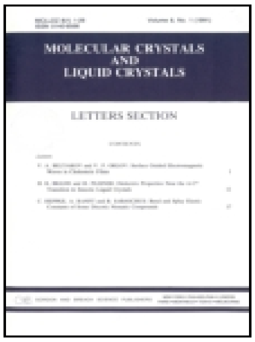

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Liquid-Crystal Micro-Lens Array with Square-Shaped Electrodes

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We propose a liquid-crystal (LC) micro-lens array with a flat external electrode in addition to two-divided and square-shaped electrodes for electrically controlling cylindrical or spherical lens properties in each LC cell of the lens array. The LC micro-lens array is useful for tuning optical properties such a focal length and deflection angle of a light emitting diode illumination system.

Keywords Liquid-crystal; micro-lens array; variable focal length; deflection; phase retardation

1. Introduction

Liquid crystal (LC) materials have a large electrical and optical anisotropies, and they are easily to be operated by low voltages. The LC molecular orientation can be controlled by applying an electric field and then its optical properties are changed. The LC materials have been widely used in flat display devices and optical devices. An LC micro-lenses with micro-sized and circularly hole-patterned electrodes have been reported [1–8]. The LC micro-lens array with the micro-sized circularly or hexagonal hole-patterned electrode has been developed and based on the orientation effects of LC molecules in inhomogeneous electric fields. The optical property such as the focal length can be varied electrically by arranging the voltage applied to the electrodes of the LC micro-lens array. The advantage of the LC lenses is such that small size, lightweight, planer and low voltage. Among them some LC lenses have been used in optical information processing or autostereoscopic two-dimensional/three-dimensional switchable displays [9].

In this study, we propose a novel LC micro-lens array with an external flat electrode in addition to the two-divided and square-shaped electrodes for electrically changing the phase retardations by adjusting the voltage to the LC micro-lens array.

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2. Structure of the LC Micro-Lens Array

Figures 1(a) and (b) show the top and side views of the LC micro-lens array. The LC micro-lens array consists of the upper glass substrate with a transparent indium tin oxide (ITO) flat electrode, transparent isolation polymer film of 5 μm thickness, the two-divided and square-shaped thin aluminium electrodes, LC layer and bottom glass substrate with a uniform ITO electrode. The two-divided and square-shaped electrodes are fabricated by a photo-lithography technique. The width of the electrode lines at the upper substrate is 50 μm and the width between two electrode lines is 30 μm. The width size of the square-shaped region is 300 μm. The left electrode lines and right electrode lines operated as the LC microlens array are located on the same side since the square-shaped apertures shift to the neighbour columns along the *y*-direction and then their positions also shift to 67.5 μm along the transverse direction. Both electrode substrates are spin-coated with a polyimide parallel alignment film, and their surfaces are rubbed to obtain homogeneous alignment parallel to the electrode lines along *y*-axis. Two substrates were overlapped with anti-parallel rubbing directions, and the cell gap was controlled by using glass ball spacers with the diameter of 110 μm. The LC material of RDP-85475 (DIC Co.) was injected into

