Phase retrieval of electron wave function with iterative denoising TIE algorithm

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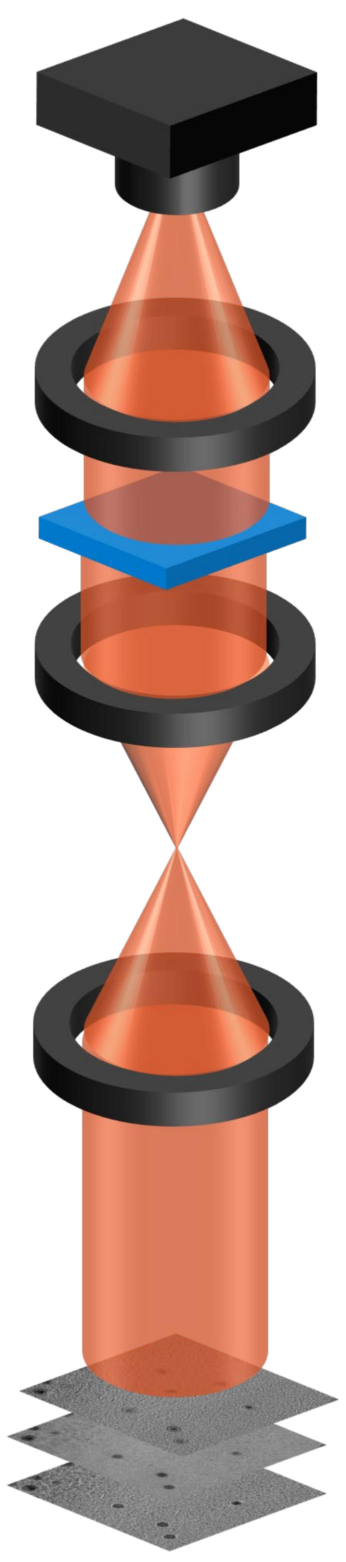
Introduction

Transmission electron microscopy (TEM) is one of the most important tools in investigating the microstructure of materials down to the atomic scale. In TEM, the incident beam energy is usually in the range of 30 keV to 300 keV, much higher than a single atomic Coulomb potential or the material mean inner potential. Thus, no electrons would be absorbed by the sample. In the dominated elastic scattering events, the phase information of the electron exit wave is crucial for resolving the structure of materials. Unfortunately, most traditional cameras can only record intensity information.

Transport of Intensity Equation (TIE) provides an elegant solution for quantitative phase imaging, simply by considering the natural behavior of wave propagation in free space. It means we can retrieve the phase of a wave function with a sequence of intensity images with different defocus in TEM. However, the low-frequency phase information of the sample could be affected in electrons TIE reconstruction by the noise in experiment. Here, we introduce an iterative denoising TIE algorithm to improve the reliability of the low spatial frequencies of the phase.

