

Chapter 13

Liquid Crystal 3D Displays

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3D display was expected to be the dominant next-generation display technology for producing more natural images. For autostereoscopic 3D technologies, observers could perceive 3D images with the naked eyes, yet still has the degradation of image quality for a given autostereoscopic 3D display. In this chapter, various LC lens (LC-lens) technologies for improving the issues are illustrated, followed by the future developments of LC-lens on 3D applications.

13.1 Introduction of 3D Display

Three-dimensional display technologies can be categorized into stereoscopic type and auto-stereoscopic type, as listed in Fig. 13.1. The stereoscopic 3D displays require the viewers to wear glasses or special devices such as active shutter glasses type, passive polarizer type, or head-mounted display (HMD), to perceive 3D images [1–8]. Thus, viewers perceive correct left and right images for the corresponding eyes through the special devices. Moreover, the stereo technique only provides the same two-view stereo image that there are no perspective images for arbitrary positions. Hence, the auto-stereoscopic (glasses-free) 3D displays are definitely the future trend.

The glasses-free 3D displays include holographic type [9–12], volumetric type [13, 14], multi-plane type [16–18], integral imaging and multiplexed-2D type [19–27]. The holographic displays use the concept of interference to reconstruct the 3D scene through reconstruction of wave intensity and phase. However, this method now is too complicated to reconstruct good dynamic and full color 3D scene due to the special light source, complicated image content, and high

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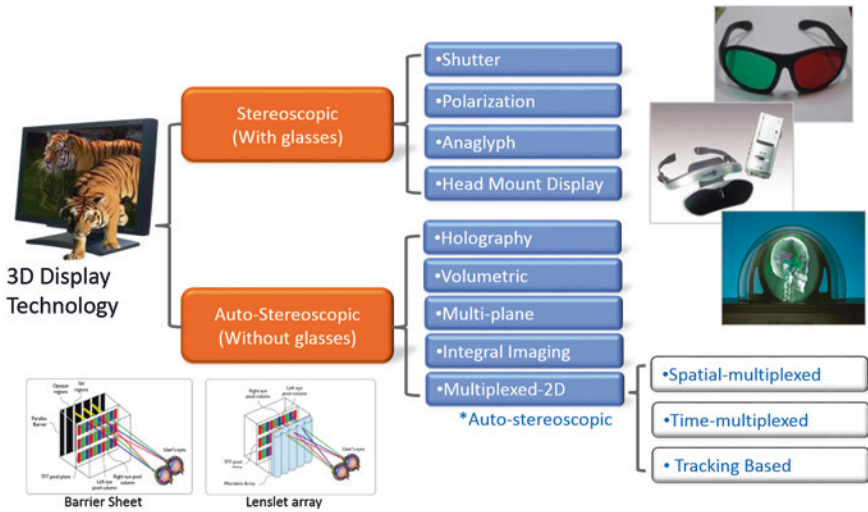


Fig. 13.1 Classification of 3D technologies

quality display requirement. The volumetric displays and multi-plane displays are good approaches while they require huge space. Therefore, recently, researchers are more attracted on the compact multiplexed-2D displays for 3D applications because it can be achieved with flat panel displays.

The spatial-multiplexed 3D displays generally includes two components, optical device and display panel. The optical device, such as the lenslet array or barrier sheet, is used to project different images to the corresponding directions. And the display panel is used to display the images. Two common optical devices, for example, used for these 3D displays are fixed barrier [21, 28] and lenticular lens sheet [25–27, 29–31]. This method provides different information to the corresponding left and right eyes simultaneously. Hence, human brain fuses this different information and then 3D sensation can be obtained. Besides, the two-view or multi-view 3D displays can be achieved by generating two or more view information to be the image content. However, current spatial-multiplexed method will much decreases the resolution of 3D images, especially can't be used for reading the text contents. Therefore, liquid crystal lens (LC-lens) was proposed for 2D/3D switching function. Except 2D/3D switching, the 3D rotation and 3D scanning function of LC-lens were also been reported to extend the application of 3D displays.

