Studies of the Dependence of the Electra-Optical Characteristics of Polymer Dispersed Liquid Crystal Films on Curing Temperature

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The electro-optical characteristics of polymer dispersed liquid crystal (PDLC) films were studied as a function of the polymer's curing temperature. The results show the film, having a smaller and more uniform LC droplet size, produced at higher curing temperatures, exhibits not only a steeper electro-optical response curve but a better transmission contrast between on- and off-state. The transient electro-optical response time of PDLC films is also a strong function of the LC droplet's sizes.

I. INTRODUCTION

Polymer dispersed liquid crystal (PDLC) films, consisting of micron-sized liquid crystalline droplets dispersed in a polymer matrix, show considerable promise for flat panel displays and variable transmittance windows. A session of the 1990 International symposium of the society for Information display (May 14-18, 1990 at Las Vegas) is devoted to this new technology. The principle of operation is based on the field-controlled light scattering from these liquid crystal microdroplets. The electric field is applied in a manner typical of most liquid crystal displays (LCDs). The device material is sandwiched between two glass slides containing a transparent conductive layer such as indium-tin-oxide (ITO). In the absence of a field (OFF state), the director axes of the droplets within a film are randomly oriented. As a result, incident light probes a range of refractive index values between \( n_p \) and \( n_e \), which are the ordinary and extraordinary refractive index of liquid crystal, respectively. Since nematic liquid crystals are optically uniaxial, the indices seen by incident light rays cannot be all equal to the polymer refractive index \( n_p \) and incoming light is scattered by the microdroplets, giving a milky appearance in the OFF state. When a sufficient electric field is applied, the LC molecules in the droplets are collectively reoriented with their director axes parallel to the applied field direction. Therefore, under the condition of \( n_p = n_e \), light is transmitted with no scattering in the ON state.

Recently, we have made preliminary observations of the effects of the density ratio
and the polymer's curing rate on the characteristics of the PDLC film. Measurements indicated that both the density ratio and the polymer's curing rate were shown to be crucial in the production of a more uniform droplet size. The slope of the film's electro-optical response curve, which determines the film's multiplexing capability, was also found to be a function of the uniformity of the NLC droplet size. In this paper, we have made further systematical observations to unambiguously confirm our previous findings. In addition, we have studied, in detail, the film's transient electro-optical response, transmission contrast between on- and off-state as a function of the polymer's curing temperature. The results obtained from these investigations are reported.

II. EXPERIMENT

The refractive index and the density of materials employed are summarized in Table I. The detailed procedures to fabricate the PDLC films and the experimental setup to measure the electro-optical characteristics of the film were given in Ref. (8). In this study two films were fabricated from each mixture, one is used to determine microdroplet size with an optical microscope, the other is for the measurements of the electro-optical characteristics. The former was fabricated by sandwiching the mixture between two cover slides (or one microscope slide and one cover slide) separated by a plastic spacer (12 μm thick). The latter was a device with a 76 μm film of the mixture sandwiched between two ITO-coated glass slides. The evaluations include the measurements of the distribution of LC droplet size, spacing and of the electro-optical characteristics of above mixtures cured at various temperatures (24°C, 60°C, 70°C, 80°C, 100°C).

The curing rates of the polymer were measured by using a Rheometric, Inc (N. J., USA) model RDA 700 mechanical spectrometer. They were determined by monitoring the viscosity change during the curing of the polymer at various temperatures.

| TABLE I. Refractive index and density of the materials used in the present investigation. |
|-----------------------------------------------|-------------------|-----------------|
| Refractive index at 25°C | Density | Remarks |
| E7 (LC) | \( n_1 = 1.736 \) | 1.0282 | nematic phase |
| | \( n_2 = 1.511 \) | | \(-10\sim70^°C\) |
| EPO-305 | 1.511 | 1.15 | curing schedule' |
| | | | \( T_{room} \sim \) overnight; 65°C-1hr |
III. RESULTS AND ANALYSIS

The curing rates of EP0305\textsuperscript{9} polymer were first measured. The results are shown in Fig. 1. As expected, the curing time $t_c$ (defined here as the time interval required for the polymer's viscosity to reach $10^4$ Pa.s from its initial viscosity), decreased as the temperature was increased.

![FIG. 1. The measured curing rates of EP0305 at various temperatures.](image1)

In practice, a liquid crystal is mixed with a suitable polymer to form the device compound. The addition of a liquid crystal to the polymer, could change its curing time. To verify this, an E7:EP0305 mixture in the proportional ratio by volume of LC\textsuperscript{10}, resin, hardener of 2:2:1 was prepared. The measured curing rate, at 100°C, of this mixture, is shown in Fig. 2. For a comparison, the curing rate of EP0305(resin:hardener=2:1) is also shown. As seen, the addition of E7 in EP0305 leads to a delay in the curing time of approximately 4 minutes at 100°C. Similar results (not shown), were found for the same mixture cured at other temperatures (24°C, 60°C, 70°C, 80°C).

