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Optical waveguides in fluoride lead silicate glasses fabricated by carbon ion implantation[*]

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The carbon ion implantation with energy of 4.0 MeV and a dose of 4.0×10^{14} ions/cm^2 is employed for fabricating the optical waveguide in fluoride lead silicate glasses. The optical modes as well as the effective refractive indices are measured by the prism coupling method. The refractive index distribution in the fluoride lead silicate glass waveguide is simulated by the reflectivity calculation method (RCM). The light intensity profile and the energy losses are calculated by the finite-difference beam propagation method (FD-BPM) and the program of stopping and range of ions in matter (SRIM), respectively. The propagation properties indicate that the C^{2+} ion-implanted fluoride lead silicate glass waveguide is a candidate for fabricating optical devices.

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As well known, the first issue is the fabrication of optical waveguide structures in the development of integrated optics, because waveguides can produce optical compact devices. An optical waveguide can confine the light propagation in the micro structure with the order of micrometers. It relies on the principle of total internal reflection, which occurs at the interface of two kinds of media with different refractive indices. Moreover, a waveguide is also applied to process optical signals in modern communication systems. An effective fabrication technique and a suitable host material are two important factors to form a high-quality optical waveguide structure[1-7].

Ion implantation technique has been widely used for doping in the field of semiconductors because it introduces impurity concentrations in selected areas and controlled depths below the surface as well as provides accurate dose. Furthermore, as an effective modification technology, ion implantation also can change the refractive index of an optical material in the near-surface region, thus forming an optical waveguide structure. The variation in refractive index is closely related to the material itself (such as composition and structure), and also depends on the species, energy and dose of implanted ions[8]. Compared with the traditional preparation methods of optical waveguide, the technique of ion implantation has its unique advantages. It can be carried out at room temperature or at low temperature[9]. The injected energy and dose can be precisely controlled, and a wide variety of ions can be chosen[10]. A number of waveguides with accepted performances have been produced by the ion implantation method[11,12]. For example, the carbon ions-implanted soda lime glass channel waveguides show good confinement with monomode and multimode[13], and the oxygen-implanted fused quartz waveguide has a low propagation loss of 0.14 dB/cm after the reasonable annealing treatment[14].

The fluoride lead silicate glass with the composition of SiO_2-PbO-R_2O-RF (R=Li, Na, K) has aroused increased interest for researches and applications in many fields of science and technology. It is physically and chemically stable, and has high transmittance in the visible and near-infrared bands[15]. It can offer adaptability to a variety of waveguide formation techniques. Therefore, here, the fluoride lead silicate glass is chosen as a host material to form an optical waveguide structure.

To the best of our knowledge, there is no report on the ion implanted fluoride lead silicate glass waveguide. It is necessary to explore the experimental conditions for the preparation of optical waveguides by ion implantation in

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the glass. In this paper, we focus on the fabrication and optical properties of the planar waveguide by using the carbon ion implantation in the fluoride lead silicate glass.

The fluoride lead silicate glass with the composition of (80−x) mol% SiO_2-x mol% PbO-20 mol% (R_2O+RF) (where R=Li, Na) was prepared by the melt-quenching method in the Chinese Academy of Sciences. The mixed batches of 1 900 g were melted in a platinum crucible at 1 380—1 440 °C for 4 h. Then, the melt was poured onto a preheated brass mold (350 °C) and subsequently annealed at 460 °C for 2 h at a muffle furnace. Finally, the glass was cut and polished into wafers with size of 10.0 mm×10.0 mm×2.0 mm for the waveguide fabrication and characteristic measurements, as shown in the inset of Fig.1.

To produce an optical waveguide, a carbon ion implantation with energy of 4.0 MeV and a dose of 4.0×10^{14} ions/cm^2 from a 2×1.7 MV tandem accelerator was carried out on the polished facet of the fluoride lead silicate glass with size of 10.0 mm×10.0 mm at room temperature in vacuum. The fabrication process of the planar waveguide is shown in Fig.1, and was performed at the State Key Laboratory of Nuclear Physics and Technology in Peking University. In order to prevent the glass from being charged and to avoid thermal effects, the current density of the implanted carbon ions was maintained at a low level.

