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Enhanced deterministic phase retrieval using a partially developed speckle field

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A technique for enhanced deterministic phase retrieval using a partially developed speckle field (PDSF) and a spatial light modulator (SLM) is demonstrated experimentally. A smooth test wavefront impinges on a phase diffuser, forming a PDSF that is directed to a $4f$ setup. Two defocused speckle intensity measurements are recorded at the output plane corresponding to axially-propagated representations of the PDSF in the input plane. The speckle intensity measurements are then used in a conventional transport of intensity equation (TIE) to reconstruct directly the test wavefront. The PDSF in our technique increases the dynamic range of the axial intensity derivative for smooth phase objects, resulting in a more robust solution to the TIE. The SLM setup enables a fast and accurate recording of speckle intensity. Experimental results are in good agreement with those obtained using the iterative phase retrieval and digital holographic methods of wavefront reconstruction. © 2012 Optical Society of America
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Deterministic phase retrieval (DPR) is a wavefront reconstruction method that uses measurements of the first derivative of intensity along the optical axis to directly recover the phase [1]. DPR has been applied in phase imaging [2], optical testing [3], and electron microscopy [4]. Another reconstruction method, iterative phase retrieval (IPR), uses intensity measurements as amplitude constraints in an algorithm based on a repetitive use of a wave-propagation equation to estimate the phase. A successful phase retrieval, in general, requires both that the intensity patterns be adequately detected and that the axial intensity has significant variance. For smooth phase objects, detecting intensity patterns adequately is difficult due to quantization error stemming from the limited digitization levels in standard 8-bit cameras; generating axial intensity variance is difficult even for large propagation distances. In an IPR technique applied to rough objects [5], the phase can be recovered using multiple axially-displaced speckle intensity patterns. Recently, a spatial light modulator (SLM) was used for IPR using a spread spectrum technique [6] and with a $4f$ setup [7,8] to record the multiple speckle patterns in a fixed camera plane. The SLM (with a switching time in the millisecond range) facilitates a fast and accurate recording of the intensity patterns. However, for smooth wavefronts, the variation (in axial intensity) is so small that an adequate detection remains a difficult challenge. In order to improve the reconstruction of smooth wavefronts via IPR, a phase diffuser is placed in the path of the wavefront, resulting in the formation of an easily detectable speckle field intensity [9]. This speckle field has a special property in that, aside from a scattered-wave component, it also contains an unperturbed-wave component, i.e., a partially developed speckle field (PDSF) [9]. In this speckle field, the unperturbed wave component (which

corresponds to the test wavefront) and the scattered wave component overlap; this increases the variation of axial intensity. A possible drawback of the speckle-based IPR technique is the multiple intensity measurements (usually 20) that are required. The speckle-based IPR technique cannot be used in the investigation of dynamic objects. In contrast to the speckle-based IPR technique, DPR requires only two measurements of intensity. To our knowledge, DPR has not been demonstrated in conjunction with a PDSF and an SLM setup.

In this Letter, we propose a novel DPR technique that uses a PDSF and the SLM setup for enhanced reconstruction of smooth wavefronts. The PDSF facilitates significant variation in the axial intensity and the SLM permits a fast and accurate recording of intensity. Figure 1 shows a schematic of the setup. A plane wave (wavelength, $\lambda = 532$ nm) illuminates a refractive object and the transmitted light forms the smooth test wavefront. The wavefront impinges on a phase diffuser (aperture diameter,

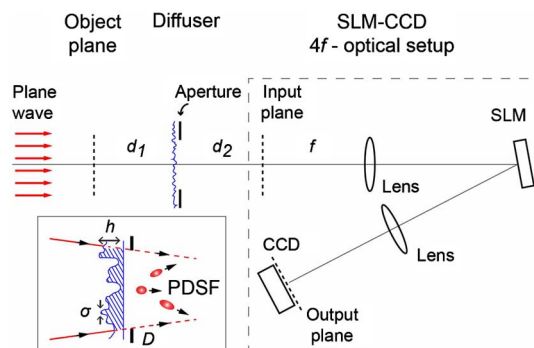


Fig. 1. (Color online) Schematic of deterministic phase retrieval using a partially developed speckle field and a spatial light modulator.

D), forming a PDSF that is then directed to the input plane of the SLM-CCD $4f$ optical setup. This is shown in the square outline. The distance to the diffuser from the object plane is d_1 and from the input plane is d_2 . The parameters λ , D , d_1 , and d_2 are important in sampling adequately the speckle field, and their accuracy of measurement is affected by the camera pixel size ($3.45 \mu\text{m}$) and the Nyquist sampling condition. The inset in Fig. 1 is a schematic for the PDSF formation. The broken lines depict the unperturbed wave (i.e., smooth test wavefront); the oblong shapes depict the perturbed wave.

