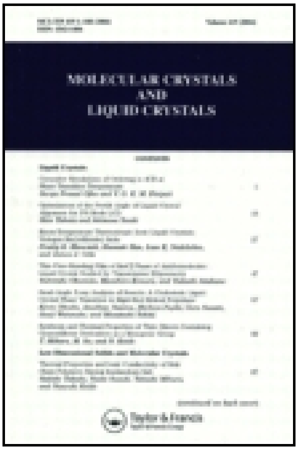

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Liquid Crystal Microlens Driven by Two Voltages

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A liquid crystal microlens driven by two voltages are reported. The two voltages cooperate to build up an axially symmetrical but spatially nonuniform electric field in a liquid crystal layer in the cell. One of the voltages remain unchanged biasing the reorientation of the liquid crystal directors outside the lens area, while the other one varies to adjust the gradient of the electric field in the lens area of the liquid crystal layer, and hence the properties of the lens. The focal length of the microlens increases monotonically with controlling voltage.

Keywords: focal length; liquid crystal microlens; two-voltage driving

Various structures of liquid crystal (LC) lens have been reported [1–6]. Recently an LC lens driven by two voltages has been proposed [7]. There are three electrodes, that is, two transparent electrodes and one opaque electrode with a round hole in the center, in the LC cell. The two voltages applied via the three electrodes on the cell set up a symmetrical but spatially nonuniform electric field in the LC layer. The LC directors acted by the electric field are re-aligned and then a lens-like refractive index distribution arises. An LC lens with focal length that is electrically tunable is then formed. The new LC lens outshines its predecessors in many respects. First, the focus is variable in a wide range, and the focal length simply increases with the increasing controlling voltage. Second, over the whole focus range, the lens preserves its optical quality. Third, it is easy to drive the lens with no disclination lines occurring. Forth, the LC layer is shielded by the electrodes and the properties of the lens are not affected by electric

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charges outside the LC cell. Fifth, to build fast LC lenses with stacked structure of thin LC layers [8], and, to build negative lenses with positive LC materials [9], become possible. In this article we report the building of a new LC microlens with the two-voltage driving structure [10]. The new LC microlens inherits the advantages of the new driving technique. The phase transformation and the focal length of the LC microlens are measured. The focal length increases with increasing controlling voltage and the LC microlens preserves its optical quality in the whole range of the focus.

The LC cell is shown in Figure 1. The LC (E44 of Merck) layer of 130 μm thickness is sandwiched between two glass substrates of 200 μm thickness, each being coated with an aluminum (Al) film with a round hole of 300 μm diameter in the center. The surfaces of the substrates contacting with the LC layer are coated with polyimide films and are rubbed in one direction, and the LC directors initially align homogeneously. The voltage V_o across the Al electrodes forms a symmetrical but spatially nonuniform electric field in the hole area that is the area in the LC layer between the holes in the Al electrodes playing the role of lens. The electric field gives rise to a spatially nonuniform reorientation of the LC directors. With appropriate geometrical sizes and voltage range, a lens-like distribution of the refractive index that is voltage dependent in the hole area may arise. In this way an LC microlens is realized [11]. Its focal length is tunable by the voltage V_o. In this work, besides the two hole-patterned electrodes, two new transparent electrodes that are formed by indium tin oxide (ITO) films are introduced into the LC cell [11], as shown in the figure. A second voltage V_c is applied via the ITO electrodes. Voltages V_o and V_c are in phase and of the same frequency of 1 kHz. The LC microlens

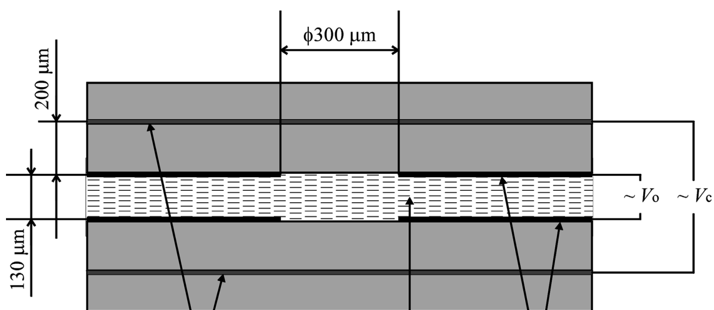

FIGURE 1 Structure of the LC microlens.

is simultaneously driven by the operating voltage V_o and the controlling voltage V_c.

In the experiment, the operating voltage V_o is fixed to $3\,V_{rms}$. The controlling voltage V_c is adjusted to control the electric field in the hole area in the LC layer. In the hole area, the intensity of the electric field is the weakest in the center and increases gradually from the center to the edge. The LC directors are re-aligned by the electric torque, and a gradient distribution of the refractive index that is the largest in the center and decreases gradually from the center to the edge of the hole area is formed. The distribution of the refractive index changes with the electric field. An incident light beam then experiences a bell-like phase retardation ϕ. Experiment shows that ϕ is close to the phase transformation of an optical lens. So the LC cell behaves as an optical microlens. The electric field in the hole area is adjusted by the controlling voltage V_c. The spatial variation of the electric field in the hole area becomes smaller as V_c increases. As a result, the gradient of the phase retardation ϕ decreases and the focal length f of the LC microlens increases with increasing V_c. In the structure of LC microlens of this work, the two voltages V_o and V_c collaborate to give the required radial variation of the director reorientation; the reorientation of the LC directors beyond the hole area is mainly determined by the operating voltage $V_o = 3\,V_{rms}$, and that of the LC directors in the hole area mainly by the controlling voltage V_c varying in the range of $0 \sim 12\,V_{rms}$.

