7.4: Extended Kerr effect in a polymer-stabilized blue-phase liquid crystal composite

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Abstract

As the electric field increases, the induced birefringence of a polymer-stabilized blue-phase liquid crystal gradually deviates from the conventional Kerr effect and finally saturates. A new convergence model, named extended Kerr effect, is proposed to explain this saturation phenomenon. This model will give a more accurate account on the electro-optic effect of the emerging blue-phase LCDs.

1. Introduction

Polymer-stabilized blue phase liquid crystal (PS-BPLC) [1-7] is emerging as next-wave display technology because it exhibits some revolutionary features, such as alignment-layer free, sub-millisecond gray-to-gray response time [8], and wide viewing angle. The underlying physical mechanism is electric-field-induced birefringence, known as Kerr effect [9]. However, the Kerr effect holds only in the low field region. As electric field increases, the induced birefringence gradually saturates and deviates from the conventional Kerr effect. This saturation phenomenon has been observed in polar solutions several decades ago [10], however it remains unexplored in PS-BPLC composites. There is an urgent need to discover the convergence form in order to model the display performance more accurately.

The objective of this paper is to investigate the convergence form of the electric-field-induced birefringence of polymer-stabilized BPLC. An exponential convergence model, called extended Kerr effect, is proposed. Good agreement between experiment and model is obtained in the entire region. Based on the extend Kerr effect, we fitted the measured voltage-dependent transmittance (VT) curve of a PS-BPLC display device with in-plane switching (IPS) electrodes. Again, good agreement is found between experimental results and our model.

2. Experiment

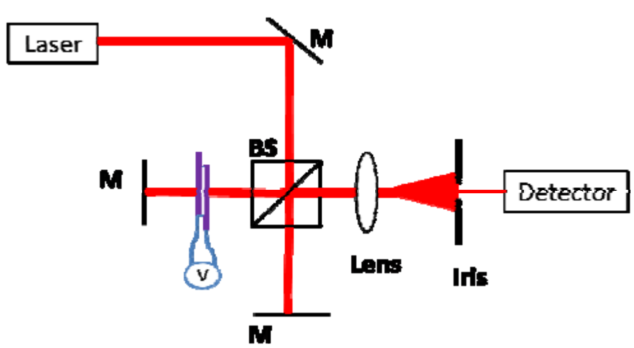

Figure 1. Experimental setup of Michelson interferometer for measuring the refractive index change of a PS-BPLC cell. M: mirror; BS: beam splitter.

We prepared a mixture consisting of 49 wt% Merck BL038, 27% chiral dopants (CB15 and ZLI-4572) and 24% monomers (EHA and RM257). The BPLC is sandwiched between two ITO glass substrates with a cell gap of 8 μm and UV cured at 40°C. The electro-optic properties of the PS-BPLC were measured using Michelson interferometer, as depicted in Fig. 1. The cell was placed in one arm and driven by a square-wave voltage with 1 kHz frequency. By measuring the light intensity thru the iris, the refractive index change can be obtained.

3. Results

3.1. Extended Kerr effect

The PS-BPLC is optically isotropic in the voltage-off state. When an electric field is applied, birefringence is induced with the long axis along the electrical field. For the PS-BPLC, the induced birefringence is due to the local reorientation of the molecules [1]. Therefore, it is quite reasonable to assume the average refractive index keeps constant at any electric field, that is, [11]

$$n_{average} \approx \frac{2n_o(E)+n_e(E)}{3} \approx n_{iso}\,. \tag{1}$$

Here, n_{iso} is the refractive index in voltage-off state. $n_o(E)$ and $n_e(E)$are the field dependent refractive index perpendicular and parallel to the electric field, respectively. With this assumption, the refractive index change under an electric field can be expressed as:

$$\delta n = n_{iso} - n_o(E) = \frac{n_e(E)-n_o(E)}{3}\,. \tag{2}$$

Eq. (2) correlates the refractive index change we measured with the induced birefringence. The induced birefringence (Δn_{ind}) of PS-BPLC under an external electric field is governed by Kerr effect as:

$$\Delta n_{ind} = n_e(E) - n_o(E) = \lambda K E^2\,, \tag{3}$$

where λ is the wavelength, *K* is the Kerr constant, and *E* is the amplitude of the electric field. In Fig. 2, the measured refractive index change (δn) is linearly proportional to E^2 as expected from Kerr effect in the weak field region. As the electric field increases, δn gradually saturates. To explain this trend, higher order electro-optical effects are taken into account and an exponential convergence model (extended Kerr effect) is proposed as:

$$\delta n = \delta n_{sat}\left(1-\exp\left[-\left(\frac{E}{E_s}\right)^2\right]\right). \tag{4}$$

