PROCEEDINGS OF SPIE

SPIE—The International Society for Optical Engineering

Rare-Earth-Doped Devices

Seppo Honkanen
Chair/Editor

10–11 February 1997
San Jose, California

Volume 2996

Stable CW operating waveguide lasers at room temperature in rare-earth-diffused lithium niobate

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ABSTRACT

A means of reproducibly fabricating stable cw channel waveguide lasers in rare-earth-doped Ti:$LiNbO_3$ is demonstrated, through careful choice of the light propagation direction. Z-propagating waveguides have been fabricated in Nd:Ti:$LiNbO_3$ and room-temperature cw laser operation has been obtained by pumping in the 800 nm-band, with greatly reduced photorefractive instability. The reduced photorefractive damage susceptibility in this waveguide configuration has been used to our advantage in the realization, for the first time, of a 980 nm-pumped laser in Er:Ti:$LiNbO_3$. The device showed a lasing threshold of 10.5 mW of absorbed pump power and a slope efficiency of 8.5%.

Keywords: Rare-earth-doped waveguide lasers, lithium niobate active devices

1. INTRODUCTION

A great deal of interest has recently been generated in rare-earth-doped planar waveguide devices, through the success of fiber lasers and amplifiers. Active planar devices are likely candidates for providing signal-processing functions on a local scale both in optical communications and sensor systems. In particular, rare-earth-doped $LiNbO_3$ is extremely attractive since it potentially permits a high degree of integration through a combination of the mature waveguide fabrication techniques that exist in this host material, its intrinsically good material properties, and the gain introduced by the rare-earth ions. Moreover, the incorporation of rare-earth ions in this crystal by indiffusion demonstrates a degree of versatility not readily available in bulk rare-earth-doped planar waveguide systems. Numerous integrated laser and amplifier devices have been demonstrated over the past few years in Nd- and Er-diffused $LiNbO_3$[1,2,3]. The most common method of waveguide fabrication in rare-earth-diffused $LiNbO_3$ is by Ti-indiffusion, as this technique allows for low propagation losses and does not appear to alter the spectral characteristics of the rare-earth ions. However, an inherent problem with Ti:$LiNbO_3$ guided wave devices is their relative instability at visible and near-infrared wavelengths as a result of photorefractive damage induced by the high power densities in these guides. This has limited the demonstration of cw room-temperature operating Nd-doped devices almost exclusively to annealed proton exchange waveguides in MgO:$LiNbO_3$, with the exception of the device reported in Ref. 1. This device constituted a Y-branch, Ti-indiffused waveguide, in a y-propagating configuration, and the reason behind the stable cw operation at room-temperature obtained in that case is still not clear. Photorefractive damage has also been one of the main reasons that the majority of Er:Ti:$LiNbO_3$ devices have been pumped at 1480 nm[2,3], albeit with excellent results. However, amplification measurements in Er-doped fibers have shown that pumping at 980 nm provides the best performance in terms of gain, gain efficiency (dB/mW) and signal-to-noise-ratios[4]. Moreover, high-powered 980 nm pump diodes are readily available and are significantly cheaper than 1480 nm diodes. It therefore appears that 980 nm pumping of EDFA's is preferred over 1480 nm pump schemes in most applications. One exception to this is a remotely pumped amplifier, where 1480 nm is the pump wavelength of choice due to the low loss of the fiber at this wavelength compared to that at 980nm. Given the fact that Er:Ti:$LiNbO_3$ lasers and amplifiers are likely to find applications on a local scale that will not require remote pumping, it is thus worthwhile investigating schemes that will allow 980 nm pumping in these devices. The only report of a 980 nm pumped Er:Ti:$LiNbO_3$ device thus far, to our knowledge, has been made by Huang and McCaughan[5]. In that report the detrimental effect of photorefractive damage on the amplifier gain was evident, and it is unclear as to whether net gain was obtained in the device.

It is widely accepted that the photorefractive effect is due to photogeneration of electrons through ionization of Fe^{2+} impurities to the Fe^{3+}state, and the subsequent migration of these electrons along the z-axis (photovoltaic effect). Trapping of the electrons, presumably in areas outside the waveguide, results in regions of space charge which perturb the waveguide modes through the electro-optic effect[6]. In general, waveguides are fabricated in $LiNbO_3$ with the propagation direction transverse to the z-axis, in order to use the highest electro-optic coefficient (r_{33}) for on-chip modulation. However, the space charge separation caused by the photovoltaic effect in this case is on the order of the mode diameter, and therefore the associated fields remain largely within the waveguide, causing the modal power to be scattered out. As was first reported by Holman[7], one way of reducing considerably this optical damage is by propagating along the z-axis. The charge separation is then along the guide length, and therefore the overlap between the fields associated with this separation and the optical mode is minimized. A disadvantage perceived by many for this z-propagation scheme is that it only allows the use of the r_{22} electro-optic coefficient, which is lower than the commonly used r_{33} coefficient by a factor of ~9. However, the voltage requirement for switching can be optimally made to be < 15 V[8,9]. Moreover, the effects of temperature changes in this waveguide orientation, where both TE and TM modes are ordinary modes, are likely to be less than other orientations, as dictated by the temperature-dependent Sellmeier dispersion equations. Also, because the z-propagating waveguide does not support extraordinary modes, measures do not have to be taken during fabrication to suppress outdiffusion, thus making the fabrication simple.

