Polymer-stabilized blue phase liquid crystal with a negative Kerr constant

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Abstract: A polymer-stabilized blue-phase liquid crystal (BPLC) with a negative Kerr constant is reported. In a voltage-on state, the double-twist BPLC molecules within the lattice cylinders are reoriented perpendicular to the applied electric field because of their negative dielectric anisotropy. As a result, the induced birefringence has a negative value, which leads to a negative Kerr constant. The negative sign of Kerr constant is experimentally validated by using a quarter-wave plate and a vertical field switching cell. Such a BPLC shows a negligible (~1%) hysteresis and fast response time (~1ms) at the room temperature, although its Kerr constant is relatively small because the employed host has a small $\Delta\varepsilon$.

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1. Introduction

Blue phase liquid crystal (BPLC) [1,2] is a self-assembled nano-structured composite. It is typically comprised of 90-95wt% nematic LC host and 5-10wt% chiral dopant with a high helical twisting power (HTP>100) [3]. Most of BPLCs studied so far employ a positive dielectric anisotropy ($\Delta\varepsilon$) LC host. If the LC host has a positive $\Delta\varepsilon$, then the electric-field-induced birefringence Δn_{ind}, which is defined as $n_e(E)$-$n_o(E)$, will also have a positive sign, and vice versa. BPLCs with negative $\Delta\varepsilon$ LC hosts have been investigated since 1980s [4,5]. However, the temperature range of such a BPLC is too narrow to be practically useful. Moreover, the measured induced birefringence is easily affected by the lattice distortion and phase transition because of the soft BPLC structure. This is evidenced by the relatively slow response time, a few milliseconds instead of submillisecond, as reported in [2].

Another approach for obtaining negative induced birefringence (or negative Kerr constant) is to utilize Debye relaxation of a positive $\Delta\varepsilon$ LC host [6]. As frequency increases, the bulky LC molecules can no longer follow the electric field so that the initially positive Kerr constant gradually decreases and eventually turns to negative. Recently, an interesting approach to obtain a negative Kerr constant with a dual frequency liquid crystal (DFLC) is demonstrated [7]. Such a BPLC exhibits an attractive feature: by switching the frequency of the applied electric field, both positive and negative Kerr constants can be realized, which results in a large refractive index change. However, to achieve a negative $\Delta\varepsilon$ the required operating frequency is usually over 100 kHz [7]. At such a high frequency, dielectric heating [8] becomes severe, which in turn shifts the crossover frequency toward the high frequency side. Another technical issue of DFLC is its relatively small $|\Delta\varepsilon|$ value, because a DFLC mixture usually consists of positive $\Delta\varepsilon$ and negative $\Delta\varepsilon$ LC compounds [9]. Small $|\Delta\varepsilon|$ leads to a small Kerr constant and high operation voltage [10], which in turn causes a large hysteresis [11].

Polymer-stabilized blue phase (PSBP) [12–14], with the assist of polymer network, has greatly expanded the BP temperature range. It is emerging as a strong contender for next-generation display [15–18] and photonic devices [19–23]. So far, almost all the PSBPs reported in literatures employ a positive dielectric anisotropy ($\Delta\varepsilon$>0) LC host, because it is

easier to obtain a large, positive Δε LC compound than the corresponding negative one. As a matter of fact, BPLC hosts with Δε>190 have been reported [24].

In this article, we report a PSBP composite with a large negative Δε (−11 at 1 kHz) LC host. The polymerization extends the BP temperature range from 8 °C to 98 °C, and therefore it enables us to study the electro-optical properties of the PSBP with a negative Kerr constant at room temperature without noticeable dielectric heating. Due to the relatively large negative Δε, the measured Kerr constant is −0.16 nm/V^2. Although this value is about 10X smaller than that of a typical positive Δε BPLC, it is ~30X higher than that of BPLC employing a DFLC [7]. To validate the negative sign of Kerr constant, we develop a simple measurement method by incorporating a quarter-wave plate between the crossed polarizers. Such a polymer-stabilized BPLC with negative Kerr constant is not only of scientific interest, it can also work as a tunable negative C-plate for controlling the viewing angle of a LCD [25].

2. Theory

Macroscopically, the electric field-induced birefringence of a BPLC follows Kerr effect in the low field region [26,27]:

$$\Delta n_{ind} = n_e(E) - n_o(E) = \lambda K E^2, \tag{1}$$

where λ is the wavelength, K the Kerr constant, and E the electric field amplitude. According to Gerber's model [28], Kerr constant could be approximated by the following equation:

$$K \approx \Delta n \Delta \varepsilon \frac{p^2}{\lambda k (2\pi)^2}, \tag{2}$$

where Δn is the birefringence, Δε the dielectric anisotropy, and k the elastic constant of the LC host, respectively, and p is the pitch length. For a positive Δn LC, Eq. (2) indicates that Kerr constant is not only proportional to Δε, but also has the same sign. For a polymer-stabilized BPLC with positive Δε, Kerr constant is positive and $n_e(E)>n_o(E)$, as Eq. (1) shows. But for a negative Δε LC, K should be negative and $n_e(E)<n_o(E)$.

