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REVIEW ARTICLE

Challenges of spatial 3D display techniques to optoelectronics

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Abstract In the development of flat panel display techniques and digital image processing techniques, the data processing ability progresses so greatly, and it makes the three-dimensional display (3D display) possible. Recently, the 3D display technique develops so fast, it changes totally the traditional 3D viewing effect and makes 3D display become a possible technique in our daily life. In this paper, the different 3D techniques will be reviewed, and much more focus on the real spatial 3D display techniques, especially the challenges of the high-quality spatial 3D display to the optoelectronics will be analyzed, which will be the sources for the future ideal 3D display technique.

Keywords spatial display, three-dimensional display (3D display), holographic display, optoelectronics

1 Introduction

Three-dimensional display (3D display) is an ideal display technique for human being. There are so many techniques to show 3D effect in different states, based on the human visual parallax, motion parallax, ocular convergence, accommodation effect, and other psychological hints. We can, currently, classify the 3D display into four kinds of different techniques according to different principles: stereographic display, holographic display, volumetric display, and integrated imaging display.

Stereographic display based on the parallax effect has a very long history [1], and lots of techniques had been developed to present the parallax effect through special glasses, for example, polarization glass, complementary color glass, time sequential shutter glass, etc. Autostereographic technique, first applied by Ives of U.S. in 1903 [2], is a technique that can show that the 3D image does not need to use glass or the other impediments to observe the 3D image. Historically, the autostereograme technique is quite difficult because of its complicated and high precision barrier structure and is only used in the static image display. Due to the development of high-density flat panel display techniques, the auto-stereographic technique progresses greatly in the last decades, the observers can see the 3D images without any glass and can move freely. High-density viewing angle autostereographic technique has been developed and makes this technique the best combination technique with the conventional flat panel display [3].

Holographic 3D display is the ideal display technique for real 3D display, because holographic display cannot only show the light intensity distribution but also the phase information of the 3D image [4]. Owning to the diffraction effect and the limitation of high density, small pixel, and high-speed spatial light modulator, currently, holographic display has a difficulty in showing a big and colored 3D dynamic image, even though it can display a perfectly still 3D image. However, there are remarkable works have been done to improve it [5].

Volumetric 3D display is a real spatial display system [6], in principle. The high-speed spatial addressing technique is used to represent the 3D image in space, which makes it a real spacing display technique. Volumetric display can present no accommodation 3D image that can offer all the observers to see the real spacing 3D image around the image [7].

Integrated imaging is using a two-dimensional (2D) lens arrays to project different view images in font of observers' eyes [8]. It is also one of the potential 3D techniques, which can provide full color, full parallax, and continuous viewing point image. There are different king of integrated 3D imaging techniques, some of them are only deliver horizontal parallax, and some of them can provide both horizontal and vertical parallax.

In this paper, we are going to review the recent remarkable progresses in the field of 3D display

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techniques. Since we will be focusing on the free state 3D display, it means that the observer can see the 3D scene without any glass or the other special device. Such kind of free state 3D display greatly improves the application possibility of 3D display in our daily real life. The new progress of our research works in the 360° full horizontal parallax display techniques, and the high-density light emitting diode (LED) panel based volumetric display techniques will be also presented in the paper.

2 Autostereoscopic 3D display

With the new development of large flat panel display technique, the high-density liquid crystal display (LCD) and plasma display panel (PDP) are available. In the last decade, the autostereoscopic displays based on the combination of flat panel display and lenticulur sheet and the parallax barrier technique have been greatly developed and progressed [3]. Although the two techniques are different in realization components, they are based on the same parallax principle.

The new development for the autostereoscopic display based on a high-density LCD panel cooperates with lenticular screens by using the lenticular screen to direct light from columns of the pixels on LCD into viewing zones across the viewing field. The liquid crystal layer lies in the focal plane of the lenses screen, and the lens pitch is slightly less than the horizontal pitch of the pixels in order to place the viewing zones at the chosen optimum distance from the screen. Early multiview displays with four zones are described in Ref. [9], and NHK developed a system in 1999 [10]. In making the 3D view smoother, the more viewing zones is necessary, but as the viewing zone increases, the resolution of the image decreases, because of the limit of the horizontal resolution of the LCD panel. Most important progress will be that the latest embodiment of the Philips display presents nine images across the viewing field [11]. Philips proposed a slanted lenticular screen that has a pitch that is 1.5 times the pixel pitch of the LCD and is slanted at an angle of $\tan^{-1}(1/6)$. The slanted lenticular screen makes the resolution of the 3D display reduce by a factor of three in both the horizontal and vertical directions for a nine view system, instead of the normal reduction of nine times in the resolution of the common vertical lenticular screen. Moreover, with the help of a switchable liquid crystal (LC) barrier screen, it is possible to construct a 2D to 3D switchable display system [12]. This is achieved with the use of an active system where a liquid crystal material is in contact with the lenses.

