Single-frame multi-wavelength coherent diffraction imaging using EUV high harmonic comb sources: supplementary material

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1. Quantitative Parameter Comparison

For the coherent diffraction imaging (CDI) experiment, the known conditions mainly come from the collected diffraction patterns. Therefore, when evaluating the reconstruction quality of different CDI algorithms for the same experimental data, the best approach is to compare the reconstructed diffraction patterns during the iterative process with the measured diffraction patterns and calculate the mean squared error (MSE) between them. Figure S1 shows the measured diffraction pattern, the diffraction pattern reconstructed using our novel mw-CDI method, and the one reconstructed using the traditional method. After calculating the MSE, the value for our method is 0.003, while the value for the traditional method is 0.14. The nearly 50-fold difference in MSE demonstrates that our method significantly outperforms the conventional approach. Notably, this comparison focuses on polychromatic diffraction pattern, not on diffraction data for individual wavelengths.

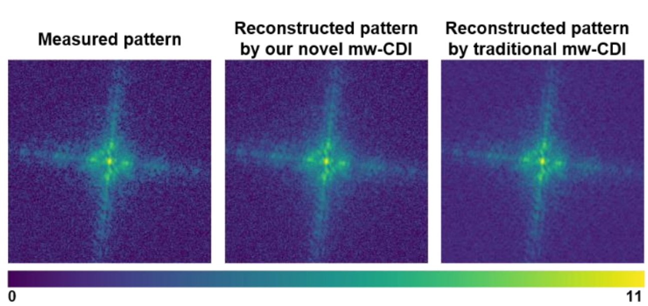

Fig. S1. The measured and reconstructed diffraction patterns.

2. Multi-exposure experiment

Due to the far-field diffraction, the energy distribution in the diffraction pattern predominantly concentrates around the central low-frequency components, whereas the high-frequency components possess significantly lower energy and are thus more susceptible to being buried in noise. Therefore, when imaging static or slowly changing samples, we can employ a multiple exposure strategy to enhance the signal-to-noise ratio (SNR) of the high-frequency components in the diffraction pattern. In our EUV experiment, we recorded three diffraction patterns, each captured from the same sample region with exposure times of 8 ms, 80 ms, and 160 ms, respectively. The three datasets were then combined to retain the high-frequency information from the long-exposure data with the unsaturated low-frequency data from the short-exposure time data, thereby enhancing the dynamic range of the diffraction pattern. It is clear that the multi-exposure diffraction pattern in Fig. S2(b) contains more information compared to the single-shot one in Fig. S2(a). Therefore, the reconstruction from multi-exposure data have higher image quality as shown in Fig. S2(f-h). Additionally, due to the improved SNR, the effective calculation window increased from 1024×1024 to 1200×1200, thereby enhancing the image resolution from 570 nm to 500 nm.

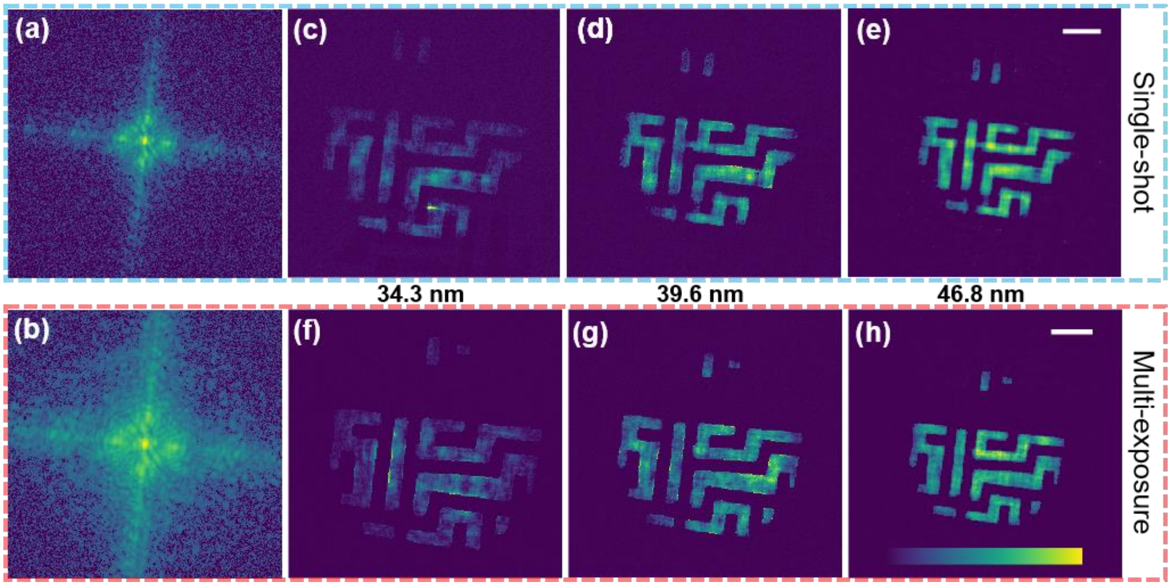

Fig. S2. Comparison of multi-wavelength reconstruction from single-shot and multiple-exposure data. (a, b) The diffraction pattern shown in log scale. (c-e) are reconstructed results using the single-shot data, and (f-h) are reconstructed results using multi-exposure data for different harmonics: 34.3 nm (c, f), 39.6 nm (d, g), 46.8 nm (e, h). Scalar bar: 7 µm.

