Superzone Fresnel Liquid Crystal Lens for Temporal Scanning Auto-Stereoscopic Display

Yi-Pai Huang, Chih-Wei Chen, and Yi-Ching Huang

***Abstract*—The fast response superzone Fresnel liquid crystal (LC) lens with multiple transparent electrodes was proposed for temporal scanning auto-stereoscopic display. The experimental results indicated that the superzone Fresnel LC lens not only performed fast switching time (∼0.2 s), but also had the benefit of low driving voltage (∼5 V_{rms}). A 4-inch 2D/3D switchable auto-stereoscopic display with superzone Fresnel LC lens was further demonstrated. Finally, by driving the multiple electrodes alternatively, the superzone Fresnel LC lens array could be moved on horizontal direction for increasing the resolution of auto-stereoscopic display.**

***Index Terms*—Liquid crystal (LC) lens, Fresnel lens, auto-stereoscopic, 3D display.**

I. Introduction

RECENTLY, developing high quality glasses-free 3D display to produce more natural images has become a cutting-edge technology. There are existing works such as holographic type [1], [2] and volumetric type [3]–[5] that have been proposed for years; nevertheless, these large volume and complicated systems are still an issue. Thus, another approach is the multiplexed-2D method [6]–[11], which is widely used now due to its easy implementation and high potential for flat panel display application. Furthermore, the electrically controlled liquid crystal lens (LC lens) [12]–[16], which can be switched on and off by changing the driving voltage, has also been proposed for 3D display application. Combining the panel with LC lens, the 2D/3D switchable display [17]–[23] is achieved and used to display high resolution images in 2D mode, and low resolution but auto-stereoscopic images in 3D mode.

Although the LC lens can supply 2D/3D switching property, the image resolution is dramatically decreased when switched to multi-view 3D mode. Thus, Huang *et al.* [24] proposed temporal scanning LC-lens to combine spatial-multiplexed and time-multiplexed method for improving the 3D image resolution, as shown in Fig. 1. However, the prior scanning LC lens had thick LC-cell gap (>60 μm) which resulted in slow response and high driving voltage. According to LC response time formula, shown in (1) [25], the response time can be accelerated by reducing the cell gap (d)

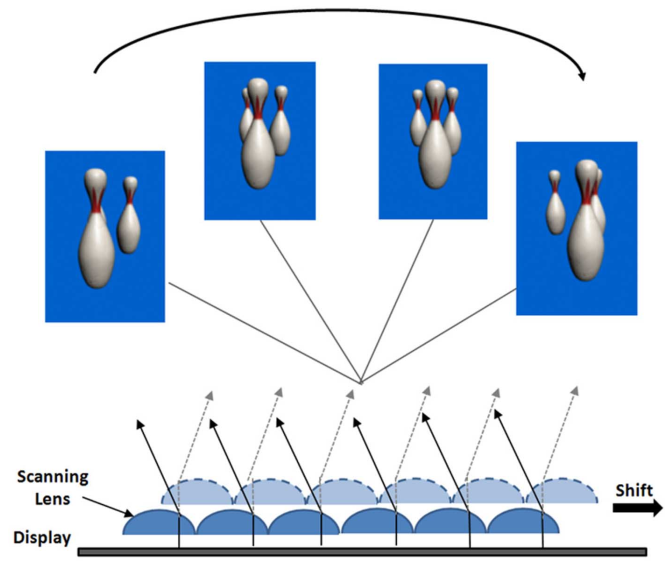

Fig. 1. Scheme of scanning time-multiplexed 3D display.

$$\tau = \frac{\gamma d^2/K\pi^2}{(V/V_{\mathrm{th}})^2 - 1} \tag{1}$$

where γ, K, d, V, and V_{th} are viscosity, elastic constant, cell gap, driving voltage, and threshold voltage, respectively.

Hence, Fresnel LC lens will be a good candidate for a temporal scanning device. However, not every kind of Fresnel LC lens can be used for temporal scanning function. Accordingly, in this paper, we propose superzone Fresnel LC lens with multi-electrode driven structure for fast switching, low-voltage operation, and temporal scanning.

