3-D Optical Metrology of Finite sub-20 nm Dense Arrays using Fourier Domain Normalization

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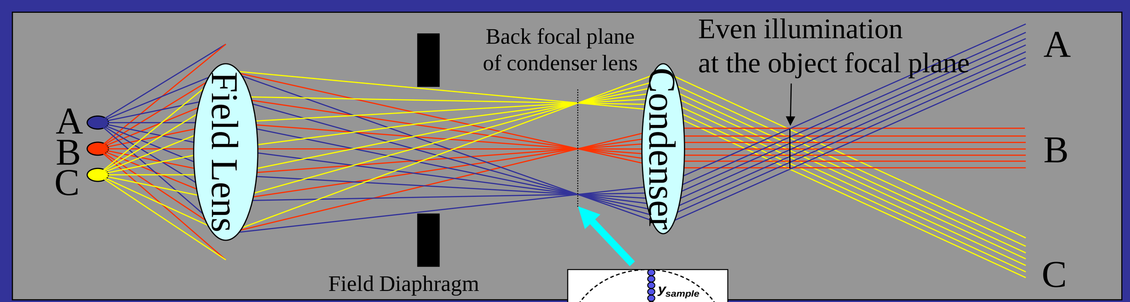
Introduction

- Reduced target dimensions require improved resolution and sensitivity
- Sensitivity to nanometer scale changes can be observed when measuring critical dimensions of 0th-order targets[1]
- Imaging methods can use all of the phase and frequency information
- There is a need to reduce overall size of a grating to 900 nm² with ~ 20 lines yet acquire more information.
- Targets that are non-repetitive, irregular, or have pitches greater than the wavelength of light scatter multiple (or even a continuum of) frequencies.
- In principle, spatial selectivity could enable in-chip measurement.

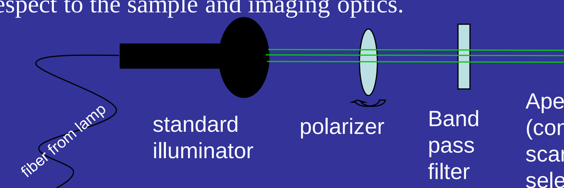
new approach

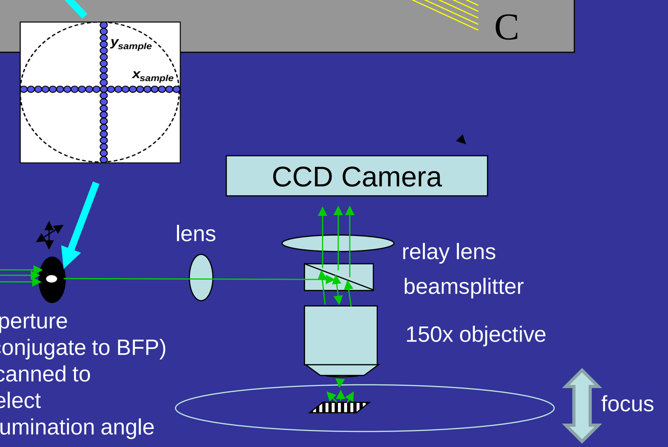
Our new approach enables rigorous analysis of 3-D focus-resolved and angle-resolved optical images that samples the three-dimensional electromagnetic field above and into finite targets, that scatter a continuum of frequency components.

We use the scatterfield microscope with high magnification imaging optics to enable spatial selectivity in both angle-resolved and focus-resolved modes.

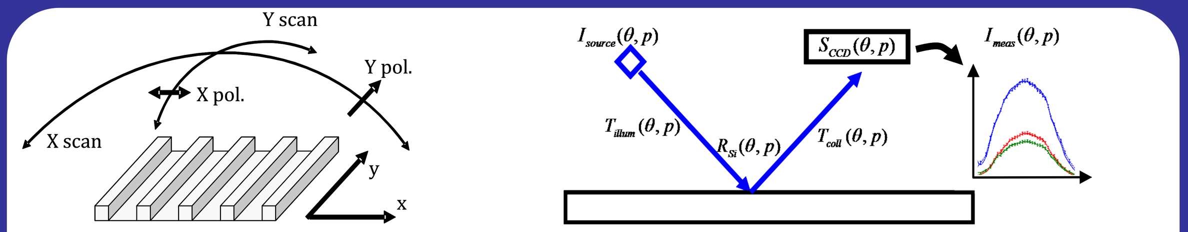


- Each point at the conjugate back focal plane maps to a plane wave of illumination at the sample.
- Scanning or fixed aperture allows selection of incident angles.
- Polarization states can be defined at the CBFP with respect to the sample and imaging optics.





