Visible and near-infrared optical properties of Nd:CLNGG crystal waveguides formed by proton implantation*

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A Nd:CLNGG waveguide structure operated at wavelengths of both 632.8 nm and 1539 nm was demonstrated for the first time to our knowledge, which was produced by the 480-keV H^+ ion implantation with a dose of 1.0×10^{17} protons/cm^2. Its propagating modes at 632.8 nm and 1539 nm were measured by the well-known prism coupling technique. The refractive index profile at either 632.8-nm wavelength or 1539-nm wavelength was optical barrier type in the proton-implanted Nd:CLNGG crystal optical waveguide, which was calculated by using the reflectivity calculation method. The near-field light intensity distributions were also simulated by the finite-difference beam propagation method in the visible and near-infrared bands.

Keywords: ion implantation, Nd:CLNGG crystal, waveguide

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1. Introduction

A planar waveguide structure usually consists of a high-refractive-index guiding core and two low-index layers, i.e., substrate and cladding. As is well known, it can act as a building block to design and fabricate photonic integrated circuits.[1] Ion exchange,[2] sol–gel deposition,[3] femtosecond-laser writing,[4] and ion implantation[5–7] have been used for the realization of optical waveguide structures. Ion implantation is a competitive technique for the fabrication of optical planar and channel waveguides in dozens of optoelectronic materials including optical glasses, functional crystals, and transparent semiconductors.[8] During the implantation process, a beam of atoms firstly are often ionized with positive charges, such as C^{3+}, O^{2+}, and so on. In detail, the atoms are converted to negative ions in an ion source and soon afterwards the ions change from negative to positive in the stripping stage. Then, they are accelerated to kinetic energies up to hundreds of keV or a few MeV. Finally, the energetic ions are bombarded into the target materials and loss their energy. The collisions between the target nuclei of the substrate and the implanted ions often cause some structural damages near the end of the irradiated ion trajectory. These structural damages can induce a reduction of the refractive index of the target material.[9,10] Therefore, the layer between the region with decreased refractive index and the surface of the implanted material (air) can act as a guiding core.

Both Nd:CNGG (neodymium-doped calcium niobium gallium garnet, Nd:$Ca_3Nb_{(1.5+1.5x)}Ga_{(3.5-2.5x)}\square_xO_{12}$) and Nd:CLNGG (neodymium-doped calcium lithium niobium gallium garnet, Nd:$Ca_3Nb_{(1.5+1.5x)}Ga_{(3.5-2.5x)}Li_xO_{12}$) laser crystals have attracted increasing attention in the last decade, owing to their outstanding physical and chemical characteristics. Their absorption and emission bands are broad, the segregation coefficient for Nd^{3+} ions reaches 0.55 at.%, the thermal conductivity is up to 3.5 W/(m·K), and the melting temperature is about 1460 °C.[11–14] Nd:CNGG and Nd:CLNGG both have disordered cubic structures and the advantages of both Nd^{3+}-doped glasses and Nd^{3+}-doped ordered crystals. However, some optical properties of Nd:CLNGG are different from those of Nd:CNGG, because Nd:CLNGG crystal has a lower vacancy concentration by the introduction of Li^+-ions compared with Nd:CNGG crystal.[13] For example, the crystal stability of Nd:CLNGG is higher than that of Nd:CNGG under the same pump conditions. As a competitive laser medium, Nd:CLNGG crystal has been used to realize continuous-wave and passively Q-switched lasers.[11] Extensive investigations on ion-implanted waveguides have been made into Nd:CNGG crystals in the last several years. The carbon ion implantation was employed to form optical planar waveguides in Nd:CNGG crystals by Wang *et al.* in 2010.[15] Liu *et al.* reported an optical He-ion implanted Nd:CNGG waveguide in 2009.[16] Afterwards, they utilized the thermal treatment at 300 °C for 45 min to optimize the optical performances of the Nd:CNGG waveguide fabricated by the oxygen-ion implantation method in 2016.[17] However, no ion-implanted Nd:CLNGG waveg-

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uide has been reported to our knowledge. It is necessary to explore the appropriate implantation conditions to fabricate high-quality optical waveguides with the Nd:CLNGG crystals. In the present work, we demonstrate for the first time the planar optical waveguide structure in Nd:CLNGG crystal produced by the H^+ ion implantation technique. The properties of the optical waveguide are investigated in detail by the measurement and simulation methods in visible and near-infrared wavelength bands.

