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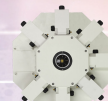
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Adaptive lens using liquid crystal concentration redistribution

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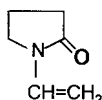
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An adaptive lens using electrically induced liquid crystal (LC)/monomer concentration redistribution is demonstrated. In the absence of an electric field, the LC/monomer mixture is homogeneously distributed. Application of an inhomogeneous electric field causes the LC molecules to diffuse towards the high field region and the liquid monomer towards the low field region. On the other hand, the LC molecules tend to diffuse from high to low concentration direction in order to balance the concentration change. A gradient LC concentration is thus obtained. Using the gradient LC concentration, we demonstrate a tunable-focus lens. Compared with a conventional LC lens, our lens has advantages in small astigmatism and without light scattering, but its response time is slower. © 2006 American Institute of Physics. [DOI: 10.1063/1.2202727]

The majority of liquid crystal (LC) display and photonic devices use electric-field-induced director reorientations.^{1,2} When an applied voltage exceeds the Fréedericksz transition threshold,³ the rodlike LC molecules are reoriented along the electric field direction. Such a molecular reorientation causes the LC refractive index to change. As a result, the polarization of the input light is altered and the transmittance through the crossed polarizer is modulated.

In this letter, we demonstrate a LC/monomer system whose electro-optic effect depends on the electric-field-induced LC concentration redistribution rather than the usual molecular reorientation. The induced LC concentration changes from homogeneous to inhomogeneous distribution which, in turn, causes an inhomogeneous refractive index distribution across the device. As a result, the gradient refractive index is formed. Such a mechanism enables an adaptive device, e.g., LC lens, to be fabricated. Compared with prior adaptive LC lenses,⁴⁻⁶ which bear strong astigmatism, distortion, or light scattering due to LC molecule reorientation, our LC lens overcomes the above problems because no LC molecular reorientation is involved during light modulation. Based on this unique operation mechanism, other adaptive devices such as micropism arrays, phase grating, and Fresnel lens can be fabricated easily.

Figure 1 illustrates the operation mechanism of the device. First, we prepared an empty homogeneous cell using two glass substrates. One-half of each substrate was coated with a thin transparent and conductive indium tin oxide (ITO) film. The inner side of each substrate was overcoated with a thin polyimide layer and then rubbed in antiparallel directions. A LC/monomer mixture consisting of 50 wt % nematic LC (ZLI-4788-000, $\Delta\epsilon=-5.7$, $\Delta n=0.1647$) and 50 wt % liquid monomer was injected into the cell, as shown in Fig. 1(a). The cell gap was controlled at $d=7\ \mu\text{m}$. The monomer used in this study is *N*-vinylpyrrolidone (NVP) with structure shown below:



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The nematic LC and monomer NVP mixed well and the mixture is highly transparent. To avoid any electric-field-induced LC molecular reorientation, the chosen LC material has a negative dielectric anisotropy ($\Delta\epsilon < 0$). If a positive $\Delta\epsilon$ LC is used, the LC molecules will follow the longitudinal field and be reoriented along the electric field direction.

In the voltage-off state, the LC molecules and liquid monomers are distributed uniformly in the cell. Since the LC has a larger dielectric constant than the monomer, when a voltage is applied across the cell as Fig. 1(b) shows, the LC molecules bear a greater force from the electric field. The force can be expressed by⁷

$$F = P \cdot \nabla E, \quad (1)$$

where P is the polarizability of the material and E is the electric field strength. Under such a circumstance, the LC molecules are sucked toward the high electric field region and liquid monomers diffused to the null field region. In the LC-rich region, the surface rubbing aligns the LC molecules, resulting in an increased refractive index. On the other hand, the monomer-rich region exhibits a lower refractive index because the selected monomer has no optical anisotropy and its refractive index is smaller than that of LC.

If the electric field across the whole cell is continuous but inhomogeneous, then the LC molecules will diffuse from low to high field region continuously. As a result, in the high electric field region, the LC concentration will increase; the

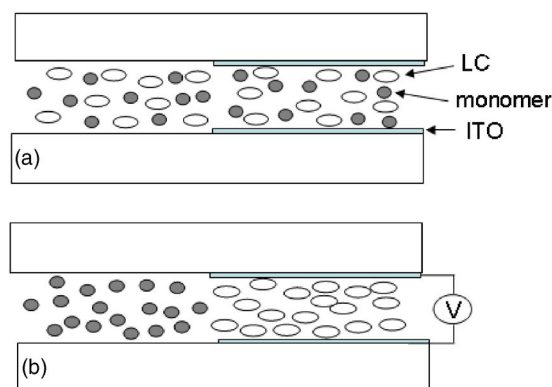


FIG. 1. (Color online) Operation mechanism of a LC concentration redistribution cell: (a) $V=0$ and (b) V is on.

