

Optical focusing feature of single element in 128×128 elements electrically controllable cylindrical liquid crystal lens array

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A 128×128 elements cylindrical liquid crystal (LC) lens array with electrically controllable focal length is proposed. The cylindrical LC lens array uses transparent indium tin oxide (ITO) films as electrode, avoiding to affect the optical path operating in the voltage-off status. As the top electrode of the cylindrical LC lens array contacts with LC, the operation voltage root-mean-square (RMS) amplitude can be as low as 1.4 V and the response time is about 20–30 ms. The special optical focusing feature of the cylindrical LC lens array is got. And the focal length of this array is about 60–450 μm .

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Cylindrical lenses are suitable for stretching images, focusing light into a slit, and converging light to a line-scanning detector. The conventional cylindrical lenses made of glass have many drawbacks such as fixed focal length and complicated fabrication process. In order to overcome those drawbacks, the liquid crystal (LC) materials, which have large electrical and optical anisotropies^[1,2], are used. Compared with the conventional cylindrical lenses, the LC cylindrical lenses^[3–7] are electrically switchable and easy to fabricate. But there are still some problems such as the high operation voltage, small aperture size, and so on.

In this letter, we demonstrate a new type tunable-focus cylindrical lens array of homogeneous LC cells, and explain the special focusing feature of this array. The focal length of the lens array is electrically controllable. Compared with other methods, the major advantages of the cylindrical LC lens array are electrical tunability at the low operation voltage, fast response between focusing and defocusing states, and transparent optical path without blocking in the voltage off state. It can be useful in photoelectric integrated system.

Figure 1 illustrates the schematic structure of the cylindrical LC lens array. The key element is the transparent top electrode contacted with LC inside. The substrates of the cylindrical LC lens array are indium tin oxides (ITO) glasses, and the ITO films are used as transparent electrodes. The top electrode pattern is 128×128 elements, fabricated by photolithography and wet etching techniques. The top and bottom electrodes contact with LC inside. Based on the former research result, the optimization ratio between the minor side length of the rectangle and the thickness of the LC layer is about 3:1^[8].

Two polyimide-coated ITO glass slides slightly rubbing with a nylon cloth along rubbing direction shown in Fig. 1 are assembled to produce an empty cell with 20- μm ball spacers. The LC (Merck, E44) is injected into the empty cell. Every element is a 60 \times 200 (μm) rectangle. According to the optimization ratio, since the thickness of LC is 20 μm , 60 μm is the optimal minor side length of the rectangle. The distance between two adjacent rectangles is 50 μm , which can reduce reaction between the electrical field of the adjacent elements. Without electrical field, LC molecules in the cell are aligned regularly as 2.3° along the horizontal direction. Loading with 1-kHz square wave whose root mean square (RMS) amplitude can be changed from 0 to 20 V, the cylindrical LC lens array with tunable focal length is formed.

Figure 2(a) presents the experimental setup for examining the programmable focusing feature of the formed cylindrical LC lens array. The incident parallel white light source is symmetrical and collimated. The cylindrical LC lens array is applied with an external square wave. A charge-coupled device (CCD) with a micro objective, linked to a computer, is placed at a distance of about 350 μm from the cylindrical LC lens array to measure the optical focusing images.

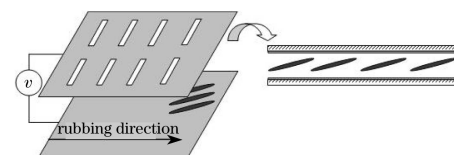


Fig. 1. Schematic structure of cylindrical LC lens array.

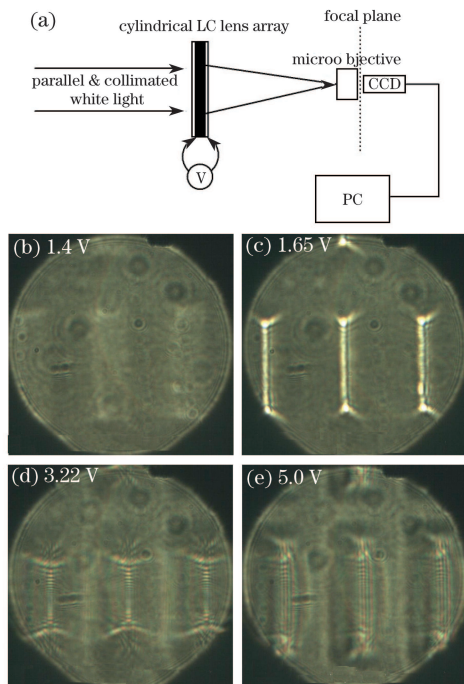


Fig. 2. (a) Experimental setup for examining the focusing properties of the cylindrical LC lens array and local images of cylindrical LC lens array focusing feature with different RMS voltages at (b) 1.4, (c) 1.65, (d) 3.22, and (e) 5.0 V.

Figures 2(b)–(e) show various focusing images with different applied RMS voltages at 1.4, 1.65, 3.22, and 5.0 V. Those images show the whole proceeding from defocusing state to focusing state, then to caustics state. The image formed by the incident parallel white light via the cylindrical LC lens array obviously changes with the increase of the voltage. The focusing is notable and the fixed distance is just the focal length of the cylindrical LC lens array, when the RMS voltage is 1.65 V.

