TOPICAL REVIEW — Physical research in liquid crystal

Latest development of display technologies

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In this review we will focus on recent progress in the field of two-dimensional (2D) and three-dimensional (3D) display technologies. We present the current display materials and their applications, including organic light-emitting diodes (OLEDs), flexible OLEDs quantum dot light emitting diodes (QLEDs), active-matrix organic light emitting diodes (AMOLEDs), electronic paper (E-paper), curved displays, stereoscopic 3D displays, volumetric 3D displays, light field 3D displays, and holographic 3D displays. Conventional 2D display devices, such as liquid crystal devices (LCDs) often result in ambiguity in high-dimensional data images because of lacking true depth information. This review thus provides a detailed description of 3D display technologies.

Keywords: display technology, two-dimensional displays, three-dimensional displays, holographic displays

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1. Introduction

Display devices are used by most people in their daily lives and it is said that approximately 80% of the information that people have obtained has been captured by visual and some electro-optical devices, such as phones, computers, televisions, and so on. Therefore, display technologies have attracted worldwide attention and they have made a significant contribution to the economy. They have also become a popular research topic. This paper reviews the latest development of two-dimensional (2D) and three-dimensional (3D) display technologies, such as organic light-emitting diodes (OLEDs), flexible OLEDs, quantum dot light-emitting diodes (QLEDs), active-matrix organic light-emitting diodes (AMOLEDs), electronic paper (E-paper), curved displays, stereoscopic 3D displays, volumetric 3D displays, light field 3D displays, and holographic 3D displays. We aim to describe their advantages and disadvantages, which might be useful for display researchers.

2. The 2D displays

Two-dimensional displays have been well developed and they have become a main-stream commercial display technology. In recent years, 2D displays have been improved, including large size, high resolution, high bright, full color, low cost, and so on. New materials, new methods, and new techniques have been used, and more and more 2D display technologies have come into application. Here, we introduce several of the current typical 2D displays.

2.1. OLED displays

Compared with LCDs, OLEDs have some advantages in terms of size, price, and quality. They have become the most dazzling display technology in the market. It can be said that a new generation of display panel technology was ushered in when they were introduced. Teng *et al.* raised a super multi-view display technology in view of planar-aligned OLED micro-displays.[1] By combining time-multiplexing with spatial-multiplexing, their prototype system is capable of providing 40 parallax views by only 10 OLED micro-displays, as is shown in Fig. 1. Iwasaki *et al.* dedicated their research to the development of next generation OLED lighting technology of evaporation process and solving process.[2] Using all phosphorescent materials at 139 lm/W, their display is the world's most efficient white OLED lighting panel, and it is a promising development of OLED lighting.



Fig. 1. Captured images with the camera located at different positions along the horizontal direction with a spatial interval of 32 mm.[1]

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A coarse-pitch circular-aligned OLED microdisplay was used in 360° 3D color display systems, which was achieved by controlled fusion of the light rays from adjacent OLED microdisplays.[3] This greatly reduces the required number of display panels for display systems and gets rid of the dependence on mechanical moving components, high speed components, and diffusion screens. A globe model was applied to validate both the idea and the system. A color image display is obtained using a CCD at different locations along the preferred path for the observation of equal angular spacing, as shown in Fig. 2(a). Figure 2(b) shows the obtained images from the verification experimental display systems

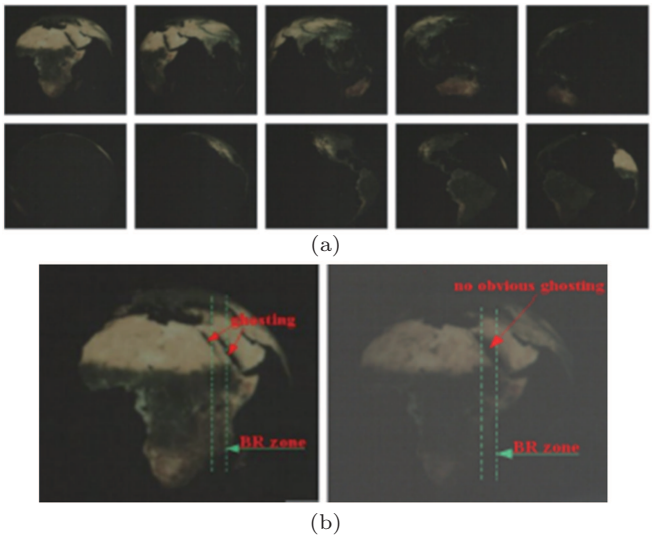


Fig. 2. (color online) (a) Captured color images by an angular spacing of 36° along the preferred observing path when the display system works. (b) The same transitional stereo image captured from the above prototype system and the verification experiment. For comparison, the two images are zoomed into the same size here.[3]

