Optical Design for Biological Experiments with Polarized-Stimulus by Use of Polarization-Coded 3D Display

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ABSTRACT

We propose an experimental system that can present the arbitrary state of polarization by changing the displayed image. In addition, this paper designs a device to keep the state of polarization while changing the viewpoint, based on the measurement results of polarization distribution and angle dependence of the display.

1 INTRODUCTION

Polarization pattern of the sky is partially polarized light of sunlight scattered in the atmosphere. There are reports of insects recognizing directions by detecting this pattern [1]. However, it is not clear what vector direction of polarization the insects respond [2]. There are different types of polarization, such as linearly and circularly polarized light. The 3D display used in this study is the best display that can present such polarization stimuli.

This paper examines an experimental device that presents a polarization-coded light stimulation pattern to an organism. We use the device of Polarization-Coded the 3D display. The polarization distribution of this display changes when we observe the 3D display from an oblique direction. The polarization distribution is caused by structural factors of the 3D display. We performed polarization and observation of the 3D display using the polarized camera to measure the Stokes parameters. Based on these results, we study a device that can maintain the same polarization state regardless of the viewing angle.

2 PRINCIPLE OF 1/4 WAVELENGTH RETARDATION FILM

A 1/4 wavelength retardation film is a wavelength plate that gives a phase difference of π/2 between the two perpendicularly polarized components of the incident light to be emitted. For example, there is a linearly polarized light whose direction of oscillation is inclined at 45 deg to the x-axis. Where A is amplitude. Eq. (1) and Eq. (2) are x- and y-axis vibration, respectively.

$$E_x(z,t) = A\,cos(kz - \omega t) \tag{1}$$
$$E_y(z,t) = A\,cos(kz - \omega t) \tag{2}$$

We use a 1/4 wavelength retardation film, which gives a phase delay of π/2 to the oscillation in the y-axis direction. The vibration in the y-axis is shown in Eq. (3) [3].

$$E_y(z,t) = A\,cos\left(kz - \omega t + \frac{\pi}{2}\right) = -A\sin(kz - \omega t) \tag{3}$$

Linear polarization becomes left-handed circularly polarized light. When a 1/4 wavelength retardation film is rotated π/2, it is given a phase delay of π/2 in the x-axis direction.

$$E_x(z,t) = A\,cos\left(kz - \omega t + \frac{\pi}{2}\right) = -A\sin(kz - \omega t) \tag{4}$$

The polarization direction is linearly polarized at -45 deg to the x-axis.

3 EXPERIMENTS

3.1 Polarization-Coded 3D Display

We use a polarization-modulated the 3D display (Mitsubishi Electric RDT233WX-3D) [4, 5]. This display emits light with right- and left-handed circularly polarized light every other line. A 1/4 wavelength retardation film is placed on top of the 3D display to convert the circularly polarized light into linearly polarized light as Fig. 1.

We formulated principle of polarization-coded the 3D display using the Stokes parameters and the Muller matrix as shown in Eq. (5), (6) [6].

$$S_{out} = \mathrm{A}(0°) \cdot Qwp(45°) \cdot \mathrm{M} \cdot S_{in} \tag{5}$$

$$\begin{bmatrix} s_0' \\ s_1' \\ s_2' \\ s_3' \end{bmatrix} = \frac{1}{2}\begin{bmatrix} 1 & 1 & 0 & 0 \\ 1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \cdot \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & -1 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix} \cdot \begin{bmatrix} m_{00} & m_{01} & m_{02} & m_{03} \\ m_{10} & m_{11} & m_{12} & m_{13} \\ m_{20} & m_{21} & m_{22} & m_{23} \\ m_{30} & m_{31} & m_{32} & m_{33} \end{bmatrix} \cdot \begin{bmatrix} s_0 \\ s_1 \\ s_2 \\ s_3 \end{bmatrix} = \frac{1}{2}\begin{bmatrix} 1 \\ \pm 1 \\ 0 \\ 0 \end{bmatrix} \tag{6}$$

Where S_{out} is emitted light, S_{in} is incident light of light source, M is the Muller matrix of the 3D display light source, A is the Muller matrix of the polarizer at 0 deg, and Qwp is the Muller matrix of the 1/4 wavelength retardation film at 45 deg.

