Thermally induced self-focusing and optical beam interactions in planar strontium barium niobate waveguides

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We present an experimental study of thermally induced self-focusing effects and interactions of incoherent light beams in strontium barium niobate waveguides. Depending on the input power, a single parallel beam is strongly focused inside the sample up to diameters of several micrometers. For higher input power we observe the splitting of the beam in a sequence of several spots. We demonstrate that these thermally induced refractive-index patterns can be used to focus and deflect an incoherent guided probe beam in the waveguide with time constants below 1 ms. © 1998 Optical Society of America

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Recently considerable interest has developed in the investigation of self-focusing effects in nonlinear optical materials because these effects permit diffraction-free or solitonlike propagation of optical light waves.[1–4] Self-focusing and self-defocusing originate from a variation of the refractive index in a plane perpendicular to the propagation direction of an optical beam. If the refractive-index change is positive, it can compensate for diffraction, and the light beam propagates without changing its diameter. This effect can be thermally because of light absorption,[5,6] it can be due to nonlinear susceptibility,[7] or it can be due to light-induced refractive-index changes in photorefractive crystals.[2,3,8,9] Potential applications are in the field of optical communication technology, such as beam deflection, switching of light beams in optical networks, and all-optical logic operations.

Here we study self-focusing effects in ion-implanted planar optical waveguides in strontium barium niobate (SBN).[10] In the bulk material, the excitation of both dark[11] and bright[12] solitons as well as fusion and birth of solitons[13,14] were observed recently. However, to our knowledge no results on self-focusing or soliton propagation in SBN waveguides have yet been published.

Strong focusing occurs when we couple the extraordinarily polarized light of an Ar^+ laser into the waveguide, and the resulting positive change of refractive index can be used to manipulate an incoherent probe beam with time constants below 1 ms. The experimental observations are explained qualitatively by a combination of the thermo-optic effect and a pyroelectric field that is screened by the large photoconductivity in the region of high light intensity.

In our experiments we use congruently melting, cerium-doped SBN crystals with concentrations of 0.025-, 0.1-, and 0.2-wt. % CeO_2. The dimensions of the samples are 2.0 mm × 5.0 mm × 2.5 mm, with the 5-mm edges along the c axis of the crystal. The propagation length is 2.0 mm. All samples are irradiated with He^+ ions at an energy of 2.0 MeV and a dosage of 1×10^{15} cm^{-2}. The sample temperature is stabilized to ~20 °C to prevent heating above the Curie temperature of $T_c \approx 80$ °C. The implantation yields a buried damaged layer of reduced refractive index $\Delta n_e = -0.027$ ($\lambda = 514.5$ nm) at a depth of 4.5 μm. Details are described in Ref. 10.

The experimental setup is shown in Fig. 1. The beams of an Ar^+ laser, a red He–Ne laser, or both are coupled into the waveguide by 20× microscope lenses (N.A., 0.4). A cylindrical lens with a focal length of 250 mm and at a distance of 290 mm from the first microscope lens is used to reduce the divergence of the light in the waveguide. The intensity distribution at the exit face of the sample is imaged onto a CCD camera, and a photodiode with a small aperture permits power measurements at different locations in the outcoupled light spectrum.

Self-focusing is observed in all waveguides, but the effects are strongest for the samples with dopings of 0.1- and 0.2-wt. % CeO_2 and for extraordinarily polarized light of the Ar^+ laser. Only a small amount of

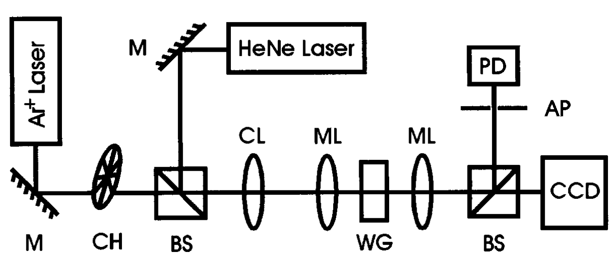

Fig. 1. Schematic of the experimental setup: M's mirrors; BS's, beam splitters; CH, mechanical chopper; CL, cylindrical lens; ML's, microscope lenses; WG, SBN waveguide; PD, photodetector; AP, aperture; CCD, CCD camera.

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self-focusing is observed for light with ordinary polarization. In the following experiments, the sample with 0.2-wt. % CeO_2 is used.

The dependence of the power measured in the center of the transmitted light beam on input power is shown in Fig. 2. No focusing of the light inside the waveguide is observed up to input powers of 1 mW. Above this threshold self-focusing starts, and in the range of input power from 2 to 4 mW the light power transmitted through the sample depends linearly on the input power.

