Nuclear Instruments and Methods in Physics Research B 307 (2013) 424–428

Contents lists available at SciVerse ScienceDirect

Nuclear Instruments and Methods in Physics Research B

journal homepage: www.elsevier.com/locate/nimb

Optical waveguide formed in Yb:GdCOB and Yb:YCOB crystals by 3.0MeV O^+ implantation

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ARTICLE INFO

Article history:
Received 8 September 2012
Received in revised form 20 October 2012
Accepted 1 November 2012
Available online 20 January 2013

Keywords:
Ion implantation
Optical waveguide
Yb:GdCOB crystal
Yb:YCOB crystal

ABSTRACT

Planar optical waveguides were formed in Yb:GdCOB and Yb:YCOB crystals by 3.0 MeV O^+ ion implantation at fluence of 2×10^{15} ions/cm^2 at room temperature, respectively. The prism coupling method was performed to characterize the dark-mode property of the waveguides. The refractive index profiles in the waveguides were reconstructed by reflectivity calculation method (RCM). The results show that after the implantation, a 1.5 μm-wide region with enhanced refractive-index was formed beneath the sample surfaces to act as waveguide structures for both Yb:GdCOB and Yb:YCOB.

1. Introduction

Calcium gadolinium oxoborate ($Ca_4GdO(BO_3)_3$, GdCOB) [1] and its family of calcium yttrium oxoborate ($Ca_4YO(BO_3)_3$, YCOB) [2] crystals are promising nonlinear optical crystals for a range of applications. They have attracted extensive attentions for their good chemical and physical properties in nonlinear optical (NLO) and self-frequency-doubling (SFD) applications, such as non-hygroscopicity, wide transparent range, high optical damage threshold and large effective NLO coefficient along phase-matching direction. The two crystals belong to the monoclinic biaxial crystal system of $Ca_4RO(BO_3)_3$ (R = rare earth element) with space group Cm [3]. The Gd or Y ions in GdCOB and YCOB crystals can be easily substituted by other rare earth ions with similar ion radii such as Nd^{3+}or Yb^{3+}. Research results show that Yb:YCOB [4,5] and Yb:GdCOB [6,7] crystals are promising laser and SFD crystals.

Optical waveguide structure is the basic component in integrated photonics, within which some optical performances of the materials can be improved because compact confinement of light propagation to tiny dimensions of order of a few microns is offered [8]. For example, waveguide lasers are usually with the lower pump thresholds and comparable efficiencies compared with bulk lasers [9,10]. And for nonlinear waveguides, the second harmonic generation (SHG) may be generated at low pump powers and be with multiple conversion mechanism from different guided modes [10]. Consequently, the combination of excellent laser performance and nonlinear optical properties of both Yb:YCOB and Yb:GdCOB crystals and waveguide technology is attractive.

Up to now, there have been several methods for surface waveguide fabrication, including sputtering, thermal diffusion, ion exchange, epitaxial growth, ion implantation, surface deposition techniques [11] and direct laser writing [12–14]. However, ion exchange and diffusion cannot be applied to GdCOB and YCOB crystals since specific chemical process is required which does not exist yet [15]. Compared with implantation waveguide, direct laser writing method cannot be used to fabricate planar waveguide. Besides, direct laser writing waveguide could only hold the light with one polarization (TE or TM) [16]. As one of the most extensively used physical methods for material modification, ion implantation has shown the unique ability for surface planar waveguide formation in a wide range of materials, including single crystals, polycrystalline ceramics, glasses, semiconductors and organic materials [11,17,18]. Planar waveguides in GdCOB [19] and YCOB [20] by He^+ ion implantation have been reported to create a lower-index optical barrier at the end of ion range, constructing guiding layer between the barrier and air cladding. More recent research works have shown that the construction mechanisms of light (H or He) and heavy ions (such as O, F, Si, P, Cu, etc.) implanted waveguides are different [17,18,21]. In this paper, we used the implantation of O^+, with energy of 3.0 MeV at fluence of 2×10^{15} ions/cm^2, to produce planar waveguides in Yb:GdCOB

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http://dx.doi.org/10.1016/j.nimb.2012.11.063

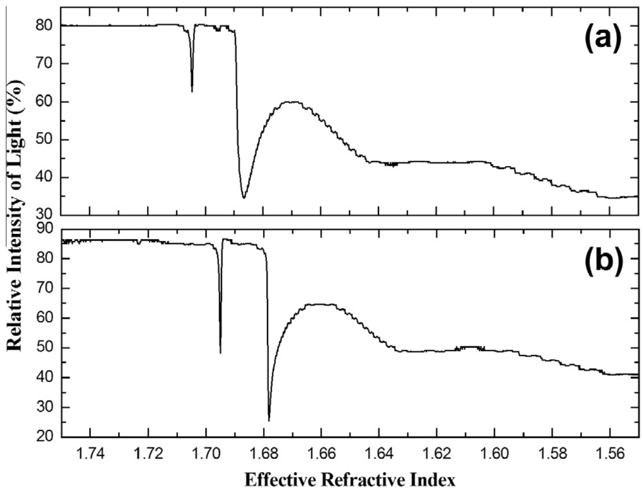

Fig. 1. The relative intensity (I) of the TE polarized light from the prism vs. the effective refractive index ($n_{eff} = n_x$) of the incident light for the 3.0 MeV 2E15 ions/cm^2 O^+ ion-implanted (a) Yb:GdCOB and (b) Yb:YCOB waveguides.