2.2. Flexible OLED displays

Recently, a large number of components and support technologies for flexible OLED displays have been developed, which have accelerated the development of flexible displays from concept to reality.[4] Compared with the OLED devices based on glass substrates, the flexible OLEDs based on film substrates have the main disadvantages of poor efficiency and short lifetime. Flexible OLEDs have a short lifetime because of the increased penetration of oxygen and evaporation of organic layers from OLED devices through a flexible polymer film substrate. Using polyethylene telephthalate (PEN) film. Cho *et al.* achieved a flexible substrate for OLEDs. The AlN_x/UVR/AlN_x type gas barrier layers were formed on top of the PEN film, which is followed by the fabrication of OLED panels. After the deposition of Al cathode, the upper part of the flexible OLED panel was laminated the same PEN film with the aid of the optical clear adhesive (OCA) of the gasket. The completed flexible OLEDs were examined through mechanical bending and lifetime tests for comparison to the rigid OLEDs based on glass substrates.

A diamond pixel structured OLED pentile display panel and selective operations were used in an auto-stereoscopic 3D display in both landscape and portrait modes, which are composed by using a detachable parallax barrier film.[5] Figure 3 shows the black and white images for the left and right eyes. Based on the view which shows that ther are no differences between the landscape and portrait modes, each point of the stereo image can be seen to be well separated. Figure 4 shows the images in two different views, and each image is well separated.

As mentioned previously, flexible OLEDs use a completely different method to manufacture liquid crystals.



Fig. 3. (color online) White and black images for each eye at the optimal viewing distance: (a) and (b) landscape mode, the first view and the second view, (c) and (d) portrait mode, the first view and the second view.[5]

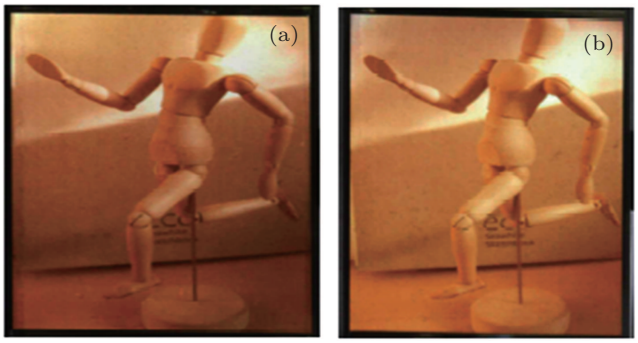


Fig. 4. (color online) Experimental results: left-eye view (a) and right-eye view (b).[5]

Flexible OLEDs can realize a flexible, transparent, ultra-thin LCD display, which is difficult to achieve for common LCDs.[6]

2.3. QLED displays

Quantum dot light-emitting diodes (QLEDs) are a novel technique that exists between liquid crystals and OLEDs. The luminescent efficiency of QLEDs is 30%–45% higher than that of OLEDs, while the energy consumption of QLEDs is 2 times less than that of OLEDs. The key technique of QLEDs is a quantum dot[7] consisting of zinc, cadmium, selenium, sulfur atoms, and so on. The scientists in Bell Laboratories did much research on these displays in 1983. According to the industry's internal information, by 2020 the application ratio of QLEDs into smart phones, tablet computers, and LCD televisions will rapidly increase to 26%, 15%, and 9%, respectively.[8]

A series of synthesized N-heterocyclic quinoxalines were applied as hole transport layers in QLEDs.[9] The resulting N-heteroacene polymer based QLED was superior to the poly(9-vinylcarbazole) based QLED. The result is shown in Fig. 5. This study presents some of the tactics that have been used to design novel N-rich molecules for the fabrication of QLEDs with improved performance.

