

# The outlook for blue-phase LCDs

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## ABSTRACT

Polymer-stabilized blue-phase liquid crystal (BPLC) has become an increasingly important technology trend for information display and photonic applications. BPLC exhibits several attractive features, such as reasonably wide temperature range, submillisecond gray-to-gray response time, no need for alignment layer, optically isotropic voltage-off state, and large cell gap tolerance when an in-plane switching (IPS) cell is employed. Fast response time not only suppresses image blurs, improves the overall transmittance but also enables color sequential display without noticeable color breakup. With time sequential RGB LED colors, the spatial color filters can be eliminated so that both optical efficiency and resolution density are tripled. High optical efficiency helps to reduce power consumption while high resolution density is particularly desirable for the future Ultra High Definition Television. However, some bottlenecks such as high operation voltage, hysteresis, low relaxation frequency, residual birefringence, image sticking, charging issue due to the large capacitance, and relatively low transmittance for the IPS mode, remain to be overcome before widespread application of BPLC can be realized. To reduce operation voltage, both new BPLC materials and new device structures have been investigated. In this paper, we highlight some recent advances in large Kerr constant, fast response time BPLC material development, and new device structures. Especially, we will focus on new BP LCDs with low operation voltage, submillisecond response time, high transmittance, and negligible hysteresis and residual birefringence. The sunrise for BP LCD is near.

**Keywords:** Blue phase liquid crystal, LCD, Kerr constant, hysteresis, response time, relaxation frequency

## 1. INTRODUCTION

Polymer-stabilized blue-phase liquid crystal (PS-BPLC)<sup>1-5</sup> exhibits three distinctive features: 1) self-assembly process so that no surfactant (e.g., rubbed polyimide layer) is needed to generate uniform molecular alignment, 2) nanoscale (~100 nm) double-twist cylinder diameter and short coherence length which leads to microsecond response time,<sup>6,7</sup> and 3) three-dimensional lattice structure resulting in optically isotropic voltage-off state. Alignment-layer-free process greatly simplifies the device fabrication process. Fast response time not only produces crisp pictures without image blurs but also enables color sequential displays.<sup>8,9</sup> By eliminating spatial color filters, both optical efficiency and resolution density are tripled. This feature is particularly important for reducing the power consumption of a high resolution display. Moreover, short coherence length significantly improves the diffraction efficiency of BPLC gratings.<sup>10</sup> Finally, optically isotropic state makes adaptive BPLC lenses polarization independent.<sup>11,12</sup> Therefore, BPLC holds promises for display and photonics applications.<sup>13</sup>

However, high operation voltage, noticeable hysteresis, and large capacitance still hinder its widespread applications. Among these three technical barriers, high voltage is the root cause. If the voltage is low (<10V), then the electrostriction effect which causes lattice distortion would be prohibited and hysteresis be negligible (<1%), and high frame rate (>180Hz) can be achieved by the bootstrapping circuits.<sup>14</sup> Therefore, the most fundamental issue for BPLC studies is to lower the operation voltage to below 10V, without sacrificing other desirable properties, such as high transmittance, submillisecond response time, high contrast ratio, and wide viewing angle. To achieve this goal, both device structures and BPLC materials have been investigated extensively. From device structure viewpoint, two major approaches have been developed: 1) implementing protrusion electrodes so that the fringing field can penetrate deeply into the LC bulk,<sup>15-17</sup> and 2) vertical field switching (VFS)<sup>18</sup> to generate uniform longitudinal field across the BPLC layer. From material aspect, developing BPLC materials with a large Kerr constant ( $K$ )<sup>19,20</sup> helps reduce driving voltage because the on-state voltage is inversely proportional to  $\sqrt{K}$ .<sup>16</sup> From Gerber's model, Kerr constant is governed by the birefringence ( $\Delta n$ ), dielectric anisotropy ( $\Delta\epsilon$ ), average elastic constant ( $k$ ), and pitch length ( $p$ ) of the chiral LC host as:<sup>21</sup>

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$$K \sim \Delta n \cdot \Delta \varepsilon \cdot p^2 / k. \quad (1)$$