II. Superzone Fresnel LC Lens for Temporal Scanning

The Fresnel LC lens can be grouped into three types: Fresnel zone plate, continuous Fresnel zone lens, and superzone Fresnel lens [26], [27], as shown in Fig. 2. Many prior approaches have illustrated the switchable LC Fresnel zone plate uses the polymer-stabilized method to form the fixed binary-zone [28]–[31]. However, it is not suitable for scanning because the phase of each zone is fixed by a polymer wall (Fig. 2). Lu *et al.* [23] proposed continuous Fresnel LC lens formed by various widths of Fresnel zone prisms (Fig. 2). Nevertheless, it is also not available for scanning movement due to the width of each Fresnel zone not the same as shown in Fig. 3(a). Therefore,

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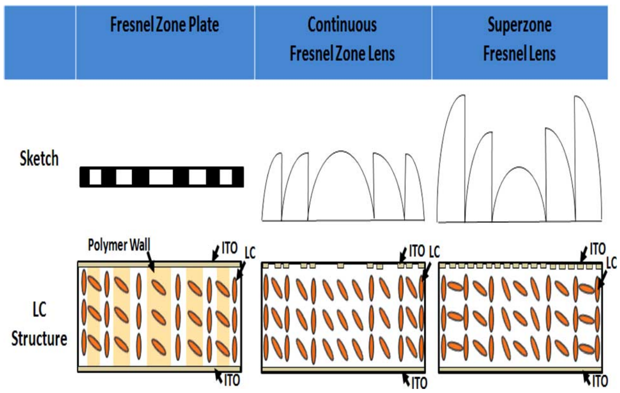

Fig. 2. Different structures of Fresnel LC lens—Fresnel zone plate, continuous Fresnel zone lens, and superzone Fresnel lens.

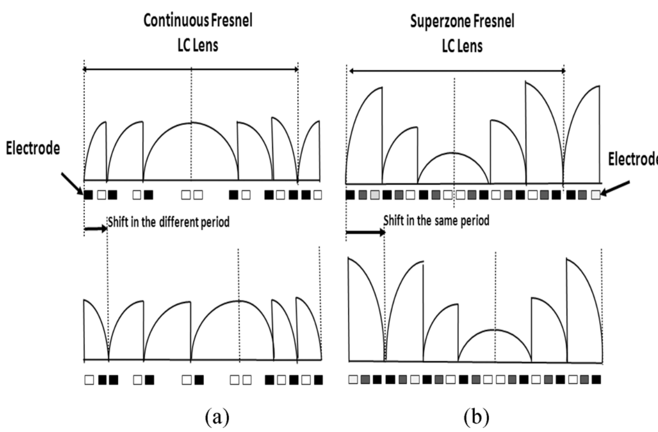

Fig. 3. Sketches illustrate that (a) the continuous Fresnel LC lens cannot be shifted for the same period; on the contrary; and (b) the scanning superzone Fresnel LC lens performs scanning function under shifting driving voltages. (Here, the lens shift from left side to right side, and the different gray levels on electrodes indicate different driving voltages.)

in this paper, we propose a superzone Fresnel LC lens with equalized ITO pitch (Fig. 2). Consequently, the superzone Fresnel LC lens can be shifted step by step by simply applying the different voltages on each electrode sequentially, as shown in Fig. 3(b). In the following section, the detail design and optimization of superzone Fresnel LC lens will be illustrated.

III. Simulation and Optimization

In this paper, the parameters of a superzone Fresnel LC lens are based on a 4-inch panel with pixel size 96 μm, and the viewing distance and view-number are of 96 cm and six-views respectively. The superzone Fresnel LC lens array is slanted 9.46° relative to vertical direction of pixel to suppress the moiré effect. Then, the corresponded six views image information is addressed according to the slanted lenses. Hence, the six views auto-stereoscopic display can be obtained [6]. Accordingly, the total pitch of a single superzone Fresnel LC lens is 188 μ, and it is divided into 6 zone prisms with equalized width. As illustrated in Fig. 4, different electrode patterns and ITO slit ratio were simulated. In the reconstructed figures, blue dash-line indicates the ideal curve of Fresnel lens, and the red solid-line shows the simulated results. Consequently, multiple ITO electrodes at both substrates with electrode to slit ratio equal to 2:1 is the optimized one, as shown in Fig. 4(b). The final parameters

