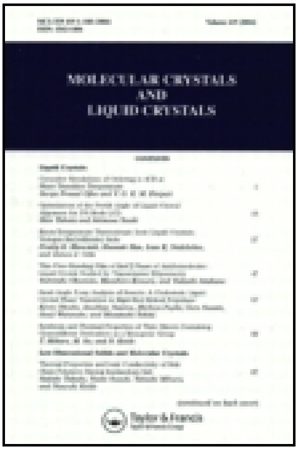

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Voltage Controlled Self-Transparency in a Twisted Nematic Liquid Crystal Cell Bounded by Parallel Polarizers

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VOLTAGE CONTROLLED SELF-TRANSPARENCY IN A TWISTED NEMATIC LIQUID CRYSTAL CELL BOUNDED BY PARALLEL POLARIZERS.

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Abstract

We report the study of non linear transparency effect given by the light induced creation of an isotropic hole in a 90° twisted nematic liquid crystal cell bounded by two parallel polarizers. The twisted structure acts as a $\pi/2$ polarization rotator so that the device is initially opaque, but becomes transparent if the twisted structure is broken, due to liquid crystal phase transition (e.g. from nematic to isotropic) or director configuration change (e.g. from twisted to homeotropic). The first, thermal, effect is driven by the impinging beam producing a nonlinear optical behaviour, while the second effect can be used to modify it. The result is a voltage controlled nonlinear thermooptical effect that presents some interest both from a fundamental and an applicative point of view. Experimental results are reported and discussed with a simple theoretical model.

1 Introduction

We report the study of non linear transparency effect given by the light induced creation of an isotropic hole in a twisted nematic liquid crystal cell bounded by two parallel polarizers. It is well known that a couple of crossed polarizers is opaque while a couple of parallel polarizers is transparent (or semi-transparent in unpolarized light). If we insert a $\pi/2$ twisted nematic liquid crystal cell between them this situation is reversed since the cell, due to the adiabatic following of the light wave travelling along the twisted structure, acts as a $\pi/2$ polarization rotator; therefore the optical system will be opaque. When the nematic-isotropic phase transition of the liquid crystal occurs, the system goes back to the usual behavior, switching to a transparent state. Another way to broke the twisted configuration is to apply an electric field in the direction orthogonal to the cell: the nematic liquid crystal configuration changes from twisted to homeotropic, so that the system switches from opaque to transparent state. As far as the transition to the isotropic state is due to heating by light absorption we may expect a nonlinear optical behavior corresponding 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 increased if 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 while 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 of the variation of the transparency of the liquid crystal alone. We studied this effect in previous papers[1, 2, 3] presenting a simple theoretical model describing the modulation of the radius of an isotropic droplet created by the TEM_{00} mode of an Ar^+ laser impinging on the cell at normal incidence. Here we show that the non linear behavior can be controlled by the application of an electric field to the twisted liquid crystal cell. The electric field reorients liquid crystal molecules in the nematic phase changing the rotation effect of the light polarization and therefore the sample transparency. The result is a voltage controlled non linear thermooptical effect that present some interest both from a fundamental and an applicative point of view.

Experimental results are reported and discussed with a simple theoretical model.

2 Theory

We use here a simple model we introduced in a previous paper[1] which has already given good agreement between theoretical and experimental results. We modify it in order to take into account the effect of the applied electric field. We deal with a twisted nematic liquid crystal cell bonded between plastic polarizers: cell thickness is of the order of few microns and the whole device has a thickness of the order of hundredth of microns. If it is kept in free air the thermal conductance K_i between the external surfaces of the cell and the plane in the middle of it is several orders of magnitude higher than the thermal exchange coefficient K_e between the cell and the room. We disregard the temperature variations along the propagation axis and we 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

$$I_r = I_0 \exp\left(-\frac{r^2}{w^2}\right) \tag{1}$$

gives a gaussian temperature rise

$$\Delta T(r) = T(r) - T_r = \Delta T_0 \exp\left(-\frac{r^2}{r_0^2}\right) \tag{2}$$

