Two-dimensional photorefractive spatial solitons in centrosymmetric paraelectric potassium–lithium–tantalate–niobate

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We report the observation of steady-state two-dimensional photorefractive self-trapping and screening spatial soliton formation in a sample of potassium–lithium–tantalate–niobate in the centrosymmetric paraelectric phase.
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Spatial solitons in centrosymmetric photorefractive media have been predicted[1] and were recently observed.[2] This interesting type of light–matter interaction is brought about by a mechanism analogous to the one at the basis of spatial solitons in noncentrosymmetric photorefractive materials, more specifically, to the so-called photorefractive screening solitons.[3–7] Although the theory[3–5] is quite elaborate, the mechanism that gives rise to soliton formation is rather intuitive. Essentially, an optical beam propagating in the photorefractive (dielectric) material generates a photoinduced internal space-charge field that modulates the local index of refraction via the electro-optic response. In noncentrosymmetric crystals the electrooptic response is linear in the polarization (the Pockels' effect), whereas in the centrosymmetric case the coupling mechanism is quadratic (the quadratic electro-optic effect). In this case the internal photoinduced electric field generates a local polarization by distorting the paraelectric cubic crystal structure inducing a localized ferroelectric phase. In a previous paper,[2] we have shown the existence of one-dimensional [(1+1) D] photorefractive solitons in centrosymmetric paraelectric potassium–lithium–tantalate–niobate (KLTN), a material which undergoes a ferroelectric–paraelectric phase transition at temperatures close to room temperature and exhibits a strong quadratic electro-optic response.[8]

From a fundamental view point, investigating spatial solitons in centrosymmetric photorefractive media, and, in particular, at the vicinity of the ferroelectric–paraelectric phase transition, is important because it brings about several intriguing effects related to near-transition phenomena and paraelectric physics. Close to the ferroelectric–paraelectric phase transition the electro-optic response is enhanced, and is affected by temperature and polarization hysteresis (for first-order phase transitions), local light intensity (through the so-called photoferroelectric effect[9]), and the local electric field.[10]

In this letter we present an experimental observation of two-dimensional (2D) spatial solitons [(2+1) D] in near-transition paraelectric (centrosymmetric) KLTN. This observation should pave the way, as it did for noncentrosymmetric screening solitons,[11] to configurations in which 2D soliton-induced waveguides are used to guide beams of wavelengths that do not participate in the nonlinear confinement mechanism. This has several important potential applications for 2D configurable interconnects and, perhaps more important, for nonlinear frequency conversion in tunable soliton-induced waveguides.[12]

Our experiments are performed in an intermediate temperature range, that is, where phase-transition effects are not drastic yet the electro-optic response is enhanced enough to allow soliton observation at moderate applied fields. Here, as for the more ''conventional'' noncentrosymmetric case, the (2+1) D soliton formation mechanism is extremely complicated and a complete theoretical description of the screening process is not available. The only understanding we have draws from experiment and analogy to the (1+1) D case.[1]

We perform our experiments on a sample of $2.6\times1.8\times6.4$ mm KLTN cut along the principal crystalline axes (which are all identical to each other, but we denote them here as x, y, z, respectively). The crystal has a ferroelectric–paraelectric phase transition at ≅18.5 °C as can be seen from measurements of ϵ_r as a function of temperature shown in Fig. 1. Figure 1 also shows the temperature hysteresis typical of first-order phase transitions. The relevant quadratic electro-optic coefficient in our experimental configuration (shown in Fig. 2) is $g_{\text{eff}}=g_{xxxx}=0.13\ \text{C}^{-2}\ \text{m}^4$ as measured in a standard cross-polarizer experiment, and the index of refraction is $n_b=2.4$ (at $\lambda=514$ nm). The basic setup is similar to previous experiments[7,11,12] and is schematically illustrated in Fig. 2. A single mode argon ion laser operating at $\lambda=514$ nm emits a y-polarized beam. This beam is sent through a $\lambda/2$ waveplate that rotates this polarization at an adjustable angle and is split into orthogonal polarized components by a polarizing beam splitter (PBS). The transmitted x-polarized beam (soliton forming beam) is first expanded and then focused by a 200 mm spherical lens onto the input face of the

