Full-color High Transparent VHOE HoloGlass Digital Signage Display for AI Holo-Avatar

Yong Seok Hwang
Nano Device Application Center
Kwangwoon University
Seoul, South Korea
thestone@kw.ac.kr

Eun-Soo Kim
Electronics Engineering
Kwangwoon University
Seoul, South Korea
eskim@kw.ac.kr

***Abstract*—In this paper, In this paper, We propose augmented reality(AR) HoloGlass Digital Signage Display for AI Holo-Avatar, which is holographic diffusing projection display established by use of photopolymer based full-color holographic diffusing diffraction film which have high optical qualities such as high transparency and high diffraction efficiency. To form diffusing diffraction pattern keeping high transparency, we fabricated the unique scattering holographic plate with wide viewing zone including the effective removal of color dispersion.**

***Keywords*—VHOE, Computational, Holographic imaging, Color dispersion**

I. Introduction

For these applications of augmented reality(AR), one of core devices is holographic optical element (HOE). A holographically recorded element is a diffractive structure very sensitive to wavelength. This property called color dispersion give a fundamental limitation in the use of such optical elements that are reconstructed with separated angle at a different wavelength than that at which they are recorded. The dispersion is perceptible substantially in broadband illumination diverging out from commercial display devices. Deteriorations coexistent with this property are image aberrations vary with wavelength. Accordingly, if holographic optical elements are to accomplish compelled full color imaging in broadband light, the dispersion and aberrations must be managed under reasonable rules in optical law. The focus of our discussions here will be on transmission type volumetric holographic optical element(VHOE) as hologram lenses, of which phase are engraved from two point sources, levitate volume or plane object images or enable beam deflection. The VHOE which is implemented in photopolymer, is constructed from interference of two light sources, that is, the reference beam and the object beam like general hologram. The basic geometry of our full color VHOE for mixed floating display consists of 2 multiple VHOEs which separated in the Fresnel diffraction distance, similar to those in conventional multiple VHOEs [1]. However, there are two parts in our differentiated approach of multiple VHOEs to accomplish clear color compensations and imaging corrections comparing with the conventional scheme. First, including those at the horizontal and inclined on-axis conventional multiple scheme with parallel input beam, it is proposed that our compensations could be performed at the off-axis input and variable inclined on-axis reconstruction scheme individually without dependency of input source by devise of more rigorous and generous holographic ray based hologram equation as well, and then the derivation of theoretical equation for our proposed geometries of the full color 2 multiple VHOEs was manifested by the computational holographic imaging and optical reconstruction experiments based on VHOE scheme with no dispersion and low aberrations in this paper.[4]

II. Principle of VHOE based Holographic Imaging

A. Interference Pattern between two Gaussian Waves

When the Bragg-matched light is incident on the VHOE, the object wave is regenerated by the Bragg diffraction law. Let the electric field of the two waves be described by Eq. (1).

$$E_R = \mathrm{E}_R exp[j(k_R \cdot (r - r_R))]/r_R\,,\quad k_R = 2\pi/\lambda_o$$
$$E_O = \mathrm{E}_O exp[j(k_O \cdot (r - r_O))]/r_O\,,\ k_O = 2\pi/\lambda_o \tag{1}$$

Where, E_R, E_O are reference and object wave, E_R, E_O are its amplitudes, respectively. K_R, K_O are the grating wave vectors of the object and reference waves, respectively. r_R, r_O are positions of two point sources as reference wave and object wave. Therefore, the intensity of interference pattern between two Gaussian waves over recording medium such as the photopolymer-based VHOE is given by Eq. (2).

$$\mathrm{I} = |\mathrm{E}|^2 = |E_\mathrm{R} + E_\mathrm{O}|^2 = |\mathrm{E}_\mathrm{R}/r_R|^2 + |\mathrm{E}_\mathrm{O}/r_O|^2$$
$$+ |\mathrm{E}_\mathrm{R}/r_R|\cdot|\mathrm{E}_\mathrm{O}/r_O|\ \exp(-jK_G \cdot r) + |\mathrm{E}_\mathrm{R}/r_R|\cdot|\mathrm{E}_\mathrm{O}/r_O|\ \exp(jK_G \cdot r) \tag{2}$$