The other similar displays are marketed by ultralarge screen autostereographics, these system use serious projectors [13] and also large screen LED display with a parallax barrier (bar array) . Because of the difficulty of having a large size high precision lenticular screen, the use of large size parallax barrier is more adaptable for a large-screen projection of 3D display application, even though it is not as perfect as the lenticular screen system in the 3D display performance.

3 Volumetric display

Volumetric display is a technique where each spatial image point is lightened in a given volume, and it reproduces the spatial properties (voxel) of the image within a defined volume of space. As volumetric displays create an image in which each point of light has a real point of origin in space, the images may be observed from a wide range of viewpoints and angles, so that it can provide not only parallax effect in both direction but also a sense of ocular accommodation. Volumetric displays can be classified into two basic types: 3D image is formed by projection the section image on a moving screen, or the voxels of 3D image are lightened spatially on static regions. A large variety of volumetric display techniques have been proposed [7,14], but few successful large-scale devices are available and have been developed. FELIX 3D display was a typical volumetric display system. As shown in Fig. 1, red/green/blue (RGB) lasers as light sources were used to scan a section image of a 3D scene and projected on a rotational helical screen [15].

The other volumetric display system based on the rotating helical screen was using a high frame speed projector to project the section image on the screen. Normally, the high-speed digital micromirror device (DMD) projector plays important role in the 3D display, because the DMD of TI can display a two-state image in 32000 frames per second [16]. Favalora et al. [17] have developed a system with a 100 million voxel resolution sufficient for video display. This is obtained by presenting 200 radically disposed slices consisting of 768×768 pixel images. These are provided from a modified projector that can supply hundreds of colors. Images are projected on to a disc that rotates at 900 rpm, and frames are updated at 30 Hz. This is being developed by Actuality Systems under the trade name Perspecta™ [18]. As shown in Fig. 2, it creates an image within a desktop 20-inch dome. It has limited immersion, no entry into volume, and is only suitable for small objects. However, it be made interactive by external cameras, which track the user's hands on the dome.

We have developed the spatial volumetric display system based on the rotation of high-density color LED display panel [19]. The 2D color LED panel has a resolution of 320×240 pixels with a size of 800 mm× 650 mm (the interval distance between two RGB LED pixels is 2.5 mm), so that the rotation of this LED panel creates a cylindrical volume of about a diameter of 800 mm with a high of 650 mm, which is the biggest volumetric display system in the world. Because the LEDs have been driven at very high speed (about 10 ns), this permits the

