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Optical ridge waveguides in Nd:CNGG disorder laser crystal produced by combination of carbon ion irradiation and precise diamond blade dicing

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ABSTRACT

Ridge waveguides have been produced in Nd:CNGG disorder laser crystal by using precise diamond blade dicing of carbon ion irradiated planar waveguide. The propagation loss of the ridge waveguide is measured to be ~3.8 dB/cm at the wavelength of 632.8 nm. The micro-Raman spectrum indicates that the microstructure of the Nd:CNGG crystal has no significant change after the carbon ion irradiation. The microphotoluminescence feature has been found well preserved in the waveguide structure. The thermal stability of the waveguide has been investigated, showing relatively stable feature below 260 °C.

1. Introduction

As one of the most promising disordered crystals, neodymium-doped calcium niobium gallium garnet (Nd:CNGG) has attracted considerable attention for its extensive application as the laser gain medium for diode pumping [1–6]. Attributing to the random distribution of the niobium, gallium and cationic vacancies in lattice site, Nd:CNGG has disordered structure and large inhomogeneous broadening in its spectra [7]. Besides low melting point of 1460 °C, Nd:CNGG presents a few superior features, such as wider absorption band width (8.5 nm) and lower thermal conductivity (0.047 W/cm °C), comparing with $Nd:YVO_4$ and Nd:YAG [8]. These remarkable properties enable Nd:CNGG crystal an excellent candidate as gain medium for developing of the solid state laser devices.

Waveguide structures, as basic components in integrated optics, can confine light propagation in a small volume of the dimensional order of several microns. Based on this advantage, higher optical intensities can be achieved than those in bulk [9], which is helpful for the realization of high optical gains and low lasing thresholds in the waveguide structures of active media. Several techniques, such as ion implantation [10] and femtosecond laser inscription [11], have been utilized to fabricate optical planar waveguide in Nd:CNGG crystal. For example, Tan et al. reported the microfabrication and characterization of Nd:CNGG cladding waveguide produced by the femtosecond laser ablation [12]. Most recently, the irradiation of swift heavy ions (i.e., with energy higher than 1 MeV/amu) has been utilized to produce optical planar waveguide structure in Nd:CNGG crystal [8]. In fact, for ion beam processed waveguides, the swift heavy ion irradiation possesses several advantages, such as lower ion fluences (down to $\sim 10^{11}$ ions/cm^2) and larger refractive index contrast, over the ion implantation [13,14]. Comparing with one-dimensional (1D) planar waveguide, two-dimensional (2D) confined waveguide structures (typically channel or ridge geometries) allow for more compact geometries and stronger spatial confinement of light fields, exhibiting superior guiding performance. Owing to the ability of combined cutting and surface polishing, the diamond blade dicing has become a fascinating technique to construct ridge waveguide structure, which has been applied to fabricate high-quality ridge waveguide structure in $LiNbO_3$ [15] and Nd:YAG [16] crystals.

In this work, ridge optical waveguides is formed on the surface of Nd:CNGG crystal by combining swift carbon ion irradiation and diamond blade dicing. Properties of the optical waveguide such as propagation properties, Raman spectrum and confocal microfluorescence image have been investigated in detail.

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2. Experimental details

The Nd:CNGG crystal used in our work was cut into the dimensions of $0.5 \times 10 \times 10\ mm^3$ with two facets ($0.5 \times 10\ mm^2$) optically polished. The biggest facet of the sample was irradiated with the carbon (C^{5+}) ions at energy of 15 MeV and at fluence of 2×10^{14} ions/cm^2 by using the 3 MV tandem accelerator at Helmholtz-Zentrum Dresden-Rossendorf, Germany. During the irradiation process, the sample was tilted by 7° off the incident beam direction to minimize the channeling effect. The mechanical method was utilized to fabricate ridge waveguide on top of the irradiation surface (i.e., the planar waveguide surface) [16]. Using a diamond rotating blade while moving in the direction parallel to the blade, grooves with depth of ~60 μm were cut into the surface of the planar waveguide. Ridge waveguide with width of 30 μm was formed by controlling the distance of the adjacent two grooves [17].

The dark-mode lines of this waveguide were measured by a prism coupler (Metricon 2010, USA) at the wavelength of 632.8 nm. Based on the dark-mode spectrum, the refractive index profile of the waveguide had been reconstructed by the reflectivity calculation method (RCM) [18]. An end-face coupling arrangement was utilized to investigate the propagation modes and to measure the propagation loss by using the back reflection method [19], at 632.8 nm from a He–Ne laser. During the experiment, the sample was holded by a 6-dimensional precise optical stage. Through a pair of microscope objective lenses (25×, N.A. = 0.4), the light was coupled into the waveguide and focused onto a CCD camera, which was utilized to detect the morphology of guiding modes.