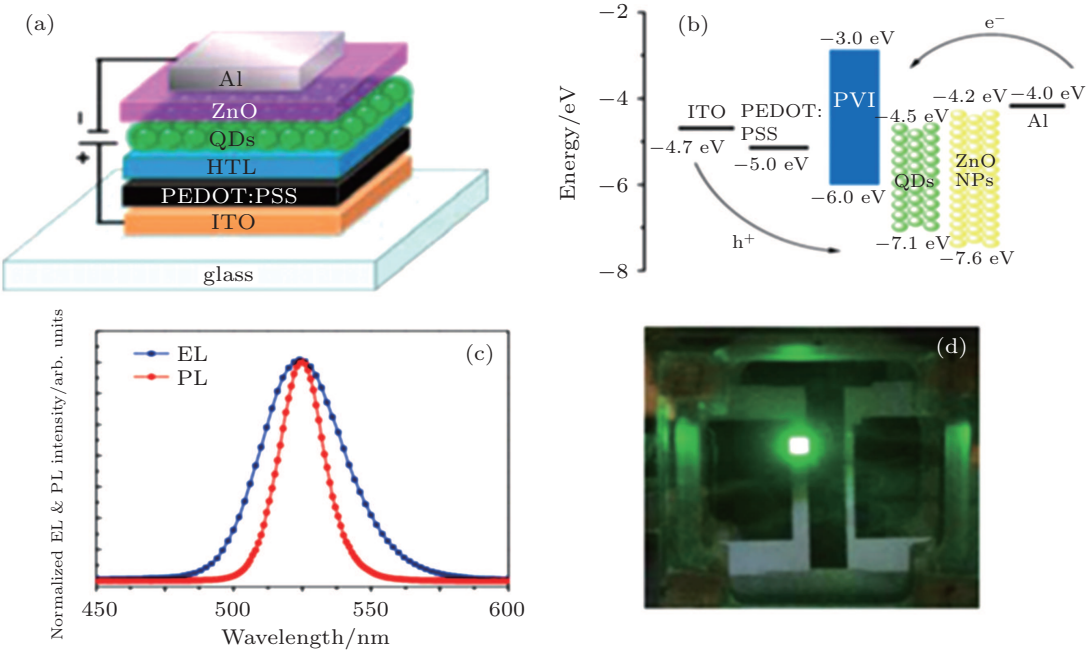


Fig. 5. (color online) (a) Schematic diagram of a layered polymer based QLED; (b) energy diagram of the device studied; (c) electroluminescence and photoluminescence spectra of the device; (d) photographic image showing highly bright electroluminescence emission from the QLED using PVI (VI) as an HTL at an applied voltage of 5 V.[9]

2.4. AMOLED displays

A high-performance, low-cost a-IGZO was used to demonstrate a 5-inch flexible AMOLED display on the PEN substrate,[10] as is shown in Fig. 6. With the thin thickness of the AMOLED panel, a 5-inch flexible monochrome bottom emission AMOLED display is shown on a PEN substrate. When the radius of curvature about the panel is up to 20 mm, it can also display the image in a clear way, and the image can be seen without significant degradation of luminance and without obvious defects.

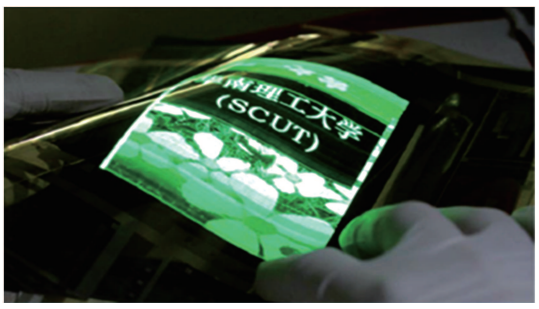


Fig. 6. (color online) The photograph of the flexible green AMOLED display driven by α-IGZO TFT.[10]

2.5. E-paper displays

Like traditional paper, E-paper is lightweight and easy to carry. By using electronic screens, duplicate information can be written and preserved for a long time without requiring a plug. E-paper can also store a large amount of information. Moreover, it is durable and does not waste forest resources. Given the modern emphasis on energy saving, it is quite an attractive product.