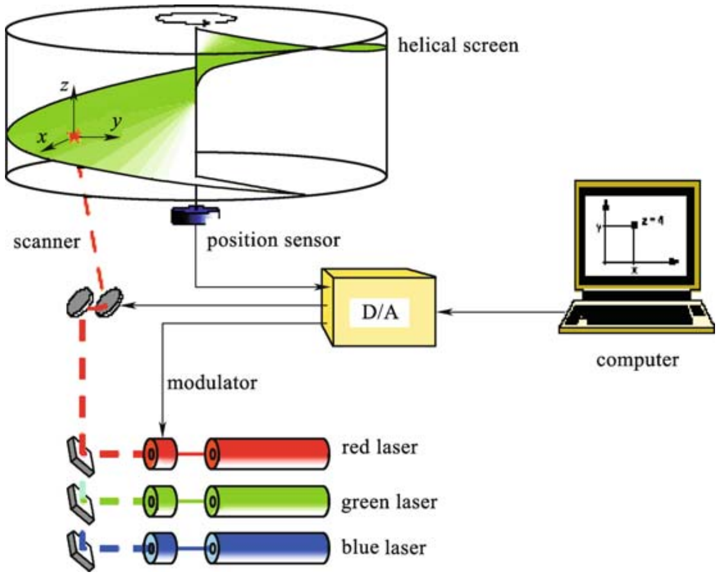

Fig. 1 Schematic of FELIX 3D display

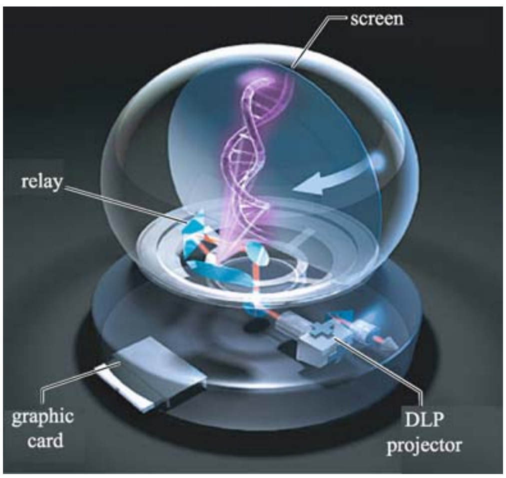

Fig. 2 Schematic of Perspecta^{TM} 3D system (DLP: digital light procession)

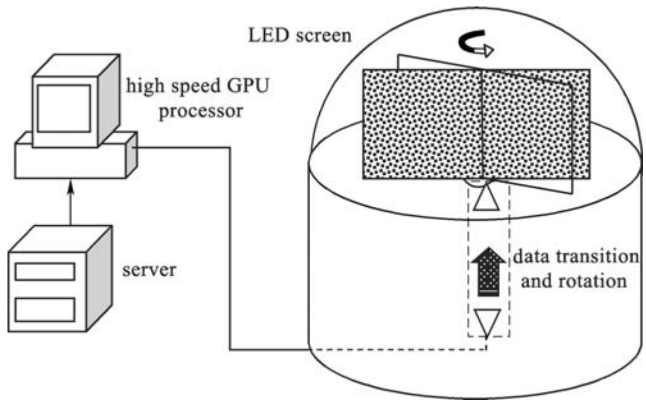

Fig. 3 Volumetric display system based on LED panel

display system to display 512 section images in one circle turn and 15 turns per second. The high-speed graphic processing unit (GPU) is used here to create 3D volumetric data, and we used a high-speed optical fiber rotary joint to connect data from a computer to the display panel, and about 3.5 Gbit/s data rate has been transmitted. In our system, there are 12.6 million voxels that can be displayed in the space, and also the volumetric display system based on LED is presented, as shown in Fig. 3. The pulse wide modulation (PWM) method is used to create a gray scale of the image, and the 3D scenes were presented, as shown in Fig. 4. This 3D volumetric display system can present a 3D scene in space, which can be viewed in 360° horizontal direction and 180° longitude direction. The adventure of the volumetric display is that it creates a spatial scene with correct full parallax image no matter how the observers view the image on any position. It is only one technique that can offer real spatial relation in 3D space, and it can adapt in the applications where the requirement of spatial relation in the 3D scene is very high or in some biological organ display.

It is important that the 3D data creation to display volumetric scene in the space is also a key factor that needs to be dealt with. There exists digitalization error in the transformation of a computer 3D digital model into the display space voxelization model [20]. The minimization of this error is important to present no distortion in the 3D scene in a volumetric display system.

However, their most important drawback of the volumetric 3D display with regards to TV displays is that they invariably suffer from image transparency where parts of an image that are normally nonocculted are seen through the foreground object. Another difficulty is the inability to

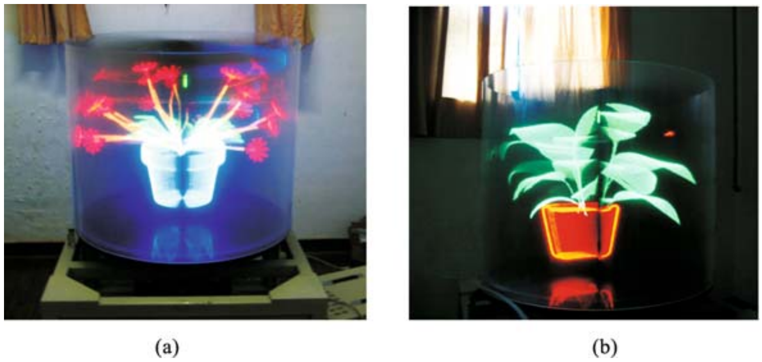

Fig. 4 3D volumetric image reproduced by LED-based volumetric display system

display surfaces due to the LED panel with a non-Lambertian intensity distribution and also the light blocking effect of neighbor LED, which will cause the existing of a black line in the center in case of displaying an object in the area near the center rotation axe. These posed a lot of challenges to an optical system on how to create the 3D system with controllable direction light and to present the normal osculation effect.

