Full-color holographic 3D printer

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Full-Color Holographic 3D Printer

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ABSTRACT

A Holographic 3D printer is a system that produces a direct hologram with full-parallax information using the 3-dimensional data of a subject from a computer. In this paper, we present a proposal for the reproduction of full-color images with the Holographic 3D printer.

In order to realize the 3-dimensional color image, we selected the 3 laser wavelength colors of red (λ=633nm), green (λ=533nm), and blue (λ=442nm), and we built a one-step optical system using a projection system and a liquid crystal display. The 3-dimensional color image is obtained by synthesizing in a 2D array the multiple exposure with these 3 wavelengths made on each 250μm elementary hologram, and moving recording medium on a x-y stage.

For the natural color reproduction in the holographic 3D printer, we take the approach of the digital processing technique based on the color management technology. The matching between the input and output colors is performed by investigating first, the relation between the gray level transmittance of the LCD and the diffraction efficiency of the hologram and second, by measuring the color displayed by the hologram to establish a correlation. In our first experimental results a non-linear functional relation for single and multiple exposure of the three components were found. These results are the first step in the realization of a natural color 3D image produced by the holographic color 3D printer.

Keyword: Holographic 3D printer, holographic stereogram, full-parallax, 3-dimensional image, and color reproduction

1. INTRODUCTION

In recent years, the necessity of an image display technology that reproduces natural color, gloss, and three-dimensional (3D) shape of the object through a network has begun to increase. One of the image display technologies available for the hardcopy output of 3D digital image data is the Holographic 3D printer as the one we have proposed before [1-5]. A Holographic 3D printer is a system that produces a holographic stereogram (HS) using the 3D data of a subject from a computer and outputs a hard copy like a conventional image printer. The image obtained by this system has parallax information on the vertical direction as well as on the horizontal direction. If the object depth and the quality of the surface of the material are reproducible, the production of realistic images can be achieved. If the system as the one we have depicted is realized, it will enable us to show the information of the object itself without actually having the real subject.

Also, the reproduction of a color is a very important factor for expressing also the quality of the surface of the material. In this paper, we present a system for the reproduction of full-color images with the Holographic 3D printer. Since the produced HS by the Holographic 3D printer is volume reflection type, we can obtain a full-color image by using 3 lasers with RGB colors. However, the quality of color is deficient in HS images as compared with the conventional printing of 2D digital images if the color recording is not made appropriately.

Our goal is to reproduce the color from the digital count defined on given chromaticity coordinates. For this purpose, we introduce the color management technology into the HS recording process. As the first step for the color management in HS, we produced the holograms of 2D color patches, and provided further insights into reproducing the color of this 2D patch. Through the experiment on color reproduction of a 2D color patch, we investigated the following points;

1. Tone reproduction characteristics of the LCD
2. Linearity of the hologram recording medium in single and multiple exposure.
3. Gray level dependence of the RGB channel chromaticity
4. The cross talk between the colors in multiple exposure

In the next, after the recording system for full-parallax and full-color holographic stereogram is presented, the concept of color management in HS recording is given in this paper. The preliminary experimental results of color reproduction characteristics are also demonstrated.

2. Recording of full-color images with the Holographic 3D printer.

2.1 Optical system

In order to obtain full-color images by using Holographic 3D Printer, we selected the 3 laser wavelengths of Red: 633nm (He-Ne) Green: 533nm (Nd-YAG-SHG) Blue: 442nm (He-Cd). The optical system of the 3D printer by using these three lasers is shown in Fig.1.

