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Guiding properties of proton-implanted Nd^{3+}-doped phosphate glass waveguides*

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We report on the fabrication and properties of an optical waveguide in Nd^{3+}-doped phosphate glass. The planar waveguide was obtained by 550-keV proton implantation with a dose of 8.0×10^{16} ions/cm^2. The proton–glass interaction was simulated by the stopping and range of ions in matter (SRIM software). The characteristics of the waveguide including the refractive index profile and the near-field intensity distribution were studied by the reflectivity calculation method and the end-face coupling technique. The optical waveguide demonstrated multi-mode behavior at the wavelength of 632.8 nm. The propagation features of the proton-implanted Nd^{3+}-doped phosphate glass waveguide shows its potential to operate as an integrated photonic device.

Keywords: waveguide, ion implantation, Nd^{3+}-doped phosphate glasses

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1. Introduction

As a necessary medium of information dissemination, an optical waveguide occupies an important position in the field of modern communications. Meanwhile, optical circuits need to be integrated as electrical circuits in the development of integrated optics, which poses a demand for the size of an optical waveguide. In addition, some advanced technologies, for example, optical computing and optical storage, rely on the development of optical waveguides. Therefore, more and more researches focus on the design and realization of low-cost optical waveguides with high-quality performances.[1–7]

The technique of ion implantation, which usually includes heavy-ion implantation and light-ion implantation, has been rapidly developed in related research fields in recent years.[8,9] It has been widely used in the formation and application of optical waveguides.[10–12] The energetic irradiation ions lose most of their energy when they slow down in the form of collisions with target electrons and by introducing atomic displacements.[13,14] It causes a negative change in refractive index at the end of the ion track, which is the principle of the ion-implanted waveguide.[15,16] The implanted ions are pure and extrinsic ions would not be introduced during the irradiation process. The doses and energies of the implanted ions can be precisely controlled.[17] Similar waveguide structures can be obtained by using the same ions and implantation parameters, which is necessary for the large-scale production of optical waveguides. Therefore, ion implantation is a competitive waveguide fabrication technology with application prospects.[18–22]

In addition to fabrication techniques, a suitable choice of the host material is another key consideration in the fabrication of optical waveguide structures. Nd^{3+}-doped phosphate glass has a high stimulated emission cross section, a low laser oscillation threshold and a small nonlinear coefficient. Its gain coefficient is larger than that of other Nd^{3+}-doped laser glass systems. Nd^{3+}-doped phosphate glass is considered to be one of the most promising candidates for use in high power laser systems. Meanwhile, it is suitable to form optical waveguides by the ion implantation method. Some kinds of ions, including helium, carbon and oxygen with different fluences, and energies have been utilized to implant into Nd^{3+}-doped phosphate glasses to fabricate optical waveguides.[23,24] However, the formation of optical waveguides in Nd^{3+}-doped phosphate glass by the proton implantation still has not been reported so far. Moreover, the depth of the proton implantation is the greatest among all the ions under the same conditions of the irradiation energy and the target substrate. Proton implantation is especially advantageous when the light with infrared wavelength propagates in the Nd^{3+}-doped phosphate glass waveguides. Furthermore, the most characteristic wavelength of the fluorescence spectroscopy in Nd^{3+}-doped phosphate glass is in the near-infrared region (1064 nm). Therefore, it is necessary to explore appropriate implanted energies and doses for the proton implantation into Nd^{3+}-doped

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phosphate glass. In this work, proton implantation with an energy of 550.0 keV and a dose of 8.0×10^{16} ions/cm^2 was employed for the waveguide formation in Nd^{3+}-doped phosphate glass. Material damage is induced in the ion implantation process, which affects the beam propagation in the waveguide region.[25] An annealing treatment was used to optimize the waveguide structure. The characteristics of the optical waveguide, such as transversal mode distribution and refractive index profile, were investigated to evaluate its optical properties.

2. Experiments

Nd^{3+}-doped phosphate glass with a composition of P_2O_5-Al_2O_3-K_2O-MgO-3.0 wt.% Nd_2O_3 was prepared by the melt-quenching method at the Xi'an Institute of Optics and Precision Mechanics of CAS. The glass formula was optimized before the preparation process. The melting and molding techniques as well as the annealing method have been a great improvement for "SHEN-GUANG" in China. The glass was cut into a rectangular plate with a size of 10.0 mm × 10.0 mm × 1.0 mm. One of the surfaces with the largest area (10.0 mm × 10.0 mm) was polished for the ion implantation and two opposite end faces (10.0 mm × 1.0 mm) were polished for the end-face coupling measurement. The polished glass is shown in the inset of Fig. 1.

