A wavefront division multiplexing holographic scheme and its application in looking through diffuser

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Abstract
We present a spatial light modulator (SLM) assisted compact holographic method and illustrate its application by imaging through a random scattering medium. The merit of the proposed method is wavefront division multiplexing, i.e. the dual wavefront modulations over a single SLM. Two different wavefront shapes: a reference-light shape and a phase object, are combined over the SLM. One advantage of this scheme is the flexible modulation of the reference light. The experimental implementation of this method is demonstrated by quantitatively reconstructing different phase objects from the randomly scattered light. This new scheme greatly simplifies the experimental configuration and presents a better stability even in presence of external vibrations, opening avenues for the holography-based scattering imaging application.

1. Introduction

In 1948, Gabor [1] invented a novel lensless imaging method known as holography. In this arrangement, the object and reference wave share the same optical path, i.e. in-line holography, which leads to issue of the ‘twin image’. Possible solution to this challenge is an off-axis holographic approach [2], which extends the concept of carrier wave in communication to optics. To realize the off-axis holography, a tilted reference beam is required, rendering the experimental implementation more complicated and unstable. It is of significance to realize the off-axis holography in the stable and compact arrangement, since it can solve the ‘twin image’ problem of an in-line geometry [3–7]. However, sharing of frequency space and possible overlapping of the desired Fourier spectrum with the un-modulated term introduces constraints on the resolution and field of view in the off-axis holography. The phase-shifting geometry in the holography helps to remove the twin image and constraint of field of view of the off-axis holography [8].

For long, imaging through a scattering medium has been the goal of extensive studies. As early as 1960s, holographic technology had been used for imaging through random media. Several representative works were proposed by Leith and Upatnieks [9], Goodman et al [10], and Kogelnik and Pennington [11]. Although, some limitations exist in their schemes, these restrictions can be conquered with the development of digital holography and modern imaging optics [5, 12–23]. With the help of techniques, including wavefront correction [14, 15], speckle noise reduction [16, 17], and lensless imaging [18], the quality of imaging through the scattering medium has been improved.

Averaging the fluctuating random field, i.e. ensemble average, is an important approach for cancelling the effect of random phase [19–25]. The ensemble average can be achieved by the time or spatial average of the speckle field, depending on the experimental conditions and ergodic properties of the stochastic process. The time-averaging-based method [22, 23] requires a rotating or moving scattering layer for average over the multiple speckles. This process requires abundant data and is time-consuming. On the other hand, if the optical field is ergodic in space, spatial-average-based method can be realized by only a single-shot
Figure 1. Schematic of the proposed method. An incident beam splits into two parts by a phase mask which is composed of an object phase and a tilted lens phase. The object beam (in blue) and the reference beam (in red) propagates on-axially and off-axially to the scattering plane, respectively. The speckles from these two beams interfere at the observation plane.

The fourth-order correlation or cross-covariance function can be obtained by the spatial average of speckle field, which is known as intensity correlation [20, 24]. The complex-valued object can be reconstructed from the intensity correlation of the speckle. Previous works to recover the complex-valued object using the Hanbury Brown–Twiss (HBT) approach are implemented on the suitable interferometer [21, 24], like Mach–Zehnder interferometer. A complicated setup for experimental implementation is required, resulting in some restrictions on the practical application. Although combination of iterative algorithm and in-line holography provides a simple configuration for implementation [26–28], these methods may encounter the uncertainty of iterative process, because of the arbitrariness of initial guess value and the non-convergence. Singh et al [19] have used three-dimensional auto-covariance of the speckle intensity in a specifically designed experimental system for 3D object imaging, and this method is applied to reconstruct the amplitude object.

In this study, we present a new method to utilize the independent propagation characteristics of light wave in a compact holography setup. In this system, both the off-axis and phase-shifting holography can be accomplished simultaneously by wavefront division multiplexing assisted with a SLM. Therefore, this arrangement simplifies the imaging system and allows us to provide a compact, stable, and lensless holographic method based on the HBT. As far as we know, this is the first attempt to develop a modified off-axis holography with the HBT approach, and yet highly compact and stable experimental geometry. As an application, quantitative images of vortex phase with different topological charges through the diffuser are experimentally reconstructed. Availability of digital reference phase with the help of SLM offers more flexibility to control the shape, position, and size of the reference light. We illustrate the outperformance of this design in scattering imaging by breaking the position limitation of the diffuser in previous experimental configuration. We also test the performance of this method in presence of external vibrations.