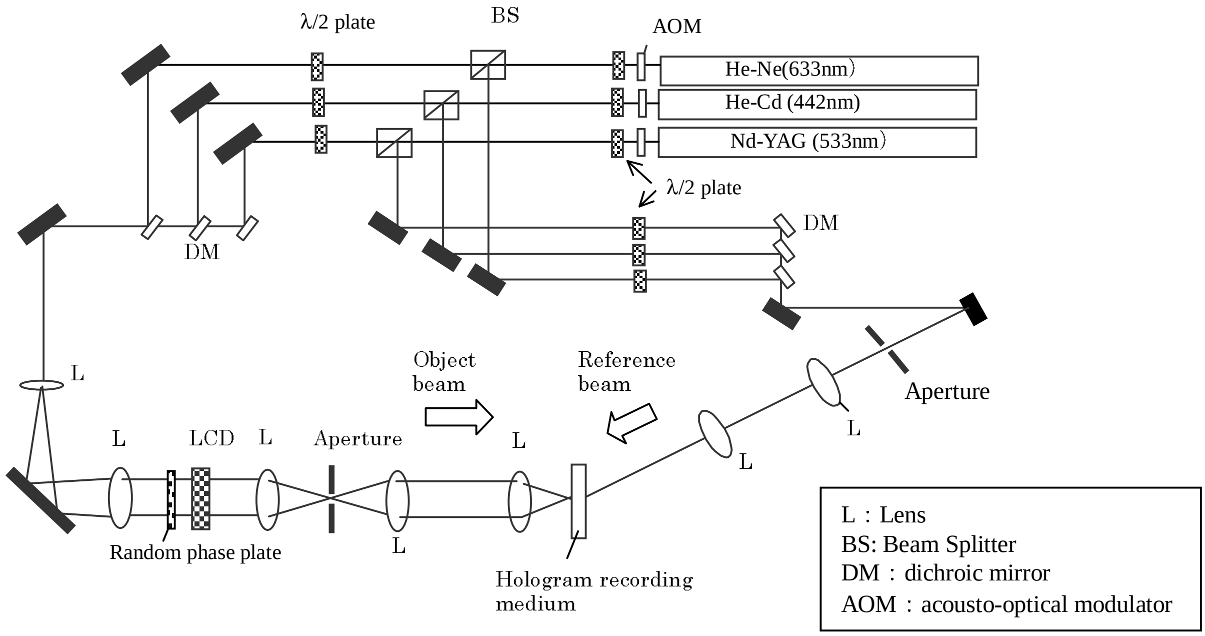


Fig.1 Set up of the optical system

The laser beam to be used for recording is switched by the AOM shutter placed in front of each laser . To adjust the intensity ratio of reference light and object light for each RGB color, we use a λ/2 plate and a polarization beam splitter for dividing the light. The laser beam of each color passes another λ/2 plate, which enables to adjust the polarization of the reference light and object light, after divided by the beam splitter, later, the laser beams of the three colors are combined into a single beam. The gathered laser beams, both reference light and object light, are focused into a mask size in the position of the recording medium. The reference beam is set to an angle of 30 deg while the optical axis of the object beam is set to an angle of 0 deg. The recording of a color image on a single elementary hologram is performed by a multiple sequential recording of the R, G, and B images.

In synthesizing a 2D array, the recording medium is set on a XY stage, and after carrying out multiple exposure of the RGB components, it moves to the following exposure portion. The size of each elementary hologram is 250μm x 250μm, where each elementary hologram holds a color image.

The LCD (liquid crystal display) panel used in the optical setup is a twisted-nematic electronically addressed liquid crystal panel. This LCD is removed from a video projector with a resolution of 640×480 pixels and image data from computer is displayed on the LCD. As can be noticed in Fig.1, there is a random phase plate placed just before the LCD panel for making uniform the intensity distribution of the object light on the recording medium, and producing a high efficiency hologram. [4]

As the recording medium, we use Russian silver halide plate PFG-03C. And the development processing is as follows.

Hardening : formalin hardener 6min
Development : CW-C1 5min
Bleaching : EDTA 10min
and performing natural dryness after the flush.

To evaluate the HS produced by the system described above, we measured the color and diffraction efficiency of HS. The next chapter mentions about this.

2.2 Measurement of brightness and color of HS

The measurement system for investigating the color and diffraction efficiency of HS is shown in Fig 2. This setup allows us to make measurements of the integral diffraction efficiency of the diffuse type holograms with a white light source. In the following experiments, we produce patches of 2.5mm squares (10x10 elementary holograms), and the color and the diffraction efficiency are measured by the setup of Fig.2.

All diffracted light from the HS, is converged with a camera lens and focused on a screen. By measuring this with a Spectral radiometer (PR650/Photo Research), the data of wavelength selectivity of diffraction efficiency is obtained. In addition, we use an aluminum mirror as the calibration sample. We measured the reflected light that is focused on the screen, and made this data a reference (illuminant spectrum).

In this paper, we obtain the diffraction efficiency value and the color (x, y) by using the hologram diffraction spectrum and illuminant spectrum data. The diffraction efficiency value is evaluated by the peak value of the hologram diffraction spectrum divided by the illuminant spectrum. (Cf. Fig.2) To calculate the color, we first calculate CIE 1931 XYZ tristimulus values by using following expression.

$$X = \int \bar{x}(\lambda)H(\lambda)I(\lambda)dx$$
$$Y = \int \bar{y}(\lambda)H(\lambda)I(\lambda)dy$$
$$Z = \int \bar{z}(\lambda)H(\lambda)I(\lambda)dz$$

$\bar{x}(\lambda), \bar{y}(\lambda), \bar{z}(\lambda)$; Color matching functions
$H(\lambda)$; Hologram diffraction spectrum
$I(\lambda)$; Illuminant spectrum

Where Xenon lamp is used as an illuminant in the evaluation. After that, we calculate (x, y) as follows ; x = X/(X+Y+Z), y = Y/(X+Y+Z).

