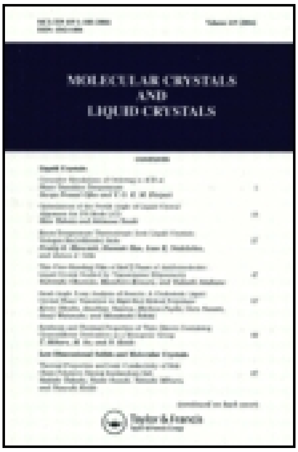

Molecular Crystals and Liquid Crystals Science and Technology. Section A. Molecular Crystals and Liquid Crystals
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/gmcl19

The Mechanism of Switching A PDLC Film

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Version of record first published: 23 Sep 2006.

Mol. Cryst. Liq. Cryst. 1995, Vol. 262, pp. 99–109
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THE MECHANISM OF SWITCHING A PDLC FILM

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ABSTRACT The switching field of a polymer dispersed liquid crystal (PDLC) film depends on a number of factors. In this paper, the switching mechanisms of a polymer dispersed liquid crystal film are studied both theoretically and experimentally. The theoretical model is based upon the balance of elastic and field torques in ellipsoidal droplets. It is used to describe how switching field depends on droplet size and shape, and to calculate the switching field analytically. In experiment, the switching field is determined from optical transmittance measurements. The possible switching mechanisms are discussed from the comparison between experimental and theoretical results on the switching field as a function of temperature.

INTRODUCTION

In polymer dispersed liquid crystal (PDLC) films nematic liquid crystals are dispersed as micro-size droplets in polymer matrix.[1,2] PDLC films can be switched from an opaque state to a transparent state upon the application of an external field. The switching field of a PDLC film depends on a variety of factors: the dielectric properties of the liquid crystal and polymer, the interaction between the liquid crystal and polymer, nematic director configuration inside droplets, droplet sizes and shapes, and the operating temperature. To date, there has been little effort to find out the contributions to the switching mechanism. Yet, it is needed to fully understand the switching mechanism of a PDLC film in order to develop improved devices.

Some research has been done in estimating the switching field of a PDLC film.[3,4] However, it is not clear which free energy, elastic deformation energy or surface interaction energy, plays a major role in the switching mechanism, or how shapes of droplets affect the switching field, and how the switching field changes with temperature, etc. In this paper, we will answer these questions from both theoretical and experimental aspects, and propose a theoretical model to calculate analytically the switching field of a PDLC film. The possible switching mechanisms are discussed from the comparison between the experimental results and theoretical calculation.

THEORETICAL MODEL

In a PDLC film, nematic liquid crystals are confined in elliposoidal droplets surrounded by a polymer binder. Director configuration of nematic liquid crystals in droplets is determined by elastic torques and surface interactions. Experimental evidence[5] from light scattering measurement suggests that the director configuration inside a droplet is of bipolar structure. To simplify the problem, we assume identical elliposoidal shaped droplets with strong surface (polar) anchoring in a PDLC film. Azimuthal anchoring is taken as negligible as usually done. Director configuration in a droplet is chosen to be of elliposoidal shape with rotational symmetry around the long axis of the elliposoidal droplet in the absence of external field. Upon application of an electric field above switching field, the rotational symmetry axis no longer exists. However, the director configuration in a droplet is still of elliposoidal shape, and the director tends to align along the electric field. These configurations are shown schematically in Figure 1.

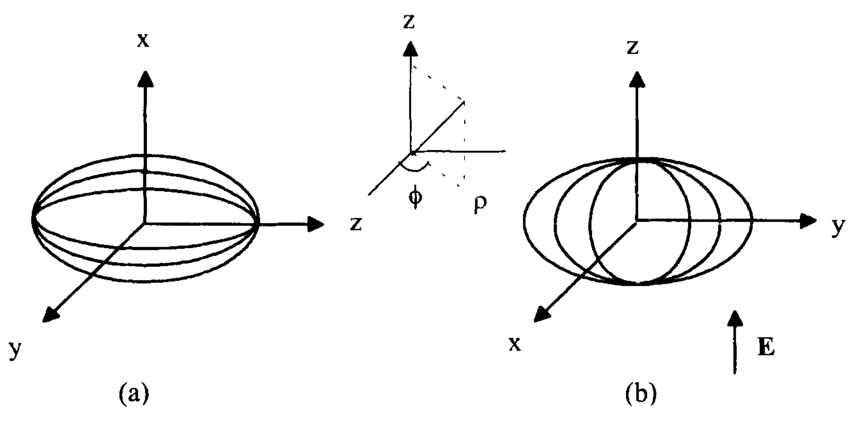

FIGURE 1 Schematic representation of nematic director configurations of elliposoidal droplets in a PDLC film: (a) before switching, (b) after switching.

