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Polymer network liquid crystals for tunable microlens arrays

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Abstract
We demonstrate a tunable-focus microlens array using polymer network liquid crystals (PNLCs). PNLCs were prepared by ultraviolet (UV) light exposure through a patterned photomask. The UV-curable monomer in each of the exposed spots forms an inhomogeneous centro-symmetrical polymer network that functions as a lens when a homogeneous electric field is applied to the cell. The focal length of the microlens is tunable with the applied voltage.

1. Introduction

Liquid crystal (LC)-based adaptive optics are important for information processing, optical interconnections, photonics, integrated optics, and optical communications due to their tunable optical properties and low operating voltage. A LC microlens array is such an example. So far, several attempts, such as a zone patterned structure [1], hole- or hybrid-patterned electrode [2–4], and surface relief profile [5, 6], have been proposed. However, most of the lens fabrication processes are rather complicated. Another challenge in microlens design is to control the focal length. The focal length is determined by the radius of the microlens aperture, LC cell gap, and refractive index profile. For practical applications, the focal length has to be larger than the thickness of the glass substrate, which is about 0.3–1.1 mm. It is also highly desirable to have a fast switching time during focus change. In addition to high performance, a simple fabrication process would reduce cost and lead to widespread commercial applications.

Recently, we have demonstrated a large aperture LC lens using a gradient refractive index polymer network liquid crystal (PNLC) [7]. The lens was fabricated by exposing ultraviolet (UV) light onto a LC/monomer mixture through a patterned photomask. However, due to the small refractive index profile, a large aperture LC lens would produce an ultra-long focal length. As a result, its application is limited to satellite imaging and astronomy.

In this paper, we demonstrate a tunable-focus microlens array using a PNLC cell. The unique feature of this approach is that we apply a uniform electric field to a homogeneous LC cell, which, in turn, generates the centro-symmetric refractive index profile for the focusing effect to occur. The UV exposure through a patterned photomask gives rise to a spatially varying polymer network concentration. The polymer-rich region exhibits a higher threshold voltage, while the LC-rich region has a lower turn-on voltage. When a uniform voltage is applied to the sample, the LC molecules have different degrees of reorientation. This gradient refractive index makes the PNLC behaves like a positive or negative lens, depending on the pattern of the photomask.

2. Basic theory and experiments

To make microlens arrays, our photomask consists of arrays of circular apertures. When the UV light passes through the pinholes, diffraction takes place. This diffraction effect is helpful for generating the gradient refractive index profile. Based on diffraction theory, when a laser beam transverses a tiny circular aperture, the diffracted light intensity profile can be expressed as [8]: $I(\theta) = I_0[2J_1(x)/x]^2$, where $I_0 \propto (\pi a)^2/\lambda^2$ is the light intensity at the central point, $x = (2\pi a/\lambda)\sin\theta$, θ is the diffraction angle, a is the radius of the pinhole, λ is the incident wavelength, and J_1 is the Bessel function of the first order. The formed diffraction pattern consists of a series of rings, but most of the light energy concentrates on the zeroth-order ring (called Airy disc), which presents a parabolic-like profile. Similarly, when an incoherent UV light passes through a pinhole, diffraction occurs and the output intensity presents a parabolic profile. Based on this idea, an array of UV light with parabolic output intensity profile can be realized when a UV light transmits a pinhole array photomask. To characterize the output intensity profile, we first detected the output intensity of an expanded UV light ($\lambda = 365$ nm, Loctite Wand System) normally through a

pinhole using a CCD camera. We then prepared PNLC cells using the photoinduced polymerization technique.

To characterize the UV output intensity profile, we measured the UV light passing through a single hole. The diameter of the hole was 30 μm and the distance from the CCD camera to the pinhole was ∼2 cm.

To prepare a PNLC microlens array, we mixed 3 wt% of diacrylate monomer BAB6 with a small amount of photoinitiator in the Merck E48 LC host ($\Delta n = 0.231$). The structure of the rod-like monomer BAB6 is as follows:

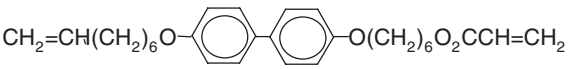

Figure 1 illustrates the fabrication method of a microlens array. The LC/monomer mixture was injected into a homogeneous empty cell composing of indium–tin-oxide (ITO) glass substrates. The inner surfaces of the ITO glass substrates were coated with a thin polyimide layer and buffed in antiparallel directions. The substrate thickness was 1.1 mm and cell gap was 15 μm. A chromium layer with circular aperture array deposited on a glass substrate was placed on the top of the cell. Two different photomasks were used: photomask-1 had a 25 μm pinhole diameter and 110 μm pitch length, while photomask-2 had a 150 μm pinhole diameter and 300 μm pitch length. The LC/monomer cell was exposed to UV light (intensity $I \sim 40\,\mathrm{mW\,cm^{-2}}$) from the photomask side. The curing time is 45 min.

