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EXPERIMENTAL AND THEORETICAL ANALYSIS OF INTRINSIC OPTICAL TRANSISTOR ACTION IN HOMEOTROPICALLY ALIGNED NEMATIC CRYSTAL FILMS

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Abstract In this work we report the first observation of intrinsic optical transistor action in a homeotropically aligned nematic liquid crystal film. The transistor action is produced by the sample intrinsic optical nonlinearities, so that no external feed-back mechanism (e.g. a Fabry-Perot resonator) is necessary. We also present a theoretical analysis of the problem in two different approximations: a linear, time-dependent approach, and a stationary non linear analysis. The theoretical results show to be in good agreement with our measurements.

INTRODUCTION

In recent years, the possibility of constructing nonlinear optical devices based on the optical-field-induced refractive indeces (Δn) has attracted a great deal of attention.[1] It is often most appealing if such devices would work with cw laser beams. This requires a nonlinear medium with an extremely large nonlinearity. Several such media have recently been discovered.[2,3,4] In particular, recent studies have demonstrated extraordinarily large optical nonlinearity of nematic liquid crystal arising from the optically induced reorientation of the molecular director axis.[5,6] The non-

linearity has been shown to be several orders of magnitude larger than that exhibited by a typical anisotropic liquid like CS_2 and is in the same order of magnitude as those observed is some nonlinear photorefractive crystals (e.g. $BaTiO_4$) or semiconductors.

In this paper we report both full experimental analysis and theoretical description of the intrinsic optical transistor action in a homeotropically aligned nematic liquid crystal film, which we have recently observed.[7] Optical transistor action here refers to the transfer of a signal carried by a low-power beam to a high-power beam, when the two interact in a medium. In our experiment, this was achieved by the interaction of two linearly polarized laser beams in a homeotropically aligned nematic film. The basic idea is as following. Consider a strong beam and a weak beam impinging concurrently on the film at normal and oblique incidence, respectively. Both are polarized in the plane of incidence. With the strong beam alone, no molecular reorientation can be induced in the sample if the beam intensity is below threshold for optical Freedericksz transition. In the presence of the weak beam, however, the threshold no longer exists, and the resultant molecular reorientation induced by the beams can produce a local Δn and lead to a phase shift in the strong beam, which can be converted into an intensity change of the strong beam.[8] An amplitude modulation of the weak beam can give rise to a corresponding amplified modulation of the strong beam. Power gain of the

order of ten have been obtained.

We also report a theoretical description of the optical transistor action in a nematic liquid crystal, which is based on a plane wave theory of the laser beam interacting with the sample. The numerical results obtained by using the above model show a very good agreement with our experimental observations.

The organization of this paper is as follows. In section II we report the description of the experimental set-up and of the experimentals results. Section III contains the general theory of the nonlinear interaction between an electromagnetic plane wave and a nematic liquid crystal. Finally, in the last two sections we develop the theory of the section III in two different situations: a linear, time-dependent approach, and a complete, stationary analysis.

II. EXPERIMENTAL SETUP AND RESULTS

The experimental arrangement is shown in Figure 1. A cw Ar^+ laser beam operating at 514.5 nm was split into a strong beam ($\simeq$50mW) and a weak beam ($\simeq$1mW). The strong one (I_0) was normally incident, and the weak one (I_1) was near the Brewster angle ($\simeq 42°$) on a homeotropically aligned 5CB nematic film 60μm thick. The power of the weak beam could be varied by using a variable attenuator. The beams were focused (with a focal length of 25cm) to a spot of $\simeq 3 \times 10^{-5}$ cm^2 and properly aligned to ensure an accurate overlapping of the two beams in the sample. The alignement was checked by observing the

