Optical equivalency of focused probe STEM ptychography and TEM Fourier ptychography

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Thanks to recent developments in electron ptychography, phase retrieval imaging techniques in electron microscopy are currently being implemented in scanning and transmission modes [1 - 3]. The advent of fast electron detection cameras has provided alternative ways of recovering the object wavefunction. Established techniques, like Fourier ptychography acquire a tilt series of images under parallel illumination that record a region of the Fourier space along each tilt direction. Most recently developed methods use focused (or defocused) scanning probes to acquire a coherent electron diffraction pattern at every position in real space. For weak scattering objects, the phase shift induced by the sample to the electron wave provides a quantitative measurement of the specimen potential, information that is lost in the imaging process, where only the intensity of the object function is recorded. Independent on the technique chosen to solve the phase problem, the resulting object wavefunction will depend on the image formation process, as well as the numerical algorithm used for the restoration and the signal-to-noise ratio of the data. Herein, we investigate how the phase restored from two optically equivalent electron ptychography techniques, such as focused probe and Fourier ptychography, compares quantitatively for a graphene object. The comparison aids to our fundamental understanding of the image formation process, and investigates dose-efficiency against information transfer.

According to the principle of reciprocity, recording a coherent electron diffraction pattern at every probe position in scanning mode (STEM) is optically equivalent to recording a tilt series of bright-field images in transmission mode (TEM). Figure 1 shows schematically this optical equivalency for a point object. To record the experimental data a double aberration-corrected JEOL Grand ARM-300F electron microscope equipped with a Medipix3 direct electron detector was used. Two analytical algorithms, based on the single side-band (SSB) approach [1] and the Wiener filter method [3], were implemented to perform the numerical reconstruction. The resulting phase is shown in Figure 2 (a) and (b) respectively, for an equivalent total electron dose. This contribution illustrates how tilt amplitude and probe convergence affect the validity of the optical equivalency, and discusses the main factors contributing to differences in the phase shifts, including contrast transfer function, algorithm efficiency against noise, image registration and evaluation of the aberrations.

[1] H. Yang et al., Nat. Comm. **7** (2016) 12532

[2] A. M. Maiden and J. M. Rodenburg, Ultramicroscopy **109** (2009) 1256

[3] A. I. Kirkland et al. Ultramicroscopy **57** (1995) 355

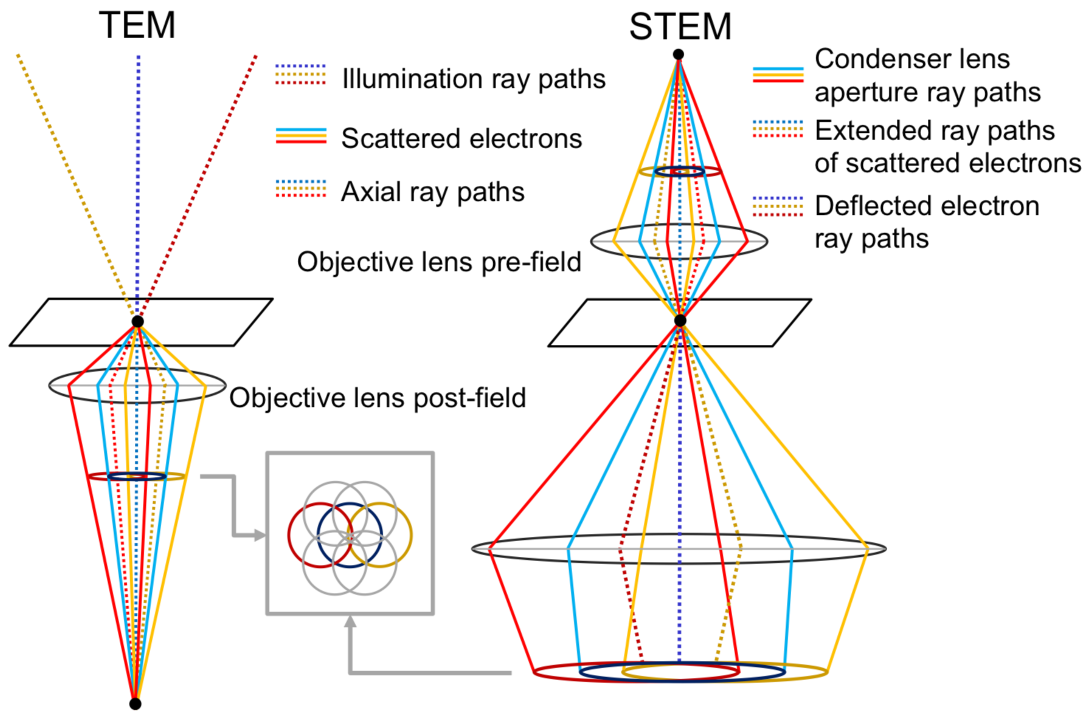

Figure 1. Ray diagram showing the optical reciprocity between tilt series Fourier ptychography and focused probe ptychography.

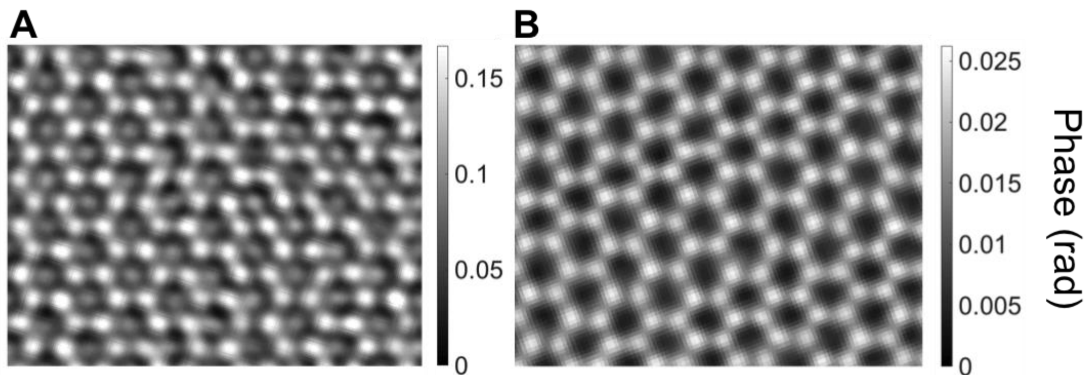

Figure 2. Restored phase of graphene using a tilt-series reconstruction (a) and a SSB restoration (b) for a tilt angle of 16 mrad and a convergence semi-angle of 22 mrad, respectively.