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Z. J. Lu
Kent State University - Kent Campus

Deng-Ke Yang
Kent State University, dyang@kent.edu

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Effect of chiral dopant on the performance of polymer dispersed liquid crystal light valve

Z.-J. Lu and D.-K. Yang
Liquid Crystal Institute and Department of Physics, Kent State University, Kent, Ohio 44242

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We have experimentally studied the effect of chiral dopant on the electro-optical performance of a polymer-dispersed liquid crystal (PDLC) light valve. Adding a small amount of chiral dopant decreases the turn-OFF time significantly but increases the drive voltage only slightly. A phenomenological theory is presented to explain the experimental results.

Polymer dispersed liquid crystals (PDLCs), a new type of light shutter which has been studied intensively in recent years,[1–4] is important for both basic research and application. In a PDLC the dispersed liquid crystal exists in the form of the droplets with diameter around 1 μm. From the physics point of view, the liquid crystal is in a confined geometry. The configuration of the liquid crystal inside the droplet depends on the size and shape of the droplet as well as on the boundary condition and the external field. From the application point of view, the PDLC has unique optical properties: opaque in a field-OFF condition and transparent in a field-ON condition. It does not require polarizers and has a very high transmittance in the ON-state. PDLCs may be used for switchable windows, displays, and projectors.

In a regular PDLC the liquid crystal used is nematic. If the liquid crystal has a tangential orientation at the polymer-liquid crystal interface, the liquid crystal inside the droplet will usually have a bipolar configuration and a director can be assigned to the droplet. The directors of the droplets are randomly oriented throughout the sample in a field-OFF condition. The material is optically scattering because of the mismatch in the refractive indices of the polymer and the liquid crystal; and the cell appears opaque. When an external electrical field above a threshold is applied to the cell, the directors of the droplets are aligned along the direction of the field and the cell becomes transparent. The threshold of the field depends on the following factors: droplet size, droplet shape, surface anchoring, and the resistivities of the liquid crystal and polymer. The voltage corresponding to the threshold is called the drive voltage. When the field is turned off, the director of the droplets will relax back to the random state. The relaxation time, or the turn-OFF time, also depends on droplet size, droplet shape, and surface anchoring. A low drive voltage and short turn-OFF time are desirable. There is usually a tradeoff between them. For a material with low drive voltage the turn-OFF time is usually long.

It is our motivation to search for PDLCs which have low drive voltage and a short turn-OFF time. We found that the electro-optical performance of a PDLC can be improved by adding chiral dopants. When a small amount of chiral dopant is added in the liquid crystal, the drive voltage is kept almost constant while the turn-OFF time is decreased significantly.

The nematic liquid crystal used in our experiment is E7 and the chiral agents are $R1011$ and $S1011$ (obtained from EM) which are enatiomers. The pitch of the mixture is given by $1/P=33(X_R-X_L)=33X$ (μm^{-1}), where X_R and X_L are the concentrations of $R1011$ and $S1011$, respectively; the chiral concentration $X=(X_R-X_L)$ is the difference of the concentrations between $R1011$ and $S1011$. The unit of concentration is mass percentage. The pitch of the liquid crystal depends on X. In our experiment the total concentration of $R1011$ and $S1011$ (X_R+X_L) was kept at 1% such that the variation of X does not change the chemical properties of the liquid crystal mixture. The epoxy used was a combination of Heloxy 97, Capcure 800, and Epon 828 with the ratio 28.5:15.2:56.3 (obtained from Miller-Stephenson Chemical Co., Inc.). The liquid crystal was mixed with the epoxy with the ratio 2:3 (by weight). The mixture was sandwiched between two glass plates with ITO electrodes. The thickness of the cell was controlled by 15 μm glass fiber. The samples were thermally cured at 75 °C. Droplets of diameter around 2 μm were formed.

The electro-optical properties were measured with a He-Ne laser light. The collection angle of the detector was 2°. V_{90} for 90% of the maximum transmittance is defined as the drive voltage. The drive voltage of the samples with various chiral concentrations X are shown in Fig. 1. The drive voltage is approximately constant when X is below 0.2%, which corresponds to a pitch length of 15 μm and $D/P=0.13$ (D is the diameter of the droplet). When X is increased above 0.2%, the drive voltage increases rapidly.

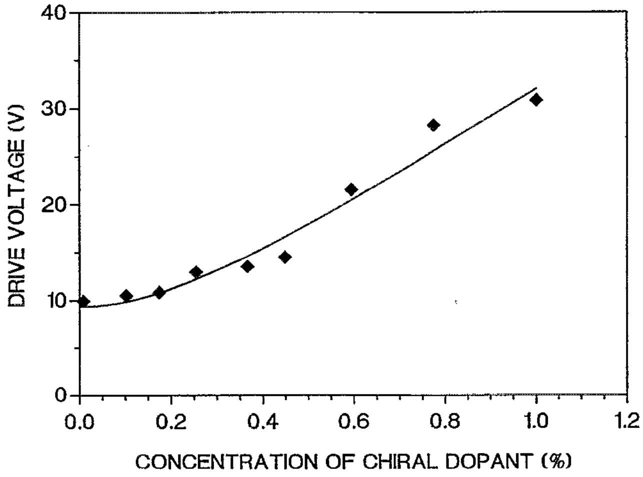

FIG. 1. Drive voltage of the PDLC vs chiral concentrations. The solid line is the theoretic fit.

