Polymer-Stabilized Blue-Phase Liquid Crystal Cured with a Visible Laser[†]

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Abstract

We report a polymer-stabilized blue-phase liquid crystal (PS-BPLC) cured with a visible laser in an in-plane-switching (IPS) cell. Its electro-optic properties are compared with those of a conventional PS-BPLC cured by ultraviolet (UV) light. Besides, a PS-BPLC grating is fabricated using visible-laser holography.

Author Keywords

Polymer-stabilized blue-phase liquid crystal; holography; grating.

1.   Introduction

Polymer-stabilized blue phase liquid crystal (PS-BPLC) is regarded as a promising candidate for next-generation display and photonic applications attributed to its sub-millisecond response time, no need for surface alignment, and an optically isotropic dark state [1-8]. PS-BPLC is usually made by mixing monomer, chiral dopant, nematic liquid crystal host and photoinitiator uniform, and then curing under ultraviolet (UV) light exposure [6]. For a long time, researchers only use UV light to cure the BP but have not considered the effect of properties of UV light. Recently, Xu *et al.* investigated the effect of the linearly polarized UV light on stabilizing a photopolymer-embedded blue phase liquid crystal precursor [9]. However, UV light may be harmful to health and difficult to operate due to its invisibility; and optical elements specially designed for UV wavelengths are needed to control its optical properties; moreover, the coherence of UV light is weak thus many optical technologies, such as holography, cannot be used [10]. On the other hand, PS-BPLC cured with visible light is safer, convenient, and more conventional optical elements and technologies can be used to fabricate various new devices. The properties of visible laser can be controlled easily, such as polarization, divergence and intensity distribution, which may affect the electro-optic performance of PS-BPLC. In this work, for the first time to the best of our knowledge, we use a visible 532 nm laser to cure PS-BPLC and compare the electro-optic properties of PS-BPLC cured with visible laser with a conventional one cured with UV light. Furthermore, we fabricated a PS-BPLC grating directly using optical holography.

2.   PS-BPLC cured with a visible laser

In the experiment, the BPLC precursor we used consisted of 85.8 wt% nematic liquid crystal host HTG135200-100 ($\Delta\varepsilon = 57.2$ at 1-kHz and $\Delta n = 0.204$, HCCH), 3.9 wt% chiral dopant R5011 (HCCH), 4.0 wt% monomer TMPTA (Aldrich), 6.0 wt% monomer RM257 (HCCH), 0.1 wt% photoinitiator Rose Bengal (Aldrich), and 0.2 wt% coinitiator N-phenylglycine (Aldrich), and was made uniform in the dark. The precursor was filled into an in-plane-switching (IPS) cell with a 7.5 µm cell gap via capillary action at 75 °C, and then cooled down to 60 °C at a rate of 0.1 °C/min. The BP temperature range of precursor is about 57 ~ 65 °C. The electrode width and gap of the IPS cell are 8 µm and 12 µm, respectively. As Figure 1 shows, a Nd:YAG laser (532 nm, 100 mW, Coherent) was employed to

cure the precursor with 80 mW/cm^2 intensity. We made two samples that one of which was exposed from the top substrate side (no electrode side) and the other was exposed from the bottom substrate side (IPS electrode side), labeled as Sample 1 and Sample 2, respectively. During the curing process, photoinitiator Rose Bengal absorbed light and initiated photo-polymerization. The polymer chains were selectively concentrated in the disclination lines because the core of disclination lines was isotropic and polymers were more miscible with an isotropic phase than a liquid crystal phase. Thus the double-twist cylinder (DTC) construction of blue phase was stabilized and the temperature range of BPLC was broadened [1]. For comparison, we made two conventional UV cured samples, labeled as Sample 3 and Sample 4, by replacing the Rose Bengal and N-phenylglycine with Darocur 1173, a photoinitiator working in the UV light range, and then exposing from the top substrate side and bottom substrate side under a UV lamp (386 nm, Instec) with an intensity of about 8 mW/cm^2, respectively. The curing time of each sample was about 15 minutes.
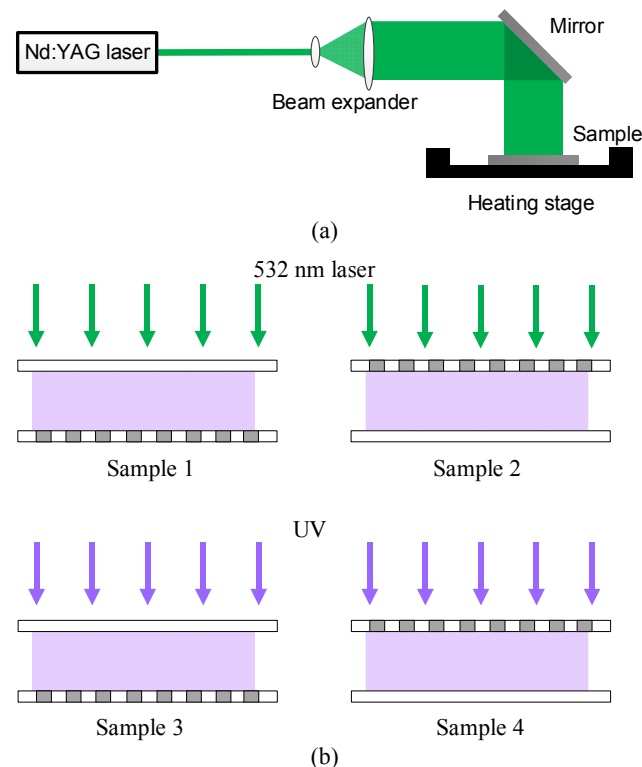

