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Continuous wave waveguide laser at room temperature in Nd^{3+}-doped Zn:$LiNbO_3$

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This work reports continuous laser action at room temperature in $LiNbO_3$:Nd^{3+} channel waveguides, fabricated by Zn diffusion. The absorbed pump power at the threshold was 1.25 mW and a slope efficiency of 20% was obtained. With our available pump power the laser could emit up to 0.14 mW without exhibiting any photorefractive damage. [DOI: 10.1063/1.1427426]

Lithium niobate is an attractive and widely used active integrated-optical medium due to its excellent electro–optic, acousto–optic, and nonlinear properties. Rare-earth doped $LiNbO_3$ allows the fabrication of efficient waveguide lasers and amplifiers.[1] The integration of phase or amplitude modulators allows the construction in this material of many interesting systems, including mode-locked or *Q*-switched laser devices.[2] Neodymium doped $LiNbO_3$ can be operated in a four level scheme and it was the first rare-earth ion to lead to laser action in this host.[3,4] However, pump induced photorefractive damage limited the laser oscillation to pulsed operation with low efficiencies. A few years later, it was discovered that MgO codoping reduced the photorefractive damage,[5] and more efficient laser oscillation was reported in Nd:MgO:$LiNbO_3$.[6,7] The following step in the use of this material has been the generation of devices in waveguide configuration. Several techniques have been used to produce low loss waveguides in $LiNbO_3$ such as proton exchange, titanium indiffusion or ion implantation, which have provided methods to produce efficient laser operation in Nd-doped $LiNbO_3$ waveguides. The first waveguide laser was demonstrated by using proton exchange in a Nd:MgO:$LiNbO_3$ substrate,[8] which was followed by ion implanted and titanium in-diffused efficient channel waveguide laser.[9,10] Nevertheless due to the high density of photons in the waveguide all these devices suffered from photorefractive damage, limiting the performance to pulsed operation or requiring the continuous annealing at high temperature.[11,12] It should be also mentioned that MgO codoping reduces the solubility of Nd ions in $LiNbO_3$, then limiting the number of active ions in the host, and it also reduces the optical quality of the crystals. To date cw lasing operation at room temperature was only reported by Amin *et al.*[13,14] in the Nd-diffused Ti:$LiNbO_3$ waveguide, using *Z*-propagating waveguides and a σ-polarized pump beam in order to minimize the photorefractive damage. Unfortunately with this configuration not only is the pump efficiency reduced (the optimum pump in these materials is π polarized) but also it is not possible to use the highest electro–optic $LiNbO_3$ coefficient r_{33} to integrate active functions within the same optical chip.

An alternative possibility in order to use transverse propagation (to the z axis) keeping a low photorefractive damage could be based in the fabrication of channel waveguides by Zn diffusion. This fabrication technique[15,16] produces waveguides that support both TE and TM modes, regardless of the crystal cut. Also, it has been reported that Zn codoping reduces the photorefractive damage even more efficiently than MgO.[17,18] Recently, a two-step diffusion procedure, which involved a first step of ion exchange in Zn vapor atmosphere followed by a second step of diffusion by annealing the sample in open air at higher temperature, has been reported to produce low-loss optical waveguide in $LiNbO_3$, with high photorefractive damage resistance,[19] and which preserves the ferroelectric domain structure of the substrate.[20]

This work reports the fabrication of channel waveguides by Zn diffusion in $LiNbO_3$:Nd^{3+}-doped crystals. The waveguides were pumped by π-polarized propagation of 816 nm, which excites the Nd^{3+} ions. Stable laser operation is observed at room temperature, with absorbed pump power at a threshold of 1.25 mW and slope efficiency of 20%.

The Nd^{3+}-doped $LiNbO_3$ crystal used in this work was grown by the Czochralski method with automatic diameter control by crucible weighting system. The starting material was congruent $LiNbO_3$ ($[Li]/[Nb]=0.945$) and the Nd concentration in melt was 1 mol %. From the crystal boule, previously x-ray oriented to assure substrate orientation, *Z*-cut samples of $10\times10\times2$ mm^3 size were obtained and then polished up to optical quality in both faces. The initial stage in the channel waveguide fabrication is the definition of the mask which stops the Zn diffusion. In order to achieve this, a 400 nm amorphous SiO_2 layer was deposited in the $LiNbO_3$ substrates by electron cylotron resonance and chemical vapor deposition techniques. Using standard ultraviolet (UV)-photolithographic techniques, the pattern of a Cr_2O_3 com-

