

## 11.3: Temperature Effect on Polymer-stabilized Blue-phase LCDs

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### Abstract

In this paper, temperature effects on polymer-stabilized blue-phase (PSBP) liquid crystal composites are analyzed. As the temperature increases, both Kerr constant and response time decrease rapidly. The proposed physical models fit well with experimental data. These results will provide valuable guidelines for optimizing PSBP material development and device performance.

### 1. Introduction

Polymer-stabilized blue phase (PSBP), or more generally polymer-stabilized optically isotropic (PSIP) LCDs, based on Kerr-effect-induced isotropic-to-anisotropic transition are emerging because of their submillisecond gray-to-gray response time, no need for alignment layers, and cell gap insensitivity. Fast response time enables color sequential displays with RGB LEDs, which will triple the optical efficiency and resolution density. According to Kerr effect, the induced birefringence ( $\Delta n_{ind}$ ) of PSIP is related to the electric field as

$$\Delta n_{ind} = \lambda K E^2, \quad (1)$$

here  $\lambda$  is the wavelength,  $K$  is the Kerr constant, and  $E$  is the amplitude of the electric field [1]. At  $E=0$ , the self-assembled nano-structured LC composite is optically isotropic. As  $E$  increases, molecular reorientations take place within the double-twisted cylinders, and the LC composite becomes birefringent. However, the conventional Kerr equation is valid only in the low field region. As  $E$  keeps increasing, the induced birefringence will gradually saturate, as clearly described by the extended Kerr effect [2] as

$$\Delta n_{ind} = \Delta n_s (1 - \exp[-(E/E_s)^2]), \quad (2)$$

where  $\Delta n_s$  is the saturated induced birefringence and  $E_s$  is the saturation electric field. In the weak field region ( $E \ll E_s$ ), we can deduce the Kerr constant as [2].

$$K \approx \Delta n_s / (\lambda E_s^2), \quad (3)$$

Kerr constant affects the operating voltage of a PSIP device, but very few experimental results and physical models for understanding the temperature effects of Kerr constant and response time have been investigated. The objective of this paper is to study the temperature effect on the electro-optic performance of PSBP/PSIP system. Our proposed models agree well with the measured data, and will play an important role for optimizing PSBP/PSIP materials and devices.

### 2. Experiment

In our experiment, the host nematic LC has a birefringence of 0.17 ( $\lambda=589\text{nm}$ ,  $T=20^\circ\text{C}$ ) and clearing temperature  $T_c \sim 94^\circ\text{C}$ . It was mixed with chiral dopants (22.7% Merck CB15 and 4.7% ZLI-4572), monomers (3.9% RM257, 4.6% Aldrich M1, and 7.7% EHA) and photoinitiator (1.5% darocur). We filled the LC mixture into an IPS cell with a cell gap  $d=7.5\ \mu\text{m}$ ; ITO electrode width and electrode gap are both  $10\ \mu\text{m}$ . The UV curing process was

performed at  $70^\circ\text{C}$  (isotropic state) for 30 min. Similar to that cured at a blue phase, the curing in an isotropic phase also produces nano-structured optically isotropic composite and its electro-optic properties still follow Kerr effect. After polymerization, the clearing temperature of the LC composite was measured to be  $T_c \sim 54^\circ\text{C}$ . We then measured the voltage-dependent transmittance (VT) and the response time of the cell by placing it between two crossed polarizers under different temperatures. A CW He-Cd laser ( $\lambda=441.8\ \text{nm}$ ) was used as the light source.

### 3. Results and Discussions

#### 3.1. Kerr Constant

Figure 1(a) shows the normalized VT curves measured from  $15.0^\circ\text{C}$  to  $37.5^\circ\text{C}$ . As the temperature increases, the on-state voltage increases. We fitted each VT curve with the extended Kerr effect model, the obtained Kerr constant (Fig. 1(b)) decreases as the temperature increases.

