Nuclear Instruments and Methods in Physics Research B xxx (2014) xxx–xxx

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research B

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

Optical waveguide properties of $Ca_{0.4}Ba_{0.6}Nb_2O_6$ crystal formed by oxygen ion irradiation

Tie-Jun Wang, Yu-Fan Zhou, Xiao-Fei Yu, Tao Liu, Lian Zhang, Hong-Lian Song, Mei Qiao, Xue-Lin Wang *

School of Physics, Key Laboratory of Particle Physics and Particle Irradiation, Ministry of Education, and State Key Laboratory of Crystal Materials, Shandong University, Jinan 250100, China

A R T I C L E I N F O

Article history:
Received 7 July 2014
Received in revised form 21 November 2014
Accepted 21 November 2014
Available online xxxx

Keywords:
Ion irradiation
Optical waveguide
CBN

A B S T R A C T

We report the fabrication of a planar optical waveguide in a $Ca_{0.4}Ba_{0.6}Nb_2O_6$ crystal by irradiation with 6.0 MeV oxygen ions. We measured the guiding mode by the prism-coupling method at 633 nm and 1539 nm. The near-field intensity distributions were measured by the end-face coupling setup at a wavelength of 633 nm. The reflectivity calculation method (RCM) was used for reconstructing refractive index profiles. SRIM was used to simulate the electronic and nuclear stopping power caused by oxygen ion irradiation, and the finite-difference beam propagation method (FD-BPM) was used to simulate the near-field intensity distributions. Micro-Raman spectra were measured at room temperature in air to study the differences between the substrate and waveguide region.

1. Introduction

Recent decades have witnessed the rapid development of methods for transmitting optical information. Integrated optical devices, particularly those based on new types of optical materials, are playing an increasingly crucial role in this context. Ferroelectric materials with a tungsten-tetragonal bronze (TTB) structure are outstanding for applications in integrated optical devices due to their excellent electro-optic, pyro-electric, piezo-electric, photorefractive properties and non-linear optical properties [1]. Strontium barium niobate ($Sr_xBa_{1-x}Nb_2O_6$, SBN) crystal, as the ferroelectric material with a TTB structure, exhibits prominent optical properties such as a large electro-optic coefficient and excellent photorefractivity. The properties of rare earth doped SBN as a kind of laser material are great, and it is so attractive as a light source for optical memories, color displays, and multi-wavelength scanners because of the low threshold power, lack of harmful speckle patterns, and high quality of colors generated [2–4], which have motivated widespread study of this material. However, the low Curie temperature (25–120 °C, depending on the composition) of SBN limits its use under high-temperature conditions [5]. Fortunately, calcium barium niobate ($Ca_xBa_{1-x}Nb_2O_6$, CBN) crystals, which exhibit a higher Curie temperature (approximately 200 °C), are quite similar to SBN crystals in terms of their optical properties, allowing for their broad applications [6–8]. CBN is a type of crystal with a TTB structure belonging to the P4bm and 4 mm point groups and has a wide spectral transparency range, covering the ultraviolet, visible and infrared bands. As a type of TTB niobate crystal, CBN features an abundance of vacancies; thus, ion implantation and dopants can be used to improve or modify the properties of CBN by choosing the appropriate processing conditions [9].

The waveguide structure is a basic component in integrated photonics whose performance is very important to the operation of integrated optical devices [10]. Optical waveguides are defined as having a high-refractive-index region surrounded by low-index regions. When light travels through a waveguide region, the light could be confined within the high-refractive-index region due to the phenomenon of total reflection. The propagation of the light can be confined within small volumes in a one-dimensional planar waveguide or in a two-dimensional channel or ridge waveguide, the latter of which has broader practical applications in devices such as optical switches, splitters, and amplifiers [11–13]. Several methods for waveguide fabrication have been developed in recent decades, such as ion irradiation, proton exchange, metal ion indiffusion, and direct femtosecond laser writing [14–18]. Ion irradiation is one of the most mature and successful methods for fabricating waveguides due to the ion species, energy, fluence, temperature and many other factors associated with the irradiated ions can be precisely controlled; furthermore, because the Curie temperature of CBN-40 is approximately 180 °C, ion irradiation is one of the most appropriate techniques for fabricating waveguides on CBN crystals.

* Corresponding author.
E-mail address: xuelinwang@sdu.edu.cn (X.-L. Wang).

http://dx.doi.org/10.1016/j.nimb.2014.11.079
0168-583X/

2. Experimental details

A CBN-40 ($Ca_{0.4}Ba_{0.6}Nb_2O_6$) crystal, with dimensions of $8 \times 10 \times 1.85$ mm^3, was optically polished and cleaned before ion irradiation. 6.0 MeV oxygen ion irradiation was performed using the 1.7 MeV tandem accelerator at Peking University, and the fluence of the oxygen ion irradiation was set to 6×10^{14} ions/cm^2. To avoid the channeling effect, the sample was rotated 7° relative to the ion-beam direction. Stopping and Range of Ions in Matter (SRIM 2013) was used to simulate the distribution of electronic and nuclear stopping power, which could indicate the energy transfer between the incident oxygen ions and the CBN-40 crystal. The prism-coupling method was used to measure the dark-mode spectra at visible (633 nm) and near-infrared (1539 nm) wavelengths in the m-line configuration with the Model 2010 Prism Coupler (Metricon). The end-face coupling method was used to measure the near-field intensity distribution of the waveguide with a He–Ne laser at 633 nm. The RCM [19] was used to reconstruct the refractive index profile of the waveguide region at 633 nm, and the FD-BPM [20] was used to simulate the modal distributions of the waveguide and compare those distributions with the experimental results. A micro-Raman spectrometer was used to record the Raman spectra of the waveguide and substrate at an excitation wavelength of 473 nm at room temperature.

