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# An electrically tunable focusing liquid crystal lens with a built-in planar polymeric lens

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An electrically tunable focusing liquid crystal (LC) lens with a built-in planar polymeric lens with a short focal length (~4.41 to 8.82 cm) is demonstrated. The focal length of the LC lens is contributed by two parts: one is the LC layer and the other is planar polymeric layer. In the image system, the object can be continuously imaged by the LC lens when the object is at the objective distance from 360 to 17 cm as the voltage is switched from 0 to 35 $V_{rms}$. The image performance is also demonstrated. The applications are cell phones, and cameras © *2011 American Institute of Physics*. [doi:10.1063/1.3559622]

Electrically tunable focusing liquid crystal (LC) lens is important in cell phones, cameras, picoprojectors, and the night vision of hand-carried weapons.[1–3] Features of LC lenses are low cost, light weight, and no requirement of a mechanical moving part. The main mechanism of electrically tunable focal length of LC lenses results from the gradient distribution of refractive indices owning to the orientations of LC directors. To achieve gradient distribution of refractive indices of LC lenses, an inhomogeneous electric field can be applied to an LC layer with an uniform cell gap or an homogeneous electric field can be applied to an LC layer with a nonuniform cell gap.[4–10] The LC lenses within the uniform cell gap under an inhomogeneous electric field have features of good image quality, uniform response time, and free from light scattering. Many LC lenses with a large aperture are proposed, such as modal control LC lenses,[5] pixilated LC lenses,[6] LC lenses with a curved-electrode,[7,8] LC lenses with a hole-pattern-electrode and an insulating layer,[9] and LC lenses with a hidden dielectric structure.[10] For the application of cell phones, the aperture size of LC lenses is small (<2 mm). To enhance the bundle of light entering to LC lenses, a short focal length (<5 cm) of LC lenses is required. Increasing cell gap or adding an extra solid lens can help to reduce the focal length of LC lenses,[1,4,7,8] however, the large cell gap causes slow response time and strong light scattering, and the extra solid lens is bulky. Therefore, to develop a LC lens with a short focal length and simple structure is urgent. In this paper, we demonstrate an electrically tunable focusing LC lens with a built-in planar polymeric lens whose focal length is short (4 to 8 cm). The focal length of the LC lens is contributed by two parts: one is the LC layer whose focal length is electrically tunable and the other is the planar polymeric layer which has a fixed focal length and determines the initial focal length. The planar polymeric lens is not only a positive lens but also an alignment layer to the LCs.[11,12] The electro-optical properties and image performance of the LC lens is investigated. The structure of our LC lens is simple and compact with large aperture.

The structure of the LC lens is depicted in Figs. 1(a) and 1(b). The LC lens consists of two ITO glass substrates coated with mechanically buffered polyvinylalcohol (PVA)) to align LC molecules, an LC layer and a polymeric layer. The top ITO layer was etched with a hole-pattern within a diameter of 1.68 mm in order to provide an inhomogeneous electric field to LC directors. To fabricate the polymeric layer, we first filled nematic LC (Merck, MLC-2070), reactive mesogen (Merck, RM 82), and photoinitiator (Merck, IRG-184) at 30:69:1 wt % ratios into two ITO glass substrates coated with mechanically buffered PVA. On the top substrate the ITO layer was etched with a hole-pattern within a diameter of 1.68 mm and the bottom ITO substrate did not etched. The cell was then applied 70 $V_{rms}$ ($f=1$ kHz) in order to reorient the LC directors to form a gradient phase profile as a positive lens and the monomer molecules were also reorient due to the electric field and the LC directors. Then we shined the UV light (~1.25 $mW/cm^2$) for 40 min to photopolymerize the monomer to form the polymeric layer. The thickness of the polymeric layer was 35 $\mu$m. After photopolymerization, we peeled off the bottom substrate by a thermal releasing process in which the bottom substrate was heated up to 100 °C for 1 min and then was peeled off. Then we sandwiched nematic LC mixture MLC-2070 (Merck, $\Delta n=0.26$ for $\lambda=589.3$ nm at 20 °C) between the polymeric layer and another ITO substrate coated with mechanically buffered PVA in order to construct the structure as shown in Fig. 1(a). The thickness of LC layer was 25 $\mu$m. The polymeric layer has a fixed focal length because of the lenslike distribution of refractive indices. The LC directors in the LC layer aligned by the polymeric layer and PVA layer were aligned homogeneously with pretilt angle ~2°.[11,12] The polymeric layer and LC layer were uniform in the hole-patterned (or aperture) region by observing under a polarizing microscopy. When

