Ridge waveguide laser in Nd:LiNbO₃ by Zn-diffusion and femtosecond-laser structuring

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Abstract.- Ridge waveguide lasers have been fabricated on Nd³⁺ doped LiNbO₃ crystals. The fs-laser writing technique was used to define ridge structures on a gradient-index planar waveguide fabricated by Zn-diffusion. This planar waveguide was formed in a z-cut LiNbO₃ substrate homogeneously doped with a 0.23% of Nd³⁺ ions. To obtain lateral light confinement, the surface was then micromachined using a multiplexed femtosecond laser writing beam, forming the ridge structures. By butting two mirrors at the channel waveguide end-facets, forming a waveguide laser cavity, TM-polarized laser action at 1085 nm was achieved by end-fire TM-pumping at 815 nm. The waveguide laser shows a threshold of 31 mW, with a 7% of slope efficiency.

Keywords.- Optical waveguide, integrated laser, rare earth, fs-laser writing, spectroscopy, modal characterization

1.- Introduction

Lithium niobate is an important material for the development of integrated photonic devices. Usually they are based on diffused channel waveguides fabricated by ion diffusion in connection with photolithographic techniques to define the optical circuits, which present low index contrast. Nevertheless, ridge guides are highly desirable, as they can reduce bending losses for small curvature radii, improving thus the level of integration. In addition, ridge structures reduce the modal sizes, enhancing the

efficiency of non-linear devices, or lowering the threshold in integrated lasers. Several etching techniques have been demonstrated so far for the fabrication of ridges waveguides in LiNbO_3 , such as plasma dry etching [1] or wet etching [2]. In particular, ion-beam enhanced etching has demonstrated to be an excellent choice to fabricate structures with high aspect ratios in lithium niobate [3]. Also, precision diamond saw cutting has proved to be an alternative route for ridge structuring [4]. Usually, these technologies start from a previously fabricated planar waveguide by conventional diffusion processes.

The fs-laser writing technique is an alternative approach to fabricate ridge optical structures in dielectrics, defining the so-called type-IV direct written waveguides [5]. The fs-laser ablation is used to remove the selected parts of the planar waveguide surface, constructing thus the ridges. In crystals, type-IV ridge waveguides have been demonstrated in several systems, such as $\beta\text{-BaB}_2\text{O}_4$ [6], Nd:YAG [7], Nd:GGG [8], Nd:GdCOB [9], TiO_2 [10], or (Yb,Nb):RTP/RTP [11], achieving applications as waveguide lasers or frequency converters. This technology does not require the use of clean room facilities, and allows rapid prototyping because it is a mask-less technology. Although the use of fs-laser technique for waveguide fabrication in LiNbO_3 has been successfully proven [12, 13], these works rely on the use of type I and II waveguides. Ridge structuring using fs-laser processing on LiNbO_3 and LiTaO_3 crystals has been also published [5, 14], but no optical characterization was given, and still the usefulness of the fs-laser ablation technique on LiNbO_3 waveguide devices remains to be assessed. Nevertheless, it is worth to mention that this technique has been successfully used to create micro-fluidic circuits engraved in LiNbO_3 substrates [15].

Here, fs-laser writing technique is used to define ridge structures in LiNbO_3 planar waveguides. We demonstrate the feasibility of the method by fabricating ridge waveguide lasers in z -cut Nd-doped LiNbO_3 substrates. Details of the ridge geometry, wall roughness and modal properties of the waveguides are given. Also, the laser characteristics are presented, and the results are discussed in terms of the spectroscopy of the Nd-ions, modal sizes and waveguide losses.

2.- Material and methods: Waveguide fabrication

The Nd^{3+} doped LiNbO_3 crystal was grown by the Czochralski method from the melt of congruent LiNbO_3 and Nd_2O_5 . The initial melt was doped with 1% mol of Nd^{3+} ions related to Nd^{5+} ions. The crystal was oriented by X-ray diffraction, and its polarized

absorption was recorded in an x -cut sample (Fig. 1).

Using the reported σ - and π -polarized absorption cross sections (σ_{σ} (810 nm) = $2.3 \times 10^{-20} \text{ cm}^2$, σ_{π} (815 nm) = $2.7 \times 10^{-20} \text{ cm}^2$ [16]), a Nd^{3+} concentration of $4.4 \times 10^{19} \text{ cm}^{-3}$ is obtained (0.23%). From the oriented crystal boule, z -cut substrates of 10 mm $\times$ 10 mm $\times$ 1.5 mm in size were obtained, which were subsequently polished up to optical grade. Ridge waveguide structures were fabricated in two steps: first, a graded-index planar waveguide is fabricated in a z -cut $\text{Nd}^{3+}:\text{LiNbO}_3$ substrate, and then the surface was structured by fs-laser writing.