In cylindrical coordinates (ρ,φ,z), the nematic director configuration in droplets for zero field case (a) is given by

$$\mathbf{n} = \left(-\frac{\rho z}{\sqrt{\rho^2 z^2 + (c^2 - z^2)^2}}, 0, \frac{c^2 - z^2}{\sqrt{\rho^2 z^2 + (c^2 - z^2)^2}} \right) \tag{1}$$

where c is the length of the long axis of an ellipsoidal droplet. The corresponding elastic free energy can be obtained as a series in $\delta \equiv 1 - \frac{a^2}{c^2}$,

$$F^{(a)} = \pi a K_1 \left(\tfrac{7}{2} + \tfrac{1}{3} + \tfrac{2}{3}\ln 2 - 0.852\delta - 0.389\delta^2 - 0.258\delta^3 \right) + \pi a K_3 \left(\tfrac{1}{2} - \tfrac{5}{12}\delta - \tfrac{1}{80}\delta^2 - \tfrac{9}{1120}\delta^3 \right) + 0(\delta^4) \tag{2}$$

where K_1 and K_3 are elastic constants associated with splay and bend, and a is the length of the short axis of an ellipsoidal droplet. For a spherical droplet, δ=0.

The director configuration of droplet for field presented case (b) is given by

$$\mathbf{n} = \left(\frac{1}{\sqrt{1 + \left(\frac{dy}{dx}\right)^2 + \left(\frac{dz}{dx}\right)^2}}, \frac{\frac{dy}{dx}}{\sqrt{1 + \left(\frac{dy}{dx}\right)^2 + \left(\frac{dz}{dx}\right)^2}}, \frac{\frac{dz}{dx}}{\sqrt{1 + \left(\frac{dy}{dx}\right)^2 + \left(\frac{dz}{dx}\right)^2}} \right) \tag{3}$$

and its elastic free energy is

$$F^{(b)} = \pi a K_1 \left(\tfrac{7}{2} + \tfrac{1}{3} + \tfrac{2}{3}\ln 2 + \tfrac{9}{8}\delta + \tfrac{15}{16}\delta^2 + \tfrac{683}{1008}\delta^3 \right) + \pi a K_3 \left(\tfrac{1}{2} + \tfrac{1}{3}\delta + \tfrac{3}{10}\delta^2 + \tfrac{2}{7}\delta^3 \right) + 0(\delta^4) \tag{4}$$

Upon the application of an electric field, one needs to include the free energy of the film associated with the electric field, which includes the free energy of both inside and outside droplets. This is due to the strong depolarizing field inside the droplets in the presence of an electric field.[6] We use an effective medium approach[7] to obtain the free energy of the film. The basic idea of the method is to consider a single nematic elliposoidal droplet surrounded by a shell of polymer which is enclosed by material with an effective dielectric constant ε_m. ε_m can be determined from a self-consistent calculation which assume the electrostatic energy stayed the same when the droplet and polymer shell are replaced by the material of the effective medium.

Setting the ratio of the long axis and the short axis of the droplet and that of the polymer shell the same, we obtain the dielectric constant of the effective medium as follows

$$\varepsilon_m = \frac{\varepsilon_p \alpha\left[1 + \frac{1}{2}\left(\frac{a}{a_2}\right)^2 \delta + \frac{3}{8}\delta^2\right] + 3 v_{lc}\varepsilon_p \varepsilon\left(1 + \frac{1}{2}\delta + \frac{3}{8}\delta^2\right) + \varepsilon_p \varepsilon(\beta\delta + \gamma\delta^2)}{\alpha\left[1 + \frac{1}{2}\left(\frac{a}{a_2}\right)^2 \delta + \frac{1}{2}\left(\frac{a}{a_2}\right)^2 \delta^2 - \frac{1}{8} v_{lc}\left(\frac{a}{a_2}\right)\right] + \varepsilon(\beta\delta + \gamma\delta^2)} \quad (5)$$

where a_2 is the length of the short axis of an ellipsoidal polymer shell, ε_p is the dielectric constant of polymer matrix which may contain certain percentage of the liquid crystal, and ε_{lc} is the dielectric constant of liquid crystal inside droplet, which is defined as[6]