4 Integrated 3D image display

The integral 3D display method was first proposed by Lippmann in 1908 [21]. It is now considered to be one of the ideal 3D systems because it would enable observers to see a 3D image as though it were a real object. The advantage of this method is that it can produce 3D images using natural light (incoherent light). Recently, several attempts have been made to obtain higher quality and moving 3D images [22–25].

The principle of the basic integral method is using a single lens array combining with display array image in the display stages. To produce an integral image, a lens array composed of numerous convex elemental lenses is positioned immediately in front of the pickup plate. The integral image is composed of numerous small elemental images that are captured and recorded on the plate. The number of images corresponds to the number of elemental lenses. The integral image is supplied to a transparent display plate. The display plate is placed where the pickup plate has been and is irradiated from behind by an incoherent light. The light beams passing through the display plate and the lens array retrace the original routes and then converge at the point where the object had been, forming an autostereoscopic image. Because of 2D lens array, this kind of integrated 3D display can offer both vertical and horizontal parallax, which is also called a full parallax display.

The drawback is that it needs a very high-density flat panel display system, so one proposes to use multi-projectors system to form an ultrahigh definition 2D display array to meet the needs of a high-performance integrated display [26].

5 Full horizontal parallax display

For the normal case, one can see a perfect 3D scene just with a full horizontal parallax, and the vertical parallax is not so critical if one looks at the display system far enough. If a display system just offers horizontal parallax, it will decrease lot of display data and make the system more practical with current technique. The full horizontal parallax display was first principally proposed by Cossairt [27], and then, Jones [28] realized a prototype system with TI high-speed projector, but they just showed a prototype of black and white system. To form a full horizontal parallax 360° color 3D display system, we have designed and set up a color 3D display system that would use an ultrahigh frame rate LED color projector, combining with a direction selective reflective-diffusive mirror to form a 360° large number of view spatial 3D display system. This system based on horizontal multiviews parallax principle uses a rotation diffusion direction selective mirror to scan each parallax view for each horizontal surrounding viewers; at the same time, the reflecting selective mirror will diffuse the light in the vertical direction and make surrounding observers of different views see the parallax image and create 3D effect in all the horizontal 360° observation.

The display system is shown in Fig. 5, the colored LED projector can project. The spatial light modulator is TI DMD Discovery 1100, which can project 8000 single-bit images per second with the resolution of 1024×768. The diffusing mirror with tilt angle of 45° is fixed on the rotation stage with a size of 160 mm×226 mm. The rotation speed of the diffusing mirror is 1444 r/min. When we lighten the red LED, 276 red images are projected in one turn (360°). In the same way, 276 green images and 276 blue images are projected in each turn successively. The refresh rate of the color 3D object is 8 Hz, which is one third of the rotation diffusion mirror

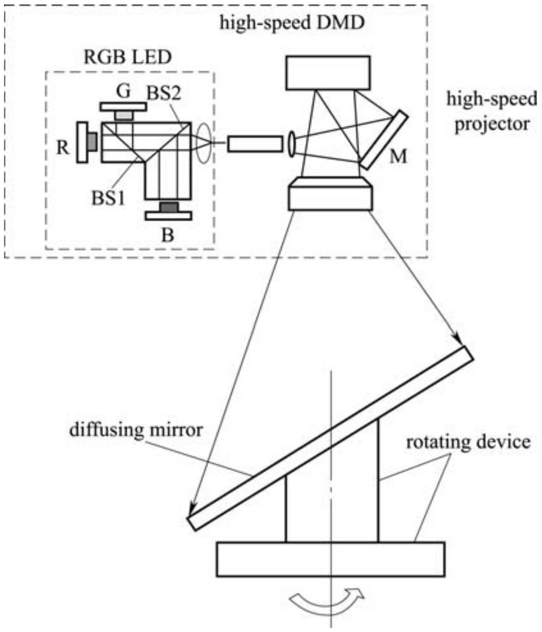

Fig. 5 Schematic of 360° full horizontal parallax display system

frequency. In our experiment, there are 276 views in one circle (360°), and the high-speed projector projects 6624 images per second. The picture time between the start of two consecutive images is 151 μs [29].

