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Optical ptychography with extended depth of field

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Abstract. Ptychography is an increasingly popular phase imaging technique. However, like any imaging technique it has a depth of field that limits the volume of a thick specimen that can be imaged in focus. Here, we have proposed to extend the depth of field using a multislice calculation model; an optical experiment successfully demonstrates our proposal.

1. Introduction

Ptychography is a coherent diffraction imaging technique that can deliver quantitative phase information at diffraction limited resolution [1]. Its conventional implementation requires a coherent illumination of finite extent to be scanned over a specimen at a raster grid of positions and the corresponding diffraction patterns to be recorded by a camera somewhere downstream [2]. The illuminated area between adjacent positions needs to partially overlap, such that redundant information exists in the recorded diffraction patterns. Since only the intensity is detected (the phase information is lost), a phase retrieval algorithm is needed to re-phase the recorded diffraction patterns and reconstruct the complex transmission function of the specimen.

However, ptychography has a limited depth of field; it requires the specimen to be thin enough such that the wavefront that exits the specimen (the exit wave) is accurately approximated by the product of the illumination function and the transmission function of the specimen [2, 3], as shown in Fig. 1a. Under the Born approximation, the depth of field of ptychography is given by Eq. (1) and explained in Fig. 1b [4]:

$$\mathrm{DOF} = \frac{1}{k_z} = \frac{\lambda}{2 - \sqrt{1 - \mathrm{NA}_I{}^2} - \sqrt{1 - \mathrm{NA}_S{}^2}}. \tag{1}$$

Here k_z is the accessible volume along optical axis in reciprocal space, λ is the wavelength of the illumination, NA_I is the numeric aperture of the illumination and NA_S is the numeric aperture of the specimen.

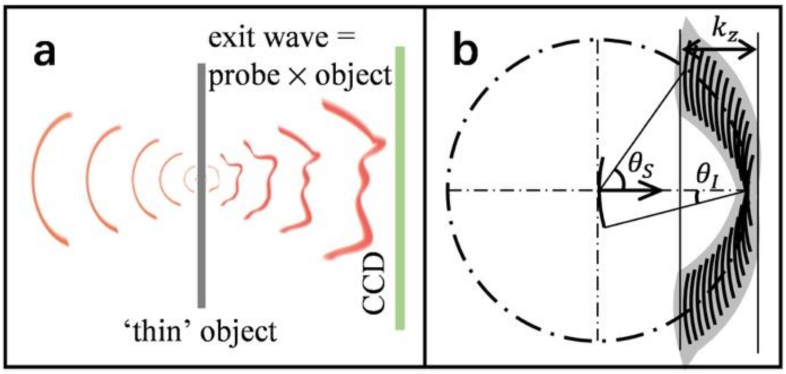

Figure 1. The exit wave formation model for a thin object. (a) The schematic diagram of the exit wave formation of a thin object. (b) The Ewald sphere construction of the configuration in (a). θ_S is the half angle of the specimen scattering angle and θ_I is the half angle of the illumination angle.

When the specimen thickness exceeds this limit, the approximation breaks down and conventional phase retrieval algorithms do not give accurate reconstructions. A computational sectioning model called the multislice method, widely used in electron microscopy [5], can be adopted to circumvent this problem. The method computationally sections a thick specimen into a set of thin slices, each of which allows the formation of its exit wave using the multiplicative approximation [3], as shown in Fig. 2. With modifications of the conventional phase retrieval algorithms [3], all the slices can be reconstructed, giving a three dimensional representation of the specimen.

