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A Study on the Angular Characteristics of Photopolymer-based Hologram Recording and Reproducing Light

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Abstract

Increasing interest in the metaverse world these days, interest in realistic content such as 3D displays is growing. In particular, hologram images seen in movies provide viewers with an immersive display that cannot be seen in conventional 2D images. Since the first discovery of holography by Dennis Gabor in 1948, this technology has developed rapidly. Spatially, this beginning of technology like Optical hologram called analog hologram and Digital hologram such as computer-generated hologram (CGH). In analog and digital holograms, a recording angle and a recording wavelength are having important role when reproducing and display hologram. In the hologram, diffraction of light causes by unexpected formed by the synthesis from interference with object and reference light. When recording, the incident light information and mismatched reproduction light reconstruct the hologram in an undesirable direction. Reproduction light that is out of sync with incident light information with initial condition of recording will cause reconstructed image in an undesirable direction. Therefore, we analyze the holographic interference pattern generated by hologram recording in volume holograms using photopolymer and analyze the characteristics that vary depending on the angle of the reproduced light. This is expected to be used as a basic research on various holographic application that may cause as holograms are applied to industries in the future.

Keywords: *Hologram, Photopolymer, Volumetric Hologram, Angular Selectivity, Hologram Reconstruction*

1. INTRODUCTION

Current holography technology requires a medium capable of recording holographic interference patterns for reproduction. We call this a holographic medium or holographic film for convenience. A holographic medium records all information of an object in the form of an interference pattern on a photosensitive material in the form of a thin film. The holographic medium is recorded as a one-off and produced semi-permanently. Representatively used media include silver-halide photopolymer, dichromatic gelatin, and photoresist. The essential elements of the medium used for holography are as follows. High-resolution pattern recording must be possible on a medium, and a constant spatial frequency response is required. In addition, since it has a wide

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spectrum, it should be possible to record colors in various wavelength bands [1-3]. In addition, since the nanoscale interference pattern is recorded as a pattern, it should have high sensitivity and response speed because the quality is deteriorated even with small vibrations. As an element for realizing an environment suitable for workers, it is good if the development is simple and unnecessary, and it is good if non-polluting chemicals can be used. In addition, for mass production or commercialization, it is good if the medium is easy to supply and demand. Silver salt emulsion is the most sensitive material among holographic media and is developed with very high resolution [4]. This is expressed using a measure of image brightness called diffraction efficiency, and has a value of over 90% at its maximum. Silver salt emulsion can produce high-sensitivity holograms, but it is difficult to develop and sensitive to humidity and temperature, so holograms can be damaged if they are not produced and stored in a 100% good environment. In addition, since all systems currently do not produce media through automation, uniform characteristics of the media used cannot be guaranteed [5]. Therefore, when producing a hologram, it is always necessary to test the efficiency and reactivity of the medium before proceeding. This acts as a major obstacle in mass production of uniform products. This problem can be solved by using a photopolymer. Since the photopolymer also has a high diffraction efficiency of 90% or more, the silver salt emulsion can reproduce a display with the same sensitivity. In addition, unlike silver salt emulsions using dichromate gelatin, it shows advantages in terms of temperature and moisture. Due to these advantages, it is widely used in fields such as optical devices and security for displays, and is attracting attention as a material for mass reproduction of full-color holograms [6,7]. In this study, while recording holograms on a volumetric holographic medium using photopolymer, we propose an analysis method for the angular characteristics that change when restoring object light using reproduction light by analyzing the form of grids. . The analysis result of this study is an analysis of the hologram reproduction environment recorded and reproduced in a volumetric hologram such as photopolymer, and it can be used as a guide for analyzing the optimal environment to restore the image of a hologram produced in the future.

2. BACKGROUND THEORY

2.1 Hologram Recording and Reconstruction

Figure 1 shows the process of recording and reproducing a hologram.