In this paper, we report our results on z-propagating rare-earth-doped waveguide lasers in $LiNbO_3$[18]. We demonstrate stable room-temperature operation of a Nd-diffused Ti:$LiNbO_3$ waveguide laser pumped ~800 nm. We also demonstrate a 980 nm-pumped Er:Ti:$LiNbO_3$ waveguide laser using the z-propagating configuration. These results open up numerous possibilities for stable, diode pumped, laser and amplifier devices in $LiNbO_3$. We would like to point out that, at the time that this work was being done, a similar study was carried out by Fujimura *et al*[17] on z-propagating Nd:Ti:$LiNbO_3$ devices.

2. DEVICE FABRICATION

Two pieces of $LiNbO_3$, from the same x-cut wafer, were used in our experiments and will be called A and B for brevity. Using e-beam techniques, 8 nm of Nd was deposited on sample A, and 15 nm of Er on sample B. The Nd^{3+} ions were then driven into sample A by indiffusion at 1100°C over a period of 240 hours, and the Er^{3+}ions into sample B at 1100°C over 144 hours. On sample A, Ti stripes 6 μm wide and 90 nm thick, were delineated using standard photolithography. A similar process was used on sample B to form Ti stripes 7 μm wide and 110 nm thick. The Ti was then diffused into the samples over a 9 hour period, with sample A diffused at 1005°C and sample B at 1030°C. The rare-earth diffusions and the waveguide diffusions were all carried out in a ceramic tube. The samples were placed on a Pt pad, which in turn was placed on an alumina pedestal. Oxygen was run through the furnace with a flow rate of 1 L/min. Finally, both samples were cut and end-polished, yielding waveguides with a range of different lengths.

3. Nd:Ti:$LiNbO_3$ DEVICE CHARACTERISATION

A near-field analysis was first performed on the Nd:Ti:$LiNbO_3$ guides using a Nd:YLF laser at 1040 nm. At this wavelength, the waveguides were slightly double-moded, with the fundamental mode diameters (1/*e* full width) 5.2 (±0.3) μm in width and 2.8 (±0.15) μm in depth. The waveguide also supported 2 modes at ~800 nm. Cut-back loss measurements were made by end-fire coupling the output of a cw Ti:Al_2O_3 laser into the guides. These measurements were carried out at 850 nm as the resonant absorption due to the dopant ions is minimal here. In this case, the guides were found to have a loss of 1 (±0.1) $dB.cm^{-1}$. The room temperature behaviour of the Nd-doped devices was then characterized by tuning the pump laser to 809 nm. Transmission measurements made at 809 nm and at 850 nm, together with a knowledge of the waveguide loss, were used to compute a coupling efficiency of 68% in this device. The lifetime of the $^4F_{3/2}$ metastable level was measured by chopping the pump beam using an acousto-optic (AO) modulator and collecting the waveguide fluorescence using a Si detector at the output end of the waveguide. A silicon filter was used to block the pump beam. With an estimated 20 mW coupled into the waveguide, a single-exponential fluorescence decay was observed, with a $1/e$ lifetime of 89 μs, close to that reported in Ref. 1. The slightly lower lifetime may be due to amplified spontaneous emission (ASE) effects in the waveguide. The AO modulator was then removed, and the lasing characteristics of a 1.8 cm long device were measured. The device lased in a stable, cw, manner at 1093.1 nm, with optical feedback provided only by the 14% Fresnel reflectance from the polished endfaces. Both the pump and the laser emission were TE polarised. Figure 1 shows the lasing characteristics of the device, with the inset showing a laser spectrum as obtained using an automatic spectrum analyser with a 0.2nm resolution. The output power indicated in Fig. 1 is the total power from the pumped and unpumped end of the device. The absorbed pump power was 70% of that launched. The threshold for laser oscillation was 68 mW of absorbed pump power, and the slope-efficiency was 40%. In this case, we were able to extract ~40 mW from the device, limited by the available pump power, without any discernible sign of photorefractive damage.

