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RESEARCH ARTICLE

Near-infrared carbon-implanted waveguides in Tb^{3+}-doped aluminum borosilicate glasses

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Abstract Ion implantation has played a unique role in the fabrication of optical waveguide devices. Tb^{3+}-doped aluminum borosilicate (TDAB) glass has been considered as an important magneto-optical material. In this work, near-infrared waveguides have been manufactured by the (5.5 + 6.0) MeV C^{3+} ion implantation with doses of (4.0 + 8.0) $\times$ 10^{13} ions$\cdot$cm^{-2} in the TDAB glass. The modes propagated in the TDAB glass waveguide were recorded by a prism-coupling system. The finite-difference beam propagation method (FD-BPM) was carried out to simulate the guiding characteristics of the TDAB glass waveguide. The TDAB glass waveguide allows the light propagation with a single-mode at 1.539 μm and can serve as a potential candidate for future waveguide isolators.

Keywords Tb^{3+}-doped aluminum borosilicate (TDAB) glass, optical waveguide, ion implantation

1 Introduction

Optical waveguides can guide the light wave to propagate in a specified direction. They are indispensable in optical systems and networks including optical communication system and fiber-optic networks [1–3]. The choice of fabrication technique is a key consideration in the realization of optical waveguides [4]. Therefore, Ti diffusion technique [5], ion implantation [6], radio frequency (RF) magnetron sputtering [7], and plasma enhanced chemical vapor deposition (PECVD) [8] are widely utilized to manufacture optical waveguide structures. The ion implantation method has emerged as a competitive technique for the waveguide preparation in a diversity of optical transparent materials [9]. In the procedure of ion implantation, the energetic ions with positive charges bombard the target material to modify the properties of the surface layer in an acceleration system [10]. The ions lose energies by interacting with the nucleus and electrons of the target material [11]. They eventually stop at the micron-order depth below the surface of the target material [12]. The refractive index (RI) in the irradiated film is changed through damages and defects induced by the implantation, forming a waveguide structure [13]. The ion-implanted waveguides usually possess stable and compact characteristics [14]. In addition, when ions are implanted into a host material, they are absorbed by the substrate and become part of the material [15]. Therefore, the implanted layer does not fall off or peel off from the matrix.

The choice of matrix material is another factor that determines the performances of an optical waveguide [16]. The Tb^{3+}-doped aluminum borosilicate (TDAB) glass is a kind of inorganic material with wide applications in the field of both functional devices and high power laser systems, due to the unique properties that include –0.33 min/(Oe$\cdot$cm) Verdet constant at 0.6328 μm, simple preparation low optical absorption, and high resistance to laser damage [17]. Especially, it can be employed to block the reflected light in photonic integrated circuits as a class of Faraday rotation materials in visible and infrared regions [18,19]. Therefore, the TDAB glass is suitable for preparing various type waveguides. The method of carbon ion implantation has been applied to manufacture waveguides on the TDAB glass [20]. However, the optical characteristics of the carbon-implanted waveguides were studied in the visible range (0.6328 μm). As well known, optical waveguides operated at ~1.5 μm are indispensable in optical communications [21]. Therefore, the exploration

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of the 1.5 μm carbon-implanted TDAB glass waveguides is urgent needed for the telecommunication system. In this work, an optical waveguide in the TDAB glass has been fabricated by virtue of the ion implantation method and its guided characteristics in near-infrared telecommunication band around a wavelength of 1.5 μm have been studied in detail. It will be able to open up possibilities for waveguide isolators.

2 Experiments and simulations

The TDAB glass was synthesized by means of a melt-quenching method from high-purity oxides including SiO_2, B_2O_3, Al_2O_3, and Tb_2O_3 in the Chinese Academy of Sciences (CAS). The raw materials were mixed and melted at 1300°C in a platinum crucible for 120 min. The liquid was cast in a preheated brass mold and subsequently annealed to remove inner tension in the muffle furnace at transformation temperature (T_g). The wafer used for the spectroscopic measurements and the waveguide fabrication was cut from the bulk TDAB glass. Its length, width and height were 10, 5 and 2 mm respectively. The two surfaces with 10.0 mm × 5.0 mm size and opposite end-faces with 2.0 mm × 5.0 mm dimension were all polished to optical quality. The polished TDAB glass with rectangular shape is shown in the inset in Fig. 1.

