Ptychography with DMD-based complex-valued probe

Igor Shevkunov[1], Alexandra Georgieva[2], Andrei Belashov[3], Nikolay V. Petrov[2,*]

[1] *Tampere University, Faculty of Information Technology and Communication, Tampere, Finland*
[2] *ITMO University, Digital and Display Holography Laboratory, St. Petersburg, 197101, Russia*
[3] *Ioffe Institute, St. Petersburg, 194021, Russia*
**n.petrov@niuitmo.ru*

Abstract: We propose a new ptychographic algorithm where the object scanning is performed by the complex-valued probe function, formed in the setup of independent amplitude-phase modulation. The results of numerical experiments demonstrate the effectiveness of the proposed approach.

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1. Introduction

Phase retrieval from a set of intensity measurements distributions is a class of inverse problem solution techniques in optics. The methods developed for this area have many applications in all-band optical radiation, from ultraviolet [1] to terahertz [2] and beyond [3]. Ptychography is a powerful approach in phase retrieval which is based on sequential scanning of the object by moving probe function with overlapping. There are a lot of modifications of ptychographic techniques, such as Fourier [4], time-domain [5], vectorial [6]. An aperture is commonly used as a probe function, which can be classified as a binary amplitude type probe function. In this work we propose a ptychography technique with complex-valued probe function formed by independent amplitude and phase modulation using binary digital micromirror device (DMD).

2. Proposed approach and experimental results

The key aspect in the proposed new technique is the use of the method of independent amplitude-phase modulation, implemented by means of a binary digital micromirror device (DMD). Our method has the following advantages: (i) there are no moving optical elements in the optical scheme; (ii) the frame rate of a DMD can reach tens of kHz, which makes it possible to apply it for a wide class of dynamic objects, including biological ones within the short speckle decorrelation time [7]; (iii) Independent amplitude-phase modulation provides the ability to implement a wide range of probe waves, not limited to binary-amplitude ones, including pure-phase and simultaneous amplitude-phase ones.

The optical setup is shown in Fig. 1 (a). A coherent light source with wavelength $\lambda = 800$ nm passing through the beam expander BE illuminates DMD. The consequent $4f$-system with spatial filtering in the Fourier plane forms the probe wave with independent amplitude and phase characteristics from binary DMD-patterns, according to Ref. [8]. Object O is placed in the modulation plane. The implemented dynamic probe scans the object and formed diffraction patterns are registered by the sensor S.

The image reconstruction was performed by means of the iterative algorithm similar to what is published in Ref. [9]. Its basic steps include forward and backward wavefront propagation between the object and detector planes with the replacement of the wavefront amplitude by the square root of observed intensity.

To demonstrate the advantage of the proposed complex-valued probe, we conduct two numerical experiments for the reconstruction of a phase object by the algorithm with the use of amplitude-only and complex-valued probes. In our validation tests, we used a set of scanning patterns with rectangular binary aperture (Fig. 1 (c)) as amplitude-only probes. The efficiency of these probes was compared with the probe-functions containing the same binary aperture together with phase, which has the profile similar to the movable in transverse direction cylindrical lens with a focal distance of 2 mm, shown in Fig. 1 (b). In addition to the DMD, similar probes may be formed in the sample output plane as the result of the noncollinear degenerate phase modulation [10] for the task of the measurement of sample local nonlinear properties [11]. The phase object is modeled as a complex-valued wavefront with uniform amplitude distribution with the absolute transmission and phase distribution corresponding to the yeast cell image of 128×128 pixels scaled to a range of [0, 0.5] radians (Fig. 1 (d)). For simplicity, we assume that the sensor and DMD have the same size of the pixel which equals 3.75μm, the distance between the sensor and object equals 4 mm, the probe width is 29 pixels, and the scanning step is 1 pixel. For proper free space propagation, we perform wavefront zero-padding.

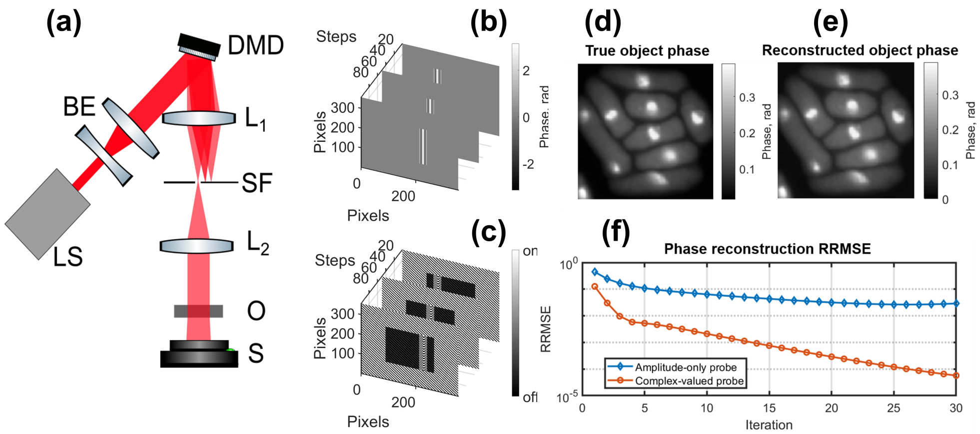

Fig. 1. Experimental setup (a), set of phase (b) and amplitude (c) probe functions; true (d) and reconstructed (e) object phases and phase RRMSE (f).

Figure 1 (e) shows a reconstructed phase from the data recorded with complex-valued probes. Figure 1 (f) demonstrates a relative root-mean-square error (RRMSE) plot of the phase reconstruction depending on the algorithm iteration number: the orange circles' curve is for the reconstruction made with complex-valued probe and the blue diamonds curve is for the amplitude-only probe. The proposed complex-valued probe provides perfect reconstruction imaging supported by the extremely low value of RRMSE below 10^{-4} after 30 iterations, while the amplitude-only probe provides the more erroneous reconstruction and stagnates after the 25th iteration.

3. Conclusion

We have proposed the novel ptychographic experimental setup with DMD independently forming a complex-valued probe. The superiority of the proposed solution has been verified in numerical experiments.

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