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

$$\Delta T_0 = \beta \; P_a \tag{3}$$

The proportionality factor β depends on the experimental set up and can be computed knowing the value of the absorbed optical power P_a^* at which the isotropic droplet appears:

$$\beta = \frac{T_c - T_r}{P_a^*} \tag{4}$$

where T_c is the critical temperature for the Nematic-Isotropic transition. In such situation we can assume that the whole sample is in the nematic phase (sample transmittance τ_N), so that the corresponding value of the impinging optical power, which can be directly measured, is

$$P_i^* = \frac{P_a^*}{(1 - \tau_N)} \tag{5}$$

For fast pulses it is commonly assumed $r_0 = w$, but for c.w. laser beams, i.e. at thermal equilibrium, we have an enlargement of the gaussian temperature distribution. To compute r_0 we set the absorbed power, P_a, equal to the heat dissipated through the cell walls

$$P_d = 2 \int_0^\infty 2\pi r dr \; K_e \Delta T(r) \tag{6}$$

Taking into account previous equations, the condition $P_a = P_d$ gives

$$r_0 = (2\pi\beta K_e)^{-\frac{1}{2}} \tag{7}$$

Disregarding light scattering the absorbed optical power is $P_a = P_i - P_t$ where P_i and P_t are the impinging and the transmitted optical power, respectively:

$$P_i = \int_0^\infty 2\pi r dr \; I_0 \exp\left(-\frac{r^2}{w_0^2}\right) = I_0 \pi w_0^2 \tag{8}$$

$$P_t = \tau_I \int_0^R 2\pi r dr\ I_0 \exp\left(-\frac{r^2}{w_0^2}\right) + \tau_N \int_R^\infty 2\pi r dr\ I_0 \exp\left(-\frac{r^2}{w_0^2}\right) \\ = P_i\left[\tau_I + (\tau_N - \tau_I)\exp\left(-\frac{R^2}{w_0^2}\right)\right] \tag{9}$$

τ_I and $\tau_N = \tau_N(E)$ are the values of the sample transmittance when the liquid crystal is in the isotropic or in the nematic phase and $R = \mathrm{R}(P_i, E)$ is the radius of the isotropic hole.

If the liquid crystal is in the nematic phase, the presence of an electric field affects the molecular director orientation in the bulk from twisted to homeotropic, so that τ_N is expected to be a function of the applied field. On the contrary τ_I, the sample transmittance in the zone where the liquid crystal is in the isotropic phase, is not affected by the electric field. The isotropic hole radius R depends on the impinging power; we obtain it as the radius where the temperature is equal to the transition value, $T(R) = T_c$, which leads to the implicit relation

$$\frac{P_i}{P_a^*}\left[\tau_I + (\tau_N - \tau_I)\exp\left(-\frac{R^2}{w_0^2}\right)\right]\exp\left(-2\pi\beta K_e R^2\right) = 1 \tag{10}$$

where P_a^* is the value of the absorbed optical power at which the nematic hole appears.

Once $\mathrm{R}(P_i, E)$ has been computed from eq.(10) the sample transmittance is obtained by eq.(9)

$$\tau(P_i, E) = \tau_I + [\tau_N(E) - \tau_I]\exp\left[-\frac{\mathrm{R}^2(P_i, E)}{w_0^2}\right] \tag{11}$$

3 Experiment and discussion

The sample is obtained by placing the liquid crystal (K15 by BDH, $T_c = 35.5\ ^\circ C$) between two dichroic polarizers (by Polaroid), 100 μm spaced, previously rubbed (one in the polarization direction and the other in the orthogonal direction) and placed with the same polarization direction. The sample is surrounded by two ITO-coated glass plates spaced 630 μm from each other in order to apply the electric field. Experimental setup is sketched in fig. 1 . Beam radius on the sample is $w_0 = 1.2\ mm$. A function generator FG and a voltage amplifier VA are used to apply a 1 KHz square wave voltage to the conducting glass plates. Two photodiode detectors, D_1 and D_2, are used to measure the reference and the transmitted beam respectively.

Since the nonlinearity is driven by the electric field trough the transmittance control, we studied it in preliminary measurements. Sample transmittance in the isotropic phase is of the order of 70 percent for polarized light ($\tau_I \simeq 0.70$) and, as expected, is unaffected by the applied electric field. On the contrary, when the

