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Adaptive liquid crystal lens with large focal length tunability

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Abstract: We demonstrate a tunable-focus lens using a spherical glass shell and a homogeneous liquid crystal (LC) cell. The inner surface of the glass shell and the bottom surface of the LC cell are coated with indium tin oxide (ITO) electrodes while the LC layer is sandwiched between the spherical and flat ITO electrodes. When a voltage is applied to the electrodes, a centro-symmetric gradient refractive index is generated within the LC layer and the focusing behavior occurs. Based on our analysis, the focal length tunability of the LC lens depends significantly on the filled material in the sag region. For the air-filled LC lens we designed, its focal length can be tuned from infinity to ~96 cm. A method for reducing the operating voltage is proposed.

OCIS codes: (010.1080) adaptive optics; (160.3710) Liquid crystals; (220.3620) lens design

References and links

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1. Introduction

Electrically tunable-focus liquid crystal (LC) lenses have promising applications in auto beam steering, mobile phone cameras, eyeglasses, and other machine visions. Various approaches such as polymer gel stabilization, [1, 2] modal control, [3] patterned electrode, [4, 5] and surface relief profile [6-10] have been demonstrated. Among them, the surface relief lens which consists of a glass lens and a homogeneous LC layer is particularly attractive because of the advantages in uniform response time, free from light scattering, single electrode, and simple fabrication. In this kind of lens, the LC layer is sandwiched between a curved and a flat indium-tin-oxide (ITO) substrates. When a voltage is applied, the inhomogeneous electric field generates a centro-symmetric refractive index distribution within the LC layer resulting in a focusing behavior. Usually, the space between the curved ITO electrode and the LC cell is filled with a transparent material, such as glass, plastic, or polymer. The filled material has an important effect on the focal length of the LC lens. Theoretical calculation shows that over half of the bulk LC makes no contribution to the light focusing effect. The main reason is that the generated gradient of electric field within the LC layer is too shallow. Let us take a converging LC lens as an example. When the distributed voltage at the border of the LC layer is far below the saturation level, the distributed voltage at the center of the lens is already over the threshold. Consequently, the electric field-induced refractive index within the LC layer is too shallow to generate a short focal length. Increasing the LC layer thickness helps to compensate for the lost phase, but the response time is increased accordingly. For practical applications, we need to optimize LC lens design in order to achieve maximum focal length tunability without increasing the LC cell gap.

In this paper, we analyze the performance of a surface-relief LC lens and give confirming experimental results. In our LC lens structure, we use a *glass shell* instead of a glass lens. Its inner surface is coated with a thin ITO electrode. When a voltage is applied to the LC cell, the electric field generates a gradient of centro-symmetric refractive index distribution within the LC layer. As a result, the focusing behavior appears. From our theoretical analysis, we find that the dielectric constant of the filled material in the sag region of the glass shell significantly impacts the electric field gradient. Results show that if the sag is filled with air (dielectric constant $\varepsilon\sim1$) rather than any other material with $\varepsilon>1$, then the lens cell can achieve the shortest focal length even if the LC layer is relatively thin. In comparison with previous surface-relief LC lenses for the same LC thickness, our air-filled LC lens exhibits the highest tunable focus power, the widest tunable focal depth, and the easiest fabrication process.

2. **Device structure**

Figure 1 depicts the cross-section of the LC lens. It consists of a spherical glass shell, a material filled in the sag of the glass shell, and a LC cell. We use a glass shell instead of a plano-convex glass lens for two reasons. First, if the ITO is deposited on the outer surface of the plano-convex glass lens, the required voltage will be very high because of the dielectric shielding of the glass. Moreover, the ITO layer could be scratched or contaminated. Second, using the glass shell allows us to choose the best material for filling the sag region. It should be mentioned that filling a material such as glass, plastic, or polymer in the sag region can cause a fixed focus in the null voltage state.

