Tm^{3+} Indiffused $LiNbO_3$ Waveguide Lasers

J. P. de Sandro, J. K. Jones, D. P. Shepherd*, J. Webjörn, M. Hempstead, J. Wang
and A. C. Tropper
Optoelectronics Research Centre, University of Southampton, U.K.

Abstract

We report the first room temperature laser operation of Tm^{3+}:$LiNbO_3$. The gain medium was a Ti-indiffused waveguide with active laser doping by thermal indiffusion. Lasing occurred at 1.85μm and results are presented for devices in single-domain, multi-domain, and periodically poled material.

Introduction

Rare-earth doped $LiNbO_3$ is interesting as a laser system due to its nonlinear, electro-optic, and acousto-optic properties which allow compact devices involving, for example, lasing combined with self-frequency doubling (1), mode-locking (2,3), Q-switching (1,4), tuning (5) etc.. Low-loss waveguides can also be fabricated in this material and combined with thermal indiffusion of the desired laser dopant (6,7) avoiding the large investment in time and equipment needed to produce bulk-doped samples. Finally this remarkable material may also be periodically poled for quasi-phase matching and/or elimination of photorefraction (8).

The Tm^{3+} ion offers several possible laser transitions in the infra-red and an upconversion-pumped blue emission which has lased in several materials including YLF (9), ZBLAN fiber (10), and YAG (11). It also has absorption bands compatible with diode-pumping. Most work to date has concentrated on the 2μm $^3F_4$ to $^3H_6$ quasi-three level transition which has made possible medical and laser radar applications.

To date laser action in Tm:$LiNbO_3$ has been restricted to an early report of a 1.85μm bulk laser operating at 77°K (12), probably due to the photorefractive damage problems associated with this crystal. Here we report the first room temperature operation of this laser in a Ti-indiffused waveguide with thermally indiffused Tm^{3+} doping. We also report the first combination of an actively doped $LiNbO_3$ waveguide with periodic poling. Finally we report laser action in a Tm:$LiNbO_3$ waveguide which was indiffused at a very high temperature, greatly reducing the required diffusion time, and which shows no signs of photorefractive damage.

Fabrication Details

Three samples were fabricated with different crystal cuts and diffusion conditions, to see what effect this had on laser performance. The first device was made on x-cut material, the second on a -z-cut wafer and the third sample was doped by thermal diffusion above the Curie temperature of $LiNbO_3$. The fabrication details of these samples are summarised in table 1. All the waveguides were made by diffusing Ti metal, defined into 3 to 16μm wide stripes. Initial studies were carried out on a 1mm thick x-cut, y-propagating, wafer (sample 1). Sample 2 was made from a 200μm thick, z-cut, y-propagating, wafer in which a number of the resulting waveguides were periodically poled. During both indiffusion stages the sample was placed +z face down on another z-cut wafer and in a Pt box to inhibit Li_2O outdiffusion from the +z face. After the diffusion processes 45μm was polished from the +z face in order to remove any outdiffused layer that may still have

Table 1. Fabrication Details

Sample	Diffused Face	Tm Diffusion Conditions	Waveguide Diffusion Conditions	Poling
1	x	22nm Tm, 1100°C, 411hours, O_2(½l/min)	85nm Ti, 1005°C, 26.5hours, Ar	Single Domain
2	-z	18nm Tm, 1100°C, 213hours, O_2(3l/min)	127nm Ti, 1005°C, 22hours, O_2(3l/min)	Some Periodically Poled Guides
3	x	40nm Tm, 1210°C, 63hours, Air	85nm Ti, 1005°C, 42hours, Ar	Multi-Domain

occurred. It was important to remove this layer as its presence would prevent poling of the waveguides. The sample was poled using the wet electrode technique described in ref.(13). Here filter paper soaked in aqueous LiCl solution was used for the electrodes, and an insulating layer of 1.5μm thick photoresist patterned on the -z surface was used to define the 9μm-period electrode. Poling was achieved with a series of electrical pulses ranging in voltage from 3.2 to 3.8kV. The resulting poled areas, defined by the photoresist, consisted of a 1mm wide, 8mm long periodically poled strip and four 100μm wide, 8mm long periodically poled regions. These were chosen to coincide with the waveguides such that a complete set of 3 to 16μm wide channels were covered. The sample was then end polished to a length of 8mm and annealed at 250°C for 3 hours to remove strain produced in the electrical poling process.

