

# Twin image elimination from two in-line holograms via phase retrieval

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The reconstruction quality of in-line holography suffers from the superposition of twin images that have different foci but identical information content. We propose a phase retrieval method using two axially displaced holograms and a finite transmission constraint to eliminate the conjugate image. The simulation and experimental results demonstrate a better elimination effect and a faster rate of convergence compared with those of previously reported methods. Two holograms can be recorded simultaneously using two cameras, thus this technique can be used in real-time imaging.

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In-line holography, which originated from Gabor holography<sup>[1]</sup>, is a well-established lensless imaging technique. The hologram is formed by the interference between the beam scattered off the object and the unscattered illuminating beam. Given the simplicity of its recording architecture, in-line holography is a mandatory technique in regions of the electromagnetic spectrum where a separate reference beam is not available<sup>[2,3]</sup>. It is also the preferred configuration in many applications<sup>[4–6]</sup>. However, twin and zero-order images manifest as interference pattern in the reconstruction image, resulting in blurred details and degraded quality of the real image.

This inherent limitation in in-line holography can be eliminated or minimized via digital decoding<sup>[7,8]</sup> or subtraction<sup>[9–12]</sup> using plural holograms recorded at different distances. However, these methods have different drawbacks, such as singularity problem<sup>[7]</sup>, sensitivity to beam fluctuation and uneven recording media<sup>[8]</sup>, restoration of only a part of the complex object<sup>[9]</sup>, weak object beam approximation<sup>[10]</sup>, inability to investigate spontaneous phenomena<sup>[11]</sup>, or object size limitations<sup>[12]</sup>. Phase-retrieval methods<sup>[13–17]</sup> provide another solution to the twin-image problem. By iteratively applying certain constraints on an estimate of an object in real and reciprocal spaces, the real image is separated well from the unwanted twin image interference that accompanies conventional reconstruction. Phase retrieval from multiple axially displaced holograms can improve the precision in quantitative X-ray in-line phase contrast imaging compared with that from a single hologram<sup>[14]</sup>. Zhang *et al.* proposed an approach conducting iterations along consecutive recording planes without imposing any constraint on the object plane. Thus, this method suffers from precarious uniqueness and slow convergence of the phase calculations. Lатычевская *et al.*<sup>[16]</sup> proposed an algorithm using the magnitude of a single normalized hologram and finite object transmission as constraints. This algorithm works well for phase objects and pure absorbing objects.

In this letter, we propose a phase retrieval method for the reconstruction of an object wavefront from two in-

line holograms at different planes. The twin image is eliminated by conducting the propagate back and forth between the object plane and the two recording planes, which in turn allows the reconstructed distribution to reach its true value. Numerical simulations and related experiments were then conducted to validate the feasibility of the method.

The iterative process of the proposed method consists of four steps: 1) the reconstruction starts by assuming a constant value as the initial constant phase. This phase is combined with the square root of the normalized hologram (amplitude) by dividing the hologram in the first sampling plane by its corresponding background image<sup>[7,16]</sup> to yield the complex amplitude at this plane. It can be propagated back to the object plane using the angular spectrum propagation (APS) integral, which is valid for short-distance propagations and keeps the image size constant when the reconstruction distances change; 2) the amplitude of the wavefront in the object plane due to the positive absorption of the object should not exceed 1. The emerging negative absorption on the object plane is the result of the interference between the twin image and the reference wave. To eliminate the twin image, amplitudes larger than 1 in these regions should be replaced by 1, and the corresponding phase values should be set to 0; 3) the object wavefront propagates forward to form the complex amplitude in the second recording plane. The phase obtained from the propagation is extracted and combined with the normalized amplitude at the second recording plane. The updated complex amplitude is then propagated back to the object plane; 4) the new complex amplitude in the object plane is modulated using the same constraint as that in step (2) and propagates forward to the first recording plane. The amplitude is replaced with the square root of the normalized hologram at that plane, whereas the phase distribution is extracted and used as the input value for the next iteration starting at step (1). The accuracy of the reconstruction is updated and corrected during the iterations. Further iterations eventually lead to the elimination of the twin image.

To validate the feasibility of the proposed method, we

simulated the reconstruction of an in-line hologram using a two-dimensional (2D) complex object with a constant absorption of 40% of the incident coherent beam and a constant phase shift of  $\pi/4$  at the 660-nm wavelength. The sizes of the planar wave beam and the complementary metal-oxide semiconductor (CMOS) sensor were both  $1024 \times 1024$  pixels, with a pitch of  $6.7 \times 6.7$  ( $\mu\text{m}$ ). Two holograms were numerically formed at distances of 140 and 150 mm away from the object, respectively, and reconstructed via both the conventional method and our proposed method.

