Angular dependence of the performance of stereoscopic liquid-crystal-display (LCD) television using shutter glasses (SG)

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Abstract — 3-D cross-talk typically represents the ratio of image overlap between the left and right views. For stereoscopic LCDs using shutter-glasses technology, 3-D cross-talk for stereoscopic LCD TV with a diagonal size of 46 in. and vertical alignment (VA) mode was measured to change from 1% to 10% when the stereoscopic display is rotated around the vertical axis. Input signals consist of the left and right images that include patterns of different amounts of binocular disparity and various gray levels. Ghost-like artifacts are observed. Furthermore, intensities of these artifacts are observed to change as the stereoscopic display is rotated about the vertical axis. The temporal luminance of the LCD used in stereoscopic TV was found to be dependent on the viewing direction and can be considered as one cause of the phenomenon of angular dependence of performance for stereoscopic displays.

Keywords — *Stereoscopic display, liquid-crystal display (LCD), shutter glasses, viewing direction, 3-D cross-talk.*

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1 Introduction

Today, 3-D displays are gaining interest in various applications, especially in theaters and in the home. With the increase in 3-D content, 3-D TV and 3-D home theater are expected to be the major application for 3-D technology.[1–5] Various types of 3-D technologies have been reported, which may or may not require special eyeglasses. Autostereoscopic technologies generally represent 3-D displays that do not require special eyeglasses. Their working principles are based on watching different images at the viewing direction of each eye. An example of autostereoscopic technology using a parallax barrier is illustrated in Fig. 1(a). Through the parallax barrier, the left and right eyes can see the pixels of either L or R. But pixels can be seen together at some positions such as P1 in Fig. 1(a). Hence, the performance of autostereoscopic displays is related to the viewer's position or the viewing direction, and this relationship has been analyzed by various measuring methods and simulations.[6–8]

A stereoscopic display using shutter glasses (SG 3D) is one of the stereoscopic technologies that uses the fast exchange of the left and right images on the imaging display in synchronization with ON/OFF of the shutter glasses that users wear. Thus, each eye can see different images sequentially. This is illustrated in Fig. 1(b). In SG 3D, the left and right images should be displayed sequentially during 1/60 sec. So, a frame rate higher than 120 Hz is required. On the other hand, displays of 120 or 240 Hz had to become available for the purpose of displaying blurless moving images. So, it is technologically possible to make SG 3D TV with the modification of the existing 240-Hz displays, and SG 3D TVs are now available in the market.[4,5,9,10]

For large-sized TV applications, users watch TV at various positions. Hence, the viewing direction of the user's position with respect to the TV is not fixed and can affect the display performance. SG 3D has been considered to be slightly dependent on the viewing direction. Yet, detailed characterization of the dependence of SG 3D on the viewing direction has not been reported thus far to the best of the author's knowledge. In SG 3D, the performance is affected by the temporal performance of the imaging display and shutter glasses. The LCD is one of the display types used as the imaging display for SG 3D. In LCDs, a phase change of light propagating through liquid crystal (LC) is dependent on the angle of the optic axis of LC with respect to the viewing direction. Therefore, phase change is affected by the viewing direction and determines the luminance of the LCD. It had been reported that the angular dependence of the temporal behavior is not negligible for some LC modes such as TN (twisted nematic) and VA (vertical alignment).[11–13] Therefore, it needs to be considered how the angular dependence of the temporal behavior of LCDs affects the angular performance of SG 3D.

In order to characterize the performance of 3-D displays, 3-D cross-talk had been widely used.[8,10,16] Also, 3-D displays with large 3-D cross-talk are reported to cause discomfort or image degradation.[14,15] Therefore, in this paper, 3-D cross-talk is used as the measuring parameter to investigate the angular dependence of stereoscopic-display performances, while other measuring parameter may also show the angular dependence.

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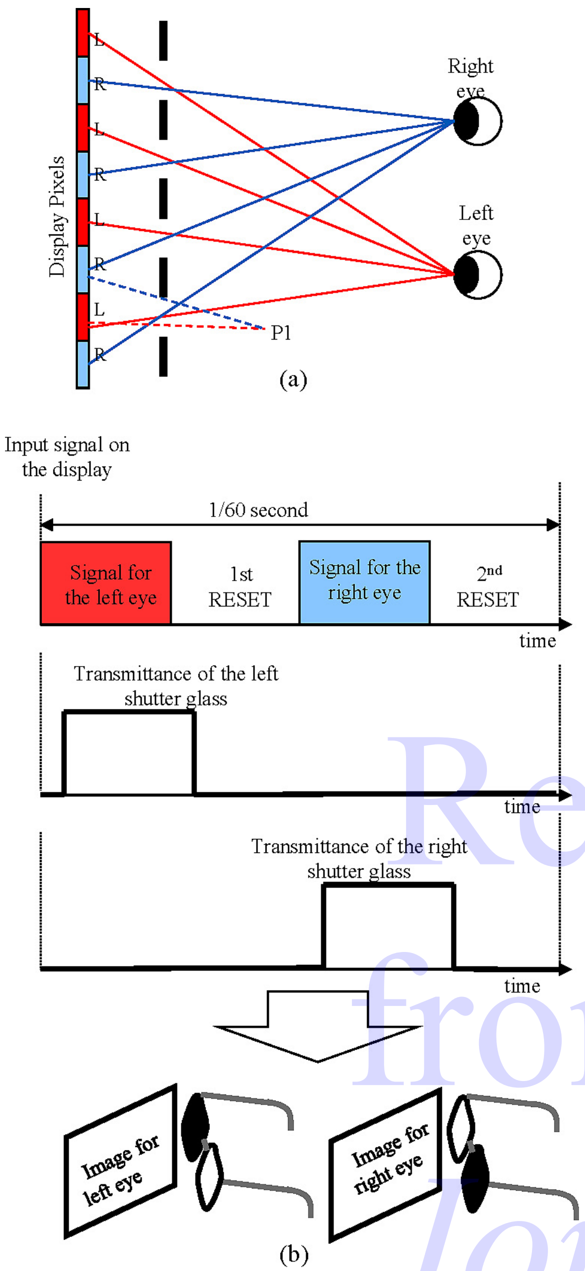