3. The performance of different algorithms in EUV CDI

Other commonly used iterative projection algorithms in broadband CDI [1,2] were also incorporated into mw-CDI for comparison with our proposed method. Only the reconstruction of the 46.8 nm wavelength among the three wavelengths was presented for comparative purpose, as shown in Fig. S3. The utilization of relaxed averaged alternating reflectors (RAAR) algorithm [3] resulted in a modest improvement of the reconstruction quality compared to the combination of ER and HIO, but it also failed to converge. The DM algorithm can effectively prevent convergence stagnation [4], thus it has found extensive application in CDI to enhance its reconstruction quality [1]. Therefore, we introduced the DM algorithm into mw-CDI, resulting in a significant improvement in reconstruction quality (shown in Fig. S3(b)). However, there are still some ambiguities in the reconstruction. Hence, we combined the ER, HIO and DM methods, preserving the stable convergence characteristics of the ER algorithm while leveraging the ability of the HIO and DM algorithms to deviate from fixed points [2]. Figure S3(c) shows that the novel combined iterative projection algorithm demonstrated excellent reconstruction quality in mw-CDI.

To explore the facilitative effect of our method in monochromatic CDI, we simulated the reconstruction performance of four iterative projection algorithms mentioned above for a complex amplitude object at a single wavelength of 40 nm. Here, we selected the 'cameraman' image (Fig. S4(b)) for amplitude information and the 'liftingbody' image (Fig. S4(c)) for phase information with a phase variation of 1.5π. The RMSE (root mean square error) is employed as an error metric to quantify the reconstruction quality. The convergence curves in Fig. S4(d) show that the combined ER and HIO, along with RAAR algorithms stagnated within 30 iterations; though the DM algorithm converges to a smaller value of 0.058. As shown in the green curve, our method is able to achieve a RMSE of 0.014, indicating it is more effective in escaping local minima, particularly when dealing with complex samples.

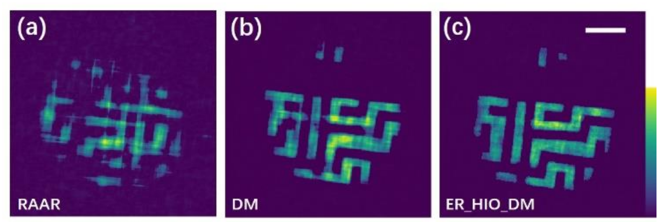

Fig. S3. Reconstruction of multi-wavelength data using different projection algorithms in mw-CDI; results presented for the 46.8nm wavelength only. (a) The mw-CDI failed to converge when using only RAAR. (b) Inclusion of DM algorithm showed significant improvement. (c) A combination of ER, HIO and DM exhibits further improvement showing clearer sample structure. Scalar bar: 8 µm.

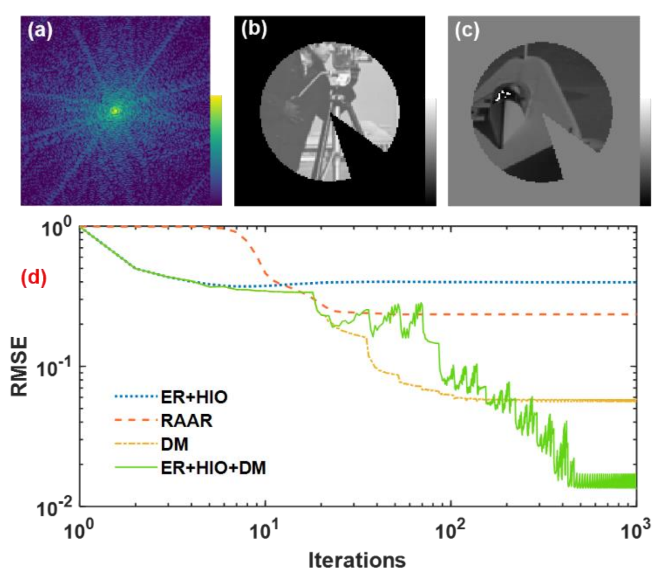

Fig. S4. Simulation of reconstructions using different algorithms under monochromatic conditions for the same dataset. (a) the monochromatic diffraction pattern at a wavelength of 40 nm. (b, c) The amplitude and phase of test sample. (d) The influence of different iterative projection algorithms on the convergence of monochromatic CDI.

References

1. J. Huijts, S. Fernandez, D. Gauthier, M. Kholodtsova, A. Maghraoui, K. Medjoubi, A. Somogyi, W. Boutu, and H. Merdji, Nat. Photon. **14**, 618 (2020).
2. C. Chen, H. Gu, and S. Liu, Light Sci Appl **13**, 9 (2024).
3. D. R. Luke, Inverse Problems **21**, 37 (2005).
4. S. Marchesini, Review of Scientific Instruments **78**, 011301 (2007).