# High resolution autostereoscopic displays with time-multiplexed directional backlight for multiple viewers

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# 1 Introduction

This chapter introduces the research field and relevant topics of 3D (stereoscopic) displays and is organized as follows: Section 1.1 discusses the background of 3D displays. Section 1.2 describes in detail the conventional research on 3D displays. Section 1.3 introduces a description of the recent problems of the 3D displays that are related to this study. Finally, Section 1.4 describes the outline of this study.

## 1.1 Background

Recently, 3D displays, also called stereoscopic displays, which allow for a sense of depth, have become popular mainly in movie theaters. Expectations for 3D displays with a high sense of realism are also rising. There are many situations where 3D displays are being used. The main application in the entertainment field includes 3D movies, 3D televisions, and game consoles. Doctors employ medical 3D displays to observe medical images of an organ and simulate a surgery to train surgeons. 3D displays are also used in automobiles to project information such as speeds or navigating arrows on a car's window shield.

3D displays provide a more realistic visual experience than 2D displays because the viewer can obtain additional depth information. However, we have been using 2D displays in most scenarios of our lives because the advantages of 3D displays are not obvious, considering the price viewers must pay, such as wearing a pair of goggles or enduring dizziness.

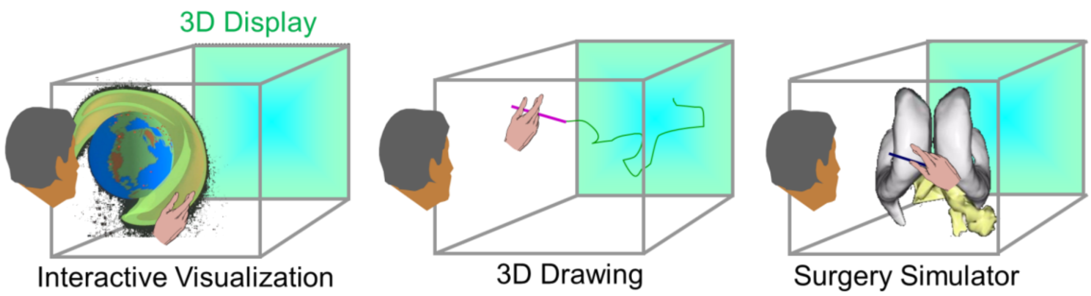


Figure 1.1.1. Interactive visualization systems.

However, Figure 1.1.1 shows that 3D displays are preferred in some circumstances, especially in the case of displays with direct manipulation. For example, when using an interactive display that allows a viewer to interact with the visual 3D contents, the viewer must perceive the depth information to match the positions of his or her hand and the virtual object. Direct manipulation operations are crucial for achieving various interactive systems, such as 3D drawing and surgery simulation. To ensure viewers' depth perception, interactive systems require 3D displays. Past surveys indicate that 3D displays are most helpful for depth-related spatial manipulation tasks [1][2][3].

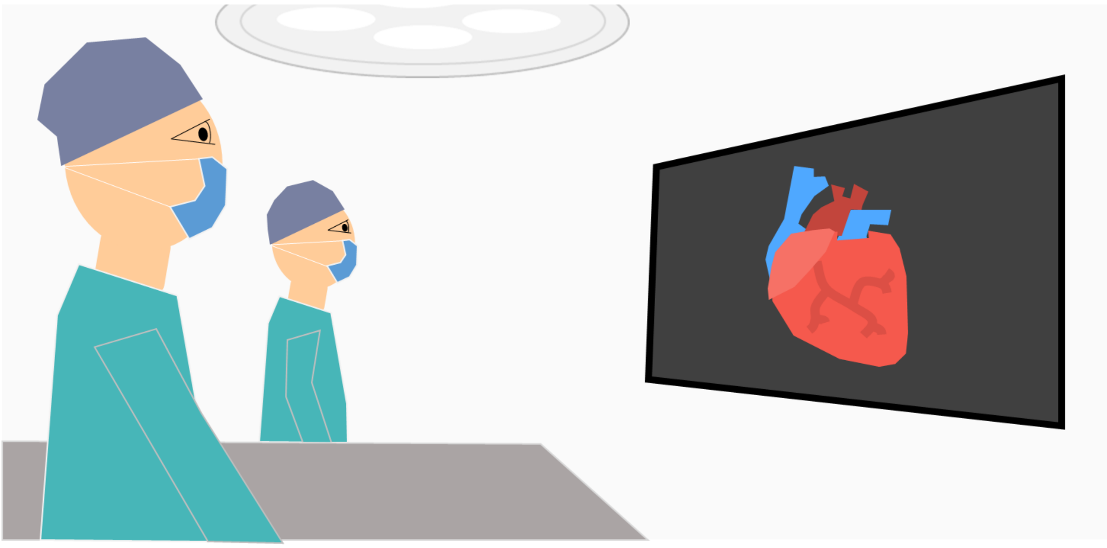

Figure 1.1.2. A medical 3D display in an operating room.

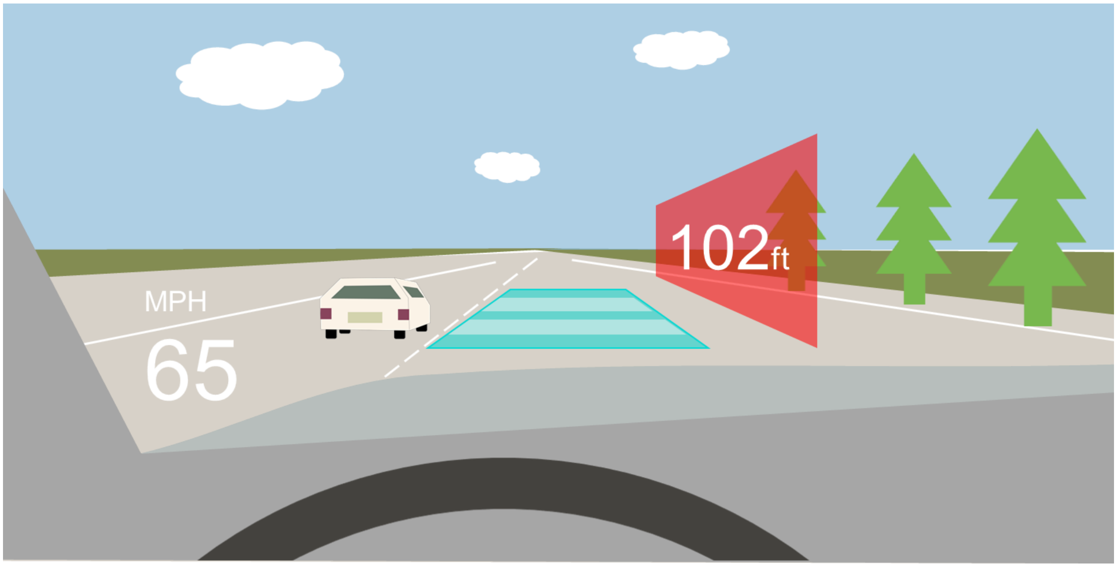


Figure 1.1.3. A Head-up display for drivers.

3D displays can be categorized into stereoscopic displays with goggles and autostereoscopic displays. A typical application of stereoscopic displays with goggles is the 3D movie theater. However, autostereoscopic displays that do not require special goggles have rarely been used compared with the conventional stereoscopic displays that require viewers to wear goggles. Some of the reasons are the lower image quality and the limited viewing zone, which is accompanied by a limited number of viewers. However, goggles are not permitted for practical use in some applications. For example, a motorist who must wear a pair of goggles while driving at night cannot observe the road conditions. Further, a medical doctor would not want to wear a pair of goggles during surgeries. Thus, 3D head-up displays for vehicles (Figure 1.1.2) or 3D medical displays in an operating room (Figure 1.1.3) must be autostereoscopic. The latter should provide 3D images with multiple viewers positioned at various locations while maintaining a high image resolution.

## 1.2 Conventional Research

This section divides the existing technologies of 3D displays broadly into stereoscopic displays that require extra goggles and autostereoscopic displays that do not require additional equipment, whose characteristics are described in detail.

### 1.2.1 Stereoscopic displays with goggles

Using stereoscopic glasses is the simplest method to achieve stereoscopy. Stereoscopic glasses for the right and left eyes with different optical elements can ensure that different images with parallax are shown to the left and right eyes simultaneously. Thus, the viewer can see stereoscopic images.

Anaglyph is an old technique for creating stereoscopic 3D images. The right and left eye images are shown to each eye by applying filters that pass certain colors through the glasses. Figure 1.2.1 shows that when applying cyan and red filters to the left and right eyes, respectively, only the BG (Green, Blue) of the RGB (Red, Green, Blue) component is visible to the left eye, while the R component is visible to the right eye. Stereoscopy is possible in this scenario because the BG and R components display the left and right-eye images, respectively. Although anaglyph can be achieved at a low cost, a full-color image cannot be achieved because of the limitation of available colors.

Anaglyph displays images with parallax to the observer's eye by separating the color components. Instead of separating the color components, applying different types of polarization to the light reaching the left and right eyes can also display images with parallax to each eye. Figure 1.2.2 shows that the images with different polarizations for the left and right eye are projected onto the screen. Each eye can observe the proper image through the glasses when two different polarizing filters applied.

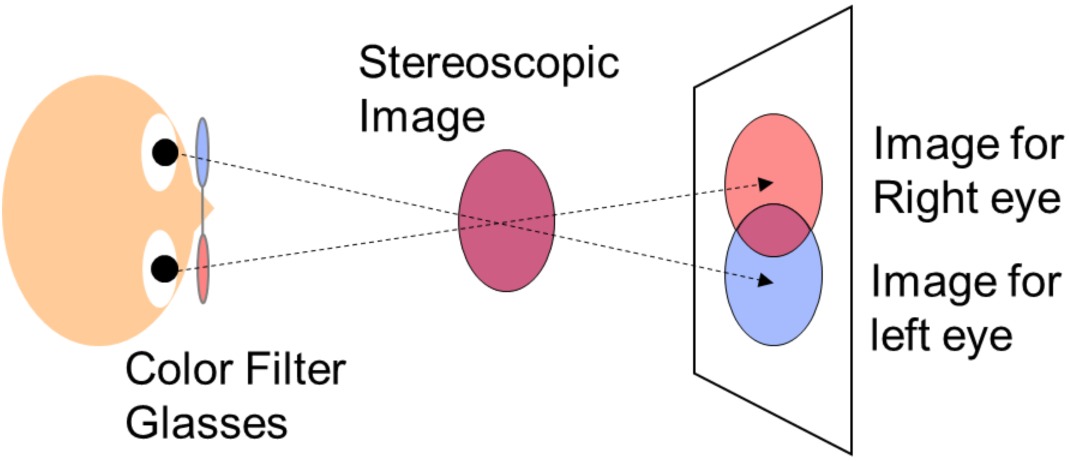


Figure 1.2.1. Anaglyph.

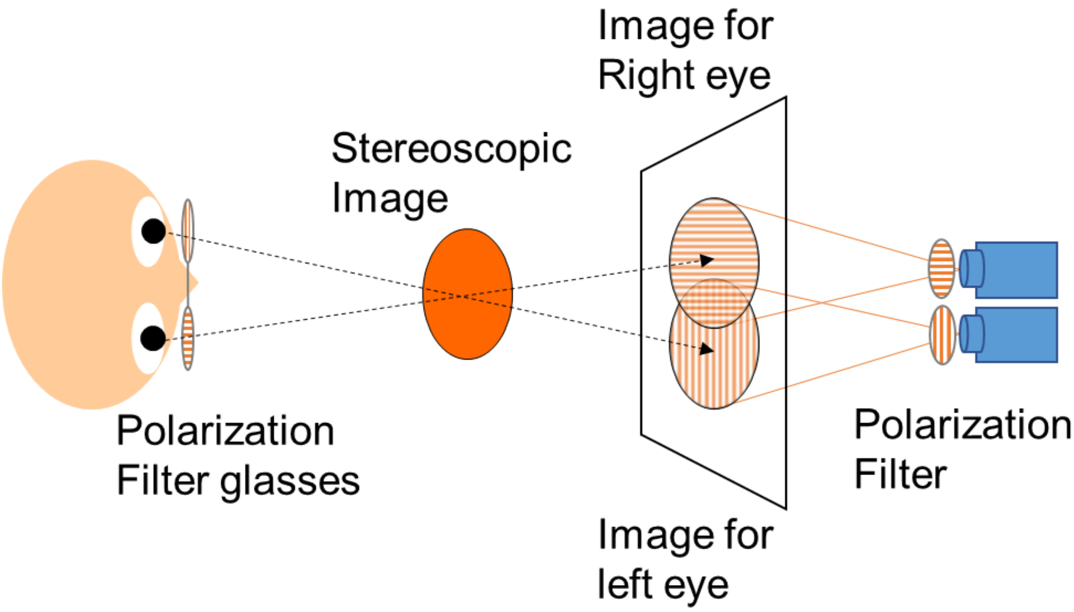


Figure 1.2.2. Stereoscopy with polarizing glasses.

Here, two types of polarization can be used: linear and circular polarization. For linearly polarized light, when the observer's head is tilted, the left and right images cannot be separated. Thus, both the left and right eye images are mixed; this phenomenon is called stereoscopic crosstalk. However, this problem does not occur with circularly polarized light.

The polarization system is easy to implement because it only requires glasses with polarizing filters. Although this method is not as cheap as anaglyph, it is the most used technology for people to experience 3D movies in cinema because it can display stereoscopic images in full color and at a low cost.

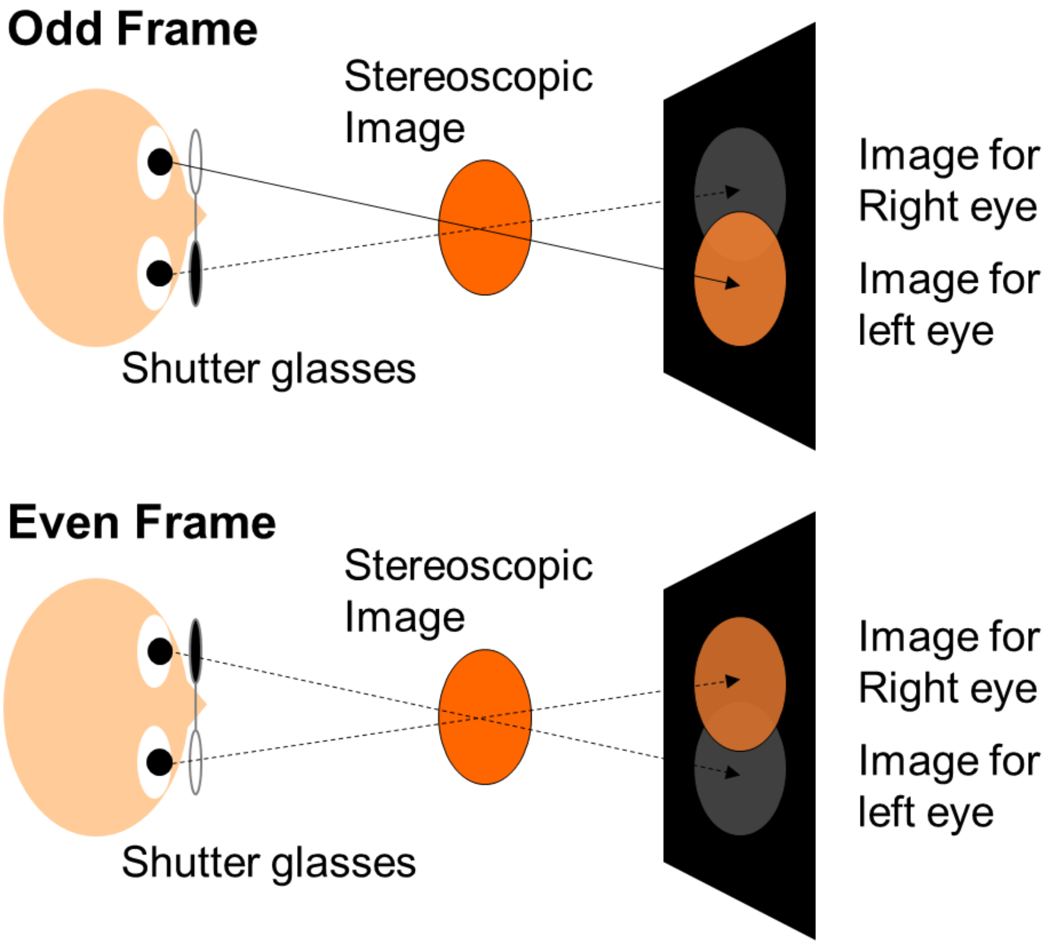


Figure 1.2.3. LCD shutter-glasses 3D display.

Using a liquid crystal shutter is another well-known method to achieve 3D displays with glasses. In this method, a shutter obstructs light from each eye when the converse eye image is displayed on the screen (Figure 1.2.3). The left and right-eye images alternate on the screen, and the shutters of the glasses open and close to synchronize with the image alternation. The alternation occurs at high speed, allowing different images to be displayed to the left and right eyes simultaneously. No resolution loss occurs because the complete left and right-eye images are displayed alternately on the screen. However, this method requires an electrically controlled shutter to switch between transparent and non-transparent states, thus increasing the manufacturing cost of the glasses. Additionally, measures must be taken to prevent crosstalk caused by the slow response time of the shutter, the response time (delay) of the Liquid Crystal Display (LCD) panel, and light leakages from the backlight while switching images [4].

Using an interference filter is a recently developed method for stereoscopy with goggles [5][6]. The typical method for reproducing a color image is combining the three primary colors, red (R), green (G), and blue (B). Figure 1.2.4 shows that three primary colors (RGB) and three additional similar colors with different wavelengths compose the image displayed on the screen. The glasses are fitted with dichroic filters, which selectively allow the light of specific wavelengths to pass through so that the wavelengths viewed by the left and right eyes will differ. The image consisting of the three original colors reaches a single eye after passing through the filter, and another image composed of the remaining three colors reaches the converse eye after passing through the other corresponding filter. Thus, images with parallax are displayed to the left and right eyes. However, the glasses are expensive in this method because of the dichroic filter.

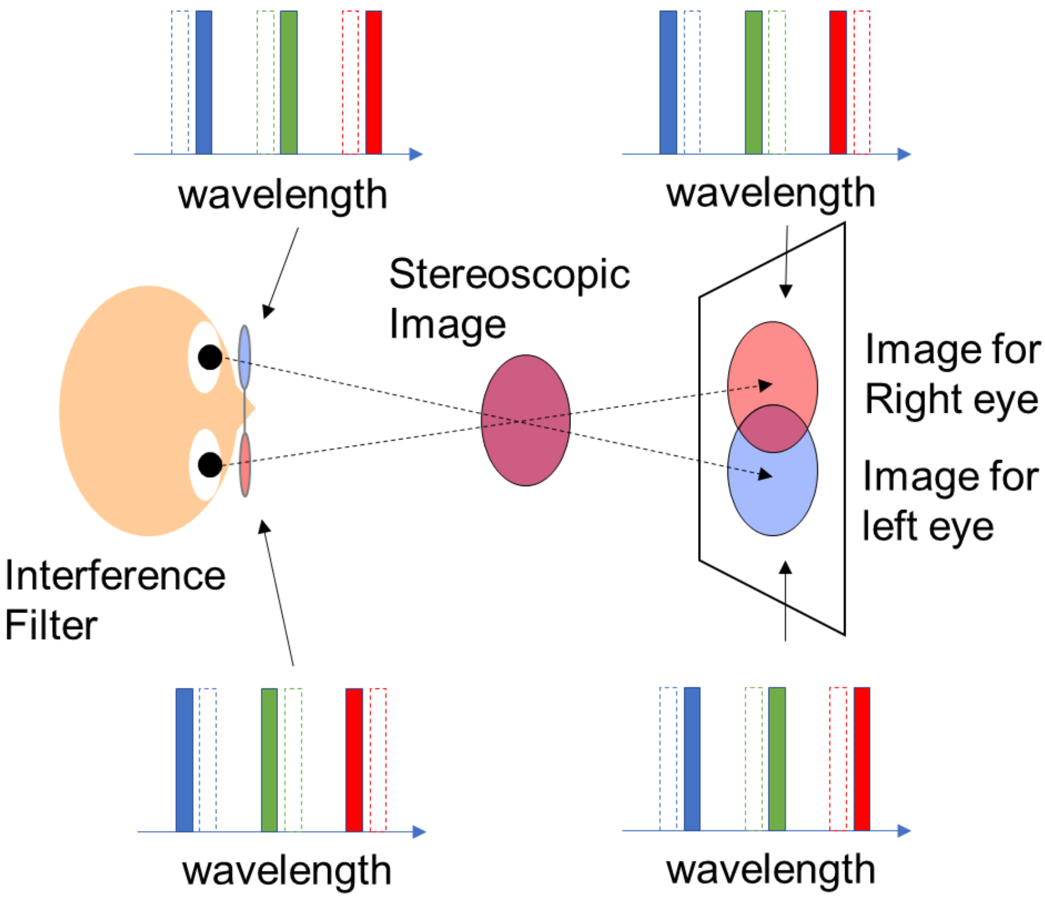


Figure 1.2.4. 3D display based on interference filter.

The common problem of stereoscopic displays with goggles is that they have lenses that restrict the visual field of viewers. This disadvantage is significant when the system is used daily or when observers require clear visibility without wearing special goggles.

### 1.2.2 Autostereoscopic displays

Parallax barriers and lenticular lenses are the most well-known autostereoscopic display methods. Both have the disadvantage of providing a lower image resolution than the LCD panel they use. The image resolution drops in half or less when the spatial multiplexing method is applied.

Figure 1.2.5 shows an autostereoscopic display based on a parallax barrier. The parallax barrier is a vertical slit array that limits the horizontal direction of light rays emitted from the pixels of the display panel. The display panel shows interleaved stripes of left and right-eye images. The striped left-eye image can be seen from the left eye through the slits, while the striped right-eye image can be seen from the right eye. The disadvantage of this basic parallax barrier method is that the viewing position is fixed, and the spatial resolution is half of the display panel. A slight deviation of the viewer's head to left or right will result in one eye seeing the other eye's image.

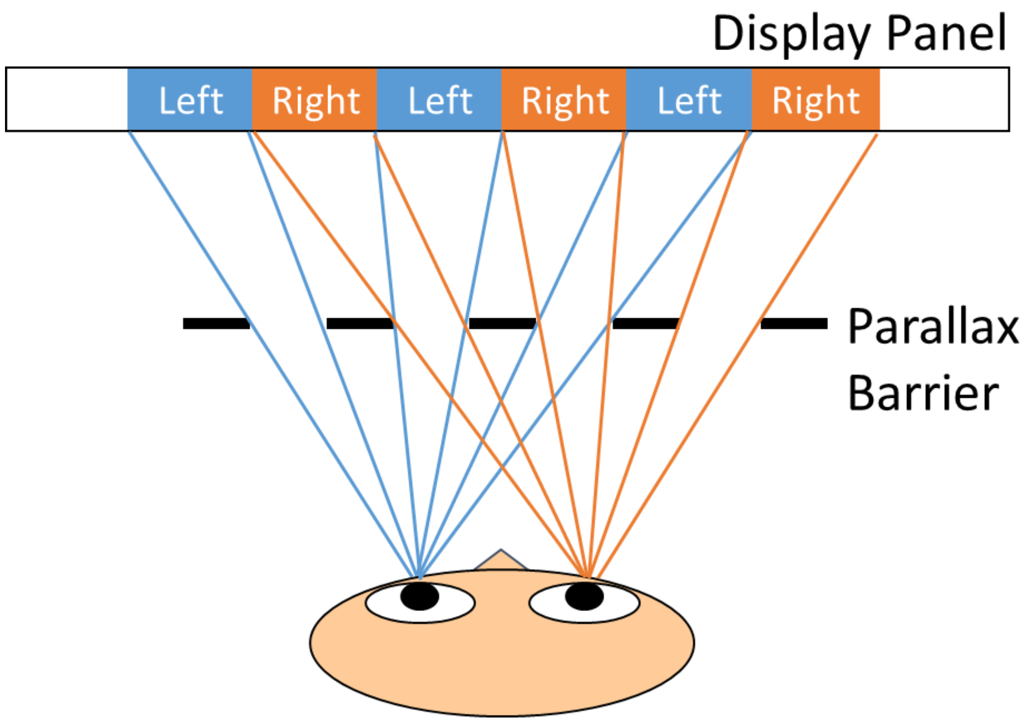


Figure 1.2.5. Autostereoscopic display system based on parallax barrier.

A lenticular lens, which is an array of cylindrical lenses, is also used to perform autostereoscopy. Figure 1.2.6 depicts an autostereoscopic display composed of an LCD panel and a lenticular lens. The horizontal distance between the pixel and the lens axis determines the direction of light rays initially emitted from the pixel after being refracted by the lens. Light rays emitted from the pixels with different horizontal positions advance in different directions. In this method, a lenticular lens focuses the light rays of the right and the left-eye images on the positions of the observer's eyes.

Thus, stereoscopic image pairs can be displayed on the left and right eyes simultaneously. The presented image is brighter than that given by the parallax barrier because the light rays are focused. However, because the optical principle of presenting autostereoscopic images is similar to the parallax barrier method, the problems of limited viewing zone and degraded resolution persist.

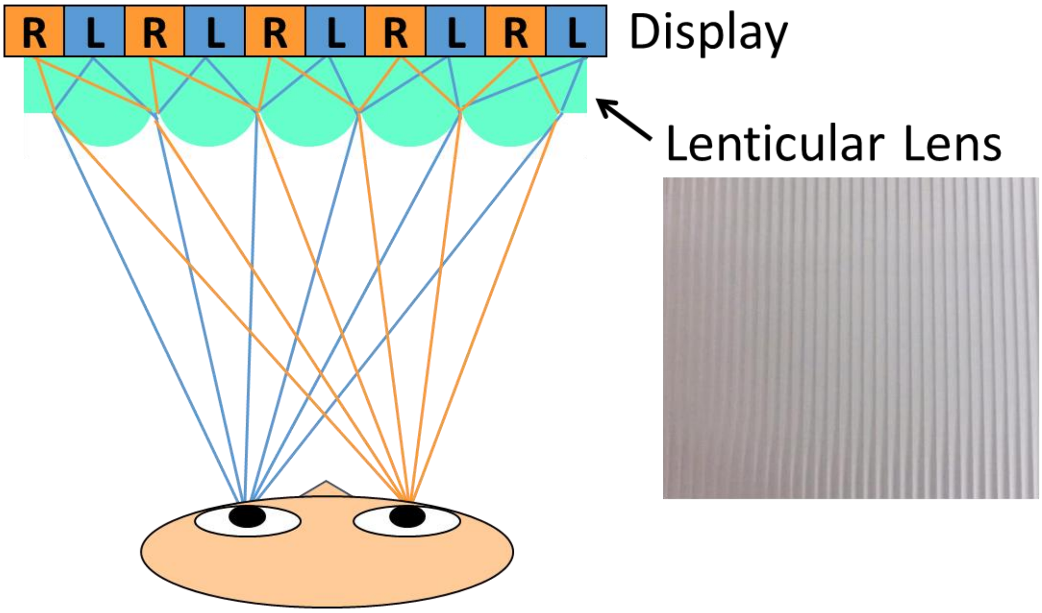


Figure 1.2.6. Autostereoscopic display system based on the lenticular lens.

