Properties of spatial solitons in chiral nematic liquid crystal cells

Urszula A. Laudyn,* Michał Kwaśny and Mirosław A. Karpierz

Faculty of Physics, Warsaw University of Technology, Koszykowa 75, 00-662 Warszawa

Received November 23, 2009; accepted December 22, 2009; published December 31, 2009

Abstract— In this work we demonstrate the properties of spatial solitary waves in chiral nematic liquid crystalline film. Such self-trapped beams were created due to the optical reorientation nonlinearity for the light power of a few tenths of milliwats at the distances of a few millimeters. Additionally, it is shown that the direction of propagation of such nematicons can be modified by changing the light beam input polarization as well as by applying an external electric field.

A lot of effort in recent years has been concentrated on the manipulation of light in nematic liquid crystals (NLCs). Due to reorientational nonlinearity it is possible to generate self-trapped non-diffractive light beams for relatively low power, called nematicons [1,2]. They are light beams that do not spread because of the balance between diffraction and self-focusing , i.e. their size is unchanged during propagation. The properties of nematicons in liquid crystal cells in different geometries and configurations have been investigated comprehensively during the last years [1-3]. However, solitons in a chiral nematic liquid crystal in geometry where incident light propagates perpendicular to the helical axis [4], have recently emerged as a new area of research. The latter structure consists of molecules arranged in thin anisotropic layers, with the successive layer rotated through a small angle, leading to a spiral configuration. Locally, chiral liquid crystals are very similar to a nematic material. The molecules orientation shows a preferred axis labeled by a director, however, the director is not constant in space – it twists and is chosen to be perpendicular to x axis. The distance over which the director twists by 360^0 is called the pitch.

In this work experimental results of all-optical soliton propagation in chiral nematic liquid crystals are considered. Such self-trapped beams were created due to the optical reorientation nonlinearity for the light power of a few tenths of miliwats at the distances of a few millimeters. We discuss the effect of input polarization on soliton direction of propagation. Additionally, we extend those measurements by considering the impact of external electric field (voltage) on soliton propagation and soliton readdressing.

* E-mail: ulaudyn@if.pw.edu.pl

To form a ChNLCs we mixed a nematic NLC material 4–trans-4'–n – hexyl–cyclohexyl - isothiocyanatobenzene (6CHBT) [6,7] with a chiral doppant. The mixture has a following properties: pitch $p = 10\mu m$, dielectric anisotropy $\Delta\varepsilon = 8$, Frank elastic constant: $K_{11} = 8.8pN$, $K_{22} = 3.7pN$, $K_{33} = 9.5pN$ and birefringence $\Delta n = 0.15$ at $\lambda = 514nm$. ChNLCs sample of thickness $d = 20\mu m$ was confined between pairs of glass plates with transparent indium tin oxide (ITO) electrodes to enable application of the electric field and was initially in the planar texture configuration with the helical axis perpendicular to the cell's surface (Fig. 1). The *y* axis is perpendicular to the helix axis and the molecules are twisted in the *yz* plane , where z is the propagation axis.

In the analyzed configuration (presented in Fig.1) a light beam propagates in the z-direction parallel to the glass plates. Assuming that the light is polarized along y-direction, it means that the beam propagates in the layer close to the plane where the ChNLC molecules are parallel to the y-axis.

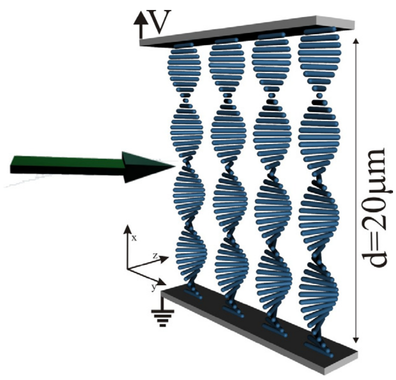

Fig.1.Configuration of the analyzed chiral nematic liquid crystal cell

The orientation of ChNLC is determined by the anchoring conditions at the boundaries where the interaction with the cell walls (glass plates) introduces a specific boundary orientation. The orientation angle between molecules direction and y axis is initially equal to: $\theta(x) = (2\pi m/d)x$, where m is an integer number.

Consequently the electric permittivity tensor in such a medium has the form:

$$\varepsilon = \begin{pmatrix} \varepsilon_\perp & 0 & 0 \\ 0 & \varepsilon_\perp + \Delta\varepsilon\cos^2\theta & \Delta\varepsilon\sin\theta\cos\theta \\ 0 & \Delta\varepsilon\sin\theta\cos\theta & \varepsilon_\perp + \Delta\varepsilon\sin^2\theta \end{pmatrix} \tag{1}$$

where: $\Delta\varepsilon = \varepsilon_\parallel - \varepsilon_\perp$ represents optical anisotropy, $\varepsilon_\perp = n_o^2$ is an ordinary and $\varepsilon_\parallel = n_e^2$ is an extraordinary electric permittivity and θ is the angle of orientation between molecules direction and y axis.