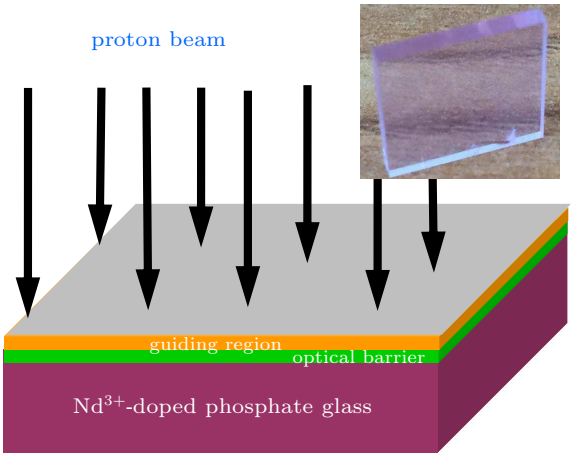


Fig. 1. (color online) Schematic for the waveguide fabrication in the Nd^{3+}-doped phosphate glass. The inset is the photo of the polished glass.

To form a waveguide structure, the proton implantation was carried out on a 10.0 mm × 10.0 mm surface of the Nd^{3+}-doped phosphate glass at room temperature. The fabrication procedure of the planar waveguide is shown in Fig. 1. The energy of the implanted proton was 550.0 keV according to the appropriate waveguide thickness and its dose was 8.0×10^{16} ions/cm^2 in consideration of the damage ratio. In order to avoid thermal effects and to prevent the sample from being charged, the ion current density was maintained at a low level (100 nA/cm^2). The proton implantation was performed on an implanter in vacuum at the Institute of Semiconductors of CAS. Then, the as-implanted glass was annealed in an open-tube furnace at 360 °C for 60 min.

After the implantation and the thermal treatment, optical microscopy was utilized to measure the microscope image of the implanted layer. The dark modes in the optical waveguide structure were measured by an m-line technique, in which a Model 2010 Prism Coupler with a He–Ne laser was employed. The near-field pattern of the proton-implanted Nd^{3+}-doped phosphate glass waveguide was recorded by the end-face coupling method. In the end-face coupling measurement, a He–Ne laser operating at 632.8 nm was focused on the polished end-face of the optical waveguide by a ×25 microscope objective lens (N.A. = 0.5), as shown in Fig. 2. The waveguide was located on a six-dimensional translation stage. When guiding modes were excited in the waveguide region, the image of the intensity distribution at the output facet of the waveguide was collected on a CCD camera by another ×25 microscope objective lens (N.A. = 0.5). Both objective lenses were mounted on three-dimensional translation stages.

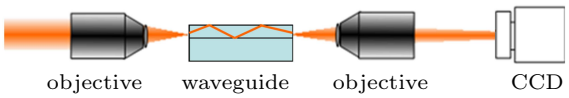


Fig. 2. (color online) Schematic for the end-face coupling measurement.

3. Results and discussion

Figure 3 shows the microscopic photograph at the end facet of the proton-implanted Nd^{3+}-doped phosphate glass obtained by optical microscopy. An obvious stripe in the microscope image indicates that an optical waveguide structure is present in the Nd^{3+}-doped phosphate glass after the proton implantation. The thickness of the waveguide layer is estimated to be about 5.7 μm. There are some scratches and dark dots on the cross section of the implanted glass owing to poor polishing.

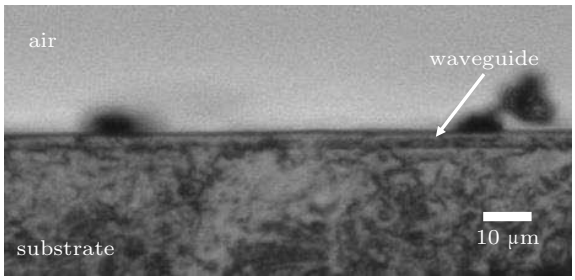


Fig. 3. Microscopic end view of the proton-implanted Nd^{3+}-doped phosphate glass.

