Self-trapping of one-dimensional and two-dimensional optical beams and induced waveguides in photorefractive $KNbO_3$

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We demonstrate self-trapping of one-dimensional and two-dimensional optical beams in a photorefractive $KNbO_3$ crystal. We study the waveguides induced by the self-trapped beams for prospective applications of tunable nonlinear frequency conversion in soliton-induced waveguides. © 1997 Optical Society of America

Since their early prediction[1] and first observation,[2] spatial solitons in photorefractive media have become an area of growing interest. Apart from the basic interest in new fundamental aspects related to photorefractive solitons [including, e.g., three-dimensional (3D) interactions and spiraling of two two-dimensional (2D) solitons behaving like a two-body system,[3] soliton fusion,[4] birth of new soliton states,[5] and self-trapping of spatially incoherent[6] and of white-light beams[7]], the fact that solitons induce waveguides[8,9] brings about several interesting applications.

Waveguides induced by photorefractive solitons are of particular interest for several reasons. First, photorefractive media support self-trapping in both transverse dimensions,[2,10] which, in turn, induce 2D waveguides.[11] Second, photorefractive solitons form at microwatt (and lower) optical power levels.[12] Third, the photorefractive response is wavelength sensitive; therefore a weak soliton beam can guide an intense beam at a less-photosensitive wavelength.[11,12] Finally, most photorefractive media are noncentrosymmetric crystals, and as such they have large $\chi^{(2)}$ nonlinearities. This suggests a unique application of waveguides induced by photorefractive solitons: tunable efficient nonlinear frequency conversion in a soliton-induced waveguide. Since the conversion efficiency of second-harmonic generation (SHG) and other $\chi^{(2)}$ parametric processes always scales with the optical intensity of the pump beam, it is desirable to confine the interacting beams in a waveguide structure. In this case phase matching is required among the propagation constants of the interacting guided modes of the waveguides (rather than among the wave vectors, as in a bulk medium). Phase matching can be obtained by either birefringence or periodic poling (quasi-phase matching). In either case, once a waveguide is fabricated, very little wavelength tuning is possible for SHG (by varying either angle or temperature),[13] because the structure is fixed (parametric amplifiers allow more tunability because one has the freedom of varying both pump and idler wavelengths). Since both angle and temperature have a rather limited tunability range for SHG in waveguides, structures with several (laterally parallel to one another) periods of poling have been fabricated,[14] giving rise to extended tuning. Obviously, it is highly desirable to have waveguide structures in which either the phase matching (via periodic poling or varying the crystalline orientations) or the waveguide properties (propagation constants) are tunable. Waveguides induced by photorefractive solitons[15] offer just that: a large degree of tuning of all the waveguide parameters. First, since the waveguide structure is induced by the soliton, one can vary the launch angle of the soliton (with respect to the crystalline axes), thus expanding the accessible tuning range in the induced waveguide to close to that obtained in a bulk crystal.[16] In addition, as we have shown recently,[15] waveguides induced by screening solitons are highly controllable by electro-optic means (no mechanical movements are needed), simply by tuning the soliton along its existence curve.

In this Letter we study self-trapping of one-dimensional (1D) and 2D optical beams and their induced waveguides in photorefractive $KNbO_3$ for prospective applications of tunable nonlinear frequency conversion in soliton-induced waveguides. Our choice of $KNbO_3$ is rather obvious: this material is highly photorefractive[17] and at the same time is phase matchable for SHG and other $\chi^{(2)}$ parametric processes using birefringence. Furthermore, $KNbO_3$ can be periodically poled,[18] thus expanding the accessible wavelength range for SHG with quasi-phase matching.[19]

We used a 5 mm × 6 mm × 4.5 mm (along the a, b, and c crystalline axes, respectively) Fe-doped $KNbO_3$ crystal. Using interferometric techniques, we measured the relevant electro-optic coefficients $r_{33} = 70$, $r_{13} = 37$, and $r_{23} = 7$ (all in picometers/volt) at the 488-nm wavelength (at 632.8 nm these values are almost unchanged). Our experimental setup is similar to that of Refs. 10 and 11. We use a 488-nm laser beam to generate the soliton and test the guiding properties of the induced waveguide with a 632.8-nm probe beam, to which the crystal is much less photosensitive. The optical beams always propagate a distance of 5 mm along the a axis, and the soliton is polarized along c, whereas we test the optical guidance of both b and c polarizations of the probe beam. The external field is always applied along the c direction. This means that for the soliton we employ r_{33}, whereas for the probe beam we employ either r_{33} or r_{23}.[20] In this Letter we study steady-state screening solitons only.[3–5,10,11,15,21–24] In all our experiments we use a uniform 488-nm b-polarized beam as background illumination to increase artificially and fine tune the dark irradiance, as was done in previous screening soliton experiments.[3–5,10,11,15,23,24]