3. Experiment

In experiment, we fabricated a BPLC composite using a large negative Δε nematic LC host SLC-10V513-200 (from SLICHEM, China). Its physical properties are listed as follows: Δε = −11 at f = 1 kHz, birefringence Δn = 0.147 at λ = 633 nm and ~22°C, and clearing temperature T_c = 93 °C. We mixed 84.3 wt % of the host LC, 5 wt % chiral dopant R5011 (HCCH, China) and 10.7 wt % monomers (4.7 wt % C12A and 6 wt % RM257) to form the precursor. Here, both chiral dopant and monomers are all nonpolar so that their dielectric anisotropy is negligible. The precursor was then filled into two cells. Cell 1 has IPS electrodes on the bottom substrate. The ITO (indium tin oxide) electrode width and gap are both 10 µm, and cell gap is 7.5 µm. Cell 2 is a VFS (vertical field switching) cell [29] consisting of two ITO glass substrates (but without polyimide alignment layer) and has a cell gap of 10 µm.

Blue phase was observed from 61.9°C to 70°C during heating process and from 68.2°C to 57.8°C during cooling process. Both cells were cured at 61.2°C during cooling by a UV light with λ~365 nm and intensity ~2 mW/cm^2 for 30 min. After UV exposure, the blue phase was stabilized with a clearing temperature T_c ~82.6°C. For benchmarking, we made another VFS cell (Cell 3) filled with JNC JC-BP01M whose host LC has a very large positive dielectric anisotropy (Δε~94) [10].

4. Results and discussions

We observed Cell 1 (IPS) under a polarizing optical microscope with crossed polarizers. The electrode direction was oriented at 45° with respect to the transmission axes of polarizers. Figure 1 shows the microscopic textures. From Fig. 1(a), at voltage-off state (V = 0) the

polymer-stabilized BPLC appears dark with some purple platelets, because the central wavelength of Bragg reflection occurs at around 390 nm. Figures 1(b) and 1(c) are with a root-mean-square voltage of $44V_{rms}$ and 60 V_{rms}, respectively. In the region between electrodes, the brightness is dramatically increased, while it remains dark on the electrodes. The increased transmittance between crossed polarizers indicates that some birefringence is induced in the horizontal direction. As the voltage increases, transmittance gradually increases. This phenomenon is similar to that of an IPS BPLC cell with a positive $\Delta\varepsilon$ LC host, but it is difficult to tell whether the induced birefringence is positive or negative. We also examined Cell 2 (VFS) under the same microscope stage and observed very similar textures at V = 0. However, as we applied a similar voltage no noticeable brightness change was observed. This is because the induced birefringence is along the longitudinal direction and the incident light experiences no phase retardation and is blocked by the crossed analyzer.
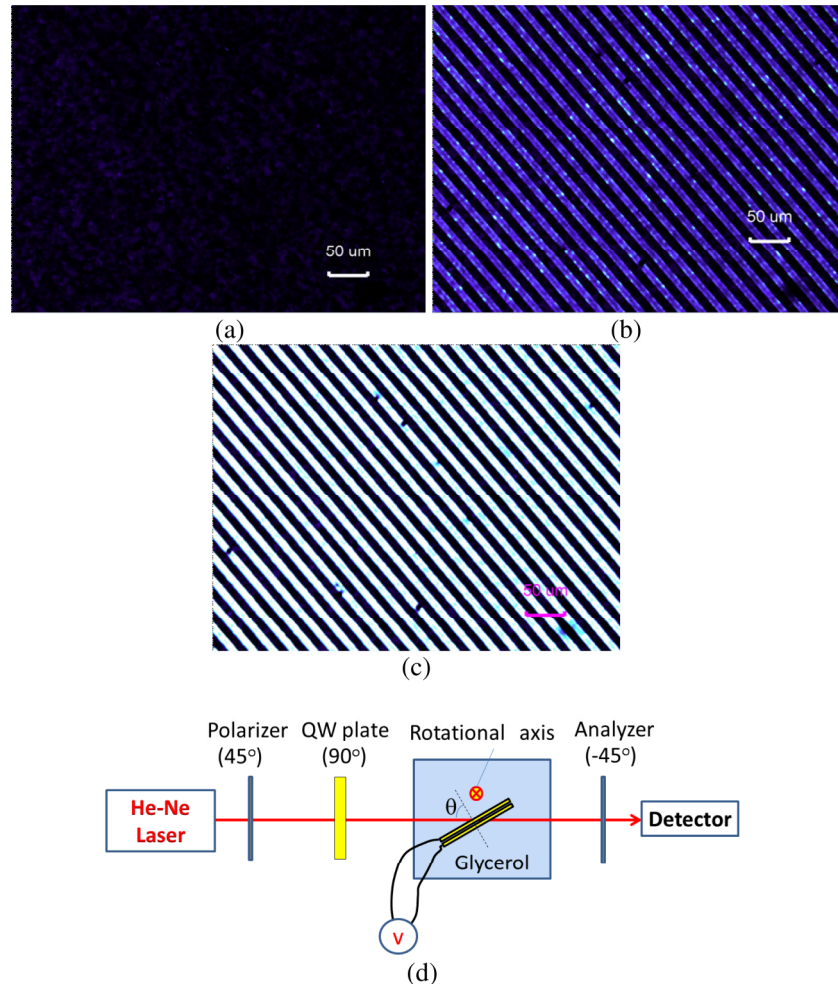