### 1.2.3 High resolution autostereoscopic displays

The active parallax barrier method can rectify the resolution loss caused by the parallax barrier mentioned in the previous subsection [7][8][9][10][11]. This method combines the parallax barrier and time division multiplexing, which is called the time-division duplexing parallax barrier. The active parallax barrier can be electronically controlled to alter the position of the slit (parallax barrier). Figure 1.2.7 shows that in an active barrier system, the time division system is made from the even and odd frames. Two types of parallax barrier patterns alternate to synchronize with the two types of images on the display panel. At odd frames, the viewer can observe half of the left- and right-eye images with each eye and observe the other half at even frames. If the even and odd frames alternate fast enough, the observer can see two complete independent images, with each image visible only to a single eye. The LCD panel requires a high refresh rate of 120 Hz or higher to display smooth images without flickering. However, the problems of fixed viewing zone and a limited number of observers remain.

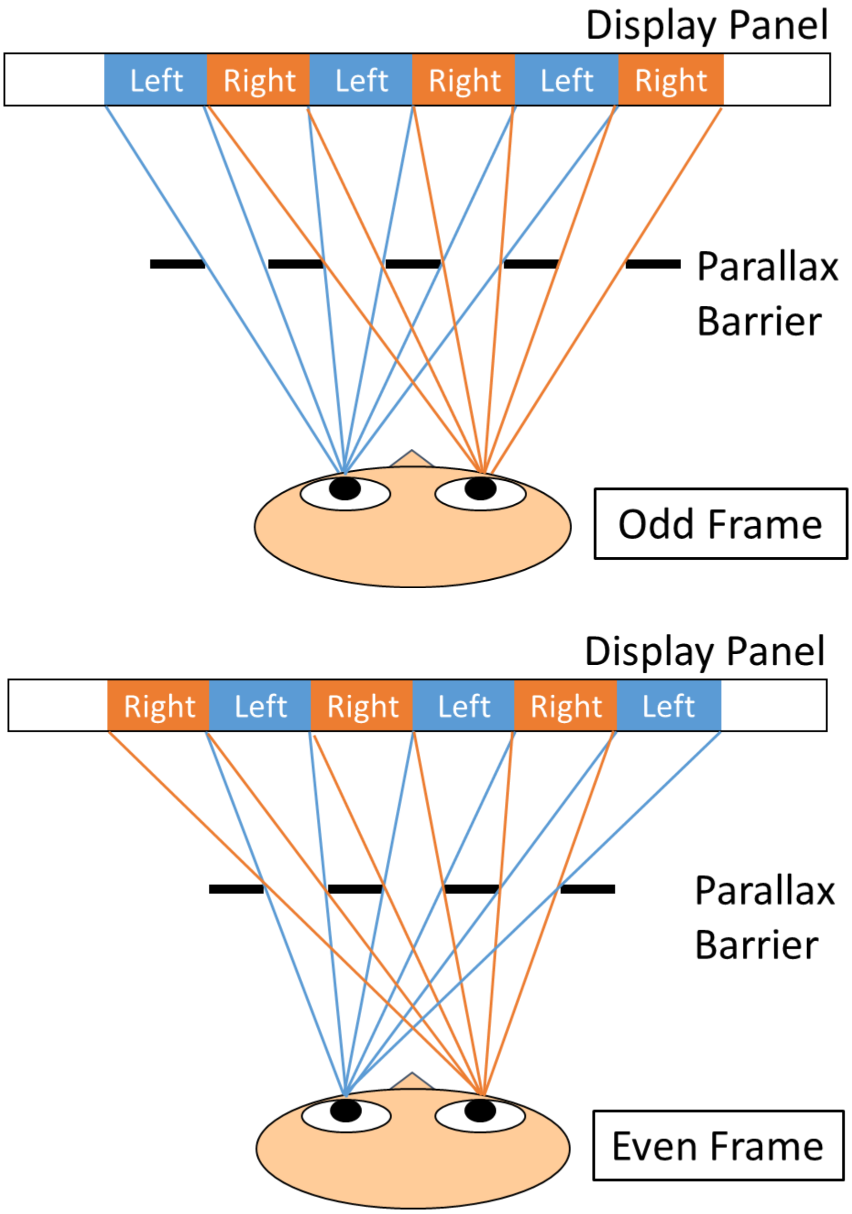


Figure 1.2.7. Full resolution autostereoscopic display system based on active parallax barrier.

Here, head-tracking is needed to maintain stereoscopy for a viewer moving freely[12][13][14][15]. Figure 1.2.8 shows that crosstalk is reduced by applying time-division quadruplexing [16][17][18][19][20]. Here, four viewpoints and the corresponding images are denoted as A, B, C, and D. Although a flicker appears because of the quadruple time division, it does not stand out when the slits of the parallax barrier are as fine as one pixel wide. The flicker can be further suppressed by applying an anaglyph parallax barrier to this system. The viewing zone without crosstalk can be extended with L-L-R-R alignment in the four view system, where the left-eye image is delivered to two viewpoints (A and B), and the right-eye image is delivered to the other two viewpoints (C and D). If the left eye and right eyes are between points A/B and C/D, respectively, then 3D images without crosstalk can be observed.

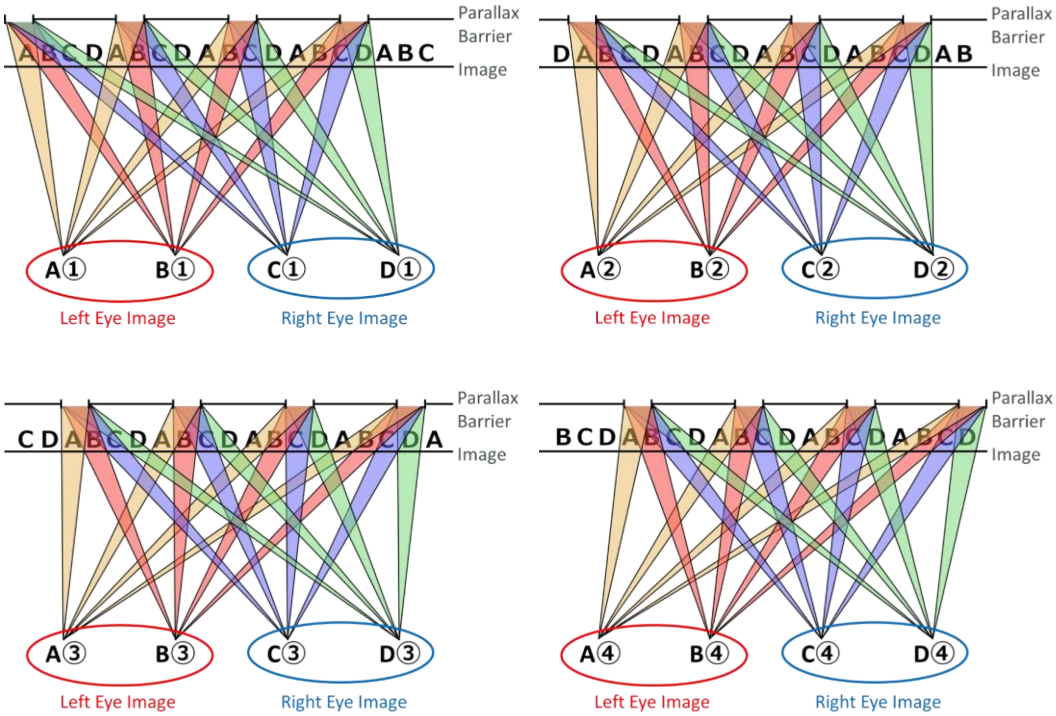


Figure 1.2.8. Principle of time-division quadruplexing parallax barrier.

Although stereoscopy is maintained for two viewers at the same depth by changing the number of time divisions adoptively [21], maintaining stereoscopy for more viewers is practically impossible as long as the parallax barrier technology is applied.

Time multiplexing directional backlight technology is another method for attaining high spatial resolution. The right- and the left-eye images are alternated on the LCD panel to synchronize with the change of backlight directionality, which maintains the spatial resolution of stereoscopic images [22][23][24].

A simple method to achieve a directional backlight is to use a large aperture lens [25] or a large concave mirror [26]. When light sources, filters [27][28][29][30][31][32], or mirrors [33] are positioned at the conjugate focal points of the observers' eyes, stereoscopic images can be delivered to the viewer without forcing him or her to wear special goggles. Although the viewing zone in the depth direction is expanded with the help of mechanical control of filters or mirrors, it is not a practical solution.

Another method to achieve a directional backlight is to use a lens array instead of a large aperture lens. Figure 1.2.9 shows the principle of the autostereoscopic display based on time-division multiplexing directional backlight using lens array [34][35][36][37]. A dot-matrix light source is placed behind a lens array so that the interval may be the same as the focal distance of the elemental lenses, which achieves collimated directional light. Directional light rays reach each eye by controlling the backlight to emit light at the position where the line connecting the observer's eye and the lens center intersects the backlight. The viewer can see a stereoscopic image without wearing special glasses when the directional backlight to each eye alternates synchronously with the alternating of left- and right-eye images on the LCD panel.

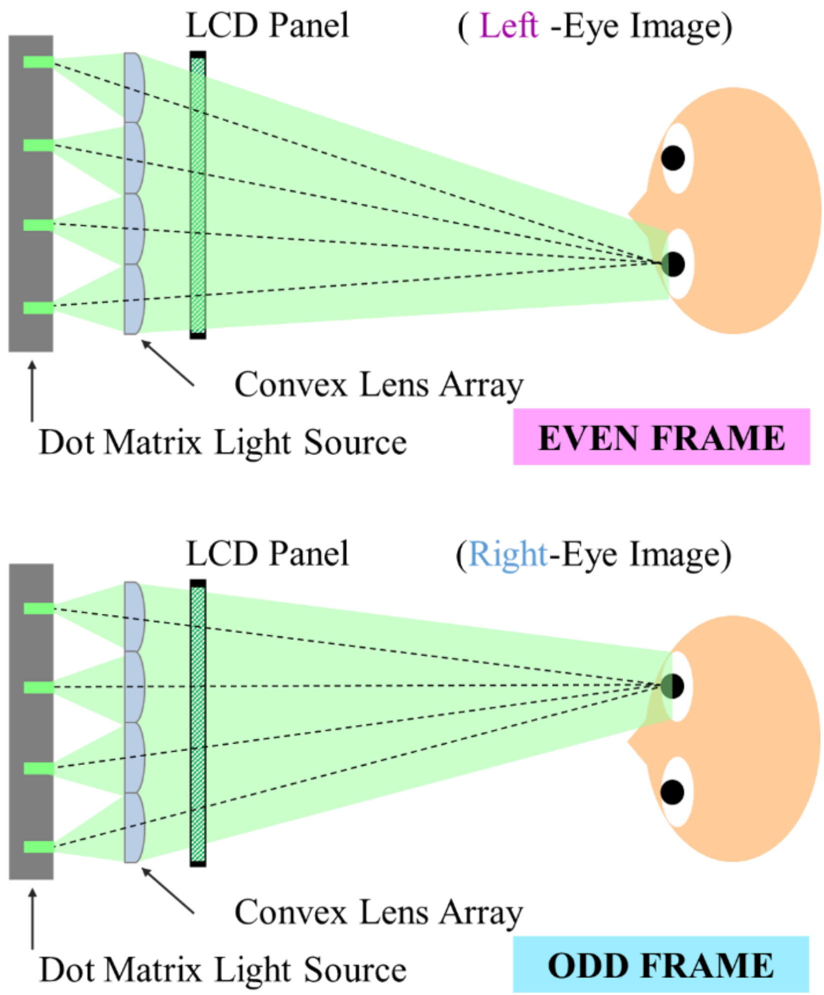


Figure 1.2.9. Principle of autostereoscopic display based on time-multiplexed directional backlight using lens array.

However, low image quality is the remaining problem of this system. Because the lens array has distinct seams and the light passing through the peripheral part of elemental lenses is weaker than that passing through the center of elemental lenses, the shape of the lens can be observed, and the intensity of the image is not uniform. To improve the image quality, Figure 1.2.10 shows a system proposed by Ishizuka et al., which combines a dot-matrix light source, a hexagonal convex lens array with delta (triangle) alignment, and a directional diffuser [38][39] to improve image quality.

Figure 1.2.11 shows that a directional diffuser can blur the seam of the lens array and smooth the uneven light intensity in each elemental lens, leading to a better quality of the presented image. Although the method can homogenize the intensity of the backlight, the viewer still observes dark and bright vertical stripes which are considered as noises. To suppress these noises, Ishizuka et al. tilted the convex lens array in Figure 1.2.11. However, slanted stripes appeared instead of vertical ones.

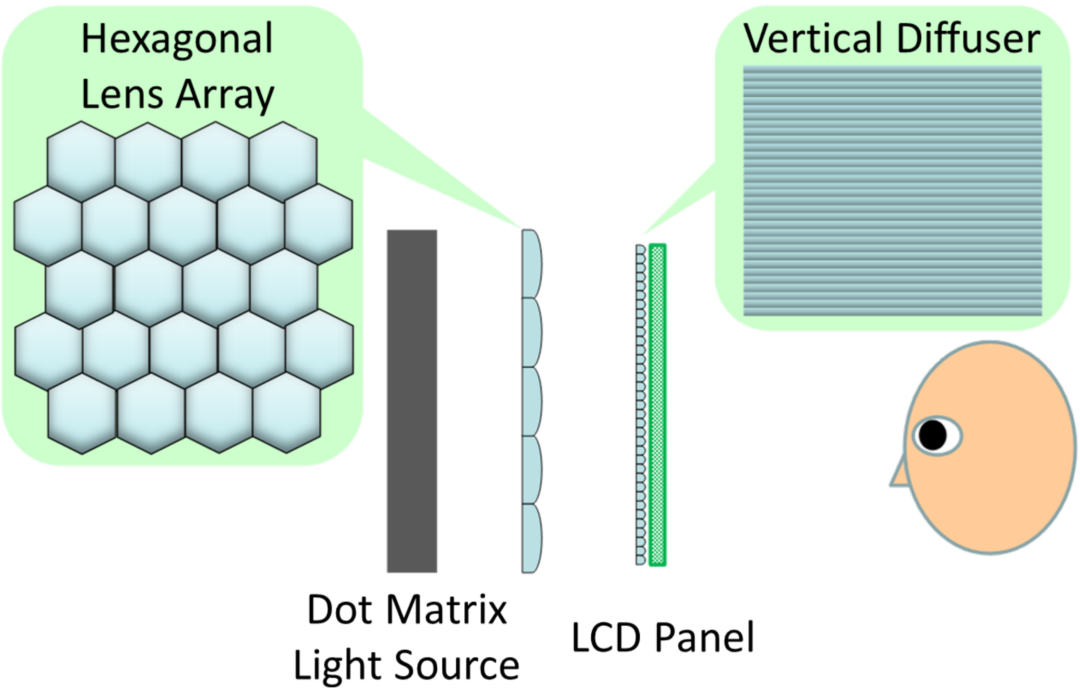


Figure 1.2.10. Autostereoscopic display system using hexagonal lens array and vertical diffuser.

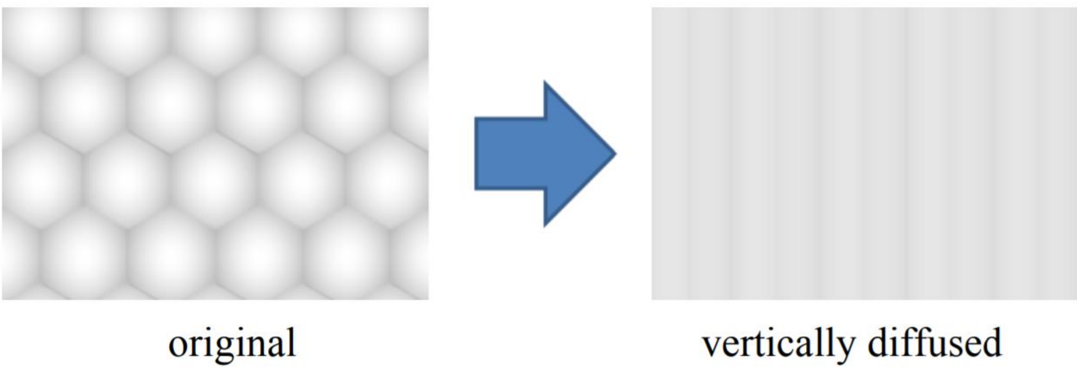


Figure 1.2.11. Vertical diffusion of hexagonal lens array.

To eliminate the noises, Ishizuka et al. further proposed a system composed of a lens array with a revised alignment of elemental lenses and a vertical diffuser, where the phases of lens placement in the horizontal direction in each row differ from one another (Figure 1.2.12) [40][41][42]. The elemental lenses are aligned so that they can be shifted in the horizontal direction by different offsets in each row. In Figure 1.2.12, 180° indicates that two elemental lenses in adjacent rows are shifted by half the width of the elemental lens. The vertical diffuser smooths the seams of the lens because the seams appear only once in the vertical direction. Thus, the intensity of the image becomes more homogeneous.

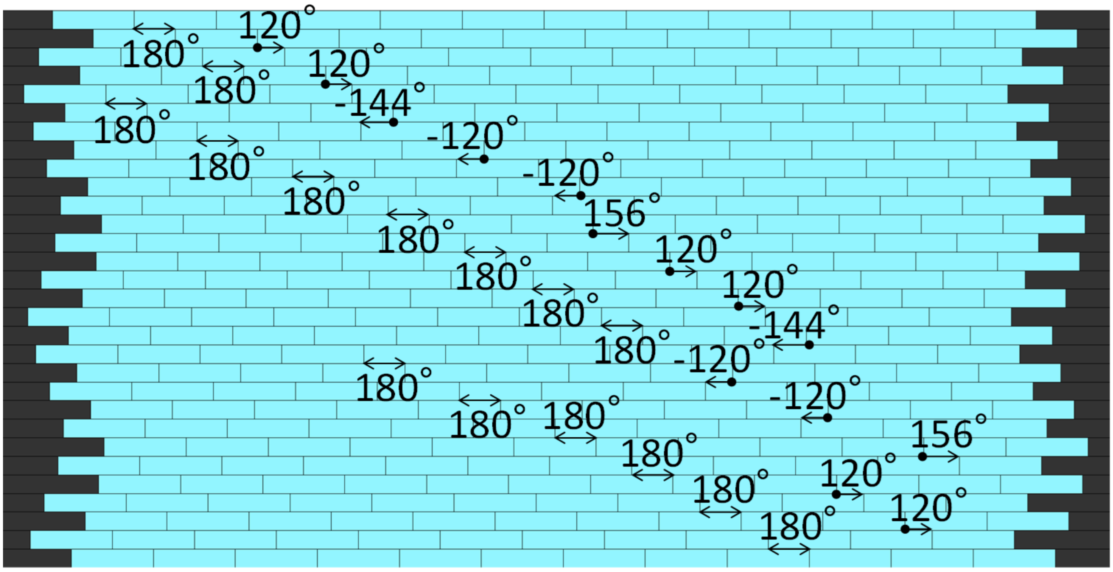


Figure 1.2.12. Alignment of the phase-shifted lens array.

## 1.3 Research Objective

As described at the beginning of this chapter, a high-resolution autostereoscopic display is desired in some situations, such as a head-up display for drivers and a medical display for doctors. However, conventional autostereoscopic displays have problems such as high crosstalk level, restriction of viewer's posture, and narrow view zone that does not allow the simultaneous observation of more than one viewer. Thus, this study addresses these problems and achieves high-resolution autostereoscopic displays that simultaneously provide multiviewers with stereo images, assuming that they can be applied as 3D head-up displays for vehicles or 3D medical displays in an operating room.

A 3D head-up display with a high spatial resolution realizes a driving environment with augmented reality, which can realize a car navigation with graphical information aid fused in the scenery. 3D medical displays can provide a surgery with graphical navigation also.

In case of surgery, multiple medical staff members collaborate with one another in the operating room. For that reason, a 3D display that provides multiple persons with 3D images is desired. The paper tries to realize a 3D display for multiple viewers to meet this demand.

## 1.4 Thesis Outline

To address the three major problems described in the previous section, the author proposes several autostereoscopic display systems, which are organized as follows in six chapters:

In Chapter 2, the author first describes the field curvature of the lens, which is the primary cause of the high autostereoscopic crosstalk level in conventional systems. Then the author proposes using one layer of decentered lens array to reduce crosstalk. Finally, the crosstalk of the prototype display system based on the proposed method is evaluated.

In Chapter 3, the author first proposes a method to further reduce the crosstalk level using a curved lens array. Further, a curved lens array composed of trapezoid lenses, which improves an image quality and a lower crosstalk level is proposed.

In Chapter 4, the author discusses the postural restriction of the viewer while observing stereoscopic images on conventional autostereoscopic displays, and proposes a novel interleaved linear Fresnel lens array for building a directional backlight system without using a diffuser. The autostereoscopic display that uses the proposed lens array allows the viewer to tilt his or her head while viewing the stereoscopic image. Finally, the author suggests an improved version of the abovementioned autostereoscopic display to achieve a uniform backlight intensity.

In Chapter 5, the author proposes an autostereoscopic display that can provide two viewers with different stereoscopic image pairs simultaneously. The viewing zone is then enlarged without interfering with each other's views. Finally, a hardware experiment is conducted to verify the validity of the proposed system.

In Chapter 6, the author proposes an autostereoscopic display that uses a large aperture lens and PDLC (Polymer Dispersed Liquid Crystal) screens to increase the number of viewers permitted and to widen the viewing zone in the depth direction. The experiment of the proposed method is then described.

In Chapter 7, the author presents the conclusion and future work of this study.

# 2 Reduction of Crosstalk Caused by Field Curvature

This chapter proposes an autostereoscopic display with time division multiplexing directional backlight using a decentered lens array. The cause of crosstalk in the conventional method is investigated in Section 2.1. Further, a decentered lens array is proposed in Section 2.2, followed by the results in Section 2.3.

## 2.1 Background

### 2.1.1 Crosstalk caused by field curvature

Figure 1.2.9 shows a conventional time division multiplexing autostereoscopic display composed of an LCD and a synchronized directional backlight using a lens array that has a high crosstalk level because of the field curvature of the elemental lenses.

Figure 2.1.1 shows that the image plane generated by a convex lens becomes a curved surface instead of a flat one because of the field curvature. The field curvature is strong when the incidence angle of light is as large as the green light rays displayed.

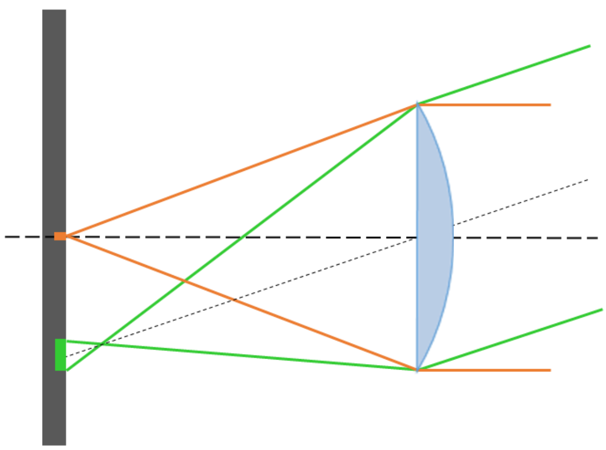

Figure 2.1.1. Field curvature of a lens.

Figure 2.1.2 shows the case of an optical system where the distance between the lens array and the dot-matrix backlight is approximately equal to the focal length of the elemental lens to generate collimated directional light rays. The greater the horizontal distance between the observer's eye and the optical axis of the elemental lens, the steeper the angle of incidence, and the stronger the field curvature. To make the entire image uniformly bright, the light rays reaching the eyes should pass through all portions of the lens. Hence, the area on the backlight where the light rays emitted from an eye position impinge on the backlight plane through the lens array (the green rectangles in Figure 2.1.2) must be fully bright. Thus, the specified luminous area of the light source plane, which belongs to an elemental lens with strong field curvature (for example, the bottom lens in Figure 2.1.2) is broadened to lighten the entire lens. Figure 2.1.3 shows that the expanded width of the luminous area results in overlaps of the areas for the right and left eyes because of the field curvature, which causes crosstalk. The left image of Figure 2.1.3 shows that the green light rays for one eye are overlapped with the orange light rays.

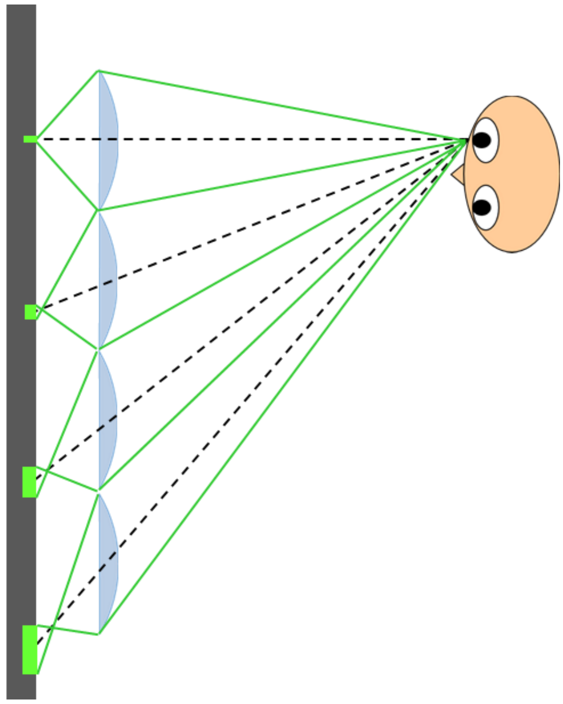

Figure 2.1.2. Field curvature of a lens array.