If E_R and E_O are sequentially mixed with E_R, the optical intensity of I will be given by Eq. (2), and the grating pattern corresponding to I is recorded in the photopolymer-based VHOE. Here, K_G is the grating wave vector of the object and reference waves and given by Eq. (3).

$$K_G = k_R - k_O \tag{3}$$

In Eq. (3), K_G is the grating vector normal to the fringes ($K_G = 2\pi/\Lambda$). Bragg grating equation between two Gaussian waves is given by Eq. (4) as follows, which means Bragg condition.

$$2\Lambda\sin\theta = \mathrm{N}\left(\frac{\lambda}{n}\right) \tag{4}$$

Where, θ can be defined as the half angle outside and inside the recording medium, which represent the intersection angles between the reference and object beam. N is a diffraction number, which has only 1st order in case of VHOE showing thick regime, λ and n are the recording wavelength and a refraction index, respectively. And, the period of the grating is expressed as a value of $\Lambda = \lambda/2n sin\theta$ in case N=1.

B. The basic concept of color dispersion and compensation

The basic concept of color dispersion and compensation is shown in Fig 1.

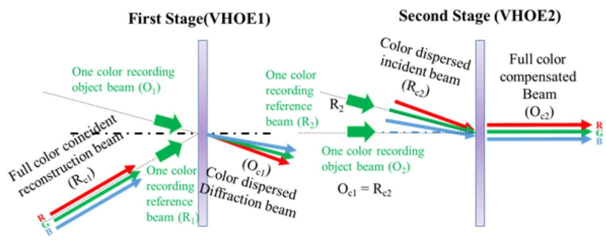

Fig. 1. Basic concept of color dispersion and compensation (red, green, blue) for VHOE 1 and 2 at the positions of the ray path of the principal ray.

When the R, G and B colors are incident on the VHOE at an angle of dispersion, theoretically all are diffracted in parallel. In order to apply VHOE to color dispersion free system, photopolymer must have some properties such as high diffraction efficiency, low distortion of the diffracted light beam, and uniformity of intensity of the diffracted light. Since this technique is based-on the VHOE made from the photopolymer, the resolution and parallax number of the proposed VHOE-based 3D display system are mainly limited by the photopolymer's physical and optical properties. Photopolymers are very attractive materials for volume holograms and optical devices because of its several attractive advantages. These advantages include a self-developing capability, dry processing, good stability, thick emulsion, high sensitivity, large diffraction efficiency, high resolution and nonvolatile storage. In the volume holograms, if the reference beam and object beam are given, a stationary interference pattern of them is formed.

III. 3. Numerical Design of Color Dispersion Compensation System

In previous session, we illustrated a multiple VHOE scheme with color compensations for our suggested holographic floating imaging which has been developed with intensive attention at AR applications. Here, our focus is on the numerical derivation for a multiple VHOE scheme considering real applications mentioned above. The numerical expression for holographic diffraction grating or lens is described in longitudinal and latitudinal equation. Longitudinal equation consists of distances for reference and object beam, and distances for construction and reconstruction as follows.

$$\frac{1}{R_I} = \frac{1}{R_c} \pm \left(\frac{\mu}{m^2}\right)\left(\frac{1}{R_o} - \frac{1}{R_r}\right) \tag{5}$$

Where $\mu = \lambda_c/\lambda_r$, and m is the enlargement of the hologram. R_I, R_c, R_o, R_r are reconstruction distance as focusing point, distance from real incident beam position to VHOE plane, recording distances of object and reference point sources, respectively. The focus direction may be given by the alternate expressions that are latitudinal direction as follows.

$$\sin\alpha_I = \sin\alpha_C \pm \left(\lambda_i/m\lambda_g\right)\left(\sin\alpha_O - \sin\alpha_R\right), \quad where\ i = r, g, b \tag{6}$$

$$\cos\alpha_I \sin\beta_I = \cos\alpha_c \sin\beta_c \pm \left(\mu/m\right)\left(\cos\alpha_o \sin\beta_o - \cos\alpha_r \sin\beta_r\right) \tag{7}$$

