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RESEARCH ARTICLE

Near-infrared carbon-implanted Er^{3+}/Yb^{3+} co-doped phosphate glass waveguides

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Abstract The Er^{3+}/Yb^{3+} co-doped phosphate (EYDP) glass waveguides operated at 1539 nm have been manufactured by using the implantation technique of carbon ions under the condition of 6.0 MeV energy and 5.0 $\times$ 10^{13} ions/cm^2 fluence in this work. The ion implantation process was computed by means of the stopping and range of ions in matter. The dark-mode spectrum at 1539 nm of the waveguide was recorded by the method of the prism coupling measurement. The microscopic image of the fabricated structure was photographed by an optical microscope. It is the first step for the application of the waveguides on the base of EYDP glasses in optical-integrated photonic devices at near-infrared band.

Keywords waveguide, Er^{3+}/Yb^{3+} co-doped phosphate (EYDP) glasses, carbon-ion implantation

1 Introduction

As one kind of laser gain material, Er^{3+}/Yb^{3+} co-doped phosphate (EYDP) glasses have been of increasing interest in the last decade for researches and applications in many fields of science and technology. It is because that they have outstanding performances in the infrared region and can be applied to optical storages and eye-safe light sources. Particularly, they emit wavelengths in the low-loss telecommunication windows around 1.5 μm. Therefore, EYDP glasses play key roles in optical communications. In addition, they can be directly pumped by using a 980-nm III-V diode laser [1–3].

A waveguide configuration constructed in the EYDP glass is considered as a promising photonic component operating at the 1.5-μm band. For example, EYDP glass waveguides can serve as lasers and amplifiers in high functionality integrated structures, which can considerably improve the emission efficiency [4]. Therefore, various techniques have been developed to form EYDP glass waveguides. In 2004, Taccheo et al. reported an active channel waveguide with a single-mode in an EYDP glass by a femtosecond laser writing technique [5]. Tan et al. used the method of He^+ ion implantation combined with Ar^+ ion beam etching to produce an optical ridge waveguide in 2007 in an EYDP glass [6]. Zhao et al. fabricated a buried EYDP glass waveguide in 2011 by the combination of the K^+-Na^+ ion exchange and the filed-assisted annealing [7]. Chen et al. in 2016 formed optical ridge waveguides in EYDP glasses by the swift heavy ion irradiation of C^{5+} followed by the femtosecond laser ablation [8]. Especially, ion implantation is one of the most competitive formation techniques for constructing wave-guide structures in the EYDP glasses, owing to its controllability, low fabrication cost and reproducibility [9–13]. Although the helium- and silicon-ion implantations have separately been performed to fabricate waveguides in EYDP glasses [6,14], the carbon ion implantation has not been employed until now on the EYDP glass. More importantly, energetic carbon ions is one of the most commonly irradiated ions for waveguide formations. It has fabricated a number of high-quality waveguide structures and novel properties on a great deal of transparent optical glasses and crystals and so on [15–20]. In addition, the features of these previous ion-implanted EYDP glass waveguides are all studied in the visible (632.8 nm) region. However, ion-implanted EYDP glass waveguide devices operated in the telecommunication window around ~1.5 μm are indispensable in functional optical-communication networks. Therefore, it is important to explore the investigation of carbon-implanted waveguides at 1.5 μm in EYDP glasses. In this report, we focused on the

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construction of optical planar waveguides in EYDP glasses by using the 6.0 MeV carbon ion implantation with a fluence of 5.0 × 10^{13} ions/cm^2. The optical characteristics of the EYDP glass waveguide were measured and simulated at 1539-nm wavelength in detail.

