Diffractive imaging based on a multipinhole plate

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We report on a noniterative method for coherent diffractive imaging based on a specially designed multipinhole (MP) plate. We demonstrated that the complex amplitude of the wavefront penetrating through an MP plate inserted between the specimen and the detector plane can be directly extracted from the Fourier transform of a single far-field diffraction intensity pattern without need of any iterative algorithm. A form of scanning diffractive imaging based on a rotatable MP plate is also demonstrated, which provides a feasible approach for lensless diffractive imaging of complex-valued objects. © 2009 Optical Society of America

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Coherent diffractive imaging (CDI) is one of the most promising techniques for high-resolution imaging of complex-valued objects, because it can retrieve the complex amplitude of the object from diffraction intensity patterns and avoid using high-quality imaging lenses. The CDI technique has been widely applied in the fields in which it is hard to produce high-quality imaging lenses, such as in x-ray-, electron-, or atom-beam situations. In the past decade, a number of successful demonstrations of CDI techniques have been reported, ranging from two-dimensional or three-dimensional nonperiodic nanostructures [1–6] to complicated biological specimens [7].

A common challenge in CDI is to retrieve the complex amplitude information of the object wave from a single or several pieces of diffractive intensity distributions. Iterative algorithms are often used to solve this so-called phase problem [8–10]. However, the conventional procedures usually require a large number of iterations and may not lead to a unique solution. Sampling a diffraction pattern of a specimen more finely than the Nyquist frequency can improve the phase-retrieving process and make the retrieved phase uniquely [1,11]. In recent years some further improved methods for CDI have also been developed, such as ptychographical method [12,13] and phase-front modification method [14]. However, all these methods still need an iterative procedure and intensive computations.

In this Letter, we report on a method that takes advantage of a rotatable plate with some specially distributed pinholes. We demonstrate that, if such a multipinhole (MP) plate is inserted between the specimen and the detector plane, the complex amplitude of the object beam penetrating through the MP plate can be directly extracted from the Fourier transform of a single far-field diffraction intensity pattern without need of any iterative algorithm. This method may be called MP scanning diffractive imaging (MP-SDI), which provides a new approach for wavefront reconstruction, different from the conventional holographic methods and the iterative methods.

Figure 1 shows the schematic of an imaging setup for MP-SDI. A specimen is illuminated by a coherent beam. The far-field diffraction intensity pattern is recorded by an image sensor located at the detector plane. An MP plate is inserted between the specimen and the detector plane. The distance between the MP plate and the detector plane is large enough that we can still record a far-field diffraction intensity of the wavefront penetrating the MP plate. Suppose the transmittance function of a pinhole located at the center of the coordinates system is \( \text{circ}(\vec{r}/R_0) \), where \( R_0 \) is the radius of the pinhole. The complex amplitude of the object wave penetrating through the \( m \)th pinhole (its center is located at the position of \( \vec{r}_m \)) is

\[
A_m = A_m \exp(j\phi_m) \text{circ}(\vec{r}/R_0),
\]

where \( A_m \) and \( \phi_m \) are respectively the amplitude and phase of the object wave sampled by the \( m \)th pinhole. If the radius \( R_0 \) of the pinholes is small enough such that the amplitude \( A_m \) and the phase \( \phi_m \) can be approximately considered as constant in the range of the \( m \)th pinhole area, the far-field diffraction intensity recorded by the image sensor can be expressed as

\[
I_p(\vec{r}) = I_0 \sum_{m=0}^{M} A_m \exp(j\phi_m) \text{circ}(\vec{r}/R_0)^2,
\]

where \( I_0 \) is a constant value associated with diffraction integrals and \( M+1 \) is the number of the pinholes of the MP plate.

Fig. 1. Schematic of the experimental setup for diffractive imaging based on an MP plate.

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For retrieving the complex amplitude from the intensity described in Eq. (1), we further calculate the inverse Fourier transform of the intensity distribution \( I_P(\rho) \) and get

\[
g(\vec{r}) = \Gamma^{-1}[I_P(\vec{\rho})] = \sum_{m=0}^{M} \sum_{n=0}^{M} P_{mn}(\vec{r}) A_m A_n \exp[j(\phi_m - \phi_n)],
\]

where \( P_{mn}(\vec{r}) = \int[\text{circ}(\vec{\alpha} - \vec{r}_m)/R_0]\text{circ}^\ast[(\vec{\alpha} - \vec{r}_n - \vec{r})/R_0] d\vec{\alpha} \). In general, retrieving the complex amplitude of the object wave from Eq. (2) is a difficult task, and an iterative algorithm is often required. Here, we find a way around this difficulty through a special MP plate with some suitably designed pinhole distributions. On this special MP plate, there exist one reference pinhole and many measuring pinholes, and the distribution manner of the pinholes on the MP plate satisfies the following condition: If one MP plate be placed over another of the same MP plates and shifted so that the reference pinhole on the first MP plate is overlapped with any one of the measuring pinholes on the second MP plate, no other pinholes are overlapped at the same time. Figure 2(a) gives one example of such MP plates, where the pinholes are equidistantly distributed in a half ring with spacing equal to or larger than twice the diameter of the pinholes. The end pinhole at the center is the reference pinhole, and the other pinholes are the measuring pinholes. From the geometrical meaning of the correlation in Eq. (2) and the distribution properties of the pinholes on the MP plate, we can deduce that the values of \( g(\vec{r}) \) near the point \( \vec{r} = \vec{r}_m \) are just equal to the correlation integral of the complex amplitudes sampled respectively by the \( m \)th measuring pinhole and the reference pinhole at the coordinate center (corresponding to \( m = 0 \)), and