For simplification, we put magnification factor m=1, Here, Equation (5) represent paraxial axis lens equations in the longitudinal direction. However, Equation (6), (7) show off-axis lens equations in the latitudinal direction, respectively. Because we consider the reconstruction image coming diffracted from the plane object image which is shifted away from VHOE device in latitudinal, we would treat our proposed compensation with respective to the off-axis incidence of plane object information. Because only a single VHOE could not be compensated, we adopt multiple volume holographic optical elements with low dispersion and low aberrations as our color compensation method. In previous paper, color compensation method using multiple HOEs represented, but our proposed holographic imaging system could not be accomplished. Therefore, firstly, our proposal is about analysis of general two multiple hologram optical element geometries regarding to off axis incidence and on axis holographic imaging, such as

$$\begin{aligned} \sin\alpha_{I1} &= \sin\alpha_{C1} \pm \left(\lambda_j/m\lambda_g\right)\left(\sin\alpha_{O1} - \sin\alpha_{R1}\right) \\ \sin\alpha_{I2} &= \sin\alpha_{C2} \pm \left(\lambda_j/m\lambda_g\right)\left(\sin\alpha_{O2} - \sin\alpha_{R2}\right) \\ & where\ i = g, j = r, g, b \end{aligned} \tag{8}$$

In case of single VHOE, it is considered that the angle equation is a combination of the interference and diffraction equation. Interference grating equation is written as follows.

$$f_i = \frac{2\pi}{\Lambda_i} = \frac{2\pi}{\lambda_i}\left(\sin\alpha_{O1} - \sin\alpha_{R1}\right), \quad i = r, g, b \tag{9}$$

Where f means a spatial frequency of grating. Λ_i and λ_i represent grating period and each recording wavelength in free space, α_{R1},$\alpha_{O1}$are reference wave and object wave for construction of interference grating, respectively. Here, in above equation, 2π could be omitted because it is used when phase value is calculated. Diffraction equation from a spatial frequency interference grating is written as follows.

$$\sin\alpha_{I1} = \sin\alpha_{C1} + n\lambda_j f_i, \quad i, j = r, g, b \tag{10}$$

Where, λ_j represents each directional incidence wavelength in free space in the diffraction grating, α_{I1},$\alpha_{C1}$are diffraction angle of output beam and incident angle of reconstruction beam for reconstruction of interference grating, respectively. n is diffraction order, which is 1 because first order is only appeared in VHOE.

From equation (8) and (10), we propose novel mathematical model compensating color dispersion regardless of wavelength of incidence beam in two multiple VHOE layers for realizing our proposed holographic optical imaging system. Firstly, we assume that the recording wavelength is only green, i.e. *i*=*g*, *j*=*g*. Then, the angle equation is as follows.

$$\begin{aligned} &\sin\alpha_{I1} = \sin\alpha_{C1} \pm \left(\lambda_g/\lambda_g\right)\left(\sin\alpha_{O1} - \sin\alpha_{R1}\right), \\ &if\ \sin\alpha_{C1} = \sin\alpha_{R1},\ \ \sin\alpha_{I1} = \sin\alpha_{O1} \end{aligned} \tag{11}$$

Accordingly, if reconstruction beam is incident on diffraction grating in direction of recording reference beam, angle of output beam coming from diffraction grating is identical to that of recording object beam. Next, in case of different wavelength reconstruction beams such as *i*=*r*, *b*, the angle equations are represented as follows.

$$\sin\alpha_{I1} = \sin\alpha_{C1} \pm \left(\lambda_i/m\lambda_g\right)\left(\sin\alpha_{O1} - \sin\alpha_{R1}\right) \tag{12}$$

From equation (12) final two equations for compensation are presented as follows,

$$\sin\alpha_{I2} = \left(\frac{\lambda_j - \lambda_g}{\lambda_g}\right)\left(\pm(\sin\alpha_{O1} - \sin\alpha_{R1})\right) + \left(\frac{\lambda_j - \lambda_g}{\lambda_g}\right)\left(\sin\alpha_{O2} - \sin\alpha_{O1}\right) + \sin\alpha_{O2} \quad (13)$$