$$\varepsilon_{lc} = \varepsilon_\perp + \frac{1}{3}(1 + 2 S_d S_f)\Delta\varepsilon \quad (6)$$

where $\varepsilon_\perp$ is the perpendicular dielectric constant of the liquid crystal, $\Delta\varepsilon$ is the dielectric anisotropy, and $\varepsilon = \varepsilon_{lc} - \varepsilon_p$. S_d is the droplet order parameter which describes the degree of orientational order of the nematic director inside droplet. We assume it is a constant and use $S_d = 0.7$ here, S_f is the order parameter of a PDLC film. v_{lc} is the volume fraction of liquid crystal droplets in the PDLC film. The parameters α, β and γ are defined as follows:

$$\alpha = \varepsilon_{lc} + 2\varepsilon_p - v_{lc}(\varepsilon_{lc} - \varepsilon_p)$$

$$\beta = \frac{1}{5} - \frac{1}{2} v_{lc} + \frac{3}{10} v_{lc}\left(\frac{a}{a_2}\right)^2 \quad (7)$$

$$\gamma = \frac{1}{4}\left[\frac{12}{35} - \frac{3}{2} v_{lc} + \frac{2}{5}\left(\frac{a}{a_2}\right)^2 - \frac{3}{70} v_{lc}^2\left(\frac{a}{a_2}\right) + \frac{4}{5} v_{lc}\left(\frac{a}{a_2}\right)^2\right]$$

The free energy density of a PDLC film associated with an electric field can then be written as

$$F_{electric} = -\frac{1}{2}\varepsilon_m E_o^2 \quad (8)$$

where E_o is an applied field.

The switching field is defined as the one that makes the total free energies for the two states (a) and (b) the same. For simplicity, the effect of field induced director reorientation will be neglected. Balancing the free energy of the two states gives rise to the switching field of a PDLC film

$$E_o = \frac{1}{a}\sqrt{\frac{1.5v_{lc}}{\lambda(\varepsilon_m(b)-\varepsilon_m(a))}\frac{(F^{(b)}-F^{(a)})}{\pi a}} \quad (9)$$

where λ is the aspect ratio of the long axis and the short axis of a droplet, i.e. λ=c/a. According to this model, the switching field of a PDLC film depends on the elastic constant of liquid crystal, dielectric constant of liquid crystal and polymer, droplet size and shape, liquid crystal volume fraction in the film, and operating temperature. From Eq. (9), one can determine the relative importance of the splay and bend elastic free energy.

EXPERIMENT

PDLC samples were made with 50% eutectic liquid crystal mixture (E7) and 50% ultraviolet curable Norland photopolymer (Norland 65). The E7 and prepolymer mixture was sandwiched between two glass plates with 0.75 in. × 0.75 in. patterned ITO electrodes, and 15μm glass fiber spacers were used to control the film thickness. In order to obtain the exact thickness of a sample, we measured the thickness of the empty cell using both optical and capacitance method, and the thickness is 13.3±0.05 μm. Droplet sizes of a PDLC film are controlled by the UV intensity applied during the curing process. We measured droplet size and shape with a scanning electron microscope. With the UV intensity of 1.9 mW/cm^2 in our experiment, we obtained a PDLC film with the radius of droplet around 1.1μm, and the aspect ratio λ is range from 1 to 1.5 from droplet to droplet. The typical value of λ is range from 1.1 to 1.2.

We used 1 kHz frequency throughout the experiment to drive the sample. The PDLC sample was placed on a computer controlled heating stage which is connected to a PolyScience 5900 temperature circulator. Temperature was controlled within ±0.1°C.

The effective dielectric constant of the PDLC film can be determined from a capacitance measurement. The dielectric constant of polymer matrix is then obtained by solving Eq. (5). In order to determine the liquid crystal volume fraction in the PDLC film, we prepared a number of PDLC samples with different liquid crystal concentrations in the mixture, and determined the dissipation peak through frequency scanning measurement for each sample. Peak in the dissipation from glass transition increases because of plasticization by liquid crystals. The liquid crystal volume fraction in the PDLC film can be determined from the curve of the dissipation peak versus the liquid crystal concentration.

Light transmittance measurements were carried out using a 633 nm HeNe laser. The transmitted light after passing through the sample was detected by a photodiode and measured with a HP 3324A digital oscilloscope. The sample was mounted on a temperature controlled stage. The switching field was determined from the inflextion point of logarithmic transmittance versus applied field, which is believed to be the point corresponding to the definition of the switching field. The measurement was made for each temperature point from $0^{\circ}C$ to $50^{\circ}C$ with $5^{\circ}C$ step. We waited for at least half hour to allow polymer relaxation before each measurement, and longer waiting periods have also been tried with no noticeable difference in measured results.

