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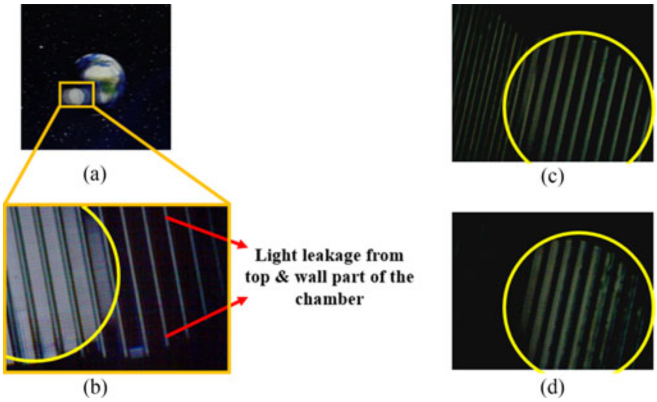

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Analysis and Reduction of Crosstalk in the Liquid Lenticular Lens Array

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Abstract: In this paper, we analyze the crosstalk of the liquid lenticular lens array and reduce the crosstalk by blocking light leakages from the top and wall parts of the chamber. A variety of factors affecting the crosstalk of the liquid lenticular lens array are proposed. The ratio of the unnecessary light from the top and wall parts of the chamber are theoretically calculated and compared with the measured values. By using laminating foil and increasing the thickness of the electrode layer compared to the conventional sample, the light leakages from the top and wall parts of the chamber are blocked, and thus, the crosstalk is reduced to 21.23%, which is similar to that of the solid lenticular lens array. Image tests were conducted to demonstrate that crosstalk is reduced using a new sample.

Index Terms: Lenticular lens array, electrowetting, crosstalk, 3-D images.

1. Introduction

The purpose of display technologies is to accurately convey real and virtual spatial information to human beings. Three-dimensional displays where two different images are sent to the left and right eyes by various methods, are an essential technology for creating a natural screen experience [1]. Three-dimensional stereoscopic images have been applied to many genres, such as movies and games, but users had to wear special glasses, which causes discomfort. Autostereoscopic 3-D displays, where special glasses are not required, will be the dominant next generation displays. Multi-view technology that forms multiple viewing zones has become the most popular type of autostereoscopic 3-D display [2]. Among the various approaches, the lenticular lens type multi-view technology [3]–[5] uses a sheet of semi-cylindrical solid lenses on the display panel to divide the visible region to both eyes, through the refraction of light, while providing high brightness and resolution.

However, it is still difficult to convert 3-D images to 2-D images and vice versa, because the solid lenticular lens array is fixed in front of the display panel. To solve this problem, various methods using liquid crystal lenses [6], [7], liquid tunable lenses [8], [9], and liquid lenticular lenses [10]–[13] have been studied. Among these, the method using the liquid lenticular lens, which is based on the electrowetting phenomenon [14]–[16] has demonstrated several advantages, such as fast response time, low power consumption, and no mechanical movement parts. The liquid lenticular

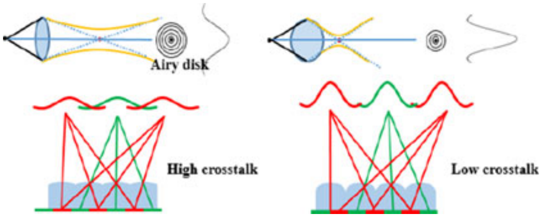

Fig. 1. Crosstalk of the lenticular lens array according to the diopter. (a) High crosstalk when using a low diopter lens. (b) Low crosstalk when using a high diopter lens.

lens is operated by changing the applied voltage, which changes the shape of the lens, and thus 3-D and 2-D images can be formed through the convex lens and flat lens, respectively. Although 2-D/3-D conversion has become possible through the liquid lenticular lens array, one of the biggest problems of the lenticular lens structure is crosstalk.

Crosstalk occurs when the image for one eye intrudes into the other eye's view. Crosstalk is an unavoidable phenomenon in the lenticular lens array structure and causes a double image and a degraded 3-D effect. Because crosstalk is an important factor, affecting the viewer's visual comfort, it is necessary to minimize the crosstalk to achieve high quality images. Many studies are underway to alleviate crosstalk [17], [18]. In the conventional liquid lenticular lens, the crosstalk value was about 32.8%, which is much higher than when using a solid lenticular lens array.

