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DELIVERABLE REPORT

WP12 Ja2 X-ray Wavefront Metrology, Correction and Manipulation

D12.5

User Experiment with OAM beam

This initiative has received funding from the EU's H2020 framework program for research and innovation under grant agreement n. 101007417, NFFA-Europe Pilot Project

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DELIVERABLE DETAILS

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D – D12.5	User Experiment with OAM beam

DELIVERABLE DESCRIPTION

Electromagnetic waves with orbital angular momentum (OAM) are increasingly used in optical communications, quantum technologies, and optical tweezers. Recently, they have shown potential for detecting helical dichroic effects in chiral molecules and magnetic nanostructures. In this study, we used single-shot ptychography on a nanostructure with extreme ultraviolet OAM beams of varying topological charge (ℓ) at a free-electron laser. By adjusting ℓ, we improved image resolution by 30% compared to standard Gaussian beams, advancing coherent diffraction imaging and enabling sub-100 nm time-resolved microscopy over large sample areas.

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NATURE

☒ R - Report

☐ P - Prototype

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☐ O - Other

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☒ P - Public

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☐ CO - Confidential, only for members of the consortium

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INTRODUCTION

The first discovery of orbital angular momentum (OAM) in electromagnetic fields was made by Allen et al. in 1992. They demonstrated that light with a spiraling phase structure, described by $\exp(i\ell\phi)$, inherently carries OAM equal to $\ell\hbar$ per photon, where ℓ, the topological charge, is an integer. This breakthrough opened up new research avenues in both fundamental and applied physics. Today, OAM beams are widely used across various fields, including studies of dichroic and chiroptical materials, particle manipulation, optical communications, quantum technologies, and imaging.

In microscopy, OAM beams have shown promise for enhancing edge detection in phase-contrast microscopy and improving spatial resolution. At shorter wavelengths, coherent diffraction imaging techniques like ptychography are regularly used to produce high-resolution images of nanostructures. Ptychography, in particular, is valuable because it captures both transmission and phase contrast images while also providing wavefront-sensing information of the illuminating beam.

In this study, we present high-quality ptychography reconstructions using OAM beams generated by a zone plate at an extreme ultraviolet (EUV) seeded free-electron laser (FEL). We found that the zone plate optics significantly enhance pointing stability, and when combined with the high intensity and wavelength precision of the FEL, allow us to capture detailed single-shot images of a nanostructured Siemens star test object. Notably, we observed that higher topological charge orders improve spatial resolution in the reconstructed images, thanks to the structured illumination provided by OAM beams. This advance pushes the boundaries of coherent diffraction imaging, enabling time-resolved, high-resolution studies of large samples.

THE EXPERIMENTAL SETUP

Figure 1(a) illustrates a typical experimental setup: the scattered beam is measured in transmission geometry, recording diffraction patterns at the detector alongside the sample coordinates. After scanning the selected sample positions, an iterative algorithm reconstructs the object and average illumination that best match the measured scattering patterns.

The imaging capabilities of ptychography with OAM beams were explored at the DiProI beamline of the FERMI FEL. The setup features an active focusing system based on Kirkpatrick-Baez (K-B) mirrors, which were configured as flat mirrors to compensate for the natural divergence of the FEL, producing a near-collimated beam. Nanofabricated spiral zone plates (SZPs) placed in the main vacuum chamber focused the EUV radiation and generated OAM beams. The FEL light, linearly polarized in the horizontal plane with a wavelength of 18.9 nm (65.6 eV), was attenuated using a 500 nm-thick Zr filter, resulting in a pre-focusing fluence of about 0.1 μJ/cm²—well below the SZPs' damage threshold, ensuring long-term stability.

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Motorized piezo stages allowed precise switching between seven SZPs to generate OAM beams with ℓ = 0, ±1, ±2, ±3. An order sorting aperture filtered higher diffraction orders, and a central beam stop blocked the unfocused direct beam. Ptychography scans were performed on a 100 nm-thick hydrogen silsesquioxane (HSQ) Siemens star, patterned on a 200 nm-thick silicon membrane. The Siemens star had a 500 μm outer diameter with 100 nm features near the center, as shown in Fig. 1(b). At each scan point, a single FEL shot illuminated the sample, and the diffracted intensity was captured by a Princeton MTE2048 CCD camera (2048 × 2048 pixels, 13.5 μm pixel size), positioned 140 mm from the sample and operated in 4×4 binning mode.

