

Full-Parallax Super-Multi-View 3D Display Based on Time-Sequential Electric Field Modulation

Xue-Rui Wen, Xing-Yu Lin, Wei-Ze Li, Yan Xing, Fan Chu*, and Qiong-Hua Wang*

School of Instrumentation and Optoelectronic Engineering, Beihang University, Beijing, 100191, China

Abstract

Super-multi-view (SMV) three-dimensional (3D) display is a glasses-free 3D display with potential for further development. The display features a large number of viewpoints, attributable to the use of vertical pixels in the horizontal direction. However, this configuration results in the loss of parallax in the vertical direction. In order to realize the parallax in both directions while maintaining a large number of viewpoints, a full parallax SMV 3D display based on time-sequential electric field modulation is proposed. The display consists of a 2D display and a dual-layer liquid crystal (LC) lens array controlled by a time-sequential voltage. The time-division multiplexing of the LC lens is carried out by using the voltage control to realize a high-resolution 3D display with parallax in both directions. The experiment results demonstrate that the proposed 3D display exhibits a high resolution with two directions of parallax simultaneously.

Author Keywords

Three-dimensional display; Super-multi-view 3D display; Viewpoints; Liquid crystal.

1. Introduction

Super-multi-view (SMV) three-dimensional (3D) display is a 3D display technology that employs an array of lenticular lenses to reconstruct a 3D image so that the viewer receives multiple viewpoints within the confines of a single eye. This approach can achieve a more realistic and natural 3D object reconstruction. As a result, the SMV 3D display is regarded as one of the most promising 3D display technologies [1-3]. However, it also has limitations because it uses a one-dimensional lenticular lens array for light modulation. Since the lenticular lens array has a focusing effect in only one direction, only one-dimensional parallax is realized, which affects the realism of the reconstructed 3D image.

Liquid crystals (LCs) possess a distinctive capacity to integrate the properties of molecular mobility and long-range ordering, which gives rise to optical birefringence, dielectric anisotropy, and a pronounced response to external stimuli [4-6]. The direction of LC molecules can thus be controlled by an electric field, resulting in a lens-like focusing effect. The application of LCs to spatiotemporal multiplexing is a viable method to improve the performance of 3D displays [7-9]. Therefore, LCs have been applied to two-dimensional (2D)/3D switchable displays by some researchers [10].

In this paper, we propose a full parallax SMV 3D display based on time-sequential electric field modulation. The display contains a 2D display and a dual-layer LC lenticular lens array. The LC lenticular lens array is modulated with a time-sequential electric field to produce a focusing effect on the light in different directions at different moments. Experiments demonstrate that the proposed display ensures high resolution while enabling full parallax in both directions.

2. Principle

Figure 1(a) shows the structure of a single-layer LC lens array. The LC lens array includes a top substrate, a top planar indium tin oxide

(ITO) electrode, an LC layer, a bottom strip ITO electrode, and a bottom substrate. The inner surfaces of the top and bottom substrates are coated with a polyimide film and rubbed in the same direction perpendicular to the bottom strip ITO electrode. Figures 2(a) and 2(b) illustrate the changes in the LC lens array and the modulation effect on the incident light under different voltage states. When the LC lens array is in the voltage-off state, the LC molecules are disordered and there is no focusing effect of the light passing through the LC lens array. Therefore, the LC layer is equivalent to a transparent glass, and the incident light does not change after passing through the LC lens array. When the LC lens array is in the voltage-on state, the LC molecules in the LC lens array will be redistributed to produce a focusing effect. At this time, the LC layer is equivalent to a lenticular lens array, and the incident light will be refracted by the LC lens array. d is the thickness of the LC layer, w is the width of the bottom strip electrode, and l is the distance between the bottom strip electrodes. All electrodes have the same thickness.

