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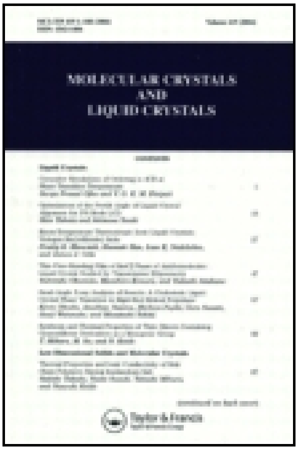

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Non-Linear Effects in NLC Media Undergoing Two Beams Irradiation

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Non-Linear Effects in NLC Media Undergoing Two Beams Irradiation

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A Nematic Liquid Crystal crossed by the overlap of multiple laser beams gives rise to different phenomena, such as the cancellation of reorientation and critical reorientation. A nonlinear 2D theoretical model is presented to describe these effects in the case of two laser beams impinging on a homeotropically aligned cell. By comparing the theoretical estimation of the re-orientational effect to the observed optical divergence of one beam, it is shown that they depend on the same phenomenon, although they are not directly correlated.

Solutions given by the model show a good agreement with experimental results.

Keywords: liquid crystals; non-linear optics

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INTRODUCTION

The Giant Optical Nonlinearity (GON) of Nematic Liquid Crystals (NLCs) determines important and useful optical properties of these materials [1,2]. This nonlinearity is due to the reorientation of the molecular director **n**, which is the unit vector that describes the mean orientation of the axis of the elongated NLC molecules [3]. As this

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vector explicitly appears in the terms that describe the interaction with an external electric field, it happens that the reorientation can be also induced by the optical field of the same radiation that experiences the nonlinear propagation. This phenomenon is called Optical Frèedericksz Transition (OFT), and its most spectacular consequence is the self-phase modulation (SPM) effect, which yields the appearance of concentric bright and dark rings [4] in the far-field zone. The effect, which has been extensively studied and characterized [5–7], is of continuing interest because of its appealing applications, both in pure NLC [8,9] and in liquid-crystalline composite materials [10]. In a previous paper [11] the observation of a new kind of OFT induced in a NLC cell by two pulsed laser beams has been reported. It has been predicted that the director reorientation induced by one electromagnetic wave can be canceled by a second, competing, wave of suitable intensity and angle of incidence [12,13]. The effect can be achieved only in a limited range of incidence angle and intensity: above a given intensity threshold, cancellation becomes unstable and a second, Light-Induced, Frèedericksz Transition (LIFT II) takes place. Investigation of the whole phenomenon is quite interesting, mainly for those applications in which the GON that is due to the OFT is exploited to create spatial solitons in NLCs [8,9]. In that case both cancellation and LIFT II effect can play crucial roles when multiple spatial solitary waves are allowed to interact with one another and produce all-optical switching and logic gating in NLC cells [14].

In this article we report a new set of experimental observations as well as a theoretical model which describes this phenomenon.

EXPERIMENT

The experimental geometry is illustrated in Figure 1(b). We exploit a particular set of cancellation conditions [7]: The average intensities of the two impinging beams are the same, and the two angles of incidence are equal. The setup is shown in Figure 1(a). The continuous source is a diode-pumped solid-state laser (DPSS Ventus 532, by Laser Quantum) which emits light at $\lambda = 532\,\mathrm{nm}$. The radiation is split into two beams of equal intensity by a beam splitter. Before reaching the sample, each beam crosses a half-wave plate followed by a polarizer, whose combined action enables varying the total power on the sample; then each beam crosses a spherical lens ($f = 150\,\mathrm{mm}$), mounted on a translation stage, needed to have two equal spot sizes (130μm in diameter) on the sample. The NLC (E7, by Merck) is sandwiched between two glass slabs and is homeotropically aligned. Suitable Mylar spacers

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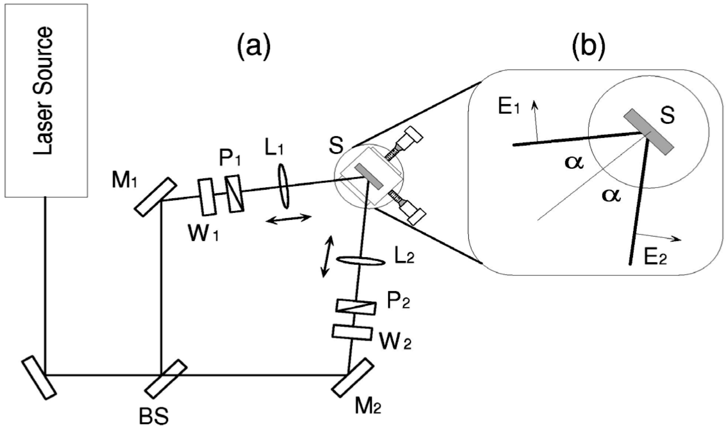


