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Characterization of High Numerical Aperture Multilayer Laue Lenses

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Very bright and coherent x-ray sources combined with efficient and high resolution x-ray optics enable imaging and spectroscopy of samples (e.g. biological specimens, functional materials and nanodevices) with unprecedented accuracy. Theoretical simulations have shown that sub-nanometer resolution is possible for perfect multilayer Laue lenses [1] and recent experimental results demonstrated sub-10 nm resolution with high focusing efficiency [2]. However, making perfect lenses is very challenging since layer thickness errors of even a fraction of an ångstrom already significantly broaden the focus. To achieve diffraction limited focusing it is therefore of utmost importance to characterize lens aberrations and correct them.

MLLs are multilayer based diffractive optical elements that work similar to lithographically produced x-ray zone plates. However, for hard x-rays theses thin Fresnel zone plates tend to be extremely inefficient due to their small depth. A zone plate with greater zone aspect ratio can be realized by depositing a multilayer on a flat substrate consisting of several tens of thousands of layers and extracting a slice with the desired depth. It is required that the thickness of each deposited layer fulfills the zone plate condition. The efficiency and effective numerical aperture (NA) can be significantly increased with wedged layers, which are oriented azimuthally on a circle with the radius of twice the focal length [3]. This can be realized by introducing a mask in the deposition process as described in [4].

After successful fabrication, wavefront metrology can be performed to characterize the lens performance. Speckle tracking [5, 6] is a highly robust method without strict coherence requirements that can be used to characterize lens aberrations. If a sample is placed sufficiently far out of focus, the image on a detector in the far field will be a magnified projection of the sample. However, a local wavefront gradient will cause a ray to propagate to a different position in the far field, which is perceived as an image distortion. If the sample is scanned across the beam, each frame will show a displaced image of the object. Features of the image are additionally displaced due the local pupil wavefront. With a first guess of the pupil wavefront, one obtains a first guess of the local displacements and can merge the different views of the object to an estimate of the entire illuminated region of the sample. This first estimation of the displacements will not be free of error, but it can be updated by comparing the location of the individual features in the recorded images with the feature location on the merged image. A more accurate displacement for each feature can be found by maximizing the Pearson correlation coefficient. By doing so, a new estimate of the displacement of each detector pixel in each image is determined. This can be repeated to iteratively retrieve the actual displacement values. These displacement values are proportional to the wavefront gradient, which can then be integrated to obtain the wavefront.

We successfully utilized an iterative speckle tracking approach to perform wavefront retrieval in different experiments and energies up to 34.5 keV. Figure 1 shows an exemplary wavefront of a set of high NA MLLs (NA=0.015) after removing aberration terms, that are caused by the lens design or alignment, namely tilt, defocus and astigmatism. Because a set of two crossed MLLs is used for 2D imaging, the retrieved wavefront can in principle be separated in a horizontal and a vertical component. By doing so one is able to unveil the aberrations caused by each individual lens. However, it is important to avoid 45° astigmatism, caused by non-orthogonality of the lenses [7]. The observed separated wavefronts (Figure 2) are dominated by systematic layer thickness error of thin layers that are highly reproducible and can then be corrected in a following deposition run. A typical correction of this kind will modify the thickness of each layer according to the measured wavefront by <0.1 nm. This is carried out over the course of a whole deposition run, which can consist of over 50,000 individual layers. Wavefront retrieval has also been conducted using ptychography. Both ptychography and speckle tracking gave a similar result. However, speckle tracking can be used even with x-rays with low spatial coherence, which is not the case for methods like ptychography. This shows the possibility to perform full wavefront characterization also with incoherent x-ray sources [8].

References:

[1] H. Yan *et a*l, X-Ray Opt. and Instr. **2010** (2010), 401854.
[2] S. Bajt *et al*, LSA **7** (2018), 17162.
[3] A. J. Morgan *et al*, Sci. Rep. **5** (2015), 09892.
[4] M. Prasciolu *et al*, Opt. Mat. Expr. **748** (2015), 228318.
[5] T. C. Chu *et al,* Exp. Mech. **25** (1985), p. 232-44
[6] S. Bérujon *et al,* PRL **108** (2012), 158102
[7] H. Yan *et* al, Opt. Expr. **25**, No. 21 (2017), p. 25234.
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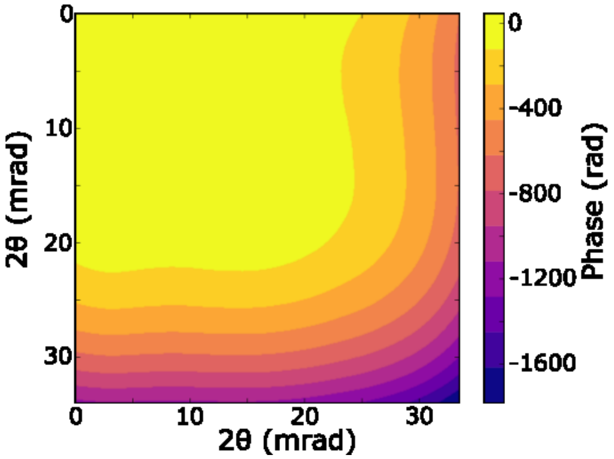

Figure. 1. Wavefront obtained with speckle tracking. The MLLs show a roll-off caused by systematic layer thickness error for high diffraction angles (thin layers).

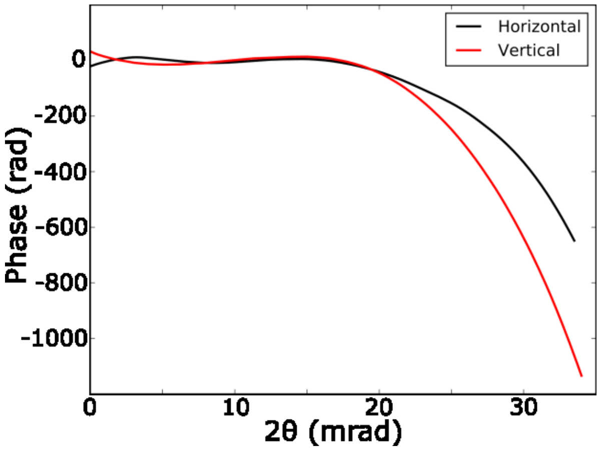

Figure. 2. Separated wavefronts of the two individual high NA MLLs. The similarity of the horizontal and vertical components indicate the high reproducibility of the underlying thickness errors.