Study of Buried Waveguide Written in $LiNbO_3$ Crystal by High Repetition Rate Femtosecond Laser

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Abstract A buried waveguide in $LiNbO_3$ crystal is fabricated, by using the femtosecond laser which repetition rate is 25 MHz. The etching region can be divided into two regions which are inner interaction region and thermally modified region respectively. The coupling experiment shows two single mode buried waveguides are generated in the thermally modified region, and the propagation loss of the two waveguides are below 1.5 dB/cm. At the same time, the inner interaction region leading to a low transmittance. The Raman spectrum of the etching region is measured which shows the light-guide region is densificated by the thermal effect of high repetition, and there is a large-scale defects in the inner interaction region.

Key words laser optics; femtosecond laser; waveguide; Raman scattering; $LiNbO_3$

OCIS codes 140.6810; 230.7380; 140.7090

高重复频率飞秒激光刻写铌酸锂光波导的研究

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摘要 利用重复频率为25 MHz的飞秒激光刻写铌酸锂掩埋式光波导,研究了在激光作用中心及热影响区域的物质结构,采用650 nm的激光进行端面耦合实验,观测刻写区域波导的光传输特性及损耗测量。研究发现,在激光刻写区域的上下两个部位分别形成了传输损耗低于1.5 dB/cm的单模光波导,而刻写区域中心未形成波导结构且光传输性能较弱。拉曼分析显示,刻写区域上下两个部位形成了致密化波导结构,而刻写中心形成了大尺度的缺陷。

关键词 激光光学; 飞秒激光; 光波导; 拉曼; 铌酸锂

中图分类号 TN249; TN25 **文献标识码** A

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1 Introduction

$LiNbO_3$ is one of the most widely used dielectric materials in photonics and optoelectronics due to its excellent nonlinear optical, electro-optical, acosto-optical, piezoelectric and photorefractive properties[1]. In many of these applications, compact active components are required that can form into optical waveguides, integrated optical circuits, and other light control systems. $LiNbO_3$ waveguide fabrication processes must induce positive refractive index changes. Several methods such as metallic elements diffusion, ion implantation and proton exchange have put forward to fabricate low- loss channel waveguides[2-5]. However, these methods still involve complex multi-step procedures that degrade the $LiNbO_3$ properties in some cases[6-7], and all these methods are limited to forming only near- surface waveguide structures. In recent years, direct laser writing has emerged as a unique and flexible method for the fabrication of three dimensional integrated optical devices[8-10]. Buried waveguides are formed by the focused femtosecond laser beam with induce nonlinear absorption in $LiNbO_3$ crystals[10-19].

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Early researches of laser-writing waveguide in $LiNbO_3$ were focused on low-repetition rate (1~5 kHz) femtosecond lasers[10,12-13]. Recently, high-repetition rate femtosecond lasers have been applied over a broader multidimensional parameter space for optimizing optical loss, mode symmetry, and processing speed[11,19]. Although there are many studies on laser-writing waveguide in $LiNbO_3$, there is seldom report about the photo-physical and photochemical mechanisms responsible for the formation of this laser-induced optical waveguide, and the micro-structural lattice modifications underlying the positive refractive index change. A clear association of the $LiNbO_3$ lattice modifications with the waveguide characteristics together with a detailed morphological characterization would provide fundamental understanding of the processes as well as insights into better controlling the waveguide properties, functionality, and stability that are necessary to broaden the range of $LiNbO_3$ photonic applications.

In this paper, the buried waveguide in $LiNbO_3$ crystal by the 25 MHz repetition femtosecond laser is fabricated, and then performed the coupling experiment to study the characteristics of the waveguides, Raman scattering measurements is performed at different regions of the cross section of the etching region to study the mechanism of $LiNbO_3$ waveguide induced by high repetition rate femtosecond laser.

2 Experiment

For the fabrication of the waveguides, an amplified Ti: sapphire laser system with central wavelength of 800 nm is used, 25 MHz repetition rate, average output power was 540 mW, and pulse duration about 100 fs. The sample was mounted upon a computer-controlled three-axis positioning system. The laser pulses were focused into a polished $LiNbO_3$ sample by a 40×microscope objective which numerical aperture (NA) is 0.65. Waveguides was fabricated by using a single translational scan along the x direction at the speed of 10 mm/s . A schematic of the setup is given in Fig.1.