As Eq. (1) indicates, to enlarge  $K$  by increasing pitch length seems to be a straightforward approach because  $K$  is proportional to  $p^2$ . However, this approach has its own limitations, as reported by Yan, et al.<sup>22</sup> Therefore, it is better to keep Bragg reflection in the UV region ( $\sim 350$  nm). From Eq. (1), the remaining approach is to boost  $\Delta n \cdot \Delta \varepsilon$  because  $k$  is more difficult to control.<sup>3</sup> The LC birefringence is mainly determined by the conjugation length. Considering the material stability, increase in birefringence is quite limited. Therefore, increasing  $\Delta \varepsilon$  becomes a popular option. Indeed, LC hosts with  $\Delta \varepsilon (>90)$  have been developed by JNC<sup>20</sup> and by Merck<sup>19</sup> independently. Such a large  $\Delta \varepsilon$  LC would require several polar groups so that its rotational viscosity and response time would increase dramatically. Indeed, the response time of JC-BP01M is about 2 ms at room temperature (RT $\sim 22^\circ\text{C}$ ) using an in-plane-switching (IPS) cell.<sup>20</sup> In addition, the hysteresis is about 6% because of the strong peak electric field near the IPS electrode edges. Besides, with low relaxation frequency (1.3 kHz), there will be dielectric heating effect and the driving voltage increases significantly for high frequency ( $\sim 1\text{kHz}$ ) operation.<sup>23</sup> A delicate balance between operating voltage, response time, relaxation frequency and hysteresis has to be taken into consideration.

In this paper, we report a large Kerr constant PS-BPLC while keeping submillisecond response time and negligible hysteresis at room temperature. The measured Kerr constant is  $33.1 \text{ nm/V}^2$  in an IPS cell and  $20.9 \text{ nm/V}^2$  in a VFS cell at  $\lambda=514$  nm. The on-state voltage of our VFS-BPLC device is  $8.4 \text{ V}_{\text{rms}}$  at  $\lambda=514$  nm, hysteresis 0.9%, and response time  $<1\text{ms}$  at RT. We also discuss the issue of low relaxation frequency and transmittance, and approaches to solve these problems.

## 2. RESULTS AND DISCUSSIONS

### 2.1 Driving voltage

#### 2.1.1 IPS BPLCD

A common driving method for BPLCD is to use fringing field generated from IPS electrodes. The major advantages of IPS mode are twofold: 1) a normal backlight can be used, and 2) wide viewing angle can be obtained by a simple biaxial compensation film.<sup>24</sup> But high driving voltage ( $\sim 50\text{V}$ ) still hinders the wide application of IPS BPLCD.

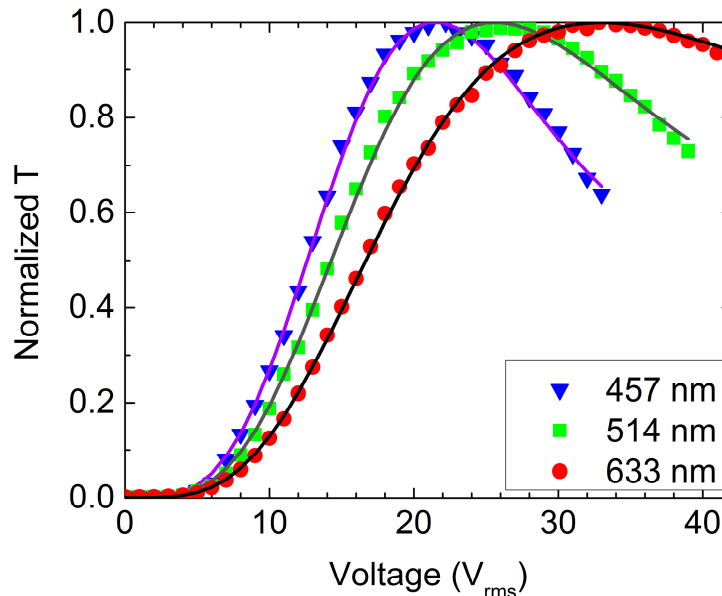


Figure 1. VT curves of the PSBP IPS cell using JC-BP06N at the specified wavelengths. Dots are measured data and lines are fitted curves with extended Kerr model.