The methods in Refs. [15] and [16] were also used for comparison. The former performed iterations among three axially different recording planes, whereas the latter conducted iterations back and forth between the object plane and the recording plane 150 mm away. For easy comparison, an additional hologram at a distance of 160 mm was used in the method in Ref. [15], and two iterations were counted as one in the method in Ref. [16]. The results are shown in Fig. 1. The structure of the reconstructed images obtained via the conventional method (Fig. 1(a)) is fuzzy and distorted because of the contamination of the twin image. The line scan of the retrieved images (Fig. 1(b)) shows that after 100 iterations, the twin image has been completely removed, and the reconstructed field has reached its predefined value; the same results are not obtained using the two other methods.

The convergence rate of the algorithm can be monitored in the iterations using the mean square error (MSE), which is defined as

$$\text{MSE}^n = \frac{1}{M \times N} \sum_{\substack{\xi=1 \dots M \\ \eta=1 \dots N}} [\rho^n(\xi, \eta) - \rho_0(\xi, \eta)]^2, \quad (1)$$

where  $\rho(\xi, \eta)$  is the retrieved distribution,  $\rho_0(\xi, \eta)$  is the original distribution of the object wavefront, and  $N$  and  $M$  are the matrix sizes of the object domain. A comparison of the convergence rates is shown in Fig. 2. Compared with previous methods, the proposed approach has a faster rate of convergence and yields better elimination results for the same number of iterations.

A demonstration experiment was performed. A plane wave derived from a 660-nm semiconductor laser source passed through the object (positive USAF resolution chart, Edmund Scientific). Three holograms were recorded at 118, 128, and 138 mm downstream of the object using a CMOS sensor with the same parameters as the simulation. The corresponding backgrounds were also recorded under the same conditions but without the object. Figure 3 shows the reconstruction results using the proposed method and the methods in Refs. [15] and [16]. Only the first two holograms were used in the proposed method; the second hologram was used in the method in Ref. [16], whereas all three holograms were used in the method in Ref. [15]. The residual fringes disappeared, and the complex field distribution was accurately recovered by the proposed method after 100 iterations. The correct complex field profile was unattainable using the other methods, and the contrast in the retrieved images was poor even after 200 iterations.

In conclusion, we present an iterative approach based

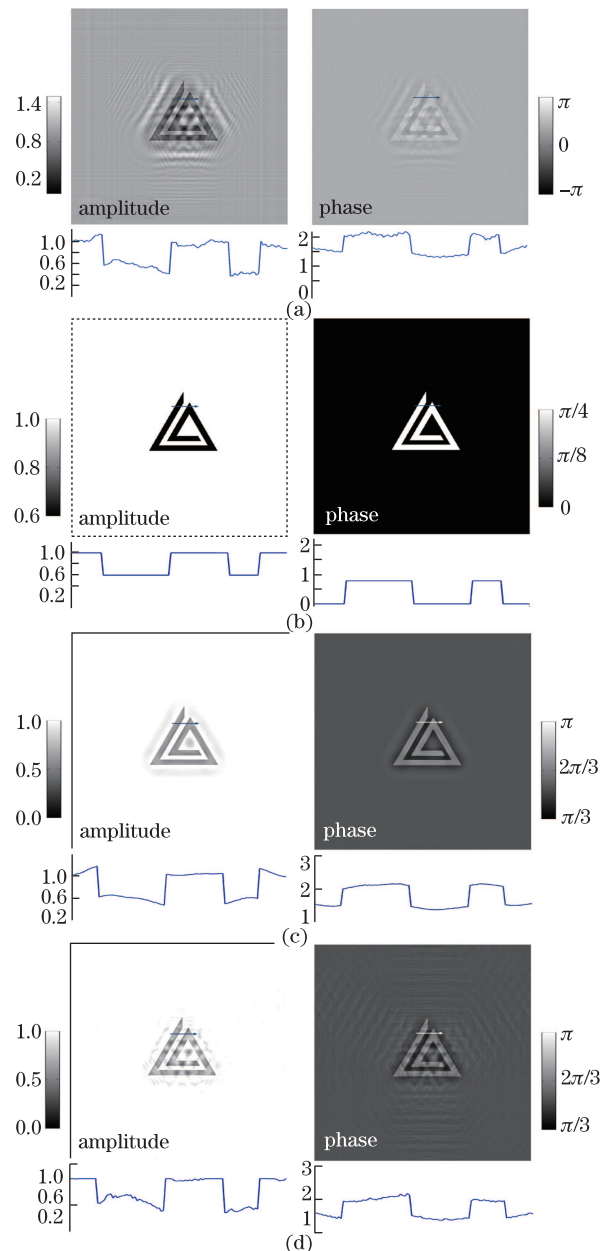


Fig. 1. Reconstruction images of a simulated 2D complex object obtained by using (a) ASP integral, (b) the proposed method, (c) method in Ref. [15], and (d) method in Ref. [16] after the 100th iteration.

