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Experimental demonstration of scanning phase retrieval by a noniterative method with a Gaussian-amplitude beam

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ABSTRACT

We present a proof-of-principle experiment of an analytic (noniterative) phase-retrieval method for coherent imaging systems under scanning illumination of a probe beam. This method allows to reconstruct the amplitude and phase distribution of a semi-transparent object over a wide area from intensities measured at three points in the Fourier plane of the object under scanning illumination of a known Gaussian-amplitude beam in the object plane. The present measurement system is very simple in contrast to ones of interferometric techniques, and also the speed of the calculation of phase retrieval in this method is faster than that in iterative algorithms since this method is based on an analytic solution to the phase retrieval. The effectiveness of this method is shown in experimental examples of the object reconstructions of a converging lens and a plastic plate for scratch standards.

1. Introduction

In the areas of optical, electron and x-ray microscopy, the imaging system with scanning illumination is utilized in many cases for obtaining the aspect of a large area of a specimen. As a probe that is scanned across the specimen, a coherent beam is frequently used with interferometric measurement systems, because the important information on the specimen is contained in the phase of its transmitted (or reflected) beam. For high-frequency waves such as electrons and x rays, however, the phase measurement by use of interferometric techniques is difficult because, in such waves, a reference wave that is coherent over a wide area is barely obtained and some severe conditions on the system are required when measuring interference fringes.

In the past two decades, noninterferometric methods [1–6], by which, from intensities of a wave field, its phase distribution is retrieved, have attracted considerable attention in the fields of coherent x-ray and electron imaging, and have been applied to imaging experiments for a lot of biological and material samples with a x-ray or electron wave. For example, there are the reconstructions of material [7,8] and biological [9,10] specimens in x-ray experiments and of a carbon nanotube [11] in electron-beam experiments by use of the iterative phase retrieval method [12], and the method based on the transport-of-intensity equation [13] has been applied to x-ray imaging for biological objects [14] and electron imaging for magnetic materials [15]. Recently, in particular, ptychography [16,17] has been used explosively in the field of the coherent imaging with scanning illumination of x-rays [18,19] and electron waves [20]. In the ptychography method, the modulus and the phase of the transmitted wave through a specimen are reconstructed by using an iterative algorithm from a series of diffraction patterns measured under illumination of multiple overlapping regions of a specimen with a probe beam.

On the other hand, we have also proposed twenty years ago another phase-retrieval method with scanning illumination of a known Gaussian-amplitude beam [21,22], by which a complex-valued object with the amplitude and phase distribution can be reconstructed analytically (noniteratively) from intensity data measured at some points in the Fourier plane of the object. So far the effectiveness of this method has been verified only by a computer simulation in one dimension [22]. In this paper, we present a proof-of-principle experiment of our method, by which a two-dimensional complex-valued object function can be reconstructed from intensity data obtained at three points in the Fourier plane of the object with raster scanning of a known Gaussian-amplitude probe beam. The present system of the intensity measurements is very simple in contrast to interferometric techniques, and also the speed of the calculation of phase retrieval is faster than that in iterative algorithms because our method employs an analytic solution to the phase retrieval [23–26]. Two types of objects are reconstructed here: one is a converging lens, and the other is a plastic plate for scratch standards on the market. The experimental results show that the profiles of the reconstructed phase of the lens are in good agreement with theoretical curves and that the reconstructed phase of the plate is in close agreement with that in another experiment by using the

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Fourier transform holography.

In Section 2, we formulate the object reconstruction in two dimensions by using the scanning phase-retrieval method with a known Gaussian-amplitude probe beam. In Section 3, we present experimental examples at optical wavelengths, and assess these performances. Concluding remarks are given in Section 4.

2. Formulation of the scanning phase-retrieval

In this section, we present an extension of the previous one-dimensional (1-D) scanning phase-retrieval method [22] for two dimensions. Fig. 1 shows a schematic diagram of the two-dimensional (2-D) scanning system. A Gaussian amplitude filter $G(x, y)$ is illuminated by a coherent monochromatic plane wave of unit amplitude with a wavelength λ. Then the amplitude of this filter is assumed to be expressed in the form

$$G(x, y) = A \exp\left(-\frac{x^2 + y^2}{2W^2}\right), \tag{1}$$

where A is the central value and W is the 1/e-width of its intensity distribution, which is assumed to be a known constant. The transmitted light through the filter is Fourier transformed by use of lens L_1 of focal length f_1, and then the resultant amplitude distribution $g(u, v)$ is utilized as a probe beam, which is given from Eq. (1) as

$$\begin{aligned} g(u, v) &= \iint_{-\infty}^{\infty} G(x, y)\exp\left[-\frac{2\pi i(ux + vy)}{\lambda f_1}\right] dxdy \\ &= 2\pi A W^2 \exp\left[-\frac{u^2 + v^2}{\left(\lambda f_1/\sqrt{2}\pi W\right)^2}\right], \end{aligned} \tag{2}$$

