Annealing effect on mono-mode refractive index enhanced $RbTiOPO_4$ waveguides formed by ion implantation

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Abstract: We reported on the annealing features of the $RbTiOPO_4$ planar waveguides fabricated by 6.0 MeV C^{3+} ion implantation. The thermal stability of the ion-implanted $RbTiOPO_4$ waveguide was investigated by annealing at different temperatures ranging from 260°C to 650°C. Results revealed that when temperatures are higher than 550°C, annealing caused the refractive indices of both n_y and n_z a saturation behavior. An increase of the n_y refractive index in waveguide region was observed after proper annealing. The low loss planar mono-mode waveguides have been achieved in $RbTiOPO_4$ crystals by applying appropriate ion implantation and annealing conditions.

OCIS codes: (230.7370) Waveguide; (220. 0220) Optical design and fabrication

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1. Introduction

Optical waveguide offers high light intensities with respect to the bulk; consequently, the nonlinearities in waveguide may be improved considerably for a nonlinear media [1]. One of the promising candidates is rubidium titanyl phosphate ($RbTiOPO_4$, RTP), classified as the isomorphic $MTiOXO_4$ family (KTP-family) of ferroelectric nonlinear optical and electro-optic crystals, where M={K, Rb, Cs or Tl} and X={P or As (for M=Cs only)} [2]. The remarkable properties of the RTP crystal, including high nonlinear optical and electro-optic coefficient, high optical damage threshold, low dielectric constant and chemical stability, make it to be widely applied in nonlinear optics and electro-optics and drew huge attentions for developing optical waveguide device in it [3].

One accurate method to form waveguide is by utilizing ion implantation to modify the refractive index of surfaces of insulators. He ion-implanted waveguide in $LiNbO_3$ was first reported in 1978 [4]. As of yet, ion implantation has been used to form waveguides in several dozens of materials. In most cases, MeV He^+ or H^+ ions have been implanted into crystals with a fluence of the order of 10^{16} ions/cm^2 to form waveguides. When implantation of light ions at energies of several MeV are performed, severe lattice damage occurs at the end of the ion track inside the substrates, resulting in a decrease of physical density by means of volume expansion and hence a reduced refractive index of an optical barrier. Such a barrier confines the light in a narrow layer with relatively high refractive index, forming an optical waveguide between itself and the crystal surface [5].

However, in 2001, a mono-mode extraordinary index (n_e) raised waveguide in $LiNbO_3$ formed by heavier ion (Si^+) implantation with low fluence (~10^{14} ions/cm^2) was reported by Hu *et al* [6]. In the waveguides formed by heavier ion implantation, positive change of the refractive index occurred in the waveguide region. Then a waveguide was formed by a region of high refractive index bounded by regions of lower index (air and substrate) [7-9]. Therefore, heavier ion implantation to form waveguides shows three advantages: (1) generally much lower ion fluences (10^{13}-10^{14} ions/cm^2) are needed compared to fluences (~10^{16} ions/cm^2) of light ion implantation; (2) mono-mode waveguide is achieved more easily; (3) it can prevent tunneling effect and offer better confinement of the light. The refractive index enhanced waveguides fabricated by ion implantation with low fluence have been reported in several crystals, such as $LiNbO_3$ and Nd:YAG [10, 11]. Jiao *et al.* have reported a waveguide formed in RTP by O^{3+} ion implantation, where a higher fluence is needed and an optical barrier has formed at the end of the track, just like the cases of light ion implanted waveguides [12]. In this paper, we report the fabrication and annealing properties of the waveguides in RTP by 6.0 MeV C^{3+} implantation at low fluences of 5×10^{13} and 1×10^{14} ions/cm^2, respectively. Positive changes of n_y refractive index occurred in the guide region after proper annealing treatment.

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2. Experiments in details

The *x*-cut RTP crystals were obtained from the School of Chemistry and Chemical Engineering, Shandong University and later were implanted with 6.0 MeV C^{3+} ions at fluences of 1×10^{14} ions/cm^2 and 5×10^{13} ions/cm^2 at Peking University, respectively. The end faces of the sample were polished to reach the requirement for direct end-fire coupling of light. A linearly polarized He-Ne laser with a wavelength of 632.8 nm was used as the light source. A neutral density filter and a half-wave plate were used for control of optical power and light polarization. A 25× microscope objective lens injects the light into the waveguide. The waveguide sample was placed on a six-dimensional (6D) optical stage, which make it both movable along the *x*, *y*, or *z* axes and rotational within the *x*-*y*, *y*-*z*, or *z*-*x* planes. Another 25× lens collected the output mode light onto a CCD camera which is controlled by a computer in order to analyze the experimental data.

