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Optical waveguides in magneto-optical glasses fabricated by proton implantation

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ABSTRACT

Planar waveguides in magneto-optical glasses (Tb^{3+}-doped aluminum borosilicate glasses) have been produced by a 550-keV proton implantation at a dose of 4.0×10^{16} ions/cm^2 for the first time to our knowledge. After annealing at 260 °C for 1.0 h, the dark-mode spectra and near-field intensity distributions are measured by the prism-coupling and end-face coupling methods. The damage profile, refractive index distribution and light propagation mode of the planar waveguide are numerically calculated by SRIM 2010, RCM and FD-BPM, respectively. The effects of implantation on the structural and optical properties are investigated by Raman and absorption spectra. It suggests that the proton-implanted Tb^{3+}-doped aluminum borosilicate glass waveguide is a good candidate for a waveguide isolator in optical fiber communication and all-optical communication.

1. Introduction

The optical isolator is an indispensable component to stabilize oscillation of a semiconductor laser diode by eliminating reflected light in advanced fiber communication systems [1–4]. The traditional bulk isolator can not be integrated in the micro-scale optical circuits. On the other hand, optical waveguide structures are important blocks for the miniaturization of electro-optic elements in integrated optics [5]. Therefore, the waveguide isolator has attracted more and more attention because it can be compatible with other optical components in integrated optics. As well known, the fabrication of a Faraday rotating waveguide is the first step to realize a waveguide isolator. The magneto-optical material and the waveguide fabrication technique are crucial issues to obtain high-quality Faraday rotating waveguides.

Magneto-optical glass is one of most used Faraday rotating materials for optical isolators and circulators in optical communication systems and high power laser systems, owing to its outstanding features (high Verdet constant, excellent homogeneity, high damage threshold and lower nonlinear refractive index). The magneto-optical glass used in the present experiments is Tb^{3+}-doped aluminum borosilicate glass (Tb_2O_3-SiO_2-Al_2O_3-B_2O_3). Its Verdet constant is −0.33 min/Oe/cm at a wavelength of 632.8 nm. The bulk laser damage threshold irradiated by a 1064-nm laser with 3 ns pulse width is more than 10 J/cm^2. The nonlinear refractive index n_2 is 2.55×10^{-13} esu. In view of the excellent performances, the Tb^{3+}-doped aluminum borosilicate glass has potential value as a Faraday rotating waveguide and an isolator.

There are several methods to fabricate Faraday rotating waveguides for integrated optics, which mainly include sputter epitaxy [6–9], direct wafer bonding [10,11] and laser annealing [12,13]. All these waveguide fabrication techniques require the deposition of a film of magneto-optical material onto a suitable substrate, which is costly and time consuming [14]. Compared with these methods, ion implantation is a process that charged energetic ions with hundreds of keV to a few MeV are introduced into the near-surface regions of target materials and optical waveguide structures can be easily constructed inside the transparent substrates [15–18]. In addition, the magneto-optical material in the present work is bulk Faraday glass. The growth or deposition of a film of magneto-optical material is not necessary. During ion implantation, radiation irradiation damage induced by the nuclear energy deposition at the end of the ion range gives rise to a decrease of the refractive index in a lot of optical materials. Therefore, a waveguide structure with a dimension of micrometer or sub micrometer scale is

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formed between the low-index optical barrier and the material surface (air). Furthermore, it has been possible to controllably alter the refractive index profile of the ion-implanted waveguide by varying the implantation and annealing parameters. Therefore, the combination of magneto-optical glasses and ion implantation is an important step towards the realization of Faraday rotating waveguides. In the present work, for the first time, ion implantation is applied to construct waveguide structures in magneto-optical glasses and optical properties of these waveguides are also presented in detail.

2. Experiments

The magneto-optical glass with dimensions of 10.0 mm × 5.0 mm × 2.0 mm is provided by the Xi'an Institute of Optics and Precision Mechanics of Chinese Academy of Sciences (CAS). The samples are optically polished before any measurement is carried out. The density is 4.98 g/cm^3, which is measured by Archimedes method with water as the immersion fluid. As shown in Fig. 1(a), the refractive index of the substrate measured by Metricon 2010 Prism Coupler is determined to be 1.7384 at 632.8 nm.

The magneto-optical glasses have been irradiated by a 550-keV proton implantation at a dose of 4.0×10^{16} ions/cm^2 from an ion implanter at the Institute of Semiconductors of CAS at room temperature. To reduce the charge pileup on the Faraday rotating glass during the proton irradiation, the surface was covered by a Au film with thickness of 2–3 nm. The proton current density was maintained at about 50 nA/cm^2 to prevent the excessive heating of the glasses during the implantation process.

Point defects and color centers would be incurred in the waveguide layer during the proton implantation process. The annealing treatment at moderate temperatures of 200–400 °C and times of 20–60 min could effectively remove these point defects and color centers. Therefore, the implanted magneto-optical glasses were furnace annealed in air at 260 °C for 1.0 h after the implantation. The annealing temperature is lower than the transition temperature (T_g) of the Tb^{3+}-doped aluminum borosilicate glass. Its structural, optical and magnetic properties are well preserved after the thermal treatment.