To determine the formation parameters of the TDAB glass waveguide formed by ion implantation, the stopping and range of ions in matter code (SRIM 2013) was adopted to calculate the process of the ion irradiation [22–24]. Then, a proton implantation with 0.4 MeV energy and 8.0×10^{16} ions·cm^{-2} dose was conducted on one of the polished 10.0 mm × 5.0 mm surfaces of the TDAB glass in Nanaln (Jinan Jingzheng Electronics Co., Ltd.), as shown in Fig. 1. In the procedure of the ion irradiation, the current density of the hydrogen ions was controlled less than 100 nA·cm^{-2} to reduce excessive thermal effect.

After the irradiation, a Model 2010 prism coupler (Metricon) was adopted to measure the m-line spectrum of the implanted TDAB glass. The prism coupling system consists of a laser, a photodetector, and a coupling head. The laser is emerged as a light source. The photodetector is utilized to monitor the light intensity reflected by the prism. The coupling head enables a waveguide to be cohered with the prism closely. Figure 2 shows the schematic set-up for the prism coupling system. During the measurement, the intensity detected by the photodetector fluctuates when the incident angle changes. For some special angles, the incident light can tunnel into the waveguide layer through the air gap between the sample and the prism, causing a decrease in light intensity at the detector. Hence, the effective refractive indices can be calculated by using computer modeling techniques.

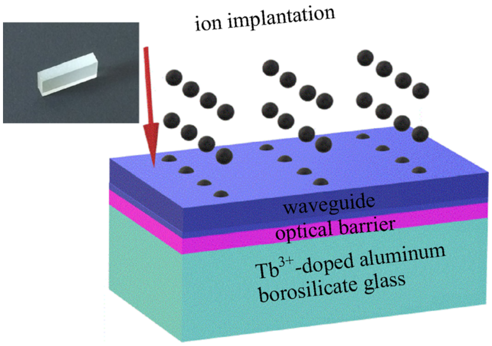

Fig. 1 Schematic of a waveguide formation by an ion implantation method. The inset is the photograph of the polished TDAB glass

3 Results and discussion

The vacancy distributions of the 5.5 (blue dot curve in Fig. 3) and 6.0 MeV (red dashed curve in Fig. 3) carbon ions irradiated into the TDAB glass were calculated by virtue of the SRIM 2013 code, as depicted in Fig. 3. The peaks of the vacancy distributions for the (5.5 + 6.0) MeV C^{3+} ion implantations are at the depths of 3.15 and 3.36 μm, respectively. The vacancy profile of double-energy carbon ions (black solid curve in Fig. 3) was obtained as simple algebraic sums of the corresponding pairs of single-energy

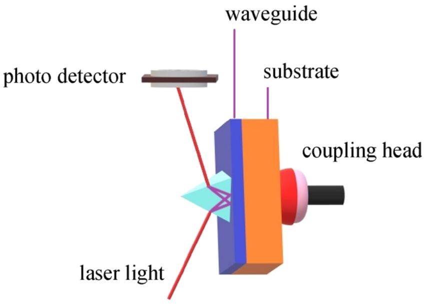

Fig. 2 Schematic of the set-up for the prism coupling method

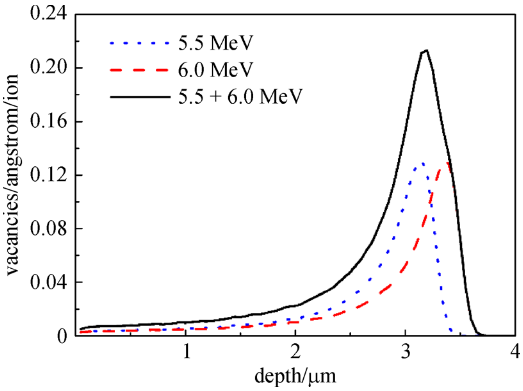

Fig. 3 Vacancy distribution versus the implantation depth for (5.5 + 6.0) MeV C^{3+} ions implanted into the TDAB glass

carbon ion profiles. The most of the vacancies of (5.5 + 6.0) MeV carbon ions are at 3.2 μm below the surface of the TDAB glass. It causes the decrease in density and RI, and hence produces an optical barrier in the TDAB glass substrate. Additionally, it is obvious to observe that the double-energy ion irradiation broadens the larger damage range than the single-energy irradiation, corresponding to a wider optical barrier layer formed at the end of the carbon-ion track. The broader optical barrier can reduce the light leakage and improve the capacity of the fabricated waveguide.

