980 nm-pumped Er- and Er/Yb-doped waveguide lasers in $LiNbO_3$

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Abstract: We demonstrate a 980 nm-pumped Er- and the first Er/Yb-doped waveguide laser in Ti:$LiNbO_3$. The devices were fabricated on x-cut $LiNbO_3$, with the guides parallel to the z-axis. This choice of waveguide orientation results in a reduced susceptibility to photorefractive damage, and allows cw room-temperature operation.

Introduction: Er-doped waveguide laser and amplifier devices operating at ~1.5 μm are attractive for providing signal processing functions on a local scale for optical communications and sensor systems. The two main technologies that have been used for demonstrations of such devices have thus far been glass and lithium niobate. Current active devices in glass are all pumped at 980 nm, where high-power diodes are readily available [1]. This appears to be the preferred wavelength for locally pumped Er-doped fiber and planar devices. This pump wavelength also allows the use of Er/Yb codoping, where the Yb^{3+} ions act as sensitisers. In materials where there is an efficient energy transfer between the Yb^{3+} ions and the Er^{3+} ions, the sensitisation acts to enhance the pumping rate to the Er metastable $^4I_{13/2}$ level. Er:$LiNbO_3$ waveguide laser and amplifier devices have, on the other hand, only been pumped at 1480 nm, albeit with excellent results [2]. This has been mainly due to photorefractive damage induced instability at visible and near infrared wavelengths in this material. Recent reports on 980 nm-pumped amplifier devices in Er:Ti:$LiNbO_3$ have clearly shown the detrimental effects of photorefractive damage [9]. However, given the good performance obtained using 980 nm pumping in Er and Er/Yb glass devices, it is worthwhile investigating further schemes which will allow this pump band to be used for Er:$LiNbO_3$ devices. To this end, we have recently utilized the z-propagation scheme in rare-earth-doped Ti:$LiNbO_3$ for pumping devices in the near infra-red [3]. Simple charge transport models show that this propagation scheme has a high resistance to optical damage effects, at the expense of allowing access to a lower electro-optic coefficient [4]. In this paper we report our results on Er and Er/Yb doped Ti:$LiNbO_3$ waveguide lasers pumped at 980 nm, using the z-propagation direction.

Fabrication: Two x-cut wafers of $LiNbO_3$ were used in the experiment, and are referred to here as samples A and B. Using e-beam techniques, 15 nm of Er was deposited onto sample A, and diffused into the substrate at 1100° C over 144 hours. A stack, consisting of alternating layers of Er and Yb_2O_3 was deposited on sample B. Each individual layer in the stack was 2 nm thick, and the total thickness of the stack was 28 nm. The layers were then diffused into the substrate at 1100°C, for a total of 360 hours. On both samples, Ti stripes which were 110 nm thick and 7 μm wide were delineated using standard photolithography. The Ti diffusion was carried out at 1030°C, for 9 hours. All the diffusions were carried out in flowing oxygen, in an alumina tube furnace with the sample sitting on a Pt pad. The finished devices yielded waveguides which were 2.9 cm long on sample A and 2 cm long on sample B.

Characterisation: near-field mode profile analysis using a 1550 nm LED revealed the waveguides on both samples to be single moded, with *1/e* mode intensity diameters of 7.9 (±0.4) μm x 4.6 (±0.25)μm. The similarity of mode sizes in the two samples indicates that the Ti diffusion conditions were not significantly different in the two samples, despite the different rare-earth diffusion conditions. The guides supported 3 transverse modes at 980 nm. The samples were then characterised using a Ti:Al_2O_3 pump source. Waveguide scattering losses at the pump wavelength of 980 nm were estimated to be ~0.55 (±0.05) $dBcm^{-1}$ in sample A, and ~1.2 (±0.1) $dB.cm^{-1}$ in sample B. The higher losses in sample B are likely due to incomplete diffusion of the stacked layers as evidenced by rough surface features seen through an optical microscope operated in the interference contrast mode. Sample A on the other hand had a smooth surface, indicating complete diffusion of the Er layer [5]. Using coupled pump powers of less than 2 mW, the Er metastable level lifetime was measured to be 2.68 (±0.1) ms in sample A, comparing favourably with that measured elsewhere[2]. The lifetime of this level in sample B was found to be similar. Using a bandpass filter at 1060 nm, the lifetime of the Yb $^4F_{5/2}$ level in sample B was measured to be ~300 μs.

