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Optical characteristics of an oxyfluoride glass waveguide formed by a proton implantation

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ABSTRACT

An optical waveguide was fabricated by H^+ ion implantation with an energy of 400 keV and a dose of 8×10^{16} ions/cm^2 in the oxyfluoride glass for the first time to the best of our knowledge. The dark mode spectra of the waveguide were measured by a prism coupling method before and after the thermal treatment. The number of modes was reduced after annealing. The implantation process of 400 keV H^+ ions into the oxyfluoride glass was simulated by using the SRIM 2013 program. The refractive index distribution of the ion-implanted waveguide was reconstructed by the reflection calculation method. The refractive index was decreased in the waveguide region and there was an optical barrier with a reduced refractive index at the end of the ion range. The proton-implanted oxyfluoride glass waveguide is a desirable alternative for the fabrication of a compact optical integrated device.

Introduction

In the last decades, the research on optoelectronic devices based on waveguide structures has been one of the hot topics [1]. The most basic challenge is to manufacture optical waveguides on transparent materials [2]. A planar waveguide can have confinement effect on light intensity in one direction, which is the simplest and most commonly used structure for light propagation. The principle of an optical waveguide is Snell's law. The light is incident on a medium with low refractive index from another high refractive-index material. When the incident angle is larger than the critical value, the total internal reflection occurs. Therefore, the incident light is totally reflected to the high-index medium and propagated inside it through multiple total reflections [3–6]. According to this theory, a variety of techniques have been adopted to manufacture optical waveguides, such as femtosecond laser inscription and ion diffusion.

Ion implantation has been widely employed in the preparation of optical waveguides, owing to its high processing accuracy, and desirable controllability and repeatability [7–10]. It can be used in a wide temperature range for a variety of optical materials [11]. High-energy implanted ions continuously collide with atomic nuclei and extra-nuclear electrons of the target material [12]. They finally stop in a certain region, owing to the gradual deposition of energy [13]. It causes damage or variation of spontaneous polarization [14]. Thereby, the refractive index of the material is changed, forming an optical waveguide [15].

As well known, the performances of physical devices depend on both preparation techniques and matrix materials [16,17]. The oxyfluoride glass is a kind of optical window material. It has attracted more and more attention, owing to its competitive thermal shock resistance, high mechanical strength, and good optical uniformity. Compared with crystal counterparts, it can be prepared to large size. In the work, the oxyfluoride glass was used as matrix material for the optical waveguide structure.

In the past years, there have been a lot of theoretical and experimental investigations on the structure and optical properties of oxyfluoride glasses [18,19]. The formation of optical waveguide structures by using femtosecond laser inscription has been reported in the glasses [20]. However, studies on the fabrication of optical waveguides in oxyfluoride glasses by ion implantation have not been explored. In this work, the optical waveguide is constructed by H^+ ion implantation in the oxyfluoride glass. The dark mode spectrum, refractive index profile and damage distribution are studied in detail.

Experiments

Oxyfluoride glasses were prepared by a melt-quenching technique with high-purity raw materials. The well mixed raw materials were

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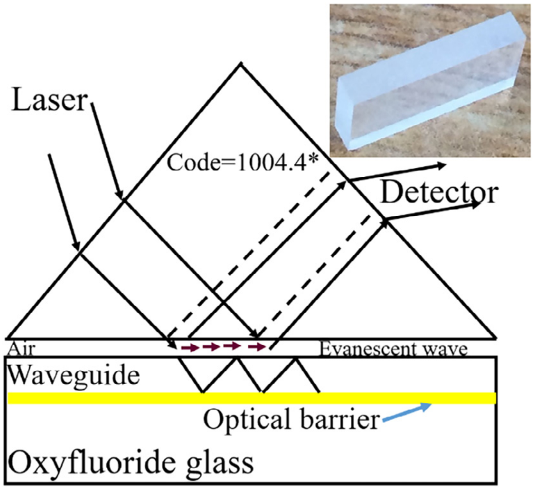

Fig. 1. Schematic of the measurement mechanism of the prism coupling technique and the inset is the photograph of the implanted oxyfluoride glass.

Table 1
The details of the annealing conditions.

Process	Annealing condition
S0	As implanted
S1	260 °C 60 min
S2	S1 + 310 °C 60 min

melted in a platinum crucible by a silicon carbide electric furnace. Then, the melt was cast into an iron mold. Finally, it was annealed at Tg (glass transition temperature) for 3 h and cooled to room temperature at a rate of 10 °C/h. The oxyfluoride glass with a size of 10 mm × 5 mm × 1.5 mm was optically polished for the formation of waveguide structures. Before the ion irradiation, the refractive index and transmission spectrum were recorded by a prism coupler and a spectrophotometer, respectively. Taking into account the thickness and refractive index profile of the waveguide to be prepared, a 400-keV H^+ ion implantation at a dose of 8×10^{16} ions/cm^2 was conducted on the optically polished surface (10 mm × 5 mm) at room temperature under vacuum. The ion beam was confined within 100 nA to prevent thermal effects during the implantation process. The irradiation was performed on an ion-implantor of Nanaln.

