Low-loss slab waveguides in $KY(WO_4)_2$ fabricated by 12 MeV carbon ion irradiation

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$KY(WO_4)_2$ is a very interesting material in integrated optics thanks to its excellent gain characteristics when doped with rare-earth ions and its relatively large non-linear index of refraction. The fabrication and characterization of slab optical waveguides in $KY(WO_4)_2$ by swift 12 MeV carbon ion irradiation using moderate fluences is presented. Losses as low as 2.5 dB/cm after annealing have been measured for an irradiation fluence of $1x10^{14}$ ions/cm^2 at 632.8 nm of wavelength. Micro-Raman spectroscopy has been utilized as a tool to characterize the damage profile induced by the ions, which agrees qualitatively with the shape of the refractive index profile obtained from micro-reflectivity measurements.

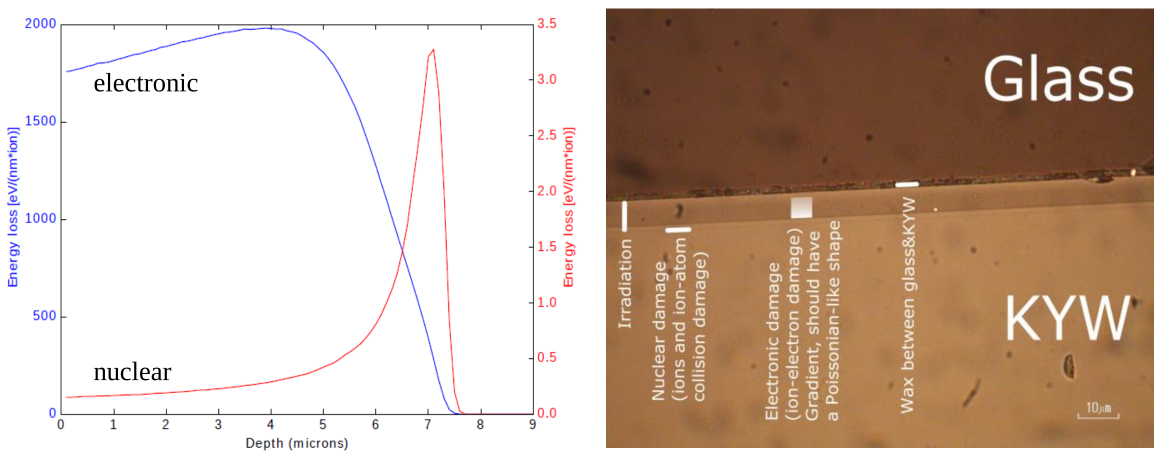
Introduction

$KY(WO_4)_2$ belongs to the family of the double tungstate (i.e., $KY(WO_4)_2$, $KGd(WO_4)_2$, $KLu(WO_4)_2$) host materials. It exhibits a monoclinic crystal structure at room temperature being therefore birefringent, with three different refractive indices depending on the propagation direction [1]. In recent years, crystalline $KY(WO_4)_2$ has been of interest for the realization of waveguide-based amplifiers [2] and lasers [3][4], due to its high absorption and emission cross-sections when doped with rare-earth ions, its relatively large nonlinear refractive index and the very even distribution of rare-earth doping up to very high concentrations [5]. High-contrast waveguides in $KY(WO_4)_2$ could further improve the mode confinement and efficiency of these devices. However, fabricating high-contrast waveguides in $KY(WO_4)_2$ provides some challenges, as the lattice mismatch with many low refractive index substrate materials including SiO_2 prevents the direct growth of thin layers of $KY(WO_4)_2$ on these materials. The state-of-the-art in the fabrication of high-contrast waveguides in $KY(WO_4)_2$ involves the lapping and polishing of a bulk (1 mm thick) crystal until the desired thickness (around 1 μm) is reached, a technology that is still under active development [6]. Ion irradiation is proposed here as a possible alternative to fabricate thin high contrast slab waveguides in bulk $KY(WO_4)_2$. This method has already been used in other crystalline materials such as $LiNbO_3$ [7]. Since both the refractive index and transition cross-sections are largest along the N_m and N_g optical axes, the crystals used in this work have been cut such that the crystal top surface is parallel to the a-c crystal plane (N_m-N_g optical plane).

