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Electrical fixing of waveguide channels in strontium-barium niobate crystals

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Abstract. We demonstrate a new method of electrical fixing of waveguiding channels in strontium-barium niobate. The method is applicable to both bulk material and planar SBN waveguides. Waveguiding is achieved for extraordinarily polarized light. We suggest that the fixing is based on a partial depoling of the crystal rather than on internal electric fields.

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Electrical fixing as a method to store permanent refractive-index structures in ferroelectric crystals has been investigated since the seventies [1, 2]. In strontium-barium niobate (SBN), ferroelectric 180° domain structures are typically generated by applying an external repoling electric field under partial illumination. However, for 180° domains, reversing the direction of the spontaneous polarization alone does not change the linear optical properties of the medium −180° domains are, in principle, invisible. Methods such as the application of DC electric fields [3], second harmonic generation [4], or two-beam coupling topography [5] have to be employed to monitor the polarization changes. Moreover, especially in the "relaxor" or "glassy" ferroelectric material SBN, the domain-switching process can be complex and is not yet fully understood. Relaxor ferroelectric materials have a disordered structure, with varying internal fields and an inhomogeneous polarization switching behaviour.

We demonstrate a new method of electrical fixing in $Sr_{0.61}Ba_{0.39}Nb_2O_6$ (SBN61). In this work, we fix permanent refractive-index structures such as one- or two-dimensional waveguides. The fixing method is mainly based on screening of an external field [6]. An electric field is applied to the crystal while a small part of the crystal is illuminated. The direction of the field is parallel to the crystal's spontaneous polarization, i.e., it enables polarization reversal in those regions where the field strength exceeds the value of the coercive field. If the illumination screens the external electric field, the polarization can only switch outside the light beam, while polarization reversal inside is prevented. The method is applied to bulk material as well as to planar SBN waveguides. In contrast to other methods, the refractive-index changes are visible without additional means under illumination with extraordinarily polarized light. We propose a new model where the fixing is based on a depoling of the material rather than on complete polarization reversal.

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1 Experimental methods

We use SBN61 crystals doped with 0.1 and 0.4 wt. % Ce with light propagation lengths of around 3 mm. The electro-optic coefficients at the wavelength 633 nm have been measured to be $r_{33} = 247$ pm/V for extraordinary and $r_{13} = 44$ pm/V for ordinary light polarization. The planar, monomode waveguides are produced by ion implantation [7]. The fixing process is performed as follows: With the help of a microscope lens, a HeNe laser beam with extraordinary or ordinary polarization is either coupled into the waveguiding layer or focused onto the bulk material. The light distribution at the crystal's endface is imaged onto a calibrated CCD camera with a second microscope lens. A cylindrical lens in front of the first microscope lens allows for the adjustment of both the input beam width and the divergence in the x-direction, which is the direction of the ferroelectric c-axis. Thereby, stripe-like beams with widths in the range from $x = 5$ to 50 μm inside the crystal are produced. Additionally, we use an incoherent homogeneous background illumination on the samples. The intensity ratio r of beam and background intensity is larger than 100 throughout the experiments to guarantee a nearly complete screening of the external electric field in the center of the light beam [8].

After the fixing process, the changes of the refractive index and the polarization are monitored. The refractive-index changes cause the guidance of light in areas with a larger refractive index and can thus be directly observed with the CCD camera when the crystal is illuminated with an expanded beam. Local changes of the spontaneous polarization are monitored with a conventional two-beam coupling experiment [7]. Here two focused extraordinarily polarized

beams of equal intensity are launched which intersect inside the crystal. We measure the intensity change caused by the two-beam coupling, ΔI_p, in one of the beams, after a steady state is reached. For small coupling strengths, ΔI_p is proportional to the exponential gain factor Γ, and the net spontaneous polarization P_s in the intersection volume [9, 10].

2 Results

The dynamics of the fixing process is shown in Fig. 1. The process is shown, for example, for the fixing of a stripe-like refractive-index distribution in a bulk SBN crystal. Before the measurement starts, the crystal is electrically poled at room temperature for at least 15 min at $E = 6\,\mathrm{kV/cm}$ to ensure that the crystal's polarization is mainly single domain. An extraordinarily polarized beam with a x-width of about 13 μm is launched perpendicular to the c-axis. The ratio of beam to background intensity is $r \approx 400$. A depoling electric field E is applied to the crystal and is increased within 3 min from zero to 3 kV/cm. The position of the initial intensity distribution is set at $x = 0$. Negative values of x point to the negative side of the c-axis, where the negative voltage is applied during the fixing process. This side is referred to as the "−" side in the following, while the other is referred to as the "+" side. With increasing negative field the beam first becomes slightly broader, because the photorefractive drift mechanism induces a noticeable self-defocusing space charge field [8]. At about 2.4 kV/cm, pronounced changes in the intensity distribution appear, because the coercive field is reached in the non-illuminated parts of the crystal and the polarization there partially flips. As a result, the intensity distribution shows a minimum at $x = 0$ and two maxima located at the borders of the initial intensity distribution, with the maximum on the "−" side being more pronounced. The width of this intensity profile is about 8 μm. The intensity distribution stays nearly constant up to $E = 3\,\mathrm{kV/cm}$, at which point the external electric field is switched off.