Laser characteristics were then measured in sample A, with cw pumping at 980 nm. The pump mode was TE polarised. The device had a mirror with a reflectivity of >99% at 1550 nm butted against its input face. The mirror transmitted 85% of the pump light. The Fresnel reflection off the opposite face of the device was used to complete the laser cavity. The device operated in a stable manner, with the signal TE polarised. Fig. 1 shows the cw laser characteristics of the device, operating at 1531.4 nm. The laser output was taken from the nonpumped end of the device. Transmission measurements on and off resonance were used to deduce a coupling efficiency of ~60%, giving a threshold of 53 mW and a slope efficiency of 1.65%. The total absorbed pump power above threshold (scattering losses + resonant absorption) was measured to be 45% of that launched into the guide. Stable output powers in excess of 1 mW were obtained from this unoptimised device.

Sample B was pumped in a similar configuration, with a high reflector at the input end and no reflector at the output end. In this case though the device barely attained threshold with the available pump power (300 mW, incident). This is thought to be due to the higher loss in this device compared to that in sample A. using a 95% reflector (at 1550 nm) at the output face, the device lased in a stable cw mode at 1531.4 nm, with a threshold of 45 mW of coupled pump power and a slope efficiency of 0.6%. The laser characteristics are shown in Fig. 2. In this device, the total absorption above laser threshold, as defined previously, was measured to be 68% of the coupled pump power.

The input and output mirrors were then replaced with mirrors which were highly reflecting at 1060 nm, for a preliminary test to see if the Yb could be made to lase at ~1μm. With the device pumped around 945 nm, stable lasing at ~1031 nm was achieved at a threshold of 120 mW of coupled pump power. Fig. 3 shows the laser spectrum, obtained using a spectrum analyser with a resolution of 0.2 nm. Further characterisation of this particular laser transition in the codoped system is underway.

Discussion: The relatively low output power obtained from sample A is thought to be due to the high lifetime of the Er $^4I_{11/2}$ pump level (~200 μs, [6]). This causes saturation of the output power at high pump powers, when the pump rate is significantly greater than the rate at which ions decay to the metastable level. Saturation was not seen in the laser characterization with the pump powers used, but is borne out in numerical models [7]. Moreover, in the Er:$LiNbO_3$ system, there is substantial resonant ESA at 980 nm from the $^4I_{11/2}$ level to the $^4F_{3/2}$ level [6], enhanced by the high lifetime of the pump level. This ESA transition results in a very strong green luminescence from the $^4S_{3/2}$ level, and may also cause a decrease in the output power due to a reduction in the population inversion. Saturation of the laser output is clearly seen in sample 2 (Fig 2). This is presumably due to the combined effect of the finite Yb→Er transfer rate and the high Er $^4I_{11/2}$ lifetime. The transfer of energy between the Yb^{3+} and Er^{3+} ions is characterised by a reduction in the Yb $^4F_{5/2}$ level lifetime. This lifetime has previously been measured to be ~600 μs in Yb-diffused $LiNbO_3$ [9]. A simple rate equation analysis shows that the transfer efficiency is given by $\eta = 1 - \frac{\tau_{Yb}^{Er}}{\tau_{Yb}}$, where τ_{Yb}^{Er} is the Yb lifetime in the presence of Er and τ_{Yb} is the Yb lifetime without any Er. Using this equation, we estimate, to first approximation, a transfer efficiency of 50% in sample B (assuming that the Yb concentration in [8] is similar to that in our sample). The transfer coefficients are difficult to calculate, given that the exact concentration of Er and Yb are not known in our device. However, given the low phonon energy of $LiNbO_3$ (800 cm^{-1}), and the associated high lifetime of the Er $^4I_{11/2}$ level, backtransfer of energy from the Er to the Yb is also highly likely. The spectroscopy of the system thus requires further investigation. The high losses in sample B are likely due to incomplete diffusion. In the absence of known diffusion coefficients for Yb, the diffusion time for the stack layer was assumed to be similar to that required for a 28 nm layer of Er at the same temperature. However, as revealed by the surface morphology, the Er/Yb coupled system appears to have a substantially different diffusion coefficient.

Conclusions: We have demonstrated Er:Ti:$LiNbO_3$ waveguide lasers and, for the first time to our knowledge, Er/Yb-doped Ti:$LiNbO_3$ waveguide lasers pumped at 980 nm. The results obtained with these preliminary devices are very encouraging, and show that 980 nm pumped laser devices are indeed possible to realize in Er:Ti:$LiNbO_3$ if the photorefractive damage can be alleviated. These demonstration devices are as yet unoptimized, and it is likely that with reduced losses, better diffusion conditions, and optimization of the Er/Yb ratios, better performance will be achieved.

