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Self Focusing in Liquid Crystalline Waveguides

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Nonlinear self-focusing of the laser beam in waveguide with nematic homeotropically aligned liquid crystalline layer is analysed theoretically and observed experimentally. The nonlinearity is caused by the reorientational effect and the stable self-trapped beams are created by the spatially periodic reorientation in the liquid crystalline layer.

Keywords: liquid crystalline waveguides; spatial solitons;

INTRODUCTION

Nonlinear optical phenomena in liquid crystals have been actively studied for not more than the last twenty years [1,2]. In the nematic phase, the correlation among molecules is very strong because of the high anisotropy as well as the collective behaviour of the molecules. This is responsible for the fact that liquid crystal molecules can easily reorient even with a very low optical fields. The use of liquid crystals leads to the numerous nonlinear optical phenomena arising from molecular reorientation or/and thermal effects such as intrinsic bistability, temporal instabilities and stochastic processes for light-induced reorientation, nonlinear phenomena on a surface and on boundaries, fluctuations and nonlinear light scattering at phase transitions. All these optical nonlinear phenomena seem to be very promising in applications to optoelectronic waveguided functional elements.

Recently, the nonlinear effects in nematic liquid crystal (NLC) waveguides were studied both theoretically and experimentally [3-6]. The obtained experimental results showed an existence of optical bistability in a directional coupler structure[4] and nonlinear transmission of the guided

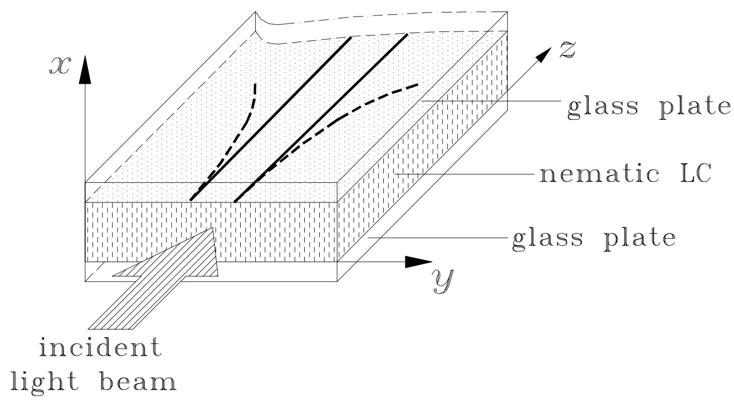


FIGURE 1 Schematic drawing of the analysed waveguide configuration. For low powers the light beam diffracts in *zy* plane (dashed lines) but for high powers it can be self-trapped (solid lines).

modes[5]. These behaviours were explained theoretically as a result of orientational effect in NLCs.

In this paper, we present for the first timeto our best knowledge experimental evidence and theoretical analysis of a self-focusing effect in a NLC waveguide. The results obtained show a possibility of existence of a stable self-collimated waves (spatial solitons) in a NLC film. The phenomena of the self-trapped beams were observed in waveguided with dfferent types of optical nonlinearity (among others in Kerr-type nonlinear media, in photorefractive media, in the second harmonic generation process)[7].The nonlinear self-focusing in a NLC waveguide reported in this paper can be very useful in all-optical switching and data processing systems due to the very low power necessary to creating such beams.

THEORY

In this work the propagation of the light beam in a planar waveguide is analysed (see Fig.1). As a guiding film a nematic liquid crystalline layer with a homeotropic aligment is considered. Assuming that the light is polarized in *y* direction, the TE guided mode can be excited with an electric field in the form:

$$\mathbf{E} = \left(0, E_y, 0\right)\exp\left(i\omega t - ikN_o z\right), \quad (1)$$

where N_o is an effective refractive index of the guided mode and $k=\omega/c$. The amplitude E_y, slowly varying in z direction can be represented in the form $E_y=A(y,z)\ \Psi(x)$, where $\Psi(x)$ is the distribution of the planar waveguide mode fulfilling the equation:

