Photorefractive solitons of arbitrary and controllable linear polarization determined by the local bias field

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Abstract: We discuss and experimentally demonstrate a scheme to achieve photorefractive solitons of arbitrary linear polarization using the quadratic electro-optic effect and describe the observation of the self-trapping of a set of linear polarized beams in different positions of a paraelectric photorefractive crystal of potassium-lithium-tantalate-niobate (KLTN) biased by the inhomogeneous field produced by two miniaturized top electrodes. The polarization of the single solitons of the set is determined by the local electrostatic configuration and the underlying tunable anisotropy, which is detected through zero-field electro-activation.

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OCIS codes: (160.2100) Electro-optical materials; (190.5330) Photorefractive nonlinear optics; (230.5440) Polarization-sensitive devices.

References and links
2. For a review, see Chapter 11 by E. DelRe, M. Segev, D. Christodoulides, B. Crosignani, and G. Salamo, in P. Gunter and J.P. Huignard (Eds.), Photorefractive Materials and Their Applications (Springer-Verlag, Berlin Heidelberg 2006).
axis, the symmetry is broken by the local bias field direction, and this implies that birefringence or organic photorefractive polymers [12, 13]. Here, in the absence of a predetermined optical permitted bias field must be parallel to it [3]. The strong birefringence of the system also means that if the beam is not linearly polarized either parallel or orthogonal to the principal axis, polarization will evolve during propagation leading to a propagation dependent nonlinearity that is not suitable for solitons, except for specific system-dependent states that are expected to support polarization-vector solitons [4]. Whereas polarization evolution has its own phenomenology (extensively investigated in optically active photorefractive samples [5, 6]) and interesting alterations to the basic photorefractive soliton scheme have been recently investigated [7, 8], to date no control on soliton polarization has been observed.

We describe and demonstrate herein a scheme based on the use of centrosymmetric photorefractive crystals to achieve photorefractive solitons of arbitrary linear polarization with respect to the crystal orientation, determined by the local orientation of the electric field, and analyze their electro-activation [9]. The key is the implementation of biased centrosymmetric (as opposed to noncentrosymmetric) samples, such as paraelectric KLTN [10], nanopoled SBN [11], or organic photorefractive polymers [12, 13]. Here, in the absence of a predetermined optical axis, the symmetry is broken by the local bias field direction, and this implies that birefringence

1. Introduction and motivation

Systems that support optical spatial solitons provide ideal settings for the control and harnessing of light signals. This is because a beam that forms a soliton is a wave that effectively behaves like a mechanical particle. It remains localized and undistorted, stable and robust, and in general follows an actual dynamical trajectory, bounces off obstacles and spirals and interacts with other similar beam-particles. One of the limitations of many optical spatial-soliton-supporting systems is that they are polarization sensitive. In other words, only specific polarization states of the light beam can actually form a soliton, and this constraint is determined by the physical nature of the underlying nonlinearity. Polarization selectivity is particularly important for solitons in biased photorefractive crystals [1, 2]. Here the nonlinearity is based on electro-optic response in anisotropic crystals, which are by their very nature birefringent. More specifically, to achieve the strong electro-optic response required for solitons, the principal crystal axis is oriented orthogonal to the beam propagation direction, and both light polarization and the applied bias field must be parallel to it [3]. The strong birefringence of the system also means that if the beam is not linearly polarized either parallel or orthogonal to the principal axis, polarization will evolve during propagation leading to a propagation dependent nonlinearity that is not suitable for solitons, except for specific system-dependent states that are expected to support polarization-vector solitons [4]. Whereas polarization evolution has its own phenomenology (extensively investigated in optically active photorefractive samples [5, 6]) and interesting alterations to the basic photorefractive soliton scheme have been recently investigated [7, 8], to date no control on soliton polarization has been observed.
can be changed and tailored on command, without having to change the actual orientation of the crystal. The underlying concept has been recently proposed and demonstrated in electroholography [14] and is the basis for polarization splitting using the (linear) electro-optic read-out of a system of conventional photorefractive solitons [15].