The third sample was made with x-cut, y-propagating material, with the rare earth doping carried out at 1210°C, which is approximately 70°C above the Curie temperature of congruent $LiNbO_3$. This high temperature allows higher dopant concentrations to be realised and also dramatically decreases the total diffusion time; however, a multi-domain structure is produced, with randomly shaped domains of around 0.5mm average dimension.

Spectroscopy and Laser Performance

Absorption spectra were made in the resulting waveguides using an unpolarised white light source and an EG&G OMA 2000 cooled silicon diode array spectrometer. A Glan-Thompson polarising cube was placed in front of the spectrometer to obtain polarised spectra. The polarised absorption spectra (fig.1) were seen to agree with those made in Czochralski-grown bulk-doped Tm:$LiNbO_3$(14). Fluorescence spectra and lifetimes were also found to be similar to the bulk doped material.

The laser results are summarised in table 2. In all cases the laser cavity was formed by butting lightweight, high reflectivity mirrors against the ends of the waveguide. These were held in place by the surface tension of a drop of fluorinated liquid. Pump light was provided by a Ti:Sapphire laser tuned to the σ polarised 794nm Tm^{3+}:$LiNbO_3$ absorption, and end-launched into the waveguides with a microscope objective.

From the results below we can see that low thresholds easily within reach of single stripe-diode lasers are possible for the 1.85μm transition in Tm:$LiNbO_3$ waveguides. Even lower thresholds are to be expected for optimised lengths of crystal for this quasi-three-level system. Comparison of the single domain samples (1 and 2) seems to show favourable performance for the z-cut waveguides. However this may be due to the fact that the x-cut guides were observed to have higher losses due to surface roughness from imperfect Ti lift-off. The z-cut sample is able to maintain cw laser action probably due simply to its lower threshold requirement, as its output is still very unstable due to photorefractive effects. Periodic poling of the waveguide with small

Table 2 Laser Performance

Sample	Length	Threshold Power Incident On Crystal	Stability
1	15mm	~250mW	Lases for ~1 second
2 (single domain)	8mm	~17mW	CW lasing, very unstable
2 (periodic domains)	8mm	~200mW	'Flash' lasing
3	6mm	40mW	CW lasing, very stable

single domain sizes should remove photorefractive problems, however we were only able to obtain 'flash' lasing in such guides. This may be due to the fact that, as revealed by subsequent etching experiments (fig. 1), the period poling achieved did not give equally sized domains within the waveguide region. Further work is aimed at producing evenly sized periodically poled, doped waveguides. Perhaps the most interesting result is found with the sample that was indiffused at a temperature higher than the Curie point. Although this fabrication procedure visibly increases transmission losses in $LiNbO_3$ a reasonably low threshold of 40mW was obtained and the output showed no signs of any instabilities related to photorefractive effects. It is not yet clear how this excellent performance has been achieved. The fact that the sample is multi-domain is not thought to be responsible as the domains are too large (~0.5mm) and irregular to cancel out the photorefractive effect. Thus it should be possible to re-pole the material to obtain lower transmission losses and regain the non-linear and electro-optic properties, although useful acousto-optic properties may still be present in the multi-domain material. Future work is aimed at identifying the important fabrication parameters involved. Whatever the reason for this behaviour this result appears to be an important step forward for $LiNbO_3$ waveguide lasers in that pumping and lasing at short wavelengths should now be possible without photorefractive damage.