After the ion implantation, the waveguide performances were measured by using a Model 2010 prism coupler manufactured by Metricon Inc., such as the distribution of the dark mode and the effective refractive index corresponding to each guided mode. The prism code was 1004.4 and the refractive indices of the prism were 1.9649 and 1.9346 at 632.8 and 1539 nm, respectively. A He-Ne laser (632.8 nm) and a semiconductor laser (1539 nm) were equipped in the prism-coupling system to serve as working sources. Fig. 1 shows the schematic plot of the prism coupling measurement. Afterwards, different annealing conditions were chosen to anneal the glass waveguide in air, as listed in Table 1. Then the above tests were repeated to study the changes of the ion-implanted oxyfluoride glass optical waveguide after annealing.

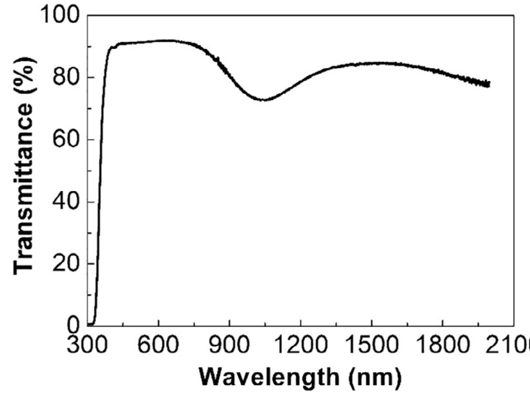

Fig. 3. Transmission spectrum of the oxyfluoride glass.

Results and discussion

The refractive index of the oxyfluoride glass was measured before the ion implantation. As shown in Fig. 2, the substrate refractive indices at wavelengths of 632.8 and 1539 nm were 1.5265 and 1.5128, respectively.

Fig. 3 shows the transmittance spectrum of the oxyfluoride glass with a thickness of 1.5 mm, which was measured by means of a JASCO U-570 UV-VIS-NIR spectrophotometer. The transmission rate was about 90% in the wavelength region of 400–2000 nm, except for a broad absorption band centered at 1053 nm.

Fig. 4 shows the reflected light intensity as a function of the effective refractive index before and after the thermal treatments at wavelengths of 632.8 and 1539 nm. It measured by the prism coupling method after the ion implantation. The effective refractive indices of the all dips were smaller than the substrate refractive index, which meant that the H^+ ion-implanted oxyfluoride glass produced an optical barrier with a decreased refractive index at the end of the ion range. The sharp dip in the dark mode spectrum represented the excited guided mode, indicating that the light entered into the waveguide region and propagated in it. For 632.8-nm light, a total of three dark modes were excited for the as-implanted waveguide in Fig. 4(a). There was two propagation modes in the dark mode spectrum for the oxyfluoride glass waveguide after the thermal treatment at 260 °C for 1 h. Only one mode was obtained in the 310-°C annealed waveguide in Fig. 4(c). Therefore, as the number of the annealing treatments

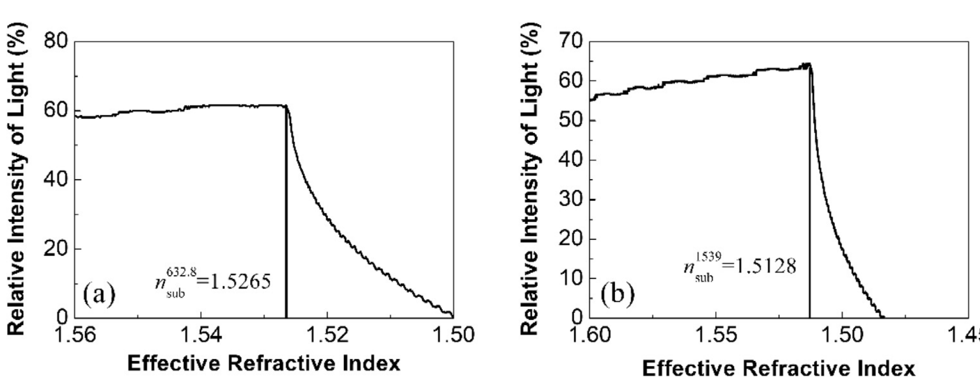

Fig. 2. Refractive index of the oxyfluoride glass substrate at wavelengths of (a) 632.8 nm and (b) 1539 nm.