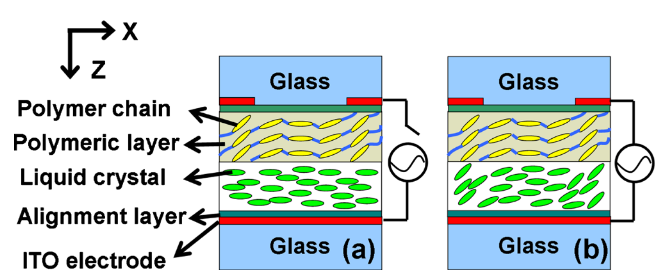


FIG. 1. (Color online) The structure of the LC lens at (a) voltage-off state and (b) voltage-on state.

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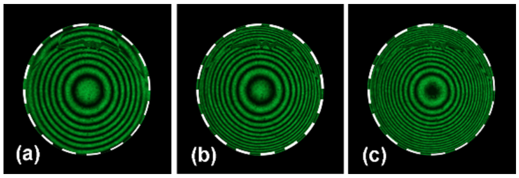


FIG. 2. (Color online) The phase profiles of the LC lens at (a) V=0 $V_{rms}$, (b) V=15 $V_{rms}$, and (c) V=35 $V_{rms}$ (λ=532 nm).

we apply a voltage (V), the focal length [f(V)] of the LC lens in Figs. 1(a) and 1(b) is contributed by two sublenses: one is the LC layer whose focal length [$f_{LC}(V)$] is electrically tunable and the other is polymeric layer whose focal length ($f_p$) is fixed. f(V) can be expressed as[13]

$$\frac{1}{f(V)} = \frac{1}{f_{LC}(V)} + \frac{1}{f_p}, \tag{1}$$

where $f_{LC}(V)$ can be expressed as[8]

$$f_{LC}(V) = \frac{\pi \times w^2}{4 \times \lambda \times \Delta\delta(V)}, \tag{2}$$

where w is the aperture size, λ is the wavelength, and $\Delta\delta$ is the phase difference. At the voltage-off state, the LC directors were aligned homogeneously as shown in Fig. 1(a). f(V) equals to $f_p$ because the $\Delta\delta$ of LC layer is zero. In Fig. 1(b) when the voltage is larger than the threshold voltage ($V_{th}$), f(V) is determined by the LC layer and polymeric layer according to Eq. (1).

To observe the phase profile of the LC lens, we observed the image of the LC lens at different voltages under crossed polarizes, as shown in Figs. 2(a)–2(c). The rubbing direction of the LC lens was 45° with respect to one polarizer. In Fig. 2(a), the concentric phase profile of the LC lens at V=0 indicates the focusing properties of the polymeric layer. We also tested the polymeric layer only by applying voltages. The phase profile of the polymeric layer did not change with the voltage ($V < 100$ $V_{rms}$). That means the polymeric layer is a lens with a fixed focal length. The focal length of the polymeric layer is ~8.82 cm according to the relation: $f = D^2/8\lambda N$, where D is the aperture size, λ is the wavelength, and N is the number of rings of the phase profile.[8] The disclination line was observed because of the polymeric layer resulting from the different orientation of LC directors during curing process. At $V > V_{th}$ ($V_{th} \sim 5$ $V_{rms}$), the number of the rings increases in Figs. 2(b) and 2(c). That means the focal length decreases. By the phase profiles, we plotted the focal length of the LC lens as a function of applied voltage, as shown in the black dots in Fig. 3. The initial focal length is 8.82 cm determined by the polymeric layer and then the focal length decreases with the voltage ($V > V_{th}$). At 35 $V_{rms}$, the LC lens has minimal focal length ~4.41 cm.

