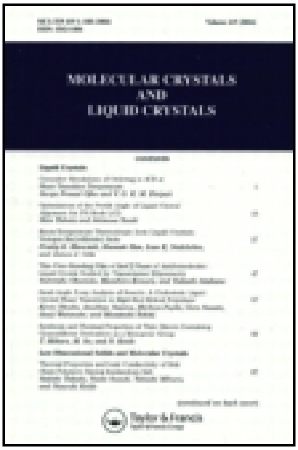

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Liquid Crystal Lens Array with High Fill-Factor Fabricated by an Imprinting Technique

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Liquid Crystal Lens Array with High Fill-Factor Fabricated by an Imprinting Technique

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We propose a high fill-factor configuration of a liquid crystal (LC) lens array fabricated by an imprinting technique. The bottom substrate of our LC lens array has a periodically concave electrode which forms an array of concave square apertures. The electrode on the imprinted concave structure produces a centro-symmetric inhomogeneous electric field which can be used for controlling the distribution of the refractive index in the LC layer. The focal length was found to vary in the range of a few centimeters. Moreover, unlike other LC lens arrays, the square aperture of each elemental lens allows for a high fill-factor. Our LC lens array is expected to be useful for various optical systems with high optical efficiency.

Keywords: fill-factor; focal length tunability; imprinting; lens array; liquid crystal

INTRODUCTION

Lens arrays with variable focal lengths have been widely used for optical information processing, optical interconnection, and three dimensional displays [1–5]. A nematic liquid crystal (LC) is a promising candidate for fabricating such lens arrays as an active medium because of its large electrical and optical anisotropies. In order to produce a bell-like phase profile in each lens element of the LC, several types of the lens configurations have been studied so far. However, existing configurations of LC lens arrays with patterned electrodes or surface relief structures [6–12] have structurally intrinsic

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drawbacks such as the limited aperture ratio and the optical efficiency. Therefore, a new concept of designing the LC lens arrays is required for practical applications.

In this work, we propose a liquid crystal lens array with a high fill-factor using an embedded electrode which forms an array of concave square apertures. A simple imprinting technique was used for fabricating the periodically concave surface on the bottom substrate. The array of elemental lenses with square apertures provides a high fill-factor as well as a very low optical loss. Using an indium-tin oxide (ITO) electrode on the bottom surface, the distribution of the refractive index in the LC layer can be controlled in a bell-shaped form under an applied voltage. Consequently, the focal length can be varied in the range of about 150 mm according to the applied voltage.

EXPERIMENTAL

The fabrication processes and the operating principles of our LC lens array are schematically illustrated in Figure 1. As shown in Figure 1(a), our LC lens array has the bottom substrate with two polymer layers, the periodically concave surface and the subsequent flat surface, fabricated using a simple imprinting technique [13,14]. After the lower concave polymer layer was produced on the bare glass

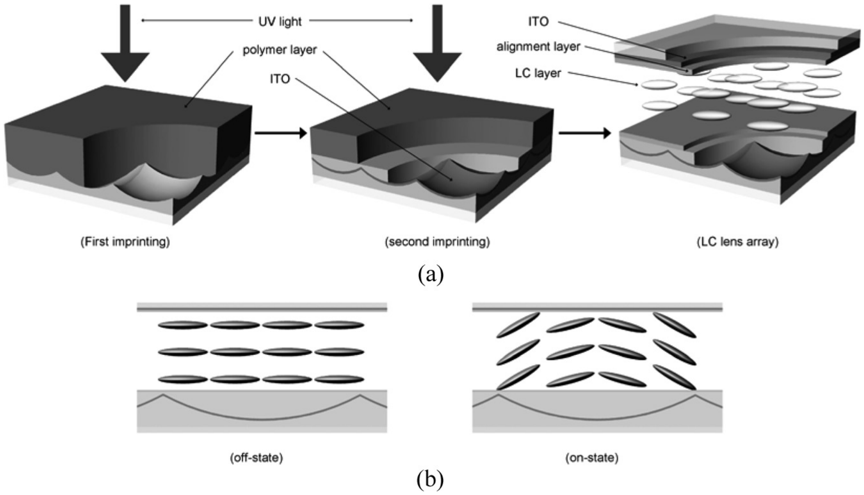

FIGURE 1 (a) The schematic diagram of the fabrication processes of our LC lens array using an imprinting technique, (b) the operating principles in the field-on and field-off states of our LC lens array.

substrate by imprinting, the ITO electrode was subsequently deposited onto the periodically concave surface at room temperature. The upper polymer layer was then prepared on it to be flat. This flattened surface allows for the uniform alignment of the LC layer. The period and the curvature radius of each concave lens element were 1 mm and 1.7 mm, respectively. The cell gap of our LC lens array was uniformly maintained using film spacer of 40 μm thick.