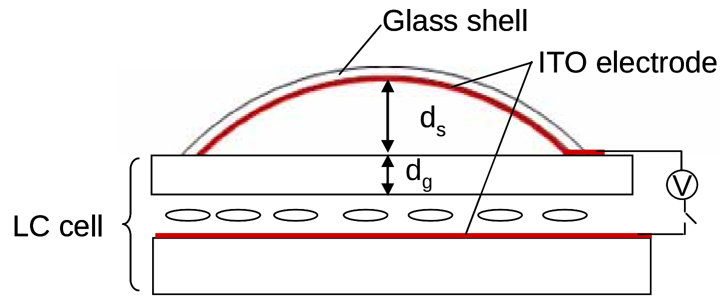

Fig. 1. Device structure of the proposed surface-relief LC lens.

To fabricate a lens cell, we first sputtered ITO electrode on the inner surface of the glass shell and then filled the sag with a transparent material. After that, we glued the filled glass shell onto the top of a homogeneous LC cell, as sketched in Fig. 1. As for the LC cell, only the inner surface of the bottom substrate has ITO electrode. The inner surfaces of the LC cell were coated with a thin polyimide alignment layer and rubbed in anti-parallel directions to generate a pretilt angle. As will be explained later, the pretilt angle used is around 6^{o}.

3. Theoretical analysis

When a voltage (V) is applied to the electrodes, the LC layer experiences an inhomogeneous electric field because the top ITO electrode has spherical shape. Within the LC layer, the electric field at the border (E_b) and center (E_c) can be calculated as follows: [10]

$$E_b = \frac{V}{\varepsilon_{LC}} / \left(\frac{d_{LC}}{\varepsilon_{LC}} + \frac{d_g}{\varepsilon_g} \right), \tag{1}$$

$$E_c = \frac{V}{\varepsilon_{LC}} / \left(\frac{d_{LC}}{\varepsilon_{LC}} + \frac{d_g}{\varepsilon_g} + \frac{d_s}{\varepsilon_m} \right), \tag{2}$$

where d_{LC}, d_g, and d_s represent the LC thickness, the LC cell's top glass substrate thickness, and maximum sag of the glass shell, and ε_{LC}, ε_g, and ε_m represent the dielectric constant of the LC medium, the top glass substrate of the LC cell, and the filled material, respectively.

To illustrate quantitatively how the filled material in the sag region affects the electric field gradient within the LC layer, we chose polymer (Norland Adhesive NOA81) and air for comparison. NOA81 is a common UV curable monomer and air has the lowest dielectric constant. The parameters for designing our lens are listed as follows: LC BL-038 ($\Delta\varepsilon$=16.4, ε_{LC}=10.7, Δn=0.272), d_{LC}=0.025 mm; d_g=0.55 mm, ε_g =7.75; the dielectric constant of polymer NOA81 was measured to be ε_p~5 (1 kHz) and air ε_{air} ~1. The thickness of the glass shell is ~0.2 mm with the maximum sag d_s=0.72 mm.

For the case of polymer NOA81, Eqs. (1) and (2) have following simple forms:

$$E_{b,p} = 1.275V \tag{3}$$

$$E_{c,p} = 0.430V \tag{4}$$

On the other hand, if the sag is empty, Eqs.(1) and (2) are reduced to:

$$E_{b,air} = 1.275V, \tag{5}$$

$$E_{c,air} = 0.118V. \tag{6}$$

From Eq. (3) and Eq. (5), the electric field at the border remains the same no matter what material is employed. This is because in the borders the ITO is in direct contact with the top glass substrate and there is no gap between the top and bottom substrates. However, at the center the filled material would contribute to the capacitance of the whole stack, as Eq. (2) shows. To see its significance, we plot Eqs. (3), (4), and (6) in the same E-V coordinate system as shown in Fig. 2. To obtain a short focal length, a large electric field gradient between the center and border is needed. From Fig. 2, the generated electric field in the center of the polymer-filled lens is much higher than that of the air-filled lens. This high electric field could reorient the LC directors in the central region and flatten the refractive index gradient which, in turn, leads to a longer focal length in the voltage-on state.