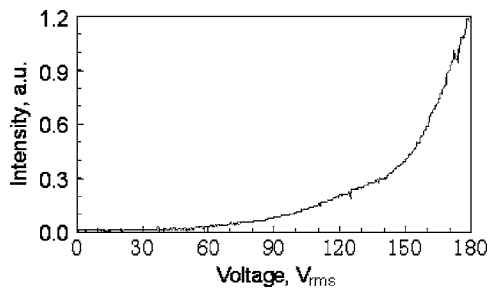


FIG. 2. Voltage-dependent transmittance of the LC/monomer cell. The cell gap is $7 \mu\text{m}$, and the weight ratio of LC: monomer is 1:1.

monomer will be diffused to the low field region. Meanwhile, the LC molecules tend to diffuse from high to low concentration direction to balance the electric force exerting on the LC molecules. As a result, the LC will exhibit a stable gradient concentration distribution and the focusing effect would take place.

To validate this molecular diffusion hypothesis, we measured the phase retardation of the LC/monomer by placing the homogeneous cell between two crossed polarizers. The rubbing direction of the cell is oriented at 45° with respect to the fast axis of the linear polarizer. Near the edge of the electrode, fringe field effect might occur. Thus, we sent a collimated He-Ne laser beam ($\lambda=633 \text{ nm}$) to the center of the ITO electrode at normal incidence. A photodiode detector was used to monitor the transmitted laser beam. A computer controlled LABVIEW data acquisition system was used for driving the sample and recording the light transmittance from the photodiode detector.

Figure 2 shows the voltage-dependent transmittance of the sample. At $V=0$, the transmittance is almost zero. If we rotate the sample in the azimuthal direction, the transmittance does not change. That means the filled LC/monomer mixture is isotropic. When the applied voltage is increased to $7 V_{\text{rms}}/\mu\text{m}$, transmittance begins to increase gradually, indicating that some LC molecules have moved into the electrode regions. When the voltage is over $20 V_{\text{rms}}/\mu\text{m}$, the transmittance changes very sharply. This is because much more LC molecules are attracted by the stronger electric field. The aggregated LC molecules are aligned by the rubbed polyimide so that the anisotropic optical property occurs.

To demonstrate a LC lens based on the above operation mechanism, we fabricated a cell with a homogeneous gap, as shown in Fig. 3. The cell is composed of a flat lens and an empty cell. The fabrication method of the cell is similar to that of the spherical lens we reported previously.⁸ The ITO electrode embedded in the upper substrate is designed to be spherical instead of planar. To prepare the LC cell, a plano-concave lens with radius $R=-7.07 \text{ mm}$, aperture $D=9 \text{ mm}$, and sag $S=1.24 \text{ mm}$ (Edmund Industrial Optics, SF11 glass,

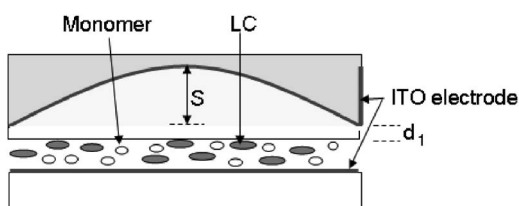


FIG. 3. Device structure of a flat spherical lens cell.

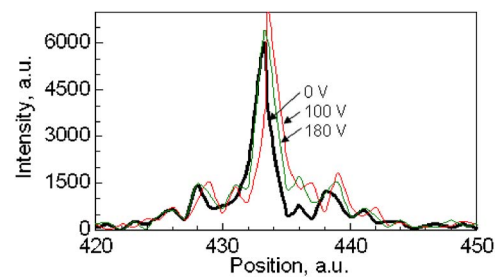


FIG. 4. (Color online) CCD images of the measured He-Ne laser beam intensity profile at $V=0, 100,$ and $180 V_{\text{rms}}$.

$n_g=1.785$) was chosen. The concave surface of the lens was coated with a thin ITO electrode. We then filled the sag with UV-curable prepolymer NOA81 (Norland Optical Adhesive, $n_p \sim 1.560$). After UV exposure, NOA81 was fully polymerized and a planar surface was obtained. Because $n_g > n_p$, the planar lens has an initial focal length $f=-40 \text{ mm}$. The planar lens was then combined with an empty LC cell. The glass substrate which is in contact with the lens has $d_1=0.55 \text{ mm}$, but no ITO electrode. The inner surfaces of the LC cell were coated with a thin polyimide layer and rubbed in antiparallel directions. The cell gap was controlled to be $\sim 25 \mu\text{m}$. The LC/monomer mixture (LC-ZLI4788-000 and NVP) was injected into the empty cell at room temperature and the filling hole was sealed using silicon glue.

To characterize the focusing properties of the fabricated lens, we measured the two-dimensional (2D) profiles of the outgoing He-Ne laser beam using a charge coupled device (CCD) camera. Because the lens cell has an initial diverging focus, we placed a convex glass lens (Newport, $f=150 \text{ mm}$) before the lens cell at 19 cm in order to get a converging beam. The CCD camera was placed behind the lens cell near the focal point. The intensity profiles were measured at $V=0, 100,$ and $180 V_{\text{rms}}$. Results are shown in Fig. 4. At $V=0$, the peak intensity reaches ~ 6000 arbitrary units. As the voltage is increased to $100 V_{\text{rms}}$, the peak intensity climbs to ~ 7000 arbitrary units. As the voltage is further increased, the peak intensity of the outgoing beam tends to decrease. At $V=180 V_{\text{rms}}$, the peak intensity drops to 6300 arbitrary units.

