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Single-shot phase-shifting digital holography with a photon-sieve-filtering telescope*

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A method of single-shot phase-shifting digital holography with a photon-sieve-filtering telescope is proposed. Three copy images with different phases are first generated by use of a monofocal photon-sieve filter in Kepler telescope, and then interfere with the reference plane wave by a beam combiner. The hologram is captured by a charge-coupled device (CCD) in one single exposure. The complex-valued amplitude of the test object can be reconstructed by three-step phase-shifting interferometry through three frames of extracted sub-interferograms from the single-exposure hologram. The principle and simulation experiments are carried out and verified the validity of our proposed method. This method can be applied for snapshot imaging and three-dimensional object construction.

Keywords: digital holography, phase shift, diffractive lenses, frequency filtering

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1. Introduction

Holography can simultaneously record the amplitudes and phases of object waves, so this technique is widely used for three-dimensional (3D) display,[1,2] topography measurement,[3,4] information encryption,[5–7] and biological cell microscopy.[8–10] Initially, the original holography[11] proposed by Gabor has many inherent shortcomings, and the DC and conjugate terms seriously reduce the image quality due to the coaxial optical system. Although the off-axis holography[12] is useful for separating different diffraction orders in the frequency region, it cannot take enough advantage of the space-bandwidth product of the recording medium. In order to overcome these drawbacks in common path, phase-shifting digital holography (PSDH) is the most effective method[13,14] to eliminate the undesired terms of the reconstructed image. Digital holography[15,16] is captured by a charge-coupled device (CCD) and used to construct the object wave by computer. In general, multiple exposures must be adopted for recording the hologram, which is not suitable for real-time imaging or dynamic monitoring. In addition, for conventional phase shifters,[17–20] mechanical operation will inevitably result in vibration, which may affect the accuracy of phase shift and degrade the image quality.

In order to improve the imaging speed, a proven technique is to reduce the exposure time. When the object wave is weak compared with the reference wave, only two holograms are required.[21] However, this method needs two CCDs to record holograms. Although diffused illumination[22] can be used for recording the hologram in one single exposure, the twin images seriously decrease the image quality. Two-step phase-shifting holography with orthogonal polarizations method[23] can also meet the requirement of one-shot condition, but it needs the additional intensity distributions of object wave and even special polarization CCD. Generally, in order to obtain multiple phase-shifting holograms, space division multiplexing is a kind of conventional approach. In addition, parallel quasi-phase-shifting digital holography[24] was proposed to realize four-step phase-shifting holography by use of array device in the reference beam.

Here, another single-shot phase-shifting digital holography is proposed. In the object beam, the test object is first copied by a photon-sieve filter in Kepler telescope. The three copy images have the same amplitude but different phases. Due to different image distances, the copy images are then incident on the CCD screen by image relay. The reference plane wave interferes with the copy images in one single exposure. Then the object wave can be reconstructed by phase-shifting interferometer.[25,26]

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2. Principle of phase-shifting holography with a photon-sieve-filtering telescope

The recording of our proposed method is schematically illustrated in Fig. 1. A plane wave laser beam is split into two parts by beam splitter 1, and both beams are expanded and collimated to plane waves through the beam expander consisting of a microscope, a pinhole, and a condenser lens. In object light path, the expanded beam first passes through a transparent test object, and then through the Kepler telescope consisting of two condenser lenses. At the same time, a photo sieve is located at the spatial frequency plane.[27] Photon-sieve-filtering telescope (PSFT) can generate three copy images in different longitudinal and radial separations, as shown in the sub-graph in Fig. 1. The intervals Δz and Δr between adjacent images are equal. These images are then directed to the CCD plane by three groups of image relays, in which each has different focal lengths in order to keep the same lateral magnification. Two beams are combined by beam splitter 2 and then form interferogram on CCD plane. There is no mechanical movement required throughout the whole recording process. The reconstructed distance can be accurately calculated by auto-focusing method with Tamura coefficient.[28]

A fact is that three copy images produced by PSFT correspond to the $+1$, -1, and zero orders. Furthermore, high-order diffraction is symmetrical about the zero order along both the optical axis and the radial direction. Although three copy images have the same shape distribution, each of them has different phases, which can be used for phase-shifting interferometer. Obviously, the phase-shifting functionality is realized by operating the multicopy images rather than the reference plane wave. In this case, we can also reconstruct the wavefront of copy image by phase-shifting interferometer. The analytic expression of diffractive field $U_0(x,y)$ at CCD plane can be derived[29] by

$$U_0(x,y) = \frac{\exp[-\mathrm{i}(\varphi_0+\varphi_{-1})/2]}{\sin[(\varphi_0-\varphi_1)/2]}\cdot(I_0-I_1) - \frac{\exp[-\mathrm{i}(\varphi_0+\varphi_1)/2]}{\sin[(\varphi_0-\varphi_{-1})/2]}\cdot(I_0-I_{-1}), \quad (1)$$

where I_0, I_1, and I_{-1} respectively correspond to zero-, positive, and negative first-order holograms. φ_0, φ_1, and φ_{-1} denote the phases of the multicopy images. Note that the constant term has been ignored. Once the wavefront of the copy image is obtained, the test object can be calculated by reverse Fresnel diffraction integral.