When the input power is increased to higher values than those needed for focusing as described above, a sequence of different (both spatially and temporally stable) symmetric light patterns is observed at the exit face of the waveguide: First the focused beam splits into two separate beams, followed by spreading of the maxima and the appearance of further peaks in the center of the light distribution. The sequence of steady-state light patterns obtained for several cw input powers is illustrated in Fig. 3. The maximum number of intensity peaks that we observe is six for an input power of 19.5 mW. We estimate the beam diameter (FWHM) inside the waveguiding layer by measuring the divergence of the outcoupled light beam without use of the second microscope lens. For the splitting into six peaks we get a value of 7 μm, for the splitting into two peaks 12 μm, for strong focusing in one beam 15 μm, and we find a value of 70 μm for the case of low input power without self-focusing.

Now we investigate the temporal development of self-focusing, using a mechanical beam chopper; i.e., we have symmetric rectangular light pulses of the green pump light at a frequency of 125 Hz. We measure the power in the center of the outcoupled light pattern (see Fig. 1) with the help of a slit that is much smaller than the intensity distribution. Four situations corresponding to four input powers are shown in Fig. 4. At low power, no focusing is observed (Fig. 4a), and the transmitted intensity does not change during a pulse. For intermediate power the beam is slightly focused and the intensity in the beam center increases (Fig. 4b). The observed time constants for the buildup of the self-focusing are approximately 1 ms. For higher input power of the pulsed pump light the beam is first focused again, followed by a partial division into two peaks (Fig. 4c). For still higher input power the pattern observed by eye, i.e., the temporally averaged intensity pattern, shows a split into three peaks: The different stages of focusing, splitting into two peaks, and splitting into three peaks (i.e., the appearance of a third spot in the center of the intensity distribution that is connected with an intensity increase on the photodiode) can be observed clearly in the temporal dependence of the power in the beam center (Fig. 4d). Notice that the power on the photodiode changes continuously. For a certain cw input power, or at a certain time when pulsed pump light is used as in the experiment of Fig. 4, the intensity distribution of the outcoupled light consists of a mixture of the patterns shown in Fig. 3.

The refractive-index profile induced by the green light can be used to deflect or switch an incoherent probe beam. This effect was studied theoretically recently.[15] In our setup, light from a red He–Ne laser together with the green pump beam is coupled into the waveguide. The red beam is adjusted to intersect the green beam under a small angle in the first half of the sample. The green light is blocked behind the sample by a bandpass filter, and the intensity distribution of the red light is imaged onto the CCD camera. When the input power of the pump beam is low, no self-focusing occurs, and the intensity distribution of the red probe beam remains unchanged. As can be seen from Fig. 5, increasing the input pump power leads to the formation of a focusing lens for the green

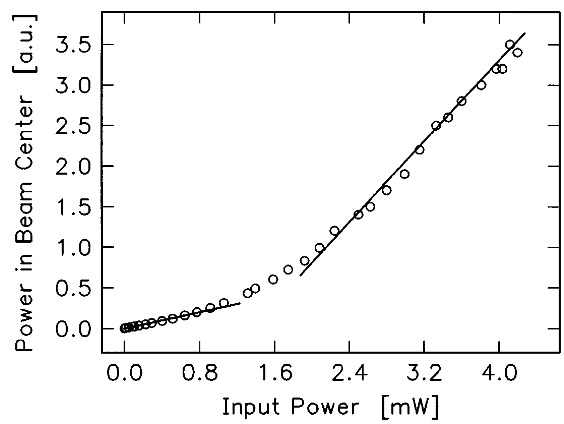

Fig. 2. Light power in the center of the outcoupled beam as a function of cw input power.

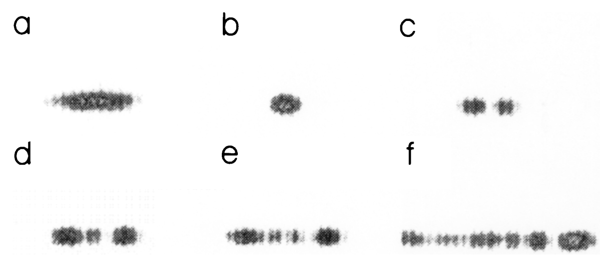

Fig. 3. Light intensity pattern coupled out of the end face of the waveguide for several cw input powers (in milliwatts): a, 0.1; b, 4.7; c, 12.0; d, 14.5; e, 15.5; f, 19.5.