Figures 2(b)–(e) present the special focusing feature of the cylindrical LC lens array. The focusing beams at the upper and lower parts of every element rectangle are like the image “V”. In Figs. 2(c) and (d), the focusing beam is very clear. This feature is dependent on the top electrode pattern of cylindrical LC lens array. As presented in Fig. 3(a), there is a top view schematic of the top electrode of the cylindrical LC lens array. In order to analyze the special focusing feature of the cylindrical LC lens array, one of the 128×128 elements is defined by points A, B, C, D, M(M’), N(N’), P(P’), and O. The plane MM’NN’ is a section plane of the LC cell. When an external voltage with variable amplitudes is applied to the LC cell, the orientation of LC molecules in the LC cell is changed. The orientation of LC molecules and refractive index of LC are related, and can be expressed as^[9]

$$n_{\text{eff}}^2(\theta) = \frac{n_o^2 n_e^2}{n_e^2 \cos^2 \theta + n_o^2 \sin^2 \theta}, \quad (1)$$

where θ is the angle between the incident light and the LC molecule. Equation (1) shows that the refractive index is dependent on LC molecule orientation. If θ is 0° (the direction of incident light is parallel to the LC molecule), the refractive index of LC is n_o . If θ is 90° (the direction of incident light is vertical to the LC molecule),

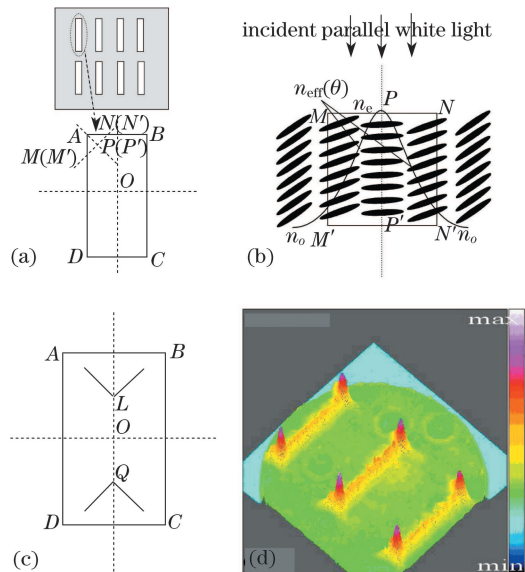


Fig. 3. Special focusing feature of cylindrical LC lens array. (a) Top electrode pattern of cylindrical LC lens array; (b) section plane of single element in cylindrical LC lens array, showing orientation of the LC molecules and refractive index of the LC cell; (c) focusing beam shape of single element rectangle; (d) three-dimensional image of the beam quality tested by the beam quality analyzer.

the refractive index of LC is n_e . The single element of cylindrical LC lens array is non-uniform electric field distributions in LC cell, and has gradient refractive index, which is n_e in the middle and n_o in the fringe, as shown in Fig. 3(b). If the plane ABCD is sliced into many section planes like the plane MM’NN’ and those section planes are analyzed by the above explanation, the shape of the parallel white light after passing through the single element will change into the shape presented in Fig. 3(c). In order to improve the above illustrations, we used beam quality analyzer (Data-ray Inc.) to test the beam at the focal plane. As shown in Fig. 3(d), it is a three-dimensional beam quality image that shows the focusing features of cylindrical LC lens array in accordance with our anticipation. The bar in Fig. 3(d) represents the light intensity. The electrical field sides AD and AB can focus light to the direction AL, the electrical field sides BC and AB can focus light to the direction BL, and AD and BC can focus light to the direction LQ. As the lights from three directions all focus to the endpoints of the focusing line (points L and Q), the intensity at the endpoints of the focusing line (points L and Q) is the highest. The new type cylindrical LC lens array is gotten. With the analysis of this new type cylindrical LC lens array, we can get the photoelectric characteristics of LC.

Figure 4 plots the measured focal length of the cylindrical LC lens array at the different applied voltages (1-kHz square wave) and the quasi-parabolic fitted curve of the measured data. It clearly shows that the focal length of the cylindrical LC lens array can be tunable by external electric field. The focal length is from 60 to 450 μm with RMS voltages from 1.4 to 5.0 V. When the applied voltage is increasing, the focal length is reducing. The applied voltage and focal length are in an inverse proportion. The operation voltage is much

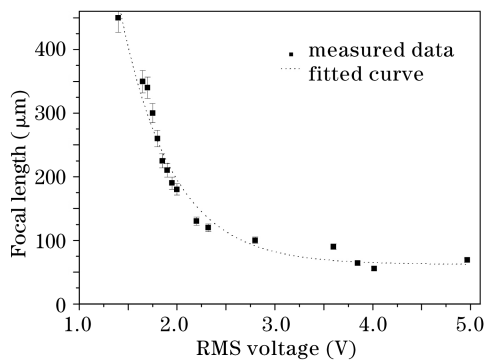


Fig. 4. Focal length of cylindrical LC lens array versus voltage.

lower and can be used in the complementary-metal-oxide-semiconductor (CMOS) circuit directly.

Notably, the cylindrical LC lens array has not only a low operation voltage, but also a fast response performance. The measured time from focusing to defocusing states is about 20–30 ms.

In conclusion, we successfully demonstrate a cylindrical LC lens array with electrically tunable focal length using photolithography and wet etching techniques. In addition, the fabrication of cylindrical LC lens array is simple, and the device has fast switching responses between focusing and defocusing states. Especially, the op-

tical focusing feature of the cylindrical LC lens array is presented, and the cause of this feature is discussed in detail.

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