Direct Inscription of Waveguides in Doped Lithium Niobate Crystal with Femtosecond Laser

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Abstract: Production of waveguides in lithium niobate crystal using a femtosecond laser is described. The direct inscription method relies on the laser light focused into the crystal. Experiments were performed for determining the ideal writing parameters.

OCIS codes: (160.3730) Lithium niobate; (230.7370) Waveguides.

1. Introduction

Lithium niobate crystal is known by its excellent electro-optic characteristics. $LiNbO_3$ is chemically very stable at room temperature and quite insensitive to humidity surroundings. Furthermore, it presents enough hardness to be regularly manipulated [1]. It is a ferroelectric crystal and has unique properties such as high Curie temperature, excellent optical transparency in the visible and infrared, high electro-optic coefficients, nonlinear optical susceptibilities and large piezoelectric and pyroelectric coefficients that make it an ideal material for electronic, photonic, sensor and MEMS applications [2]. Besides, $LiNbO_3$ doping with appropriate materials can enhance interesting properties or provide new ones. Particularly, lithium niobate crystals doped with erbium allowed the development of a whole class of new waveguide devices as efficient waveguide lasers, modulators and wavelength filters and tunable lasers [3]. Additionally, Er^{3+}:$LiNbO_3$ is an excellent laser material for integrated optics, integrated lasers with grating resonators, acoustic-optic tunable Fabry Pérot type lasers and ring laser structures [4]. These devices are particularly interesting for telecommunications as they operate at 1.5 and 1.6 µm [5].

There are some well-established techniques used to produce waveguides in lithium niobate crystals, such as ion exchange or proton exchange [6] and locally changes of the structure by means of focused ultra-short laser pulses [7,8]. Particularly ultrafast laser inscription presents itself as a powerful and flexible technology for real world applications [9]. The use of femtosecond laser pulses to produce waveguides in lithium niobate crystals is already known. With a Ti:Sapphire femtosecond laser system (150 fs, 1 KHz) at 775 nm, focused by a 20× microscope objective lens, parameters for waveguide inscription of average energy of a single-pulse energy of 10 J for the sample moved with a velocity of 50 µm/s were described [10]. In another work, to produce waveguides in lithium niobate with high confinement at 1550 nm, were used speeds of 2, 5, 10 and 20 µm/s with energy of 300 and 400 nJ. The system contained an amplified Ti:Sapphire laser at 800 nm (520 fs, 5 kHz) focused by a 20× microscope objective lens, but the high confinement was lost after 1 month [11]. For an amplified Ti:Sapphire laser system at 800 nm (100 fs, 25 MHz) focused by a 50× microscope objective lens, written waveguides in a lithium niobate sample with parameters of translational scan speed of 200 µm/s and laser power exceed 30 mW were reported [12]. However, waveguide inscription in doped lithium niobate crystals still needs to be investigated. For a better waveguide fabrication, each system configuration presents its own set of writing parameters, such as laser power and speed of displacement of the sample with respect to the laser beam, taking into account the material on which waveguides shall be written. The guiding characteristics depend strictly on the possibility of obtaining the best electromagnetic wave confinement and propagation conditions by controlling the waveguide optical properties and geometrical configuration [6]. In this work, the methodology for determining these parameters for $LiNbO_3$ Er^{3+} codoped with MgO is presented, as well as a preliminary investigation about the guiding properties.

2. Methodology and discussion

Waveguides were produced in $LiNbO_3$ crystal doped Er_2O_3 codoped with MgO. The crystal was cut and polished manually, to eliminate effects of scattering and diffusion on the surface, resulting in a crystal piece (5.3 x 3.9 x 2.9) mm^3. A Ti:Sapphire laser (Coherent, Libra) at 800 nm with pulses of 100 fs at a repetition rate of 1kHz, focused by a 20× microscope (Thorlabs, LMH-20×-1064) objective lens with numerical aperture (NA) of 0.4, was used to produce structural changes in the crystal structure. Movement of the crystal with respect to the laser light was performed with the help a translation stage (Newport, M-UTM50PP.1) controlled by a computer unit (Newport, PM500C), that can be can be configured to provide different speeds. The laser pulse power was controlled by using a linear attenuator disk and a power meter (FieldMaster II). Each waveguide was written by performing a unique translation along the x-axis, as shown in Figure 1 (a). A total of seven inscriptions, 400 µm apart each other, were produced along the y-axis with the laser focused 0.5 mm under the crystal surface. Translational velocities and laser power employed are described in Table 1.

