Speckle-free digital holographic recording of a diffusely reflecting object

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Abstract: We demonstrate holographic recording without speckle noise using the digital holographic technique called optical scanning holography (OSH). First, we record a complex hologram of a diffusely reflecting (DR) object using OSH. The incoherent mode of OSH makes it possible to record the complex hologram without speckle noise. Second, we convert the complex hologram to an off-axis real hologram digitally and finally we reconstruct the real hologram using an amplitude-only spatial light modulator (SLM) without twin-image noise and speckle noise. To the best of our knowledge, this is the first time demonstrating digital holographic recording of a DR object without speckle noise.

OCIS codes: (090.1995) Digital holography; (090.2870) Holographic display; (070.6120) Spatial light modulators.

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1. Introduction

Digital holographic imaging has a long standing history [1–4] and holographic display systems based on computer-generated holography (CGH) have been proposed for 3D display [5–9]. Recently, a 3D holographic imaging system that records a complex hologram of a diffusively reflecting (DR) object using digital holography and reconstructs the hologram using a phase-type spatial light modulator (SLM) has been demonstrated [10]. However, as usual the demonstrated 3D holographic imaging system is severely contaminated by speckle noise. This is due to the coherent nature of standard digital holography. Speckle noise is the well-known drawback of coherent imaging systems and this has been a severe hindrance for 3D holographic imaging systems involving diffusively reflective objects [11]. Meanwhile, optical scanning holography (OSH) has been proposed to record a hologram by scanning the object and investigated for 3D holographic imaging [12,13]. It has been demonstrated already in OSH the recording of a complex hologram of an object without twin image noise [14]. In this paper, we demonstrate that OSH can record the hologram of a diffusively reflective (DR) object without speckle noise as well as twin image noise. To the best of our knowledge, this is the first time to demonstrate the digital holographic recording of a DR object without speckle noise. As such, OSH must be working in an incoherent mode of operation. In other words, only intensity distribution of the object is holographically recorded. We want to point out that besides OSH capable of holographic recording incoherently, there is a recent incoherent digital holographic technique called Fresnel incoherent correlation holography (FINCH) [15]. In OSH, a DR object is scanned by a time-dependent Fresnel zone pattern (interfering between a spherical wave and a plane wave of different temporal frequencies) and the reflected light from the DR object is detected by a spatially integrating photo-detector tuned to the difference between the different temporal frequencies. These features make up the incoherent mode of operation of OSH [16] and make it possible to generate a complex hologram of a DR object without speckle noise, which we demonstrate in this paper. We also demonstrate a closed loop 3D holographic imaging system that is composed of 'digital holographic recording stage,' 'digital processing stage' and 'optical reconstruction stage.' First, in the digital holographic recording stage, using the incoherent mode of operation of OSH, we record a complex hologram of a DR object without speckle noise as well as the twin image and background noise. Second, in the digital processing stage, the complex hologram is converted to an off-axis hologram by digital processing. Finally, in the optical reconstruction stage, the off-axis hologram is reconstructed using an amplitude-only spatial light modulator (SLM).

2. Digital holographic recording stage: optical scanning holography

Figure 1 shows the OSH setup that records the complex hologram of a DR object. OSH is an unconventional digital holographic technique that consists of a Mach-Zehnder interferometer and an electronic processing unit. The interferometer includes acousto-optic modulators (AOM1 and AOM2) and beam expanders (BE1 and BE2) with a focusing lens (L1). The frequencies of the upper and lower path of the laser beams are up-shifted by operating frequencies $\Omega + \Delta\Omega$ and Ω of AOM1 and AOM 2, respectively. The spatial pattern of the upper beam, with BE1 and L1, becomes a spherical wave toward the object, while the lower beam with BE2 becomes a plane wave toward the object. The two beams are combined at beam splitter BS2. The intensity of the combined beam is given by:

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$$
\begin{aligned}
&I_s(x,y,z;t) \\
&= \left| \exp\left\{ j\left[\left(\omega_o + \Omega\right) t \right] \right\} + \frac{j}{\lambda z} \exp\left\{ j\left[\frac{-\pi}{\lambda z}\left(x^2+y^2\right) + \left(\omega_o + \Omega + \Delta\Omega\right) t \right] \right\} \right|^2 \qquad (1) \\
&= \ 1 + \frac{1}{\left(\lambda z\right)^2} + \frac{2}{\lambda z} \sin\left[\frac{\pi}{\lambda z}\left(x^2+y^2\right) - \Delta\Omega\, t \right],
\end{aligned}
$$