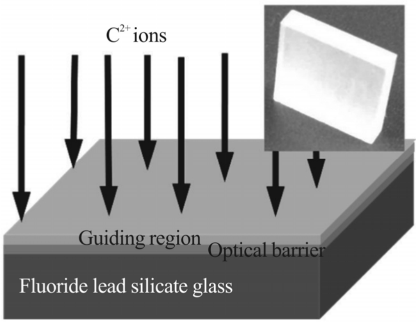


Fig.1 Schematic for the waveguide fabrication in the fluoride lead silicate glass (The inset is the photo of the polished glass.)

Before the ion implantation process, the bulk refractive index and transmittance spectrum of the fluoride lead silicate glass were measured by a Metricon 2010 Prism Coupler and a Lambda 950 UV-VIS-NIR spectrophotometer, respectively. SRIM 2010 (stopping and range of ions in matter) was employed to choose the appropriate species and energy of the implanted ions. After the irradiation, the prism coupling method was used to measure the dark-mode spectrum of the carbon-implanted fluoride lead silicate glass. The reflectivity calculation method (RCM) was utilized to calculate the refractive index profile. The finite-difference beam propagation method (FD-BPM) was applied to simulate the transverse mode distribution in the waveguide.

Fig.2(a) shows the relative intensity of the incident light with wavelength of 632.8 nm reflected from the Metricon 2010 prism coupler versus the effective refractive index for the fluoride lead silicate glass. Its refractive index at wavelength of 632.8 nm is 1.585 6, as shown in Fig.2(a). Fig.2(b) shows the transmittance spectrum of the fluoride lead silicate glass with a thickness of 2.0 mm in the wavelength range of 250—2 500 nm. It can be seen from Fig.2(b) that its transmission ratio can reach up to 90%. In addition, there is a protuberance at 848 nm, which is due to the change in the laser wavelength[16].

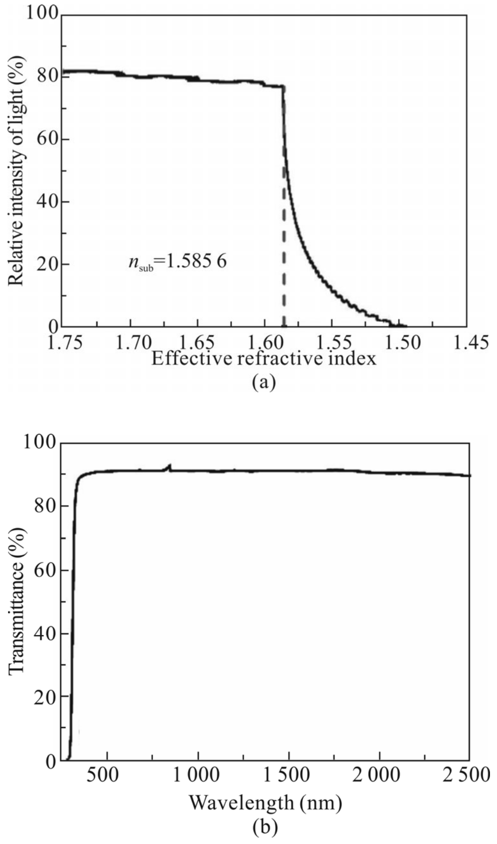


Fig.2 (a) Refractive index and (b) transmittance spectrum of the fluoride lead silicate glass

When C^{2+} ions with energy of 4.0 MeV implant into the fluoride lead silicate glass, there will be the electronic energy loss and nuclear energy loss. Therefore, SRIM 2010[17] was employed to calculate the energy loss profiles, as shown in Fig.3. The inset of Fig.3 shows the lateral straggling of the implanted carbon ions in the fluoride lead silicate glass. The electron energy loss is mainly concentrated on the glass surface (0—3.50 μm), and its maximum value is 1.48 keV/nm. While at the end of the C^{2+} ions range (i.e., a depth of 3.65 μm), there is most of nuclear energy loss, resulting in damage in the glass. The damage leads to a decrease in the density of the glass, forming an optical barrier of low refractive index[18,19].