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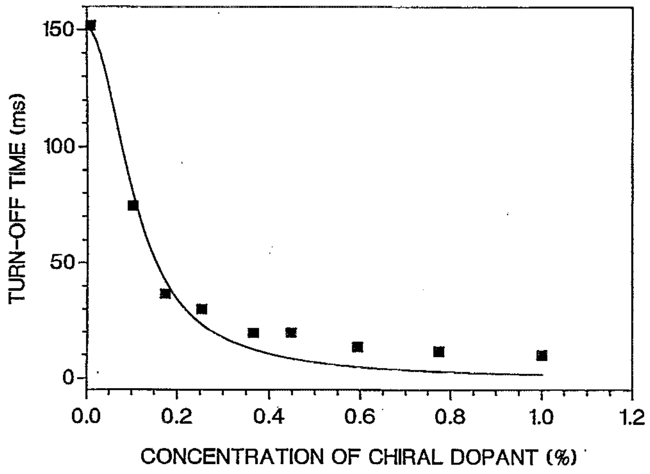

FIG. 2. Turn-OFF time of the PDLC vs chiral concentrations. The solid line is the theoretic fit.

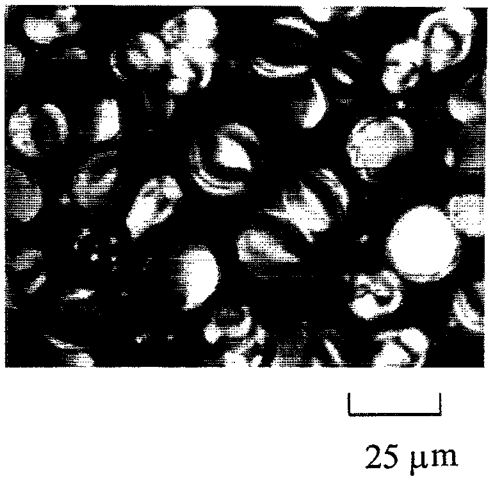

FIG. 4. The microscope photograph of the twisted bipolar droplets of diameter around 20 μm.

The turn-OFF time was measured as the time interval when the intensity of transmitted light decreased from 90% to 10%. The turn-OFF time versus the chiral concentration X is shown in Fig. 2. The turn-OFF time is decreased dramatically at low chiral concentrations. The dynamic response of the PDLC with various concentrations of chiral dopant is shown in Fig. 3 where the voltage is turned off at $t=225$ ms. When the chiral concentration is low, the decay of the transmittance consists of two processes with different decay constants, corresponding to the rotation of the droplet director and formation of the helical structure, respectively. When the chiral concentration is high, the decay of the transmittance is dominated by the twisting due to the helical structure.

In order to study the configuration of the liquid crystal inside the droplets at low chiral concentration we used PVB [poly (vinyl butyral), obtained from Scientific Polymer Products, Inc.] and $E7$ to make large droplets so that optical microscope could be used to study the texture. PVB produces a tangential boundary condition. In this system large droplets are much easier obtained than the epoxy system. In order to obtain the same liquid crystal configuration the chiral concentration was also adjusted such that D/P is in the same regime as the light valve samples. The microscope photograph is shown in Fig. 4, where the diameter of the droplet is around 20 μm and $D/P=0.2$. The configuration of the liquid crystal inside the droplet is believed to be a twisted bipolar as shown in Fig. 5 (Ref. 5). When the chiral concentration was further increased and the diameter of the droplet became comparable to the pitch, a spherulite structure was obtained.[6]

Based on the twisted bipolar configuration we developed a phenomenological theory for the drive voltage and turn-OFF time of the PDLC with low concentration chiral dopant. The twisted bipolar configuration can be described by the orientation angle θ of the droplet director and the average twisting angle ϕ. The helical axis is perpendicular to the

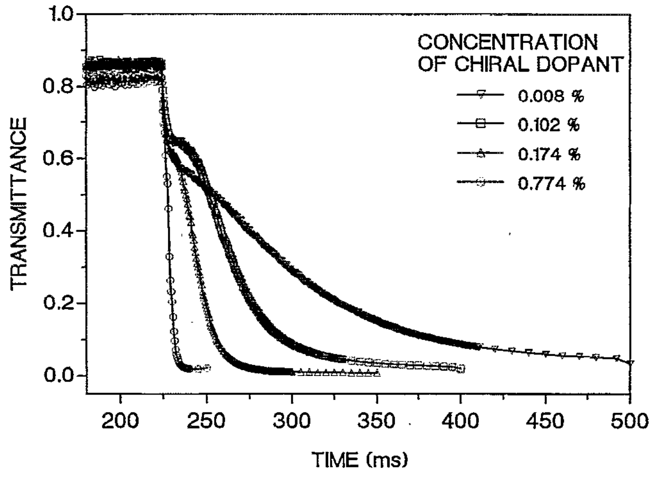

FIG. 3. Dynamic response of the PDLC at various chiral concentrations.

