Discrete solitons in liquid crystals waveguide arrays

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Discrete diffraction and discrete optical solitons are investigated in a voltage controlled channel waveguide array in nematic liquid crystals. A large nonresonant nonlinearity, proper waveguide design and voltage tunability of the coupling strength provide a unique and versatile test-bed for the addressed phenomena.

Keywords: guided-wave optics, liquid crystals, electro-optic devices, switching, optical solitons

In the past decade, families of optical spatial solitons have been investigated theoretically and demonstrated experimentally in media characterized by various kinds of nonlinearity, including cubic Kerr, photorefractive and parametric nonlinear responses. Theoretical analyses and experiments were performed in various configurations and dimensionalities, i. e., in planar waveguides and in bulk, demonstrating that it is possible to obtain stable spatial solitons both in one and two transverse dimensions, respectively.[1]

More recently, linear and nonlinear effects in discrete systems such as photonic structures with a periodic modulation of the refractive index (or waveguide arrays) have become the subject of intensive investigations. This interest is also motivated by the potentials of discrete solitons. [2,3] Similarly to continuous systems, in fact, stable spatial solitons can be generated in discrete waveguide arrays when self focusing is strong enough to balance (discrete) diffraction. The properties of discrete optical solitons have been described by Christodoulides at el. [3] and studied theoretically in a host of nonlinear materials. They have been experimentally observed in AlGaAs, in silica, in photorefractive SBN-crystals and also in Lithium Niobate. [4] It has been shown that discrete optical solitons are very promising in novel generations of all-optical switching circuits and optical networks. [2,5]

Using a different nonlinear mechanism, it has been demonstrated that spatial solitons can be efficiently generated in nematic liquid crystals (LC) and propagate for distances of a few millimeters (i. e., much larger than the Rayleigh range). In such media, soliton formation occurs due to the large non-resonant, saturable and non-local nonlinearity arising from molecular reorientation.[6] Their large birefringence with their giant nonlinear response makes nematic liquid crystals a very promising medium for nonlinear optics applications and solitons.[7] In fact, it has been shown that, at variance with other nonlinear responses, the reorientational nonlinearity in nematic liquid crystals allows generation of spatial solitons in both waveguide and bulk geometries, requiring only a few mW of light power. [6-7] Finally, nematic LC are highly anisotropic and exhibit large electro-optic and magneto-optic responses: this implies that their optical properties can be tuned/controlled by applying an external electric or/and magnetic field.

Combining the specific properties of discrete (linear and nonlinear) systems and the unique nonlinear response of nematic liquid crystals, we propose hereby the realization of liquid crystalline waveguide arrays. In this Communication we introduce the concept of a periodic photonic structure with refractive index changes controlled by an electric field. We show that such a voltage-tunable geometry, in conjunction with a reorientational nonlinearity, offers a wealth of possibilities for the study of discrete optical phenomena.

A sketch of the proposed device is presented in Fig. 1. A glass cell (formed by two parallel slides) is filled with the nematic LC of appropriate thickness, making a planar waveguide (in the x coordinate). The anchoring conditions at both top and bottom surfaces determine the planar alignment of the molecules, i.e. with their longer axes parallel to the surfaces and the direction of light propagation. To introduce a refractive index modulation and obtain a voltage-adjustable nonlinear response, a set of periodically-spaced electrodes is deposited on the top surface to apply a reorientational bias across the cell.

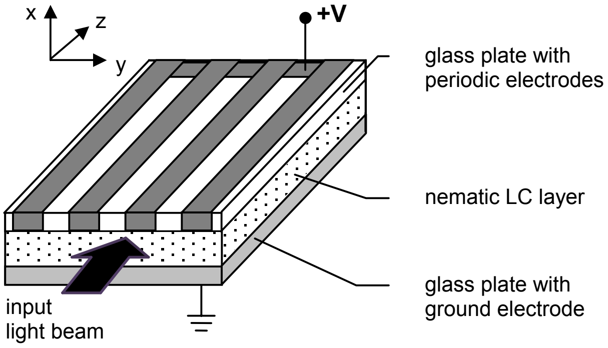

Figure 1. Sketch of the LC waveguide array.

The application of an appropriate voltage allows to reorient the LC molecules (which tend to be parallel to the direction of the electric field), increasing the refractive index and thereby defining channel waveguides through lateral confinement along y. An example of refractive index distribution is shown in Fig 2a.