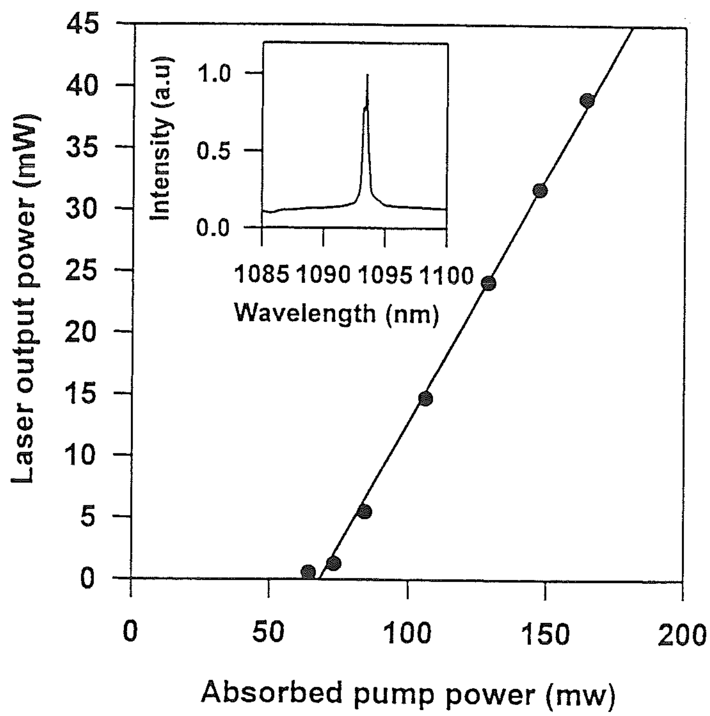

Figure 1. CW laser characteristics of a z-propagating Nd:Ti:$LiNbO_3$ device. The output power in this figure is the total power emitted from both ends of the device. The inset shows the laser spectrum.

4. Er:Ti:$LiNbO_3$ DEVICE CHARACTERISATION

Near-field analysis was carried out on the Er:Ti:$LiNbO_3$ devices using a 1.5 μm LED, revealing the 7 μm-wide Er:Ti:$LiNbO_3$ waveguides to be single-moded at this wavelength, with $1/e$ mode diameters of 7.9 (±0.4) μm x 4.6 (±0.25) μm (width x depth). The guides supported 3 modes at 980 nm. Once again, loss measurements were made using cut-back techniques, with a Ti:Al_2O_3 laser tuned to 900 nm to eliminate any effects due to resonant absorption. The loss was in this case 0.55 (±0.05) dB.cm^{-1}. No attempt was made to determine the propagation loss around 1.5μm but, given the wavelength separation between the pump and signal, we estimate this to be ≤ 0.4 dB.cm^{-1}. The

$Ti:Al_2O_3$ laser was then tuned to 980 nm and, using techniques similar to those described above, the lifetime of the Er $^4I_{13/2}$ metastable level was determined by pumping a 2.9 cm long waveguide. ASE effects were kept to a minimum in this case by using a coupled pump power <1 mW, and the fluorescence was detected using a high-gain InGaAs detector after blocking the residual pump using an AR-coated Si filter. The $1/e$ lifetime, as obtained from a single-exponential fit to the measured decay, was 2.68 ms. This is not the best way to determine the lifetime of a three-level system, due to possible artifacts caused by reabsortion of the signal[10]. However, in the absence of a suitable bulk-doped crystal, this technique suffices in giving an approximation to the lifetime, and our lifetime corresponds very favourably with that measured elsewhere[11]. Laser characteristics were then measured in this 2.9 cm long device, with cw pumping from the $Ti:Al_2O_3$ at 980 nm. The pump mode was TE polarized. A mirror with a reflectivity of >99% at 1530 nm, and which transmitted 85% of the pump, was attached to the front face of the device, and fluorinated liquid provided index-matching. At the output end of the device, no mirror was attached, and Fresnel reflection from the polished end-face was used to complete the laser cavity. The device operated in a stable mode, with the output TE polarized. Figure 2 shows the cw laser characteristics. The inset shows the laser spectrum at 1531.4 nm. The laser output power in this case is that emitted only from the output, nonpumped end of the device. The coupling and absorption efficiencies of the device were measured as described above, using transmission measurements on and off resonance. In this case, we measured a coupling efficiency of 60%. The absorbed pump power above laser threshold was 20% of the coupled pump power. The lasing threshold was measured to be 10.5 mW of absorbed pump power, and the device exhibited a slope-efficiency of 8.5%. Stable output power in excess of 1 mW was obtained, and was limited by the available pump power. In general, it was possible to make the device lase with any combination of mirrors, and even with no mirrors on either face. However, we could not characterise the laser performance without mirrors due to the limited pump power. A very strong green fluorescence, obtained through a resonant two-photon excited-state absorption (ESA) mechanism, was visible in the 980 nm-pumped devices[12]. We did not see any lasing in the green though, even when high reflectors at ~540 nm were butted to both faces.

