Optical Waveguide Formed in Yb:$KLu(WO_4)_2$ Crystal by 6.0 MeV O^+ Implantation *

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A planar optical waveguide is formed in monoclinic double rare-earth-tungstate laser crystal Yb:$KLu(WO_4)_2$ by 6.0 MeV oxygen ion implantation with a dose of 2×10^{15} ions/cm^2 at room temperature. Subsequently, annealing at 300° C for an hour in air is performed on the sample to decrease colour centres to improve the thermal stability of the waveguide. The refractive index profiles of the waveguide are reconstructed by an effective refractive index method. Dark modes of the waveguide are observed at wavelengths of 633 nm and 1539 nm. TRIM'98 is used to simulate the damage profile caused by the implantation process. It is found that the refractive index change may be mainly due to the damage induced by the nuclear energy loss.

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The monoclinic double rare-earth tungstates of $KR(WO_4)_2$ are excellent laser host materials, which provide high laser efficiency with both lamp and laser-diode (LD) excitations.[1,2] $KLu(WO_4)_2$ crystal is a member of this family, and the demonstration of cw and quasi-cw laser actions of Nd^{3+}ions in KLuW crystals pumped by an LD has been reported in 1992.[3] Yb-doped media generally have long radiative lifetimes (there is no concentration quenching effect for high Yb doping concentration) and high quantum efficiency. The doping Yb^{3+} ions possess no up-conversion effect or excited state absorption, which greatly reduces thermal effects in the crystal. Yb:$KLu(WO_4)_2$ is a Yb-doped crystal with the double rare-earth tungstate structure newly grown by the Czochralski method. Efficient continuous-wave, diode-pumped lasers and passively mode-locked oscillators have been successfully fabricated in Yb:$KLu(WO_4)_2$ crystals.[4,5] Since waveguide structure can greatly reduce laser thresholds, it is of great interest to develop optical waveguide structures in Yb:$KLu(WO_4)_2$ crystals.

Several waveguide fabrication techniques have been developed to obtain the waveguide structures, such as metal diffusion, ion exchange, thin film deposition and ion implantation.[6−9] In recent years, fabricating waveguides using light ion implantation, such as H and He, has become an effective method in most optical materials due to its controllability and reproducibility.[10] More recently, the implantation of heavier ions, such as C, O and Si, has attracted much attention for use in waveguide fabrication because it usually requires a much lower dose and offers better confinement of the light in the waveguide.[11−13] Recently, Rivier *et al.* reported on Yb:$KLu(WO_4)_2$ films grown by epitaxy for mode-locked lasers.[14] There is no report on investigating the waveguide structure of Yb:$KLu(WO_4)_2$ crystals. In this Letter, we report the fabrication of a planar optical waveguide in Yb:$KLu(WO_4)_2$ crystal by 6.0-MeV O^+ implantation with a dose 2×10^{15} ions/cm^2 at room temperature. The refractive index profile of the waveguide is analysed by using an effective refractive index method.

Optical polished Yb:$KLu(WO_4)_2$ (doped with 10% Yb) samples with a size of $5 \times 5 \times 2$ mm^3 were provided by the State Key Laboratory of Crystal Materials, Shandong University. The refractive index of the crystal was measured before implantation. The 6.0-MeV oxygen ion implantation to the dose of 2×10^{15} ions/cm^2 was performed at the 1.7 MV tandem accelerator of Peking University at room temperature. The ion beam was electrically scanned to ensure a uniform implantation over the samples. The beam current was about 100 nA and in order to avoid any channelling effect the samples are titled 7° off the beam direction. The samples were annealed in a furnace at 300°C for an hour in air to decrease colour centres and investigate the thermal stability. The prism coupling method was used to observe waveguide modes with a Model 2010 prism coupler (Metricon, USA). A laser beam stroke at the base of a prism, and hence the laser beam was coupled into waveguide region. A photodetector was used to detect the reflected beam. The prism, waveguide and photodetector were mounted on a rotary table so that the incident angle of the laser beam could be changed. The intensity of the reflected

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light was plotted as a function of incident angle, where a sharp drop in the intensity profile would correspond to a possible mode. Laser beams with wavelengths of either 633 nm or 1539 nm were used in the measurement.