To measure the tunable focusing properties of the imaging system, the LC lens and a polarizer were attached on a webcam. The webcam consists of a lens module with the effective focal length of 4.86 mm and an image sensor with 3.4 mega pixels. The transmissive axis of the polarizer is parallel to the rubbing direction of the LC lens. The image sensor was placed at 4.49 mm behind the lens module. We recorded the objective distance of a focused (or clear) image of a resolution chart by changing the different voltages of the LC lens. The spatial frequency of the resolution chart was

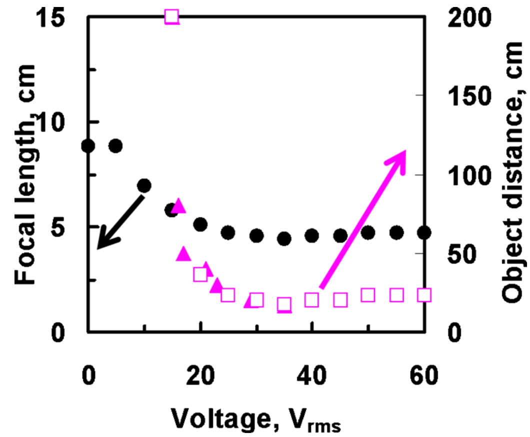


FIG. 3. (Color online) The focal length of the LC lens as the function of the applied voltage (black dots), the measured object distance as the function of the applied voltage (solid triangles), and the calculated object distance as the function of the applied voltage (hollow squares).

0.625 line pairs per millimeter (lp/mm) at the objective distance of 17 cm and 0.05 lp/mm at the objective distance of 200 cm. The measured objective distance as a function of voltage of the LC lens (solid triangles) is shown in Fig. 3. The objective distance of the system is switched from 360 to 17 cm when the voltage was switched from 0 to 35 $V_{rms}$.

According to the equation of image formation, the objective distance of the system (p) as a function of f(V) can be expressed as[2]

$$\frac{1}{p} = \frac{1}{f_m} - \frac{1}{q} + \frac{1}{f(V)}, \tag{3}$$

where $f_m$ is the focal length of lens module (~4.86 mm) and q is image distance (~4.49 mm). In addition, f(V) was measured in Fig. 3, and $f_{LC}(V)$ can be obtained according to Eq. (1). Thus, the calculated objective distance as a function of voltage of the LC lens is plotted in Fig. 3 (hollow squares). In Fig. 3, the calculated results (hollow squares) are closed to the experimental results (solid triangles). To obtain a LC lens with a short focal length, we can fabricate a polymeric layer with a short focal length or a LC layer with large phase difference. From Eq. (1), f(V) is approximately equals to $f_p$ when $f_p \ll f_{LC}(V)$. That means the focal length of the LC lens is not tunable even though the focal length of the polymeric layer is short. When $f_p \gg f_{LC}(V)$, f(V) approximately equals to $f_{LC}(V)$. That means the focal length of the LC lens is determined by the LC layer. However, the focal length of the LC layer cannot be short enough because of the limitation of birefringence of LC materials. Increasing the thickness of LC layer can lower the focal length of the LC layer but the tradeoffs are poor image quality and slow response time. In our LC lens, the voltage is reduced (~35 $V_{rms}$) compared to the LC lens using a glass substrate as an insulating layer (~52 $V_{rms}$) (Ref. 8) because the polymeric layer is thin (~35 μm) even though the dielectric constant of the polymeric layer (~4.2) is lower than that of the glass substrate (~5). To further reduce the voltage, we can reduce the thickness of the polymeric layer, increase the dielectric constant of the polymeric layer, and also design the distribution of dielectric constants of the polymeric layer.