The polarization camera can measure the Stokes parameters to reveal the intensity, ellipticity, polarization, and orientation of polarized light [7]. In this experiment, we measured the polarization distribution and the angle dependence of the 3D display.

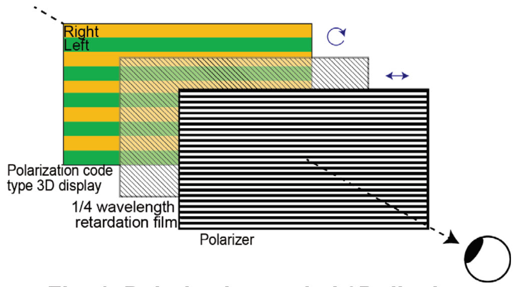

Fig. 1 Polarization-coded 3D display.

3.2 Viewing-Angle Dependence

We observed the changes in the vertical visibility of the 3D display. We defined upward as positive value and downward as negative value from the front side of the display at 0 deg as Fig. 2. The display was rotated 90 deg and placed on a rotating table with the long side perpendicular to the ground. We measured the ellipticity and degree of polarization of the polarized light of the 3D display using the polarization camera. We adjusted the measurement distance so that the full screen of the 3D display was visible.

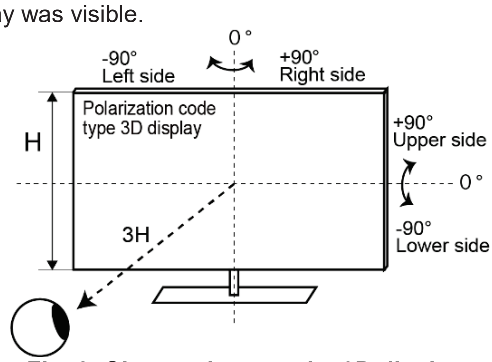

Fig. 2 Observations on the 3D display.

3.3 Relationships Between Polarizer Angle and Luminance Value

We measured the luminance from a point (3 cm × 3 cm) of the 3D display. Changing the angle of a polarizer from the vertical direction of the 3D display. We used the 15cm cubic glass tanks (5 mm thickness) and acrylic tanks (2.5 mm thickness) each side, as shown in Fig. 3. Fig. 4 shows the measurement conditions of luminance: direct measurement, glass, glass and water, acrylic, and acrylic and water. The depth of the water in the tank is 1 cm.

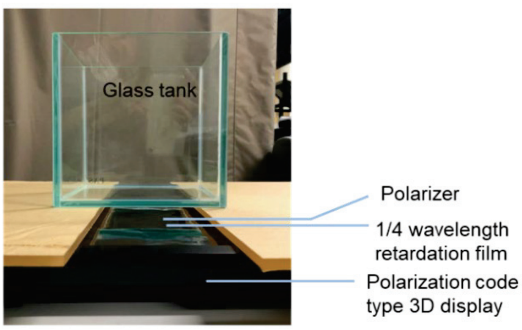

Fig. 3 The actual equipment.

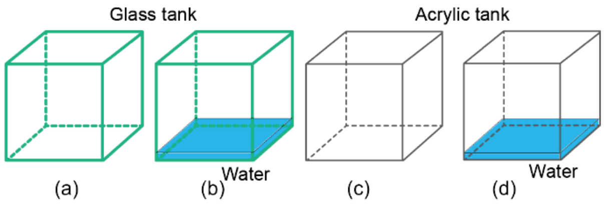

Fig. 4 Measurement conditions: (a) glass, (b) glass and water, (c) acrylic, (d) acrylic and water.