FIGURE 1 — Examples of 3-D technologies. (a) Autostereoscopic displays using parallax barrier. (b) Stereoscopic display using shutter glasses.

In this paper, angular dependence of the performance SG 3D LCDs is investigated by the measurement of 3-D cross-talk. As a matter of interest, a stereoscopic display is rotated about the vertical axis. Various test images are used to evaluate how this change in 3-D cross-talk actually affects the observed images under the rotation of a stereoscopic display. Finally, this dependence is discussed in relation to the characteristics of the LCD used for stereoscopic display.

2 Experimental setup

Figure 2(a) illustrates the top-down view of the schematic setup for the luminance measurement of a stereoscopic display. The left side of the shutter glasses is placed in front of the detector such as the luminance measurement device (LMD), camera, and photodiode. A CS2000 from Minolta was used as the LMD. The measuring distance is selected as three times the height of the active area of the stereoscopic display, and the measuring point is located at the center position of the active area of the stereoscopic display as illustrated in Fig. 2(b). To measure the effect of user's viewing direction on the performance of the stereoscopic display, the stereoscopic display is placed on a rotating stage. The rotation axis of the display is parallel to the vertical direction and through the center of the display. Therefore, the measuring point is not changed under rotation of the display. It is measured in a dark room where the ambient illumination is kept below 5 lux. A commercial SG 3D LCD TV, 46 in. on the diagonal, with a vertical-alignment (VA) mode, pixels of 1920 × 1080, and manufactured in the spring of 2010, is used for the measurement. The width and height of the active area of the stereoscopic TV are 101 and 57 cm, respectively. In 2-D mode, the frame rate is 240 Hz. In 3-D mode, the frame rate for each eye is 60 Hz as each frame

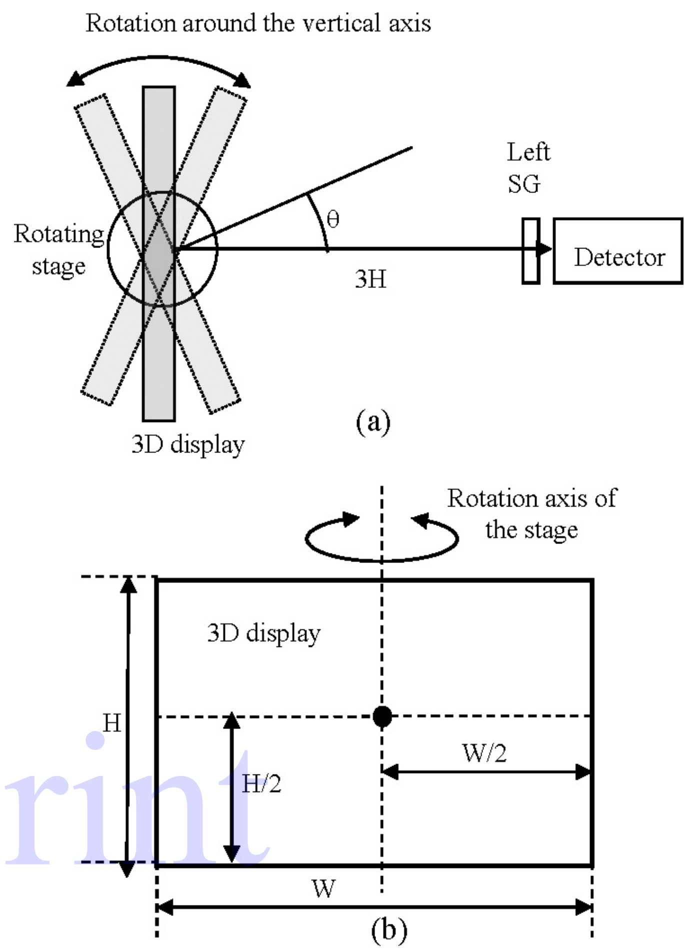

FIGURE 2 — (a) Top-down view of measurement setup of stereoscopic display. Stereoscopic display is placed on a rotating stage and is rotated about the vertical axis. Left side of shutter glasses is placed in front of detectors such as a LMD (luminance measurement device), camera, or photodiode. (b) Luminance measuring point is located at the center of stereoscopic display. *H* and *W* represent the height and the width of the active area of the stereoscopic display.