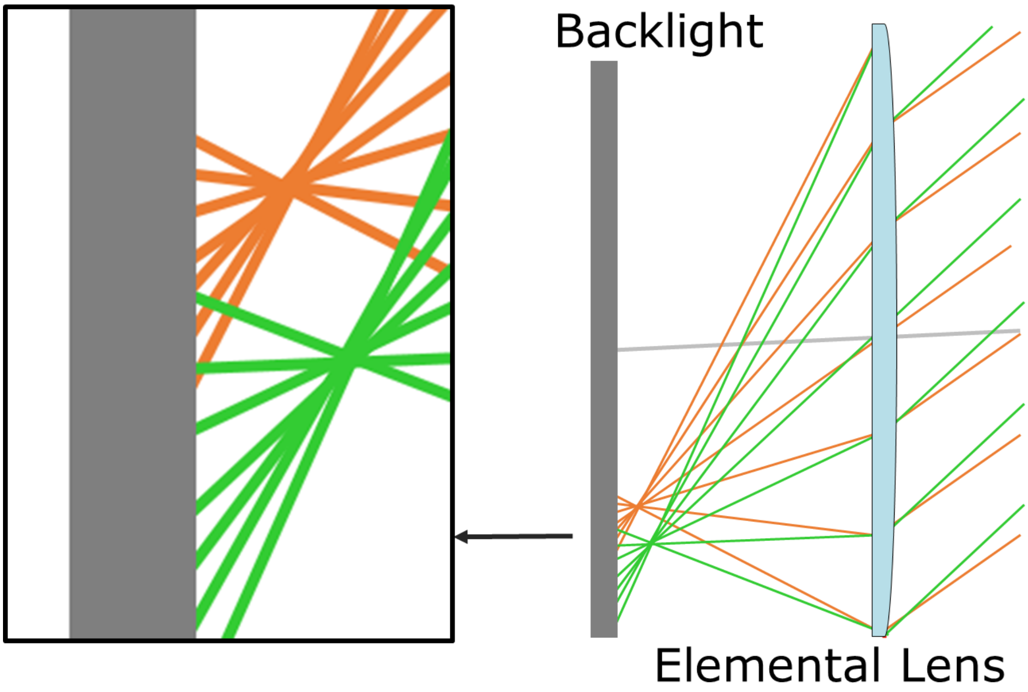


Figure 2.1.3. Crosstalk due to the field curvature.

The crosstalk caused by the field curvature of a lens increases as the incidence angle increases, indicating that the crosstalk level is high in the peripheral part of the autostereoscopic display.

### 2.1.2 Conventional approaches

To reduce the crosstalk caused by the field curvature, Mukai et al. proposed a method to use a large aperture lens to suppress the effect of field curvature [42] (Figure 2.1.4). Mirrors placed between the backlight and lens array to prevent the intrusion of light from adjacent segments further reduce crosstalk.

Figure 2.1.5 shows that the light ray paths between the large aperture lens and the lens array become parallel with the optical axis of all lenses when the large aperture lens is placed behind the LCD panel. Thus, the incidence angles of light rays to each elemental lens in the lens array are reduced, and the influence of field curvature is minimized by applying a large aperture lens.

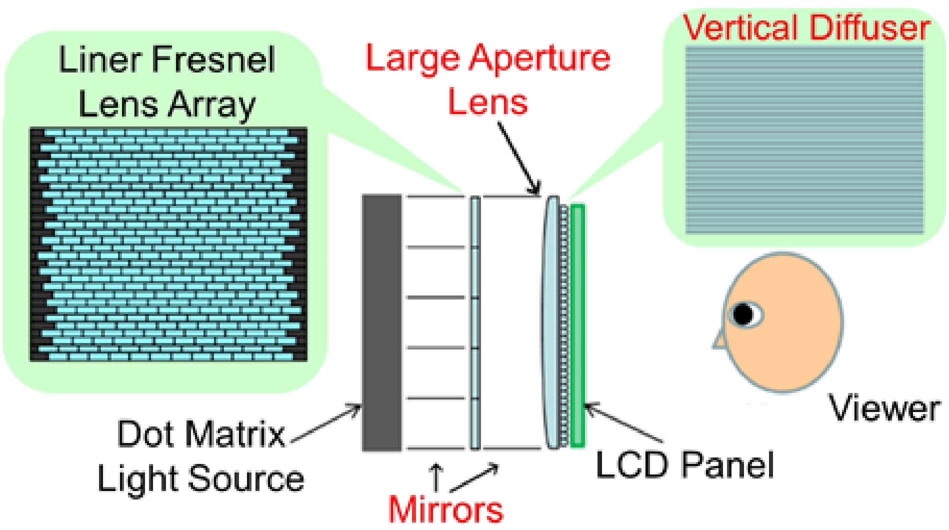


Figure 2.1.4. Crosstalk reduction by adding a large aperture lens.

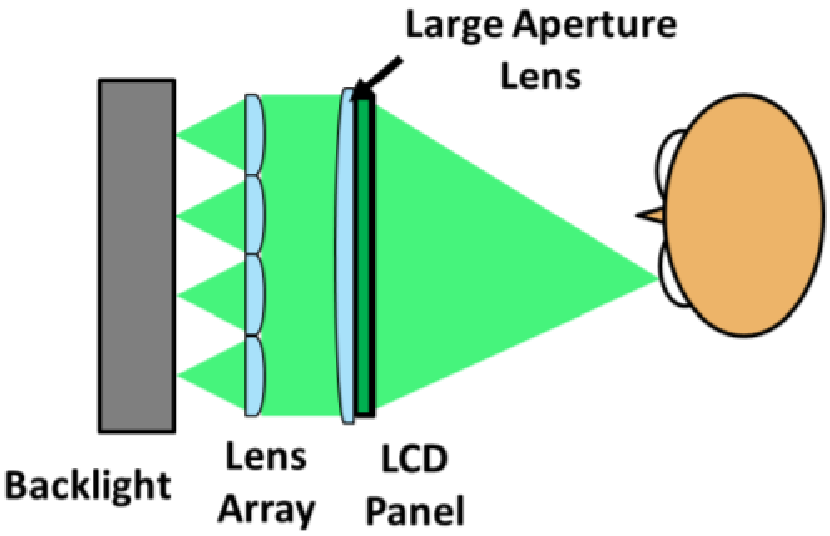


Figure 2.1.5. The optical path of the conventional system with a large aperture convex lens placed behind the LCD panel.

Two layers of Fresnel lenses used in the conventional system, however, require extensive optical calculation and produce stray light, which causes crosstalk. The angle of the prism increases and the groove deepens in the area far from the lens center. Figure 2.1.6 shows that stray light traveling along an unintended light path emerges, causing an optical noise. Additionally, the double layers of Fresnel lenses increase the crosstalk level because of the reflection between them.

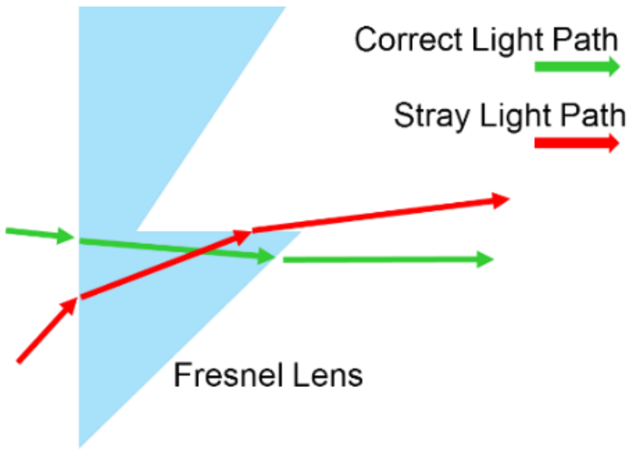

Figure 2.1.6. The problem of stray light.

To solve these problems, a directional backlight system based on a single layer of a decentered lens array is proposed.

## 2.2 An Autostereoscopic Display using Decentered Lens Array

Compared with the normal lens, whose center is at its geometric center, the center of the lens proposed in this section is displaced from its geometric center and is called a decentered lens.

Figure 2.2.1 shows that when a conventional elemental lens is used under a large incidence angle, the positions to emit light for the two eyes overlap because of the field curvature, which results in the emergence of crosstalk. The influence of field curvature is reduced by applying a decentered lens to relieve the overlap described above.

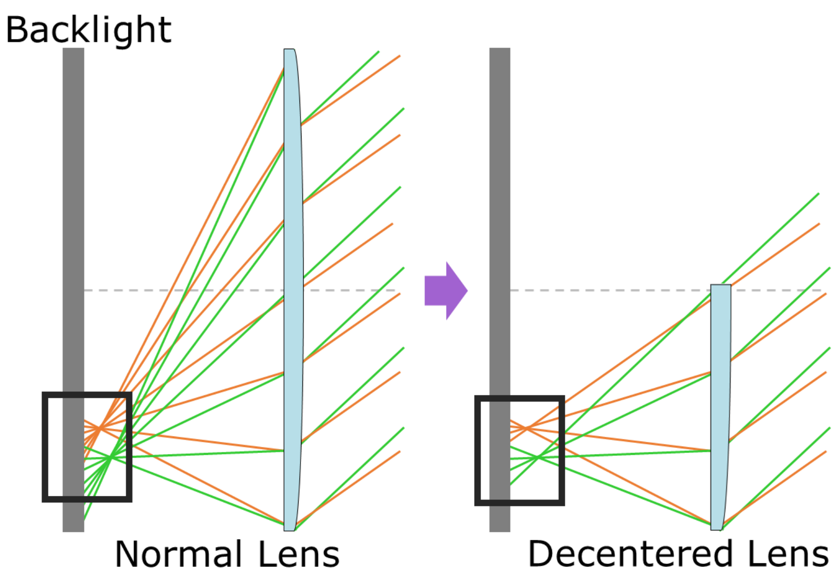

Figure 2.2.1. Reduction of crosstalk using a decentered lens.

Table 2.2.1 shows the specifications of the decentered Fresnel lenses used in the proposed method.

Table 2.2.1. Specification of elemental lenses.

| Decentered lens | Size | Focal length |
|---|---|---|
| horizontal refraction | 51×19.5×2 mm | 60 mm |
| vertical refraction | 306×19.5×2 mm | 60 mm |

The lens array of the proposed system has a two-layer structure with horizontal and vertical refraction that is closely aligned with each other. The distance between the lens array and the backlight panel is equal to the focal length of the elemental lens. The arrangement of the decentered lens array is based on the following two rules. First, as the lens becomes farther from the center of the display, the geometrical center of the elemental lens becomes farther from the optical center. The reason for this rule is that the peripheral elemental lens, which is far from the center of the display, has a large incidence angle, implying that the lens must be strongly decentered. Second, Figure 2.2.2 shows that the amount of shift (decentering) is determined so that the line connecting the center of the viewing zone (point $\mathrm{A}$) and the optical centers of an elemental lens (point $\mathrm{C}$) intersect the backlight panel (point $\mathrm{G}'$) behind the geometrical center of the elemental lens (point $\mathrm{G}$). When the area around the point $\mathrm{G}'$ is lightened, collimated light rays refracted by the lens pass through the viewing zone around point $\mathrm{A}$. This rule is to ensure maximum usage of available space of the backlight panel because the viewing zone is centered around point $\mathrm{A}$.

The viewing zone is centered to be around point $\mathrm{A}$, which is 840 mm away from the lens array in the depth direction. Let $\left|\overrightarrow{\mathrm{C'G'}}\right|$ be the distance between the optical and the geometric center. It is given as follows:

$$\left|\overrightarrow{\mathrm{C'G'}}\right| = \frac{\left|\overrightarrow{\mathrm{CC'}}\right| \times \left|\overrightarrow{\mathrm{OG'}}\right|}{\left|\overrightarrow{\mathrm{AO}}\right|} = \frac{\left|\overrightarrow{\mathrm{OG'}}\right|}{15}, \tag{2.1}$$

based on the similarity of $\Delta\mathrm{AG'O}$ and $\Delta\mathrm{CG'C'}$. Further, the position of the optical center based on the geometric center of the lens can be calculated. The positions of geometric centers are defined by the phases of each row, which are designed to avoid the periodical lens alignment in the same way as the conventional method [41]. Figure 2.2.3 depicts the horizontal refraction layer of the lens array.

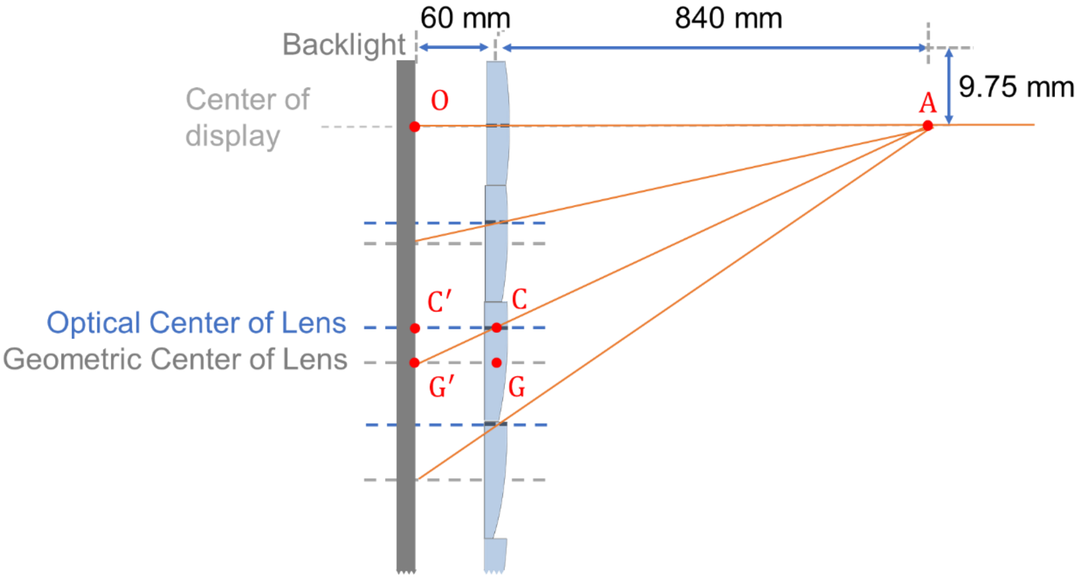


Figure 2.2.2. Arrangement of lens array.

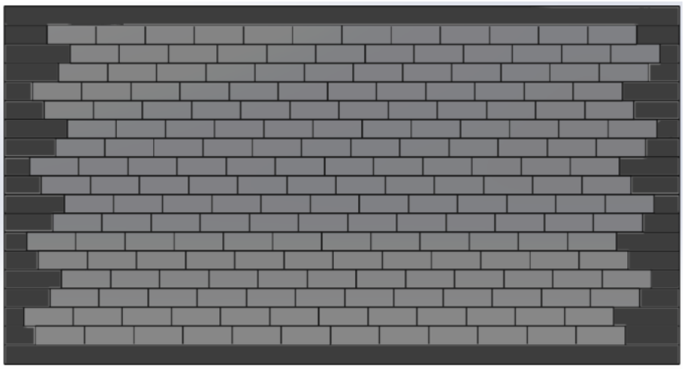

Figure 2.2.3. Lens array layer of horizontal refraction decentered lens.

The lower lenses in the vertical refraction layer of a decentered lens array (Figure 2.2.4) are more decentered than the upper ones since the height of the viewing zone is close to that of the lens array's upper edge.

Figure 2.2.4. Lens array layer of vertical refraction decentered lens.

Figure 2.2.5 shows that the dot-matrix light source consists of a constant LED backlight and a 27-inch LCD panel with a 120 Hz refresh rate. As in conventional research, the lens array is aligned with stepwise phase shifts, and a vertical diffuser is used to achieve a uniformly bright image. Mirrors are inserted between the lens array and the dot-matrix light source to separate the light sources for different rows of elemental lenses.

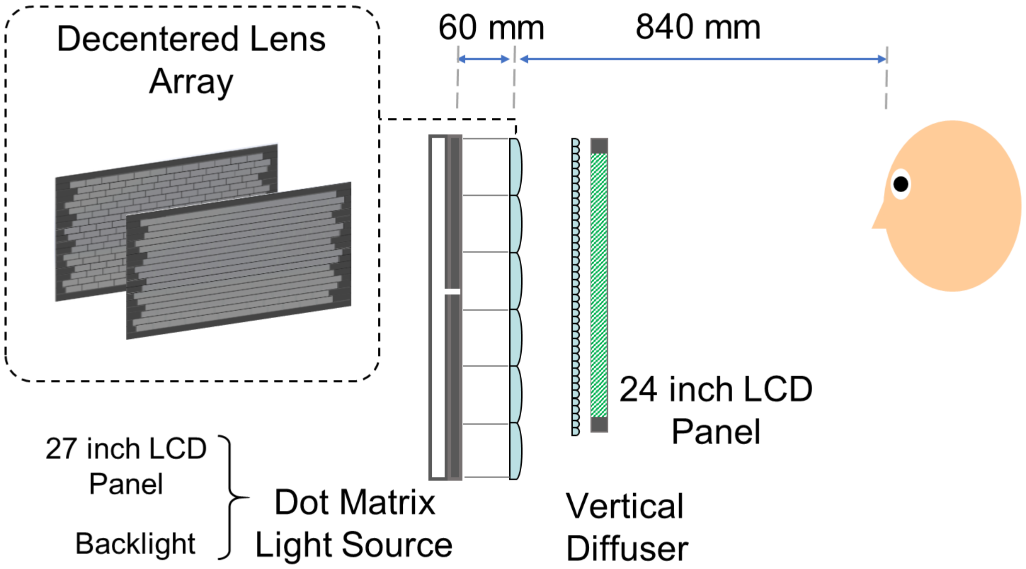


Figure 2.2.5. Autostereoscopic display system using a decentered lens array.

## 2.3 Results

Figure 2.3.1 shows the proposed lens array, which is composed of decentered elemental lenses. Figure 2.3.2 shows a prototype system based on the design of Figure 2.2.5, and its crosstalk level is evaluated.

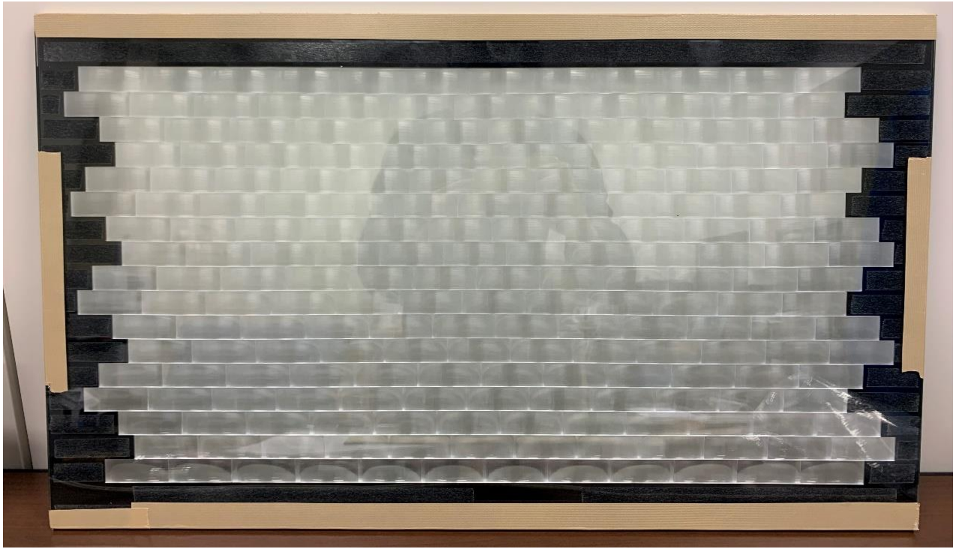

Figure 2.3.1. Lens array using decentered elemental lenses.

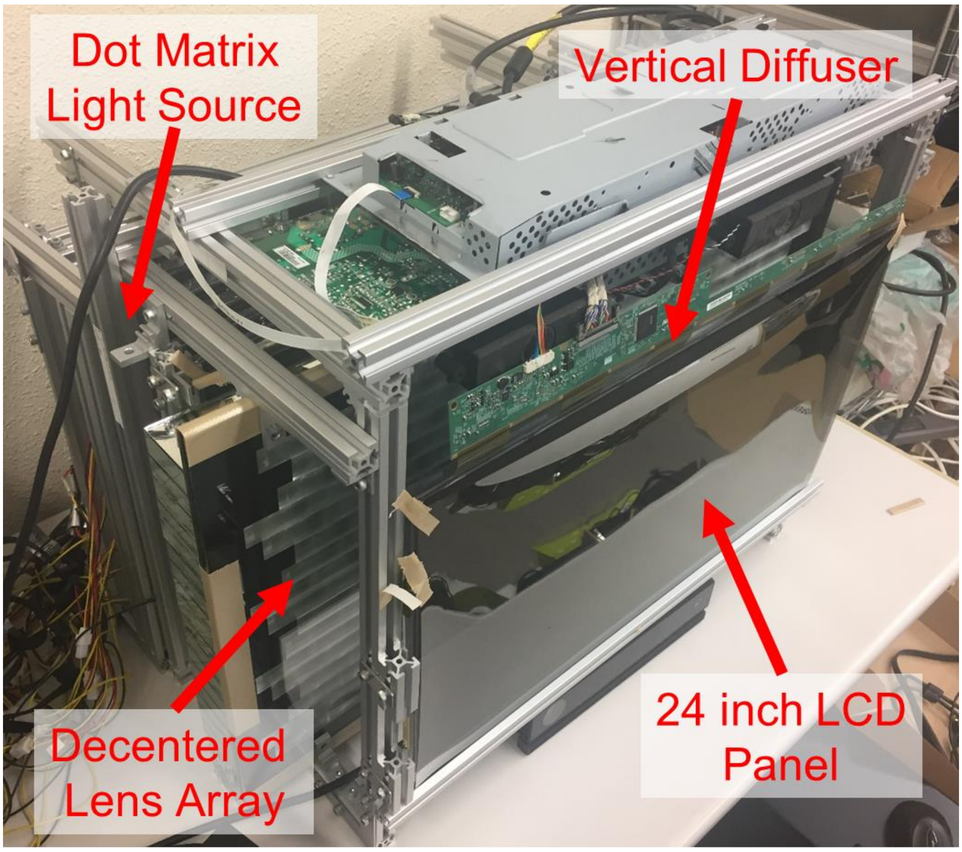


Figure 2.3.2. Prototype display system using a decentered lens array.

A luminance meter (Kaise digital light meter KG-75) is used to measure and evaluate the crosstalk level. The luminance was measured under the following three conditions: View 0 (both the left- and the right-eye images were black to measure the ambient illuminance); View 1 (the left- and the right-eye images were white and black, respectively); View 2 (the left- and the right-eye images were black and white, respectively). The brightest position under condition View 1 was set to be the starting point. Luminance was measured every time a luminance meter was moved by 10 mm under the three conditions. Figure 2.3.3 illustrates the result.

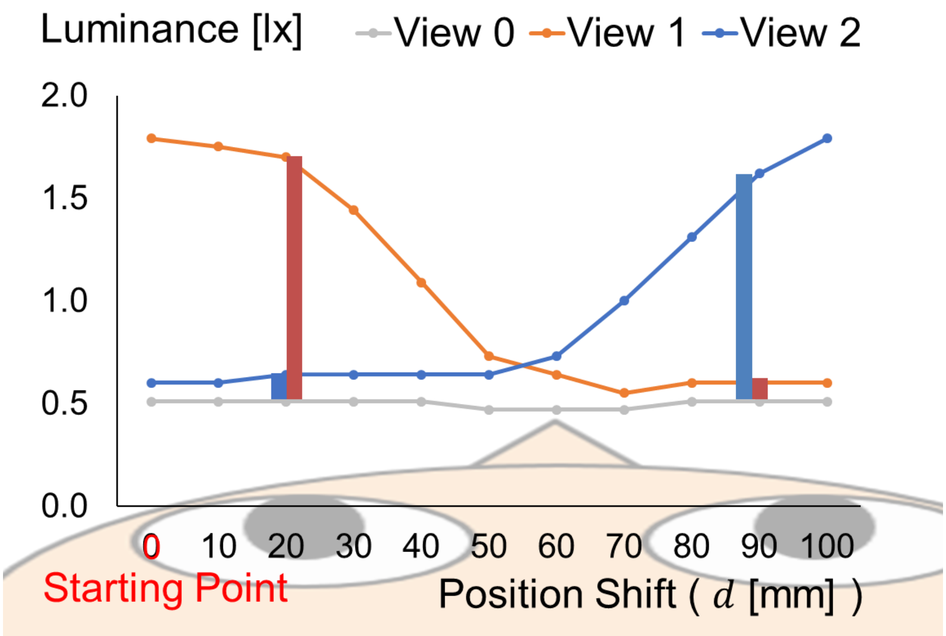


Figure 2.3.3. The result of the experiment.

The data at $d = 20$ [mm] and $d = 90$ [mm] are selected as the luminance for the left- and right-eye positions respectively, so that the crosstalk level will be minimized while maintaining the interval at the same distance as the human interpupil. The observed crosstalk level is defined by the following equation:

$$Crosstalk\ Level = \frac{1}{2}\left(\frac{L_{v2}-B_l}{L_{v1}-B_l} + \frac{R_{v1}-B_r}{R_{v2}-B_r}\right), \tag{2.2}$$

where $L_{v1}$ and $L_{v2}$ are the luminance at the left-eye position ($d = 20$) under Views 1 and 2, $R_{v1}$ and $R_{v2}$ are the luminance at the right-eye position ($d = 90$) under Views 1 and 2, and $B_l$ and $B_r$ are the ambient luminance at the left- and right-eye positions. By substituting the experimental data into Equation (2.2), the crosstalk level is calculated to be 9.5%. The crosstalk level is reduced significantly by the proposed method because the crosstalk level of the conventional display system is 13.4%.

## 2.4 Summary

This chapter proposes an autostereoscopic display with time division multiplexing directional backlight using a decentered lens array. Using a single decentered lens array in this method reduces the impact of field curvature without applying an additional large aperture Fresnel lens. The crosstalk level is significantly reduced because the stray light from the multiple layers of the Fresnel lens has been suppressed.