As different diffusers facilitate different speckle field formations, we distinguish below the suitable diffuser for our setup. If an ordinary ground glass diffuser were used wherein the phase shift range is greater than π , the resultant light would be completely scattered, forming a fully-developed speckle field (FDSF). The FDSF would not be useful in the proposed setup because the unperturbed wave component would be completely destroyed. In our phase diffuser, a photoresist plate (index of refraction, $n = 1.65$) was exposed to a diffused ultraviolet light, leaving random indentations on the surface that diffuse an incident wavefront [9]. It was found that the roughness of the indentations has a mean transverse scale $\sigma = 22 \mu\text{m}$ and a maximum roughness height $h = 0.348 \mu\text{m}$. Under 532 nm illumination, the maximum phase shift at the surface points is 0.85π , thereby facilitating PDSF formation.

We used an optical linear filtering processor facilitated by the SLM [7] to record two axially-displaced speckle patterns. The transfer function for free space propagation is displayed on the SLM; by varying that function we achieved, at the output, propagated representations of the input field. Generally, the optimal propagation or defocus distance for the intensity measurements used in DPR depends on the spatial frequencies present in the phase object [10]. By using a diffuser with known uniform statistics, we are able to optimize the defocus distance. In this study, the first speckle pattern is measured near the input plane and the defocus distance between the planes is 2 mm . The 2 mm distance is considered comparable to the length of the “speckle cigars,” i.e., the axial correlation length of the diffuse field.

For the reconstruction, the two speckle patterns are used in solving the conventional transport of intensity equation (TIE) [1]: $-k\partial I/\partial z = \nabla \cdot I\nabla\varphi$, where $k = 2\pi/\lambda$, φ is phase, I is intensity, and ∇ denotes the gradient operator in the lateral direction only. In order to solve for both phase and amplitude, we use the method described in [1], where an auxiliary function, $\nabla\psi = I\nabla\varphi$, is defined in order to solve a Poisson equation for ψ by an FFT-based Poisson solver of the form

$$\tilde{\psi}(u, v) = \frac{F(u, v)}{-4\pi^2(u^2 + v^2 + \epsilon)}, \quad (1)$$

where $\tilde{\psi}(u, v)$ is the Fourier transform of ψ , $F(u, v)$ is the Fourier transform of $-k(\partial I/\partial z)$, (u, v) are the spatial frequency variables, and ϵ is a small-valued regularization parameter that eliminates a division-by-zero instability [11]. The regularization parameter ($\epsilon = 0.25 \times 10^{-5}$) acts to filter out the high frequency structures corresponding

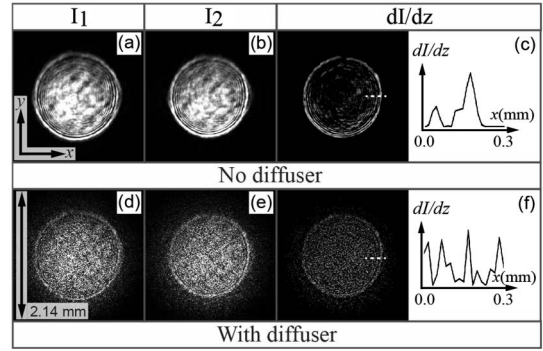


Fig. 2. Intensity patterns and the axial intensity derivative for setups (a)–(c) without and (d)–(f) with a phase diffuser.

to the scattered wave component of the PDSF and also sets a limit to the wavefront details that can be retrieved.

Figure 2 shows the intensity measurements (I_1 , I_2) and the calculated axial derivative (dI/dz). The first row corresponds to the case when there is no diffuser in the setup (i.e., test wavefront-aperture-SLM setup). The second row corresponds to the case when the diffuser is inserted into the setup (i.e., test wavefront-diffuser-aperture-SLM setup). Figures 2(a) and 2(b) show circular patterns due to the regular diffraction at the aperture rim. The nonuniformity in the beam profile is attributed to imperfections in the setup. The focusing effect of the lens object causes the circular diffraction pattern to become slightly smaller in diameter in Fig. 2(b) compared to that in Fig. 2(a). The intensity distributions within the inner central portions, however, are similar. Figure 2(c) (left sub-image) shows the intensity derivative signal obtained after subtracting the two diffraction patterns and dividing the result by the distance between the planes. To investigate the quality of the axial derivative signal, a line scan is performed at the indicated section near the rim (broken line). The magnitude is higher towards the outer portion compared with the inner portion in the scanned section [Fig. 2(c) (right subimage)]. With the diffuser in the setup, Figs. 2(d) and 2(e) show two recorded speckle patterns. The speckle patterns have a prominent low frequency circular diffraction pattern due to the aperture rim. This indicates the unperturbed-wave component. The high frequency intensity modulation, on the other hand, represents the scattered-wave component. The high contrast speckle patterns also exhibit wavefront focusing, as is evident in the slightly smaller circular diffraction pattern in Fig. 2(e) compared to that in Fig. 2(d). The high-frequency structures present in the axial derivative signal [Fig. 2(f) (left subimage)] demonstrate significant intensity variation along the axial direction. The line scan [Fig. 2(f) (right subimage)] exhibits high dynamic range that is maintained throughout the scanned region. Figures 3(a) and 3(d) show the continuous phase maps at the input plane for a setup without and with diffuser, respectively. The phase map in Fig. 3(a) deviates from a circular distribution. The poor reconstruction especially in the relevant inner central portion is due to the lack of variation in the axial intensity.

