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Single-Shot On-Axis Fizeau Polarization Phase-Shifting Digital Holography for Complex-Valued Dynamic Object Imaging

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Supplementary Materials

This document provides supplementary information to "Single-shot on-axis Fizeau polarization phase-shifting digital holography for complex-valued dynamic object imaging".

1. Digital reconstruction scheme.

The digital processing procedure to reconstruct the complex-valued object with the proposed technique is represented in Figure S1. The step-by-step analysis procedure is demonstrated using the experimental results of complex-valued object with "Chinese characters 'Hua(华)' with an amplitude distribution and 'Da (大)' with a phase distribution consisting of size 3.9mm×3.9mm". The recorded intensity of single-shot hologram and the retrieved phase-shifted holograms are shown in Figure S1 with respective captions. The complex amplitude information at the sensor plane is retrieved by utilizing the multiple phase-shifted holograms[1,2]. The amplitude and phase distribution of the complex-valued object at any arbitrary plane is reconstructed using the complex-amplitude distribution at the sensor plane by angular-spectrum-based digital propagation[3,4].

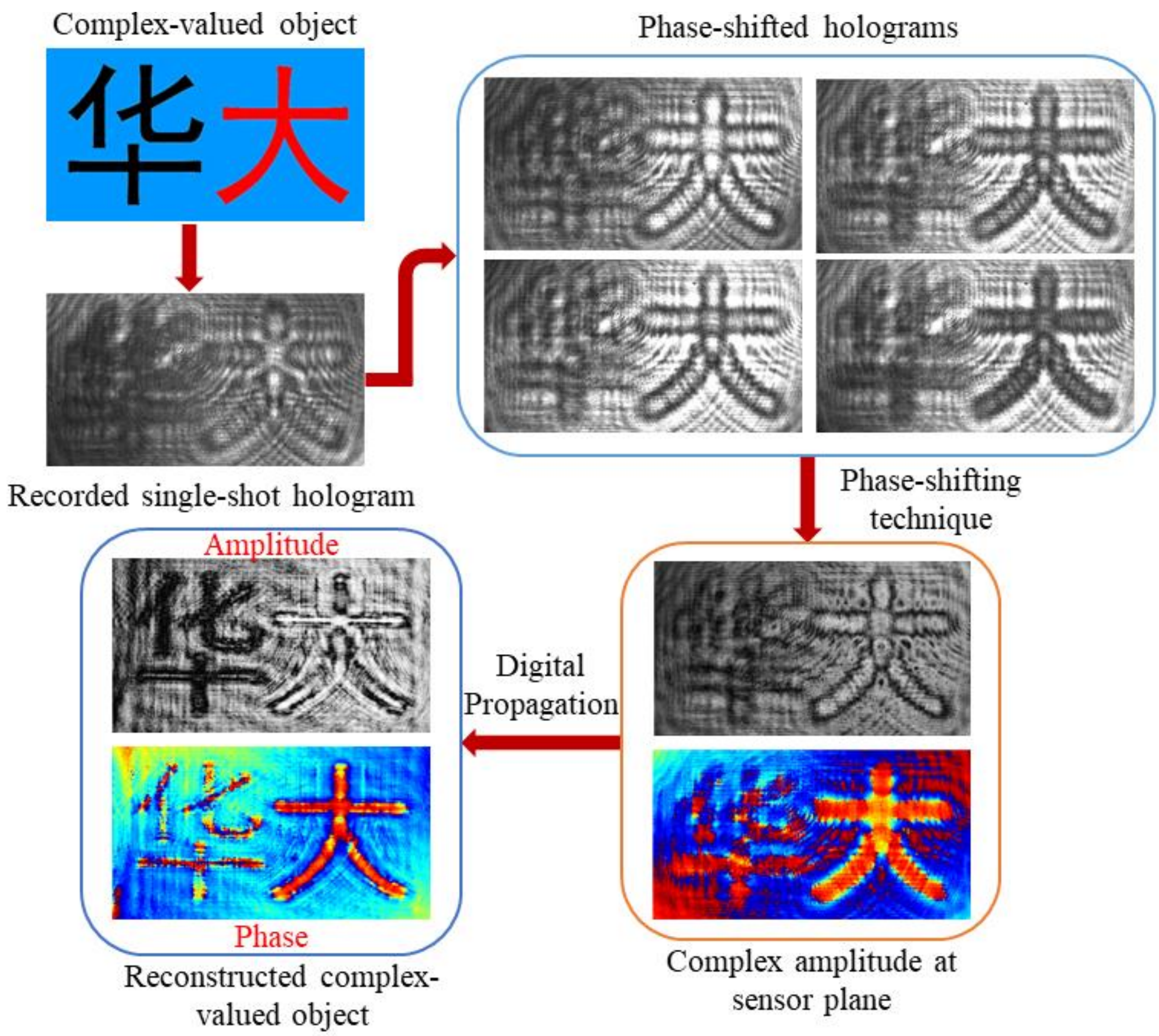

Figure S1. Step by step reconstruction process complex-valued object from recorded single-shot hologram using proposed technique.