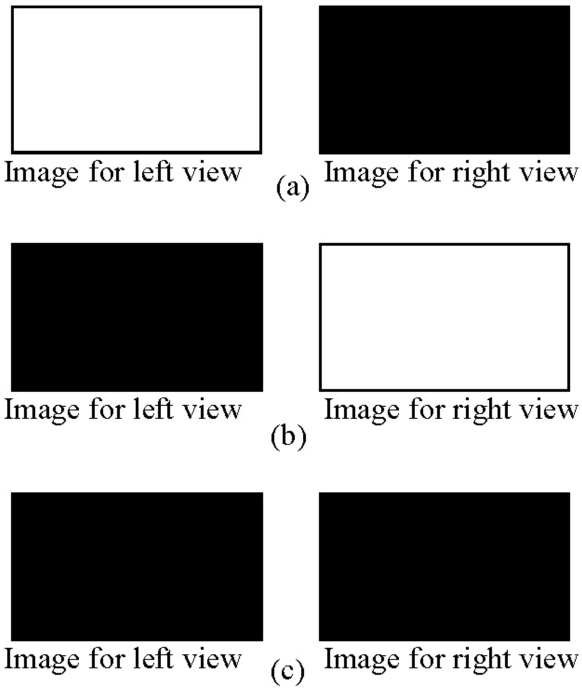

FIGURE 3 — Test images used for the measurement of 3-D cross-talk of the left eye. Images for the left and right views are (a) white, black; (b) black, white, and (c) black, black.

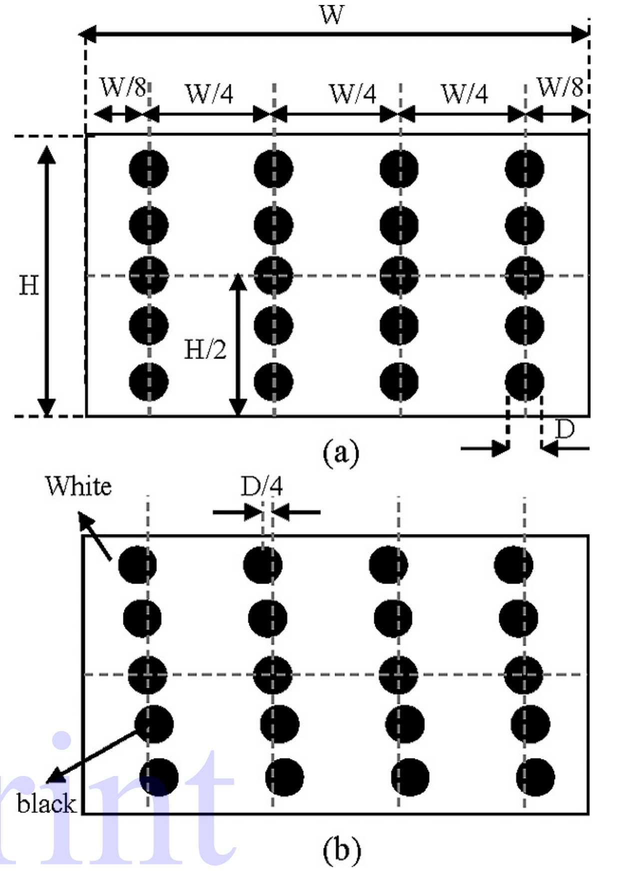

FIGURE 4 — Test images that consist of white background and black circles with a different amount of disparities for (a) the left view and (b) the right view. *H* and *W* represent the height and the width of the active area of the 3-D display. The ratio between *H* and *W* is 16/9. The diameter of circle, *D*, is *W*/15. Along the up-down direction, binocular disparity changes by *D*/8 for each row. Binocular disparity for the circles of the third row is zero.

consists of four subframes for 1/240-sec interval. Four subframes consist of the signals for the left view, the reset, the right view, and the reset.

3-D cross-talk is a measurement parameter that characterizes the interaction between images for the left and right eyes. In stereoscopic displays using glasses, 3-D cross-talk for the left eye is defined in the following equation[16]:

$$\text{3-D cross-talk for the left eye} = \frac{Lum(left:black, right:white) - Lum(left:black, right:black)}{Lum(left:white, right:black) - Lum(left:black, right:black)}. \quad (1)$$

Three input signals used for (left image, right image) are (black, white), (white, black), and (black, black), respectively. Test images for a full screen of a black or white background are used as illustrated in Fig. 3. A stereoscopic display was rotated in steps of 5° intervals about the vertical axis, and the luminance was measured through the left shutter glasses for three input signals. From these measured luminance data and Eq. (1), 3-D cross-talk for the left eye at the each viewing direction was determined. 3-D cross-talk for the right eye is similarly defined, placing the right shutter glasses in front of the LMD and interchanging the test images for the left and right eyes as shown in Fig. 3.

To investigate how 3-D cross-talk affects the observed images, test images shown in Fig. 4 are used as the input signal. In these test images, black circles of different values of binocular disparity are placed on a white uniform background. The diameter of the black circle, *D*, is *W*/15, where *W* is the width of the active area of the stereoscopic display. The amount of binocular disparity between the left and right views are *D*/4, *D*/8, 0, –*D*/8, and –*D*/4, respectively, for circles of each row. The plus sign of the disparity represents the circles perceived to be in front of the display, while the minus sign of the disparity represents the circles perceived to be behind the display. The displayed test images shown in Fig. 4 were captured by a camera by placing the shutter glasses in front of the camera, using the setup shown in Fig. 2.