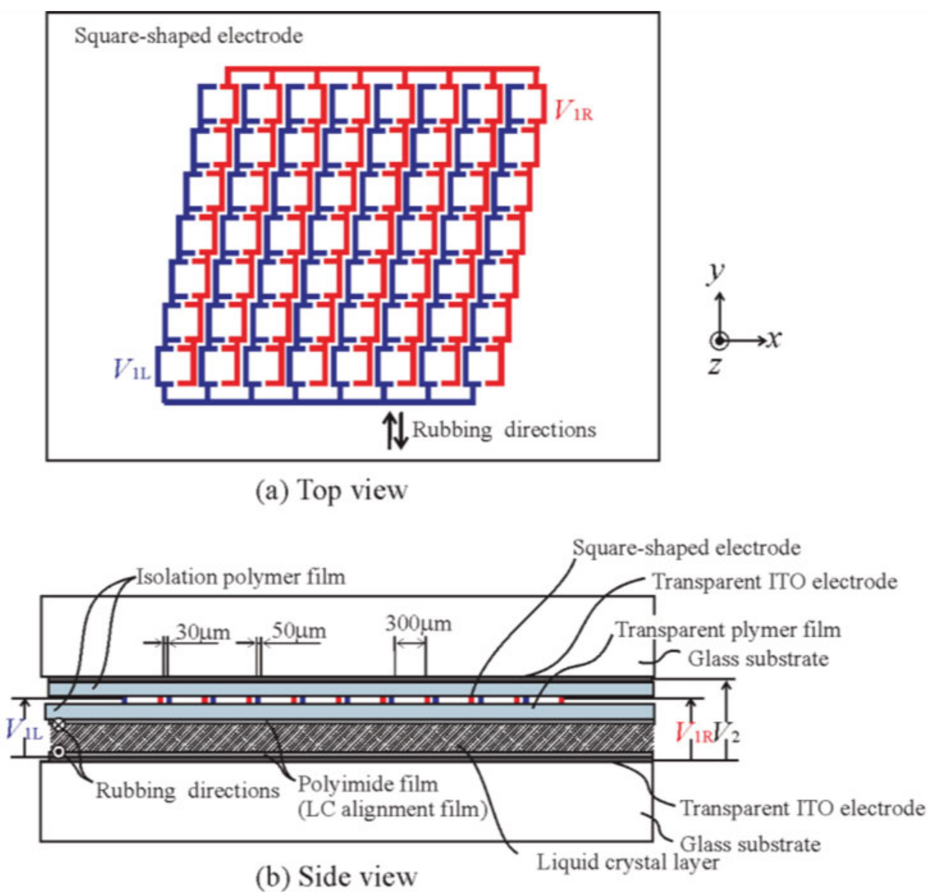

Figure 1. LC micro-lens array.

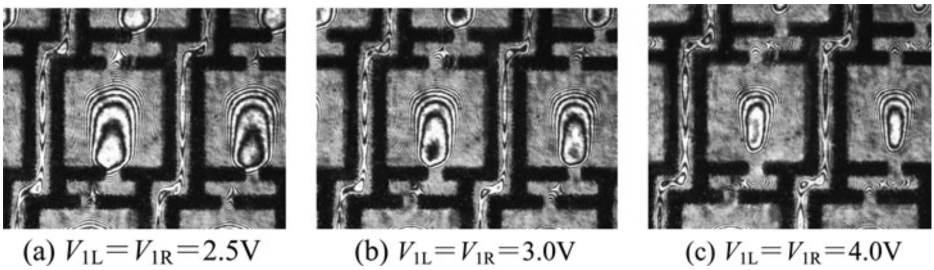

Figure 2. Interference fringes of the LC micro-lens array under same voltages at $V_2 = 0$ V.

the empty LC cell. AC voltages of $f = 1$ kHz; V_{1L} and V_{1R} are applied to the left and right electrode lines and V_2 is applied to upper flat electrode to bottom electrode by using a function generator.

4. Results and Discussion

Figures 2(a) ~ (c) show photo images of the interference fringes of the LC micro-lens array by using a polarizing microscope under crossed polarizers when the same voltage of $V_{1L} = V_{1R}$ is applied from 2.5 V to 4.0 V to the two-divided electrodes and V_2 is 0 V. The rubbing direction of the LC cell is 45 degrees with respect to the polarization directions of the polarizer and analyzer. The LC molecular orientations can be obtained by observing fringe patterns produced by the interference between ordinary and extraordinary rays through the LC cell. When the electric field is applied to the cell, the LC molecules are tilted toward the normal direction of the substrates. Since there is distance between the hole-patterned electrodes and the LC layer, a non-uniform electrical field is produced and the induced electric charges at the transparent polymer film are distributed over the LC layer. As increasing voltages; V_{1L} and V_{1R} applied to the two-divided electrodes, elliptically distorted interference fringes can be obtained. The center of the interference fringe seems to shift along the rubbing directions. The cause is that the LC molecules under the applied side of the electrode are tilted toward the normal direction of the substrates, resulting in the decrease of the effective refractive index and the appearance of the fringes.