where λ is the wavelength of the laser and z is the distance measured away from the back focal plane of Lens L1. The above spatial pattern of the interfering beam is called the time-dependent Fresnel zone plate (TD-FZP) [4, 13]. The TD-FZP is modulated by the frequency difference $\Delta\Omega$ between the upper and lower beams. In the experiment, AOM1 and AOM2 operate at 40MHz and 40.01MHz, respectively and thus, the TD-FZP is modulated at 10 KHz and the beam is used to raster scan a DR object (a dice in the experiment) as shown in Fig. 1. The reflected light from the DR object is collected by lens L2. In the incoherent mode of operation of OSH, lens L2 collects the reflected light, which is then spatially integrating by photo-detector PD. The scanning action corresponds to spatial convolution between the intensity of the scanning beam, $I_s(x,y,z;t)$, and the object's intensity distribution $I_0(x,y;z)$. The total intensity reflected from the target is given by:

$$
I\left(x,y\right) \propto \iiint I_s(x',y',z;t) I_o(x+x',y+y';z) dx'dy'dz. \qquad (2)
$$

where $I_0(x,y;z)$ is the DR object's planar intensity distribution located at z as the 3D object is assumed to be a collection of planar objects. The electrical signal from the PD is a heterodyne current, which is then demodulated by the in-phase and quadrature phase demodulators (the electronic multipliers and the low pass filters as shown in Fig. 1). Indeed the phase of the heterodyne current carries the holographic information of the 3-D intensity distribution [4]. The demodulation process extracts the convolution between the TD-FZP and the object's intensity distribution. The two demodulated signals become a real part and an imaginary part of a hologram and a complex addition of the two holograms generates a complex hologram given by [4, 13]:

$$
H_{com}\left(x,y\right) \propto \int I_0(x,y;z) \otimes \frac{j}{\lambda z} \exp\left\{ j \frac{\pi}{\lambda z}\left(x^2+y^2\right) \right\} dz. \qquad (3)
$$

where $\otimes$ represents convolution operation involving x and y. Integrating along z represents the contributions from all the planar distributions along z (depth) of the 3D object. In the experiments, we record the complex hologram of a dice that is of the size of 3mm by 3mm. The x-y scanning region is 13.5mm by 13.5mm and the diameter of the collimated beam is 25.4mm, and the focal length of lens L1 is 500mm. Figure 2(a) and 2(b) show the real and imaginary parts of the complex hologram, $H_{com}\left(x,y\right)$, respectively. Note that the hologram is as clear as we can see the fringe pattern without speckle noise due to the incoherent nature of OSH. Figure 3(a) shows the numerical reconstruction of the complex hologram, which is obvious not contaminated by speckle noise as compared to the image observed by a CCD camera upon coherent illumination of the dice (Fig. 3(b)).

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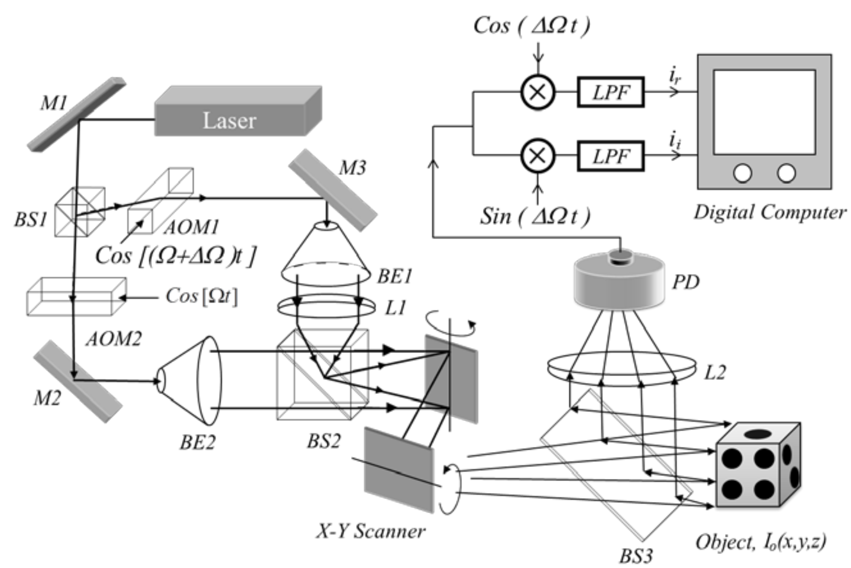

Fig. 1. Optical Scanning Holography (M's, mirrors; AOM1,2, acousto-optic modulators; BS1,2,3 beam splitters; BE1,2, beam expanders; L, focusing lens; x, electronic multiplexer; LPF, low pass filter).

