Physical mechanism for flat-to-lenticular lens conversion in homogeneous liquid crystal cell with periodically undulated electrode

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Abstract: A convertible lenticular liquid crystal (LC) lens architecture is demonstrated using an index-matched planarization layer on a periodically undulated electrode for the homogeneous alignment of an LC. It is found that the in-plane component of the electric field by the undulated electrode plays a primary role in the flat-to-lens effect while the out-of-plane component contributes to the anchoring enhancement of the LC molecules in the surface layer. Our LC device having an index-matched planarization layer on the undulated electrode is capable of achieving the electrical tunability from the flat surface to the lenticular lens suitable for 2D/3D convertible displays.

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References and links
15. Data sheet of ZLI-4151–000 provided by Merck Ltd.
1. Introduction

Liquid crystals (LCs) are an important class of soft matters that produce a variety of surface phenomena and electro-optic (EO) effects [1]. The basic principles the LC devices rely mainly on the delicate interplay between the surface anchoring of the LC molecules and an external perturbation such as a static electric or magnetic field, an optical field, and a mechanical force. Recently, a variety of electrically tunable lenses based on an LC have attracted much attention for a wide range of optical applications such as optical interconnections, the EO components in adaptive optics, and focusing devices in high-density data storage [2, 3]. Among them, spherical LC lens structures are most extensively studied [4–7]. Of particular interest is a convertible lenticular LC array which serves as one of the essential components for realizing 2-dimensional (2D)/3-dimensional (3D) convertible displays [8–10]. In order to obtain the characteristic of the flat-to-lens conversion, either a homogeneous electric field in the LC layer with a nonuniform cell gap [11] or an inhomogeneous electric field in the LC layer with the uniform cell gap [12], for example, the in-plane switching (IPS) method [9] is necessarily employed. The IPS approach allows, in principle, a simple scheme of modulating the EO effect of the LC but it suffers intrinsically from the existence of inactive regions of the LC layer on the electrodes and in the vicinity of the substrate with no electrodes. In another case, the use of an extra solid lens involves a complex fabrication process and a bulky structure of an LC lens array [13]. Note that the resolution format of a lenticular LC array will govern primarily the image quality of the 2D/3D display.

In this paper, we demonstrated a convertible lenticular LC array using an index-matched planarization layer on a periodically undulated electrode allowing the flat-to-lens conversion over the entire area of the LC cell through the electric field modulation. It was found that the in-plane component of the modulated electric field plays a primary role in the flat-to-lens effect while the out-of-plane component contributes to the anchoring enhancement of the LC molecules in the surface layer. The contribution of the out-of-plane electric component to the focusing effect in a lenticular LC array has not been described previously in the case of an inhomogeneous electric field. The periodically modulated electric field produces the periodic LC distortions on a planar surface along the direction perpendicular to the electrode undulation. As a result, our LC device gives rise to the flat-to-lens capability over the whole region in contrast to the IPS case. Numerical simulation results, obtained using a relaxation method [14] within the framework of the elasticity formalism [1], agree well with the experimental results.

2. Schematic and operation principles

The schematic diagram of our convertible lenticular LC array is depicted in Fig. 1(a). An indium-tin-oxide (ITO) coated glass substrate is used as the top substrate. The bottom substrate consists of a planarization material (PM), an undulated ITO electrode, and a lenticular cast on a glass substrate. The key requirement is that the refractive index of the PM should be equal to that of the lenticular cast for index matching. The inner surfaces of the two substrates are spin-coated with polyimide (PI), baked, and rubbed unidirectionally to promote the planar alignment of the LC. The surface pretilt angle at the rubbed substrate was measured to be about 2°, eliminating the reverse-tilt at the boundary. The rubbing direction on the top substrate and that on the bottom substrate are denoted as RT and RB, respectively. Figures 1(b) and 1(c) represent the operational principles of our lenticular LC array. When the optic axis of the LC layer coincides with the polarization of an input beam through a linear polarizer (see, the white arrow in Fig. 1(a)), the field-off state corresponds to an optically uniform state with no LC distortions as indicated by the thick red arrows in Fig. 1(b). In the field-on state, the LC distortions are periodically modulated along the y-axis due to the undulated electrode. This means that the effective refractive index (n_eff) becomes periodically modulated and the
The lenticular lens effect is produced. Note that in contrast to the IPS case, there are no inactive regions of the LC layer for the optical modulation in our case.

