Full Complex Hologram Representation Method Using DOE Phase Mask

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***Abstract*— A hologram is a 3D image technology that can represent both intensity and phase of light and provide people with stereoscopic and accommodation effect. Currently, various researches on development of holographic display are in progress and one of the key issues is complex hologram representation which modulates both amplitude and phase. The ideal complex hologram is free from DC and twin problems that hinder hologram image observation. However, currently available spatial light modulators, which are widely used display devices in holographic displays, can only modulate either amplitude or phase. In this paper, we propose a full complex hologram representation method based on DOE phase mask. It will be useful for amplitude type SLM based holographic display.**

I. Introduction

The hologram is now familiar to everyone through SF movies and various pseudo-holographic techniques such as floating imaging. Although the current pseudo-holographic technology is fancy, it is far from ideal holographic technology. The reason why hologram is spotlighted as the ultimate 3D technology is that it can only provide all 3D depth cues that human expects from real world.

We can recognize a certain object by seeing the reflected light from the object through our eyes. Thus, if we can express all of the light reflected from an object, we can see the object even if the actual object does not exist. That is the principle of holography [1], [2], [3].

We can more easily understand the characteristics of the holography by comparing it with the two-dimensional (2D) photography. The light has intensity and phase information. The hologram can record both intensity and phase information while photography can record intensity only. Therefore, we can feel the full parallax within the viewing angle provided by the holography, and we can focus on the desired depth from the holographic image as if we are looking at real objects. However, the hologram needs a special coherent light such as laser instead of normal lights used to record the photograph.

In recent, the digital holography is widely researched since there is no time consuming chemical processing and it has advantages on digital signal processing. The digital hologram can be obtained by directly recording an interference pattern via image sensors [4] or by calculating the interference pattern using computer generated hologram (CGH) [5]. The digital hologram can be numerically reconstructed or optically reconstructed by using a spatial light modulator (SLM) which is a special device can modulate either amplitude or phase of the light, but not both. Thus, general SLMs cannot represent the hologram perfectly since hologram is complex data. Insufficient hologram representation causes annoying optical noises such as zero-order light (DC) and twin image. In fact, the optical noises can be physically filtered by using off-axis method and single-sideband hologram [6] [7], but it increases a system volume and needs additional cost. Thus, many researches on the development of the complex SLM have been done, but still there is no commercialized complex SLMs. The detour phase hologram [8] and double-phase hologram [9] methods are good practical candidates to realize the complex hologram using conventional SLMs.

In this paper, we propose a full complex hologram representation method using diffractive optical element (DOE) phase mask. We exploit the amplitude modulation and Burckhardt's detour phase encoding method [8] to realize the complex hologram. The main problem of the Burckhardt encoding based complex hologram implementation is how to make three basis phases. For that, we employ DOE phase mask that is designed to have different phase for every three lines. Complex modulation is possible if this phase mask is used with amplitude modulation. We verify this approach by computational simulation and optical reconstruction.

II. Principle of Hologram

A. Hologram

Hologram is a result of the interference between the object beam and reference beam as shown in Fig. 1. Basic principle of holography is simple. For hologram recording, we generate a laser light and split into two wavefronts, one directly goes onto the film, and the other one is reflected from the surface of an object and then goes to the film. Then, two light wavefronts interfere together and make a fringe pattern. The film records this fringe pattern. If we directly record this fringe pattern via digital camera, the recorded image is a digital hologram.

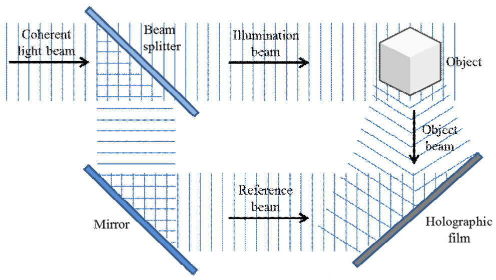

Fig. 1. Hologram recording

Mathematically, hologram can be expressed as

$$H = |O + R|^2 = |O|^2 + |R|^2 + OR^* + O^*R \,, \quad (1)$$

where O and R are the object beam and reference beam, respectively and * means complex conjugate. The first and second terms in (1) are intensities of two wavefronts and their sum is DC (or zero-order). The third and fourth terms in (1) are interference terms and they are recorded original image and its twin image, respectively [10]. The hologram can be reconstructed by illuminating the same reference beam as shown in Fig. 2.