The SRIM 2010 software (stopping and range of ions in matter 2010)[26] with the aid of the Monte Carlo method was

applied to simulate the interactions between the implanted protons and the target Nd^{3+}-doped phosphate glass. Figure 4 shows the damage ratio caused by the 550-keV proton implantation as a function of the penetration depth in the Nd^{3+}-doped phosphate glass according to the SRIM 2010 software. The damage ratio is almost zero at the near-surface and rapidly reaches to a maximum peak at the end of the implanted ion trajectory, which is in accordance with the lateral straggling of the implanted ions in the inset. The depth of the implanted layer is equal to 5.75 μm. The optical barrier is relatively narrow and the multi-energy implantation can broaden it.

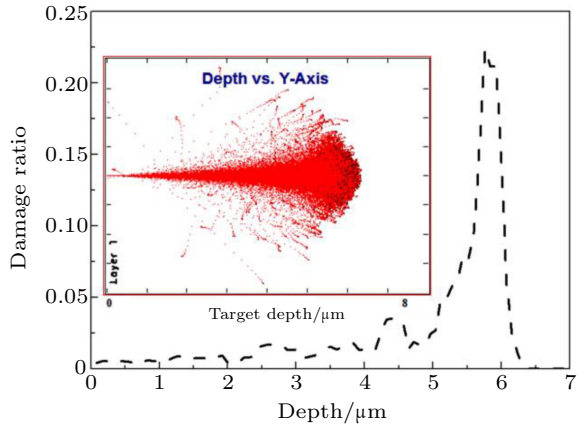


Fig. 4. (color online) Damage ratio versus the penetration depth and the inset is the lateral straggling of the implanted hydrogen ions.

The prism coupler system was used to couple the propagating beam into the waveguide structure. A 632.8-nm beam struck the base of the prism that tightly attached to the waveguide and was reflected onto a photodetector. Photons could tunnel from the rutile prism into the waveguide and a propagation mode was excited at certain discrete incident angles, resulting in a drop in the intensity on the photodetector. In Fig. 5(a), the substrate refractive index of the Nd^{3+}-doped phosphate glass is 1.5391 at the wavelength of 632.8 nm. As can be seen from Fig. 5(b), three dips are obtained in the dark-mode spectrum of the proton-implanted Nd^{3+}-doped phosphate glass waveguide. It means that the waveguide structure may contain three propagation modes. The effective refractive indices of the modes are listed in Table 1, which are all lower than that of the glass substrate.

Table 1. Measured and calculated effective refractive indices for the proton implanted Nd^{3+}-doped phosphate glass waveguide.

Mode order	Effective refractive index		
	Exp.	Cal.	Diff.
0	1.4970	1.4932	3.8×10^{-3}
1	1.4866	1.4870	-4.0×10^{-4}
2	1.4685	1.4783	-9.8×10^{-3}

The refractive index distribution of an optical waveguide structure is an important factor that affects the design and application of a waveguide device. Therefore, it is of great significance to reconstruct the refractive index distribution of a waveguide. The reflectivity calculation method (RCM)[27] was adopted to calculate the refractive index distribution of the fabricated waveguide at the wavelength of 632.8 nm, as shown in Fig. 6. The refractive index reduces by 2.8% in the near-surface region with respect to the virgin glass. The maximum decrease in refractive index for the optical barrier is 0.094 with reference to the refractive index of the substrate ($n_{sub} = 1.5391$). The optical barrier is 5.68 μm underneath the surface, which is in agreement with the waveguide thickness in Fig. 1. Therefore, the waveguide layer comes into being between air and the optical barrier.