2. Theory

The schematic of the proposed method is shown in figure 1. It utilizes the independent propagation characteristics of light wave. A coherent light from the source plane emerges and illuminates on two different portions of the scattering plane. Propagation direction of two sources at the scattering plane is controlled by the phase modulations at the source plane. The object beam (in blue) propagates on-axially to the scattering plane. The reference beam (in red) becomes a converging spherical wave and focuses at the scattering plane, because of introducing a tilted lens phase. These two wavefronts are multiplexing over a SLM (on source plane).

One widely-used method to solve the ‘twin image’ problem in holography is introducing an off-axis reference light. Such a scheme complicates the experimental configuration and is sensitive to vibrations and disturbances of the environment. To address this issue, a compact scheme with robustness to vibrations is designed, which possesses the advantage of wavefront division multiplexing with the help of SLM. To illustrate the application of the proposed scheme, we reconstruct the phase objects hidden behind a scattering medium. Therefore, a scattering plane is introduced in figure 1.

A monochromatic polarized light can be represented by two orthogonal components as

\[ \hat{e}_x E_x(r) + \hat{e}_y E_y(r), \]

where \( \hat{e}_x \) and \( \hat{e}_y \) denote the horizontal and vertical polarization, respectively. Assuming
a linear polarizer rotated at 45° after the diffuser, the complex field immediately after the scattering medium is represented as

\[
\begin{pmatrix}
E'_x(r_1) \\
E'_y(r_1)
\end{pmatrix} = \mathbf{P}(\theta) \cdot \begin{pmatrix}
E_x(r_1) \\
E_y(r_1)
\end{pmatrix} \cdot e^{i\varphi(r_1)},
\]

(1)

where \(r_1\) denotes the transverse spatial coordinates at the scattering plane, \(\mathbf{P}(\theta) = \begin{pmatrix}
1/\sqrt{2} & 1/\sqrt{2} \\
1/\sqrt{2} & -1/\sqrt{2}
\end{pmatrix}\) is the Jones matrix of linear polarizer of 45°. \(\varphi(r_1)\) is the random phase introduced by random media, which imposes the same modulation for these two orthogonal components \(E_x(r_1)\) and \(E_y(r_1)\).

The polarization component at the observation plane is related to the source plane as

\[
E_m(r_2) = \int E_m'(r_1) G(r_2, r_1) \, dr_1,
\]

(2)

where \(m = x, y\) and \(r_2\) is the transverse spatial coordinates at the observation plane. \(G(r_2, r_1) = \exp(\frac{ik|r_2 - r_1|^2}{2z})\) is the Fresnel propagation kernel for a free space. Here, \(\lambda, k = 2\pi/\lambda,\) and \(z\) are the wavelength, the wave number of light, and the propagation distance, respectively.

The field at the observation plane is composed of the contributions from these two independent sources at the scattering plane: object and reference, as shown in figure 1. The electric field in one of the polarization directions is the superposition of two source fields, i.e. \(E_m(r_2) = E^O_m(r_2) + E^R_m(r_2)\), here \(O\) and \(R\) represent the object and reference, respectively. The speckle intensity at the observation plane can be obtained by: \(I(r_2) = |E^O_m(r_2) + E^R_m(r_2)|^2 + |E^O_m(r_2) - E^R_m(r_2)|^2\).

Assuming that the random field obeys the Gaussian statistic, the cross-covariance function of the speckle is defined as [29, 30]

\[
C(\Delta r) = \langle \Delta I(r_2) \cdot \Delta I(r_2 + \Delta r) \rangle = \sum_{mn} \left[W^O_{mn}(\Delta r) + W^R_{mn}(\Delta r)\right]^2,
\]