3. Results and discussion

Figure 2 shows the measured UV intensity profile when light passes through the single hole. As expected, the intensity distribution presents a parabolic-like profile but without higher order diffraction rings. If the LC/monomer mixture is cured using such a UV light, the stronger intensity in the central region will accelerate the polymerization rate and form a denser polymer network. This is known as the polymer-rich region. At the borders, the weaker UV intensity will have a slower polymerization rate, resulting in a looser polymer network (i.e. LC-rich region). Therefore, a centro-symmetric inhomogeneous polymer network is formed. If there is a need to change the spot diameter, we could either modify the photomask patterns or adjust the distance between the LC sample and the photomask. The latter is simpler as it does not need to redesign the photomask.

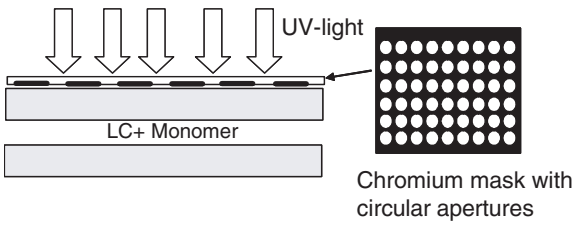

Figure 1. Left: method for fabricating PNLC microlens arrays. Right: the photomask showing the patterned pinhole structures.

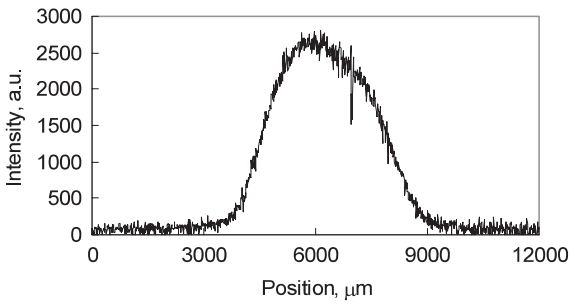

Figure 2. The intensity profile recorded by a CCD camera when UV light passes through a pinhole. Pinhole diameter is 30 μm, pitch length is 110 μm, and $\lambda = 365$ nm.

We used a polarizing optical microscope to inspect PNLC cell-1, which was prepared using photomask-1, at different applied voltages. The rubbing direction of the cell was oriented at 45° with respect to the axis of the linear polarizer. The analyser was crossed to the polarizer. Three photographs at $V = 0\,\mathrm{V_{rms}}$, $5\,\mathrm{V_{rms}}$, and $20\,\mathrm{V_{rms}}$ were taken, as shown in figures 3(*a*), (*b*), and (*c*), respectively.

At $V = 0$, the UV exposed area is almost homogeneous and no focusing effect occurs. When an electric field is applied to the cell and increased slowly, the UV cured spots become noticeable. In the meantime, the colour change starts from the borders and gradually migrates to the centre. Figure 3(*b*) shows such an example. This implies that the threshold voltage at the spot centre is higher than that at the borders. Such results confirm the expected gradient phase retardation. When the LC sample was rotated such that its rubbing direction is parallel to the polarizer's axis, the array spots appear dark. This means the PNLC microlens is polarization sensitive. As the applied voltage is sufficiently higher than the threshold, most of the bulk LC directors are reoriented perpendicular to the substrates. Under such a circumstance, the refractive index profile is flattened and the focusing effect is vague, as shown in figure 3(*c*).

To characterize the light focusing properties of the microlens arrays, a linearly polarized He–Ne laser beam ($\lambda = 633$ nm) was used. The polarization axis of the laser beam is parallel to the cell rubbing direction. In order to resolve the output intensity profiles clearly, a 10× beam expander was used behind the sample. Behind the beam expander, a CCD camera (SBIG Model ST-2000XM) was used to record the output light intensity. A computer controlled LabVIEW data acquisition system was used for driving the cell, and the recorded data were analysed by the computer.