In a nonlinear regime, for higher light intensity, the liquid crystal molecules are forced to reorient to be parallel to the electric field. The value of E_x and E_z components are assumed to be much weaker than the E_y component , and the E_x component has a π/2 phase shift versus the E_y [7]. This causes reorientation to occur only in *yz* planes and to be connected with the twist deformation. Moreover, significant changes in the orientation angle will be in the directions of *x* and *y* axis. In such a case the minimization of free energy leads to the Euler-Lagrange equation in the form:

$$\frac{\partial^2\theta}{\partial x^2} + \frac{\partial^2\theta}{\partial y^2} + \frac{\varepsilon_0\Delta\varepsilon}{4K_{22}}\left[\left(E_z^2 - E_y^2\right)\sin 2\theta + 2E_zE_y\cos 2\theta\right] = 0 \tag{2}$$

where K_{22} is a twist deformation elastic constant. Although the above equation is formally the same as for NLCs, its periodic solutions are proper for ChNLCs. With an increase in light intensity, the width of the region with θ=0 increases and it also increases the effective refractive index. This results in self-focusing of a light beam in y-direction and finally the nematicon creation.

Light beam propagation in ChNLC film was carried out twice. Firstl,y, the propagation of light was tested using linearly polarized Ti:Sapphire laser ($\lambda = 793nm$) and secondly, an argon laser ($\lambda = 514nm$) was used. The cell was kept in place by a series of micro-translation stages in the x; y and z direction. The experimental setup allowed focusing the laser beam into the cell by means of an objective lens. An additional waveplate and polarizer were used to control the polarization of light. NLCs scatter light due to the fluctuations in director orientation. Thanks to this the beam traveling laterally in the cell was observed by a 16x microscope objective lens connected with a CCD camera mounted in a *x*; *y* and *z* stage.

For low input power (linear case) the input beam ($\lambda = 793nm$) diffracts in y-z plane parallel to the z axis. Increasing the input beam power leads to self-focusing and finally for the average optical power $P \geq 10mW$ the spatial soliton is formed (the first picture in Fig. 2). The initial input beam waist was estimated to be about 2μm by measuring the divergence of the beam during linear propagation in the liquid crystal film. Due to structural anisotropy connected with chiral orientation the beam walks off from the initial direction while changing the polarization of an input light beam. For TE-like polarization the nematicon propagates parallel to the z-axis. Crossing from TE-like to TM-like polarization causes the nematicon to propagate at different direction (Fig. 2). For the TM-like polarization (for which nematicon does not exist) light beam propagates again parallel to the z-axis.

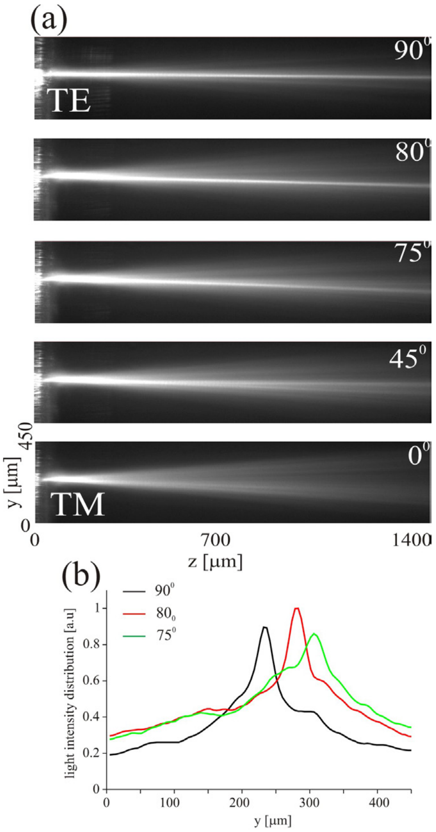

Fig. 2. (a) Experimental results showing the beam walk-off effect by changing the polarization of input light beam for light power P~10mW; (b) normalized intensity distribution for three different input polarizations for which the soliton changed its direction of propagation for the propagation distance $\Delta z = 1000\mu m$.

