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Complex amplitude reconstruction by iterative amplitude-phase retrieval algorithm with reference

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ABSTRACT

Multi-image iterative phase retrieval methods have been successfully applied in plenty of research fields due to their simple but efficient implementation. However, there is a mismatch between the measurement of the first long imaging distance and the sequential interval. In this paper, an amplitude-phase retrieval algorithm with reference is put forward without additional measurements or priori knowledge. It gets rid of measuring the first imaging distance. With a designed update formula, it significantly raises the convergence speed and the reconstruction fidelity, especially in phase retrieval. Its superiority over the original amplitude-phase retrieval (APR) method is validated by numerical analysis and experiments. Furthermore, it provides a conceptual design of a compact holographic image sensor, which can achieve numerical refocusing easily.

1. Introduction

Direct measurement of the wavefront has not yet been achieved due to the insufficient response rate of even state-of-the-art detectors, compared to the electromagnetic frequency of light. However, the phase information plays a significant role in numerous fields, including biological imaging [1–4], X-ray crystallography [5–7], digital refocusing [8] and optical metrology [9–10]. Thus so far, there have been plenty of solutions to the classical issue, so-called phase problem. Among them, the iterative phase retrieval method has been successfully applied because of its less demanding experimental implementation in contrast to interferometry [11] and holography [12] as well as having higher resolution than Shack-Hartmann wavefront sensor [13].

As the commencement of it, the Gerchberg–Saxton (GS) algorithm [14] initially needed the known amplitude distribution at both the object plane and the image plane. Then, Fienup [15] proved that the GS algorithm mathematically is an Error Reduction (ER) algorithm in nature. The requirement of a known object amplitude map can be removed by applying a support constraint. Also, to avoid stagnation in the ER algorithm, he put forward the hybrid input–output (HIO) algorithm by introducing the feedback. Recently, the priori knowledge of a tight support was waived by the shrinkwrap algorithm [16], which updates the support region during iteration from a support estimate with autocorrelation and has been verified in many X-ray single-shot coherent diffractive imaging experiments [17–18].

Multi-image phase retrieval algorithms were proposed [19–22] afterwards. According to the strategy of generating multiple measurements, they can be categorized into two groups: lateral and axial scanning. Ptychography [19,23] is the representative of lateral scanning techniques. As for axial scanning, the single-beam multiple-intensity reconstruction (SBMIR) algorithm [20] and the multi-stage algorithm [21] both serially update the complex amplitude estimates during the iteration. Differently, the APR algorithm [22] copes with the update in a parallel way and employs the average operator, which enhances the noise robustness. Till now, the APR algorithm has been successfully applied in encryption [24,25] and coherent diffraction imaging [26,27]. Besides, the effect of position measurement error [28], experimental noise [29] and tilt illumination [27] has been fully discussed.

To conclude, all multi-image phase retrieval algorithms are reference free, which means they do not demand the known object amplitude distribution. But a reference could effectively avoid the local minimum problem and accelerate the convergence speed. Thus, we consider to take the pattern at the first measuring plane as the ‘object’. Based on the idea, the known ‘object’ amplitude intrinsically included in the multi-image dataset can be utilized to design a new algorithm, which is named after APR with reference (APRr). As is shown below, the known ‘object’ amplitude can actually accelerate the convergence speed and helps acquire reconstruction with higher fidelity, especially for phase retrieval. Furthermore, taking the experimental Poisson noise into account, a weighted estimation formula is elaborated to suppress the noise

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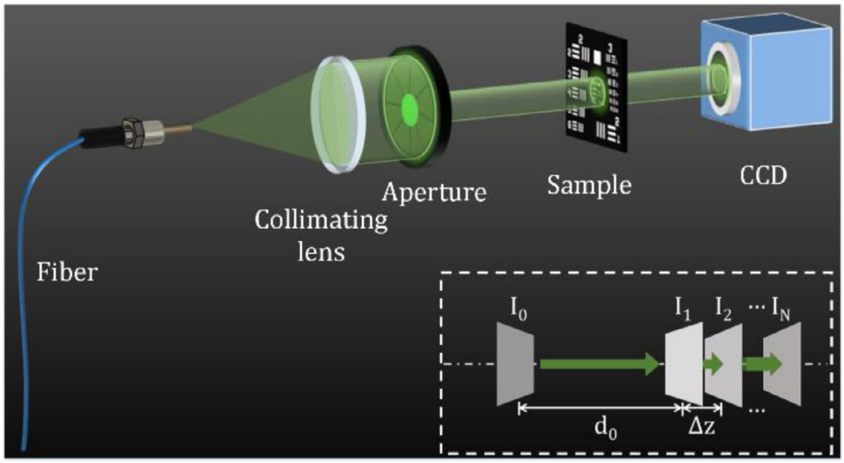

Fig. 1. Schematic diagram of experimental setup and the corresponding simulation model (in the inset box).