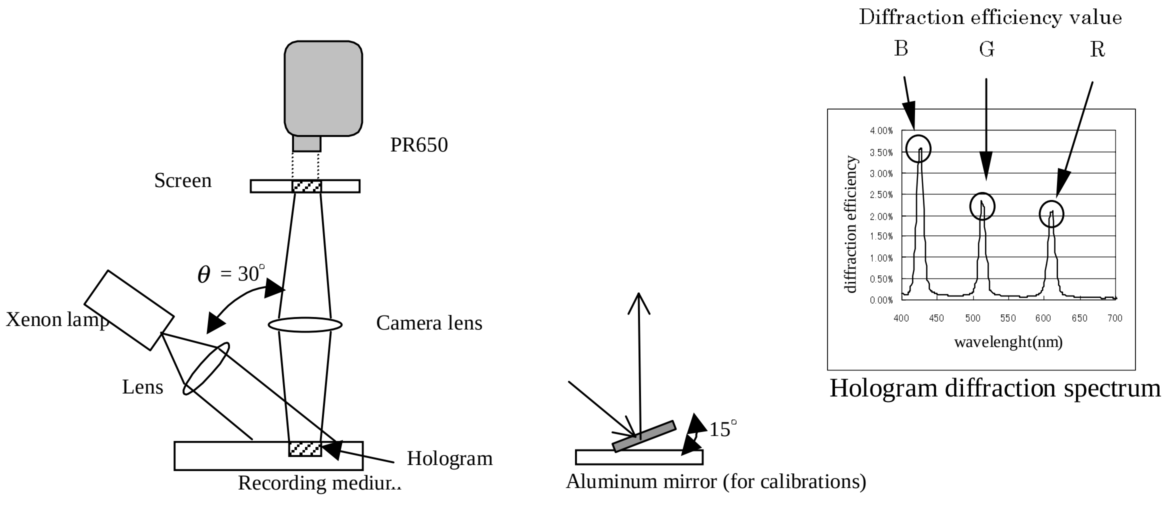


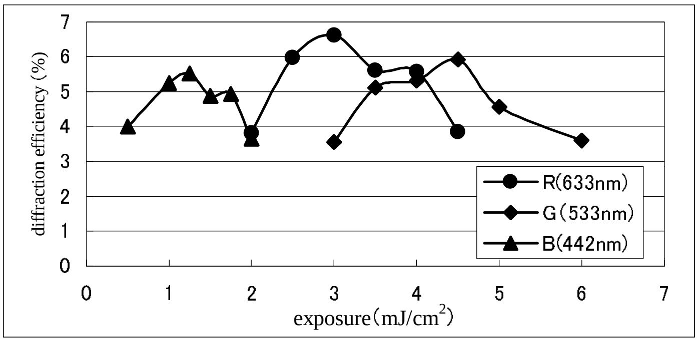
Fig.2 Measurement of brightness and color of HS

2.3 Experiment

2.3.1 Single- exposure

In order to know the sensitivity of the recording medium for each color with this system, we investigated the optimum exposure conditions of each color in monochromatic exposure. First, we examined S/R ratio (S; Object light, R; Reference light). In our experiment it was found that an S/R ratio of 1:1 or 1:2 does not show any difference in the maximum diffraction efficiency available. However, when the S/R ratio is 1:1, compared with the case of S/R ratio being 1:2, the exposure required is less, and consequently exposure time becomes short. Therefore, we set the S/R ratio to 1:1 during the further analysis with single-exposure .

Next, we examined the amount of exposure of each color. We set the S/R ratio to 1:1, and exposed in the order of R, G, and B. We displayed on the LCD panel a uniform image whose tone value for R, G, and B is maximum, i.e., 255, as the digital count driving the LCD has 8bits gray-scale (255 levels). We produced a HS of 10x10 dots per condition and measured the diffraction efficiency as described in section 2.2. The result is shown in Fig.3.



Exposure
= Object light + Reference light

Fig.3 Relation between the exposure amount and the diffraction efficiency for each color

As Fig.3 shows, the conditions for acquiring the highest diffraction efficiency for each R, G, and B colors in single exposure are as follows.