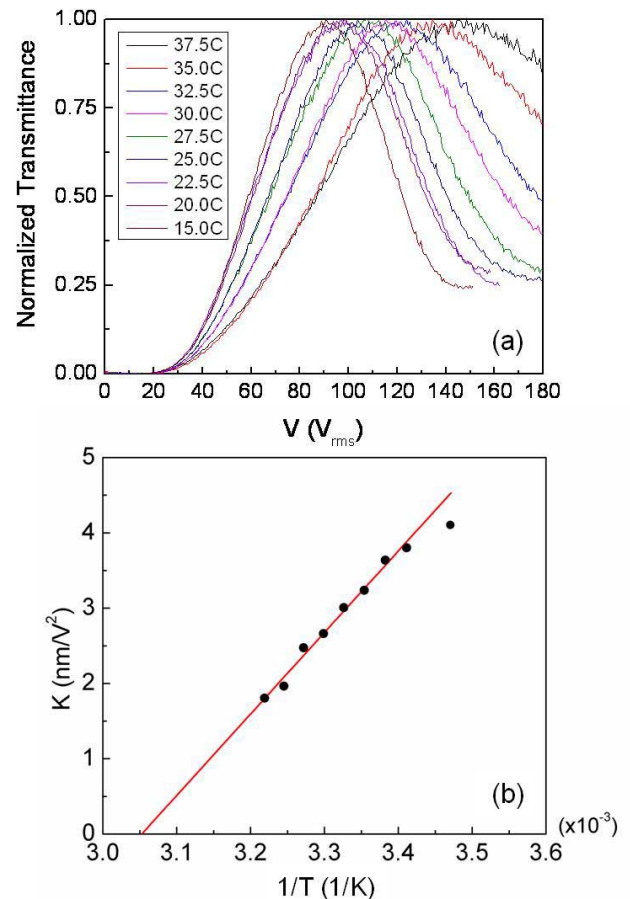


Figure 1. a) Measured VT curves of the IPS LC composite cell, and b) Linear fit of the Kerr constant.

To explain this phenomenon, we follow Gerber's model [3] in which the Kerr constant is approximated as

$$K \approx \Delta n \cdot \Delta \varepsilon \frac{\varepsilon_o P^2}{k \lambda (2\pi)^2}. \quad (4)$$

Here  $\Delta n$ ,  $\Delta \varepsilon$  and  $k$  are the birefringence, dielectric anisotropy, and elastic constant of the host LC material. These parameters are related to the nematic order parameter ( $S$ ) as  $\Delta n \sim \Delta n_o S$ ,  $\Delta \varepsilon \sim S/T$ , and  $k \sim S^2$  [4]. According to Ref. 5, the pitch length  $P$  is insensitive to the temperature and can be treated as a constant. Thus, we have:

$$K \approx \Delta n \cdot \Delta \varepsilon \frac{\varepsilon_o P^2}{k \lambda (2\pi)^2} \sim \Delta n_o S \cdot S/T \cdot \frac{1}{S^2} \cdot \frac{\varepsilon_o P^2}{\lambda (2\pi)^2} \sim \alpha \cdot \frac{1}{T}, \quad (5)$$

where  $\alpha$  is the proportionality constant. However, when the temperature approaches  $T_c$  of the LC composite, both  $\Delta n$  and  $\Delta \varepsilon$  should vanish, so Kerr constant should also vanish (or at least dramatically decreased). To satisfy this boundary condition, we rewrite Eq. (5) as follows:

$$K = \alpha \cdot \left( \frac{1}{T} - \frac{1}{T_c} \right). \quad (6)$$

Eq. (6) predicts that Kerr constant decreases linearly with the reciprocal temperature ( $1/T$ ) and eventually reduce to zero as the temperature reaches clearing point ( $T_c$ ) [6]. From the fittings depicted in Fig. 1(b), we find  $\alpha = 1.08 \times 10^{-5} \text{ m} \cdot K/V^2$  and  $T_c = 327.58 \text{ K}$  (54.43 °C). The fitted  $T_c$  matches very well with the measured clearing temperature (54 °C) of the LC composite, which actually validates Eq. (6) and reduces the adjustable parameter to only one ( $\alpha$ ).