The imprinting stamp, having replica patterns in the master mold of a commercial lens array (Fresnel Technologies Inc.), was made using polydimethylsiloxane (PDMS) (Sylgard 184, Dow Corning Co.) [13] An ultraviolet (UV) curable photopolymer (NOA65, Norland products Inc.) was used for the fabrication of two polymer layers. The nematic LC used as an active medium in our lens array was MLC-6082 of Merck, which has the ordinary and extraordinary refractive indices, n_o and n_e, of 1.4935 and 1.6414, respectively. The polyimide of JALS 146-R50 (Japan Synthetic Rubber Co.) was spin-coated on the inner sides of both substrates to promote homogeneous alignment of the LC molecules.

Under an applied voltage, the modulation of the electrical field can be produced due to the presence of the embedded ITO electrode with concave square apertures. The effective voltage through the LC layer [12], V_{LC} is given by

$$V_{\mathrm{LC}} = \left[\frac{\varepsilon_{\mathrm{LC}}}{\varepsilon_{\mathrm{polymer}}} \cdot \frac{d_{\mathrm{LC}}}{d_{\mathrm{polymer}}}\right]^{-1} \cdot V_{\mathrm{applied}}.$$

The dielectric constants of the LC and that of the polymer layer are denoted as $\varepsilon_{\mathrm{LC}}$ and $\varepsilon_{\mathrm{polymer}}$, respectively. The thickness of the LC and that of the polymer layer are represented by d_{LC} and d_{polymer}, respectively. Due to the modulation of the effective voltage, variations of the effective refractive index were produced in each elemental lens. Under an applied voltage, the distortions of the LC distribution are larger at the edge of each elemental lens and smaller at the center due to the concave shape of each electrode pattern as shown in Figure 1(b). This gives the centro-symmetrical modulation of the refractive index in a bell-shape, providing the tunability of the focal length according to the applied voltage in our lens array. Under no applied voltage, no focusing effect is produced because the refractive index is uniform through the whole LC layer.

In addition, our lens array has a high fill-factor. In conventional lens arrays, there is such inherent problem as a large optical loss resulting from the inactive areas in the arrangement of circular elemental lenses. As shown in Figure 2, the fill factor is limited to about

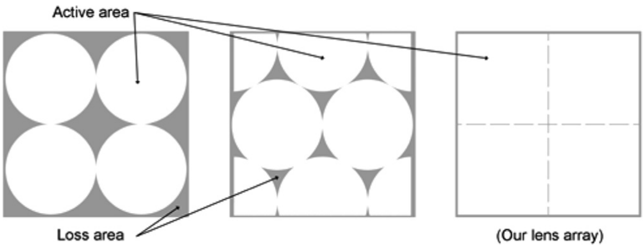

FIGURE 2 The relative fill-factor of the lens array resulting from the shape and the arrangement of geometrical apertures.

0.78 in the case of the lens array where circular apertures are arranged in a square lattice form. In contrast, the high fill-factor can be obtained in a periodic array of square apertures like in our LC lens array as shown in Figure 2. Accordingly, a less optical loss is achieved.

RESULTS AND DISCUSSION

Figure 3 shows the focusing and defocusing properties of our LC lens array. The CCD images and three-dimensional intensity profiles were