2.1.- Planar waveguides

The planar waveguides were fabricated by Zn-diffusion, following a two-step procedure [17]. In the first step, the sample is placed in a Zn vapor atmosphere, with pressure controlled by an Ar buffer at 55 mbar, and heated for 2 h at 550 °C. After this step, the substrates were annealed in open atmosphere at 850 °C during 4 hours. This procedure gives rise to the formation of graded-index planar waveguides at both sides of the substrate, which can support both TE and TM propagation modes. The choice of Zn instead of Ti diffusion come from the fact that the use of Zn ions in LiNbO_3 crystals reduces significantly the photorefractive damage [18], which is an important issue when dealing with high optical intensities (f.i., waveguide laser devices). Also, it has been reported that the diffusion of Zn in doped $\text{Nd}^{3+}:\text{LiNbO}_3$ crystals do not affect the spectroscopic properties of the rare ions in the matrix [19].

2.2.- Ridge structuring

The ridge structures for light confinement in the lateral direction were fabricated by fs-laser structuring [11] with a multiplexed writing laser beam. To obtain the rib structures, two parallel channels were micromachined by fs-laser ablation on the surface of the planar waveguides. The channels were fabricated using a Tsunami titanium sapphire (Ti:Za) laser working at 800 nm wavelength together with an Spitfire amplification system. The Ti:Za laser was pulsed at 1 kHz repetition rate with a pulse duration of 100 fs. The laser wave-front was modulated using a spatial light modulator (SLM, Hamamatsu X8267) in order to generate a multiplexed focused beam at the sample to perform the so-called *approximation scanning* technique [20]. This approach is implemented to minimize the roughness in the walls of the channels and thus obtain low losses waveguides. With this purpose, several parallel scans, partially overlapped, each one slightly closer to the ridge are used. In the present work, a configuration with seven spots diagonally displaced was performed [11, 21]. The phase mask imprinted in

the SLM to generate the multiplexed beam array was obtained using a weighted Gerchberg-Saxton algorithm [22]. Two subsequent scans were performed with pulse energies between 2.3 and 3.5 μJ at a scanning speed of 100 $\mu\text{m/s}$, with a total processing time lower than 3 minutes.

3.- Results and discussion

3.1.- Ridge waveguide characterization

The dark mode measurements of the graded-index planar waveguide after the two-steps Zn-diffusion were carried out by means of a high-index rutile prism. Using polarized light from a He-Ne laser operating at 633 nm, two TM-guided modes were observed. The angular position of the modes, besides the whole reflectivity spectra, allows obtaining the refractive index profile of the waveguide. The data are well fitted with a semi-Gaussian index profile of maximum index increase of $\Delta n = 3.0 \times 10^{-3}$, substrate index of $n_s = 2.2038$ and a depth of 5.5 μm . The cover region is assumed to be air, with $n_c = 1$. These values are typical of Zn-diffused waveguides in LiNbO_3 crystals [18].

In order to verify the confidence of these parameters, near-field images of the waveguide modes were recorded at different wavelengths. In particular, near field intensity profiles of the fundamental TM-modes at 700 nm and at 980 nm were taken by imaging the waveguide-end using a $\times 40$ microscope objective and collecting the output light by a CCD camera. Besides the experimental profiles, the intensity profiles obtained by a multilayer approach [23] were simulated using the above mentioned set of waveguide parameters, showing a good accordance between the numerically calculated profiles and the measured intensity profiles.

After the fs-laser micromachining of the planar waveguide, the morphology of the ridge structures was characterized by conventional microscopy. The two parallel fs-laser scans along the sample surface give rise to ridge structures with trapezoidal profiles. Fig. 2 presents a picture of the transversal cross section of a typical channel waveguide (left), where the sketch of the ridge and its relevant parameters are indicated for further numerical modeling (right). There, W denotes the top-width of the ridge, θ the inclination of the lateral wall, and H is the micromachined depth.

Several waveguides were fabricated with variable widths (from 4 to 30 μm), showing similar values of wall inclination. Also, the parameters used in the fs-writing process

produced ridges with heights greater than the penetration depth of the diffused waveguide, and therefore the waveguide modes are well confined in the ridge. The roughness of the lateral walls was measured by AFM (see Figure 3), where statistical analysis gives a mean roughness of $\sigma = 0.5 \mu\text{m}$ and a correlation length of $L_c = 0.9 \mu\text{m}$. This roughness is similar to that reported in micro-fluidic channels fabrication by fs-laser ablation ($\sigma = 0.3 \mu\text{m}$) [15], but rather high when compared with other more standard methods (f.i. a mean roughness of 4.5 nm has been reported for ridges waveguides fabricated by ultra-precision cutting method [4]). Also, it is worth to mention that some chirping was observed at the edges of the ridge waveguides, likely due to a non-optimized polishing stage.

Losses in the channel waveguides were measured at 860 nm (beyond the absorption of the Nd^{3+} ions). The loss value decreases as the ridge width increases, giving a value of 4 dB/cm for a 27 μm width waveguide. The main origin of the propagation losses is likely to be the lateral roughness of the ridges, and thus for narrower waveguides the rough sidewalls affect the light propagation more strongly. That value, although higher than those reported in channel waveguides fabricated with other techniques (0.3 dB/cm using wet etching methods [2], 0.6 dB/cm using ultra-precision cutting method [4]), has allowed laser emission in waveguide configuration, as we show in the next section.