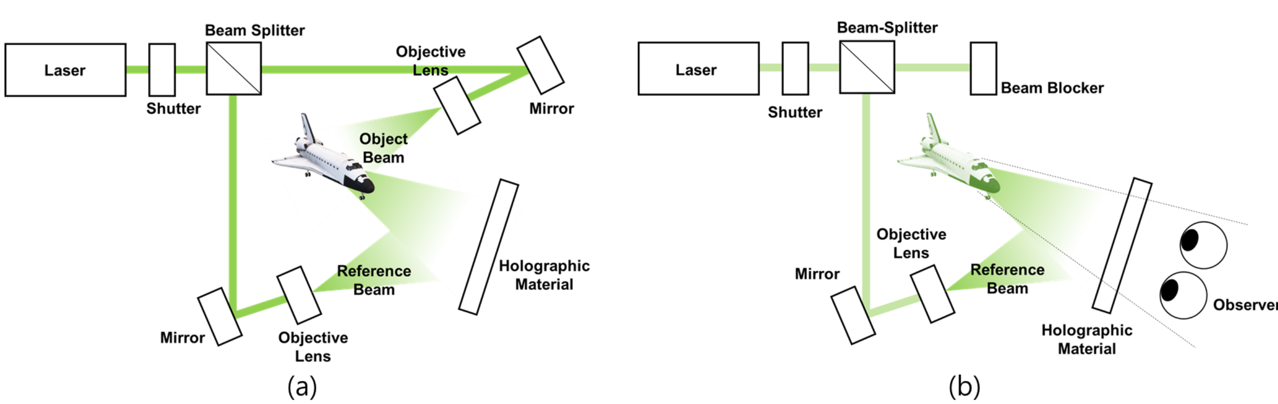

Figure 1. (a) Hologram Recording (b) Hologram Reconstruction

The light emitted from the laser is divided into two through a beam splitter, and one is used as a reference light that shines on the holographic medium as it is, and the other is used as an object light to reflect object information and transmit it to the medium. Both lights travel in the form of a uniform spherical wave after the light emitted from the laser is diffused through the objective lens. In this process, since no lens is used to create an image of an object, holography is also called lensless photography technology. When the object is viewed as an aggregate of all point sources, the holographic interference pattern created in this way includes an amplitude, which is information about brightness, and a phase, which indicates information about direction, in each point source. In order to reproduce a 3D image in a hologram, the technology to record and restore this phase information is the key [8-10]. This phase information interferes with the direction information of the object we know and the standard light called reference light, and the phase difference is recorded on the holographic medium. In this case, if only the reference light is illuminated at the same angle after the recording is completed, the phase difference as well as the amplitude information is restored and the object is reproduced in its original position [11].

2.2 Holographic Interference Pattern

A hologram starts from interfering reference light and object light with each other. When the part with the largest amplitude, that is, the part with the highest wave, meets each other, it is amplified, and when the part with the highest amplitude and the lowest part meet, they are canceled. A pattern of light and dark is formed in space from the intensity of a point light source coming from an object. This interference pattern changes from the relationship of the relative positions of the two light sources [12]. Figure 2 shows the shape of the holographic interference pattern.

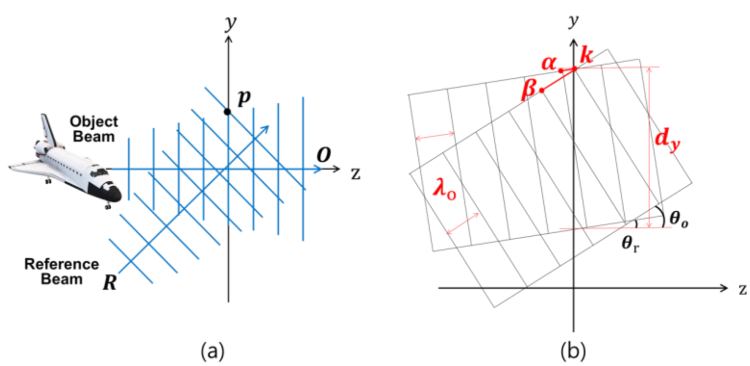

Figure 2. (a) Pattern for interference (b) Interference pattern formation at point p

If both waves are regarded as plane waves for simplicity and intuitive understanding of the equation, if the reference light and the object light are incident at point p on the hologram surface, the angles of incidence are θ_r and θ_o with respect to the axis, respectively and the wavelength is λ_o like figure 2(a). if the amplitudes of both lights are maximum at point p, we say that the phases are the same. When we see figure 2(b), the result of interference at this location is the formation of a bright fringe.

