

# Non-Photorefractive CW Tm-Indiffused Ti:LiNbO<sub>3</sub> Waveguide Laser Operating at Room Temperature.

J.P. de Sandro, J.K. Jones, D.P. Shepherd,

M. Hempstead, J. Wang and A.C. Tropper

Optoelectronics Research Centre

University of Southampton

Highfield, Southampton SO17 1BJ, UK.

## *Abstract*

We report laser operation at 1.81  $\mu\text{m}$  and 1.85  $\mu\text{m}$  in a Tm<sup>3+</sup>:LiNbO<sub>3</sub> Ti-diffused waveguide doped by thermal indiffusion at high temperature. We believe this is the first time lasing has been seen in Tm:LiNbO<sub>3</sub> at room temperature. Continuous-wave operation was achieved at room temperature with a threshold of  $\sim 42$  mW absorbed power. The output power was observed to be stable, without any sign of photorefractive damage.

## I. INTRODUCTION

Rare-earth-doped LiNbO<sub>3</sub> has been widely investigated as a promising material that combines the lasing properties of the lanthanide ions with the electro-optic, acousto-optic and nonlinear-optic properties of LiNbO<sub>3</sub>. Nd, Ho, Tm, Er and very recently Yb ions have been doped into LiNbO<sub>3</sub>, either in the bulk or by local indiffusion, and shown lasing properties [1-4]. Simple and efficient devices, using the electro-optic effect such as FM mode-locked, Q-switched and tunable Y-junction lasers have been fabricated in LiNbO<sub>3</sub> waveguides [5-6]. The acousto-optic properties of LiNbO<sub>3</sub> have also been successfully used to produce an Er:LiNbO<sub>3</sub> tunable waveguide laser [7]. Most recently integrated gratings for distributed Bragg reflectors have been demonstrated in doped LiNbO<sub>3</sub> [8].

The Tm<sup>3+</sup> ion offers numerous features of interest including a suitable absorption for diode pumping and several active infrared transitions. Upconversion-pumped blue emission has also been demonstrated in many host materials in both bulk and waveguide configurations [9-11]. Tm:LiNbO<sub>3</sub> lasing action at 1.85  $\mu\text{m}$  was demonstrated at 77°K almost 30 years ago in a bulk-doped sample [1]. Despite this early result no further improvement has been reported since. This is probably due to the photorefractive effect, well known in LiNbO<sub>3</sub>, which reduces the attractiveness of LiNbO<sub>3</sub> for use as a new laser host.

Thermal indiffusion is a very flexible technique for integrated device fabrication in LiNbO<sub>3</sub>. It allows the indiffusion of the active layer as well as the titanium channel waveguides that can guide both polarizations with low propagation losses. Thermal indiffusion, however, can be a very time consuming method when thick layers need to be driven in.

We report here the fabrication of a Tm:LiNbO<sub>3</sub> channel waveguide laser in which Tm has been indiffused at very high temperature, greatly reducing the diffusion time.

Surprisingly, CW laser operation at room temperature with a stable output has been achieved and the sample shows no sign of photorefractive damage.

## II. SAMPLE FABRICATION

A clean 1 x 50 x 25 mm (X,Y,Z) X-cut wafer, supplied by Photox (UK), has been coated under vacuum with a 40 nm Tm film in an Edward E306 thermal evaporator. A small part of the sample was left uncoated for purposes of loss comparison between doped and undoped waveguides. The thermal indiffusion was carried out at 1210°C for 63 hours. The coated sample was loosely enclosed in a platinum box in order to avoid out-diffusion of Li<sub>2</sub>O from LiNbO<sub>3</sub> during indiffusion. Significant surface roughness was found after the Tm indiffusion indicating that the diffusion time was less than the depletion time required to exhaust the surface layer. The depletion time has been calculated by extrapolating maximum solid solubility and diffusion coefficient for Er in LiNbO<sub>3</sub> [12], because such parameters are not yet known for Tm. As the indiffusion happened above the Curie point ( $\approx 1142^\circ\text{C}$  for congruent LiNbO<sub>3</sub>), in the paraelectric phase of LiNbO<sub>3</sub>, the diffusion coefficient might be slightly different from that in the ferroelectric phase. The difference between the Er<sup>3+</sup> and Tm<sup>3+</sup> ionic radii is also a potential source of variation. Nevertheless a 35-nm layer of Tm has recently been completely indiffused at 1210°C into a LiNbO<sub>3</sub> x-cut crystal in 80 hours, which is 10 times less than the depletion time required for the diffusion of the same layer performed at 1100°C.