References:

1. J.Amin *et al*, *Proc SPIE* **2996** (*Photonics West '97*).
2. I.Baumann *et al*, *J. Selected Topics in Quantum Electronics* **2**, 355 (1996).
3. J.Amin *et al*, *Applied Physics Letters* **69**, 3875 (1996).
4. R.L.Holman, *Proc. SPIE* **408** (1983).
5. I.Baumann *et al*, *Applied Physics A* **64**, 33 (1997).
6. J.Amin *et al*, *J. of Luminescence* **69**, 17 (1996).
7. C.Barnard *et al*, *J.of Quantum Electronics* **30**, 1817 (1994).
8. J.K.Jones *et al*, *Optics Letters* **20**, 1477 (1995).
9. C-H.Huang *et al*, *Electronics Letters* **32**, 215 (1996).

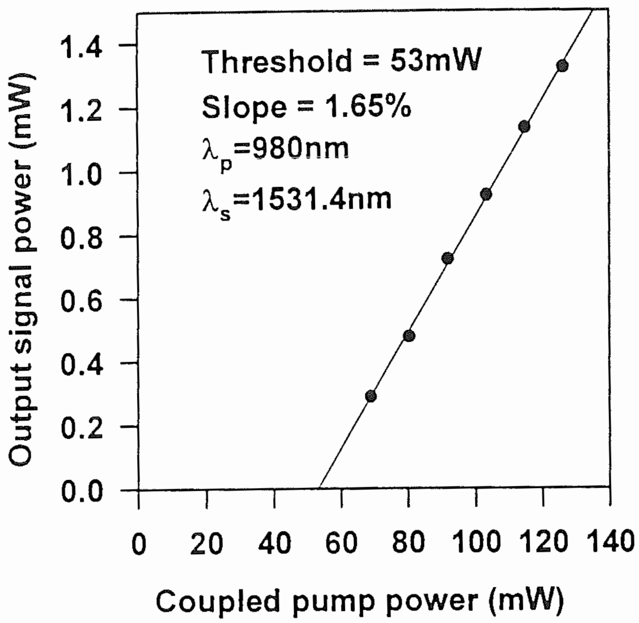

Fig 1. Laser characteristics for the $Er:Ti:LiNbO_3$ device.

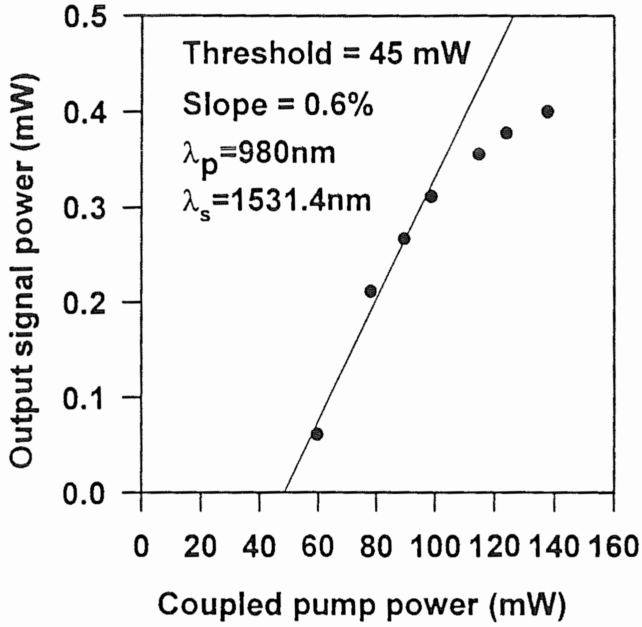

Fig 2. Laser characteristics for the $Er:Yb:Ti:LiNbO_3$ device.

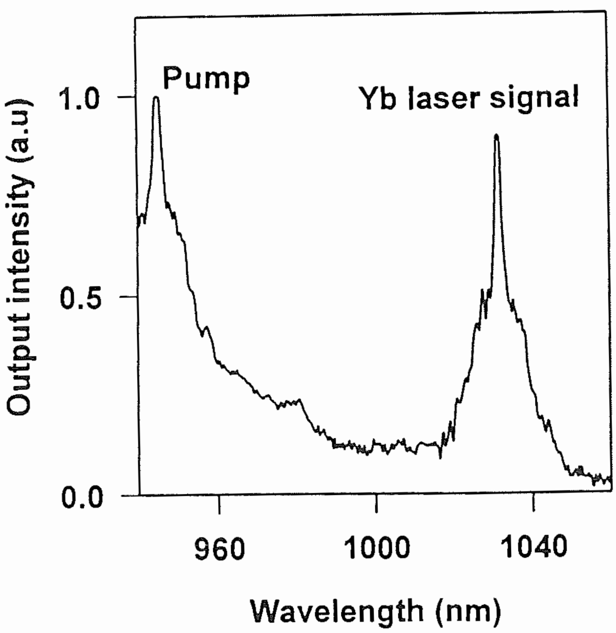

Fig 3. Spectrum showing the Yb laser signal in the codoped device