

A Microsecond-Response Blue Phase Liquid Crystal Device

Yuan Chen, Jin Yan, Jie Sun and Shin-Tson Wu

College of Optics and Photonics, University of Central Florida, Orlando, Florida 32816, USA

Xiao Liang

Department of Chemistry, Tsinghua University, Beijing 10084, China

Shih-Hsien Liu, Pao-Ju Hsieh and Kung-Lung Cheng

Material and Chemical Research Laboratories, Industrial Technology Research Institute, Hsinchu, Taiwan

Jyh-Wen Shiu

Display Technology Center, Industrial Technology Research Institute, Hsinchu, Taiwan

Abstract

A polymer-stabilized blue-phase liquid crystal (BPLC) with microsecond response time is demonstrated using a vertical field switching cell. The measured decay time is 39.4 μs at room temperature (21°C) and then decreases to 9.6 μs at 44.3 °C. Such a response time is 1-2 orders of magnitude faster than that of a typical BPLC device. The responsible physical mechanisms are the collective effects of short pitch length, strong polymer network, and low viscosity through elevated temperature effect. The on-state voltage of our BPLC device is 44.2 V, hysteresis is below 0.7%, and contrast ratio is over 1300:1.

1. Introduction

Polymer-stabilized blue-phase liquid crystal (PS-BPLC) [1-5] has opened a new door for next-generation display and photonic applications [6,7] because of its revolutionary features, such as submillisecond gray-level response time, no need for surface alignment layer, and optically isotropic dark state. However, high operation voltage and hysteresis still hinder its widespread applications. To reduce operation voltage, three approaches are commonly practiced: 1) to develop BPLC materials with a large Kerr constant (K) because the on-state voltage is inversely proportional to \sqrt{K} [8], 2) to implement protrusion electrodes so that electric field can penetrate deeply into LC bulk [8,9], and 3) to use vertical field switching (VFS) mode which generates uniform longitudinal electric fields [10-12].

Kerr constant is related to the birefringence (Δn), dielectric anisotropy ($\Delta\epsilon$), elastic constant (k), and pitch length (p) of the LC host as [13]:

$$K \approx \Delta n \cdot \Delta\epsilon \frac{\epsilon_0 p^2}{\lambda k (2\pi)^2}. \quad (1)$$

To obtain a large K , a LC host with $\Delta\epsilon \approx 94$ and $\Delta n \approx 0.17$ has been developed by Chisso (now JNC) (JC-BP01M) [14]. Based on Eq. (1), a large $\Delta\epsilon$ helps to lower the operation voltage. However, to achieve such a large $\Delta\epsilon$ several polar groups have to be used, which would undoubtedly result in an increased rotational viscosity (γ_l). The decay time of a BPLC is governed by rotational viscosity, elastic constant and pitch length as [13]:

$$\tau = \frac{\gamma_l p^2}{k (2\pi)^2}. \quad (2)$$

From Eq. (2), three approaches can be considered for improving response time: 1) to reduce pitch length by increasing chiral concentration, 2) to increase elastic constant by strengthening polymer network, and 3) to reduce viscosity by operating the cell at an elevated temperature. However, each approach has its pros and cons. In approach (1), reducing pitch length by increasing chiral concentration could lead to a higher operation voltage [as described in Eq. (1)] and lower clearing temperature of the BPLC composite. For example, CB-15 is a chiral compound; its clearing point is 4 °C. Adding CB-15 to a BPLC mixture would dramatically lower the clearing temperature, which is undesirable for practical applications. In approach (2), a strong polymer network helps to reduce response time and suppress hysteresis, but its operating voltage would be inevitably increased. In approach (3), elevated temperature would substantially reduce rotational viscosity, but the tradeoffs are reduced Kerr constant and increased operation voltage. Therefore, a delicate balance between abovementioned parameters needs to be taken.

In this paper, we compare two PS-BPLC samples using different types of monomers (C12A or TMPTA), and find out that the response time of the PS-BPLC with TMPTA is much faster. Furthermore, we experimentally demonstrate a microsecond-response PS-BPLC device using a VFS cell instead of commonly employed in-plane-switching (IPS) cell. In an IPS cell, the strong fringing field near the electrode edge could cause lattice distortion locally, which in turn increases the response time and hysteresis. In contrast, VFS mode has uniform longitudinal field which would effectively avoid the lattice distortion and improve the response time. At room temperature (21°C), the measured decay time is 39 μs , but at 44.3 °C the decay time drops to 9.6 μs . The on-state voltage of our BPLC device is 44.2 V which corresponds to $K \approx 0.6 \text{ nm}^2/\text{V}^2$, hysteresis is below 1%, and contrast ratio is over 1300:1.

