Boundary-artifact-free phase retrieval with the transport-of-intensity equation from the images obtained with an aperture

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The transport of intensity equation (TIE) [1] is a differential equation that describes the relation between the intensity distribution and phase distribution. The equation can be solved by converting to a Poisson equation [1]. The commonly used FFT based TIE solver [2], however, implicitly assumes a periodic boundary condition, and often gives a huge slowly varying background when a set of the images to be used does not satisfy the presumed boundary condition. Recently, in optics, a TIE-based phase retrieval method with putting an arbitrarily shaped "hard" aperture into the optical wavefield is proposed [3]. In this technique, the TIE can be solved under nonhomogeneous boundary conditions by iterative discrete cosine transforms (DCT). Along this line, we use a selected area aperture placed at the image plane of the objective lens and observe the propagated image wave that passes through the aperture.

Figure 1(a) to (c) show a set of three though-focus images of a 10-micron SA aperture obtained by JEOL ARM-200F with CEOS double correctors operated at 200 kV. The defocus images are obtained by changing the intermediate lens (IL) to observe the propagated wave that passes though the SA aperture. Changing the IL lens to obtain defocused images has another advantage to make the illumination condition same for those images. The defocus step by IL in the object plane was estimated by measuring the lateral image displacement of "diffraction images" of MgO 020 spot for a known number of focal steps [4]. The obtained images are solved by an iterative scheme using DCT for the Neumann boundary condition [5]. Figure 1(d) demonstrates that the phase image retrieved shows a huge phase modulation. This phase modulation is not an artifact, but the curvature of field [6]. The estimated radius of the phase modulation is almost identical to the geometrical estimate.

Comparing to the existing methods, the proposed method is applicable for any types of phase distribution under nonhomogeneous boundary conditions, and thus will facilitate the use of the TIE for quantitative phase characterization in the TEM.

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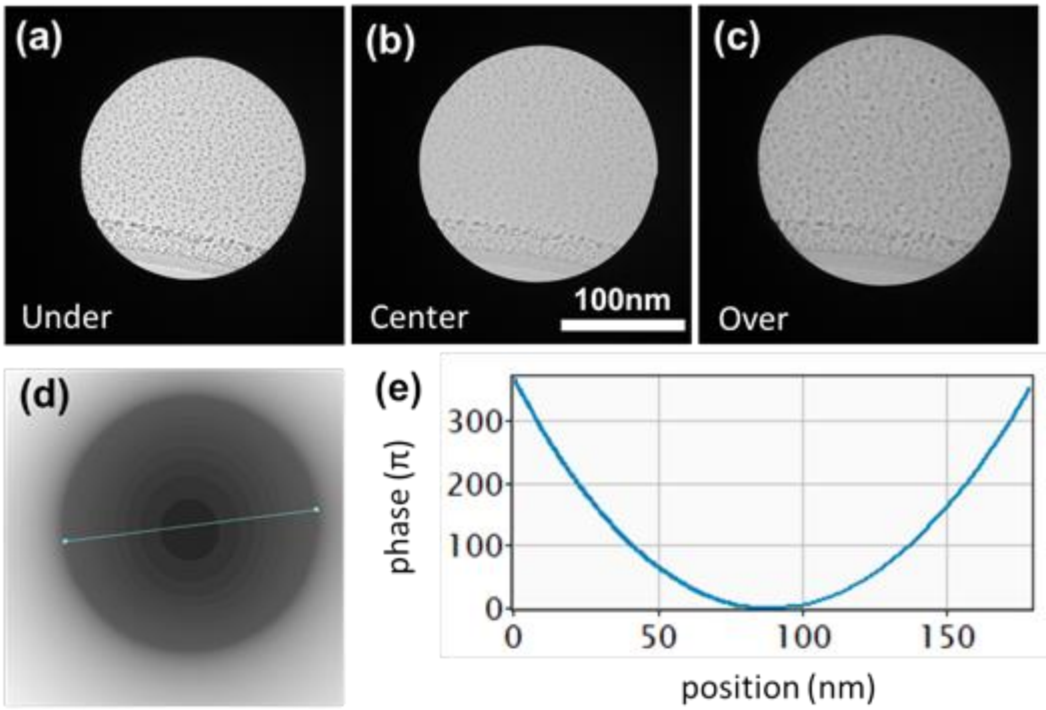

Figure 1. (a) to (c): Experimental images of a selected area (SA) aperture. (d) Retrieved phase distribution and (e) the line profile at the center area.