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# Optical waveguides in $LiTaO_3$ crystals fabricated by swift $C^{5+}$ ion irradiation

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ABSTRACT

We report on the optical waveguides, in both planar and ridge configurations, fabricated in $LiTaO_3$ crystal by using carbon ($C^{5+}$) ions irradiation at energy of 15 MeV. The planar waveguide was produced by direct irradiation of swift $C^{5+}$ ions, whilst the ridge waveguides were manufactured by using femtosecond laser ablation of the planar layer. The reconstructed refractive index profile of the planar waveguide has showed a barrier-shaped distribution, and the near-field waveguide mode intensity distribution was in good agreement with the calculated modal profile. After thermal annealing at 260 °C in air, the propagation losses of both the planar and ridge waveguides were reduced to 10 dB/cm.



## 1. Introduction

Lithium tantalate ($LiTaO_3$) crystal has been widely used for electrooptic, pyroelectric, and nonlinear optical applications [1,2], owing to its multiply excellent features [3]. The periodically poled $LiTaO_3$ (PPLT) wafers serve as efficient frequency converters of light [4,5], which have been applied in a number of topics of photonics. As compact, integrated platform for photonic applications, waveguides play important role in the construction of cost-effective, miniaturized microphotonic chips [6]. Planar waveguides confine light fields in one dimension of the cross section, whilst ridge waveguides offer two-dimensional confinement of light, in which higher intracavity optical intensities could be reached. As a result, some features of the bulk materials might be varied or even enhanced in waveguide regions. By using ion beam techniques, waveguides could be produced in a number of materials [6–10]. Normal light ion (He or H) implantation was successfully applied to fabricate $LiTaO_3$ waveguides [11,12] of "optical barrier" type due to the nuclear collisions of incident ions with lattice atoms at the end of ion range. Recently swift heavy ions (with energy no less than 1 MeV/amu), for example, O [13], F [14], Cl [15], Ar [16] and Kr [17], have been utilized to irradiate optical materials and achieve refractive index changes of certain regions; and in some cases, waveguides could be constructed mainly by electronic damage induced by the irradiated ions even at very low fluence (as low as $\sim 10^{11}$ ions/cm$^2$) [6]. It has been found that the electronic stopping power ($S_e$) plays dominant role for the electronic damage generation. Irradiation of swift C ions has recently been used to manufacture waveguides in crystals, such as Nd:YAG [18], Nd:GGG [19], and Nd:GdCOB [20], and efficient lasing and second harmonic generation have been realized in these ion irradiated crystalline waveguides. In addition, femtosecond (fs) laser ablation has been emerged as a powerful technique to microstructure versatile materials with high resolution. The combination of ion irradiation and fs laser ablation has become an efficient method to construct ridge waveguides [19] in optical materials. In this work, we fabricate both planar and ridge waveguides in $LiTaO_3$ crystals using C ion irradiation, and investigate the guiding properties of the structures.

## 2. Experimental details

Initially, the congruent $LiTaO_3$ crystal was cut to dimensions of $10(x) \times 15(y) \times 1(z)$ mm$^3$ and optically polished. The $C^{5+}$ ions at the energy of 15 MeV and fluence of $2 \times 10^{14}$ ions/cm$^2$ were irradiated onto one sample surface ($10 \times 15$ mm$^2$) at room temperature by using the 3 MV tandem accelerator at Helmholtz-Zentrum Dresden-Rossendorf, Germany, to form a planar waveguide layer. The ion current density was kept at about 6–8 nA/cm$^2$ to avoid the

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heating and charging effect of the sample. To form the ridge waveguides, a Ti:Sapphire laser system delivered 120 fs pulses of linearly polarized 796 nm light with a repetition rate of 1 kHz was used for the parallel air grooves ablation on top of the ion irradiated planar waveguide surface. The laser beam was focused by a 20× microscope objective (with numerical aperture of 0.6). The geometrical focus of the objective was located on the irradiated surface of the sample and the pulse energy was set to 4.2 μJ. The laser scanning speed was ~50 μm/s. In this way, a number of parallel air grooves were produced at the surface of the ion irradiated planar waveguide. With the lateral confinement of microstructured grooves and vertical restriction of ion irradiated planar waveguide, the ridge waveguide was therefore produced in $LiTaO_3$ crystal. [21]. The sample was annealed in an oven at 260 °C for 1 h to improve the waveguide quality.

To investigate the planar waveguide characteristics, a prism coupler (Metricon 2010, USA) was used for the dark-mode spectra measurements at wavelength of 632.8 nm. The modal profiles of planar and ridge waveguides were obtained using an end-face coupling system at 632.8 nm. The propagation loss for the planer waveguide was measured by the back-reflection method [22]. For the ridge waveguide, the Fabry–Perot resonance method [23] was utilized to measure the losses.

