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Ridge waveguide laser in Nd:$LiNbO_3$ by Zn-diffusion and femtosecond-laser structuring

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ABSTRACT

Ridge waveguide lasers have been fabricated on Nd^{3+} doped $LiNbO_3$ 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 $LiNbO_3$ substrate homogeneously doped with a 0.23% of Nd^{3+} 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.

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-liner 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 β-BaB_2O_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

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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 × 10^{-20} cm^2, σ_π (815 nm) = 2.7 × 10^{-20} cm^2 [16]), a Nd^{3+} concentration of 4.4 × 10^{19} cm^{-3} is obtained (0.23%). From the oriented crystal boule, *z*-cut substrates of 10 mm × 10 mm × 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 Nd^{3+}:$LiNbO_3$ 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 h. 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 Nd^{3+}:$LiNbO_3$ 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 μm/s, with a total processing time lower than 3 min.

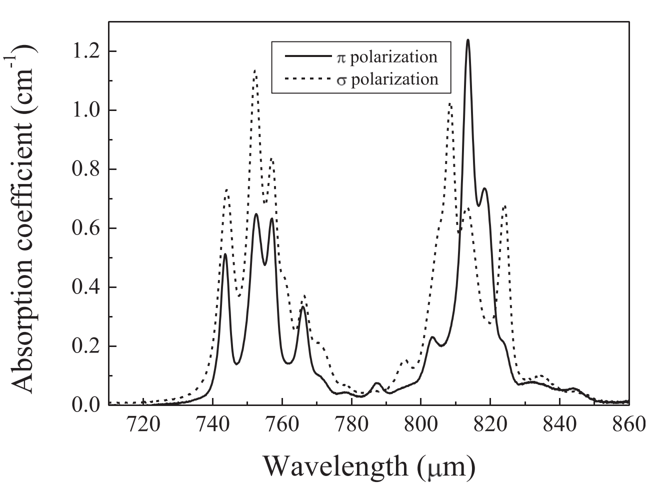

Fig. 1. Polarized absorption spectra of the Nd^{3+} doped $LiNbO_3$ crystal in the pump region, taken at room temperature.

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 Δn = 3.0 × 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 ×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 micromaching 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 Fig. 3), where statistical analysis gives a mean roughness of σ = 0.5 μm and a correlation length of L_c = 0.9 μm. This roughness is similar to that reported in micro-fluidic channels fabrication by fs-laser ablation (σ = 0.3 μm) [15], but rather high when compared with other more standard methods (f.i. a mean roughness of 4.5 nm