Swift heavy ion irradiation

Two main types of ion-material interaction can be identified when ions are implanted into a material. During the penetration of the accelerated ion into the material, the first type of ion-material interaction, known as irradiation, is a combination of electron-ion interactions, causing electronic excitation in the material and elastic collision of ions with the atoms in the target material. The second type of ion-material interaction is the deposition of the ions into the material, which is referred to as implantation. Ion implantation occurs near the end of the ion trajectory, when the ions have lost most of their energy by irradiation interactions. The elastic collisions of the ions during irradiation cause damage that together with the ion implantation is called nuclear damage. The energy loss via electronic interactions causes thermal spiking along each ion track. When the damage induced by the different ion-tracks starts to overlap, damage builds up in the crystal until amorphization of the crystal is reached [8].

In this research, the use of irradiation damage to fabricate high contrast slab waveguides is investigated, because it can provide a large refractive index change with modest ions fluence, the damage does not diffuse, which is especially important under the high powers expected for lasing, and it does not repair as a function of time but as a function of temperature. SRIM (Stopping and Range of Ions in Matter) software was used for the calculations. Carbon ions with an energy of 12 MeV were utilized so that the maximum of the electronic damage layer lies 4 µm below the surface to facilitate the characterization of the damage (i.e., typical microscope characterization is limited by diffraction to about 200 nm resolution). Figure 1 shows both the energy loss (in eV/nm/ion) in $KY(WO_4)_2$ due to electronic and nuclear interactions. It also shows a bright field microscope image of the polished end-facet of the irradiated sample, showing both the electronic and nuclear barriers.

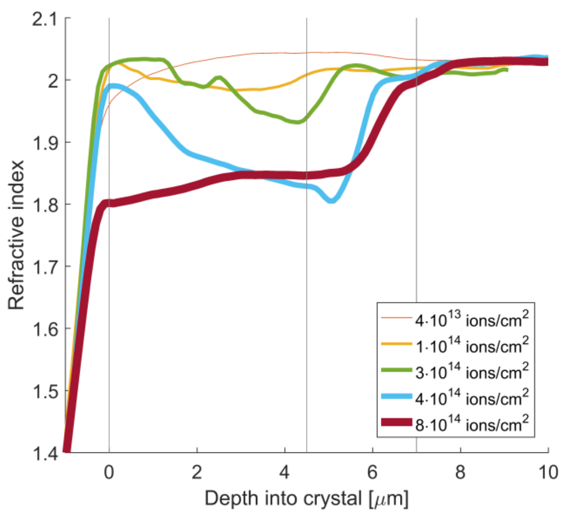


(a) (b)

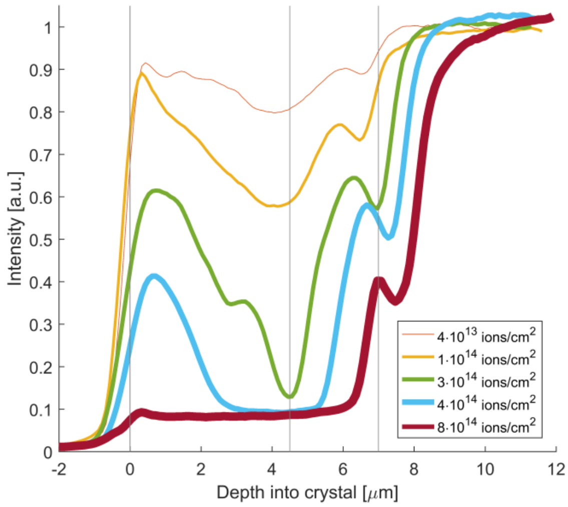
Figure 1: (a) Energy deposition from 12 MeV carbon ions into KYW as a function of depth, calculated using SRIM. Note the orders of magnitude difference between the electronic and nuclear energy deposition, as well as the clear separation between the range of maximum energy deposition for both regimes. (b) Bright field microscope image of the polished end-facet of an 12 MeV carbon irradiated $KY(WO_4)_2$ crystal showing the different damage regions.