In this paper, we analyzed the cause of the high crosstalk in the liquid lenticular lens array and demonstrated that the crosstalk can be changed by various factors, and quantified them. We also reduced the crosstalk value of the liquid lenticular lens array to 21.23% by blocking unnecessary light. The rest of the paper is organized as follows. Section 2 provides the theoretical background of crosstalk in the liquid lenticular lens array. In Section 3, we present the experiments and results, and compare the theoretical values with the experimental values. Finally, Section 4 concludes with a discussion of the proposed system and its performance.

2. Theoretical Background

In the liquid lenticular lens system, crosstalk can be defined as

$$\text{Crosstalk}(\%) = \frac{\text{leakage}}{\text{signal}} \times 100 \tag{1}$$

where "leakage" is the maximum luminance of light that leaks from the unintended area to the intended area, and 'signal' is the maximum luminance of the intended area. Crosstalk observed at the n^{th} optimal viewing position on the N-view 3-D display is defined as

$$\text{Crosstalk}(\%)_i = \frac{\sum_{n=1}^{N} I_n - I_i}{I_i} \times 100 \tag{2}$$

where I_i denotes the light intensity measured at the i^{th} optimal viewing position. The first method for reducing crosstalk is to increase the diopter of the lens. The lens diopter is determined by the radius of curvature and the refractive index of the lens material. Higher diopter means that the lens is more convex and the focal point of the lens is closer to the lens, which helps the light to diffract less and makes the airy disk of the lens smaller, as shown in Fig. 1. In a previous study [11], a thin polycarbonate chamber was used and the diopter of the liquid lenticular lens array was measured to about 1666.7D, which is enough to realize 3-D images.

The second method of reducing crosstalk is to block the unnecessary light from the chamber as shown in Fig. 2. The same images ("image 1") from the display panel pass through the liquid lenses and form a view ("1$^{\text{st}}$ view") at a specific area. However, an overlap between the first and other viewing zones occurs due to the structure of the lenticular lens. Although this overlap is inevitable in

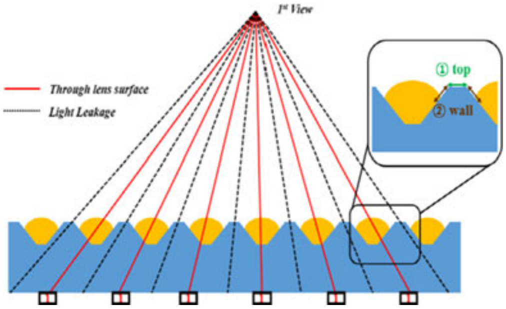

Fig. 2. Schematic of the optical paths through the liquid lenses and light leakages.

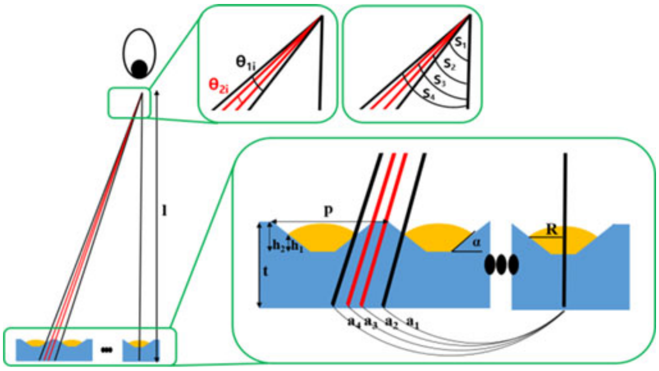

Fig. 3. Schematic of the light leakage of the liquid lenticular lens array and the ratio of the light leakage from the top and the wall parts of the chamber according to various parameters: observation length (*l*), chamber thickness (*t*), lens pitch (*p*), slanted angle (α), lens border height (*h1*), chamber height (*h2*), and the number of lenses in the array (*i*).

the lenticular lens system, the crosstalk of the liquid lenticular lens system is much higher than that of the solid lenticular lens system because the liquid lenticular lens requires a chamber to contain a liquid, which also serves as a lens. As a result, unnecessary light leaks out from the top and wall parts of the chamber.