3. Results and discussion

Fig. 1 shows the measured relative intensity of transverse electric (TE) and transverse magnetic (TM) polarized light reflected from the prism versus the effective refractive index of the CBN-40 waveguide formed by 6.0 MeV oxygen irradiation with a fluence of 6×10^{14} ions/cm^2. A lack of reflected light will result in a dip in the dark-mode spectrum when the laser beam is coupled into the waveguide region, which can provide the data regarding the waveguide mode and the corresponding effective refractive index. The waveguide modes along different axes of a sample can be determined by adjusting the electric field vector of the light along different cut directions. Two lasers, the 633 nm He–Ne laser and the 1539 nm diode laser, were used to study the characteristics of the CBN waveguide in a visible and near-infrared telecommunication bands. As shown in Fig. 1, several resonance dips were detected. Generally, a single narrow and deep dip in the guide mode profile indicates that there is a real guided mode in the planar waveguide. For instance, the three left-most dips in Fig. 1(a) are very sharp and most likely correspond to the real guided modes; thus, it can be concluded that the TM_0, TM_1, TM_2, TE_0, TE_1 and TE_2 modes exist at the wavelength of 633 nm in the O-irradiated CBN-40 waveguide structure. On the other hand, at the wavelength of 1539 nm, the waveguide can only carry the TE_0 mode. The normalized waveguide width V, is given by

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

λ is the wavelength of light; d is the waveguide width; n_1 is the refractive index of the waveguide; n_2 is the refractive index of the substrate; V is a measure for the total number of waveguide modes [21]. There will be more waveguide modes with the increasing of the value of V, and this determines that the waveguide can carry more modes at 633 nm than at 1539 nm which is in good agreement with our data. Fig. 1(a) and (c) shows the TE mode with TE-polarized incident light at wavelengths of 633 nm and 1539 nm. We observed that the surface refractive index (n_{sur} = 2.3050 at 633 nm and 2.2245 at 1539 nm of TE mode) of the CBN-40

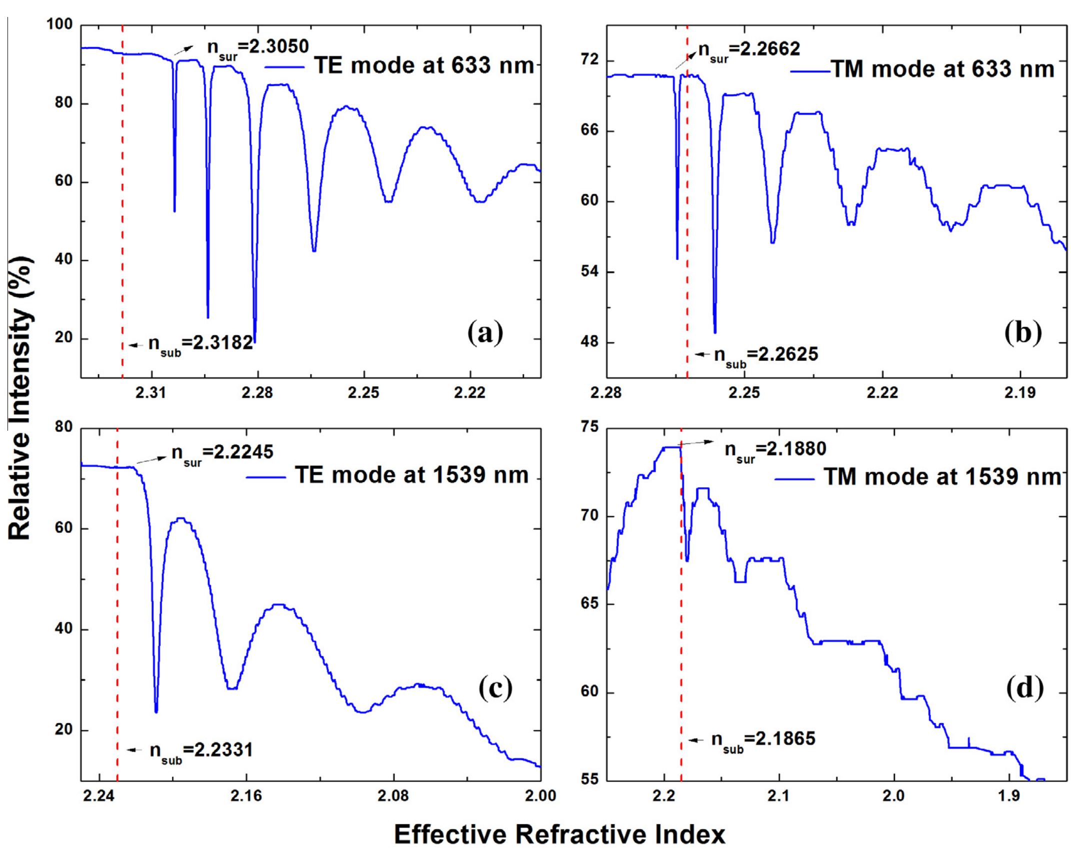

Fig. 1. Relative intensity of incident light versus the effective refractive index of the CBN-40 waveguide for (a) TE mode at 633 nm, (b) TM mode at 633 nm, (c) TE mode at 1539 nm, and (d) TM mode at 1539 nm.

Please cite this article in press as: T.-J. Wang et al., Optical waveguide properties of $Ca_{0.4}Ba_{0.6}Nb_2O_6$ crystal formed by oxygen ion irradiation, Nucl. Instr. Meth. B (2014), http://dx.doi.org/10.1016/j.nimb.2014.11.079