TABLE I
Parameters of the Optimized Superzone Fresnel LC Lens

Parameters	Value
Lens Pitch (L)	188μm
Electrode Width (W_E)	5.3μm
Slit Width (W_S)	2.7μm
Cell Gap (d)	28μm
LC material	E7(Δn=0.22)
Focal length (f)	0.5 mm

for fabrication are listed in Table I. Each superzone Fresnel LC lens has 24 fine electrodes at both substrates inside the LC cell. And the cell gap of superzone Fresnel LC lens is almost half of the prior scanning LC-lens [24]. Thus, the response time of the superzone Fresnel LC lens are expected to be reduced to at least a quarter of the prior approach. Finally, the focal length of the LC lens also can be calculated from the following formula [21]:

$$f = \frac{(L/2)^2}{2\Delta n d}. \tag{2}$$

IV. Experiment

In this experimental session, the response time of proposed superzone Fresnel LC lens is first illustrated. Following the lens quality and proto-type of the auto-stereoscopic display are demonstrated. Finally, the superzone Fresnel LC lens array is driven to further perform scanning function on the horizontal movement for increasing 3D image resolution.

In the measurement, a 632.8 nm He-Ne laser and a fast CCD located at the focal plane were used to measure the intensity distribution and response time. The overdrive method was also used to further accelerate the response time. A pulse voltage (3 times the stable driving voltage with 100 ms pulse width) was firstly applied to electrodes to induce strong electric field in the LC cell, and then switch to the stable driving voltage (5 V_{rms}, 1 kHz) to perform the final lens curvature. Fig. 5 shows the measured results. For the prior scanning LC-lens, its response time was more than 6 s (green line), which was not enough for temporal scanning. For the proposed superzone Fresnel LC lens, its response time could be extremely reduced to 0.2 s with applying overdriving method [32], [33] (purple line). The captured images for the superzone LC lens switching from off state to on state are also shown in Fig. 6. Moreover, in order to reduce the lens' total switching time($\tau_{\text{rising}} + \tau_{\text{decay}}$), Chen *et al.* [34] also proposed a dual-directional overdriving method which can provide vertical and lateral electric field to accelerate both LC lens' rising and decay time.

For evaluating the lens profile, Fluorescence Confocal Polarizing Microscope (FCPM) [35], as shown in Fig. 7(a), was utilized. The FCPM can measure the LC orientation of each horizontal layer (x–y plane) according to the captured intensity. Fig. 7(b) shows a sampled intensity image of a single layer within the LC cell. In the measurement, LC cell was divided into 10 layers along the cell gap, z-direction, as illustrated in Fig. 7(c). The 1st and 10th layers were located at the boundaries of top and bottom substrate respectively. Finally, the profile of superzone Fresnel LC lens was reconstructed by integrating the

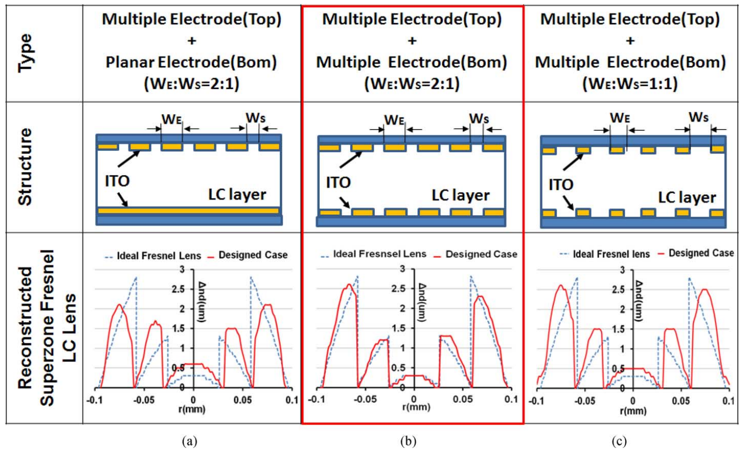

Fig. 4. Simulated cases for finding out the optimized structure design—Multiple electrode on both top and bottom side of substrate.