While 3-D cross-talk is currently defined only for input signals of the black and white states, the real image consists of various gray levels. Hence, the test images of Fig. 5 are also used to evaluate the relationship between the viewing direction and the observed luminance at intermediate gray levels. These test images consisting of 0, 63, 127, 191, and 255 gray levels, where the 0 and 255 gray levels correspond to the input signal of the black and the white states. The width of the box pattern is *W*/5 for the left view and *W*/25 for the right view.

The temporal luminance of the stereoscopic display was measured for a time interval of 0.08 msec using a photodiode to analyze the detailed temporal behavior of the stereoscopic display.

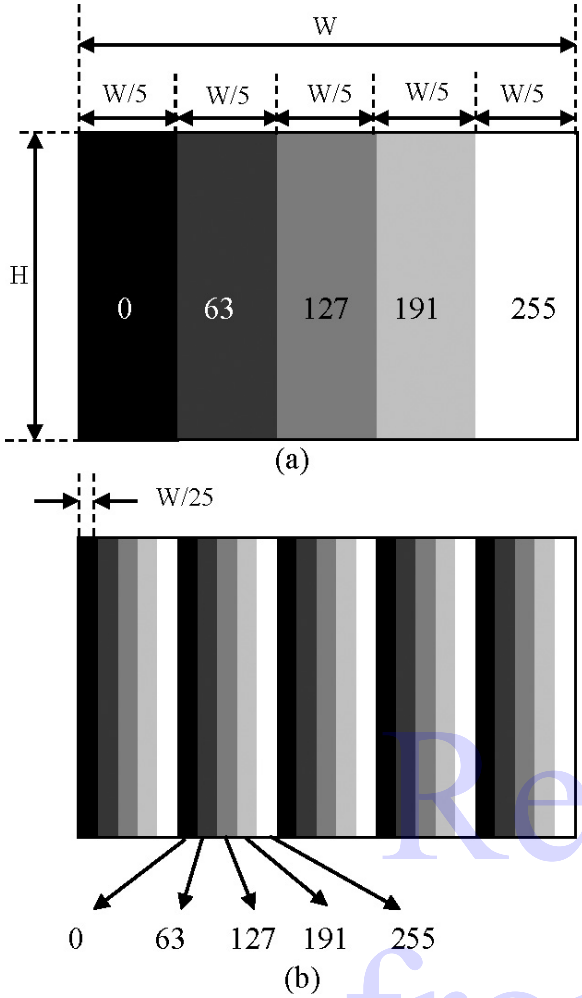

FIGURE 5 — Test images consisting of various gray levels for (a) the left view and (b) the right view. Numbers in the figure represent the gray levels used in the test images. 0 and 255 represent the black and the white states. *H* and *W* represent the height and the width of the active area of 3-D display.

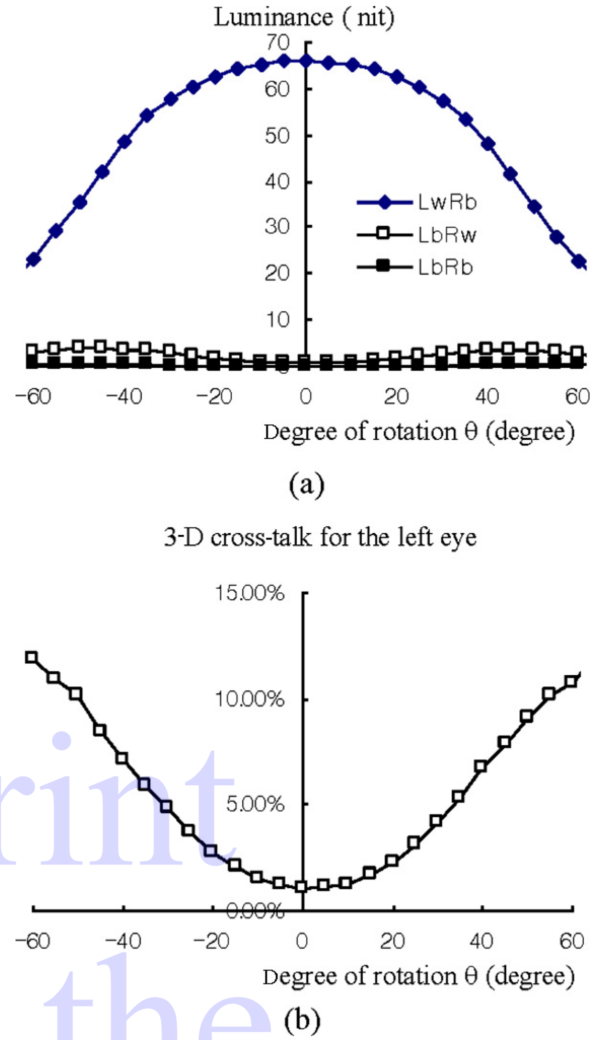

FIGURE 6 — Measured result of (a) the luminance of test images of Fig. 3 and (b) 3-D cross-talk for the left eye where the left side of the shutter glasses is placed in front of LMD. Horizontal axis of the graphs is the degree of rotation and corresponds to angle θ of Fig. 2(a). Luminance is measured as the 3-D display is rotated with respect to the vertical axis in 10° steps. LwRb, LbRw, and LbRb in the figure represent the input signals of (left : white, right : black), (left : black, right : white), and (left : black, right : black), respectively.

