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# Optically induced photorefractive waveguides in KNSBN:Ce crystal

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**Abstract**

We present our experiments on fabricating fiber-like and planar photorefractive waveguides in a KNSBN:Ce crystal solely by laser irradiation with the wavelength of 632.8 nm and 532 nm, respectively. The high refractive index regions induced by thin cylindrical beams or thin sheet beams propagating through the crystal are used as waveguide structures. The refractive index changes in the waveguide region are measured by a Mach–Zehnder interferometer using the phase-stepping method, and the refractive index profiles are mapped. The optically induced distributions of refractive index changes observed in our experiments are discussed according to the transport mechanism of the photo-induced charge carriers in the crystal. The asymmetry of the light-induced space charge fields in the absence of external electric field may cause the asymmetry of the refractive index distributions. The guidance of the waveguides fabricated in our experiments shows that the probe beams are trapped in the waveguide regions. It is shown that fabricating photorefractive waveguides by use of light-induced refractive index changes in KNSBN:Ce crystals is feasible.


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*Keywords:* KNSBN:Ce crystal; Photorefractive waveguides; Light-induced refractive index changes

## 1. Introduction

The photorefractive waveguide devices may be found many important applications in optical computing, optical interconnection, and all-optical switching etc. Traditionally, ion diffusion, ion exchange, ion implantation, etching, and epitaxial growth are some of the ways to obtain waveguides in photorefractive materials [1,2]. Recently, the light irradiation method has been considered to be an effective way for fabricating spatial waveguides in some bulk photorefractive materials [3–8]. Compared with the waveguides fabricated by traditional methods, the optically induced waveguides possess many advantages. For example, they can be fabricated solely by laser beam illuminating with milliwatt power level, both surface and buried waveguides can be easily formed, and the waveguide structures can be easily erased or fixed, even modified. So far, various materials have been investigated to fabricate waveguides by light irradiation, including UV-cured epoxy [3], bulk photopolymers [4], $LiNbO_3$ [5–7], SBN [8], and $KNbO_3$ crystals [9], even glasses [10]. As one of the most promising photorefractive materials, the KNSBN crystal family attracts much attention in

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the fields of optical information processing, optical phase conjugation and optical network system, due to its excellent properties. However, to our knowledge, it has not been investigated to fabricate photorefractive waveguides in the KNSBN crystal by light irradiation. In this paper, we experimentally study the feasibility of fabricating photorefractive waveguides by use of light-induced refractive index changes in a KNSBN:Ce crystal.

## 2. Waveguide formation and index distribution measurement

The experiments on fabricating fiber-like and planar waveguides by light irradiation are performed at room temperature on a poled single crystal of KNSBN doped with 0.07 wt% Ce, whose dimension is $8 \times 7 \times 6$ mm$^3$. The experimental setup for waveguide formation and refractive index change measurement is shown in Fig. 1, where the $c$-axis is parallel to the $z$-axis. In Fig. 1(a), a thin cylindrical writing beam parallel to the $y$-axis propagates through the crystal to fabricate fiber-like waveguide. For fabricating planar waveguide, as shown in Fig. 1(b), a thin sheet writing beam formed by a cylindrical lens parallel to the $xy$-plane propagates through the crystal. A Mach–Zehnder interferometer is used to measure the index changes in crystal, being shown in Fig. 1(c). Where the power density of the probe beam from a He–Ne laser is decreased to guarantee that the waveguide structures are not to be erased. And the polarized direction of the probe beam is adjusted to be parallel to the $c$-axis, for getting a larger index change. The propagating directions of the probe beams used to probe index changes in the KNSBN:Ce crystal are shown in Fig. 1(a)and (b). The writing beams we used come from a He–Ne laser (at wavelength of 632.8 nm) with 30 mW power and a LD-pumped solid-state laser (at wavelength of 532 nm) with 60 mW power, respectively. The diameter of the thin cylindrical beam for fabricating fiber-like waveguides is 1.0 mm (wavelength: 632.8 nm) or 0.5 mm (wavelength: 532 nm). And the exposure time is correspondingly 10 or 5 s. The thickness of the thin sheet beam for fabricating the planar waveguides is 1.0 mm (wavelength: 632.8 nm) or 0.5 mm (wavelength: 532 nm). And the exposure time is 30 or 15 s. Considering the larger scattering effect induced by extraordinary light than that by ordinary, the writing beam polarization is perpendicular to the $c$-axis.

Figs. 2 and 3 show the distorted interference patterns in the waveguide regions and the corresponding refractive index distributions obtained by counting the interference fringes for fiber-like waveguides and the planar waveguides, respectively. The obtained index changes are positive (i.e. the refractive index will increase after illuminated by laser beams), and there is no negative refractive index changes ever found in our experiment. And there exists a saturation value of the extraordinary index change, approximately to $10^{-4}$ order. Noticing Figs. 2 and 3, the distributions of the index changes along the $c$-axis in the waveguide regions are asymmetric, and the distributions induced by the 0.5 mm beams are more asymmetric than that by 1 mm.