A large  $\Delta \varepsilon$  would help to improve Kerr constant and hence reduce the driving voltage. Here we prepared a LC host with  $\Delta \varepsilon \sim 470$  JC-BP06N (by JNC) whose clearing point is  $T_c=73.8^\circ\text{C}$ .<sup>25</sup> The rotational viscosity of JC-BP06N is over

1470mPa.s due to the huge  $\Delta\epsilon$ . The blue phase precursor consists of 88.17 wt% JC-BP06N with 2.92 wt% of chiral dopant R5011 (HCCH), 5.24 wt% RM257 (Merck), 3.46 wt% TMPTA (1,1,1-Trimethylolpropane Triacrylate, Sigma Aldrich) and 0.21 wt% photoinitiator. We filled the BPLC precursor into an IPS-5/5 cell: the electrode width and gap are both  $5\mu\text{m}$ , and cell gap is  $7\mu\text{m}$ . Afterwards the cell was placed on a Linkam heating/freezing stage controlled by a temperature programmer. The cell was cooled to blue phase and then exposed to UV light ( $\lambda\sim 365\text{ nm}$ ) with intensity of  $2\text{ mW/cm}^2$  for 30 min. After UV irradiation, nano-structured BPLC composites were self-assembled. The measured Bragg reflection wavelength is  $\sim 380\text{ nm}$ , which is about the same as that of JC-BP01M (our benchmarking BPLC material).

The IPS cell was then sandwiched between two crossed polarizers and the voltage dependent transmitted light was focused by a lens so that different diffraction orders<sup>10</sup> can be collected by the detector. The peak transmittance of the IPS-5/5 cell is about 60% because of the dead zones on top of the electrodes. Figure 1 plots the normalized transmittance (T) at different wavelengths. From Fig. 1, we find the on-state voltage (corresponding to peak transmittance)  $V_{on} = 22.2, 25.4$  and  $32.8\text{ V}_{\text{rms}}$  at  $\lambda = 457, 514$  and  $633\text{ nm}$ , respectively. Through fitting the data with the extended Kerr model,<sup>4,26</sup> we get  $K = 39.7, 33.1,$  and  $26.9\text{ nm/V}^2$ , correspondingly. By contrast, the Kerr constant of our BPLC is  $\sim 2.1\text{X}$  larger than that of JC-BP01M at room temperature (also in IPS cell).<sup>27</sup>

### 2.1.2 VFS BPLCD

As Fig. 1 depicts, the driving voltage of JC-BP06N BPLC in IPS cell is still very high. For IPS, the non-uniformity in electric field, including dead zones on top of electrode, causes less efficient driving and lower transmittance. Meanwhile, the strong peak electric fields near the electrode edges result in hysteresis and slow response time. Another possible driving method is to use vertical field switching (VFS) mode,<sup>18</sup> in which the electric field is in longitudinal direction. VFS mode offers several spectacular properties, such as low voltage, high transmittance, fast response time, and negligible hysteresis, but it requires a directional backlight and phase compensation in order to achieve wide view.<sup>28</sup>

We prepared a VFS cell using the same BPLC precursor. The VFS cell is comprised of two ITO (indium tin oxide) glass substrates, but without polyimide alignment layer. The cell gap was controlled at  $\sim 3.2\mu\text{m}$ . In order to acquire phase retardation, the laser beam was incident on the VFS cell at  $70^\circ$  oblique angle. The VFS cell was immersed in a transparent 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.<sup>18</sup> The container was placed between two crossed polarizers, and the light transmittance was measured. The cell was driven at 100 Hz. The Kerr constant would decrease as the driving frequency increases according to the extended Coles-Coles model.<sup>23</sup> Ideally, a driving frequency higher than 180Hz is required for color sequential displays. If the driving frequency was increased to 240 Hz, Kerr constant would drop by 8%, which in turn increase the on-state voltage by  $\sim 4\%$ .

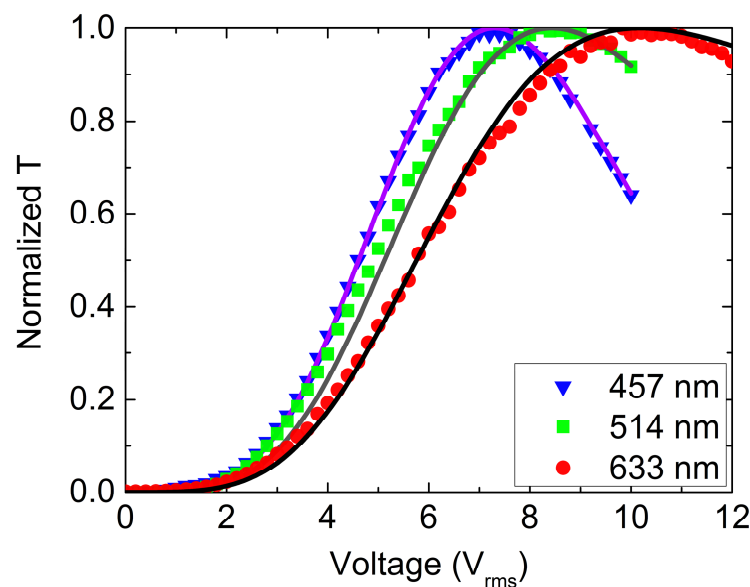


Figure 2. VT curves of the PSBP VFS cell using JC-BP06N at the specified wavelengths. Dots are measured data and lines are fitted curves with extended Kerr model. Cell gap  $d = 3.2\mu\text{m}$ .