The focal length of an LC lens can be calculated from the following equation: [11]

$$f = \frac{r^2}{2 d_{LC} \delta n}, \tag{7}$$

where r is the radius of the lens aperture and δn is the effective refractive index difference between the lens center and border. When the LC lens, as shown in Fig. 1, is activated the LC directors at the border are reoriented first because of the strongest electric field. As the voltage gradually increases, the LC reorientation spreads toward the lens center. From Fig. 2, for a given voltage the electric field at border is always stronger than that at the lens center. This implies that the LC directors will have a larger tilt angle in the border than in the center.

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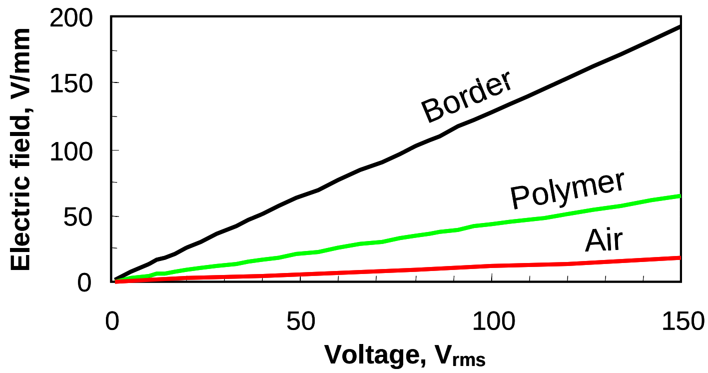

Fig. 2. Electric field within the LC layer at the lens border and lens center with various voltages applied across the electrodes. The LC cell gap is 25 μm and the sag of the glass shell is 0.72 mm. The filled material is either polymer NOA81 or air.

From Eq. (7), to obtain the shortest focal length for a given lens aperture we need to maximize δn. This condition can be achieved when the LC directors at the lens border are reoriented vertically while the LC directors at the lens center still keep the horizontal alignment, i.e., near the threshold. Under such an ideal circumstance, the δn in Eq. (7) can be replaced by the LC birefringence Δn. In reality, the LC directors in the border are difficult to be reoriented completely because of the anchoring energy effect of the substrate surfaces. From Fig. 2, the air-filled lens exhibits the largest electric field gradient within the LC layer. Any other material with dielectric constant ε_m>1 would enhance the electric field strength in the lens center, as described in Eq. (2), and reduce the refractive index gradient.

For a tunable-focus LC lens, such as camera zoom lens, the required voltage should be as low as possible. For a homogeneous LC cell, the threshold voltage is related to the splay elastic constant (K_{11}), permittivity of free space (ε_0), and LC dielectric anisotropy ($\Delta\varepsilon$) as: [12]

$$V_{th} = \pi\sqrt{\frac{K_{11}}{\varepsilon_0 \Delta\varepsilon}} \tag{8}$$

From Eq. (8), the BL-038 LC we employed has V_{th}=0.96 V_{rms}. To decrease the threshold, we intentionally increase the pretilt angle to ~6°. High pretilt angle helps to suppress the threshold behavior and lead to more uniform LC alignment without losing much phase.

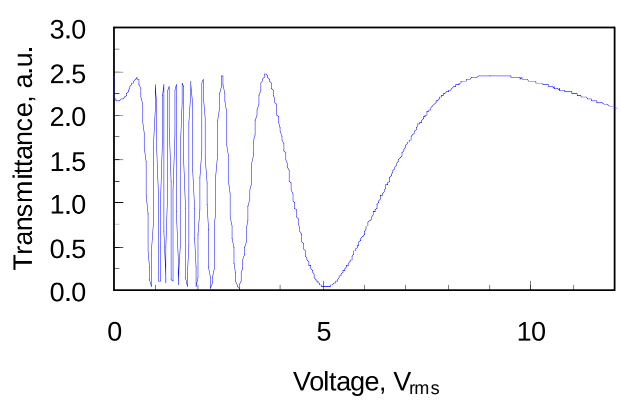

Fig. 3. Voltage-dependent transmittance of a homogeneous LC cell between crossed polarizers. LC is BL-038, cell gap d_{LC}=25 μm, and λ=633 nm.