3. Experimental

For our study, a lenticular cast of a ultraviolet (UV) curable polymer (NOA65, Norland Products Inc.) was produced on a glass substrate using a mold of poly(dimethylsiloxane) (PDMS, GE silciones) and irradiated with UV light for 10 minutes [7, 11]. Subsequently, a 100 nm-thick ITO electrode was deposited onto the lenticular cast by thermal evaporation. The width \( w \) and the height \( h \) of the lenticular cast were 25 and 7.2 µm, respectively. The PM was finally spin-coated on the undulated electrode for planarization. An image of a scanning electron microscope (SEM) and the surface profile of the undulated electrode on the lenticular cast are shown in Fig. 2(a). Due to index matching of the lenticular cast with the planarization layer, the bottom substrate is optically uniform as shown in Fig. 2(b). A commercial PI (RN-1199A, Nissan Chemical Industries, Ltd.) for the homogeneous alignment and a nematic LC (ZLI-4151-000, Merck Ltd.) with a positive dielectric anisotropy were used. The material parameters [15] of ZLI-4151-000 are three elastic constants, \( k_1 = 1.15 \times 10^{-11} \text{ N}, k_2/k_1 = 1.62, k_3/k_1 = 2.90 \), and the dielectric anisotropy \( \Delta \epsilon = 10.6 (\epsilon_1 = 15.0) \). The ordinary and extraordinary refractive indices are \( n_o = 1.51 \) and \( n_e = 1.66 \), respectively.

The cell gap \( d \) was maintained using 20 µm-thick glass spacers and the LC was injected by capillary action. Figures 2(c) and 2(d) show the microscopic images of the lenticular LC cell observed when the crossed polarizers (A and P) make an angle of 45° and 0° with respect to the rubbing direction (R), respectively. Clearly, the LC was well aligned homogeneously on the substrate with the undulated electrode after planarization.
4. Results and discussion

We first examine the tunable focusing properties of our lenticular LC lens using an array of 2D circular (10 µm in diameter) patterns as an input image. The schematic diagram for the experiment was depicted in Fig. 3(a). The measurements were carried out at room temperature using a polarizing optical microscope (Optiphoto2-Pol, Nikon) and a He-Ne laser with the wavelength (λ) of 543.5 nm. The input beam was linearly polarized along the rubbing direction. As shown in Fig. 3(b), under no applied voltage, the image of the circular pattern observed with a charge-coupled device (CCD) is the same as the original pattern whose diameter is 10 µm. This means that the LC cell behaves as an optically uniform plate and no lens effect occurs. At the applied voltage of 5 V, the image of the circular pattern was blurred as seen in Fig. 3(c) due to the graded index (GRIN) effect resulting from the periodic distortions of the LC by the undulated electric field. At 10 V, two images (or two viewing points) were observed in Fig. 3(d) since the focal length was increased. The ray focusing properties of the lenticular LC lens under different applied voltages were seen from the images [insets in Figs. 3(b)-3(d)] of a collimated laser beam in the focal plane. The electrically tunable focal length of the lenticular LC array was measured as a function of the applied voltage by focusing the blurred image. The experimental results will be discussed together with numerical simulations below.