Figure 2 depicts the measured VT curve at different wavelengths. Here, the transmittance is normalized to that of two parallel polarizers. From Fig. 2,  $V_{on} = 7.3, 8.4$  and  $9.9$  V<sub>rms</sub> for  $\lambda=457, 514$  and  $633$  nm, respectively. Through fitting the VT curves,<sup>4</sup>  $K=\Delta n_s/(\lambda E_s^2)=24.9, 20.9$  and  $17.4$  nm/V<sup>2</sup> for  $\lambda=457, 514$  and  $633$  nm, respectively. For comparison, at  $\lambda=633$  nm the Kerr constant of our BPLC is  $\sim 2.3X$  larger than that of JC-BP01M (also from VFS cell). This improvement is close to  $2.1X$  by using the IPS cells, considering the measurement and fitting errors. So, on average our PS-BPLC shows a  $2.2X$  larger Kerr constant than JC-BP01M.

## 2.2 Relaxation frequency

Since the relaxation frequency  $f_r$  is proportional to  $1/(\eta l^3)$ ,<sup>29</sup> a large  $\Delta\epsilon$  LC would result in lower relaxation frequency; e.g., JNC JC-BP01M has a relaxation frequency of  $1.3$  kHz, and its Kerr constant decreases by  $\sim 2X$  as the frequency increases from  $60$  Hz to  $1$  kHz<sup>23</sup>. When driving this BPLC at  $1$  kHz for color sequential displays, two serious problems are encountered: 1) the operation voltage is increased by  $\sim 40\%$ , and 2) the dielectric heating effect<sup>30-32</sup> due to the imaginary part (absorption) of dielectric constant, which has a peak value at the relaxation frequency, will affect the performance stability of the BPLC device.

Figure 3 depicts the measured the  $\epsilon_{\perp}'$  and  $\epsilon_{\parallel}'$  (real part of the permittivity) of JC-BP06N. The dots are the measured  $\epsilon_{\parallel}'$  for JC-BP06N and the lines are fitting results with Debye relaxation equation:<sup>33,34</sup>

$$\epsilon_{\parallel}' = \epsilon_{\infty} + \frac{\epsilon_0 - \epsilon_{\infty}}{1 + (f / f_r)^2} \quad (6)$$

From these data, we obtain  $\epsilon_0=491$  at low frequency region for JC-BP06N. As the frequency increases,  $\epsilon_{\parallel}'$  decreases dramatically due to the slow dielectric relaxation time resulting from the large viscosity and bulky molecular structure.<sup>29</sup> Through fitting with Eq. (6), we find  $f_r=1.07$  kHz. For conventional low viscosity nematic LCs, the relaxation frequency is usually quite high ( $>50$  kHz). An effective diluter would help to dramatically reduce the viscosity and increase the relaxation frequency. After doping a small amount of diluter (5wt% of SCC3), the  $f_r$  shifts to  $1.92$  kHz because of the dramatically reduced viscosity.<sup>35</sup> However,  $\epsilon_0$  drops nonlinearly from  $491$  to  $311$  after adding 5wt% SCC3.<sup>25,36</sup>