## 3. Results and discussion

The microscopic image of the cross section of the sample end face is shown in Fig. 1. It is clearly seen that the thickness of the layer (i.e., the planar waveguide) modified by the $C^{5+}$ ion irradiation is ~8 μm, which is in good agreement with the projected range of the 15 MeV $C^{5+}$ ions in the $LiTaO_3$ crystal estimated by the calculation with the SRIM-2011 (Stopping and Range of Ions in Matter) code [24].

Fig. 2 shows the dark-mode spectra of TE (transverse electric) modes in the carbon ion-irradiated $LiTaO_3$ waveguide. According to the *m*-line data, we used a computer program based on the well-known reflectivity calculation method (RCM) [25] to reconstruct the refractive index ($n_o$) profile of the waveguide, and the profile is shown in Fig. 3. As is indicated, the distribution is a "barrier" pattern. As one can see, one optical barrier with negative refractive index change ($\Delta n = -0.01$) was created at depth of ~5.9 μm below the surface, whilst a smaller negative change of $\Delta n = -0.002$ was found on the near-surface region. This could be also estimated from the dark mode spectrum (Fig. 2).

The electronic and nuclear stopping power distributions ($S_e$ and $S_n$) of the 15 MeV $C^{5+}$ ions at the fluence of $2 \times 10^{14}$ ions/cm$^2$ were

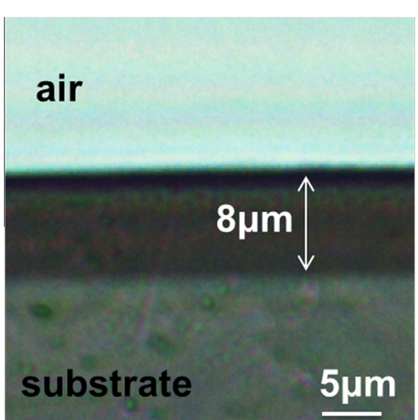


**Fig. 1.** Optical microscope image of cross section of the $LiTaO_3$ planar waveguide irradiated by 15 MeV $C^{5+}$ ions.

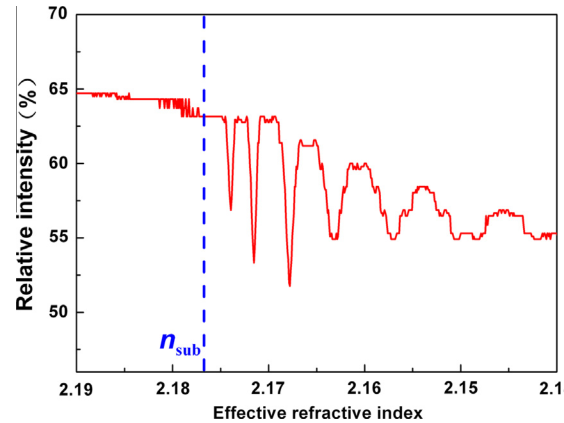


**Fig. 2.** Dark-mode spectrum of TE modes for the 15 MeV $C^{5+}$ ion irradiated $LiTaO_3$ planar waveguide. The dashed line shows the refractive index of the substrate.

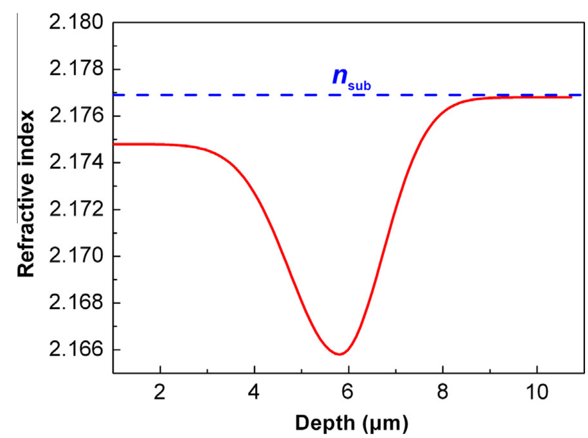


**Fig. 3.** Reconstructed refractive index ($n_o$) profile of the $LiTaO_3$ planar waveguide irradiated by 15 MeV $C^{5+}$ ions. The dashed blue line shows the refractive index of the substrate. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

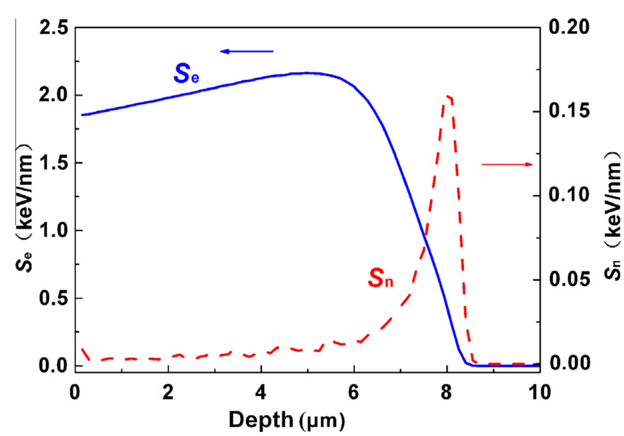


**Fig. 4.** Electronic (the solid line) and nuclear (the dashed line) stopping powers curves as a function of the penetration depth of the 15 MeV $C^{5+}$ ions in $LiTaO_3$ crystals.