2. Experiment

In the experiment, we prepared a nematic LC host designated as JM2069-145 (ITRI, Taiwan). It is a multi-component mixture comprising of cyano-biphenyl and terphenyl compounds. Its physical properties are listed as follows: $\Delta n = 0.215$ at $\lambda = 633 \text{ nm}$, $\Delta\epsilon = 50$ at 1 kHz and 21 °C, and clearing temperature $T_c = 80$ °C. In order to induce chirality into the host nematic LC, we mixed 93 wt% JM2069-145 with 7 wt% of a high helical twisting power (HTP $\approx 100/\mu\text{m}$) chiral compound [15]. Blue phase was found from 57 °C to 62 °C during the heating process. From the chiral concentration and HTP, we estimated that the pitch length is about

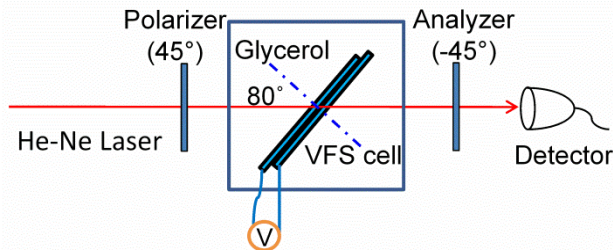


Figure 1. Experimental setup for electro-optic measurement of the VFS cell.

140 nm. To compare the influence of the polymer network on the electro-optic properties of PS-BPLC, we prepared two samples with different monomer composition. Sample A is using C12A while Sample B is using TMPTA. For each sample, 10 wt% of monomers [6 wt% RM257 (Merck) + 4 wt% C12A or TMPTA] and 0.8 wt% of photoinitiator were blended with 89.2 wt% of the BP host to form the precursor. Next, we injected the LC/monomers mixtures into vertical field switching (VFS) cells in isotropic phase. The VFS cell was comprised of two ITO (indium tin oxide) glass substrates, but without polyimide alignment layer. The cell gap was measured to be 5.44 μm (For Sample A) and 5.27 μm (Sample B), respectively. Afterwards the cells were placed on a Linkam heating/freezing stage controlled by a temperature programmer (Linkam TMS94). The cells were cooled to BP phase, and then exposed to UV light ($\lambda=365\text{ nm}$) with intensity of 2 mW/cm^2 for 30 minutes. After UV irradiation, polymer-stabilized BPLC nano-composites were self-assembled. The Bragg reflection is in the UV range due to the short pitch length.

Figure 1 depicts the measurement setup. A linearly polarized He-Ne laser ($\lambda=633\text{ nm}$) was used as probing beam. In order to acquire phase retardation, the laser beam was incident on the VFS cell at an 80° oblique angle. The VFS cell was immersed in a glass container filled with glycerol ($n=1.47$) so that the beam could enter the LC layer at a large angle due to the refractive index match between the glass and glycerol. The container was placed between two crossed polarizers, and the light transmittance was measured by a photodiode detector and recorded digitally by a LabVIEW data acquisition system.

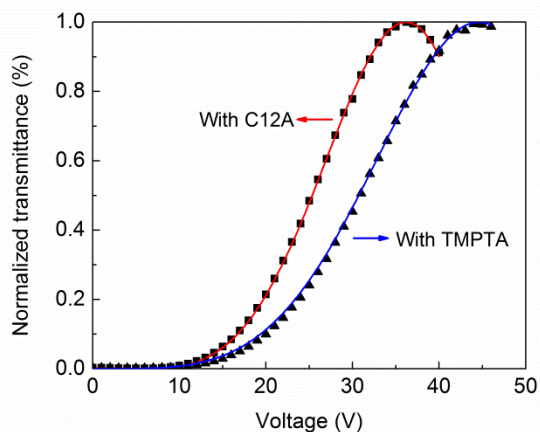


Figure 2. Blue line: VT curve for cell with TMPTA; Red line: VT curve for cell with C12A. Dots: experimental data.

