

Low Voltage Polymer-stabilized Blue Phase with Red-shifted Bragg Reflection

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Abstract

We demonstrated a low voltage polymer-stabilized blue phase liquid crystal (BPLC) by red-shifting the Bragg reflection to the visible region. To retain high contrast ratio, the BPLC is sandwiched between two crossed circular polarizers. The driving voltage is reduced by 35% compared to that of a transparent BPLC, while keeping submillisecond response time. The proposed approach would accelerate the emergence of BPLC for next-generation display applications.

1. Introduction

Polymer-stabilized blue phase liquid crystal (PS-BPLC) [1-11] exhibits several attractive features, such as submillisecond response time, no need for surface alignment layer, and cell gap insensitivity provided that in-plane-switching (IPS) electrodes are employed. It is a strong contender for next-generation display and photonic applications. However, the bottleneck is the relatively high operation voltage (~50V), which originates from a relatively small Kerr constant of the employed BPLC materials. To reduce the operation voltage to below 10V, several device structures have been proposed [8-11]. Although these device structures are helpful for reducing voltage, they do increase the manufacturing complexity. Therefore, there is an urgent need to reduce the operation voltage from material composition aspect.

In this paper, we demonstrate a method to enhance the Kerr constant of BPLC by shifting the Bragg reflection from ~350 nm to ~600 nm without sacrificing contrast ratio. To retain high contrast ratio, in the experiment we take following steps: first we choose a right-handed circular polarizer (RCP) as the front polarizer so that the transmitted light before entering the BPLC cell is right-handed, then we use a left-handed chiral dopant so that in the voltage-off state the BPLC cell transmits the incoming right-handed circular light [12-14]; and finally we choose a left-handed circular polarizer (LCP) as the analyzer so that the outgoing right-handed circular light from the BPLC cell is absorbed. As a result, we keep a high contrast ratio while reducing the driving voltage by 35% and maintaining submillisecond response time.

2. Experiment

For the same device structure, the driving voltage of BPLC is inversely related to the pitch length as [15]:

$$V_{on} \sim 1/P. \quad (1)$$

From Eq. (1), shifting the Bragg reflection to near infrared region would lower the operating voltage significantly while keeping the sample clear in the visible region. However, one important factor has to be taken into account, which is blue phase appears only

when the chirality exceeds a certain value. If the chiral concentration is too low, then the blue phase may not exist. Since the pitch length is inversely proportional to chiral concentration, the pitch length cannot be increased unlimitedly. Moreover, response time will get slower as pitch length increases. Here due to the limitation of employed materials we choose to shift the Bragg reflection wavelength to ~600 nm.

To compare the performance of short-pitch and long-pitch PS-BPLCs, we prepared two samples. The BPLC precursors consist of nematic LC host HTG 135200 (HCCH, China), chiral dopant S5011 (HCCH, HTP~120/μm), two kinds of monomers [6 wt% RM257 (Merck) and 4 wt% TMPTA (1,1,1-Trimethylolpropane Triacrylate, Sigma Aldrich)], and a small amount of photoinitiator (~0.5 wt%). The nematic LC host has following properties: Δn=0.2 at λ=633 nm, Δε=96 at 1 kHz and 21°C, and clearing temperature T_c=96°C. The differences between these two samples are the concentrations of chiral dopant. Sample I contains 5.48 wt% of chiral dopant while sample II contains 3.15 wt%. As a result, the reflection peak of sample I occurs at ~350 nm and that of sample II at ~600 nm. For each sample, we prepared three IPS cells. The interdigitated electrodes are on the bottom substrate and both the electrode width and gap are 5μm. The cell gaps are ~8.5 μm. The differences between the three cells are: 1) cell 1 has no alignment layer, 2) cell 2 has one rubbed alignment layer on top substrate, and 3) cell 3 has two rubbed alignment layers on both top and bottom substrates. The three cells were prepared under the same conditions. UV curing process was performed near the transition temperature between chiral nematic phase and blue phase with an intensity of 2 mW/cm² for 30 min. After UV curing, the clearing temperature of sample I was found to be ~80°C, while that of sample II was ~90°C due to less chiral dopant. Wider BP range is always preferable.