\[
g(\vec{r}_m) = P_0 A_0 A_m \exp[i(\phi_m - \phi_0)] \quad (m = 1, 2, 3 \ldots N),
\]

where \( P_0 \) is the area of one pinhole and \( A_0 \) and \( \phi_0 \) are respectively the amplitude and phase sampled by the reference pinhole (or the zeroth pinhole). Equation (3) reveals the fact that, if the amplitude \( A_0 \) on the reference pinhole is unequal to zero, the complex amplitudes sampled by our MP plate as shown in Fig. 2(a) can be simply extracted from the corresponding points of the Fourier transform of the far-field diffraction intensity pattern.

Figure 2(b) gives a visual example of the Fourier transform pattern described by Eq. (2) when the MP plate as shown in Fig. 2(a) is adopted. The spots marked by dotted lines in Fig. 2(b), which have the same positions as the pinholes in Fig. 2(a), indicate the points where the complex amplitudes are equal to the correlation integral between the complex amplitudes passing through the corresponding pinholes and the central reference pinhole of the MP plate. Therefore the complex amplitudes at the centers of these spots are directly proportional to the complex amplitudes sampled by the corresponding pinholes, as given in Eq. (3).

Based on the principle above, we can develop the following method for imaging a complex-valued wavefront: (A) insert a rotatable MP plate such as shown in Fig. 2(a) between the specimen and the detector plane, (B) record the far-field diffraction intensity pattern \( I_P(\vec{\rho}) \) of the wavefront penetrating through the MP plate, (C) calculate the inverse Fourier transform \( g(\vec{r}) \) of the intensity distribution \( I_P(\vec{\rho}) \), (D) extract the amplitude \( A_m \) and the phase \( \phi_m \) from the complex value of \( g(\vec{r}_m) \), (E) rotate the MP plate a small angle \( \Delta \theta \) around the central reference pinhole and repeat the steps from (B) to (D), and (F) repeat (E) until the total rotation angle is equal to \( N \Delta \theta = 360^\circ \), where \( N \) is the rotation times.

Using the sampled complex-amplitudes distribution measured by the method above, we then can implement the imaging of the specimen at any distance in a computer, even if the specimen is a complex or three-dimensional object.

In principle, the MP-SDI method could be applicable to many types of coherent diffractive imaging, like imaging using laser light, x-rays, electrons, and atom beams. We demonstrated the MP-SDI method experimentally using an He–Ne laser with a wavelength of 632.8 nm. In our experiment, the test specimen is a transparency of the letters DM with the size of 1.6 mm × 0.8 mm. We designed a series of the pictures of the MP plates with different rotation angles and displayed them on a liquid-crystal spatial light modulator (LC-SLM) in sequence. The LC-SLM used in our experiment has a pixel number of 1024 × 768 and a pixel size of 26 μm × 26 μm with an aperture ratio of 67%. Because each pinhole of the MP plate displayed on the LC-SLM is presented as one pixel, the pinhole size of the MP plate formed on the LC-SLM is about 21 μm × 21 μm. The number of the pinholes on each MP plate is 64 (excluding the central reference pinhole). The MP plate is located about 800 mm downstream from the specimen and adjusted to guarantee a nonzero amplitude passed through the reference pinhole. We recorded 66 far-field diffraction intensity patterns by a CCD image sensor in one scanning cycle, each recorded after rotating the MP plate about 5.5°. Figure 3(a) is one example of these recorded diffraction-intensity patterns. Then we calculated the Fourier transforms of them, extracted the complex values from the corre-
sponding points according to the method above, and assembled them together in the rotation sequence. Figures 3(b) and 3(c) give the measured amplitude and phase distribution of the wavefront on the MP plate, respectively. The enlargement of a small portion in Fig. 3(c) shows the sampling structure of the measured wavefront because of the introduction of the MP plate. Then we can digitally reconstruct the wavefront of the specimen at any distance, making use of this measured complex distribution. Figure 3(d) is a reconstructed image of the measured complex amplitude shown in Figs. 3(b) and 3(c) after backpropagating to the specimen plane.

In conclusion, we have demonstrated our MP-SDI method that completely avoids any iteration procedure. This technique is also suitable for x rays and electron beams, although our demonstration was implemented using visible light, as the preparation or fabrication of the MP plate suitable for x rays and electron beams is realizable in today's microfabrication technique. Furthermore, in the scanning diffractive imaging techniques reported in recent years [12–14], only after multiple diffraction intensity patterns in one scanning cycle having been recorded can the phase-retrieval process start, and an iteration procedure between multiple diffraction patterns must be adopted. In our MP-SDI method, the phase-retrieval process is carried out in each diffraction pattern without involving other diffraction patterns. Therefore we can immediately retrieve the phase as soon as one diffraction pattern is obtained in the scanning process. These advantages not only can eliminate the stringent limitations to the specimen and the experimental setup but also speed up the imaging process, making the realization of real-time coherent diffractive imaging more feasible.

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References

Fig. 3. (a) One example of the far-field diffraction intensity patterns recorded in experiments. (b) Measured amplitude distribution of the wavefront on the MP plate. (c) Measured phase distribution of the wavefront on the MP plate. (d) Image reconstructed by the measured complex amplitude shown in (b) and (c) after backpropagating to the specimen plane.