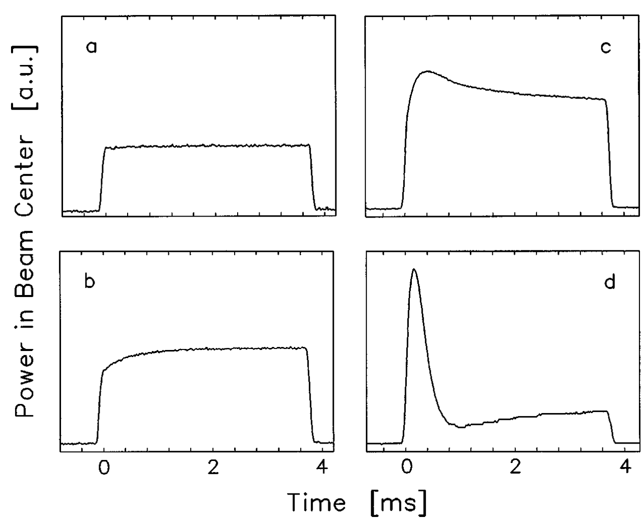

Fig. 4. Temporal evolution of the power in the center of the outcoupled light beam for several pulsed input powers (in milliwatts): a, 2.0; b, 3.9; c, 5.0; d, 14.1.

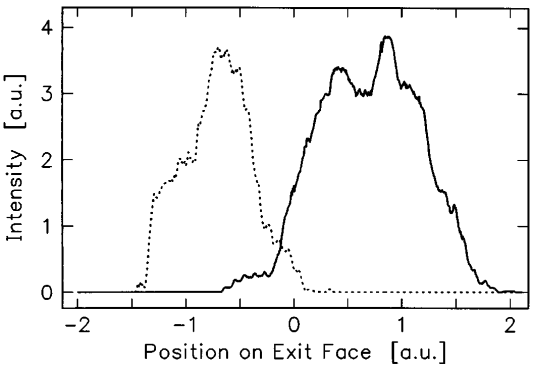

Fig. 5. Intensity distribution of the red probe beam on the exit face of the waveguide for high (10-mW, dashed curve) and low (1 mW, solid curve) cw input powers of the green pump beam. The red probe beam propagates under a small angle with respect to the green pump beam, intersecting it in the first half of the sample.

light, and at the same time it deflects and focuses the red-light beam; i.e., both beams interact with the same refractive-index profile. Thus the time constant for the switching of the probe beam, i.e., for deflecting it from one to the other position, is the same as the time for self-focusing of the green pump beam: For high input pump power switching times below 1 ms are reached.

The observed positive refractive-index changes can be explained qualitatively by thermal effects induced by light absorption. Charge redistribution by diffusion is neglected with this estimate because of the relatively large initial beam diameter. The total refractive-index change $\Delta n(z)$ perpendicular to the propagation direction then consists of thermo-optic and pyroelectric contributions,[16] $\Delta n(z) = \Delta n_{\mathrm{to}}(z) + \Delta n_{\mathrm{pyro}}(z)$, with

$$\Delta n_{\mathrm{to}}(z) = \frac{\delta n_e}{\delta T} \Delta T(z)\,, \tag{1}$$

$$\Delta n_{\mathrm{pyro}}(z) = \frac{{n_e}^3 r_{33}}{2\epsilon_{33}\epsilon_0} \frac{\delta P_s}{\delta T} \Delta T(z) F(z)\,, \tag{2}$$

where $\delta n_e/\delta T > 0$ and $\delta P_s/\delta T < 0$ are thermo-optic and pyroelectric coefficients, respectively, T is the temperature, r_{33} is the electro-optic tensor element, and ϵ_{33} and ϵ_0 are a dielectric constant and vacuum permittivity, respectively.

The function $F(z)$ accounts for screening of the pyroelectric field in the region of the guided light inside the waveguide, originating from the photoconductivity $\sigma_{\mathrm{ph}} = {\sigma_{\mathrm{ph}}}^0 I$ that is large compared with dark conductivity σ_d. With a Gaussian intensity distribution $(I)z - I_0 \exp(-2z^2/\rho^2)$ we can write[9]

$$F(z) = \sigma_d / [{\sigma_{\mathrm{ph}}}^0 I(z) + \sigma_d]\,. \tag{3}$$

Because of thermal diffusion the width of the temperature profile $T(z)$ is large compared with width ρ of the intensity distribution. Thus the resulting pyroelectrically induced refractive-index change in the surround of the guided light is negative, with a positive dip in the region of high intensity that forms a focusing lens.

For the steady-state condition, i.e., for illumination times that are large compared with the time constants of self-focusing, the pyroelectric field can be compensated for completely by thermally excited charges.[16] The contribution of the pyroelectric effect would be small in this case. On the other hand, we observe a change in the sides of the intensity distribution of a self-focused green beam if we apply an external electric field along the c axis (z direction) of the sample. No change is observed in the central part of the beam where the light intensity is high. If the external electric field is in the direction of the pyroelectric field, self-focusing is enforced, and if it is opposite, the effect decreases. A decrease of self-focusing is also observed when the electrodes on the two z faces of the sample are short-circuited. Thus we believe that pyroelectric fields influence self-focusing in the steady-state condition, too.

In conclusion, we have observed strong self-focusing in planar SBN waveguides. The experiments were explained qualitatively by a combination of thermo-optic and pyroelectric effects. Using the optically induced refractive-index increase, we have demonstrated fast spatial switching of an incoherent probe beam.

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