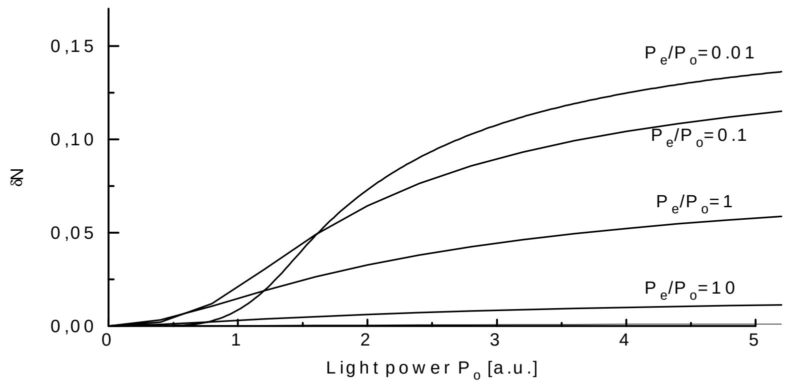


FIGURE 2 Effective index changes δN versus light power for TE and TM fundamental modes in the same phase

$$\left[\frac{\partial^2}{\partial x^2}+k^2\left(\varepsilon_\perp - N_o^2\right)\right]\Psi = 0. \tag{2}$$

For small changes of the dielectric tensor ε in the NLC layer the amplitude A is calculated from the wave equation:

$$\left[\frac{\partial^2}{\partial y^2}-2ikN_o\frac{\partial}{\partial z}+k^2 2N_o\delta N\right]A = 0, \tag{3}$$

where δN defines changes of the effective refractive index due to the local changes of the NLC molecule orientation angle θ:

$$2N_o\delta N = \int \Delta\varepsilon \sin^2\theta\Psi^2 dx \Big/ \int \Psi^2 dx, \tag{4}$$

where $\Delta\varepsilon=\varepsilon_\parallel-\varepsilon_\perp=n_e^2-n_o^2$ is the dielectric anisotropy of the nematic liquid crystal. For the perfect homeotropic texture θ=0 and then δN=0. However, in the presence of the strong electric fields of the electromagnetic wave guided in the waveguide the reorientation occurs and in one-elastic constant approximation ($K_1= K_2= K_3=K$) it can be calculated from the equation[4]:

$$\frac{\partial^2\theta}{\partial x^2}+\frac{\varepsilon_o\Delta\varepsilon}{4K}\left[\left(E_xE_y^*+E_xE_y^*\right)\cos 2\theta+\left(\left|E_y\right|^2-\left|E_x\right|^2\right)\cos 2\theta\right]=0, \tag{5}$$

where additionally the electric field of the light polarized in the x direction (TM modes) is assumed. The reorientation depends on the square of the electric field and therefore the refractive index changes δN depends on the light power P_o guided in the TE mode:

$$P_o \propto \int \left|E_y\right|^2 dx = \int |A|^2\Psi^2 dx, \tag{6}$$

as well as the light power P_e guided in the TM mode:

$$P_e \propto \int \left|E_x\right|^2 dx, \tag{7}$$

and the phase difference between both modes. In the Fig.2 the refractive index changes δN *versus* the light power guided in the TE mode are plotted for different ratios between P_o and P_e for the same phase of the guided fundamental modes.

As it can be expected, the appearence of the TM mode causes the diminishing of the reorientation and refractive index changes. However, for obtaining the stable self-trapped beams the nonlinear changes of the refractive index can not be too large. It is well known from the soliton theory[7,8] that for the nonlinearity in the form $\delta N = N_2 P^m$, the stable spatial solitons exist in the planar waveguides only if m<2. For higher order nonlinearities (m≥2) the self-focusing phenomena creates unstable nonlinear beams. Therefore we can expect that for pure TE modes the self-focusing phenomena in our configuration will be unstable and to obtain the stable self-trapped beam both TE and TM polarized waves should be excited.