A layer of titanium 85 nm thick was thermally evaporated onto the substrate and photolithographically patterned into stripes 3 to 16  $\mu\text{m}$  wide, aligned with the y axis. These stripes were thermally indiffused at 1005°C in the platinum box for 42 hours in a wet argon atmosphere flowing at 1.5 litres.min<sup>-1</sup>. Observation of the waveguide under a high

magnification ( x 1000 ) optical microscope and with an  $\alpha$ -step surface profiler revealed some roughness. This was believed to be due to some residual thulium left on the surface after the first indiffusion. This roughness could not be removed even after a further period of indiffusion time and is a likely source of scattering losses, preventing fabrication of very low-loss waveguides.

As a consequence of the use of diffusion temperature above the Curie point of  $\text{LiNbO}_3$ , the sample was found to be multi-domain after cooling down to room temperature. After etching of the sample with HF acid for 12 hours, examination of the Y and Z faces revealed the structure to be composed of randomly shaped single domains of  $\sim 0.5$  mm average dimension.

The sample was not re-poled before optical characterization. Two samples of length 6 mm and 3 mm were cut from the wafer and the end faces polished perpendicular to the waveguides to allow efficient end-launching of the pump laser light.

### III. OPTICAL CHARACTERISATION

In order to evaluate the average rare-earth concentration in the sample the strength of the 794-nm absorption was measured. Ti-sapphire laser light was launched into different waveguides through a x10 microscope objective. By comparing the transmission values at 794 nm and with the laser tuned off resonance at 840 nm we were able to determine a value of  $5.6 \text{ cm}^{-1}$  for the absorption coefficient. By comparison with the absorption of a bulk doped sample of concentration  $1.7 \times 10^{20} \text{ at.cm}^{-3}$ , the average concentration in our indiffused waveguide was estimated to be  $2.4 \times 10^{20} \text{ at.cm}^{-3}$ , assuming the  $\text{Tm}^{3+}$  absorption cross-section to be the same for bulk and indiffused material.

An absorption spectrum was obtained by launching unpolarized white light into the

6 mm long waveguides with a x40 objective and imaging the output onto the entrance slit of an EG&G OMA2000 cooled silicon diode array spectrometer. Fluorescence measurements were made by pumping the 3 mm long waveguide on the  $\sigma$  polarisation with a mechanically chopped Ti:sapphire laser tuned to 794 nm. The output from the waveguide was passed through a monochromator, and the light from the monochromator was then focused onto an InGaAs detector. Figure 1 shows the absorption and fluorescence features in the 0.8  $\mu\text{m}$  and 1.8  $\mu\text{m}$  regions respectively. They appear to be very similar with the ones observed in Czochralski-grown bulk doped Tm:LiNbO<sub>3</sub> [13,14]. The fluorescence lifetime was also measured from an oscilloscope display of the detector output. When the pump was blocked by the chopper the resulting fluorescence decay could be seen and a lifetime of  $2.70 \pm 0.05$  ms was deduced from the shape of the decay curve. This also is in good agreement with the value published for a bulk doped Tm:LiNbO<sub>3</sub> crystal [14].

The pump output beam diameter was observed with a CCD camera and image analyzer for two waveguides diffused from 3 and 14  $\mu\text{m}$  wide titanium stripes. The output spot diameter was found to be  $\sim 11$   $\mu\text{m}$  and single mode in the X direction. In the Z direction the 3  $\mu\text{m}$  stripe was single mode with a spot size of  $\sim 6$   $\mu\text{m}$ , and the 14  $\mu\text{m}$  stripe was multi-mode with an  $\sim 8$   $\mu\text{m}$  spot size for the lowest order mode.

The 6 mm long sample was used to measure laser characteristics. Pump light was launched into the waveguides from an argon-ion pumped Ti:sapphire laser using a x5 microscope objective. The output signal was collected on the InGaAs detector with a x10 microscope objective through a monochromator. When pumped with up to 200 mW at 794 nm in the  $\sigma$ -polarisation no lasing was observed with feedback provided only by the Fresnel reflection at the end faces ( 14 % ). Lasing occurred with a laser cavity formed by butting two highly reflecting ( 99.9% ) lightweight mirrors against the ends of the crystal. These

mirrors were held in place by the surface tension of a film of fluorinated liquid. The output was found to be very stable, the sample showing no sign of the normally observed photorefractive damage. A threshold of  $\sim 42$  mW of launched power was achieved in a waveguide diffused from a  $14 \mu\text{m}$  wide stripe. The sample was found to be lasing at  $1.81 \mu\text{m}$  and  $1.85 \mu\text{m}$  simultaneously.