13.2 LC Lens for 3D Display

In 1979, the LC material was first employed for lens applications [32]. The LC is injected into the space between the plano and concave glass substrates, or plano and convex glass substrates, respectively. The transparent electrodes are coated on

the glasses, as shown in Fig. 13.2. Applying the driving voltages on the electrodes, the LCs is re-aligned according to the potential distribution within the cells. Thus, the optical powers of the concave and convex lenses can be tuned without physically change the lens shape. The polarized light is also needed in order to meet effective refractive index changing of the LC lens (i.e., the un-polarized light cannot meet the index changing that the incident light path cannot be changed after passing through the LC cell).

13.2.1 2D/3D Switching Function of LC-Lens

For 2D/3D switching LC-lens, three approaches, polarization active micro-lens, Active LC lenticular lens, Electric-field-driven LC(ELC) lenticular lens, had been reported and described in detail in this session.

13.2.1.1 Polarization Active Micro-Lens

The polarization activated micro-lens was proposed by G.J. Woodgate, and J. Harroldas in 2003 [33, 34], which the basic structure is shown in Fig. 13.3. The polarization of incident light is not changed after encountering the polarization switching cell (TN cell) when applying driving voltage on the TN cell. Thus, the 2D mode can be obtained when the polarization of polarized light do not be changed. On the other hand, the polarization of polarized light is changed that the light is focused after passing through micro-lens layer without applying driving voltage on the TN cell. Hence, the 3D mode is achieved.

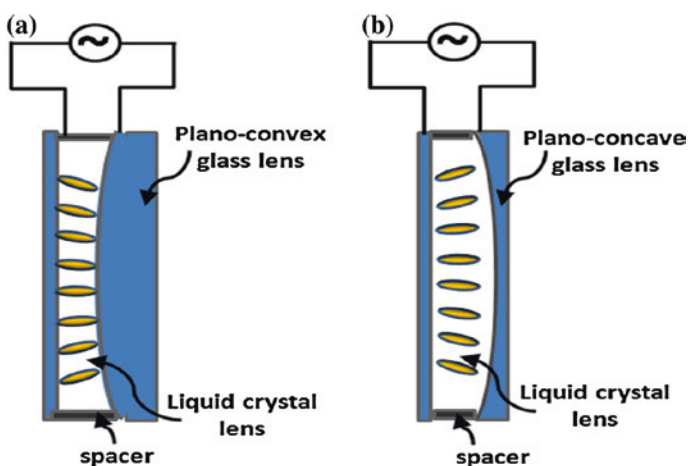


Fig. 13.2 The first proposed LC lenses in 1979. **a** Plano-convex cell, and **b** plano-concave cell