Using the material constants of the LC and the geometrical parameters such as the width and height of the lenticular cast given above, we carried out numerical simulations of the spatial variations of $n_{eff}$ and the resultant focal length variations of our convertible lenticular LC array by employing both a relaxation method [14] in the elasticity theory and a commercial program, FemLab™ (COMSOL). A typical example of the equipotential lines at 7 V obtained using the COMSOL program was shown in Fig. 4(a). The white lines and red arrows represent the equipotential lines and the electric field directions, respectively. It should be noted that in the case of an inhomogeneous (or non-uniform) electric field, either the transverse component or the longitudinal component contributes to the suppression of the LC distortions as if it would enhance the LC anchoring in the surface layer [16]. In our lenticular LC array with the undulated electrode, the $y$-component of the electric field ($E_y$) is expected to enhance the LC anchoring in the surface layer, meaning that there exists the interplay between the $z$-component of the electric field ($E_z$) and $E_y$ in the LC distortions. More specifically,
denoting the LC director as \((0, \sin \theta, \cos \theta)\), the dielectric energy density can be then written as
\[-\Delta \varepsilon E^2 (\sin \theta \cos ky + \cos \theta \sin ky)^2\]
provided that \(E_y = E \sin ky\) and \(E_z = E \cos ky\). Here, \(\theta\) represents the tilt angle of the LC director with respect to the \(z\)-axis and the undulation period of the electrode \(k = 2\pi/w\). The term of \(-\Delta \varepsilon E^2 (\cos^2 \theta \sin^2 ky + 2 \sin \theta \cos \theta \cos ky \sin ky)\) resulting from non-zero \(E_y\) component was found to suppress the director distortions in the out-of-plane. Such contribution has not been considered previously in a uniform LC layer under the undulated electric field.

![Diagram](image)

Fig. 3. The tunable focusing capability of the lenticular LC lens: (a) the schematic diagram of the experiment using an array of circular patterns as an input image and the microscopic images of the circular patterns observed through the lenticular LC array at an applied voltage of (b) 0 V, (c) 5 V, and (d) 10 V, respectively. Each inset shows the CCD image of a collimated laser beam in the focal plane.

The effect of \(E_y\) on \(n_{\text{eff}}\) is shown in Fig. 4(b). The variations of \(n_{\text{eff}}\) along the \(y\)-axis become much enhanced by \(E_y\), particularly, in the high-field regime. Under no applied voltage, \(n_{\text{eff}}\) remains uniform over the entire LC cell in a planar configuration. In the presence of an applied voltage, \(n_{\text{eff}}\) becomes modulated in the symmetry which reflects the shape of the lenticular cast. This is consistent with the CCD images shown in Fig. 3. Figure 4(c) shows both the experimental and simulation results for the focal length variations of our lenticular LC array with the applied voltage. Clearly, the calculated focal length with the contribution of \(E_y\) was found to agree well with the experimental results. This means that the anchoring enhancement by the \(E_y\) component plays an important role on the EO properties of the LC. In our simulations, the anchoring energy of the PI alignment layer alone was treated as a parameter to be determined from the best fit of the experimental data to the calculated focal length in Fig. 4(c). The anchoring energy was determined to be \(6.6 \times 10^{-6} \text{ J/m}^2\), which is consistent with the previous result [17]. Our LC lens cell is convertible from an optically uniform plate (a flat surface) to a lenticular array with the focal length ranging from about 5 mm to 10 mm in the presence of an applied voltage. In general, both the in-plane and the out-of-plane components of an external electric field should be taken into account for the reorientation of the LC director in the case of an inhomogeneous electric field.
5. Conclusion

We demonstrated that a delicate interplay between the in-plane and out-of-plane components of an inhomogeneous electric field plays a critical role on the flat-to-lenticular lens conversion in a homogeneously aligned LC cell. The framework of the refractive index-matching between the lenticular cast and the PM layer provides a practical route to construction of a variety of electrically tunable, convertible LC devices in a planar geometry. Finally, our concept of using the electric field modulation on a flat surface should be directly applicable for constructing 2D/3D convertible displays and optical focusing elements in photonics. Moreover, the fine pitch of 25 µm in our lenticular LC array is suitable for the high-resolution image in 3D displays.

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