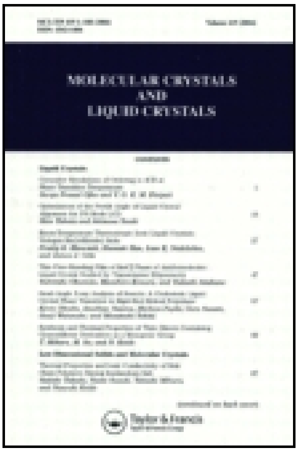

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NONLINEAR THERMOOPTICAL EFFECTS INDUCED BY LIGHT MODULATION OF AN ISOTROPIC HOLE IN A TWISTED NEMATIC LIQUID CRYSTAL CELL

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Abstract We report the study of the light induced creation of an isotropic hole in a twisted nematic liquid crystal cell bounded by two polarizers. Bistability and self transparency occur for the case of crossed and parallel polarizers respectively. Experimental results are reported and discussed by a simple theoretical model.

INTRODUCTION

The nonlinear optical behavior due to thermal effects in nematic liquid crystals deserves a great attention because the material parameters of nematics are very sensitive to temperature variations. In particular the gradients of the refractive indexes (dn_o/dT; dn_e/dT) are generally one or two order of magnitude higher than in usual liquids and are strongly enhanced near to the nematic-isotropic transition temperature[1].

Moreover it is interesting to study the nonlinear optical behavior which comes from a light induced phase transition from the nematic to the isotropic phase. Some papers have already been devoted to nonlinear optical effects due to the formation of an isotropic droplet in a nematic liquid crystal cell[2-6].

In this paper we report the study of the nonlinear optical phenomena originated by the light induced creation of an isotropic hole in a twisted nematic liquid crystal cell bounded by two dichroic polarizers.

It is well known that parallel polarizers are transparent (or semi-transparent in white light) and crossed polarizers are opaque. If we insert a twisted nematic liquid crystal cell between them this situation is reversed since the cell acts as a polarization rotator by $\pi/2$, because of the adiabatic following of the lightwave travelling along the twisted structure: the optical system will be transparent with crossed polarizers and opaque with parallel polarizers. When the nematic-isotropic phase transition of the liquid crystal occurs, the system goes back to the usual behavior. As far as the transition to the isotropic state is due to heating by light absorption we may expect a nonlinear optical behavior correspondent to the jump between the different transmission states and affected by the change of absorbance of the liquid crystal material in the two different phases. This nonlinear behavior can be strongly enhanced if the dichroic polarizers act as cell walls, since light absorption is mainly due to them.

The polarization of the light through the first polarizer is rotated by the cell until it is in the nematic phase. When an isotropic hole is created in the cell, the polarization of the light through it is unaffected. Therefore the light absorption in the second polarizer depends on the hole diameter. Since the polarizers are in direct thermal contact with the cell, their light absorption affects the hole diameter. Resulting nonlinear thermooptical effects are driven by the variation of the transparency of the whole device instead than by the variation of the transparency of the liquid crystal alone. Moreover this geometry allow to study the rise of the isotropic droplet under light illumination just detecting the change of transmissivity. In the following we present a simple theoretical model describing the modulation of the radius of an isotropic droplet created by the TEM_{00} mode of an Ar^+ laser normally incident on the cell. Then we report experimental observation of bistability for the case of crossed polarizers and of self-transparency for the case of parallel polarizer. Good agreement is shown between theoretical and experimental results.

THEORY

We consider here a simple model to give a quantitative interpretation of experimental results. We will show that it is able to accomplish this task despite the heavy assumptions we make.

We consider a twisted nematic cell where the typical thickness of the polarizers which limit the cell is of the order of hundred microns while the thickness of the liquid crystal film is of the order of few microns. Moreover we notice that the thermal conductance K_i between the external surfaces of the cell and the plane in the middle of it is several order of magnitude higher than the thermal exchange coefficient K_e between the cell and the room. Therefore, at thermal equilibrium, we can disregard the temperature variations along the propagation axis and we can assume that the temperature doesn't depend on z.