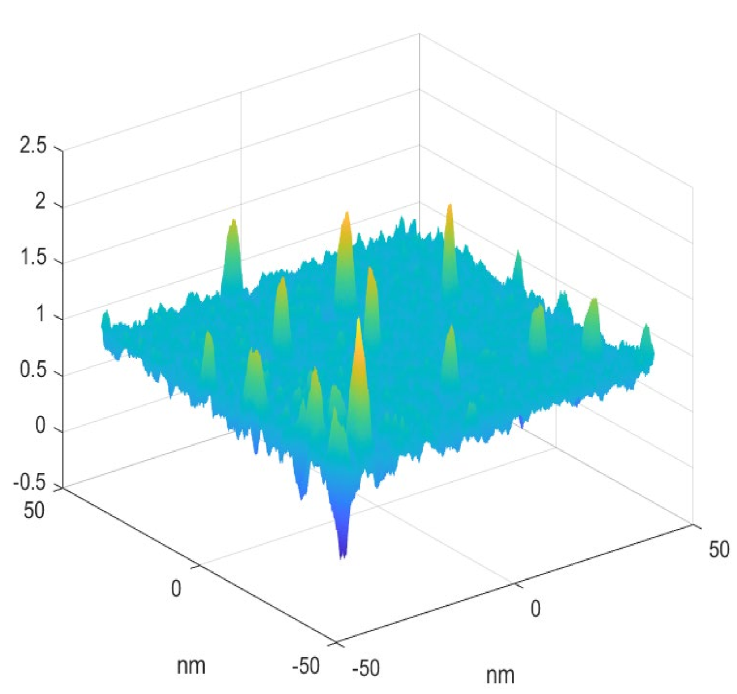


$I = |\varphi|^2$

Image stake

Transport of Intensity Equation

$$-k\frac{\partial I}{\partial z} = \nabla \cdot [I \nabla \phi]$$



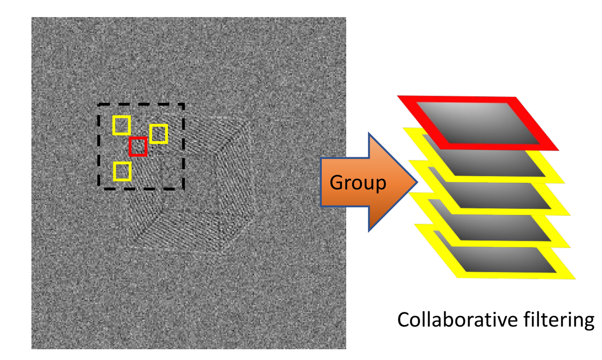
Reconstructed Phase of exit-wave

Flowchart

Use image stake to calculate the axial intensity derivative

↓

Use BM3D algorithm to reduce image noise



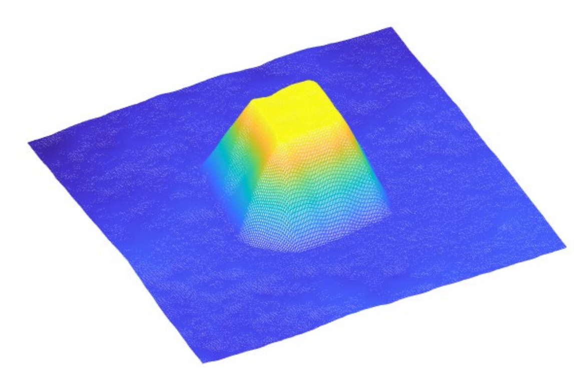
↓

Retrieve phase by FFT-TIE method

$$-k\frac{\partial I}{\partial z} = \nabla \cdot [I \nabla \phi]$$

↓

Converged? — YES →



↓ No

Gradient flipping

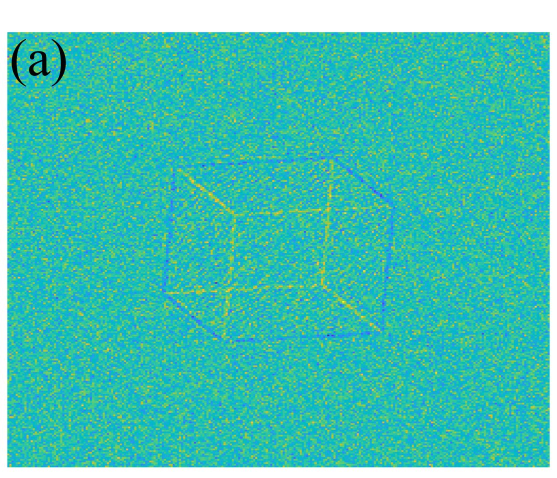
$$\vec{G}'(\vec{r}_\perp) = \begin{cases} \vec{G}(\vec{r}_\perp) & if \|\vec{G}(\vec{r}_\perp)\|_1 > \delta \\ -\beta \vec{G}(\vec{r}_\perp) & if \|\vec{G}(\vec{r}_\perp)\|_1 \le \delta \end{cases}$$

↓

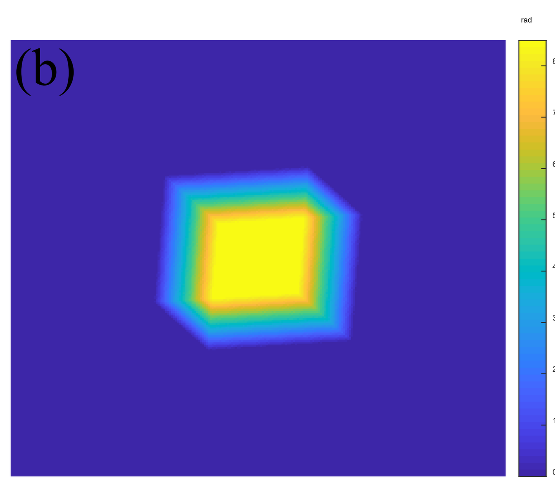
Refresh axial intensity derivative (→ back to BM3D step)