Images obtained with an optical microscope (Olympus BX51M-BX51RF) with a camera (CoolSNAP-Pro CF COLOR) showed waveguides 3.9 mm long with average diameter of 10 µm. Figure 1 (b) shows the set of obtained waveguides.

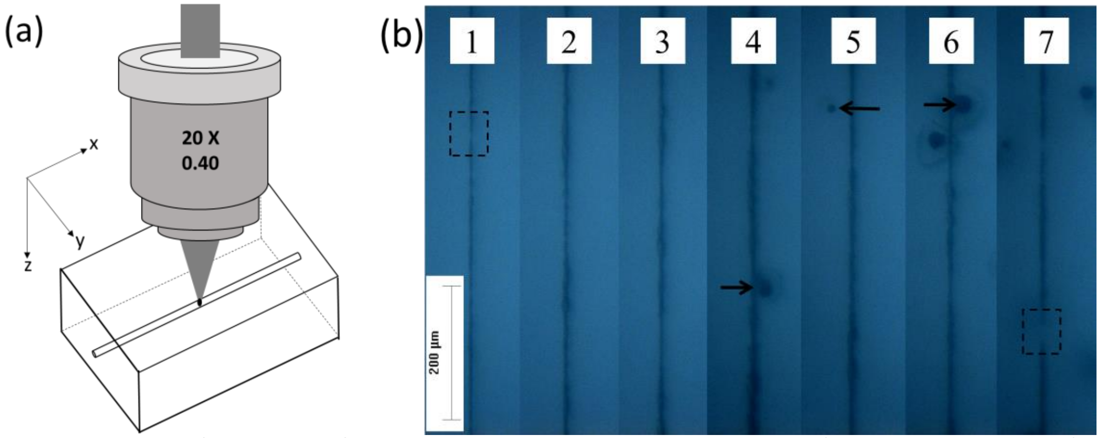

Figure 1: (a) Schematic diagram of the waveguide fabrication experimental setup. (b) Microscopic image of waveguides produced. The failures are indicate with the dashed square and crystals defects with the arrows.

Table 1: Laser power values and translational velocity for each laser inscription of waveguides.

Waveguide	**1**	**2**	**3**	**4**	**5**	**6**	**7**
Power (mW)	255	300	340	380	380	380	380
Velocity (µm/s)	50	50	50	50	20	15	10

It was noticed that the structures 1 and 7 shows failures resulting from the recording process. Therefore, despite the power of 255 mW was enough to change the refractive index of the crystal, for a displacement speed of the sample of 50 µm/s relative to the laser beam, an inhomogeneous structure was observed in waveguide 1, indicated by the dashed square in Figure 1 (b). The homogeneity of the sample also affects the production of structures. Despite the writing parameters of waveguide 7 were enough to produce a continuous structure, this waveguide was written in a crystal region containg defects. The laser light was scattered, inhibiting the process of homogeneous writing in some regions (dashed square in Figure 1 (b))

Guiding capability was assessed by using a coupling system to measure the near field diffraction profile of each waveguide. Results are showed in Figure 2 for waveguides 2 and 3.

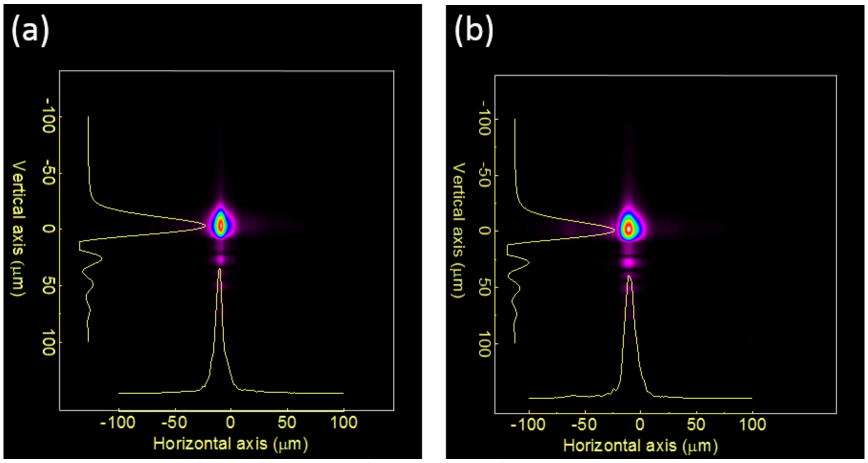

Figure 2: Near field diffraction profiles at 635 nm for waveguides: 2 (a) and 3 (b).