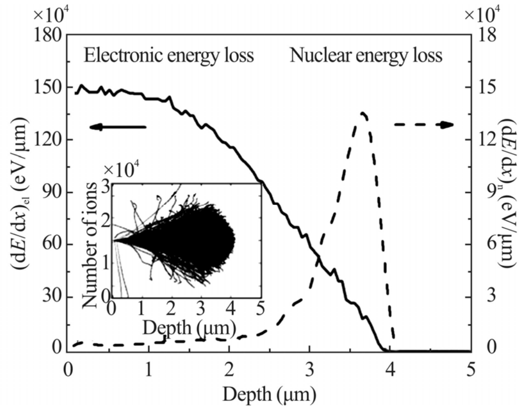
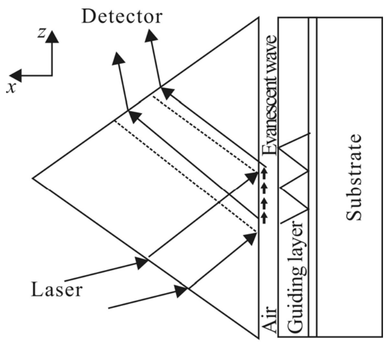
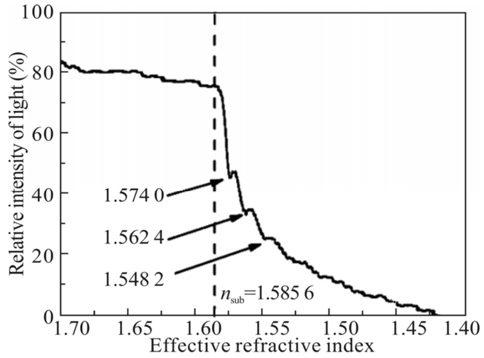


Fig.3 Nuclear energy loss and electronic energy loss versus the penetration depth for the 4.0 MeV C^{2+} ions implanted in the fluoride lead silicate glass (The inset shows the lateral straggling of the implanted carbon ions in the fluoride lead silicate glass.)

The prism coupling method is one of the most effective techniques to couple light into an optical waveguide[20]. Fig.4(a) shows the schematic diagram of the prism coupler. In the experiment procedure, a prism with high refractive index is placed on one of the polished surface of the waveguide, leaving a narrow air gap between it and the waveguide surface. The incident light is totally reflected at the bottom of the prism, and the evanescent field is formed in the air gap. If the air gap is thin enough ($8/\lambda$—$4/\lambda$), the evanescent field can reach the surface of the waveguide. When the z-axis component of the wave vector in the prism is equal to the propagation constant of the light in the waveguide, the incident light can be coupled into the waveguide through the field[21]. Fig.4(b) shows the relative intensity of light as a function of the effective refractive index, which is measured by the prism coupling method. The effective refractive indices of the first three modes are 1.574 0, 1.562 4 and 1.548 2, as shown in Fig.4(b). They are all less than the substrate refractive index (n_{sub}=1.585 6), which indicates that a waveguide structure with an optical barrier at the end of the ion range can be fabricated in the carbon-implanted fluoride lead silicate glass.



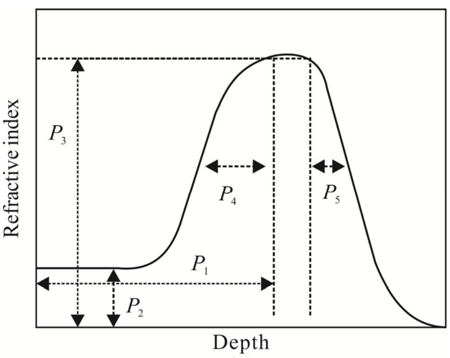
(a)



(b)

Fig.4 (a) Schematic for the principle of the prism coupling method; (b) Dark mode spectrum of the C^{2+} ion-implanted fluoride lead silicate glass measured by the prism coupling method

