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Investigation of Planar Optical Waveguide Formed by MeV He^+ Ion-Implantation into $NaEr(WO_4)_2$ Crystal

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Abstract

$NaEr(WO_4)_2$ is a new laser material. The planar optical waveguide was formed in $NaEr(WO_4)_2$ crystal by 2.6 MeV He^+ ion implantation at doses of $1.0\text{-}1.5\times10^{16}$ ions/cm^2 at room temperature. The effective refractive indices of the dark modes were measured using the prism coupling method. Four TE modes and five TM modes were observed in the waveguide. The refractive index profiles were analyzed using the reflectivity calculation method (RCM). The influence of heat treatment at moderate temperature on the refractive index profiles of the waveguide was also investigated. We used the TRIM'98 (Transport of Ions in Matter) code to simulate the damage profile in the $NaEr(WO_4)_2$ crystal by 2.6 MeV He^+ ion implantation which is helpful for a better understanding of the waveguide formation.

1. Introduction

Waveguide is one of the high-technology fields related to integrated optics such as optical communication, optical signal processing and optical computing. There are several techniques for fabricating optical waveguides, including sputtering, epitaxial growth, metal diffusion, ion exchange and pulsed laser deposition (PLD) [1-4]. However, due to a certain reason, some waveguides could not be formed in some materials using these techniques. For example, $KNbO_3$ and SBN waveguides could not be produced by means of diffusion or PLD for their very low Curie temperatures. Recent research reveals that ion implantation may be a universal method for fabricating waveguide structures in most optical materials because it could be performed at lower temperatures. It also offers the possibility to bury a waveguide at various depths below the substrate surface by changing the ion species and energies of the implantation. Ion implantation of high-energy light ions (e.g. MeV He^+ or H^+) has become a relatively mature method to produce refractive index changes and hence optical waveguide. In this case, a low refractive index "optical barrier" has happened at the end of the track where most of the displacement damage occurs. And such an optical barrier confines the light to a narrow layer or "optical well" (act as a waveguide) between itself and the surface [5]. Furthermore, waveguide lasers have been formed in at least seven crystals by the He^+ ion implantation. $NaEr(WO_4)_2$ is a tetragonal scheelite-like crystal, which exhibits good up-conversion property for output of green light [6]. In the present work, we report, for the first time, the formation of planar waveguide in $NaEr(WO_4)_2$ crystal by means of MeV He^+ ion implantation, and analyze the refractive index profiles of the waveguide.

2. Experimental Details

The $NaEr(WO_4)_2$ samples were provided by the Crystal Material Institute of Shandong University. They were optically polished and cleaned. Before the implantation, their refractive indices were measured. The samples were implanted by 2.6 MeV He^+ at doses of $1\text{-}1.5\times10^{16}$ ions/cm^2 at room temperature, respectively. The ion beam was electrically scanned to ensure a uniform implantation over the sample. In order to minimize the channeling effect, the sample was tilted by 7° off the beam direction. The ion implantation was performed at 1.7 MV tandem accelerator of Peking University.

The prism-coupling method was used to observe the modes in waveguide. The effective refractive indices of the observed dark modes were measured with Model 2010 Prism Coupler (Metricon Corporation, USA). A laser beam at 633 nm from a He-Ne laser struck at base of a rutile prism, and hence the laser beam was coupled into the waveguide region. A computer was used to control the measurement system via an interface attached to the control pad.

3. Results and Discussion

Figure 1 shows the relative intensity of the reflected light of (a) TE mode and (b) TM mode as a function of effective refractive index obtained by Model 2010 Prism Coupler for $NaEr(WO_4)_2$ waveguide formed by 2.6 MeV He^+ ion implantation at the dose of 1.5×10^{16} ions/cm^2 at room temperature. When the light was coupled into the waveguide region, a lack of reflected light would result in a dip. But as more and more light is tunneling out of the barrier by decreasing the effective refractive index of the incident light, the dips become broader and broader. As indicated in this figure, 4 TE modes and 5 TM modes were observed, while only the first two dips in Fig. 1(a) and first three ones in Fig. 1(b) were relatively sharp. This may mean that the light in these modes corresponding to sharp dips was well confined in the waveguide region. The broader dips may be the result of optical interference between the multiple reflections occurring