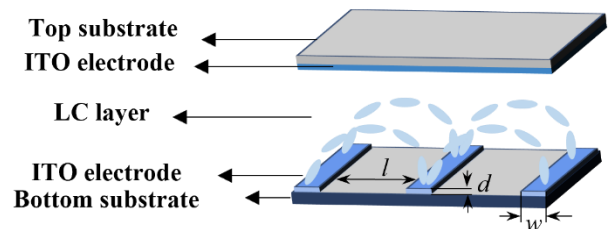


Figure 1 Schematic structure of a single-layer LC lens array.

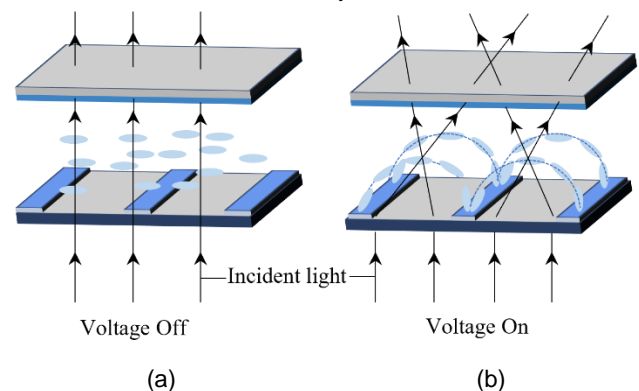
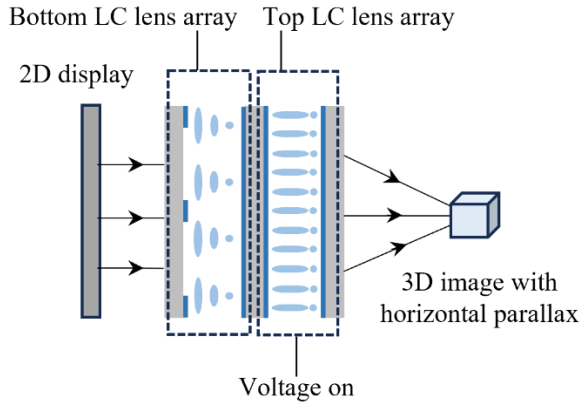


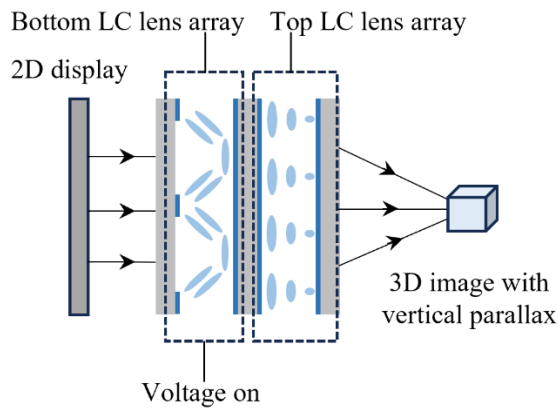
Figure 2. Schematic diagram of the operation of the LC lens array under (a) voltage-off state and (b) voltage-on state.

Figure 3 shows the side view of the operating state of the proposed SMV 3D display at different moments, which consists of a 2D display and a dual-layer LC lens array. The 2D display emits light, which is refracted by the corresponding LC lens array to reconstruct a 3D image. In Figure 3(a), at t_1 , the bottom LC lens array is in the voltage-off state, which is equivalent to a layer of transparent glass, and the light emitted from the 2D display is not refracted and directly enters the top LC lens. The top LC lens array is in the

voltage-on state, and the LC molecules are arranged as a lenticular lens array in the vertical direction. The light is refracted and the 3D image is reconstructed with horizontal parallax. At t_2 , the bottom LC lens array is in the voltage-on state. The LC molecules change directions to form horizontally lenticular lens arrays. The light emitted from the 2D display passes through the bottom LC lens array, undergoes refraction, and enters the top LC lens array. At this time, the top LC lens array is in the voltage-off state, and the LC molecules are arranged in disorder. The top LC lens array is equivalent to a layer of transparent glass for the incoming light, which is not refracted, and the outgoing light reconstructs a 3D image in space with vertical parallax, as shown in Figure 3(b).



