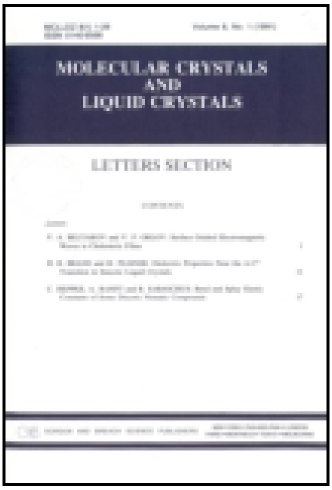

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Polarization-Independent and Fast Response Microlens Arrays Based on Blue Phase Liquid Crystals

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Polarization-Independent and Fast Response Microlens Arrays Based on Blue Phase Liquid Crystals

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This work proposes a simple method of fabricating microlens arrays with the unique characteristics of polarization independence and fast response time. This microlens arrays were composed of a concave polymer microlens arrays and blue phase liquid crystals (BPLCs). The experimental results showed that the microlens arrays were fast switched between positive and negative focal lengths via controlling the electric fields, and the response time was a few hundred microseconds. Additionally, the focusing efficiency was not dependent on the polarization of incident light.

Keywords Microlens arrays; blue phase liquid crystals; polarization independence; fast response

1. Introduction

Tunable-focus liquid crystal (LC) lens and LC microlens have been of interest and investigated widely for increasing various optoelectronic applications, including 3D displays, image processing, photonic devices [1–3]. There are a variety of the LC lens making methods, such as Fresnel zone plates [4], patterned electrode [1, 3], polymer- stabilized LC [5], and surface relief structure [2, 6–8].

In recent years, blue phase liquid crystals (BPLCs) have been widely investigated because of their unique characteristics of fast response time, optically isotropic behavior [9, 10], and their potential applications [4, 10, 11]. BPLCs can been found at temperature range between the cholesteric phase and the isotropic phase. In an external electric field, BPLCs exhibit the locally small reorientation of LC directors, transformation of crystal orientation, and electrostriction, all of which lead to the phase shift and the Kerr effect [9–11]. However, this work proposes a simple method of fabricating microlens arrays based on a surface relief structure with the BPLC material. The BPLC microlens possess polarization-independent characteristic, and it can be fast tuned focal lengths and fast switched between positive lens and negative lens via controlling strength of the electric fields.

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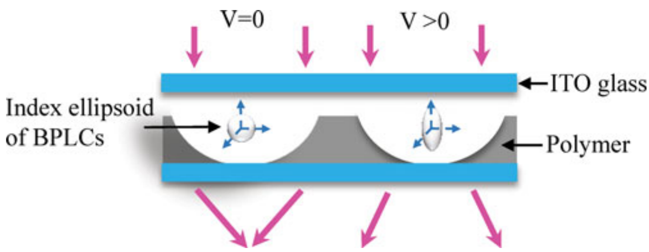

Figure 1. Basic configuration and operating principles of the BPLC microlens arrays without electric state (right) and with electric state (left).

2. Experiments

Figure 1 shows schematic diagram and the operating principles of the BPLC microlens arrays. The cell of microlens arrays was fabricated by using a pure ITO glass and other ITO glass that had concave polymer structure [6]. The cell gap of the cell was separated by 3.5 μm-thick spacers. BPLC mixture was then injected into the empty microlens cell. Without external field, the optical refractive-index ellipsoid of BPLC was circle. BPLC was approximated as optically isotropic, and its refractive index was the same in either direction and could be regarded as

$$n_{\text{iso}} = (n_{\text{e}} + 2n_{\text{o}})/3$$

where n_{e} and n_{o} were the extraordinary and ordinary refractive indices of the LC host, respectively. When a vertical electric fields was applied in the BPLC layer, the birefringence of BPLC was induced by extended Kerr effect [9, 10]. Therefore, the refractive-index ellipsoid of BPLC transformed from spherical to ellipsoidal where the optic axis of ellipsoidal refractive-index ellipsoid was parallel to the electric field direction [10, 11]. So the normally incident light propagating along the optic axis of BPLC. This light sensed the BPLC effective refractive index n_{o}(E) depended on the external electric field E and did not depended polarization direction of the incident light. Based on the above electro-optical properties of BPLCs, the refractive index of BPLC could be tuned from the range of $n$iso to n_{o}(E) via varying the electric field. In short, this refractive index of BPLC was $n_{\text{o}}(E = 0) = n$iso at V = 0 and was n_{o}(E) at an applied voltage(V>0) for a normally incident light propagates along direction of optic axis.