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Figure 3 shows the optical transmission of a 25-μm homogeneous BL-038 LC cell. The cell was placed between two crossed polarizers with its LC directors oriented at 45° to the optic axis of the front polarizer. A He-Ne laser (λ=633 nm) was used as the light source. From Fig. 3 the threshold is smeared and reduced to ~0.3 V_{rms} because of the relatively large pretilt angle. When the applied voltage is scanned from 0 to ~5 V_{rms}, a large phase change (~19π) is obtained. In the V>5 V_{rms} region, there remains about 2π phase shift. Although the voltage across the LC layer is only 5 V_{rms}, the corresponding external applied voltage is already 156 V_{rms} due to the dielectric shielding of the relatively thick middle glass substrates. At V=156 V_{rms}, the voltage in the polymer-filled lens center is ~1.63 V_{rms} which far exceeds the LC threshold (~0.3 V_{rms}). In contrast, the corresponding voltage for the air-filled lens center is ~0.45 V_{rms} which is very close to the threshold. As a result, the refractive index gradient of the air-filled LC lens is sharper than that of the polymer-filled lens. A shorter focal length in the voltage-on state is therefore expected.

5. Experiment

To validate the above theoretical prediction, we fabricated two LC lenses with the same structure except one glass shell was filled with polymer NOA 81 and the other with air. The aperture of the glass shell is 6 mm and all the other parameters for the two lenses are the same as those used in the simulations. The two lenses were tested side-by-side. When an external voltage was applied to the two lenses, interference rings occurred from the border almost simultaneously. Increasing the voltage could produce more rings gradually and these rings spread from border to center. The phase difference between two adjacent rings is 2π. When the applied voltage reaches 60 V_{rms}, both the polymer-filled lens and air-filled lens generate about 5.5 interference rings. From Eq. (7), the calculated focal length is ~4.96 m. As the applied voltage is increased, the interference rings from the polymer-filled lens began to decrease and swallow in the center, while the air-filled lens still produces more rings before the voltage reaches 140 V_{rms}.

Figure 4 shows the interference rings of the two lenses at 140 V_{rms}. Only a portion of the lens is shown because the lens aperture is relatively large when observed under a polarized optical microscope. From Fig. 4, the polymer-filled lens has 4 rings, but the air-filled lens has 8.5 rings corresponding to a focal length of ~0.96 m, which is ~5X shorter than that of the polymer-filled LC lens. When the external voltage exceeds 140 V_{rms}, the interference fringes from the air-filled lens begin to decrease. This is because the inner voltage in the lens center has already exceeded the LC threshold which leads to a decreased refractive index gradient. Thus, the effective focal length is longer, i.e., the tunable range is narrower.

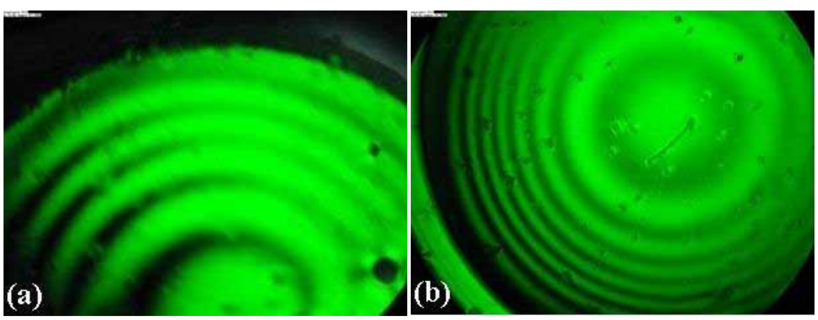

Fig. 4. Interference rings of the LC lens at V=140 V_{rms}. (a) polymer-filled lens and (b) air-filled lens.