We investigated the propagation of a light beam in the nematic LC layer with the Beam Propagation Method, using TM polarized Gaussian beams as the input. The refractive index changes were calculated from the Euler-Lagrange equation describing the LC molecular reorientation due to the bias and the electric field of the electromagnetic (optical) wave. Typical results of our numerical simulations, as presented in this summary, were obtained for the characteristic constants of the nematic 6CHBT, which exhibits refractive indices n_o=1.52 and n_e=1.69 at 1064nm.

In the proposed geometry, it is possible to obtain discrete diffraction via the coupling between adjacent and parallel 2D waveguides. Moreover, the magnitude of the discrete diffraction can be easily modified in our LC array not only by varying physical or geometrical parameters, but also by controlling the applied voltage. This bears important consequences on both the linear and the nonlinear properties of this discrete system, and the efficiency of nonlinear processes can be ameliorated in properly designed devices.

First, let us consider the requirements for 2D guidance in the linear (low light excitation) regime. In this case the electric bias plays a crucial role in the reorientation process. Figure 2b shows how the coupling strength between channels and the character of the resulting discrete diffraction change with applied voltage. As one can intuitively expect, by increasing the bias it is possible to induce a higher and higher refractive index change within each channel, progressively reducing the directional power transfer between them. On the other hand, however, excessive voltages tend to saturate and flatten the index profile, thereby weakening the transverse definition of the channels. It should be underlined, in fact, that the reorientation has a nonlocal (and for high voltages saturating) character, and substantial electric fields increase the refractive index not only under but also between the electrodes.

As shown for two cases in Fig. 2, we calculated and optimized LC thickness, electrode spacing and electrode width in order to obtain properly coupled and well defined channel arrays with suitable values of the applied voltage across the cell.

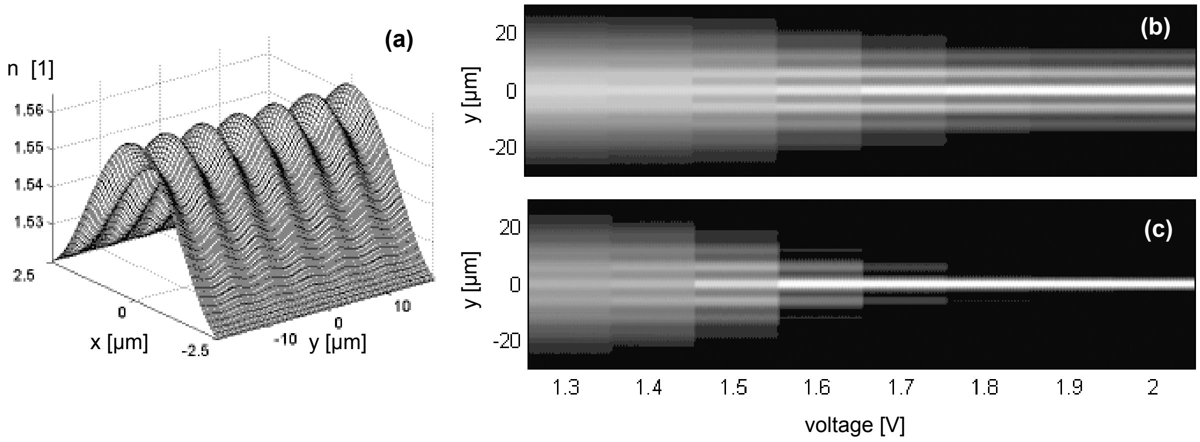

Figure 2. (a) Refractive index modulation obtained for an LC thickness of 5μm, electrode width and spacing are 3μm and V=1.65V. (b)-(c) Linear coupling between channels and its dependence on applied voltage for LC thicknesses of 5μm and 2.5μm, respectively. The graphed field is evaluated after propagation over 1mm.

In particular, by reducing the LC thickness we obtained better defined guides, in the sense that the difference between the refractive indices within each channel and in the gaps between the finger electrodes could be maximized (see two cases in Fig 2b-c). The spatial intensity distribution of the light is shown versus applied bias after 1mm of linear propagation and corresponding to a Gaussian input of waist w_o=2μm. In both cases, the top electrodes have a width of 3μm, while the LC thickness goes from 5 to 2.5μm. In the latter case the injected light remains confined in a single channel for voltages higher than 1.7V, i. e., when the channels are effectively de-coupled: even in the linear regime the beam is trapped into a single waveguide and discrete diffraction cannot be observed.