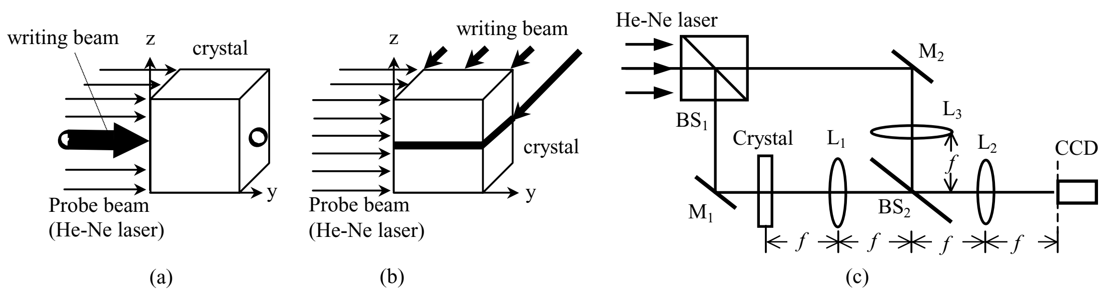


Fig. 1. Schematic of the experimental setup for waveguide formation and index change measurement. (a) For fiber-like waveguide; (b) for planar waveguide; (c) for measurement of the refractive index change profiles. M: mirrors; BS: beam split prism; $L$: lens; CCD: CCD camera.

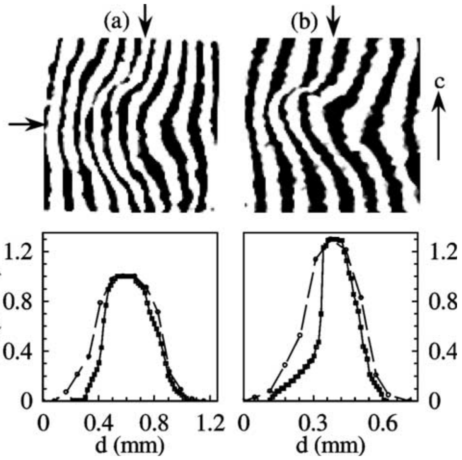


Fig. 2. The index distributions of the fiber-like waveguides formed in KNSBN:Ce crystal. Top: the interference patterns in the waveguide regions. (a) For 632.8 nm; (b) for 532 nm. Bottom, corresponding index change distributions along the arrows. Dashed line for horizontal arrows; solid line for vertical arrows.

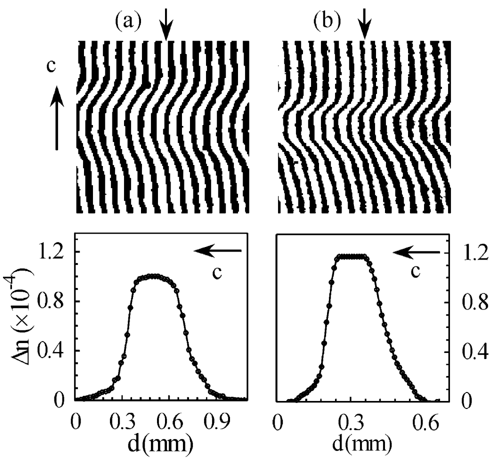


Fig. 3. The measured index distributions of planar waveguides. Top: the interference patterns in the waveguide regions. (a) For 632.8 nm; (b) for 532 nm. Bottom: corresponding index change distributions along the arrows.

Additionally, the index changes induced by 532 nm are a little larger than that by 632.8 nm.

## 3. Guiding test

The experimental setup for guiding test is shown in Fig. 4. An extraordinary collimated He–Ne laser beam as the probe beam is focused onto

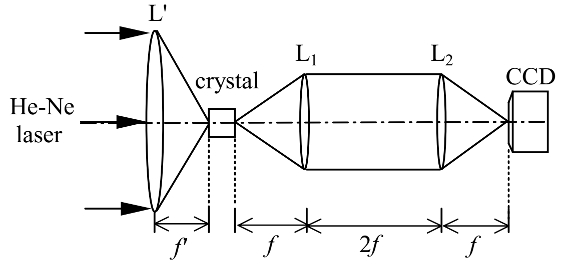


Fig. 4. The experimental setup for guiding tests. $L'$, $L_1$, $L_2$: lenses; CCD: CCD camera.

the front face of the crystal by lens $L'$ ($f \approx 4$ mm), to excite the guiding mode in the waveguides. The power density of the probe beam is reduced to very low to avoid erasing the waveguide structures. The rear face of the crystal is imaged onto the photosensitive chips of a CCD camera through a $4f$-system. If there is a waveguide structure in the crystal, a sharp and intense pattern produced by the guided beam should be observed. Otherwise, the pattern changes to a broad and weak intensity pattern produced by defocused beam.