Additionally, because the principles of E-paper are that is formed of black and white beads in two transparent glass or plastic substrate with a poured charge, when the board is powered, different colors of beads will be tempted to float or sink, which forms a picture. Compared with TFT-LCDs, it is not

necessary to install filters or other parts. E-paper can reflect ambient light as well as having the ability of the electrophoresis principle. There is no need to charge the E-paper, even if updating the screen. The cost of power consumption is lower than that of TFT-LCDs.

QR-LPD technology was used to develop a thin, light flexible E-paper display.[11] Because of its simple display structure (no TFT) and robust image holding property, QR-LPD is suitable for flexible displays and can achieve a "real paper like" flexible E-paper. The fabrication of electronic ink displays on a bendable active-matrix-array sheet has been achieved by Chen *et al.*[12] Figure 7(a) shows the working principle of an electronic ink screen. The direction of the applied voltage controls the relative movement of negatively charged black and positively charged white particles. Figure 7(b) shows the view of letters in the bend of an E-paper display, which has a resolution of 96 d.p.i., a white-state reflectance of 43%, and a contrast ratio of 8.5:1. Such an ultrathin, flexible substrate can greatly extend the applications of display technology.

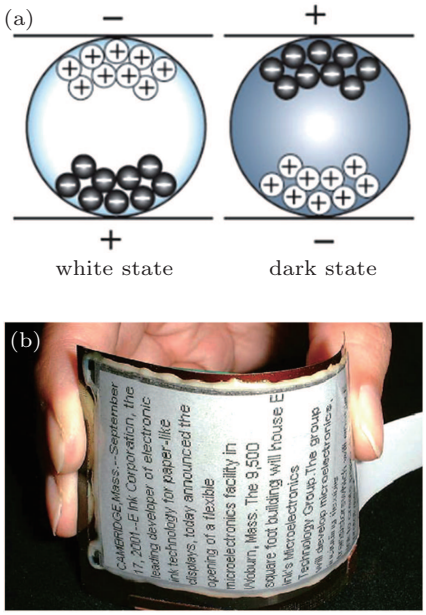


Fig. 7. (color online) Flexible active-matrix electronic-ink displays. (a) The working principle of an electronic ink screen. (b) A view of the letters in the bend of an E-paper display.[12]

2.6. Curved displays

Curved display technology has been recognized and accepted by many people, it has been also applied to almost all kinds of display devices, including televisions, monitors, and mobile phones. Increasing attention has been paid to relative technologies of curved televisions. Hsiao *et al.* developed theories that are different between flat televisions and curved televisions.[13] Simultaneously, they developed the world's largest 110-inch curved television, which is more lightweight and thinner than ever before. As shown in Fig. 8, for large flat-panel televisions the distance between eyeball and edge of the screen goes beyond the distance between the eye and the middle of the screen. While for curved televisions the distance difference between eyeballs and any position of the screen can be minimized.

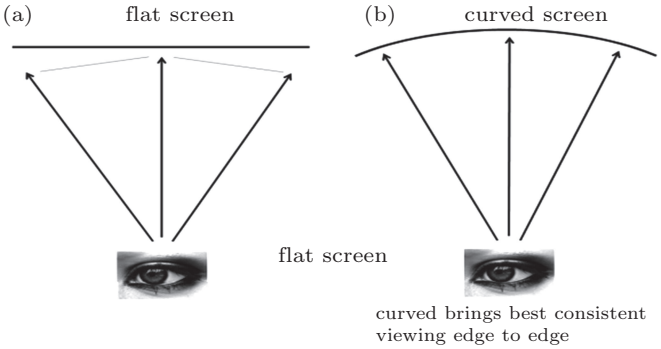


Fig. 8. Comparison of visual effects between flat televisions (a) and curved televisions (b).[13]

The world's first curved television was developed by LG in 2013 and was named EG9900. As shown in Fig. 9, a new anti-glare filter is creatively applied in the 4 K curved panels of the LG OLED television, which is powered by a new ten-core processor that runs LG's WebOS 2.0. This television achieves the application goal of turning a flat mode into a bending mode.[14]