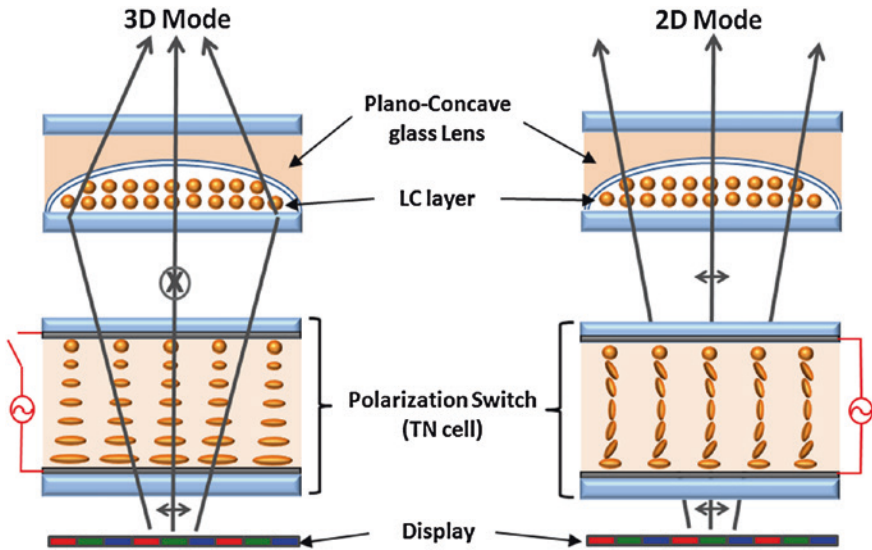


Fig. 13.3 On and off state of polarization active micro-lens

13.2.1.2 Active LC Lenticular Lens

Just like the structure of inhomogeneous LC-lens, S.T. de Zwart et al., developed an active LC lenticular lens for 2D/3D switchable display [35, 36]. As shown in Fig. 13.4, the LC molecules (positive dielectric anisotropy) are aligned perpendicular to the plane. The refractive index of the concave glass lens, n_g , is chosen equal to ordinary refractive index, n_o . The incident polarized light from the underlying LCD is with polarization perpendicular to the plane (i.e., extra-ordinary light). Hence, the polarized light encounter a difference of refractive index distribution from n_e (the extra-ordinary refractive index of LCs) to n_o (the refractive index of glass lens) without applying driving voltage. It results in a net lens-action to form a 3D mode, i.e., the spatial-multiplexed type 3D display; on the other hand, the LCs reorient according to the potential distribution thus the incident extra-ordinary light encounters the ordinary refractive index of LCs, n_o , when applying the driving voltage on the planar electrodes. Since the ordinary refractive index matched the refractive index of the glass lens, the LC lens acts as a normal glass plate and the light is not refracted. A display which can display normal 2D images could be achieved.

Nevertheless, there are some drawbacks of the above two methods, active LC lenticular lens and polarization active micro-lens, such as mismatching of LC alignment at the interface and the tough fabricating process for the concave lens.

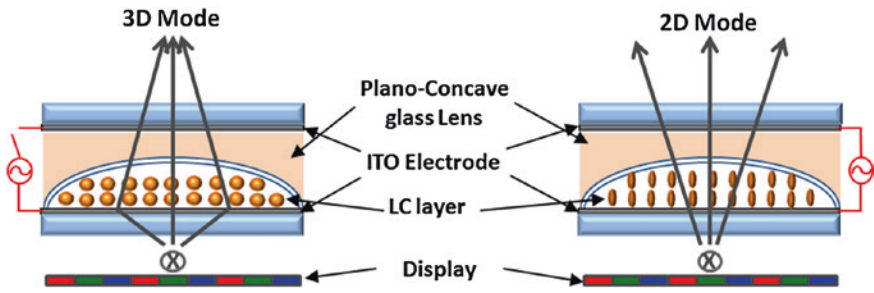


Fig. 13.4 Active LC lenticular lens

Hence, the simplest LC lens, homogeneous LC layer and homogeneous glass structure, for 3D displays was invented to overcome these issues.

13.2.1.3 Electric-Field-Driven LC (ELC) Lenticular Lens

For the Electric-field-driven LC (ELC) lens [37–40], the electrodes are designed to be the symmetric structure with respect to the centerline, and the different driving voltages are connected to the electrodes which are located at different layers, as shown in Fig. 13.5. The electrode layers are fabricated on the side of bottom substrate, and an insulator layer (SiO_2 layer) is sandwiched between these electrode layers. Applying specific different voltages on the different electrode layers, the phase retardation profile, which approach to the parabolic curve, of the LC layer can be obtained. The ELC lens also can be utilized for switching between 2D and 3D mode by changing the driving voltage on and off. However, the assembly and response time are two issues of this kind of LC lens.

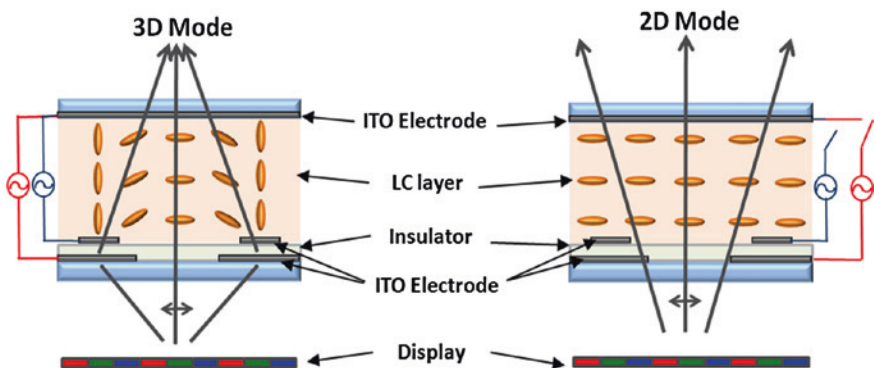


Fig. 13.5 Principle of electric-field-driven LC lens [20–24]