Table.1 Conditions for acquiring the highest diffraction efficiency for each R, G, and B

Wavelength	Exposure	η (Diffraction efficiency)
R (633nm)	3.0mj	6.5%
G (533nm)	4.5mj	6.0%
B (442nm)	1.25mj	5.5%

S/R ratio = 1:1

2.3.2 Determination of a standard on multiplex exposure balance

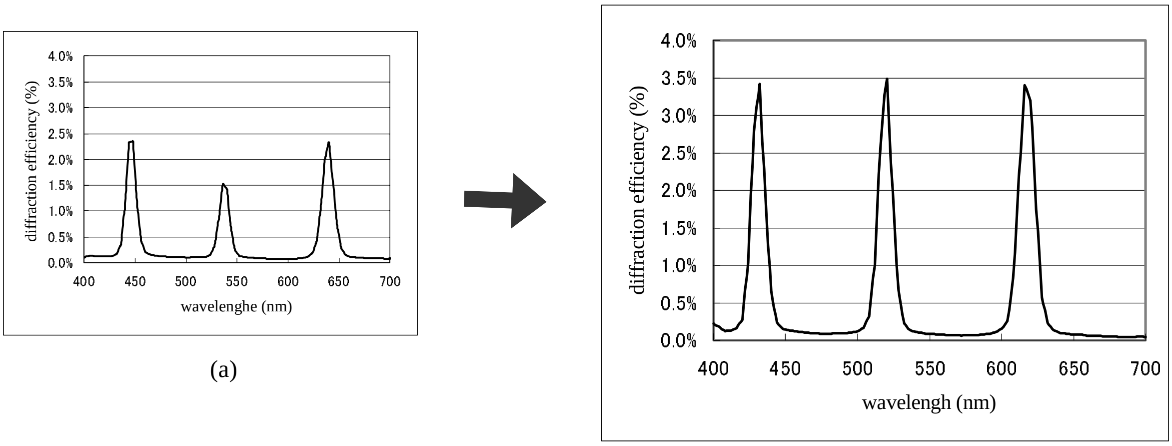
As it was pointed out before, a full-color HS is obtained by carrying out multiple-exposure with 3 laser colors (R, G, and B). When carrying out multiple recording, the refractive-index modulation of the recording medium is shared among the holograms, and the complicated structure of interference fringes requires a high-resolution sensitized material. Then, the exposure conditions and the diffraction efficiency differ from the previous case of single exposure.

We investigated multiple exposure conditions when the diffraction efficiency for each color becomes equal. We set the S/R ratio to 1/1, and exposed in the order of R, G, and B. We displayed on the LCD panel a uniform image whose tone value for R, G, and B is 255, and produced a HS of a white patch, whose diffraction spectrum is evaluated by the method of section 2.2.

In determining the amount of exposure, at the beginning, we assume that the share of refractive-index modulation of the recording medium is carried out equally in each of R, G, and B. So, we made each amount of exposure the same in the multiple exposure. However, since each diffraction efficiency of R, G, and B that were actually obtained did not become same level (Fig. 4 (a)), we changed the amount of exposure of each color from there little by little, and determined multiple exposure conditions.

In this way, the multiple-exposure conditions where the three diffraction efficiencies becomes almost the same and hologram diffraction spectrum as shown in Fig. 4(b) is obtained. In the following experiment, we use this condition as the standard reference point of multiple exposure.

We calculated the chromaticity (x, y) of the hologram obtained in these conditions and the standard white (a perfect diffuser) when illuminating with a xenon lamp. We obtained the following calculation results; the chromaticity of the hologram of white patch (x, y) = (0.368, 0.379), and the chromaticity of the standard white board (x, y) = (0.3311, 0.3289).

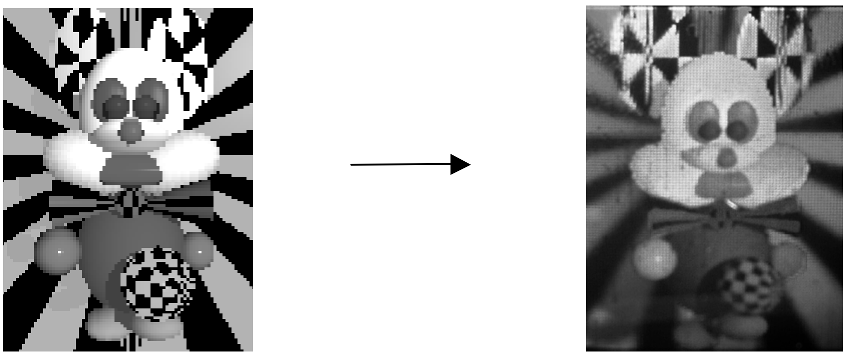


R （λ = 633nm）：0.67mj/cm^2
G （λ = 533nm）：2.0mj/cm^2
B （λ = 442nm）：0.42mj/cm^2

(b)