Summary

We have demonstrated the first room temperature operation of a 1.85μm Tm:$LiNbO_3$ laser. The host was doped with Ti and Tm by thermal indiffusion to give a waveguide refractive index profile and the laser gain respectively. Laser thresholds are low enough to allow diode pumping but the output stability is typically limited by photorefractive effects. In an effort to overcome this we have demonstrated the first combination of periodic poling with a laser doped waveguide, but unequal domain sizes still led to photorefractive problems. However photorefractive effects have been eliminated, and stable cw operation obtained, in a waveguide indiffused at a temperature above the Curie point. The cause of this improvement is still to be determined but it is not thought to be due to the fact that the sample is multi-domain. Thus it is believed that this sample could be re-poled without losing this effect, allowing non-photorefractive, but still electro-optic, $LiNbO_3$ devices.

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References

1. T.Y.Fan, A.Cordova-Plaza, M.J.F.Digonnet, R.L.Byer, and H.J.Shaw, J. Opt. Soc. Am. B **3**, 140 (1986).
2. E.Lallier, J.P.Pocholle, M.Papuchon, Q.He, M.de Micheli, D.B.Ostrowsky, C.Grezes-Besset, and E.Pelletier, Electron. Lett. **27**, 936 (1991).
3. H.Suche, L.Baumann, D.Hiller, and W.Sohler, Electron. Lett. **29**, 1111 (1993).
4. E.Lallier, J.P.Pocholle, M.Papuchon, Q.He, M.de Micheli, and D.B.Ostrowsky, Electron. Lett. **28**, 1428 (1992).
5. J.Amin, M.Hempstead, J.E.Román, and J.S.Wilkinson, Opt. Lett. **19**, 1541 (1994).
6. R.Brinkmann, W.Sohler, and H.Suche, Electron. Lett. **27**, 415 (1991).
7. M.Hempstead, J.S.Wilkinson, and L.Reekie, IEEE Photon. Technol. Lett. **4** 852 (1992).
8. E.J.Lim, M.M.Fejer, and R.L.Byer, Electron. Lett. **25**, 174 (1989).
9. T.Herbert, R.Wannemacher, R.M.Macfarlane, and W.Lenth, Appl. Phys. Lett. **60**, 2592 (1992).
10. J.Y.Allain, M.Monerie, and H.Poignant, Electron. Lett. **26**, 166 (1990).
11. B.P.Scott, F.Zhao, R.S.F.Chang, and N.Djeu, Opt. Lett. **18**, 113 (1993).
12. L.F.Johnson and A.A.Ballman, J.Appl.Phys. **40**, 297 (1969).
13. J.Webjörn, V.Pruneri, P.St.J.Russell, J.R.M.Barr, and D.C.Hanna, Electron. Lett. **30**, 894 (1994).
14. L.Núñez and F.Cussó, J.Phys.:Condens. Matter **5**, 5301 (1993).

Fig. 1 Polarised absorption spectra for Tm doped Ti:LiNbO$_3$ waveguide.

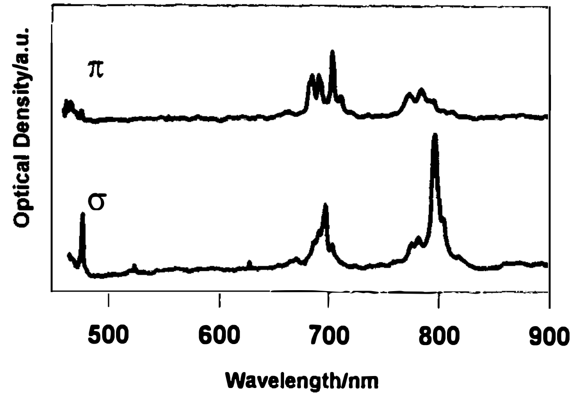

Fig. 2 Periodically poled 16μm wide, Tm doped Ti:LiNbO$_3$ waveguide.