(a)



(b)

Figure 3. Schematic diagram of the proposed 3D display reconstructing a 3D image with (a) horizontal parallax and (b) vertical parallax respectively.

In the SMV 3D display, the information of a 3D object needs to be collected from multiple angles, and the captured information is processed to obtain an element image array (EIA) for 3D display. Subpixels conveying different information are encoded in the captured parallax image array, and then they are assigned to the corresponding positions on the 2D display. In this way, viewers at different viewing positions are able to see the reconstructed 3D image with different angles. Figure 4(a) illustrates the sub-pixel encoding method used to generate an EIA with horizontal parallax in the proposed 3D display. For the top LC lens array, the subpixel at (j, k) is encoded as $n_{j, k}$, which is expressed as

$$n_{j,k} = \left\lceil \frac{[3(j-1) + 3(k-1) \tan \varphi + s - 1] \bmod P_h}{p} \right\rceil, \quad (1)$$

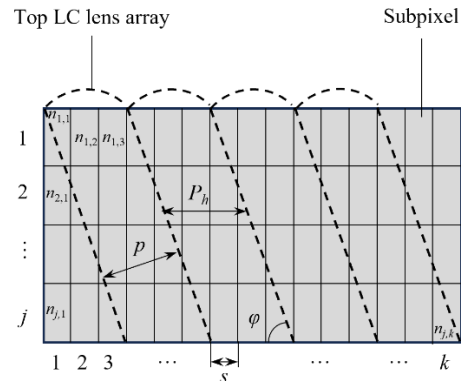
$$P_h = \frac{P}{\cos \varphi}, \quad (2)$$

where j denotes the number of rows and k denotes the number of columns. p denotes the top LC lens array pitch and s denotes the length of the short side of the subpixel. P_w denotes the length of the top LC lens element in the horizontal direction. In conventional LCD displays, the subpixels are arranged in RGB strips. To prevent the occurrence of moiré fringes resulting from the interaction between the subpixels and the lens array structure, the top and bottom LC lens arrays are positioned at an angle relative to the 2D display. The angle between the top LC lens array and the 2D display is identical to that between the bottom LC lens array and the 2D display, which is denoted as φ . In order to generate an EIA containing parallax information in the vertical direction, it is necessary to use different sub-pixel encoding methods. In Figure 4(b), for the bottom LC lens array, the subpixel at (j, k) is encoded as $m_{j,k}$, which is expressed as

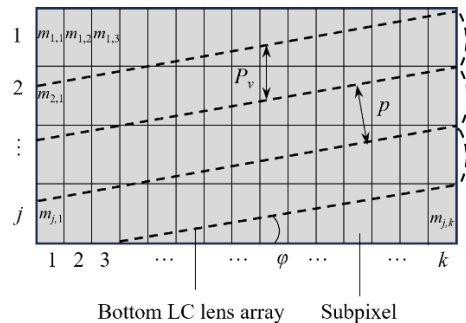
$$m_{j,k} = \left\lceil \frac{[3(N-j+1) + 3(M - (k+s-2)) \tan \varphi] \bmod P_v}{p} \right\rceil, \quad (3)$$

$$P_v = \frac{P}{\sin \varphi}, \quad (4)$$

where p denotes the bottom LC lens array pitch and P_v denotes the length of the bottom LC lens element in the vertical direction.



(a)



(b)

Figure 4. Schematic diagrams of the pixel encoding used in reconstructing (a) a 3D image with horizontal parallax and (b) a 3D image with vertical parallax, respectively.

Based on the position of the sub-pixels on the 2D display, the corresponding parallax image in the obtained parallax image array is selected and the corresponding sub-pixel information therein is loaded onto the corresponding positions of the 2D display. Subsequent to the pixel mapping procedure, the EIA can be generated and displayed on the 2D display. The refraction of the LC lens array allows the presentation of the corresponding views at different angles, thereby enabling the reconstruction of the 3D object.

