Digital Holographic Observation of a Wavefront Generated by a Digitally Designed Holographic Optical Element (DDHOE)

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ABSTRACT

Using digital holography, we observe a wavefront generated by a digitally designed holographic optical element (DDHOE). Experimental results show the performance of digital holographic observation as an evaluation tool for DDHOEs. Quantitative wavefront sensing has the potential to evaluate a DDHOE fabricated by a wavefront printer in detail.

1 INTRODUCTION

A digitally designed holographic optical element (DDHOE) [1] has been proposed to enable generation of an arbitrary wavefront and arbitrary optical components such as a mirror, a lens, a micro-lens array, and a concave reflector. By using designed DDHOEs and a projector, see-through three-dimensional displays have been successfully demonstrated [1-4]. Distortion in a wavefront of incident light can be removed for a large area by designing a DDHOE that generates a wavefront to cancel the distortion factor. DDHOEs are fabricated using a wavefront printer, which records tiles of sub-holograms optically on to the recording medium. Although it is important to evaluate a fabricated DDHOE quantitatively, up to now evaluations are limited to measurements of diffraction angles of DDHOEs. It is worth that evaluations are conducted for wavefronts generated by DDHOEs and quantitative wavefront-sensing techniques have the possibility for contributing the evaluations.

Digital holography [5,6] is a wavefront-sensing technique that can achieve both three-dimensional (3D) imaging and quantitative phase-image sensing. By using digital holography, quantitative phase imaging of transparent objects [7], refractive-index imaging [8], and 3D tomographic imaging of phase objects [9] have been presented. One of the characteristics in digital holography is the ability for complex-amplitude imaging of an object without the use of lenses between an object and an image sensor. As a result, there is no phase aberration due to an imaging lens when conducting quantitative phase imaging of a wavefront. Furthermore, recent progress for the specification of an image sensor makes it possible to record a high-resolution digital hologram and acquire a quantitative phase image that is reconstructed from a single hologram. Therefore, it can be considered that this technique is suitable for quantitative evaluation of a wavefront generated by a DDHOE.

In this research, we used digital holography as a wavefront-sensing technique and observed a wavefront diffracted from a DDHOE quantitatively with digital holography. By using digital holography, a wavefront is recorded without both an imaging lens and array of lenses and therefore distortions caused from these lenses can be avoided. As a feasibility study, we fabricated a DDHOE whose wavefront of a diffraction wave was a plane wave and then we recorded a digital hologram of the diffraction wave. After signal processing to a digital hologram we obtained an intensity and quantitative phase images of the diffraction wave generated by a DDHOE.

2 EXPERIMENT

2.1 Optical system

For the quantitative observation of a wavefront diffracted from a DDHOE, we constructed a digital holography system based on Michelson interferometer as illustrated in Fig. 1. The oscillation wavelength of the diode pumped solid state laser used as a light source was 532 nm (JUNO532S, Showa Optronics). Coherence length of the laser was longer than 10 meters. A monochrome CMOS image sensor with 2.2 μm pixel size and 8 bits was set to obtain a digital hologram with 2592 × 1944 pixels. The fabricated DDHOE had an optical function of a reflection mirror and was set in the object arm to record the wavefront diffracted from a DDHOE. An off-axis digital hologram of the 1st-order diffraction wave generated from the DDHOE was recorded and then an image reconstruction procedure for an off-axis digital hologram was applied. The applied procedure was illustrated in Fig. 2. A 2D Fourier transform of a recorded digital hologram was calculated and spatial spectrum of an object wave was extracted from the Fourier transform image by using digital spatial filtering. A 2D inverse Fourier transform was calculated to the spatial spectrum of an object wave and then spatial carrier was removed from an object wave on the image sensor plane in the space domain. By calculating diffraction integral to the complex amplitude image of an object wave, intensity and quantitative phase images on the DDHOE plane were retrieved. This image-reconstruction procedure is based on the Fourier transform method [6] with the calculation of diffraction integral.

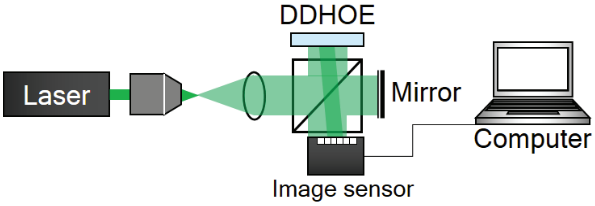

Fig. 1 Digital holography system to observe a wavefront diffracted from a DDHOE.