Fig.4 Hologram diffraction spectrum of multiple-exposure
(a) Each amount of exposure is the same, (b) Multiple-exposure conditions

Subsequently, we produced HS of 250x300mm (100x120dots) size by the optical system of Fig.1 using the above-mentioned conditions. Reproduced image is shown in Fig.5



＜Original image＞ ＜Reproduced image of HS＞

Fig.5 Comparison between the original and the HS

As mentioned previously, a full color and full-parallax HS was produced by the optical system of 3D printer. For the recording of this image, almost pure colors were used and color management is not involved in the recording

3. Color reproduction management approach

3.1 The concept of color management in HS recording

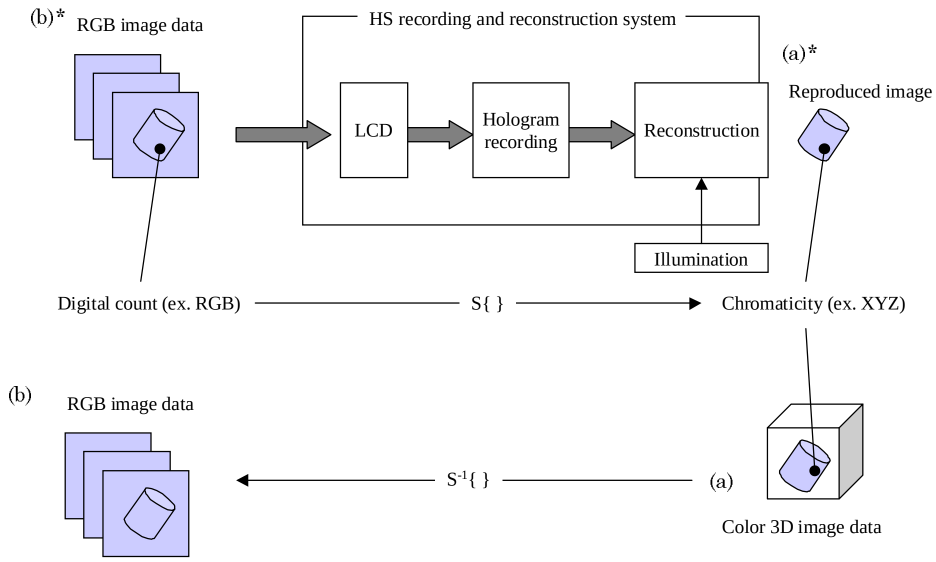


Fig.6 Concept of color management in HS

In the preceding chapter, we presented the system for full-color and full-parallax images with 3D printer. However, the color of the image is not reproduced perfectly. Our eventual goal is to display the color (Fig, 6 (b)) exactly from the tristimulus values on given chromaticity coordinates for any point of the 3D image (Fig, 6 (a)). For this purpose, we take the approach of color management technology. We try to perform a matching between the arbitrary color of the original image (Fig, 6 (a)) and the color obtained from the produced hologram (Fig, 6 (a)*) through using a color chart constructed from experimental data. First, we investigate the relation between the input digital count (b)* and reproduced color (a)*. To obtain this relation, we produced hologram color patches of various set of the liquid-crystal transmittance R, G, and B components, and measured the diffraction efficiency and color of each one. Once the model formula (S{}) could be derived from this relation, , we would obtain the color data (Fig, 6 (b)) by calculating inverse operation of model formula (Fig. 6 S^{-1}{})

We consider to make model formula by presuming that the shape and the peak wavelength of the hologram diffraction spectrum doesn't change. Therefore, we investigated the relation of the LCD transmittance and the diffraction efficiency in the following experiment.

3.2 Tone reproduction characteristics of the LCD

First, the relation between gray scale displayed on the LCD and the LCD transmittance is measured for 26 gray levels ranging from 0 to 250, as shown in Fig.7.