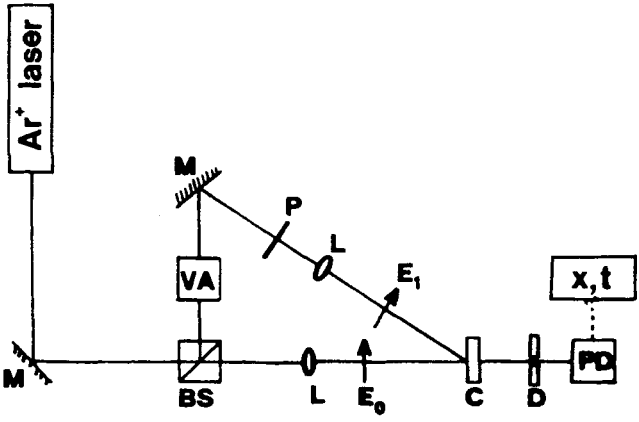

FIGURE 1. Experimental layout: M's, mirrors; L's, lenses; BS, beam splitter; VA, variable attenuator; P, polarizer; C, liquid crystal cell; D, diaphragm; PD, photodiode; (X,t), (x,t) recorder.

far-field ring patterns induced by the spatial phase modulation on both beams.[6,8] Both beams were polarized in the plane of incidence. The beam powers were chosen so that

$$I_1 \ll I_0 \lesssim I_{th} = A \times I_{Fr} \qquad (1)$$

where I_{Fr} ($\simeq$1.8 KW/cm^2) is the Freedericksz threshold for homeotropic alignment, and A the laser beam cross section in the focus.

Since $I_0 < I_{th}$, no molecular reorientation in the sample took place when $I_1 = 0$, and no field-induced phase shift appeared on the strong beam. For $I_1 \neq 0$, however, a small molecular reorientation was initially started by the weak beam. As soon as the molecular reorientation set in, the strong beam also become operative in reorienting the molecules. The two beams then cooperatively drove the molecular

reorientation toward the final equilibrium configuration. This lead to a spatially varying optical birefringence in the medium and hence to a spatial modulation on the beams. We noted that the far-field ring pattern of the transmitted strong beam had a sensitive dependence on the weak beam intensity. As many as 30 rings (corresponding to a phase shift of $\approx 60\pi$) with a 20° angular spread were induced by 1mW in the weak beam. Thus, the strong beam could be phase modulated by an intensity variation of the weak beam. This modulation became more effective as I_0 approached the Freedericksz threshold intensity I_{Fr}. For $I_0 > I_{th}$, however, the weak beam had only a negligible influence on the self-phase modulation on the strong beam.

In order to obtain the optical transistor action, the phase modulation on the strong beam should be converted in to an intensity modulation. We used the following scheme. A diaphragm, approximately the size of the input strong beam, was placed about 20cm beyond the sample, and the beam passing through it was detected (Fig.1). In the absence of a spatial phase modulation, the strong beam was hardly blocked by the diaphragm. With a strong spatial phase modulation, however, a significant part of the strong beam was diffracted into rings, and the beam power transmitted through the diaphragm diminished.

In Figure 2 , the observed output through the diaphragm, I_{out}, is plotted against the input weak beam power (I_1). It is seen that I_{out} can be reduced from 48 to 10 mW by ap-

plicating a 4 mW weak beam, exhibiting a static power gain of about 10. The slope of I_{out} versus I_1 in some region appears to be fairly steep. For I_0=42mW, and $I_1 \simeq$3.6mW, a variation of I_{out} from 15 to 35 mW cold be obtained by a variation of I_1 of only 0.2mW. Thus, the dynamic power gain is of the order of 100.

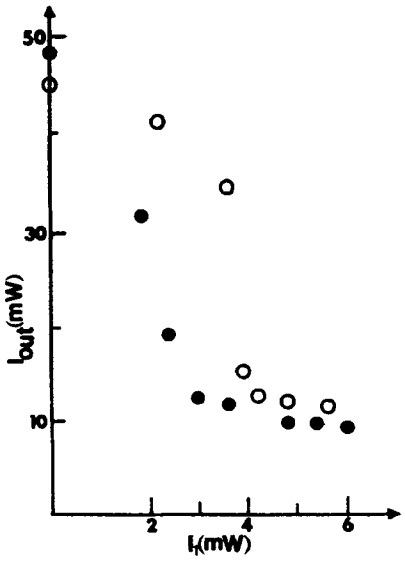

Figure 2. Output power I_{out} versus I_1, for I_0=48mW (●), and I_0=42mW (○).

Unfortunately, the response time is slow because of the strong molecular correlation. In Table I we show the observed time, τ, required for reducing I_0 to 1/e of its original value, as a function of I_1 for two different values of I_0.

