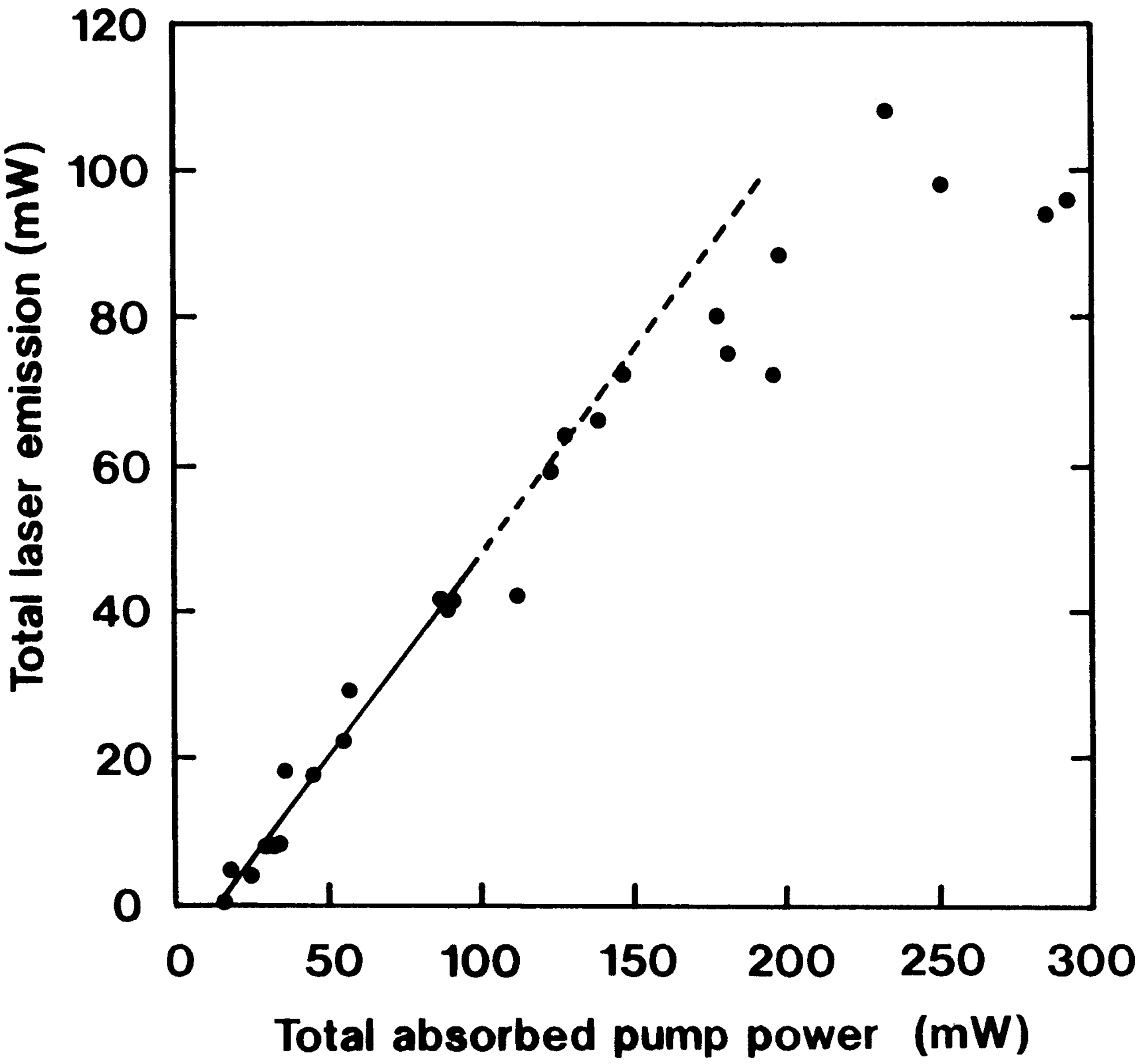
Total laser emission (mW)
0
20
40
60
80
100
120
0
50
100
150
200
250
300
Total absorbed pump power (mW)

FIG 3