2. Experiments and calculations

The Nd:CLNGG crystal with 0.5 at.% Nd^{3+} ions was cut into a wafer with dimensions of 9.0 mm×3.0 mm×1.5 mm. Its two parallel surfaces (9.0 mm×3.0 mm) and two opposite end faces (3.0 mm×1.5 mm) were polished to optical quality. The room temperature transmittance spectrum of the Nd:CLNGG crystal in the range of 500–1000 nm was recorded by using a ultraviolet–visible–near infrared (UV–VIS–NIR) spectrophotometer (JASCO U-570). The substrate refractive indices ($n_{\rm sub}$) of the Nd:CLNGG crystal at wavelengths of 632.8 nm and 1539 nm were recorded by using a Metricon 2010 prism coupler.

One of the polished Nd:CLNGG surface (9.0 mm×3.0 mm) was irradiated by a beam of H^+ ions with a kinetic energy of 480 keV and a dose of 1.0×10^{17} protons/cm^2. The beam current density was about 50 nA/cm^2 during the implantation. The Nd:CLNGG crystal was tilted relative to the normal incidence by 7° for the proton implantation in order to avoid a channeling effect. The irradiation was performed by using an implanter at room temperature in the Institute of Semiconductors of CAS.

After the proton implantation, the conventional prism-coupling method was employed to record the effective refractive index of the propagation mode in the visible (632.8 nm) and near-infrared (1539 nm) optical regions. The refractive index profiles and the near-field light intensity distributions at wavelengths of 632.8 nm and 1539 nm were calculated by the reflectivity calculation method and the finite-difference beam propagation method, respectively.

3. Results and discussion

3.1. Optical characteristics of Nd:CLNGG

The measured transmission spectrum of the unimplanted Nd:CLNGG disordered crystal with a thickness of 1.5 mm is shown in Fig. 1. The absorption peaks in the transmission spectrum are ascribed to the transitions of Nd^{3+}ion in the Nd:CLNGG crystal from the $^4I_{9/2}$ ground state to the various excited states including $^4F_{3/2}$, $^4F_{5/2}$, and so on. For example, the band centered at 807 nm corresponds to the $^4I_{9/2}\rightarrow{}^4F_{5/2}+{}^2H_{9/2}$ transition. It can be seen that the transparent rate T (uncoated) is over 80.0% at most of the measured region in Fig. 1.

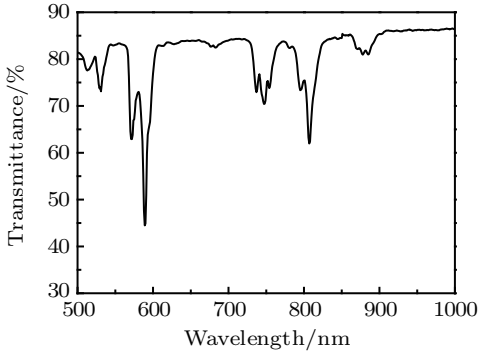


Fig. 1. Transmittance spectrum of the polished Nd:CLNGG crystal.

Figures 2(a) and 2(b) severally show the refractive index of the bulk Nd:CLNGG crystal at the wavelengths of 632.8 nm and 1539 nm, which was measured by the Metricon model 2010 prism coupler with an accuracy of 0.0002. The polished Nd:CLNGG crystal was clamped against the rutile prism by a coupling head and the refractive index was determined by a critical knee. As shown in Fig. 2, the abscissa value corresponding to the dashed line of the dark-mode spectrum is the substrate refractive index. Therefore, the refractive index of the bulk Nd:CLNGG crystal is 1.9815 at the wavelength of 632.8 nm ($n_{\rm sub}^{632.8}=1.9815$) and 1.9409 at the wavelength of 1539 nm ($n_{\rm sub}^{1539}=1.9409$), respectively.