For the radial profile of the temperature rise we make the usual assumption that a gaussian input intensity

$$I(r) = I_0 \exp\left(-r^2/w^2\right) \qquad (1)$$

gives a gaussian temperature rise

$$T(r) - T_r = \Delta T_0 \exp\left(-r^2/r_0^2\right) \qquad (2)$$

where T_r is the room temperature and the maximum temperature rise ΔT_0 is taken proportional to the absorbed power P_a, i.e.

$$\Delta T_0 = \beta P_a \qquad (3)$$

The proportionality factor β clearly depends on the experimental set up. We can calculate it by measuring the critical absorbed power P_c at which the isotropic droplet appears. β is given by

$$\beta = \left(T_c - T_r\right) / P_c \tag{4}$$

where T_c is the critical temperature for the Nematic-Isotropic transition. For fast pulses it's commonly assumed $r_0 = w$. But at equilibrium we must expect some spreading of the gaussian temperature distribution. In order to compute r_0 we just set the absorbed power equal to the heat dissipated by the cell walls towards the external air

$$\begin{aligned} P_d &= 2 \int_0^{\infty} K_e \, \Delta T_0 \, \exp\left(-r^2/r_0^2\right) \, 2\pi \, r \, dr \\ &= 2 \pi \beta K_e P_a r_0^2 = P_a \end{aligned} \tag{5}$$

getting

$$r_0 = (2 \pi \beta K_e)^{-1/2} \tag{6}$$

Moreover we disregard light scattering and assume the absorbed power P_a to be

$$P_a = P_i - P_t \tag{7}$$

where P_i and P_t are the input and transmitted power respectively.

If τ_I and τ_N are the transparencies in the isotropic and in the nematic phase respectively, for the transmitted power P_t we have

$$P_t = \tau_I \int_0^R I_0 \exp\left(-r^2/w^2\right) 2\pi r\, dr + \tau_N \int_R^\infty I_0 \exp\left(-r^2/w^2\right) 2\pi r\, dr \quad (8)$$

where R is the isotropic droplet radius. Integrating we get

$$P_t = P_i \left[\tau_I + \left(\tau_N - \tau_I\right) \exp\left(-R^2/w^2\right)\right] \quad (9)$$

Finally, the isotropic droplet radius R is calculated as the point where temperature of the liquid crystal is equal to T_c. It's given by the solution of the transcendental equation

$$\frac{P_c \exp\left(2\pi \beta K_e w^2 \rho^2\right)}{P_i \left[1 - \tau_I - \left(\tau_N - \tau_I\right) \exp\left(-\rho^2\right)\right]} = 1 \quad (10)$$

where $\rho = R/w$. Numerical solution of this transcendental equation can be easily obtained by literature computer routines[6].

CROSSED POLARIZERS - BISTABILITY

Two plastic polarizers are used to build a twisted nematic liquid crystal cell. The first polarizer is treated to get planar alignment of the molecular director parallel to its polarization direction. The other polarizer can be parallel or crossed to first one. If it is parallel it has surface planar treatment perpendicular to its polarization direction while if it is crossed it has surface planar treatment parallel to its polarization direction. The cell is filled with liquid crystal in the nematic phase at room temperature. Owing to surface treatments the cell is twisted. Let us consider first the case of crossed polarizers.

The linearly polarized gaussian TEM_{00} mode of an Ar^+ laser (wavelength $\lambda=514.5$nm) impinges at normal incidence on the sample and the transmitted beam is collected by a detector. The polarization of the light passing through the first polarizer is rotated 90^0 by the twisted nematic liquid crystal cell. It is unaffected by the second polarizer and cell acts as a polarization rotator. In this process a fraction of the total power is absorbed and produces a temperature rise in the sample. Increasing the input power, at a certain value P_c of the absorbed power, the liquid crystal's temperature becomes higher than the critical temperature for the N-I transition T_c. An isotropic droplet is created in the nematic liquid crystal. The polarization of the light passing through the droplet is unaffected by the liquid crystal so that the beam is completely absorbed by the second polarizer. This effect produces a positive feedback: namely it increases the sample heating with a consequent enlargement of the droplet radius which becomes larger than the beam spot. Thus transmission drops and the beam is cut off. Decreasing the input power the temperature decreases slowly because now the sample absorbs almost all the input power. When the isotropic droplet disappears the sample goes back to the previous state. This nonlinear thermooptical effects is based on the change of absorbance of a polarizer when the light polarization is rotated and not on the small change of the absorption coefficient of the liquid crystal itself between the nematic and isotropic phases. Therefore the hysteresis loop is very large and the contrast ratio is high.