13.2.2 Rotation Function for Mobile Application

Due to the raising requirement of portable device, the rotatable function of display on 3D mode, as shown in Fig. 13.6, also become popular. To achieve rotatable function of lenticular LC lens, the two sets of stripe electrode should be arranged in different directions. However, when we apply the voltage to the top or bottom electrode, there is no full flat electrode on the other side. According to the structures and electrode field of LC cell, the LC cell won't be generated as a lenticular lens. To form the shape of lenticular lens, the variation of electrode field should be change only in one direction. Therefore the function of high resistance layer can be used to overcome this issue.

According to the switchable function of electrode, Chang et al. [41] proposed rotatable lenticular LC lens which is coated high resistance on both inner electrodes. In order to form lenticular lens in two directions, the top electrodes and the bottom electrodes should almost perpendicular to each other. To achieve switchable function in two directions, top and bottom electrodes are coated with high-resistance material, as shown in Fig. 13.7. When all bottom electrodes are connected to Vcom and top electrodes are driven by interlaced voltage, VD and Vcom, the LC lenticular lens will arrange in horizontal direction. Due to the same driving voltage, the bottom high resistance layer becomes a full electrode with ground voltage. On the other hand, distribution of voltage on the top side becomes a gradient and continuous distribution, because of the function of high resistance layer. Alternatively, in vertical direction, the bottom electrodes are driven by VD and Vcom individually, and whole electrodes on the top are operated by Vcom.

Except crossed electrodes, M. Kashiwagi and S. Uehara optimized the LC alignment direction (LCAD) and Electrode array direction (EAD) to realize the rotatable 2D/3D display with wider vertical and horizontal viewing angles in both landscape