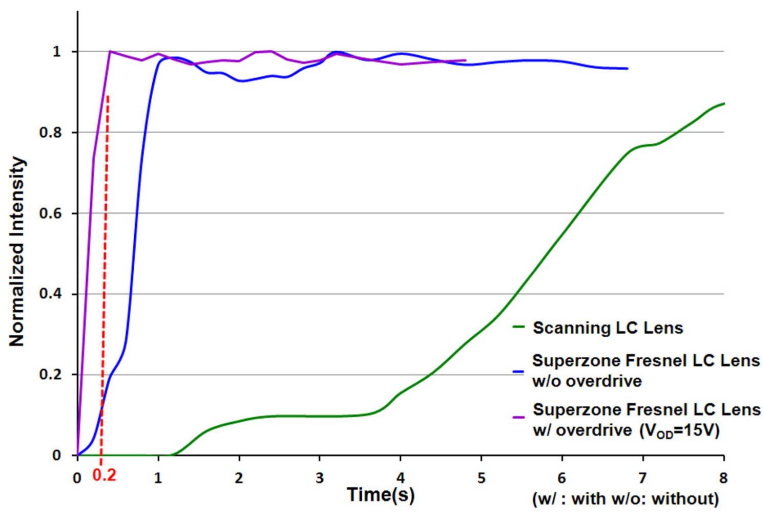

Fig. 5. Response time curves of prior scanning LC lens, and superzone Fresnel LC lens with/without overdrive method.

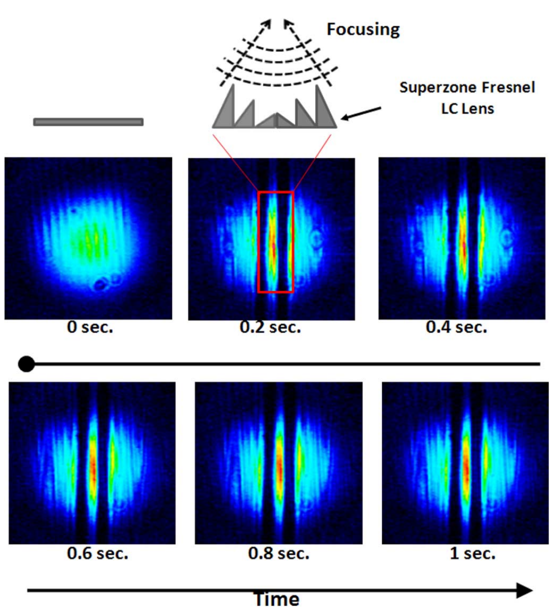

Fig. 6. Focusing images of the superzone Fresnel LC lens with overdrive method. The proposed superzone Fresnel LC lens becomes stable after 0.2 sec.

10 layers (Fig. 8). The result shows that the superzone Fresnel LC lens was really established, yet the phase change was not as ideal as simulated. By further analyzing the detail, it was caused by the cell gap variation, which is smaller in fabricated sample than that of ideal simulating condition.

After demonstrating a single superzone Fresnel LC lens, the lens array for 4-inch 3D display was further fabricated. The light intensity distributions of each viewing zone are shown in Fig. 9. The distance between each view is 65 mm which is the average gap of human eyes. The crosstalk of using superzone Fresnel LC lens for 3D display here is around 25% according to (3), where I_1 is the maximum intensity value for a single viewing zone at a specific position, and I_2 is the intensity value of the nearest neighboring zone at the same position. Additionally, the prototype 4-inch 3D display with superzone Fresnel LC-lens is shown in Fig. 10, which demonstrated the switched 2D and 3D images respectively. And the captured images under 3D mode are also clearly illustrated the different perspectives of the objects (e.g., the chairs)

$$\text{Crosstalk} = \frac{I_1}{I_1 + I_2} \times 100\%. \tag{3}$$

In addition, we also briefly analyze the diffraction effect of using our superzone Fresnel LC lens: for the lens-off state (2D mode), because the Fresnel LC lens is aligned as homogeneous cell (very small phase difference), as well as the ITO pattern is thin (∼100 nm thickness) and high transparent, the diffraction