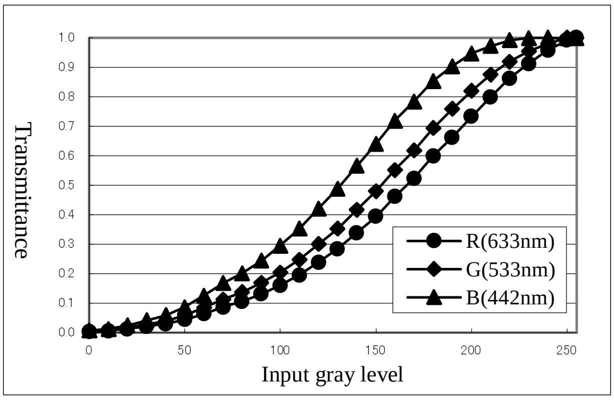
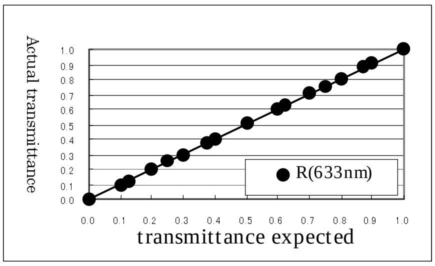
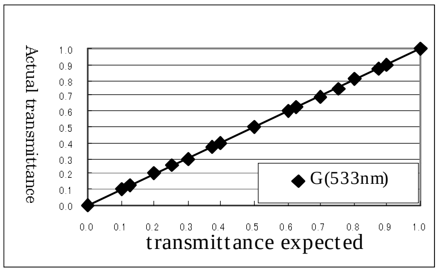


Fig.7 Transmission vs. gray level characteristic of LCD

Even though the same LCD panel is used for R, G, B components, the tone curves are different each other as shown in Fig 7. From the interpolation curves in Fig.7, we define inverse transform to compensate the nonlinearlity, and the results after compensation are shown in Fig.8, where almost linear relationships are obtained. In the following experiments, we apply the transform as in Fig.8, so that nonlinearlity of the LCD can be neglected.

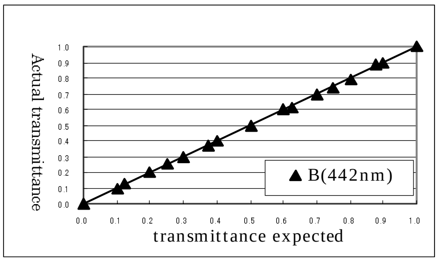


a



b

a：R (633nm)
b：G (533nm)
c：B (442nm)



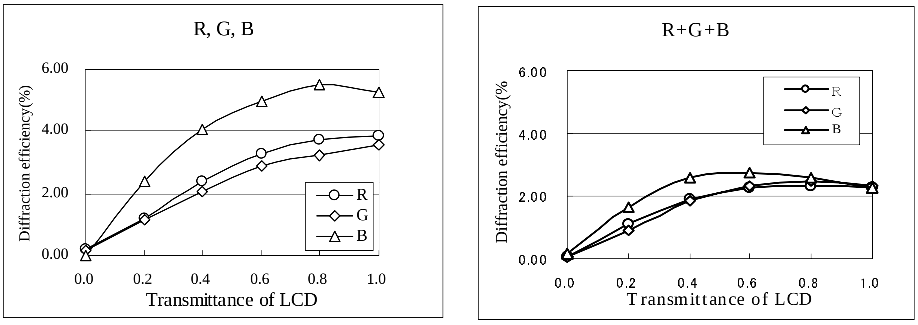
c

Fig.8 Characteristic of transmittance of LCD for each color after the compensation

3.3 Linearity of the hologram recording in single and multiple exposure.

To analyze the characteristics of the hologram recording medium, we investigated the relation between the transmission of the LCD and the diffraction efficiency for both monochrome and multiple exposure.

In the experiment, color patches consisting of 10x10 dots (25x25mm) are recorded with changing the transmittance of LCD between 0.0 to1.0. Then, we measured each produced color patch using the optical system shown in Fig.2, and investigated the diffraction efficiency of each color. The relation between each liquid-crystal transmittance for R, G, and B and their diffraction efficiency is shown in Fig.9.



(a) Monochrome exposure (b) Multiple exposure

Fig.9 Relation between the transmittance of LCD and the diffraction efficiency

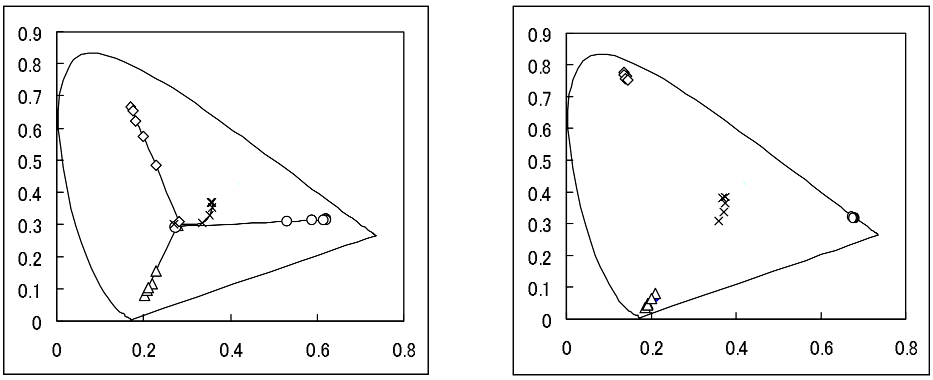
The above result showed that the relation between the transmittance of liquid crystal and diffraction efficiency is nonlinear in both monochrome and multiplex exposure.