Fig. 13.6 The schematic plot of rotatable 3D display for mobile application

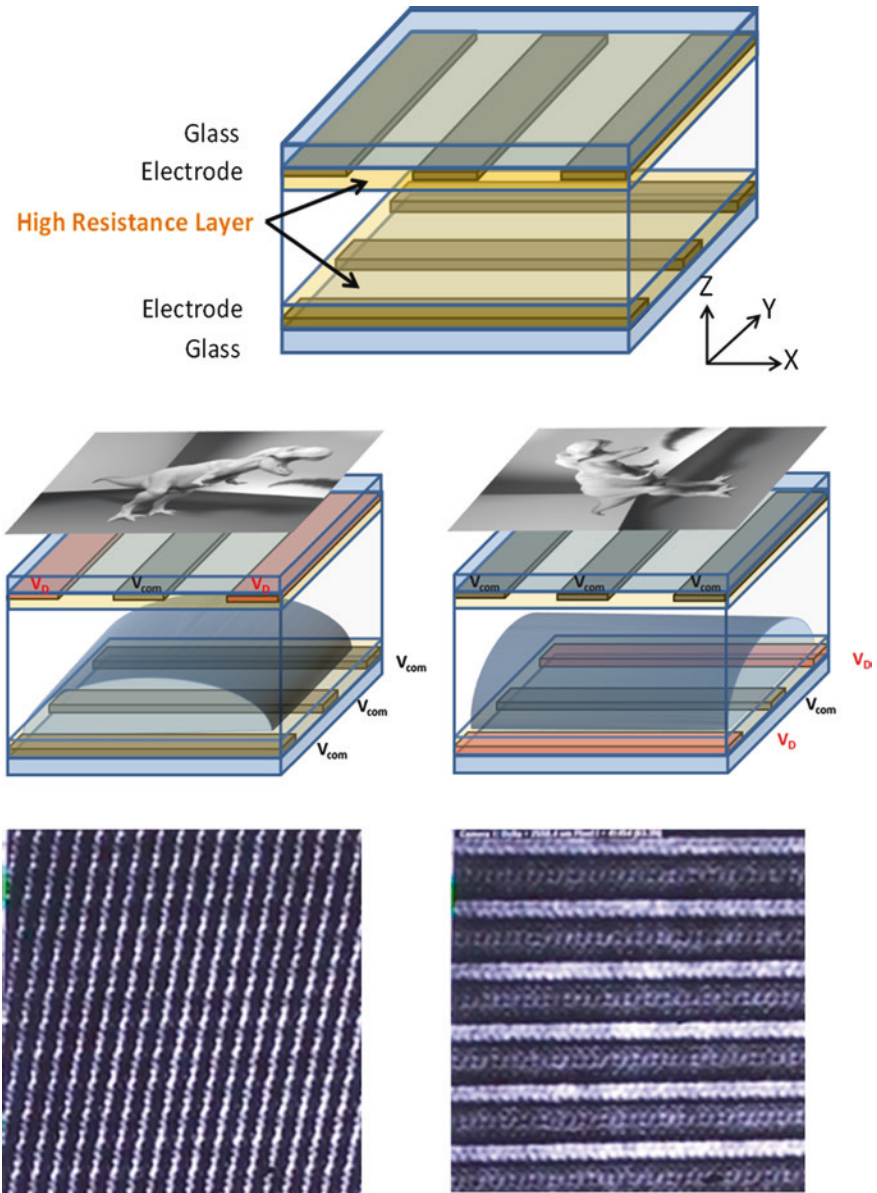


Fig. 13.7 The schematic plot of rotatable LC lens and the focused pattern on vertical and horizontal direction

and portrait orientations [42]. The conditions of two electrode directions and LC alignment direction are both less than 50° of θ_R , the results show that 3D viewing azimuth angle is over 30° in both landscape and portrait orientations (Fig. 13.8).

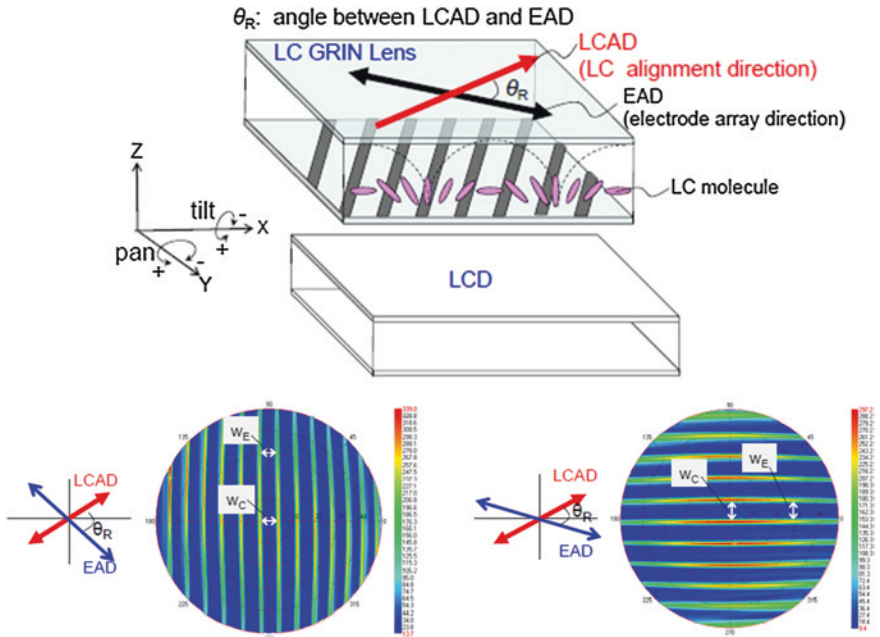


Fig. 13.8 Optical model and luminance measurement results of non-orthogonal electrodes array system proposed by Uehara et al. [42]

By using LC lens, the reduction of 2D resolution can be solved, yet 3D image isn't. For having more freedom of views for multi-users, the view-points have to be increased. The pixel resolution (spatial domain) for 3D image has to be sacrificed for yielding more views to widen the viewing angle (Spatial-multiplexed). Consequently, in order to have a full resolution 3D display, "temporal domain" or "time-multiplexed" technologies have to be considered.