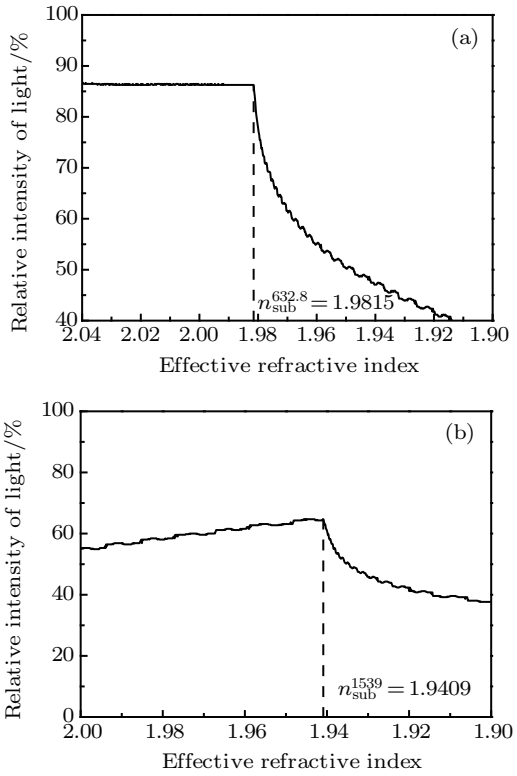


Fig. 2. Substrate refractive index at (a) 632.8 nm and (b) 1539 nm of the Nd:CLNGG crystal.

3.2. Waveguide characterization

The SRIM 2010 (stopping and range of ions in matter 2010 code)[18] is often employed to simulate the interactions of energetic ions with amorphous materials. It depends on the Monte Carlo computer program. In the present simulation process, an ensemble of 100000 protons was set for statistically significant number. As shown in Fig. 3, the SRIM 2010 was performed to calculate the damage profile and the lateral straggling of the implanted ions which were induced by the 480-keV proton implantation with a dose of 1.0×10^{17} protons/cm^2 in the Nd:CLNGG crystal. The implanted protons slow down on their path into the Nd:CLNGG crystal owing to the energy deposition from interactions with nuclei and electrons of the Nd:CLNGG crystal in the implantation process.[19,20] The nuclear collision leads to a structural damage and a volume expansion (swelling), which is accompanied by a reduction of the refractive index of the irradiated Nd:CLNGG crystal. Therefore, a layer with low refractive index is formed in the near-surface of the Nd:CLNGG crystal. A sharp maximum of damage ratio is at a depth of 3.58 μm below the surface of the Nd:CLNGG substrate in Fig. 3. It is in accordance with the deposition position of the irradiated H^+ ions in the inset of Fig. 3.

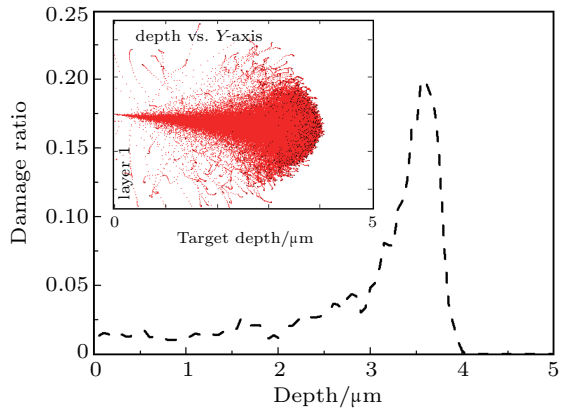


Fig. 3. (color online) Damage ratio induced by the 480-keV proton implantation versus the penetration depth of the implanted H^+ ions in the Nd:CLNGG crystal. The inset represents the lateral straggling of the irradiated protons.

Figures 4(a) and 4(b) show the relative intensity of the transverse electric (TE) polarized light with wavelengths of 632.8 nm and 1539 nm reflected from the rutile prism of the Metricon 2010 prism coupler versus the effective refractive index of the propagating modes for the Nd:CLNGG crystal waveguide formed by the 480-keV H^+ ion implantation at a dose of 1.0×10^{17} protons/cm^2, respectively. A beam of polarized light of TE mode from a He–Ne laser (for Fig. 4(a)) or a diode laser (for Fig. 4(b)) was injected into the proton-implanted Nd:CLNGG waveguide by means of a high-refractive-index rutile prism during the dark-mode spectrum measurement. The incident light was efficiently injected to the optical waveguide region, as it was coupled to a synchronous angle corresponding to a guiding mode. At the same time, the reflectivity showed a sharp dip in the light intensity.[21] In general, a dip in the dark-mode spectrum (relative intensity of light as a function of effective refractive index) indicates a guided mode for an optical waveguide produced by the technique of ion implantation. As shown in Fig. 4(a), there are three dips in the m-line spectrum at the wavelength of 632.8 nm, whose effective refractive indices are 1.9787, 1.9666, and 1.9529, respectively. However, only one dip with an effective refractive index of 1.9407 is found in Fig. 4(b) for the case of 1539 nm wavelength. It is because that the mode number becomes less when the wavelength of the light propagated in the waveguide is longer. In addition, the substrate refractive index of the Nd:CLNGG crystal (1.9815 for 632.8 nm and 1.9409 for 1539 nm) is larger than the effective indices of the corresponding propagation modes.