Fig. 9. (color online) 77″ bendable OLED television: EG9900.[14]

3. 3D displays

In theory 3D displays should include intensity and phase information, and 2D displays should just contain intensity information, which means that the former contains the depth information of an object. Therefore, an observer can obtain a depth cue from 3D images. Our world is a 3D space and humans are used to watching 3D scenes or objects. In future, 3D displays may become the main display technique. To display excellent 3D images, 3D systems should produce an adequate number of light rays or pixels in a frame. The main difference between 2D and 3D displays is the direction-selective light emission property. This review explains the fundamental principles of 3D displays, providing means to realize different technologies. Here, we present stereoscopic 3D displays, light

field 3D displays, volumetric 3D displays, and holographic 3D displays. Among these, holographic displays are considered to be the most promising technique to provide real objects or scenes because of their ability to reconstruct both the intensity and the wave front information, allowing observers to perceive the light as it would be scattered by the real object itself, with no need for special eyewear.

3.1. Stereoscopic 3D displays

Stereoscopic 3D displays, a kind of 3D displays based on the principle of binocular parallax,[15] can be divided into two types: glass-based stereoscopic displays and naked-eye stereoscopic displays (see Fig. 10). The principle of the lenticular lense display is to set lenticular lenses with LCD screens. Each image pixel is divided into sub-pixels. These sub-pixels are projected to different directions in the observers' left and right eyes, respectively, therefore the observers have a 3D sense. Aflaki *et al.*[16] designed two sets of experiments using subjective quality assessment to search fine methods to code the asymmetric stereoscopic video. They concluded that the mixed-resolution stereoscopic video, with down sampling ratio 1/2 along both coordinate axes, has a similar result with the full-resolution video. Therefore, the mixed-resolution stereoscopic videos could be more useful and valuable due to their lower processing complexity. Shah *et al.* proposed the further reduced resolution depth coding method for stereoscopic 3D video coding systems.[17] Their method is able to deliver good quality stereoscopic 3D videos on both stereoscopic and autostereoscopic displays at much lower bit rates. Stereoscopic 3D displays involve less information and can be compatible with current display information systems.[18] However, there are still some problems restricting the realization of comfortable displays.

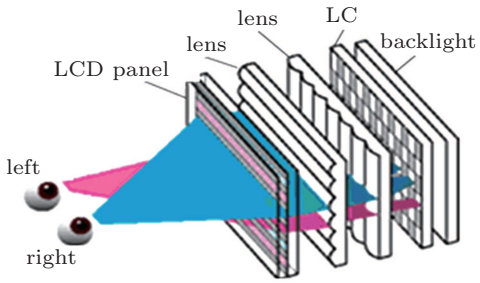


Fig. 10. (color online) Auto-stereoscopic display or naked-eye stereoscopic display.[18]

3.2. Light field 3D displays

The light field 3D display technique is a safer technique than the other 360 degree visual scanning 3D displays, allowing observers to touch 3D scenes. It also offers a new possibility for interaction. Xia *et al.* created a light field of 3D scenes, just like a real 3D object floating in the air above the spinning screen, by combining a high-rate color projector and a scanning screen.[19] Moreover, the system that they developed showed potential for the next generation 3D presences or 3D televisions by obtaining an animation of 3D scenes. Inoue *et al.* proposed a table screen 360-degree display system,[20] which localized the viewing zone, with an increased screen size that was scanned circularly around the table screen. They achieved 360-degree 3D images. As shown in Fig. 11, different angle 3D images can be simultaneously observed by different viewers in corresponding directions around the table. Song *et al.*[21] developed a new type of selective-diffusing screen using two field lenses and one lenticular lens. They obtained dynamic light field imaging by full color and high density with multiple low-speed projectors. In Fig. 12, the observers can see a virtual teapot model pouring water into a real wineglass in the photos and they can find the correct spatial relation between the two.

