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A method of solving tilt illumination for multiple distance phase retrieval

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ABSTRACT

Multiple distance phase retrieval is a technique of using a series of intensity patterns to reconstruct a complex-valued image of object. However, tilt illumination originating from the off-axis displacement of incident light significantly impairs its imaging quality. To eliminate this affection, we use cross-correlation calibration to estimate oblique angle of incident light and a Fourier-based strategy to correct tilted illumination effect. Compared to other methods, binary and biological object are both stably reconstructed in simulation and experiment. This work provides a simple but beneficial method to solve the problem of tilt illumination for lens-free multi-distance system.

1. Introduction

Iterative phase retrieval has evolved into a tool to recover a complex-valued image by algorithmic post processing, providing a detailed visualization of material and biological specimen [1–5]. Fundamental to progress in these algorithms has sparked a revolution in the application of astronomy [6], super resolution [7], electron microscope [8], 3D imaging [9–12], and optical encryption [13–16]. Traditional methods, such as GS algorithm [2] and hybrid input-output algorithm [3] both require a finite object support. Also, the sensitivity to initial guess and slow-rate convergence limit further application of these methods. To tackle this problem, multi-image phase retrieval methods are created by means of measurement diversity in the recording plane [17–21].

The key of high-rate convergence for iterative phase retrieval lies on how much the recorded intensity distribution differentiates. As the measuring number of appreciable diffraction patterns goes up, the convergence speed of multi-image phase retrieval will be highly enhanced. As a representative modality of multi-image phase retrieval, ptychographic iterative engine (PIE) algorithm [17] reconstructs full complex amplitude with a series of overlapped diffraction patterns, which are obtained by a scanning pinhole across the sample. After many years of attempts, PIE algorithm is well developed into a useful imaging technique, and thus has formed a set of improved methods so that it can be applied in extended object [22], single-shot measurement [23], partially coherent illumination [24] and wavelength scanning [25]. Different from lateral scanning, multi-image phase retrieval is also workable while using other measurement strategies, including multi-wavelength [26,27], tunable lens [28,29], random coded mask [30], multiple distance [18,20,31], and spatial light modulation [32], which are proved to have good recovery of both amplitude and phase in reality. For aforementioned measurement strategies, multiple distance measurement takes advantage of low cost and compact implementation, which is successful to be used in coherent diffractive imaging [33], lens-based system [34,35] and speckle-based imaging [18,36,37].

Until now, multiple distance phase retrieval is composed of two types, namely serial and parallel computing modality. As a representative serial method, the single-beam, multiple-intensity reconstruction technique (SBMIR) algorithm [18] embeds the propagation computation into adjacent recording plane and passes iteratively through every plane at each iteration. On the contrary, the amplitude-phase retrieval (APR) algorithm [20] simultaneously copes with each diffraction pattern by back-and-forth propagation and then averages all computed guesses to produce a new estimation for the next iteration. However, these multiple distance phase retrieval methods [18,20,31,38] are obstructed by off-axis displacement of incident light. Consequent tilt illumination will give rise to the asymmetry of diffraction patterns so that the reconstructed image is to be blurred or even mistaken. A direct approach to avoid tilt illumination is that placing a diffuser upstream from sample to introduce a speckle field for illumination. As is proved in Refs. [39,40], speckle illumination could lead to a unique and stable reconstruction to solve the problem of ambiguity, trivial and nontrivial for phase retrieval. Accordingly, speckle illumination caused by diffuser has been introduced into multi-distance phase retrieval for a unique and fast solution in Refs. [18,36,37]. However, it is a challenge to separate incident speckle pattern from reconstructed exit wave function.

In our previous work [33], a method based on tilt diffraction modality (APRT algorithm) was proposed to solve the problem of tilt illumination and it is demonstrated to retrieve a full complex amplitude of binary sample again. However, APRT algorithm requires to trackback its

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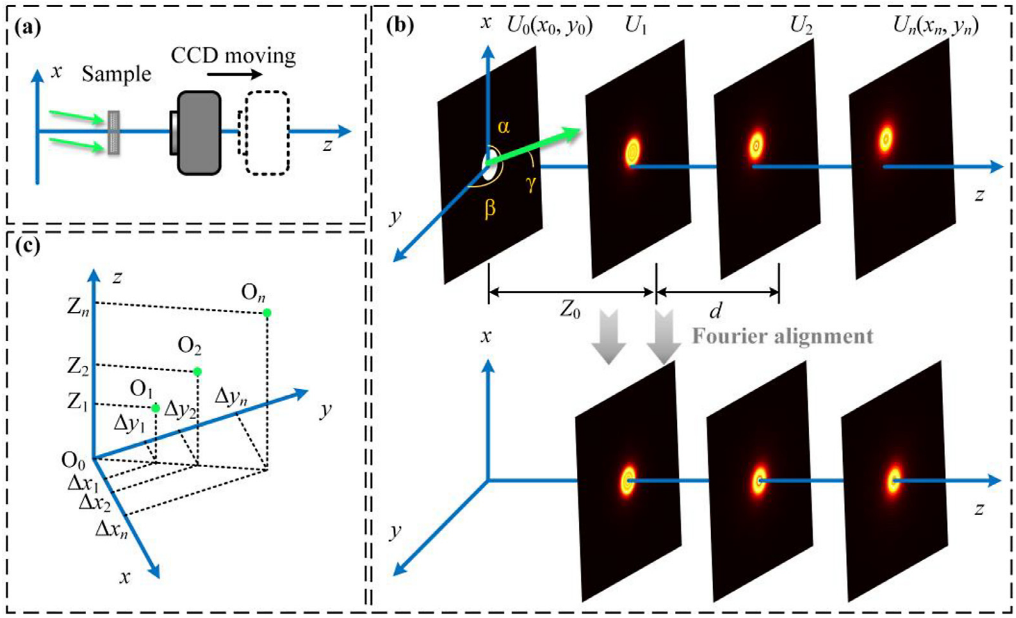

