

Z-propagating waveguide lasers in rare-earth-doped Ti:LiNbO₃

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A means of reproducibly fabricating stable cw lasers in rare-earth-doped Ti:LiNbO₃ has been demonstrated through judicious choice of waveguide orientation. Z-propagating waveguides have been fabricated in Nd- and Er-diffused Ti:LiNbO₃ and room-temperature laser operation with greatly reduced photorefractive instability has been obtained. The reduced photorefractive damage susceptibility in this waveguide configuration has led to the realization of a 980 nm pumped laser in Er:Ti:LiNbO₃, with a threshold of 10.5 mW of absorbed pump power and a slope efficiency of 8.5%. © 1996 American Institute of Physics. [S0003-6951(96)03151-8]

The success of fiber amplifiers and lasers has recently stimulated a great deal of interest in rare-earth-doped planar waveguide devices for providing signal-processing functions on a local scale both in optical communications and sensor systems. In particular, rare-earth-doped LiNbO₃ 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, it has intrinsically good material properties, and the gain is 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 LiNbO₃.^{1,2} The most common method of waveguide fabrication in rare-earth-diffused LiNbO₃ is by Ti-indiffusion, as this technique allows for low propagation losses and does not alter the spectral characteristics of the rare-earth ions. However, an inherent problem with Ti:LiNbO₃ 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:LiNbO₃, 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:LiNbO₃ devices have been pumped at 1480 nm. The only report of a 980 nm pumped Er:Ti:LiNbO₃ device thus far, to our knowledge, has been made by Huang and McCaughan.³ 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 Fe²⁺ impurities to the Fe³⁺ state, and the subsequent migra-

tion 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.⁴ In general, waveguides are fabricated in LiNbO₃ 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,⁵ one way of considerably reducing 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.^{6,7} 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 letter, we report our results on z-propagating rare-earth-doped waveguide lasers in LiNbO₃. We demonstrate stable room-temperature operation of a Nd-diffused Ti:LiNbO₃ waveguide laser pumped ~ 800 nm. We also demonstrate a 980 nm pumped Er:Ti:LiNbO₃ waveguide laser using the z-propagating configuration. These results open up numerous possibilities for stable, diode-pumped, laser and amplifier devices in LiNbO₃.

Two pieces of LiNbO₃, 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 Nd³⁺ ions were then driven into sample A by indiffusion at 1100 °C over a period of 240 h, and the Er³⁺ ions into sample B at 1100 °C over 144 h. On sample A, Ti stripes 6 μ m wide and

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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 h period with sample A diffused at 1005 $^{\circ}\text{C}$ and sample B at 1030 $^{\circ}\text{C}$. 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.

A near-field analysis was first performed on the guides on sample A 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 μm in width and 2.8 μm in depth. The waveguide also supported two modes at ~ 800 nm. Cut-back loss measurements were made at 850 nm by end-fire coupling the output of a cw Ti:Al₂O₃ laser into the guides. This wavelength was chosen 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 dB cm^{-1} . The room-temperature behavior of the Nd-doped devices was then characterized by tuning the pump laser to 809 nm. Transmission measurements made at 809 and 850 nm, together with the 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 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) in the waveguide. The acousto-optic (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 the feedback provided by the 14% Fresnel reflectance from the polished endfaces. Both the pump and the laser emission were TE polarized. Figure 1 shows the lasing characteristics of the device, with the inset showing a laser spectrum as obtained using an automatic spectrum analyzer with a 0.2 nm 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.

Near-field analysis was then carried out on the Er:Ti:LiNbO₃ devices using a 1.5 μm light-emitting diode (LED), revealing the 7- μm -wide Er:Ti:LiNbO₃ waveguides to be single-moded at this wavelength, with $1/e$ mode diameters of 7.9 $\mu\text{m} \times 4.6$ μm (width $\times$ depth). The guides supported three modes at 980 nm. Loss measurements were again made using cut-back techniques, with a Ti:Al₂O₃ laser turned to 900 nm to eliminate any effects due to resonant absorption. The loss was in this case ~ 0.55 dB cm^{-1} . No