The peak intensity observed in the near field diffraction profiles indicates the light confinement due to guiding capability of these structures produced inside the crystal. The profiles also show an intense region of guidance with close to 20 µm in horizontal axis and 30 µm in vertical axis for waveguides 2 and 3. Color scale depicts the diffraction intensity on the detector, from red (higher intensity) to violet (lower intensity). The two graphs with scales at bottom and right stands for the spatial distribution of this intensity along the guide cross-section. For the waveguide 2 (Fig.2 (a)) the FWHM was 16.4 µm on vertical axis and 9.6 µm on horizontal axis. For the waveguide 3 (Fig. 2 (b)) the FWHM was 16.2 µm on vertical axis and 11.9 µm on horizontal axis. These dimensions correspond to the core of the waveguide, the region with guidance condition which insures wave propagation. Despite the waveguides 4, 5 and 6 present a degree of uniformity along the modified region observed by optical microscopy (Fig.1 (b)), it was not possible to obtain the near field profiles due to the crystals defects in the surroundings of these waveguides, indicated by the arrows in Figure 1 (b). Such defects scatter the laser light during guiding tests. Observations after five months from the recording process showed that the waveguides remained unchanged.

3. Conclusions

The proposed experimental setup proved to be able to produce structures by direct inscription employing a femtosecond laser in $LiNbO_3$ crystal doped with Er_2O_3 and MgO. This preliminary investigation allowed finding the optimized writing parameters to be used with the setup, namely translational velocity of 50 µm and laser power from 300 to 340 mW. However, non-homogeneities in the crystal structure impacted the waveguide inscription process affecting guiding properties. Additional experiments are being carried out to further characterize the method performance. Medium-term time experiments showed a stability of produced structures.

4. Acknowledgements

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4. References

[1] L. Arizmendi, “Photonic applications of lithium niobate crystals,” Phys. status solidi, **201**, no. 2, 253–283 (2004).

[2] P. Rabiei and P. Gunter, “Optical and electro-optical properties of submicrometer lithium niobate slab waveguides prepared by crystal ion slicing and wafer bonding,” Appl. Phys. Lett., **85**, no. 20, 4603-4605 (2004).

[3] I. Baumann, S. Bosso, R. Brinkmann, R. Corsini, M. Dinand, A. Greiner, K. Schäfer, J. Söchtig, W. Sohler, H. Suche, and R. Wessel, “Er-Doped Integrated Optical Devices in LiNbO,” IEEE J. Sel. Top. QUANTUM Electron., **2**, no. 2, 355–366 (1996).

[4] W. Sohler, B. K. Das, D. Dey, S. Reza, and H. Suche, “Erbium-Doped Lithium Niobate Waveguide Lasers,” no. 5, pp. 990–997, 2005.

[5] D. Gill, L. McCaughan, and J. Wright, “Spectroscopic site determinations in erbium-doped lithium niobate.,” Phys. Rev. B. Condens. Matter, **53**, no. 5, 2334–2344 (1996).

[6] M. N. Armenise, “Fabrication techniques of lithium niobate waveguides,” IEE Proc. J Optoelectron., vol. 135, no. 2, p. 85, 1988.

[7] K. M. Davis, K. Miura, N. Sugimoto, and K. Hirao, “Writing waveguides in glass with a femtosecond laser.,” Opt. Lett., **21**, no. 21, 1729–1731 (1996).

[8] K. Miura, J. Qiu, H. Inouye, T. Mitsuyu, and K. Hirao, “Photowritten optical waveguides in various glasses with ultrashort pulse laser,” Appl. Phys. Lett., **71**, no. 23, 3329-3331 (1997).

[9] G. Brown, R. R. Thomson, A. K. Kar, N. D. Psaila, and H. T. Bookey, “Ultrafast laser inscription of Bragg-grating waveguides using the multiscan technique.,” Opt. Lett., **37**, no. 4, 491–493 (2012).

[10] L. Gui, B. Xu, and T. C. Chong, “Microstructure in Lithium Niobate by Use of Focused Femtosecond Laser Pulses,” IEEE Photonics Technol. Lett., **16**, no. 5, 1337–1339 (2004).

[11] R. R. Thomson, S. Campbell, I. J. Blewett, a. K. Kar, and D. T. Reid, “Optical waveguide fabrication in z-cut lithium niobate (LiNbO[sub 3]) using femtosecond pulses in the low repetition rate regime,” Appl. Phys. Lett., **88**, 111109-1 - 111109-3 (2006).

[12] H. Chen, T. Lv, A. Zheng, and Y. Han, “Directly writing embedded waveguides in lithium niobate by a femtosecond laser,” Opt. - Int. J. Light Electron Opt., **124**, no. 3, 195–197 (2013).