The theory underlying the above observations is a simple extension of the single beam case developed earlier.[6,9] The interference of the two beams can yield a spatial varia-

tion of molecular reorientation in the form of a three-dimensional grating structure.

TABLE I The computation time as a function of I_1 for two different values of I_0.

I_0 = 48 mW		I_0 = 42 mW	
I_1 (mW)	τ (sec)	I_1 (mW)	τ (sec)
9.00	5.3	7.60	10.5
6.25	7.5	6.85	10.5
5.60	9.0	6.00	15.0
5.00	9.8	4.60	15.0
3.75	10.5	4.20	16.5
3.15	12.0	3.90	18.8
2.50	12.3	3.60	22.0

However, in our experimental configuration, the optical paths of the two beams was differing much more than the laser coherence length, so that the grating structure was rapidly fluctuating in time and could not affect the molecular orientation. With the grating effect neglected, the situation then crudly resembles that of a single beam incident upon the nematic film at an oblique angle; the angle of incidence increases as the weak beam power increases.

III. PLANE WAVE THEORY

In this section we briefly outline the genaral theory of the non linear interaction between an electromagnetic plane wave and a nematic liquid crystal.

The optical torque per unit volume, τ, produced by a TM plane wave impinging on the crystal at an angle α is given

by [10]

$$\tau(s) = -\frac{\varepsilon_a K_{33}}{16\pi}\left(\sin(2\Theta)(|E_x|^2 - |E_z|^2) + \cos(2\Theta)(E_x E_z^* + E_x^* E_z)\right) \quad (2)$$

where $s=\sin\alpha$, K_{33} is the Frank elastic constant, and $\varepsilon_a = \varepsilon_{\parallel} - \varepsilon_{\perp}$, with $\varepsilon_{\parallel}$ and $\varepsilon_{\perp}$ the dielectric constants in a direction parallel and perpendicular to molecular director $\bar{n}$, respectively. By choosing the z-axis along the sample normal, $\Theta(z,t)$ represents the director tilt angle.

In the quasi-optical approximation, the components of the electric field within the liquid crystal are [10]

$$E_x(z,s) = E(\varepsilon_{zz} - s^2)^{1/4}\exp(i\Psi(z,s))$$
$$E_z(z,s) = -E\left[\frac{\varepsilon_{xz}(\varepsilon_{zz} - s^2) + s(\varepsilon_a + \varepsilon_{\parallel})^{1/2}}{\varepsilon_{zz}(\varepsilon_{zz} - s^2)^{1/4}}\right]\exp(i\psi(z,s)), \quad (3)$$

where E is the electric field amplitude, $\varepsilon_{xz} = \varepsilon_a \sin\Theta\cos\Theta$, and $\varepsilon_{zz} = \varepsilon_{\perp} + \varepsilon_a\cos^2\Theta$. The phase $\Psi(z,s)$ is given by

$$\Psi(z,s) = \frac{2\pi}{\lambda}\int_0^z \frac{\varepsilon_{\parallel}\varepsilon_{\perp}(\varepsilon_{zz}(z') - s^2)^{1/2} - s\varepsilon_{xz}(z')}{\varepsilon_{zz}(z')}dz' \quad (4)$$

where λ is the laser wavelength.

Since, as already discussed, the spatial interference terms can be neglected in our case, the strong (α=0) and weak (α=42°) beams interact independently with the liquid crystal, so that the total optical torque per unit volume is simply

$$\tau_{opt} = \tau(0) + \tau(\sin 42°). \tag{5}$$

The equation of motion for molecular reorientation in the nematic cell is

$$-\eta \frac{\delta\Theta}{\delta t} + (K_{11}\sin^2\Theta + K_{33}\cos^2\Theta)\frac{\delta^2\Theta}{\delta z^2} - (K_{33}-K_{11})\sin\Theta\cos\Theta\left(\frac{\delta\Theta}{\delta z}\right)^2 = \tau_{opt}, \tag{6}$$

where η is a Leslie viscosity coefficient, K_{11} is the splay elastic constant and τ_{opt} is obtained through Eq.(2) and (5).