Figures 3(a) ~ (c) show the interference fringes of the LC lens array under crossed polarizers when the voltages of $V_{1L} = V_{1R}$ are applied from 2.5 V to 4.0 V to the two-divided electrodes and the voltage $V_2 = 1.0$ V is applied to the upper transparent electrode. The almost circular interference fringe pattern can be obtained. The center of the interference

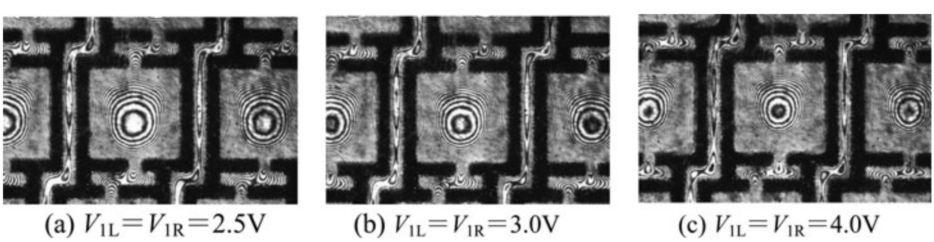

Figure 3. Interference fringes at $V_2 = 1.0$ V.

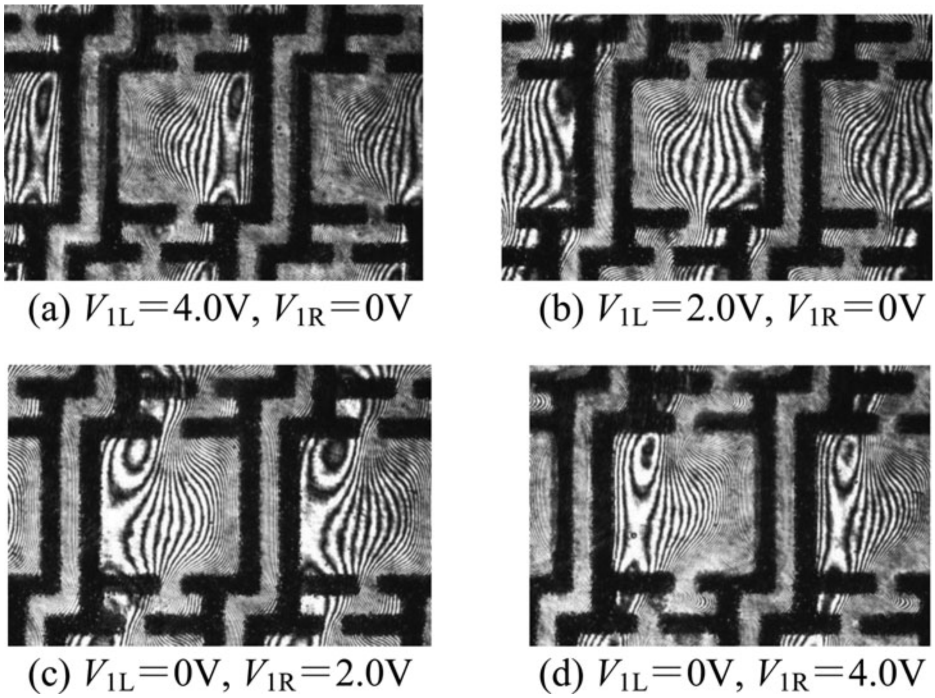

Figure 4. Interference fringes of the LC micro-lens array under different voltages at $V_2 = 1.0$ V.

fringe shifts to the middle position of the square-shaped electrode as increasing the voltage applied to left and right electrodes, and then the circular interference fringes become asymmetric.

When the voltage V_{1L} only applied to the left electrode is higher than that applied to the right electrode, the more interference fringes seems to be obtained on the left electrode as shown in Figs. 4(a) and (b). Since the voltage is applied to one side of the electrode line, the deformed interference fringe seems to shift to the electrode side of the low voltage. On the other hand, the interference fringe of the right electrode side increases when the voltage V_{1R} is applied to the right electrode line [Figs. 4(c) and (d)].