In Fig. 1(b), as the temperature continues to decrease the Kerr constant gradually deviates from the linear extrapolation. This is because in the low temperature region the higher order term of the elastic constant  $k = a_1 S^2 + a_2 S \bar{P}_4$ , where  $a_1$  and  $a_2$  are coefficients, and  $\bar{P}_4$  is the fourth rank of the order parameter, becomes increasingly important and should be included. From previous experimental results [7],  $\bar{P}_4$  is negligible in the high temperature region but not the low temperature region,

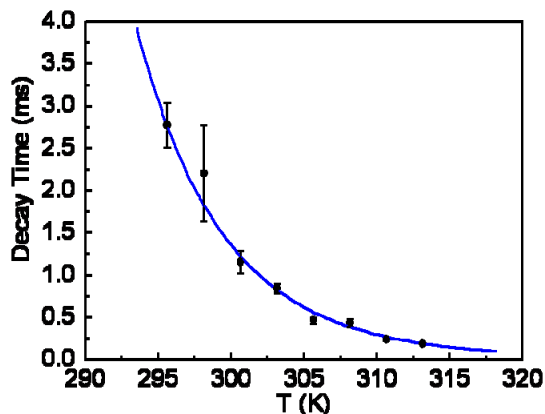


Figure 2. Temperature dependent decay time: dots are experimental data and the blue line represents fitting.

and the second term  $a_2 S \bar{P}_4$  makes ~30-40% contribution to enhance the elastic constant. Thus, the Kerr constant in the lower temperature region may not increase as rapidly as the fitting line shows and should saturate as the temperature lowers to a certain limit.

### 3.2. Response Time

Plotted in Fig. 2 is the measured decay time of the LC composite from 22.5 °C to 40 °C. As the temperature increases, the decay time decreases rapidly. And this changing rate is more sensitive than most nematic LCs.

To understand this peculiar phenomenon, we need to develop a physical model to correlate the temperature dependent response time with LC parameters. The free relaxation time of a PSBP LC composite can be approximated by

$$\tau \approx \frac{\gamma_1 P^2}{k (2\pi)^2}, \quad (7)$$

with  $\gamma_1$  being the rotational viscosity,  $P$  the pitch length, and  $k$  the elastic constant [8]. From mean field theory,  $k$  is related to the nematic order parameter ( $S$ ) as  $k \sim S^2$ . With the modified Arrhenius model, viscosity  $\gamma_1$  can be described as

$$\gamma_1 \sim S \cdot \exp(E_a / K_B T), \quad (8)$$

where  $E_a$  is the activation energy of molecular rotation and  $K_B$  is the Boltzmann constant [9]. Treating  $P$  as a constant, we have:

$$\tau \approx \frac{\gamma_1 P^2}{k (2\pi)^2} \sim \frac{S \cdot \exp(E_a / K_B T) \cdot P^2}{S^2 \cdot (2\pi)^2} \approx B \cdot \frac{\exp(E_a / K_B T)}{(1 - T/T_c)^\beta}. \quad (9)$$

As shown in Fig. 2, Eq. (9) fits quite well with the measured response time data. We obtain the two unknowns  $B = 7.16 \cdot 10^{-23} \text{ ms}$  and  $E_a = 1.31 \text{ eV}$ . The host nematic LC has a similar  $\gamma_1$  and  $E_a$  as E7, but the obtained  $E_a$  of the LC composite is ~3X higher than that of E7. The increased  $E_a$  may originate from the chiral dopants, and results in a larger viscosity and a slower response time.

There is also tradeoff between optimizing response time and Kerr constant. From Gerber's model for Kerr constant and Eq. (9) for response time, a smaller elastic constant leads to a larger Kerr constant (lower operating voltage), but a slower response time. Similarly, a larger dielectric anisotropy enhances Kerr constant, but it could dramatically increase viscosity. The PSIP LC composite is a complex system, to better evaluate the performance, a delicate balance between each material parameter, and the UV curing process need to be considered.

## 4. Conclusion

We have studied the temperature effects on PSIP LCDs. An analytical approximation for correlating temperature dependent Kerr constant is proposed. The temperature dependency of response time is also validated. Proposed physical models fit well with experimental results and will provide valuable guidance in further optimizing the PSIP material development and device performance.

## 5. References

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