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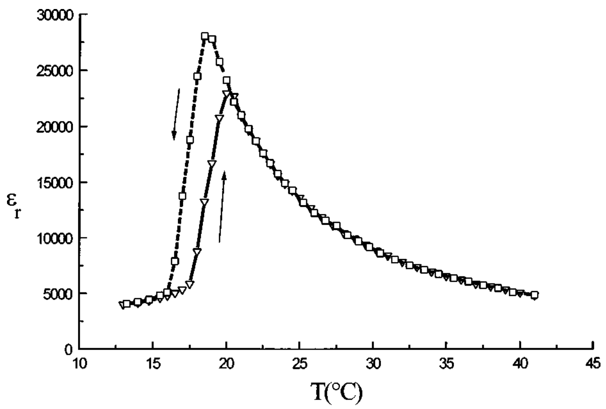

FIG. 1. Measured values of ϵ_r as a function of temperature T. The two curves represent values measured for decreasing (squares) and increasing (triangles) temperatures.

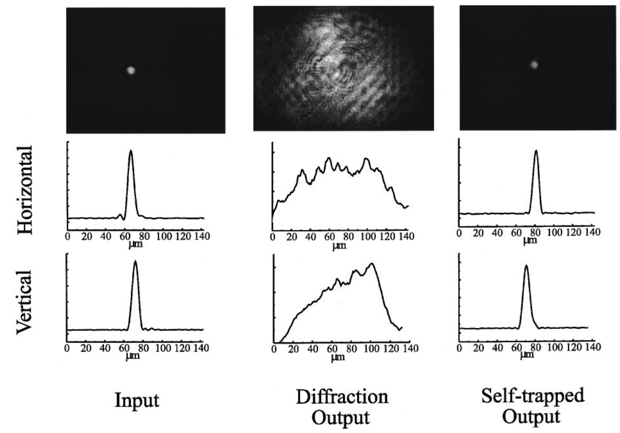

FIG. 3. Photographs and profiles of the beam at the input and output faces of the crystal.

crystal. The reflected y-polarized beam serves as the background beam:[1] it is first expanded and then recombined with the focused soliton beam (by means of a beamsplitter), so that these copropagating beams experience the same absorption in the crystal (which makes stationary solitonlike propagation possible[7]). The background beam is illuminating the crystal uniformly at all times. The beam at the input (with zero field applied) and the output (with and without field applied) faces of the crystal is imaged onto a charge coupled device (CCD) camera and recorded. The crystal is kept at a constant temperature T and a voltage V is applied between the x faces of the crystal.

In Fig. 3 we show typical experimental results. In this particular case, the intensity ratio (the ratio between the peak soliton intensity and the background intensity, u_0^2), is roughly 156 with an applied voltage of $V \cong 1.15$ kV at $T = 29$ °C. The input beam, shown in the left column, has a intensity full width at half maximum (FWHM) of 7 μm (equal in the horizontal and vertical directions) and, in the absence of applied field, diffracts to approximately 90 μm (middle column, as expected from normal Gaussian beam propagation). When the appropriate field is applied, the beam self-focuses to 7 μm in the horizontal direction and 8 μm in the vertical direction (right column). Note that the astigmatism is very small and is mostly in the tail of the vertical profile. In our experiments, with the proper voltage applied, this slight astigmatism is never larger than 1 μm (the difference in the widths in both directions). We attribute it primarily to local striations in the crystal that affect only the margins of the beam (as we always try to launch the soliton as far from the striations as possible, typically ''sandwiching'' it between two striation lines).

