Wavefront Metrology for X-Ray Free Electron Laser Instruments

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The availability of intense, coherent x-rays from free-electron lasers (FEL) opens new opportunities for many areas of science and technology. Preserving the coherence and high quality wavefront of the x-ray beam is essential for many of the FEL applications. Given the very short wavelengths of x-rays, the requirement on optical performance of FEL instruments is extremely tight. For example, at 9.5 keV photon energy, a 10 milli-wave wavefront error corresponds to path error of only 1.3 picometers. For commonly-used grazing incidence mirrors, this will translate to a surface error of only several nanometers, across the length of usually meter-class mirrors. A capable yet easy to operate wavefront metrology technique is needed to accurately measure the wavefront of the FEL beam to guide the qualification, alignment, and optimization of the FEL instruments. Wavefront measurement results can also provide feedback to the tuning of FEL source.

Here we report a robust, sensitive and accurate single-shot wavefront sensor for X-ray FEL beams using single grating Talbot interferometry. When illuminated by coherent x-rays, gratings made with E-beam lithography form high contrast self-images at fractional Talbot planes, from which wavefront errors can be extracted. Experiments performed at the Linac Coherent Light Source (LCLS) demonstrate 3σ sensitivity and accuracy, both better than $\lambda/100$, and retrieval of hard X-ray ($\lambda = 0.13$ nm, E = 9.5 keV) wavefronts in 3D. Extending the technique to soft X-rays (500-1500 eV) was also realized, with modified grating and Talbot plane configurations. The results provide valuable information to systematically study the wavefront evolution from the FEL output, through beam transport optics and experimental instrument focusing optics, all the way to the sample.

1. Yanwei Liu et al, "High-accuracy wavefront sensing for x-ray free electron lasers," Optica 5, 967-975 (2018)

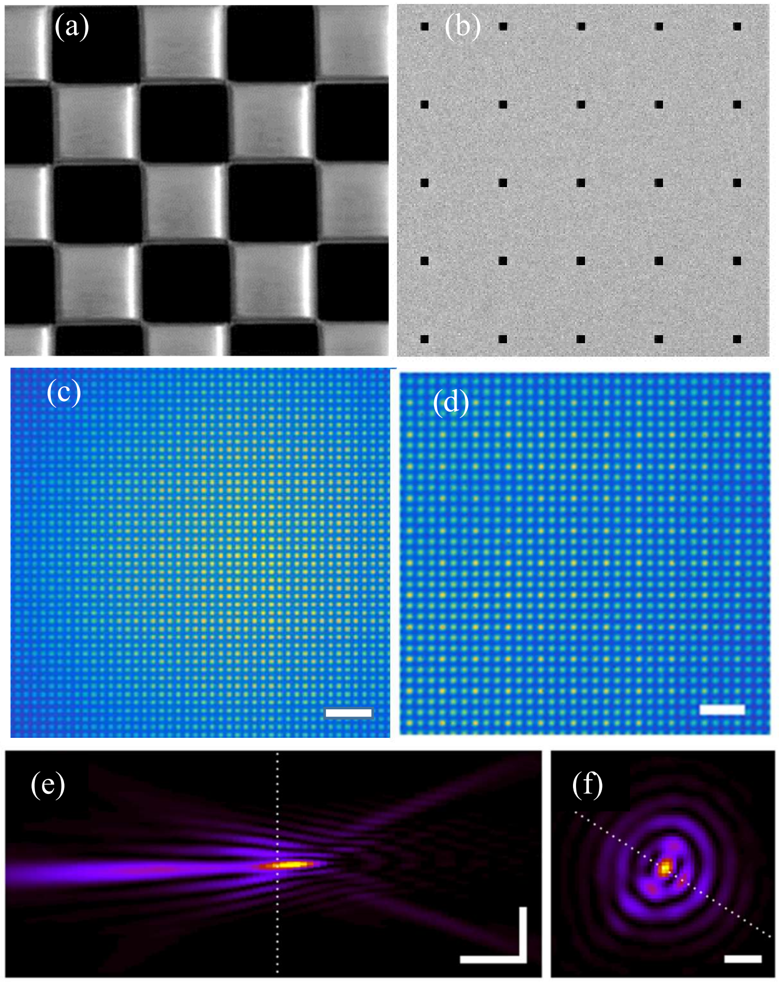

Figure 1. (a-b) SEM images of a checkerboard phase grating (a) and a binary grating (b), both fabricated with e-beam lithography as the objects to form Talbot images. Each square in checkerboard grating (a) is 10 μm in size and etched 14 μm deep into Silicon substrate. The square apertures in (b) are 4 μm squares and the spacing is 40 μm. (c) Observed Talbot images with 9.5 keV hard x-ray using the phase grating as in (a). Scale bar is 50 μm. (d) Observed Talbot images with 1.0 keV soft x-rays using the binary grating as in (b). Scale bar is 100 μm. (e-f) Through-focus and focal plane intensity profiles of a focused hard x-ray beam, retrieved using the Talbot wavefront sensor. The scale bar in (a) has a length of 5 mm along the beam axis (horizontal direction) and 2 μm in the transverse direction, and the scale bar in (f) has a length of 500 nm.