2. Basic model

Paraxial light propagation along the $z$ direction is described by the parabolic equation for the slowly varying envelope $A = (A_x, A_y)$ of the optical electric field, \[ (\partial_t + (i/2k)\nabla^2)A_i = -(ik/n_0)\Delta n_{ij}A_j, \] where $k = (2\pi/\lambda)n_0$ is the wavevector, $\lambda$ the wavelength, $n_0$ the unperturbed index of refraction, $\Delta n_{ij}$ is the tensorial electro-optic index modulation, summing on repeated indices $i, j = \{x, y\}$) is used and $\nabla^2 \equiv (\partial_{xx} + \partial_{yy})$.

For the case of an $m3m$ symmetry, such as that describing paraelectric KLTN [17], assuming that the $x$, $y$, and $z$ coincide with the crystalline axes, we have [14]

\[ \Delta n_{ij} = a \begin{pmatrix} g_{11}E_x^2 + g_{12}E_y^2 & 2g_{44}E_xE_y \\ 2g_{44}E_xE_y & g_{11}E_y^2 + g_{12}E_x^2 \end{pmatrix}. \] (2)

Here $a = -(1/2)n_0^2\varepsilon_0(\varepsilon_r - 1)^2$, $E = (E_x(x,y), E_y(x,y))$ is the local electric field (the result of the superposition of the bias field and the space-charge distribution), $\varepsilon_r$ is the low frequency dielectric constant at the given temperature $T$, $g_{11}$, $g_{12}$ and $g_{44}$ are the non-zero components of the electro-optic quadratic tensor. Solitons will form for beams with a polarization along the direction $\hat{\mathbf{x}}'$ of $\hat{\mathbf{y}}'$, for which the matrix of Eq.(2) is locally diagonal (eigenvectors). The matrix of eq.(2) has eigenvalues $\lambda_{\pm}(x,y) = (a/2)[(g_{11} + g_{12})(E_x^2 + E_y^2) \pm \sqrt{(g_{11} - g_{12})^2(E_x^2 + E_y^2)^2 + 16g_{44}E_xE_y^2}]]$ and the corresponding eigenvectors $\hat{\mathbf{x}}'$ and $\hat{\mathbf{y}}'$, where $\hat{\mathbf{x}}'(x,y) = u_x/|u_x|$, with $u_x = (2ag_{44}E_y/(\lambda_+ - a(g_{11}E_y^2 + g_{12}E_x^2)), 1)$, and analogously $\hat{\mathbf{y}}'(x,y) = u_y/|u_y|$. Although the inspection of these eigenvectors indicates that we can thus span all orientations for the soliton polarizations using an appropriate $E$, in general neither $\hat{\mathbf{x}}'$ nor $\hat{\mathbf{y}}'$ are parallel to $E$. Now, a beam of a linear polarization along $\hat{\mathbf{x}}'$ or $\hat{\mathbf{y}}'$ can self-consistently support solitons if the transverse scale of the beam (the soliton width) is smaller than the transverse scale of the inhomogeneity introduced by the boundary conditions (bias fields). Consequently, for the beam, the locally inhomogeneous matrix of eq.(2) can have a diagonal form. Birefringence is complicated by the fact that the soliton-supporting pattern is also anisotropic, the direction of anisotropy being that of prevalent charge migration, i.e., the local direction of the bias field [18]. The actual polarization eigenstates will be of the combined effect of both sources of birefringence.

