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Field-varying aberration recovery in EUV microscopy using mask roughness

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Abstract: We derive and solve a simplified, self-calibrated inverse problem to characterize the field-dependent aberrations of an EUV synchrotron-based full-field microscope, using images of the surface roughness of an EUV photomask under several angles of illumination. We demonstrate diffraction-limited imaging performance at the center of its field-of-view.

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Aberration characterization is crucial in assessing the performance of photo-lithography tools, which aim to achieve diffraction-limited resolution. Measuring aberrations usually requires resolution targets [1], which are not readily available for the extreme ultraviolet (EUV) wavelength ($\lambda = 13.5$ nm) due to fabrication constraints. Previous EUV microscope characterization has used point-like contacts [2] and custom features [3], but they were limited to specific aberrations and relied on known patterns, often with imperfections and prone to sample-induced aberrations [4].

Here, we demonstrate a speckle-based method which has been shown to probe the space-invariant aberrations of an imaging system in the visible range [5], treating field-dependent aberrations as locally space-invariant. In EUV lithography, blank photomasks (molybdenum/silicon multilayer, 70% reflectivity) present an intrinsic random surface roughness on the order of $2\mathring{A}$ that acts as a weak phase object and generates broadband speckle under coherent illumination. Stationarity of the random surface means we need not know the precise surface shape, but rather only a few statistical parameters. This enables a simplified, real-valued and self-calibrated model. Based on these properties, we derive a forward model to describe the DC-suppressed spectra of intensity measurements, $|\widehat{I_{\varnothing,j}}|$, as a function of illumination angle (indexed by j) and aberrations:

$$|\widehat{I_{\varnothing,j}}| \approx \mathbb{1}[\mathscr{U}_j] \circ \left(2\eta|\widehat{\varphi_d}| \cdot |\sin(\mathbf{A}_j\mathbf{c})|\right), \ \eta \sim \text{Rayleigh}(\sigma), \tag{1}$$

in which $\mathbf{c}$ is a vector of Zernike coefficients, $\mathbf{A}_j$ maps coefficients to normalized spatial frequencies, $|\widehat{\varphi_d}|$ is the deterministic envelope of the mask spectrum, η is white noise, $\mathbb{1}[\mathscr{U}_j]$ is the characteristic function specifying the validity of the forward model, and $\circ$ denotes an element-wise product. The quantities $\mathbf{A}_j$ and $\mathbb{1}[\mathscr{U}_j]$ are fully specified by illumination angle, and $|\widehat{\varphi_d}|$ and σ can be estimated from data. It is important to note that for on-axis illumination, all *odd* Zernike polynomials $(f(u) = -f(-u))$ are in the null space of $\mathbf{A}_j$. Hence, the recovery of arbitrary aberration functions requires off-axis illumination, whereby translation in the spatial frequency domain gives odd aberrations measurable even components. Our model suggests the following nonlinear least squares (NLS) inverse problem, which we solve to obtain the Zernike coefficients (excluding tip, tilt, and piston):

$$\mathbf{c}^\star = \arg\min_{\mathbf{c}} \sum_{j=1}^{K} \left\| \mathbb{1}[\mathscr{U}_j] \circ \left(\frac{|\widehat{I_{\varnothing,j}}|}{2 \cdot |\widehat{\varphi_d}|} - \mathbb{E}[\eta] \left| \sin\left(\mathbf{A}_j\mathbf{c}\right) \right| \right) \right\|^2, \tag{2}$$

where K is the number of images used. We solve this optimization problem for each segment of the field-of-view (FOV) using gradient descent with backtracking line search from multiple random initializations.

Our experiments were done on SHARP [6] at Lawrence Berkeley National Lab, a synchrotron-based full-field EUV microscope, featuring a Fourier synthesis illuminator [7] to steer the illumination angle. The mask blank was coherently illuminated with a central ray angle of 6°, and imaged using an off-axis Fresnel zoneplate (120 μm diameter, 500 μm focal length, 0.082 NA).