The output efficiency of the sample was tested by replacing the output high-reflector mirror with an output coupler of 90% reflectivity at  $1.81 \mu\text{m}$  and 89% at  $1.85 \mu\text{m}$ . With this output coupler, and using a silicon filter to cut out the pump signal, lasing action was observed at a launched pump power of  $\sim 50$  mW in the same channel. The lasing characteristic is shown in figure 2. The output power was found to show no sign of photorefractive instabilities. The maximum pump power launched was limited by the power available from the Ti:sapphire laser. The slope efficiency was estimated to be  $\sim 1\%$ . Producing samples with less surface roughness and cutting down the sample to one absorption length (  $1.8 \text{ mm}$  ) to reduce propagation and reabsorption losses should improve slope efficiency while decreasing the threshold.

From the difference in threshold observed with the high reflector and the output coupler we estimated the waveguide loss at the laser wavelength. The threshold power was assumed to be proportional to  $(L + T + 2N\sigma\ell)$  in the expression given for a quasi three-level system [15] where  $L$  is the round-trip waveguide propagation loss,  $T$  is the output coupling,  $N$  the population density of the lower laser level at threshold,  $\sigma$  is the absorption cross section and  $\ell$  is the length of the crystal.  $N\sigma$  was estimated from the value of the unpumped absorption coefficient at  $1.85 \mu\text{m}$  ( measured to be  $7 \times 10^{-2} \text{ cm}^{-1}$  for a bulk doped crystal of  $1.7 \times 10^{20} \text{ at.cm}^{-3}$  concentration) and found to be equivalent to a loss of  $0.4 \text{ dB.cm}^{-1}$ . The waveguide propagation loss was then found to be  $1.45 \text{ dB.cm}^{-1}$  which is consistent with

the value of  $1.2 \pm 0.4 \text{ dB.cm}^{-1}$  obtained from the transmission measured off the absorption at 840 nm. The uncertainty in the loss measurement results from uncertainty in the value of the coupling efficiency, which we estimated to be between 70% and 80%. Losses are thought to be due to surface roughness as well as introduced by the multi-domain structure. Titanium-diffused waveguides of  $0.5 \text{ dB.cm}^{-1}$  propagation loss have subsequently been fabricated in a rare earth doped  $\text{LiNbO}_3$  substrate with a multi-domain structure. This shows that, despite the structure, multi-domains waveguides of loss comparable to that obtained in a single domain sample can be fabricated and should lead to improved laser performance.

The reason why no signs of any instabilities related to the photorefractive effect has been observed is not yet fully understood. The fact that the sample is multi-domain is not thought to be responsible as the domains are too large (  $\sim 0.5 \text{ mm}$  average dimension ) and irregular to cancel out the photorefractive effect. Thus it may be possible to re-pole the material, without losing the resistance to photorefractive damage, 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. Present work is aimed at identifying the important fabrication parameters involved in producing the photorefractive-damage-resistant  $\text{LiNbO}_3$  waveguides.

#### IV. SUMMARY

We have demonstrated the first room temperature operation of a  $\text{Tm}:\text{LiNbO}_3$  laser in the  $1.8 \mu\text{m}$  region. The host was doped with Ti and Tm by thermal indiffusion to give a waveguide refractive index profile and the laser gain respectively. Tm indiffusion was performed at  $1210^\circ\text{C}$ , well above the Curie point of  $\text{LiNbO}_3$ , and led to high dopant concentration with a short diffusion time. Stable CW operation was obtained with laser

thresholds low enough to allow future single-stripe diode pumping. The cause of photorefractive damage resistance 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 to allow non-photorefractive and electro-optic Ti:LiNbO<sub>3</sub> devices. Whatever the reason for this behaviour this result appears to be an important step forward for Ti:LiNbO<sub>3</sub> waveguide lasers in that pumping and lasing at short wavelengths should now be possible without photorefractive damage.