3. Results and Discussion

3.1. Voltage Dependent Transmittance

A 1-kHz square-wave AC signal was applied to the VFS cell. Figure 2 depicts the measured voltage-dependent transmittance (VT) curves, where the dots represent the measured data and the lines are the fitting curves. For Sample B, the first transmission peak occurs at $V_p=44.2\text{ V}$, which corresponds to an electric field of 8.39 $\text{V}/\mu\text{m}$. In the voltage-off state, blue phase is optically isotropic. The contrast ratio is defined as T_p/T_{dark} , where T_p is the peak transmittance at V_p and T_{dark} is the dark state light leakage at $V=0$. Our measured contrast ratio is over 1300:1, indicating that the dark state is pretty good due to the short pitch length of the BPLC. As voltage increases, the induced birefringence increases as described by the following extended Kerr model [16]:

$$\Delta n_{\text{ind}} = \Delta n_s (1 - \exp[-(E/E_s)^2]), \quad (3)$$

where Δn_s is the saturated induced birefringence and E_s is the saturated electric field. Through fitting [4], we obtained the Kerr constant $K=\Delta n_s/(\lambda E_s^2)=0.6\text{ nm}/\text{V}^2$. By contrast, the on state voltage for Sample A is 35.8 V and the Kerr constant is 0.97 nm/V^2 . Since the pitch length, Δn and $\Delta \epsilon$ are the same for both Samples, we find that the elastic constant of Sample B is 1.6X larger than that of Sample A. The increased elastic constant is believed to originate from the strong polymer network [17] formed with RM257 and TMPTA which has three functional groups while C12A only has one. A strong polymer network helps to reduce hysteresis and response time.

3.2. Hysteresis

Hysteresis affects gray scale accuracy of a BPLC device and should be minimized. To measure hysteresis, we drove the VFS cell by ascending the voltage to V_p and then gradually descending it to 0. Hysteresis is defined as $\Delta V/V_p$, where ΔV is the voltage difference between the forward and backward scans at half of the peak transmittance, shown in Fig. 3. For Sample B, the measured $\Delta V/V_p$ is only 0.68%. Although the maximum electric field is as strong as 8.39 $\text{V}/\mu\text{m}$, the hysteresis is still negligible, indicating the polymer network is quite stable [18]. If the cell is driven to 31 V (i.e., 50% of the peak transmittance) and then back to zero (result not shown), hysteresis is too small ($<0.1\%$) to be detected by our measurement system. For Sample A, the hysteresis is free

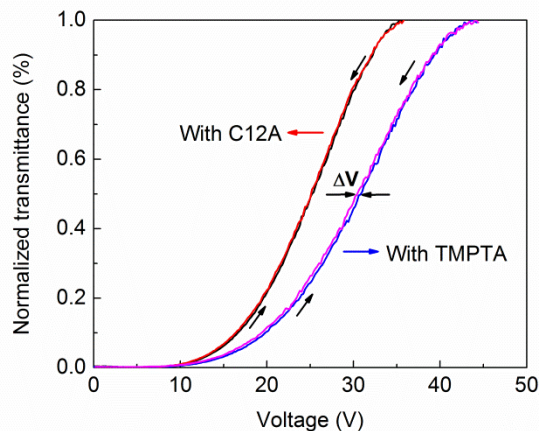


Figure 3. Hysteresis loop for Sample A and Sample B.

Sample	Compositions					V_{on} (V)	K (nm/V ²)	Hysteresis		Decay time (μ s)
	BP host	RM257	C12A	TMPTA	PI			Drive to 35.8V	Drive to 44V	
A	89.2 wt%	6 wt%	4 wt%	0	0.8 wt%	35.8	0.97	~0	1.8%	332.5
B	89.2 wt%	6 wt%	0	4 wt%	0.8 wt%	44.2	0.6	~0	0.68%	39.4

Table 1. Comparison between Sample A and Sample B.

when driving to its peak voltage of 35.8V but increases to 1.8% when driving to 44.2V. This again indicates that the polymer network with TMPTA is stronger than that with C12A. The comparison between Sample A and B is listed in Table 1.

3.3. Response time

Fast response time is probably the most attractive feature for BPLC. Both rise time and decay time were measured between 10% and 90% transmittance change. The measured decay time at room temperature (21 °C) for Sample A is 332.5 μ s, and rise time is 541.9 μ s. On the other hand, Sample B exhibits much faster response, with decay time of 39.4 μ s, and rise time of 46 μ s. We believe that the fast response time originates from the short pitch length and strong polymer network. Based on Eq. (2), the decay time is proportional to p^2 , so a shorter pitch length would lead to a faster response time. On the other hand, TMPTA is a tri-functional monomer, while the normally used EHA or C12A [19,20] are mono-functional monomers. The crosslink between TMPTA and RM257 is much stronger, which helps the molecules to relax back when the voltage is released.

