Focusing with multilayer Laue lenses

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Multilayer Laue Lenses (MLLs) are diffracting optics similar to X-ray zone plates but are fabricated by layer deposition and hence can achieve higher resolution (thinner layers or zones), higher aspect ratio, and higher efficiency. In principle, nanometer size beams can be produced with crossed multilayer Laue lenses (MLL) or a circular MLL.

The aim of our experiment was to demonstrate sub 10 nm focusing of hard X-rays using 1D ptychography. The 1D version of ptychography was first demonstrated by Chapman and used to measure the phase of soft X-ray zone plates [1]. In this method a 1D structure such as an edge or transmission grating is scanned across the beam, and far-field diffraction patterns are measured at each point of the scan. For a 1D MLL focus, the diffraction pattern is ideally one dimensional, although in practice we measure a 2D pattern at each point. The determined complex-valued pupil function of the lens can be propagated into the focal plane to ascertain the focusing performance and resolution. With hard X-rays a cleaved Si wafer can be used to produce a phase edge as the scanned object. Using such an object to measure the lens pupil function by ptychography is very similar to the classical Foucault test used in optical testing.

The fabrication of our MLLs was based on our extensive experience in the development of high reflectivity, low stress and high stability, high thickness multilayer structures for volume diffraction. For example asymmetrically cut thick multilayers act as very efficient and highly dispersive gratings [2]. The new fabrication methods that we have invented have opened new applications such as pulse shaping [3] and pulse compression of free electron laser (FEL) beams. Our MLLs were designed using the Beam Propagation Method (BPM), which is simpler and computationally more efficient than x-ray dynamical diffraction theory. To achieve a minimum focus size (i.e., high numerical aperture and small wavefront errors) it is important that the layers are smooth and abrupt. Improvements in multilayer technology and understanding material properties enabled us to deposit layers that are ~1 nm thick. In addition to a quadratic variation of the period with depth (following the zone plate law, see Fig. 1a) the layers should be wedged along the optical axis to maintain the Bragg condition throughout the entire stack and thereby achieve high efficiency. We achieved the variation of thickness in depth and lateral profile by deposition, and then cut out the MLL to the desired thickness of 6 μm using a focused ion beam (FIB) (Fig. 1b). Our MLL was optimized to focus 17 keV X-rays to a 5 nm focal line with a focal length of 1.2 mm. The multilayer was deposited on a flat substrate, starting with the thinnest layers (2 nm) and ended with the thickest (9 nm) layers. This partial MLL consisted of 5500 layers and deflected and focused the x-ray beam towards the optical axis.

The MLL performance was tested at the P11 beamline. In-house developed high-resolution micro-deflector sample holders enabled precise tilt and rotation of the MLL with sub-μrad precision. The incident monochromatic, coherent beam of desirable energy (17 keV) illuminated the functional part of the structure. The 1D MLL is an off-axis section of the full ideal zone plate, and so the focused beam is deflected from the direction of the incident and undiffracted (zeroth order)

transmitted beam. We blocked this undiffracted beam with a stop (second slit) made out of a high Z material. The individual components were positioned with piezo-driven fine stages. Measurements were carried out with the DESY-developed "LAMBDA" detector, which has an operating range between 6 and 25 keV with a 55 μm pixel size. Our MLLs were pre-characterized with AFM, SEM and TEM and showed a nicely layered structure with low interface roughness. However, because these structures are depth graded and very thick, standard grazing incidence x-ray based reflectometry could not be used to measure the depth layer profile.

Our MLL deflected 22 keV X-ray by the predicted angles and the far-field divergent beam appeared to be intense with uniform intensity over the whole angular range of the MLL (Fig 1c). The initial 1D ptychography reconstruction points to a sub 10 nm line beam.