The changed peak intensity can be explained as follows: At $V=0$, the mixture in the lens cell is homogeneous; neither LC nor monomer makes any contribution to the focusing effect. The intensity profile is solely from the focus of the planar diverging lens and the convex glass lens. The focal plane of the CCD camera is behind the focal point of the incident beam, as shown in Fig. 5(a). When a voltage is applied, the electric field across the lens cell is centrosymmetric. The electric field in the middle is weaker than that at the edges. As a result, the LC molecules are driven toward the edges and monomers are diffused toward the center. Because the electric field is inhomogeneous, the LC concentration from edges to center has a gradient distribution. Higher LC concentration presents a higher refractive index, and higher monomer concentration presents a lower refractive index. Therefore, the device functions as a negative lens. At $V=100 V_{\text{rms}}$, the lens cell presents a divergent focus which helps to elongate the effective focal length. In this case the focal point is nearer the focal plane of the CCD camera, as shown in Fig. 5(b). Therefore, the peak intensity increases noticeably. As the voltage is increased further, the gradient of

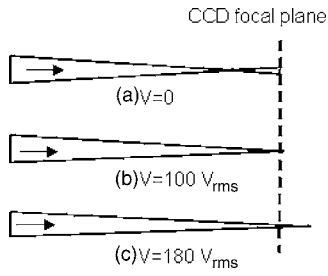


FIG. 5. Sketched position of focal point at different applied voltages. (a) $V=0$, (b) $V=100$, and (c) $V=180$ V_{rms} . The dashed lines indicate the focal plane of the CCD camera.

the LC concentration distribution is increased. Thus, the diverging power of the lens cell is increased accordingly. The focal point of the laser beam is beyond the focal plane of the CCD camera, as shown in Fig. 5(c). Therefore, at $V=180$ V_{rms} the peak intensity drops. Because the aperture of the lens is relatively large and the LC cell gap is thin, the observed intensity change is not significant.

From Figs. 4 and 5, the diverging effects of the lens cell imply that the redistributed LC concentration functions as a lens. The focal length can be expressed by⁹

$$f = \frac{r^2}{2[n_2(V) - n_1(V)]d}, \quad (2)$$

where r is the radius of the lens aperture, d is the gap of the lens cell, and n_1 and n_2 are the refractive indices of the mixture at the edges and at the center of the lens cell, respectively. At $V=0$, the mixture is homogeneous everywhere, so n_1 and n_2 can be expressed by

$$n_1(0) = n_2(0) = n_e C_{\text{LC}} + n_p(1 - C_{\text{LC}}), \quad (3)$$

where n_e is the extraordinary refractive index of the LC and C_{LC} is the LC concentration. At $V=0$, the focal length is at infinity. At a sufficiently high voltage, LC concentration can reach 100% at the highest voltage region and monomer concentration can reach 100% at the lowest voltage region. In this case, the focal length is the shortest and can be written as

$$f_{\text{shortest}} = \frac{r^2}{2(n_p - n_e)d}. \quad (4)$$

From Eqs. (2)–(4), a tunable focal length from $-\infty$ to f_{shortest} can be obtained when the refractive index is tuned from n_1 to n_e and monomer from n_1 to n_p , correspondingly.

From Figs. 2 and 3 the operating voltage of our device is relatively high. This is due to the small dielectric constant of the negative LC employed. Choosing a LC material with a

larger dielectric constant would be helpful to reduce the operating voltage. To increase the optical power of the lens, a high extraordinary refractive index of the LC material (n_e) and a low refractive index of monomer (n_p) are helpful.

The response time of the lens cell was measured to be about ~ 3 min during focus switching. The response time is governed by several factors, such as applied voltage, monomer concentration, material viscosity, and lens dimension. Because our lens cell has a relatively large diameter (9 mm), the molecular diffusion will take a long time. Therefore, the response time is very slow. However, if we make a microlens array, the monomer diffusion should be faster because of the shorter travel distance. For a microlens with 50 μm aperture, the estimated response time is about ~ 1 s at room temperature. Electrically tunable LC concentration redistribution is more suitable for microlens and other micron-sized devices, such as microprism array and Fresnel lens.

Compared with other tunable LC lens, our LC lens works based on LC concentration redistribution, not molecular reorientation. Therefore, the lens astigmatism should be reduced significantly. In the meantime, there is no distortion or light scattering during focus change. Based on this operation mechanism, a polarization-independent lens can be fabricated by using two isotropic materials but with different dielectric constants and refractive indices.

In conclusion, we have demonstrated an electrically tunable-focus lens based on LC and monomer concentration redistribution. Without a voltage, LC concentration is uniform in the bulk. When an inhomogeneous electric field is applied to the lens cell, the gradient LC concentration is generated which forms a lens. By designing the electrode shape, various types of optical devices, such as microprism array and Fresnel lens, can be fabricated. Because the diffusion speed is relatively slow, this mechanism is more suitable for microdevices.

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