This system can give us a vivid colorful 3D scene display and the observers look at a 3D scene show all around the display system with a comfortable native parallax effect. The other advantage of this display system is that it can offer an occultation display and present the 3D scene as the people see the natural object.

Due to the development of high-speed spatial light modulator (SLM), for example, the DMD can modulate the light image at more than 32000 frames per second. This technique can also be possible to show the 3D video dynamic scene. Therefore, the full horizontal parallax display is a very good candidate for the current 3D spatial display technique. It can really show the 3D object as it is in its natural form, can be used in an antique show in some museum, etc., and will be very good display system in the current and future virtual reality applications. This display may be entering the market in the near future. Figure 6 shows a 360° view of Beijing 2008 Olympic Mascot "Ying Ying" by our full parallax display system. One can view the different side of the mascot from different viewing direction, and the image is vivid floating in the space.

6 Holographic display

Holography is an ideal real 3D display technology and was well established for statistic image display. However, the dynamic holograms or holographic movies are quite difficult and attracted lots of research and development in the last decades [30–37]. Here, the holographic display system is just limited on the electronic holographic system. Thus, the advantages of a holographic display are the recording of the true 3D wavefront of a scene and the retention of motion parallax. However, a full parallax, large area, interactive, moving, and color holographic display, which is thought by many to be the ultimate goal of 3D TV, requires incremental and parallel development in many essential areas of technology for electro-holography, especially for the new optoelectric materials.

The electro-holographic display can now be classified into two techniques: one is based on the development of high performance spatial light modulator (SLM), and the other is trying to develop new video frame rewritable high-resolution emulsions for recording and reconstruction [14]. No matter which kind of technique, for a high-performance holographic display, the computer generated holographic technique is critical in image forming [38].

There are currently three kinds of SLM that can be used in the dynamic electro-holographic display: LCD (small-sized high-density LCD), DMD, and liquid crystal on silicon (LCOS); at the same time, MIT holovideo system had proposed an electro-holographic system based on acoustic optic modulator (AOM) together with one-dimensional (1D) scanning mirror, which entails omitting vertical parallax [31].

All these current SLMs have limit on the resolution, pixel density, and modulation rate. Normal LCD SLM is a transparent device; it can offer phase only modulation and intensity modulation and also both mix modulation. The problem is that as the resolution increase, the device transmittance decrease. Because LCD is using a thin film transistor (TFT) as pixel driver, the pixel density cannot be very high, and the fill factor (means the ratio between the LC area to the pixel area) is as low as about 0.7, so LCD is not ideal for electro-holography display. The most high-resolution SLM current is LCOS; it uses complementary metal oxide semiconductor (CMOS) array as the LC driver, so that we can get LCOS SLM of resolution higher than 4000×2000, and with a pixel size of 6 μm×6 μm (LCOS is the SLM of smallest pixel, and it can decrease to 4 μm×4 μm for one pixel). Moreover, the LCOS technology is the high fill factor of up to 93%, so LCOS is much more adaptable for electro-holography display. One important thing to do is that one has to develop a mosaic type multi-LCOS high-resolution holographic display system or to develop an ultrahigh resolution LCOS SLM.