calculated using the SRIM-2011 computer code, and the curves are depicted in Fig. 4. By comparing Figs. 3 and 4, for the case of the $C^{5+}$ ions irradiation, the maximum electronic stopping power $S_{e,max}$ ≈ 2.2 keV/nm occurred at a depth of 5.7 μm, which is in accordance with the maximum refractive index change position. In this sense, it seems that the reason for the $LiTaO_3$ waveguide formation was the electronic damage induced by swift C ions. In this case, since $S_{e,max} \approx 2.2$ keV/nm, which is not a high value, the induced damage may be due to the impact of a few ions instead of single-ion induced amorphous track. Nevertheless, the detailed information requires further investigation.

Fig. 5(a) shows the near-field TE mode distribution from the $LiTaO_3$ planar waveguide measured at 632.8 nm. Based on the refractive index profile shown in Fig. 3, we calculate the modal profile of the waveguide by using the finite-difference beam propagation method (FD-BPM) [26]. The distribution is shown in Fig. 5(b). As one can see, by comparing Fig. 5(a) and (b), the calculated profile is in good agreement with the experimental distribution that additively verifies the refractive index profile reconstruction.

Fig. 6(a) shows the microscopic image of the cross section of the $LiTaO_3$ ridge waveguide made by fs laser ablation. As it is indicated, the distance between the two air grooves was 36 μm, and the depth of the air groove was ~55 μm. Fig. 6(b) depicts the measured near-field mode distribution (quazi $TE_{30}$ mode) from the $LiTaO_3$ ridge waveguide at 632.8 nm. Experimentally, the excitation of different-order modes requires carefully adjustment of the light incident angle against the ridge waveguide direction.

The propagation losses of the $C^{5+}$ ion irradiated $LiTaO_3$ waveguides (as-implanted) were very high (more than 20 dB/cm). After annealing at 260 °C in air for an hour, their propagation losses became lower and fall below the ~10 dB/cm for both planar and ridge waveguides. Although the improvement of the propagation quality has been achieved, further investigation of the thermal treatment effects in the $LiTaO_3$ implanted waveguides is topical for obtaining lower-attenuation guiding structures.

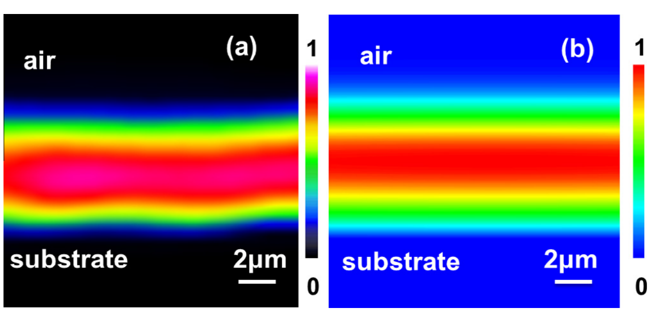


**Fig. 5.** (a) Measured and (b) calculated near-field mode profiles along the TE polarization of the $LiTaO_3$ planar waveguide produced by 15 MeV $C^{5+}$ ion irradiation.

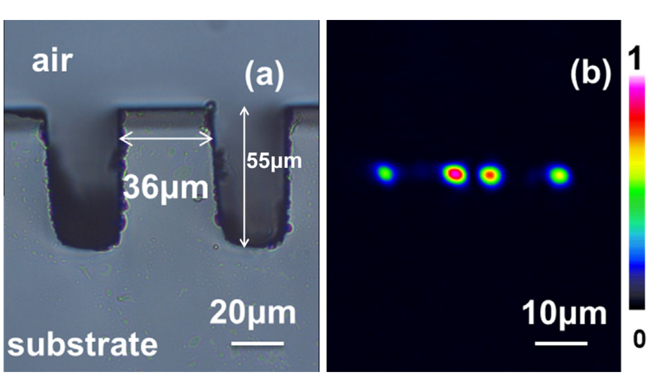


**Fig. 6.** (a) Optical microscope image of cross section and (b) measured near-field mode distribution ($TE_{30}$ mode) of the $LiTaO_3$ ridge waveguide produced by 15 MeV $C^{5+}$ ion irradiation and fs laser ablation.

## 4. Conclusion

We have reported on the optical waveguides in $LiTaO_3$ crystal fabricated by the irradiation of 15 MeV $C^{5+}$ ions at the fluence of $2 \times 10^{14}$ ions/cm$^2$. It was found that the electronic damage might be the key factor for the waveguide appearance. The ridge waveguides were produced by using further fs laser microstructuring of the planar waveguide surface. After suitable thermal annealing treatment, the propagation losses of the waveguide were reduced to 10 dB/cm. Further investigation on the post-irradiation processing of the structures will be performed to achieve acceptable guiding properties of the $LiTaO_3$ waveguides.

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