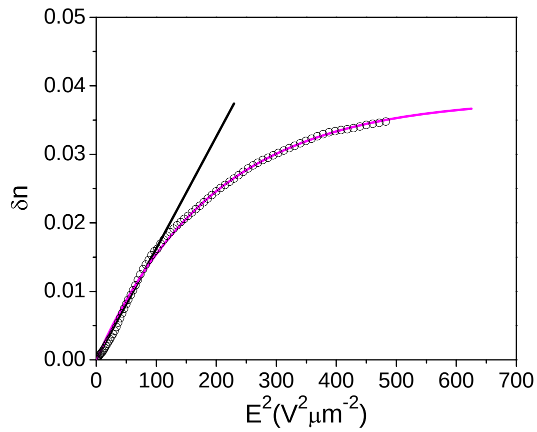

Figure 2. Measured refractive index change (circles) and fittings with Kerr effect (black line) and extended Kerr effect (magenta).

In Eq. (4), δn_{sat} stands for the saturated refractive index change and Es represents the saturation field. Eq. (4) is used to fit the experimental data leaving δn_{sat} and E_s as adjustable parameters. The fitting with experimental data is quite good in the entire region and it shows a saturation trend in the high field region, as expected. The parameters obtained are δn_{sat} = 0.038, and E_s = 13.9 V/μm. It is interesting to note that if we expand Eq. (4) into power series, we will obtain the E^2 term (Kerr effect) under weak field approximation; the higher order terms become increasingly important as E increases.

The employed LC host has an intrinsic birefringence of 0.272. Taking into account the LC concentration and the factor of 1/3 in Eq. (2), the obtained δn_{sat} is still ~18% smaller than the ideal value, which is 0.045. The difference is attributed into two reasons, one is that a portion of liquid crystal is bounded by the polymer network, and some BPLCs are strongly anchored by the nano-structured double-twist cylinder boundaries so that they do not respond to the electric field, and the other factor is the relatively low clearing temperature (~60°C) of the PS-BPLC which accordingly reduces the order parameter at the room temperature (~23°C) [12].

3.2. Comparisons

To validate the extended Kerr effect in a real display device, we incorporated Eq. (4) into our simulation program [5] and tried to fit the experimental VT curve reported by Kikuchi and co-workers [13] in an IPS cell. Figure 3 shows the experimental data and fittings. The red line is the fitting using the extended Kerr effect. For comparison, the fitting using the truncation model [4] is also included. In the truncation model, the induced birefringence is described as $\Delta n_{ind} = (\Delta n)_o (E/E_s)^2$ when $E<E_s$ and $\Delta n_{ind} = \Delta n_o$ when $E \geq E_s$. The abrupt change is used to prevent the indefinite increase in the induced birefringence but may not be realistic. Thru fittings, we find δn_{sat} ~0.068 for both cases and E_s ~ 2.02 V/μm which implies to a Kerr constant of ~2.63×10^{-8} m/V^2 in the low voltage region. On the other hand, the Kerr constant obtained using the truncation model is ~1.62×10^{-8} m/V^2. A larger Kerr constant leads to a higher transmittance in the low voltage region. Besides, the slower increase of induced birefringence at high voltage region results in a smoother transition near the peak transmittance.

