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质子注入掺镱磷酸盐玻璃平面光波导的近红外特性

吕婧妍[1]，郭海涛[2]，徐君[3]，刘春晓[1]
（1 南京邮电大学 电子与光学工程学院、微电子学院，南京 210023）
（2 中国科学院西安光学精密机械研究所 瞬态光学与光子技术国家重点实验室，西安 710119）
（3 西安航空学院 电子工程学院，西安 710077）

摘　要：在能量为(0.5＋0.55)MeV 和剂量为(1.0＋2.0)×10^{16} ions/cm^2 的条件下，通过氢离子注入制备了掺 Yb^{3+} 磷酸盐玻璃波导，并研究了该波导在近红外波段的特性.棱镜耦合法测量的离子注入波导的导模的有效折射率与反射计算法计算的有效折射率基本吻合.通过模拟辐照引起的空位分布，探讨了离子注入平面波导的形成理论.利用 FD-BPM 对波导中的传播模式进行了模拟，结果表明高能量的氢离子注入掺 Yb^{3+} 磷酸盐玻璃能够制备出近红外波导结构.

关键词：波导；近红外波段；离子注入；掺镱磷酸盐玻璃；折射率分布
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Near-infrared Properties of Optical Planar Waveguides Formed by H^+ Ion Implantation in Yb^{3+}-doped Phosphate Glasses

LÜ Jing-yan[1], GUO Hai-tao[2], XU Jun[3], LIU Chun-xiao[1]
(1 *College of Electronic and Optical Engineering & College of Microelectronics, Nanjing University of Posts and Telecommunications, Nanjing* 210023, *China*)
(2 *State Key Laboratory of Transient Optics and Photonics, Xi'an Institute of Optics and Precision Mechanics, Chinese Academy of Sciences, Xi'an* 710119, *China*)
(3 *School of Electronic Engineering, Xi'an Aeronautical University, Xi'an* 710077 *China*)

Abstract: The Yb^{3+}-doped phosphate glass waveguides by the hydrogen-ion implantation under the condition of energies of (0.5＋0.55) MeV and doses of (1.0＋2.0) × 10^{16} ions/cm^2 were fabricated, and characteristics of the waveguide were studied in the near-infrared band. The change of refractive index after the implantation was measured by the prism coupling method, which corresponded well with the calculated effective refractive index by the reflectivity calculation method. The formation theory of the ion-implanted planar waveguides was discussed through simulating the vacancy distribution induced by the irradiation. The propagation mode of light in the waveguide was simulated by using the FD-BPM, which suggested that the near-infrared waveguide structure could be fabricated by irradiating the Yb^{3+}-doped phosphate glass with the energetic hydrogen ions.

Key words: Waveguide; Near-infrared band; Ion implantation; Yb^{3+}-doped phosphate glass; Refractive

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First author: LÜ Jing-yan (1999－), female, B.S. degree candidate, mainly focuses on the design and development of compact waveguide devices. Email:742804007@qq.com

Supervisor (Contact author): LIU Chun-xiao (1982－), male, assistant professor, Ph.D. degree, mainly focuses on optical waveguides and optical isolators. Email:chunxiaoliu@njupt.edu.cn

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0　Introduction

Optical waveguides are known as important information transmission carriers in the information era[1]. They are also the basic components in integrated circuits and optoelectronics[2]. A waveguide consists of one layer with high refractive index and two layers with low refractive index[3]. Such special structure enables itself to confine light propagation according to the total internal reflection[4]. Various techniques including diffusion of metal materials[5], ion exchange[6], femtosecond laser writing[7], ion implantation[8], chemical vapor deposition[9] are applied to fabricate waveguides. Among these techniques, ion implantation shows its priority in lower expenditure in whole process and is prone to be controlled[10]. When ions are implanted at energies of different keV and MeV, a majority of damage occurs at the end of the ion track inside the substrates, which accounts for the decrease in physical density by means of volume expansion[11]. It is such decline in density that causes the decrease in refractive index[12]. Ion implantation technique is wildly used in waveguide fabrication for its ensured uniform irradiation over sample surface[13].