DMD is a kind of microelectromechanical system (MEMS) device that forms another group of systems for spatial light modulation. DMDs consist of an array of tiltable micromirrors (±12°) mounted on hinges over a CMOS static random access memory (SRAM) chip [16]. It is currently one of the highest resolution SLM, as high as 4000×2000 is available, with pixel pitches less than 12 mm. The mirrors can be turned for±12°, addressable via binary data sent to the SRAM, which produces the individual mirrors to tilt either ON or OFF at high speed

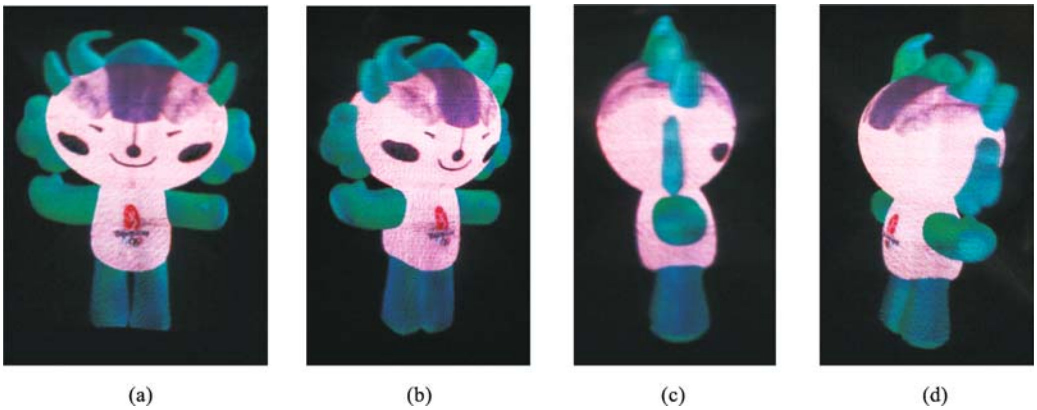

Fig. 6 360° view of Beijing 2008 Olympic Mascot "Ying Ying" by full parallax display system

(frame rate > 32000 Hz). DMDs have been utilized in an array to enable holographic video display [39]. The advantage of DMDs over LC type SLMs is that the incident light is reflected with high efficiency, polarization insensible, and high speed, while the liquid crystal type SLM's systems always suffered from the loss of light energy of polarization, a certain amount of light absorption, and also, the problem caused by the phase changing after modulation.

The drawback of current SLMs compared to conventional emulsion-holograms is the lower space-bandwidth product (SBP) of these devices. SBP is defined as the product of the device dimension and the pixel frequency. With a resolution of 3000 line-pair/mm and a size of 20 cm, a conventional hologram has an SBP in the region of 1000, whereas current SLMs just approach 100. The reduction of pixel size in combination with an increasing number of pixels leads to a decreasing speckle size in the reconstructed image and is the key factor to promote the progress of electro-holographic display.

7 Conclusions

It is clear that to get high-performance 3D display, especially for vivid 3D spatial display, there are still lots of challenges for different of display technologies. As mentioned above, no display method is without its problems or limitations. The autostereographic display is a more mature display technique that can offer 3D effect only for certain watching region, and the limit of lenticular screen production techniques and the resolution of flat panel display are still a challenge for bigger number of views autostereographic image display. As for volumetric display, even though it is only one spatial display technique that can offer real full parallax 3D scene for all the direction, the nonoccultation effect makes it have a limited application. With the development of laser plasma air lighten effect, a new kind of nonrotational screen, no display medium techniques for volumetric display will be possible [40]. The integrated 3D display can offer both horizontal and longitude parallax 3D scene but demands again on the high-resolution lenticular screen and also on the high-density high-resolution display panel. It is a near-future true 3D display technique, with great potential to display the object with correct parallax and easily show high-quality color 3D scene. With the help of multi-mini-projectors system, the limit of resolution may be solved, so it is a very good 3D candidate technique without any moving part in the near future, and also, the technique takes lots of attention from current researchers. For the electro-holographic display, we are waiting for the high-resolution rewritable photorefractive thin film materials or the high-resolution and high-density SLM. The full horizontal parallax display can show us a vivid 3D scene in 360° horizontal direction and is a technique ready to go to product stage with the improvement of color performance and data transitions rate.

In a word, given the current state-of-the-art nonholographic displays, such as the full horizontal parallax display and volumetric or autostereographic display, are in a more advanced state of development, and it is felt that they are more likely to reach the market place in a shorter time.

It is not clear which particular technology will dominate future 3D displays. However, it is thought that it will be entering the stage of application driven the technology development. The progress of the optoelectronics, especially, the flat panel display, high-density SLM device, high-speed addressable luminescent effect and light direction controllable mirror (electro-optical effect) will great improve the display performance of 3D display system. The different techniques need different optoelectronic devices and techniques, which will be one of the motivations for the progress of optoelectronic technology.

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