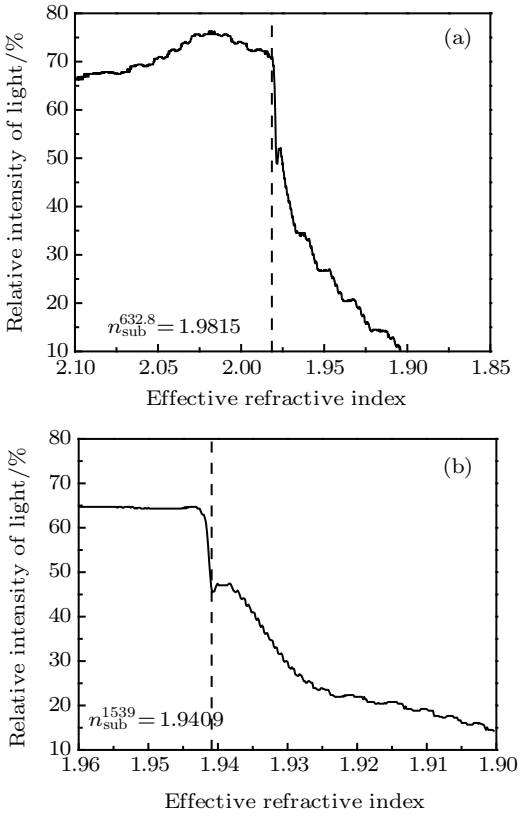


Fig. 4. Dark-mode spectra at (a) 632.8 nm and (b) 1539 nm for the TE mode in the proton-implanted Nd:CLNGG waveguide.

As mentioned earlier, the volume expansion and structural damage, which are induced by the nuclear energy loss in the process of the ion irradiation, result in the refractive-index modification near the end of the implanted ion trajectory inside the target materials. However, the refractive-index change cannot be determined by a direct experiment measurement, because the thickness of a waveguide fabricated by the ion implantation method usually is several-micrometers. The combination of the reflectivity calculation method[22] and the

effective indices of the guided modes in the dark-mode spectrum was carried out to reconstruct the refractive index distribution of the proton-implanted Nd:CLNGG crystal waveguide. During the simulation process for the refractive index profile, some parameters demanded constant change and adjustment until the effective refractive indices of the calculated distribution matched the measured ones best. Figures 5(a) and 5(b) show the refractive index distributions reconstructed by the RCM versus the penetration depth of the implanted ions for the proton-implanted Nd:CLNGG crystal waveguide at wavelengths of 632.8 nm and 1539 nm, respectively. It should be noted that the refractive index profile at 1539 nm was reconstructed based on the effective refractive index of the one mode and some parameters obtained from the simulation of the refractive index profile for the 632.8-nm wavelength. The refractive index profiles at the wavelengths of 632.8 nm and 1539 nm, as one can see, are both typical barrier-confined distributions. The refractive index firstly experiences a slight negative change ($\Delta n_{\rm w}$) in the main region of the implanted ion range, e.g., $\Delta n_{\rm w} = -0.0004$ for 632.8 nm and $\Delta n_{\rm w} = -0.0002$ for 1539 nm. On the other hand, the decreases of the refractive index at the optical barrier are -0.019 for 632.8 nm and -0.011 for 1539 nm, respectively. Therefore, the light with either 632.8 nm wavelength or 1539 nm wavelength can be guided in the narrow layer between the surface of the implanted Nd:CLNGG crystal (air) and the optical barrier by total internal reflection. Table 1 compares the measured effective refractive indices and the calculated mode indices.