The imaging system FOV was approximately $25 \times 25\mu m^2$, with $900\times$ magnification and an effective pixel size of 15 nm. We collected 10 coherent images of the blank area. An image taken with central illumination and large defocus was used to estimate distribution parameters. The other 9 were used in the inverse problem and included measurements with various illumination angles with a departure of 1.5° (0.3×NA) from the central ray angle. We performed the analysis on 256×256 pixel ($3.8 \times 3.8\mu m^2$) regions with 128 pixel overlap across the FOV (Fig. 1a)

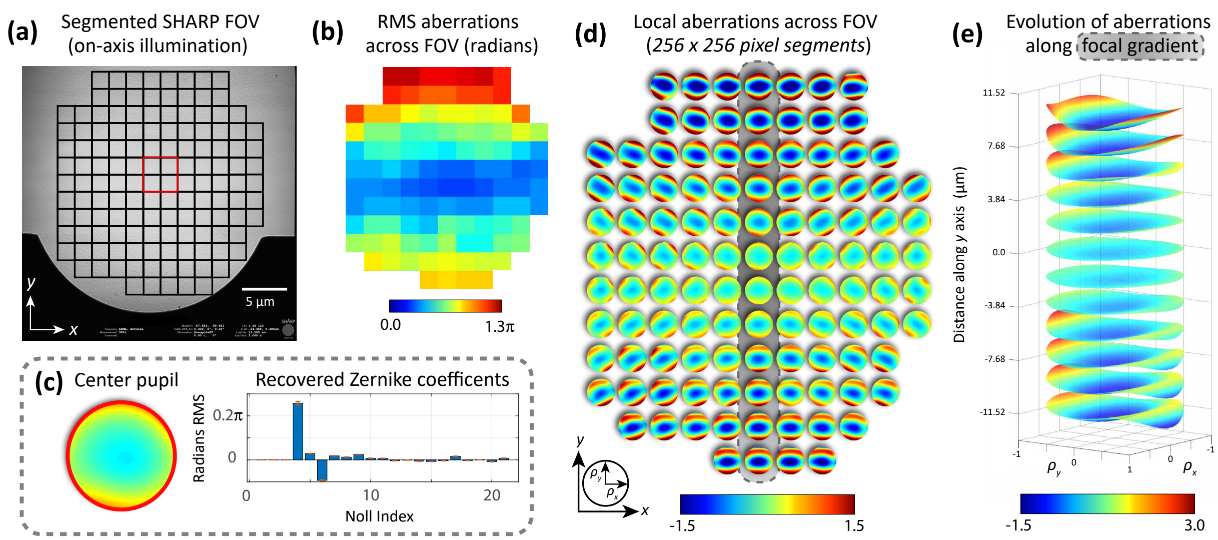

Fig. 1. (a) Image of photomask taken by SHARP with segmentation grid overlaid; (b) RMS wavefront error across the FOV; (c) aberrations in the 'sweet spot' (red box); (d) all reconstructed aberrations across FOV; (e) smooth evolution of aberration magnitude along a line in phase space.

The results show that aberrations are minimal at the so-called 'sweet spot', the center of the FOV (Fig. 1b), and progressively increase (coma, astigmatism and spherical) towards the edges (Fig. 1d). The sweet spot had a total wavefront error of 332 mrad-RMS (after the removal of residual defocus), corresponding to λ/19-RMS (Fig. 1c), in excellent agreement with the nominal optical performance for a single-lens design, for which the region where the aberrations are contained below $\lambda/20$ is approximately $5 \times 5\mu m^2$ [8,9]. Defocus dominates along the vertical direction (Fig. 1e) because of the off-axis imaging scheme. Simulations indicate that we are able to recover the aberrations with relative error under 3% with respect to true Zernike coefficient values. These results allow an analysis of the tool performance beyond the experimental demonstration of diffraction-limited imaging [6], using a readily available mask blank.

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