$$\alpha k - \beta k = d_y(\sin\theta_r - \sin\theta_o) = \lambda_o \tag{1}$$

In Equation (1), α is the wavelength before the object light meets the x-axis, β is the wavelength before it meets the x-axis, k is the point where the wavelength is located on the x-axis, and d_y is the distance between P and Q, representing the pattern interval in the x-axis direction. If q is the position on the x-axis that becomes brighter next, the object light and the reference light are shifted by one wavelength at this position. Therefore, the distance between p and q becomes the pattern spacing in the x-axis direction, and if this is denoted as d_y, the following equation (1) is established [13]. At points below p, the value of $\sin\theta_r - \sin\theta_o$ increases. Therefore, if the wavelength is constant, d_y becomes smaller and the pattern becomes more detailed. This is the reason why patterns with different intervals and directions are formed depending on the position of the hologram face. If the position of R or O is changed, the interference pattern changes. When an object has a three-dimensional shape, object light overlaps light emitted from each point from the surface. In addition, since a complex wavefront is formed instead of a simple spherical wave, it is difficult to record the same hologram if there is no object used for recording or if the location is slightly different. In the case of photopolymer, it is a medium that is 6 to 7 times thicker than silver salt emulsion [14]. If so, it is necessary to analyze the characteristics of these spacings and directions in more detail. When recording a reflective hologram to realize an environment that can be viewed by an observer, the condition of the reference light must be incident with a waveform of the same wavelength and position during recording [15]. Otherwise, the observer may experience inconvenience in having to use different angles or different wavelengths of illumination. In addition, photopolymer has a great advantage as a translucent screen because it blocks diffraction of external noise light due to its narrow reproduction spectrum, but if accurate reproduction is not performed, irregular modulation in which the angle and wavelength are shifted may occur

3. METHODOLOGY

3.1 Numerical Analysis of Reconstruction Images

In Equation (2), Assuming that R is a divergent spherical wave, a (+) sign is used, and if it is a converging light, a (-) sign is used. Calculate hologram can be said to be the set of all point sources emanating from an object. That equation is an equation for calculating the restoration point of the reproduced image numerically through the lens equation [16].

$$1/(1/R_o - 1/R_r) = (R_o R_r)/(R_r - R_o) \tag{2}$$

Through this, it can be confirmed as shown in Figure 3 how the image changes according to the position of the playback lighting source. Figure 3(a) shows the process of recording a hologram using a light source, and Figure 3(b) shows that the playback position changes when the light source is changed.

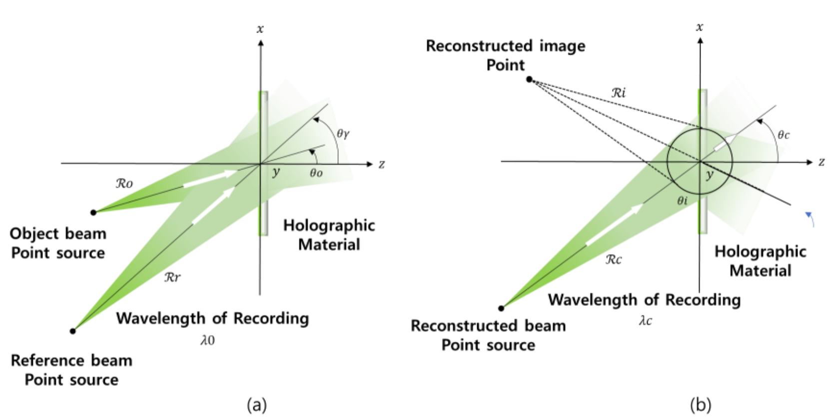

Figure 3. (a) Hologram Recording with point source (b) Hologram Reconstruction with point source

The analysis in this study will use two parallel beams with a diameter of 1 cm. The reason is that most measuring devices that measure the amount of light have a sensor size of 1cm2, so it is easy to measure. In this paper, we experiment and analyze how the diffracted restored light changes the playback position by using the playback light that slightly deviate from the angle at which the hologram was initially recorded as above.

3.2 Optical System Configuration

Figure 4 shows the optical setup configured for the experiment.