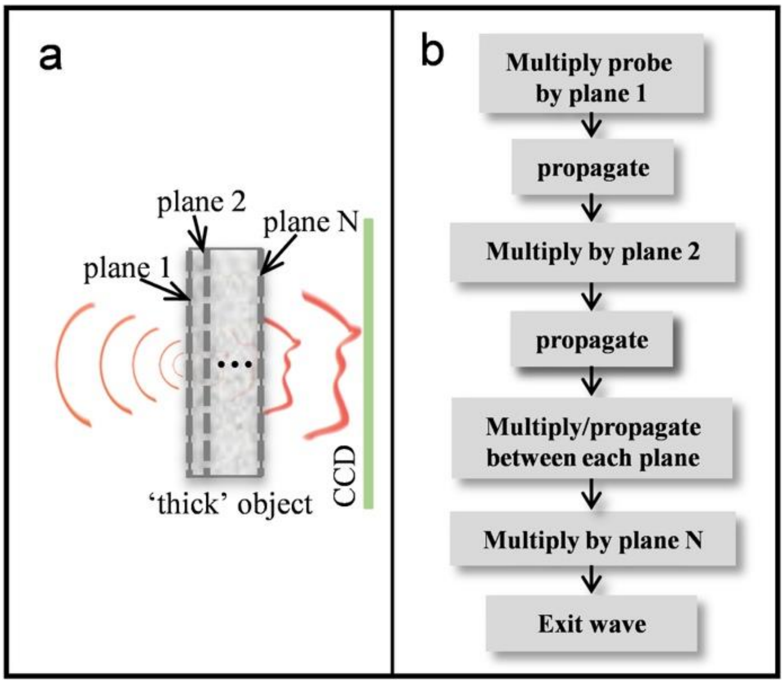

Figure 2. The exit wave formation model for a thick object. (a) The schematic diagram of the exit wave formation of a thick object. (b) The computational model of the multislice calculation.

Instead of pursuing the 3D imaging performance of multislice ptychography, here we demonstrate its ability to extend the depth of field via an optical experiment. This has been demonstrated in x-ray regime [6], although in this case the breakdown of the multiplicative approximation is nowhere near as severe as that in the visible light regime, due to the strong penetration power of x-rays.

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2. Experiment and results

The optical setup is illustrated in Fig. 3a. The illumination source is a 635nm laser diode. The ptychographic scans consisted of a 15×15 raster grid of specimen positions with a nominal 20µm step size, plus ±20% random offsets. The confined illumination was formed by focusing a collimated laser beam via a lens of 35mm focal length. A piece of plastic film was used to increase the angular range of the illumination. An objective lens with a NA of 0.65 combined with a tube lens of 100mm focal length magnified the near-field diffraction pattern onto a CCD detector. The calibrated magnification for our system was 21. The CCD detector had 2048×2048 pixels with a pitch of $7.4\mu m^2$. The distance from the specimen to the virtual CCD plane was set at 0.5mm. The recorded diffraction patterns were binned by a factor of 2 before processing, and an example is shown in Fig. 3b.

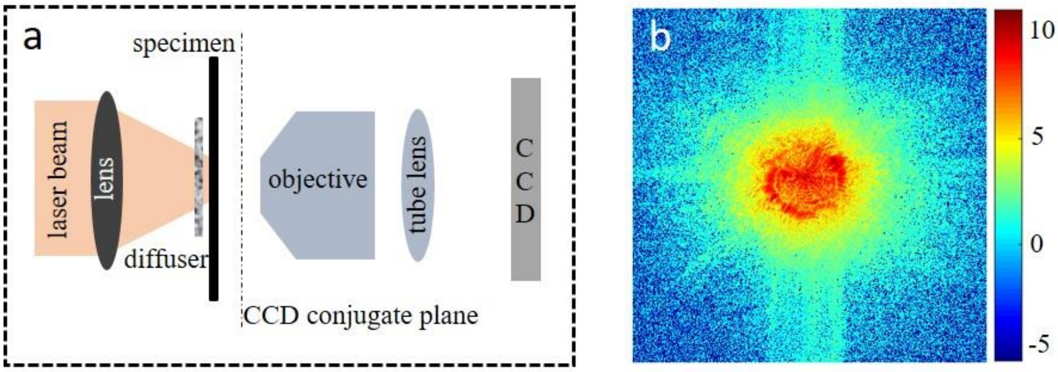

Figure 3. The optical experiment. (a) The experimental configuration. (b) An example diffraction pattern.

The reconstruction was performed by scaling all the diffraction patterns down onto the virtual CCD plane. The propagation between the specimen and the virtual CCD plane was modelled using the angular spectrum propagator [7]. The pixel size of the specimen was equal to the pixel size of the virtual CCD, namely 2×7.4/21=0.70µm. For comparison, an incoherent light microscope image of the specimen (a microscope slide of honeybee mouth parts), taken with a $10\times$ objective (0.25 NA) and focused at the bottom surface of the specimen, is given in Fig. 4a. As we can see, the specimen is quite thick, so there are many out of focus features – this results in a 2D image which is difficult to interpret, because the out of focus light masks the in focus structures.