Yb^{3+}-doped Phosphate Glass (YDPG) is intriguing for fabricating waveguides, owing to its excellent material features. Yb^{3+}-doped phosphate glass has long fluorescence lifetime, which is conducive to energy storage. The thermal load of Yb^{3+}-doped phosphate glass is relatively low. Even at high pump power density, the temperature change in the material is small. Moreover, the Yb^{3+} level structure is relatively simple, so there is no excitation state absorption at the pump wavelength and the signal wavelength. Optical conversion efficiency is very high[14]. Yb^{3+}-doped phosphate glass has advantages over other glass systems. Its absorption band is in the wavelength range of 800～1 100 nm. The choice of pump source is more flexible, and the wide emission band is beneficial to the realization of laser output[15-18].

Although researchers have applied ion implantation techniques to fabricate optical waveguides on Yb^{3+}-doped phosphate glasses[19], the optical properties of the ion-implanted waveguides in near-infrared waveguides have not been reported. In this work, we fabricate the planar waveguide in the YDPG via the double-energy proton implantation. The properties of the optical waveguide including the dark-mode curve and the refractive index profile are studied in detail in the near-infrared region.

1　Experiments

The Yb^{3+}-doped phosphate glass was prepared by the melt-quenching technique at the Xi′an Institute of Optics and Precision Mechanics of Chinese Academy of Science. After cutting, grinding and polishing, several glass samples with sizes of 10 mm×5 mm×2 mm were chosen for the property measurement and waveguide preparation. The refractive indices of the YDPG are 1.534 4 at 632.8 nm and 1.521 0 at 1 539 nm, respectively.

In order to form an optical waveguide structure, H^+ ions with energies of (500＋550) keV were implanted into one of the polished surfaces (10 mm×5 mm) of the Yb^{3+}-doped phosphate glass at room temperature according to the desired thickness of the optical waveguide, as shown in Fig. 1. The corresponding doses were (1.0＋2.0)×10^{16} ions/cm^2 in consideration of the damage ratio. To prevent thermal effects during the implantation process , the ion beam was controlled within 0.9 μA. The ion

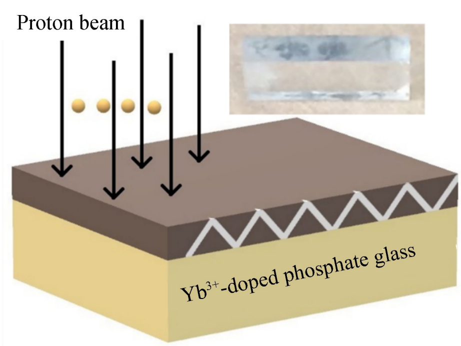

Fig.1　Schematic of the proton implantation into the Yb^{3+}-doped phosphate glass and the inset is the glass photograph

implantation was performed on an ion implanter at the Institute of Semiconductors of Chinese Academy of Sciences.

The ion-implanted Yb^{3+}-doped phosphate glasses were optically measured by using Model 2010 prism coupler to study the dark mode properties. The prism code was 1 004.4 and the refractive index of the prism was 1.934 6 at 1 539 nm. A semiconductor laser with a wavelength of 1 539 nm was equipped in the prism-coupling system to serve as a working source. During the measurement process, the laser beam with a wavelength of 1 539 nm was coupled into the waveguide layer through the bottom of the prism. Then, the guided mode was excited and the intensity of the reflected light was reduced. Therefore, a relationship curve between the effective refractive index of the incident light and the intensity of the reflected light was obtained. The refractive index corresponding to the dip in the curve was the effective refractive index of the guided mode.