In addition, the decay time decreases as the temperature increases, as described by following equation [21]:

$$\tau \approx B \cdot \frac{\exp(E_a / K_B T)}{(1 - T / T_{c_BP})^\beta}, \quad (4)$$

where B is a proportionality constant, E_a is the activation energy, K_B is the Boltzmann constant, and T_{c_BP} is the clearing point of the

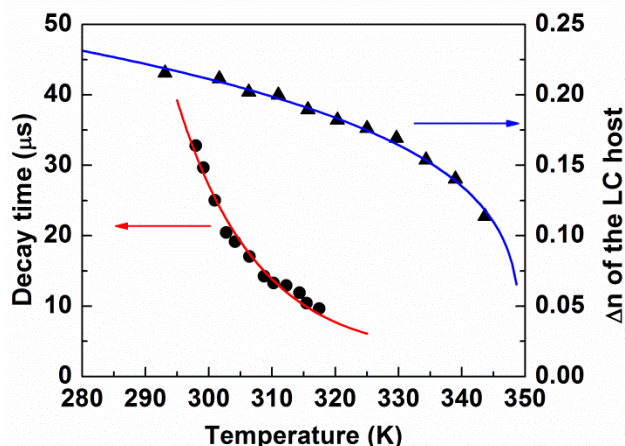


Figure 4. Blue line: Temperature dependent Δn of the LC host; Red line: Temperature dependent decay time for the VFS PSBP cell (Sample B). Dots: experimental data.

PS-BPLC. Eq. (4) is derived based on the order parameter S as described in Ref. 21, and the denominator $(1 - T / T_{c_BP})^\beta$ is the approximated expression for S using Haller's semi-empirical equation [20]. This approximation is valid only for the temperature not too close to T_{c_BP} (e.g., $T_{c_BP} - T > 1^\circ\text{C}$). Although Eq. (4) has three unknowns (B , E_a , and β), β can be obtained by measuring the temperature dependent birefringence of the LC host JM2069-145 or the BPLC composite [23]. The Δn of the LC host was measured through phase retardation of a homogeneous cell sandwiched between two crossed polarizers. The experimental detail has been described in Ref. 24. The birefringence is related to the order parameter S as [25]:

$$\Delta n = \Delta n_o S \approx \Delta n_o (1 - T / T_c)^\beta, \quad (5)$$

where Δn_o denotes the birefringence at $T=0$ K. The blue line in Figure 4 shows the measured temperature dependent Δn of our LC host at $\lambda=633$ nm. Through fitting, we found $\Delta n_o=0.350$ and $\beta=0.267$.

Next, we measured the temperature dependent decay times of our Sample B, since it has a much faster response time. Results are depicted in Fig. 4. As the temperature increases from 25.4 °C to 44.3 °C, the peak voltage increases slightly from 44.2 V to 50 V because of the reduced Kerr constant. Meanwhile, the decay time is reduced from 32.8 μ s to 9.63 μ s. We used the same β value to fit the decay time data by Eq. (4), and found quite good agreement. From the fitting, we obtained $E_a=613.5$ meV and $B=7.35 \cdot 10^{-10}$ μ s. This activation energy is smaller than that of Chisso's JC-BP01M whose $\Delta n \approx 94$, Kerr constant is 7.5 nm/V², but its response time at 23°C is 870 μ s in a 5.74 μ m VFS cell [10,14].

4. Conclusions

In conclusion, we compared two PS-BPLC samples using different types of monomers (C12A or TMPTA), and find out that the response time of the PS-BPLC with TMPTA is much faster. By using TMPTA, we demonstrated a microsecond-response and "hysteresis-free" ($\leq 0.68\%$) polymer-stabilized BPLC device. The decay time at room temperature is 39.4 μ s, and is reduced to 9.64 μ s as the temperature increases to 44.3 °C. The peak voltage is 44.2 V and the contrast ratio is over 1300:1. With these attractive features, our PS-BPLC exhibits great potential for next generation high speed display and photonics devices.

5. Acknowledgements

The authors are indebted to the financial support by ITRI (Taiwan).