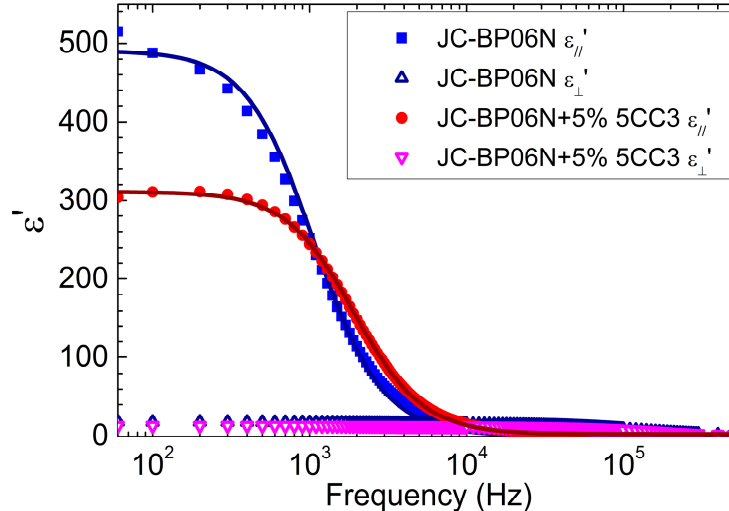


Figure. 3. Frequency-dependent  $\epsilon_{\parallel}'$  and  $\epsilon_{\perp}'$  of JC-BP06N before and after adding 5% SCC3.

Moreover, the relaxation frequency decreases exponentially with temperature, therefore low temperature and high frequency operation for large viscosity PS-BPLCs would be limited.<sup>37</sup> Even the temperature is still above the melting point of a blue phase, the dramatic plunge of  $\Delta\epsilon$  results in a high driving voltage, which makes the device difficult to operate. Again, an effective diluter would help to increase the relaxation frequency and benefit the low temperature operation.<sup>35</sup>

### 2.3 Hysteresis

Hysteresis affects grayscale control accuracy of a BPLC device and should be minimized.<sup>38</sup> To characterize hysteresis, we drove the VFS cell by ascending the voltage to  $V_{on}$  and then gradually descending it to 0. Hysteresis is defined as  $\Delta V/V_{on}$ , where  $\Delta V$  is the voltage difference between the forward and backward scans at half of the peak transmittance. For the VFS cell, the measured hysteresis is only  $\sim 0.9\%$  ( $\Delta V=0.08V$ ) at  $\lambda=514$  nm, which is negligible. If the applied voltage exceeds  $8.4 V_{rms}$ , then the hysteresis will gradually increase. Here we define a critical field as  $E_c=V_{on}/d$ . For the BPLC we studied, its  $E_c=2.67$  V/ $\mu m$ . Above  $E_c$ , hysteresis will gradually grow and response time becomes slower.<sup>39,40</sup> Therefore, the cell gap of a VFS cell plays an important role affecting the on-state voltage and hysteresis. On the other hand, for IPS cell the peak electric field near the electrodes is usually very strong and can easily exceed  $E_c$ . Thus, the hysteresis in an IPS cell is usually larger than that of a VFS cell. Low driving voltage or smooth electrode design helps to reduce hysteresis in IPS BPLCD.<sup>41</sup>

### 2.4 Response time

Fast response time is a very attractive feature for PS-BPLC. The relaxation time of a BPLC is governed by rotational viscosity ( $\gamma_1$ ), elastic constant and pitch length as:<sup>11</sup>

$$\tau = \frac{\gamma_1 p^2}{k(2\pi)^2} \quad (5)$$

where  $\gamma_1$  is the rotational viscosity. It is known that the BPLC response time in the low field region where lattice distortion does not occur is primarily governed by the viscosity, average elastic constant, and pitch length.<sup>7,21,42</sup> Polymer structure and polymer concentration also play important roles.<sup>32</sup> Although the viscosity of our JC-BP06N is quite high, the monomer (TMPTA) we employed has three functional groups which provide strong crosslinking networks and helps reduce the response time. We measured the rise time and decay time of the VFS cell by swinging the voltage between 0 and  $V_{on}$ . The response time is defined as 90% to 10% transmittance change. At  $\lambda=514$  nm and room temperature, the rise time is 460  $\mu s$  and decay time is 950  $\mu s$ . Adding  $\sim 5\%$  diluter would dramatically reduce the viscosity and response time, while keeping Kerr constant more or less unchanged.<sup>35</sup>

### 2.5 Contrast ratio

In the voltage-off state, blue phase is not perfectly optically isotropic but with a tiny optical rotatory power.<sup>43</sup> At  $\lambda=514$  nm, our measured contrast ratio (CR) of the VFS cell is 580:1 under crossed polarizers. If we rotate the analyzer by  $1.8^\circ$ , CR is boosted to 1900:1. It can be further improved by shifting the Bragg reflection wavelength to the shorter wavelength side, but the operating voltage will increase. The depolarization from the oblique incidence might also degrade CR. For the IPS cell, the CR is better due to the normal incidence.