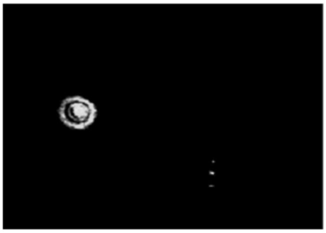
FIGURE 1 Setup: W, $\lambda/2$ plate; Ps polarizers; Ms, mirrors; B.S., 50% beam splitter; CC, corner-cube retroreflector; Ls, lenses; S, sample; SC, screen. (b) Experimental geometry.

ensure a uniform thickness (L = 75μm) of the cell, which is placed on a rotating xyz stage, needed to adjust two equal and opposite angles of incidence. Images after the sample are projected onto a white screen which enables observation of Self Phase Modulation (SPM) rings in the far-field zone, an effect widely investigated in the past [5,6,15], which can be used to monitor the director reorientation.

Using an angle of 50° between the beams, we can obtain a well-balanced competition of the two extraordinary waves. Indeed, when their intensity is the same and the total average intensity on the sample remains below the LIFT II threshold, we obtain an unperturbed orientational state of the director, which we refer to as "spatial cancellation" of the reorientation. The situation is shown in Figure 2(a), where no SPM rings are observed in the far field zone. If we stop one beam, the action of the other one gives rise to the formation of four SPM rings [Fig. 2(b)].

When the total impinging intensity reaches the threshold value, a LIFT II effect takes place. The formation of more than 15 SPM rings in the far-field zone of one of the two beams (Fig. 3) emphasizes that we are in the presence of a new reorientation of the director in the (x, z) plane. Furthermore, if we stop the beam that exhibits the smallest divergence (first beam), we observe a decrease in the divergence of the second beam. However, if we stop the second beam, we observe a decrease in the divergence of the first beam, followed by the formation of a new ring pattern.

(a)



(b)

FIGURE 2 (a) Cancellation effect. The presence of two dotlike spots shows that there is no nonlinear phase shift. (b) Starting from the previous cancellation state, typical self-phase-modulation rings (which are due to director reorientation) are observed in the far-field zone of the first beam when the second beam is stopped. The impinging intensity of the first beam is the same as in (a).

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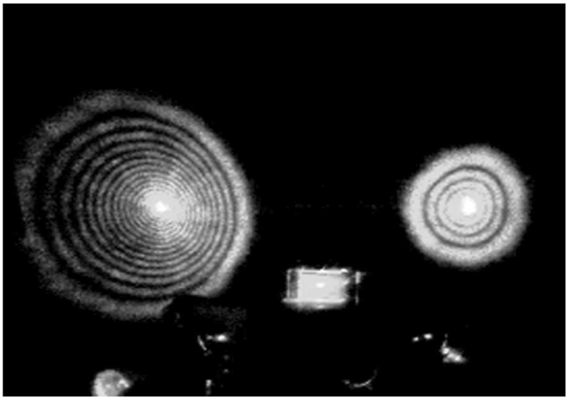

FIGURE 3 Self-phase-modulation rings that appear in the farfield zone of both beams when the total impinging intensity exceeds the threshold value of the LIFT II effect.

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THEORETICAL MODEL

From a theoretical point of view, the general system we want to study is the one sketched in Figure 4.

A NLC cell of length d, and width L is crossed by N impinging laser beams E_j, each with an incidence angle α_j. We chose the x-axis along the cell width and the z-axis along the cell length and we write the director reorientation equation (already considered in a previous article [16]) for the case of an interaction of the NLC director with N impinging light beams:

$$\gamma \frac{\partial \theta}{\partial t} = \mathscr{K} \nabla^2 \theta + \frac{\varepsilon_0 \Delta\varepsilon}{4} \sum_{i,j-1}^{N} E_i E_j^* \sin(2\theta - \alpha_i - \alpha_j), \tag{1}$$

Here t is the time, γ the viscosity constant and $\mathscr{K}$ the elastic constant of the medium in a "one constant" approximation; $\Delta\varepsilon = n_e^2 - n_o^2$ indicates the optical anisotropy, n_e and n_o being the extraordinary and ordinary refractive index respectively, and ε_0 is the electric permittivity of vacuum. Where light propagation is concerned, we use the fundamental Gaussian beam solution of Maxwells equations [17], taking into account that the jth beam crosses the sample with an angle α_j; this corresponds to a propagation with coordinates:

$$\begin{aligned} x_{\alpha j} &= x \cos\alpha_j - z \sin\alpha_j \\ z_{\alpha j} &= x \sin\alpha_j + z \cos\alpha_j \end{aligned} \tag{2}$$