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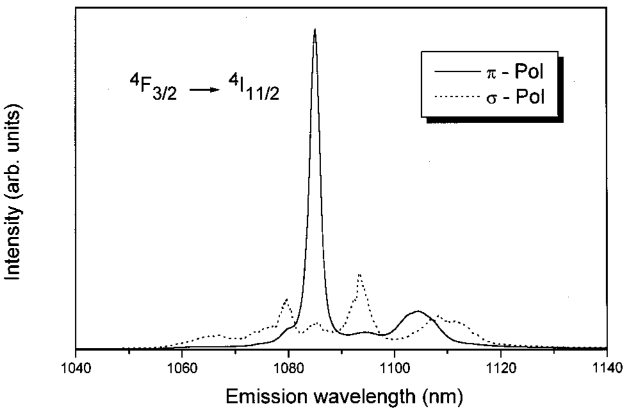

FIG. 1. σ- and π-polarized infrared emission spectra at room temperature of the neodymium ions in Zn-diffused $LiNbO_3$ channel waveguides, under σ-polarized excitation with $\lambda_{exc} = 816$ nm.

mercial mask on quartz substrate, consisting of a series of straight lines, is transferred to a photoresist film covering the SiO_2 layer. After developing the activated photoresist by an UV mercury lamp, the SiO_2 is etched by reactive ion etching, using CHF_3 and SF_6 gases.[16] Once the channels are opened in the SiO_2 mask, the waveguides are obtained by Zn diffusion following a two step process.[19] The *Z*-cut substrates were placed in a Zn vapor atmosphere, with pressure controlled by an Ar buffer, and heated for $\frac{1}{2}$ h at 550 °C. After this step, the substrates were annealed in open atmosphere at 900 °C for 2 h. As the substrate is surrounded by the Zn vapor, besides the channel waveguides formed in the photolithographically patterned SiO_2 face, in the rear face of the substrate a planar waveguide is also created. This surface allows us to characterize the waveguide by the *m* lines method, giving the ordinary and extraordinary index profiles of the planar waveguide. The measurements indicate that the waveguides are monomode at 0.81 and 1.08 μm for transverse electric (TE) propagation, being slightly bimodal at 0.81 μm and monomodal at 1.08 μm for transverse magnetic (TM) propagation. Using the refractive index profiles an effective area of the fundamental mode at $\lambda = 0.81\,\mu$m, for a 10 μm channel waveguide, $A_{eff} = 30\,\mu m^2$ is obtained. Propagation losses in Zn-diffused channel waveguides were measured at 0.63 μm and at 1.5 μm by monitoring the scattered light along the channels and by the Fabry–Pérot method, respectively, giving a value of 0.5 and 0.3 dB/cm, respectively. Therefore the losses at the signal wavelength $\lambda_s = 1.085\,\mu$m can be estimated as 0.4 dB/cm.

The polarized fluorescence spectra of the Nd ions in the waveguide, corresponding to the $^4F_{3/2} \rightarrow {}^4I_{11/2}$ transition, are shown in Fig. 1. The pump beam (argon pumped Ti:sapphire laser) was coupled into the waveguide with a × 10 microscope objective, and the luminescence collected at the output of the waveguide with another × 10 microscope objective was imaged on the detection system. The signal was directed onto the entrance slit of a monochromator (ARC SpectraPro 500-I) and detected with a photodiode (InGaAs). The luminescence from the waveguide shown in Fig. 1 is coincident with the luminescence of bulk-doped $LiNbO_3:Nd^{3+}$,[21] having the same polarization and structure. The fluorescence lifetime was measured under pulsed excitation using a MOPO ($\lambda_{exc.} = 816$ nm, laser pulse≅10 ns). The fluorescence was now detected synchronously and recorded by a digital oscilloscope. A single-exponential fluorescence decay was observed, with a lifetime of 114 μs, close to that reported for bulk luminescence,[21] indicating that Zn diffusion does not affect the optical properties of the Nd ions.

Laser characteristics in the $LiNbO_3$:Nd:Zn waveguides were measured in a 10 μm wide channel guide, having a device 0.9 cm long. The laser cavity was made by butting flat mirrors to the polished crystal faces. A mirror of reflectivity >99.9% at 1085 nm and 98% transmitting at 816 nm, was attached to the front face. At the other end, a 97% at 1085 nm and >99.8% at 816 nm reflecting mirror was used as an output coupler. The device was pumped using a Ti:sapphire laser tuned at 816 nm, and polarized with the electric field perpendicular to the *z* axis (TE, σ polarization). The active waveguide operating in free running mode lased in a cw manner at 1084.6 nm. The laser characteristics are given in Fig. 2, where the laser output power versus the absorbed pump power is presented. The absorbed pump power needed to reach the laser threshold was $P_{th} = 1.25$ mW and the ratio of output power to absorbed pump power above threshold