# 3 Reduction of Crosstalk and Realization of Uniform Backlight Intensity

This chapter proposes autostereoscopic displays with novel directional backlight designs to reduce crosstalk. A directional backlight system that suppresses the effect of field curvature with a single layer of the curved lens array is proposed in Section 3.1. In Section 3.2, the uniformity of backlight intensity is also increased by replacing rectangle elemental lenses with trapezoid elemental lenses.

## 3.1 Crosstalk Reduction by Curved Lens Array

### 3.1.1 Relief of the field curvature

To further suppress crosstalk, a curved-shaped lens array is proposed (Figure 3.1.1). Since the incidence angles from the center of the viewing zone to the peripheral lenses increase in the conventional flat lens array, the luminous area generating directional lights for the right and left eyes overlap because of the field curvature of lenses; the incidence angles are kept almost constant when the lenses are aligned in a curved shape, which avoids the overlap of luminous areas. Because the point of observation is centered around the circular arc, the lines connecting the point of observation and the center of lenses are nearly orthogonal to the arc, implying that the incidence angles to the lenses are always close to zero. Under this ideal condition, the influence of field curvature is minimized.

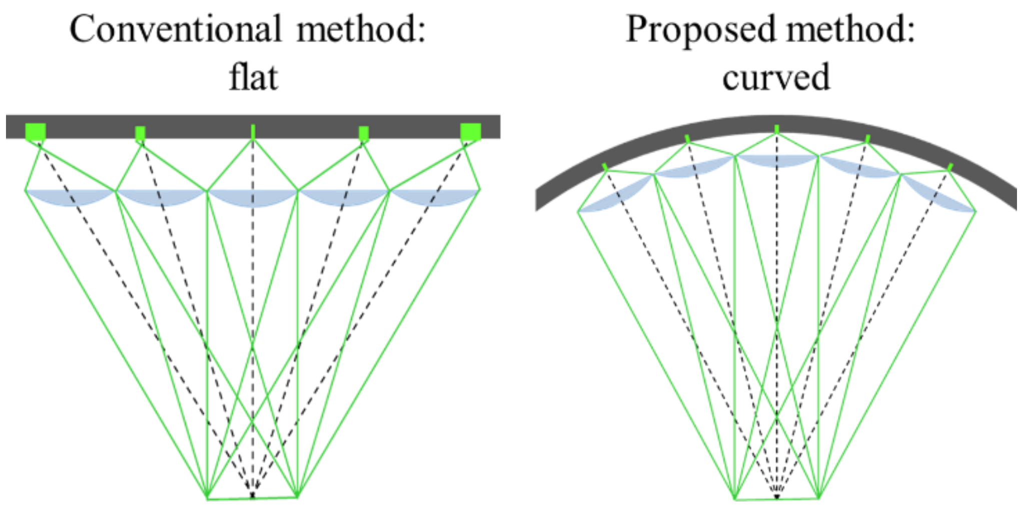


Figure 3.1.1. Comparison between a flat and curved arrangement of lenses.

### 3.1.2 An autostereoscopic display using a curved lens array

Figure 3.1.2 shows a dot-matrix light source, which is composed of an LED surface light source and a 27-inch LCD panel with an R1800 curve. As the backlight is on a circular arc with a radius of 1800 mm, the lenses are arranged on a circular arc sharing the same center of the circle with the backlight, so that the gap between the lens array and LCD panel is always equal to the focal length. As with the conventional research, the lens array is aligned with stepwise phase shifts, and a vertical diffuser is used to achieve a uniformly bright image. Additionally, partial ring-shaped mirrors are placed to separate the light sources for different rows of elemental lenses.

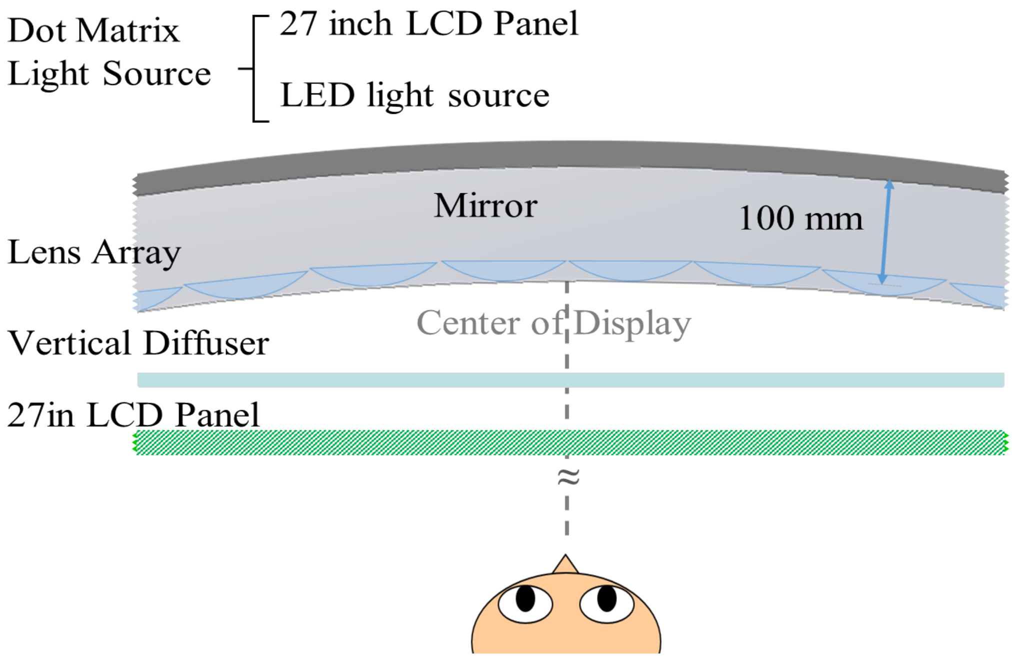

Figure 3.1.2. Autostereoscopic display system using a curved lens array.

### 3.1.3 Results

A prototype display system based on the proposed method is implemented, and its crosstalk level is evaluated. Figure 3.1.3 shows elemental lenses made by cutting circular acrylic plates with a thickness of 15 mm. The lens has a width, height, and focal length of 48, 15 and 100 mm, respectively. Figure 3.1.4 shows that each row of lenses was shifted in the horizontal direction by different offsets to remove the periodicity in the same method as the conventional approaches [41].

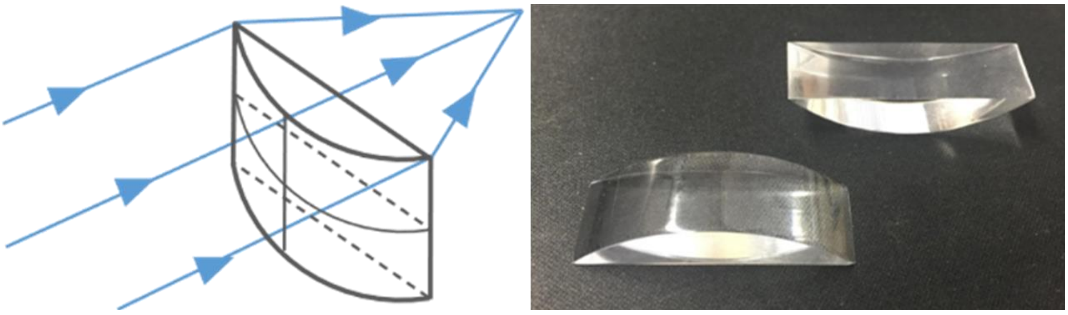

Figure 3.1.3. Cylindrical elemental lens.

Figure 3.1.4. Proposed curved lens array.

Figure 3.1.5 depicts the prototype system. A pair of LCD panels with a 2560 × 1440 resolution and 144 Hz maximum refresh rate was used. The LCDs were taken from commercially available computer monitors (ASUS ROG SWIFT PG27V).

The crosstalk evaluation has similar crosstalk evaluation processes as those in Section 2.3. A measuring surface 800 mm away from the display is set to compare the results with the conventional system under the same condition. First, the point where the normal line of display surface passing through the center of display intersects the measuring surface is called original point 0. Then, the point is shifted to the right (when facing the display) by 100 and 200 mm, resulting in two new points are called original points 1 and 2, respectively. The luminance was measured under the three conditions (Views 0, 1 and 2) every time the luminance meter was moved by 10 mm to the left and right, starting from original points 0, 1, and 2. Figure 3.1.6 depicts the experimental result at original point 0.

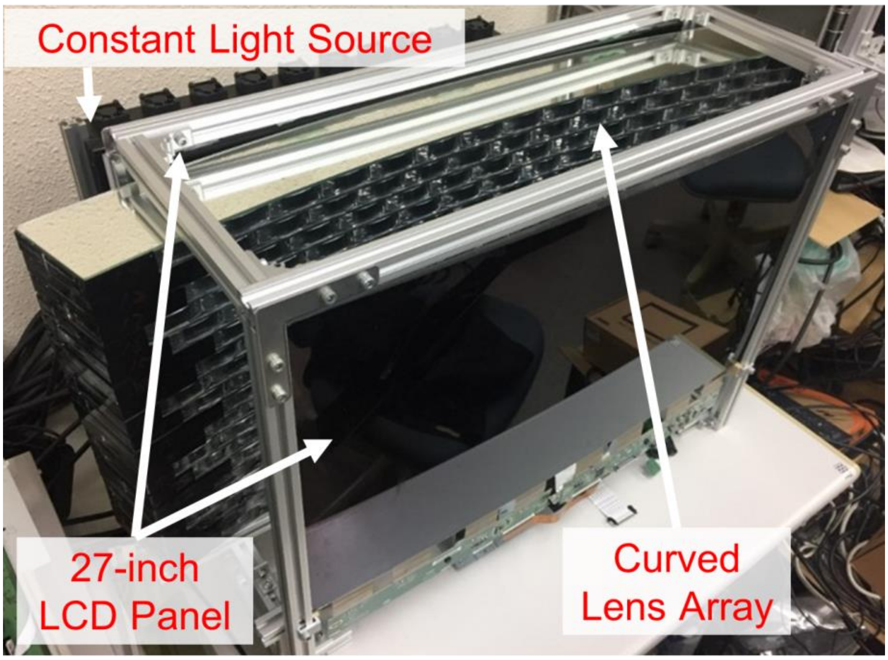


Figure 3.1.5. Prototype display system using a curved lens array.


Figure 3.1.6. The experimental result at original point 0.

The eye positions are chosen to minimize the crosstalk while restricting the interpupil distance to 60 or 70 mm. Table 3.1.1 summarizes the crosstalk levels of the three original points. The crosstalk levels in the conventional methods are 9.5% or higher at the center (Section 2.2), which implies that the crosstalk level is reduced significantly by the proposed method.

Table 3.1.1. Minimum crosstalk levels around three original points.

| Original point No. (shift distance [mm]) | Interpupil distance [mm] | Crosstalk level |
|---|---|---|
| 0 (0) | 60 | 4.6% |
| | 70 | 5.8% |
| 1 (100) | 60 | 6.2% |
| | 70 | 6.3% |
| 2 (200) | 60 | 12.7% |
| | 70 | 9.0% |

## 3.2 Realization of Uniform Backlight Intensity by Trapezoid Elemental Lenses

### 3.2.1 Insufficient backlight uniformity and extra crosstalk

When a curved lens array described in Section 3.1 is used, the uniformity of backlight is not sufficient, leading to low image quality [Figure 3.2.1 (left)], where a pure white image is shown. The reasons for low uniformity are the gaps between lenses, which emerge because of assembly errors of the handmade lens array, and the peripheral darkening in the lens surface (the light going through the peripheral part of elemental lenses is weaker than that going through the center of lenses). Additionally, Figure 3.2.1 (right) shows that light leakage from the gap between the elemental lenses also causes crosstalk, where a pure black image is shown. To solve the problems of degraded image quality and crosstalk, the use of a lens array composed of trapezoid-shaped lenses is proposed.

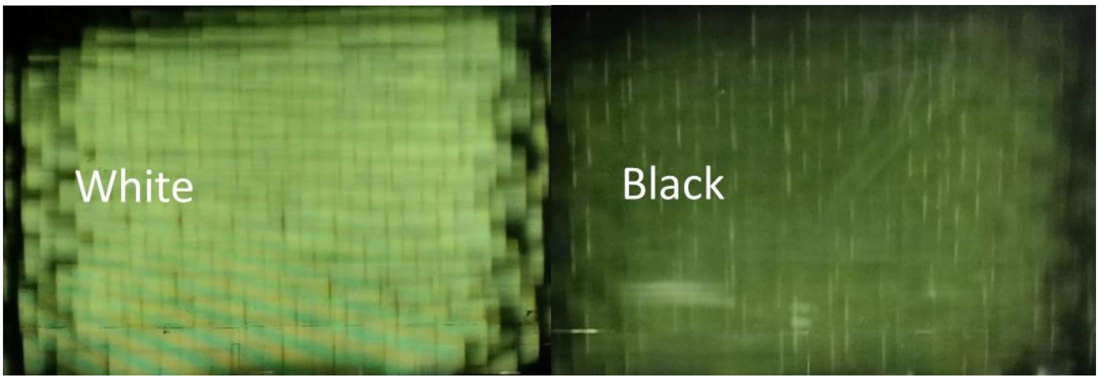


Figure 3.2.1. Low image quality and the crosstalk of the system with a curved lens array.

### 3.2.2 An autostereoscopic display using a lens array composed of trapezoid-shaped lenses

Figure 3.2.2 shows a trapezoid lens used for the elemental lens array. The elemental lenses are set so that the neighboring two lenses will be upside down (Figure 3.2.3). The darkening of light becomes severe in the edge part of elemental lenses, as explained above. By using trapezoid lenses, the dark part in the edge and the brighter part in the center are mixed when the light is mixed with a vertical diffuser, thus increasing the uniformity of backlight intensity.

Additionally, the connecting part between the lenses is an oblique cut surface that is wider than a cutting edge of the rectangle elemental lens in the conventional method, which avoids the emergence of gaps between the aligned lenses. Thus, fewer influences of lens array's assembly errors and more minor leakages of light are expected in this method.

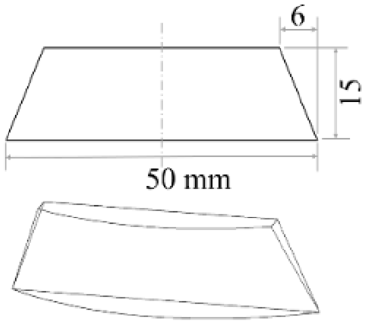


Figure 3.2.2. Trapezoid elemental lens.

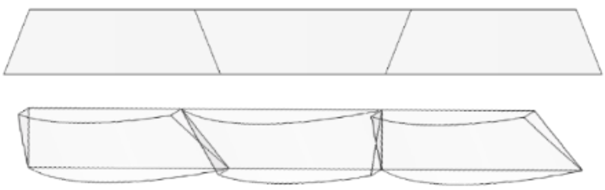

Figure 3.2.3. A part of the trapezoid lens array.

### 3.2.3 Results

A prototype display system based on the proposed method is implemented, and its crosstalk level is evaluated using the same method shown in the previous section. The elemental lenses were made by cutting circular acrylic plates with a thickness of 15 mm. The lens has width, height, and focal length of 50, 15, and 100 mm, respectively. Further, the lens is processed into the trapezoid shape (Figure 3.2.2).

Figure 3.2.4 shows comparisons of the observed backlight pattern between the rectangle and the trapezoid lens arrays, where pure green and red images are shown to the left and right eye, respectively. The uniformity of backlight is improved when trapezoid elemental lenses are used in place of rectangle elemental lenses.

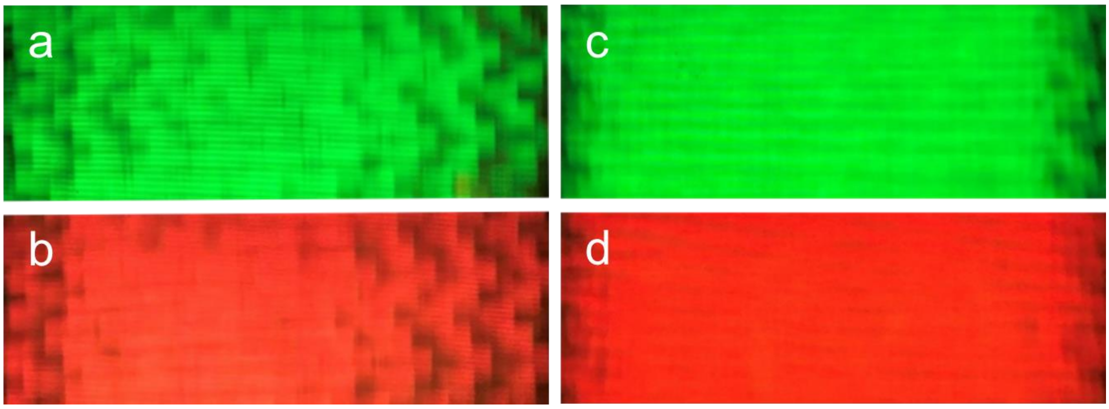


Figure 3.2.4. Photos of the system when displaying all green and red; the conventional method using rectangle elemental lenses (a, b) and the proposed method using trapezoid elemental lenses (c, d).

A luminance meter is used to measure and evaluate the crosstalk level. Table 3.2.1 shows the experimental result of crosstalk measurement; the crosstalk level is further reduced as expected.

The width of the viewing zone is examined to see how far a viewer can move without noticing intrusion of the other color when pure green and red images are shown to the left and right eyes, respectively. The viewer can move 550 mm in the horizontal direction without noticing crosstalk when the distance between the front panel and the viewer is 800 mm and move 680 mm wide when the distance from the display is 1200 mm.

Table 3.2.1. The minimum crosstalk level of a prototype using trapezoid elemental lenses.

| Original point No. (shift distance [mm]) | Interpupil distance [mm] | Crosstalk level |
|---|---|---|
| 0 (0) | 60 | 3.6% |
| | 70 | 4.6% |
| 1 (100) | 60 | 7.4% |
| | 70 | 4.8% |
| 2 (200) | 60 | 10.1% |
| | 70 | 8.7% |

## 3.3 Summary

In this chapter, a directional backlight system using a curved rectangle lens array is proposed in place of a flat lens array. The proposed system suppresses the influence of field curvature to reduce the overlap of light rays to the left and right eyes without placing an additional lens layer. A lower crosstalk level is confirmed in the experiment using a luminous meter. The crosstalk level in the conventional autostereoscopic systems that use a directional backlight is 9.5% or higher, whereas that of the proposed system is 4.6–5.8%. Additionally, an improved system is developed using trapezoid elemental lenses instead of rectangle lenses. A lower crosstalk level of 3.6–4.6% is attained, resulting in better image quality with more uniform backlight.

# 4 Alleviation of Postural Restriction and Improvement of Backlight Brightness

This chapter proposes a novel Fresnel lens array to achieve a uniform directional backlight with two-dimensional directionality. An autostereoscopic display with the proposed lens array improves the quality of image output and relieves the viewer's postural restriction without any additional eye aid. In the proposed lens array described in Section 4.2, tiny prisms composing two adjacent linear Fresnel lenses are interleaved so that the two lenses will virtually overlap and work independently, which implies that the light going through the two lenses is mixed and results in improved luminance uniformity. In Section 4.3, the widths of elemental prisms are changed based on the distance from the center of each lens to further improve uniformity. A prototype of an autostereoscopic display based on the time-multiplexed directional backlight is made with the proposed lens array, which attains uniform luminance and low crosstalk between left- and right-eye images.

## 4.1 Background

### 4.1.1 Postural restriction and low brightness caused by the vertical diffuser

An autostereoscopic display with full resolution of the display panel is achieved based on the basic principle of time-division multiplexing directional backlight composed of a lens array (Figure 1.2.9). Ishizuka et al. achieved a homogenous brightness of the image using vertical diffusers while aligning the lenses so that the lens arrangement phase in each row will be different from each other [40][41][42]. Additionally, two advanced versions of the system for reducing crosstalk were proposed in Chapters 2 and 3. However, the drawback of all methods relying on vertical diffusers to attain homogenous backlight is the collapse of stereoscopy when the observer tilts his or her head.

Figure 4.1.1 shows an optical system containing a lens array and a vertical diffuser. A light ray emitted from the dot-matrix light source is refracted horizontally by elemental lenses of the lens array and then vertically diffused by a diffuser. Vertical diffusion causes postural restriction for viewers and luminance loss. This optical process leads to two vertically expanded viewing zones for each eye because of the diffusion, which disables stereoscopy when the observer's head is tilted strongly (Figure 4.1.2). The light rays entering the observer's eye come from a small part of the original light of the dot-matrix light source. Thus, the strength of the constant light source of the dot-matrix light source must be extremely powerful to maintain an acceptable luminance in an indoor environment.

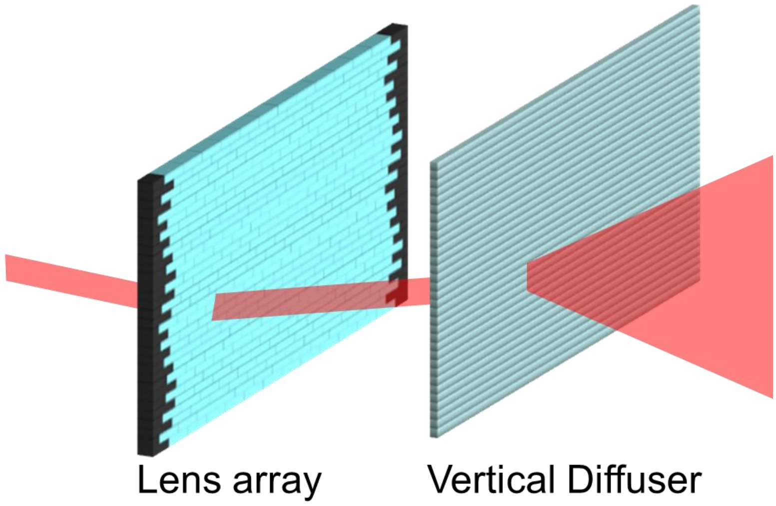


Figure 4.1.1. The optical system containing a lens array and a vertical diffuser.

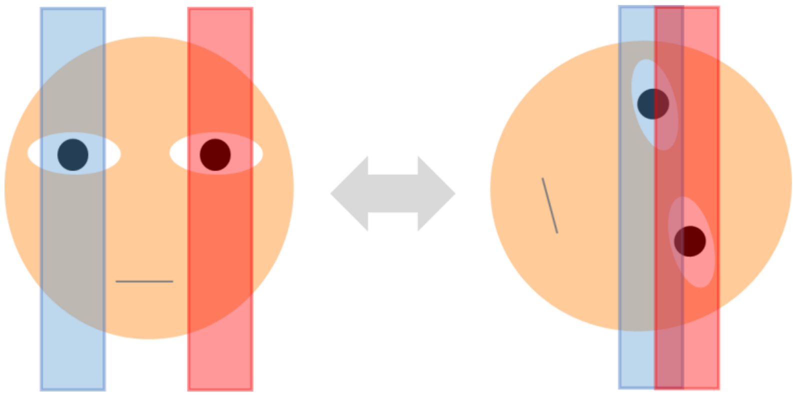

Figure 4.1.2. An overlap of viewing zones for different eyes when the viewer tilts their head.

### 4.1.2 Conventional approaches without a vertical diffuser

A lens array can be used to attain autostereoscopy in different ways besides the directional backlight. For example, integral imaging uses a lens array to achieve a multiview display. To obscure the distinct seam of lenses in the coarse integral volumetric imaging display [43][44][45][46][47][48], Kakeya et al. proposed a method of using a unique linear Fresnel lens array (Figure 4.1.3) [49]. As the figure shows, the small elemental prisms for the left and right lenses are interleaved in the connecting part of the lenses, making the seam of adjacent lenses less distinct. A convex lens array with non-distinct seams is achieved using two layers of these lenses.

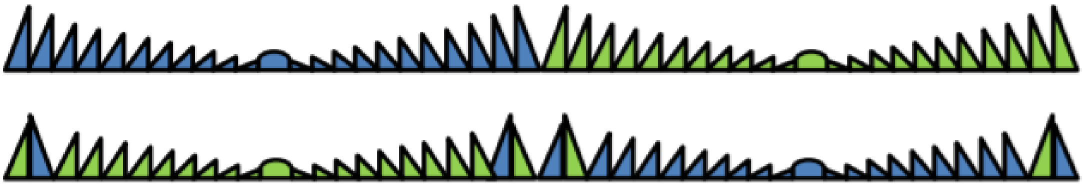

Figure 4.1.3. Linear Fresnel lens with non-distinct seam; standard Fresnel elemental lenses aligned side by side (above) and the elemental lenses with interleaved grooves in the connecting part (below).

To achieve the non-distinct seam in the horizontal and vertical directions, Kakeya et al. stacked horizontal and vertical linear Fresnel lens arrays, each of which has horizontally or vertically interleaved grooves. Figure 4.1.4 depicts the lens array they created. The central part of each elemental lens is the ordinary lens, and the peripheral part has an interleaved structure.

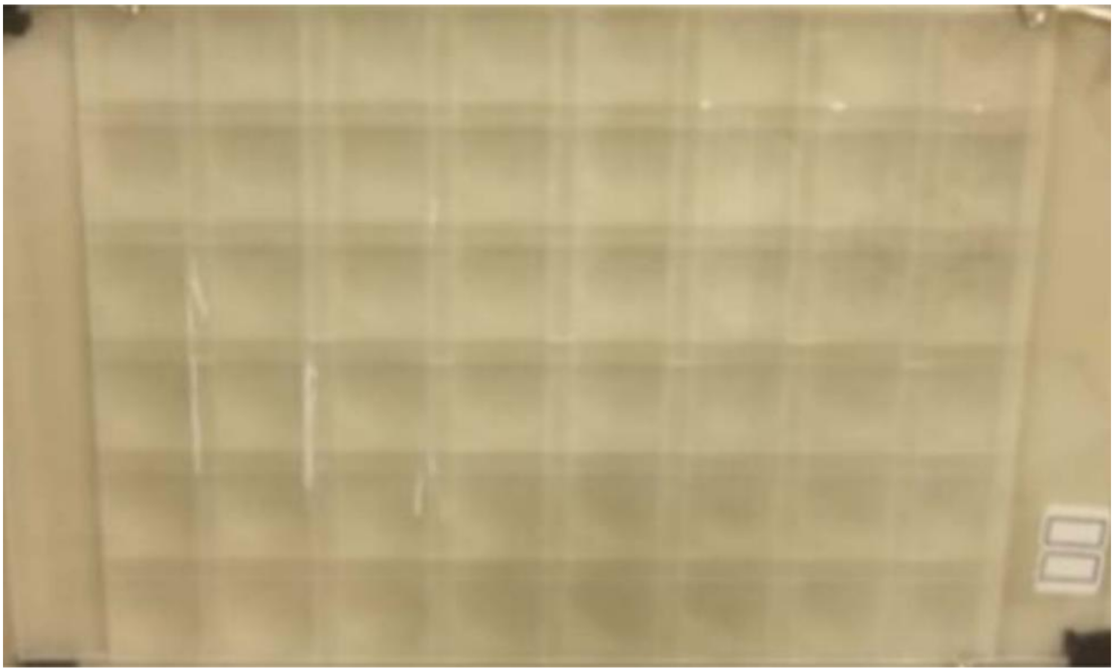

Figure 4.1.4. Elemental lens array with interleaved grooves in the conventional method[49].