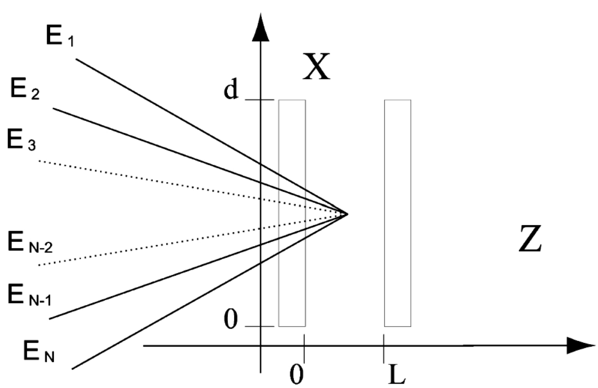

FIGURE 4 Sketch of a NLC cell, crossed by N light beams.

While crossing the medium, the jth beam experiences a refractive index $n(\alpha_j, \theta)$given by:

$$n(\alpha_j, \theta) = \frac{n_o n_e}{\sqrt{n_e^2 \cos^2(\alpha_j - \theta) + n_o^2 \sin^2(\alpha_j - \theta)}} \tag{3}$$

where θ is given by the solution of Eq. (1). Since we are going to obtain this solutions by means of a numerical approach, for sake of generality we eliminate the dependence of our results on the particular value choosen for the cell width L by introducing normalized spatial coordinates $\xi = x/L$, $\xi = z/L$ and normalized time $\tau = t/\tau_R$, where $\tau_R = \gamma L^2/\mathscr{K}$ is the tipical reorientation time of the NLC director [1]. We also introduce the normalized parameters $\Lambda = \lambda/L$ and $w_0 = W_0/L$ (W_0 being the minimum spot size and λ the wavelength), and a normalized expression for the electric field:

$$e_j = \sqrt{L^2 \varepsilon_0 \Delta\varepsilon / 4\mathscr{K}} \cdot E_j.$$

Thus the normalized electric field of the jth Gaussian beam is written as:

$$e_j = \frac{e_0 w_0}{w_j} \exp\left\{ -i[k(\xi \sin\alpha_j + \zeta \cos\alpha_j) - \eta_j] + (\xi \cos\alpha_j - \zeta \sin\alpha_j)^2, \right.$$
$$\left. \times \left[\frac{1}{w_j^2} + \frac{ik}{2r_j} \right] \right\} \quad j = 1, \ldots, N \tag{4}$$

Here $\eta_j = \eta(\zeta, \alpha_j), w_j = W(\zeta, \alpha_j, w_0)$ and $r_j = R(\zeta,\ \alpha_j)$, where $W(z) = W_0\sqrt{1 + z^2/z_0^2}$ is the spot size, $z_0 = \pi n(\theta) W_0^2/\lambda$ the confocal parameter, $\eta(z) = \arctan(z/z_0)$ and $R = z + z_0^2/z$ is the radius of curvature of a generic gaussian beam. In normalized coordinates, Eq. (1) becomes

$$\frac{\partial\theta}{\partial\tau} = \nabla^2\theta + \sum_{i,j-1}^{N} e_i e_j^* \sin(2\theta - \alpha_i - \alpha_j), \tag{5}$$

where ∇^2 indicates now $(\partial^2/\partial\xi^2 + \partial^2/\partial\zeta^2)$.

NUMERICAL SOLUTIONS AND RESULTS

System 4–5 can be used to study a large number of experimental configurations, but it is highly non linear and, in general, cannot be solved by analytical methods.

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We have chosen a numerical approach creating a lattice of computational grid points (*i,j*) in the ξ-ζ plane, where lattice steps $\Delta\xi$ and $\Delta\zeta$ allow to go from i to $i+1$ and from j to $j+1$ respectively. Evolution of the optical field in the ζ direction is then simulated by determining the value of the field at the (i, $j+1$) point by means of the field values at previous points. The lattice also evolve in time with $\Delta\tau$ steps, taking into account the time-dependent molecular director reorentation. We have used a second order Runge Kutta time scheme and a central difference scheme for spatial derivatives. Simulations have been carried out utilizing $n_0 = 1.5216$ and $n_e = 1.7462$, (corresponding to values of the commercial NLC E7 by Merk), $\lambda = 532\,\text{nm}$, and several different values of the control parameters which determine the behavior of the system.

We have considered two beams of equal intensity, and used $\theta(\xi,\zeta,0) = 0$ as the initial condition in time and $\theta(\xi,0,\tau) = \theta(\xi,1,\tau) = 0$ as border conditions in space; this choice accounts for strong anchoring conditions in a homeotropic cell, were the molecular director is oriented perpendicularly to the cell plates.