Typical experimental results are shown in Fig.1 where the output power is reported vs. the

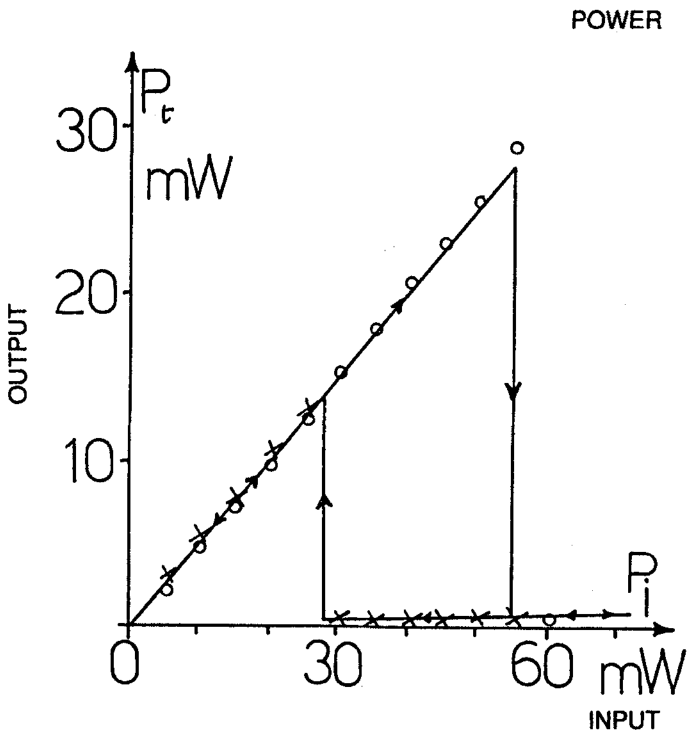

Fig. 1 - Experimental data for K15 by BDH. Experimental data obtained increasing (circles) or decreasing (crosses) power are compared with theoretical calculations (full line).

input power. Liquid crystal is K15 by BDH. Circles are experimental data obtained increasing the input power, crosses are experimental data obtained decreasing it, full lines are calculated by the simple model presented in the former section. Initial transparency of the sample is *0.56* as can be deducted by the initial slope of the curve. At about 55mW of input power, transparency drops to *0.01* because of the formation of the isotropic hole. The width of the bistability loop $W=(P_{OFF}-P_{ON})/P_{OFF}$ is very large since $W=0.49$ Data are taken at equilibrium. For some of them complete stability was checked measuring the transmitted signal keeping constant the input power for several hours. Far from the switching powers (i.e. below P_{ON}, above P_{OFF}, and in the region between P_{ON} and P_{OFF}), variation of the input power didn't cause switching and the transmitted power moved on the same branch of the curve. Despite of the simplicity of the model, good agreement is observed between experimental results and theoretical calculations, confirming the validity of our assumptions.

PARALLEL POLARIZERS - SELF TRANSPARENCY

In the case of parallel polarizers the laser beam is focused by a lens (focal length $f=0.5$m) on the sample located at 43cm from the lens in order to have a spot size of 150μm. The polarization of light passing through the first polarizer is rotated by 90° by the twisted nematic liquid crystal cell and the input power is almost completely absorbed. Increasing the Ar^+ input power an isotropic droplet appears. Light polarization in the droplet is unaffected by the liquid crystal so that the transmitted optical power is determined by the radius of the isotropic hole and therefore by the input power. The radius of the isotropic droplet at equilibrium can be calculated by Eq.(10).

Measurements were performed with three liquid crystals (K18, K15 and E7; all by BDH). Experimental results are given in Fig.2. The transparency $\tau = P_t / P_i$ is reported versus the input power P_i for the three liquid crystals. Full