Applying an electric field to the sample frustrates the cell to behave like homeotropically aligned NLCs. The electrical field (voltage) was along *x* axis, thus parallel to the helix axis (Fig. 3a) and the reorientation of the director is mostly connected with bend deformation. In the cholesteric cell, the twist at 0V varies linearly from 0 to 4π. By increasing the applied voltage, the molecules start to reorient in xy plane and the $\pi/2$ rotation is concentrated around the midplane. In order to demonstrate the ability of beam steering we measure, for a given layer, the changes of the nematicon position in the ChNLC as a function of the applied voltage. When a nematicon was generated (for input power 15.4mW and $\lambda = 514nm$) the beam propagates undiffracted. Applying an electrical field changes the director orientation and consequently the soliton starts to propagate at some angle to *z* axis. Fig. 3a shows the representative output intensity pattern for three values of applied voltage. When there was no voltage applied to the cell, soliton propagated parallel to *z* axis. Applying an external field causes changes in the direction of soliton propagation. Figure 3b shows such a case corresponding to $P = 15.4mW$ and the distance $z = 600\mu m$. Increasing the electric field further above the threshold effect leads to optical nonlinearity no longer prevailing electrical reorientation and the beam not following the molecules direction, which results in linear diffraction of the beam. When the electric field was turned out we again observed soliton propagation parallel to *z* axis. Noticeably, the magnitude of the direction changes are $20\mu m$ at a distance $z = 600\mu m$.

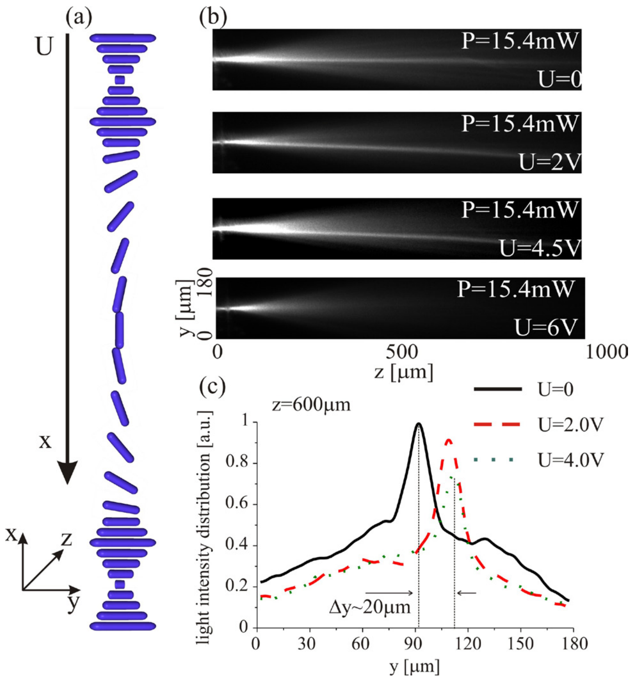

Fig.3. Experimental results on applied electric field (a) schematic drawing of the investigated geometry under the influence of external electric field; (b) soliton propagation for input power P~15mW and by increasing the applied voltage; (c) normalized intensity distribution for three voltages for which the soliton changed its direction of propagation.

In conclusion, we have reported the most important experimental results showing soliton propagation and beam steering by applied voltage as well as input polarization. It is worth emphasing, that the proposed configuration can be applied to low power light beam switching in optical systems. All these properties cause the nematicon to be a very promising application in all-optical steering and switching elements that require low power instead of fast switching.

The work of U. A. Laudyn has been supported by the European Union in the framework of European Social Fund through the Warsaw University of Technology Development Programme.

References

[1] Karpierz, M. A., *Soliton Driven Photonics*, Boardman, A. D., Sukhorukov, A.P., (Eds.), p. 41, Kluwer Academic Publishers: Dordrecht (2001).

[2] Assanto, G., Peccianti, M., Conti, C., *Opt. Photon. News* **14**, 44, (2003).

[3] M. Peccinati, G. Assanto, A. De Luca, C. Umeton, I. C. Khoo, *Appl. Phys. Lett*. **77**, 7 (2000); M. Peccianti, K. A. Brzdakiewicz, G. Assanto, *Opt. Lett.* **27**, 1460 (2002)

[4] U. A. Laudyn, K. Jaworowicz, M. A. Karpierz, *Mol. Cyst. Liq. Cyst.* **489**, 1563(2008); U. A. Laudyn, M. Kwasny, M. A. Karpierz, *Appl. Phys. Lett.* **94**, 091110 (2009)

[5] J. Baran, Z. Raszewski, R. Dąbrowski, J. Kędzierski and J. Rutkowska, Mol. Cyst. Liq. Cyst. 123, 237 (1985)

[6] R. Dabrowski, J. Dziaduszek and T. Szczuciński, Mol. Cyst. Liq. Cyst. 124, 241 (1985)

[7] M. A. Karpierz, *Acta Phys. Polonica A*, **99**, 161, (2001).