13.2.3 3D Scanning LC-Lens for Full Resolution 3D Image

Resolution decreasing is always a major issue of auto-stereo 3D display. To improving the resolution. Huang, et al., proposed the active scanning Multi-electrode Driven LC lens (MeD-LC lens) [43, 44]. The MeD-LC lens can not only formed ideal parabolic lens curvature for 2D/3D switch with low crosstalk, but also can scan the electrode voltage to move the lens for multi-view points.

At the voltage on state, local electric fields are formed by the gradient distribution of electric field. Hence, the lenticular MeD-LC lens array can be obtained by making repeated patterns as well. In addition, by applying the operating voltage sequentially on each electrode, the LC in MeD-LC lens reorients and builds

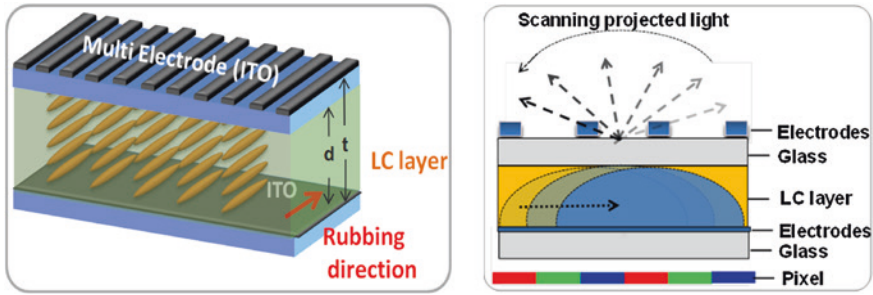


Fig. 13.9 Multi-electrode structure and scanning of LC-lens

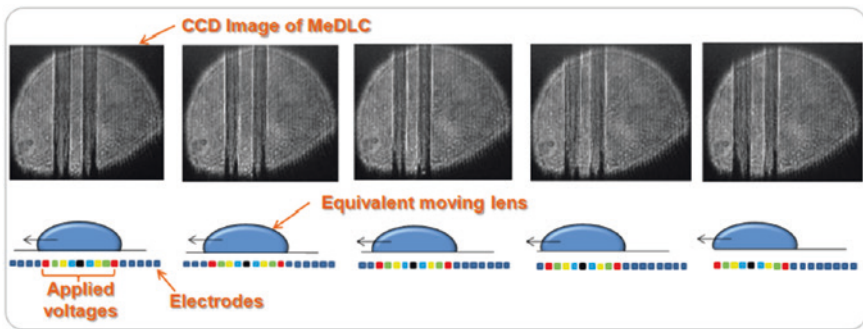


Fig. 13.10 Experiment results of scanning effect

in a lens-like shape, thus the lens could move (shift) sequentially on the horizontal direction to project the images to different viewing angle, as the schematic shown in Fig. 13.9.

Due to the multi-electrodes are periodic, the scanning function could be operated by changing the voltage sequentially. The captured image with scanning MeD-LC lens is demonstrated in Fig. 13.10. Currently, however, the response time of MeD-LC lens is still not adequate for super time-multiplexed 3D display.

13.3 Conclusions and Future Developments

For various types of the 2D/3D switching displays, the liquid-crystal (LC) lens was one of the most favorable designs for such display applications. The LC lens would focus and just pass the incident light with and without supplying the operating voltage.

Three types of LC lens, polarization active micro-lens, Active LC lenticular lens, and Electric-field-driven LC (ELC) lenticular lens, had been reported

and successfully demonstrated. To further using crossed electrode coated by high resistance material or controlling the LC alignment direction (LCAD) and Electrode array direction (EAD), 3D rotation display can be obtained.

However, the resolution decreasing is still an issue with 3D images. Therefore, temporal scanning mode, Multi-electrode Driven (MeD) Fresnel LC-lens was proposed. Although the response time of above LC-lens were not adequate in current stage due to the thick cell-gap, but illustrated a future development on wide viewing angle with high resolution 3D display.