First we generate 1D solitons and investigate the induced 1D waveguides. Using a cylindrical lens, we launch a 488-nm 1D beam that is narrow in the *c* direction and uniform in the *b* direction. Our results are presented in Fig. 1. Figure 1(a) shows photographs and beam profiles of the input 17-μm-wide (FWHM) 1D beam (top), the diffracted 37-μm beam at zero voltage (middle), and the output soliton 17-μm-wide beam (bottom). The soliton forms at $V = 4500$ V applied between electrodes separated by $l = 4.5$ mm. The ratio between the peak intensity of the soliton and the intensity of the background beam is 8. We emphasize that, as shown for all screening solitons, the parameters must lie on the soliton existence curve (or very close to it), and more than 10–20% deviations from this curve lead to both transverse and longitudinal instabilities (the 1D beam breaks up into multiple filaments, as observed in Refs. 24 and several other places) that are especially noticeable if the nonlinearity is too high. With the proper parameters, however, the 1D soliton is stable despite the fact that it propagates in a 3D bulk medium, and no transverse instability is observed, as shown in Fig. 1. We now investigate the guiding properties of the 1D waveguide included by the soliton, by launching a 1D *c*-polarized 632.8-nm probe beam. The results are shown in Fig. 1(b). The top photograph and beam profile show the 17-μm-wide (FWHM) input, which diffracts to 47 μm and becomes heavily distorted in the absence of the soliton (zero voltage) or is guided to 16 μm in the soliton-induced waveguide when the soliton is on, as shown in the middle and bottom parts (respectively) of Fig. 1(b). Notice that, at zero voltage, the diffraction of the probe beam is larger than that of the 488-nm beam owing to the longer wavelength of the probe. The confinement of the guided probe beam is tight, and its intensity profile is as narrow as that of the soliton. Finally, we rotate the polarization of the probe beam to *b* polarization. The results are shown in Fig. 1(c). Although the input and the diffracted beams are almost identical to those of the *c*-polarized probe (the diffracted *c*-polarized probe exhibits somewhat larger distortions), the waveguiding effect is considerably smaller for the *b* polarization and the FWHM of the guided probe is 27 μm. This is because the effective waveguide is supported by the r_{23} electro-optic coefficient, which is 10 times smaller than r_{33}, implying that the maximum change in the refractive index is 10 times smaller for the *b* polarization.

Next we study self-trapping of 2D beams and their induced 2D waveguides. We launch a circular, 16-μm-wide (FWHM), *c*-polarized, 488-nm beam with a spherical lens and attempt to generate 2D solitons, as was done in strontium barium niobate (SBN) crystals.[3,4,10,11] The intensity ratio (between the input peak intensity and that of the background illumination) is 8. Our results are presented in Fig. 2(a), in which the photographs and both horizontal and vertical beam profiles are shown for the input (top), the diffracted output at zero voltage (middle), and the self-trapped output beam at $V = 4500$ V and $l = 4.5$ mm (bottom) cases. It is obvious that, although the 2D beam clearly exhibits strong self-trapping effects, the self-trapped beam is elliptical: 23 μm × 13 μm (in the *b* and *c* directions, respectively). This is in contrast to SBN, for which we and other groups have reported circular 2D solitons that were obtained for all intensity ratios above unity.[2–5,10,11] Finally, we study the waveguiding effects on a *c*-polarized probe beam and show the results in Fig. 2(b). At zero voltage (no soliton), the 12-μm (FWHM) circular input beam (top) diffracts and becomes heavily distorted after 5 mm (middle). On the other hand, when the soliton is on, the probe beam is guided by the induced elliptical 2D waveguide to a 33 μm × 13 μm beam. The waveguiding effects are very strong (high confinement) as compared with those of the diffracted beam.