4 RESULTS

4.1 Comparison of Images for Several Viewing Angles

The results of comparison of images for several viewing angles are shown in Fig. 5 and Fig. 6. Fig. 5 shows the observation result from right and left sides. Fig. 6 shows the observation results from upper and lower sides. The result of observation, the 3D display was a gradual reversal of color around 15 deg, 30 deg and 50 deg. The strongest part of the color appeared to be every about 20 deg.

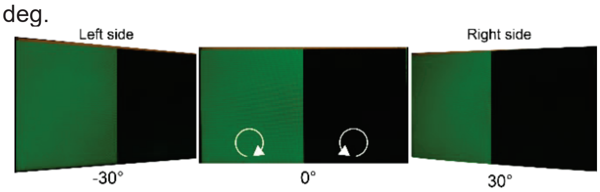

Fig. 5 Comparison of Images for each viewing angles of right and left sides.

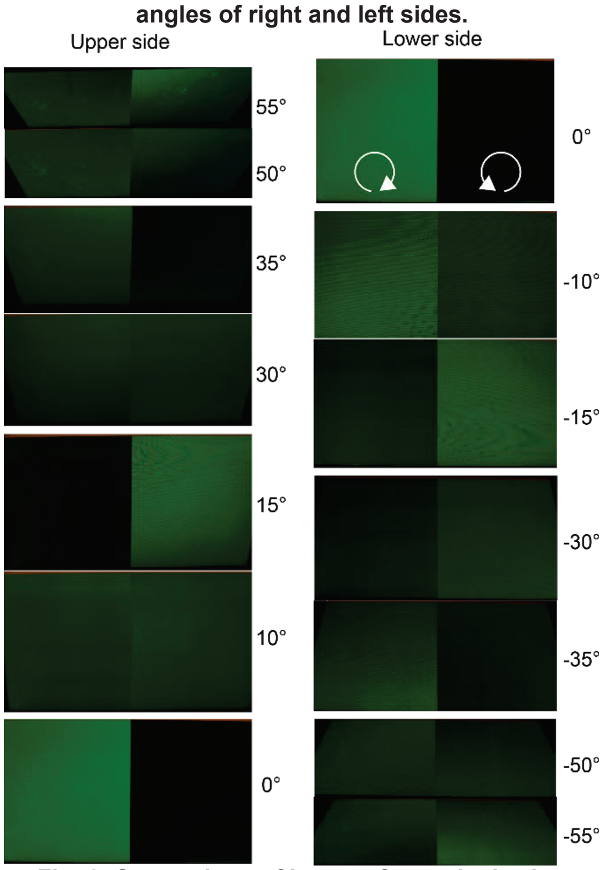

Fig. 6 Comparison of Images for each viewing angles of upper and lower sides.

4.2 Polarization Camera

Fig. 7 shows results of polarization measurements. There was no significant change in the polarization state at viewing angles of ±5 deg from the front. We found that both right- and left-handed circularly polarization lights are elliptically polarization close to circle. The circular polarization is uniform in the right and left sides of the 3D display, but changes in the upper and lower sides.

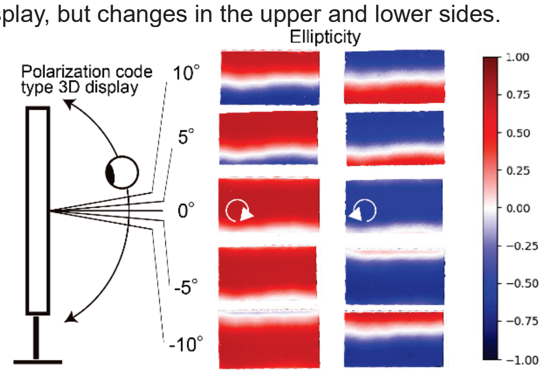

Fig. 7 Comparison of the right- and left-handed circularly polarized light.

4.3 Relationship Between Polarizer Angle and Luminance Value

Fig. 8 and Fig. 9 shows the luminance value of right- and left-handed circularly polarized light turning the polarizer from 0 deg to 90 deg, respectively. Fig. 10 shows contrast ratios for each condition. We defined the maximum luminance as I_{max}, and the minimum luminance as I_{min} in all values of each conditions.