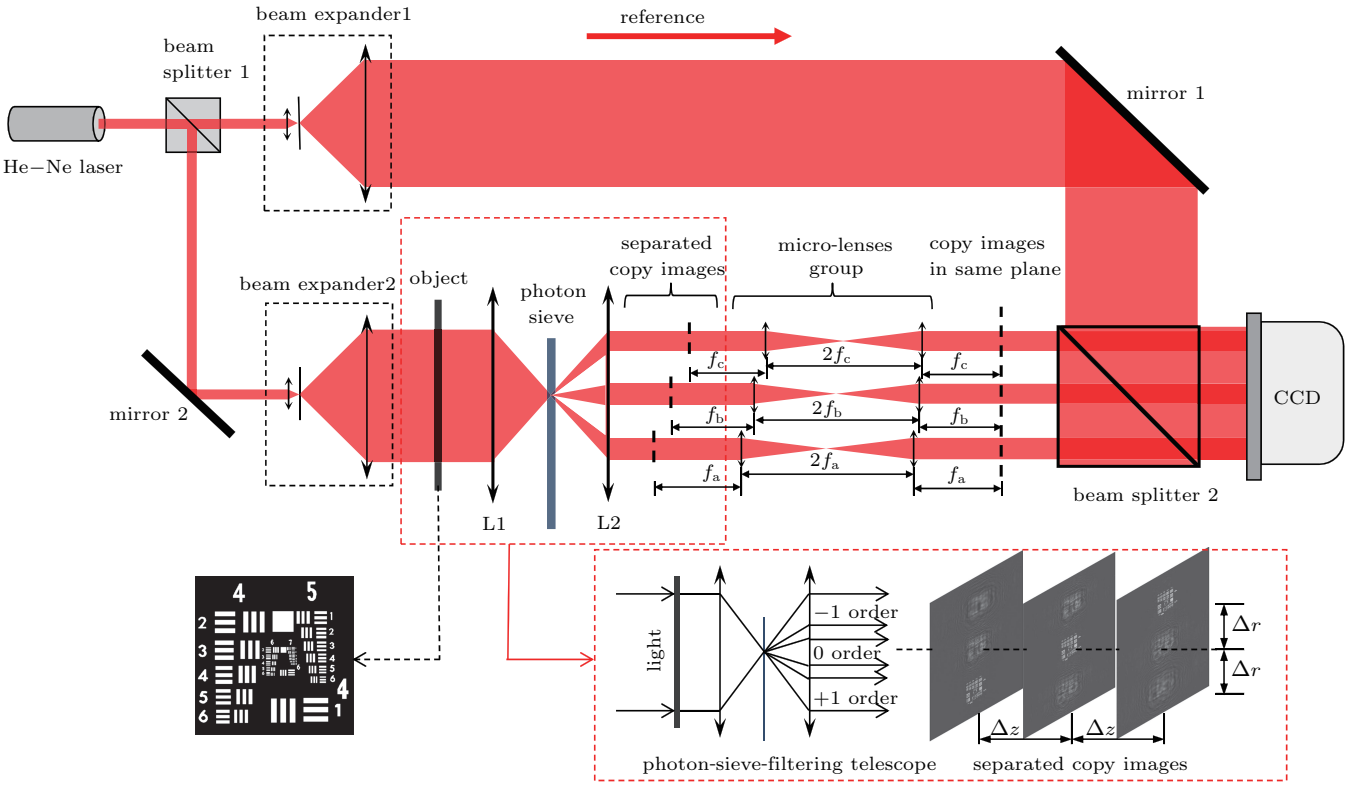


Fig. 1. Schematic diagram of optical setup for single-shot phase-shifting holography with a photon-sieve-filtering telescope.

3. Experiment and discussion

To well understand the phase-shifting amount, here, a transparent ring with an outer diameter of 1.7 mm and an inner diameter of 0.9 mm is fabricated on a chrome plate and is then reconstructed in experiment. In Fig. 1, if a quarter wave plate is inserted in the reference beam and the micro-lenses

group is removed, the optical setup can be used for reconstruction of the three copy images. For two-step phase-shifting holography, the two interference patterns (denoted by h_1 and h_2) separately correspond to the 0- and $\pi/2$-reference waves. In this case, the wave-front E_o on the screen can be given as $E_o = (h_1 - I_o - I_r) + i * (h_2 - I_o - I_r)$,[30] where I_o and I_r are the intensities of object and reference waves on the screen, respectively. Note that the constant has been ignored.