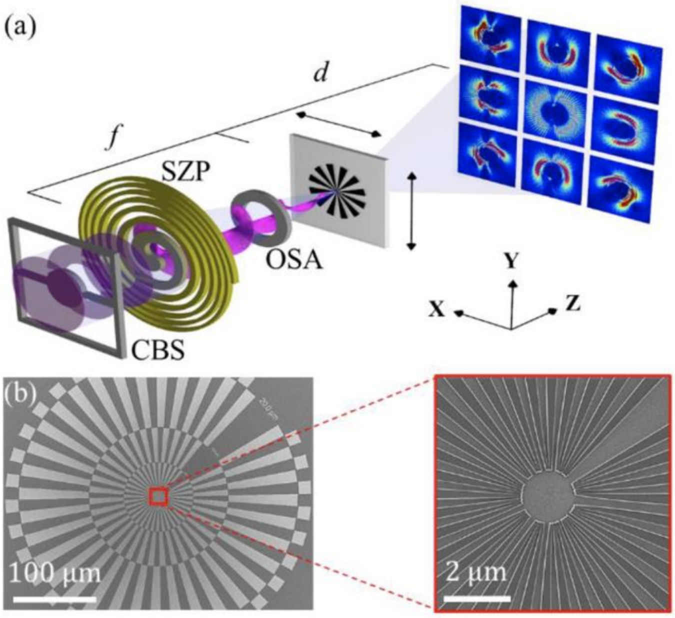

Fig. 1. (a) Schematics of the experimental setup for ptychography. The OAM beam is generated and focused on the sample plane (at a distance f) using a spiral zone plate (SZP). The order sorting aperture (OSA) allows only light from the first diffraction order to reach the sample, while the higher orders are blocked. Upstream to the SZP optics, a central beam stop (CBS) blocks the direct beam that does not carry OAM. The sample is then scanned in the XY-plane in order to record a set of diffraction patterns with a CCD camera (placed at a distance d), to be used for the ptychography reconstruction of both the object and the illumination functions. (b) Scanning electron microscopy image of the Siemens star used as a test transmitting sample, and magnification of the central part, where the smallest features have a size of 100 nm.

RESULTS

For each ℓ value, three ptychographic scans were recorded, and representative reconstructions are shown in Fig. 2. Each panel is composed by amplitude and phase of the main illumination mode, and by the corresponding object amplitude.

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Figure 2 shows that the fine details in the central part of the Siemens star can readily be identified, allowing to estimate a resolution comparable with the pixel size (96 nm), an order of magnitude better with respect to a SASE FEL source and comparable with more stable sources, like table-top lasers for high-harmonic generation and synchrotron radiation facilities. A clear improvement of about 30% in the image resolution is observed for the SZP with the highest topological charge order ($|\ell| = 3$) with respect to conventional Gaussian beam illumination ($\ell = 0$). We ascribe this resolution improvement to the beam structuring and to its consequent enhancement of the probe spatial-frequency spectrum.

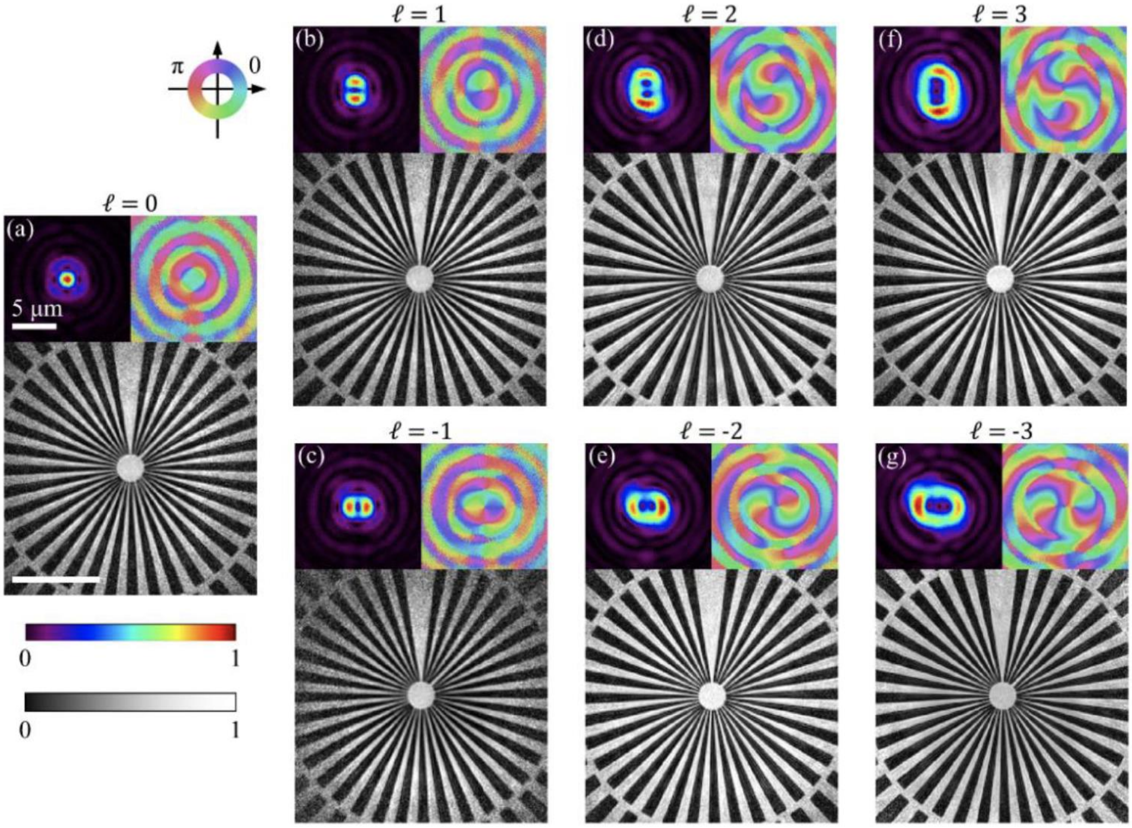

Fig. 2. (a)-(g) Ptychographic reconstructions of the Siemens star for $\ell = 0, \pm1, \pm2, \pm3$. For each panel, the main illumination amplitude, the main illumination phase and the object amplitude are shown. Both the white markers in (a) correspond to a length of 5 µm, and they differ by a factor of two.

CONCLUSIONS

Our analysis shows a significant enhancement in spatial resolution and beam stability—over an order of magnitude better than previously reported FEL experiments. We also identified a clear correlation between image resolution and the topological charge $|\ell|$: the greater the $|\ell|$, the higher the resolution and overall image quality.

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