For + sign, summing up above equation,

$$\sin\alpha_{I2} = \left(\frac{\lambda_j - \lambda_g}{\lambda_g}\right)\left(\sin\alpha_{O2} - \sin\alpha_{R1}\right) + \sin\alpha_{O2}, \quad (14)$$

Here, condition of color compensation regardless of wavelength is $\alpha_{O2} = \alpha_{R1}$. Then, α_{I2} always is same as α_{O2}. It means that direction of reconstruction beam which is incident on plane of VHOE is to be identical to that of recording beam. In this case, diffraction angle of output beam should be identical to that of incident imaging beam. It means that optics axis of VHOE devices could be inclined but, output holographic imaging should be formed along to optics axis of input object beam. Thus, this part is not suitable to our proposed scheme. For - sign, summing up above equation,

$$\sin\alpha_{I2} = \left(\frac{\lambda_j - \lambda_g}{\lambda_g}\right)\left(\sin\alpha_{R1} + \sin\alpha_{O2} - 2\sin\alpha_{O1}\right) + \sin\alpha_{O2} \quad (15)$$

Here, condition of color compensation regardless of wavelength is as follows

$$\sin\alpha_{O1} = (1/2)(\sin\alpha_{R1} + \sin\alpha_{O2}) \quad (16)$$

It means that direction of reconstruction beam which is incident on plane of VHOE is to be reversed laterally to that of recording beam. In summary, we could design our device using the equation (16) mentioned above for getting our proposed color compensated holographic imaging which has off-axis input beam with imaging information and on-axis or other-axis output beam having different angle with that of input beam. Using the proposed mathematical model, laterally color dispersion could be minimized with two multiple single color VHOE planes regardless of any kind of VHOE function such as lens, mirror, grating.

IV. Experiments and Results

Through our rigorous derived equations, conditions of color compensation regardless of wavelength are suggested for off-axis input and variable on-axis reconstruction at two multiple VHOEs based schemes such as combination of two holographic lenses in above session. The verifications of our theoretical derivation for the color compensation are visualized by the computational holographic imaging as follows.

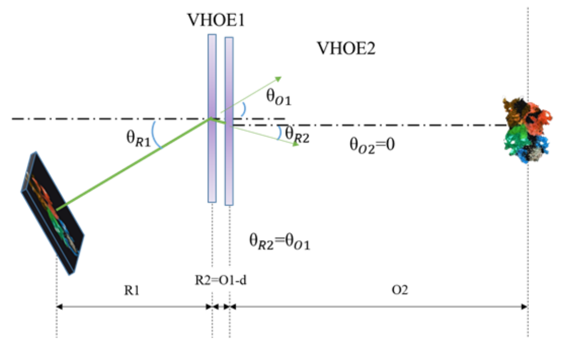

Fig. 2. Principle of color dispersion compensation system for 3D object reconstruction

Fig. 2 shows the display panel, VHOE 1, VHOE 2, and the set-up for taking pictures. The light from the display panel is diffracted at the VHOE 1, travel to the VHOE 2, diffracted again at the VHOE 2 and travels horizontally to the optic table. At the VHOE 1, the incident angle and diffraction angle are 30° and 14.47° respectively. At VHOE 2, the incident angle is 14.47° and the diffraction angle is 0°, that is, parallel to the table. These angles are determined according to our derived equation for color compensation of the proposed VHOE scheme, and the results of the computational reconstruction are matched as we expected, well as follow.

As shown in Fig. 3. We testified color dispersion status and compensation status using 3 color point sources, that is, red, green, blue wavelength with 633nm, 532nm, 450 nm, as incidence on the VHOE scheme comparing these two statuses along to longitudinal direction, respectively.