Table 1. Parameters of the isochronally additive annealings for the RTP waveguide formed by 6.0 MeV C^{3+} ion implantation with a fluence of 1×10^{14} ions/cm^2. All the annealing treatments were performed in atmosphere.

Annealing Conditions	1	2	3	4	5	6	7	8	9
Temperature (°C)	260	300	350	400	450	500	550	600	650
Time (min)	30	30	30	30	30	30	30	30	30

The RTP waveguide formed by 6.0 MeV C^{3+} ion implantation with a fluence of 1×10^{14} ions/cm^2 was subjected to isochronally additive annealings from 260°C to 650°C for each 30min in air ambient (see Table 1). It can be found that RTP waveguide has high thermal stability. Another RTP waveguide formed by 6.0 MeV C^{3+} ion implantation with a fluence of 5×10^{13} ions/cm^2 was annealed from 260°C to 400°C for each 30min in atmosphere with the same procedure. The samples were placed in a furnace with the temperature firstly increased 3°C per minute to the annealing temperature and then maintained for 30 min. Finally the temperature was reduced gradually to room temperature. After each annealing process the effective refractive indices of the RTP waveguides were measured by using prism coupling technique with an accuracy of 0.0002 at λ=633 nm.

3. Results and discussion

3.1 RTP waveguide at a fluence of 1×10^{14} ions/cm^2

During ion implantation some point defects could be produced in the waveguide region as a result of ionization and excitation from the ions that travel through the region. These isolated point defects can induce absorption and scattering loss in the guiding layer. It has been found that post-implant annealing can reduce aggregation of these defects. The annealing process has emerged as an important technique for the fabrication of low-loss optical waveguide [13]. Figure 1 shows the evolution of effective refractive indices with different annealing temperatures for the RTP waveguide formed by 6.0 MeV C^{3+} ion implantation at a fluence of 1×10^{14} ions/cm^2. The symbols (squares, triangles, circles) in Fig. 1 represent the measured experimental points; the curves indicate the change trendline of effective refractive indices of the modes with different annealing conditions. As shown in Fig. 1, the effective refractive indices of n_x, n_y and n_z rise up gradually when the annealing temperature increases. However, when the annealing temperatures are higher than 550°C, the effective refractive indices of n_y and n_z almost keep a constant. The experiments show that annealing at temperature higher than 550°C results in saturation behavior of the refractive indices of n_y and n_z. It should be remarked that dark modes could be measured even after the annealing treatment performed at temperature of 650°C, which shows that the RTP waveguide has a high thermal stability.

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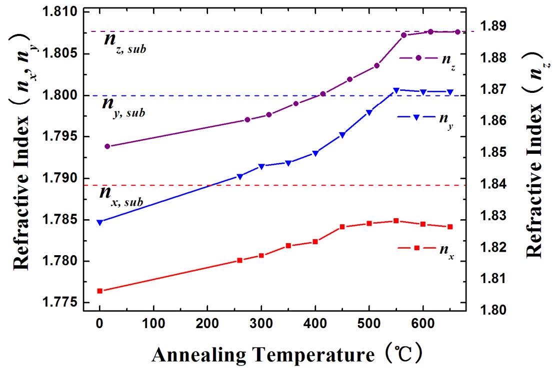

Fig. 1. Evolution of effective refractive indices versus annealing temperatures for the RTP waveguide formed by 6.0 MeV C^{3+} ion implantation at a fluence of 1×10^{14} ions/cm^2.

The dark mode spectroscopy of the RTP waveguide was measured by using a prism coupling arrangement for a variety of annealing conditions. When the annealing temperature reaches above 550°C, the behaviors of the mode of n_x, n_y and n_z show difference. The mode of n_x becomes faint, meanwhile the effective refractive index of n_x is still lower than that of virgin RTP ($n_{x,sub}$=1.7892); while the effective refractive index of n_y becomes higher than the one of the virgin RTP ($n_{y,sub}$=1.8000); the value of the effective refractive index of n_z is lower but near the virgin RTP ($n_{z,sub}$=1.8886). The modes of n_y and n_z are very sharp, which means a good confinement of light propagation. Figure 2 shows the measured relative intensity of the light reflected from the prism versus the effective refractive index n_y of the incident light for the RTP waveguide, which was formed by 6.0 MeV C^{3+} ion implantation at a fluence of 1×10^{14} ions/cm^2 and annealing at 550°C for 30 min. As indicated in Fig. 2, a sharp dip was observed. The measured effective refractive index of the mode was higher than that of the virgin RTP crystal, which means an index enhanced layer has been formed.

