

# Multi-Phase Convex Lens Array for Directional Backlights to Improve Luminance Distribution of Autostereoscopic Display

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**SUMMARY** We realize homogenous luminance of the directional backlight for the time-division multiplexing autostereoscopic display using a convex lens array with the elemental lenses whose phase of placement in each row differs from one another. The validity of the proposed optical design is confirmed by a prototype system.

**key words:** *autostereoscopic display, homogeneous brightness, liner Fresnel lens array*

## 1. Introduction

With the recent advances of LCD technologies, LCD panels that attain short response time have been developed, which has enabled commercialization of 3D LCD TV sets. The advanced LCD technologies with high refresh rates can also be applied to autostereoscopic displays with high resolutions.

Most of the conventional autostereoscopic display systems are based either on parallax barrier technology or on lenticular lens technology, both of which display stereoscopic images with lower resolutions than those of the display panels. Time-division multiplexing technique with a fast response panel has enabled presentation of a stereoscopic image with the same resolution as that of the display panel.

The conventional ways to attain high resolution autostereoscopy with time division multiplexing are roughly divided into two types.

One way is to use an active parallax barrier [1]–[3]. A fixed parallax barrier generating two viewpoints reduces the resolution of the image by half. This problem is avoided by turning on the odd columns and the even columns of the striped barrier alternately. When the alternation of the parallax barrier is synchronized with that of the image on the display panel, the viewer is able to observe a full resolution 3D image.

The other way is to use a directional backlight composed of a light guide film and two light sources [4]–[6]. In this system autostereoscopy is realized by switching the light sources and the image on the display panel synchronously.

The common drawback of the autostereoscopic displays introduced so far is the limited number of viewers. Basically they can display the stereoscopic image only to

one viewer. Though there have been a few trials to increase the number of possible viewers [7], [8], the viewing position is still limited.

One way to attain autostereoscopy with more viewpoints is to use a directional backlight composed of a large aperture convex lens and a dot-matrix backlight panel [10]. The same optics is also attained by using a concave mirror [11]. These systems, however, require deep optical distance.

To reduce the thickness of the display hardware, use of a convex lens array instead of a large aperture convex lens was proposed [12]–[15]. The image quality attained by this system, however, is poor due to the distinct seam of the lens array, which has prevented this method from being put to practical use. Though use of a vertical diffuser combined with a lens array and projection light [16], [17] mitigates the problem of distinct lens seam, the system becomes thick again due to the projection optics.

Ishizuka et al. proposed a method to solve the above problem without projection optics [18]. The proposed system uses a hexagonal lens array in place of the conventional lens array, accompanied by a vertical diffuser behind the display panel, which blurs the distinct seam of the lens without destroying stereoscopy. In this system projection light is not necessary because the optical parameters are set so that the optical aberration may not cause the overlap of the backlight areas for the left eye and the right eye [19].

Use of a vertical diffuser, however, does not eliminate the lens seam completely due to the periodical lens alignment. Though this problem is partially solved by tilting the hexagonal lens array, slanted stripe noise still appears especially when the viewer observes the image from a wide angle.

In this paper, we propose a new method to realize the uniformity of the directional backlight for autostereoscopic displays. This paper is organized as follows. The conventional method is reviewed in Sect. 2 and the proposed method is explained in Sect. 3. The result of the hardware experiment is given in Sect. 4 and the paper is concluded in Sect. 5.

## 2. Conventional Method

The principle of the conventional directional backlight using a convex lens array is shown in Fig. 1. When dot matrix light sources are placed behind the convex lens array so that the distance between them may be equal to the focal distance of

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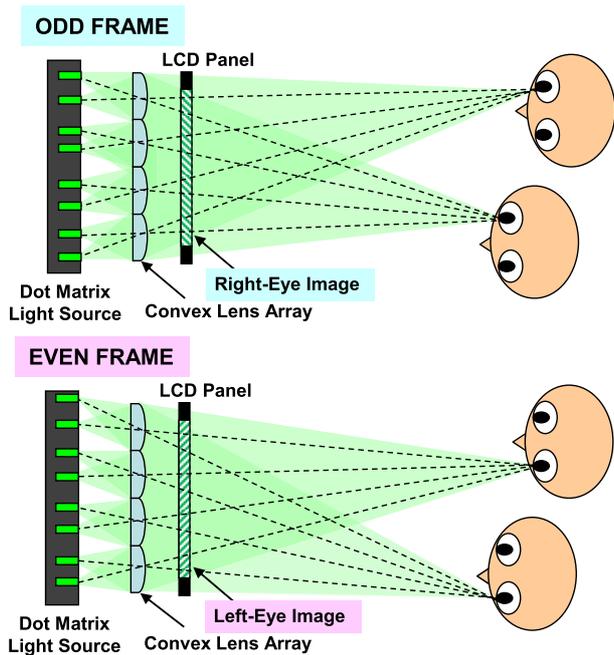