We analyzed this unnecessary light from the top and wall parts of the chamber. The ratio of the light leakage from the top and the wall parts of the chamber was also theoretically calculated by using various parameters: observation length (*l*), chamber thickness (*t*), lens pitch (*p*), slanted angle (α), lens border height (h_1), chamber height (h_2), and the number of lenses in the array (*i*). As shown in Fig. 3, the values of a_1 to a_4 which represent the distance from the reference point to the i^{th} lenticular cell, need to be known.

$$a_1 = \frac{1}{l - (t - h_2 - h_1)(pi + R)l} \tag{3}$$

$$a_2 = \frac{l}{(l - t)(\frac{p-y}{2} + pi)} \tag{4}$$

$$a_3 = \frac{1}{(l - t)(\frac{p+y}{2} + pi)} \tag{5}$$

$$a_4 = \frac{l \times (p - R + pi)}{\{l - (t - h_2 + h_1)\}}. \tag{6}$$

In Fig. 3, θ_{1i}, θ_{2i} and θ_{3i} represents light passing through the top and wall part, only the top part, and only the wall part of the chamber, respectively. These values can be obtained from the values of S_1 to S_4 which can be expressed by the values of a_1 to a_4 as follows:

$$\tan S_1 = \frac{pi + R}{l - t + h_2 - h_1} \tag{7}$$

$$\tan S_2 = \left(\frac{1}{l - t}\right) \cdot \left(\frac{p - y}{2} + pi\right) \tag{8}$$

$$\tan S_3 = \left(\frac{1}{l - t}\right) \cdot \left(\frac{p + y}{2} + pi\right) \tag{9}$$

$$\tan S_4 = \frac{p - R + pi}{l - t + h_2 - h_1}. \tag{10}$$

From these values, θ_{1i}, θ_{2i} and θ_{3i} can be obtained as

$$\theta_{1i} = S_4 - S_1 = \tan^{-1}\left[\frac{p - R + pi}{l - t + h_2 - h_1}\right] - \tan^{-1}\left[\frac{pi + R}{l - t + h_2 - h_1}\right] \tag{11}$$

$$\theta_{2i} = S_3 - S_2 = \tan^{-1}\left[\left(\frac{1}{l - t}\right) \cdot \left(\frac{p + y}{2} + pi\right)\right] - \tan^{-1}\left[\left(\frac{1}{l - t}\right) \cdot \left(\frac{p - y}{2} + pi\right)\right] \tag{12}$$

$$\begin{aligned}\theta_{3i} = \theta_{1i} - \theta_{2i} = {} & \tan^{-1}\left[\frac{p - R + pi}{l - t + h_2 - h_1}\right] - \tan^{-1}\left[\frac{pi + R}{l - t + h_2 - h_1}\right] \\ & - \tan^{-1}\left[\left(\frac{1}{l - t}\right) \cdot \left(\frac{p + y}{2} + pi\right)\right] - \tan^{-1}\left[\left(\frac{1}{l - t}\right) \cdot \left(\frac{p - y}{2} + pi\right)\right].\end{aligned} \tag{13}$$

In this study, the observation length (l) was assumed to be 25 cm and other variables were fixed through the fabrication process (t: 0.5 mm, p: 414 μm, α : 54.7°, h_1: 90 μm, h_2: 120 μm, i : 253). Using the above equations, it can be theoretically calculated that the ratio of light leakage from the top and wall parts of the chamber is 58.55:41.45.

3. Experiments and Results

The chamber fabrication for the liquid lenticular lens involves pitch selection, silicon lithography, electroplating for the nickel mold, and hot embossing process for the polymer-based chamber [10]–[13]. A polycarbonate chamber was used for the high diopter, which is the same as the conventional fabrication process. Like the conventional liquid lenticular lens fabrication process, the liquid lenticular lens array was fabricated by depositing Ag electrode layer and parylene C dielectric layer, injecting oil, and sealing with an ITO glass, as shown in Fig. 4. However, there were two differences, as shown in Fig. 5. First, a laminating foil was used before depositing the electrode to prevent light leakage from the top parts of the chamber, as indicated in Fig. 5(a). Ag electrode layer was deposited by tilting the sample during the e-beam evaporation process as shown in Fig. 4(f). Because the Ag source in the e-beam evaporator goes straight, the electrode is relatively less deposited in the top part of the chamber than in the wall part of the chamber. The black foil was adhered to the top part of the chamber by applying a constant pressure at 120 °C. When the lamination process was completed, only the top part of the chamber was covered by the foil, and thus the unnecessary light leakage from the top part of the chamber could be blocked. In the second modification, the electrode was changed from Au to Ag to reduce cost, and the thickness of the electrode was increased to 100 nm, in comparison with 20 nm in the existing process. By thickening the electrode layer, the light leakage from the wall part of the chamber was prevented, as shown in Fig. 5(b).

