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Mid-infrared ridge waveguide in $MgO:LiNbO_3$ crystal produced by combination of swift O^{5+} ion irradiation and precise diamond blade dicing

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ABSTRACT

We report on the fabrication of ridge waveguide operating at mid-infrared wavelength in $MgO:LiNbO_3$ crystal by using O^{5+} ion irradiation and precise diamond blade dicing. The waveguide shows good guiding properties at the wavelength of 4 μm along the TM polarization. Thermal annealing has been implemented to improve the waveguiding performances. The propagation loss of the ridge waveguide has been reduced to be 1.0 dB/cm at 4 μm after annealing at 310 °C. The micro-Raman spectra indicate that the microstructure of the $MgO:LiNbO_3$ crystal has no significant change along the ion track after swift O^{5+} ion irradiation.

1. Introduction

The mid-infrared (MIR) spectral region, which usually refers to the wavelength range $\lambda = 2–25$ μm, is characterized by the strong vibrational absorption lines of various molecules and is also well-known as the "molecular fingerprint" region. Inherently, the availability and performance of photonic components with transmission in this spectral region has attracted a significant amount of interests in recent years, thus be further applied for a host of applications in spectroscopy and environmental and bio-chemical sensing [1].

Optical waveguides are basic photonic components which confine the light propagation in very small volumes with dimensions of micron or sub-micrometer scales. The light inside the guiding structures could reach relatively high optical intensities compared to the bulk geometries [2,3]. One-dimensional (1D) waveguides (planar or slab waveguides) restrict light in one dimension, while two-dimensional (2D) waveguides (channel or ridge waveguides) confine light propagation in two transverse dimensions [4,5]. Compared with 1D waveguides, 2D waveguides have feature of more compact geometries and stronger spatial confinement of light fields, and exhibit superior guiding performance. Moreover, 2D waveguides may be efficiently connected together with optical fibers for construction of integrated photonic systems [5–7]. Recently, waveguides operating at MIR wavelength bands have attracted much attention due to the possible applications in many aspects [8–11].

Lithium niobate ($LiNbO_3$) is one of the most attractive materials for various photonic applications owing to its unique combination of excellent electro-optic, acousto-optic and nonlinear optical properties [12]. The transparency of $LiNbO_3$ crystals ranges from 420 nm to 5200 nm, covering bands from violet till MIR regimes. These intriguing properties enable $LiNbO_3$-based waveguides, such as optical modulators, frequency converters (with periodically poled $LiNbO_3$, PPLN), optical amplifiers, and waveguide lasers , to be widely used in the areas of optical information processing and telecommunications [13–16]. Magnesium doped $LiNbO_3$ ($MgO:LiNbO_3$) crystals exhibit high optical damage resistant performance, which could offer a unique platform for construction of high-damage-threshold waveguide devices [17]. As of yet, a few techniques have been developed for waveguide fabrication in various $LiNbO_3$ crystals, including metal indiffusion (Ti, Zn, or Fe), proton exchange, ion implantation/irradiation, and femtosecond (fs) laser writing [18–25]. The fs laser ablation of ion-irradiated planar waveguide has been utilized to fabricate 2D ridge waveguides in Yb:YAG crystal [26]. Partly attributed to the considerable roughness of the side walls of the fs-laser-ablated ridge waveguides

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structures, the propagation losses are still relatively larger. At the same time, precise diamond blade dicing has become a promising method to fabricate 2D ridge waveguides due to its advantage of combined cutting and surface polishing ability. By using this technique high-quality ridge waveguides with smooth side walls have been constructed in Nd:YAG crystals and the propagation losses could be consequently reduced [27].

In this work, ridge waveguide in MgO:$LiNbO_3$ crystal has been fabricated by combining swift O^{5+} ion irradiation and precise diamond blade dicing. The guiding properties at mid-infrared wavelength of 4 μm and micro-Raman spectrum have been measured and discussed in detail.

2. Experiments in details

The *z*-cut MgO:$LiNbO_3$ crystal (doped by 2 mol%) used in this work was cut into dimensions of $10(x) \times 10(y) \times 2(z)\,mm^3$ and optically polished. Fig. 1 shows the schematic process of the ridge waveguide fabrication in MgO:$LiNbO_3$ crystal. In the first step, the O^{5+} ions beam at energy of 15 MeV and fluence of 2×10^{14} ions/cm^2 was irradiated on one surface ($10 \times 10\,mm^2$) of the crystal through the 3MV tandem accelerator at Helmholtz-Zentrum Dresden-Rossendorf, Germany. The O^{5+} ions beam was set to be tilted by 7° off the vertical plane of the sample surface to minimize the channeling effect, and the beam current density was kept at a low level (about 6–8 nA/cm^2) to avoid the heating and charging of the sample. In this way a waveguide layer with a thickness of $\sim$7 μm was constructed beneath the sample surface. Afterwards, a diamond rotating blade on top of the irradiated planar waveguide surface moving in the direction parallel to the blade was used to construct air grooves with depth of 10 μm. The rotating speed and cutting velocity were set to 20,000 rpm and 0.2 mm/s, respectively. As a result, a ridge waveguide with width of 15 μm was formed by controlling the distance of two adjacent grooves.