Figure 3(d), on the other hand, shows the phase map in the aperture area with improved symmetry. Using a

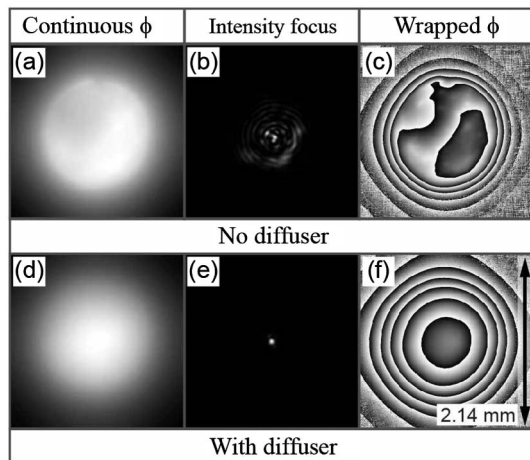


Fig. 3. Reconstructed wavefront phase, focused intensity, and digitally wrapped phase map for setups (a)–(c) without and (d)–(f) with a phase diffuser.

scaled phase map, the complex field is propagated to the known focal plane (140 mm from the input plane) of the lens object. Without the diffuser in the setup, Fig. 3(b) shows the intensity focus that is highly scattered. With the diffuser in the setup, on the other hand, Fig. 3(e) shows a much more accurate intensity focus. Numerical focusing confirms the enhanced DPR using PDSF. To better visualize the phase changes, the retrieved phase maps are digitally wrapped [Figs. 3(c), 3(f)]. The parabolic fringes in Fig. 3(f) correspond to the shape of the refractive lens object used.

Figure 4 shows comparisons of the proposed technique with IPR and digital holography or the interferometric reconstruction method. Here, the experimental control includes a refractive test object (lens, $f = 250$ mm), the phase diffuser (aperture diameter, 3 mm), and the SLM $4f$ setup. Figure 4(a) shows a digital hologram formed with a reference beam facilitated by a beam splitter inserted before the output plane in the setup. The inset shows a zoomed-in section where the holographic carrier fringes are evident. Figure 4(b) depicts a schematic for the multiple-intensity iterative phase retrieval technique using 20 speckle patterns. Here, the distance between adjacent planes is 3 mm and number of iterations used is 10. Figure 4(c) shows the first two speckle patterns being used in the proposed DPR technique. Figures 4(d)–4(f) are the corresponding phase maps of the test wavefront through the diffuser that agree well with each other, confirming the effectiveness of the proposed technique. The filtered phase map in Fig. 4(f) is an effect of the regularization parameter. It is noted that, for digital holography in general, PDSF is not required and may introduce unwanted speckle noise in the reconstruction. Here, the PDSF was employed in digital holography only as an experimental control to confirm our results.

In conclusion, we developed a novel technique for deterministic phase retrieval that takes advantage of the spatial features of a partially developed speckle field using a diffuser-SLM setup. We demonstrated that the superposition of the unperturbed and scattered wave

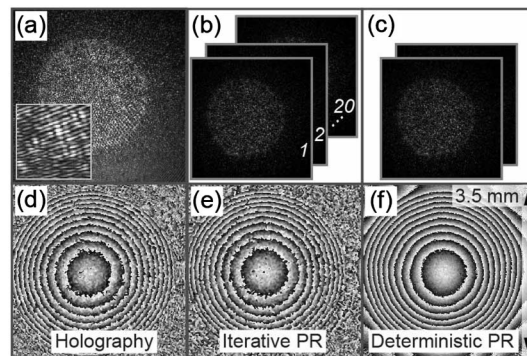


Fig. 4. (a)–(c) Intensity patterns and (d)–(f) phase maps reconstructed using digital holography, multiple-intensity iterative PR, and the proposed deterministic PR technique.

components results in greater variation in axial intensity. This enhances the signal from weak phase objects and gives a more precise value of the axial derivative of the intensity, a value critical in solving the TIE. The experimental results obtained agree well with those obtained using iterative phase retrieval and digital holography. The technique can be applied in phase imaging of unstained biological specimens and in stress analysis of loaded refractive objects.

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