(3)

where \(\Delta r\) is the coordinates difference of two points in space for intensity correlation and \(\langle \rangle\) represents the ensemble average. \(\Delta I(r_2) = I(r_2) - \langle I(r_2) \rangle\) is the spatial fluctuation of intensity with respect to its mean value. \(W^O_{mn}(\Delta r)\), with \(m/n = x, y\), denotes the element of coherence-polarization (CP) matrix \(\begin{pmatrix} W_{xx}(\Delta r) & W_{xy}(\Delta r) \\
W_{yx}(\Delta r) & W_{yy}(\Delta r) \end{pmatrix}\) [31]. \(W^O_{mn}(\Delta r)\) and \(W^R_{mn}(\Delta r)\) are the object and reference coherence functions, respectively. The reference complex coherence function \(W^R_{mn}(\Delta r)\) in equation (3) is introduced to cover the support of \(W^O_{mn}(\Delta r)\).

\[
W_{mn}(\Delta r) = \langle E_m(r_2) \cdot E_m^*(r_2 + \Delta r) \rangle = \int I_{mn}(r_1) \cdot \exp\left(-\frac{k}{z} \Delta |rr_1|\right) \, dr_1,
\]

(4)

where \(^*\) represents the complex conjugate and \(I_{mn}(r_1) = E_m(r_1) \cdot E_m^*(r_1)\) is the polarized source at the scattering plane. Equation (4) is the van Cittert–Zernike theorem form for the CP matrix [32]. For the reference source, \(I_{mn}^R(r_1) = \text{circ}[\{r_1 - r_0\}/a]\) denotes an off-axis point source. Here, \(r_0\) and \(a\) are the off-axis position and the radius size of reference source, respectively. For the source object, \(I_{mn}^O(r_1)\) is a complex quantity for \(m \neq n\) and \(I_{mn}^O(r_1)\) is real for \(m = n\).

Equations (3) and (4) indicate that the original intensity distribution of the source object at the scattering plane can be reconstructed from the Fourier transform of the cross-covariance of the speckle. To obtain the phase of polarized source object, phase-shifting method is utilized. Due to the polarization modulation property of the SLM, phase shifts are introduced only in the \(x\) component of the polarized source object. Therefore, only the complex term \(I_{xy}^O(r_1)\) \((m \neq n)\) is modulated by the phase shifts. Term \(I_{xy}^O(r_1)\) can be represented as

\[
I_{xy}^O(r_1) = |E^O_x(r_1)| \cdot e^{[\frac{i\pi}{2} N - 1]} \cdot E^O_y(r_1), \quad N = 1-4,
\]

(5)

where \(E^O_x(r_1) = |E^O_x(r_1)| \cdot e^{i\varphi}\) is the complex field of the object. \(\varphi\) denotes the phase of object. \(N\) represents the number of phase shifts. \(N = 1-4\) correspond to phase shifts 0, \(\pi/2,\) and \(3\pi/2,\) respectively.

Therefore, the phase shifts are incorporated in the non-diagonal elements of the object CP matrix.

The Fourier transform of the cross-covariance function is modulated by the phase shifts as

\[
\text{FT} \{ C_N(\Delta r) \} = \text{DC} + 2I_{xy}^O(r_1) \otimes I_{xy}^R(r_1) + 2I_{xy}^R(r_1) \otimes I_{xy}^O(r_1),
\]

(6)

where FT denotes the two-dimensional Fourier transform and \(\otimes\) represents the convolution operator. The direct current (DC) term, which includes twenty terms, is unmodulated and suppressed to highlight the
second and third terms in equation (6) [25]. These two conjugate spectra, incorporating the phase of object and the modulation of phase shift, are separated by the corresponding reference source \( I_{Rxy}(r_1) \) or \( I_{Rxy}^*(r_1) \). The reference sources remain intact during the phase-shifting.

The phase \( \varphi \) of the polarized source object can be obtained by substituting the intensity in the conventional phase-shifting formula with the Fourier transform of the cross-covariance function as [21]

\[
\tan(\varphi) = \frac{C_4' - C_2'}{C_1' - C_3'}.
\]

where \( \tan() \) is the tangent function and \( CN' = \text{FT} \{C_N(\Delta r)\} \).