In the investigated structure, when transverse coupling is present but the intensity of the input beam is large enough, the nonlinear response can balance discrete diffraction, thereby resulting in discrete solitons. Moreover, due to the inherent 2D light confinement, the threshold power required for spatial soliton formation can be lower than in slab or “continuous” waveguides. Going from the linear to the nonlinear regime as the input intensity is increased, the refractive index of the excited waveguide(s) is modified by the reorientational nonlinearity. Under particular conditions, then, high power beams can propagate and maintain a stable transverse profile. The optical field is localized in a limited transverse portion of the array or, at high enough excitation levels, in a single channel. It is important here that, in the case of a reorientational nonlinearity, saturation and nonlocality contribute to and affect the overall phenomenology.

The plots in Fig. 3 (a thru c) present the evolution of the light beam from discrete diffraction (a) to discrete soliton (b-c) as the input power was increased from 0.3 to 1.1 mW (for a bias voltage of 1.65V). The graphs (d) thru (f) show the corresponding refractive index distributions at the output (L=1.5mm).

Fig. 3(a) is an example of discrete linear diffraction, and the input excitation spreads among 9 adjacent channels. When the power is increased, diffraction is reduced and a spatial discrete optical soliton is generated, either “wide” because the overall energy is carried by a few channels (Fig. 3b) or “narrow”, when all the light is essentially confined in the input guide (Fig. 3c).

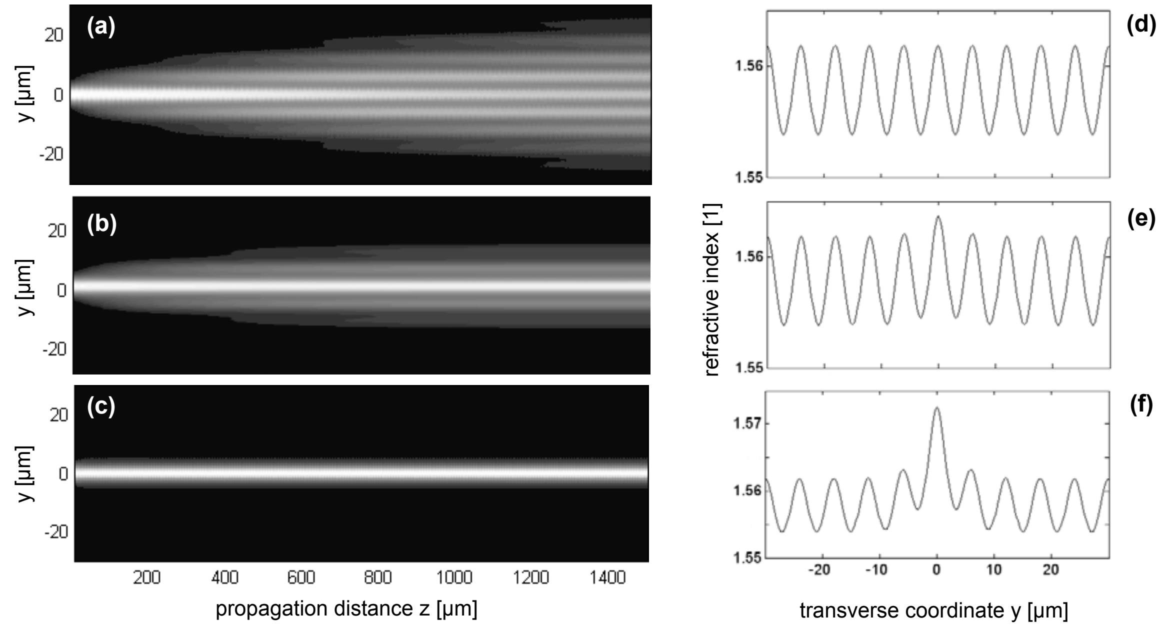

Figure 3. a) Discrete diffraction for a w_0=2µm Gaussian beam launched into one of the guides; b)-c) Generation of discrete spatial solitons as the input light power was increased from 0.3mW (b) to 1.1mW (c); e)-d) Refractive index distributions in the middle of the LC layer (i.e. in x=0µm with reference to Fig. 2c) corresponding to cases a) thru c), respectively.

To study the role of the input conditions, we varied the input profile of the beam (its waist) and its direction of propagation with respect to the channel axis in the array. When a wide beam was employed (e.g. w_0=8µm), the stronger linear coupling was such that a higher excitation of 15mW was required to obtain single waveguide trapping (a “narrow” soliton).

In conclusion, we have proposed a novel linear /nonlinear array of 2D waveguides obtainable and controllable through the reorientational response of nematic liquid crystals. The combination of discrete diffraction and a large nonlinearity in such system allows to predict discrete solitons at mW power levels. The flexibility offered by voltage-controlled transverse coupling between provides an ideal test-bed for a thorough investigation of discrete diffraction and soliton phenomena.

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