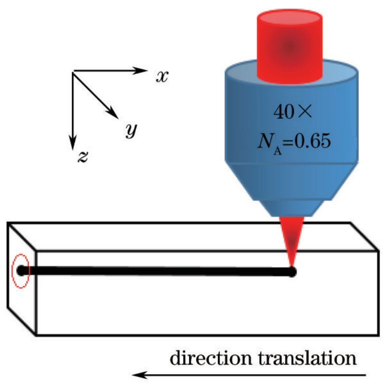

Fig.1 Scheme of the writing process in $LiNbO_3$ crystal using fs laser pulses

Figure 2 shows the microscopic image of the waveguide. The laser modification zone in Fig. 2 (a) extends to 20 μm width, and the bright white color zone extends to 11 μm, greatly exceeding the 2 μm beam diameter

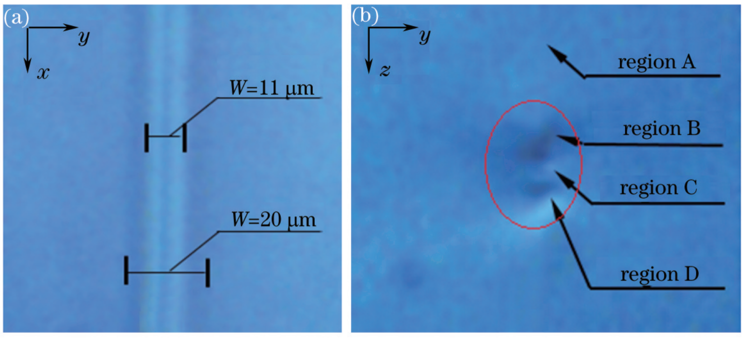

Fig.2 Microscopic image of femtosecond laser induced structure change in $LiNbO_3$.
(a)Top view of the waveguide and (b) cross section of the waveguide

due to the heat accumulation effect[20]. Figure 2 (b) shows the cross section of the waveguide, which including three regions (B, C, D), and the diameter of region B and region D is about 9 μm.

For the coupling experiment, the laser, as light source, which wavelength was 650 nm, the laser beam diagnostics as receptor, and using a nine-dimensional adjustment bracket to adjust the position of the sample, make sure the laser was coupled precision with the waveguide. Measuring the light intensity distribution of the laser that transmitted through waveguide, and the results are shown in follow Figs.3 (a)~(c).

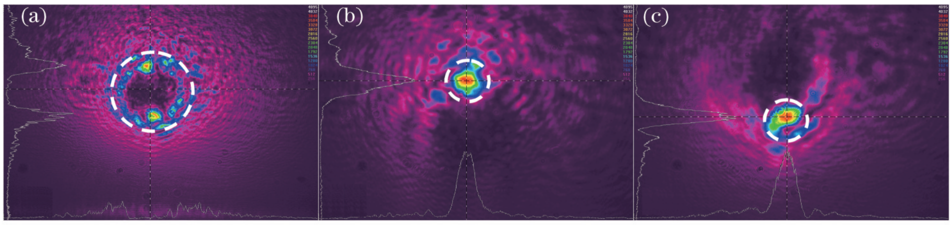

Fig.3 Light intensity distribution, the near-field map of 650 nm light guided within the three different regions of the waveguide. (a) Light intensity distribution of the whole region induced by fs laser, (b) region B and (c) shows the region D

According to Fig.3 (a), the light of region C was weakness, therefore, the transmittance of this region is lower, and region C does not possess the characteristics of optical waveguide, and neither does the annular region outside of region C (except region B and D, with those regions have light transmitted). However, according to Fig.3 (b) and (c), region B and region D have the characteristics of optical waveguide, the light intensity of region B and D are approximately to Gaussian distribution. With the light intensity distribution and the size of region B and D, it is concluded that the regions B, D generated a single mode waveguide[21]. The experiment of propagation loss in two waveguides show that the region B was 1.2 dB/cm at 650 nm, and 0.9 dB/cm in region D.

3 Analysis

For the study of the mechanism of the fabrication of waveguide in $LiNbO_3$ by high repetition rate femtosecond laser, Raman scattering measurements at the different regions of the cross section of the waveguide are performed, and the result is shown in Fig.4.