The properties of the LC microlens are measured by interference method [7]. From the observed interference patterns, the phase retardation ϕ of an incident light beam linearly polarized in the rubbing direction can be obtained. Figure 2 shows ϕ at various values of V_c. The symbols in the figure are the measurements and the curves represent regressions with the quadratic equation $\phi = \phi_0 - a\rho^2$ where ρ represents the radial position in the hole area. Phase ϕ_0 is determined by the choice of the zero-phase position and is irrelevant to the lens's properties. $\phi_0 = 22.65$ and $a = 0.0013$ for $V_c = 0$, $\phi_0 = 18.95$ and $a = 0.00012$ for $V_c = 4\,V_{rms}$, $\phi_0 = 16.51$ and $a = 0.0010$ for $V_c = 8\,V_{rms}$, and $\phi_0 = 12.57$ and $a = 0.0008$ for $V_c = 12\,V_{rms}$. It can be seen that nearly parabolic phase distributions are obtained; the LC microlens transforms the phase of a plane light wave to a parabolic shape, just as an optical lens does. The phase transformation of the LC microlens changes with the controlling voltage V_c and the microlens preserves similar quality over the whole range of V_c from 0 to $12\,V_{rms}$.

The focal length (in μm) $f = 1/(2\lambda a)$ where the unit of λ is μm [12]. It increases with the increasing V_c. Figure 3 shows the focal length f as a function of the controlling voltage V_c. The symbols are the

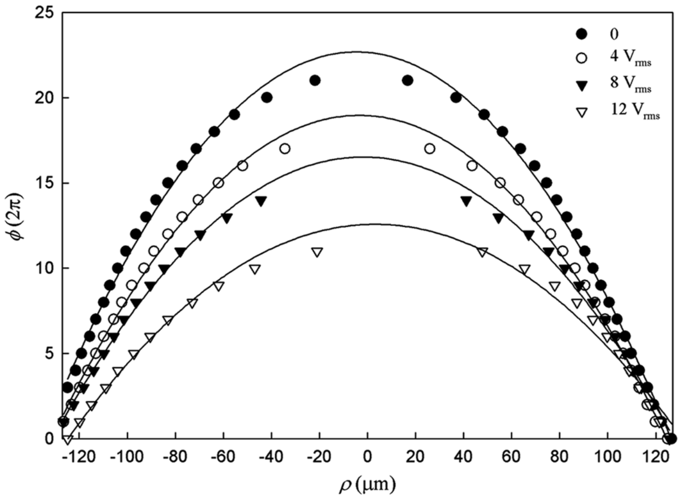

FIGURE 2 Phase retardations ϕ at various values of controlling voltage V_c.

measurements. The simple relation of f and V_c can be expressed by a simple equation such as $f = c + p\exp(qV_c)$ where $c = 490.5\,\mu\text{m}$, $p = 109.2\,\mu\text{m}$, $q = 0.1327\,\text{V}^{-1}$. The curve in the figure represent the regression with the equation.

In a traditional LC microlens, the focal length first decreases and then increases with increasing controlling voltage. The relationship

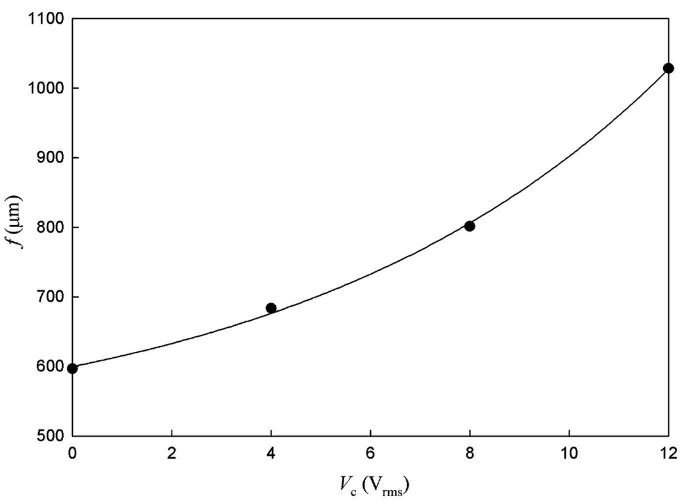

FIGURE 3 Focal length f as a function of controlling voltage V_c.

between the focal length and the controlling voltage of the LC microlens in this work becomes very simple. The focal length f increases monotonically with controlling voltage V_c. Furthermore, the optical quality is preserved in the entire focus range, while a traditional LC microlens manifests its highest quality only when the focal length is the shortest.

In conclusion, an LC microlens driven by two voltages are reported. One of the voltages remaining unchanged builds up a symmetrical but spatially nonuniform electric field in the LC layer. The other voltage, that is, the controlling voltage varies to adjust the gradient of the electric field, and hence the properties of the lens. The microlens preserves similar quality over the whole range of the controlling voltage, and its focal length increases with the controlling voltage.

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