3 Results and analysis

The luminance and 3-D cross-talk were measured through the left side of the shutter glasses with respect to the rotation about the vertical axis for the setup shown in Fig. 2 and the input signals of Fig. 3. Figure 6 shows those results. The luminance at the input signal of left : black and right : white was measured to increase the larger rotation angle. 3-D cross-talk was also measured to increase the larger rotation angles irrespective of the sign of the rotation angle.

The performance of the right eye was measured through the right side of the shutter glasses by interchanging the input signals as well. These results are similar to those for the left eye.

3-D cross-talk of 2–7% has been reported to induce a ghost-like artifact and cause degradation of the image quality or discomfort.[14] 3-D cross-talk at a rotation angle of 0° is measured to be about 1% and below the 3-D cross-talk range that causes discomfort. However, 3-D cross-talk is measured to be larger than this range at larger rotation angles. 3-D cross-talk at an oblique viewing direction, therefore, may cause degradation in image quality or discomfort, and the angular behavior of 3-D cross-talk needs to be considered in characterizing the performance of SG 3D displays.

Figure 7 shows the photo captured through the left side of the shutter glasses when the test image shown in Fig. 4 is displayed on a stereoscopic display. As 3-D cross-talk of 1% is quite small, the observed luminance of the left image is slightly affected by the input signal of the right image. A ghost-like artifact can be observed beside the black circles where binocular disparity exists, yet these artifacts are barely noticeable. In Fig. 6(a), the measured luminance at θ = 0 for the input signal of (left : black, right : black) and (left : black, right : white) are 0.04 and 0.7 nits, respectively. Figure 8 is a photo captured for the same configuration except that the stereoscopic display is rotated about the vertical axis. Ghost-like artifacts are quite noticeable and the region

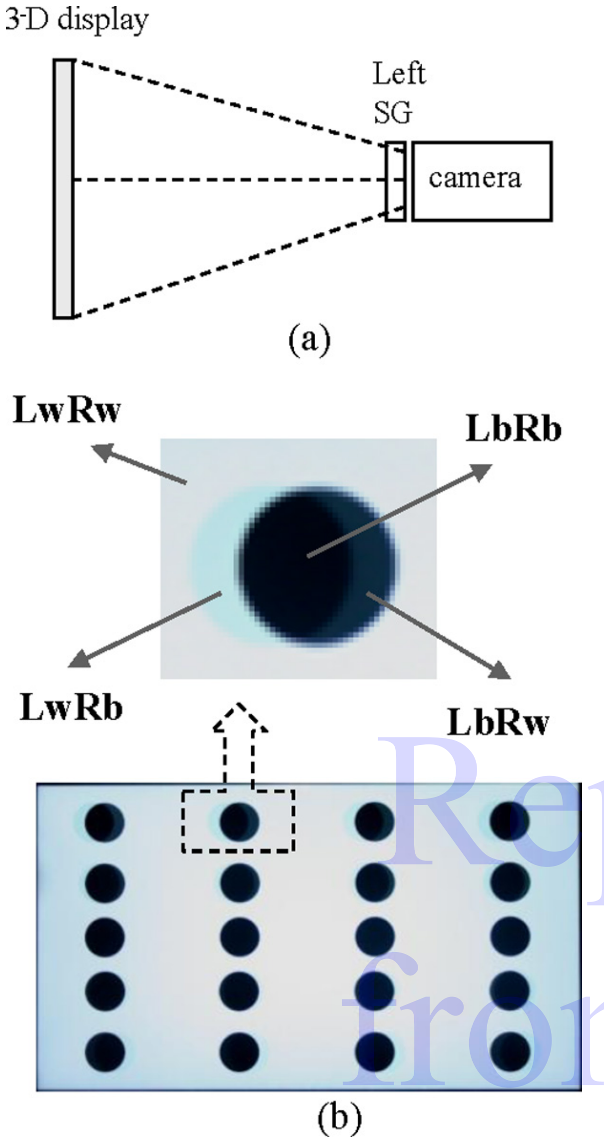

FIGURE 7 — (a) Top view of the setup for photograph (b) Photograph of the 3-D image captured through the left side of the shutter glasses. Enlarged photo shows that luminance observed through the left side of the shutter glasses is affected by the input signal of the right view. LwRw, LwRb, LbRw, and LbRb represent the input signals of (left : white, right : white); (left : white, right : black); (left : black, right : white); and (left : black, right : black), respectively.

of the input signal of (left : black, right : white) looks brighter compared with that shown in Fig. 7. These trends observed in Figs. 7 and 8 match the measured results shown in Fig. 6(a), where a luminance of LbRw increases to be larger than 3 nits when the rotation angle is larger than 30–35°.

A similar change of luminance is also observed along the up–down directions as well.

Figure 9 showns the photo captured through the left side of the shutter glasses when the test images of Fig. 5 are displayed on the stereoscopic display. For the ideal case of zero 3-D cross-talk, the photo shown in Fig. 9 should be similar to the test image for the left view shown in Fig. 5(a). Because the 3-D cross-talk is not zero, the pattern of the test image for the right view is observed as a ghost-like artifact.