The measure the response times of the LC lens are shown in Figs. 4(a) and 4(b). The response time was

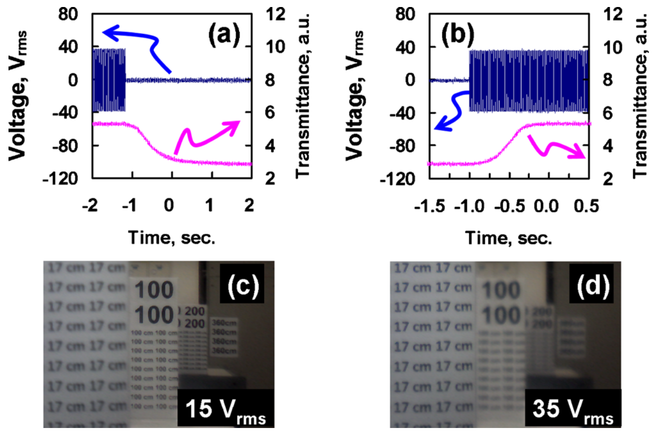


FIG. 4. (Color online) The measured response time of the LC lens when the voltage is switched from (a) 35 to 0 $V_{rms}$ and (b) 0 to 35 $V_{rms}$. The image performance of the LC lens. The clear image for the objective distance of (c) 200 cm at 15 $V_{rms}$ and (d) 17 cm at 35 $V_{rms}$.

~350 ms and ~740 ms when the voltage of the LC lens is switched from 0 $V_{rms}$ to 35 $V_{rms}$ and from 35 $V_{rms}$ to 0 $V_{rms}$, respectively. To further improve response time, we can reduce the thickness of the LC layer, or reduce the viscosity of LC materials, or add polymer networks to enhance the anchoring force.[1] Moreover, different driving scheme can be adopted to improve the response time, such as overdriving method, under shooting method, and bias voltage method.[14] Figures 4(c) and 4(d) show the image performances of the imaging system consisting of a polarizer, the LC lens, a lens module, and the image sensor. The photos were taken under an ambient white light. The numbers in the photos indicate the locations of the objects. For example, 17 cm on a white paper means the object was 17 cm away from the LC lens. The clear image was at 200 cm as $V=15$ $V_{rms}$ and at 17 cm as $V=35$ $V_{rms}$. In Figs. 4(c) and 4(d), both of the polymeric lens and sub-LC lens contribute to the aberration of images. To reduce the aberration, the phase profile of polymeric lens and sub-LC lens should be parabolic. In addition, the images are slightly blurred due to Rayleigh scattering. The scattering may results from the mismatch of the refractive indices between LC and polymer because the extraordinary refractive index of polymer ($n_e$) is 1.768, ordinary refractive index of polymer ($n_0$) is 1.558, and the averaged refractive index ($n_e+2\ n_0/3$) of LC ($n_e=1.7828$ and $n_0=1.5219$) is ~1.6088. However, the measured transmittance of the polymeric layer is high (~98%) because of low concentration of LC in the polymeric layer. As a result, the scattering mainly results from two parts: one is the large thickness of LC layer, and the other is the weak LC alignment between the LC layer and polymeric layer. To reduce the Rayleigh scattering, we can optimize the concentration of the LCs in the polymeric layer to enhance the capability of alignment. As to the multiple beam interference between the interfaces, the transmittance from the interfaces around 99.33% ~99.99% is high; therefore, the multiple beam interference can be neglected in the image system.

In conclusion, we have demonstrated an electrically tunable focusing LC lens with a built-in planar polymeric lens with a short focal length. The polymeric layer is a positive lens with a fixed focal length and it can help to reduce the focal length of the LC lens. Moreover, it aligns the LCs. The structure of the LC lens is compact and simple. The total thickness of the LC lens is ~1.26 mm. The driving is simple and the voltage is low. The problems remain to be solved are requirement of a polarizer, slow response time, and image quality. To remove the polarization dependency, we can change different LC mode in the LC layer. The response time can also be improved by improve the materials of LC or change the driving scheme or adopting the method of two mode switching. The potential applications are autofocusing cell phones and cameras.

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