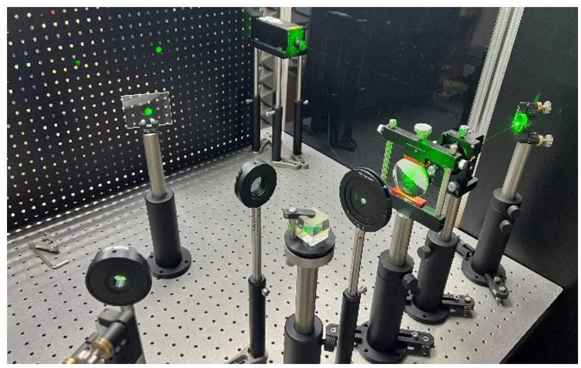

Figure 4. Photopolymer recording system setup

Light from a green laser with a wavelength of 532 nm is refracted by 90 degrees after passing through the first mirror. This beam passes through a collimation lens after passing through a spatial filter to filter noise components and then being diffused. The collimated beam is divided into two object beams and reference beams through a beam splitter. In this process, it passes through various optical components such as beam splitters, mirrors, lenses, and filters. Since most of the systems are implemented by hand by optical designers, it cannot be guaranteed that the angle of reflection is completely inconsistent with the design. Therefore, in order to maximally match the polarization of the two beams recorded on the final hologram surface, as shown in Figure 5, the P-polarization beam splitter is placed in front of the wave plate and the power of the object light and reference light is adjusted so that the maximum amount of light is output.

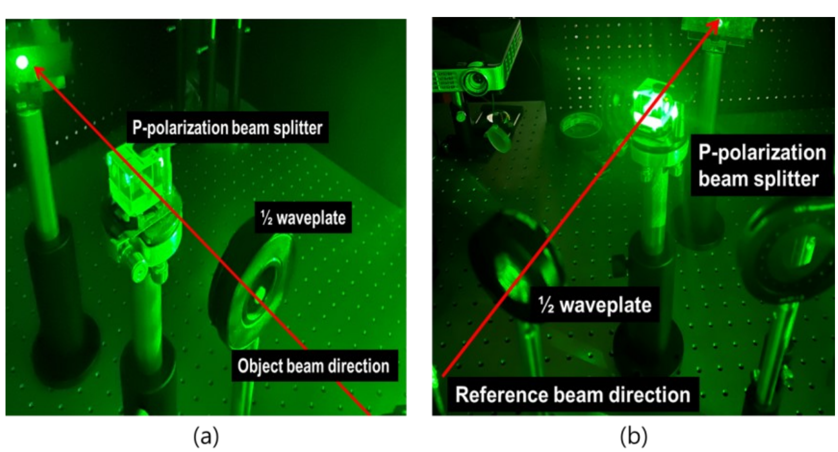

Figure 5. Polarization matching on recording plane
(a) Object beam direction (b) Reference beam direction

Fig. 5(a) shows the setup to match the polarization in the object light direction and Fig. 5(b) the polarization in the reference light direction. Since the P-polarized beam splitter passes only the P-polarized wave, even if it is not precisely matched with linear polarization, the direction of polarized light can be matched on the recording surface, enabling high-efficiency hologram recording.

4. RESULTS AND DISCUSSION

4.1 Efficiency Change According to the Playback Light Angle

Figure 6 shows the optical configuration for measuring the efficiency depending on the angle with the playback after recording the hologram.

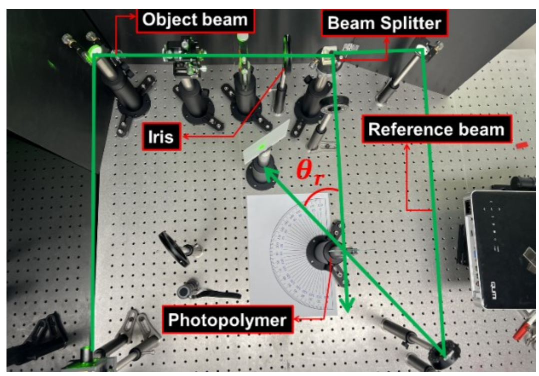

Figure 6. Efficiency analysis according to the reference light angle optical composition after hologram recording

The output of the laser was set to an output of 100mW. The laser light thus oscillated is refracted at 90 degrees through the mirror. The refracted light passes through a spatial filter and passes through a collimation lens having a focal length of 100 mm to produce parallel light. Here, for the convenience of measuring the amount of light, as previously described, a circular collimated light having a diameter of 1 cm is made using an aperture and introduced into the beam splitter.

