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Single-shot phase retrieval based on axial phase diversity

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ABSTRACT

A single-shot phase-retrieval algorithm based on axial phase diversity using a distorted phase grating is proposed. In this proposed scheme, an image array corresponding to different defocus distances of the object is formed on the fixed and static detector plane and is recorded simultaneously with one camera shot. After the recorded image array is split into separated sub-images, an iterative phase-retrieval algorithm is applied to retrieve the complex amplitude of the object. Compared with the method of multiple recordings, the proposed scheme has the advantages of fast data acquisition and a corresponding high temporal resolution, making it very suitable for high-speed phase imaging or pulsed laser beam diagnosis. Computer simulations are performed to verify the feasibility of the proposed scheme.

1. Introduction

The phase distribution of a light field usually provides more information than the intensity distribution. However, photon detectors such as charge-coupled devices (CCDs) and complementary metal–oxide semiconductors can only measure the intensity of the light field; the phase is lost during the recording process. Phase retrieval [1–6] is a method for recovering the phase information of the light field via intensity measurements with iterative algorithms. It has been widely studied in fields such as crystallography [7], adaptive correction [8], biological imaging [9], and wave-front sensing [10]. The traditional coherent diffractive imaging algorithms [11–16] include Gerchberg–Saxton's G–S algorithm and Fienup's Hybrid Input and Output and Error Reduction algorithms. Although these algorithms have various applications in the fields of material science and biological sample observations, they suffer from disadvantages such as stagnation, low convergence, a limited field of view (FOV), and low reconstruction quality. To improve the performance of traditional phase-retrieval techniques, ptychographical iterative engine (PIE) [17–20] and axial phase diversity method [21–23] were developed. The former records several tens of diffraction patterns or more while laterally scanning the sample with a localized laser beam to a grid of positions, and the latter involves recording multiple diffraction patterns while moving the detector along the optical axis to different positions. Because the information retardation is significantly improved in these two techniques, both PIE and axial phase diversity algorithms are robust with regard to noise immunization and have high reliability. As less frames of diffraction patterns are required, the axial phase diversity method usually has a higher speed than the PIE for data acquisition. Various methods for introducing axial phase diversity have been demonstrated to realize faithful reconstruction [21–23]. Almoro et al. [22] introduced an axial phase diversity method called single-beam multiple-intensity reconstruction, where many diffractions patterns are recorded while the CCD is translated to different positions along the optical path and an iterative phase-

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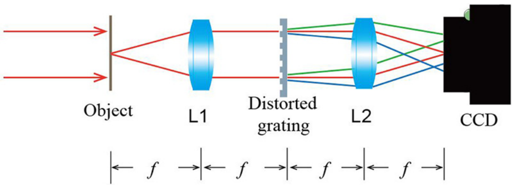

Fig. 1. Line tracing of the single-shot phase-retrieval scheme.

retrieval algorithm is adopted to obtain the phase and amplitude of the object. However, the mechanical shift error of the translation stage may serially degrade the reconstruction. Camacho et al. [23] reported an improved scheme for multiple-plane phase retrieval employing a spatial light modulator (SLM) to replace the mechanical displacement of the CCD detector: a set of lenses with different focal lengths are displayed on the SLM sequentially to generate intensity variation on at a fixed CCD plane, which is equivalent to translating the CCD axially. The reconstruction obtained via this method showed a high degree of correlation with ordinary digital holographic microscopy. However, although replacing the mechanical displacement with the SLM significantly increased the speed of data acquisition, owing to the response time of the SLM and the scheme of multiple measurements, this method still cannot be adopted for high-speed imaging, single-pulse wave-front sensing, etc.

For real-time phase retrieval with axial phase diversity, a single-shot scheme is proposed to realize axial phase diversity using a distorted grating [24–26]. A diffraction pattern array corresponding to various defocuses generated on a fixed camera plane is recorded simultaneously with a single camera shot, and the corresponding reconstruction algorithm is developed to reconstruct the complex amplitude of the sample iteratively. It was demonstrated numerically that a reconstruction error less than 5% can be reached within 50 iterations using 3 × 3 diffraction patterns. As a real-time phase-retrieval technique, this proposed scheme can generate faithful reconstruction with both the fast data acquisition and rapid reconstruction. The effectiveness of the proposed scheme is demonstrated by computer simulations; thus, it can find many applications where high-speed phase imaging is required.

2. Methods

The optical setup of the proposed scheme is shown in Fig. 1. An object placed at the front focal plane of L1 is illuminated by a collimated laser beam. The existing object wave passes through L1, is split by the distorted phase grating placed at the confocal plane of L1 and L2, and finally reaches the CCD after passing through L2. The distorted phase grating is carefully designed. It is combined with a set of superposed multi-focal off-axis Fresnel lenses and a two-dimensional grating. As indicated by the light rays drawn in Fig. 1, images on the CCD plane corresponding to different orders of the grating are defocused with different distances. For clarity, only the 0^{th} and $\pm 1^{\text{st}}$ orders are shown in Fig. 1.

The distorted grating is designed and optimized using the weighted Gerchberg–Saxton (GSW) [27] algorithm, which is commonly used for generating optical trap arrays [27,28] in Holographic Optical Tweezers [29–32]. Fig. 2 shows the wave propagation from the grating plane to the front focal plane of the lens, where j and m represent the index of the pixel and the diffraction order, respectively; (x_m, y_m, z_m) represents the coordinates of order m; and x_j, y_j, are j^{th} the pixel coordinates of the grating. According to Ref. [27], the complex amplitude of the wave field at the j^{th} pixel of the grating plane is

$$u_j = |u| \exp(i\phi_j), \tag{1}$$

where λ is the wavelength, f is the focal length of the lens, and ϕ_j is the corresponding phase shift at the j^{th} pixel of the grating. The complex amplitude v_m of the wave field at the position of order m is obtained by summing the contributions from all of the pixels of the grating:

$$v_m = \sum_j |u|\ e^{i(\phi_j - \Delta_j^m)}, \tag{2}$$

where

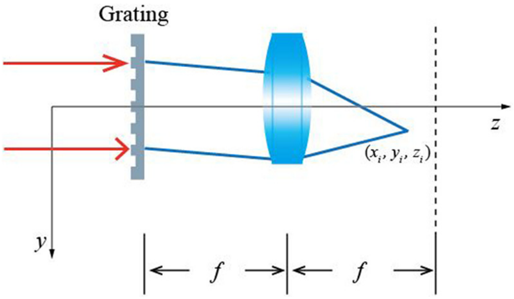

Fig. 2. Schematic of wave propagation from the grating plane to the front focal plane of the lens.