Fig. 1 Autostereoscopy with a directional backlight using a convex lens array

the elemental lens of lens array, collimated directional light is realized. By changing the position of the luminous light sources, the directionality of light is controlled. When the directional backlight to each eye alternates synchronously with the alternation of left-eye and right-eye images on the LCD panel, the viewer can see a stereoscopic image without wearing special glasses. By increasing the number of light sources, multiple viewers can observe the stereoscopic image simultaneously.

The problem of the conventional system shown in Fig. 1 is poor image quality due to the distinct seam of coarse lens array. Also the intensity of image is not uniform because the intensity of light rays generally weakens as the angles become wider, which causes emergence of bright area and dark area in each elemental lens. To remove the seam of lens and the non-uniformity of intensity from the image, two methods have been proposed so far.

The first method is to use a hexagonal lens array and a vertical diffuser as shown in Fig. 2. The hexagonal lens array is used because it has two complementary phases, which avoids concentration of bright area and dark area in each vertical line. The diffuser is inserted to blur the seam and non-uniform intensity of lens array. To maintain autostereoscopy, the rays into the left eye and the right eye of the viewer should be separated. The ray diffused only in the vertical direction maintains directionality of light in the horizontal direction, which does not destroy stereopsis. Though this method homogenizes intensity to a certain degree, dark and bright stripes remain.

The second method is to tilt the convex lens array in the first method as shown in Fig. 3. Though the vertical stripes disappear with this method, slanted stripes become distinct

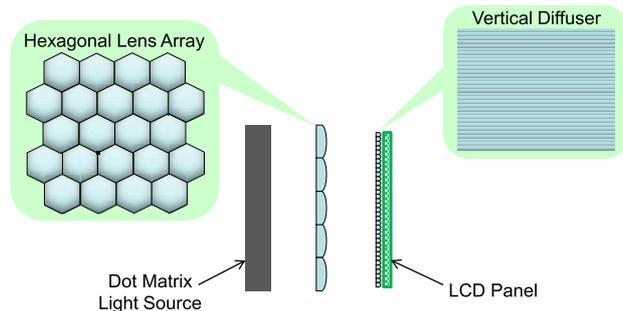


Fig. 2 Autostereoscopy with a directional backlight using a convex lens array and a vertical diffuser.

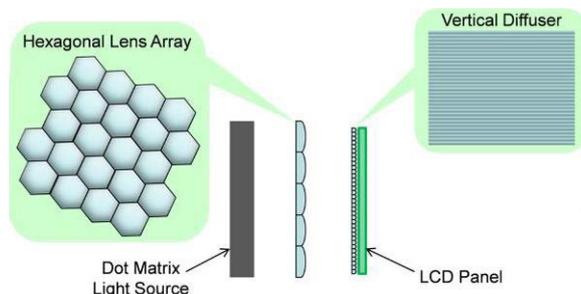


Fig. 3 Autostereoscopy with a directional backlight using a tilted convex lens array and a vertical diffuser.

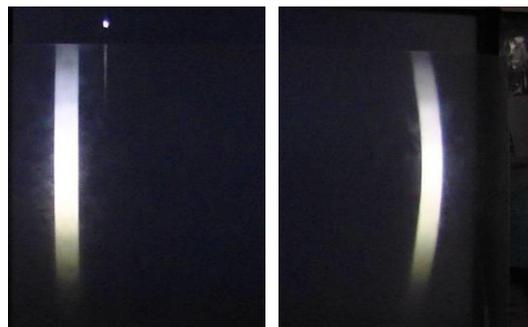


Fig. 4 The blur effect of the vertical diffuser observed from different angles.

especially when the viewer observes the image from a wide angle

The reason of the emergence of stripes is explained as follows. Figure 4 shows how a white square light looks after diffusion with the vertical diffuser. The left picture shows how the diffused square looks from right in front of the display and the right picture shows how it looks from a side angle of the display. When the position of light is right in front of the observer, a straight vertical line is observed. When the observer moves sideways, the line is curved in a bow shape. The slanted stripes are generated because of this curved diffusion. When the inclination of the curved diffusion matches the inclination of the tilted lens array, the bright part and the dark part of the elemental lenses are not mixed, which results in the emergence of stripes.