To demonstrate how this new method affected the crosstalk of the liquid lenticular lens array, two-view image tests were conducted with different states. In Fig. 6(a), the experimental setup used to measure the crosstalk of the liquid lenticular lens array is shown. The liquid lenticular lens array

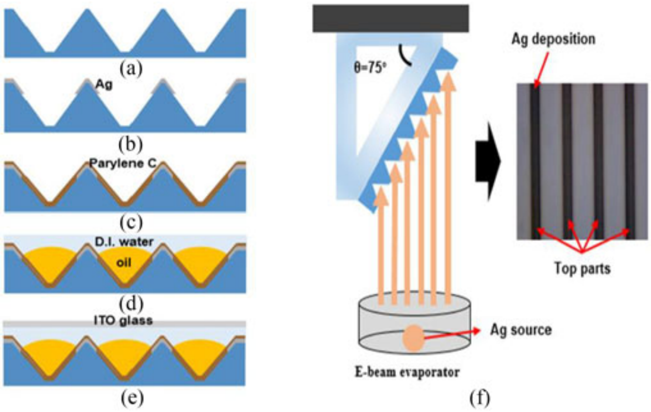

Fig. 4. Fabrication process. (a) Polycarbonate chamber. (b) Ag deposition. (c) Parylene C deposition. (d) Oil dosing in D.I. water bath. (e) Sealing with an ITO glass. (f) Ag deposition by tilting the sample.

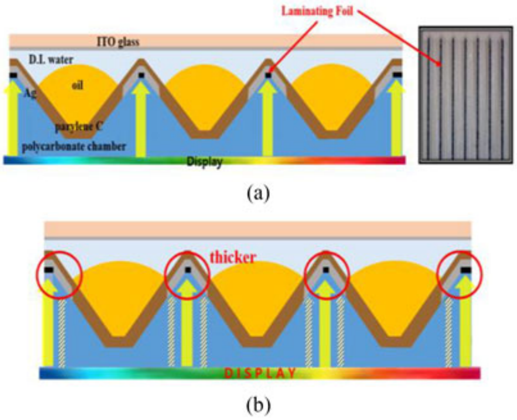

Fig. 5. Blocking the light leakage. (a) Blocking the top part of the chamber using the laminating foil. (b) Blocking the wall part of the chamber by depositing a thicker electrode.

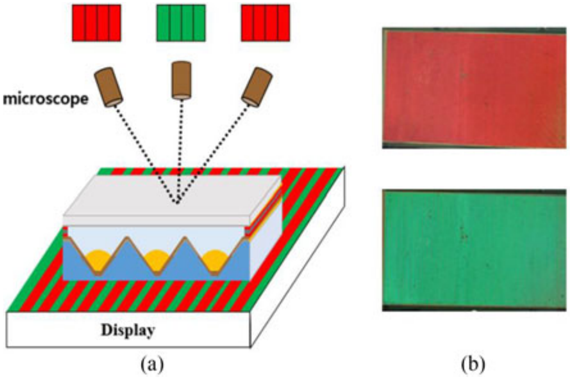

Fig. 6. Measuring the crosstalk of the liquid lenticular lens array according to the viewing angle. (a) Experimental setup. (b) Red and green images are shown according to the viewing direction.

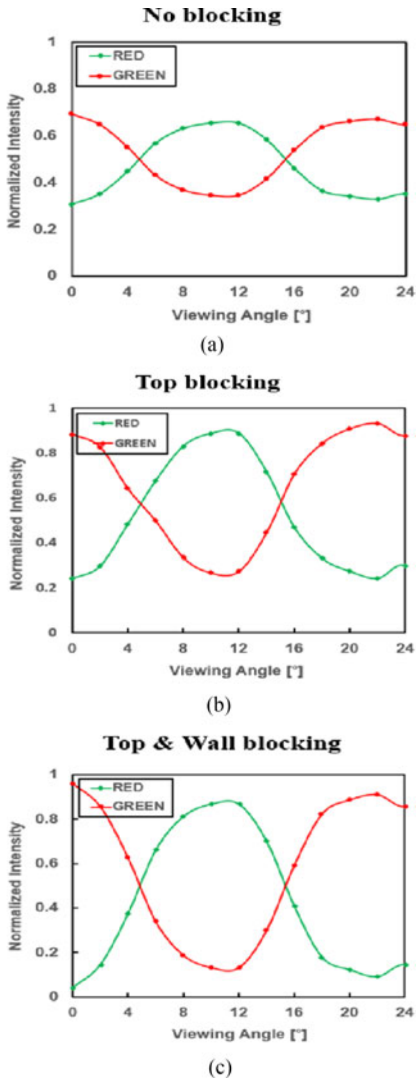

Fig. 7. Normalized intensities according to the viewing angle. (a) No blocking. (b) Blocking only top parts of the chamber. (c) Blocking both the top and wall parts of the chamber.

was placed on the display screen where the red and green patterns alternate. It is very important to align the liquid lenticular lens array on the display panel correctly because the misalignment causes crosstalk and low 3-D quality. The intensities of red and green were then measured depending on the viewing direction, and the crosstalk was calculated. At this time, the microscope objective was tilted according to the viewing direction, which keeps the observation distance constant.