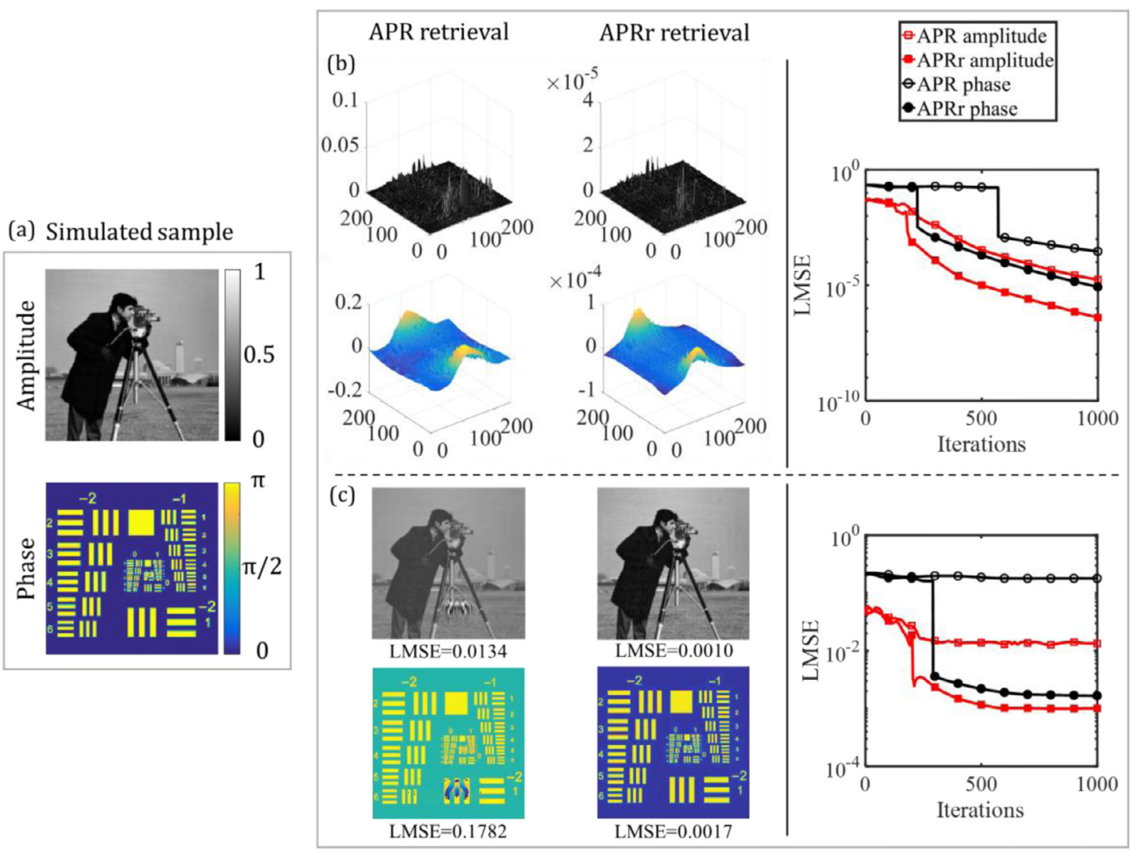

Fig. 2. Numerical analysis of APR and APRr. (a) Simulated complex object; (b) Noise free: error distribution of the final amplitude (upper row) and phase (lower row) reconstructions of two algorithms and their corresponding convergence curves; (c) Poisson noise ($R_{noise} = 10\%$): the final amplitude (upper row) and phase (lower row) reconstructions of two algorithms and their corresponding convergence curves.

effect. Last but not least, the new designed algorithm can realize a prototype of a compact holographic image sensor.

2. Reconstruction scheme

The optical system is illustrated in Fig. 1, which is a basic coherent diffraction imaging (CDI) system. The working wavelength is 532 nm (MW-SGX, Changchun Laser Optoelectronics Technology). Shaped by an aperture, it generates the plane illumination on the sample. Then, a CCD (GS3-U3-41S4M, Point Grey Research) mounted on the translation stage (M-403, Physik Instrumente) moves along the optical axis and several intensity patterns I_1–I_N are recorded. Accordingly, the distance between the sample I_0 and the first measuring plane I_1 is denoted by d_0 with an internal of Δz in sequential measurements, shown in the inset box of Fig. 1.

After the multi-image dataset is acquired, it will be fed into our designed algorithm as follows:

(i) Initialize a random phase guess φ_1 at the first measuring plane and combine it with the square root of the first intensity pattern to obtain the complex amplitude estimate

$$E_1 = \sqrt{I_1} \exp\left(i\varphi_1\right); \tag{1}$$