3. Results

Figures 5(a) and 5(b) show the cross sections of the director distribution of LC molecules within the LC layer for different voltage states respectively. Under the voltage-on state, a specific electrostatic field distribution is generated between the planar electrode and the rectangular electrode. The LC molecules are affected by the electrostatic field, and the orientation of the molecules changes. The LC molecules at the center of the LC lens array remain unchanged in their orientation because they are subjected to the same electric field force in all directions, whereas the LC molecules at the boundaries maintain a larger tilt angle due to the imbalance of the electric field distribution. LC molecules with different orientations have different refractive indices for light, so the refraction of LC molecules in the LC layer is distributed in a trapezoidal shape, which can form a focusing effect on the linearly polarized light whose direction of polarization is parallel to the LC molecules. We can obtain the focusing effect of the LC lens array from Figure 6. When the voltage V_{on} is 6V, the phase distribution of the proposed LC lens array is found to be in close alignment with that of the ideal lens, indicating that the proposed LC lens array has a good focusing effect.

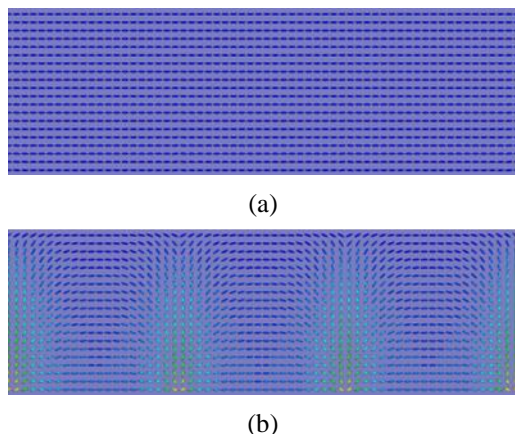


Figure 5. Cross sections of the director distribution of LC molecules within the LC layer for (a) voltage-off state and (b) voltage-on state respectively.

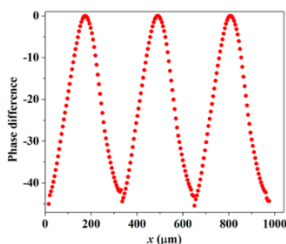


Figure 6. Phase difference for the extraordinary ray of the proposed LC lens array at $V_{on} = 6V$.

The reconstructed images are presented in Figures 7(a) and 7(b). Some “desserts” are employed as the 3D object, and a time-sequential modulated electric field is introduced to the proposed 3D display. The reconstructed 3D images are recorded at different moments from different directions. Figure 7(a) shows the reconstructed 3D image with horizontal parallax and Figure 7(b) shows the reconstructed 3D image with vertical parallax. It can be seen that different sides of the “cheese” can be seen when the viewing angle is changed. The proposed 3D display prototype has a viewing angle of 10.6° . The experimental results show that the reconstructed 3D images have parallax in both horizontal and vertical directions.