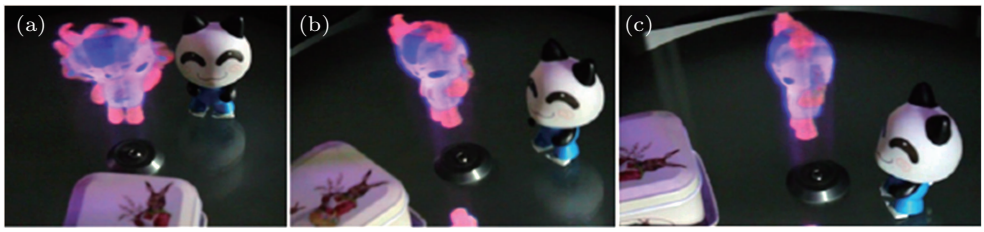


Fig. 11. (color online) Photos taken from different directions of the floating 3D scene. (a) 0°; (b) 40°; (c) 80°.[19]

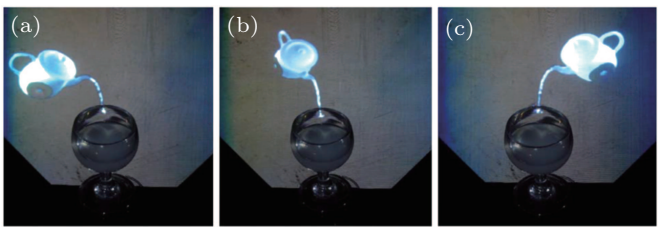


Fig. 12. (color online) Photographs of a displayed object with a real wineglass in reconstructed floating display in different directions.[21]

3.3. Volumetric 3D displays

Many methods have been reported to achieve stereoscopic 3D displays.[22,23] A solid volumetric display was achieved by adopting a two-frequency, two-step up conversion technique.[24] Several kinds of sweep volumetric displays were developed to achieve a large size image. The image planes were linearly swept by using multiple liquid crystal devices with a high-speed projector or an active optical element with a high-speed CRT monitor, as illustrated in Fig. 13.

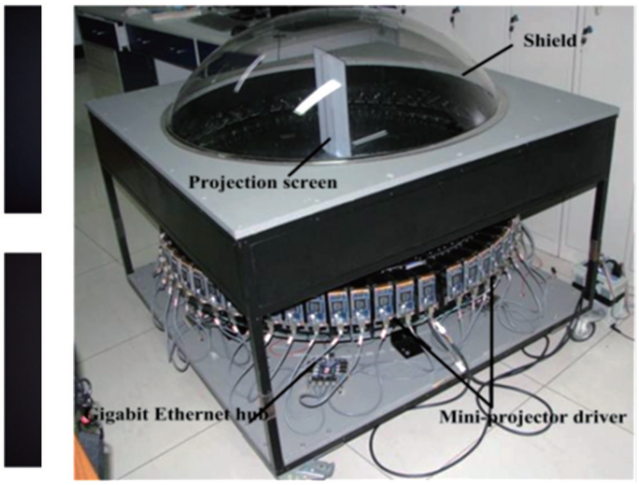


Fig. 13. (color online) Parts of the synchronous illumination optical subsystem. (a) and (b) 3D images processed using pseudo colorization formed with the volumetric display, and (c) and (d) 3D images formed with the volumetric display. The images have been taken from different view positions.[24]

3.4. Holographic 3D displays

Holography is considered to be a good candidate for true 3D displays.[25] Digital holographic 3D displays depend on electro–optical spatial light modulators, which have limitation of display size and pixel size. Therefore, achieving a large size and large view angle 3D displays using digital holography is still under research. Recently, optical holography has attracted much attention, particularly in holographic materials. Here, we present some results of the development of dynamic optical holographic displays.

Holographic materials have been a popular topic in the research of holographic 3D video displays. Many definite improvements in this topic have been presented. Blanche *et al.* reported a near real-time dynamic holographic display using a new photorefractive polymer with a refreshing time of 2s,[26] in which full-parallax 3D reconstructed images could be perceived, as shown in Fig. 14. Ishii *et al.* developed a photochromic polymer that yielded a refresh speed close to the time resolution of human eyes,[27] as shown in Fig. 15.

