Tabletop coherent diffractive imaging with a gas-discharge extreme ultraviolet light source

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Application Note

Introduction

We present coherent diffractive imaging using a tabletop, partially coherent, gas-discharge extreme ultraviolet light (EUV) source. We demonstrate a successful reconstruction of a simple test object from its far-field diffraction pattern. Furthermore, our experiment explores the feasibility of coherent diffraction imaging with bright EUV light sources emerged from the source development for EUV lithography paving the way for laboratory-scale CDI application.

Conventional imaging techniques are subject to limits in resolution, which is especially critical in the short wavelength range of extreme ultraviolet (EUV) and soft X-ray radiation (wavelengths about 1–50 nm, photon energies about 25 –1000 eV). The use of focusing elements with EUV light faces problems of strong absorption preventing the use of refractive optics. Another problem is limited resolution of reflective optics due to the surface errors (surface figure and finish error as well as mid-spatial frequency roughness). Diffractive optics, e.g. zone plates, also have substantial limitations due to relatively large size of the diffracting structures achievable so far.

Coherent diffraction imaging (CDI) is an alternative method allowing to achieve the diffraction limited resolution not affected by drawbacks of the conventional optics. CDI is a lensless imaging technique, where a coherent electromagnetic wave illuminates an object, which far-field diffraction intensities are measured by an area detector. The well-known phase problem is solved by combining the oversampling method with iterative algorithms [1-3]. If sufficiently oversampled, an image of a sample with nanoscale lateral dimensions with a resolution only limited by diffraction is obtained from its diffraction pattern. Since the first experimental demonstration using X-Rays in 1999 [4], CDI has been broadly applied to image a variety of samples ranging from nanocrystals, nanoparticles, biomaterials, magnetic structures, cells, and cellular organelles to viruses. While CDI has been actively explored across different fields, a major limitation has been the availability of coherent x-ray sources, e.g. synchrotrons or x-ray free electron lasers. To overcome this limitation, a tabletop CDI experiment using laser-generated high harmonics was recently reported [5], reaching a lateral resolution of 22 nm at 13 nm wavelength.

Experimental set-up

We report about a tabletop CDI experiment using a discharge-produced plasma EUV light source developed at the Fraunhofer Institute for Laser Technology in Aachen [6-8].
The experimental setup is shown in Fig. 1.

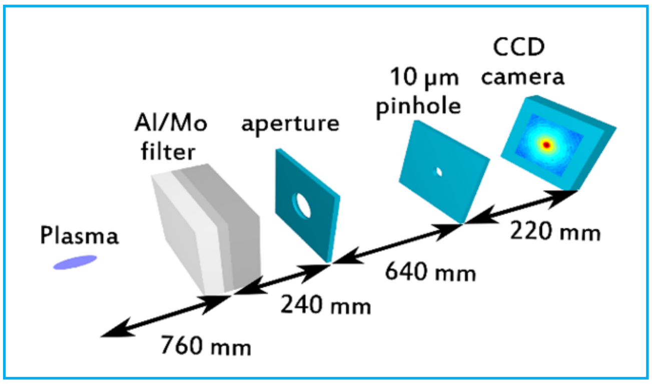

Fig. 1: Optical setup of the CDI experiment. The EUV light generated by gas-discharge is passing through an Al (200 nm)/Mo (60 nm) filter for spectral filtering and through an aperture (300 µm in diameter) for spatial filtering. Then, the light is diffracted by the test sample (another aperture with 10 µm diameter) and recorded by the Andor iKon-M SO CCD camera.

First, the EUV radiation passes through an Al (200 nm)/Mo (60 nm) filter for spectral filtering. Aluminum absorbs wavelengths below the Al 2p absorption edge (about 17 nm), whereas molybdenum strongly absorbs radiation between 20 nm and 30 nm (Fig. 2). The double layer filter is used to select the 17.3 nm line from the oxygen spectrum (Fig. 2 (a)) providing a high temporal coherence.