Figure 1. (a) Experimental setup of PS-BPLC cured with a 532 nm laser, (b) Four samples made with 532 nm laser and UV light by top substrate side (no electrode side)and bottom substrate side (IPS electrode side) exposure, respectively.

The morphologies of Sample 1 and Sample 3 are shown in Figure 2, where the self-assembled BPLC shows a characteristic platelet texture when observed under an optical polarizing microscope in the reflective mode at room temperature. It can be seen that the reflected light wavelengths are almost the same between Sample 1 and Sample 3 which indicates the pitch length of BP is same in two samples. The temperature ranges of Sample 1 ~ 4 after cure are all over 60 °C.
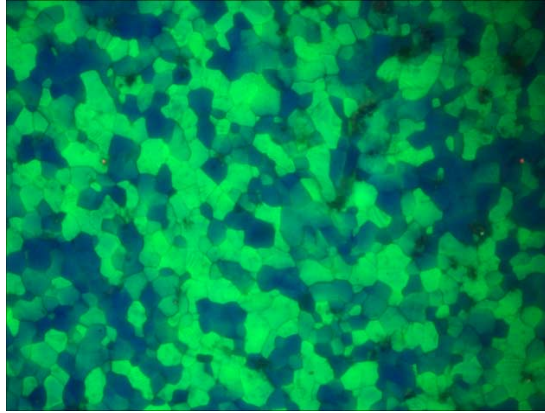
(a)
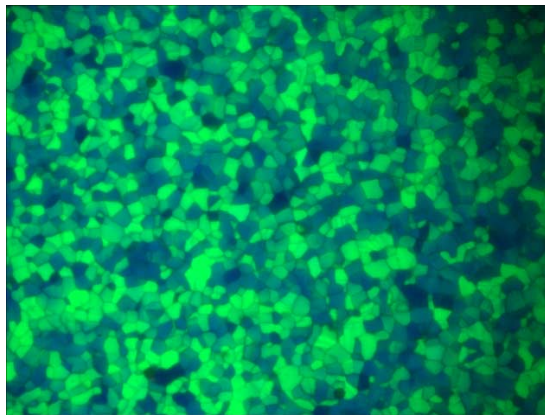
(b)

Figure 2. Plate textures observed under an optical polarizing microscope of Sample 1 (a) and Sample 3 (b).

We measured the driving voltage and response time of each sample with a 1-kHz frequency square-wave voltage source. The normalized transmittance values versus applied voltage of Sample 1 ~ 4 are plotted in Figure 3. For Sample 1 and Sample 2 the driving voltage is about 92 V both, and for Sample 3 and Sample 4 the driving voltage is about 86 V and 100 V, respectively. The driving voltage difference between Sample 3 and Sample 4 mainly arises from the short UV penetration depth inside the BPLC layer [11]. The driving voltage of Sample 1 and Sample 2 is the same means a more uniform polymer network is formed in Sample 1 and Sample 2 according to the discussion in Ref. 11.
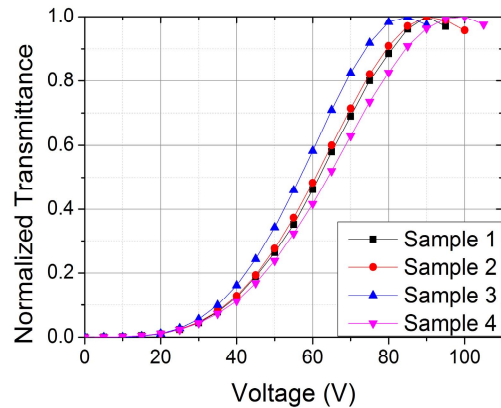

Figure 3. Normalized transmittance versus applied voltage of Sample 1 ~ 4.

Also, we researched the effect of exposure intensity on PS-BPLC cured with 532 nm laser. We made other three samples were exposed with 20, 40, 60 mW/cm^2 intensity, labeled as Sample 5 ~ 7, respectively. The driving voltage of Sample 5~7 are listed in Table 1. It can be seen that the exposure intensity have negligible effects on the driving voltage of the PS-BPLC cured with the 532 nm laser. However, when the laser intensity is much weaker, the photo-polymerization is too weak to stabilize the blue phase, resulting in a cholesteric phase.

Table 1. The response time and driving voltage of Sample 1 ~ 7.