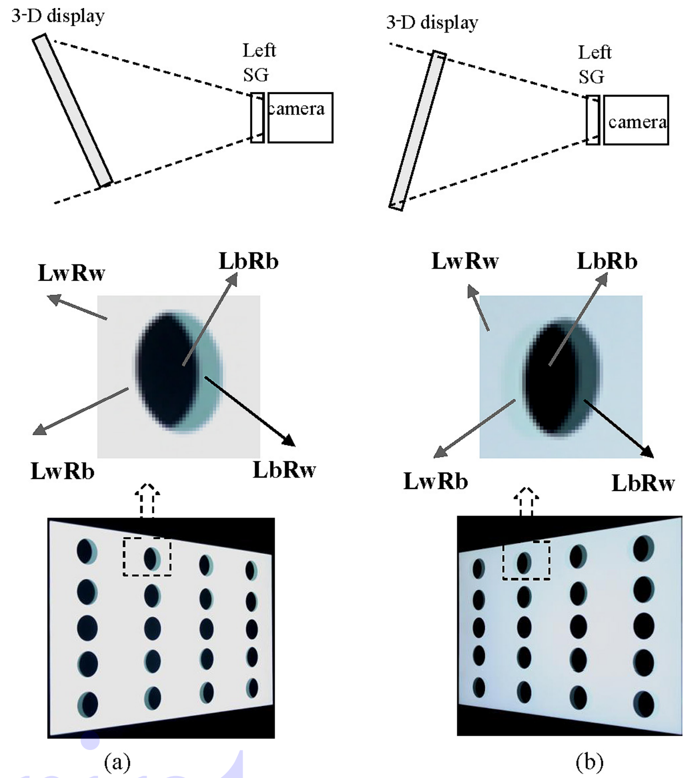

FIGURE 8 — Configuration for photograph and captured photo of the 3-D image through the left side of the shutter glasses with the rotation of the stereoscopic display: (a) counterclockwise and (b) clockwise. LwRw, LwRb, LbRw, and LbRb represent the input signals of (left : white, right : white), (left : white, right : black), (left : black, right : white), and (left : black, right : black), respectively. Regions of LbRw look brighter than that of Fig. 7.

This ghost-like artifact is observed more clearly in Figs. 9(a) and 9(c), compared with that in Fig. 9(b), especially on the left side of each photo where the left input signal is either the 0 or 64 gray level.

Because the luminance of the LCD and the transmittance of the shutter glasses change in the time domain, the 3-D temporal luminance can be written as the multiplication of the LCD temporal luminance and the shutter-glasses temporal transmittance. 3-D luminance can be obtained by the integration of the 3-D temporal luminance in the time domain. These relationships are given in Eqs. (2) and (3), where t is the time and θ_ is the angle of the shutter glasses with respect to the LMD.

$$\begin{aligned} &\text{3-D temporal luminance } (\theta, t) \\ &= \text{LCD temporal luminance } (\theta, t) \\ &\times \text{shutter temporal transmittance } (\theta_0, t), \end{aligned} \tag{2}$$

$$\begin{aligned} &\text{3-D luminance } (\theta) \\ &= \int [\text{LCD temporal luminance } (\theta, t) \\ &\times \text{shutter temporal transmittance } (\theta_0, t)]\, dt, \end{aligned} \tag{3}$$

When 3-D luminance is measured under the rotation of the stereoscopic display, the rotation angle θ changes while θ does not change as illustrated in Fig. 2. Therefore, the only factor that depends on the rotation angle θ is the

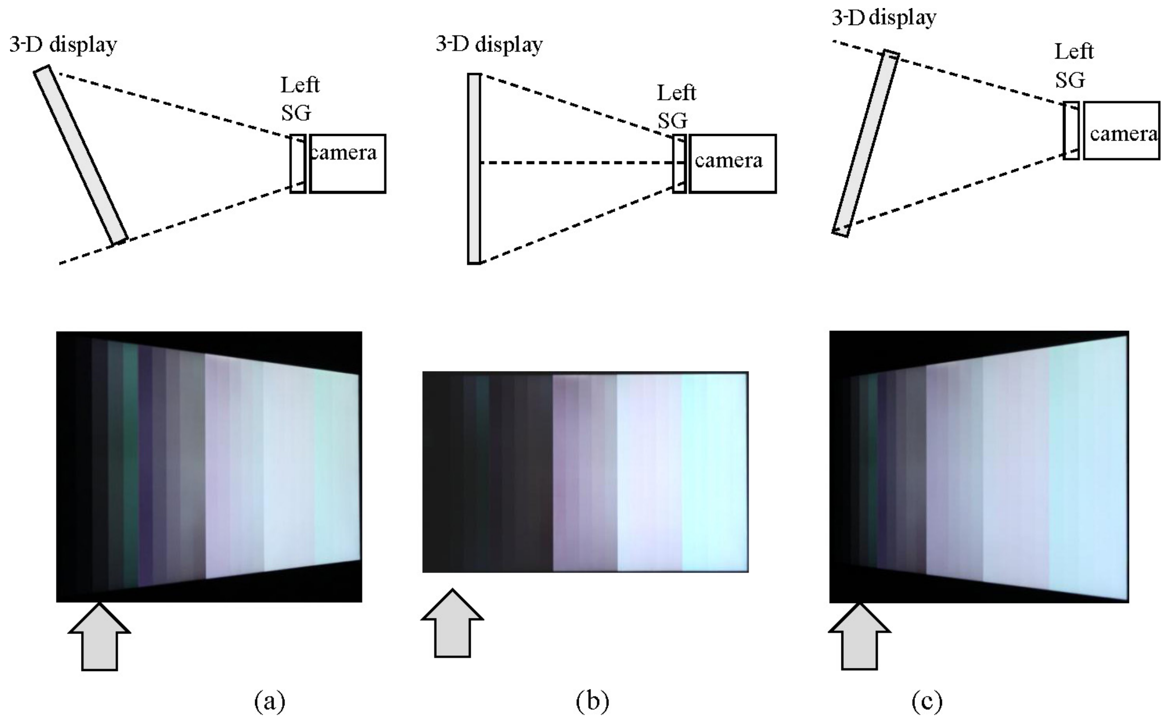

FIGURE 9 — Configuration for photograph and the captured photo of the 3-D image through the left side of the shutter glasses as when test images of Fig. 5 are used as the input signals. Stereoscopic display is rotated about the vertical axis clockwise or counterclockwise. Thick arrows represent the region where the gray level of the input signal for the left view is zero.