The phase change for the strong beam electric field E_0 (α=0), after passing through the liquid crystal film is

$$\Delta\Psi_0(\mathbf{L},0) = \frac{2\pi L\,\varepsilon_\perp^{1/2}}{\lambda}\left[\frac{\varepsilon^{1/2}}{L}\int_0^L \frac{dz}{\varepsilon_{zz}^{1/2}} - 1\right]. \tag{7}$$

Eq.(6) is a nonlinear, inhomogeneous, partial differential equation (in space and time), and an analytical solution cannot be found. In the next two sections we shall obtain solution of Eq.(6) in two different approximations. Firstly, in the case of very small angles, we shall outline a very simple, linear, time-dependent theory; secondly, we shall find a solution in the stationary case ($\frac{\delta\Theta}{\delta t}$=0). A comparison between theoretical and experimental results will also be discussed.

IV. LINEAR THEORY

In the limit of small angles of molecular reorientation, an analytical solution of the problem can be obtained. The small-angle approximation ($\Theta << \frac{\pi}{2}$) reduces Eq.(6) to the following linearized equation[12]

$$-\frac{\eta L^2}{K_{33}}\frac{\delta\Theta}{\delta t} + L^2\frac{\delta^2\Theta}{\delta z^2} + B\Theta + D = 0, \tag{8}$$

where

$$B = \pi^2 (I_0/I_{th})\left[1 + \frac{(I/I_0)\cos\alpha(1-2(\sin\alpha/n_e^2)^2}{(1-(\sin\alpha/n_e^2)^2)^{1/2}}\right],$$

$$D = -(\pi^2/n_o)(I_1/I_{th})\sin\alpha\cos\alpha .$$

In Eq.(8) $n_o = (\varepsilon_\perp)^{1/2}$, and $n_e = (\varepsilon_\parallel)^{1/2}$ are the ordinary and extraordinary refractive indices, respectively, and I_{th} denotes the Freedericksz threshold for homeotropic alignment, viz

$$I_{th} = (c\,A(n_e^2/n_o)\,K_{33}(\pi/L)^2)/(n_e^2 - n_o^2), \tag{9}$$

where c is the speed of light.

Assuming strong anchoring boundary conditions with $\Theta(0) = \Theta(L) = 0$, the solution can be written in the form

$$\Theta(z,t) = \sum_{n=1}^{\infty} C_n(t)\sin(n\pi z/L). \tag{10}$$

we find

$$C_n = 0 \qquad \text{,for odd n}$$

$$C_n = -4D \frac{1-\exp((B-n^2\pi^2)K_{33}t/(\eta L^2))}{n\pi(B-n^2\pi^2)} \quad , \quad \text{for even } n.$$

Knowing $\Theta(z,t)$, one can then calculate the optical-field-induced refractive index $\Delta n(z,t)$, and, hence, the induced phase shift $\Delta\Psi_0$ (see Eq.(7)) of the strong beam in passing through the sample.[8] The result is

$$\Delta\Psi_0 = \pi n_o (L/\lambda)(\delta - (n_o/n_e)^2) \sum_{n=1}^{\infty} C_{2n}^2(t) \qquad (11)$$

The theoretical calculations have been carried out for a homeotropically alignment 5CB nematic film, with $L=60\,\mu m$, and an incident angle $=42°$. For 5CB, $\eta=0.25$ poise, $K_{33}=9\times10^{-7}$ dyn, $n_o=1.533$, $n_e=1.703$, and $I_{th}\simeq1.8 KW/cm^2$.

To compare theory and experiment we have measured the time required to obtain an induced phase shift of 4π (wich corresponds about 2 diffraction rings in the far-field pattern) on the strong beam as a function of the weak beam power for a fixed input strong beam. The phase-change of 4π corresponds to a maximum molecular reorientation of $\simeq 20°$ at the middle of the cell. This guarantees the applicability of the above small angle approximation. The comparison between experimental and theoretical results is given in Figure 3, in the case of $I_0=48mW$. As shown, the agreement between theory and experiment is good, considering that we have simply taken the material constant from the literature, and neglected the finite-beam-size effect.