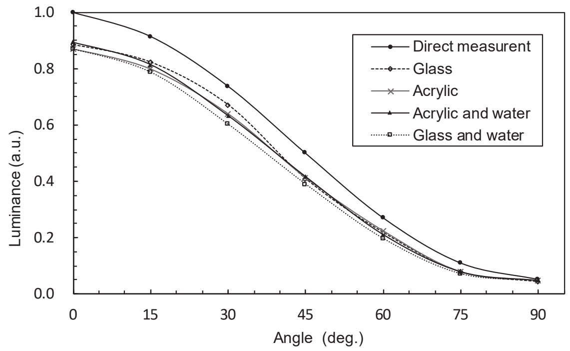

Fig. 8 Luminance change of right-handed circularly polarized light by polarizer angle.

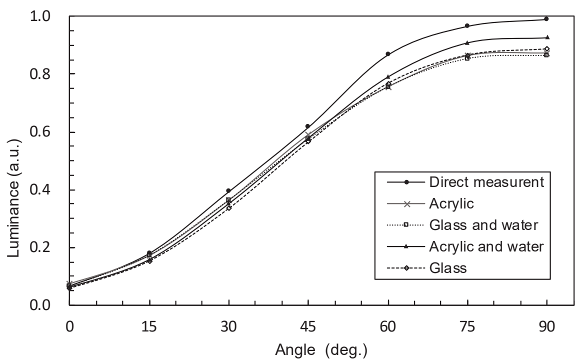

Fig. 9 Luminance change of left-handed circularly polarized light by polarizer angle.

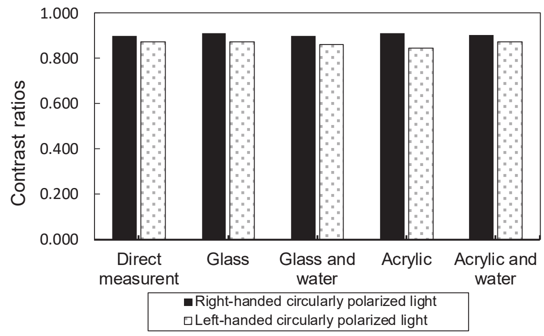

Fig. 10 Contrast ratios of the luminance value. Contrast ratios = (I_{max} - I_{min}) / (I_{max} + I_{min}).

5 DISCUSSION

We had become clear that the viewing angle from the front of the 3D display was about 10 deg. And, we could not see any difference in luminance through the tank and water. We would like to be realize a device that shows images to three sides (bottom and facing sides) of the tank using the 3D display as a light source. A polarization-coded 3D display panel is used as the light source. In this study, we limited the movement range of the organisms to the inside of a cube tank. We set up to obtain light from the front and oblique direction to consider three directions on one screen.

First, we will discuss the case using a point of light source in shown Fig. 11 (a). We formulated principle of a device of the distance between the 3D display and bottom of the tank with reference Fig. 11 (a) as shown in Eq. (7). Where W is length of a side of the tank, d is distance between the 3D display and bottom of the tank, and Q is viewing angles from front of the 3D display.

$$d = \frac{W}{2\tan Q} \tag{7}$$

Then, we replace W with 15 cm and Q with 5 deg; therefore, we obtain that d is 54 cm. At this value, it is unsuitable for experiments to present the state of state of polarization on the polarization-coded 3D display to organisms. Because it is difficult for organisms to observe the state of polarization on the polarization-coded 3D display. This problem results from too much distance between the 3D display and bottom of the tank like Fig. 11 (b). Thus, we discuss about using three points of light source as shown in Fig. 12 (a) to improve this problem. We define three light sources: the center and both ends, and place the tank at a height where the range of observable viewing angle of the 3D display overlap as Fig. 12 (b). Arranging a polarizer on the bottom of the tank such as Fig. 12 (c) to prevent organisms from light of the polarization state has changed. Therefore, we could close the distance between the 3D display and bottom of the tank as Fig. 12 (a).