3.4 Gray level dependence of the RGB channel chromaticity

To examine the gray level dependence of RGB channel chromaticity, the color of the reconstructed images from the hologram color patches obtained above are plotted on x-y chromaticity diagram. As it is shown in Fig.10 (a), the result shows that the chroma of the hologram decreases as the transmittance of liquid crystal becomes low; as it approaches the conditions of transmittance t =0.0. This is because the background light is imposed in the reconstructed image. To take into account of the background light effect, we consider the model of color reproduction process as [8]

(Reconstructed color) = (Color component modulated by R, G, B primaries) + (Background light) .

Then the chromaticity of the background light is assumed to be that of liquid-crystal transmittance=0.0, and is subtracted from the reproduced color of each hologram so as to obtain the color component modulated by R, G, B primaries. This result is shown in Fig.10 (b).



(a) Before compensation (b) After compensation

Fig.10 Chromaticity diagram of before and after background noise compensation

The above two graphs showed that chroma of a hologram is not decreasing if the background color is subtracted. Then, in the experiment of future color evaluation, we perform the compensation by background color subtraction.

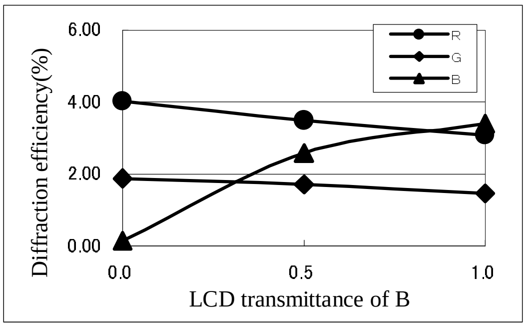
3.5 The cross talk between the colors on multiple-exposure

Next, we recorded different samples by multiplex exposure, changing the liquid-crystal transmittance of R, G, and B in three stages (0.0, 0.5, and1.0), and produced a total of 27 patterns hologram color patch, based on the procedure described in section 2.2. The exposure conditions are summarized in Table.2.

Table.2 Exposure condition of Hologram color patch

No	R	G	B	No	R	G	B	No	R	G	B
1	1.0	1.0	1.0	10	0.5	1.0	1.0	19	0.0	1.0	1.0
2			0.5	11			0.5	20			0.5
3			0.0	12			0.0	21			0.0
4		0.5	1.0	13		0.5	1.0	22		0.5	1.0
5			0.5	14			0.5	23			0.5
6			0.0	15			0.0	24			0.0
7		0.0	1.0	16		0.0	1.0	25		0.0	1.0
8			0.5	17			0.5	26			0.5
9			0.0	18			0.0	27			0.0

As an example, the measurement results of some color patchs produced on the condition of Table.2 are shown in Fig.11



←Summary of the data; No4, 5, 6

Fig.11 Relation between the transmittance of LCD and the diffraction efficiency

The results a Fig.11 show that each R, G, and B component influences the other. Therefore, the diffraction efficiency of R, G, and B cannot be dealt with as independent parameters.

We selected typical colors, i.e., red, yellow, green, cyan, blue, magenta, and white from the 27 hologram color patches in Table.2, computed the chromaticity coordinate, and plotted them on a chromaticity diagram. This is shown in Fig.12. In Fig.13, and also we plotted the chromaticity of the same colors at the time of assuming that linear color mixture was performed.