### 2.6 Transmittance

High transmittance is very important since it helps to reduce power consumption. For VFS BPLCD, the transmittance of the cell is approaching 100%. However, the sophisticated phase compensation and optical design<sup>44</sup> decreases the transmittance to  $\sim 85\%$ . Optimization in the design is needed. On the other hand, the transmittance for typical IPS BPLCD is quite low,  $\sim 60\%$  due to the dead zones on top of electrodes. By reducing the width ( $w$ ) and gap ( $l$ ) of the IPS electrodes, the operation voltage is reduced while the transmittance keeping above 80%.<sup>45</sup> Reducing the ratio of  $l/w$  would also help to reduce the dead zone area ratio and improve the transmittance. A refraction model has been developed to better predict the transmittance of IPS BPLCD and promising approaches, such as etched electrode design, for achieving high transmittance and low operation voltage have been demonstrated.<sup>46</sup>

## 3. CONCLUSION AND OUTLOOK

Polymer-stabilized blue-phase liquid crystal (BPLC) opens a gateway for next-generation display and photonic applications because it exhibits several attractive features, such as submillisecond response time, no need for alignment layer, and optically isotropic voltage-off state. Some bottlenecks including high operation voltage, low relaxation frequency, hysteresis, and relatively low transmittance have been gradually overcome recently. Especially, we demonstrate a hysteresis-free BP LCD with fast response time, high transmittance, negligible hysteresis and low operation voltage. The dawn of BPLCD is near.