12 MeV carbon ion irradiated slab waveguides characterization

$KY(WO_4)_2$ irradiated with 12 MeV carbon ions has been characterized by micro-Raman spectroscopy [9] (WiTec alpha300R/S/A confocal Raman microscope), micro-reflectivity measurements [10] (WiTec alpha300R/S/A microscope) and mode refractive index measurements [11] (Metricon 2010/M prism coupler). The Raman peak intensity of the 908 cm^{-1} peak (figure 2(b)) shows a significant change as a function of depth, which matches with the deposition of energy by electronic and nuclear interactions predicted by SRIM (figure 1(a)). This indicates that the crystalline structure of the material is damaged by the ion energy deposition, causing a decrease in the refractive index of the crystal. The evolution of the refractive index is shown in figure 2(a). Both the micro-Raman and micro-reflectivity measurements show the ion irradiation effect starts at the maximum of the electronic damage, and then extends towards the crystal surface for increasing ion fluence. For fluences above 4x10^{14} ions/cm^2, an amorphous layer of $KY(WO_4)_2$, with a refractive index of ~1.85, is formed at the peak of the electronic damage (i.e., ~4 μm under the surface). Mode refractive index measurements confirm the value of the refractive index of the formed barrier. As the fluence increases, the additional damage in the core region reduces its refractive index and increases the scattering losses. In order to conserve the $KY(WO_4)_2$ refractive index in the core while minimizing the irradiation damage in this region, a fluence of 1x10^{14} ions/cm^2 was chosen. A refractive index contrast of ~0.1 between core and cladding can be achieved for this fluence.



(a)



(b)

Figure 2: (a) Refractive index as a function of depth for several fluences of 12 MeV carbon irradiated $KY(WO_4)_2$ measured by microreflectivity; (b) Evolution of the 908 cm^{-1} Raman peak as a function of depth for several fluences of 12 MeV carbon irradiated $KY(WO_4)_2$.

The damage induced by ion irradiation causes the production of color centers and scattering points in the crystal, which can be partially removed by annealing to decrease the overall transmission losses in the slab waveguide. It is expected that scattering losses are the most dominant of the losses in these waveguides. Figure 3 shows the transmission losses in the slab waveguide as measured by a camera recording the perpendicular (out-of-plane) scattering from the waveguide as a function of the propagation distance. The figure clearly shows that annealing causes an improvement of the transmission. A transmission loss of 2.5 dB/cm (at a wavelength of 632.8 nm) is the lowest value currently reached for any irradiation fluence of 12 MeV carbon in $KY(WO_4)_2$. Because Rayleigh scattering is proportional to $1/\lambda^4$ the transmission losses are expected to decrease when considering transmission at 1550 nm.

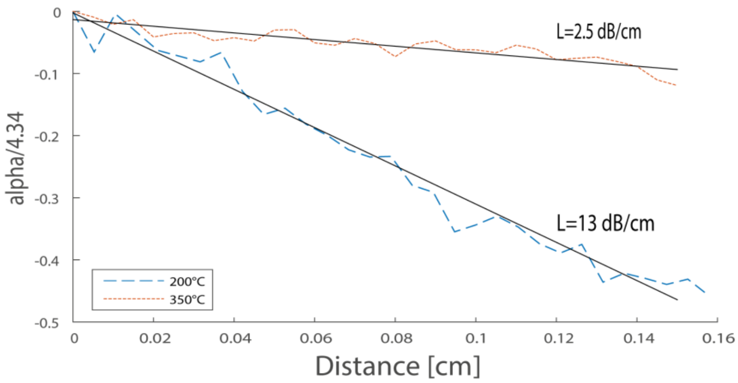


Figure 3: Transmission loss in the 12 MeV $1x10^{14}$ ions/cm^2 irradiated $KY(WO_4)_2$ crystal at 632.8 nm, calculated from the measured out of plane scattering from the slab waveguide. A decrease in transmission losses for higher annealing temperature is clearly observed.

Conclusion

Ion implantation is shown to be a promising method to fabricate low-loss (<2.5 dB/cm at 632.8 nm) transmission through a high contrast slab $KY(WO_4)_2$ waveguide. Investigation will continue at higher annealing temperatures and fine-tuning of the fluence to reach the lowest transmission losses possible. Transmission losses are expected to be even lower in channel waveguide structures because of the higher beam confinement provided by these structures. Channel waveguides will be etched using reactive ion etching (RIE) to measure transmission losses in these structures.

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