In the work, the focal length of microlens could be tuned by utilizing the difference of refractive indices between BPLC and concave polymer structure. Since polymer layer was concave shape, the BPLC layer was like plano-convex lens. The refractive index of concave polymer structure n_{p} was 1.56, and the BPLC mixture included a nematic LC composite (its extraordinary and ordinary refractive indices were $n_{\text{e}} = 1.77$ and $n_{\text{o}} = 1.51$, respectively) and a left-handed chiral dopant S811 was at a ratio of 65:35 wt%. BPLC microlens cell was heated up to above its clear point and then was cooled from isotropic state down to the blue phase at cooling rate of 0.01°C/min by controlling temperature. In our experiment, the measures of BPLC microlens arrays were at the temperature 40°C.

Figure 2 depicts the experimental setup for measuring focus properties and response time of the BPLC microlens arrays by using a CCD camera and a photo detector. A circularly polarized red beam (from a He-Ne laser, wavelength: 633 nm) was magnified with a beam expander, which passed through a polarizer to change polarization direction of the normally incident light and then illuminate the cell of the BPLC microlens arrays.

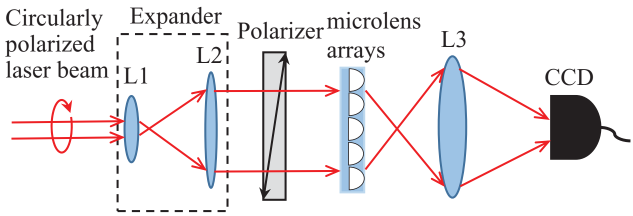

Figure 2. Experimental setup for measuring the focusing properties of the BPLC microlens arrays.

Utilizing an imaging lens (L3) allowed the transmitted light from the sample to be focused on CCD camera. The CCD camera was placed near the focal point in order to analyzed the focusing light intensity of the microlens arrays. The sample was linearly moved on the optical path in order to determine the effective focal length [7].

3. Results and Discussion

Figure 3(a) shows the polarizing microscopic image of the BPLC microlens arrays without an applied voltage. The domain diameters of BPLCs was over 100 μm without the external field state. Because BPLCs had lager domain size, the scattering effect of the multi-domain could be reduced in the microlens arrays. Figure 3(b) show a focused image of the microlens arrays taken from CCD camera without applied voltage. In the initial measurement, we could observe that the focus of each microlens was uniform and consistent at the focal plane.

The measured the focal length of the microlens is shown in Fig. 4. At $V = 0$, the focal length of the microlens was about 4.0 mm. In the largest difference of refractive index, the focal length could be the shortest. After the voltage higher than the threshold Vth ~20 V, the focal length increased via the increase of the applied voltage in the positive lens. At about applied voltage range of 60–70 V, the BPLC effective refractive index n_o(E) matched with polymer refractive index n_p, so the refraction of the concave-shaped structure was nearly disappeared and the focal length was infinite. In the negative lens, the focal length decreased from −12.0 mm to −3.7 mm by increasing applied voltage from 80 to 150 V. The focal lengths tunability was range of 2 mm in the positive lens and was range of 8.3 mm in the negative lens. Therefore, by varying the voltage, the focal length could be

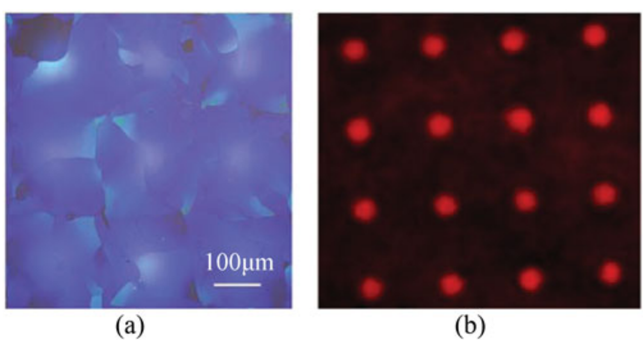

Figure 3. (a) Polarizing microscopic image of the BPLC microlens arrays without an applied voltage. (b) The focusing image of the BPLC microlens arrays at V = 0.