After the fixing procedure, the refractive-index pattern as well as the pattern of the spontaneous polarization are investigated. Illuminating the crystal with an expanded beam of extraordinary polarization, we again find two waveguiding channels that are located at the borders of the initial intensity distribution. In some experiments, stronger guidance is observed on the "−" side.

As an example, in Fig. 2 the refractive-index structure on the "−" side is investigated. In Fig. 2a extraordinarily polarized read-out light is used. Guidance of the beam is observed inside a 13-μm-wide channel. The waveguiding channel is present without development time and is stable at room temperature for at least 90 h. No guidance can be seen if ordinarily polarized light is used (see Fig. 2b). In Fig. 2c the fixed structure has previously been erased by applying a homogeneous external electric field of 6 kV/cm for 15 min with only the background illumination present. Obviously, guidance of extraordinarily polarized light no longer occurs.

Next, we monitor the polarization pattern induced in the fixing process with a two-beam coupling experiment. An example is shown in Fig. 3. The steady-state change of the probe beam intensity ΔI_p due to the two-beam coupling is measured as a function of the crystal location x. The resolution, i.e., the cross-sectional area of the two beams, is about 20 μm in the x-direction. The value of ΔI_p is normalized to the beam-coupling change, $\Delta I_{p,0}$, in the poled crystal before the fixing process is performed. Negative values of $\Delta I_p/\Delta I_{p,0}$ mean that the probe beam is depleted due to a net reversal of P_s in the intersection volume of the two beams. The position of the initial intensity distribution of the fixing process is marked by $x = 0$. As can be seen, the polarization at the initial beam position is nearly maintained, while the polarization direction outside the light beam has been changed. Moreover, the switching process is clearly asymmetric. The

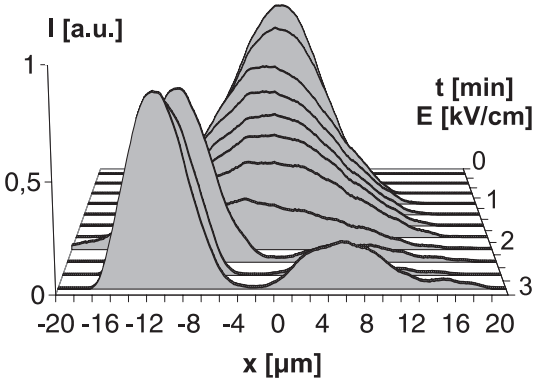

Fig. 1. Dynamics of the fixing process (see text)

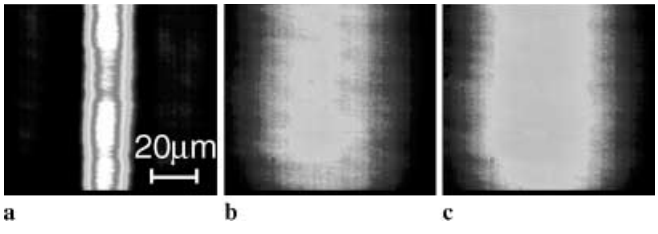

Fig. 2a–c. Illumination of the fixed structure **a** with extraordinarily polarized light, **b** with ordinarily polarized light and **c** with extraordinarily polarized light after erasure at 6 kV/cm for 15 min

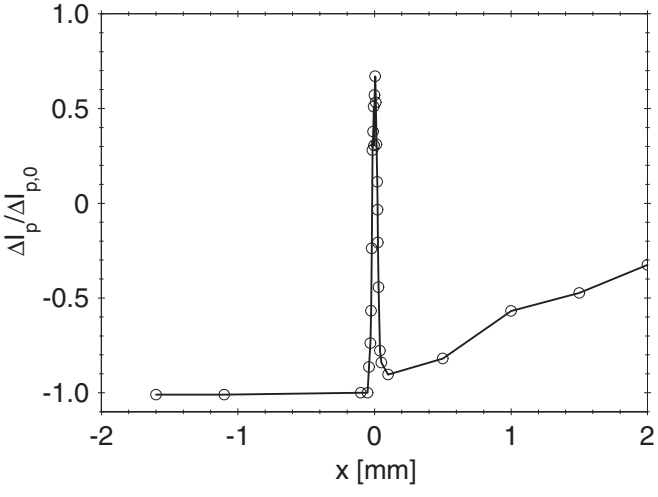

Fig. 3. Steady-state change of the probe beam intensity $\Delta I_p/\Delta I_{p,0}$ due to two-beam coupling versus the crystal location x