In experiment, the test object is located in the front focal plane of the lens L1. Figures 2(a) and 2(b) show the two frames of phase-shifting hologram. Figures 2(c), 2(d), and 2(e) show phase distributions of three copy images. For Kepler telescope, the focal lengths of the front and rear condenser lenses are both 150 mm. A 180 mm focal-length photon sieve is fabricated on a chrome plate to operate at a wavelength of 632.8 nm. In this case, the intervals Δz is 125 mm, thus the corresponding phase shift can be given by $\Delta\varphi = \mathrm{mod}(k \cdot \Delta z, 2\pi)$, where k is the wave number, $k = 2\pi/\lambda$; the function mod$(\cdot)$ is modulo operation. Obviously, the theoretical phase shift is -1.47 radian. By contrast, the constructed phase distributions of three copy images are shown in Figs. 2(c), 2(d), and 2(e), and the experimental phase values approximately equal -1.44 and -1.36 radian, which is in good agreement with the theory. It should be noted that in Fig. 2, the maximum of peak to valley is less than 0.4 except some abnormal phase values introduced by the system disturbance. From the experimental results, we know that there exists a fixed phase difference between any two adjacent copy images. The phase-locking property meets the requirement of the phase-shifting interferometry.

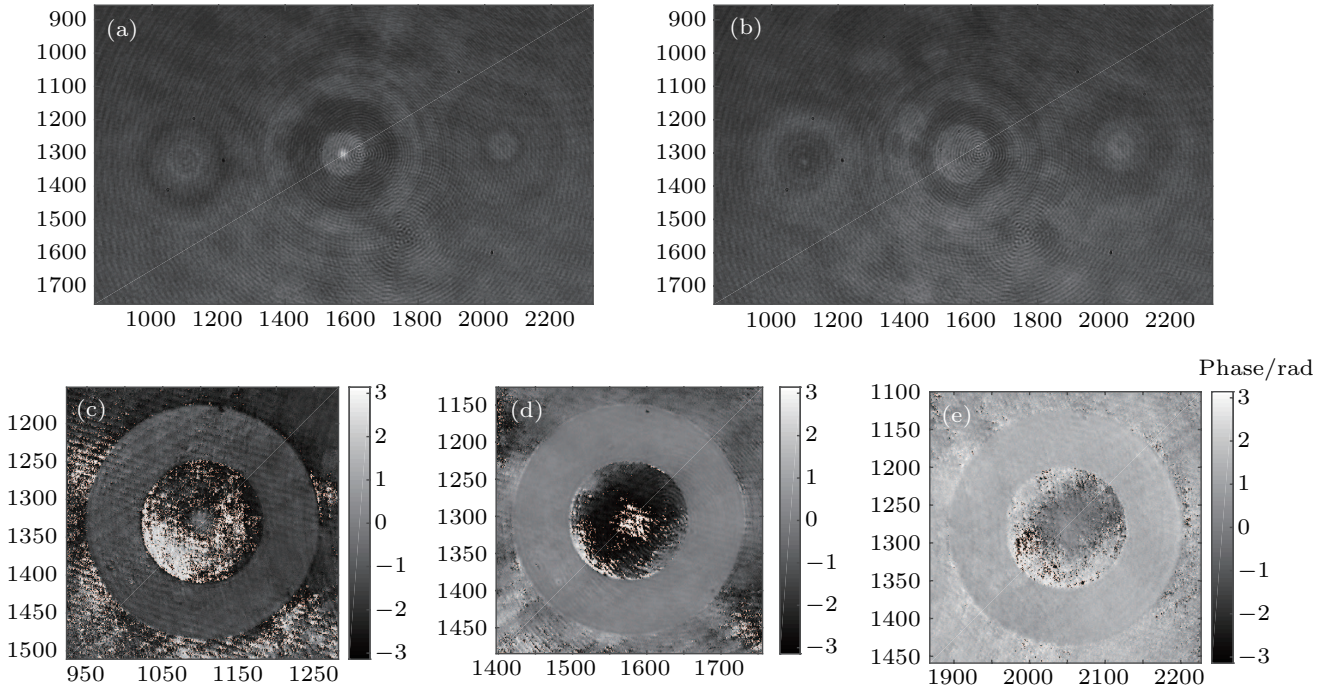


Fig. 2. Holograms and phase distributions of three copy images. (a) and (b) Phase-shifting holograms; (c) +1 order, $\varphi_1 = -1.31$ radian; (d) 0 order, $\varphi = 0.13$ radian; (e) -1 order, $\varphi_{-1} = 1.49$ radian.

