X-ray Shaping Using Gratings and Zone Plates and Wavefront Measurements on the Free-electron Laser

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X-ray free electron lasers (XFEL) have produced a lot of remarkable and influential results on multiple disciplines due to its high power and high spatial coherence. Diffractive optics such as gratings and zone plates have previously been used to shape synchrotron x-ray beams. Challenges in doing this for x-ray free electron lasers include nanofabrication of materials that withstand high power x-ray beams and precise nanofabrication over large areas. Here we report x-ray beam shaping and wavefront measurements for (1) diamond grating x-ray beam splitters, and (2) spiral zone plates for producing femtosecond x-ray beams with orbital angular momentum (OAM).

Binary phase gratings can be used to split a single beam into multiple beams (orders) for beam sharing by multiple end stations or to provide in-situ beam monitoring and wavefront measurements[1]. In order to improve durability and reduce radiation damage, we developed a fabrication technique for hard x-ray gratings based on diamond. The diamond grating is designed to be 2 mm×2 mm in order to accept all coherent flux and 600 nm pitch corresponding to a diffraction angle of 0.22 mrad at 9.5 keV. The grating was patterned using e-beam lithography and etched into diamond up to 6.2 μm deep with oxygen RIE using electroplated metal as the mask.

Spiral zone plates were used to generate hard x-ray femtosecond OAM beams[2]. Applications of this could include phase sensitive imaging or OAM dichroic spectroscopy[3]. These zone plates were fabricated on silicon nitride membrane using e-beam lithography, followed by metallization with gold electroplating. The zone plates have 200 nm finest zone width and up to 2 μm thickness which corresponds to a π phase shift at 9.5 keV.

X-ray experiments were carried out at the LCLS free electron laser using both the diffraction grating and spiral zone plates. Diffraction efficiency (split ratio) was measured as a function of grating thickness (varying x-ray beam incident angle corresponds to varying effective thickness), and a 1:1 ideal split ratio was obtained with a 20º tilt (Fig. 2). Results were also compared with simulations. X-ray OAM beams were also generated and measured (Fig. 3). Wavefront measurements were carried out for both the diamond grating and zone plates using a Talbot interferometer.

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[1] M. Lebugle, et al. Optics letters 42.21 (2017): 4327-4330.
[2] A. Sakdinawat, and Y. Liu. Optics letters 32.18 (2007): 2635-2637.
[3] V. Michel, and I. McNulty. Physical review letters 98.15 (2007): 157401.

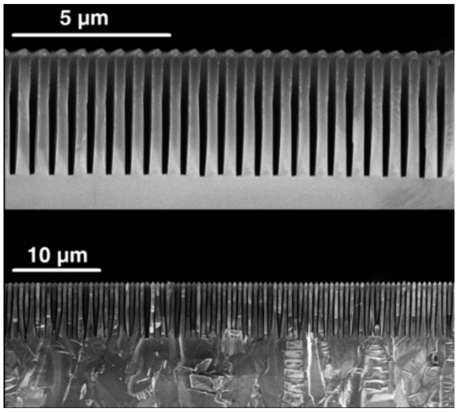

Figure 1: Diamond gratings with 600 nm period. Top: etched 3.8 µm deep, Bottom: etched 6.2 µm deep.

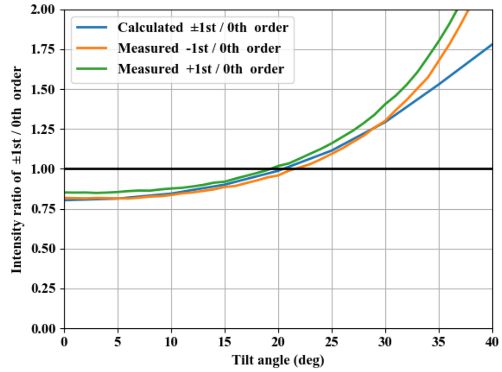

Figure 2: Measured and calculated results of x-ray beam split ratio vs. grating tilt angle for the 6.2 µm deep diamond grating. A 1:1 split ratio is obtained at around 20⁰ tilt.

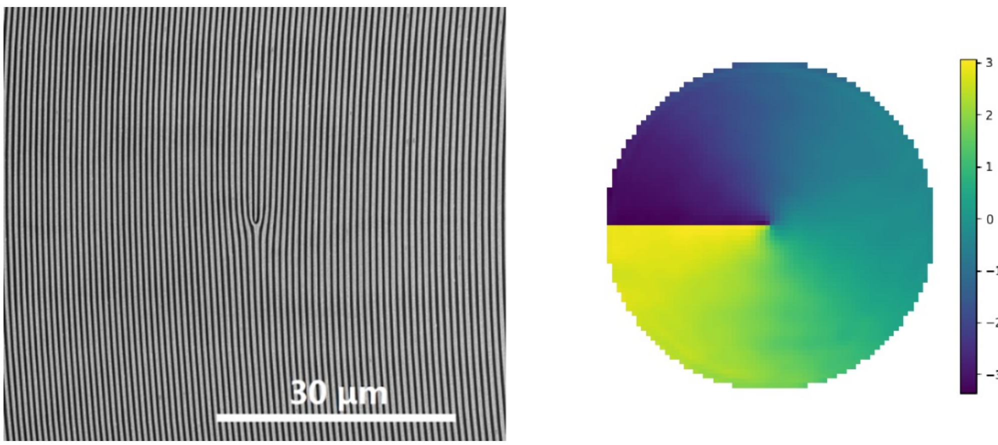

Figure 3: (Left) SEM image of the central region of an off-axis spiral zone plate of charge 1. (Right) Wavefront of x-ray orbital angular momentum beams obtained using spiral zone plates of charge 1.