The refractive index distribution, which determines the guiding properties in the planar waveguide structure, is considered as one of the most important parameters. It is simulated by the RCM for the fluoride lead silicate glass waveguide. Fig.5(a) shows the schematic for the principle of the RCM, which is firstly proposed by Chandler and Lama[22]. During the simulation process, some parameters are given as follows. The distance (P_1) at which the maximum barrier height occurs is set as 3.61 μm. The decrease values of refractive index at the surface (P_2) and at the maximum barrier position (P_3) are set as 0.008 6 and 0.02, respectively. The standard deviations of the barrier rising (P_4) and falling (P_5) edges are set as 0.406 57 and 1.586 8, respectively. Fig.5(b) shows the refractive index profile of the ion-implanted waveguide simulated by the RCM with the given parameters. In Fig.5(b), the planar waveguide with a refractive index of 1.578 2 is surrounded by air on the top and the barrier region with a minimum index of 1.566 9 at the bottom. The refractive index values of the theoretical modes for the reconstructed refractive index profile are 1.575 7, 1.569 0 and 1.558 1. Tab.1 lists the measured effective refractive indices and calculated values, as well as the differences between each other for the propagation modes in the C^{2+}-ion implanted fluoride lead silicate glass waveguide. The RCM-reconstructed profile is a reasonable refractive index distribution for the fabricated waveguide, because the differences are in the order of 10^{-3}.



(a)

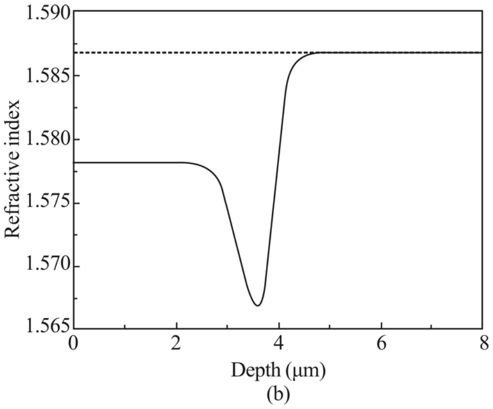


Fig.5 (a) Schematic for the principle of the RCM; (b) Reconstructed profile of refractive index for the C^{2+} ion-implanted fluoride lead silicate glass waveguide by the RCM

Tab.1 Measured and calculated effective refractive indices for the C^{2+} ion implanted waveguide in fluoride lead silicate glasses

Mode order	Effective refractive index		
	Experimental	Calculated	Different
0	1.574 0	1.575 7	-1.7×10^{-3}
1	1.562 4	1.569 0	-6.6×10^{-3}
2	1.548 2	1.558 1	-9.9×10^{-3}

Fig.6 shows the near-field intensity profile of the propagation modes in the C^{2+}-ion implanted fluoride lead silicate glass calculated by the FD-BPM[23]. It can be seen that there is no light leakage phenomenon at the interface between the substrate and the waveguide. The bright and uniform optical field in the horizontal direction shows that the light can be well confined in the vertical direction for the planar waveguide[24].

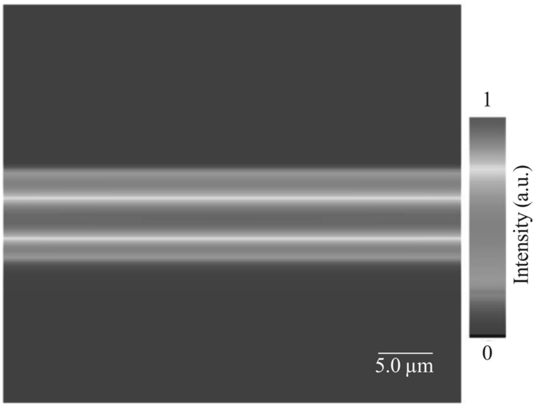


Fig.6 Calculated mode profile of the C^{2+} ion-implanted fluoride lead silicate glass waveguide

We examine the experimental and simulative results on the optical waveguide in the fluoride lead silicate glass formed by the carbon ion implantation with energy of 4.0 MeV and a dose of 4.0×10^{14} ions/cm^2. The dark-mode spectrum suggests that the waveguide can contain three propagation modes. The refractive index in the waveguide region is 0.011 3 higher than that of the optical barrier. The near-field light intensity profile based on the FD-BPM suggests that the light can propagate in the waveguide structure. The optical planar waveguide has the potential to operate as an integrated photonic device.

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