where unimportant multiplicative constants associated with the diffraction integrals are ignored and u and v are coordinates in the object plane. A thin object of complex-amplitude transmittance $f(u, v)$ is illuminated by the probe beam. Then the object plane is defined as the plane immediately behind the object perpendicular to the optical axis. We here refer to the complex amplitude distribution $f(u, v)$ in the object plane as the object function to be reconstructed. In the present system we scan the object with respect to the probe and measure intensities in the Fourier plane transformed by a lens L_2 of focal length f_2. In the Fourier plane the measureable intensity distribution is given by

$$\begin{aligned} &|h(x', y'; u_o, v_o)|^2 \\ &= \left|\iint_{-\infty}^{\infty} g(u, v) f(u - u_o, v - v_o)\exp\left[-\frac{2\pi i(ux' + vy')}{\lambda f_2}\right] dudv\right|^2, \end{aligned} \tag{3}$$

where u_o and v_o denote the positions of the object with respect to the probe in the directions of u and v axes, respectively. Substituting Eq. (2) into Eq. (3) and combining the Gaussian function and the Fourier transform kernel into one exponential function, we obtain

$$\begin{aligned} |h(x', y'; u_o, v_o)|^2 &= \alpha^2 \exp\left[-\frac{\beta^2\left(x'^2 + y'^2\right)}{2\gamma^2}\right] \\ &\times \left|\iint_{-\infty}^{\infty} g\left(u + i\beta^2 x'/2\gamma,\ v + i\beta^2 y'/2\gamma\right) f(u - u_o, v - v_o)\, dudv\right|^2, \end{aligned} \tag{4}$$

where $\alpha = 2\pi A W^2$, $\beta = \lambda f_1/\sqrt{2}\pi W$, and $\gamma = \lambda f_2/2\pi$. In the present system we reconstruct the object function from three series of intensity data measured at the points of P_0, P_1, and P_2 in the Fourier plane by scanning the object across the Gaussian probe. The coordinates of the points of P_0, P_1, and P_2 are assumed to be $(0, 0)$, $(c, 0)$, and $(0, c)$, respectively, where c is a known constant.

The procedure of the object reconstruction consists of four steps: (1) Calculate 1-D phases of $h(0, 0; u_o, v_o)$ along lines parallel to the u axis from two series of intensity data at the points of P_0 and P_1 in the scanning of u direction ; (2) calculate a 1-D phase along a line parallel to the v axis from two series of intensity data at the points of P_0 and P_2 in the scanning of v direction; (3) retrieve a 2-D phase of the function $h(0, 0; u_o, v_o)$ by adding the calculated 1-D phase in the v direction to the calculated 1-D phases in the u direction as constant phase differences among those 1-D phases; (4) eliminate the effect of the Gaussian probe function from an estimated convolution consisting of the measured modulus (i.e., square root of $|h(0, 0; u_o, v_o)|^2$) and the retrieved 2-D phase of $h(0, 0; u_o, v_o)$, which yields $f(u_o, v_o)$, an estimate of the object. Details of the four steps are as follows.

First, to calculate 1-D phases of $h(0, 0; u_o, v_o)$, we utilize two series of intensities measured at two points P_0 and P_1 as a function of object position (u_o, v_o), which are written from Eq. (4) as

$$|h(0, 0; u_o, v_o)|^2 = \alpha^2 \left|\iint_{-\infty}^{\infty} g(u, v) f(u - u_o, v - v_o)\, dudv\right|^2, \tag{5}$$

and

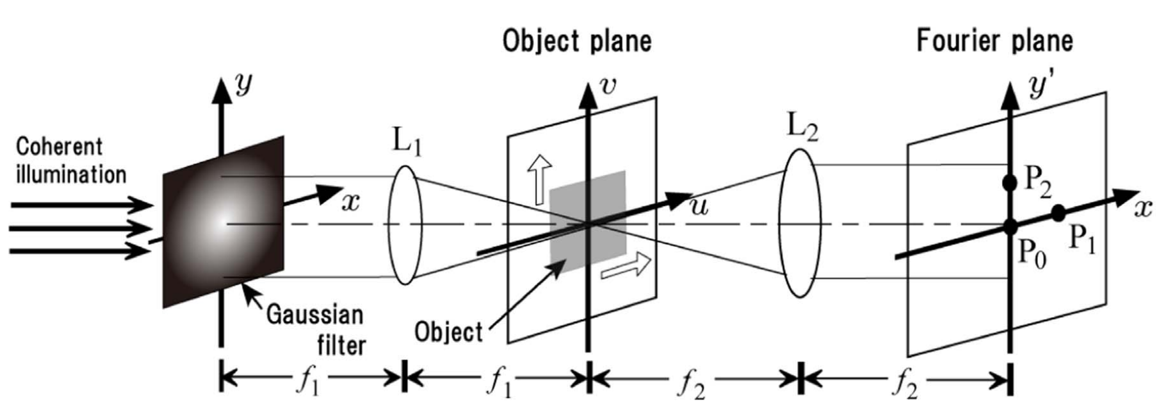

Fig. 1. Schematic diagram of the geometry of the scanning phase-retrieval system with a Gaussian-amplitude beam. The object function is reconstructed from intensities measured at three coordinates in the Fourier plane as a function of the object position.