Fig. 1. (a) Microscopic image of Cell 1 under crossed polarizers at V = 0, (b) at V = $44V_{rms}$, and (c) at V = $60V_{rms}$; (d) Experimental setup for measuring the electro-optic properties of the VFS cells.

To further investigate the electro-optic properties of Cell 2 (VFS), we used a similar measurement method as reported in [29]. The setup is shown in Fig. 1(d). A He-Ne laser beam (λ = 632.8 nm) was used as a probing light source. The VFS cell was immersed in a glass container with glycerol (n = 1.47) so that the laser beam could enter the cell at a large angle

due to matched refractive index. Otherwise, the incident angle would be limited by Snell's law. The cell was sitting on a rotary stage so that the incident angle (θ) could be controlled easily. The transmission axes of polarizer and analyzer were set at 45° and −45° with respect to the rotational axis of the cell, so that the ordinary (o) wave and extraordinary (e) wave would have the same amplitude, and the phase retardation could be extracted by the measured transmittance. A quarter-wave (QW) plate was placed after the polarizer but before the VFS cell, with its optical axis oriented at 90° to the VFS cell's rotational axis. Therefore, the total phase retardation after passing the QW plate and VFS cell would be $\delta = \pi/2 + \delta_{VFS}$, where δ_{VFS} = $[n_{eff}(E)-n_o(E)]d/\sin\theta$, and $n_{eff}(E) = [(1 + tg^2\theta)/(1/n_o(E)^2 + tg^2\theta/n_e(E)^2)]^{1/2}$. For a BPLC with a positive induced birefringence (i.e., positive Kerr constant), $n_e(E)>n_{eff}(E)>n_o(E)$ and δ_{VFS} increases with voltage, so the total phase $\delta = \pi/2 + \delta_{VFS}$ increases with a starting point of $\pi/2$. As a result, the transmittance $\sin^2\delta/2$ under crossed polarizers should first increase with applied voltage in the low field region ($0<\delta_{VFS}<\pi/2$ and $\pi/2<\delta<\pi$). On the other hand, for a BPLC with a negative induced birefringence (i.e., negative Kerr constant), $n_e(E)<n_{eff}(E)<n_o(E)$ and δ_{VFS} is a negative value, which decreases with voltage. Therefore, $\delta = \pi/2 + \delta_{VFS}$ should decrease as voltage increases and we should observe a decreased transmittance in the low field region ($-\pi/2 <\delta_{VFS}<0$ and $0<\delta< \pi/2$).
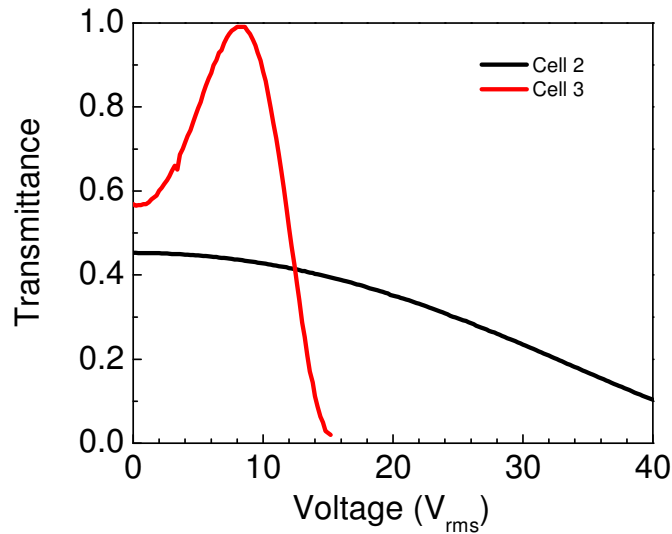

Fig. 2. Measured VT curves of Cell 2 and Cell 3 using the experimental setup in Fig. 1(d) with a QW plate sitting in front of the VFS cells.