LCD temporal luminance and this can be assumed as the cause of the dependence of 3-D luminance on θ.

The angular temporal luminance of the stereoscopic display was measured with a time interval of 0.08 msec where the left side of the shutter glasses was placed in front of the photodiode. The measuring directions were at θ = 0 and 45°. Figure 10 shows the measurement results of the normalized temporal luminance when the input signal of (left : white, right : black) of Fig. 3(a) was used. In Fig. 10, peaks of luminance exist with a period of 16.7 msec. These peaks correspond to the images that the left eye sees in the period of 1/60 sec. The temporal-luminance profile does not have the shape of a simple peak and shows abrupt changes as the shutter glasses and LCD are controlled separately.[10] Results of 0° and 45° show a noticeable difference, especially in the time interval of 9–12 and 26–29 msec. These time intervals correspond to the time where the first RESET signal of Fig. 1(b) is applied.

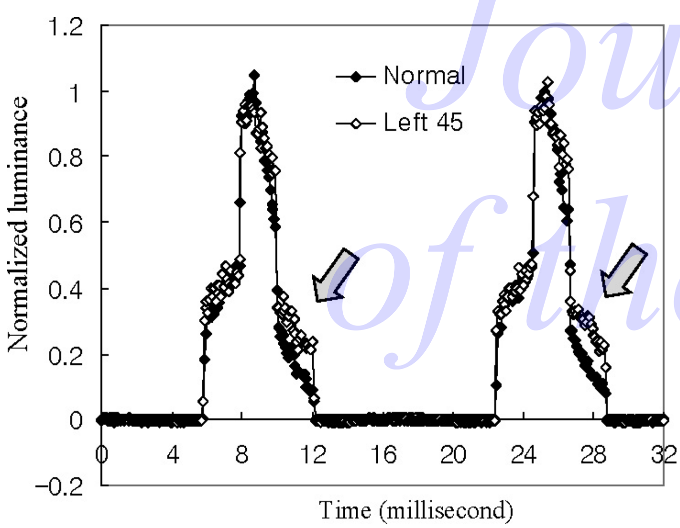

FIGURE 10 — Temporal luminance of a stereoscopic LCD TV measured with the left side of the shutter glasses in front of the photodiode at a rotation angle = 0 or 45°. Thick arrows represent the time interval where the difference between the conditions at 0 and 45° is noticeable.

It had been reported that the temporal luminance of an LCD is affected by the viewing direction, depending on the characteristics of LC mode.[11–13] A simple configuration for the LC molecules of an LCD with respect to the viewing direction is illustrated in Fig. 11. The direction of the LC optic axis θ_s is controlled by the input signal. The transmittance of an LCD is related to the effective refractive index n_{eff}. This relationship depends on various factors such as LC mode and the structure of the compensation films.[17] The effective refractive index is determined by the angle between the optic axis of the LC molecules and the viewing direction. For different viewing directions 1 and 2, these angles defined as θ_1 and θ_2 in Fig. 11(b) result in a different value for the effective refractive indices and the transmittance. If LC molecules are under motion, θ_s becomes a function of time. And this means that the temporal luminance at the viewing directions 1 and 2 become different.

For the VA mode, the transition time of the LC cell from the white state to the black state had been reported to increase as the angle increases.[13] The expected trend of the temporal transmittance profile of the VA mode is illustrated in Fig. 12. Input signals for 3-D sputter glass for each frame