6. References

- [1] H. Kikuchi, M. Yokota, Y. Hisakado, H. Yang and T. Kajiyama, "Polymer-stabilized liquid crystal blue phases," *Nature Mater.* **1**, 64-68 (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**, 250-256 (2009).
- [6] Y. H. Lin, H. S. Chen, H. C. Lin, Y. S. Tsou, H. K. Hsu, and W. Y. Li, "Polarizer-free and fast response microlens arrays using polymer-stabilized blue phase liquid crystals," *Appl. Phys. Lett.* **96**, 113505 (2010).
- [7] J. Yan, Y. Li, and S. T. Wu, "High-efficiency and fast-response tunable phase grating using a blue phase liquid crystal," *Opt. Lett.* **36**, 1404-1406 (2011).
- [8] L. Rao, Z. Ge, S. T. Wu, and S. H. Lee, "Low voltage blue-phase liquid crystal displays," *Appl. Phys. Lett.* **95**, 231101 (2009).
- [9] M. Kim, M. S. Kim, B. G. Kang, M. K. Kim, S. Yoon, S. H. Lee, Z. Ge, L. Rao, S. Gauza, and S. T. Wu, "Wall-shaped electrodes for reducing the operation voltage of polymer-stabilized blue phase liquid crystal displays," *J. Phys. D: Appl. Phys.* **42**, 235502 (2009).
- [10] H. C. Cheng, J. Yan, T. Ishinabe, and S. T. Wu, "Vertical field switching for blue-phase liquid crystal devices," *Appl. Phys. Lett.* **98**, 261102 (2011).
- [11] Y. Chen, J. Yan, J. Sun, S. T. Wu, X. Liang, S. H. Liu, P. J. Hsieh, K. L. Cheng and J. W. Shiu, "A microsecond-response polymer-stabilized blue phase liquid crystal," *Appl. Phys. Lett.* **99**, 201105, (2011).
- [12] H. C. Cheng, J. Yan, T. Ishinabe, N. Sugiura, C. Y. Liu, T. H. Huang, C. Y. Tsai, C. H. Lin, and S. T. Wu, "Blue-Phase Liquid Crystal Displays With Vertical Field Switching," *J. Display Technol.* **8**, 98-103 (2012).
- [13] P. R. Gerber, "Electro-Optical Effects of a Small-Pitch Blue-Phase System," *Mol. Cryst. Liq. Cryst.* **116**, 197-206, (1985).
- [14] L. Rao, J. Yan, S. T. Wu, S. Yamamoto, and Y. Haseba, "A large Kerr constant polymer-stabilized blue phase liquid crystal," *Appl. Phys. Lett.* **98**, 081109 (2011).
- [15] A., P. Kirsch, D. Pauluth, J. Krause and M. Heckmeier, "Chiral Compounds," US Patent 7,223,150 B2, May 29, (2007).
- [16] J. Yan, H. C. Cheng, S. Gauza, Y. Li, M. Jiao, L. Rao, and S. T. Wu, "Extended Kerr effect of polymer-stabilized blue-phase liquid crystals," *Appl. Phys. Lett.* **96**, 071105 (2010).
- [17] J. Sun, H. Xianyu, Y. Chen, and S. T. Wu, "Submillisecond-response polymer network liquid crystal phase modulators at 1.06 μm wavelength," *Appl. Phys. Lett.* **99**, 021106 (2011).
- [18] L. Rao, J. Yan, S. T. Wu, Y. H. Chiu, H. Y. Chen, C. C. Liang, C. M. Wu, P. J. Hsieh, S. H. Liu, and K. L. Cheng, "Critical field for a hysteresis-free BPLC device," *J. Display Technol.* **7**, 627-629 (2011).
- [19] 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**, 49-51, (2010).
- [20] J. Yan and S. T. Wu, "Effect of polymer concentration and composition on blue phase liquid crystals," *J. Display Technol.* **7**, 490-493 (2011).
- [21] L. Rao, J. Yan, and S. T. Wu, "Prospects of emerging polymer-stabilized blue-phase liquid-crystal displays," *J. Soc. Inf. Display* **18**, 954-959 (2010).
- [22] I. Haller, "Thermodynamic and static properties of liquid crystals," *Prog. Solid State Chem.* **10**, 103-118 (1975).
- [23] M. Jiao, J. Yan, and S. T. Wu, "Dispersion relation on the Kerr constant of a polymer-stabilized optically isotropic liquid crystal," *Phys. Rev. E* **83**, 041706 (2011).
- [24] S. T. Wu, U. Efron, and L. D. Hess, "Birefringence measurements of liquid crystals," *Appl. Opt.* **23**, 3911-3915 (1984).
- [25] S. T. Wu, "Birefringence dispersions of liquid crystals," *Phys. Rev. A* **30**, 1270-1274 (1986).