3. Experiment

To implement the proposed scheme in figure 1, we design a compact experimental configuration, as shown in figure 2. Linearly polarized light from a He–Ne laser of 632.8 nm is spatially filtered and collimated by a microscope objective (MO), a pinhole (Pin), and a lens (L). A half-wave plate (HWP) is inserted to provide a linear polarized light of 45° with respect to the horizontal direction. The collimated beam illuminates a reflective-type phase-only spatial light modulator (SLM, PLUTO-VIS, HOLOEYE Photonics AG) with a pixel pitch of 8 \( \mu \)m, which is used to impose the phase of object, introduce the phase shifts, and load the phase of reference (digital lens or axicon phase). The SLM modulates only the horizontal polarization component of incident light and hence the vertical component remains unmodulated. This couples polarization and spatial modulation and hence offers an opportunity to accomplish a compact holography scheme. The phase of lens imposed on the SLM contributes to a reference point source at its focal plane. This arrangement helps to remove the carrier wave or reference arm from the traditional Mach–Zehnder interferometer, constructing a simple and compact imaging geometry. All the polarization components from the SLM propagate towards the ground glass (GG, DG05-220, Thorlab, 2 mm thickness) plane and then are scattered by the GG, which is positioned at the focal plane of the digital lens introduced by the SLM. Light from the GG plane propagates to far field. The speckle is formed and recorded by the CCD camera (AVT PIKE F421B) located at \( z = 150 \) mm from GG. The excellent advantage of this setup is that it does not require any optical elements for splitting, rotating, and moving, which strengthens the robustness of the scheme to external vibrations.
4. Experimental results and discussions

The phase maps imposed on the SLM are shown in the inset of figure 2. Each phase map includes a vortex phase and a spherical (lens) phase, which are separated in the transverse plane. This design is wavefront division multiplexing and to form coherent waves at the GG plane. Here the vortex phase (topological charge 1) is the object to be reconstructed, which is incorporated in $E_O(x)$. To realize the four-step phase-shifting, another three object phase maps corresponding to phase shifts $\pi/2$, $\pi$, $3\pi/2$ are also required to impose on the SLM. The tilted spherical phase is used as the phase of reference beam and remains intact during the phase-shifting. This is to solve the problem of phase lost in the intensity correlation method. The spherical phase, which is initially incorporated only in the horizontal modulation component $E_R(x)$ of the SLM, focuses at a laterally separated point on the GG plane. The lateral position depends on the off-axis factor $(x_0, y_0)$ in the lens function $T = \exp\left\{-\frac{i\lambda}{2f}[(x - x_0)^2 + (y - y_0)^2]\right\}$. Here $f$ is the focal length of the digital lens.

Wavefront division multiplexing utilizes the different modulation portions of the SLM. With the help of a polarizer (P) of 45° rotation in front of the GG, only the incident polarization components $E_O(x)$, $E_R(x)$, and $E_R(y)$ propagate towards one spatial location at the GG, but component $E_R(z)$ is spatially separated and focused at an off-axis position on the GG.

Figure 3 shows the flowchart of phase reconstruction from speckles. Firstly, four speckle patterns are recorded by CCD camera. Then, cross-covariance functions of these four speckle patterns are estimated by...
Figure 5. (a) and (b) are the lens phase and axicon phase, respectively, used as the reference light in the experiment. \(d\) is the distance between SLM and diffuser GG in figure 2, where \(d = 220\) mm denotes the GG is positioned at the focal plane of the digital lens on SLM. (a1)–(a3) are the speckle patterns of different distances using lens phase as reference light. The speckle grain size is related to the distance. (a4)–(a6) are the reconstructed vortex phases (topological charge 1) of different distances. (a7) is the difference between (a4) and (a5). (a8) is the difference between (a5) and (a6). (b1)–(b3) are the speckle patterns of different distances using axicon phase as reference light. (b4)–(b6) are the reconstructed vortex phases of different distances. (b7) is the difference between (b4) and (b5). (b8) is the difference between (b5) and (b6).

Figure 6. (a) and (b) are the lens phase and axicon phase, respectively, used as the reference light in the experiment. \(d\) is the distance between SLM and diffuser GG in figure 2, where \(d = 220\) mm denotes the GG is positioned at the focal plane of the digital lens on SLM. (a1)–(a3) are the speckle patterns of different distances using lens phase as reference light. The speckle grain size is related to the distance. (a4)–(a6) are the reconstructed vortex phases (topological charge 1) of different distances. (a7) is the difference between (a4) and (a5). (a8) is the difference between (a5) and (a6). (b1)–(b3) are the speckle patterns of different distances using axicon phase as reference light. (b4)–(b6) are the reconstructed vortex phases of different distances. (b7) is the difference between (b4) and (b5). (b8) is the difference between (b5) and (b6).