3. Experiment

To demonstrate the idea we carried out experiments in a sample of photorefractive KLTN, $z$-cut and measuring $3.0(3) \times 1.0(3) \times 2.4(2)$mm. The crystal was operated in the paraelectric phase at $T = 16^\circ$C, above its Curie temperature at $T_C \approx 11^\circ$C. Here it has $\varepsilon_r \approx 1.5 \cdot 10^4$, $n_0 \approx 2.4$, $g_{11} \approx 0.16m^4C^{-2}$, $g_{12} \approx -0.02m^4C^{-2}$, $g_{44} \approx 0.08m^4C^{-2}$. Instead of changing the bias field in a single position we used an inhomogeneous bias field that allows the trapping of different polarizations in different transverse positions. We implemented the geometry illustrated in Fig.(1), i.e., we used one-sided electrodes [19]. On the $xz$ facet of the sample we placed two miniaturized electrodes spaced in the $x$ direction 250 $\mu$m apart. Even for a constant bias $V$, the resulting field is suitably inhomogeneous and we can expect different linear polarization to self-trap simultaneously without having to change the electrode geometry.
Fig. 1. Left: Electrode geometry. Right: relative position (a)-(e) of the input-beam/soliton set and calculated external electric bias field lines in the experimental conditions. (a) Input and (b) output intensity distribution with $V = 0$.

4. Results

Following this approach, we launched soliton beams in the positions illustrated in Fig. (1). In each case the beam was a fundamental gaussian mode focused on the input $xy$ facet to a FWHM (Full-Width-at-Half-Maximum) $\Delta x \approx \Delta y \approx 6 \mu m$ (see Fig. (1a)). In the absence of self-action, i.e., for $V = 0$, the beam diffracts to $33 \mu m$ (Fig. (1b)). For $V = 380 V$, with a ratio between the peak beam intensity and the background homogeneous illumination of $I_p/I_b \approx 25$ [10], the beam self-traps as shown in Fig. (2a-e) in the respective positions (a)-(e) indicated Fig. (1), when the input polarization is as shown in Fig. (2), approximately parallel to the local direction of $E$. In fact, for KLTN $g_{44} \approx g_{11}$ and $|g_{12}| \ll |g_{11}|$, so that we find $\lambda_+ \approx (a/2)g_{11}(E_x^2 + E_y^2)$ and $\lambda_- \approx 0$, and $x'$ is approximately parallel to $E$ in all positions. Congruently, taking the polarization parallel to the local field, no appreciable change in polarization was observed. Observed output $\Delta x \approx \Delta y \approx 6 \mu m$ for positions (a), (c), and (e), whereas a noticeable elliptic profile is observed for the two positions (b) and (d), where the beam had $\Delta x_{(b)} \approx 7 \mu m$ and $\Delta y_{(b)} \approx 8 \mu m$ and $\Delta x_{(d)} \approx 6 \mu m$ and $\Delta y_{(d)} \approx 9 \mu m$. In both cases the beam width in the direction of the bias field was smaller than in the orthogonal direction, suggesting that in these positions a higher value of $V$ is required [20]. We found that increasing $V$ in fact allows the observation of more circular symmetric outputs, but this then does not allow the simultaneous generation of the entire soliton set for the one given equal input beam. To characterize the robustness of the phenomena on the actual position in the pattern, we found that for a region of $50 \times 50 \mu m^2$ in the immediate vicinity of the indicated positions (Fig. (1)), phenomenology was consistent with that reported (Fig. (2)).

5. A rotating anisotropy

Anisotropy plays a principal role in two-dimensional soliton formation and essentially amounts to the fact that the self-focusing nonlinearity is different in the direction parallel and orthogonal to the external bias field. In the present case it can allow us to fully characterize the underlying physical mechanism and eventually validate the idea of an underlying rotating nonlinearity. In fact, the basic novelty of the present situation is that the anisotropy should turn out to be different in different positions, supporting in each its own corresponding self-trapping process [18]. There are essentially three ways to detect this rotating anisotropic effect along the set. One anisotropic signature is the appearance of ellipticity in the soliton shape, but its magnitude can be altered by the specific value of $V$, and ultimately eliminated for beams with a small enough FWHM [20]. One highly directional and generally detectable signature of anisotropy is associated with the interplay between this anisotropy and the response nonlocality, a coupling that produces self-bending, a characteristic parabolic alteration in an otherwise straight beam.
Fig. 2. Soliton output intensity distribution in the positions of the set, (a)-(e). Large arrows indicate both the approximate direction of \(E\) and of the optical polarization, crosses indicate the center of the diffracted output distribution, and the ellipses schematically indicate the local orientation of the index ellipsoid section.