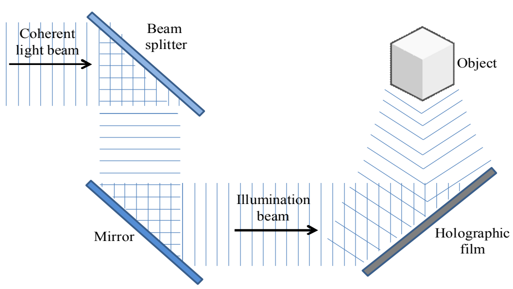

Fig. 2. Hologram reconstruction

To separate the wanted hologram from the DC and twin noises, the off-axis hologram [11] setup is used in general and it is shown in Fig. 3. An off-axis angle (θ) between the object and reference wavefronts prevent overlapping.

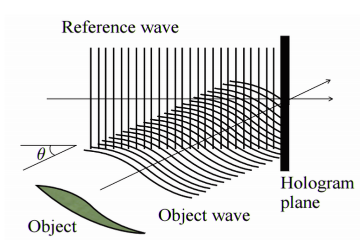

Fig. 3. Off-axis hologram recording

In off-axis hologram, θ should be large to avoid the overlap. The spatial locations of the each term in (1) are now separated shown in Fig. 4.

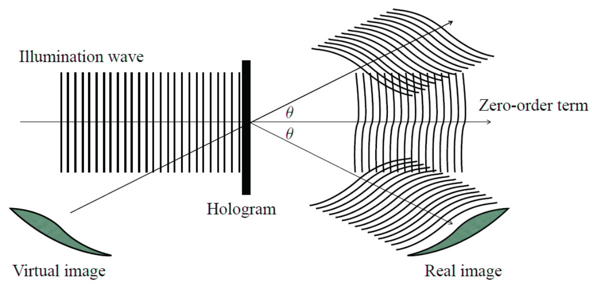

Fig. 4. Off-axis hologram reconstruction

B. Burckhardt Encoding

The data of each pixel in the digital hologram can be conceived as a vector of the complex plane. Therefore, it is important to express the vector of this complex plane more accurately. An amplitude-modulated hologram is made by taking only the real or imaginary part of a complex vector, and the phase modulation is expressed by a vector of various phase values having the same intensity. Thus, amplitude modulation and phase modulation represent only some of the intensity and phase of the original vector.

Burckhardt [8] proposed a method of expressing a complex vector using three vectors with different phases (0 degree, 120 degree, 240 degree) as shown in Fig. 5.

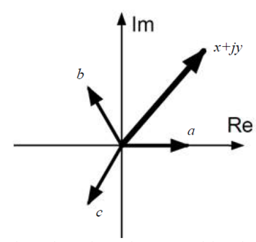

Fig. 5. Complex plane based on Burckhardt encoding

The Burckhardt encoding is expressed as

$$x + yi = a + be^{j\frac{2\pi}{3}} + ce^{-j\frac{2\pi}{3}} \,. \quad (2)$$

Here, a complex-valued function can be decomposed into three real and positive components. When expressing any vector on the complex plane, one of the three basic vectors is necessarily zero.

To do this, first three consecutive pixels are defined as one macro-pixel, only one of them is taken, and two complex values are discarded. Then, one complex value is decomposed into three basic vectors, and one complex pixel is formed by three consecutive amplitude pixels. Then, for three consecutive pixels, light having a phase difference of 120 degrees must be incident. Using the above method, complex modulation is possible using amplitude modulation even though the diffraction efficiency is low.

III. Proposed Complex Hologram Representation

A. *Complex Hologram*

In order to verify the performance of the complex hologram implementation based on the amplitude modulation described above, a comparison experiment between the conventional amplitude hologram and the complex hologram is performed. The experiment verifies the numerical reconstruction of the hologram generated through CGH. The CGH generation condition is a wavelength of 532 nm and a pixel pitch of 4μm. The size of the hologram is 960 × 720 and the reproduction distance of the hologram is 50 cm. Compare both the on-axis hologram and the off-axis hologram under the same conditions [12]. Fig. 6 shows the restored results in the on-axis environment. In the case of the amplitude-modulated hologram, it is not easy to observe the reproduced hologram because both the DC and the twin image are overlapped. In the case of complex hologram, DC and twin image were not observed. In the case of the proposed method the hologram was separated from DC and twin noises like off-axis hologram, and the center region shows characteristics similar to the complex modulation.