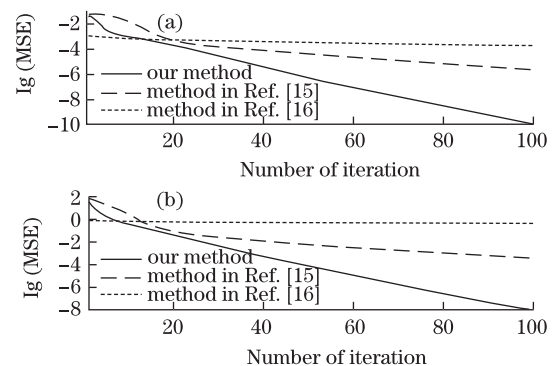


Fig. 2. Comparison of the convergence rates of (a) amplitude and (b) phase reconstructions of the simulated object.

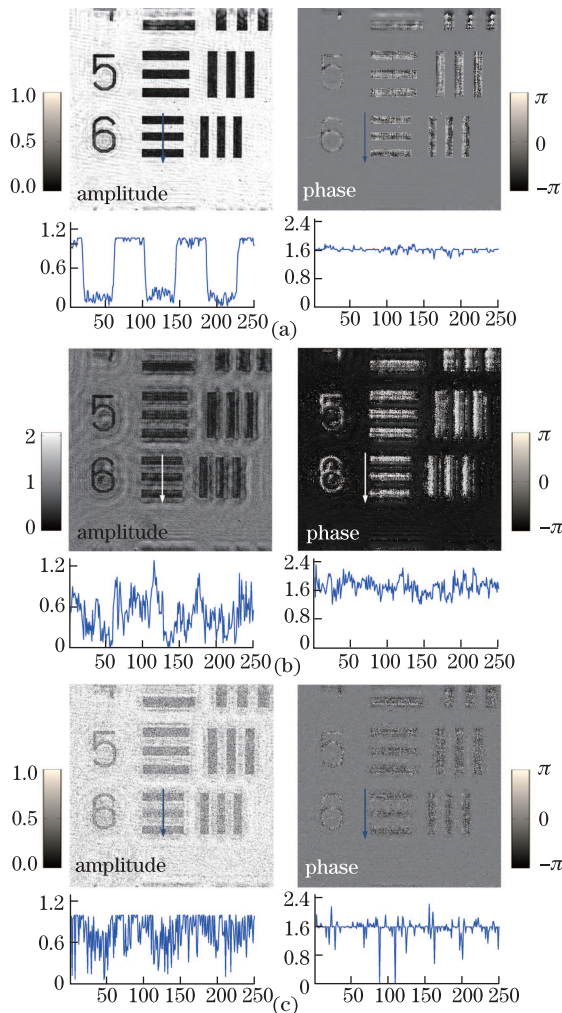


Fig. 3. Reconstructed images of a positive USAF resolution chart obtained by using (a) our method after 100th iteration, methods in (b) Ref. [15] and (c) Ref. [16] after 200th iteration. The dark area in the amplitude image (a) corresponds to the chrome symbol, through which no light passed during the recording process, so that ambiguity may be present in the chrome-coated area in the phase map. The fine fringes present in (a) are attributed to interference fringes caused by glass window above the CMOS chip.

on phase retrieval to eliminate the twin image in inline holography. By using two holograms at different sampling planes and imposing constraints on the object plane, the correct complex field distribution is retrieved at a faster rate of convergence compared with previous

iterative approaches using one hologram<sup>[16]</sup> or multiple holograms without the object constraint<sup>[15]</sup>. No assumptions are made on the object size, absorbance and phase-shifting properties, and its surrounding environment. The effectiveness of the proposed method is demonstrated in both simulation and related experiment. The proposed method requires two holograms at different planes, which can be recorded simultaneously by adding a beam splitter downstream and using two cameras. Thus, the increased acquisition rate, together with the improved reconstruction capability of the proposed method, may be applicable in recording fast phenomena.

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