We utilized an optical microscope (Axio Imager, Carl Zeiss) operating in transmission mode to photograph the cross section of the fabricated ridge waveguide. An end-face coupling arrangement, as shown in Fig. 2, was applied to experimentally characterize the near-field modal profiles of the guided modes. The light propagation direction in the waveguide was along *y*-axis of the crystal. The incident light at mid-infrared wavelength of 4 μm was generated in the Tunable Laser System – MIR™ 8025 (Daylight Solutions, Inc.). A pair of MIR microscope objective lens (ZnSe, LFO-5-12-3.75, N.A. = 0.13) were used to couple the linearly polarized light into and out of the ridge waveguide, and then an MIR CCD camera connected to the computer was employed to observe and record the data at 4 μm wavelength. In addition, the propagation loss of the MgO:$LiNbO_3$ ridge waveguide was estimated by measuring the incident and output light powers of the waveguide. Afterwards, we carried thermal annealing treatments at 210 °C (Step 1), 260 °C (Step 2), 310 °C (Step 3) and 360 °C (Step 4) in sequence, for 1 h each step, to investigate the effect of annealing treatment and the thermal stabilities. The guiding properties and propagation losses were measured again after each step.

In order to study the physical mechanism of the 15 MeV O^{5+} ion irradiated MgO:$LiNbO_3$ ridge waveguide formation, the micro-Raman spectra of the sample was measured by using a confocal Raman spectrometer (Horiba/Jobin Yvon HR800) at room temperature. To detect the Raman intensity distributions along the ion tracks, a continuous wave laser beam at 473 nm was used as the excitation source and focused onto the end facet of the waveguide sample at different positions from the surface to a depth of 9 μm with an interval of 2 μm. The spot diameter of the Raman excitation laser was 1 μm and all the spectral scans were performed in the range of 100–900 cm^{-1}.

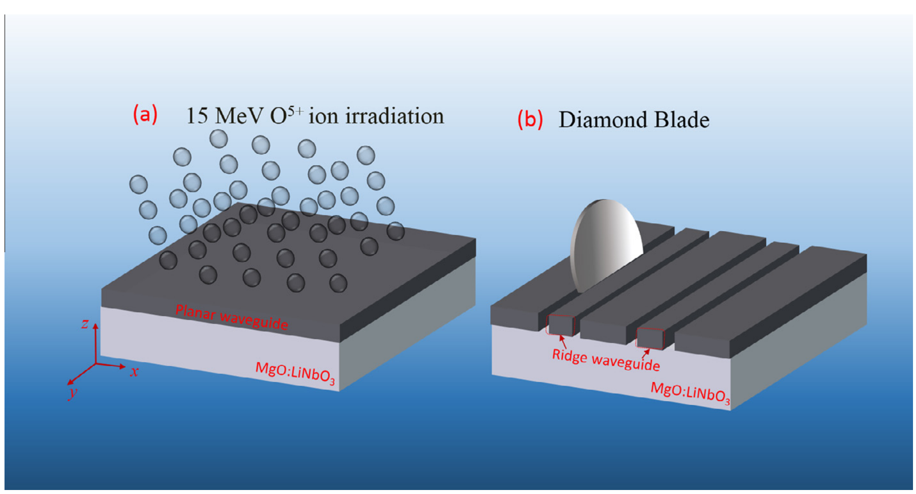

Fig. 1. The schematic process of (a) 15 MeV O^{5+} ions irradiation and (b) diamond blade dicing for the MgO:$LiNbO_3$ ridge waveguide fabrication.

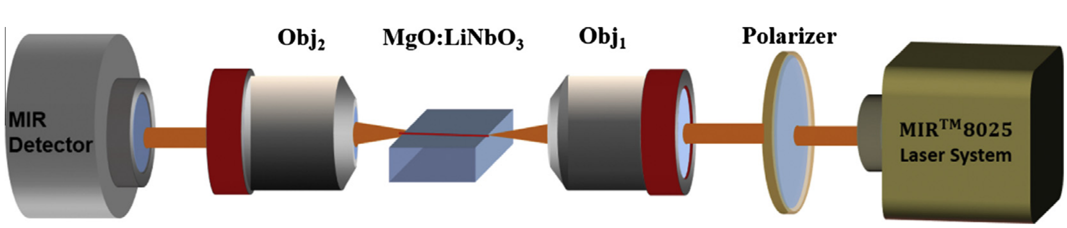

Fig. 2. The schematic plot of the end-face coupling arrangement used to investigate the guiding properties of the ridge waveguide in MgO:$LiNbO_3$ crystal.