To validate the above analyses, we measured the voltage-dependent transmittance (VT) curves of Cell 2 and Cell 3, and the results are plotted in Fig. 2. Here the transmittance is normalized to that of two parallel polarizers. Since the BPLC has a relatively small negative Kerr constant, we chose a large incident angle $\theta = 80°$ in a VFS cell in order to accumulate sufficient phase retardation. The electric field frequency is 1 kHz. As expected, Cell 2 and Cell 3 exhibit an opposite transmittance change in low field region, indicating their Kerr constants are indeed with an opposite sign. The transmittance of Cell 3 (positive $\Delta\varepsilon$) increases with voltage until $8V_{rms}$ and then decreases as voltage further increases. This is because the positive $\Delta\varepsilon$ BPLC in Cell 3 has a large Kerr constant, and the phase retardation δ_{VFS} reaches $\pi/2$ ($\delta = \pi/2 + \delta_{VFS} = \pi$) at V = $8V_{rms}$, where peak transmittance occurs. On the contrary, the transmittance of Cell 2 (negative $\Delta\varepsilon$) decreases as voltage increases and does not reach a minimum due to its relatively small Kerr constant. Ideally, at V = 0 both cells should be at 50% transmittance. But as Fig. 2 shows, there is a small displacement. This phenomenon can

be explained as follows: 1) The transmittance $\sin^2\delta/2$ has the largest slope near $\delta = \pi/2$, therefore, even a small phase retardation deviation will be magnified. 2) In our VFS cell, the incident angle is quite large (80°). A small residual birefringence from the BPLC sample or depolarization from any optical component could lead to small phase retardation.

Next we removed the QW plate and measured the VT curve of Cell 2 again. As shown in Fig. 3, the transmittance peak occurs at $80V_{rms}$ and the hysteresis [30] (defined as $\Delta V/V_p$, where ΔV is the voltage difference at half-maximum transmittance between forward and backward, and V_p is the peak-transmittance voltage) is quite small (~1%). The dark state of the VFS cell is not very good because of the large incident angle (80°). We used extended Kerr model [31] to fit the VT curve, and obtained Kerr constant $K = -0.16$ nm/V^2. The small Kerr constant is mainly due to the relatively small dielectric anisotropy ($\Delta\varepsilon = -11$) of the host LC.
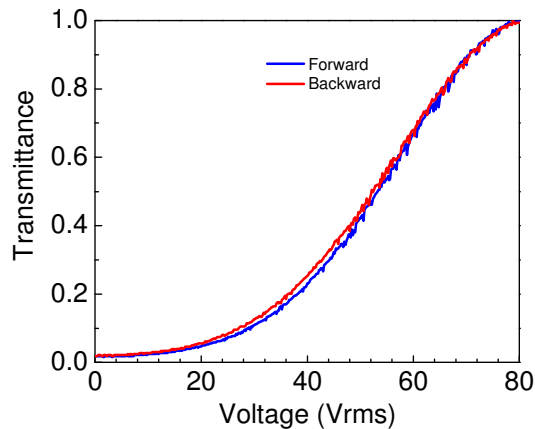

Fig. 3. Measured VT curve of Cell 2 using the experimental setup in Fig. 1(d) without a QW plate in front of the VFS cell.

We also measured the response time (between dark state and peak-transmittance state) of Cell 2 (VFS) at the room temperature. The rise time and decay time are all about 1 ms. As the temperature increases, the response time decreases sharply, which is similar to that of positive $\Delta\varepsilon$ BPLC materials [10].

5. Conclusion

We report the results of a polymer-stabilized BPLC with a negative Kerr constant, which originates from the negative $\Delta\varepsilon$ of the employed LC host. To experimentally prove that indeed the BPLC has a negative induced birefringence ($n_e < n_o$), we incorporated a quarter-wave plate in our measurement system. Our material shows a negligible (~1%) hysteresis and fast response time (~1ms) at the room temperature, although its Kerr constant is ~10X smaller than that of a typical PSBP with a positive LC host, but this value is ~30X higher than that using a DFLC [7]. The flattened refractive index ellipsoid can be used as a tunable C-plate for controlling the viewing angle of a LCD.

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