Tunable hard x-ray nanofocusing with Fresnel zone plates fabricated using deep etching: supplement

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1. Zone plate testing apparatus

In Fig. 1 we show the experimental end station [1] at the NSLS-II Hard X-ray Nanoprobe (HXN) beamline that we used for testing zone plate focusing efficiency and spatial resolution.

2. Zone plate efficiency versus thickness

The $d r_N = 16$ nm Fresnel zone plate studied in our main manuscript had a thickness of $t_{zp} = 1.8$ μm, but we have also reported [2] the fabrication of $d r_N = 16$ nm zone plates with thicknesses up to $t_{zp} = 8$ μm. If one uses a simple scalar diffraction calculation for conventional zone plates with these thicknesses, one sees in Fig. 2 that $t_{zp} = 1.8$ μm leads to an estimated optimum photon energy of about 9.9 keV for best diffraction efficiency, while a $t_{zp} = 8$ μm thick zone plate should have a maximum diffraction efficiency at about 45.9 keV. More accurate calculations take into account the fact that the zone doubling process produces zones with a line:space ratio that varies across the zone plate [3], as well as volume diffraction effects [4, 5].

3. Astigmatism due to zone plate tilt misalignment

The aberrations of Fresnel zone plates that are tilted with respect to the illumination direction have been considered earlier [6], leading to optical path length differences $\ell$ of

$$\ell = \frac{r_N^3}{2f^2} \theta - \frac{3r_N^2}{4f} \theta^2$$

(1)

where $r_N$ is the radius, $f$ the focal length of a zone plate and $\theta$ is the tilt angle. In separate work [7] we have shown that the former term is wavelength dependent, but that the latter term is not, and that the latter term dominates the tilt limit for hard x-ray zone plates. Applying the Rayleigh quarter wave criterion for maximum optical path length errors, it is shown in Eq. 15...
of [7] that this gives an astigmatism tilt limit $\theta_a$ of

$$\theta_a < \frac{1}{\sqrt{3N}}$$  \hspace{1cm} (2)

where $N = r_N/(2dr_N)$ is the number of half-period zones in a zone plate with no central stop. In our case we have $r_N = 60 \mu m$ and $dr_N = 16 \text{ nm}$, giving $N = 3750$ and a tilt limit from Eq. 2 of $\theta_a < 0.54^\circ$. In Fig. 3(c) of the main article, we observed a full tilt range tolerance of $1.1^\circ$ (or $0.55^\circ$ on either side of the optical axis), independent of x-ray wavelength. This observation is consistent with the astigmatism tilt limit of Eq. 2.

4. Theoretical calculation of the zone plate probe function

In Fig. 4(c) of the main manuscript, the theoretical integral of the probe intensity is shown. For a conventional (that is, not zone-doubled) Fresnel zone plate with $dr_N = 16 \text{ nm}$ outermost zone width and no central stop, one would expect the Airy intensity function to reach its first zero at a value of $1.22dr_N = 19.5 \text{ nm}$ (the classical Rayleigh spatial resolution), and the probe to have a FWHM size of $16.5 \text{ nm}$. However, zone plates used in scanning microscopes typically employ a central stop and an order-selecting aperture to isolate the first-diffraction-order focus [8], leading to a modification of the complex amplitude of the focus [9, 10]. The resulting positions of the first and second minima in the modified Airy distribution are shown in Fig. 4(c) in the main manuscript. This modification reduces the position of the first minimum in the diffraction pattern, while simultaneously increasing the energy in subsidiary diffraction rings around this central spot (see for example Fig. 4.33 in [11]).

5. Multiple probe modes in the ptychographic image

In Section 4 “Experimental demonstration” and especially Fig. 4 of the main manuscript, it was noted that “the zone plate was only partially coherently illuminated in order to provide sufficient flux for ptychographic imaging during the allotted beamtime.” Because the illumination involved $p_x \cdot p_y = 6.7$ spatially coherent modes, we used a multiple probe mode reconstruction method [12] as implemented in software developed at Brookhaven Lab [13]. In the main manuscript, Fig. 4(c) showed probe mode $M = 1$ as well as the sum of probe modes $M = 2–5$. We show here in Fig. 3 each of the $M = 8$ probe modes, along with their relative power.

Figure 4(b) of the main manuscript showed the FWHM probe width of the $M = 1$ probe mode in each of the $x$ and $y$ directions as a function of defocus $\Delta z$. We show here in Fig. 4 the equivalent curves for the sum of probe modes $M = 1–8$. As with the $M = 1$ probe mode, these curves again show a slight degree of astigmatism in the probe, with a FWHM probe size of $46 \times 60 \text{ nm}$.

6. References

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Fig. 1. X-ray microscope system [1] used for the zone plate tests reported here. In the CAD drawing at left, one can see the optic mount with tilt adjustments in both orientations relative to the x-ray beam, the bracket used to support an order selecting aperture (OSA) used to isolate the first order focus, and the specimen mount used to scan the specimen using piezo scanners (P) for short range positioning and stepping motor scanners (S) for positioning. In order to mount the zone plate as perpendicular to the x-ray beam as possible prior to final adjustment, the 12 keV x-ray beam was brought through a helium-filled tube (not shown) to a fluorescent screen with a hole in the middle. This screen was positioned so that the x-ray beam was able to go through the hole, after which a visible light laser was mounted and made to shine through the hole and hit the zone plate. Using the visible light laser beam reflected off of the zone plate substrate, one can tilt the zone plate until the reflected beam hits the hole in the fluorescent screen, and thereby know that the zone plate was aligned normal to the x-ray beam with an accuracy of about 0.1°.
Fig. 2. Scalar diffraction efficiency [14] calculated for conventional (that is, not zone-doubled [15]) zone plates with various thicknesses of platinum.
Fig. 3. Images of the $M = 8$ probe modes reconstructed from a ptychographic scan of a test pattern. Figure 4(c) of the main manuscript shows mode $M = 1$ and the sum of modes $M = 2$–5. We show here the individual modes $M = 1$–8, as well as a plot of the total energy contained in each mode. A multiple probe mode reconstruction was required because of the use of partially coherent illumination; the $M = 1$ probe mode represents what we would expect for the focus of the MACE/ALD zone plate if fully coherent illumination was used.
Fig. 4. Probe size with all probe modes included, as a function of defocus. The equivalent plot for the $M = 1$ probe mode is shown in Fig. 4(b) in the main manuscript.