Figure 4.1.5 shows the images presented by the ordinary and novel lens arrays with interleaved grooves. It is confirmed that the novel lens array can erase the distinctive discontinuity.

Figure 4.1.5. The images are presented by the ordinary lens array (left) and the novel lens array (right)[49].

## 4.2 Linear Fresnel Lens with an Interleaved Structure

### 4.2.1 Extension of the interleaved structure

To overcome the drawback of the conventional systems described in Section 4.1, a method using the linear Fresnel lens with an interleaved structure is proposed to achieve a homogenous backlight.

Figure 4.2.1 shows the proposed lenses used to achieve a homogenous backlight. Although the basic principle of the lens for obscuring the seam is the same as that in Figure 4.1.3, the prisms are interleaved not only in the peripheral part of the elemental lenses but also in the central part, which implies that the elemental prisms are interleaved across the entire Fresnel lens.

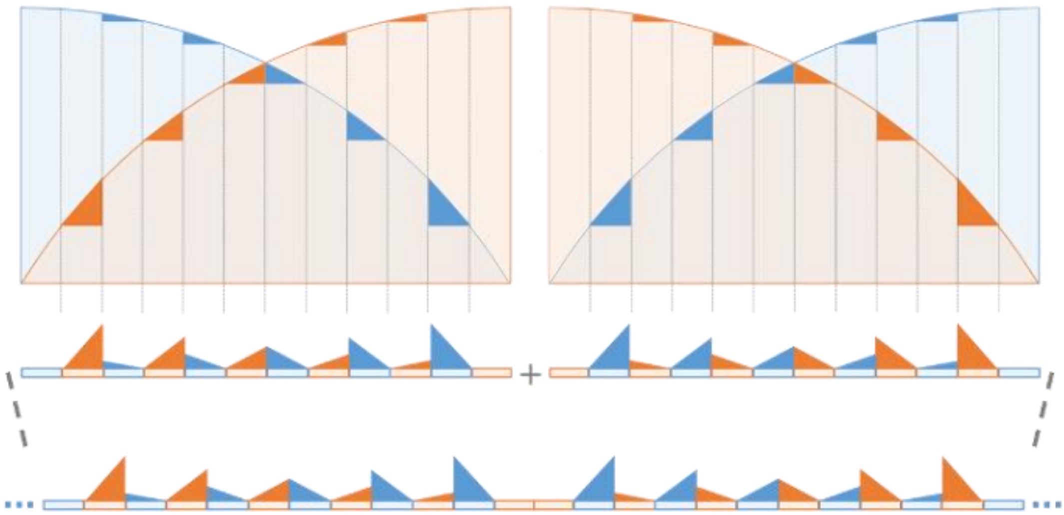

Figure 4.2.1. The proposed linear Fresnel lens.

Figure 4.2.2 shows that when two layers of the normal linear Fresnel lens (two elemental lenses aligned in horizontal and vertical directions with one elemental lens highlighted) are stacked orthogonally [Figure 4.2.2 (a)], it is optically equivalent to a stack of cylindrical lens array [Figure 4.2.2 (b)] or a layer of convex lens array [Figure 4.2.2 (c)]. Thus, the intensity of the backlight is not homogenous [Figure 4.2.2 (d)].

When two layers of the novel linear Fresnel lens (four elemental lenses each overlapped in horizontal and vertical directions with one elemental lens highlighted) are stacked orthogonally [Figure 4.2.2 (e)], it is optically equivalent to a stack of overlapping cylindrical lens array [Figure 4.2.2 (f)] or a layer of overlapping convex lens array [Figure 4.2.2 (g)]. By applying this lens array, the uniformity of luminance is expected to increase [Figure 4.2.2 (h)] without adding a vertical diffuser.

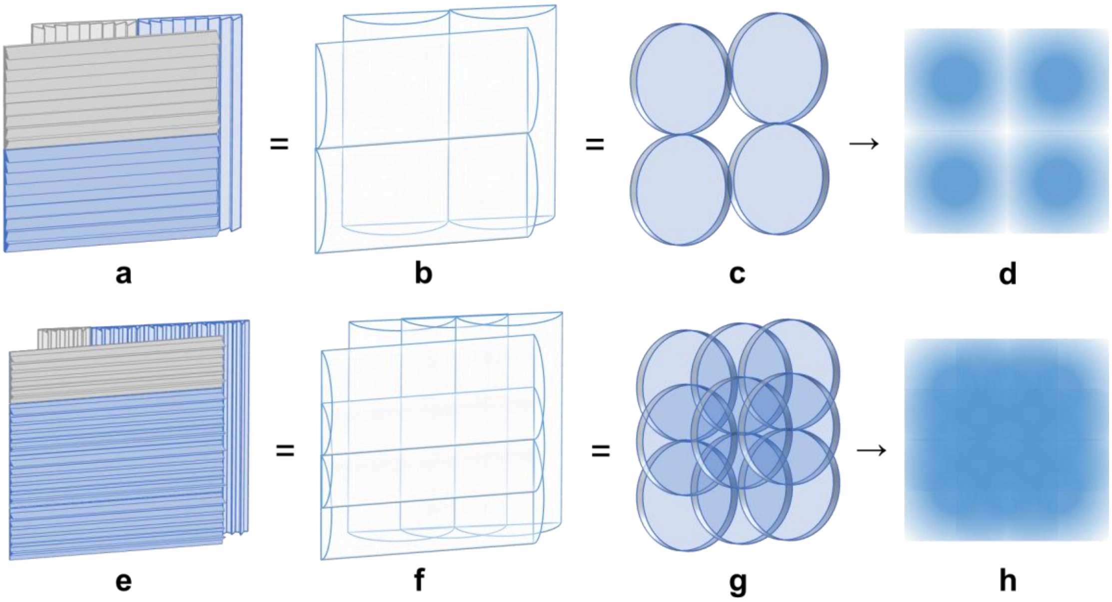


Figure 4.2.2. Structure of the lens array.

Figure 4.2.3 shows the optical layout of the autostereoscopic display using the lens array described above. The dot-matrix light source is composed of a LED surface light and a 27-inch LCD panel. The lens array, which consist of two layers of the novel linear Fresnel lens is placed 100 mm from the dot-matrix light source so that the gap between them will be equal to the focal length. A 24-inch LCD panel for displaying the images for two eyes is placed between the lens array and the observer.

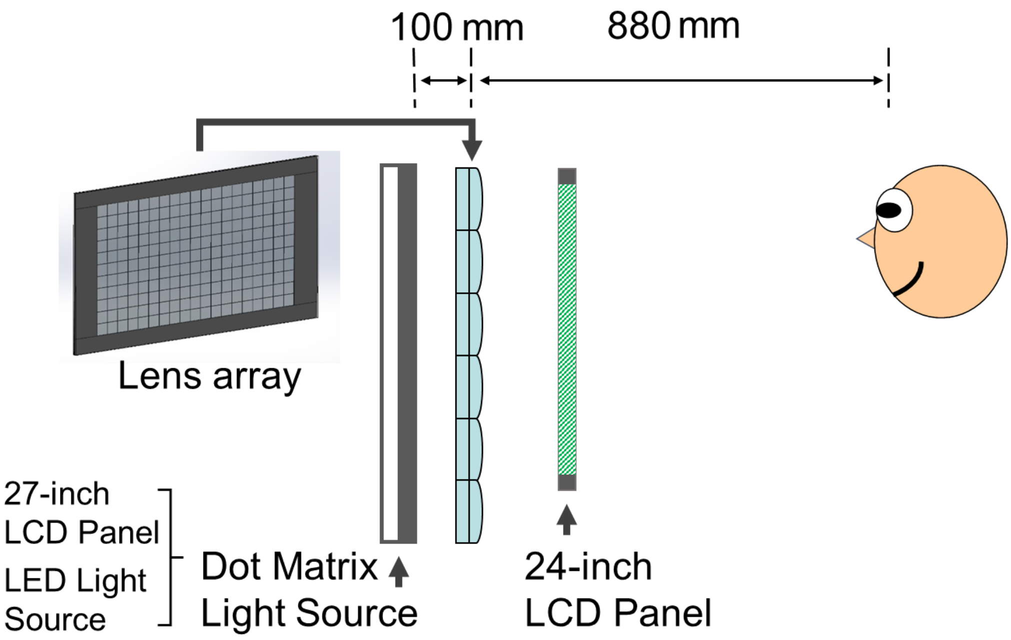


Figure 4.2.3. The optical layout of the autostereoscopic display system based on the linear Fresnel lens with an interleaved structure.

### 4.2.2 Results

A prototype display system is built based on the design of Subsection 4.2.1, and its crosstalk level is evaluated.

Figure 4.2.4 shows an interleaved linear Fresnel lens designed with a width and focal length of 30 and 100 mm, respectively, based on the principle explained in the previous subsection. The width of the elemental prism pair is 0.6 mm. Note that the width of the unit lens is approximately 60 mm because of the overlap. The size of the lens array is 510 mm (W) × 300 mm (H), with 17 and 10 elemental lenses in the horizontal and vertical directions, respectively. The elemental lenses are produced by plastics (PMMA) injection molding, with a metal mold based on the design of Figure 4.2.1. Figures 4.2.5 and 4.2.6 show the images of the lens array and the prototype display system. The LCD panels applied in the prototype had a resolution of 1920 × 1080 and a 120 Hz maximum refresh rate.

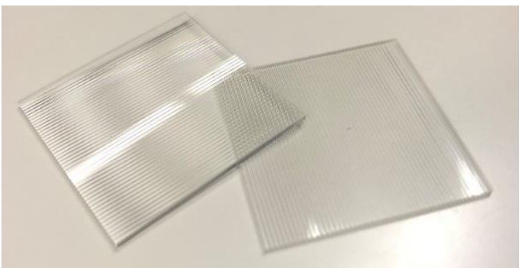

Figure 4.2.4. Photo of the proposed linear Fresnel lens with an interleaved structure.


Figure 4.2.5. Image of the proposed linear Fresnel lens array with an interleaved structure.

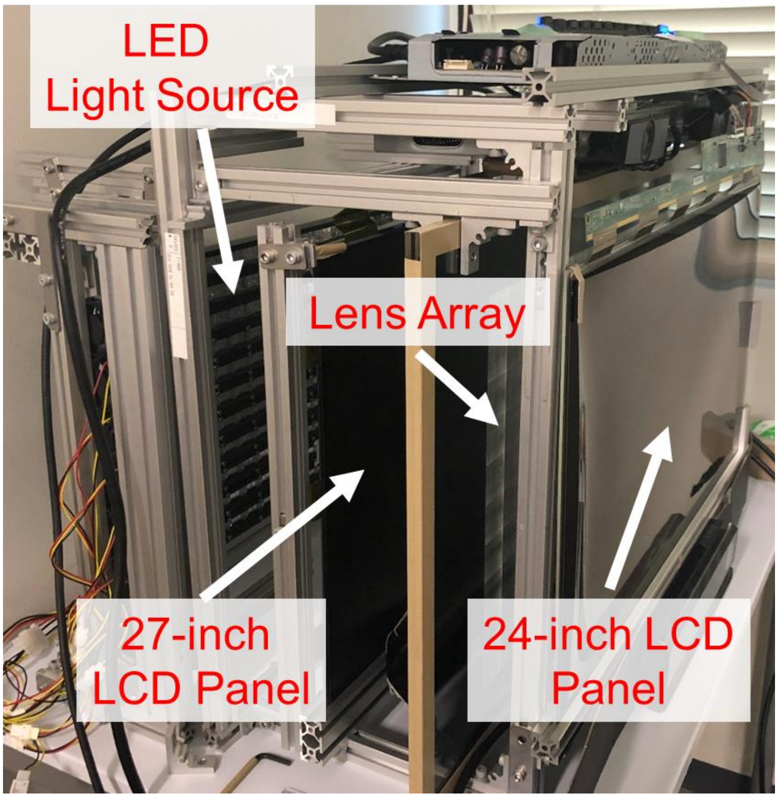


Figure 4.2.6. Prototype display system using linear Fresnel lens array with an interleaved structure.

Figure 4.2.7 depicts the results of the observation. Here full red image and green images were displayed for the left and right eyes, respectively, for testing. It can be observed that the central area of the image is more uniform than the peripheral area. Leakages of light between the elemental lenses are also visible because the lens units are assembled by hand.

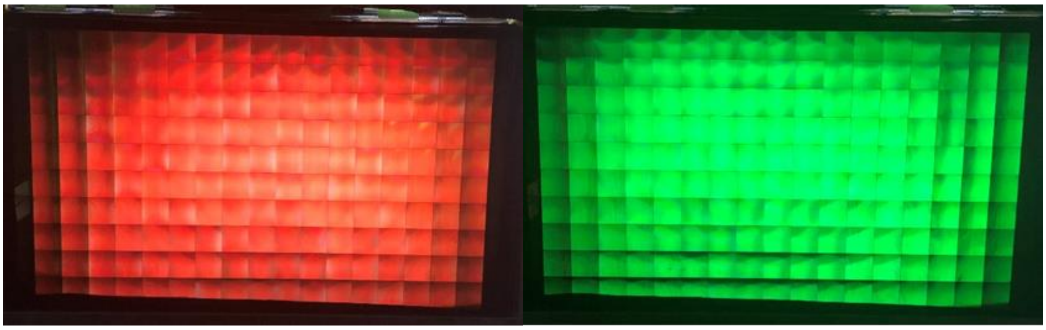

Figure 4.2.7. Observation of test image using the prototype display system.

The same crosstalk evaluation processes in Section 2.3 are applied here. The original point of measurement is set in the center of the display panel, while the distance is 800 mm away from the panel. The luminance was measured every time a luminance meter was moved by 10 mm horizontally. The distance of the luminance meter moved from the original point is denoted as *d*. Figure 4.2.8 depicts the result of the experiment.

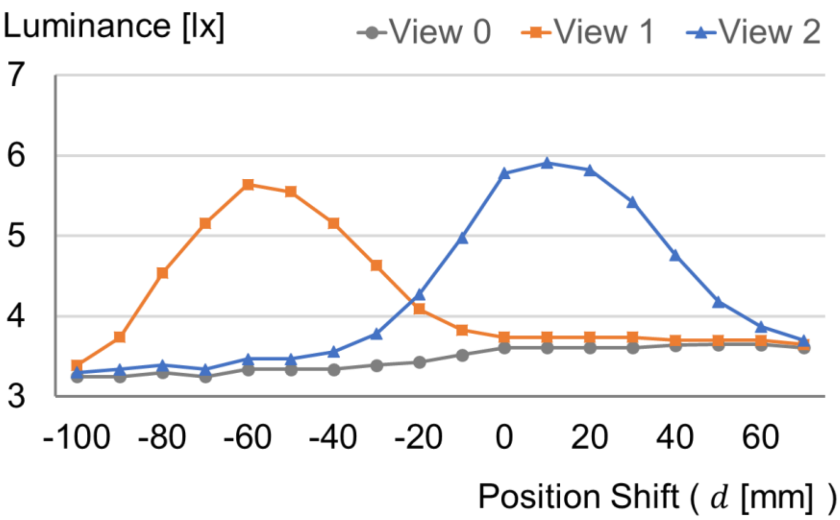


Figure 4.2.8. Result of crosstalk measurement.

The suitable eye position for stereoscopy is decided to minimize crosstalk while the interpupil distance (PD) is restricted to 60 or 70 mm. By substituting the experimental data into Equation 2.2, the crosstalk level is determined to be 5.8% (PD = 60 mm) and 5.4% (PD = 70 mm). The lowest crosstalk level in the conventional autostereoscopic systems with a directional backlight using a diffuser is 4.6–5.8% (Subsection 3.2.3), indicating that the crosstalk level of the proposed method is on the same level as that in the previous study.

## 4.3 Improvement of Backlight Uniformity

### 4.3.1 Redesign of the linear Fresnel lens with an interleaved structure

Figure 4.3.1 shows that the problem of the lens proposed in Subsection 4.2.1 is a discontinuity in the center of lenses, where the fragments of steep prisms face the opposite directions, causing a sudden change in luminance.

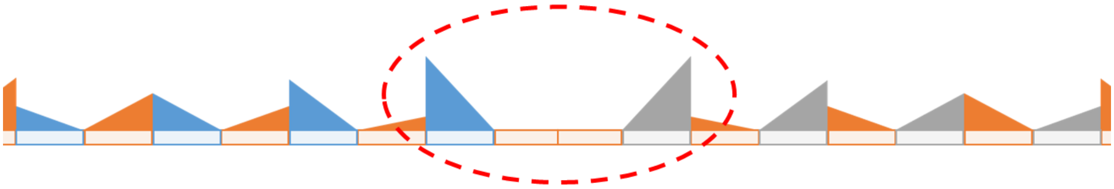

Figure 4.3.1. The discontinuity of lenses.

This problem can be solved by gradually shortening the width of steeper prisms to suppress the sudden change in luminance. The upper part of Figure 4.3.2 shows a partial cross-section of the conventional linear Fresnel lens with an interleaved structure. The light going through the prism with a steep tilt angle ($\alpha_r$) is weaker than that going through the prism with a shallow tilt angle ($\alpha_l$), while their horizontal widths of elemental prisms are all equal. Additionally, the dotted circle in Figure 4.3.2 shows that a sudden height drop occurs in the connecting part of the elemental prisms.

An improved design of the interleaved linear Fresnel lens is proposed to solve this problem. The lower part of Figure 4.3.2 shows that the facet of the prism whose tilt angle ($\alpha_l$) is smaller than the other ($\alpha_r$) in the prism pair is extended to intersect the facet of the other prism, as shown by the dotted lines. Further, the width ratios of prisms to the total width of the prism pair are rearranged based on the intersection point so that the width of the steeper prism becomes shorter. Thus, improved continuity of light luminance going through the lens is expected. This also makes the brighter part of the lens wider, which contributes to the increase in overall luminance. The structure of the lens becomes simpler by removing the vertical sudden drops in the connecting part of two prism segments.

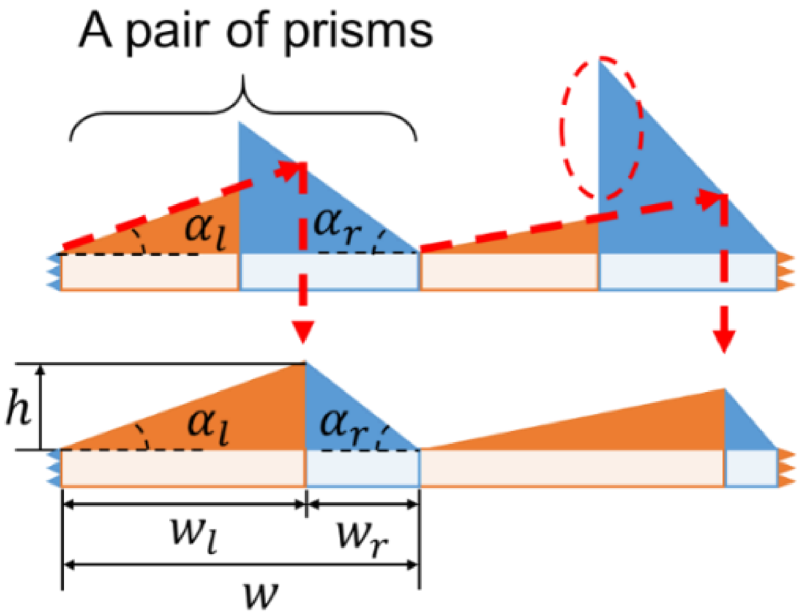


Figure 4.3.2. Improved redesign of the conventional linear Fresnel lens with the interleaved structure.

The width of each prism segment is easily calculated from the trigonometric function according to Figure 4.3.2. Let the total width of prism pairs be $w$, the tilt angles of each prism be $\alpha_l$ and $\alpha_r$ respectively. Then, the widths of the two elemental prisms, $w_l$ and $w_r$, are given as follows:

$$w_l = \frac{h}{\tan \alpha_l}, \tag{4.1}$$

$$w_r = \frac{h}{\tan \alpha_r}, \tag{4.2}$$

where $h$ is the height. Since $w = w_l + w_r$ holds, $h$ is given as follows:

$$h = \frac{w \tan \alpha_l \tan \alpha_r}{\tan \alpha_l + \tan \alpha_r}. \tag{4.3}$$

By substituting Equation 4.3 into Equation 4.1 and 4.2, $w_l$ and $w_r$ are obtained as follows:

$$w_l = \frac{w \tan \alpha_r}{\tan \alpha_l + \tan \alpha_r}, \tag{4.4}$$

$$w_r = \frac{w \tan \alpha_l}{\tan \alpha_l + \tan \alpha_r}. \tag{4.5}$$

Thus, the ratio of $w_l$ to $w_r$ is given as follows:

$$\frac{w_l}{w_r} = \frac{\tan \alpha_r}{\tan \alpha_l}. \quad (4.6)$$

### 4.3.2 Results

The width ratio of the interleaved linear Fresnel lens, with a width and focal length of 30 and 100 mm, respectively, was adjusted based on the principle explained in the previous subsection (Figure 4.3.3). The width of the elemental prism pair was 0.6 mm. The width of unit lens was virtually 60 mm because of the overlap. The manufacturing process of lenses was the same as that in Subsection 4.2.2.

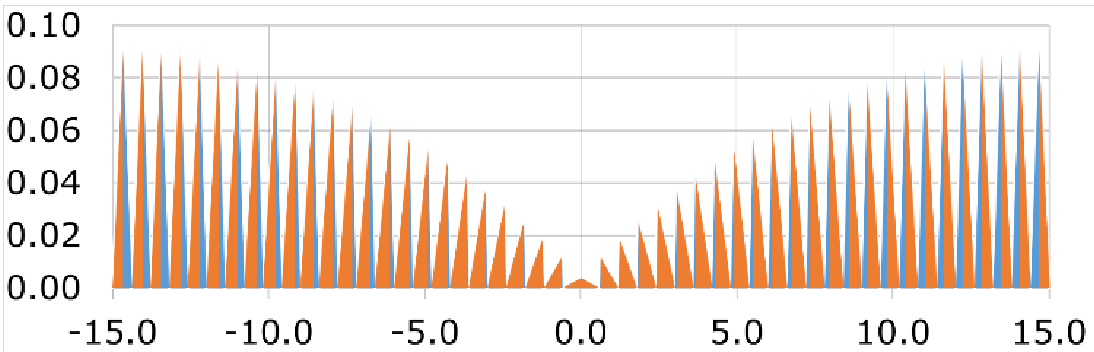


Figure 4.3.3. Improved design of the interleaved linear Fresnel lens [mm].

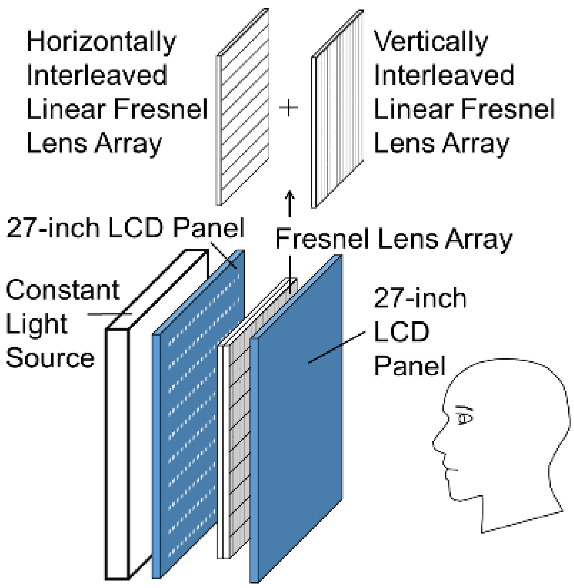


Figure 4.3.4. Optical layout of the proposed system and the prototype autostereoscopic display system.

A prototype autostereoscopic display system was created by stacking two layers of the above lens array orthogonally and tested to verify that it worked as expected. Figure 4.3.4 and Figure 4.3.5 shows pictures of the optical layout and the prototype system, respectively. The 27-inch LCD panel used for the prototype system has a resolution of 1920 × 1080 and a 240 Hz maximum refresh rate. A dot-matrix light source was simulated by combining a LED surface light and a 27-inch LCD panel that synchronized with the LCD in front at the same refresh rate. Two layers of novel Fresnel lens array were stacked orthogonally to compose the lens array. The lens array size was 540 mm (W) × 300 mm (H), with 18 and 10 elemental lenses in the horizontal and vertical directions, respectively.