Fig. 1. Tilt illumination and Fourier-based correction: (a) denotes oblique modality to be solved. (b) The schematic of lens-free diffraction model under tilt illumination and its improved method. (c) The geometrical relationship of tilt diffraction.

original diffraction center for computation. With this limitation, APRT algorithm is sensitive to the imaging size of system, i.e., field-of-view (FOV). If the FOV of lens-free system do not cover entire computational area that APRT requires, the retrieved image will be deteriorated on the edge. Especially for a non-isolated sample, the satisfied FOV is so large that the computation are time-consuming and complicated.

Hence it is imperative to find a fast, simple and broad applied method for multiple distance phase retrieval. For this purpose, we use cross-correlation calibration to estimate the oblique angle of light and correct APR with a Fourier-based strategy to realize image reconstruction under tilt illumination. Here APR, APRT, SBMIR algorithm and its improved methods are performed with the built-in tilt illumination. After this correction, the binary and biological objects are clearly and rapidly reconstructed again. Corresponding simulation and experiment are addressed to verify our method.

2. Method

Here we define APR algorithm in free space coherent diffraction field for test and use the recorded diffraction patterns in the downstream of sample to retrieve the object image. In lens-free multi-distance system, tilt illumination is difficult to be eliminated by mechanical operation, and is described in Fig. 1(a), where sample is illuminated by a beam of tilted incident light. In this case, the center of diffraction pattern shifts sequentially as CCD traverses along z axis, which could lead to an unsuccessful reconstruction while the center shifts goes beyond given threshold. Here our correction aims at the situation of Fig. 1(a).

Off-axis displacement of incident light could give rise to an oblique angle for illumination. Let us consider the modality of tilt illumination in Fig. 1(c). In scalar diffraction, if sample positioned in z = 0 is illuminated by plane beam with an oblique angle and the receiving plane is perpendicular to z axis, the exit wave function of sample is expressed as $U_0 = U_s \exp[\mathrm{j}\frac{2\pi}{\lambda}(x_0\cos\alpha + y_0\cos\beta)]$, where U_s is object function of sample. The symbols α and β denote the oblique angle of incident light corresponding to x, y axis. The receiving planes are placed at the back of sample with an initial distance Z_0 and interval d. After traversing a distance of $Z_n = Z_0 + (n-1)d$ by a free space diffractive transfer function $H_F(f_x, f_y) = \exp\{\mathrm{j}kZ_n[1 - \frac{\lambda^2}{2}(f_x^2 + f_y^2)]\}$, the receiving signal of nth receiving plane is described as

$$\begin{aligned} U_n(x_n, y_n) &= \mathcal{F}^{-1}\{\mathcal{F}[U_0(x_0, y_0)]H_F(f_x, f_y)\} \\ &= \mathcal{F}^{-1}\left\{\mathcal{F}[U_s(x_0, y_0)]H_F\left(f_x - \frac{\cos\alpha}{\lambda}, f_y - \frac{\cos\beta}{\lambda}\right)\right\} \\ &= \exp\left[\frac{-\mathrm{j}kZ_n}{2}(\cos^2\alpha + \cos^2\beta)\right] \\ &\quad \times F^{-1}\{F[U_s(x_0, y_0)]H_F(f_x, f_y)\} \otimes \delta(x_n - Z_n\cos\alpha, y_n \\ &\quad - Z_n\cos\beta), \end{aligned} \tag{1}$$

where $\otimes$ denotes convolution operation and F represents Fourier transform. Assuming that the receiving plane in the non-tilt diffraction modality is presented as

$$U'_n(x_n, y_n) = \mathcal{F}^{-1}\{\mathcal{F}[U_s(x_0, y_0)]H_F(f_x, f_y)\}, \tag{2}$$

the nth receiving plane under tilt illumination is expressed as

$$U_n(x_n, y_n) = \exp\left[\frac{-\mathrm{j}kZ_n}{2}(\cos^2\alpha + \cos^2\beta)\right]U'_n(x_n - Z_n\cos\alpha, y_n - Z_n\cos\beta). \tag{3}$$

Hence the lateral shifts of the nth tilted diffraction pattern are derived into $\Delta x_n = Z_n\cos\alpha$ and $\Delta y_n = Z_n\cos\beta$, whose geometrical relationship is displayed in Fig. 1(c). Note that tilt illumination leads to a shift of diffraction pattern for amplitude and adds an extra distance-based matrix modulation for phase. In fact, the CCD camera merely receives the intensity data and the corresponding phase is lost. Thus, the only impact of tilt illumination on lens-free multi-distance system lies on the lateral shift of diffraction pattern, which could lead to a false recovery for image reconstruction.

Based on this principle, the oblique angles of incident light are easy to be derived from the relative shifts of intensity patterns. Here the relative shifts between intensity patterns are estimated by cross-correlation calibration [31]. The theoretical expression of the relative shift (R_X, R_Y) between adjacent intensity patterns corresponding to interval d is calculated as

$$\begin{cases} R_X = d\cos\alpha_{\mathrm{est}}, \\ R_Y = d\cos\beta_{\mathrm{est}}, \end{cases} \tag{4}$$