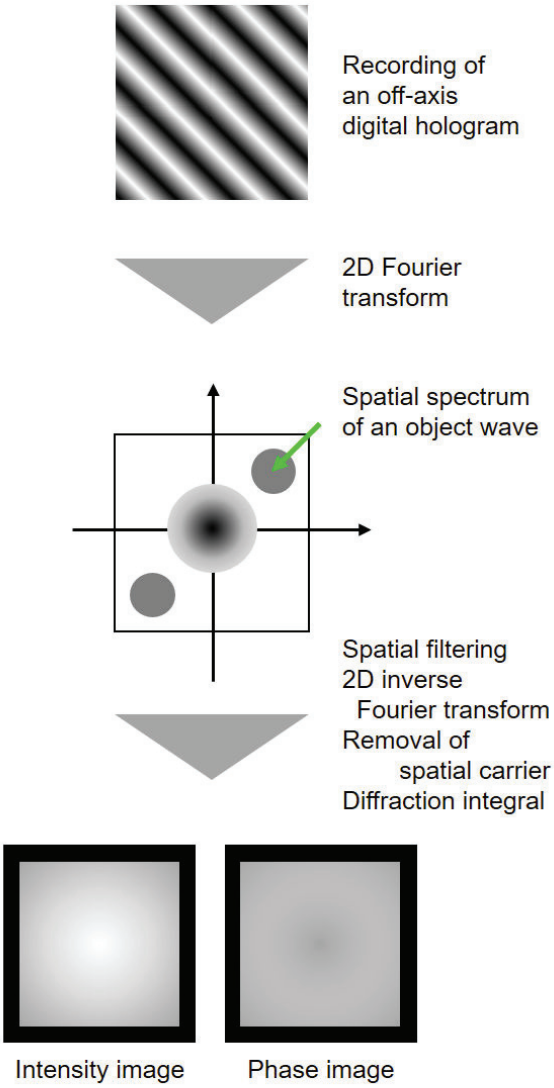

Fig. 2 Flow of the adopted image-reconstruction procedure for an off-axis digital hologram.

2.2 Experimental results

Figure 3 shows experimental results. A wave diffracted from the DDHOE was a plane wave and therefore variation of the phase distribution was little as shown in Figs. 3(b) - 3(d). Standard deviation of the phase image was less than $\pi/5$ and it means that its specification is higher than the reflection mirror with the standard deviation of $\lambda/20$. Slightly seen lines in the intensity and phase images are considered due to the interference of stray light in the recording of the digital hologram. Slightly seen phase variation shown in Fig. 3(c) is also considered due to the superimposition of stray light. The stray light was generated from the beam splitter shown in Fig. 1 by multiple reflection of illumination light in the splitter. Antireflection coating for the splitter will be effective to remove or suppress the stray light. Thus, quantitative phase imaging of a DDHOE fabricated by a wavefront printer was conducted. These results indicate the performance of digital holographic observation as an evaluation tool for DDHOEs.

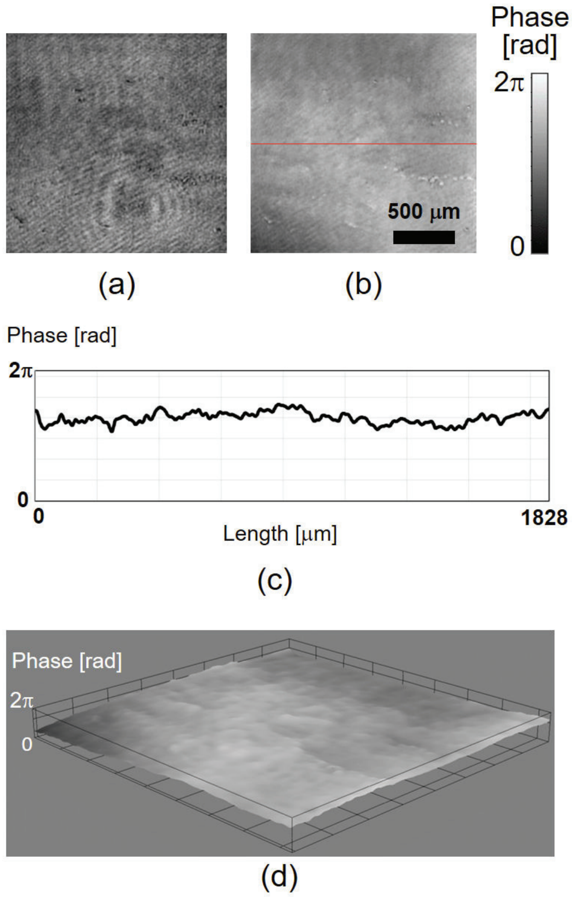

Fig. 3 Experimental results. (a) Intensity and (b) phase images obtained from single off-axis hologram. (c) Plot of the phase profile marked by red line in (b). (d) 3-D rendering of (b).

3 CONCLUSIONS

We have observed a wavefront diffracted from a DDHOE by using digital holography. An off-axis digital holography system based on Michelson interferometer was constructed and then complex amplitude distribution of a wavefront was acquired from a single hologram by using a single-shot exposure of an image sensor and signal processing of digital holography with the Fourier transform method. Experimental results show the performance of digital holographic observation as an evaluation tool for DDHOEs. Standard deviation of the phase image was less than $\pi/5$ and it means that its specification was higher than the reflection mirror with the standard deviation of $\lambda/20$. Our next steps are to improve the quality of a DDHOE by using the obtained quantitative phase images and to acquire not only intensity and phase images of a wavefront but also other optical properties of a DDHOE for further quantitative evaluations. One of the possible solutions to extend the measurement range of phase information and obtain the information of more optical properties is to adopt multiwavelength digital holography [10-12]. We will choose a digital holographic technique according to phase profiles and optical properties of a DDHOE. By using digital holographic observation, it is expected that complex amplitude distribution of a wavefront by a DDHOE can be analyzed in detail and compensated against the distortions and variations of a diffracted light.

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