New lenses for high resolution hard X-ray microscopy

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Hard X-rays, due to their large penetration depth and short wavelengths, enable high-resolution imaging of samples in three dimensions without sectioning or staining. Such imaging requires the combination of ultra-bright X-ray sources, efficient X-ray optics and detectors. To achieve a resolution below 10 nm, optical elements are needed with a nanometer fabrication precision. There are several types of X-ray lenses that could meet these specifications; one is with multilayer Laue lenses (MLLs). Simulations predict that focusing to nanometer size beams is achievable with two crossed MLLs. Just like a cylindrical lens or one-dimensional zone plate, a MLL focuses X-rays only in one direction so two MLLs with slightly different focal lengths are needed to produce a focused spot. For 10 keV photon energy, such lens structures are typically tens of micrometers to about 100 μm tall (aperture size) with focal lengths of about 1 to 10 mm, fabricated from many thousands of layers several nanometers thick. The layers vary in spacing so as to diffract collimated light to a common focus according to the construction of Fresnel zone plates. The focusing behavior and efficiency is described by dynamical diffraction theory, which shows that efficiencies over 70% can be reached with a depth (in the direction of the optic axis) of several microns. Such thick diffracting structures obey Bragg's law, implying that the layers must be tilted so as to reflect rays towards the focus. It is thus easy to see that the layers must lie normal to a cylinder of radius equal to twice the focal length. Without this so-called "wedged" construction, the numerical aperture of the lens is severely limited.

A MLL is prepared by sputtering a multilayer onto a flat substrate, which is then sliced in a direction perpendicular to the layers to create a block of the desired depth. To form layers with the necessary tilt, we introduced a new method to deposit the layer materials within the penumbra of a straight mask. This has allowed us to fabricate wedged high-numerical aperture (NA) MLLs with high accuracy and control. We demonstrated 8 nm focusing in 1D (with one MLL) [1] and more recently demonstrated focusing and imaging in 2D with sub-10nm resolution (using two MLLs made in two independent depositions) [2]. The performance of the lenses was characterized with a combination of interferometry and ptychography. It may be possible to use such X-ray optics to focus X-ray Free Electron Laser pulses to create beams with intensities well above 10^{20} W/cm^2, which are required for imaging of non-periodic matter at atomic resolution. We will present our latest results on the development and performance of MLLs as well as discuss the future outlook of this state-of-the-art X-ray optics.

References

[1] Morgan *et al.*, "High numerical aperture multilayer Laue lenses", *Sci. Rep.* 5, 09892 (2015).

[2] Bajt *et al.,* "X-ray focusing with efficient high-NA multilayer Laue lenses", accepted in *Light: Science and Applications* (2018).