Figure 4 shows the images of the focusing properties (left) of the microlens array as well as the corresponding CCD intensity profiles (right) at different voltages. The sample cell was set at 2 cm in front of the beam expander. Figure 4(*a*) shows the sample microlens arrays at $V = 0$. Since there is

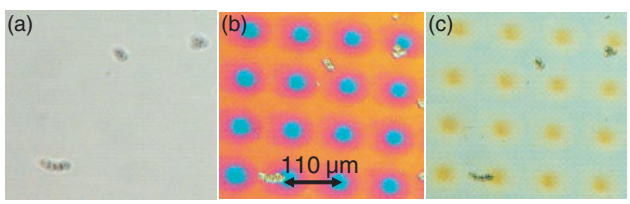

Figure 3. Photographs of PNLC cell-1 at different operating voltages: (*a*) $V = 0\,\mathrm{V_{rms}}$, (*b*) $V = 5\,\mathrm{V_{rms}}$, and (*c*) $V = 20\,\mathrm{V_{rms}}$. Polarizers are crossed. The LC used is E48 and cell gap $d = 15\,\mu$m.

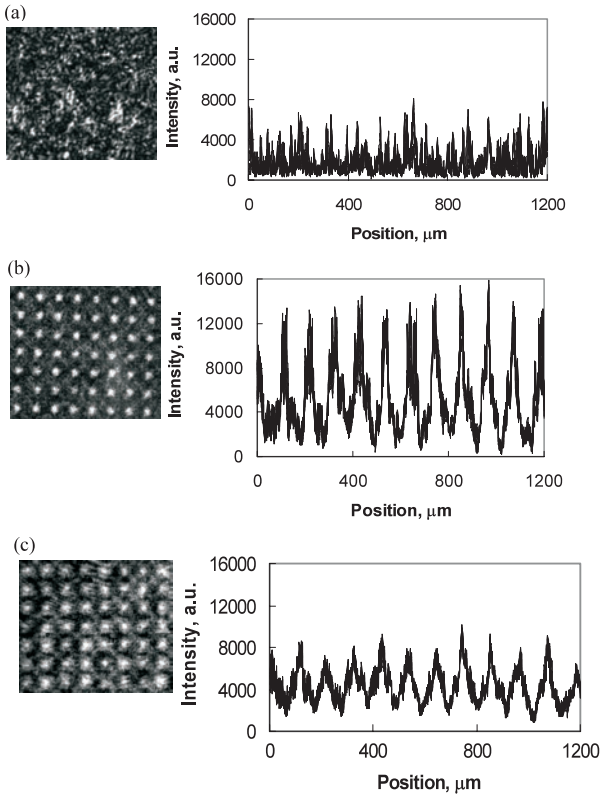

Figure 4. Focusing properties and intensity profiles of PNLC cell-1 recorded by the CCD camera at different operating voltages: (*a*) $V = 0\,V_{rms}$, (*b*) $V = 5\,V_{rms}$, and (*c*) $V = 20\,V_{rms}$. The cell gap $d = 15\,\mu m$ and $\lambda = 633\,nm$.

no focusing effect, the output He–Ne laser beam is relatively uniform and its intensity reaches ~4000 arbitrary units. As the voltage increases to $5\,V_{rms}$, the focusing effect manifests. Arrays of bright spots are clearly observed, as shown in the left side of figure 4(*b*). The measured intensity of each microlens exceeds ~12 000 arbitrary units, as shown in the right side of figure 4(*b*). At $V = 20\,V_{rms}$, the LC directors in the polymer-rich and LC-rich regions are all reoriented along the electric field direction. The curvature of the refractive index profile is gradually flattened. As a result, the focal length of the microlens arrays increases and the measured light intensity at the CCD focal plane decreases, as shown in figure 4(*c*).

The voltage-dependent focal length of the microlens arrays was investigated and results are plotted in figure 5. At $V = 0$, the PNLC exhibits a homogeneous alignment, and thus, no focusing effect occurs. As the voltage increases, the focal length decreases first, reaches a minimum at $\sim 5\,V_{rms}$, and then increases again. The error bars shown in figure 5 indicate the measurement accuracy. The focal length of an LC lens can be evaluated using Fresnel's approximation [9] and is determined by three parameters as

$$f = \frac{r^2}{2\delta n d} \tag{1}$$

where r is the radius of the lens, d is the cell gap, and δn is the refractive index difference between the lens centre and border. Although the pinhole radius of photomask-1 is $12.5\,\mu m$, the actual spot radius is about $50\,\mu m$ due to the

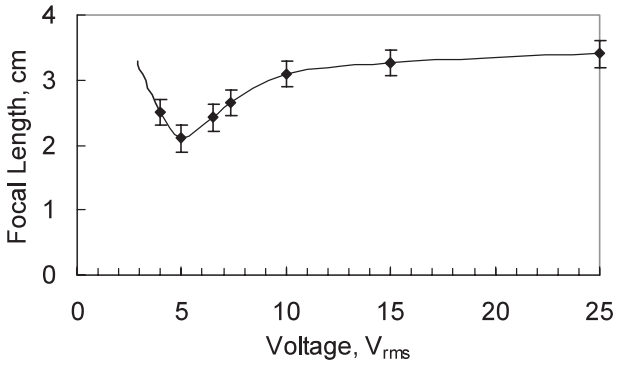

Figure 5. Voltage-dependent focal length of the microlens arrays in PNLC cell-1. The LC used is E48, $d = 15\,\mu m$ and $\lambda = 633\,nm$.