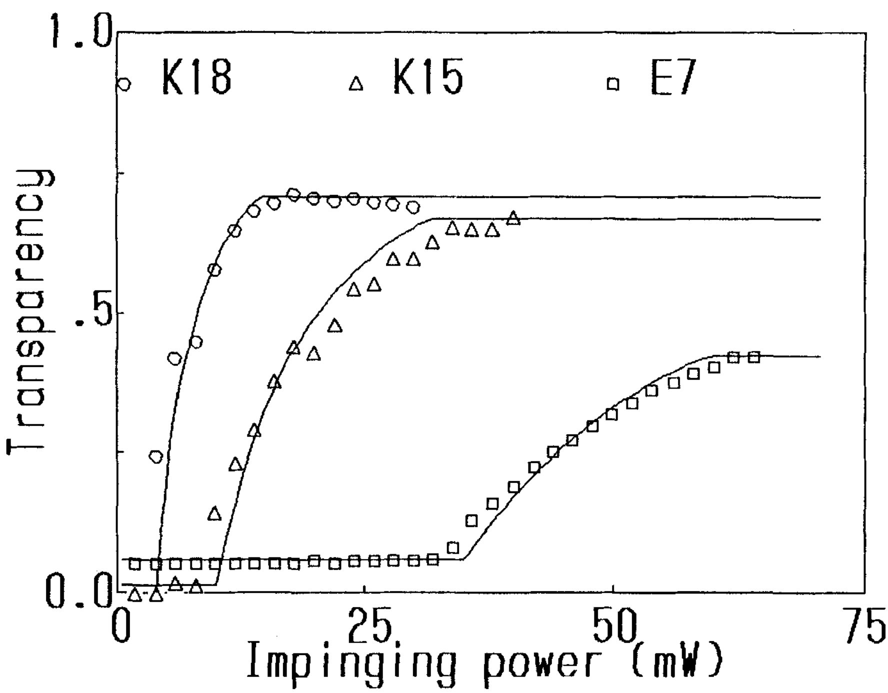

Fig.2 - Comparison between experimental data and theoretical evaluations of the transparency for different liquid crystals.

lines represent theoretical results. Also here good agreement is observed between experimental results and theoretical calculations.

We must underline that the different behavior for each liquid crystal is essentially due to the different transition temperature T_c. In fact an higher value of T_c requires an higher optical power for the onset of an isotropic droplet and produces a slower slope in the self transparency effect. The slope is strongly dependent on the way how the isotropic droplet increases its size and it is well explained by Fig.3 where the radius of the isotropic droplet is reported vs. the impinging power as calculated

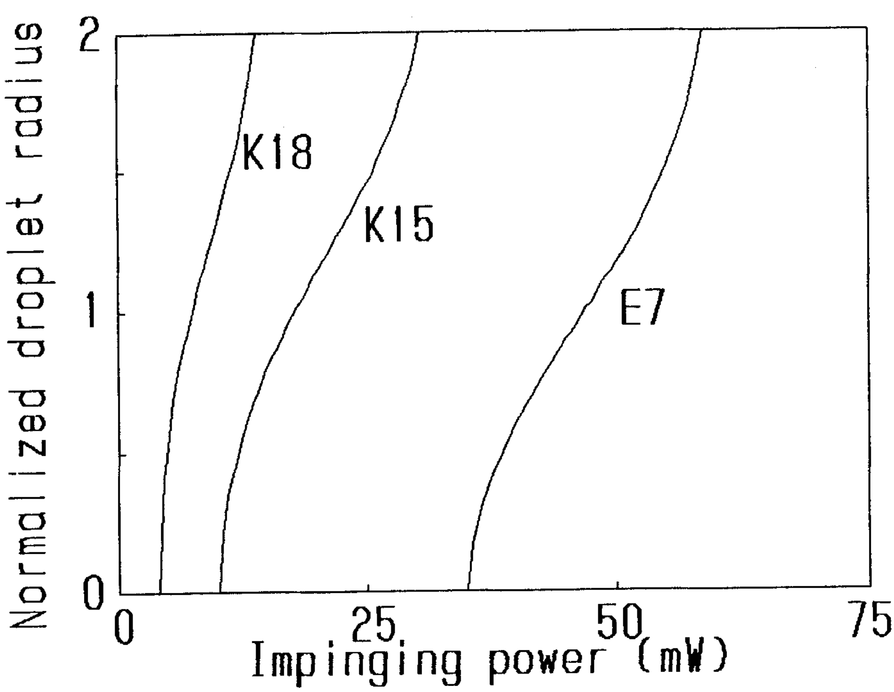

Fig.3 - Theoretical values of the normalized droplet radius for different liquid crystals.

by Eq.(10). These values have been used to fit data reported in Fig.2.

Also from this point of view the agreement appears very satisfactory. The main discrepancy occurs near the threshold power where the nematic liquid crystal begin to loose is rotatory power even before the creation of the isotropic hole. We attribute the different saturation values reached in the three cases to the quality of the nematic cells and to the different role of the light scattering for the three liquid crystal cells.

CONCLUSIONS

We have reported the nonlinear optical behavior of a twisted nematic liquid crystal cell due to thermooptical effects leading to the formation and modulation of an isotropic droplet in the nematic phase. These effects are strongly enhanced by using dichroic polarizers as boundary walls of the nematic cell.

The main results are a wide bistable behavior ($W=0.49$) in the transmitted light for crossed polarizers with a high contrast ratio ($\tau_N/\tau_I=56$) and a self transparency effect for parallel polarizers where a strong variation of transmittance ($\tau_I/\tau_N=66$) is also observed. The experimental observations have found a satisfactory interpretation using a simple model for the droplet formation.

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