The optical planar waveguides in Tb^{3+}-doped aluminum borosilicate glasses were characterized by the prism-coupling and end-face coupling methods. In the former case, the polarized light from a He-Ne laser struck the base of a rutile prism, which was brought into contact with the waveguide. The intensity of the reflected light from the prism bottom was detected by a silicon photodetector. In the latter case, a laser beam was end-fire coupled to the waveguide, which was located on a 6D optical stage. The mode pattern of the transmitted light was imaged on a CCD camera connected to a computer.

The Raman spectra before and after the irradiation were recorded on a laser Raman spectrometer (LabRAM HR800, Horiba Jobin Yvon). The absorption spectra of both the unimplanted and implanted Tb^{3+}-doped aluminum borosilicate glasses were measured by a UV–vis–NIR spectrophotometer (JASCO U-570).

3. Results and discussion

In Fig. 1, a well-known *m*-line technique (Metricon 2010 Prism Coupler) was used to measure the substrate refractive index and the dark-mode spectra of the planar waveguide in the Tb^{3+}-doped aluminum borosilicate glass formed by a 550-keV proton implantation at a dose of 4.0×10^{16} ions/cm^2 after the annealing treatment. When the propagation constant of the incident beam along *z*-axis in the prism matches the propagation constant of a waveguide mode, a lack of reflected light would result in a dip, which may correspond to a propagation mode. As shown in Fig. 1(b), four obvious modes are observed, and the effective refractive indices of the modes are listed in Table 1. The first three dips are relatively sharp and narrow, indicating that they are most likely to correspond to the guided modes. The fourth dip is also clearly seen, but it shows an appreciable broadening, which represents a leaky mode. As one can see, all the effective refractive indices of the TE modes are less than the substrate refractive index of the Tb^{3+}-doped aluminum borosilicate glass, which means a barrier-type waveguide is fabricated in the glass after the proton implantation.

The ion-implanted waveguide usually is several-micrometers thick and the direct measurement of its refractive index profile is quite complicated. The reflectivity calculation method (RCM) that has been proven to be particularly successful for multi-mode waveguides fabricated by ion implantation was used to fit the refractive index profile of the proton-implanted Tb^{3+}-doped aluminum borosilicate glass waveguide based on the effective refractive indices of the guided modes and the numerical optimization [19]. Fig. 2 shows the refractive index profile of the fabricated waveguide according to RCM and Table 1 also gives the theoretical mode index values. As mentioned in the prism-coupling measurement, it is a typical barrier-confined refractive index profile. The proton implantation induced a slight negative index change about −0.0002 in the guiding region and a large negative index change about −0.002 at the end of the ion trajectory, where an optical barrier located about 3.75 μm below the surface is formed. Therefore, the region between the optical barrier and the

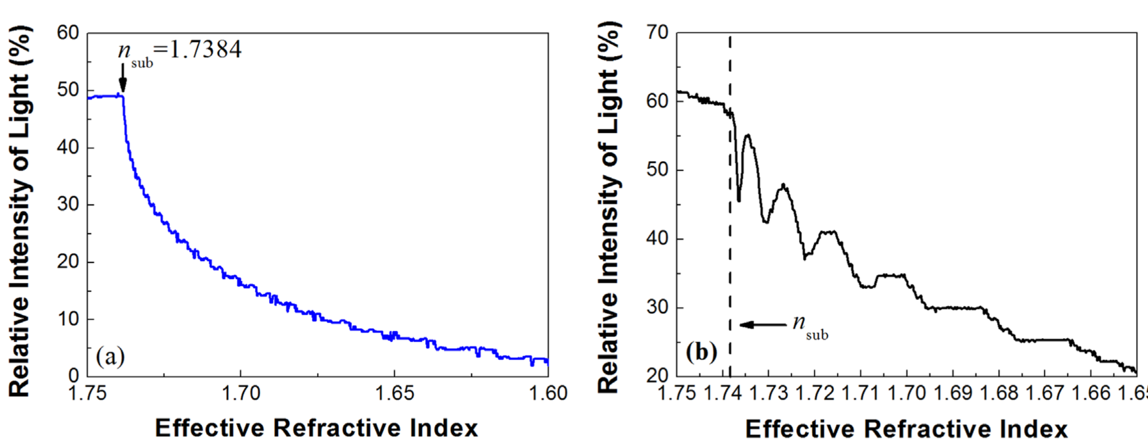

Fig. 1. Relative intensity of TE polarized light reflected from the prism as a function of effective refractive index at 632.8 nm for (a) the Tb^{3+}-doped aluminum borosilicate glass substrate and (b) the proton-implanted Tb^{3+}-doped aluminum borosilicate glass waveguide.