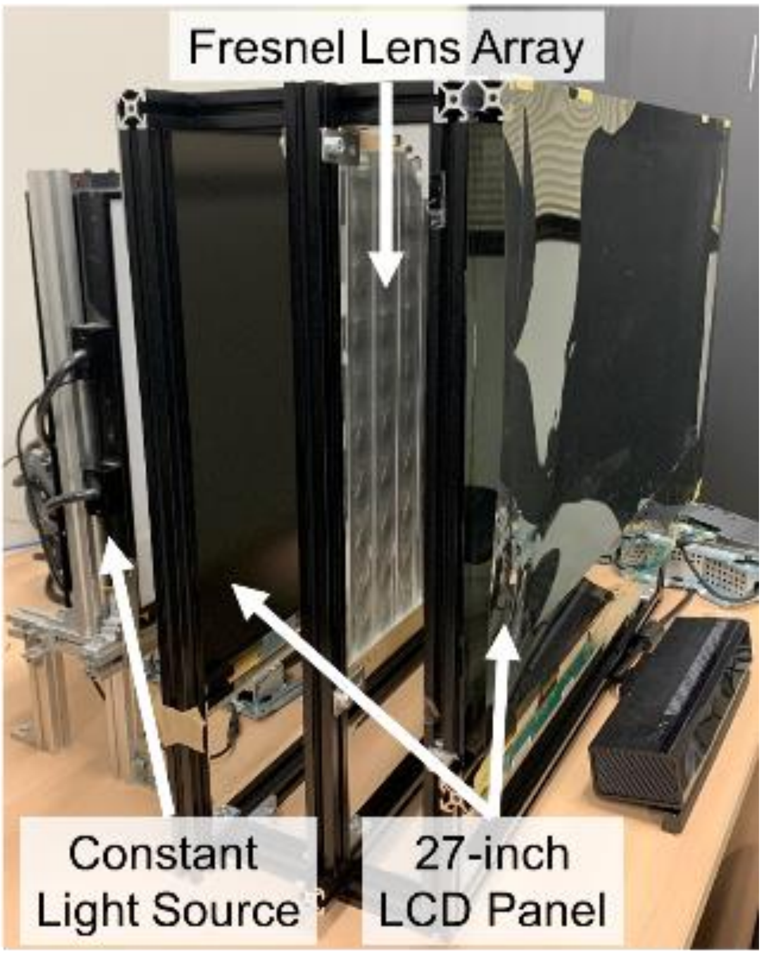


Figure 4.3.5. Prototype system.

The homogeneity of luminance is evaluated in the proposed system. Figure 4.3.6 depicts the angular distribution of the light exiting the LCD panel placed behind the lens array. A luminance colorimeter, TOPCON BM-7AC, is used throughout the experiment. First, the sRGB gray levels given by a digital camera (Panasonic DMC-FZH1) and its corresponding luminance were measured under the experimental environment while displaying pure gray color, and the polynomial trendline of the corresponding value was obtained (Figure 4.3.7).

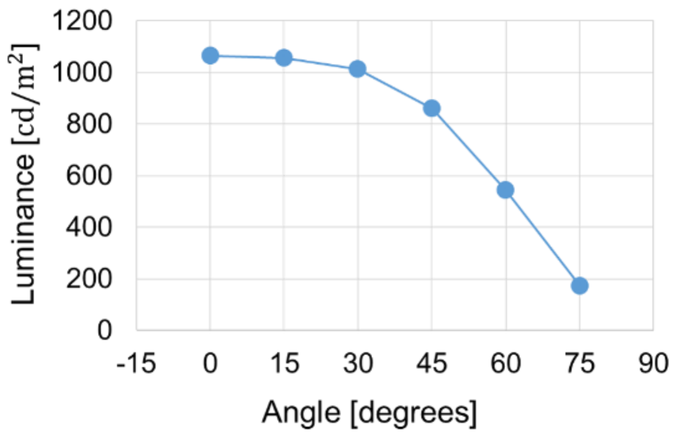


Figure 4.3.6. Angular distribution of luminance exiting the LCD placed behind the lens array.

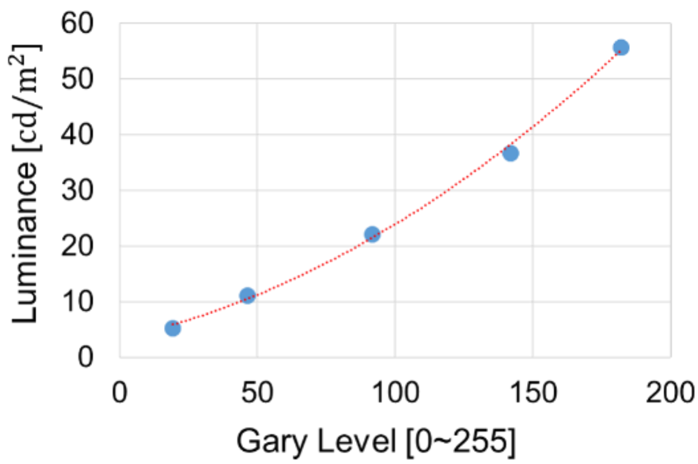


Figure 4.3.7. Correspondence between the sRGB gray level and the luminance.

Figure 4.3.8 (a) shows a captured image (640 × 480 resolution by a digital camera) of the central part of the prototype display using the conventional interleaved lens array proposed in Section 4.2. Figure 4.3.8 (b) shows the captured image of the prototype display using the proposed lens array. Figure 4.3.8 (x) shows the histograms of gray-level distributions given by Figure 4.3.8 (a) and Figure 4.3.8 (b). The horizontal axis of the histogram represents the gray-level intensity of pixels ranging from 0 to 255, while the vertical axis represents the number of pixels in each intensity. Figure 4.3.8 (y) shows the distributions of luminance values obtained from the correspondence in Figure 4.3.7. Table 4.3.1 shows that the average intensity increases and the standard deviation of the intensity decreases when using the proposed lens array.

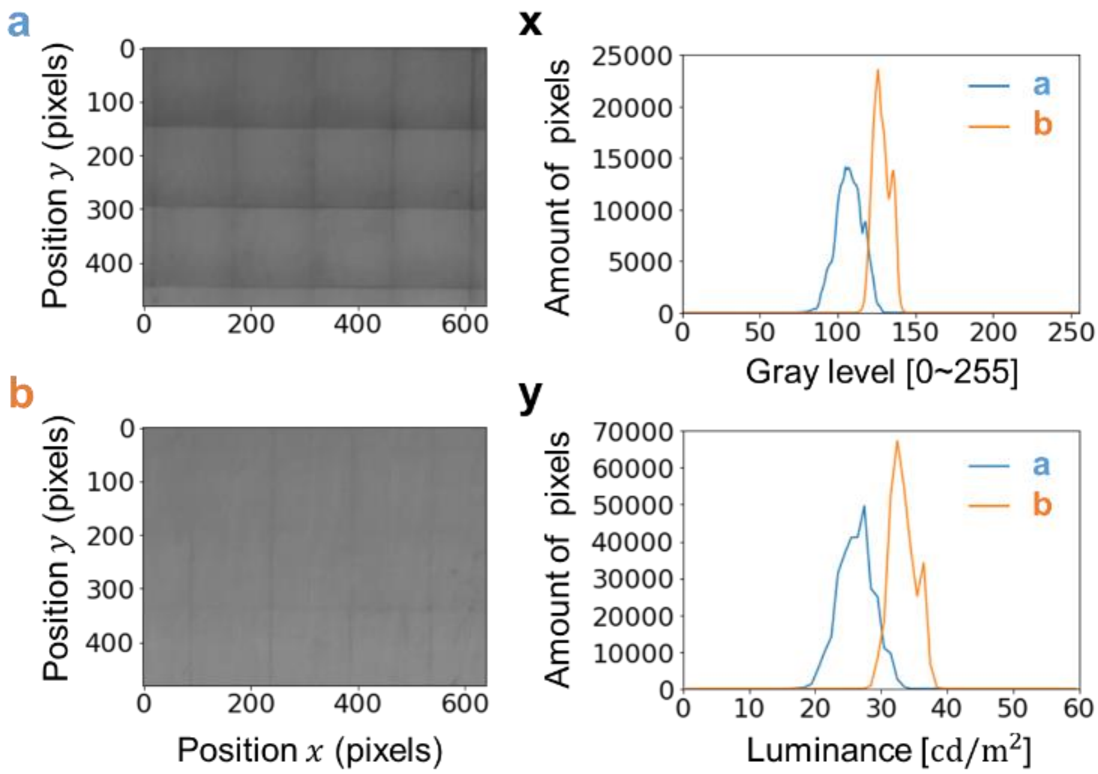


Figure 4.3.8. The intensity distribution of the captured image; photos of the conventional method (a) and the proposed method (b) on the left, and the gray-level distributions (x) and luminance distributions (y) on the right, where a and b correspond to the distributions in the images on the left side.

Table 4.3.1. Statistical data of intensity distribution.

| | | Conventional Method | Proposed Method |
|---|---|---|---|
| Average Value | Gray Level | 107.4 | 128.4 |
| | Luminance | 26.2 | 33.3 |
| Standard Deviation | Gray Level | 8.4 | 5.3 |
| | Luminance | 2.7 | 1.9 |

Further, the crosstalk level is measured by the luminance colorimeter. To evaluate the crosstalk level, the luminance was measured under the following three conditions: View 0 (both the left- and the right-eye images were black to measure the ambient luminance); View 1 (the left- and the right-eye images were white and black, respectively); View 2 (the left- and the right-eye images were black and white, respectively). The original point of measurement is set in the center of the display panel, while the distance is 800 mm away from the panel. The luminance was measured every time the viewing zones for each eye were moved 10 mm horizontally. The distance of the viewing zones moved from the original point is denoted as $d$. In the experiment, the size of the bright area corresponding to each viewpoint is 6 × 6 mm. The bright areas for the left and right eyes were separated so that the interpupil distance will be 65 mm. Figure 4.3.9 shows the results of the experiments with the conventional (Section 4.2) and proposed systems.

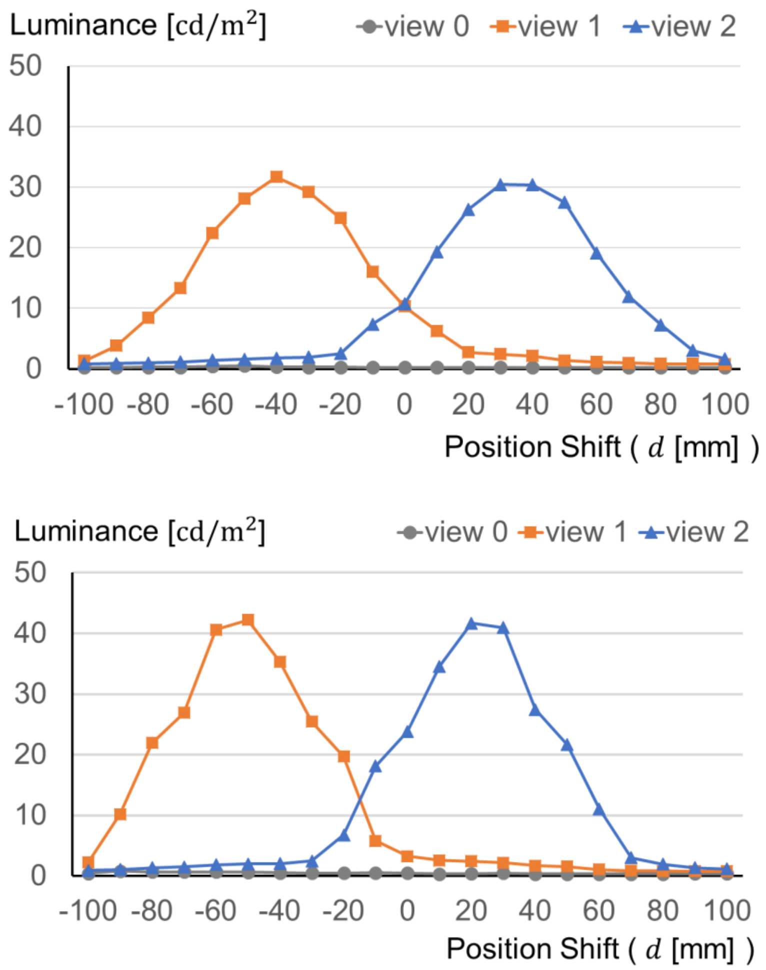


Figure 4.3.9. The result of crosstalk measurement. Conventional method (above) and the proposed method (below).

A suitable eye position for stereoscopy is chosen so that the crosstalk will be minimized while the interpupil distance (PD) is restricted to 60 or 70 mm. By substituting the experimental data into Equation 2.2, the crosstalk level is calculated as 6.5% (PD = 60 mm) and 5.8% (PD = 70 mm). The crosstalk levels of the conventional autostereoscopic systems are 9.2% (PD = 60 mm) and 8.3% (PD = 70 mm), which implies that the crosstalk level given by the proposed method is lower than that of the previous method.

## 4.4 Summary

In this chapter, a method for achieving directional backlight using a novel Fresnel lens array with an interleaved structure that does not require diffusers to achieve homogenous light intensity was proposed. The conventional systems rely on vertical diffusers to attain homogenous backlight impair stereoscopy when the observer tilts his or her head. The proposed method maintains autostereoscopy even when the head is inclined at 90 degrees. Additionally, the width ratios of prisms are rearranged to attain a uniform intensity of the backlight. The autostereoscopic display using the lens array with the prisms' width ratios rearranged achieves a more uniform backlight intensity and a lower crosstalk level than the display using a linear Fresnel lens array with prisms of the same width interleaved.

# 5 Realization of Unique Autostereoscopic Views for Each Viewer

This chapter proposes a novel autostereoscopic display with a directional backlight unit using a linear Fresnel lens array. In the proposed system, different stereoscopic image pairs can be provided to each of the two viewers simultaneously, and the viewing zone where two viewers can see specific views for their own eyes without interfering with each other's views is enlarged.

## 5.1 Background

Using time division multiplexing directional backlight with a lens array can attain high-resolution autostereoscopy with the same resolution as that of the display panel (Figure 1.2.9). Figure 5.1.1 shows that multiple viewers can share the stereoscopic image simultaneously by adding the light sources to the dot-matrix backlight for each viewer.

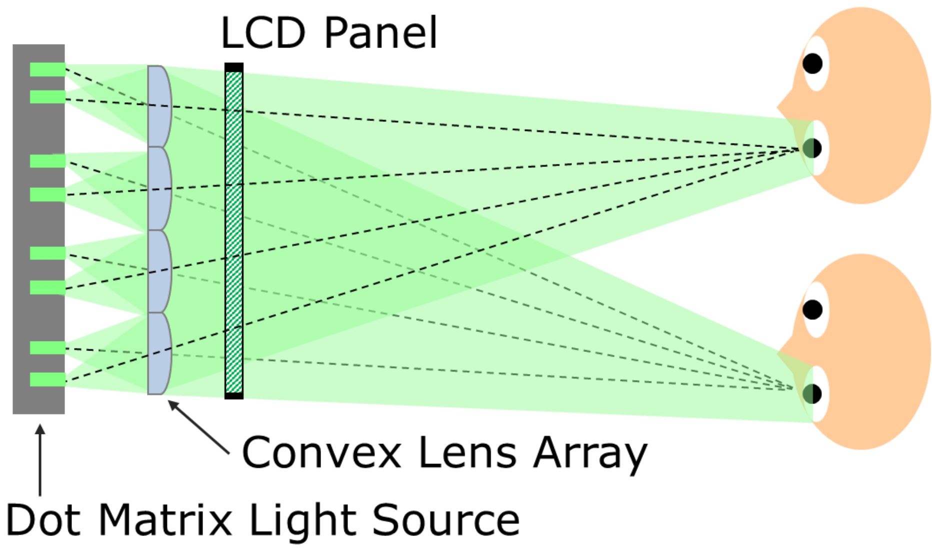


Figure 5.1.1. Autostereoscopic display for two viewers.

The uniformity of luminance is increased by applying the novel lens array with the interleaved structure proposed in Chapter 4. Although it is possible to simultaneously display autostereoscopic images to two viewers using the conventional method described above, the same stereoscopic image is shared between the two viewers. Further, the viewing zone where two viewers can observe the stereoscopic images without accidental overlap is narrow. Figure 5.1.2 shows a basic optical layout of an autostereoscopic display for two viewers using the lens array proposed in Chapter 4 when the heights of two viewers' eyes from the floor are proximate. The blue lighting spots on the dot-matrix and the blue light rays are for one viewer. The number of existing viewpoints originating from the lighting spot, O, is equal to the number of lenses. Viewpoint Y is the theoretic viewing position of the viewer, and the other viewpoints, like X, are the spots where the other viewer can see the image as crosstalk. No crosstalk zone for the other viewer is between X and Y, as marked with a red double-headed arrow. The width of the no crosstalk zone for the other viewer is given as follows:

$$|\overrightarrow{XY}| = \frac{100+800}{100}|\overrightarrow{AB}|, \qquad (5.1)$$

based on the similarity of $\Delta OAB$ and $\Delta OXY$. Since the distance between lens centers $|\overrightarrow{AB}|$ is 30 mm, the no crosstalk zone for the other viewer is 270 mm, which is less than viewers' shoulder breadth.

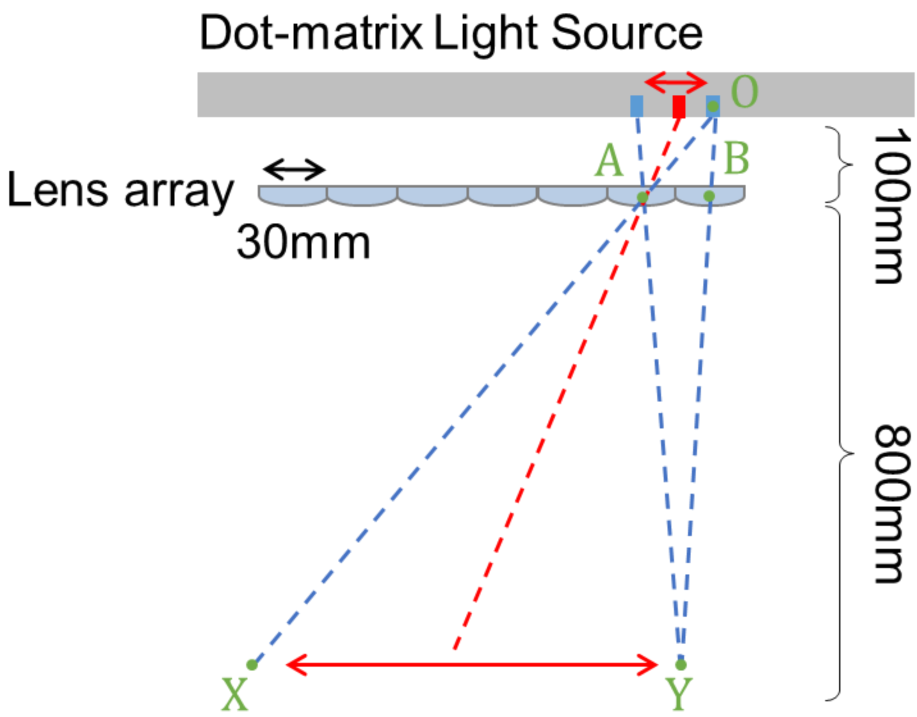

Figure 5.1.2. Basic optical layout of an autostereoscopic display for two viewers.

This chapter proposes an autostereoscopic display for two viewers with a directional backlight unit using the linear Fresnel lens array. In the proposed system, a pair of stereoscopic images can be displayed to two viewers simultaneously, and the viewing zone where they can see their views without interfering with each other's views is enlarged.

## 5.2 Extension of viewing zone by angle adjustment of lens array

Since four views are required when stereoscopic images specific to each viewpoint are shown to two viewers, our method applies a time-division quadruplexing at 240 Hz so that two viewers can see stereoscopic images with parallax simultaneously (Figure 5.2.1). An LCD panel with 240 Hz is applied to our system to display a 60 Hz high-resolution 3D image to each eye of the viewers.

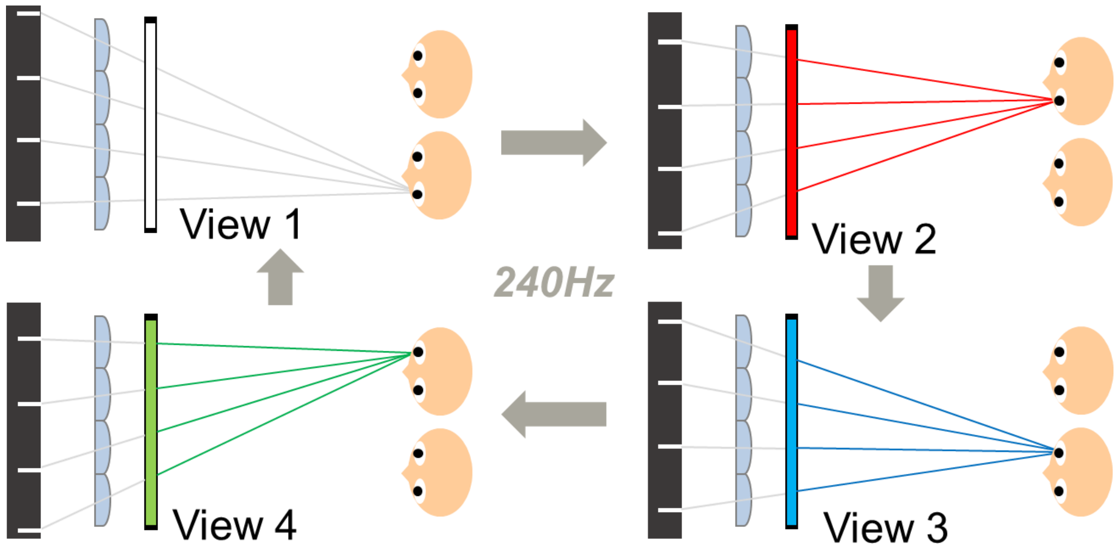


Figure 5.2.1. Time-division quadruplexing in 240Hz.

The lighting spots on the backlight for different viewers overlap with each other, causing interference with the images for another viewer. Figure 5.2.2 (above) shows the small gray rectangles representing the lighting spots for one viewer, and the orange rectangles are for the other viewer when two viewers' heads are at the same height. The double-headed arrow in Figure 5.2.2 (above) shows that the area where the orange rectangles can move without overlapping with the gray rectangles is narrow. The area can be enlarged by tilting the lens array [Figure 5.2.2 (below)]. The lens array is tilted by arctan (1/3) in the prototype display system.

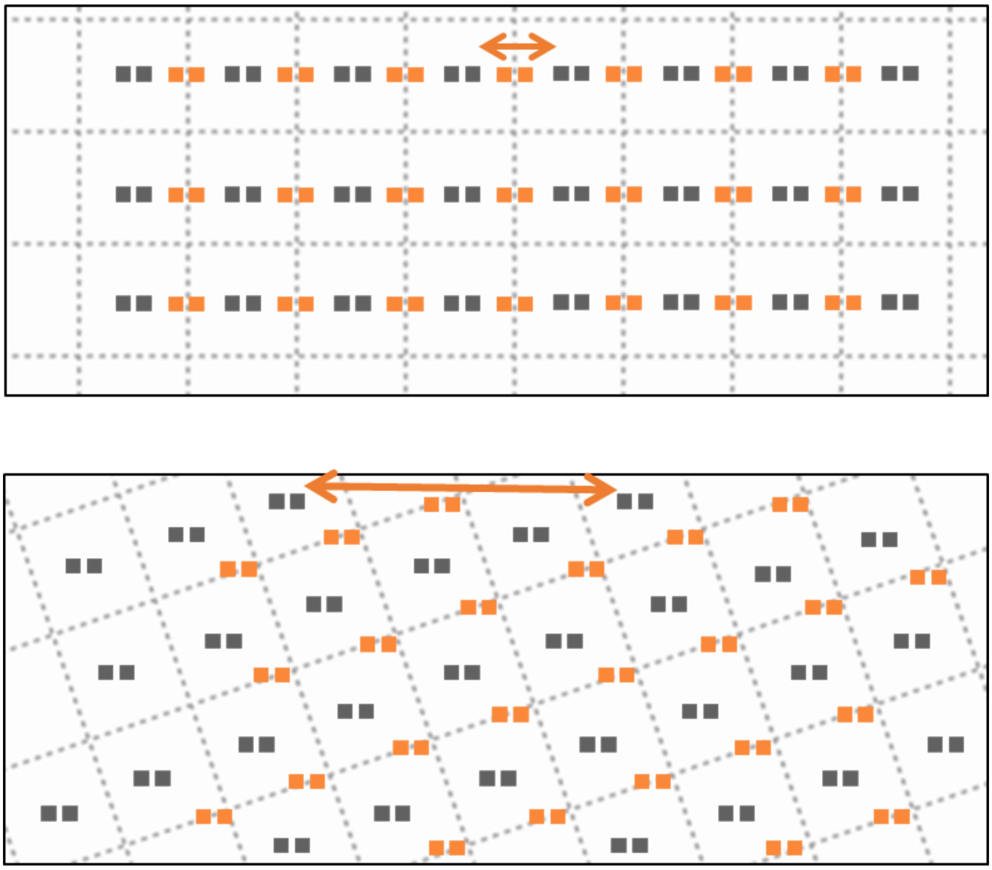

Figure 5.2.2. Enlargement of the viewing zone by rotating the lens array.

## 5.3 Experiments with hardware

A prototype system is designed based on the proposed method described in Section 5.2, and an observation experiment is conducted.

Figure 5.3.1 shows the tilted lens array. The size of the inscribed rectangle of the lens area of this lens array is 431.5 × 626.1 mm.

Figure 5.3.1. Photo of the tilted lens array.

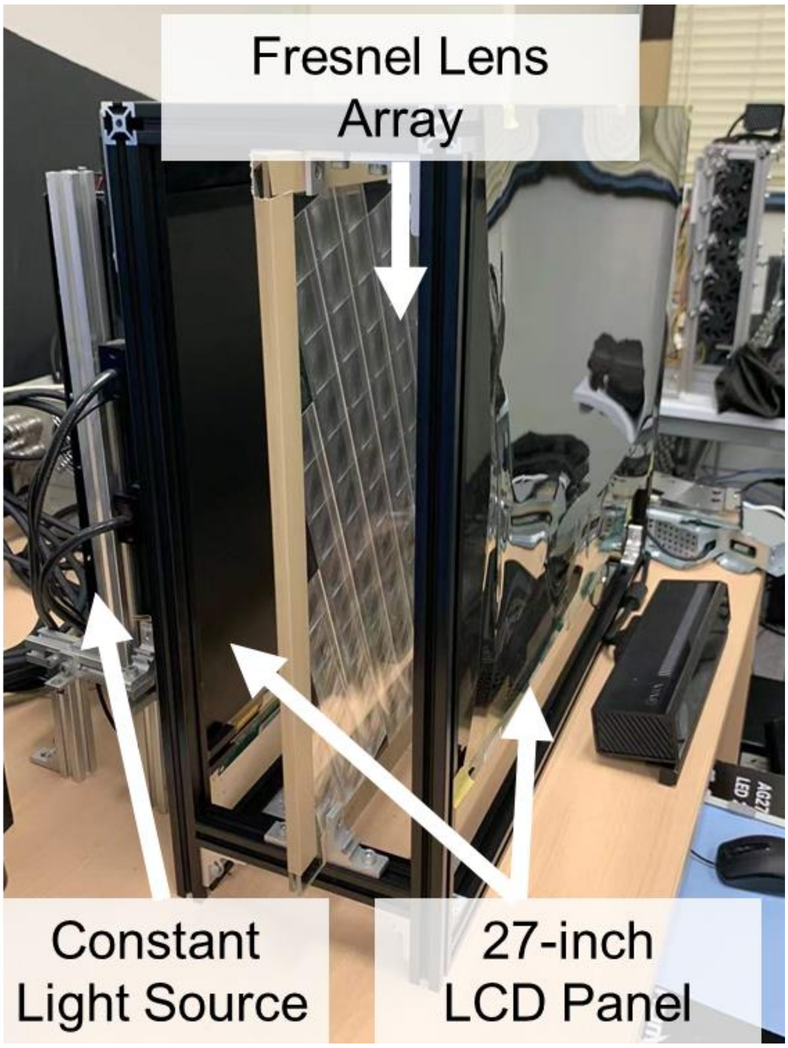


Figure 5.3.2. A prototype display system using a tilted lens array.