Shrestha *et al.* reported a holographic display based on OASLM which could modulate wave front of a read-out beam with loading a hologram based on the intensity distribution of a recording beam[28] as shown in Fig. 16. Gao *et al.* obtained a super-fast holographic display with holographic response time below an order of a microsecond in doped liquid crystals, as shown in Fig. 17. Using doped liquid crystals could realize holographic video displays perfectly,[29–38] as shown in Fig. 18. Optical holographic displays based on holographic materials need no pixilation and the holographic screen is usually easy to fabricate. Large scale, large view angle, high definition and color holographic 3D displays can be realized based on this in the near future. Therefore, this display is thought to have tremendous application potentials in true 3D display areas, such as holographic 3D televisions, projectors, monitors, and phones.

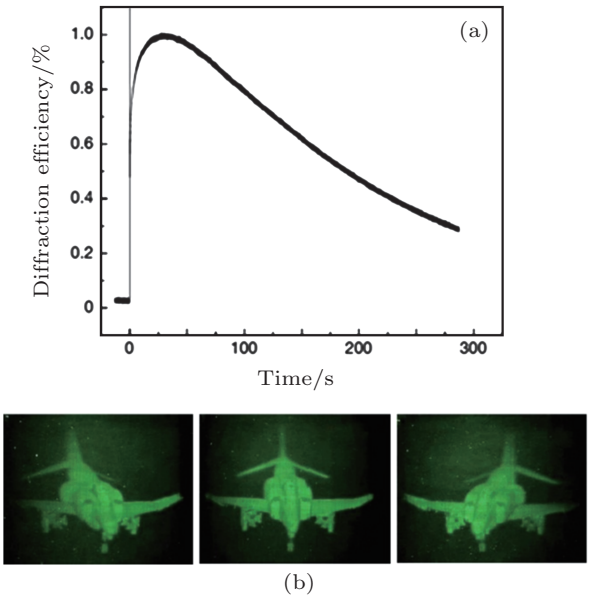


Fig. 14. (color online) (a) An example of diffraction efficiency dynamics under single nanosecond pulse writing. (b) Images from a hologram observed by a camera when pointed to the left, straight ahead, and right, respectively.[26]

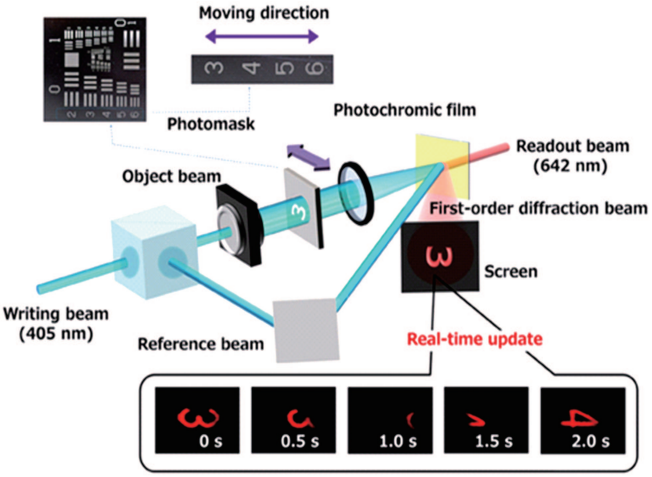


Fig. 15. (color online) Optical setup for real-time holographic recording and the real-time display of 2D holographic images.[27]

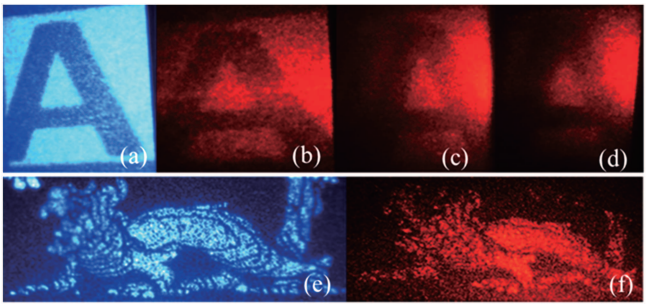


Fig. 16. (color online) (a) Image produced by a 2 mm pixel size hologram on glass as illuminated by a 405 nm laser; (b) replay of 1:1 image reproduced by the OASLM; (c) replay of de-magnified image (1:0.42) with a pixel size of 0.84 mm reproduced by the OASLM; (d) replay of de-magnified image (1:0.36) with a pixel size of 0.72 mm reproduced by the OASLM; (e) image of a dragon generated by a 2 mm pixel size hologram on glass as illuminated by a 405 nm laser; (f) replay of 1:1 image reproduced by the OASLM. OASLM, optically addressed spatial light modulator.[28]