2. Complex-valued object.

To provide the complex-amplitude modulation with the phase-only SLM (PLUTO-VIS, Holoeye with total pixels 1920×1080, pixel pitch of 8μm, and an image frame rate of 60Hz), we made a complex-valued object of Chinese characters 'Hua(华)' with an amplitude distribution and 'Da (大)' with a phase distribution consisting of size 3.9mm×3.9mm as shown in Figure S2. The amplitude modulation is achieved by encoding the object information with a checkerboard phase-mask pattern (shown in Figure S2(b)) by adding phase values of 0 and π to alternate pixels with the respective grey scale values[5,6]. The checkerboard pattern consists of binary uniform phase distribution with phase values 0 and π, which represents a uniform amplitude with opposite direction in X-axis in its complex plane representation. Therefore, the illumination of light field to the phase mask encoded phase-only SLM generates an average amplitude distribution of zero from the checkerboard phase mask. The phase distribution 'Da (大)' is directly encoded in the SLM with a uniform grey scale value (shown in Figure S2(c)) having a phase value of π.

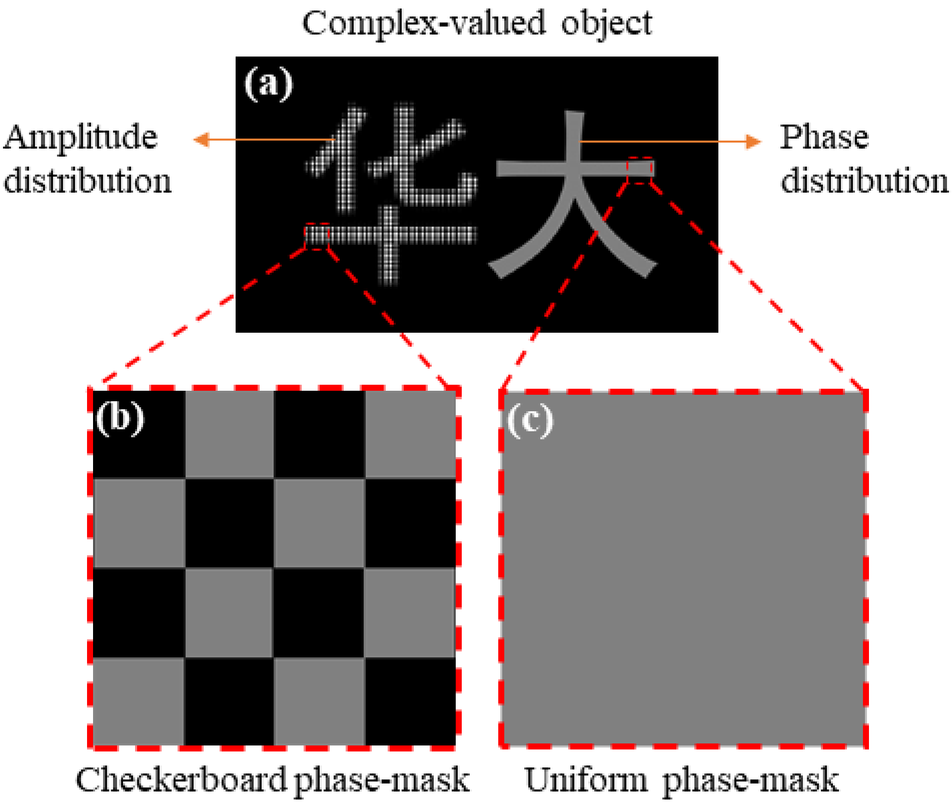

Figure. S2. (a) Phase-mask of the com plex-valued object encoded in the phase-only SLM; (b) Checkerboard pattern used to modulate the amplitude; and (c) Uniform phase-mask.