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**REFERENCES**

- [1] L.F. Johnson and A.A. Ballman, "Coherent emission from rare earth ions in electro-optic crystals," *J. Appl. Phys.*, vol. 40, pp. 297-302, 1969.
- [2] R. Brinkman, W. Sohler, and H. Suche, "Continuous-wave erbium-diffused LiNbO<sub>3</sub> waveguide laser," *Electron. Lett.*, vol. 27, No. 5, pp. 415-417, 1991.
- [3] E. Lallier, J.P. Pocholle, M. Papuchon, M. de Micheli, M.J. Li, Q. He, D.B. Ostrowsky, C. Grezes-Besset and E. Pelletier, "Nd:MgO:LiNbO<sub>3</sub> channel waveguide laser devices," *IEEE J. Quantum Electron.*, vol. 27, No. 5, pp. 618-625, 1991.
- [4] J.K. Jones, J.P. de Sandro, M. Hempstead, D.P. Shepherd, A.C. Large, A.C. Tropper and J.S. Wilkinson, "Channel waveguide laser at 1  $\mu$ m in Yb-indiffused LiNbO<sub>3</sub>," to be published in *Opt. Lett.*
- [5] E. Lallier, J.P. Pocholle, M. Papuchon, Q. He, M. de Micheli and B. Ostrowsky, "Integrated Q-switched Nd:MgO:LiNbO<sub>3</sub> waveguide laser," *Electron. Lett.*, vol. 28, No. 15, pp 1428-1429, 1992.
- [6] J. Amin, M. Hempstead, J. Román, and J.S. Wilkinson, "Tunable coupled-cavity waveguide laser at room temperature in Nd-diffused Ti:LiNbO<sub>3</sub>," *Opt. Lett.*, vol. 19, No. 19, pp. 1541-1543, 1994.
- [7] I. Bauman, D. Johlen, W. Sohler, H. Suche and F. Tian, "Acoustically tunable Ti:Er:LiNbO<sub>3</sub>-waveguide laser," in *Proc. ECOC'94*, Postdeadline-paper, Vol 4, pp. 99-102, 1994.
- [8] R. Groß, J. Söchtig, I. Baumann, W. Sohler, H. Schütz, R. Widmer, "Integrated DBR laser in erbium-diffusion-doped LiNbO<sub>3</sub>," in *Proc. ECIO'95*, pp 571-574, 1995.
- [9] D.C. Nguyen, G.E. Faulkner, M. Dulich, "Blue-green (450-nm) upconversion Tm<sup>3+</sup>:YLF laser," *Appl. Opt.*, vol. 28, No. 17, pp. 3553-3555, 1989.

- [10] D.P. Shepherd, A.C. Large, T.J. Warburton, A.C. Tropper, D.C. Hanna, C. Borel, A. Rameix, P. Thony, B. Ferrand, S. Guy, B. Jaquier, and M.F. Joubert, "Epitaxial Tm:YAG waveguide lasers at  $2\mu\text{m}$  and upconversion fluorescence in the blue and U.V. regions," in *Proc. CLEO Europe 1994*, Post-deadline paper CPD1.8, 1994.
- [11] B.P. Scott, F.Zhao, R.S.F. Chang and N. Djeu, "Upconversion-pumped blue laser in Tm:YAG," *Opt. Lett.*, vol. 18, No. 2, 1993.
- [12] C. Buchal and S. Mohr, "Ion implantation, diffusion, and solubility of Nd and Er in  $\text{LiNbO}_3$ ," *J. Mater. Res.*, vol. 6, No. 1, pp. 134-137, 1991.
- [13] L. Nunez and F.Cusso, "Polarized absorption and energy levels of  $\text{LiNbO}_3\text{:Tm}$  and  $\text{LiNbO}_3\text{:MgO:Tm}$ ," *J. Phys. Condens. Matter*, vol. 5, pp. 5301-5307, 1993.
- [14] L. Nunez, J.O. Tocho, J.A. Sanz-Garcia, E. Rodriguez, F.Cusso, D.C Hanna, A.C. Tropper and A.C. Large, "Optical absorption and luminescence of  $\text{Tm}^{3+}$ -doped  $\text{LiNbO}_3$  and  $\text{LiNbO}_3\text{(MgO)}$  crystals," *J. Lumin.*, vol. 55, pp. 253-263, 1993.
- [15] W.P. Risk, "Modeling of longitudinally pumped solid-state lasers exhibiting reabsorption losses," *J. Opt. Soc. Am. B*, vol. 5, No. 7, pp. 1412-1423, 1988.

**Figure Captions**

Figure 1. Tm:LiNbO<sub>3</sub> waveguide absorption and fluorescence.

Figure 2. Waveguide laser output versus absorbed pump power with a 90% reflectivity output coupler.