Fig. 5 shows the guiding test results of the waveguides fabricated by the laser beam at 532 nm. Where (a) and (b) show the intensity patterns recorded by the CCD camera, and (c) show the

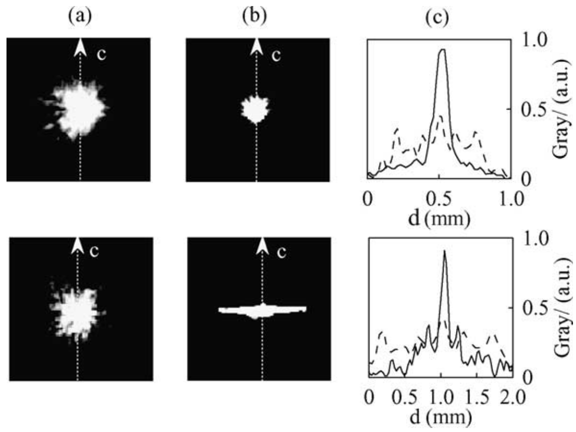


Fig. 5. The experimental results for guiding test of the waveguides fabricated by the laser beam at the wavelength of 532 nm. Top for fiber-like waveguide; bottom for planar waveguide. The intensity patterns of the probe beam are shown: (a) without guidance; (b) with guidance. The corresponding gray distributions along the white arrows are shown in (c): dashed line for (a), solid line for (b).

gray distributions along $c$-axis at the center of the laser beams. It is obvious that the intensity patterns of the probe beam without guidance at the rear face of the crystal are broad and weak; in contrast, that of with guidance are very sharp and intense. Additionally the similar results are also got at 632.8 nm.

## 4. Discussion

### 4.1. The photo-induced refractive index changes in the KNSBN:Ce crystal

The distributions of the light-induced index changes observed in our experiments described in Section 2, must relate to the light-induced space charge fields, which modulate the crystal refractive index through linear electro-optic effect. It's well known that the transport mechanism dominating the transport of the light-induced charge carriers in the absence of external electric field is diffusion in the KNSBN crystal. In this case, the diffusion length determines the magnitude of the space charge field in the crystal. When the KNSBN:Ce crystal is illuminated by a laser beam with a relatively large size along the $c$-axis, the influence of the internal electric field caused by the surface charge compensation, could not be ignored [11]. Under this condition, the buildup of the light-induced space charge field in the KNSBN:Ce crystal thanks to the drift under the internal field and the diffusion caused by the density gradient. So the electric field distributions are very similar to that of Fig. 2.5 in Ref. [1], except that the intensity profile of the laser beam in our experiments is a Gauss distribution. Furthermore, the space charge field modulates the refractive index of the KNSBN:Ce crystal through linear electro-optic effect, so the electric field along the $+c$-axis (the direction of the spontaneous polarization) causes the refractive index to decrease linearly, whereas the electric field along the opposite direction of the $+c$-axis, causes the refractive index to increase linearly. Considered the directions of the internal field and the diffusion field, the magnitude of the positive index change is much larger than that of the negative. And the region with increased index used as waveguide structure has much larger scale than that with decreased index. Noticing the asymmetry of the light-induced electric field distribution shown in Fig. 2.5 in Ref. [1], we can understand the asymmetry of the index distributions. With the diffusion field being enhanced, the asymmetry of the total electric field becomes more obvious. This may be the reason for the distributions induced by the 0.5 mm beams are more asymmetric than that by 1 mm. No index decrease is found there, this may be caused by the weak electric field along the $+c$-axis after the diffusion field combined with the drift field. When the magnitudes of the total electric field reach the value of the internal field, the index changes may arrive at a saturation value. The index changes induced by 532 nm are a little larger than those by 632.8 nm, this is due to the larger absorption at 532 nm in KNSBN:Ce crystal than that at 632.8 nm.

### 4.2. Waveguide structures formed by light irradiation

The experimental results of the guiding tests for the waveguides we have fabricated show that the probe beams are trapped in the waveguide regions. So the feasibility of fabricating photorefractive waveguides by use of light induced refractive index changes in KNSBN:Ce crystal is demonstrated. The fabrication of the waveguide is fairly simple, and after fabrication the waveguide structures can be easily erased by uniform laser illumination. Nevertheless in order to get permanent waveguides the refractive index changes must be fixed because the general decay time of the light-induced index changes is from several hours to days. Fortunately, the electric fixing of the refractive index changes in KNSBN has been investigated in detail [12]. Additionally, adjusting the size of the illuminating laser beam can control the dimensions of the waveguides easily.

## 5. Conclusion

Fiber-like and planar photorefractive waveguides in KNSBN:Ce crystal are fabricated by laser irradiation, the refractive index distributions in the waveguide regions are measured and mapped. The optically induced distributions of refractive index change observed in our experiments are discussed according to the transport mechanism of the photo-induced charge carriers in the crystal. The asymmetry of the light-induced space charge fields in the absence of external electric field may cause that of the refractive index distributions. And the guiding tests are also performed, which experimental results show that the probe beams are trapped in the waveguide regions. We demonstrated it is feasible to fabricate photorefractive waveguides by use of light-induced refractive index changes in KNSBN:Ce crystal.

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