One-dimensional (1D) spatial soliton formation occurs, as predicted by theory[1] when the minimal set of soliton parameters satisfy a particular relationship, known as the soliton existence curve. Essentially, given a value of u_0^2 and an input beam width at a fixed T, there is a restricted (rather narrow) range of values of applied voltage V that can give rise to solitary propagation solutions. Applied field values that are too low do not fully compensate for the diffraction, whereas values that are too high try to transform the beam into a soliton that is much narrower than the incident beam, thereby leading to instability.[13]

In analogy to the (1+1) D case,[1,2] one can plot the soliton formation experiments on an existence curve that shows the soliton width (in normalized units) as a function of intensity ratio u_0^2. Since the theory of (2+1) D solitons in photorefractive centrosymmetric media is not available yet, we use the scaling of the existing (1+1) D theory[1] that has been experimentally verified.[2] As in the (1+1) D case, *two dimensional soliton formation is observed only for particular values of V, given a value of* u_0 *and a fixed input beam width*. Figure 4 shows the experimental points in parameter space for which (2+1) D steady-state solitons are observed. The vertical scale is the normalized soliton intensity FWHM (the same in the x and y directions as almost circular self-

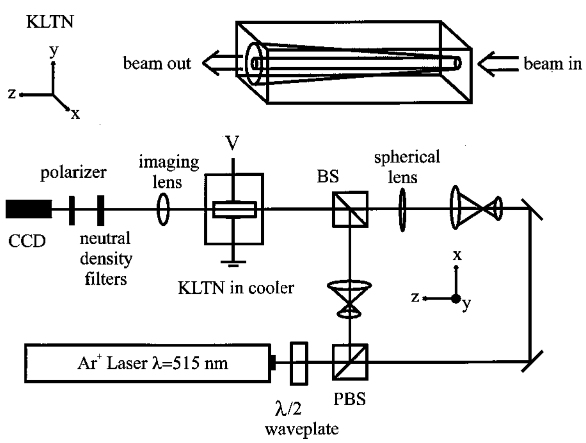

FIG. 2. Experimental setup and crystalline configuration.

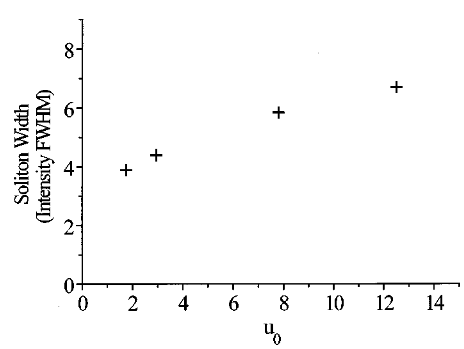

FIG. 4. Experimental 2D soliton existence points. The solitons in this plot have all been observed for $T = 29$ °C.

trapping is observed) in units of $\Delta\xi=\Delta x/d$, where $d=(-2kb)^{-1/2}$, $b=(k/n_b)[(1/2)n_b^3 g_{\mathrm{eff}}\epsilon_0^2(\epsilon_r-1)^2(V/l)^2]$, and $k=2\pi n_b/\lambda$, where λ is the wavelength, V is the applied voltage, and l the width of the crystal in the x direction. Existence points for low intensity ratios ($u_0<1.5$) are not available, as we were never able to get soliton formation in this range. *This means that the nonlinearity must be saturated to support the formation of (2+1) D solitons*. This is not too surprising, since at $u_0\ll 1$ the nonlinearity is in the Kerr limit, for which (2+1) D solitons are unstable (the beam undergoes catastrophic self-focusing). This last issue resembles observations in SBN for which (2+1) D solitons are observed only for $u_0>0.3$, i.e., the nonlinear change in the refractive index must be in the saturation regime (albeit a different form of nonlinearity than in the present case) to support soliton propagation. This property is universal to all solitons in saturable nonlinearities, and is manifested here in an elegant way: the (2+1) D solitons can be observed only in the range at which they are truly stable. This is due to the inhomogeneities that are present in the crystal and introduce noise which can be ''arrested'' only when the nonlinearity is saturated.[14]

In conclusion we have presented our observation of (2+1) D spatial solitons in photorefractive centrosymmetric media, and have thus proven that paraelectric KLTN indeed supports 2D spatial confinement. This opens up a variety of interesting possibilities such as 2D spatial soliton fixing (making use of possible near-transition hysteresis), which will give rise to three-dimensional ''waveguide circuitry'' in the volume of a bulk photorefractive crystal. The next step is to operate closer to the phase transition and investigate how to permanently fix the 2D waveguides induced by the photorefractive spatial solitons.

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