Figure 1 shows the relative intensity of the reflective light as a function of effective refractive index measured in the Yb:KLu$(WO_4)_2$ waveguide formed by 6.0-MeV O^+ implantation to the dose of 2×10^{15} ions/cm^2 at room temperature. When the light is coupled into the waveguide region, a lack of reflected light would result in a dip, which may correspond to a propagation mode. As shown in Fig. 1, six and eight dips are observed for refractive index n_x (Fig. 1(a)) and refractive index n_z (Fig. 1(b)), respectively. However, only the first three dips ($n = 1.8$) seem to be much sharp, the others are broader. This means that those three dips may be real propagation modes, in which light could be well confined. The broader dips may correspond to leaky modes, which are often the result of the multiple reflections at the interface between the waveguide and substrate.

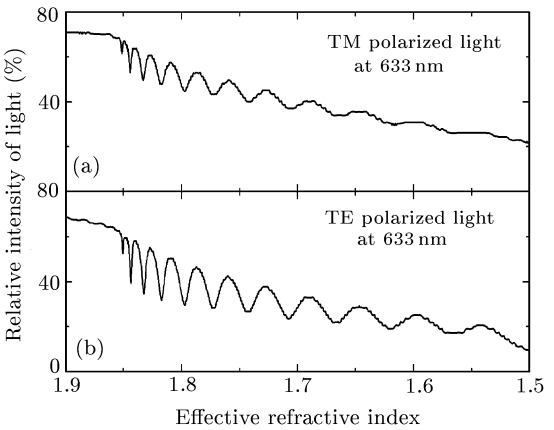

Fig. 1. Relative intensity of transverse electric (TE) polarized light (a) and transverse magnetic (TM) polarized light (b) at 633 nm reflected from a prism versus the effective refractive index of incident light in the Yb:KLu$(WO_4)_2$ waveguide formed by 6.0-MeV oxygen ion implantation to a dose of 2×10^{15} ions/cm^2 at room temperature.

Figure 2 shows the relative intensity of the reflective light as a function of effective refractive index of n_z of the as-implanted sample (Fig. 2(a)) and the sample after annealing (Fig. 2(b)). It can be seen that the observed dips become deep and sharp after annealing, which implies a better confinement of propagating light and a low propagation loss. This should result from the decreasing number of colour centres. It is also noticed that the effective refractive indices of the observed modes decrease after annealing. This may be due to the partial recrystallization induced by the thermal treatment. The similar changes can be observed in the refractive index n_x. The annealed sample was annealed at 300°C for further two hours and no further change was observed for the refractive index of waveguide, which suggests that the waveguide structure formed by ion implantation and subsequent annealing may have fine temperature stability.

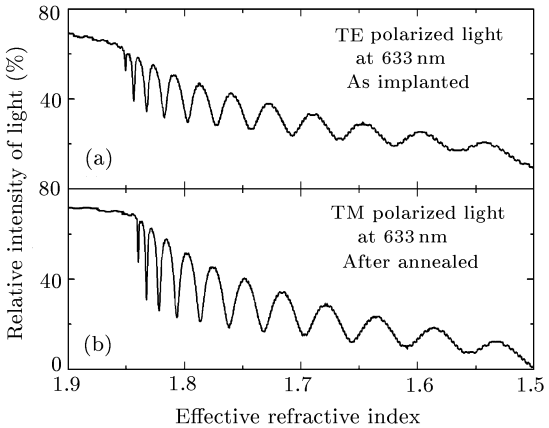

Fig. 2. Relative intensity of TE-polarized light reflected from a prism versus the effective refractive index of incident light at 633 nm in the Yb:KLu$(WO_4)_2$ waveguide formed by 6.0-MeV oxygen ion implantation at the dose of 2×10^{15} ions/cm^2: (a) as-implanted sample, (b) sample annealed at 300°C for 60 min in air.

Since the information of refractive index profile of waveguides is specially important, we reconstruct the refractive index profile of formed waveguides by the reflectivity calculation method (RCM).[15] RCM is a successful tool to characterize the non-stationary waveguides, particularly ion-implanted ones. A least-squared fitting program based on RCM is available to calculate the refractive index profile by adjusting certain parameters until the theoretical mode indices match the experimental ones within a satisfactory error. Figure 3 shows the reconstructed refractive index (n_z) profiles of as-implanted sample (solid line) and the sample annealed (dot-dashed line). The refractive index n_z of a virgin Yb:KLu$(WO_4)_2$ crystal is also presented for comparison. It is noticed that an "optical barrier" with a refractive index decrease of about 6.2% compared to the refractive index n_z of a virgin crystal is formed at the depth 2.87 μm in the as-implanted waveguide. The structure of a region of high refractive index bounded by regions of lower index forms the waveguide. The refractive index change at the barrier decreases to 5.9% after annealed at 300°C for an hour. However the peak position and the width of the optical barrier almost remain unchanged after annealing.