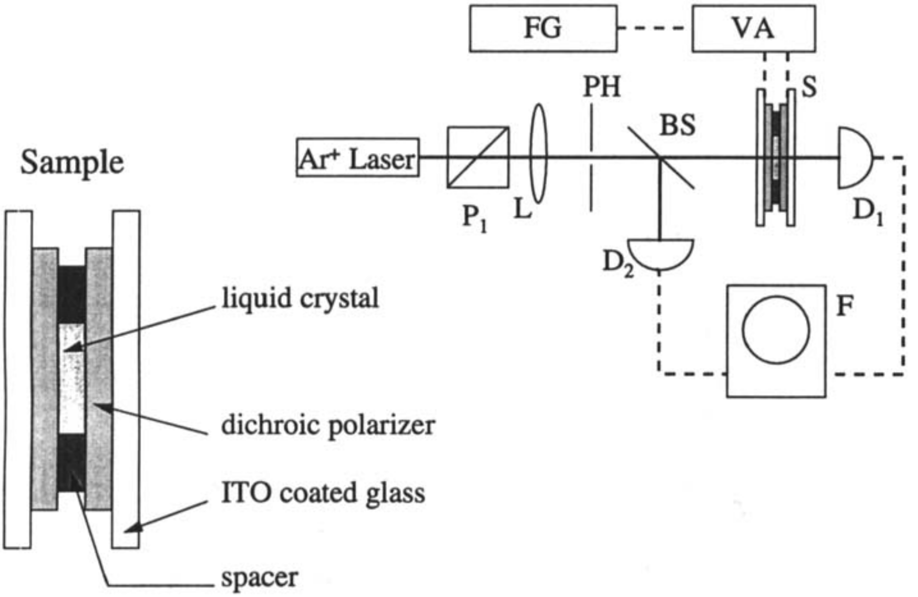

Figure 1: Experimental setup and sample cross section. FG: function generator, VA: voltage amplifier, P_1: polarizer, L: lens, PH: pin hole, BS: beam splitter, S: sample, D_1, D_2: photodiode detectors, F: oscilloscope.

liquid crystal is in the nematic phase ($T_r = 24.7\ °C$) the sample is almost completely opaque ($\tau_N \simeq 0.04$) and its transmittance is augmented by an electric field. The transmittance behavior versus the applied field is reported in fig. 2. As it can be seen, the curve shows a smooth threshold effect followed by a saturation zone when the electric field changes the bulk liquid crystal configuration from twisted to homeotropic.

Fig. 3 shows the measured sample transmittance for different values of the applied electric field ($E = 0$, $E = E_1 = 71.4\ kV/m$ and $E = E_2 = 357\ kV/m$) measured by means of a low power impinging beam ($P_i = 1.78\ mW$). From fig. 2 we get the corresponding values of the sample transmittance when the liquid crystal is in the nematic phase: $\tau_{N|E=0} = 0.04$, $\tau_{N|E=E_1} = 0.30$ and $\tau_{N|E=E_2} = 0.54$. Since τ_N increases with applied field, if all other parameters were not affected by the field, from eq.(5) we would expect P_i^* to increase with field: sample is initially more transparent so that a higher impinging power is required to reach the transition temperature T_c. However experimental data show that the application of an electric field substantially reduces P_i^* from $\sim 7\ mW$ to $\sim 2\ mW$: the transmittance is initially higher but sample switches to the transparent state at a lower value of the

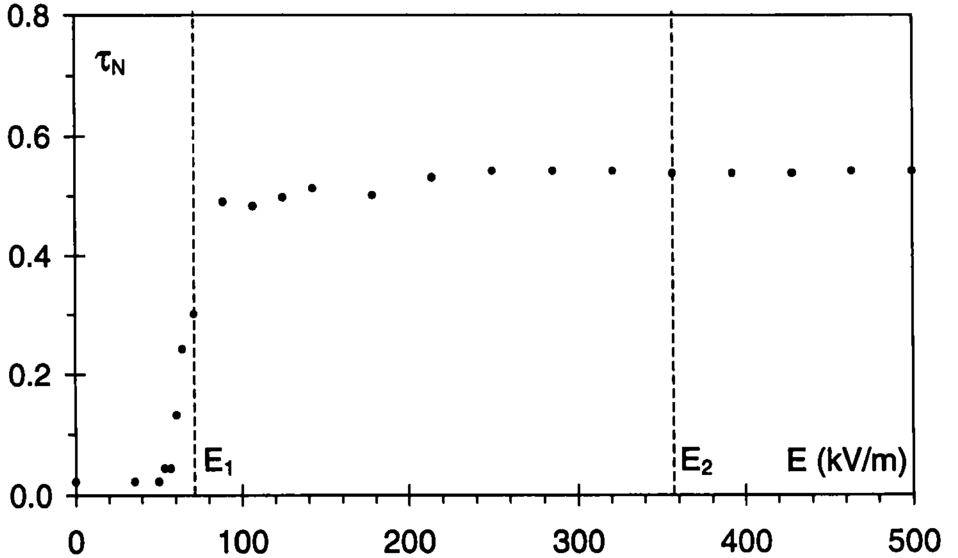

Figure 2: Sample transmittance vs. applied field, with liquid cristal in the namatic phase (impinging power: $P_i = 1.78\ mW$). $E_1 = 71.4\ kV/m$ and $E_2 = 357\ kV/m$: values of the applied fiels used in subsequent experimental runs.