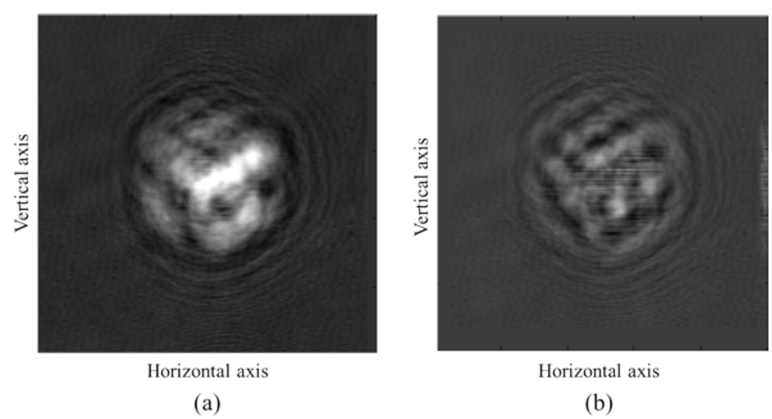

Fig. 2. (a) Real part of the complex hologram. (b) Imaginary part of the complex hologram.

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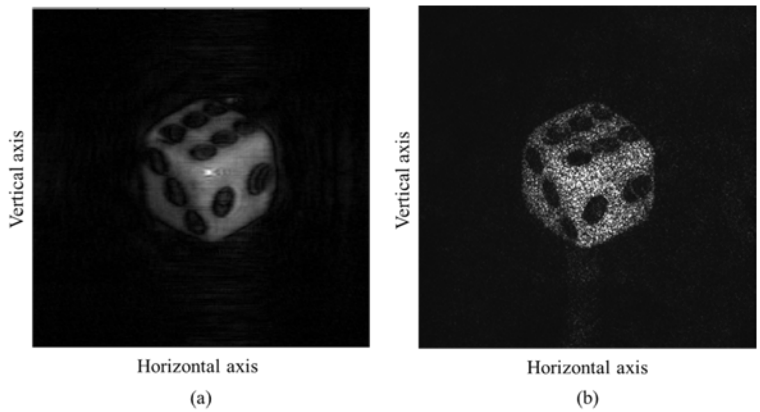

Fig. 3. (a) Numerical reconstruction of the complex hologram (free of speckle noise). (b) CCD imaging of a coherently illuminated dice.

3. Digital processing stage: conversion of complex hologram to off-axis real hologram

With reference to Eq. (3), the hologram is complex and hence does not contain any twin image and background (zeroth-order light in holography terminology) information [14]. But conventional SLMs cannot represent complex number. Recently, there is a proposed optical system that can display the real and imaginary part of the hologram using a single SLM for complex hologram display [16] However, we choose to employ a simpler method to reconstruct the hologram optically. We convert the complex hologram to an off-axis hologram that can be presented by an amplitude-type SLM [17]. The off-axis hologram is achieved by first multiplying a spatial carrier that is a complex sinusoidal signal along the x-direction, i.e., $\exp(\text{-j}2\pi\sin\theta x/\lambda)$, to the complex hologram, taking the real part of the resulting product, and finally adding a DC to avoid any negative values in the real hologram:

$$H_{real}^{off-axis}\left(x,y\right)=\mathrm{Re}\left[\mathrm{H_{com}}\left(x,y\right)\exp(\text{-j}2\pi\sin\theta\ x/\lambda)\right]+dc\ , \qquad (4)$$

where θ is the off-axis angle that separates the desired 3D image from the twin image and the DC background upon reconstruction, $\mathrm{Re}\left[\ \right]$ stands for taking the real part of the content being bracketed, and dc is a DC bias added to make the off-axis real hologram become a positive real value. Figure 4(a) shows the off-axis real hologram based on Eq. (4), where we set the off-axis angle $\theta=0.56^{\circ}$ in order to separate the desired 3D image of the object from the twin image and the DC background. Here in Fig. 4(b) we can see the grating pattern along the x-axis in the enlarged image of the real hologram.

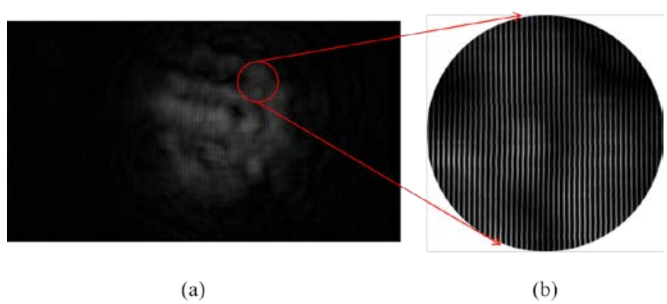

Fig. 4. (a) Off-axis real hologram with spatial carrier, (b) Enlarged image within the red circle of (a), showing grating structure of the spatial carrier.