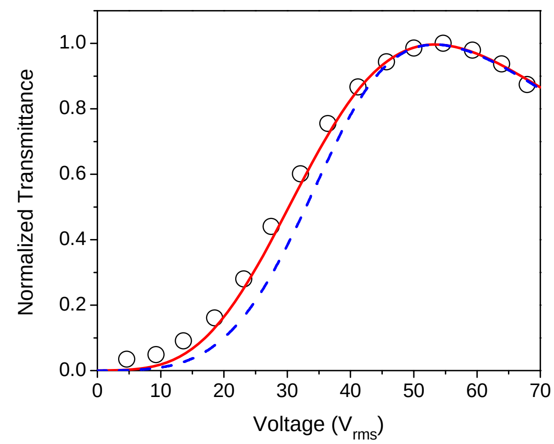

Figure 3. Model fittings with experimental data (circles; Ref. 11) of an IPS cell using the truncation model (blue dashed lines) and extended Kerr effect (red).

4. Conclusion

Polymer-stabilized blue phase liquid crystal is emerging as next-generation display technology. There is an urgent need to understand the underlying physical mechanism. Our experimental results indicate that, as the electric field increases the induced birefringence will gradually deviate from the conventional Kerr effect and finally saturate. To explain this trend, higher order electro-optic effects are taken into account and an exponential convergence model is proposed. This model, called extended Kerr effect, helps to explain the macroscopic behavior of the electric-field-induced birefringence and will make a significant impact to the optimization of blue-phase display devices.

5. Acknowledgements

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6. References

[1] H. Kikuchi, M. Yokota, Y. Hisakado, H. Yang, and T. Kajiyama, "Polymer-stabilized liquid crystal blue phases," *Nature Mater*. **1**, 64 (2002).

[2] Y. Hisakado, H. Kikuchi, T. Nagamura, and T. Kajiyama, "Large Electro-optic Kerr Effect in Polymer-Stabilized Liquid-Crystalline Blue Phases," *Adv. Mater*. **17**, 96 (2005).

[3] S. W. Choi, S. I. Yamamoto, Y. Haseba, H. Higuchi, and H. Kikuchi, "Optically isotropic-nanostructured liquid crystal composite with high Kerr constant", *Appl. Phys. Lett.* **92**, 043119 (2008).

[4] Z. Ge, S. Gauza, M. Jiao, H. Xianyu, and S. T. Wu, "Electro-optics of polymer-stabilized blue phase liquid crystal displays," *Appl. Phys. Lett.* **94**, 101104 (2009).

[5] Z. Ge, L. Rao, S. Gauza, and S. T. Wu, "Modeling of Blue Phase Liquid Crystal Displays," *J. Display Technol.* **5**, 250

(2009).

[6] L. Rao,Z. Ge,S. T. Wu, and S. H. Lee, “Low voltage blue-phase liquid crystal displays,” *Appl. Phys. Lett.* **95**, 231101 (2009).

[7] M. Jiao, Y. Li, and S. T. Wu, “Low voltage and high transmittance blue-phase liquid crystal displays with corrugated electrodes,” *Appl. Phys. Lett.* **96**, 011102 (2010).

[8] K. M. Chen, S. Gauza, H. Xianyu, and S. T. Wu, “Submillisecond gray-level response time of a polymer-stabilized blue phase liquid crystal,” *J. Display Technol.* **6**, 49 (2010).

[9] J. Kerr, “A New Relation between Electricity and Light: Dielectrified Media Birefringent,” *Philos. Mag.* **50**, 337 (1875).

[10] C. T. O'Konski, K. Yoshioka, and W. H. Orttung, “Electric Properties of Macromolecules IV. Determination of Electric and Optical Parameters from Saturation of Electric Birefringence in Solutions,” *J. Phys. Chem.* **63**, 1558 (1959).

[11] J. Yan, H. C. Cheng, S. Gauza, Y. Li, M. Jiao, L. Rao, and S. T. Wu, “Extended Kerr effect of polymer-stablized blue-phase liquid crystals,” *Appl. Phys. Lett.* **96**, 071105 (2010).

[12] S. T. Wu, “Birefringence dispersions of liquid crystals,” *Phys. Rev. A* **33**, 1270 (1986).

[13] H. Kikuchi, Y. Haseba, S. Yamamoto, T. Iwata and H. Higuchi, *SID Symposium Digest* **40**, 578 (2009).