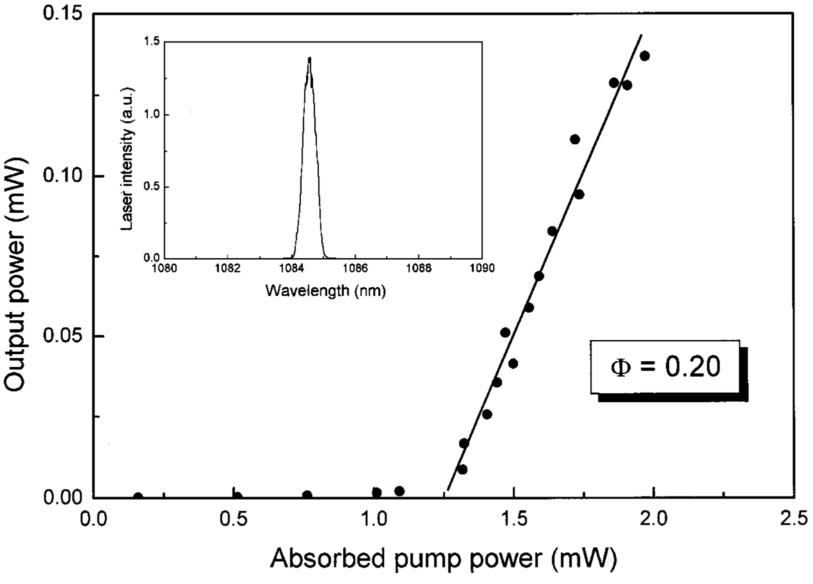

FIG. 2. cw laser output power as a function of absorbed pump power at 816 nm. A slope efficiency of $\Phi = 20\%$ and a threshold of 1.25 mW were obtained. The inset shows the laser spectrum.

was $\Phi = 20\%$. In this measurement a filter was used to block the residual pump beam. The inset in Fig. 2 shows the laser spectrum as obtained by using a 0.4 nm resolution monochromator. The laser emission was π polarization. These values can be compared with theoretical estimations using the expression of the threshold of absorbed pump power to reach oscillation and the slope efficiency[21]

$$P_{\mathrm{th}} = \frac{1}{2} \cdot \frac{h\nu_P}{\eta\sigma_e\tau_f} \cdot \delta A_{\mathrm{eff}}, \tag{1}$$

$$\Phi = \eta \cdot \frac{(1-R_2)}{\delta} \cdot \frac{\nu_s}{\nu_p}, \tag{2}$$

where ν_s and ν_p are the signal and pump frequencies, σ_e is the effective stimulated emission cross section, τ_f is the fluorescence lifetime, η is the fraction of absorbed photons that contribute to the population of the $^4F_{3/2}$ metastable state, A_{eff} is the effective pump area, R_2 is the output mirror reflectivity at the signal wavelength, and δ is the round-trip cavity loss exponential factor. Using the spectroscopic parameters of Nd in $\mathrm{LiNbO_3}$ ($\sigma_e = 1.7\times 10^{-19}\,\mathrm{cm}^2$,[21] $\lambda_s = 1084.6\,\mathrm{nm}$, $\lambda_p = 816\,\mathrm{nm}$, $\eta = 0.98$,[22] $\tau_f = 114\,\mu\mathrm{s}$) and the experimental threshold (1.25 mW) and slope efficiency (0.20) values, the overall propagation losses can be estimated from Eqs. (1) and (2). We find $\delta = 0.358$, a value higher than that estimated from the waveguide attenuation and the nominal reflectivity values $[\delta = 2\alpha l - \ln(R_1R_2)]$ which leads to a value of $\delta = 0.2$. This discrepancy between experimental and calculated values for the round-trip cavity losses can be attributed to the fact that the mirrors have been butted and therefore an air layer between crystal and mirrors is present, lowering the effective reflectivity and then increasing the effective round-trip losses. With our available pump power the laser could emit up to 0.14 mW in a cw manner in a simple transverse mode. The laser emission was TM polarized at all the power levels. The emission was stable without any instability or reduction in output power (photorefractive damage) after more than 20 min of operation at maximum pump power.

In conclusion, the Zn diffusion is an effective technique for the fabrication of waveguide lasers, avoiding photorefractive damage and allowing the design of active devices in $\mathrm{LiNbO_3}$ substrates. The $\mathrm{LiNbO_3{:}Nd^{3+}}$ waveguide laser was successfully demonstrated, showing a threshold of 1.25 mW absorbed pump source at 816 nm, and a slope efficiency of 20%. The device operated at cw at room temperature, in a single mode in a stable way, at the maximum output power of 0.14 mW.

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