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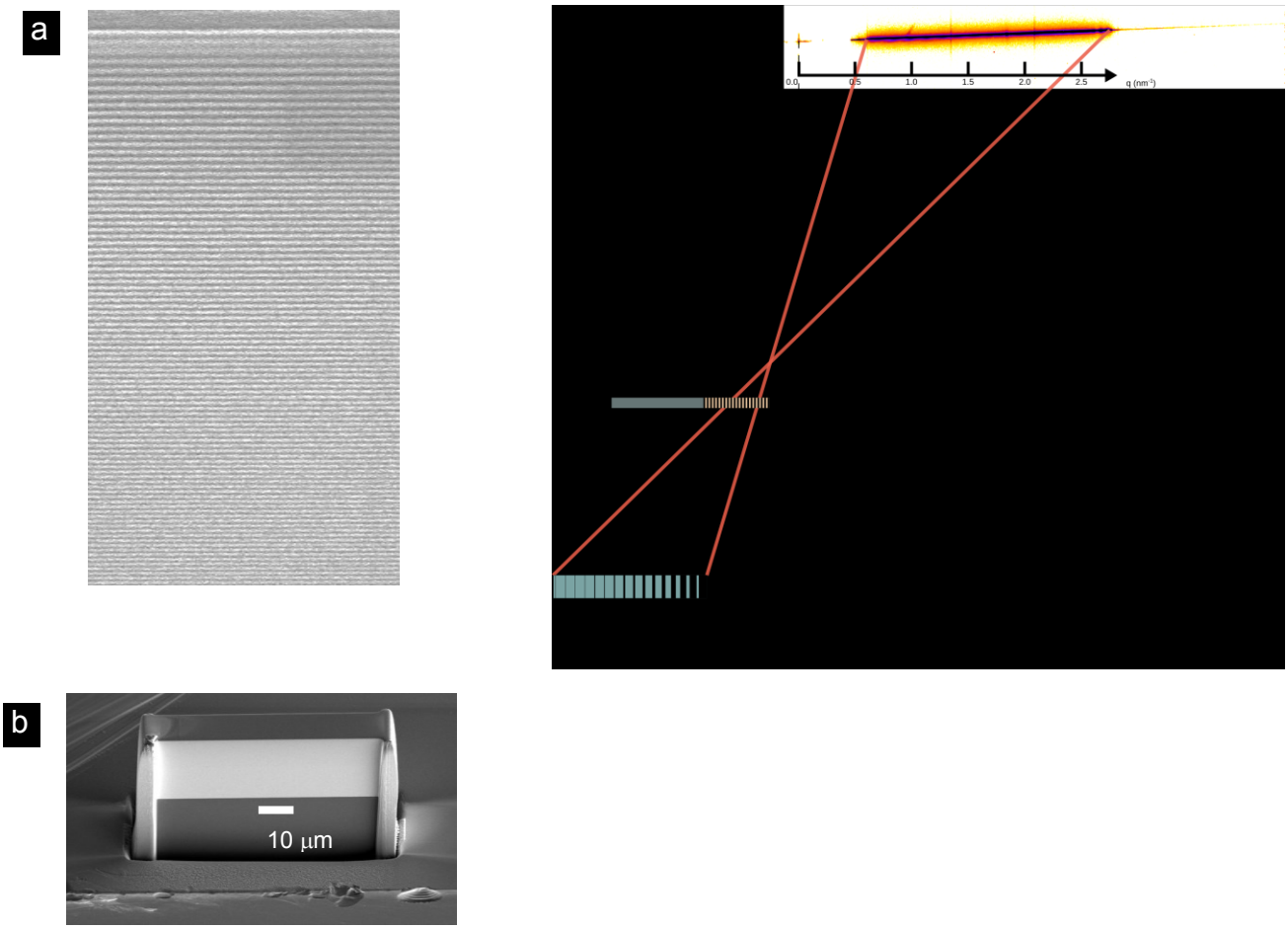

Figure 1: TEM cross section of a section of depth-graded multilayer (a); a wedged MLL (b) and far-field diffraction pattern of the MLL, showing its relationship with the beam diverging past the focus (c).

References

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