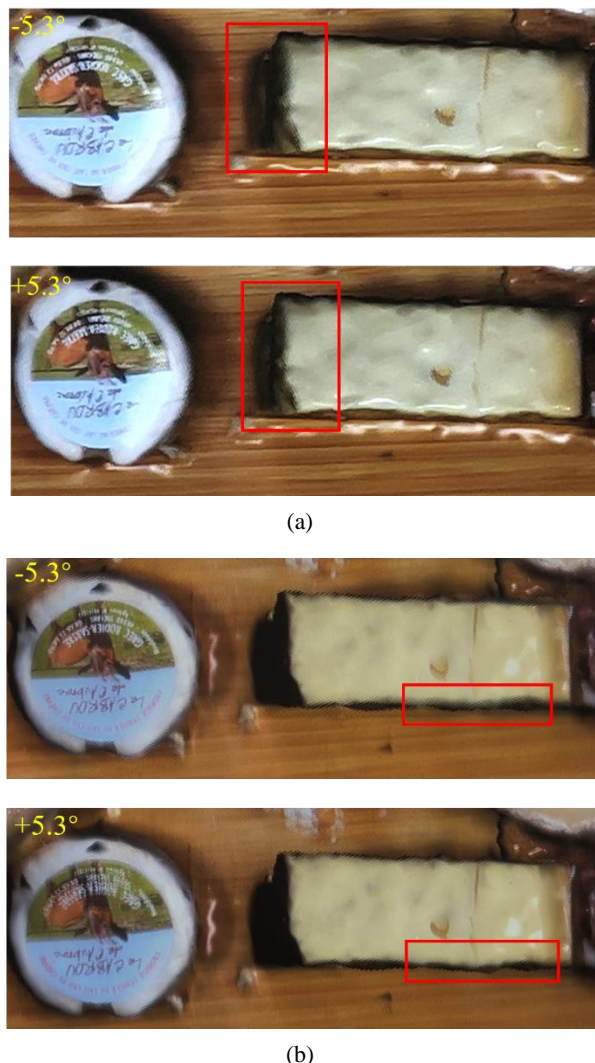


Figure 7. 3D image reconstructed by the proposed 3D display with (a) horizontal parallax and (b) vertical parallax.

Figures 8(a) and 8(b) show the resolution results of the proposed 3D display in different voltage states. A 1951 United States Air Force (USAF) resolution test chart is employed to test the imaging qualities. As illustrated in Figure 8(a), when the top LC lens array is in a voltage-on state and the bottom LC lens is in a voltage-off state, the lens array has a horizontal focusing ability and a higher resolution in the vertical direction. The vertical resolution can reach the 6th element of group 1. When the top LC

lens array is in a voltage-off state and the bottom LC lens is in a voltage-on state, the lens array has a vertical focusing ability and the resolution in the horizontal direction is higher. The horizontal resolution can also reach the 6th element of group 1, as shown in Figure 8(b).

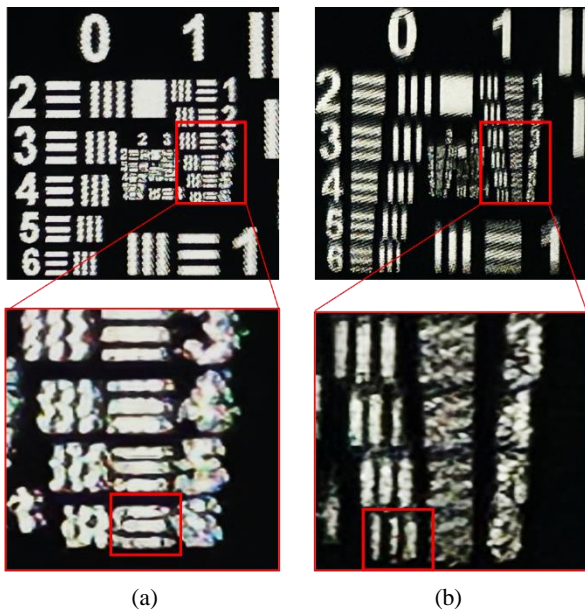


Figure 8. Reconstructed USAF image with (a) horizontal parallax and high vertical resolution and (b) vertical parallax and high horizontal resolution.

4. Conclusion

We propose a full parallax SMV 3D display based on time-sequential electric field modulation. The 3D display system consists of a 2D display and a dual-layer LC lens array, and the light emitted from the 2D display is refracted by the corresponding LC lens array to reconstruct a 3D image with one-dimensional parallax. The full parallax 3D display is realized by time-sequential electric field modulation and time-division multiplexing of the dual-layer LC lenses. In the proposed 3D display, different pixel coding methods are used in different voltage display states to obtain image information in the horizontal and vertical directions to realize full parallax information acquisition. The experimental results confirm that the proposed 3D display can realize a full parallax 3D display while still having a high resolution.

5. Acknowledgements

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6. References

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