Figure 5.3.3 shows photos of the observation experiment. The left and right images for two viewers are captured using a camera. The parallax between left and right images and the difference between two different viewpoints can be observed. Figure 5.3.4 shows that the lighting spots for two viewers on the dot-matrix light source function as expected, thus ensuring a wide viewing zone for two viewers. The results described above verify that two viewers can see the stereoscopic images simultaneously, which is specific to each viewpoint within an enlarged viewing zone without interfering with each other's views.

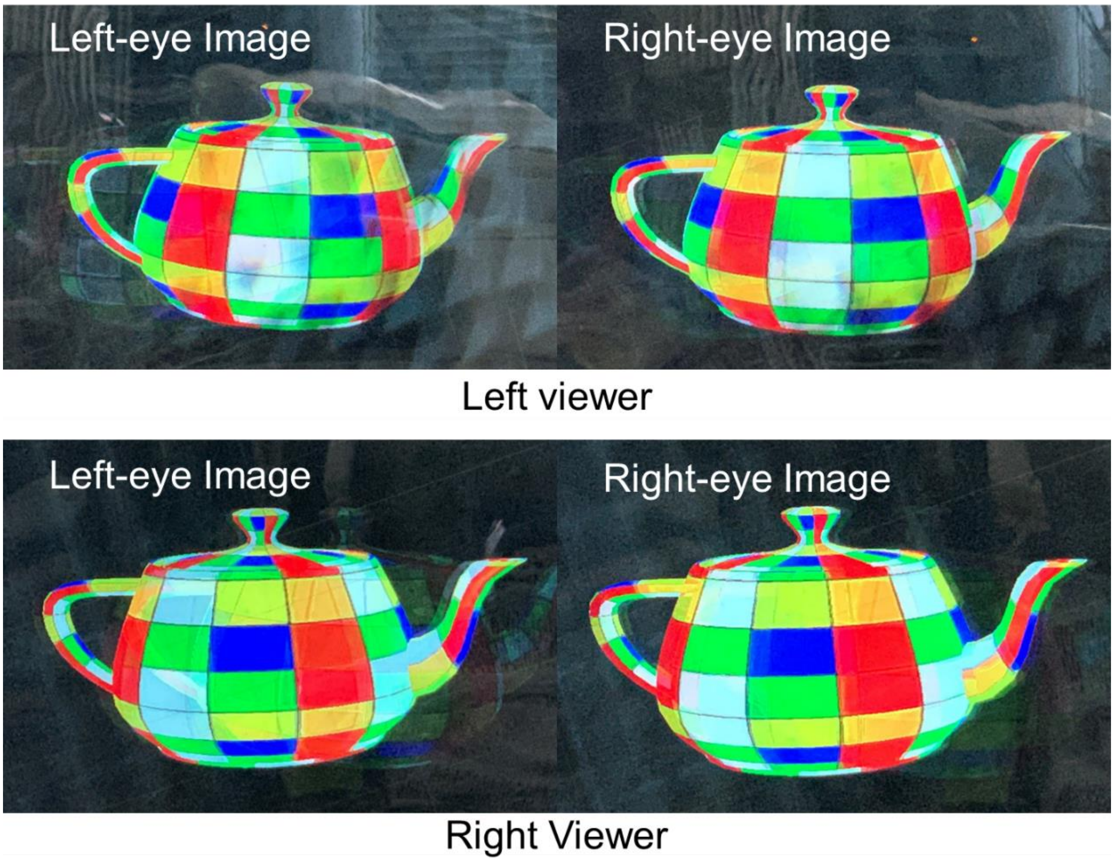


Figure 5.3.3. Photos of four viewpoints displaying a colorful teapot.

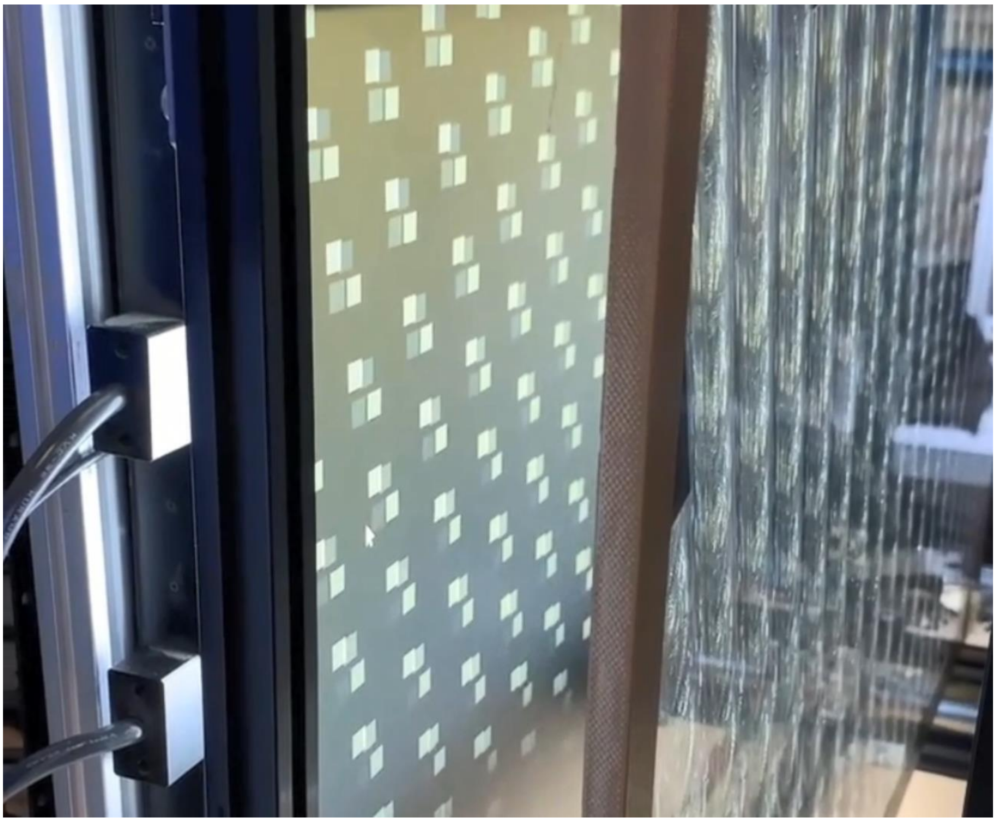

Figure 5.3.4. Photo of the dot-matrix light source for two viewers.

## 5.4 Summary

Besides multiview displays whose image resolution drops inevitably because of spatial multiplexing, autostereoscopic displays for multiple viewers proposed thus far provide the viewers with the same stereoscopic image and have narrow viewing zones. A novel autostereoscopic display with a directional backlight unit using a linear Fresnel lens array with an interleaved structure was proposed in this chapter. In the proposed display system, a pair of high-resolution stereoscopic images specific to each viewpoint is shown to two viewers simultaneously, with a wide viewing zone where two viewers can see their individual views without interfering with each other's views.

# 6 Autostereoscopic Display for Multiple Viewers Positioned at Different Distances

A directional backlight composed of a DMD (Digital Mirror Device) projector, a large aperture Fresnel lens, and multiple layers of PDLC screens with segmented electrodes that are electrically controlled to change the position of light diffusion is proposed in this chapter. A high-resolution autostereoscopy for multiple viewers positioned at different distances from the screen is achieved with this configuration.

## 6.1 Background

Hattori et al. merged an optical system using a pair of Fresnel lenses and a half mirror [25] to achieve an autostereoscopic display because the response time of LCD panels was not fast enough to be used for time-division multiplexing. Because LCD technology has advanced to the point where it can function at 120 Hz or more, the same goal can now be achieved with a single Fresnel lens optical system (Figure 6.1.1)

A directional backlight consists of a dot-matrix light source and a large aperture Fresnel lens. Directional light is delivered to each eye by emitting light at the conjugate focal points of the observer's eyes. As the directional backlight to each eye alternates synchronously with the alternation of left- and right-eye images on the LCD panel in front, the viewer can see a stereoscopic image without wearing special goggles. However, as the viewer moves in the depth direction, the interval between the backlight and the lens must be changed mechanically to maintain stereoscopy.

Using a lens array instead of a large aperture lens is a technique of eliminating mechanical control (Figure 1.2.9). When the viewer moves in the depth direction, the interval between the backlight for the left and right eyes is changed to maintain stereoscopy. However, this method has limitations because the backlight area for each eye is broadened due to the defocusing effect. Although some viewers can simultaneously share the stereoscopic image by adding the light source for each viewer, the number of viewers is limited because of the interference of backlights.

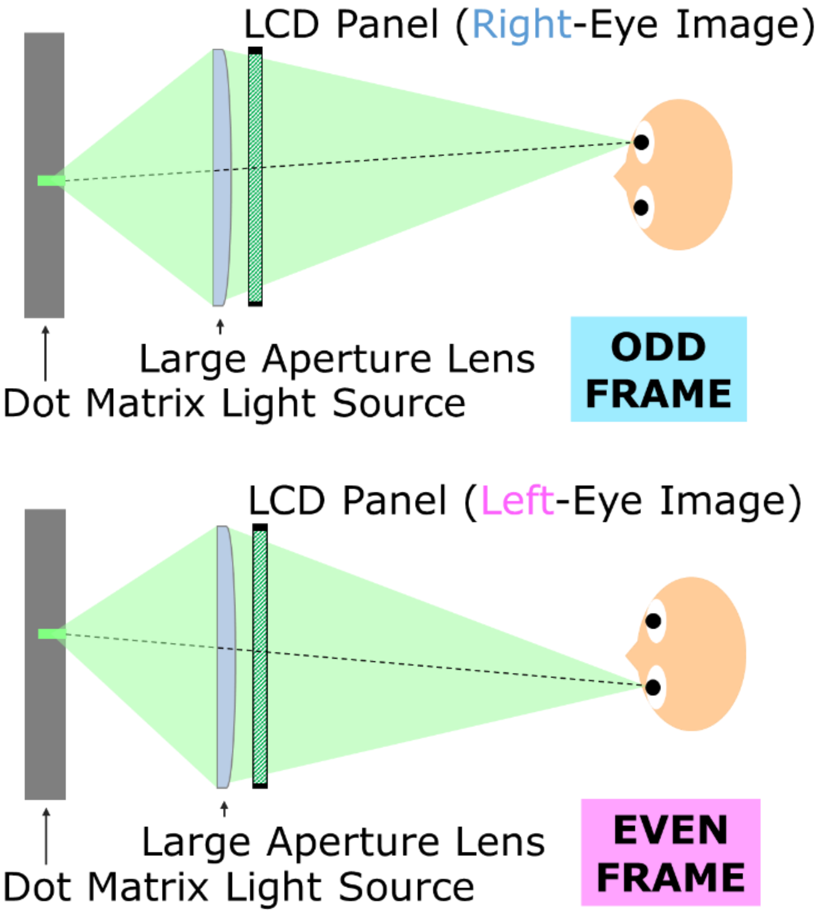


Figure 6.1.1. Principle of the autostereoscopic display based on time-multiplexing backlight using a large aperture Fresnel lens.

## 6.2 Directional Backlight System Using Polymer Dispersed Liquid Crystal (PDLC) Screens and a Projector

This section proposes an autostereoscopic display that enables autostereoscopy for multiple viewers positioned at different distances from the screen. Figure 6.2.1 shows the basic mechanism of the proposed system; the system is composed of a DMD projector, an LCD panel, a large aperture lens, and three PDLC screen layers.

The projector and the PDLC screens serve as a time-multiplexed dot-matrix light source, while the large aperture lens and LCD panel are similar to the conventional system (Figure. 6.1.1).

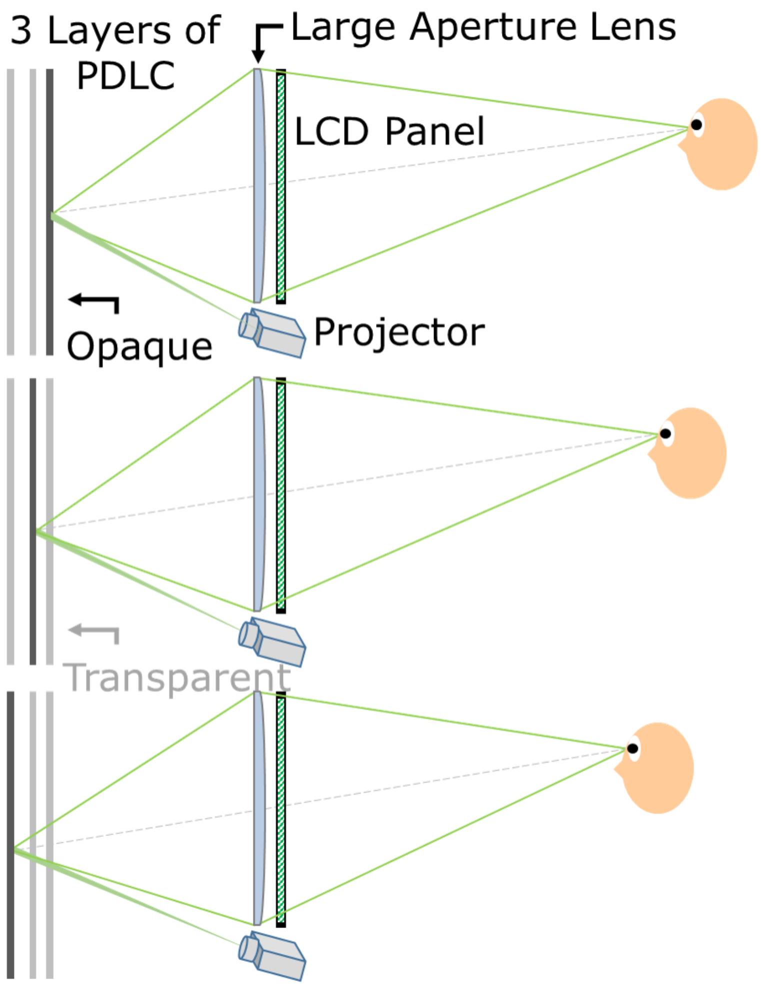


Figure 6.2.1. The basic principle of the proposed method composed of a projector and PDLC screens.

PDLC is usually opaque (white) and becomes transparent when voltage is applied. The distance between the dot-matrix light source and the large aperture lens can be controlled by placing multiple layers of PDLC and leaving only one of the PDLC layers opaque. By choosing the opaque PDLC layer to follow the real image of the observer generated by the large aperture lens, proper stereoscopy is maintained even when the observer moves in the depth direction.

When the observer is near the display panel, the PDLC layer farthest from the projector is opaque, while the other layers are transparent. However, when the observer moves farther from the display panel, the PDLC layer closer to the projector turns opaque, while the other layers turn transparent simultaneously, allowing the light source to follow the real image of the observer.

Since each PDLC layer has a depth range of viewing zone without crosstalk, discrete switches of PDLC screens can ensure a continuous viewing zone in the depth direction. Figure 6.2.2 shows the range of viewing zone without crosstalk given by a single layer of backlight (PDLC screen).

Let $d'$ be the distance between the viewer and the lens, $d$ be the distance between the real image of the viewer and the lens, $g$ be the gap between the backlight segments for each eye, and $r$ be the aperture of the lens. Then, the gap $(g')$ of the viewing zone for each eye at distance $(d')$ is given as follows:

$$g' = \frac{d'}{d} g \tag{6.1}$$

based on the similarity of $\Delta$AOB and $\Delta$A′OB′. When the viewer approaches the lens closer than $d' - w_n$ or moves away from the lens farther than $d' + w_f$, the light rays for the left and right eyes overlap with each other. The similarity of $\Delta$LPK and $\Delta$A′PB′ gives:

$$w_n = \frac{g'd'}{r+g'}, \tag{6.2}$$

while the similarity of $\Delta$KQL and $\Delta$A′QB′gives:

$$w_f = \frac{g'd'}{r-g'}. \tag{6.3}$$

Thus, the depth range of no crosstalk zone $w$ is given as follows:

$$w = w_n + w_f = \frac{2rgdd'^2}{r^2d^2 - g^2d'^2}. \tag{6.4}$$

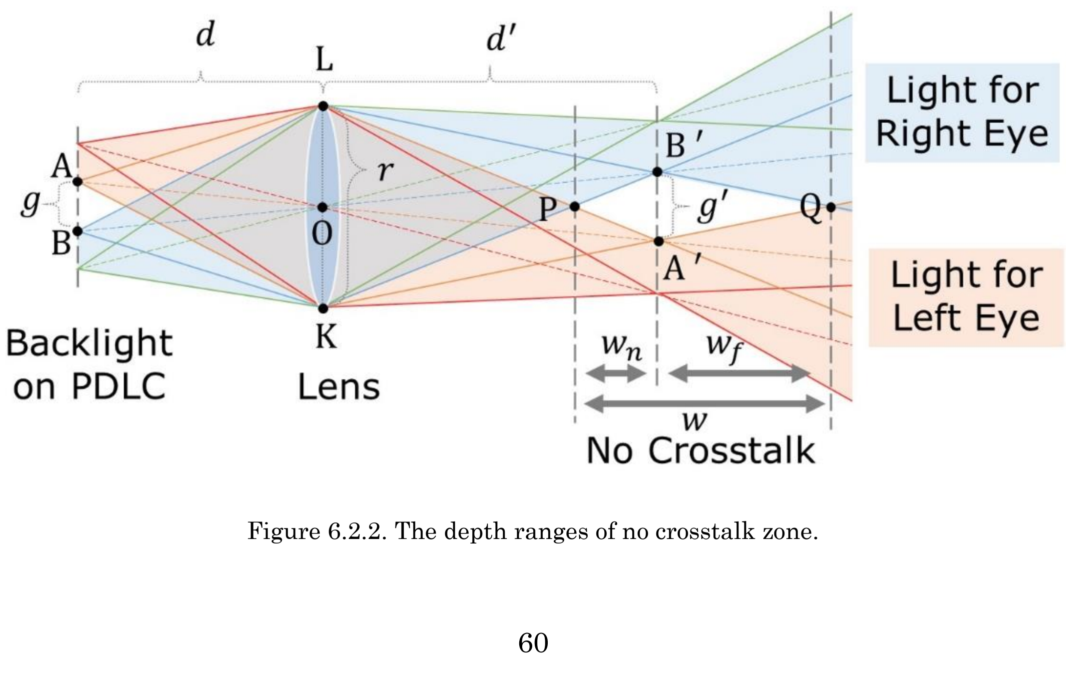


Figure 6.2.2. The depth ranges of no crosstalk zone.

Based on the mechanism described above, the proposed system can be extended to a multiple-viewer version (Figure 6.2.3). Changing the PDLC layer makes it possible to provide autostereoscopic images with multiple viewers at different depth positions simultaneously.

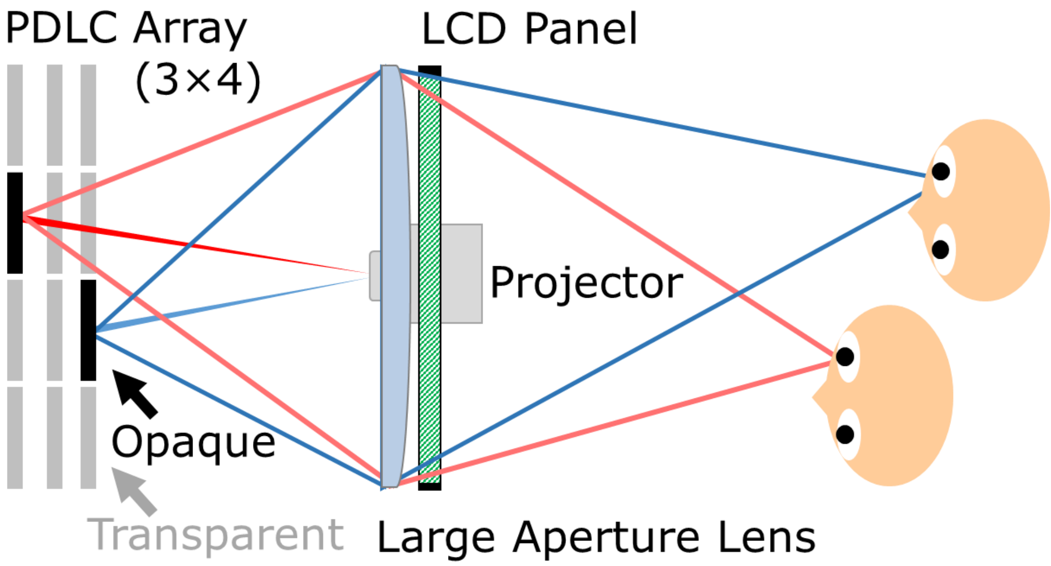


Figure 6.2.3. The operation of the proposed method for two viewers.

Figure 6.2.3 shows a layer of PDLC array that is composed of four vertical stripes with independent electrodes. Each PDLC segment can be transparent or opaque as desired. The PDLC segments close to the real images of the observers' faces generated on the opposite side of the large aperture lens are kept opaque, while the other segments are turned transparent. Thus, stereoscopy is maintained for multiple viewers positioned at different depths. When each PDLC layer is divided into finer segments, the system can maintain stereoscopy for more viewers in a packed situation. Additionally, the viewing zone in the depth direction can be expanded by increasing the number of PDLC layers.

## 6.3 Experiments with Hardware

A prototype system is built based on the proposed method and tested to ensure it works as expected. Figure 6.3.1 shows the picture of the prototype system. Table 6.3.1 shows the specifications of the DMD projector (Optoma HD27H) used in the proposed system. Table 6.3.2 shows the specifications of the PDLC screens that are commercially available and sold by Decocar.

The DMD projector's color wheel is removed to achieve synchronization with the LCD panel and to obtain a brighter white time-multiplexed backlight. The PDLC arrays are placed behind the large aperture Fresnel lens. An LCD panel with a full HD resolution (1920 × 1080) and 120 Hz refresh rate for displaying the left and right eye images are placed in front of the lens. The projector is placed under the lens and the LCD panel facing the PDLC arrays. Figure 6.3.2 shows that the opaque and transparent PDLC layers were switched electronically to follow the motion of the viewer.

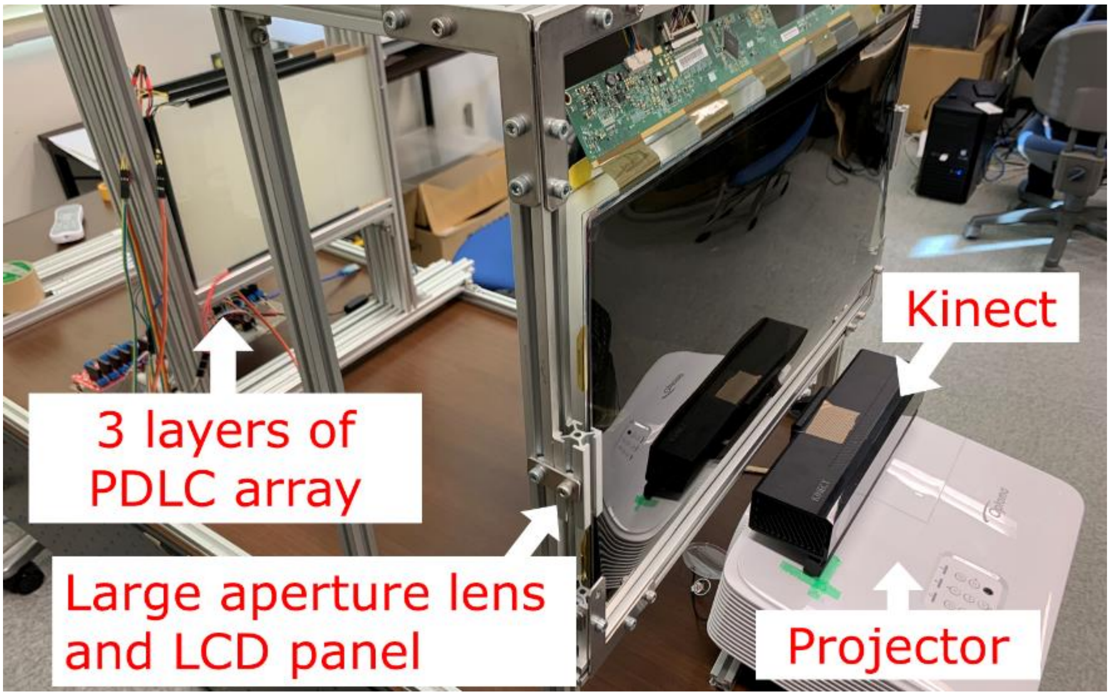


Figure 6.3.1. A prototype system based on the proposed method.