2 Results and discussion

Fig.2 shows the vacancy profiles of the 500 and 550 keV protons implanted into the YDPG, which was calculated by the stopping and range of ions in matter code (SRIM 2013)[20]. As shown in Fig.2, a majority of the vacancy was introduced at the end of the ion track inside the target glass. In other words, most of the vacancies were concentrated at the depth of 4.48 mm. The physical density in the vacancy deposition region would be decreased by volume expansion, and hence an optical barrier with reduced refractive index occurred at the same area.

The dark-mode curve was measured by the prism coupling system, which can calculate the refractive index of the propagation mode in the waveguide. Fig.3 shows the relationship between the intensity of reflected light and the effective refractive index. The x axis denotes the refractive index and the y axis suggests the relative intensity. The dip in the dark-mode curve represents a stimulated optical propagation mode, denoting that photons enter into the waveguide layer. We can see from Fig. 3 that there are three dips in the dark-mode curve of the Yb^{3+}-doped phosphate glass waveguide at 1 539 nm. The first dip is relatively sharp and hence indicates the guided mode. With the increase of the ordinal of the propagation mode, the dip gradually becomes wider. It indicates that the waveguide has a worse ability to confine the higher order mode. In addition, the refractive indices of the three dips are smaller than that of the substrate, which suggests that the H^+ ion implantation into the YDPG produces an optical barrier with reduced refractive index at the end of the ion range.

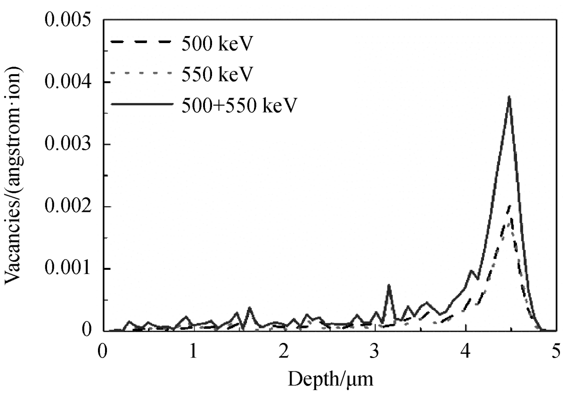

Fig.2 Vacancy profile as a function of irradiation depth for (500+550) keV protons implanted into the YDPG

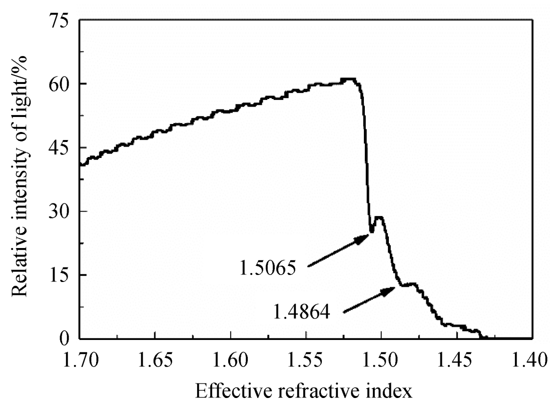

Fig.3 Dark-mode curve of the YDPG waveguide at 1 539 nm

It is essential to know the profile of the refractive index in a waveguide structure, because that the refractive index distribution plays a decisive role in the propagation characteristics of an optical waveguide. However, the refractive index profile is difficult to measure directly. Therefore, there are several different techniques for calculating the refractive index profile, such as the parameterized index profile reconstruction[21], the inverse Wentzel-Kramers-Brillouin[22] and the Reflectivity Calculation Method (RCM)[23]. Among these methods, RCM is more suitable for simulating the refractive index distribution of an optical waveguide produced by the technique of ion implantation. During the simulation based on RCM, the refractive index profile can be approximately described by two Semi-Gaussian curves. For a set of given parameters, a digital program can be used to calculate the refractive index of the guided mode. The refractive index profile can be adopted when the standard deviation between the calculated and measured effective refractive index is minimized. Fig. 4 shows that the refractive index profile reconstructed by using RCM for the Yb^{3+}-doped phosphate glass waveguide manufactured by the proton implantation at 1 539 nm. In Fig. 4, there is an optical barrier whose depth and refractive index reduction determine the performances of the waveguide to some extent. The depth of the optical barrier is dependent on the energy of the implanted ion. The higher the energy, the deeper the depth of the barrier. As we can see from Fig.4, the optical barrier is at a depth of approximately 4.5 μm. On the other hand, the refractive index reduction of the optical barrier is related to the dose of the implanted ion. The greater the dose is, the more the refractive index decreases. The refractive index of the optical barrier is reduced by 0.045 with respect to the refractive index of the substrate, as shown in Fig.4. It is worth mentioning that the variation of the refractive index is −0.005 3 in the near-surface region. Therefore, a waveguide layer is formed between the air and the optical barrier layer. In addition, Table 1 compares the effective refractive indices of the calculated modes with the measured ones. As we can see that the calculated indices are in agreement with the measured values. Therefore, the profile curve in Fig.4 can accurately describe the refractive index distribution of the waveguide.