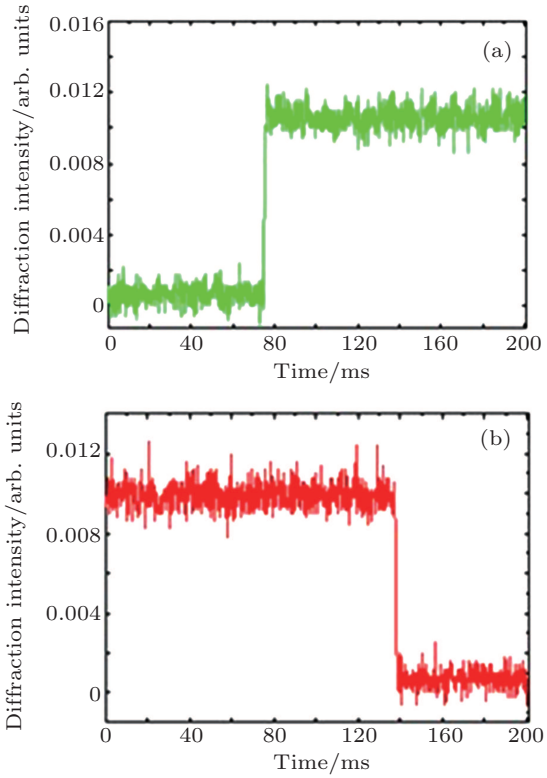


Fig. 17. (color online) (a) and (b) Hologram formation and self-erasure processes in super-fast liquid crystal film, respectively.[34]

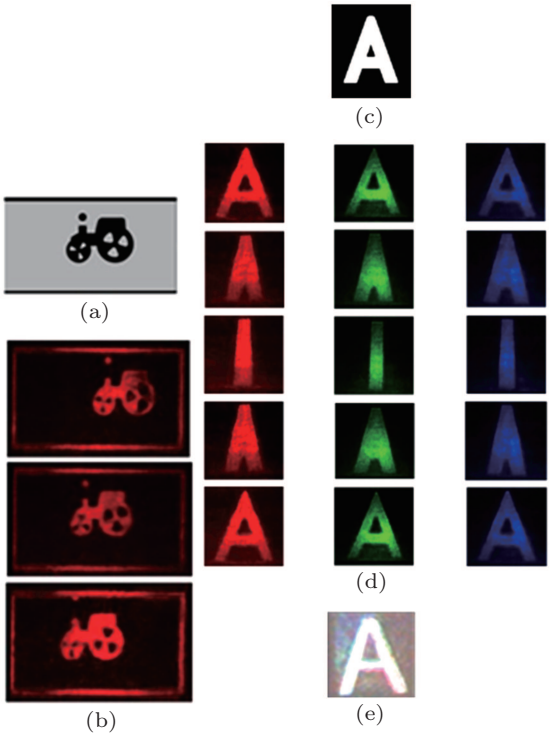


Fig. 18. (color online) (a) An incident image on the computer screen, (b) snapshots from a holographic video, (c) an incident image on the computer screen, (d) snapshots from a R/G/B holographic video displaying a moving image, and (e) snapshots from color holographic video.[36,37]

4. Conclusion

Display technologies are of significant scientific and practical interest. They are important for modern industry and they can truly influence our daily lives. In this review we have present the latest developments of typical 2D and 3D display technologies. Basic introductions of OLEDs, flexible OLEDs, QLEDs, AMOLEDs, E-paper, curved displays, stereoscopic 3D displays, volumetric 3D displays, light field 3D displays, and holographic 3D displays were given. It was pointed out that in the near future 2D displays will be larger, lighter, thinner, more colorful, lower cost, more flexible and they will have lower-power consumption. Moreover, 3D displays, which still need more improvement to become comfortable and true, will meet the needs for human observation of real objects or scenes and they are expected to be the ultimate display that will be used in the future.

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