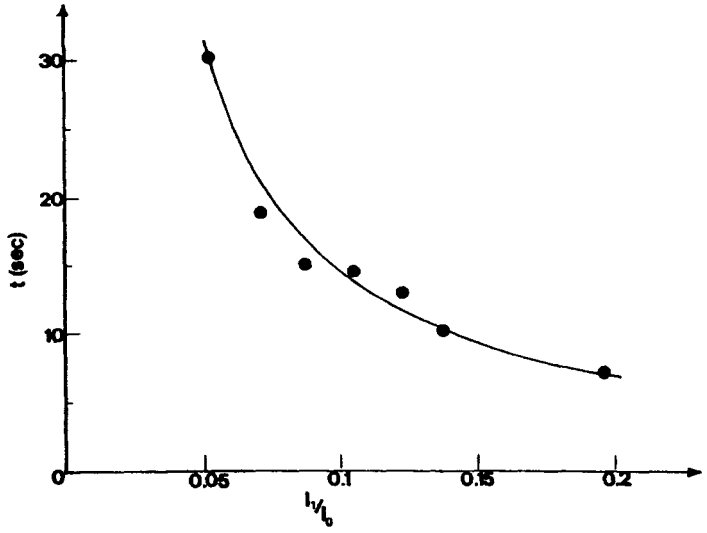

FIGURE 3. Comparison between the experimental (●) and theoretical (solid line) times required for obtaining a phase shift of 4π, as a function of I_1/I_0, for I_0=48mW.

V. STEADY-STATE ANALYSIS

We have also studied the stedystate approximation of Eq.(6). The exact, steady-state solution of Eq.(6) can be obtained by putting $\partial\Theta/\partial t=0$. In this case, Eq.(6) reads

$$(K_{11}\sin^2\Theta+K_{33}\cos^2\Theta)\frac{\partial^2\Theta}{\partial z^2}-(K_{33}-K_{11})\sin\Theta\cos\Theta\left(\frac{\partial\Theta}{\partial z}\right)^2=\tau_{opt}$$

We have solved this equation numerically, thus obtaining the tilt angle $\Theta=\Theta(z)$ as a function of z. The knowledge of $\Theta(z)$ allows one to calculate the integral in Eq.(7) and, consequently, the phase change for the strong beam

electric field E_0 after passing through the liquid crystal film. This is roughly equivalent to calculate the maximum number of rings obtained in far-field pattern after a steady state condition has been ceached.

In Figure 4 we report the comparison between the calculated (continous line) and experimental measured number of rings in the far-field pattern as a function of the ratio I_1/I_0, for I_0=48mW.

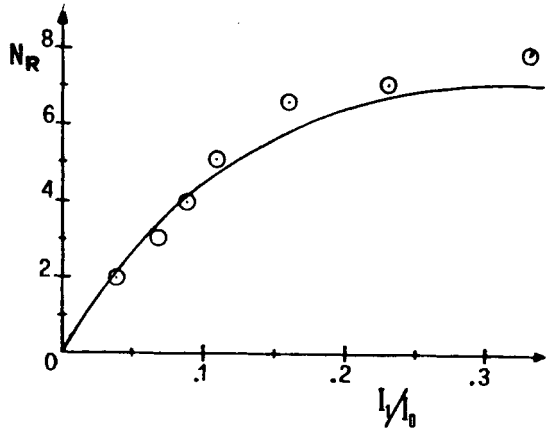

FIGURE 4. Comparison between experimental (O) and calculated (solid line) maxmum number of rings in the far-field pattern in a steady-state condition, as a function of I_1/I_0, for I_0=48mW.

As easly seen, the agreement is thouroughly satisfactory also in the steady-state case. Similar results have been obtained also for I_0=42mW.

CONCLUSIONS

In this work we have reported the first obsarvation of intrinsic optical transistor action in a homeotropically aligned nematic liquid crystal film. A very interesting feature in our results is that the transistor action is produced by the sample intrinsic optical nonlinearities, so that no external feed-back mechanism is necessary. In our experiment we have observed static optical power gains of the order of 10 and dynamic power gains of the order of 100.

The main draw back of the all-optical device described in this paper is the slow response time wich due to the strong molecular correlation showed by liquid crystals (see Table I). Much work is, obviously, required in this direction in the future.

We have also obtained solutions to the general problem of the nonlinear interaction among two light beams and a nematic liquid crystal. In particular, we found an analytical solution in the case of small angles of molecular reorientation, and a numerical exact solution for the case of a steady-state regime. In both cases very good agreement between predicted an experimentalty measured values was obtained.

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