The prism coupling method is an efficient technique to couple the incident light into a waveguide and measure the effective RIs of the propagation modes. Figure 4 displays the dark-mode profile recorded by means of the Model 2010 prism coupling system after the double-energy carbon ion irradiation. In Fig. 4, the x axis denotes effective RI and the longitudinal coordinate suggests relative intensity of light. The sharp dip on the m-line spectrum represents the excited waveguide mode, suggesting that the light enters into the waveguide layer and propagates therein. Therefore, there is an optical propagation mode in the carbon-ion implanted TDAB glass waveguide from Fig. 4. The effective RI of the dip (1.7162) is smaller than the RI of the TDAB glass substrate (1.7172), which is due to the modified waveguide layer induced by the ion implantation. It indicates that the energetic carbon ion irradiation into the TDAB glass produces a reduced RI layer near the end of the carbon ion trajectory.

The finite-difference beam propagation method (FD-BPM) is one of the most commonly used calculation ways for studying the optical characteristics of light waves inside waveguide structures [25–27]. The optical field distribution in the TDAB glass waveguide fabricated by the (5.5 + 6.0) MeV C^{3+} ion irradiation with doses of $(4.0 + 8.0) \times 10^{13}$ ions·cm^{-2} was calculated by the FD-BPM software. Figure 5 illustrates the calculated field intensity profile of the fundamental mode. The formed waveguide was found to be single-mode in the vertical direction. The simulated effective RI of the fundamental mode in the computed transverse mode distribution is close to the counterpart on the dark-mode curves. The width of the calculated near-filed intensity image in the vertical direction is in agreement with the peak position of the vacancy distribution.

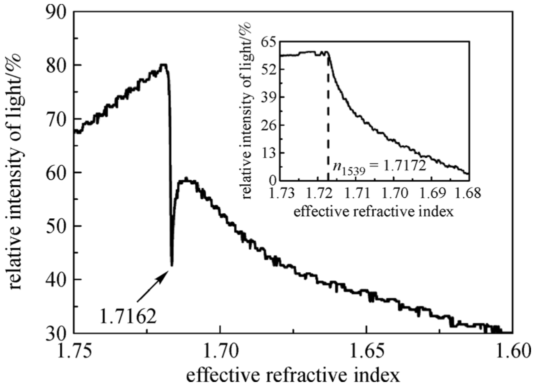

Fig. 4 Relative light intensity versus effective RI for the double-energy carbon ion implanted TDAB glass and the inset is the RI of the unimplanted TDAB glass

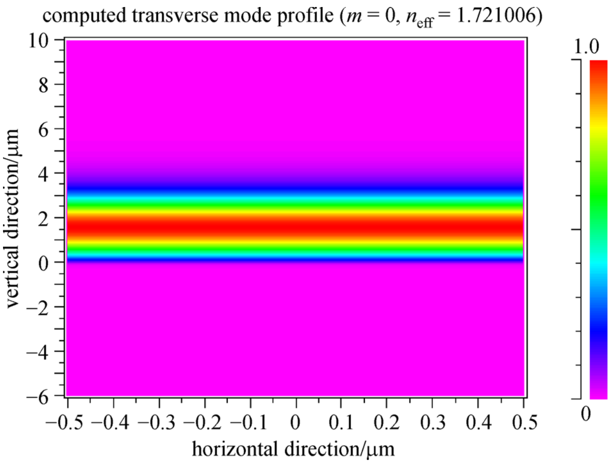

Fig. 5 Simulated guided mode intensity profile for the double-energy carbon ion implanted TDAB glass waveguide

4 Conclusion

A planar waveguide operating at 1.539 μm has been manufactured by utilizing the double-energy carbon ion irradiation with energies of (5.5 + 6.0) MeV and fluences of $(4.0 + 8.0) \times 10^{13}$ ions·cm^{-2} in the TDAB glass. The waveguide has a single-transverse-mode in near-infrared region from the m-line spectrum. The near-filed image calculated by the FD-BPM suggests that the TDAB glass waveguide can support single mode propagation at the wavelength of 1.539 μm. It is promising for the further development and application of waveguide-based optical isolators.

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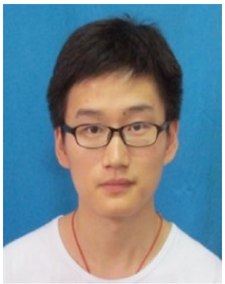

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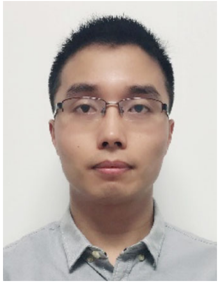

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