Equation (3). Finally, the phase is reconstructed by taking the results of Fourier transform of cross-covariance functions into equation (7). The reconstructed phase of vortex with different topological charges and its ground truth value are presented in figure 4. We test both the integer and fractional order vortex in the experiment. Figures 4(a)–(c) show the speckle patterns corresponding to vortex phase with topological charge 1.5, 2, and 3, respectively (without phase shifts). Figures 4(d)–(f) are the ground truth value of vortex phase with topological charge 1.5, 2, and 3, respectively. Figures 4(g)–(i) are the recovered vortex phases using the proposed method. The experimental reconstruction results in the presence of the diffuser are in a very good quantitative agreement with the ground truth value. We also reconstruct the vortex phase for without scattering case and the corresponding results are shown in figures 4(j)–(l). It is implemented experimentally by removing the GG and moving the CCD to the GG plane in figure 2. The experimental results with and without diffuser are also in good quantitative agreement.

One advantage of the proposed scheme is the flexible modulation of the reference light. In a traditional scheme, the off-axis reference light is introduced by a lens or microscope objective [24]. The diffuser should be placed in the vicinity of the focal plane of the lens or microscope objective to ensure a constant reference wave in equation (3). To break this restriction, we use an axicon phase as the reference beam, as shown in figure 5(b). The axicon phase is able to generate a focal spot with long diffraction-free distance, therefore the position of the diffuser can be flexibly adjusted. Figure 5 shows the comparison of the reconstructed vortex phase using the axicon and lens phase as the reference light. The reconstructed results using the lens phase as the reference light indicate that the vortex phase can be well reconstructed only if the diffuser is placed near the focus \((d = f = 220\) mm, where \(d\) denotes the distance between SLM and GG, and \(f\) is the focus length of the digital lens), and the reconstruction deteriorates with the defocus \((d = 70\) mm/430 mm), as shown in figures 5(a4)-(a6). However, the reconstructed result using the axicon phase as the reference is not affected by the defocus, because of the diffraction-free characteristic of beam with axicon phase, as shown in figures 5(b4)-(b6). To test the performance of the proposed method in unstable environment, we perform the experiment on a platform without vibration-isolation and add a mobile vibration source close to the GG and CCD in figure 2. We use the vortex phase with topological charge ‘one’ as the test object and record 20 sets of speckles in the presence of vibrations during a 6 min measurement. Each set of speckle includes four measurements because of four-step phase-shifting. Three representative points of each reconstructed vortex phase are selected to estimate the stability, as shown in figure 6(a). Figure 6(b) shows the fluctuation of phase value of these three representative points with the number of recording. Although the standard deviations (STD) of the absolute phase value for with external vibrations (without vibration isolation) is slightly higher than for stable environment (with vibration isolation), a good consistency is
Figure 6. The stability of proposed method in presence of vibrations and stable conditions, (a) is the reconstructed vortex phase of topological charge 1. Three marked dots are in black, red, and yellow, respectively, (b) is the fluctuation of phase value of these three marked dots in stable and with external vibrations environment and (c) is the zoom version of the curve in green rectangle in (b).

maintained in these results, indicating that the proposed method is robust to external disturbances. This lies in the coaxial propagation of two orthogonal polarization components, one (horizontal polarization component) as object beam and the other one (vertical polarization component) as the carrier beam.

5. Conclusions

In conclusion, we proposed a new experimental scheme for un-conventional holography based on intensity correlation. This scheme provides a compact, stable, and simple setup. We further explored the application of this scheme in imaging through the diffuser. The proposed method is able to faithfully reconstruct the objects from the far field laser speckle. This compact holography setup solves the problem of twin-images in the in-line scheme. In particular, flexible modulation of the reference light in the proposed scheme provides a potential solution for imaging through a thick scattering medium. Moreover, the proposed method is immune to external vibrations and disturbances.

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