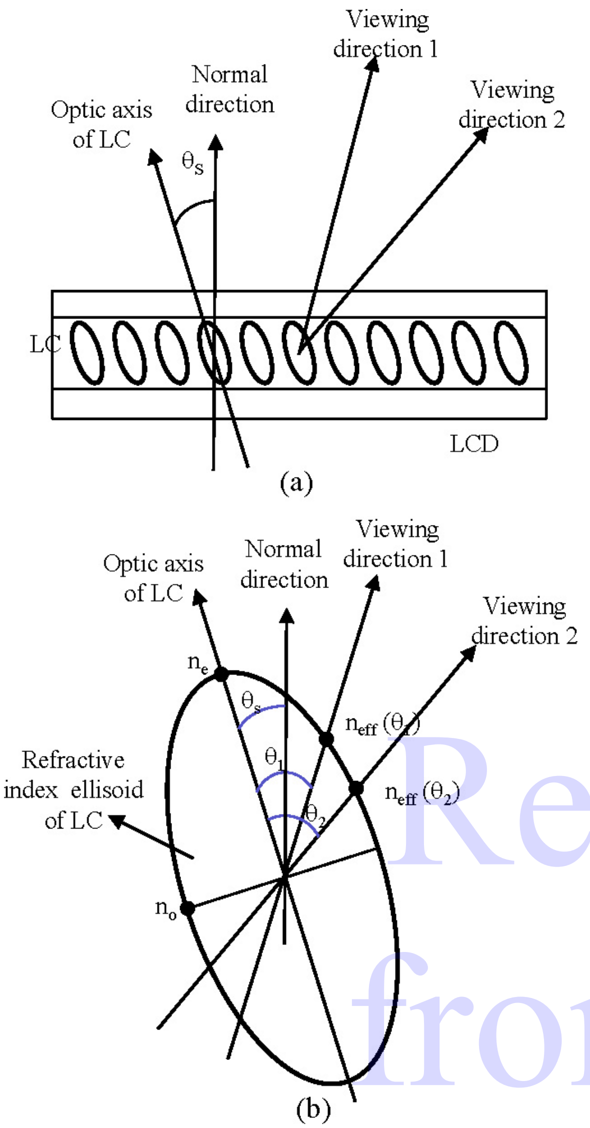

FIGURE 11 — (a) Configuration of LC molecules with respect to the viewing direction. (b) Refractive-index ellipsoid of LC molecules and the effective refractive index n_{eff}.

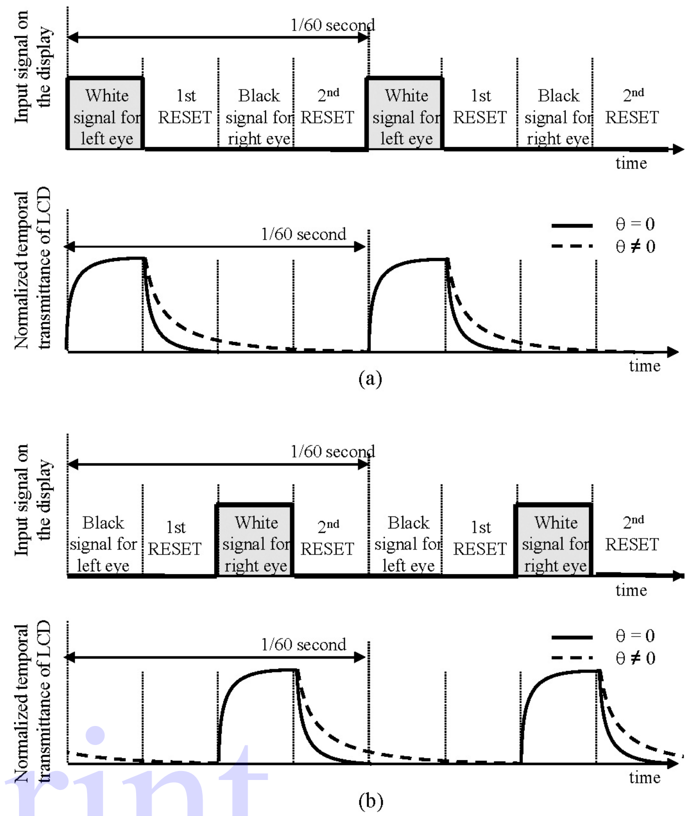

FIGURE 12 — (a) Input signal of (left: white, right: black) and the expected trends of temporal transmittance of VA mode at a rotation angle of zero and nonzero. (c) Input signal of (left: black, right: white) and the expected trends of temporal transmittance of VA mode at a rotation angle of zero and nonzero.

are illustrated as well. The left side of the shutter glass will be at the ON state in synchronization with the time where signals for the left view are applied. When an input signal of (left : white, right : black) is used as in Fig. 12(a), the transmittance is expected to decrease more slowly at a nonzero angle at the first RESET time, compared with θ = 0°. This trend matches the measured result of the temporal luminance profile shown in Fig. 10, where a luminance at 45° is larger than that at a 0°.

Figure 12(b) illustrates the case when an input signal of (left : black, right : white) is used. The LC state begins to change from the white state to the black state by the second RESET signal. If the transition time is long enough, the transmittance will not reach zero even at a time interval when the left signal is being applied. Then, this will cause an increase in the observed luminance through the left side of the shutter glasses. This expectation matches the measured result of Fig. 6(a) where the luminance of LbRw increases for larger rotation angles.

Hence, the assumption of an increase in transition time for a large viewing direction can provide the trend of matching the observed phenomena.

4 Conclusion

3-D cross-talk for the VA mode of SG 3D LCD TV was measured to be dependent on the viewing direction with respect to the stereoscopic display and shows the trend of increasing for larger viewing directions. When images of various binocular disparities are displayed, ghost-like artifacts were observed. The intensities of these artifacts are also observed to change, depending on the viewing direction. These changes are especially noticeable when the input signals of the observed view are the indicators of low-gray levels. The temporal luminance of VA-mode stereoscopic LCD TV was measured to be dependent on the viewing direction. As the shutter glasses is kept at a fixed direction, the angular dependence of SG 3D cross-talk is related to the angular characteristics of an LCD that is used for stereoscopic display.

3-D cross-talk for LCDs with a diagonal size of 46 in. is measured to be larger than 5% for an angle of 35° and is larger than 10% for an angle of 55°. As 3-D cross-talk in the

2–7% range is reported to cause discomfort or image degradation, angular 3-D performance of SG 3D should be considered for defining comfortable 3-D viewing zones. For TV application, the viewing directions of the viewers are widely spread. Therefore, performance should be considered for all viewing directions as well as the normal direction.

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