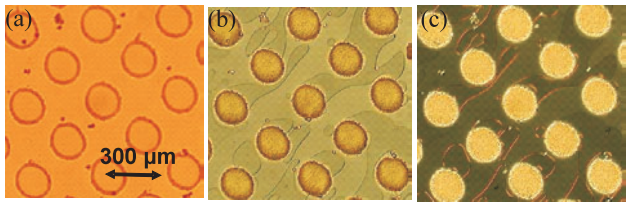

Figure 6. Photographs of PNLC cell-2 sample at different operating voltages: (*a*) $V = 0\,V_{rms}$, (*b*) $V = 10\,V_{rms}$, and (*c*) $V = 20\,V_{rms}$. The aperture size of each hole in the photomask is $150\,\mu m$.

diffraction effect. Plugging $a = 50\,\mu m$, $d = 15\,\mu m$, and $f \sim 2\,cm$ into equation (1), we find that $\delta n \sim 4.2 \times 10^{-3}$. As the voltage exceeds 5 V, the focal length starts to increase. Theoretically, a sufficiently high electric field would reorient the bulk LC director perpendicular to the substrates. Under such a circumstance, $\delta n \to 0$ and $f \to \infty$. However, in our microlens arrays the polymer networks exert a weaker stabilization force on the LC molecules at the border than those at the centre of the microlens, and thus the radius of the microlens has the tendency to shrink at a high voltage. In this condition, the focal length cannot be lengthened; it will gradually saturate as the voltage exceeds $10\,V_{rms}$, as shown in figure 5.

In contrast to PNLC cell-1, cell-2, which was prepared using photomask-2, exhibits clear UV exposed array dots in the null voltage state. Three photographs of cell-2 at $V = 0\,V_{rms}$, $10\,V_{rms}$, and $20\,V_{rms}$ were taken using a polarizing optical microscope, as shown in figures 6(*a*), (*b*) and (*c*), respectively. From figure 6(*a*), a dot array contour is already formed at $V = 0$. This result indicates that the phase separation structure in the UV exposed spot is obviously different from that of the uncured regions. When a voltage is applied to the cell and increased, the observed results are similar to that in figure 3.

To characterize the optical properties of the UV cured spots in the null voltage state, we used the same experimental set-up to record the output light intensity, except that the beam expander was removed. The CCD camera was set at 8.5 cm, 9.5 cm, and 10.5 cm behind the sample, and the photos are shown in figures 7(*a*), (*b*), and (*c*), respectively. From figure 7(*b*), the UV exposed dot is seen to already exhibit a focusing effect at $V = 0$, although the focusing ability is rather weak. The observed focal length is ~9.5 cm. Unlike the result shown in figure 4(*a*), where no focusing effect was observed, each of the UV cured spots in PNLC cell-2 presents a more

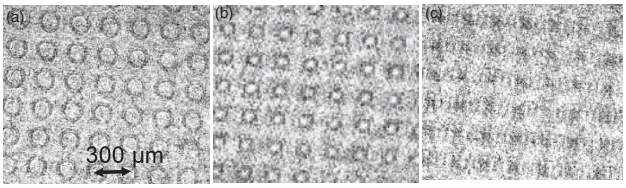

Figure 7. Focusing properties of the PNLC cell-2 microlens arrays recorded by the CCD camera at $V = 0$. The distance of the CCD camera from the sample is (*a*) 8.5 cm, (*b*) 9.5 cm, and (*c*) 10.5 cm.

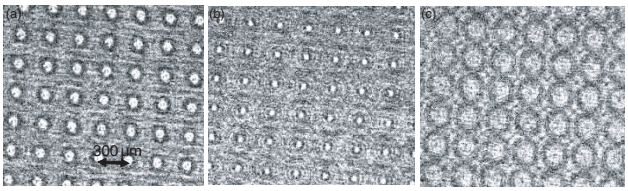

Figure 8. Focusing properties of PNLC cell-2 microlens arrays recorded by the CCD camera at different operating voltages: (*a*) $V = 3\,V_{rms}$, (*b*) $V = 4\,V_{rms}$, and (*c*) $V = 5\,V_{rms}$. The cell gap $d = 15\,\mu$m and $\lambda = 633$ nm.

significant gradient profile due to the phase separation between LCs and polymer. From equation (1), we estimated the index change, $\delta n \sim 1.8 \times 10^{-3}$, across the 150 μm diameter.