2 Experiments

The EYDP glass with composition of P_2O_5-K_2O-Nb_2O_5-BaO-Sb_2O_3-La_2O_3-Al_2O_3-Er_2O_3-Yb_2O_3 was synthetized by means of the standard melt-quenching technique. The glass contained the contents of Er_2O_3 and Yb_2O_3 were 2 and 1 mol.%, respectively. The mixture of raw oxides with calculated quantities was melted in an electric furnace at a temperature of 1200°C for a time of 3 h. Afterwards, the glass melt was cast into a mold that was heated previously and annealed at the transition temperature (T_g) in a muffle furnace to avoid thermal stresses. The as-grown EYDP glass was cut into rectangular parallelepipeds with sizes of 10.0 mm × 5.0 mm × 2.0 mm. Both sides of the each glass wafer were polished to optical quality.

Before the ion implantation, some spectroscopic properties of the host EYDP glass were measured as follows. The absorption spectrum was recorded from 300 to 1800 nm by a JASCO U-570 UV-VIS-NIR spectrophotometer. The refractive index was determined by an m-line technique with an accuracy of 0.0002. The photoluminescence spectrum in the vicinity of 1.5 μm and the decay curve of fluorescence lifetime were measured by an Edinburgh FLS920P spectrometer.

The carbon ion beam used for implantation was generated by a 2 × 1.7 MV tandem Van de-Graaff accelerator in Peking University. The energy was chosen to be 6.0 MeV and the fluence was selected to be 5.0 × 10^{13} ions/cm^2 in consideration of the thickness of the optical waveguide and the damage ratio, respectively. In such a case, a waveguide layer came into being beneath the surface of the EYDP glass. The optical characteristics of the waveguide including the microscope image of the waveguide cross section and the dark-mode spectrum were measured as follows. The microscopy photograph of the implanted end face was recorded by a microscope operating in transmission mode. The *m*-line spectrum including the effective refractive indices of the guided modes was collected by a metricon prism coupler system with a semiconductor laser (Model 2010).

3 Results and discussion

Figure 1(a) shows the transmittance spectrum of the as-synthesized EYDP glass in the wavelength range of 300 – 1800 nm. Its thickness is measured to be 2.0 mm, as mentioned in the experiment section. The transparency is relatively high in Fig. 1(a) and even reaches up to 97% in the wavelength range of 1050 – 1450 nm. Six dominating absorption bands are observed in the transmittance spectrum. They correspond to the following transitions of Er^{3+} ions: $^4I_{15/2} \rightarrow {}^4G_{11/2}$ (378 nm), $^4I_{15/2} \rightarrow {}^4F_{7/2}$ (486 nm), $^4I_{15/2} \rightarrow {}^2H_{11/2}$ (521 nm), $^4I_{15/2} \rightarrow {}^4F_{9/2}$ (649 nm), $^4I_{15/2} \rightarrow {}^4I_{11/2}$ (975 nm), and $^4I_{15/2} \rightarrow {}^4I_{13/2}$ (1532 nm). The protuberance at about 853 nm is due to the change of light sources. Figure 1(b) depicts the refractive index of the substrate (n_{sub}) for the EYDP glass measured by a Metricon 2010 prism coupler at a wavelength of 1539 nm. The n_{sub} is 1.5205 at 1539 nm, as the dashed line represented.

Figure 2(a) shows the luminescence emission spectrum in the wavelength range from 1400 to 1650 nm for the EYDP glass. It is excited with a wavelength of 980 nm. There is a characteristic band centered at 1534 nm, which is originated from the transition from the meta-stable level of $^4I_{13/2}$ to the terminal level of $^4I_{15/2}$. The full width at half maximum (FWHM) at the peak is 34 nm. Figure 2(b) illuminates the fluorescent decay curve of the $^4I_{13/2} \rightarrow {}^4I_{15/2}$ transition for the Er^{3+} ions in the EYDP glass. The fluorescence lifetime of ~8.3 ms is calculated by fitting the fluorescence decay curve with the first exponential equation.