3. Results and discussion

Figure 1 shows the polarizing optical microscope (POM) images with two crossed linear polarizers. Since the reflection wavelength of sample I is in the UV region, it is optically isotropic in the visible region. Therefore, all three cells appear dark under crossed polarizers. Here, we choose one cell to represent sample I, as shown in Fig. 1(a). Sample II reflects visible light and the reflection changes the incident polarization state, so that a color image can be observed. For cell 1 without alignment, the blue phase lattices have different orientations (multi-domain) and therefore reflect different colors [Fig. 1(b)]. The rubbed alignment layers in cell 2 and cell 3 help form a mono-domain texture [14, 16] so that a single color can be observed in Figs. 1(c) and (d). Especially from cell 2, we found that single side alignment is sufficient to create mono-domain structure. In Fig. 1, the dark state of sample II is degraded significantly compared to sample I.

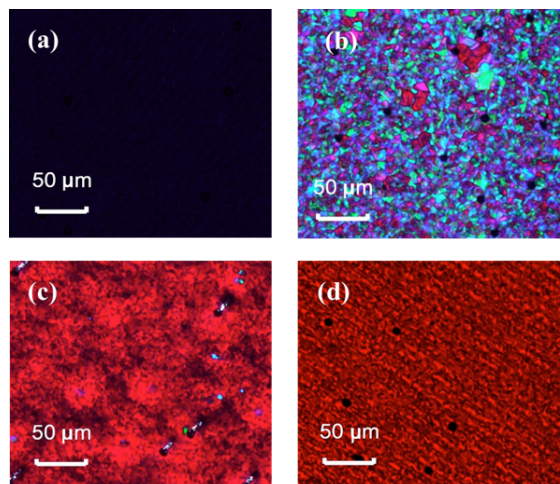


Figure 1. (Color online) Polarizing optical microscope (POM) images with two crossed linear polarizers: (a) sample I cell 2, (b) sample II cell 1, (c) sample II cell 2, and (d) sample II cell 3.

To obtain a good dark state, we used two broadband and wide-view circular polarizers, as Fig. 2 depicts. A white light source was employed and a few collimating lens were used (not shown in the figure). In the experiment, we chose a right-handed circular polarizer (RCP) as the front polarizer. Next, we prepared the PS-BPLC by employing a left-handed chiral dopant so that the BPLC sample transmitted the incoming right-handed circular light in the voltage-off state. Finally, this right-handed circular light was absorbed by the rear left-handed circular polarizer (LCP) resulting in a good dark state.

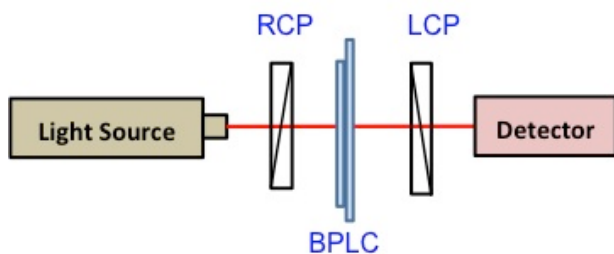


Figure 2. Diagram of experimental setup using circular polarizers. RCP: right-handed circular polarizer; LCP: left-handed circular polarizer.

Figure 3(a) shows the measured dark state of the six PS-BPLC cells between two crossed linear polarizers. Sample I (short-pitch) shows a good dark state while sample II (long pitch) exhibits a large light leakage in the visible spectrum. With circular polarizers, the dark state of sample II is greatly improved, as shown in Fig. 3(b). Figure 4 depicts the transmittance of four PS-BPLC cells in the voltage-off state with a white light source. In Fig. 4(a), a linear polarizer was placed in front of the cells. Sample I is transparent in the displayed spectrum. For sample II, the cell without alignment layer (cell 1) exhibits a fairly large scattering, especially in the shorter wavelength region. Cell 2 and cell 3 show a reflection band near 600 nm. The differences between cell 2 and cell 3 originate from the non-uniformity of the cells due to the capillary filling. In Fig. 4(b), a RCP was placed in front of the cells. With this circular polarizer, the transmittance of

sample II is similar to that of sample I. The reason for the better dark state and higher transmittance by employing a RCP is that these BPLC cells are designed to reflect left-handed circular light so that the right-handed circular light can pass through the cells with high transmittance.