A waveguide is frequently characterized by its normalized width V, which can determine the total number of waveguide modes.[16] V can be found by the following equation:

$$V = \frac{2\pi d}{\lambda}\sqrt{n_1^2 - n_2^2}, \qquad (1)$$

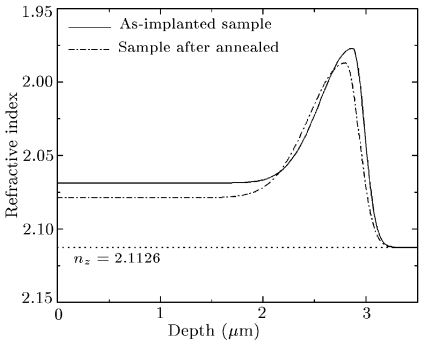

Fig. 3. Reconstructed refractive index n_z of the formed waveguide for as-implanted sample (solid line) and annealed sample (dot-dashed line). The refractive index n_z of the virgin Yb:KLu$(WO_4)_2$ crystal is also presented (dotted line).

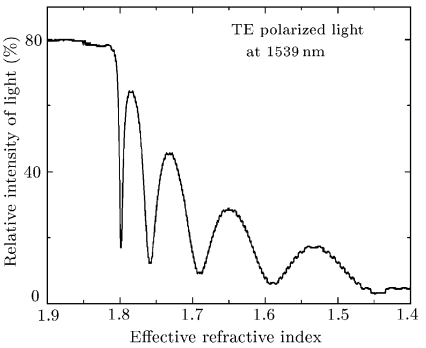

Fig. 4. Relative intensity of TE polarized light at 1539 nm reflected from a prism versus the effective refractive index of incident light in the Yb:KLu$(WO_4)_2$ waveguide formed by 6.0-MeV O^+ implantation at the dose of 2×10^{15} ions/cm^2 and annealed at 300°C for 60 min in air.

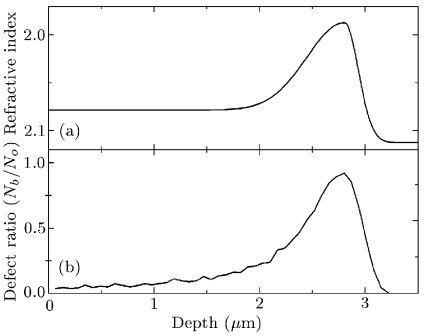

Fig. 5. Comparison of reconstructed refractive index n_z of the formed waveguide (a) and the normalized nuclear energy loss as a function of penetration depth of 6.0-MeV O^+ implanted into Yb:KLu$(WO_4)_2$ crystal based on TRIM'98 (b).

where δ is the wavelength of light, d is the waveguide width, n_1 and n_2 are the refractive indices of the waveguide and substrate, respectively. The larger the value of V, the larger the number. For a finite waveguide structure, the longer the wavelength λ, the less the number of modes which can be excited. A wavelength of 1540 nm is preferred in optical fibre communication systems due to a minimum of fibre loss. This is longer than the wavelength of Yb^{3+} fluorescence (about 1032 nm). If the light of 1540 nm could form guiding modes, light at 1032 nm should also be able to form modes. Figure 4 shows the relative intensity of 1539 nm light (TE polarized) reflected from a prism versus the effective refractive index of incident light in the Yb:KLu$(WO_4)_2$ waveguide. Four dips are observed while only the first one is sharp and dip which may correspond to real propagation mode.

We simulate the implanting process of 6.0-MeV O^+ into Yb:KLu$(WO_4)_2$ crystal by transportation of ions in matter (TRIM'98) code.[17] Figure 5 shows the comparison of the nuclear energy loss as a function of the penetration depth (vacancy distribution) and the reconstructed refractive index profile of the as-implanted sample. We find that the shapes of vacancy distribution and the index profile are similar. This means that the damage induced by nuclear energy deposition is an important factor that causes the change of the refractive indices in the crystal. Still, a detailed understanding needs further investigation.

In summary, planar optical waveguide has been fabricated in Yb:KLu$(WO_4)_2$ crystal by 6.0-MeV O^+ implantation to a dose of 2×10^{15} ions/cm^2 at room temperature. Propagation modes have been observed at wavelengths 633 nm and 1539 nm. The refractive index profiles of the formed waveguide are reconstructed using the RCM. The TRIM'98 simulation suggests that the nuclear energy deposition may be an important factor for refractive index change.

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