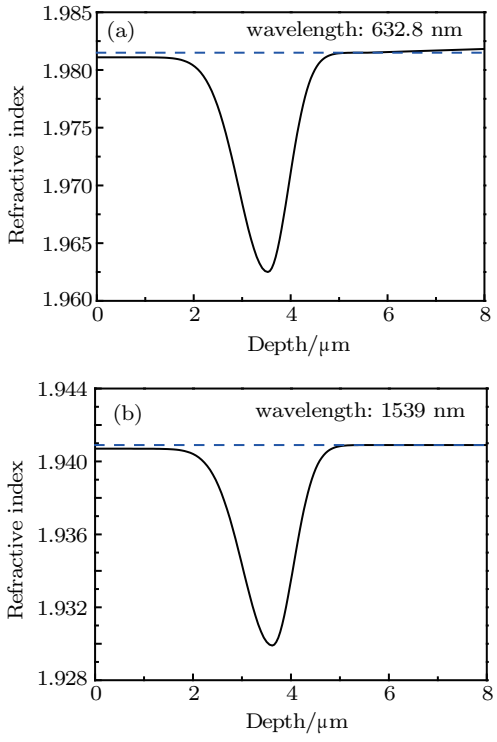


Fig. 5. (color online) Refractive index profiles at wavelengths of (a) 632.8 nm and (b) 1539 nm in the proton-implanted Nd:CLNGG crystal waveguide.

Table 1. Measured and calculated effective refractive indices for the proton-implanted Nd:CLNGG waveguide.

Wavelength	Mode order	Effective refractive index		
		Exp.	Cal.	Diff.
632.8 nm	0	1.9787	1.9781	6.0×10^{-4}
	1	1.9666	1.9704	-3.8×10^{-3}
	2	1.9529	1.9608	-7.9×10^{-3}
1539 nm	0	1.9407	1.9320	8.7×10^{-3}

The finite-difference beam propagation method (FD-BPM) is efficient for calculating and analyzing the propagation of electromagnetic waves in a waveguide structure.[23,24] Figures 6(a) and 6(b) show the near-field optical intensity profiles at 632.8 nm and 1539 nm in the proton-implanted Nd:CLNGG waveguide, which were calculated by the FD-BPM according to the reconstructed refractive index profiles in Figs. 5(a) and 5(b). As one can see, two smooth and homogeneous stripes are in the mode intensity profiles of Figs. 6(a) and 6(b). It suggests that the light with either 632.8-nm wavelength or 1539-nm wavelength may be confined in the proton-implanted Nd:CLNGG waveguide structure. However, the propagation loss of the optical waveguide could be relatively high owing to the high-dose proton implantation (1.0×10^{17} protons/cm^2).

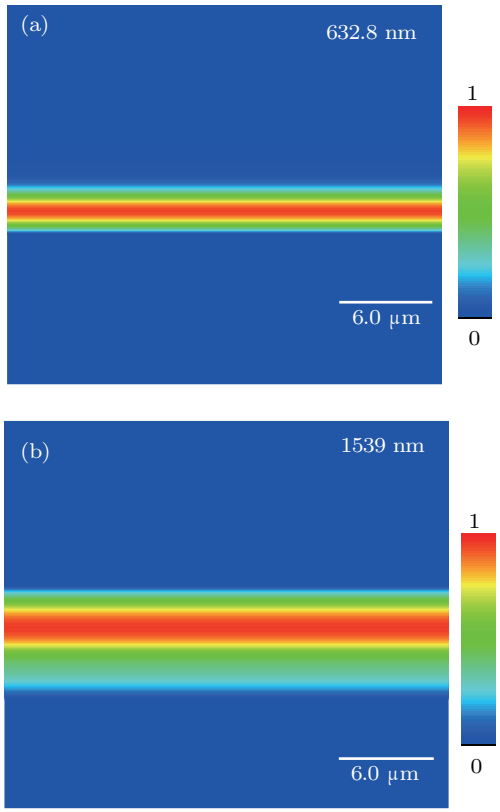


Fig. 6. (color online) Simulated mode intensity profiles with (a) 632.8 nm and (b) 1539 nm wavelengths for the proton-implanted Nd:CLNGG waveguide.

4. Conclusion

The visible and near-infrared planar waveguide structure was fabricated by the H^+ ion implantation at a fluence

of 1.0×10^{17} protons/cm^2 and an energy of 480 keV in the Nd:CLNGG crystal. The proton irradiation induced a negative change of the refractive index at the optical barrier. The decrease values of refractive index were -0.019 at 632.8 nm and -0.011 at 1539 nm, respectively. The dark-mode spectra show the waveguide contained three propagation modes at the wavelength of 632.8 nm and one propagation mode at 1539 nm. The near-field light intensity profile calculated by the FD-BPM suggests that the Nd:CLNGG waveguide produced by using H^+ ion implantation may confine the light in the visible and near-infrared region. The proton-implanted Nd:CLNGG waveguides maybe contribute to the realization of integrated photonic devices.

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