Figure 5 shows the phase profiles of the air-filled lens operated at 40, 60, and 140 V_{rms}. The curves have a nearly parabolic shape whose curvature depends on the applied voltage. As V increases, the gradient becomes sharper. In comparison with the previously published results, [7, 8] the present air-filled LC lens exhibits a larger focal length tunability although its LC layer is much thinner. To improve the focusing power, we can increase the LC thickness or decrease the aperture size of the glass shell. The major tradeoff of increasing LC cell gap is the slower response time. The response time of the 25-μm LC lens is ~1s at T~22°C.

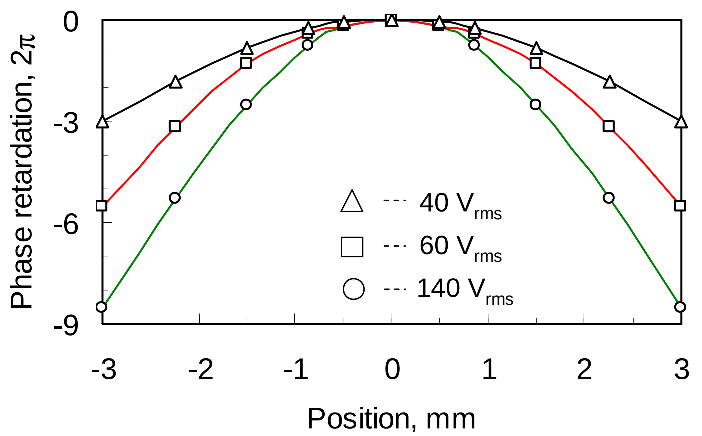

Fig. 5. Profiles of phase retardation of the air-filled LC lens at V= 40, 60, and 140 V_{rms}.

From Fig. 5, the required external voltage of the air-filled LC lens at the shortest focal length is still quite high. From Eq. (1) and the lens parameters we employed, the external voltage V=140 V_{rms} corresponds to $d_g \varepsilon_{LC} / \varepsilon_g d_{LC}$ ~27. To reduce the required voltage to ~20 V_{rms}, we should reduce the $d_g \varepsilon_{LC} / \varepsilon_g d_{LC}$ ratio by an order of magnitude. To achieve nearly complete LC reorientation, we still assume the LC voltage at the border remains at ~5 V_{rms}. To lower the ratio of $d_g \varepsilon_{LC} / \varepsilon_g d_{LC}$ to 3, we could take two approaches: 1) to use a thin (d_g ~0.11 mm) commercially available glass plate as the LC top glass substrate, and 2) to increase the LC cell gap to d_{LC} ~50 μm or use a high Δn LC material.[13] Under these conditions, the external voltage is decreased to 20 V_{rms} without changing other parameters. From Eq. (7), an LC lens with 50 μm cell gap would double the focusing power although its response time during focus change would be 4X slower. Thus, using a high Δn LC is a preferred approach.

In principle, the spherical glass shell should have an initial focus. However, it is so thin that its initial focus can be neglected. If an initial focus is desired, we can use a crescent-shaped glass lens instead of the glass shell. Such a lens not only provides an initial focus but also preserves the function of the glass shell. Due to the geometrical symmetry of the thin glass shell or crescent-shaped glass lens, the image quality produced by the LC layer should not be degraded. In our air-filled LC lens, the interference rings induced by the external voltage are highly symmetrical and circular during focus change. Moreover, the LC layer is relatively thin so that the spherical aberration should be negligible.

6. Conclusion

We have demonstrated a tunable-focus lens using a glass shell and a homogeneous LC layer. This lens can highly exert its focal length tunability if the sag of the glass shell is empty. Such a lens can provide a focal length which is variable in a very wide range. By comparison with the polymer-filed LC lens, the focusing power of the air-filled LC lens is improved by ~5X. By reducing the top LC substrate thickness and increasing the LC cell gap, the operating voltage for achieving the shortest focal length can be reduced significantly.

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