For the ptychographic imaging, first we tried a reconstruction assuming a single slice in the specimen, which gave the phase reconstruction shown in Fig. 4b. The reconstruction did not completely fail due to the weak scattering of the specimen, however it is blurred and the fine features, such as the bee's hairs, are invisible. Next, we used four slices with equal separations of 33µm in a second reconstruction using the multislice algorithm described in [3], which resulted in the images shown in Fig. 4c. Features at different axial positions are now separated in different slices, although there is still cross-talk between slices. To obtain the 2D image with extended depth of field, we summed up the four phase images, as shown in Fig. 4d. Compared to the single slice reconstruction, the extended depth of field image enables all the features in a thick specimen to be nicely in focus.

3. Conclusions

In this work, we have demonstrated the potential of multislice ptychography in extending the depth of field via an optical experiment. It enables ptychography to image a thick specimen with all the features in focus.

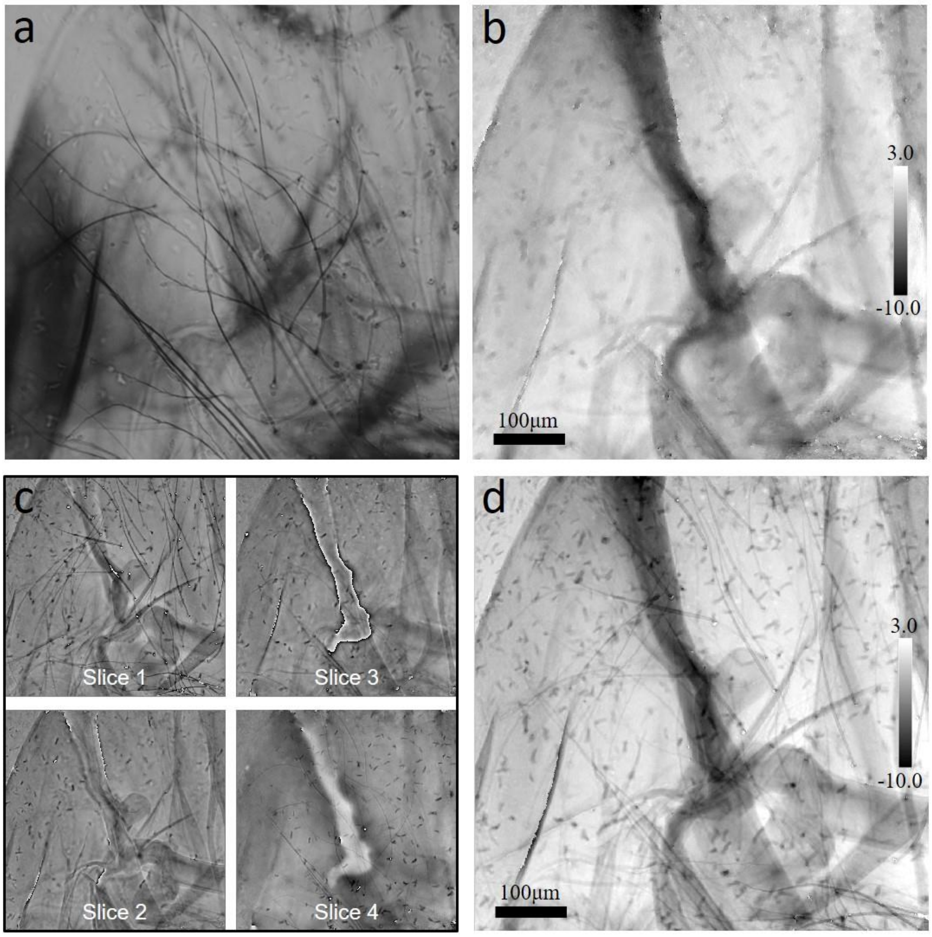

Figure 4. The specimen reconstruction results. (a) The incoherent light microscope image focused on the bottom surface. (b) The ptychographic reconstruction assuming single slice of the specimen. (c) The reconstruction of multislice ptychography using four slices with a constant separation of 33μm. (d) The extended depth of field image by summing up the four slice reconstructions.

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