Table 6.3.1. Specifications of the DMD projector.

| | Specifications |
|---|---|
| Display Technology | DLP |
| Resolution | Full HD (1920 × 1080p) |
| Refresh Rate | 120 Hz |

Table 6.3.2. Specifications of the PDLC screen.

| | Specifications |
|---|---|
| Thickness | 0.5 mm |
| Rated Voltage | 60 V (AC 50Hz) |
| Power Consumption | 5 $W/m^2$ |
| Transmittance | 78%–82% |

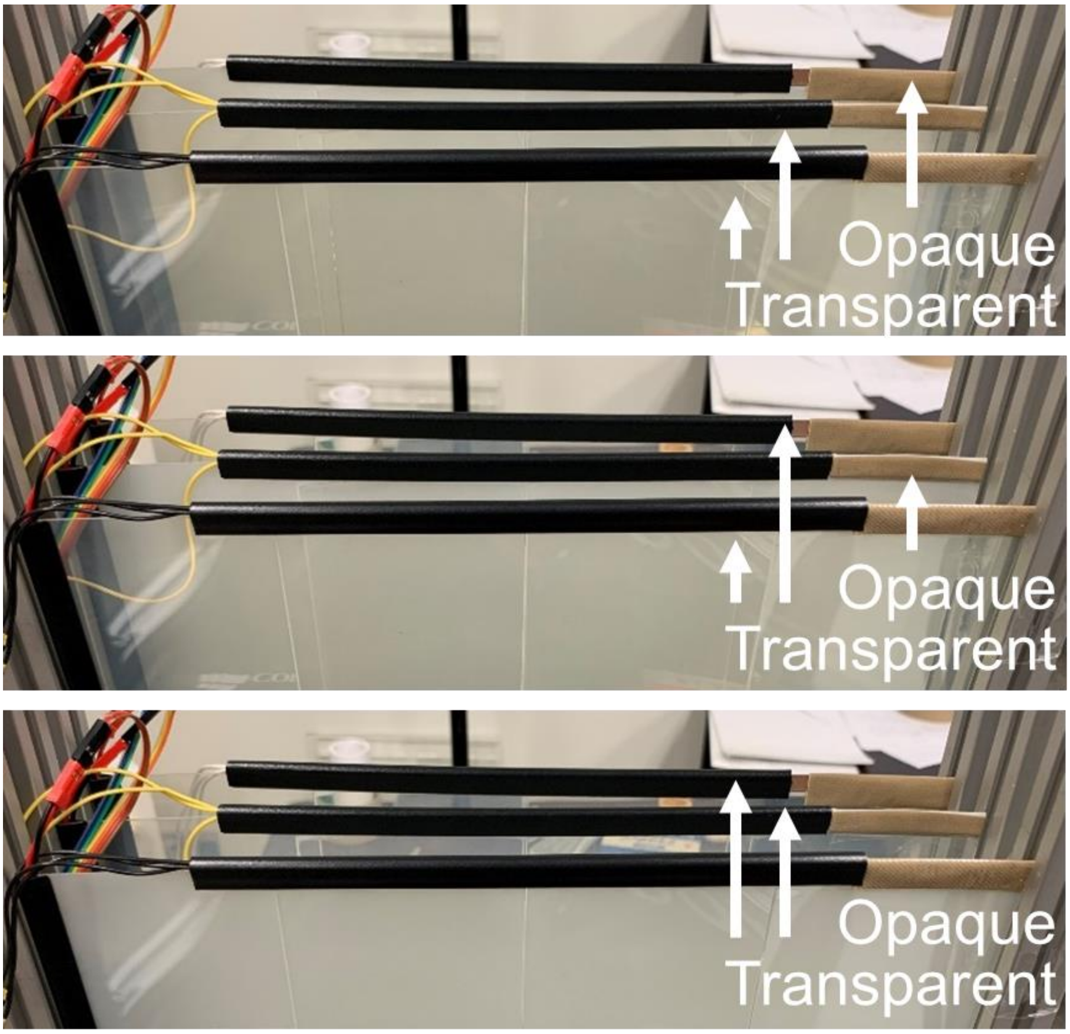


Figure 6.3.2. Electronic switching of three PDLC layers.

In the prototype system, the focal length, $f$, of the large aperture lens (combined lens) is 0.4 m. The distances between the lens and the three PDLC layers, $d_1$,$d_2$ and $d_3$, are 0.63 m, 0.60 m, and 0.58 m, respectively. Since

$$\frac{1}{d}+\frac{1}{d'}=\frac{1}{f} \tag{6.5}$$

holds, the stereoscopic images without crosstalk are observed around $d'_1 =$ 1.1 [m], $d'_2 = 1.2$ [m] and $d'_3 = 1.3$ [m] from the lens.

In the prototype system, the aperture of lens is $r = 0.53$ [m] and the gaps between the backlight segments are $g_1 = 0.019$ [m], $g_2 = 0.015$ [m] and $g_3 = 0.011$ [m] for each PDLC layer. From Equation 6.5, $w_1 = 0.14$ [m], $w_2 = 0.13$ [m], and $w_3 = 0.12$ [m] are obtained, thus ensuring a continuous viewing zone in the depth direction. It is confirmed that stereoscopic images with little crosstalk were observed at 1.1–1.3 m from the lens by switching the PDLC layers accordingly.

First, a one-viewer observation experiment was conducted. The left side of Figure 6.3.3 shows the “Art” stereo pair from Middlebury [50] with a left/right label on the display, and a 3D web camera (ELP 960P) was used to record the observed image. The right side of Figure 6.3.3 shows the screenshot of the video. The squares-framed areas are magnified and displayed at the bottom. The magnified part of the image can show the difference, and the left and right labels at the bottom of the image can be easily distinguished.

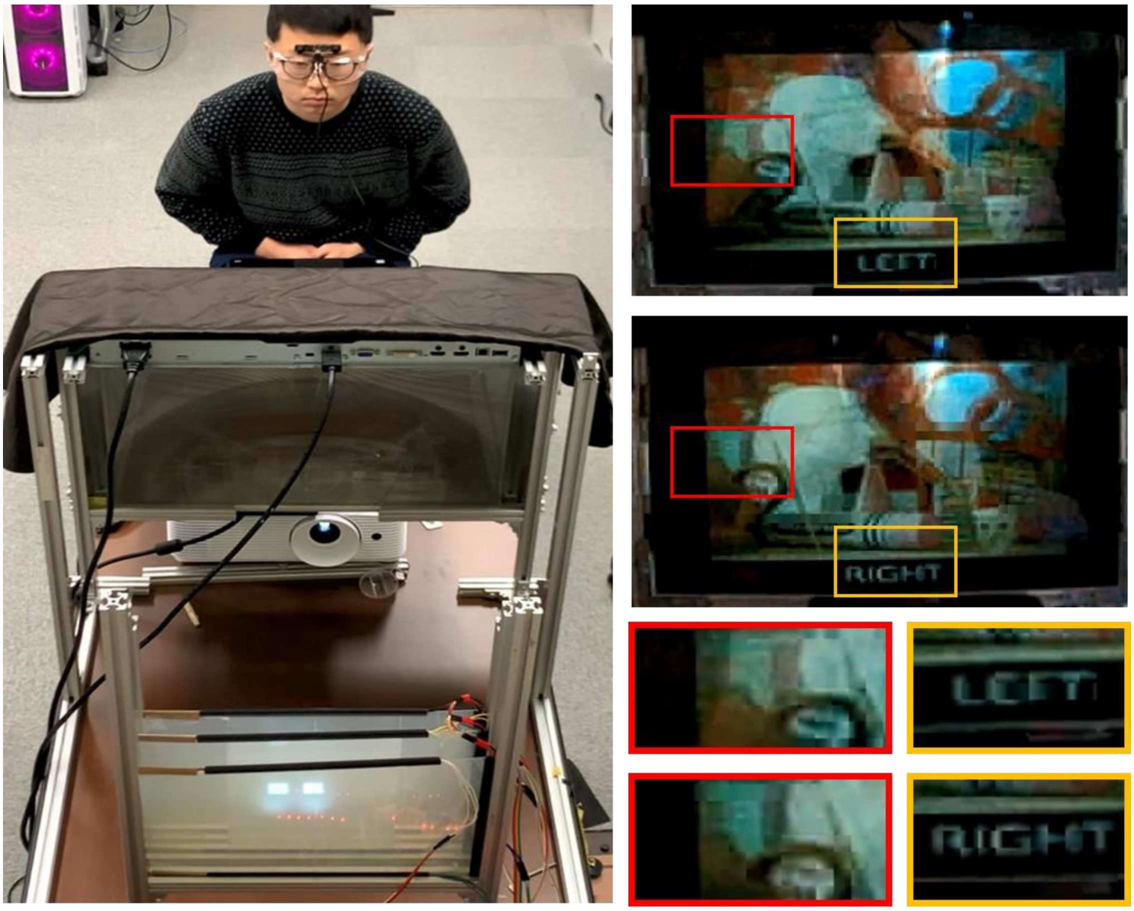


Figure 6.3.3. Experimental observation.

With the help of the eye-tracking device, Kinect V2, stereoscopy is maintained when the viewer moves in both horizontal, vertical, and depth directions.

A two-viewer observation experiment was also conducted. The light source spots were projected on the PDLC arrays for two viewers at different depths (Figure 6.3.4). Two pairs of backlight segments correspond to the backlight for two viewers, with each square segment corresponding to each eye. The proper PDLC segments became transparent, whereas others remained opaque. Using this control, both viewers can simultaneously observe proper stereoscopic images with little crosstalk as expected.

Figure 6.3.4. Experiment when the number of viewers is two.

Figure 6.3.3 shows that the crosstalk and flicker do not stand out in the prototype system. Since the system operates at 120 Hz as the time-division multiplexing stereoscopic system with shutter glasses, the flicker is not noticed by the viewer. Crosstalk can be caused by the delay of LCD because of the limitation of the response time of liquid crystal material or the reflection of ambient light on the PDLC screen. The latter can be addressed by covering the entire optical system to shut out the ambient light.

The luminance of the image is changed when the PDLC screen is switched in the prototype system because of the limited transmittance of PDLC screens. The light diffused on the PDLC screen is attenuated when it passes through multiple PDLC layers. Thus, the image becomes darker when a screen farther from the lens is used; this can be addressed by adjusting the luminance of the light projected by the DMD projector. Since the luminance of each backlight segment can be controlled independently by the projector, stable luminance for multiple viewers can be attained using this method.

## 6.4 Summary

This chapter proposes an autostereoscopic display system that achieves high-resolution stereoscopy for multiple viewers positioned at different distances from the screen. In the proposed system, PDLC screens with segmented electrodes are electrically controlled to change the position of light diffusion, while a DMD projector at 120 Hz projects the time-multiplexed backlight. The light is diffused at the conjugate focal points of the observers' eyes to deliver directional light to each eye. The right- and the left-eye images are alternated on the LCD panel in front of the lens to synchronize with the backlight.

By applying multiple layers of PDLC structure combined with a projector that is synchronized with an LCD panel, the autostereoscopic display can provide a deep viewing zone by electronically changing the depth of light sources. Further, by extending the PDLC structure into layered PDLC arrays that are controlled by independent electrodes, multiple viewers at different depths can see the stereoscopic image simultaneously.

It is confirmed that the prototype system successfully displays stereoscopic images to two viewers simultaneously.

# 7 Conclusion and Future Work

## 7.1 Conclusions

In this study, the high-resolution autostereoscopic displays that can present accurate depth information and allow multiple people to observe 3D images simultaneously were proposed. These technologies can be used for a head-up display for automobile drivers or a medical display for doctors. The autostereoscopic displays based on the time-multiplexed directional backlight method were improved by reducing crosstalk level, alleviating postural restriction, homogenizing luminance intensity, and enabling simultaneous observation by multiple viewers. Experimental evaluations demonstrate that the prototype systems performed as expected.

In Chapter 1, existing 3D displays (stereo displays) were reviewed and divided into stereoscopic displays with goggles and autostereoscopic displays. Further, the required specifications for practical autostereoscopic displays, such as 3D head-up displays for vehicles or 3D medical displays in an operating room, which include high-resolution and simultaneous observation by multiple viewers were discussed. Next, a time-multiplexed directional backlight for autostereoscopic display that combines a dot-matrix light source and a convex lens or a convex lens array was reviewed. The conventional approaches that use this method have low resolutions, strict postural restrictions, and narrow view zones, thus making it difficult for multiple viewers to observe simultaneously.

In Chapter 2, the field curvature, which causes a high crosstalk level in the conventional method, was discussed. Although some conventional methods have attempted to reduce the influence of field curvature, the crosstalk level remains high because of the stray light caused by layered lens structure, which also makes optical calculations more complex. To solve this problem, an autostereoscopic display with a time-division multiplexing directional backlight that use a decentered lens array was proposed. A low crosstalk level was attained using a single layer of the decentered lens array because the impact of field curvature was reduced without employing an additional Fresnel lens, which also makes optical calculation simpler and faster. The validity of the proposed method was confirmed by implementing a prototype display system and measuring its crosstalk level, which is 9.5%. Since the crosstalk level of the conventional method is 13.4%, it was reduced significantly by the proposed method.

In Chapter 3, further crosstalk reduction of the autostereoscopic display is tried for the autostereoscopic display using time multiplexing directional backlight. The use of a curved-shaped lens array in place of a flat lens array was proposed. A layer of the proposed curved lens array, which is composed of rectangle-shaped cylindrical elemental lenses is expected to suppress the impact of field curvature while maintaining a simple optical calculation. A lower crosstalk level was attained via crosstalk evaluation based on the prototype display system. The crosstalk level of the system in Chapter 2 is 9.5%, whereas that of the proposed system is 4.6–5.8%. Additionally, the rectangle elemental lens was redesigned into a trapezoid shape to achieve a more uniform distribution of the backlight luminance. The prototype system achieves more uniform luminance and a crosstalk level as low as 3.6–4.6%.

In Chapter 4, the problem of postural restriction during observation of stereoscopic images was addressed. Stereoscopy collapses in the conventional systems when the observer tilts his or her head because of the vertical diffusion to homogenize luminance. To solve this problem, a novel linear Fresnel lens array with interleaved structure was proposed, which enables autostereoscopy with less postural restriction under a low crosstalk level (5.4–5.8%). However, the intensity of the backlight luminance was not uniform enough. To achieve a more uniform luminance, the novel linear Fresnel lens was redesigned so that the widths of elemental prisms in the interleaved linear Fresnel lens array vary gradually depending on the positions. A prototype display system was built using the proposed method and the results indicated that the luminance becomes higher and more uniform as the stereoscopic crosstalk decreases.

Although the autostereoscopic display introduced in Chapter 4 can be modified to show stereoscopic images to two viewers, the viewing zone without interfering with each other's view is narrow. In Chapter 5, the cause of the limited viewing zone was analyzed and an autostereoscopic display that can simultaneously provide two viewers with different stereoscopic image pairs was proposed. Time-division quadruplexing at 240 Hz was applied to produce four viewpoints for the four eyes of two viewers, while the lens array was tilted by $\tan^{-1} 1/3$. An observational experiment conducted by the two viewers confirms that the prototype worked as expected under a low crosstalk level.

Without mechanical control, the viewing zone provided by the conventional autostereoscopic display system using a large aperture lens to achieve a directional backlight was limited in the depth direction. To solve this problem, an autostereoscopic display system based on time-multiplexed directional backlight using a projector and PDLC screen layer was proposed in Chapter 6. High-resolution stereoscopy for multiple viewers positioned at different distances from the screen was achieved in the proposed system. A prototype display system based on the proposed method where two viewers positioned at different depths can observe the correct stereo images even when they move in different directions was implemented.

Throughout this study, autostereoscopic displays where multiple viewers can experience high-quality stereoscopic images simultaneously with little limitation of viewpoint and posture were attained, opening up possibilities of more widespread use of autostereoscopic displays.

## 7.2 Future Work

The technologies introduced in this study can be employed in several applications, which are discussed below.

The autostereoscopic display for two viewers, which provides images specific to each viewpoint can be combined with a tactile display system to show 3D virtual objects that the viewers can interact with. For example, two people can simultaneously and collectively play a virtual Rubik's Cube game (Figure 7.2.1). Since each viewer sees the views specific to each viewpoint, they share the same 3D space, which enables spatial collaboration in the virtual 3D space.

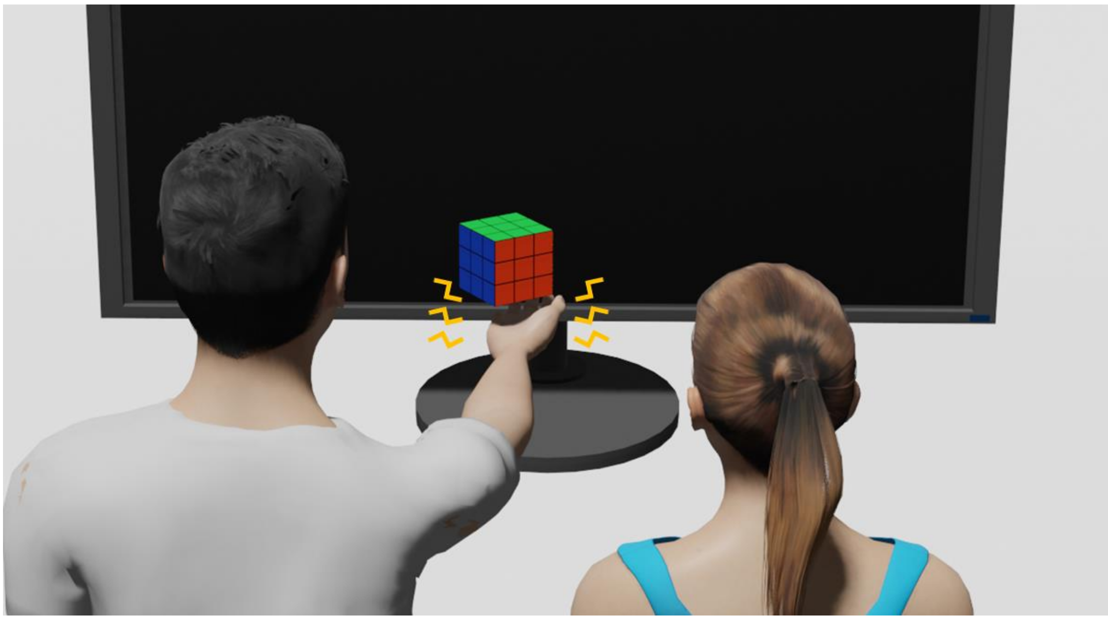

Figure 7.2.1. The combination of a 3D display and a tactical presentation system.

As for the autostereoscopic display for multiple viewers proposed in Chapter 6, increasing the number of PDLC layers and dividing each PDLC layer into finer segments can achieve autostereoscopy for more viewers. With this technology, multiple students in a classroom can see 3D images simultaneously (Figure 7.1.2) or multiple customers can see 3D commercial advertisements on the street (Figure 7.1.3) without making them wear special glasses, thus opening up new possibilities for wider use of 3D displays.

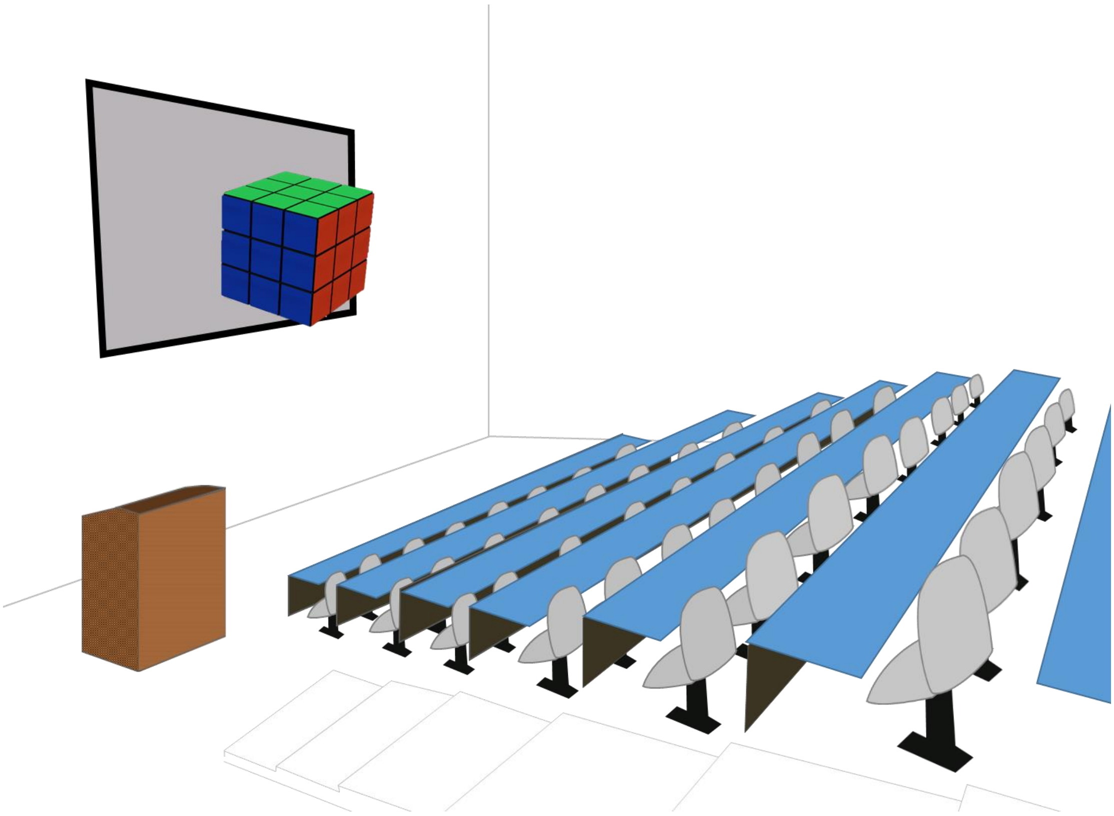

Figure 7.2.2. A 3D display for multiple students in a classroom.

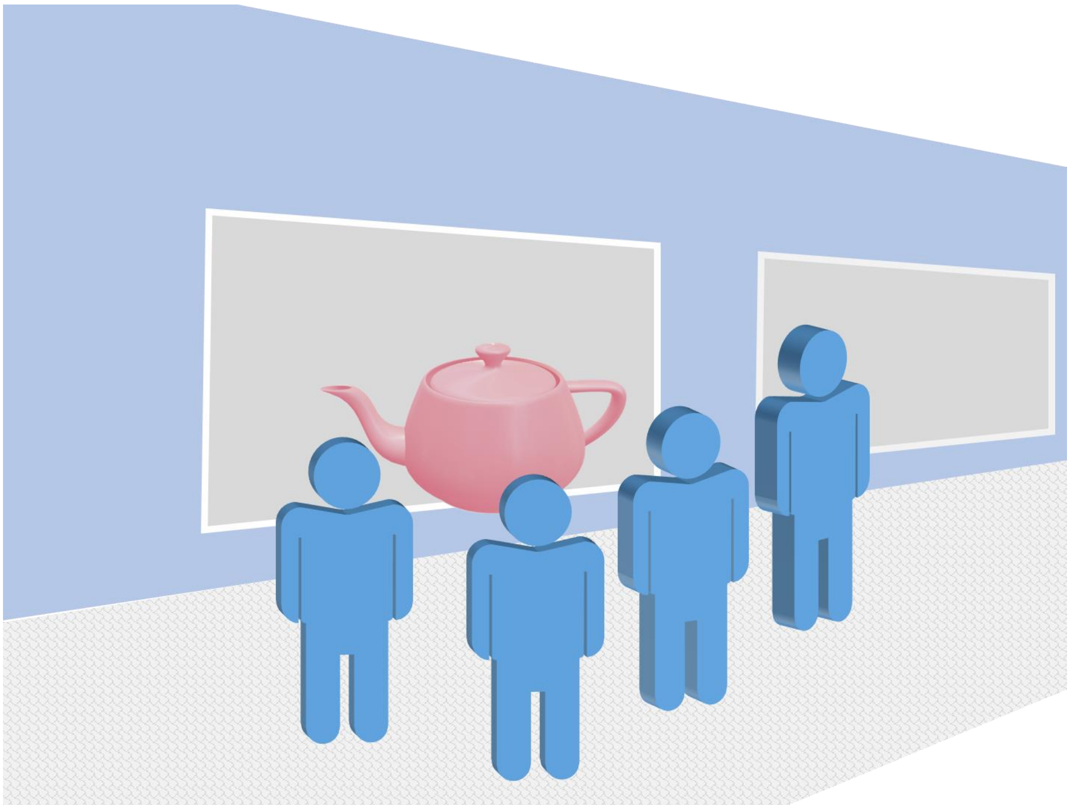

Figure 7.2.3. A 3D display of commercial advertisement on the street.

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- Garimagai Borjigin and Hideki Kakeya: "Autostereoscopic displays with time multiplexed directional backlight using curved lens arrays," ITE Transactions on MTA 9(1): 80–85, 2021.
- Garimagai Borjigin and Hideki Kakeya: "Autostereoscopic display for multiviewers positioned at different distances using time-multiplexed layered directional backlight," Applied Optics, 60(12):3353-3357, 2021.
- Garimagai Borjigin and Hideki Kakeya: "Backlight system using an interleaved Fresnel lens array that attains a uniform luminance and two-dimensional directional light control," Optics Letters, 47(2):301-304, 2022.

### Reviewed Conference Proceedings

- Garimagai Borjigin and Hideki Kakeya: "An autostereoscopic display with time-multiplexed directional backlight using a decentered lens array," in Digital Holography and Three-Dimensional Imaging, OSA Technical Digest, paper W2A.2, Bordeaux, France (May 2019).
- Garimagai Borjigin and Hideki Kakeya: "An Autostereoscopic Display with Time-Multiplexed Directional Backlight Using a Curved Lens Array," International Display Workshops, Proceedings of IDW'19, 3DSA5/3D5-4, Sapporo, Japan (December 2019).
- Garimagai Borjigin and Hideki Kakeya: "An Autostereoscopic Display with a Deep Viewing Zone Using Time-Multiplexed Directional Backlight," SID Display Week, SID Symposium Digest of Technical Papers, 51(1): 1615-1618, Online Conference (July 2020).
- Garimagai Borjigin and Hideki Kakeya: "An Autostereoscopic Display with Time-Multiplexed Directional Backlight Using a Novel Linear Fresnel Lens Array," International Display Workshops, Proceedings of IDW'20, 482-485, Online Conference (November 2020).

### Nonreviewed Reviewed Proceedings

- Garimagai Borjigin and Hideki Kakeya: "An autostereoscopic display with time division multiplexing directional backlight using a decentered lens array," Proceedings of the ITE Winter Annual Convention 2018, Tokyo, Japan (December 2018). [in Japanese]

- Garimagai Borjigin and Hideki Kakeya: "Autostereoscopic Display for Two Viewers Providing Images Specific to Each Viewpoint," Proceedings of the ITE Winter Annual Convention 2021, Online Conference (December 2021). [in Japanese]