![FIG. 2. The measured curing rates of EP0305 at 100°C with and without the addition of liquid crystal E7.](image2)
Figure 3 shows the bottom droplet morphology of E7-EPO305 mixtures cured at temperatures 24°C (D7), 60°C (D9), 70°C (D6), 80°C (D4), and 100°C (D3). The measured
electro-optical responses of these films are shown in Fig. 4. As seen from these two figures, the uniformity of the size, spacing improved with increasing cure temperature. The device,

FIG. 3. The distribution of size, spacing of LC droplets bottom morphology, observed under a microscope of E7-EPO305 mixture cured at various temperatures (a) 24°C(D7), (b) 60°C(D9), (c) 70°C(D6), (d) 80°C(D4), and (e) 100°C (D3).

FIG. 4. The measured electro-optical responses of device D7, D9, D6, D4, and D3. The bottom droplet morphology of these devices are shown in Figures 3(a), 3(b), 3(c), 3(d) and 3(e), Respectively. The incident intensity $I_0$, is the transmitted intensity through the cell with no LC-polymer film.
having a better size uniformity, shows unambiguously not only a steeper electro-optical
response curve but a better transparency contrast between on- and off-state. These results
can be explained as follows. According to the Stokes\textsuperscript{1} equation, the terminal velocity \( V_t \)
of a dispersed droplet driven by the sedimentation force is

\[
V_t = \frac{2g \left( \rho_p - \rho_{LC} \right) R^2}{9\mu},
\]

(1)

where

- \( g \) : gravitational acceleration
- \( \rho_p \) : polymer\textsuperscript{1} density
- \( \rho_{LC} \) : liquid crystal\textsuperscript{1} density
- \( \mu \) : dynamic viscosity of polymer matrix
- \( R \) : droplet radius

As seen in Eq. (1), the terminal velocity \( V_t \) of a dispersed droplet is inversely proportional
to the dynamic viscosity \( \mu \). The sedimentation-induced motion can lead to collisions. As
a result, the size uniformity of the droplets is expected to be more uniform as \( \rho_{LC}/\rho_p \)
approaches unity.\textsuperscript{8} In the case of the E7-EPO305 mixture (\( \rho_{p} - \rho_{LC} \approx 0.12 \)),
the droplet motion driven by the sedimental force will be prohibited as the polymer is curing to reach a
threshold viscosity. Since the curing time is decreased as the curing temperature is in-
creased, as shown in Fig. 1, we should expect to have a smaller and more uniform sized
droplet using a faster polymer curing rate (higher curing temperature). Moreover, the
opacity of the film in the off-state is due to light scattering from the droplets.\textsuperscript{4,12} A light
ray will be scattered many times before emerging from the film. The degree of off-state
scattering is, thus, dependent on both size and the number density of the liquid crystalline
droplets. For the same mixture material and thickness, we should expect the transparency
contrast between off-state and on-state is improved as the droplets are smaller.

The transient electro-optical responses of these devices were also measured. A DC
voltage pulse of sufficient strength (-130 V) and duration (40 ms) was applied to the
sample. The measured results of 10-90% rise- and decay-times of these devices are
summarized in Table II. For references, Figs. 5 and 6 show the transient electro-optical
response of device D4 (cured at 80°C) and D7 (cured at 24°C). It is seen from Table II that
a device, cured at higher temperatures, rises a bit slower but decays faster in response to a
DC voltage pulse. Qualitatively, this result can be understood by the fact that the LC
molecules anchoring at the droplet wall is rather strong. The strength of the field required
to reorient the smaller droplets (cured at higher temperatures) should be stronger. We, thus,
expect a slower rise-time for a film having smaller sized droplets excited by a DC voltage
pulse. But, once the applied voltage is removed, the relaxation torque, due to the wall
anchoring force, is also stronger for such a film, it thus decays faster. It should be noted
that the response times of a PDLC film are dependent on many factors, such as the used
liquid crystal and polymer, the viscosity of the liquid crystal, anchoring of the liquid crystal
TABLE II. The measured rise-and decay-times of devices D7, D9, D6, D4, and D3 to a DC excitation pulse. The bottom droplet morphology of these devices are shown in Fig. 3.

<table>
<thead>
<tr>
<th>Device</th>
<th>Cure temp.</th>
<th>Rise-time</th>
<th>Decay-time</th>
</tr>
</thead>
<tbody>
<tr>
<td>D7</td>
<td>24°C</td>
<td>1.9ms</td>
<td>13.5ms</td>
</tr>
<tr>
<td>D9</td>
<td>60°C</td>
<td>2.7ms</td>
<td>6.4ms</td>
</tr>
<tr>
<td>D6</td>
<td>70°C</td>
<td>3.1ms</td>
<td>2.3ms</td>
</tr>
<tr>
<td>D4</td>
<td>80°C</td>
<td>4.6ms</td>
<td>2.0ms</td>
</tr>
<tr>
<td>D3</td>
<td>100°C</td>
<td>4.5ms</td>
<td>1.9ms</td>
</tr>
</tbody>
</table>

molecules at the polymer wall, etc

FIG. 5. The transient electro-optical response (bottom curve) of device D4 under DC pulse (upper curve). The droplet size of this device is shown in Figure 3(d).

FIG. 6. The measured transient response (bottom curve) of the device D7 under a DC pulse excitation (upper curve). The droplet sizes of this device is shown in Figure 3(a).

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REFERENCES


9. This epoxy was purchased from Epoxy Technology Inc., 14 Fortune Drive, Billerica, MA 01821.

10. This liquid crystal was purchased from BDH company.