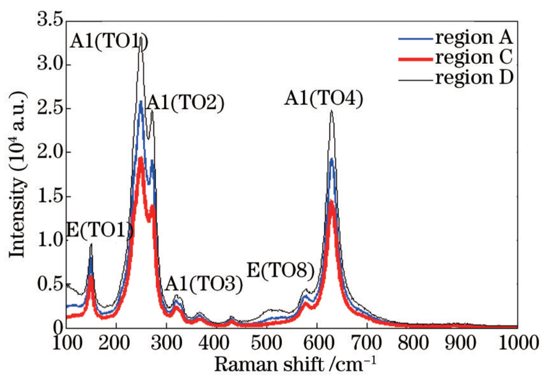

Fig.4 Typical micro-Raman spectra recorded from three regions of the $LiNbO_3$ sample and labeled with the six main phonon modes accessible for Raman configuration

Following the spectral classification of previous studies[22], the main phonon modes accessible with this configuration are identified in the figure and summarized as follows table.1.

Table 1 Summary of the results obtained for the analyzed Raman modes and a short description of the characteristics of each one

Phonon mode	Description
A1(TO1)	Movement of the ions in Nb^{5+} sites along the Z-axis direction and against the oxygen plane.
A1(TO2)	Displacement of ions in Nb^{5+} and Li^{+} sites along the Z-axis, oxygen remains motionless.
A1(TO3)	Deformation of the oxygen octahedron in the XY plane.
A1(TO4)	Deformation of the oxygen octahedron in the XY plane.
E(TO1)	Nb^{5+}/O vibrations in the XY plane.
E(TO8)	Deformation of the oxygen octahedron.

The previous studies indicates that A1 (TO4) mode corresponds to distortions of the oxygen octahedron only, along the x-y plane, and responds with much higher sensitivity to change the volume of the $LiNbO_3$ unit cell than the other phonon modes of $LiNbO_3$[22]. Local densification and existence of compressive stress would cause phonon mode intensity at all Raman modes increase, and stronger for A1 (TO4)[23]. Therefore, this mode is high relevance in assessing the compaction, and hences the refractive index changes, that is laser-induced in the $LiNbO_3$. From Fig.4 the Raman intensity of waveguide region D is more stronger than unmodified region A, and the A1 (TO1) mode increases more. Therefore, region D is mainly caused by densification and existence stress. However, the presence of large-scale defects would cause reduction in the overall Raman intensity[24]. From Fig.4 the Raman intensity of center region C is weaker than unmodified region A, and from Fig.3 the region C has a little bit of transmission light, thus, the center region forms a large-scale defects which induced by femtosecond laser leading to low transmittance.

From the above analysis it is suggested that: the center of etching region (region C) is ablated by the high temperature due to the thermal effect of 25 MHz femtosecond laser interaction with $LiNbO_3$, and caused a large-scale defect for the performance of light transmittance reduced significantly in this region. However, regions B and D far from center region with densified structure induced by the force of heat flux, and formed waveguide in those regions.

4 Conclusion

In conclusion, by using tightly focused 25 MHz femtosecond laser to etch $LiNbO_3$ crystal, at the scanning speed of 10 mm/s, two buried single waveguides are generated in the top and below of the etching region, and which separated about 10 μm, the propagation loss of the two waveguides are below 1.5 dB/cm at 650 nm , however, waveguide could not be generated in the etching center, and the light transmission of this region significantly reduced. In general, low propagation waveguide can be fabricated in $LiNbO_3$ by high repetition femtosecond laser and lower plus energy or faster scanning speed may optimize its properties.

References

1 Wong K K. Properties of Lithium Niobate[M]. London: IET Press, 2002.

2 Cantelar E, García J A S, Lifante G, *et al.*. Single polarized Tm^{3+} laser in Zn diffused $LiNbO_3$ channel waveguides[J]. Appl Phys Lett, 2005, 86(16): 161119.

3 Horn W, Kroesen S, Herrmann J, *et al.*. Electro-optical tunable waveguide Bragg gratings in lithium niobate induced by femtosecond laser writing[J]. Optics Express, 2012, 20(24): 26922-26928.

4 Wang L, Wang K M, Chen F, *et al.*. Optical waveguide in stoichiometric lithium niobate formed by 500 keV proton implantation[J]. Opt Express, 2007, 15(25): 16880-1685.