Then, in order to investigate the image resolution, a simulation experiment about a resolution test target is given. This time, the three copy images are incident on the CCD plane by image relay, which is realized by a pair of micro-lenses. Each micro-lens has a different focal length to meet the requirement of the image relay. Concretely, the focal length of the micro-lens group in Fig. 1 satisfies the following equation: $f_a - f_b = f_b - f_c = \Delta z/4$. The second beam is first collimated and expanded and then passes through a mirror and a beam splitter, and then interferes with the copy images. The single-exposure hologram is captured by a CCD (Prosilica GT 3300, 3296×2472 pixels of 5.5 μm×5.5 μm size).

The object is a USAF1951 test resolution target. Figure 3 shows the single-shot phase-shifting digital hologram captured by CCD. Figures 3(a_1), 3(a_2), and 3(a_3) indicate the phase-shifting sub-holograms that can be extracted from the single hologram. Each sub-hologram corresponds to the interference pattern between the phase-shifting image and reference plane wave. The reconstructed object is shown in Fig. 3(b). Figure 3(c) presents the auto-focusing curve. The reconstructed distance is -49.9 mm. In this image, group 5, element 4 can be resolved clearly. Each sub-hologram contains 760×760 pixels, thus the corresponding theoretical resolution[31] is 9.22 μm. Obviously, the undesired terms have been eliminated due to the correct phase-shifting operation.

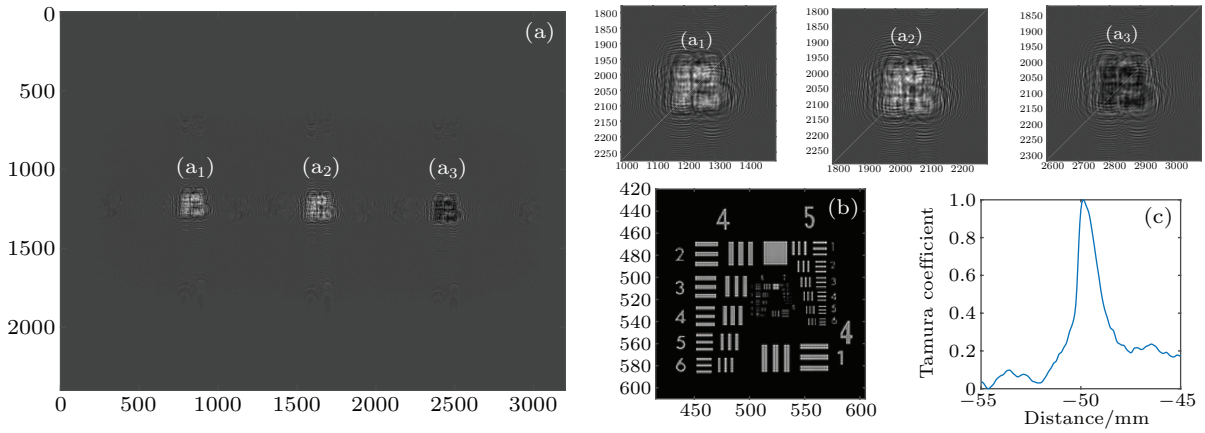


Fig. 3. Recording and reconstruction of test resolution target with single-shot phase-shifting digital hologram. (a) Single hologram captured by CCD; (a_1), (a_2), and (a_3) Sub-interferograms of $+1$, 0, and -1 orders, respectively; (b) reconstructed image; (c) auto-focusing curve.

Although there is no mechanical movement throughout the whole process of recording, some problems need to be considered before experiment. The positions of the micro-lens telescope must be strictly aligned corresponding to the location of the three copy images. Otherwise, the inevitable errors of the phase shifts will be introduced into each copy image. In order to ensure the correct state of the holographic recording, we can monitor the interference patterns between the reference plane wave and the multi-copy object waves without test object in the object beam. Only in this case, the test object can be reconstructed correctly. But more importantly, different from the conventional phase shifters, PSFT provides another kind of technique to realize phase-shifting operation. In addition, the photon sieve is essentially an amplitude-only diffractive lens, which can be used for soft x-ray focusing and imaging.

4. Conclusions

In conclusion, a principle experiment and a simulation experiment are carried out to verify our proposed method single-shot phase-shifting digital holography with a photon-sieve-filtering telescope. Multicopy images with different phase shifts are generated by photon-sieve-filtering telescope, and direct on the detector array by image relay, and then interfere with the reference plane wave. Three frames of sub-holograms can be extract from the single exposure and used for three-step phase-shifting interferometer. Single-exposure technique greatly improves the system stability during the process of the recording or monitoring. PSFT not only realizes the beam splitting function, but also extends the filtering technology. If the monofocal photon sieve is replaced by other kind of multifocal photon sieve, it will provide more sophisticated functionality which can be very useful for optical diagnostics and optical imaging.

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