## REFERENCES

- [1]. Kikuchi, H.; Yokota, M.; Hisakado, Y.; Yang, H.; Kajiyama, T., "Polymer-stabilized liquid crystal blue phases," *Nat. Mater.* 1 (1), 64-68 (2002).
- [2]. Hisakado, Y.; Kikuchi, H.; Nagamura, T.; Kajiyama, T., "Large electro-optic Kerr effect in polymer-stabilized liquid-crystalline blue phases," *Adv. Mater.* 17 (1), 96-98 (2005).
- [3]. Choi, S. W.; Yamamoto, S.; Haseba, Y.; Higuchi, H.; Kikuchi, H., "Optically isotropic-nanostructured liquid crystal composite with high Kerr constant," *Appl. Phys. Lett.* 92 (4), 043119 (2008).
- [4]. Ge, Z.; Gauza, S.; Jiao, M.; Xianyu, H.; Wu, S. T., "Electro-optics of polymer-stabilized blue phase liquid crystal displays," *Appl. Phys. Lett.* 94 (10), 101104 (2009).
- [5]. Yan, J.; Rao, L.; Jiao, M.; Li, Y.; Cheng, H. C.; Wu, S. T., "Polymer-stabilized optically isotropic liquid crystals for next-generation display and photonics applications," *J. Mater. Chem.* 21 (22), 7870-7877 (2011).
- [6]. Chen, K. M.; Gauza, S.; Xianyu, H. Q.; Wu, S. T., "Submillisecond Gray-Level Response Time of a Polymer-Stabilized Blue-Phase Liquid Crystal," *J. Display Technol.* 6 (2), 49-51 (2010).
- [7]. Chen, Y.; Yan, J.; Sun, J.; Wu, S. T.; Liang, X.; Liu, S. H.; Hsieh, P. J.; Cheng, K. L.; Shiu, J. W., "A Microsecond-Response Polymer-Stabilized Blue Phase Liquid Crystal," *Appl. Phys. Lett.* 99 (20), 201105 (2011).
- [8]. Bos, P.; Buzak, T.; Vatne, R., "A Full-Color Field-Sequential Color Display," *Proc. SID* 26 (2), 157-161 (1985).
- [9]. Gauza, S.; Zhu, X.; Piecek, W.; Dabrowski, R.; Wu, S. T., "Fast switching liquid crystals for color-sequential LCDs," *J. Display Technol.* 3 (3), 250-252 (2007).
- [10]. Yan, J.; Li, Y.; Wu, S. T., "High-efficiency and fast-response tunable phase grating using a blue phase liquid crystal," *Opt. Lett.* 36 (8), 1404-1406 (2011).
- [11]. Li, Y.; Wu, S. T., "Polarization independent adaptive microlens with a blue-phase liquid crystal," *Opt. Express* 19 (9), 8045-8050 (2011).
- [12]. Lin, Y. H.; Chen, H. S.; Lin, H. C.; Tsou, Y. S.; Hsu, H. K.; Li, W. Y., "Polarizer-free and fast response microlens arrays using polymer-stabilized blue phase liquid crystals," *Appl. Phys. Lett.* 96 (11), 113505 (2010).
- [13]. Coles, H. J.; Morris, S., "Liquid-crystal lasers," *Nat. Photonics* 4 (10), 676-685 (2010).
- [14]. Tu, C. D.; Lin, C. L.; Yan, J.; Chen, Y.; Lai, P. C.; Wu, S. T., "Driving Scheme Using Bootstrapping Method for Blue-Phase LCDs," *J. Display Technol.* 9 (1), 3-6 (2013).
- [15]. Jiao, M.; Li, Y.; Wu, S. T., "Low voltage and high transmittance blue-phase liquid crystal displays with corrugated electrodes," *Appl. Phys. Lett.* 96 (1), 011102 (2010).
- [16]. Rao, L.; Ge, Z.; Wu, S. T.; Lee, S. H., "Low voltage blue-phase liquid crystal displays," *Appl. Phys. Lett.* 95 (23), 231101 (2009).
- [17]. Kim, M.; Kim, M. S.; Kang, B. G.; Kim, M. K.; Yoon, S.; Lee, S. H.; Ge, Z.; Rao, L.; Gauza, S.; Wu, S. T., "Wall-shaped electrodes for reducing the operation voltage of polymer-stabilized blue phase liquid crystal displays," *J. Phys. D: Appl. Phys.* 42 (23), 235502 (2009).
- [18]. Cheng, H. C.; Yan, J.; Ishinabe, T.; Wu, S. T., "Vertical field switching for blue-phase liquid crystal devices," *Appl. Phys. Lett.* 98 (26), 261102 (2011).
- [19]. Wittek, M.; Tanaka, N.; Wilkes, D.; Bremer, M.; Pauluth, D.; Canisius, J.; Yeh, A.; Yan, R.; Skjonnemand, K.; Klasen-Memmer, M., "New materials for polymer-stabilized blue phase," *SID Int. Symp. Digest Tech.* 43 (1), 25-28 (2012).
- [20]. Rao, L.; Yan, J.; Wu, S. T.; Yamamoto, S. I.; Haseba, Y., "A large Kerr constant polymer-stabilized blue phase liquid crystal," *Appl. Phys. Lett.* 98 (8), 081109 (2011).
- [21]. Gerber, P. R., "Electro-optical effects of a small-pitch blue-phase system," *Mol. Cryst. Liq. Cryst.* 116 (3-4), 197-206 (1985).
- [22]. Yan, J.; Luo, Z.; Wu, S. T.; Shiu, J. W.; Lai, Y. C.; Cheng, K. L.; Liu, S. H.; Hsieh, P. J.; Tsai, Y. C., "Low voltage and high contrast blue phase liquid crystal with red-shifted Bragg reflection," *Appl. Phys. Lett.* 102 (1), 011113 (2013).
- [23]. Li, Y.; Chen, Y.; Sun, J.; Wu, S. T.; Liu, S. H.; Hsieh, P. J.; Cheng, K. L.; Shiu, J. W., "Dielectric dispersion on the Kerr constant of blue phase liquid crystals," *Appl. Phys. Lett.* 99 (18), 181126 (2011).
- [24]. Zhu, X.; Ge, Z.; Wu, S. T., "Analytical Solutions for Uniaxial-Film-Compensated Wide-View Liquid Crystal Displays," *J. Display Technol.* 2 (1), 2-20 (2006).
- [25]. Chen, Y.; Xu, D.; Wu, S. T.; Yamamoto, S.; Haseba, Y., "A low voltage and submillisecond-response polymer-stabilized blue phase liquid crystal," *Appl. Phys. Lett.* 102 (14), 141116 (2013).