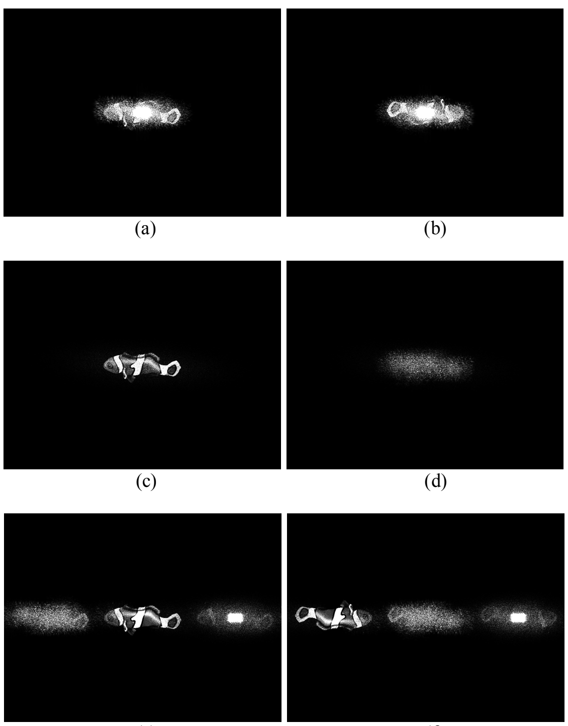

Fig. 6. Comparison numerical reconstructions of amplitude hologram and complex (on-axis): (a) amplitude hologram at 50cm, (b) amplitude hologram at -50cm, (c) complex hologram at 50cm, (d) complex hologram at -50cm, (e) proposed hologram at 50cm, (d) proposed hologram at -50cm

In off-axis configuration, the reconstructed hologram from the amplitude-modulated hologram is separated from the DC and the conjugate as shown in Fig. 7.

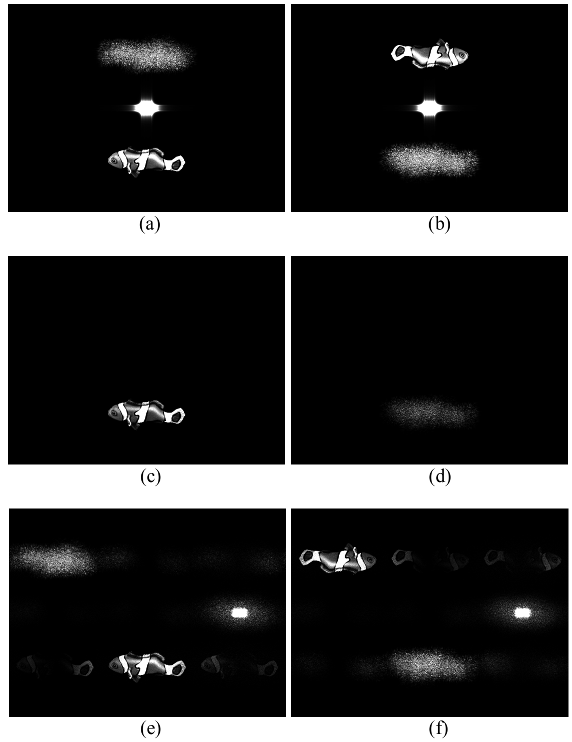

Fig. 7. Comparison numerical reconstructions of amplitude hologram and complex (off-axis): (a) amplitude hologram at 50cm, (b) amplitude hologram at -50cm, (c) complex hologram at 50cm, (d) complex hologram at -50cm, (e) proposed hologram at 50cm, (d) proposed hologram at -50cm

As a result of this experiment, the complex hologram technique based on amplitude modulation using Burckhardt encoding showed complex modulation characteristics within a limited range. However, the viewing region was reduced to one-third, and the overall characteristics of the off-axis amplitude hologram were seen in the on-axis environment.

B. *DOE Phase Mask*

The transmissive phase mask was fabricated by direct writer lithography of 600nm process, and the substrate was silicon wafer and photoresist was used as phase modulating material. To reduce the slope phenomenon caused by direct writer lithography, stepper photolithography is used together. Fig. 8 shows the cut surface of 3.74μm pitch phase mask taken by scanning electron microscopy (SEM). The slope region is about 300~600nm depending on the level and the flat region is about 90%.

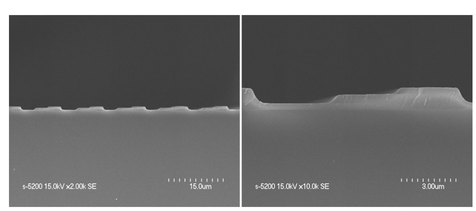

Fig. 8. DOE phase mask with 3.74μm pixel pitch

IV. Experimental Results

To verify the proposed complex hologram representation method using DOE phase mask, we conduct the numerical simulations and optical experiment based on the actually fabricated DOE mask. For amplitude modulation, we use the binary amplitude hologram, since our equipment can only manufacture binary amplitude modulation mask. The pixel pitch is 3.74μm and wavelength of the light is 660nm. We make a hologram for 2mm cube model using Fresnel CGH method. Fig. 9 shows the numerical simulation results for binary amplitude hologram and its complex representation using Burckhardt encoding and phase mask. The complex hologram shows the better quality since it does not have noises caused by DC and twin.