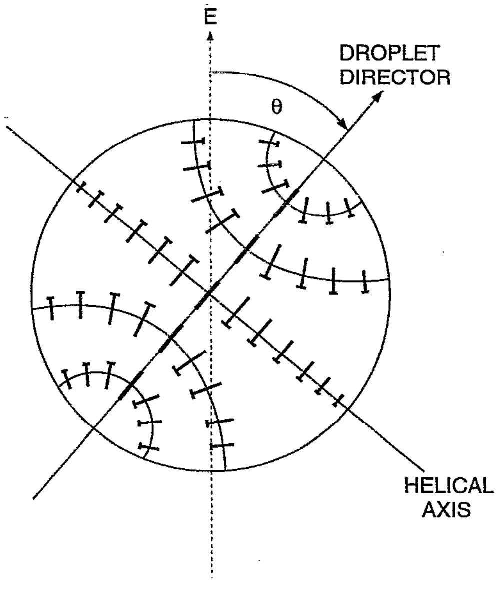

FIG. 5. The director of the liquid crystal inside a twisted bipolar droplet.

droplet director. When we consider the drive voltage, it is assumed that the addition of the chiral dopant does not change the anchoring energy, the elastic energy due to the confinement of the droplet (when the droplet is a slightly deformed sphere), and the electrical energy (the director of the droplet is random throughout the sample in the OFF-state). In order to align the liquid crystal molecules along the field, the electrical energy has to overcome the anchoring energy and the elastic energy due to the confinement as well as the twist energy which is given by, $\frac{1}{2}K_2q^2v$ where K_2 is the twist elastic constant, q is the chirality, and v is the volume of the droplet. Therefore we have the equation

$$\Delta F_e = \Delta F_N + \tfrac{1}{2}K_2q^2v, \tag{1}$$

where ΔF_e is the electrical energy difference between the aligned and unaligned droplet, ΔF_N is the elastic and anchoring energy difference between the unaligned and aligned nematic droplet. $\Delta F_e = avV_D^2$ where a is a constant and V_D is the drive voltage. The chirality is given by $q = 2\pi/P = 2\pi * 33X$. Using Eq. (1) we obtain

$$V_D = \sqrt{V_N^2 + bX^2}, \tag{2}$$

where V_N is the drive voltage of the PDLC without chiral dopant and b is a constant. $V_N = 9.4$ V was obtained experimentally when $X=0$ (nematic case). In Fig. 1, the solid line is the theoretical fit with the fitting parameter $b = 9.39\times10^6$ V^2.

Now we consider the turn-OFF time. The intensity of transmitted light is a function of the orientation angle θ of the droplet director and the average twisting angle ϕ

$$\frac{\partial I}{\partial t} = \frac{\partial I}{\partial \theta}\frac{\partial \theta}{\partial t} + \frac{\partial I}{\partial \phi}\frac{\partial \phi}{\partial t}. \tag{3}$$

The decrease of the transmittance from the ON-state to the OFF-state is approximately taken as an exponential decay. When $X=0$, the nematic case, we have $\partial I/\partial t = (\partial I/\partial \theta)(\partial \theta/\partial t) = -I/\tau_N$. It is well known that $\partial\phi/\partial t \propto q^2 \propto X^2$, that is, ϕ relaxes faster at higher chiral concentration.[7] It is, however, very difficult to find the exact relation between the transmittance and the twist angle.[8] We assume that $\partial I/\partial\phi \cdot \partial\phi/\partial t = -I/\tau_C$ where τ_C is given by

$$\frac{1}{\tau_C} = CX^2. \tag{4}$$

Putting Eq. (4) into Eq. (3) we obtain

$$\frac{1}{I}\frac{\partial I}{\partial t} = -\frac{1}{\tau_N} - CX^2, \tag{5}$$

I decays exponentially with the decay constant given by

$$\tau = \frac{1}{(1/\tau_N) + CX^2}. \tag{6}$$

The turn-OFF time is proportional to the decay constant and given by $\tau_{\mathrm{OFF}} = 1/(1/\tau_{N\,\mathrm{OFF}} + CX^2)$, where $\tau_{N\mathrm{OFF}}$ is the turn-OFF time for the PDLC without chiral dopant and C is the fitting constant. $t_{N\mathrm{OFF}} = 151$ ms was obtained experimentally when $X=0$. In Fig. 2, the solid line is the theoretical fit with $C = 56\times10^2\ \mathrm{ms}^{-1}$.

Our results demonstrate that the electro-optical performance of PDLC's are able to be improved by doping a chiral agent. In the regime of low concentration of chiral dopant (the pitch$\gg$the droplet radius), the turn-OFF time can be decreased significantly while the drive voltage is increased slightly. Our phenomenological theory shows fairly good agreement with the experimental results.

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