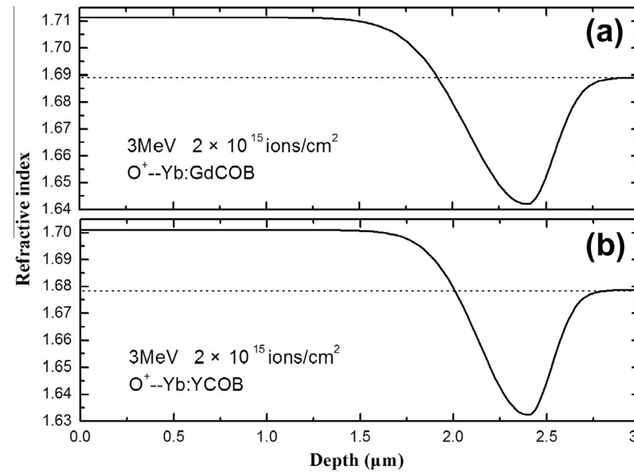

Fig. 3. The refractive index (n_x) profiles of the (a) Yb:GdCOB and (b) Yb:YCOB waveguides from RCM reconstruction.

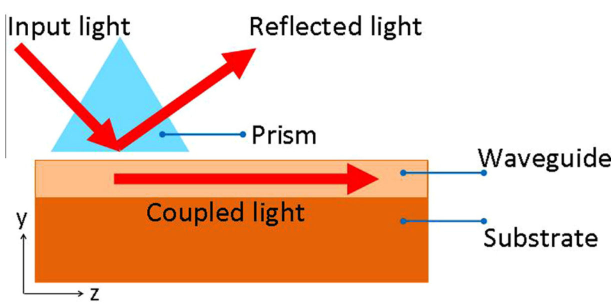

Fig. 2. The schematic diagram for prism-coupling experiments.

Table 1
The comparison of the measured mode indices with fitted values of the indices for the formed Yb:GdCOB and Yb:YCOB waveguides by 3MeV O^+ ion implantation at a dose of $2{\times}10^{15}$ ions/cm^2 at room temperature.

		3MeV $2{\times}10^{15}$ O^+-Yb:YCOB			3MeV $2{\times}10^{15}$ O^+-Yb:GdCOB		
		Exp.	Calc.	Error	Exp.	Calc.	Error
n_x	0	1.6949	1.6950	−0.00011	1.7047	1.7047	0.00003
	1	1.6781	1.6780	−0.00003	1.6862	1.6863	−0.00007

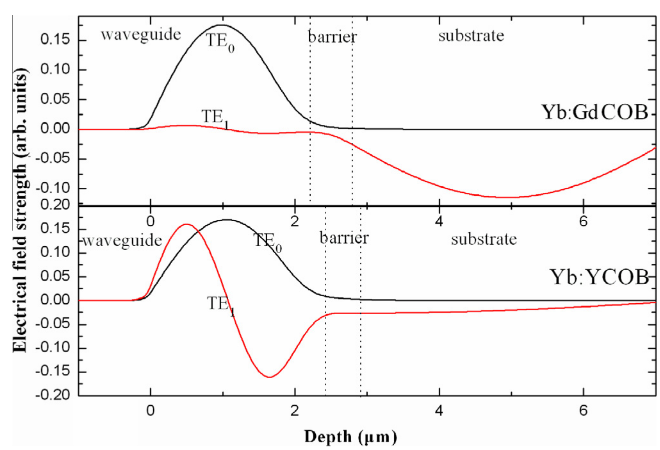

Fig. 4. The electrical field intensity distribution of TE modes for Yb: GdCOB and Yb: YCOB waveguides.

and Yb:YCOB, and reconstructed the refractive index profiles (n_x) in the waveguides. The possible reasons for the waveguide formation are discussed.

2. Experimental

The y-cut Yb:GdCOB and Yb:YCOB crystals grown by the Czochralski pulling method were provided by the Institute of Crystal Materials, Shandong University. The doping concentration of Yb in GdCOB and YCOB crystal is 30% and 15%, respectively. Before the implantation, the samples were optically polished and cleaned with the size of $4 \times 1.5 \times 4.5$ mm^3, and their refractive indices were measured. The samples were implanted by 3.0 MeV O^+ ions at fluence of 2×10^{15} ions/cm^2 at room temperature. The ion beam was electrically scanned to ensure a uniform implantation over the samples. The beam current was about 100 nA. During the implantation the samples were tilted by 7° off the beam direction in order to minimize the channeling effect. The implantation process was performed at 1.7 MV tandem accelerator of Peking University. The samples were annealed in a furnace in air to decrease color centers and investigate the thermal stability.

The prism-coupling method was used to characterize the dark modes in the waveguide. The effective refractive indices were measured with a model 2010 prism coupler (Metricon, USA). During the measurement, a light beam from a 633 nm He–Ne laser struck the base of a rutile prism, and was coupled into the waveguide region. A silicon photodetector was used to detect the reflected beam. The prism, sample and photodetector were mounted on a rotary table so that the angle of the incident beam could be changed. The intensity of the reflected beam was plotted on a PC screen as a function of the incident angle, where a sharp drop, so-called a "dip" in the intensity profile would correspond to a mode. The PC was used to control the measurement via an interface attached to the control pad. By adjusting the incident laser polarization, TE or TM modes can be excited in the waveguide and corresponding refractive index distribution could be obtained. In the case of y-cut samples, n_x and n_z were characterized by TE polarization modes while n_y was determined by TM polarization modes.

3. Results and discussion

Figs. 1(a) and (b) show the relative intensity (I) of the TE polarized light from the prism versus the effective refractive index (n_x)