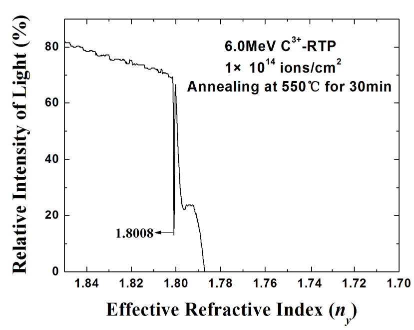

Fig. 2. Measured relative intensity of the light reflected from the prism versus the effective refractive index (n_y) of the incident light for the RTP waveguide formed by 6.0 MeV C^{3+} ion implantation with a fluence of 1×10^{14} ions/cm^2 after annealing at 550°C for 30 min.

Properties of the RTP planar waveguide implanted at the fluence of 1×10^{14} ions/cm^2 were investigated by the end-coupling method. Figure 3(a) and (b) show the 2D and 3D plots of the near field intensity profiles of the output beam when a light of 633 nm wavelength was coupled to the RTP waveguide after annealing at 550ºC for 30 min in air, respectively. The bright near field intensity distribution of the transverse-electric mode in the annealed waveguide was collected and studied. The light can be guided in a well confined way almost without leakage. For the 25× lens, scales were given out in Fig. 3 and through which we could estimate the width of the planar waveguide was about 4.5 μm. Compared with the average C ions range of 4.3 μm simulated by SRIM (The Stopping and Range of Ions in Matter) [14], we conclude that there is a reasonable agreement between the experimental and the calculated results. The waveguide loss evaluation requires the end-fire coupling of laser light into the planar waveguide, and the measurement of two optical powers: the laser powers at the entrance and the output plane of the waveguide. A cylindrical lens was used to compensate the beam divergence inside the planar waveguide. The Fresnel losses as well as the overlapping integral of the fiber and the waveguide output mode fields were taken into account [15, 16]. After annealing at 550ºC for 30 min in air, propagation loss of the waveguide was determined to be about 0.8 dB/cm at wavelength of 633 nm. Considering the end-faces polishing quality and lens transmittance, high accuracy is very difficult to achieve and the experimental error of loss measurement is less than 0.2 dB/cm.

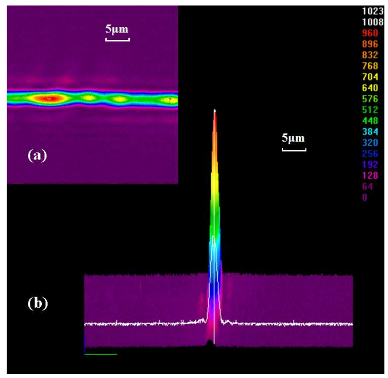

Fig. 3. Measured (a) 2D and (b) 3D near field intensity profiles of the RTP planar waveguide mode which was collected by CCD camera. The RTP planar waveguide was formed by 6.0 MeV C^{3+} ion implantation at a fluence of 1×10^{14} ions/cm^2 and after annealing at 550ºC for 30 min.

3.2 RTP waveguide at a fluence of 5×10^{13} ions/cm^2

The guiding modes of the RTP waveguide formed by 6.0 MeV C^{3+} ion implantation at a fluence of 5×10^{13} ions/cm^2 were observed at wavelength of 633 nm before and after isochronally additive annealing at 260°C, 300°C, 350°C and 400°C for 30 min. The prism-coupling method was used to characterize modes and the results were shown in Fig. 4. Figure 4(a) represents the TE polarized light propagating along *y* direction, which corresponds to effective refractive index n_y. When the annealing temperature was up to 260°C and 300°C, no modes could be found even if the measurement has been tried for any size and pressure of the optical contact. A noticeable phenomenon can be found that the effective refractive index of the n_y mode has a trend of enhancement as the annealing temperature is 350°C. There is a sharp mode as the annealing temperature is at 400°C, which is confined by the n_y raised region because of the high mode effective index comparable with the virgin crystal. In particular, the fact that no TE modes from n_y-raised region can be detected in the RTP waveguide with annealing temperature lower than 350°C, revealed that there is a "critical annealing temperature" is present for the refractive index enhanced RTP waveguide formed by 6.0 MeV C^{3+} ion implantation at a fluence of 5×10^{13} ions/cm^2.