3.2.- Laser experiments

To obtain feedback for laser action, two flat multilayer dielectric mirrors were butted at the two end-faces of the channel waveguides, which were previously polished at right angle to obtain flat facets. A mirror of reflectivity >99% at 1085 nm and 99% transmitting at 815 nm was attached to the front waveguide facet. At the other end, a 95% at 1085 nm and >99% at 815 nm reflecting mirror was used as the output coupler of the laser cavity. This configuration allows end-fire pumping using a long-focal length microscope objective.

Laser experiments were carried out by using a continuous-wave Ti-Za laser as pump source. The Ti-Za laser was TM-polarized and tuned at 815 nm, which corresponds to the wavelength for the higher absorption of the Nd^{3+} ions (π -polarized light, see Fig. 1). Laser emission from the channel waveguides was observed to occur at 1085 nm, and presented TM-polarization. Both wavelength and polarization correspond to the reported higher emission cross section of the Nd^{3+} ions in LiNbO_3 crystals [16].

Near field profile of the laser emission from the ridge waveguide was recorded by a

CCD camera (Fig. 4a). This profile has been compared with the intensity map of the simulated quasi-TM fundamental mode of the channel waveguide at 1085 nm (Fig. 4b) by means of 3D-BPM numerical techniques [24], and using the data from the planar waveguide and the transversal dimensions of the ridge ($W = 27 \mu\text{m}$, $H = 8 \mu\text{m}$, $\theta = 15^\circ$). The numerically calculated intensity profile shows a good accordance with the experimental profile. The overlap between the intensities of the fundamental modes at the pump wavelength (815 nm) and at the laser operation (1085 nm) has been numerically computed, giving a value of $\Gamma = 0.95$.

The pump power from the Ti-Za was selected by using a set of neutral filters. The output power from the ridge waveguide laser was monitored by a power-meter, after blocking the residual pump by a dichroic filter. Fig. 5 represents the laser output as function of the absorbed pump power for a waveguide length of 8.2 mm. The graph shows that the threshold pump power for laser oscillation is around 31 mW, while a slope efficiency of 7% is obtained. No sign of photorefractive damage was observed, even using intensities as high as 100 kW/cm^2 for pump.

Using the reported π -polarized emission cross section of the $^4F_{3/2}$ multiplet at 1085 nm ($\sigma_{\text{emi}} = 2.7 \times 10^{-19} \text{ cm}^2$), its radiative lifetime ($\tau = 90 \mu\text{s}$) [16], and the effective pump area ($A_{\text{eff}} = 86 \mu\text{m}^2$), the slope efficiency and the threshold can be theoretically estimated [25]. We have found discrepancy between the theoretical and the experimental results, which can be due to scattering from non-perfect end-facets, lowering the effective reflectivity of the feedback mirrors. It is worth to mention that the laser threshold here reported is less than half of the one found in ridge waveguide lasers in Nd:YAG processed by fs-laser writing [26]. Recently, Tan et al. have reported laser operation in femtosecond written lithium niobate waveguides [27], showing a slope efficiency of 27% and a laser threshold of 71 mW, although the reported laser waveguides were laser-written type II waveguides, which in general show lower propagation losses, at expenses of a lower lateral confinement.

4.- Conclusions

Active devices in LiNbO_3 crystals in ridge waveguide configuration have been fabricated by fs-laser ablation technique in combination with metal diffusion technology. Despite the relatively high propagation losses here reported, π -polarized laser action was achieved at $1.085 \mu\text{m}$, showing a slope efficiency of 7% and a

threshold of 31 mW. Thus, this fabrication technology appears to be a promising approach for the fabrication of integrated lasers or amplifiers in LiNbO₃ crystals in waveguide geometries. In this respect it is worth noting that the processing time for laser writing the ridge structure was just lower than 3 minutes. Further experiments are in progress to improve the lateral wall roughness, which will allow a decrease of the pump threshold and an increase of the laser efficiency.

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Figure captions

Figure 1.- Polarized absorption spectra of the Nd^{3+} doped LiNbO_3 crystal in the pump region, taken at room temperature.

Figure 2.- Left: picture of the transversal cross section of a ridge channel waveguide fabricated by fs-laser writing on diffused planar waveguides. Right: sketch of the ridge and its relevant parameters used for numerical modelling.

Figure 3.- AFM picture of the lateral wall edge of the ridge processed by fs-laser writing.

Figure 4.- Measured (a) and simulated (b) intensity distributions of the fundamental TM mode at 1085 nm, corresponding to a 27 μm wide ridge waveguide on the 5.5 μm depth diffused planar waveguide.

Figure 5.- Laser performance of the Nd^{3+} -doped LiNbO_3 ridge waveguide.

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5