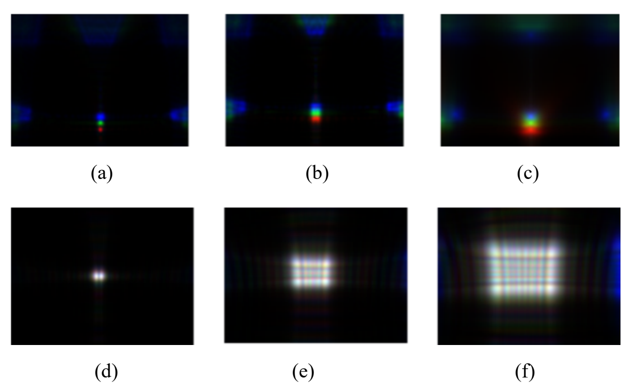

Fig. 3. The reconstruction for incidence of full color point sources (a), (b), (c) on the single VHOE constructed for off-axis incidence and on-axis reconstruction and (d,) (e), (f) on multiple VHOE designed to be compensated at condition constructed with off-axis input reference beam and on-axis reconstruction beam.

As shown in Fig. 4, the optical reconstruction for incidence of a color image of ‘jellyfish’ on the single VHOE which constructed from off-axis incidence and on-axis reconstruction beam designed to be compensated under the condition of off-axis input reference beam and on-axis reconstruction beam are confirmed along to longitudinal direction.

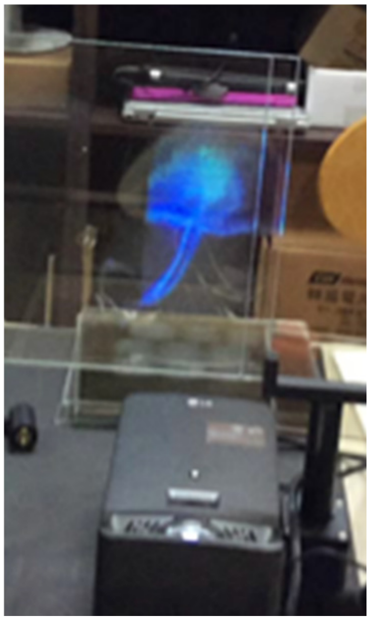

Fig. 4. The reconstruction for incidence of a color image of 'jellyfish' on the single VHOE constructed from off-axis incidence and on-axis reconstruction beam designed to be compensated at condition constructed from off-axis input reference beam and on-axis reconstruction beam

V. CONCLUSION

In this paper, a full-color holographic display system based on VHOEs is newly implemented optically, and we present a new type of AR projection display for AI Holo-avatar could be implemented. For this, a two-stage diffraction method with two kinds of VHOEs is proposed for the effective removal of color dispersion. Future work will be researched on designing methods to implement the optimized optical system for practical applications and research to solve the color dispersion problem that appears at the boundary of the holographic screen.

ACKNOWLEDGEMENT

This work was partially supported by the MSIT (Ministry of Science and ICT), Korea, under the ITRC support program (IITP-2017-01629) supervised by the IITP, and Basic Science Research Program through the NRF of Korea funded by the Ministry of Education (No. 2018R1A6A1A03025242).

REFERENCES

[1] Bobrinev, V I., Son, J.Y., Kim, S.S., Kim, S.K., "Analysis of color distortions in a transmission-type holographic screen," Appl.Opt. 44(15), 2943-2948 (2005).

[2] S.H. Hwang, V.I. Bobrinev, J.Y. Son, S.A. Shestak, H.W. Jeon, "Achromatized transmission-type holographic screen for a multiview stereoscopic image system," Applied Optics 36(26), 6605-6610 (1997)

[3] Y.S. Hwang, B.M. Kim, E.S. Kim, "Optimized design of directional backlight system for time-multiplexed autostereoscopic display based on VHOE," Proc SPIE (2014).

[4] A.Klein, "Dispersion Compensation for Reflection Holography," Doctoral dissertation Massachusetts Institute of Technology, (1996).

[5] B.M. Kim, Y.S. Hwang, E.S. Kim, "A novel backlight unit for volume-holographic optical elements-based time-multiplexed three-dimensional displays," Optics and Lasers in Engineering 74, 28-39 (2015)

[6] H. Kogelnik, "Coupled wave theory for thick hologram gratings," Bell Labs Technical Journal 48(9), 2909-2947 (1969)

[7] Y.S. Hwang, F.K. Bruder, T. Fäcke, S.C. Kim, G. Walze, R. Hagen, and E.S. Kim, "Time-sequential autostereoscopic 3-D display with a novel directional backlight system based on volume-holographic optical elements," Optics Express 22(8), 9820-9838 (2014).