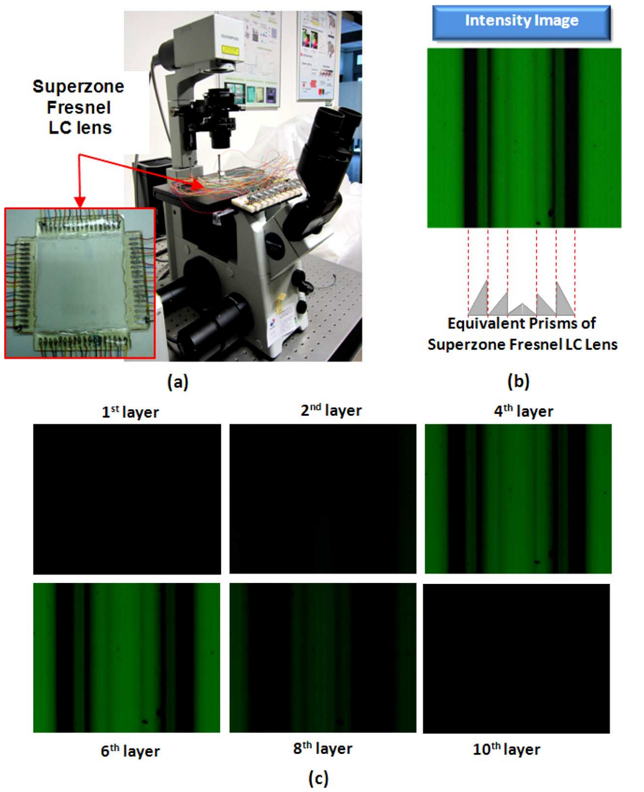

Fig. 7. (a) Confocal microscope system. (b) A sampling intensity image captured by the confocal microscopy of a single layer inside the superzone Fresnel LC lens. (c) Different images captured along the cell gap, z-direction. (LC cell was separated into 10 layers for measuring in this paper.)

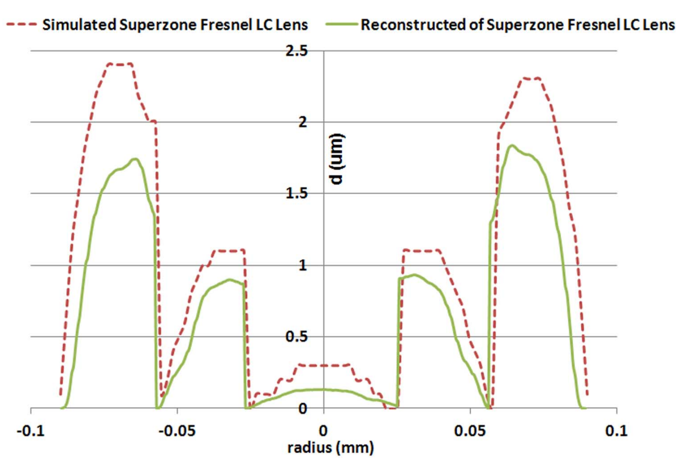

Fig. 8. Reconstruction of superzone Fresnel LC lens from experiment and simulation.

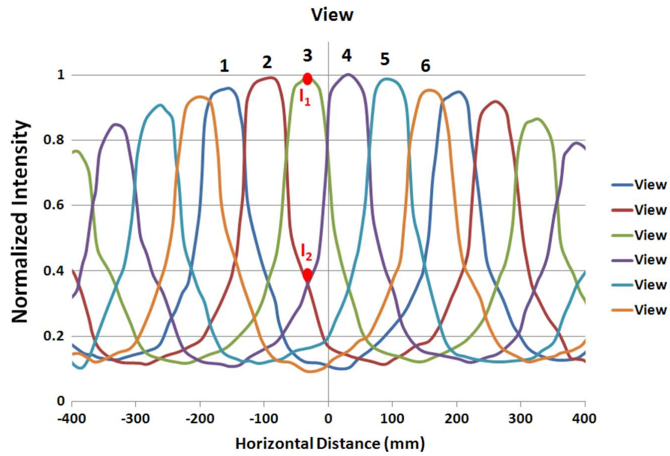

Fig. 9. Light distributions for 6-views 3D display using superzone Fresnel LC lens. The distance between each view is 65 mm at the viewing plane, and the horizontal-axis represents left-right direction of viewer.