To enhance the light focusing ability of the PNLC microlens array, it is necessary to apply a suitable voltage to the cell. Figures 8(*a*), (*b*), and (*c*) show the light focusing properties of the PNLC-2 sample at 3 V_{rms}, 4 V_{rms}, and 5 V_{rms}, respectively. The CCD camera was set at 9.5 cm behind the sample. Comparing with the result shown in figure 7(*b*), where $V = 0$, the light focusing ability of the microlens manifests when a 3 V_{rms} voltage is applied to the cell. At $V = 4\,V_{rms}$, the focusing effect is even stronger. However, at $V = 5\,V_{rms}$, the focal length has moved further away from the CCD camera position so that the image is smeared.

From the above results, the PNLC is a promising method for generating the required gradient refractive index profile for making tunable microlens arrays. Depending upon the aperture size of the hole-patterned photomask, various sizes of microlenses can be fabricated. However, according to diffraction theory, a smaller aperture size would cause a larger diffraction angle and weaker output intensity. From figure 3(*b*), we find that the actual cured spot size is $\sim$50 μm, which is about 4$\times$ larger than the photomask pattern, while in PNLC cell-2 the size of the cured spot is almost the same as that of photomask-2. The PNLC microlens fabricated using photomask-2 exhibits a relatively large refractive index gradient due to the sharper UV intensity profile. The second advantage of using a large aperture size is that the photosensitive monomers will receive more UV energy during the exposure period, so that the phase separation rate is faster and the formed polymer network is more stable in the high voltage state.

From our PNLC microlens operation mechanism, it is difficult to realize a sufficiently short focal length due to the small gradient profile induced by the homogeneous electric field in LC bulk. Another issue for PNLC microlens array is the long-term stability, which is an important aspect for practical applications. Like conventional PNLC, if a PNLC microlens cell is driven continuously by applying the saturation voltage, the polymer network in the looser region will be destroyed first, which, in turn, disturbs the LC alignment. Under such circumstances, the light focusing ability of the PNLC lens would be decreased. Increasing the polymer concentration could enhance the network stability; however, light scattering would occur. To solve this problem, one should choose a thinner LC cell gap and use a high-birefringence LC material. From equation (1), if we double Δn, then the cell gap, d, can be decreased by 2$\times$. In such a thin cell, the strong surface anchoring helps to stabilize LC orientation. The lifetime issue of the PNLC lens is currently under investigation.

While comparing with other tunable microlens technologies, the major PNLC advantages are in the uniform cell gap and using a single electrode on both substrates. Besides, the PNLC lens exhibits a reasonably fast switching speed (<20 ms), wide-range tunable focal length (after having optimized the cell structure and UV curing conditions), and relatively low operating voltage. The focal length (a few centimetres) of the PNLC microlens arrays is in a convenient range for optical fibre switches and incoherent correlator applications.

4. Conclusions

We have demonstrated a method of fabricating tunable microlens array using polymer stabilized nematic LCs. By exposing the LC/monomer cell with UV light through a hole-patterned photomask, a centro-symmetrical polymer network is formed. With the application of a homogeneous electric field across the LC cell, a gradient refractive index profile is generated at the exposed spots. Using this fabrication method, a LC microlens or lens arrays with tunable focal length can be easily fabricated.

Acknowledgments

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References

[1] Patel J S and Rastani K 1991 *Opt. Lett.* **16** 532–4
[2] Nose T, Masuda S, Sato S, Li J, Chien L C and Bos P J 1997 *Opt. Lett.* **22** 351–3
[3] Masuda S, Nose T and Sato S 1998 *Appl. Opt.* **37** 2067–73
[4] Klaus W, Ide M, Hayano Y, Morokawa S and Arimoto Y 1999 *Proc. SPIE* **3635** 66–73
[5] Commander L G, Day S E and Selviah D R 2000 *Opt. Commun.* **177** 157–70
[6] Choi Y, Park J H, Kim J H and Lee S D 2002 *Opt. Mater.* **21** 643–6
[7] Ren H and Wu S T 2003 *Appl. Phys. Lett.* **82** 22–4
[8] Hecht E 1987 *Optics* 2nd edn (Reading, MA: Addison-Wesley) chapter 10
[9] Goodman J W 1968 *Introduction to Fourier Optics* (New York: McGraw-Hill)