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4. Optical reconstruction stage: reconstruction off-axis hologram using amplitude-only SLM

We now can reconstruct the off-axis real hologram using an amplitude-only SLM that modulates the amplitude of the optical field. Figure 5 shows the optical system that optically reconstructs the off-axis real hologram. The optical system is composed of a laser, a beam expender(BE), a polarizing beam splitter(PBS), an amplitude type spatial light modulator(SLM) and an analyzer(AL). The beam radiating from a laser is collimated by the BE and divided into s-polarized beam and p-polarized beam by the PBS. One of the divided beams illuminates the amplitude only SLM that is loaded with the off-axis real hologram shown in Fig. 4. The illuminated beam is spatially modulated according to the loaded off-axis real hologram. The spatially modulated beam reflects from the amplitude-only SLM and passes the analyzer (AL). The beam through the analyzer is optically reconstructed in air and captured by a CCD camera. In the optical reconstruction, we use ND-YAG laser (λ = 532nm) that is the same wavelength of the laser used in the recording stage using OSH. In this experiment, we have modified a commercially available beam projector (Sony VPL-HW20 Projector) to become an amplitude type SLM. The number of pixels of the SLM is 1920×1080 and the pixel pitch is 7 μm. The size of the SLM is 15.5 mm $\times$ 15.5 mm. The optically reconstructed hologram is recorded by a digital single-lens reflex (DSLR) camera with a lens. In this experiment we have used Nikon D5100.

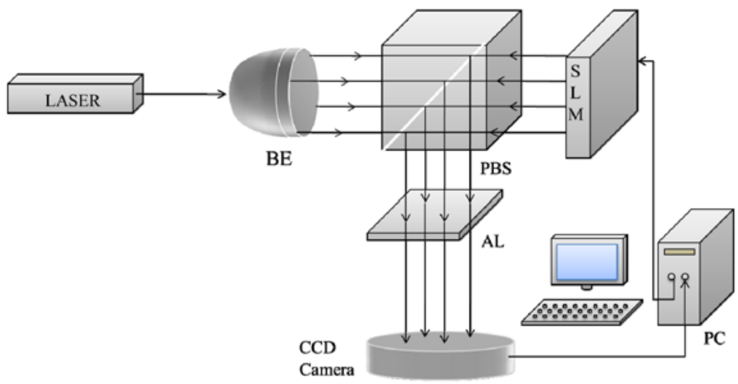

Fig. 5. Optical reconstruction system (BE: Beam Expander; PBS: Polarizing Beam splitter; SLM: Spatial Light Modulator; AL: Analyzer).

Figure 6 shows the optically reconstructed hologram that is captured by the DSLR camera. This shows that the off-axis real hologram of the dice is reconstructed in air without twin image and the background noise. This corresponds to the numerically reconstructed hologram shown in Fig. 3(a). Compared to the numerical reconstruction, we can see the granular pattern that is caused by the low resolution of the SLM used.

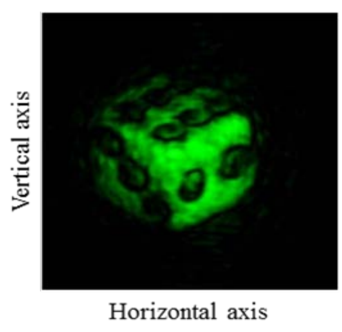

Fig. 6. Optically reconstructed hologram of the off-axis real hologram.

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5. Conclusion

We have recorded a complex hologram of a diffusely reflecting (DR) object using optical scanning holography (OSH) operating in the incoherent mode of operation. This shows that using OSH, we can record the hologram of a DR object without speckle noise which has been a severe drawback of 3D digital holographic imaging. To the best of our knowledge, this is the first time to show the recording of the hologram of a DR without speckle noise. We also show ~~that~~ the closed loop of 3D holographic imaging system that is composed of digital hologram recording stage, digital processing and optical reconstruction stages. In the hologram recording stage, OSH gives a robust and clean complex hologram of a DR object. In the digital processing stage, we have shown that the complex hologram can be easily converted to an off-axis real hologram that is suitable to be displayed by a conventional SLM. In the optical reconstruction stage, we have shown that the hologram of a DR object can reconstruct clearly without speckle noise, twin-image noise, and background noise

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