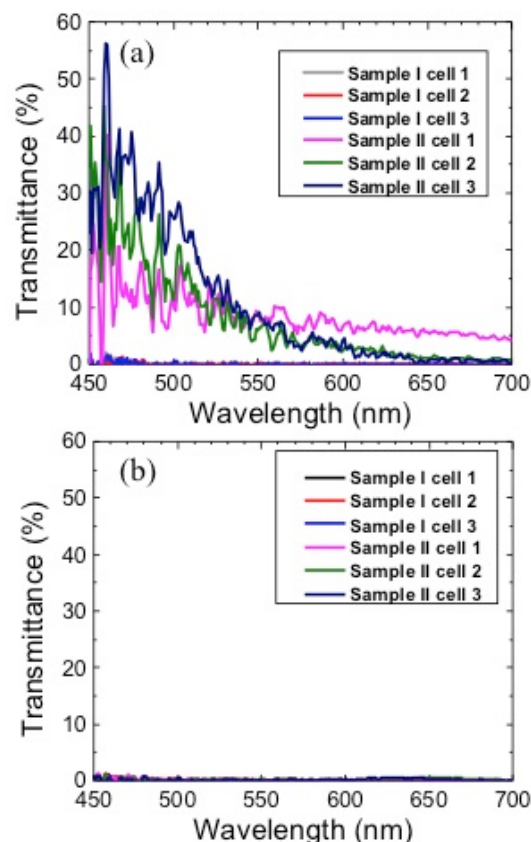


Figure 3. (a) Dark state spectrum using two crossed linear polarizers. (b) Dark state spectrum using two crossed circular polarizers.

Figure 5 depicts the measured voltage-dependent transmittance (VT) curves using two circular polarizers. An Argon-ion laser with $\lambda = 514$ nm was employed as probing light source. The measurements were conducted at room temperature (21°C) and driving frequency $f = 1$ kHz. From Fig. 5, sample I cell 1 has an on-state voltage of 54V and the corresponding Kerr constant is $K \sim 7.4$ nm/V². Sample I cell 3 requires a much higher voltage than sample I cell 1, because the alignment layer shields a large portion of the applied voltage, especially for PS-BPLC composites with a large dielectric constant [17]. It is interesting to note that sample I cell 2 has a similar or slightly lower driving voltage than sample I cell 1. This is because the electric fields are concentrated near the bottom substrates so the alignment layer on the top substrate does not shield voltage. Meanwhile, the top alignment layer helps create mono-domain structure to reduce light scattering. Therefore, sample II cell 2 shows a higher transmittance than sample II cell 1. Most importantly, the driving voltage for sample II cell 2 is only 35 V, which is reduced by 35% in comparison with sample I cell 1. The corresponding Kerr constant is $K \sim 17$ nm/V².

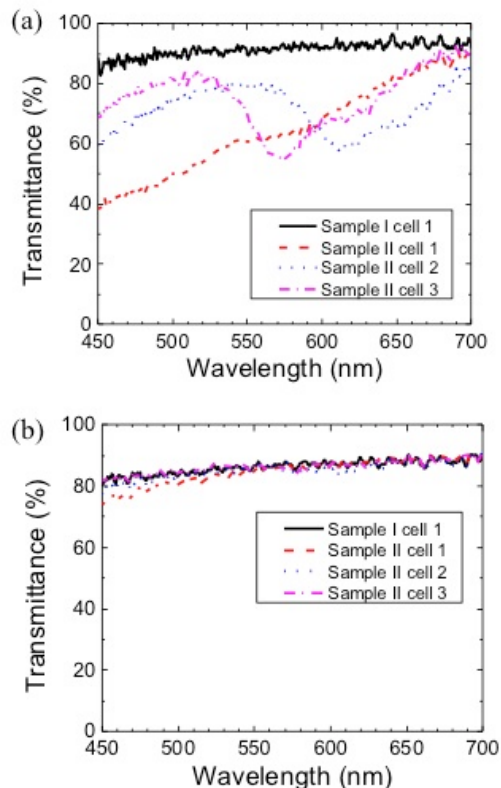


Figure 4. (Color online) Measured transmittance of four BPLC cells in the voltage-off state. (a) A linear polarizer is placed in front of the cells. (b) A right-handed circular polarizer is placed in front of the cells.