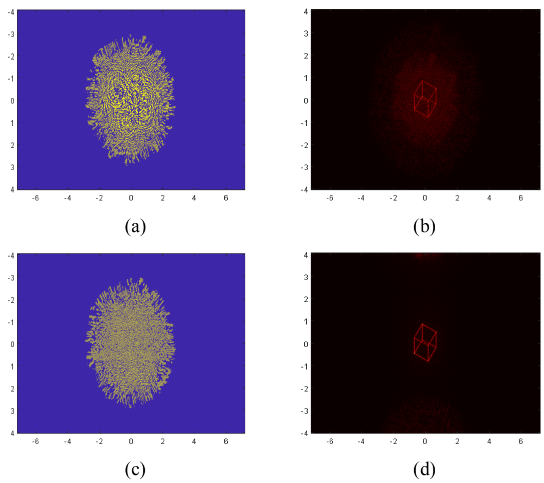

Fig. 9. Numerical simulation results: (a) binary hologram, (b) numerical reconstruction of (a), (c) Burckhardt encoded binary hologram, (d) numerical reconstruction of (c)

The optical reconstruction results are shown in Fig. 10. The off-axis holograms are used to separate the DC and twin. The proposed complex hologram shows the sharper object but viewing region is reduced and diffraction efficiency is lower than binary amplitude hologram.

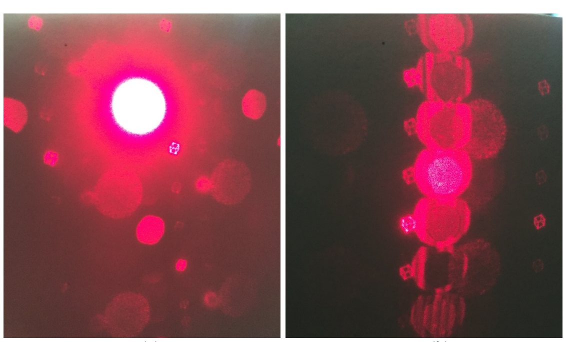

Fig. 10. Optical simulation results: (a) optical reconstruction of binary hologram, (b) optical reconstruction of Burckhardt encoded binary hologram

V. Conclusions

The complex hologram representation is important issue for the development of digital holographic display since it is free from DC and twin noises. The full complex hologram representation method using DOE phase mask is proposed in this paper. We confirm that the proposed method shows the characteristics of full complex hologram within limited region by numerical simulation and optical experiments. In the future, we will improve the accuracy of the DOE phase mask and apply this scheme to actual amplitude modulating SLM such as LCD panel.

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References

[1] D. Gabor, "A new microscopic principle," Nature 161, No. 4098, pp. 777-778, 1948.
[2] M. Park, H.-E, Kim, H.-G, Choo, J. Kim, and C.H. Park, "Distortion Compensation of Reconstructed Hologram Image in Digital Holographic Display Based on Viewing Window," ETRI Journal, vol. 39, no. 4, pp. 480-492, 2017.
[3] M. Kim, S, Lim, G, Choi, Y. Kim, H. Kim, and J. Hahn, "Expanded Exit-Pupil Holographic Head-Mounted Display With High-Speed Digital Micromirror Device," ETRI Journal, vol. 40, no. 3, pp. 366-375, 2018.
[4] J. W. Goodman and R. W. Lawrence, "Digital image formation from electronically detected holograms," Appl. Phys. Lett., vol. 11, no. 3, pp. 77-79, 1967.
[5] J. P. Waters, "Holographic image synthesis utilizing theoretical methods," Appl. Phys. Lett., vol. 9, no. 11, pp. 405-406, Dec. 1966.
[6] T. Mishina, F. Okano, and I. Yuyama, "Time-alternating method based on single-sideband holography with half-zone-plate processing for the enlargement of viewing zones," Appl. Opt. 38, pp. 3703–3713, 1999.
[7] Y. Takaki and Y. Tanemoto, "Band-limited zone plates for single-sideband holography," Appl. Opt. 48, H64–H70, 2009.
[8] C. B. Burckhardt, "A simplification of Lee's method of generating holograms by computer," Appl. Opt. 9(8), pp. 1949–1949, 1970.
[9] C. K. Hsueh and A. A. Sawchuk, "Computer-generated double-phase holograms," Appl. Opt. 17(24), pp. 3874–3883, 1978.
[10] J. W. Goodman, Introduction to Fourier Optics 3rd, Roberts& Company, 2005.
[11] E. Cuche, P. Marquet, and C. Depeursinge, "Spatial filtering for zero-order and twin-image elimination in digital off–axis holography," Appl. Opt., vol. 39, no. 23, pp. 4070-4075, 2000.
[12] M. Lee, G. M, N.-W. Kim, B.T. Lee, and J.-H. Song, "Fast Holographic Image Reconstruction Using Phase-Shifting Assisted Depth Detection Scheme for Optical Scanning Holography," ETRI Journal, vol. 38, no. 4, pp. 599-605, 2016.