Fig. 7(a)–(c) shows the intensities when no blocking process was done, like the conventional liquid lenticular lens array sample; when only the top part of the chamber was blocked; and when both the top and wall parts of the chamber were blocked, respectively. From (2), crosstalk is obtained by measuring the ratio of the red image that invades in the area of the green image. The measured crosstalk when only the top part of the chamber was covered with the black laminating foil was 26.78% and the crosstalk when both the top and wall parts of the chamber were blocked was 21.23%. More than 10% of the crosstalk was reduced by the modifications, compared to that of the conventional case (32.81%). It was also demonstrated that when the diopter of the liquid lenticular lens array was high enough to achieve a 3-D effect, the gap with the crosstalk of the solid lenticular

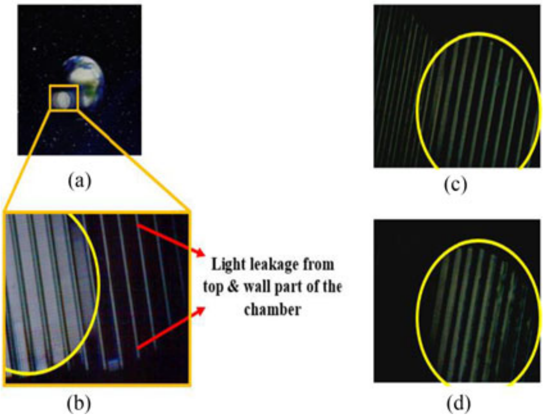

Fig. 8. Image tests. (a) Double image occurs when there is no blocking. (b) Unnecessary light leaks from the top and wall parts of the chamber with an applied voltage of 25 V. (c) With 0 V, after blocking the top and wall parts of the chamber. (d) With 25 V, after blocking the top and wall parts of the chamber.

lens array was reduced by blocking the unnecessary light from the top and wall parts of the chamber. Although total light was decreased because of higher blocking materials, Fig. 7 focuses on how clear each image can be observed without the other image. And these normalized intensities are relative values, not absolute values. We also calculated the ratio of the light leakages from the top and wall parts of the chamber and compared them with the theoretical values. From the values of each case, the ratio was determined to be about 52.07:47.93, which is slightly different from the theoretical values (58.55:41.45). In theory, it was assumed that the electrode was exactly 1/4 of the wall of the chamber, but in fact, it was not exactly 1/4, and because it is not easy to adjust the amount of oil precisely, as with the theoretical value, an error occurred in the values of h_1 and h_2 in Fig. 3.

An image test was conducted using the newly fabricated sample as shown in Fig. 8. Since the number of views of the image was three, the 1st to 3rd viewing zones were shown in order. Ideally, the afterimage of the moon should not be seen, if the diopter of the lens is high enough to realize the 3-D effect. However, it was not completely separated and the images were overlapped, despite of the high diopter, as shown in Fig. 8(a). In Fig. 8(b), the moon image has been enlarged and the leakage of light from the unintended area can be seen. This occurred because light leaked from the top and wall parts of the chamber. The image test was conducted again after blocking the top and wall parts of the chamber. At 0 V, when the shape of the liquid lens was concave, the double image still occurred, as shown in Fig. 8(c). When the applied voltage was increased to 25 V, and the shape of the lens was convex and the diopter of the lens was high, a separated view was achieved and only one moon image was observed, as shown in Fig. 8(d). From these image tests, it was demonstrated that the crosstalk of the liquid lenticular lens was reduced by blocking the top and wall parts of the chamber.

4. Conclusion

In this paper, we analyzed the crosstalk of the liquid lenticular lens array and proved that the crosstalk of the liquid lenticular lens array can be changed by various variables, such as observation length, chamber thickness, lens pitch, slanted angle, lens border height, chamber height, and the number of lenses in the array. The ratio of unnecessary light from the top and wall parts of the chamber was theoretically calculated to be 58.55:41.45. By using laminating foil and increasing the thickness of the electrode layer compared to the conventional sample, the light leakages from the top and wall parts of the chamber were blocked, and the crosstalk was subsequently reduced to 21.23%, which is similar to that of the solid lenticular lens array. The ratio of the light from the top and wall parts of the chamber was measured to be 52.07:47.93, and compared with the theoretical value. Using image tests with the new sample, it was demonstrated that a clear image could be observed after blocking the unnecessary light, with an applied voltage of 25 V.

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