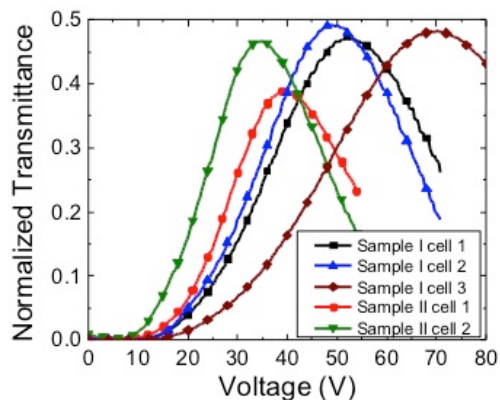


Figure 5. (Color online) Measured voltage-dependent transmittance curves using two crossed circular polarizers. $\lambda = 514\text{nm}$, $T = 21^\circ\text{C}$, and $f = 1\text{ kHz}$.

Table I summarizes the performances of the five cells. Although increasing the pitch length reduces the driving voltage, there are tradeoffs. The first one is that it slows down the response time. The decay time of a BPLC can be approximated as [18]:

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

where γ_l is the rotational viscosity and k is averaged elastic constant of the PS-BPLC composite. In Table I, the decay time for sample II is slower than that of sample I due to the longer pitch length, but it is still in the submillisecond range.

The second tradeoff is the larger hysteresis. Hysteresis is related to the peak electric field strength [19-21]. For a BPLC with a longer pitch, the lattice structure is looser and easier to be distorted. Therefore, the critical field of sample II should be lower than that of sample I. The hysteresis can be improved by designing smooth electrode shape to reduce the peak electric field [22]. It is also interesting to note that cell 2 has smaller hysteresis than cell 1 for both samples. The strong anchoring from the alignment layer provides a restoring force which might be helpful for reconstructing the BPLC structure during the backward scan. On the other hand, the larger hysteresis of sample I cell 3 compared to cell 2 might be due to the higher applied voltage.

Contrast ratio is affected by both intrinsic light leakage at voltage-off state and residual birefringence after voltage actuation. Table I lists the intrinsic contrast ratio before voltage actuation at $\lambda = 514\text{ nm}$. The contrast ratio for sample II has been greatly improved by using circular polarizers. Although sample II cell 1 shows a poor contrast ratio because the scattering degrades the dark state, the contrast ratio for cell 2 is comparable to sample I cell 1. The contrast ratio for $\lambda = 633\text{ nm}$ would be lower because it is closer to the reflection band and the broadband circular polarizer is not designed for reflection band at $\sim 600\text{ nm}$. After driving several times, the contrast ratio is degraded because of the residual birefringence.

TABLE I: Summarized performance of five BPLC cells. τ : decay time; CR: contrast ratio. $\lambda = 514\text{nm}$, $T = 21^\circ\text{C}$, and $f = 1\text{ kHz}$.

Cell	Voltage (V_{rms})	T	τ (μs)	Hysteresis	CR
Sample I cell1	54	47%	382	5.3%	6300:1
Sample I cell2	49	49%	324	3.5%	>10000:1
Sample I cell3	70	48%	360	5%	10000:1
Sample II cell1	40	39%	648	8%	300:1
Sample II cell2	35	47%	814	6%	6500:1

4. Conclusion

We have demonstrated a low voltage blue phase liquid crystal device by red-shifting the pitch length and using circular polarizers. The driving voltage is reduced by 35% and the Kerr constant is improved by 2.3X. The response time is still in submillisecond range. The contrast ratio is comparable to the BPLC sample with a short pitch length. If we further use a larger Kerr constant material [23,24], the driving voltage is expected to be reduced from 33V to 22V with our IPS 5-5 structure at $\lambda = 514\text{ nm}$. With a 2- μm protruded electrode, the operation voltage should be reduced to below 10V for low power consumption.

5. Acknowledgements

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6. References

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