References

1. N. Holliman, 3D Display System (2002)
2. L. Hill, A. Jacobs, 3-D liquid crystal displays and their applications. *Proc. IEEE* **94**, 575–590 (2006)
3. A.K. Srivastava, J.L. deB, D.L. Tocnaye, L. Dupont, Liquid crystal active glasses for 3D cinema. *J. Disp. Technol.* **6**, 522–530 (2010)
4. S. Pastoor, M. Wopking, 3-D displays: A review of current technologies. *Displays* **17**, 100–110 (1997)
5. Y.J. Wu, Y.S. Jeng, W.M. Huang et al., Stereoscopic 3D display using pattern retarder. *Proc. SID Symp. Dig.* **39**, 260–263 (2008)
6. S.M. Jung, I.J. Chung et al., A novel polarizer glasses-type 3D displays with an active retarder. *Proc. SID Symp. Dig.* **40**, 348–351 (2009)
7. M.G. Tomilin, Head-mounted displays. *J. Opt. Technol.* **66**, 528–533 (1999)
8. K. Keller, A. State, H. Fuchs, Head mounted displays for medical use. *J. Disp. Technol.* **4**, 468–472 (2008)
9. B. Javidi, E. Tajahuerce, Three dimensional object recognition using digital holography. *Opt. Lett.* **25**, 610–612 (2000)
10. J.Y. Son, B. Javidi, S. Yano, K.H. Choi, Recent developments in 3D image technologies. *J. Disp. Technol.* **6**, 394–403 (2010)
11. Y. Takaki, N. Okada, Reduction of image blurring of horizontally scanning holographic display. *Opt. Express* **18**, 11327–11334 (2010)
12. Y. Takaki, M. Yokouchi, N. Okada, Improvement of grayscale representation of the horizontally scanning holographic display. *Opt. Express* **18**, 24926–24936 (2010)
13. P. Soltan, J.A. Trias, M. McDonald et al., Laser based 3-D volumetric display system. *Nav. Eng. J.* **107**, 233–243 (1995)
14. H.H. Refai, Static volumetric three-dimensional display. *J. Disp. Technol.* **5**, 391–397 (2009)
15. M. Gately, L. Sawalha et al., A three-dimensional swept volume display based on LED arrays. *J. Disp. Technol.* **7**, 503–514 (2011)
16. S. Suyama, S. Ohtsuka, H. Takada, K. Uehira, S. Sakai, Apparent 3-D image perceived from luminance-modulated two 2-D images displayed at different depths. *Vis. Res.* **44**, 785–793 (2004)
17. H. Kuribayashi, M. Date, S. Suyama, H. Tatada, A method for reproducing apparent continuous depth in a stereoscopic display. *J. Soc. Info. Disp.* **14**, 493–498 (2006)
18. C.Y. Hsu, Y.P. Huang, Y.C. Chang, Wide viewing angle 3D depth-fused display (DFD) system. *Proc. SID Symp. Dig.* **39**, 1655–1658 (2008)
19. C.V. Berkel, J.A. Clarke, Characterization and optimization of 3D-LCD module design. *Proc. SPIE* **3012**, 179–187 (1997)
20. S.J. Young, B. Javidi, Three-dimensional image methods based on multi-view image. *J. Disp. Technol.* **1**, 125–140 (2005)