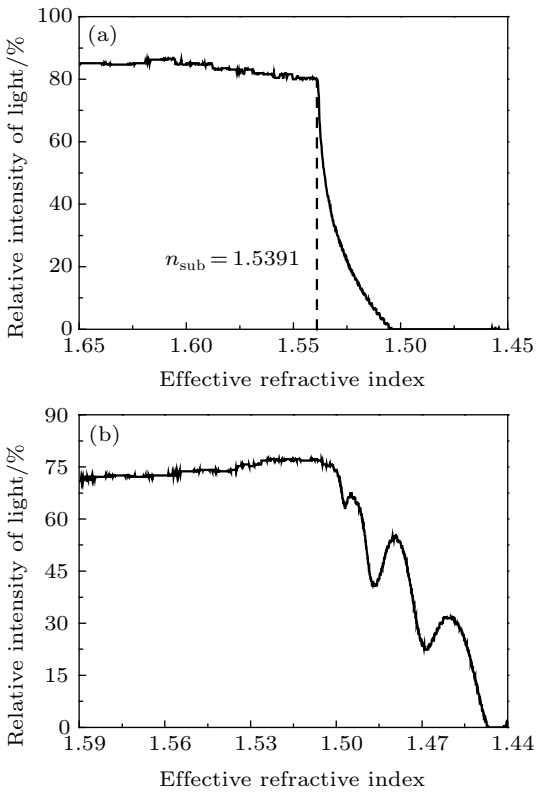


Fig. 5. Relative intensity of light as a function of effective refractive index for (a) unimplanted and (b) implanted Nd^{3+}-doped phosphate glasses.

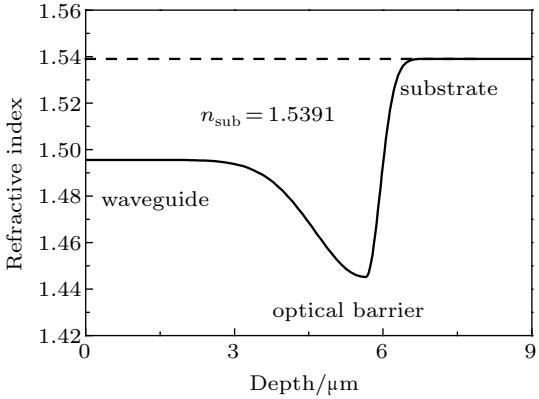


Fig. 6. Calculated refractive index distribution for the proton-implanted Nd^{3+}-doped phosphate glass waveguide.

In Figs. 7(a) and 7(b), the finite-difference beam propagation method (FD-BPM)[28] and the end-face coupling method were applied to investigate the optical guiding properties of the waveguide in Nd^{3+}-doped phosphate glass. The fundamental mode intensity distribution calculated by the FD-BPM in Fig. 7(a) suggests that the glass waveguide can well confine the light with 632.8-nm wavelength in the vertical direction. The intensity profile of the first propagation mode measured by the end-face coupling technique in Fig. 7(b) confirms the good optical confinement in the proton-implanted Nd^{3+}-doped phosphate glass waveguide. There are some narrow gaps in the measured light intensity distribution, which may be caused by poor polishing. The calculated and measured mode intensity distributions are a good match (comparing Fig. 7(a) with Fig. 7(b)). The propagation loss is considered to be one of the most important parameters to characterize optical waveguide performances. The propagation loss of the proton-implanted Nd^{3+}-doped phosphate glass waveguide was estimated to be 4.24 dB/cm by the back-reflection method.[29]

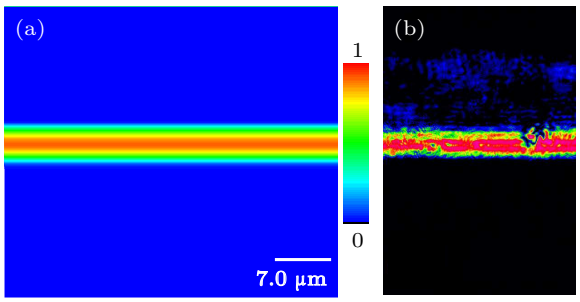


Fig. 7. (color online) (a) Calculated and (b) measured mode intensity distributions of the fundamental modes in the proton-implanted Nd^{3+}-doped phosphate glass waveguide.

4. Conclusion

A Nd^{3+}-doped phosphate glass waveguide structure was designed and formed by using implantation of protons at a dose of 8.0×10^{16} ions/cm^2 and an energy of 550.0 keV. The near-field intensity profile shows good confinement of the first mode with a wavelength of 632.8 nm. The calculated mode intensity profile is similar to the measured one. The refractive index of the waveguide layer is 0.05 higher than that of the optical barrier, according to the simulation of the RCM. The waveguide thickness is consistent with the theoretical simulation. The proton-implanted Nd^{3+}-doped phosphate glass waveguide is a promising candidate for electro-optical integrated circuit applications.

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