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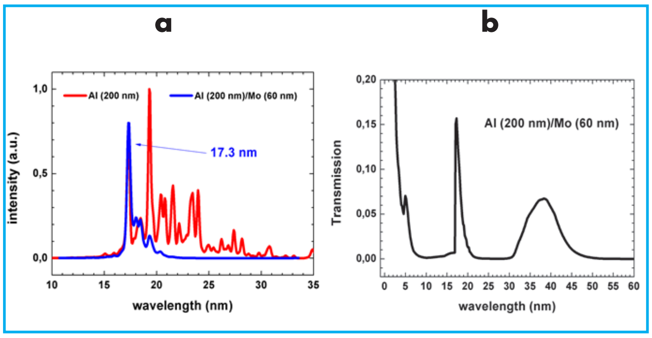

Fig. 2: (a) Emission spectrum of multiply ionized oxygen (O^{4+}, O^{5+}) atoms measured with Al-filter (red line) and Al-Mo-filter (blue line) by a transmission grating spectrometer. The Mo layer suppresses wavelengths above 20 nm. (b) Transmission of the Al-Mo-filter extracted from the database of the Center for X-Ray Optics [11].

Downstream the spectral filter, an aperture of 300 µm is placed, thus decreasing the effective pinch size and therefore increasing the spatial coherence length. The object used for CDI experiments is a precision pinhole with about 10 µm diameter, which diffraction pattern is recorded by the Andor iKon-M SO CCD camera DO934P-BN which has a back illuminated sensor. We estimate that the coherent photon flux in the image plane is about 10^5 photons/s.

Results

The measured pinhole diffraction pattern (Airy pattern) is presented in Fig. 3 (a).

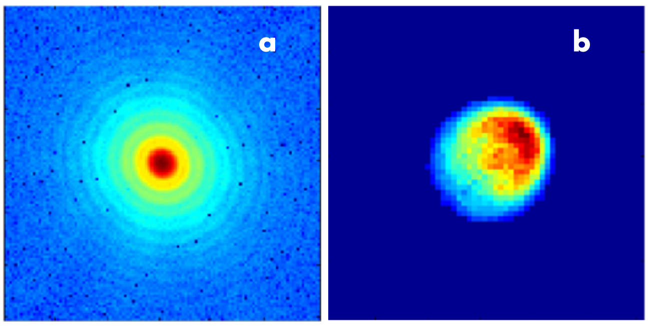

Fig. 3: (a) Diffraction pattern (122 pixel x 122 pixel, logarithmic scale) of a pinhole (about 10 µm diameter) measured with oxygen spectrum from Fig. 2 (a), blue line. (b) Result of the reconstruction of the pinhole transmission function from its diffraction pattern.

The data refinement procedure comprises several steps. Firstly, the background of the signal has to be subtracted from the measured signal. Following this step, hot pixels are detected and removed. In order to achieve a linear oversampling degree [9] of about five, a 5x5 binning is applied to the measured signal. The latter step is executed in order to reduce unnecessary high oversampling, which otherwise would require much computational capacity during the iterative reconstruction. Moreover, the signal-to-noise ratio is improved. Finally the center of symmetry is found by comparing sub-regions around the central lobe. Once the center is found, the data is aligned accordingly. An Oversampling Smoothness (OSS) algorithm [10] is applied to reconstruct the sample. 128 independent initial phase estimates are generated and used to run the OSS in a first cycle of 100 iterations. The best 5 reconstructions are chosen for a second cycle of the OSS. The best reconstruction is defined by the lowest R_F factor [10]

$$R_F = \frac{\sum_{\boldsymbol{k}} \big| |F_m(\boldsymbol{k})| - |F_n(\boldsymbol{k})| \big|}{\sum_{\boldsymbol{k}} |F_m(\boldsymbol{k})|},$$

where $|F_m(k)|$ denotes the measured diffraction amplitude for the wavevector k and $|F_n(k)|$ is the calculated diffraction amplitude for the reconstructed object after the nth iteration. The reconstructed pinhole (Fig. 3 (b)) has a diameter of about 11.2 µm. From the reconstructed image it is clear that due to slight misalignment the pinhole was placed at the slope of the Lorentzian illumination profile during the measurement.

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Summary
In our experiment, we demonstrated a successful application of a partially coherent gas-discharge EUV light source for coherent diffraction imaging. We measured the diffraction pattern of a simple test object and reconstructed the complex illumination wavefront (phase and amplitude). In the next step, we plan to increase the coherent photon flux optimizing the output of the EUV light source as well as optimizing the optical setup for CDI measurements. We also plan to perform ptychographic measurements moving an aperture across the sample. This would allow to image samples for industrial applications, e.g. masks for EUV lithography.

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