5 Young W M, Feigelson R S, Fejer M M, *et al.*. Photorefractive damage resistant Zn-diffused waveguides in MgO∶$LiNbO_3$ [J]. Opt Lett, 1991, 16(13): 995-997.

6 Paipulas D, Kudriašov V, Malinauskas M, *et al.*. Diffraction grating fabrication in lithium niobate and KDP crystals with femtosecond laser pulses[J]. Applied Physics A, 2011, 104(3): 769-773.

7 Chen F, Wang X L, Wang K M. Developments of ion implanted optical waveguides in optical materials: A review[J]. Optc

Mater, 2007, 29(11): 1523-1542.
8 Ferreira P H D, Stefanutti R, Pavinatto F J, *et al*.. Femtosecond laser fabrication of waveguides in DR13-doped PMMA[J]. Optics Communications, 2014, 318: 53-56.
9 Dong M M, Wang C W, Wu Z X, *et al*.. Waveguides fabricated by femtosecond laser exploiting both depressed cladding and stress-induced guiding core[J]. Optics Express, 2013, 21(13): 15522-15529.
10 Nejadmalayeri A H, Herman P R. Ultrafast laser waveguide writing: Lithium niobate and the role of circular polarization and picosecond pulse width[J]. Opt Lett, 2006, 31(20): 2987-2989.
11 Nejadmalayeri A H, Herman P R. Rapid thermal annealing in high repetition rate ultrafast laser waveguide writing in lithium niobate[J]. Opt Express, 2007, 15(17): 10842-10854.
12 Dong M M, Lin G, Zhao Q Z. Progress on femtosecond laser- fabricated waveguide deveces in transparent dielectrics[J]. Laser & Optoelectronics Progress, 2013, 50(1): 010002.
13 Burghoff J, Grebing C, Nolte S , *et al*.. Efficient frequency doubling in femtosecond laser written waveguides in lithium niobate[J]. Appl Phys Lett, 2006, 89(8): 081108.
14 Zhou G, Gu M. Direct optical fabrication of three-dimensional photonic crystals in a high refractive index $LiNbO_3$ crystal [J]. Opt Lett, 2006, 31(18): 2783-27850.
15 Thomson R R, Campbell S, Blewett I J, *et al*.. Optical waveguide fabrication in *z*- cut lithium niobate ($LiNbO_3$) using femtosecond pulses in the low repetition rate regime[J]. Appl Phys Lett, 2006, 88(11): 109-111.
16 Burghoff J, Nolte S, Tünnermann A. Origins of waveguiding in femtosecond laser-structured $LiNbO_3$[J]. Appl Phys A, 2007, 89(1): 127-132.
17 Burghoff J, Hartung H, Nolte S, *et al*.. Structural properties of femtosecond laser-induced modifications in $LiNbO_3$[J]. Appl Phys A, 2007, 86(2): 165-170.
18 Bookey H T, Thomson P R, Psaila N D, *et al*.. Femtosecond laser inscription of low propagation loss waveguides in *Z*-cut lithium niobate[J]. IEEE Photon Technol Lett, 2007, 19(12): 892-894.
19 Long X W, Bai J, Liu X, *et al*.. Buried waveguide in neodymium-doped phosphate glass obtained by femtosecond laser writing using a double line approach[J]. Chin Opt Lett, 2013, 11(10): 102301.
20 Eaton S, Zhang H, Herman P, *et al*.. Heat accumulation effects in femtosecond laser- written waveguides with variable repetition rate[J]. Opt Express, 2005, 13(12): 4708-4716.
21 Yurii A V, Sharee J. Losses in single-mode silicon-on-insulator strip waveguides and bends[J]. Opt Express, 2004, 12(8): 1622-1631.
22 Caciuc V, Postnikov V, Borstel G. Ab initio structure and zone-center phonons in $LiNbO_3$[J]. Phys Rev B, 2000, 61(13): 8806-8813.
23 Jayaraman A, Ballman A A. Effect of pressure on the Raman modes in $LiNbO_3$ and $LiTaO_3$[J]. Appl Phys, 1986, 60(13): 1208-1212.
24 Kostritskii S M, Moretti P. Micro-Raman study of defect structure and phonon spectrum of Heimplanted $LiNbO_3$ waveguides [J]. Phys Stat Sol (c), 2004, 1(11): 3126-3129.

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