Fig. 4a–g. Fiber-like structure fixed in a planar SBN waveguide. The crystal is moved in the x-direction while it is illuminated with an extraordinarily polarized beam. The images belong to different x positions. **a** $x = -27.8\,\mu$m; **b** $x = -15.4\,\mu$m; **c** $x = -10.0\,\mu$m; **d** $x = -4.0\,\mu$m; **e** $x = 0.5\,\mu$m; **f** $x = 4.3\,\mu$m; **g** $x = 12.1\,\mu$m

polarization at the "+" side is not completely reversed after a fixing procedure of 3 min. However, we find that the amount of the switched polarization outside the light beam is not critical for the guidance properties of the fixed structures. In most experiments we observe guidance channels which are symmetrically located at both borders of the initial intensity distribution, even if the two-beam coupling experiment shows a distinctly lesser amount of switched polarization at the "+" side.

The fixing method also works for fiber-like waveguides fixed in a planar SBN waveguide. As an example, we perform a fixing process with a beam focused onto the endface of the crystal to a x-width of 9 μm. The resulting fixed structure can be seen in Fig. 4. Here we illuminate the waveguiding layer with an extraordinarily polarized light beam, while the crystal position is changed. Again, a distinct waveguiding channel with a width of 6.5 μm can be observed at the position $x = -4.0\,\mu$m. Obviously only one guidance channel is observable here.

3 Discussion

Because the waveguiding channels are present without development time and are located symmetrically on both sides of the initial intensity distribution, our results cannot be explained with a photorefractive or electro-optic mechanism due to bond charges at the domain borders of the fixed polarization pattern. Instead, we propose a new model, by which positive refractive-index changes for extraordinary polarized light are induced due to a partial depolarization of the crystal.

It was shown that the birefringence $|n_e - n_o|$ of extraordinary and ordinary refractive index considerably increases for unpoled SBN crystals by about 7×10^{-4} when compared to the poled material [11]. Since the ordinary refractive index is not highly affected, e.g., when approaching the phase-transition temperature, it can be assumed that it is mainly n_e which increases in an unpoled crystal. Indeed, by measuring the refractive-index increase of an unpoled and a poled SBN61 prism directly, a difference $\Delta n_e = 1.2 \times 10^{-3}$ was found for the wavelength 633 nm, while the ordinary refractive index was nearly unaffected by the poling state. In SBN61, needle-like domains with widths of about 20 nm and lengths in the direction of the c-axis on the order of 100 nm have been found [12]. The small dimensions of these domains cause a high density of domain walls in depolarized crystal areas and thus make the large refractive-index change from the unpoled to the poled state plausible.

From the two-beam coupling experiments we know that the polarization direction is quite homogeneously maintained inside the light beam, while it is nearly homogeneously switched outside. On the other hand, this experiment does not provide an exact polarization topology. Due to its limited resolution, we cannot observe the exact poling state at the borders between dark and illuminated parts. However, it is unlikely that a sharp border exists between the switched and unswitched domains. Due to the disordered structure of SBN, internal and external electric fields fall off inhomogeneously. We therefore propose that during the fixing process numerous microdomains [13] grow at the borders of the initial intensity distribution. For extraordinarily polarized light, these areas would have a larger refractive index than the more homogeneous surroundings, which explains the observed waveguiding channels.

The kinetics of the domain switching process is important in our experiments. Upon application of an external electric field above the coercive field, a fast polarization change (time range of milliseconds) is followed by a slower one (time range of minutes) until a steady state is reached [14]. Fixed guidance channels are present if the fixing process is stopped shortly after the "fast" reversal of domains at the first attainment of the coercive field strength. Longer application of the external electric field can enhance the refractive-index contrast and is correlated with a more complete polarization reversal ("slow" process) outside the light beam. If a small beam is used for the fixing process (as shown in Fig. 1) the beam tends to follow the refractive-index changes induced in the coercive field. Due to photorefractive diffusion effects [15], the beam is mainly deflected to the "−" side of the crystal, so the intensity is concentrated at the "−" maximum. If the external electric field is applied much longer after the coercive field is reached, an erasure of the "+" maximum, which is no longer protected by screening effects, could occur. In this case, only the "−" maximum will be present after the fixing process. This mechanism can be used to fix only one refractive-index channel (on the "−" side), as is shown in Fig. 4.

4 Conclusion

In summary, we have fixed waveguide channels in SBN61 bulk crystals and planar waveguides. The permanent channels guide extraordinarily polarized light and are located at the borders of the initial intensity distribution used in the fixing process. The channels can be read out without development time. The fixing of permanent refractive-index changes can be explained with the formation of inhomogeneous areas with a high density of domain walls at the borders of the initial intensity distribution. These depolarized regions have a larger refractive index than the polarized material. We assume that this mechanism contributes at least partially to the observed refractive-index changes obtained by electrical fixing in SBN61.

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