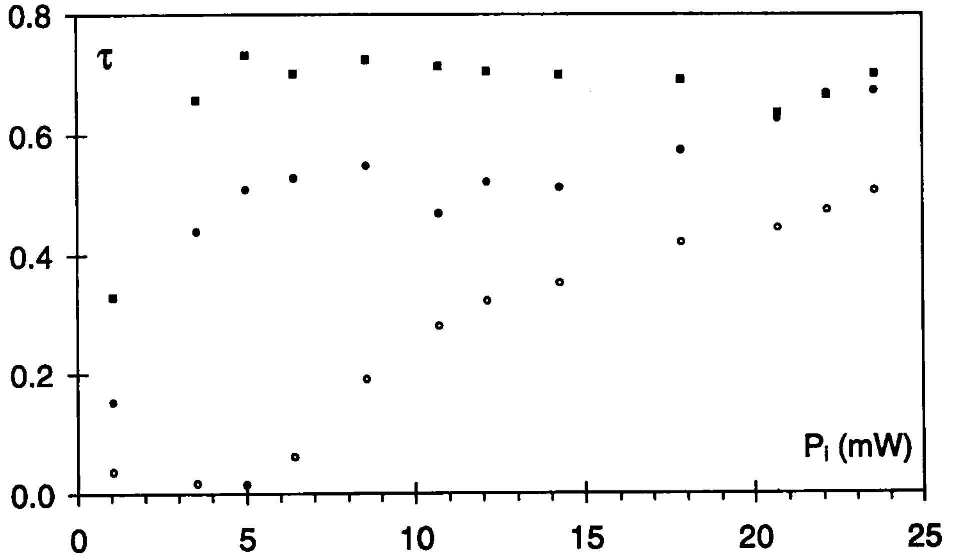

Figure 3: Experimental values of the sample transmittance vs. impinging optical power, for different values of the applied electric field (circles: no field, full dots: $E = E_1 = 71.4\ kV/m$, full squares: $E = E_2 = 357\ kV/m$).

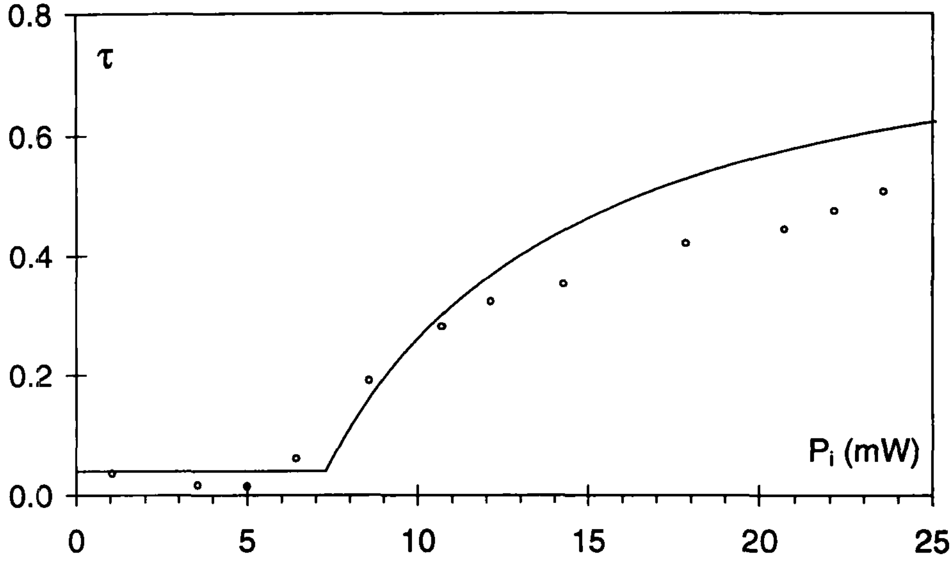

Figure 4: Sample transmittance vs. impinging optical power, no applied electric field. Comparison of experimental data with values obtained using our model ($\tau_{N|E=0} = 0.04$, $P^*_{a|E=0} = 7.0\ mW$).

impinging power. It seems that when the liquid crystal structure is distorted by the electric field, increasing temperature, the twisted structure is broken before the liquid crystal becomes isotropic. Since our model is not intended to describe the local configuration and interactions of the liquid crystal molecules we take into account this behavior assuming that P^*_a decreases with applied field ($P^*_{a|E=0} = 7.0\ mW$, $P^*_{a|E=E_1} = 1.5\ mW$ and $P^*_{a|E=E_2} = 1.0\ mW$). The results obtained by the simple model described here are shown in figs. 4, 5 and 6.