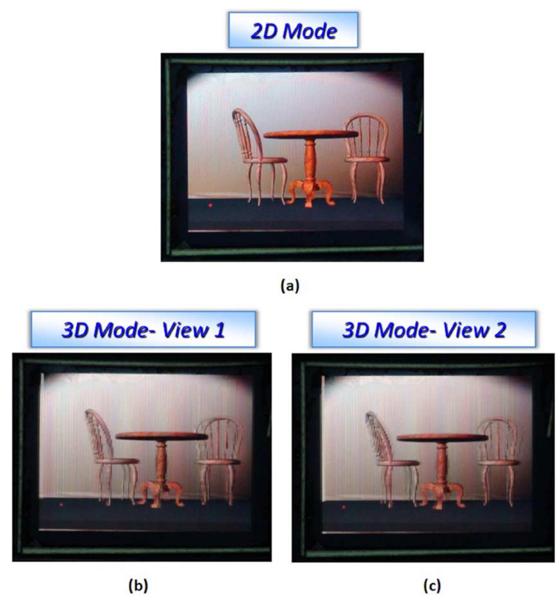

Fig. 10. Snapshots under 2D and 3D modes from the proposed 2D/3D switchable display using superzone Fresnel LC lens array. The captured images in 3D mode from two different viewing positions (view1 & view2) illustrate different perspectives.

effect is not obvious (2D mode in Fig. 10); for the lens-on state (3D mode), however, we can find slight color dispersion which may caused by the discrete Fresnel prisms. Thus, suppressing the color dispersion can be the next research topic.

Developing the fast response superzone Fresnel LC lens was not only for switching between 2D/3D images, but also for temporal scanning to produce high 3D image resolution. In our experiment, 3 frames scanned ($0.2 \times 3 = 0.6$ s) across a period of LC lens, which means the 3D image resolution can be ideally increased by a factor of 3. Fig. 11 shows the scanning results, where the scanning time was illustrated from top to bottom, and the focus of the lens moved from left to right. The result demonstrates that the proposed superzone Fresnel LC lens successfully performs scanning function; however, the response time, which is only 200 ms, still has to be improved for future temporal scanning 3D display. Using the fast response LC material can be the next step.

The blue phase LC (BP-LC) [36]–[38], ferroelectric LC (FLC) [39], [40], and high birefringence LC (HB-LC) [41], [42], are the three candidates. The BP-LC and FLC had been demonstrated with sub-millisecond response speed. For HB-LC, the cell gap of LC lens can be further reduced. Consequently, by using the fast response LC material with the proposed superzone Fresnel LC lens structure, a temporal scanning 3D display for high resolution auto-stereoscopic image can be achieved in the future.

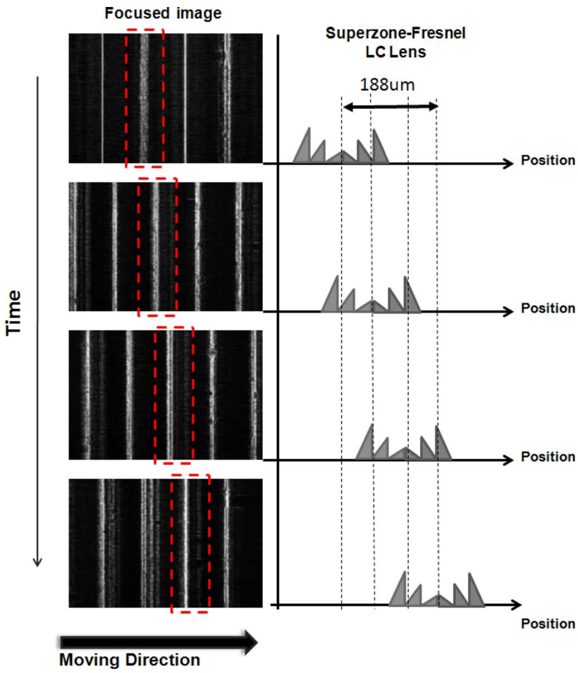

Fig. 11. Captured images of scanning superzone Fresnel LC lens across a period of a LC lens (0.2 s/frame).

V. Conclusion

The 3D image resolution of current multi-view 3D display is a major issue which needs to be improved. In prior approaches, scanning LC lens for increasing the image resolution in temporal domain was proposed, yet it still suffered from the slow response time. In this paper, we proposed superzone Fresnel LC lens to reduce the lens's response time (from 6 sec to 0.2 sec), as well as the driving voltage (from 30 $V_{\rm rms}$to 5 $V_{\rm rms}$). Not only was a single lens, but also lens array was fabricated for a 4-inch auto-stereoscopic display, which could perform fast switching between 2D and 3D images. Moreover, the superzone Fresnel LC lens with the equalized ITO pitch could be shifted step by step by simply applying the different voltages on each electrode sequentially. Finally, the scanning function was successfully demonstrated in the experimental result. In the future, a full resolution temporal scanning 3D display could be achieved by further implementing fast response or high birefringence LC materials.

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