RESULTS AND DISCUSSIONS

The dissipation peak as a function of liquid crystal concentration is shown in Figure 2. Initially, the dissipation peak shifts toward higher frequency when the liquid crystal concentration in the polymer increases; then the peak levels off when the concentration increases beyond a critical value. This critical value is the maximum percentage of liquid crystal that can be dissolved in the polymer without phase separation. Phase separation of the liquid crystal and polymer mixture can only take place when the liquid crystal concentration is above the critical value, which is 21% from Figure 2. The liquid crystal volume fraction is then obtained to be 0.367 for the 50% E7/50% Norland 65 PDLC film. Figure 3 shows the measured effective dielectric constant of the PDLC film and dielectric constant of polymer binder as a function of temperature. The polymer binder includes the polymer and the liquid crystal dissolved in the polymer. The dielectric constant of the polymer binder increases quickly as temperature rises. The large change of the dielectric constant with temperature is due to the glass transition of the polymer.

Using the temperature dependent elastic constants and dielectric constants of liquid crystal[8] and polymer, one can calculate the switching field of the PDLC film from Eq.(9). Figure 4 shows switching field as a function of aspect ratio λ for different droplets of radii 0.8, 1, and 1.2μm at 20°C, respectively. Deformed droplets are assumed to be of the same volume as the spherical droplet with the given radius. Switching field increases with aspect ratio λ, and decreases as droplet size increases. To the first order

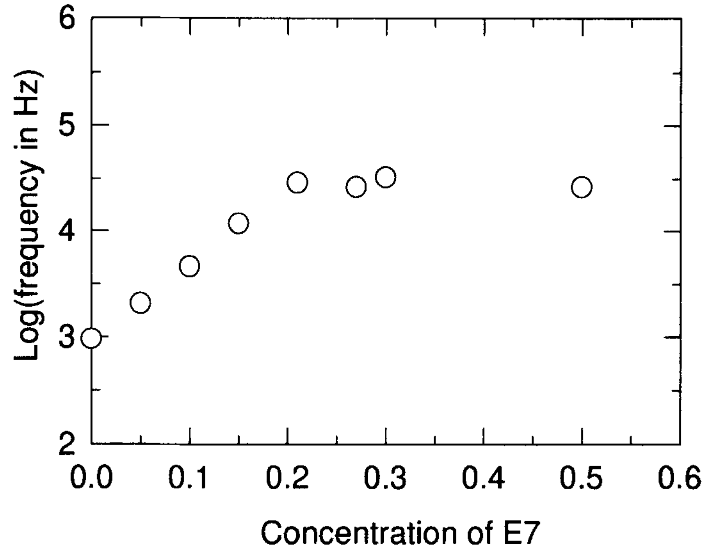

FIGURE 2 Dissipation peaks in logarithmic frequency vs. concentration of liquid crystal E7 in the polymer.

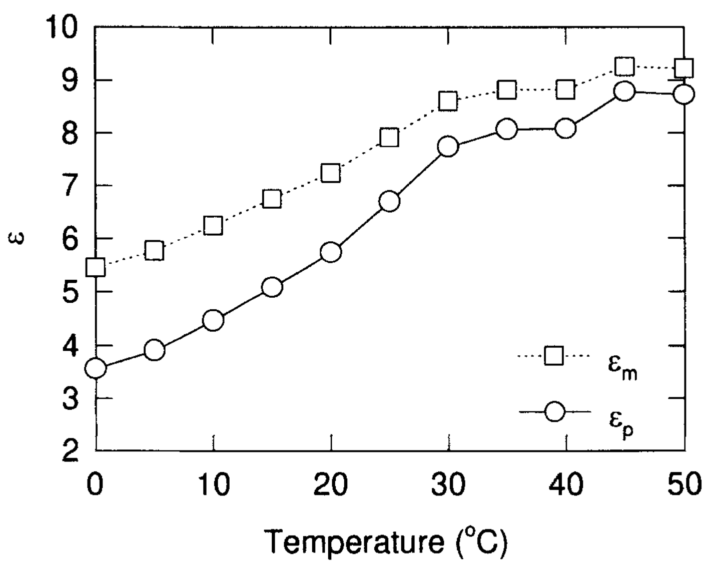

FIGURE 3 The effective dielectric constant ε_m of the PDLC film and the dielectric constant ε_p of polymer binder as a function of temperature.

approximation, switching field is proportional to the factor of droplet shape $\frac{1}{a}\sqrt{\frac{\delta}{\lambda}}$. This is different from previous work[3] where the aspect ratio λ was not included in their expression. Figure 5 shows switching field as a function of temperature for different aspect ratio λ=1.2, 1.4 and 1.6 at a fixed droplet radius of 1.1μm. The curve with larger value of λ is steeper than the one with smaller value of λ, and the switching field decreases as temperature increases.