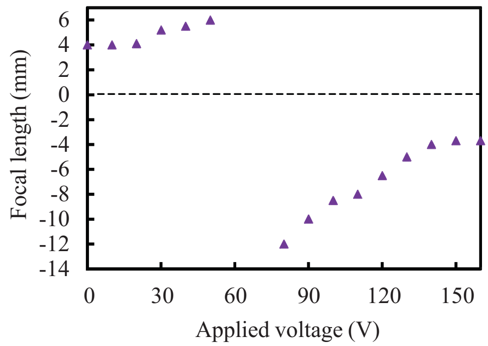

Figure 4. Measured focal length of the BPLC microlens as a function of applied voltage.

continuously tuned between the positive lens and the negative lens. Under a high electric field, the BPLC effective index n_o(E) was gradually close to n_o. In the process of tuning focal length, matching of the refractive index difference plays an important role. Therefore, the microlens might be formed via either a convex or a concave lens, depending on the difference values between n_p and n_o(E).

Figure 5 plots the measured focusing intensity of a BPLC microlen lens with various linear polarization direction of a normally incident light. Under an applied voltage of 30 V, the photo detector was placed on the focus of positive lens and measured the focusing intensity. When the change in the polarization direction of the incident light occurred, the intensity of the focused point was still equal. Because the BPLC was optically isotropic for the incident light without the external electric field. Under a vertical electric fields, electrically tunable refractive index was insensitive to variation of polarization, because the propagation of a normally incident light was along the optic axis of the birefringence of BPLC. This implies that such the microlens possesses the characteristic of polarization independence.

In our experiment, the response time was measured via switching focal length of the microlens. The focusing intensity of single microlens was measured by switching an applied voltage which was 40 V with the square wave of 1 KHz. The measured response times of the BPLC microlens were at a rise time τ_{rise} of $\sim$585 μs and a decay time τ_{decay} of

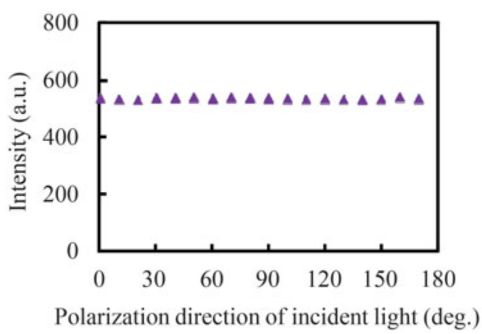

Figure 5. Measured focusing intensity of single BPLC microlens under applied voltage $V = 30$ V with various polarization states of an incident light.

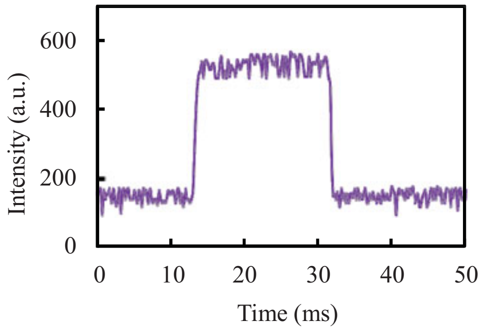

Figure 6. Measured focusing intensity of the BPLC microlenses with the applied voltage switched between 0 and 40 V.

~694 μs, as shown in Fig. 6. The response times of the BPLC are much shorter than those of the conventional nematic LC.

4. Conclusion

This work demonstrates a polarization-independent microlens arrays based on BPLCs. In this method of fabricating microlens arrays, the BPLC material can be applied in the microlens array device. It simplifies the fabrication process, and it also promotes the properties of polarization independence and fast response. In addition to the advantage that the microlens can be tuned by the focal lengths, the microlens also can be switched between positive and negative lenses.

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