propagation [21]. Images in Fig.(2) are taken so that each frame is centered on the center of the initial output diffraction distribution \((V=0)\), so they also give information on self-bending. Unfortunately its simple interpretation is not straightforward because of a second self-bending contribution. In fact, the one-sided-electrode bias delivery, introducing an electrostatic inhomogeneity, tends to make the solitons drift away for the region under the electrodes themselves [19], and we should observe the combination of the standard soliton self-bending, i.e., a bending in the direction opposite the bias field, with the bending away from the electrode region. This picture provides a key to understanding the actual relative position of the solitons and the crosses (i.e., the center of the diffraction) in the cases of positions (a), (c), (d), (e) (see Fig.(2)a,c,d,e), but results in position (b) do not fit into this simple picture. A clearer and conclusive detection of the rotating anisotropy is offered by zero-field soliton-activation [18]. As described in Ref.[9], first the soliton is obtained with the bias field \(E_0\) (and bias \(V\)) which combines with the space-charge field \(E_{sc}\) to give \(E = E_{sc} + E_0\). Next the intensity is reduced so as to leave \(E_{sc}\) unchanged but the application of \(V' \neq V\) leads to a different \(E_0\) and hence \(E\). The response of eq.(2) that involves quadratic terms in the components of \(E\) leads to a whole family of different "readout" index patterns. For \(V' = 0\) (zero-field soliton-activation) guiding regions for \(V\) become antiguiding, whereas the antiguiding ones, such as the lateral lobes that represent the anisotropic components underlying the soliton, become guiding. Results are shown for the positions (a)-(e) in Fig.(3) which now contain full evidence of why the scalar (i.e., without polarization evolution) solitons form in the given positions, as they highlight that in these the basic anisotropy and hence birefringence forms in parallel to the local direction of \(E_0\).

6. Discussion

The confirmation of the fact that for each soliton the trapped optical polarization is parallel to the direction of the lobe structure, parallel in turn to the local bias field, indicates that soliton physical behavior is approximately rotationally invariant around its propagation axis (i.e., rotating \(A\) and \(E\) but keeping the crystal fixed, phenomenology is rotated but unchanged). This is consistent with the fact that when \(g_{12} \ll g_{11}\) and \(2g_{44} \simeq g_{11}\), the matrix of eq.(2) is simply \(\Delta n_{ij} = a g_{11} E_i E_j\) which, operating on \(A\) gives \(\Delta nA = a g_{11}(E \cdot A)E\). This term is evidently in-
variant for simultaneous rotations of $\mathbf{A}$ and $\mathbf{E}$, as is the linear diffraction term on the LHS of eq. (1), so that the entire propagation described by eq. (1) is rotationally invariant. Interestingly, this property is not confined to the specific case of KLTN, because the values of $g_{ij}$ are similar for different crystals that belong to the same class, i.e., those with a perovskite structure (such as paraelectric BaTiO$_3$, SBN, and so forth). Differences generally occur because of elasto-optic components to the index response that intervene for low frequency bias fields (clamped and unclamped conditions).

7. Conclusion

In conclusion, we have shown how solitons with different polarization states can be trapped in the region underlying a pair of side-electrodes in a sample of photorefractive KLTN. The present finding represents the demonstration of how the linear polarization of a photorefractive soliton can be controlled by tuning the direction of the bias field and can allow the design of miniaturized electro-optic circuits with polarization functionality, like a versatile polarization splitter. A second possible goal will be the development of soliton waveguides and associated handling that is insensitive to polarization, permitting an efficient operation directly in fiber links, where polarization tumbles because of thermal and mechanical fluctuations.

Acknowledgements

Research was funded by the Italian Ministry of Research through the FIRB Basic Research fund. E.D.R. is also with the Centro SOFT, CNR-INFM, Universita’ di Roma ”La Sapienza”, 00185 Roma, Italy.