Since both TM and TE fundamental modes have different refractive indices N_e the largest reorientational effect occurs in the regions where both modes are in the same phase and the reorientation will appear periodically with the period equal to the beat length L_B :

$$L_B = \lambda/(N_e - N_o) \approx \lambda/(n_e - n_o).$$

EXPERIMENT

The experimental setup is presented in Fig.3. The single mode semiconductor laser at λ=842 nm pigtailed to the single-mode fiber was

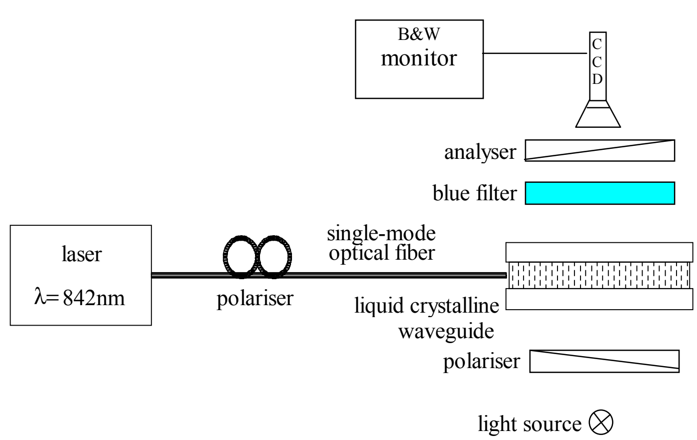
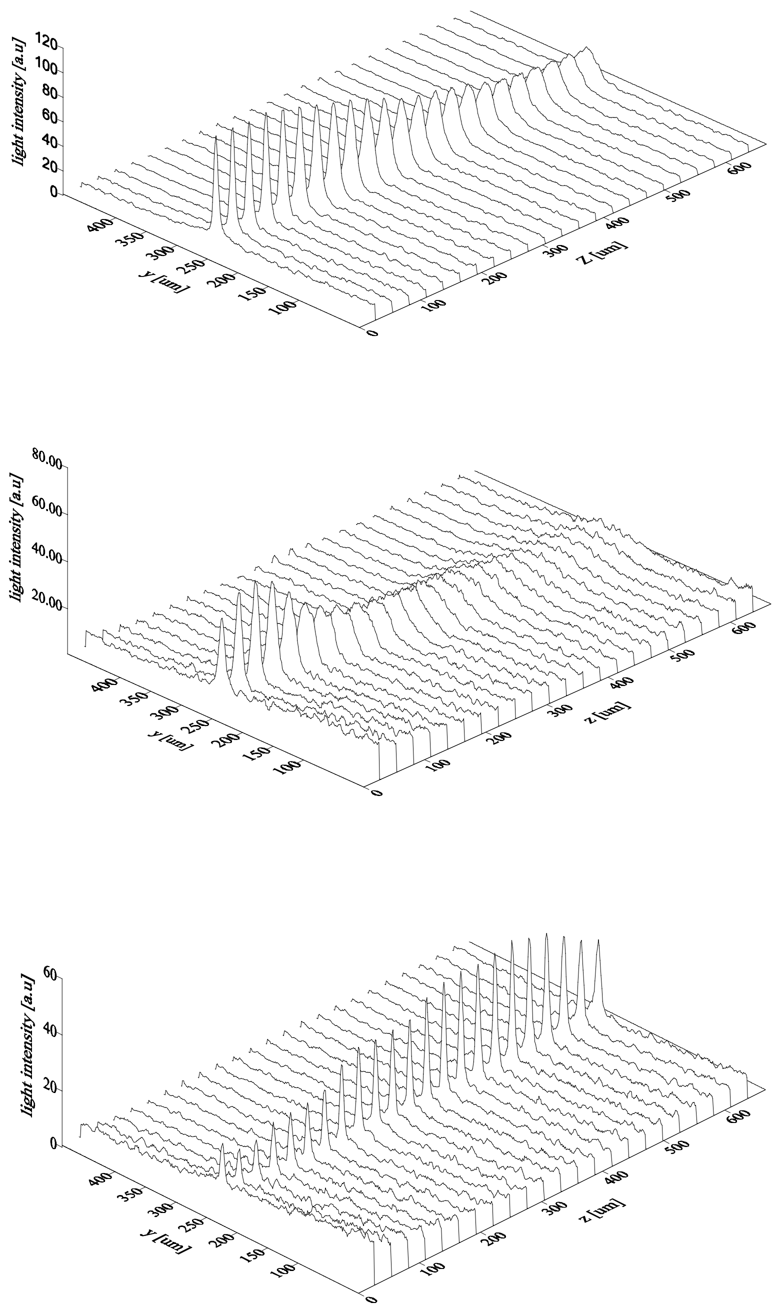