The nuclear energy loss and electronic energy loss during the ion implantation process were calculated by the

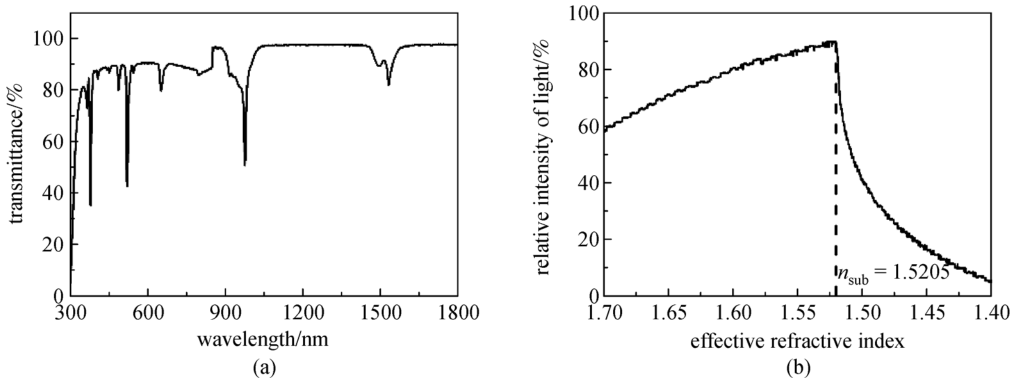

Fig. 1 (a) Transmittance spectrum and (b) refractive index of the EYDP glass

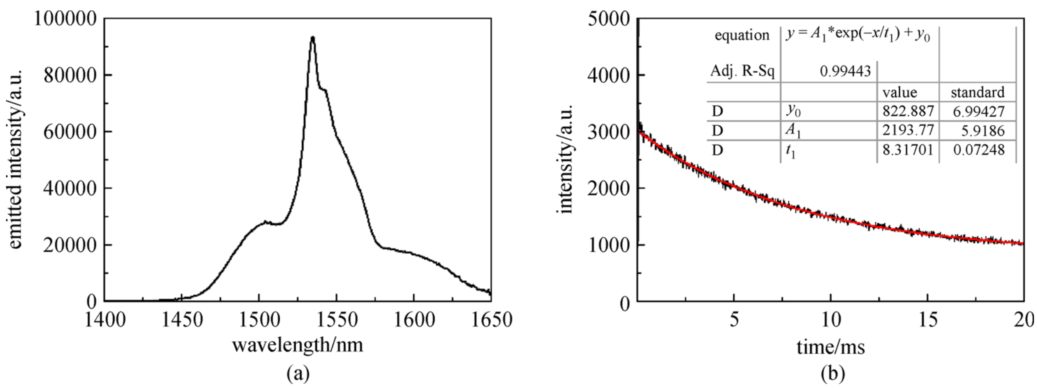

Fig. 2 (a) Photoluminescence spectrum and (b) lifetime curve of the EYDP glass

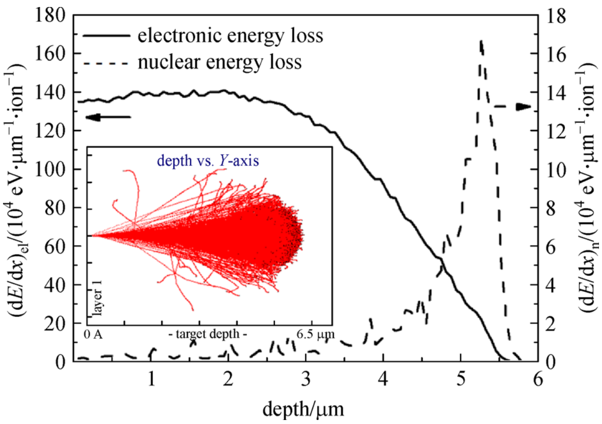

Fig. 3 Energy losses versus the penetration depth for the 6.0 MeV carbon implantation into the EYDP glass