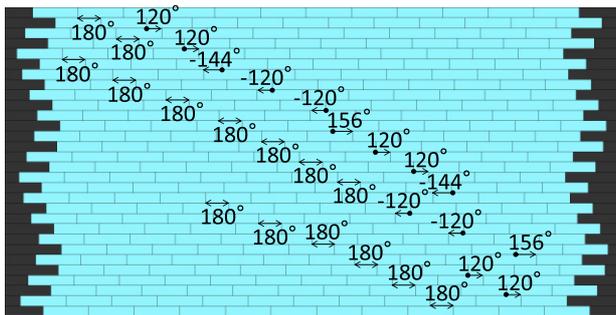


Fig. 5 The proposed alignment of elemental lenses.

### 3. Proposed Method

In this paper we propose a method to attain homogenous image intensity from any viewing angle. The feature of the proposed system is the alignment of the elemental lenses. In the proposed method the elemental lenses are aligned so that the phase of lens placement in each row may differ from one another as shown in Fig. 5. Since the seam of the lenses appear only once in the vertical direction, the vertical diffuser can smooth the seam enough and the image with homogeneous intensity can be attained. Also because of the various phase shift, inclination angle of the phase shift is not uniform, which can avoid a singular match between the inclination of the diffusion curve and that of the lens shift. Here note that the position of the bright part of the backlight should be shifted in accordance with the shift of the lens to maintain proper directional light for stereoscopy.

To realize the image intensity as homogenous as possible, the order of phase shift is important. To avoid regularity of inclination, we align the lenses as follows. Here we explain the case where the number of rows is 30. 30 is decomposed into prime factors 2, 3, and 5. Note that  $360/2 = 180$  and  $360/3 = 120$ . First, two lenses with 180 degree phase shift are placed next to each other. Then three pairs with 120 degree phase shift or  $-120$  (240) degree phase shift are placed next to one another. Mixing 120 degree and  $-120$  degree phase shift is important to remove periodicity only in one direction. Finally five groups of six lenses are placed with  $-144$  (216) or 156 degree phase shift alternately again to remove periodicity.  $156 (= 180 - 24)$  and  $-144 (= -180 + 36)$  degrees are selected so that every row may have a different phase. This alignment contributes to suppress emergence of bright and dark stripes when the viewer observes the image from a wide angle.

To mix the bright part and the dark part enough, it is favorable to use the elemental lenses short in height, which in turn allows intrusion of the backlight for the neighboring elemental lenses. To avoid it, we place mirrors between the backlight and the elemental lenses so that each row of the elemental lenses are separated from one another.