Flow chart of the iterative denoising TIE algorithm

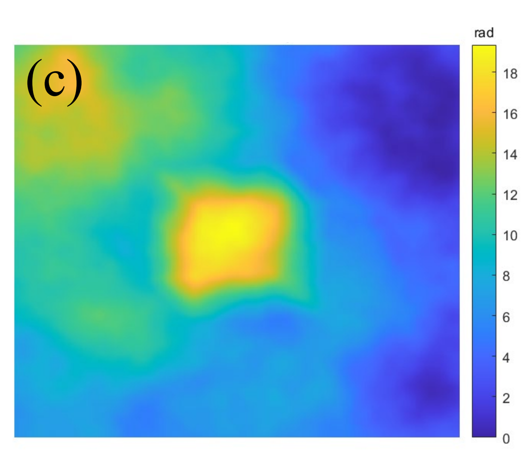
Simulation



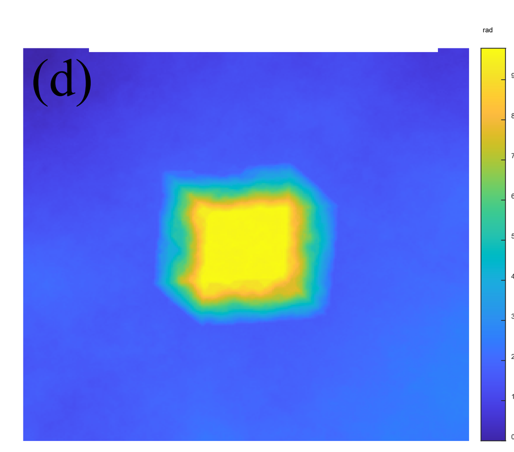
(a) Axial intensity derivative with noise



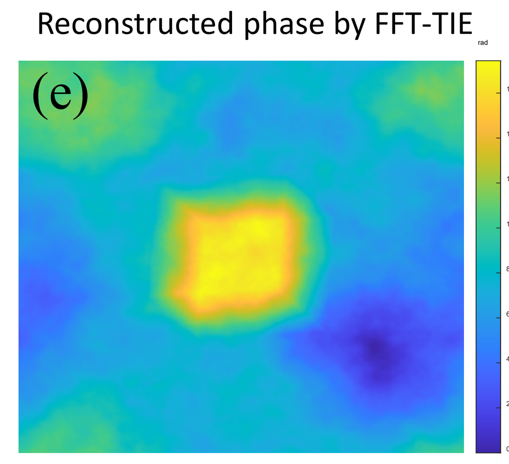
(b) Preset phase



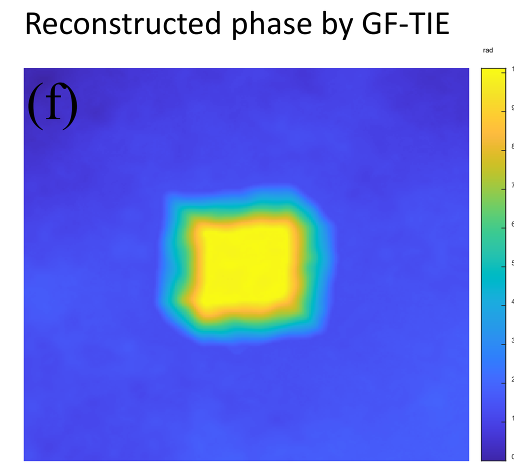
(c) Reconstructed phase by FFT-TIE



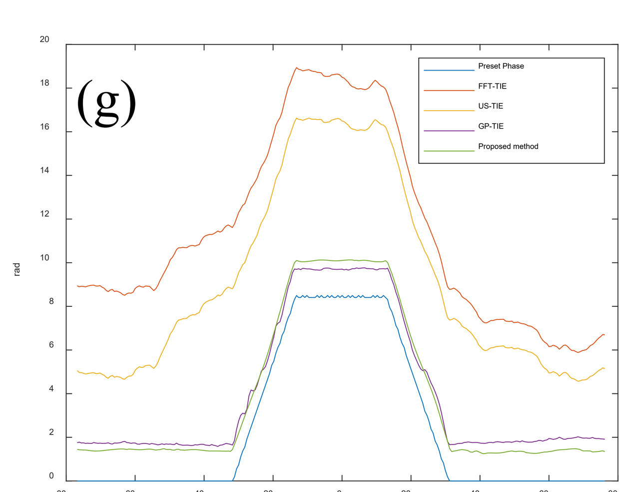
(d) Reconstructed phase by GF-TIE



(e) Reconstructed phase by US-TIE



(f) Reconstructed phase by proposed method



(g) Line profile of Phase(y=0)

Using Different TIE Methods to Retrieve the Phase through a series of MgO simulated TEM Images with noise. Their results are shown in Fig. (c)-(f). And make line profiles of all results at y=0 for further analysis

Conclusion

We propose an iterative denoising phase retrieval method based on gradient flipping algorithm and compare it with other TIE based phase retrieval algorithms in simulation, which proves proposed algorithm can enhances the reliability of the low spatial frequencies of the phase.

Reference

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[2] Dabov K, Foi A, Katkovnik V, et al. Image denoising by sparse 3-D transform-domain collaborative filtering[J]. IEEE Transactions on image processing, 2007, 16(8): 2080-2095..

[3]Teague, M.R., DETERMINISTIC PHASE RETRIEVAL - A GREEN-FUNCTION SOLUTION. Journal of the Optical Society of America, 1983. 73(11): p. 1434-1441.