Sample	Driving voltage (V)	Kerr constant (nm/V^2)	Response time (µs)
Sample 1	92	3.6	743
Sample 2	92	3.6	732
Sample 3	86	4.0	771
Sample 4	100	3.0	726
Sample 5	94	3.3	761
Sample 6	92	3.6	734
Sample 7	91	3.5	748

The electro-optical properties of PS-BPLC can be described by extended Kerr effect. A larger Kerr constant indicates a lower driving voltage. According to Gerber's model [12], the Kerr constant (K) can be approximated as

$$K \approx \Delta n \cdot \Delta \varepsilon \frac{\varepsilon_0 P^2}{k \lambda (2\pi)^2}$$

and the response time (τ) can be estimated by

$$\tau \approx \frac{\gamma_1 P^2}{k(2\pi)^2}$$

where Δn is the intrinsic birefringence of LC host, ε_0 is the vacuum dielectric constant, $\Delta \varepsilon$ is the dielectric anisotropy of the LC host, λ is the wavelength, k is the averaged elastic constant, γ_1 is the rotational viscosity of the LC host, and P is the pitch length.

The Kerr constant and response time of each sample are also listed in Table 1. The response times are defined as 90% to 10% of the transmittance change. The Kerr constants of samples (Samples 1, 2, and 5 ~ 7) cured with 532 nm laser are between Sample 3 (3.0 nm/V^2) and Sample 4 (4.0 nm/V^2), range from 3.3 nm/V^2 to 3.6 nm/V^2. For Sample 1 ~ 7, the response times are all below 1 ms.

3. PS-BPLC grating fabricated with holography

Based on the approaches discussed above, we fabricated a PS-BPLC grating using optical holography. We filled the same precursor into a cell with a 5 μm cell gap and then cured under holographic exposure. As shown in Figure 4, two beams generated by the Nd:YAG laser intersected inside the cell and produced alternating bright and dark interference fringes. The beams were set to *p*-polarization, with a total intensity of 80 mW. The intersection angle was 1.8º. During the holographic exposure, the polymerization preferentially occurred in bright regions to cure blue phase, creating a monomer concentration gradient between bright and dark regions. This caused the diffusions of monomers [13] and polymers concentrated in the bright region, where blue phase is cured. In the dark region, blue phase was not cured, which might result from the low concentration of polymers after monomer diffusion, and thus cholesteric phase appeared once temperature was out of the BP range.
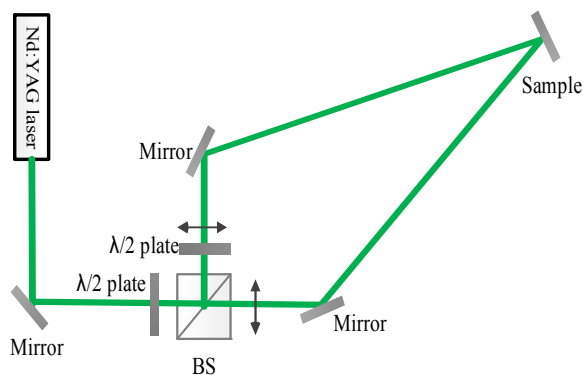
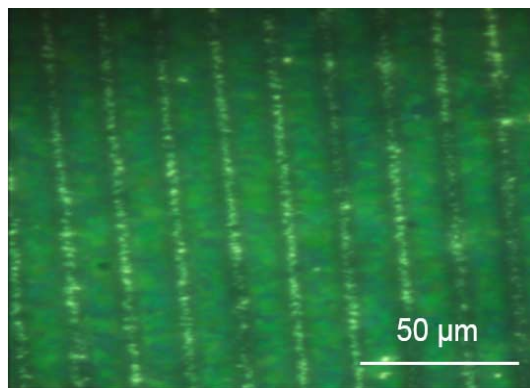**Figure 4.** Experimental setup of fabricating the PS-BPLC grating using holography.

Figure 5. PS-BPLC grating morphology observed under an optical polarizing microscope.

Figure 5 shows the morphology of the PS-BPLC grating under the optical polarizing microscope. It can be seen that most of the area is in blue phase and only little is in cholesteric phase. Upon holographic exposure, the intensity distribution of interference pattern is sinusoidal. In most area the intensity of light is high enough to cure the blue phase, while around the minimum intensity region the blue phase is not cured due to the weak light intensity. The grating period $\Lambda \approx 17$ μm and the diffracted efficiency is about 6 %. The diffraction efficiency η is calculated as a ratio of the diffracted power of the first order to the total output power.

4. Conclusions

In this work, we have proposed and experimentally demonstrated a polymer-stabilized blue-phase liquid crystal (PS-BPLC) cured with a visible laser in an IPS cell, and compared the electro-optic properties of the PS-BPLC with that of a conventional one cured with ultraviolet (UV) light. Curing with visible light is more convenient, safe and easy to control. Moreover, by taking advantage of the high coherence of the visible laser, we fabricated a PS-BPLC grating using optical holography. The curing of PS-BPLC using visible lasers, combined with conventional optical elements and technologies, could enable versatile electro-optical BPLC devices for various applications.

5. Acknowledgements

6. References

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