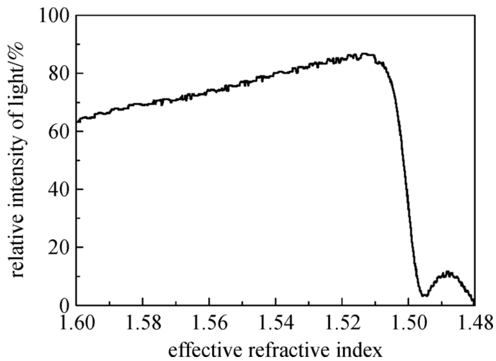

Fig. 4 Relative intensity of light as a function of the effective refractive index at a wavelength of 1539 nm for the modes in the carbon-implanted EYDP glass waveguide

stopping and range of ions in matter code (SRIM 2010) for the 6.0 MeV carbon ion implantation into the EYDP glass [21], as shown in Fig. 3. On the EYDP surface within the range of 0 – 5.2 μm, the electronic energy loss is dominant over the nuclear one. It should be noted that the electronic energy loss remains ~ 1.4 keV/nm from 0 to 2.5 μm and then declines rapidly to 0 at the end of the ion track. On the other hand, the nuclear energy loss is approximately equal to zero in the near surface region (0 – 4.0 μm) and reaches rapidly to the maximum value (0.17 keV/nm) at a depth of 5.26 μm.

Figure 4 shows the *m*-line spectrum at a wavelength of 1539 nm collected by a Metricon Model 2010 prism coupler system with a resolution of 0.0002 for the planar waveguide structure in the EYDP glass manufactured by the 6.0 MeV carbon ion irradiation at fluence of 5.0×10^{13} ions/cm^2. The rutile prism was attached by the implanted surface of the EYDP glass and the photodetector were mounted on a rotation stage in the prism coupling system. To couple light waves into the optical waveguide, adequate pressure must be applied by a coupling head between the implanted surface and the prism. Propagation modes may be excited in the carbon-implanted EYDP glass waveguide by varying the angle at which the incident semiconductor laser beam struck the base of the rutile prism. Then a drop in the intensity came into being on the photodetector. As shown in Fig. 4, there is one dip in the *m*-line spectrum at 1539 nm. It suggests that the waveguide is found to maintain only one guided mode on the basis of the prism-coupling theory. Therefore, a confinement of light can be realized in the fabricated waveguide. As one can see, the effective refractive index of the propagation mode is 1.4955 at 1539 nm, which is less than the substrate index. It means that the single-mode waveguide structure is an "optical barrier" type.

Figure 5 shows the cross-sectional end-face of the waveguide structure produced by the implantation of carbon ions in the EYDP glass. It was observed by a phase contrast microscope in which the difference in color represented the change in refractive index. A stripe with smooth and homogeneous shape was presented on the near-surface of the EYDP glass, which suggests that an optical planar waveguide structure was fabricated after the carbon irradiation [22]. The width of the stripe cross-section is approximately equal to 5.3 μm, corresponding to

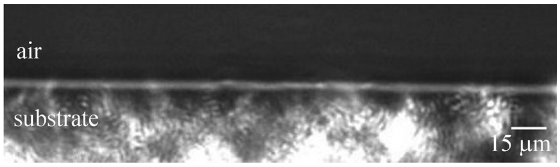

Fig. 5 Microscope image of the cross section for the carbon-implanted EYDP glass waveguide

the calculated range of the 6.0 MeV carbon implantation into the glass based on SRIM.

4 Conclusion

Waveguiding configurations have been formed in EYDP glasses by using the 6.0 MeV carbon ion implantation at a fluence of 5.0×10^{13} ions/cm^2. The waveguide is single mode at a wavelength of 1539 nm based on the dark-mode spectrum. The carbon-implanted EYDP glass waveguide has the potential to act as a near-infrared photonic element for optical communications.

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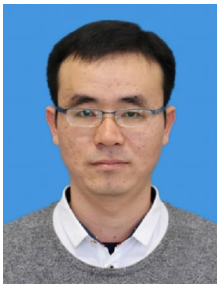

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