Next, we examine a side of the tank. Fig. 13 shows the 3D display on the side of the tank by reflecting it in a mirror.

In addition, the device presents arbitrary polarization depending on presentation images and the direction of the 1/4 wavelength retardation film for organisms. First, we discuss the experimental optical system of circularly polarized light. We describe the case without a polarizer and the 1/4 wavelength retardation film from Fig. 11 (b) and Fig. 13. Only the circularly polarized light of the 3D display is presented. Therefore, the stimulus of right- or left-handed circularly polarized light can be selected by simply changing the displayed image. Next, we explain an experimental optical system that allows us to select the direction of linear polarization by changing the orientation of the quarter-wave plate in Fig. 11(b) and Fig. 13 without polarizer. We can choose the state of polarization; which is horizontal or vertical, and diagonally right and left 45 deg, from the traveling direction of polarization.

6 CONCLUSION

We have examined a device to measure the polarization of a 3D display to enable it to present the maintained polarized state from anywhere. We have discussed a device to achieve a desired polarization state by adjusting the displayed image.

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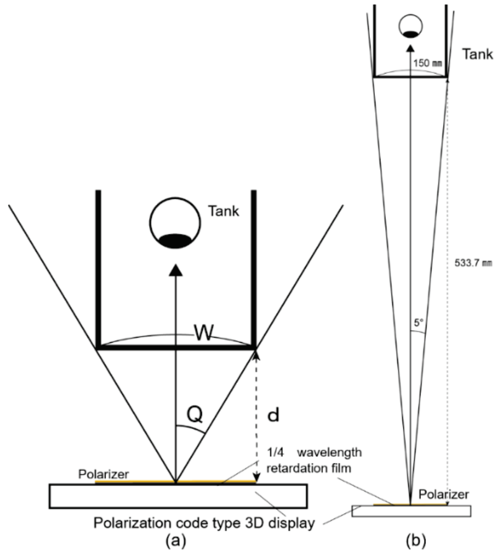

Fig. 11 (a) The optical system of the bottom of the tank, (b) Drawing to scale of the optical system of the bottom of the tank.

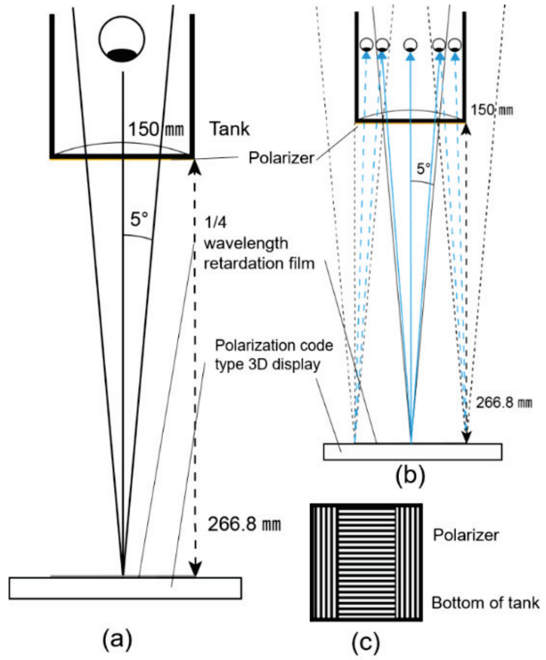

Fig. 12 (a) Drawing to scale of the optical system of the bottom of the tank , (b) Principle of visibility, (c) Polarizer at the bottom of the tank.

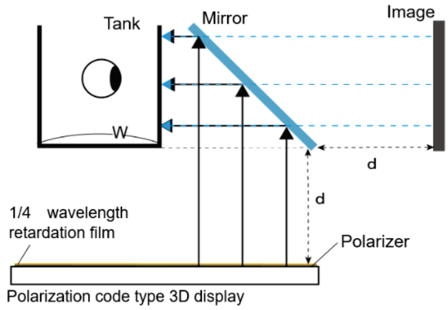

Fig. 13 The optical system of one direction of tank.