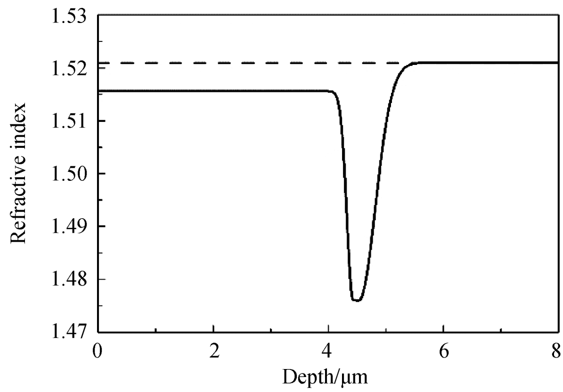

Fig.4 Refractive index distribution of the H^+-ion implanted Yb^{3+}-doped phosphate glass waveguide at the wavelength of 1 539 nm

Table 1 The comparison of the measured and calculated effective refractive indices for the proton implanted waveguide in the Yb^{3+}-doped phosphate glass

Mode	Effective refractive index		
	Exp.	Cal.	Diff.
TE_0	1.506 5	1.508 6	-2.1×10^{-3}
TE_1	1.486 4	1.486 1	3.0×10^{-4}
TE_2	1.445 0	1.445 5	5.0×10^{-4}

The Finite-difference Beam Propagation Method (FD-BPM) is one of the most effective techniques for dealing with the propagation of light waves in optical waveguide devices[24]. Fig.5 shows the near-field intensity distribution of the H^+-ion implanted Yb^{3+}-doped phosphate glass planar waveguide simulated by the FD-BPM. The light is limited mostly in the waveguide region in Fig. 5. From the figure we can observe that the line is continuous and generally uniform, which indicates that the light field structure in the waveguide region is relatively good . It is shown that the planar Yb^{3+}-doped phosphate glass waveguide can confine the propagation of light with a wavelength of 1 539 nm in the vertical direction.

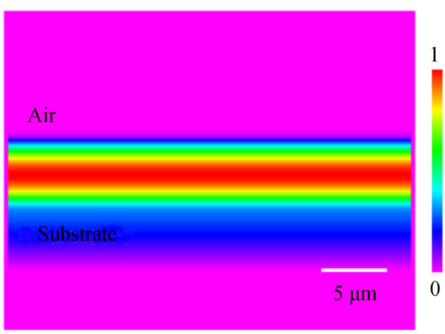

Fig.5 Near-field intensity distribution of the YDPG waveguide formed by the H^+-ion implantation

3 Conclusion

The near-infrared planar waveguide in the Yb^{3+}-doped phosphate glass was produced by the H^+ ion implantation. The waveguide contains three modes from the m-line curve measured by the prism-coupling system. The refractive index profile of the waveguide is a well-known "barrier"-type model. The refractive index difference between the waveguide layer and the optical barrier was on the order of 10^{-2} according to the RCM-simulation. The mode profile calculated by the FD-BPM suggests that the waveguide can confine the light with a wavelength of 1 539 nm.

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