4 Conclusions

We have reported the study of non linear transparency effect given by the light induced creation of an isotropic hole in a twisted nematic liquid crystal cell bounded by two parallel polarizers. We have experimentally shown that the non linear behavior can be controlled by the application of an electric field to the twisted liquid crystal cell. We have used a simple mathematical model to give a quantitative interpretation of the experimental results. We have obtained good agreement between theoretical predictions and experimental data, but further studies are required to

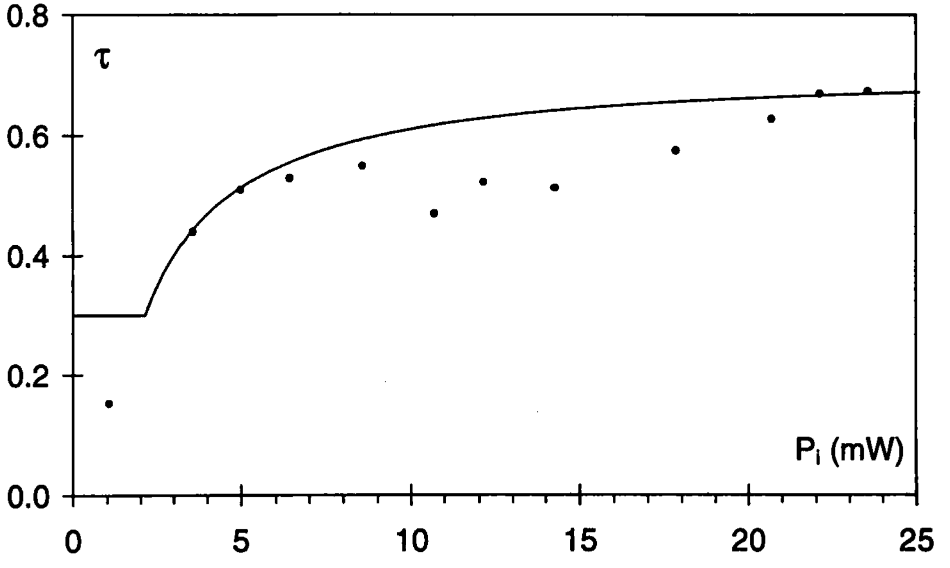

Figure 5: Sample transmittance vs. impinging optical power, applied electric field: $E = E_1 = 71.4\ kV/m$. Comparison of experimental data with values obtained using our model ($\tau_{N|E=E_1} = 0.30$, $P^*_{a|E=E_1} = 1.5\ mW$).

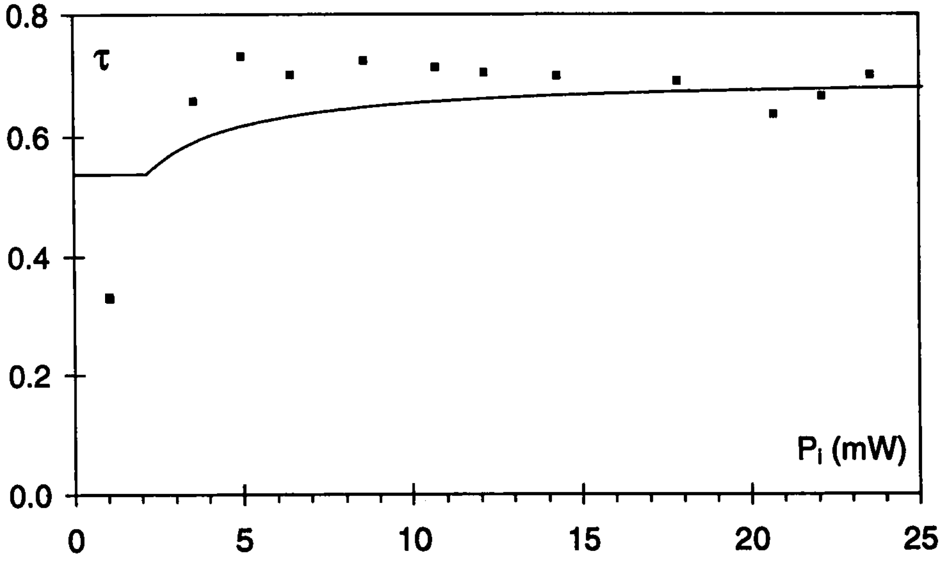

Figure 6: Sample transmittance vs. impinging optical power, applied electric field: $E = E_2 = 357\ kV/m$. Comparison of experimental data with values obtained using our model ($\tau_{N|E=E_2} = 0.54$, $P^*_{a|E=E_2} = 1.0\ mW$).

fully understand the effect of the application of the electric field.

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