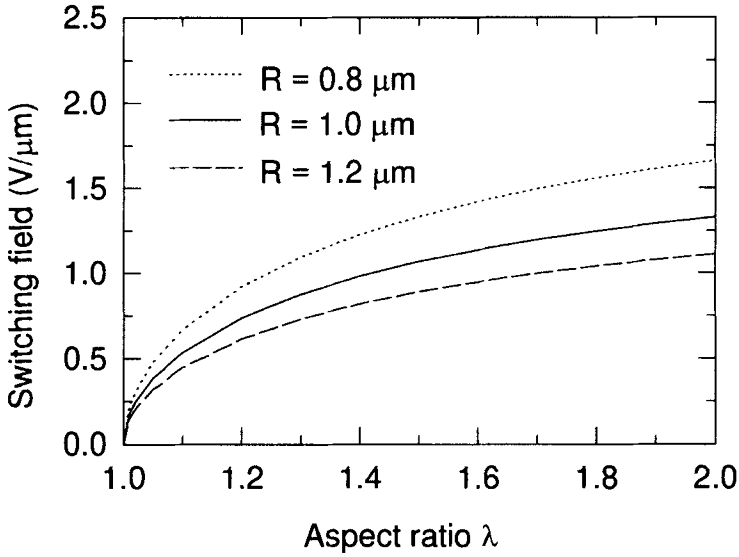

FIGURE 4 Switching field as a function of aspect ratio λ for different droplet sizes.

Different elastic constants are used in our calculation. The contributions to switching field from the splay and bend elastic energy at 20°C are shown in Figure 6. The sum of the splay and the bend energy differences between state (a) and state (b), i.e. $(F^{(b)}_{splay} - F^{(a)}_{splay}) + (F^{(b)}_{bend} - F^{(a)}_{bend})$, determines the switching field. The splay plays a more important role than the bend, and the relative importance of the splay increases as droplet aspect ratio increases.

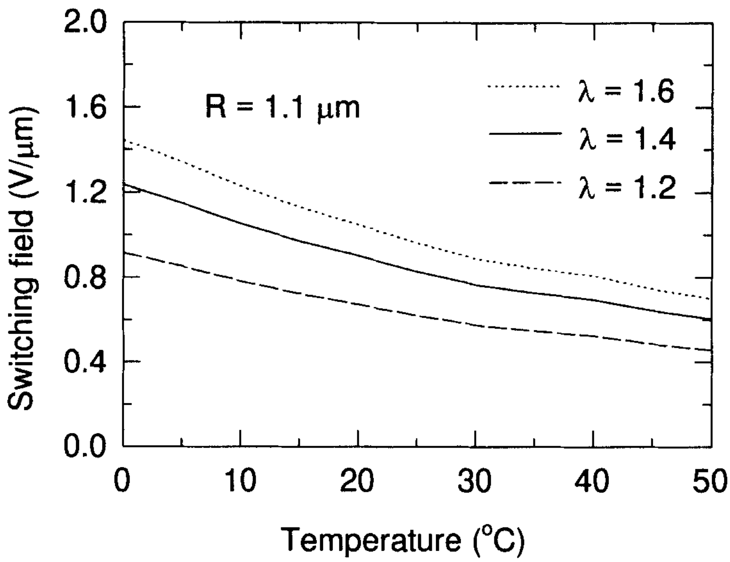

FIGURE 5 Switching field as a function of temperature for different aspect ratios at a fixed droplet size.