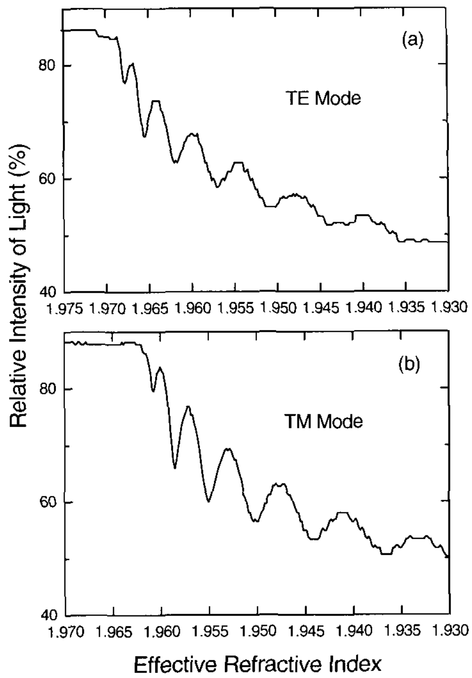

Fig. 1. Relative intensity of light as a function of effective refractive index of (a)TE and (b)TM modes for $NaEr(WO_4)_2$ waveguide formed by 2.6 MeV He^+ with the dose of 1.5×10^{16} ions/cm^2 at room temperature.

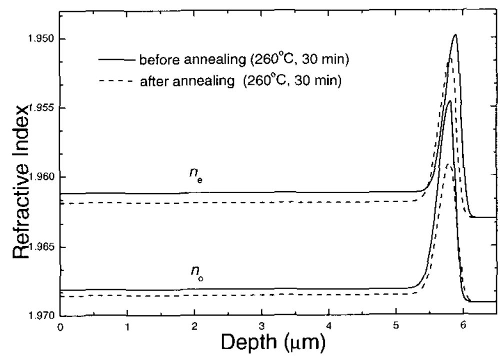

Fig. 2. The refractive index profile (n_o and n_e) in $NaEr(WO_4)_2$ waveguide formed by 2.6 MeV He^+ at a dose of 1.5×10^{16} ions/cm^2 before and annealing at 260ºC for 30 min.

at the interfaces of the waveguide, and the modes corresponding to these dips can be called "substrate modes".

Reflectivity calculation method (RCM) was used to analyze the refractive index profile of the $NaEr(WO_4)_2$ waveguide [7]. The refractive index distribution was approximated by two half Gaussians. A least-squared fitting program based on RCM was available to calculate the refractive index profile by adjusting certain parameters until the theoretical modes indices match the experimental ones within a satisfactory error. The method is particularly suitable for waveguides formed by ion implantation. Fig. 2 indicates the refractive index profiles of the $NaEr(WO_4)_2$ waveguide formed by 2.6 MeV He^+ ion implantation with the dose of 1.5×10^{16} ions/cm^2 before and after annealing for 30 min at 260℃. As for n_e, about a 0.66% index decrease was found in the optical barrier with He^+ ion implantation, and the index decrease was about 0.58% after post-annealing at 260℃ for 30 min. Similarly, for n_o, 0.75% and 0.51% index decease occurred in the optical barrier region before and after the annealing, respectively. However, the peak position and the width of the optical barrier almost remained unchanged after the annealing.

The lattice damage produced by ion implantation is considered to be the main reason for refractive index change in the ion-implanted waveguide, particularly for the light-ion implanted one. The damage leads to a decrease in physical density and hence to a reduced refractive index. Here we used TRIM'98 code (Transport of Ions in Matter) to simulate the process of the implantation in order to get some information of the lattice damage [8]. Figure 3 represents the nuclear energy loss distribution in $NaEr(WO_4)_2$ crystal by 2.6 MeV He^+ ion implantation. As we can see, the shape of the damage distribution and that of the refractive index profile are quite similar except for little difference on the peak position. Such is a vivid proof that the lattice damage produced by nuclear collisions should be most responsible for the refractive index change in the waveguide.

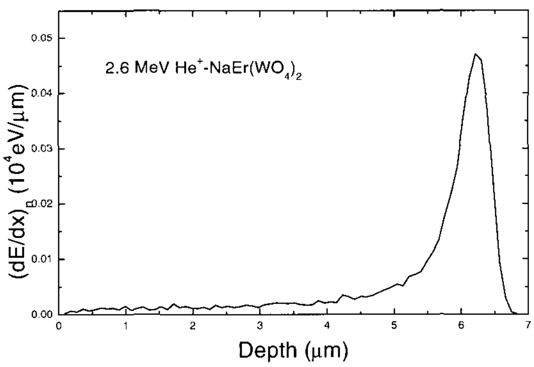

Fig. 3. Nuclear Energy loss of 2.6 MeV He^+ in $NaEr(WO_4)_2$ crystal due to nuclear collision as a function of penetration depth based on TRIM'98

4. Conclusion

The $NaEr(WO_4)_2$ waveguide was formed by 2.6 MeV He^+ ion implantation at doses of 1-1.5×10^{16} ions/cm^2 at room temperature. The refractive index profile (n_o and n_e) was analyzed using RCM. It is found that the height of the optical barrier decreased to a certain extent while the position and the width of the barrier almost remained unchanged after annealing at 260℃ for 30 min. The lattice damage produced by the MeV He^+ ion implantation seemed to be the main reason of the refractive index change of the crystal.

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