Among the beams divided into two optical paths from the beam splitter, the light vertically incident on the photopolymer was set as the object light, and the light propagated to the remaining path through the medium at an angle of θ_r passing through the medium through the two mirrors was set as the reference light. The θ_r value is scheduled to be recorded at 40 degrees, and using a marker that can indicate the angle under the medium with this reference angle as the center, the playback light is changed at angles of 30 degrees, 35 degrees, 40 degrees, 45 degrees, and 50 degrees. conducted an experiment. The light quantity ratio of the reference light and the object light is 1:1, and exposure is performed with a total light quantity of 4mW, each 2mW on the medium side. Figure 7 shows the result of the change in efficiency according to the angle of the playback light. Fig. 9(a) shows the result of the regenerated diffraction beam, and Fig. 7(b) shows the intensity of the regenerated light at a standardized level as a graph. Due to the nature of the photopolymer, exposure above a certain saturation range is sufficient. If you look at the photopolymer data sheet, it says that 20mJ of energy per cubic centimeter is required, so a 10-second exposure is sufficient, but for convenience, a recording time of 30 seconds was used. 30degree, 35degree, 40degree, 45degree, 60degree light intensity and diffraction efficiency of the reproduced image of the restored image using the reproduced light, and the restored image is extracted as 2D data, standardized to 255 levels, and converted into gray scale as shown in Figure 7. showed up This is the result of using the same amount of light, 2mW, to irradiate the medium with the reference light during recording, but using different angles of the reproduction light with θ_c. After recording at a recording angle of 40 degrees, irradiation at a reproduction light angle of 40 degrees shows an efficiency of 71.5%. Theoretically, the current recording system shows the highest efficiency, and it can be seen that the efficiency decreases whenever the angle changes. At a reproduction angle of 30 degrees, the reproduction light intensity was 0.81mW, and the efficiency was 40.5%. At a reproduction angle of 35 degrees, the reproduction light intensity was 1.20mW, and the efficiency was 60.0%. At a reproduction angle of 45 degrees, the reproduction light intensity was 1.35mW, and the efficiency was 67.5%. At a reproduction angle of 50 degrees, the reproduction light intensity was 0.78mW, and the efficiency was 39.0%.

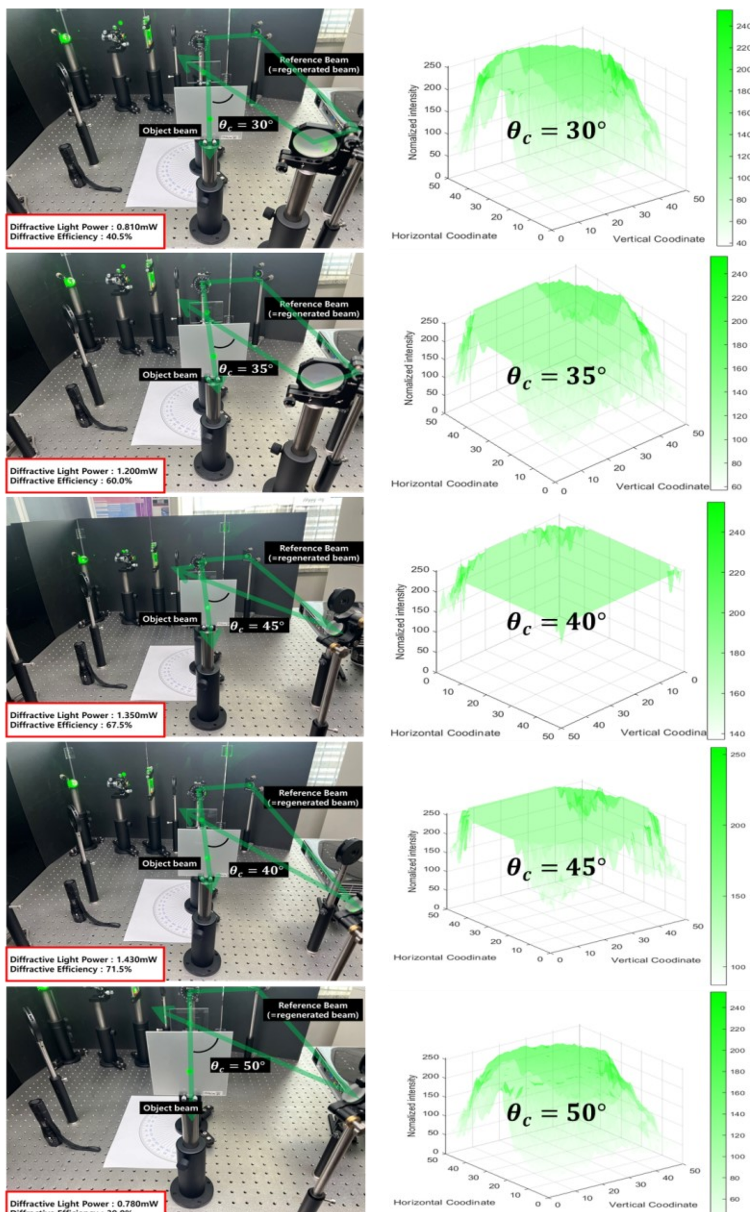

Figure 7. (a) Reconstructed diffraction beam results for each angle (b) Normalized intensity simulation results for each angle