To summarize, we have demonstrated 1D and 2D self-trapping effects in photorefractive $KNbO_3$ and 1D and 2D induced waveguides.[25] Our results suggest that efficient frequency conversion in a flexible soliton-

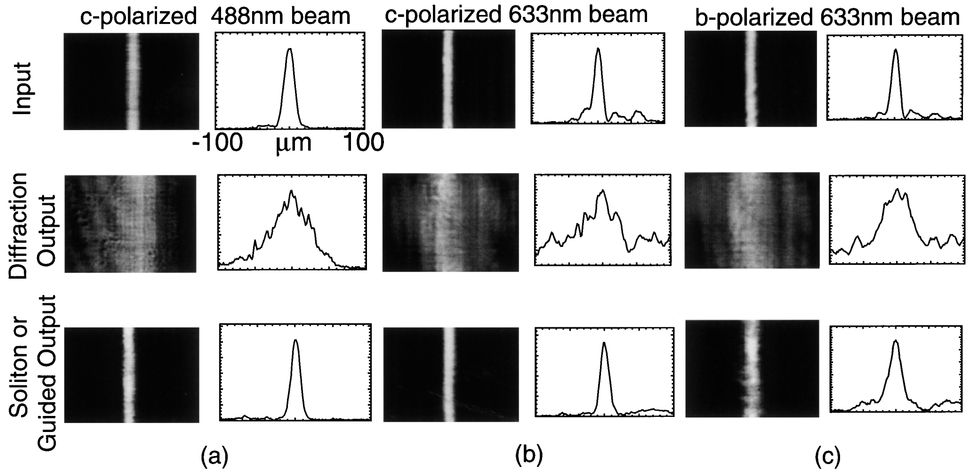

Fig. 1. Photographs and beam profiles of (a) a *c*-polarized 488-nm 1D soliton-forming beam, (b) a *c*-polarized 632.8-nm 1D probe beam, and (c) a *b*-polarized 632.8-nm 1D probe beam. The top photographs and beam profiles show the input beam, the middle photographs and profiles show the diffracted beams at zero voltage, and the bottom photographs and profiles show the soliton and the probe beams guided in the soliton-induced waveguide.

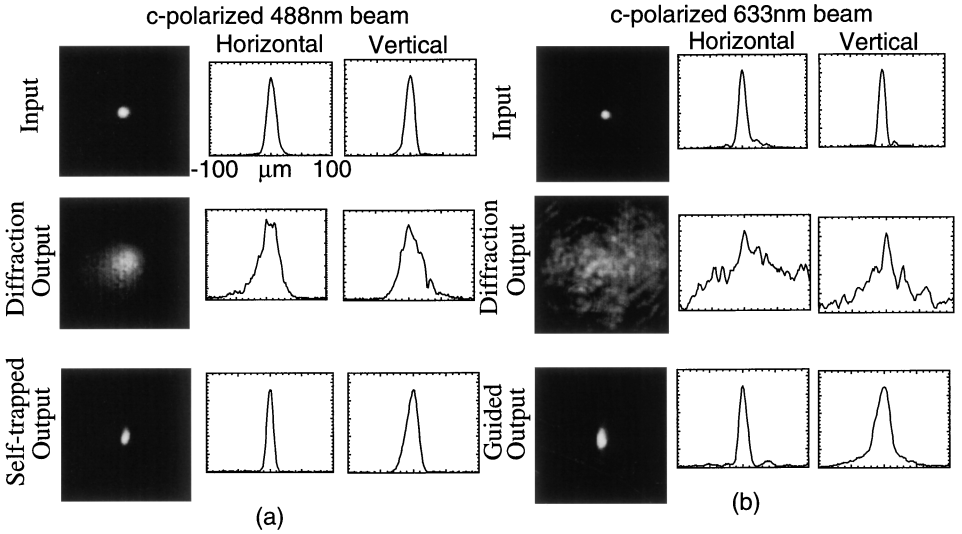

Fig. 2. Photographs and beam profiles (cross sections) of (a) a *c*-polarized 488-nm 2D soliton-forming beam and (b) a *c*-polarized 632.8-nm 2D probe beam. The top photographs and cross sections show the input beams, the middle photographs and profiles show the diffracted beams at zero voltage, and the bottom photographs and profiles show the elliptical self-trapped 2D beam and the probe beam guided in the 2D induced waveguide.

induced waveguide is indeed feasible in a medium that (i) supports photorefractive solitons, (ii) has large $\chi^{(2)}$ effects, and (iii) is phase matchable by use of birefringence. We have shown that both *c*- and *b*-polarized beams can be guided in a soliton-induced waveguide. The present results, combined with our earlier studies on the tunability of the propagation constants of the guided modes in photorefractive soliton-induced waveguides in other materials[15] and on the flexibility of generating photorefractive solitons in directions that deviate considerably from principal crystalline axes,[16] suggest that the realization of highly tunable, efficient, nonlinear frequency-conversion devices is within reach.

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