A confocal micro-Raman spectrometer (Horiba/Jobin Yvon HR800) was utilized to measure the μ-Raman spectrum of the sample at room temperature. The exciting laser beam was with the wavelength of 473 nm and the diameter of the focused point (size of the detected region) was ~1 μm. The Raman spectra of the waveguide and the bulk were detected at the range of 100–1000 cm^{-1}, respectively. The confocal fluorescence image was also measured by using the Horiba/Jobin Yvon HR800 with the excitation wavelength of 473 nm, exciting the transition of Nd^{3+} ions through $^4F_{3/2} \rightarrow {}^4I_{9/2}$ emission.

The sample was annealed in an open oven to investigate the thermal stabilities. We proceeded a series of thermal annealing treatment, at 180 °C (Step 1), 220 °C (Step 2), 260 °C (Step 3), and 300 °C (Step 4) in sequence, for 30 min each step. The guiding property and propagation loss were measured after each step.

3. Results and discussion

Fig. 1(a) depicts the microscopic photograph of the cross section of the planar waveguide, which is obtained by a polarized microscope (Axio Imager, Carl Zeiss). It was clear that the ion beam modified region of the Nd:CNGG was with a thickness of ~10 μm, which was in a good accordance with the projected range of the 15 MeV C^{5+} ions in Nd:CNGG calculated by the Stopping and Range of Ions in Matter (SRIM-2008) software [20]. The insets Fig. 1(b) and (c) exhibit the top view and cross section of the ridge waveguide with the width of 30 μm fabricated by precise diamond blade dicing, respectively. Fig. 1(d) shows the simulated electronic energy deposition (S_e) and nuclear damage distribution (S_n) of the 15 MeV C^{5+} ions. As can be appreciated, the nuclear damage of the waveguide was practically absent within the first 10 μm and climbs to 0.14 keV/nm only at the depth of ~10 μm. In the case of electronic stopping power, within the range of 0–10 μm the values of S_e were non-vanishing and peak at about 1.7 keV/nm at approximately 7 μm beneath the sample surface, which seemed too low to produce enough electronic damage for effective refractive index change.

According to the dark-mode-line spectrum of the planar waveguide characterized by the prism-coupling method, the refractive index profiles of the planar and ridge waveguides were reconstructed by using a computer code based on the RCM [18] shown in Figs. 2(a) and (d). As one can see, the reflective index profile of the waveguide had a typical "barrier" pattern distribution, which had a negative index change of ~0.0065 at the end of the incident ions' tracks, meanwhile the refractive index near the surface region was little changed. Confined by the air and the optical barrier, the planar waveguide structure was formed near the surface. For the ridge waveguide, grooves and the planar waveguide work together to keep the light transmission along the direction of the ridge waveguide.

Based on the reconstructed refractive index profile of planar and ridge waveguides, propagation modes were simulated by the finite-difference beam propagation method (BPM) [21], depicted in Figs. 2(b) and (e). Meanwhile, the images of near-field light intensity distributions from the output interface of the sample with the TE polarization were measured, shown in Figs. 2(c) and (f). By comparing Figs. 2(b) and (c), as well as Figs. 2(e) and (f), it can be concluded that there is a reasonable agreement between the calculated and experimental modal distributions, which further confirmed the reasonable of the reconstructed refractive index distribution. The propagation loss of the planar waveguide was measured to be ~2.6 dB/cm at the wavelength of 632.8 nm.

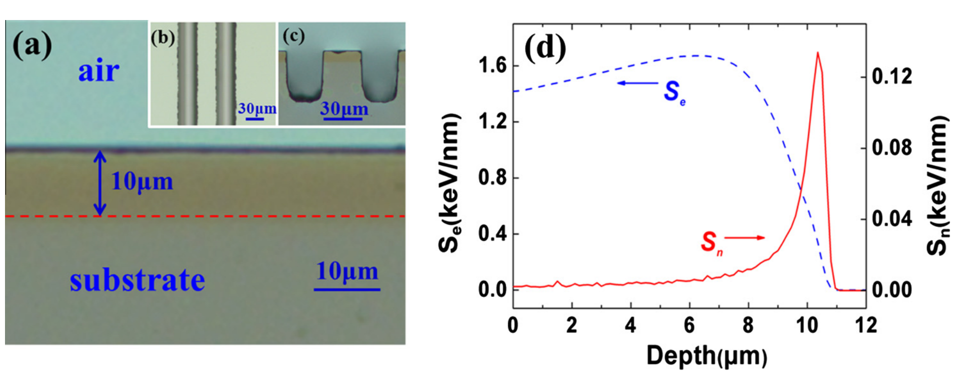

Fig. 1. (a) Optical microscope image of cross section of the Nd:CNGG planar waveguide irradiated by 15 MeV C^{5+} ions. The insets show the microscope image of the (b) top view, and (c) cross section of the ridge waveguide produced by diamond rotating blade cutting. (d) Electronic (blue) and nuclear (red) stopping power curves as a function of the depth from the sample surface of the Nd:CNGG waveguide. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)