4.2 Analysis of Restoration for Each Angle According to the Distance of Playback Light

Figure 8 shows the result of analysis of the reconstructed image, which differs in the case of parallel light and spherical wave emanating from a point light source.

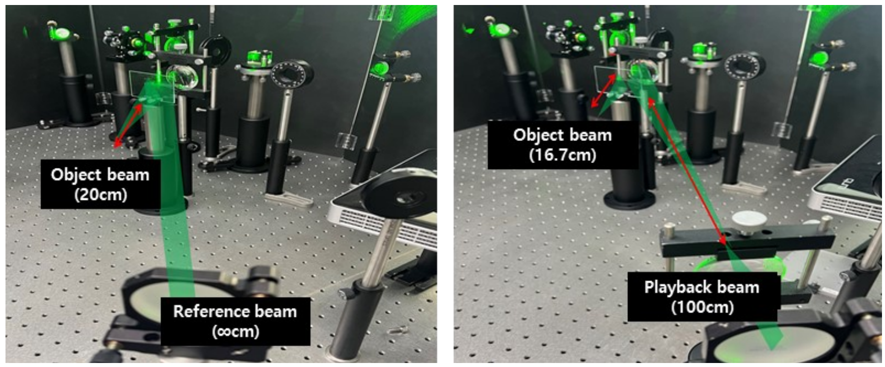

Figure 8. (a) Hologram recording using plane wave
(b) Hologram reconstruction using distance of 100cm light

Based on the reflective hologram recording method, the reference light recorded was an infinite distance, that is, parallel light, and the recording angle was 45 degrees. As shown in Fig. 8(a), the object light converged on the holographic medium at 100mm in front of the beam splitter by using a convex lens with a focal length of 300mm in front of the beam splitter. In this way, it becomes a hologram in which light converges at a focal distance of 20 cm from the medium. Figure 8(b) shows the changed position of the converging light according to the distance of the hologram reproduction light. The reproduction illumination light was incident on the hologram by using a point light source of 100 cm as the reproduction light, unlike the parallel light of infinite distance at the time of recording. At this time, the restored hologram showed a restored image in which light converged in the form of focusing at a position of 16.7 cm. This proves the numerical analysis of Equation (2) below at which position the replayed image is restored.

5. CONCLUSION

We analyzed the recording characteristics of a volumetric hologram using photopolymer as a medium and conducted a study on the angle using reproduction light. In particular, the efficiency varies depending on the recording angle and playback angle of the hologram, and to compensate for this later, a research method for the values to be analyzed in advance was proposed, and reliability was demonstrated through experiments. Looking at the recent trends in hologram research, photopolymers are being used more often than silver salt media. The reason is simple. The silver salt medium reacts sensitively to the exposure energy. Therefore, it is not only difficult to record, but also requires a separate wet post-processing process after recording. The bleaching and developing process must also follow the exact time and process. However, in the case of a photopolymer, since a monomer chemical reaction is used for photosensitization, even if energy is applied over a certain period of time, the hologram is not damaged or the efficiency is not rapidly lowered due to overexposure. We use various light sources to reproduce the hologram after recording. I observe holograms in natural light under the sun, and I try to observe holograms by adjusting the angle well under general building lighting. The most accurate thing is to reproduce it by matching the exact wavelength, recording angle, and reproduction distance at the time of recording, but it is too difficult for the general public who are not familiar with holograms. Therefore, the research on angular characteristics in this paper is thought to be available as a research material that can analyze angular characteristics from more diverse perspectives to the public who experience holograms or to scientists researching related fields in the future. This is applied to the field of realistic content reproduction such as holographic optical element (HOE), holographic HUD (Head-Up Display), holographic HMD (Head-Mounted Display), etc. I hope that the industrial development of holograms will continue in the future.

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