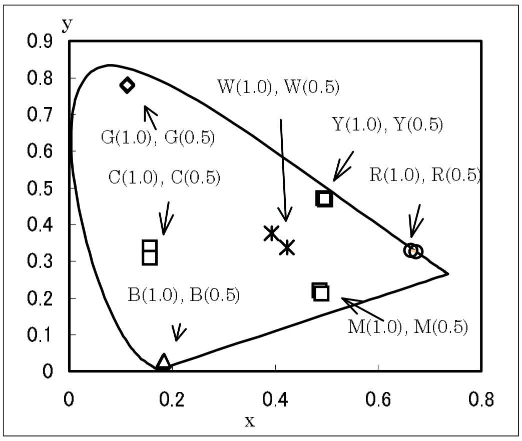


Fig.12 Chromaticity diagram of experimental result

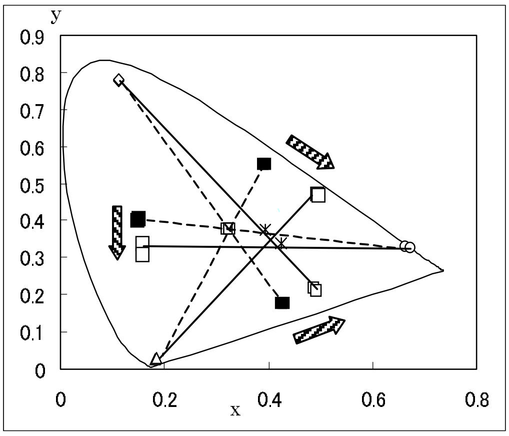


Fig.13 Comparison to the chromaticity diagram when linear color mixture was performed

Fig.12 and Fig.13 show that the color mixture obtained by the above-mentioned experiment are shifted from the position which are calculated by assuming the linear color mixture. These chromaticity diagram also shows that the nonlinear relation between the reproduced color and liquid-crystal transmittance. Therefore, in order to perform color reproduction in a future experiment, we need to manage this nonlinear feature by using a look up table as the approach we took to perform color matching.

4. Conclusion

We built a system for the reproduction of full color images with the holographic 3D printer. By using this system, 3-D images with full color and full-parallax are obtained.

Moreover, we present the concept of color reproduction in HS recording, in order to improve the quality of image of HS produced by Holographic 3D printer. For this purpose, we investigated experimentally the relation between the transmittance of each color of R, G, and B of the liquid crystal in the recording system of the hologram, and the reproduced color of produced hologram. Consequently, it turns out that a nonlinear relation is shown by the case of the both sides of monochrome exposure and multiple exposure. Therefore, in order to perform color reproduction of a hologram, it is necessary to carry out digital processing using the technology of color management.

In the future experiment, we will further examine the nonlinear feature between the reproduced color and liquid-crystal transmittance, so that the color reproduction model of HS will be derived. It is also the future work to improve the stability of color reproduction, as the repetitive reproducibility is not so precise in our experiment. In addition, the accuracy evaluation using the color difference, for example in DE in CIELAB space, is expected to be explored.

References

1. M.Yamaguchi, "Holographic 3-D printer for image hardcopies," Ph.D. thesis, Tokyo Institute of Technology, Tokyo (1994) (in Japanese)
2. M.Yamaguchi, N.Ohyama, and T.Honda, "Holographic 3-D printer," in Practical Holography Ⅳ, S. A. Benton, ed., Proc. Soc. Photo-Opt. Instrum. Eng. 1212, (1990) 84-90
3. M.Yamaguchi, N.Ohyama, and T.Honda, "Holographic three-dimensional printer: new method," Appl. Opt.31 (1992) 217-222
4. M.Yamaguchi, H. Endoh, T. Honda, and N. Ohyama, "High-quality recording of a full-parallax holographic stereograms using a digital diffuser," Opt.Lett.19, (1994) 135-137
5. M.Yamaguchi, T. Koyama, H. Endoh, and N. Ohyama, "Development of a prototype full-parallax holoprinter," in Practical Holography Ⅸ, SPIE, vol. 2406, pp. 50-56, 1995

6. M. A. Klug, M. W. Halle, and P. M. Hubel, “Full Color Ultragrams,” in Practical Holography Ⅵ, SPIE, vol. 1667, pp. 110-119, 1992.
7. Masahiro YAMAGUCHI, Hisashi ENOMOTO, Toshio HONDA, Nagaaki OHYAMA, "High quality recording method for full-color holographic 3D printer," Proceedings of the 12th International Display Research Conference, Hiroshima, Japan, (1992) 319-322
8. L. Jiménez del Barco, J. A. Díaz, J. R. Jiménez, M. Rubiño, "Considerations on the calibration of color displays assuming constant channel chromaticity," *Color Res. and Appl.* 20, No.6 (1995) 377-387
9. L. Huff and Fusek, “Color holographic stereograms” ,Optical Engineering,vol 19-5, pp. 691-695, September/October, 1980.
10. P. Hubel and M. Klug, “Color holography using multiple layers of Du Pont photopolymer”, in Practical Holography Ⅵ, SPIE, vol. 1667, pp. 215-224, 1992.