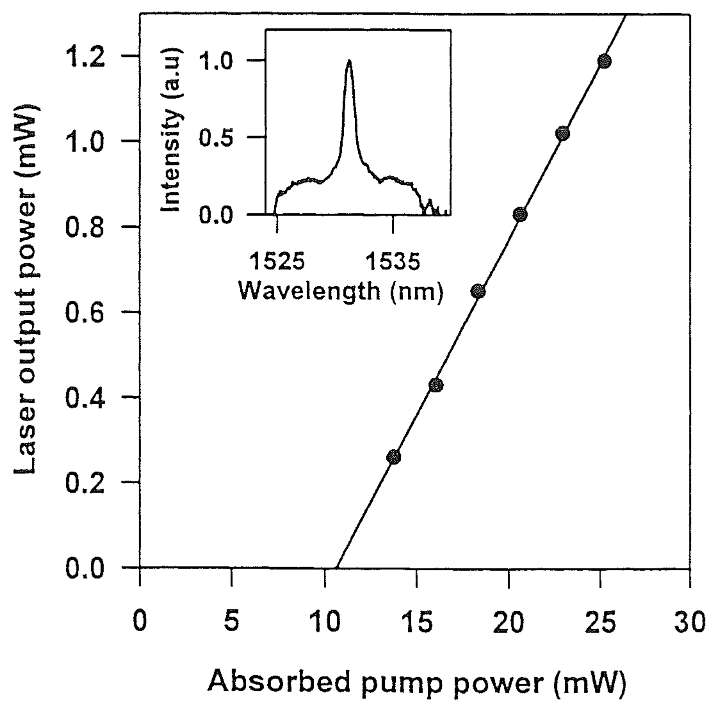

Figure 2. CW laser characteristics of a 980 nm pumped, z-propagating, $Er:Ti:LiNbO_3$ device, with the laser spectrum shown in the inset. The output power in this figure is that measured from the non-pumped end of the device.

It should be noted that we also tried to pump this device in the 800 nm absorption band. Substantial green fluorescence was exhibited by the device, but we were not able to see any lasing at either ~1.5μm or in the green. This, however, was not entirely surprising, given the fact that the ground-state absorption coefficient at ~800 nm in Er:$LiNbO_3$ is about an order of magnitude smaller that at 980 nm or 1480 nm. Also, ESA is expected to be significantly higher at this wavelength, based upon measurements carried out in fiber amplifiers[4].

5. CONCLUSIONS

We have demonstrated stable, room-temperature operating lasers fabricated by Ti-indiffusion in rare-earth-doped $LiNbO_3$. The z-propagation scheme has been employed here, allowing effective curbing of the optical damage. A Nd:Ti:$LiNbO_3$ device lased continuously using only the polished endfaces to provide feedback. The absorbed pump power at threshold was 68 mW and the slope efficiency was 40%. A similar z-propagating Er:Ti:$LiNbO_3$ device was made to lase by pumping at 980 nm, with an absorbed pump power threshold of 10.5 mW and a slope efficiency of 8.5%, obtained using a high reflector on the input face and only the polished output face as the second mirror. We believe that the performance of these demonstration devices can be significantly improved by fabricating waveguides with lower losses and incorporating pump reflectors at the output end of the device to improve the absorption efficiency.

The results presented herein show that 980 nm pumping is clearly possible for Er:Ti:$LiNbO_3$ active devices if the photorefractive damage issue is combated. This is a very important result, in view of the cheap and readily available pump laser diodes at this wavelength. It also opens up many opportunities for advanced active circuits incorporating, for example, on-chip WDM's for independent pump and signal routing[13]. Other possible ways of achieving low-photorefractive damage devices are also being investigated in our laboratories, including waveguides fabricated either by Zn[14] or Ni[15] diffusion. Preliminary results obtained with ZnO:Mg:Er:$LiNbO_3$ by Huang and McCaughan look very promising for 980 nm-pumped devices[16]. We hope to carry out experiments in the near future to determine the efficiencies of the 980 nm and 1480 nm pumping schemes. Also, we aim to carry out stability analysis of the z-propagating waveguide devices, to evaluate the effects of residual photorefractive damage over an extended time period. Experiments are also in progress with other rare-earth ions using the z-propagating scheme, including Er/Yb codoping.

ACKNOWLEDGEMENTS

The authors thank D.L.Veasey for useful discussions, and M.J.Buckley for help in the fabrication of the devices.

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