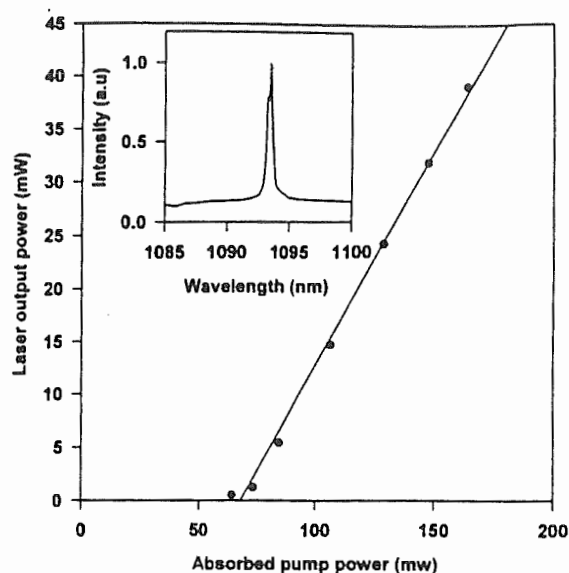


FIG. 1. cw laser characteristics of a z-propagating Nd:Ti:LiNbO₃ device. The output power in this figure is the total power emitted from both ends of the device. The inset shows the laser spectrum.

attempt was made to determine the propagation loss at around 1.5 μm , but given the wavelength separation between the pump and signal we estimate this to be about 0.4 dB cm^{-1} . The Ti:Al₂O₃ laser was then tuned to 980 nm, and, using techniques similar to those described above, the lifetime of the Er⁴I_{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 anti-reflection (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 reabsorption of the signal.⁸ 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 favorably with that measured elsewhere.⁹ Laser characteristics were then measured in this 2.9-cm-long device, with cw pumping from the Ti:Al₂O₃ 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 very stably, 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, non-pumped 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%; 20% of the coupled pump power was absorbed above laser threshold. The lasing threshold was measured to be 10.5 mW of absorbed pump power, and the device exhibited a slope-

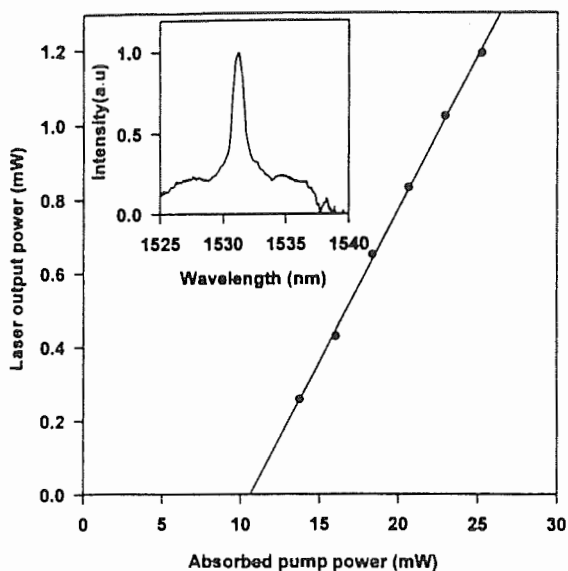


FIG. 2. cw laser characteristics of a 980 nm pumped, z -propagating, Er:Ti:LiNbO₃ device, with the laser spectrum shown in the inset. The output power in this figure is that measured from the nonpumped end of the device.

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 characterize 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 mechanism, was visible in the 980 nm pumped devices.¹⁰ We did not see any lasing in the green though, even when high reflectors at ~ 540 nm were butted to both faces.

Stable, room-temperature operating lasers fabricated by Ti-indiffusion in rare-earth-doped LiNbO₃ have been demonstrated. The z -propagation scheme has been employed here, allowing effective curbing of the optical damage. A

Nd:Ti:LiNbO₃ 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:LiNbO₃ 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. This demonstration of an Er:LiNbO₃ waveguide laser pumped at 980 nm 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 wavelength diversion multiplexers for independent pump and signal routing. 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. In the case of the Er device, we hope to carry out experiments in the near future to determine the efficiencies of the 980 and 1480 nm pumping schemes. Experiments are also in progress with other rare-earth ions using the z -propagating scheme.

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