Jiang *et al.* reported that lattice damage played an important role for the refractive index changes in the ion-implanted $LiNbO_3$ waveguide. The ordinary refractive index n_o continually decreases during the lattice damage, while the extraordinary refractive index n_e would have a refractive index enhancement when the lattice damage ratio is less than 65%, and then decreases during the lattice damage increasing [17]. In the ion-implanted RTP waveguides, the lower index n_y maybe decreases when the lattice damage ratio is larger than certain percent, while after annealing the surface of the RTP crystal recovered [18], n_y maybe increases due to the fact that after annealing the lattice damage ratio decreased. Nevertheless,

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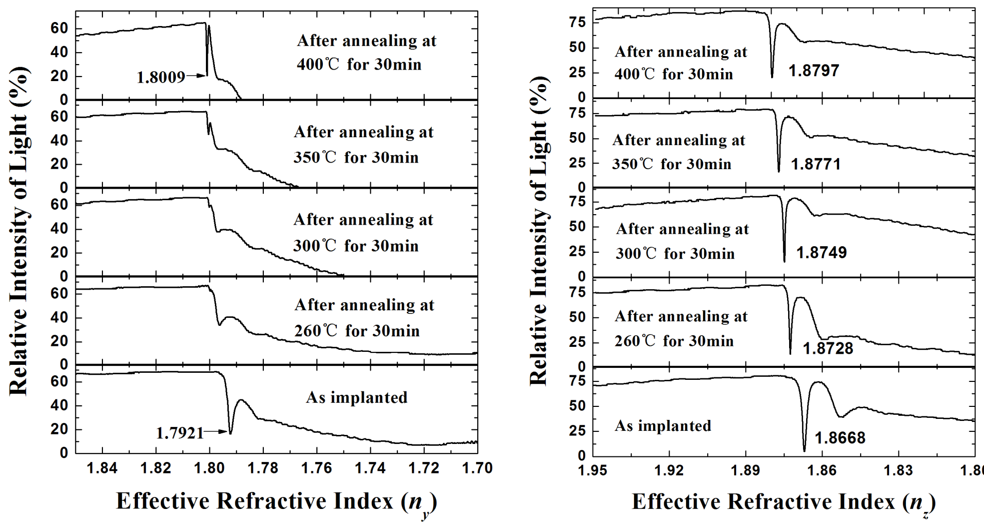
a detailed understanding of such properties of the RTP waveguide before and after annealing still needs further investigation.



(a) (b)

Fig. 4. The guiding n_y (a) and n_z (b) modes of the RTP waveguide formed by 6.0 MeV C^{3+} ion implantation with a fluence of 5×10^{13} ions/cm^2 at wavelength of 633 nm before and after annealing at 260°C, 300°C, 350°C and 400°C for 30 min.

Figure 4(b) represents the TE mode (n_z) of the RTP waveguide. Effective refractive indices of n_z modes measured for a variety of annealing conditions were given for comparison. Different from the results of Fig. 4(a), the effective refractive indices of n_z increase gradually as the annealing temperature increases, while the values of the effective refractive indices are still lower than the virgin RTP crystal. A possible explanation for the differences between n_y and n_z is that RTP is a biaxial crystal with $n_y<n_z$. Ion beam damage results in isolated point defects and ionic displacements at a low fluence which allows some relaxation and distortion of the lattice [19, 20]. For a biaxial material this initially raises the lower indices and decreases the larger one.

4. Summary

The low loss planar mono-mode waveguides in RTP crystals were formed by 6.0 MeV C^{3+} ion implantation at fluences of 1×10^{14} ions/cm^2 and 5×10^{13} ions/cm^2, respectively. The changing behaviors of effective refractive indices with annealing temperature were investigated by a series of annealing treatments. The results showed that mono-mode RTP waveguide with a raised index layer can be formed by single energy implantation with low fluence and appropriate annealing process. The results were considered to be helpful to fabricate the optical waveguide devices on RTP crystals by using the low fluence implantation and appropriate annealing technique.

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