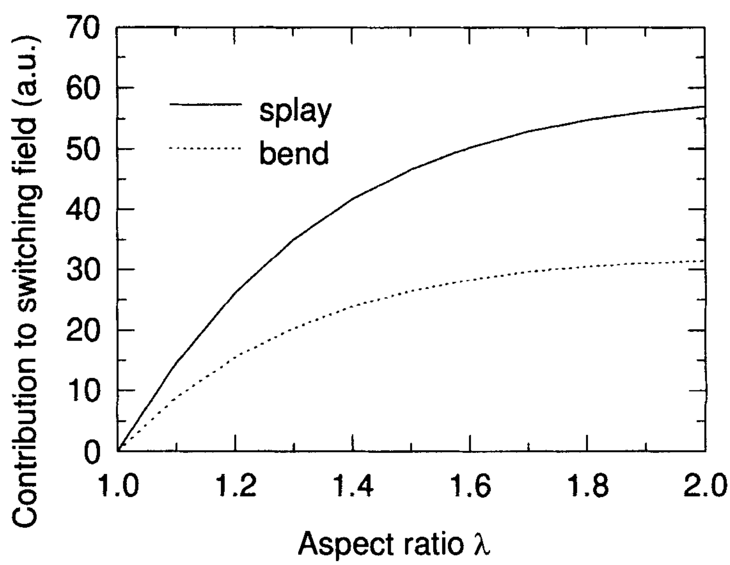

FIGURE 6 Contributions to switching field from the splay and bend elastic energy.

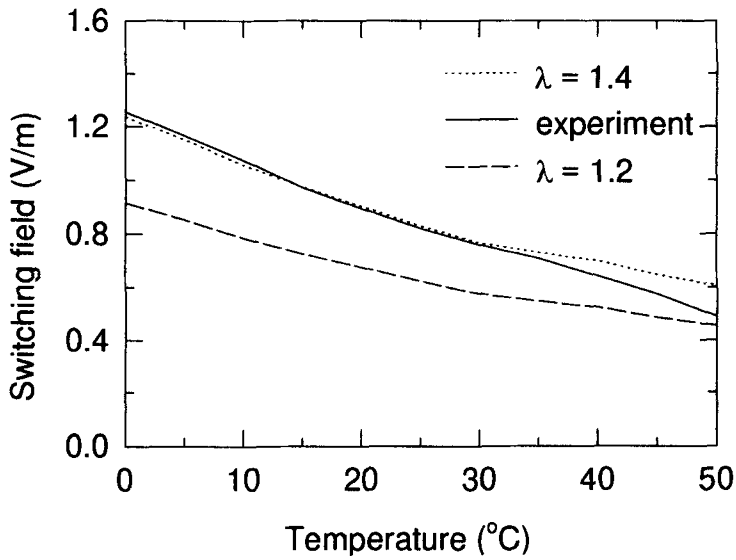

FIGURE 7 Comparison between experimental and theoretical results on the switching field as a function of temperature.

Figure 7 shows both experimental and theoretical values of the switching field vs. temperature. We choose the aspect ratio $\lambda=1.4$ to obtain the dotted curve which agrees well with the experimental results except at the higher temperature region. However, the aspect ratio we used here is not a reasonable value. For a reasonable value $\lambda = 1.2$, the model gives the dashed curve in Figure 7, which is lower and flatter than the experimental curve. However, we notice that the discrepancy becomes smaller when temperature rises. Recent experimental results[9] suggest that the surface interaction between liquid crystal and polymer play a major role in a PDLC system. The experimental results show that polar anchoring is very strong between the polymer and liquid crystal interface and no observable change in the temperature range we investigated, which indicates that the strong polar anchoring approximation is valid. However, azimuthal anchoring shows an obvious decline when the temperature reaches to the polymer glass transition temperature. The glass transition temperature of pure Norland 65 is around room temperature, but the dissolved liquid crystal in the polymer binder has lowered the mixture's glass transition temperature significantly as observed in the DSC measurement. This may be the main reason that the switching field from our calculation varies with temperature slower than that from the experiment. The azimuthal anchoring energy is not included in our calculation, which we now expect to be important in determing the switching field. The presence of the azimuthal anchoring will introduce the twist energy of the nematic liquid crystal in droplets, and this may increase the switching field significantly. Finally, we would like to point out that a PDLC system is a very complex system, and other mechanisms may also play roles here.

CONCLUSION

We have presented an elastic model to calculate the switching field of a PDLC film. The dependence of the switching field on droplet size, shape, and temperature has been studied using this elastic model. The inclusion of a droplet shape and temperature dependent dielectric constant of polymer binder in this calculation has resulted in a qualitative agreement with experimental results of the switching field. But quantitative discrepancy still exists. However we believe that better agreement with experiment can be achieved by including the azimuthal anchoring in our model.

ACKNOWLEDGMENT

This research was supported in part by the National Science Foundation under grant No. ECS-9020420 and through ALCOM contract DMR89-20147.

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