Figures 5(a) and (b) show the cross-sectional distributions of the phase retardation of one region in the LC micro-lens by counting the interference fringes along the x-axis, where the voltage $V_2 = 1.0$ V applied to upper external flat electrode. The phase retardation of the neighbour interference fringe is 2π (rad). The phase retardation can be distributed symmetrically or asymmetrically by controlling the voltages of V_{1L}, V_{1R} and V_2. The phase retardation increases further as increasing the voltage applied to the either left or right electrode. By applying voltage to one side of the electrode lines, the cylindrical refractive index distribution can be induced in the square-shaped electrode. With the voltage exceeds to about 4.0 V to one of two electrodes, the LC molecules in the side of the electrode without the applied voltage are also tilted, thus the interference fringe moves and the retardation decreases.

The deflection angle can be estimated and its range varies from -10.4° at the applied voltages of $V_L = 4.0$ V and $V_R = 0$ V to 12.1° at the voltages of $V_L = 0$ V and $V_R = 4.0$ V. The wavefront through the LC micro-lens array is deformed in its aperture. The appropriate

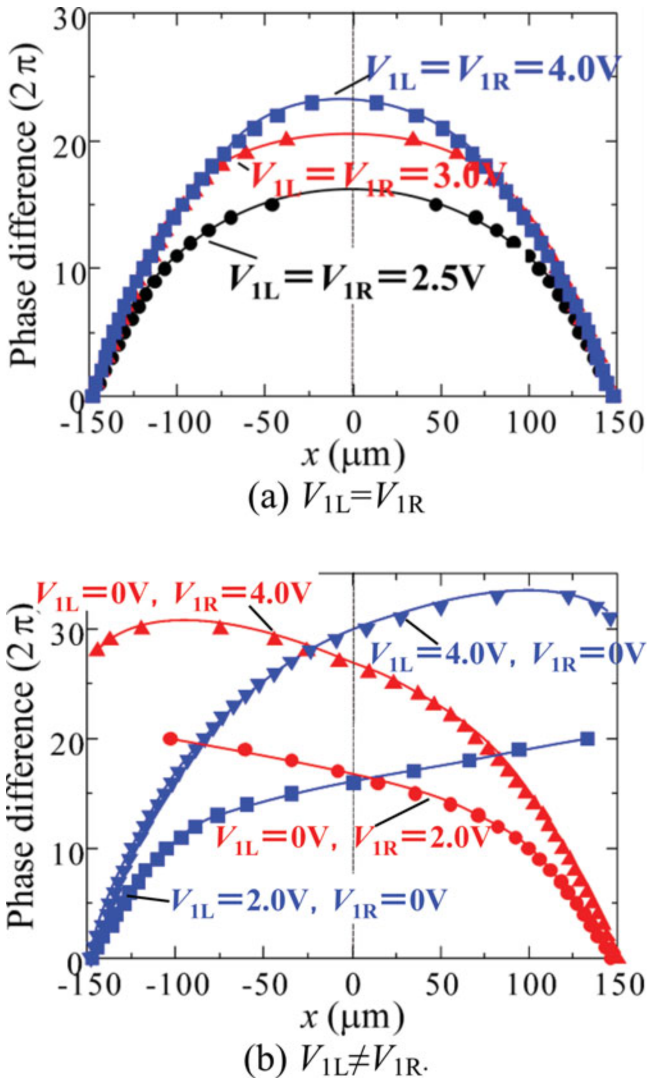

Figure 5. Phase retardation distributions.

beam steering will be realized to fabricate the new structure of the LC micro-lens array with an assist electrode to increase the electric field at the edge around the square-shaped electrode.

5. Conclusion

The LC micro-lens array with the structure of square-shaped and external transparent electrodes was proposed. The squared-shaped electrodes are divided into two parts. The refractive indices of the cylindrical and spherical lens properties in each LC micro lens can be controlled by arranging the voltages applied to left and right side electrodes. The LC micro-lens array with the light-scattering and deflecting effects is useful for an LED illumination system to control the light distributions without any mechanical movements.

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