FIGURE 3 Experimental setup



(A)

(B)

(C)

FIGURE 4 Scattered light intensity measured for the input power (A) P<20mW, (B) P≈20mW and TE-like polarized input, and (C) P≈30mW and TM-like polarization.

used as a light source. The nematic liquid crystal 4-trans-4'-n-hexyl-cyclohexyl-isothiocyanatobenzene (6CHBT) with the refractive indices n_o=1.52 and n_e=1.67 filled the layer between two glass plates separated by MYLAR spacers of a thickness d=10 μm. The polarization of the light coupled from the optical fiber to the planar waveguide was controlled by an all-fiber polarizer. In the experiment only the fundamental TE and TM modes in liquid crystalline waveguides were excited.

First, the direct scattering of the light guided in the waveguide were observed (in the experimental setup without the external light source, the analyser, and the filter, see Fig.3). The scanned pictures obtained by the CCD camera are presented in Fig.4. For the low power (Fig.4A), a typical diffraction pattern was observed. Above a critical power of the light outcoming from the fiber (P~20mW for the TE wave) the self-focusing is observed. However for the TE waves this phenomenon produces after some distance an unstable self-defocusing beam (Fig.4B). For the TM-like mode the self-focusing begins at higher input powers (P~30mW) and the stable self-trapped beam is created (Fig.4C).

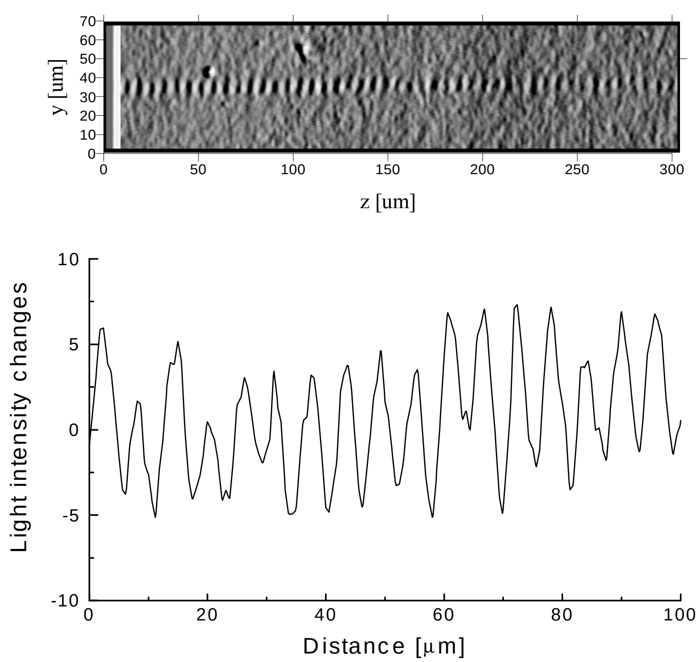


FIGURE 5 Observation of fringes caused by reorientation in the nematic liquid crystal layer

For the stable self-collimated beam the reorientation of the liquid crystal layer was also investigated. In this case, the external light source was used (fig.3) and changes in the light transmission through two crossed polarized were observed. The use of a blue filter diminished the scattered light at λ=842nm. Fig.5 presents obserwed intensity changes along the NLC waveguide. The distance between fringes corresponds to the birefringence $\Delta n \approx 0.14$ which is in a perfect agreement with the 6CHBT birefringence.

CONCLUSIONS

In this paper we have reported the observation of the stable self-traping of the laser beam in nematic liquid crystalline waveguide. The obtained experimental results are in good agreement with the theoretical predictions. The self-focusing effect is caused by the reorientation in the NLC layer due to the electric field of the guided electromagnetic waves. The existence of the TM-polarized waves decreases nonlinear changes of the refractive index and stabilizes the self-collimation of the guided beam.

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