- [26]. Yan, J.; Cheng, H. C.; Gauza, S.; Li, Y.; Jiao, M.; Rao, L.; Wu, S. T., "Extended Kerr effect of polymer-stabilized blue-phase liquid crystals," *Appl. Phys. Lett.* 96 (7), 071105 (2010).
- [27]. Rao, L.; Yan, J.; Wu, S. T.; Yamamoto, S.; Haseba, Y., "A large Kerr constant polymer-stabilized blue phase liquid crystal," *Appl. Phys. Lett.* 98 (8), 081109 (2011).
- [28]. Cheng, H. C.; Yan, J.; Ishinabe, T.; Lin, C. H.; Liu, K. H.; Wu, S. T., "Wide-View Vertical Field Switching Blue-Phase LCD," *J. Display Technol.* 8 (11), 627-633 (2012).
- [29]. Blinov, L. M., "Electro-optical and magneto-optical properties of liquid crystals," Wiley, 1983.
- [30]. Metaxas, A. C.; Meredith, R. J., "Industrial Microwave Heating," IET: London, 1983.
- [31]. Schadt, M., "Dielectric heating and relaxations in nematic liquid-crystals," *Mol. Cryst. Liq. Cryst.* 66 (1), 319-336 (1981).
- [32]. Wen, C. H.; Wu, S. T., "Dielectric heating effects of dual-frequency liquid crystals," *Appl. Phys. Lett.* 86 (23), 231104 (2005).
- [33]. Frank, F. C., "I. Liquid crystals. On the theory of liquid crystals," *Discuss. Faraday Soc.* 25 19-28 (1958).
- [34]. Xianyu, H.; Wu, S. T.; Lin, C. L., "Dual frequency liquid crystals: a review," *Liq. Cryst.* 36 (6), 717-726 (2009).
- [35]. Chen, Y.; Yan, J.; Schadt, M.; Liu, S. H.; Cheng, K. L.; Shiu, J. W.; Wu, S. T., "Diluter effects on polymer-stabilized blue phase liquid crystals," *J. Display Technol.* 9 (7), 592-597 (2013).
- [36]. Dakin, T. W. In "Engineering Dielectrics," Bartnikas, R.; Eichhorn, R. M.; Brook, B., Eds., 1983, Chap. 8.
- [37]. Peng, F.; Chen, Y.; Chen, H.; Yuan, J.; Wu, S. T., "Low temperature and high frequency operation limits of blue phase liquid crystals," submitted (2013).
- [38]. Chen, K. M.; Gauza, S.; Xianyu, H.; Wu, S. T., "Hysteresis Effects in Blue-Phase Liquid Crystals," *J. Display Technol.* 6 (8), 318-322 (2010).
- [39]. Rao, L.; Yan, J.; Wu, S. T.; Lai, Y. C.; Chiu, Y. H.; Chen, H. Y.; Liang, C. C.; Wu, C. M.; Hsieh, P. J.; Liu, S. H.; Cheng, K. L., "Critical field for a hysteresis-free BPLC device," *J. Disp. Technol.* 7 (12), 627-629 (2011).
- [40]. Yan, J.; Chen, Y.; Wu, S. T.; Liu, S. H.; Cheng, K. L.; Shiu, J. W., "Dynamic response of a polymer-stabilized blue-phase liquid crystal," *J. Appl. Phys.* 111 (6), 063103 (2012).
- [41]. Rao, L.; Yan, J.; Wu, S. T.; Lai, Y. C.; Chiu, Y. H.; Chen, H. Y.; Liang, C. C.; Wu, C. M.; Hsieh, P. J.; Liu, S. H.; Cheng, K. L., "Critical Field for a Hysteresis-Free BPLC Device," *J. Display Technol.* 7 (12), 627-629 (2011).
- [42]. Yan, J.; Wu, S. T., "Effect of Polymer Concentration and Composition on Blue Phase Liquid Crystals," *J. Display Technol.* 7 (9), 490-493 (2011).
- [43]. Liu, Y.; Lan, Y. F.; Zhang, H.; Zhu, R.; Xu, D.; Tsai, C. Y.; Lu, J. K.; Sugiura, N.; Lin, Y. C.; Wu, S. T., "Optical rotatory power of polymer-stabilized blue phase liquid crystals," *Appl. Phys. Lett.* 102 (13), 131102 (2013).
- [44]. Yan, J.; Xu, D.; Cheng, H. C.; Wu, S. T.; Lan, Y. F.; Tsai, C. Y., "Turning film for widening the viewing angle of a blue phase liquid crystal display," *Appl. Opt.* 52 (36), 8840-8844 (2013).
- [45]. Chen, K. M.; Yan, J.; Wu, S. T.; Chang, Y. P.; Tsai, C. C.; Shiu, J. W., "Electrode Dimension Effects on Blue-Phase Liquid Crystal Displays," *J. Display Technol.* 7 (7), 362-364 (2011).
- [46]. Xu, D.; Chen, Y.; Liu, Y.; Wu, S. T., "Refraction effect in an in-plane-switching blue phase liquid crystal cell," *Opt. Express* 21 (21), 24721-24735 (2013).