We have realized a number of "two step" simulation: at first only one beam crosses the sample, so that a director reorientation is induced. The system proceeds this way until $\partial\theta_c/\partial\tau \leq 0.01$ where θ_c indicates the reorientation angle in the center of the sample; then the second beam is switched on at the symmetric incident angle ($\alpha_1 = \ -\alpha_2$), again until $\partial\theta_c/\partial\tau \leq 0.01$. After that, two different non-linear behaviors are predicted (in agreement with previous experimental results [11]), depending both on light intensity and incidence angle:

(a) Cancellation. In this case, the second beam competes with the first one and the final effect is a reorganization of the NLC director in such a way that the reorientation produced by the first beam is almost completely cancelled by the second one; this corresponds to the experimental situation described above and shown in Figure 2(a), where no SPM rings are present at the end of the process. A simulation is illustrated in Figure 5 showing the uniformity of the director orientation at the end of the process.

(b) LIFT II (Second Light Light Induced Frèedericksz Transition): above a given intensity threshold, the second beam adds its reorientational effect to the first one, thus causing a critical director reorientation (Fig. 6).

A number of simulations have been carried out, which demostrate that: (a) critical reorientation occurs only for angles of incidence

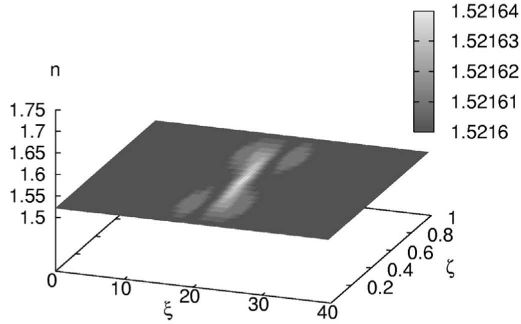

FIGURE 5 Map of the refractive index in the sample at the end of the cancellation (CAW) process. The simulation has been carried out for an angle of incidence $\alpha = 1$ rad and a normalized field amplitude $e_0 = 3$. The sample is illuminated at first by a single beam, then a second beam is swiched on at $\tau = 0.34$, and the whole process ends at $\tau = 0.76$.

smaller than the critical value $\alpha_{th} \approx 0.8$ rad, (b) results are independent of the used liquid crystal, and are specific of the system geometry only. In particular, for equal intensities of the two beams, two equilibrium states exist, as shown in Figure 7.

At small incidence angles ($\alpha < 0.78$ rad, corresponding to great angles between field vectors e_1 and e_2) the cancellation effect is favored; on the contrary, for great incidence angles ($\alpha > 0.78$ rad) a critical reorientation occurs. Furthermore, for values $e_0 < 2$, the reorienting effect is well contrasted by the elastic force; the maximum reorientation angle is small enough and the cancellation effect is in any case favored.

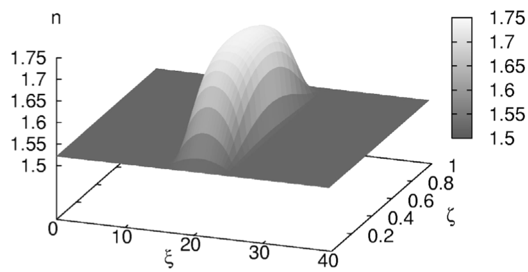

FIGURE 6 Map of the refractive index in the sample at the end of the Lift II process. The simulation is carried out for $\alpha = 0.2$ rad and $e_0 = 3$. The sample is illuminated at first by a single beam, then a second beam is swiched on at $\tau = 0.34$, and the whole process ends at $\tau = 0.76$.

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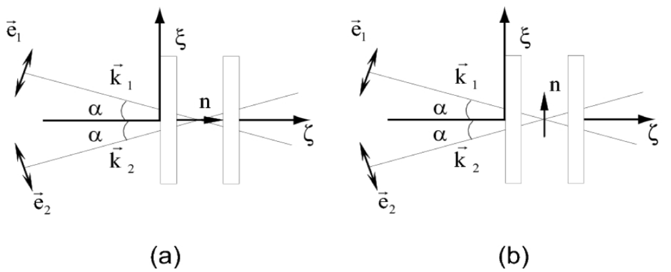

FIGURE 7 Equilibrium states in the case of equal impinging intensity, Vectors $\mathbf{e}_{1,2}$ represent the electric fields of light beams, **n** is the molecular director. (a) Initial homeotropic state or consequence of a complete cancellation effect; (b) complete planar reorientation.

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CONCLUSIONS

In conclusion, we have realized a simple and general model for the interactions of N gaussian light beams with a physical system studied and used up to now as a non linear medium, that is a homeotropic NLC cell with strong anchoring conditions. The model has been checked for the case of two beams in a particular geometry and it shows a good agreement with previous observations. Results give a new light on these kind of saturable non-linear media, stimulating investigation of the intriguing phenomena that can take place.

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