3. Experimental designs of MP-MZI and PP-MZI

To evaluate the robustness of the system in environmental fluctuations and other noise mechanisms, we estimate the phase stability and sensitivity of FP-PSDH system and compared with other phase-shifting based methods. The performance is evaluated by a time sequential detection of single-shot holograms in FP-PSDH; and comparing with the two configurations of Mach Zehnder interferometry (MZI) based phase-shifting scheme, namely multiple-shot phase-shifting MZI (MP-MZI) and single-shot polarization phase-shifting MZI (PP-MZI). The experimental geometry corresponding to MP-MZI and PP-MZI are shown in Figure. S3(a) & S3(b), respectively. A vertically polarized He-Ne laser source of wavelength 632.8 nm, acts as the source beam for the MZI system. The beam is spatially filtered and collimated to generate a uniform beam with a plane wavefront. In MP-MZI scheme, a half wave plate (HWP) converts the linearly vertically polarized light beam to a horizontally polarized light beam. The beam is divided into two beams by a non-polarized beam splitter (BS1), where the transmission beam serves as the object beam, and the reflected beam serves as the reference beam. A spatial light modulator (SLM, PLUTO-VIS, Holoeye, reflective type) is included in the reference beam to implement the phase-shifting in the interferometry scheme. The object beam transmitting from the BS1 is folded by a mirror (M) and combines with the reference beam using BS3. A CCD camera (Prosilica GT1910, Allied Vision, 1920×1080 pixels with a pixel pitch of 5.5μm) is used to record the intensity corresponding to the phase-shifting scheme. In MP-MZI system, a sequential detection of 50 holograms for each of the four phase shifted holograms were carried out, and the corresponding phase is recovered using phase-shifting technique. On the other hand, the PP-MZI scheme utilizes a 45-degree polarized beam generated by the laser source and HWP combination as the input light source as shown in Figure. S3(b). The light beam is divided into two beams by a polarization beam splitter (PBS), where the transmission beam is a p-polarized light, and the reflected beam is a s-polarized light. These orthogonal polarization components are folded by mirrors M1 and M2 and combined by the beam splitter (BS). These propagated polarized light fields transmit through the quarter wave plate (QWP) with its fast axis oriented at 45° and converts the linearly polarized light beams into respective circularly polarized light beams before reaching the polarization camera. The camera is 5.1 mega pixel with Sony IMX250MZR CMOS polarized sensor (active pixels 2464×2056 with pixel size 3.45μm and having 74 frames per second). The polarized camera records the raw intensity distribution, and then simultaneously extracts the four multiple phase-shifted holograms. In the case of PP-MZI, sequential detection of 50 single-shot holograms with the polarized camera in sample-free configuration were carried out with a time interval of 0.1s and the phase map is recovered from respective digitally processed multiple-phase shifted holograms.

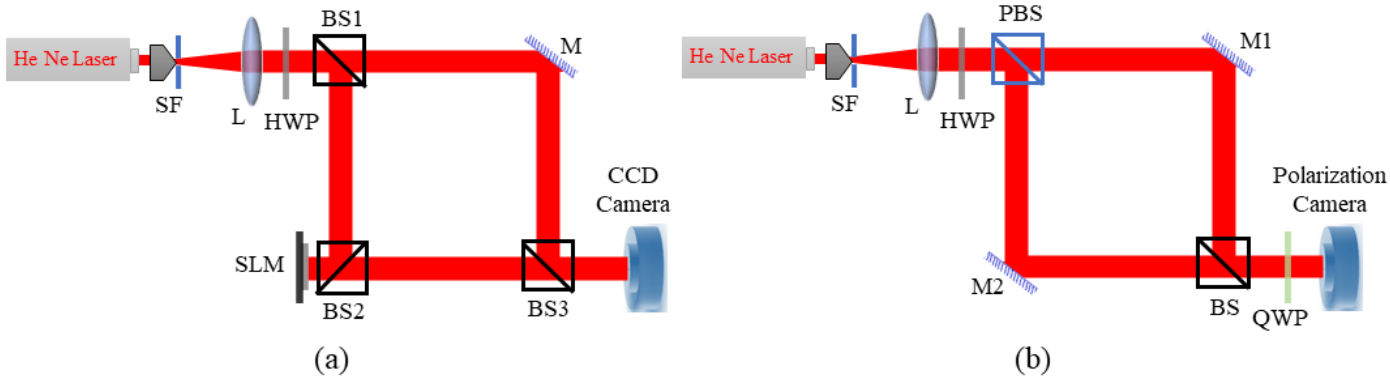

Figure. S3. Experimental geometry: (a) Multiple-shot phase-shifting Mach Zehnder interferometry (MP-MZI); (b) Single-shot polarization phase-shifting Mach Zehnder interferometry (PP-MZI); He-Ne laser, Helium-Neon laser source; SF, spatial filter; M, mirror; HWP, halfwave plate; L, lens; BS, non-polarizing beam splitter; PBS, polarization beam splitter; SLM, spatial light modulator; QWP, quarter wave plate; CCD camera, charge coupled device camera.

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