### 4. Result

We made a prototype system based on the proposed method

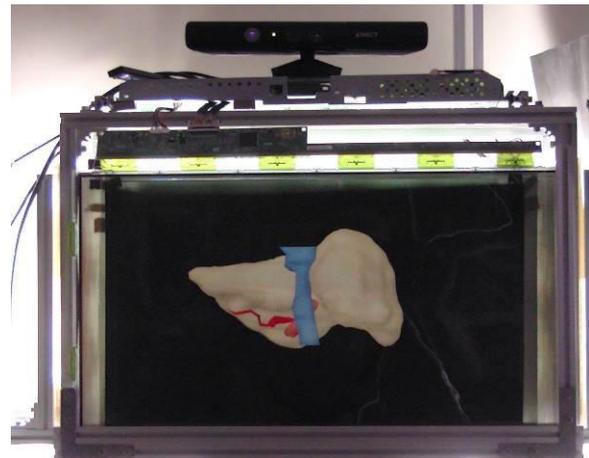


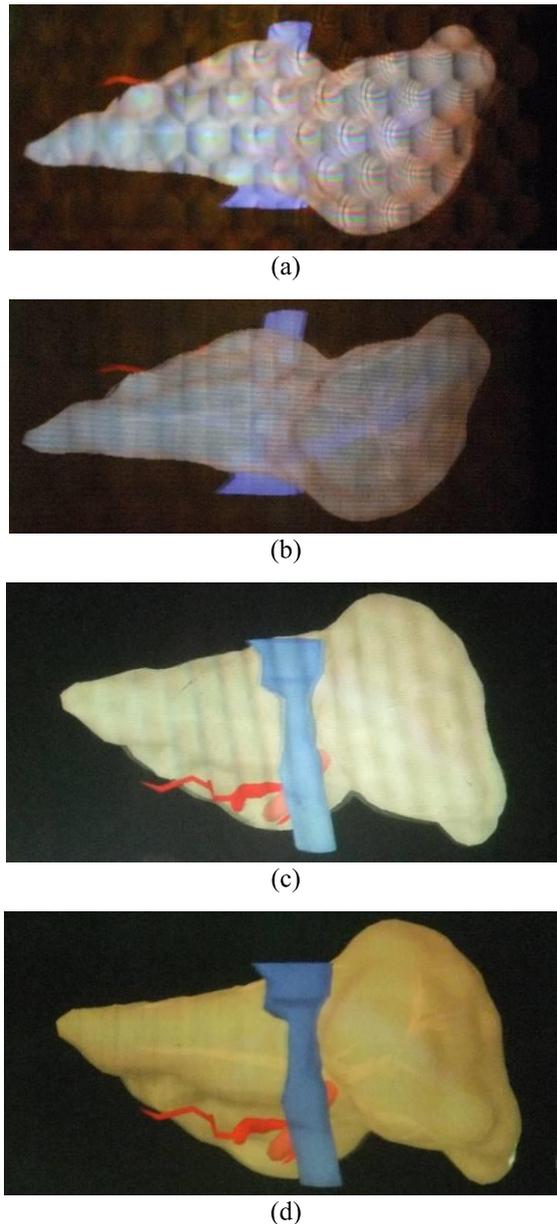
Fig. 6 Prototype system.

described in the previous section as shown in Fig. 6. As the LCD panels for the image display panel and the dot-matrix backlight, we used a pair of BenQ XL2420T, which can show 24 inch full HD images with 120 Hz refresh rate. As for the vertical diffuser we used a fine lenticular lens with 0.1 mm pitch and 0.05 mm radius, which was placed just behind the front image panel and 150 mm in front of the convex lens array. As for the convex lens array we used a 43.8 mm (W)  $\times$  10 mm (H) linear Fresnel lenses whose focal length was 45 mm. Here linear (cylindrical) lenses can be used in place of standard convex lenses because the directionality of light only in the horizontal direction matters to realize stereoscopy. Note that the partition (mirror) to separate each lens row is essential when linear lenses are used, for the light is not converged in the vertical direction.

In Fig. 7 we compare the images presented by the conventional methods and the proposed method. In the conventional systems regular hexagonal elemental lenses that have 25 mm focal length and 12.5 mm sides accompanied by the same LCD panels as those of the proposed system were used. The image given by the system shown in Fig. 1 includes distinct seams of lenses and the image quality is poor (Fig. 7 (a)). After insertion of a vertical diffuser, the image becomes more uniform, while the vertical seam is still noticeable (Fig. 7 (b)). After tilting the lens array, the oblique periodical noise stands out (Fig. 7 (c)). As opposed to these conventional systems, our proposed method realizes an image without any apparent seam or stripe noise (Fig. 7 (d)). Thus the validity of the proposed method is confirmed.

### 5. Conclusion

In this paper we propose the new alignment of the convex lens array where the phase of lens placement in each row may differ from one another to realize homogenous intensity of the directional backlight. In the proposed system the forward and the backward phase shifts are mixed so that the seam of the lenses may not concentrate in any inclination angle. It is confirmed with the prototype system that the



**Fig. 7** Comparison of the images presented by the conventional methods (hexagonal lens array without vertical diffusion (a), hexagonal lens array with vertical diffusion (b), inclined hexagonal lens array with vertical diffusion (c)) and the proposed method (d).

proposed method successfully removes the stripe noises as expected.

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