21. C.H. Chen, Y.P. Huang, H.P.D. Shieh et al., Liquid crystal panel for high efficiency barrier type autostereoscopic three-dimensional displays. *Appl. Opt.* **48**, 3446–3454 (2009)
22. W. Maphepo, Y.P. Huang, H.P.D. Shieh, Enhancing the brightness of parallax barrier based 3D Flat panel mobile displays without compromising power consumption. *J. Disp. Technol.* **6**, 60–62 (2010)
23. M. Tsuboi, S. Kimura, Y. Takaki, T. Horikoshi, Design conditions for attractive reality in mobile-type 3-D display. *J. Soc. Info. Disp.* **18**, 698–703 (2010)
24. Y. Takaki, Multi-view 3-D display employing a flat-panel display with slanted pixel arrangement. *J. Soc. Info. Disp.* **18**, 476–482 (2010)
25. Y. Takaki, K. Tanaka, J. Nakamura, Super multi-view display with a lower resolution flat-panel display. *Opt. Express* **19**, 4129–4139 (2011)
26. N.S. Holliman, N.A. Dodgson, G.E. Favalora, L. Pockett, Three-dimensional displays: a review and applications analysis. *IEEE Tran. Broadcast.* **57**, 362–371 (2011)
27. J. Nakamura, T. Takahashi, C.W. Chen, Y.P. Huang, Y. Takaki, Analysis of longitudinal viewing freedom of reduced-view super multi-view display and increased longitudinal viewing freedom using eye-tracking technique. *J. Soc. Info. Disp.* **20**, 228–234 (2012)
28. G. Hamagishi, Analysis and improvement of viewing conditions for two-view and multi-view display. *Proc. SID Symp. Dig.* **40**, 340–343 (2009)
29. H.J. Im, S.M. Jung, H.N. Shin et al., Mobile 3-D display based on a LTPS 2.4-in. VGA LCD panel attached with lenticular lens sheets. *Proc SID Symp. Dig.* **39**, 256–259 (2008)
30. B. Javidi, F. Okano, *Three-Dimensional Television, Video, and Display Technologies* (Springer, New York, 2002)
31. J.Y. Son, B. Javidi, Three-dimensional image methods based on multi-view images. *J. Disp. Technol.* **1**, 125–140 (2005)
32. S. Sato, Liquid-crystal lens-cells with variable focal length. *Jpn. J. Appl. Phys.* **18**, 1679–1684 (1979)
33. G.J. Woodgate, A new architecture for high resolution autostereoscopic 2D/3D displays using free-standing liquid crystal microlenses. *Proc. SID Symp. Dig.* **36**, 378–381 (2005)
34. G.J. Woodgate, High efficiency reconfigurable 2D/3D autostereoscopic display. *Proc. SID Symp. Dig.* **34**, 394–397 (2003)
35. O.H. Willemsen, S.T. De Zwart, 2D/3D switchable displays. *J. Soc. Inf. Disp.* **14**(8), 715–722 (2006)
36. C.M. Krijn, S.T. de Zwart, 2D/3D displays based on switchable lenticulars. *J. Soc. Inf. Disp.* **16**(8), 847–855 (2008)
37. Y. Li, S.T. Wu, Polarization independent adaptive microlens with a blue-phase liquid crystal. *Opt. Express* **19**, 8045–8050 (2011)
38. H.W. Ren, S.T. Wu, Getting in tune: electronically controlled liquid crystal yields tunable-focal-length lenses. *SPIE's optics express magazine* (2004), pp. 24–27
39. A.F. Naumov et al., Liquid-crystal adaptive lenses with modal control. *Opt. Lett.* **23**(13), 992–994 (1998)
40. M. Ye, S. Sato, Low-voltage-driving liquid crystal lens. *Jpn. J. Appl. Phys.* **49**, 100204-1–100204-3 (2010)
41. Y.C. Chang, T.H. Jen, Y.P. Huang et al., High-resistance liquid-crystal lens array for rotatable 2D/3D autostereoscopic display. *Opt. Express* **22**, 2714–2724 (2014)
42. S. Uehara, M. Baba et al., LC GRIN lens mode with wide viewing angle for rotatable 2D/3D tablet. *Proc. SID Symp. Dig.* **42**, 154–157 (2013)
43. Y.P. Huang, L.Y. Liao, C.W. Chen, 2D/3D switchable autostereoscopic display with multi-electrically driven liquid crystal (MeD-LC) lenses. *J. Soc. Inf. Disp.* **18**(9), 642–646 (2010)
44. Y.P. Huang, C.W. Chen, Superzone fresnel liquid crystal lens for temporal scanning autostereoscopic display. *J. Disp. Technol.* **8**(11), 650–655 (2012)