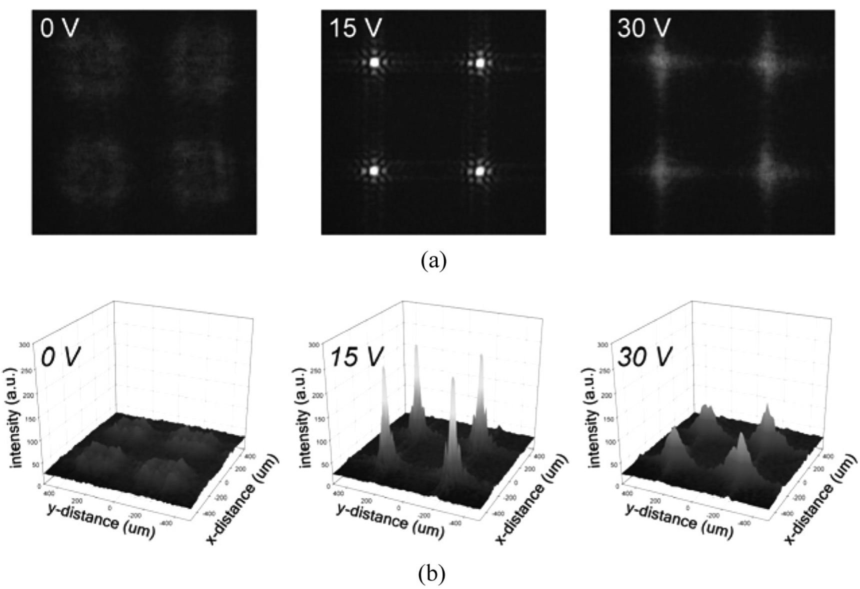

FIGURE 3 (a) The CCD images and (b) the light intensity profiles under various applied voltages. Each intensity profile corresponds to the CCD image.

measured to determine the tunable focusing effect. As a light source, a He-Ne laser with a wavelength of 543.6 nm, polarized parallel to the LC alignment direction, was used. The CCD images were taken in the focal plane at the applied voltage of 15 V, and were then converted into the intensity profiles for further analyses. In the filed-off state, the light beam passing through the lens array produces no focusing effect. With increasing the applied voltage up to 15 V, the outgoing light beam through the lens array gradually converges as shown in Figure 3(b). Under the applied voltage of 15 V, the light intensity at the center reaches a maximum with a very low circumferential intensity distribution, corresponding to a focused state. As the applied voltage increases beyond 15 V, the defocusing effect becomes to appear.

Figure 4 shows the focal length variations of our LC lens array with the applied voltage. In the low voltage regime below 10 V, because no bell-shaped distribution of the LC phase profile is produced, no lens effect exists. The shortest focal length, about 90 mm, was measured at the applied voltage of 15 V. This means that the difference in the refractive index between at the center and at the edge in each elemental lens is largest at 15 V. The focal length becomes longer with increasing the applied voltage except for low voltages. The focal length of about 270 mm at 0 V is attributed to the initial geometrical curvature of the LC layer on a slightly curved polymer layer. In fact, it is desirable to maintain the flatness of the polymer layer for the ideal case. Based on the measured depth (about 4.5 μm), the curvature radius (about 27.8 mm), and the refractive index (1.52) of the slightly

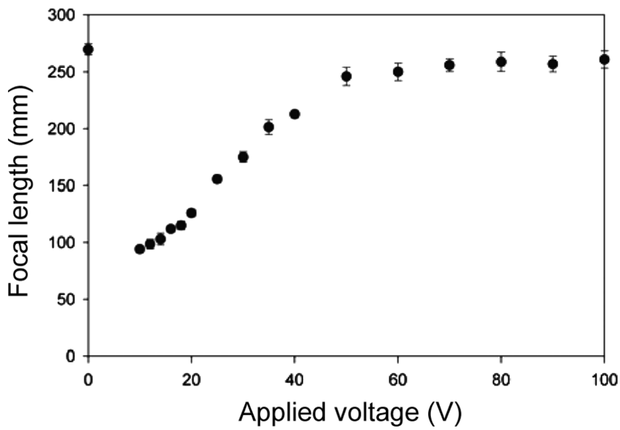

FIGURE 4 The focal length variations with the applied voltage. The tuning range of the focal length is from 90 mm to 270 mm.

curved polymer layer, the focal length in the field-off state was estimated as about 236.6 mm. This is quite consistent with the measured focal length of 270 mm at 0 V. Except for the low voltage regime, our lens has the focal length tunability in the range between 90 mm and 270 mm at the applied voltage starting from 15 V.

CONCLUSION

We proposed a LC lens array with a high fill-factor using an array of concave square apertures on an embedded ITO electrode. The square aperture of each elemental lens gives a high optical efficiency due to the elimination of inactive areas. The focal length of our LC lens array was found to be electrically tunable in the range from about 90 mm to 270 mm. The simple imprinting technique describe here is powerful for fabricating arbitrary curved, concave and convex, surfaces for various LC devices. Finally, the high fill-factor and the focal length tunability of our LC lens array are expected to play a significant role for constructing a variety of optical information systems including three-dimensional displays.

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