Advanced Tool Characterization



$$I_{source}(\theta,p)\times T_{illum}(\theta,p)\times R_{Si}(\theta,p)\times T_{coll}(\theta,p)\times S_{CCD}(\theta,p)=I_{meas}(\theta,p),$$
$$T_{0-order}=I_{meas}(\theta,p)/R_{Si}(\theta,p)\Rightarrow R_{sample}(\theta,p)=I_{sample}(\theta,p)/T_{0-order}$$

Illumination path: use analyzer and PD to measure the intensity distribution $I_{PD}(\theta,\varphi,pol)$

$$\vec{E}_{PD}=\begin{bmatrix}PD_{ss} & 0\\ 0 & PD_{pp}\end{bmatrix}\cdot\begin{bmatrix}A_{ss} & A_{ps}\\ A_{sp} & A_{pp}\end{bmatrix}\cdot\begin{bmatrix}I_{xs} & I_{ys}\\ I_{xp} & I_{yp}\end{bmatrix}\cdot\begin{bmatrix}Ex\\ Ey\end{bmatrix}$$

Collection path: measure the intensity distribution $I_{CCD}(\theta,\varphi,pol)$

$$\begin{bmatrix}\sqrt{I_{PD}(\theta,\varphi,ss)}+\sqrt{I_{PD}(\theta,\varphi,ps)}\\ \sqrt{I_{PD}(\theta,\varphi,sp)}+\sqrt{I_{PD}(\theta,\varphi,pp)}\end{bmatrix}=\begin{bmatrix}PD_{ss} & 0\\ 0 & PD_{pp}\end{bmatrix}\cdot\begin{bmatrix}A_{ss} & A_{ps}\\ A_{sp} & A_{pp}\end{bmatrix}\cdot\begin{bmatrix}I_{xs} & I_{ys}\\ I_{xp} & I_{yp}\end{bmatrix}\cdot\begin{bmatrix}Ex\\ Ey\end{bmatrix}$$

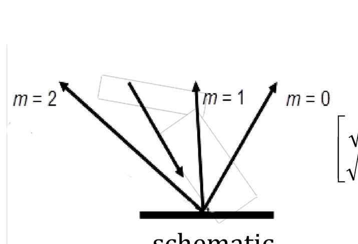
using a known Si reflector as sample

$$\begin{bmatrix}I_{xs} & I_{ys}\\ I_{xp} & I_{yp}\end{bmatrix}\cdot\begin{bmatrix}Ex\\ Ey\end{bmatrix}=\begin{bmatrix}A_{ss} & A_{ps}\\ A_{sp} & A_{pp}\end{bmatrix}^{-1}\cdot\begin{bmatrix}PD_{ss} & 0\\ 0 & PD_{pp}\end{bmatrix}^{-1}\cdot\begin{bmatrix}\sqrt{I_{PD}(\theta,\varphi,ss)}+\sqrt{I_{PD}(\theta,\varphi,ps)}\\ \sqrt{I_{PD}(\theta,\varphi,sp)}+\sqrt{I_{PD}(\theta,\varphi,pp)}\end{bmatrix}$$

$$\vec{E}_{CCD}=\begin{bmatrix}C_{ss} & C_{ps}\\ C_{sp} & C_{pp}\end{bmatrix}\cdot\begin{bmatrix}S_{ss} & S_{ps}\\ S_{sp} & S_{pp}\end{bmatrix}\cdot\begin{bmatrix}I_{xs} & I_{ys}\\ I_{xp} & I_{yp}\end{bmatrix}\cdot\begin{bmatrix}Ex\\ Ey\end{bmatrix}$$

$$\begin{bmatrix}\sqrt{I_{CCD}(\theta,\varphi,ss)}+\sqrt{I_{CCD}(\theta,\varphi,ps)}\\ \sqrt{I_{CCD}(\theta,\varphi,sp)}+\sqrt{I_{CCD}(\theta,\varphi,pp)}\end{bmatrix}=\begin{bmatrix}A_{ss} & A_{ps}\\ A_{sp} & A_{pp}\end{bmatrix}\cdot\begin{bmatrix}C_{ss} & C_{ps}\\ C_{sp} & C_{pp}\end{bmatrix}\cdot\begin{bmatrix}RSi_{ss} & RSi_{ps}\\ RSi_{sp} & RSi_{pp}\end{bmatrix}\cdot\begin{bmatrix}I_{xs} & I_{ys}\\ I_{xp} & I_{yp}\end{bmatrix}\cdot\begin{bmatrix}Ex\\ Ey\end{bmatrix}$$

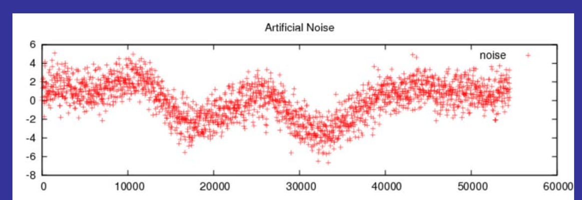
$$\begin{bmatrix}A_{ss} & A_{ps}\\ A_{sp} & A_{pp}\end{bmatrix} is \begin{bmatrix}1 & 0\\ 0 & 0\end{bmatrix},\begin{bmatrix}0 & 1\\ 0 & 0\end{bmatrix},\begin{bmatrix}0 & 0\\ 1 & 0\end{bmatrix},\begin{bmatrix}0 & 0\\ 0 & 1\end{bmatrix}$$



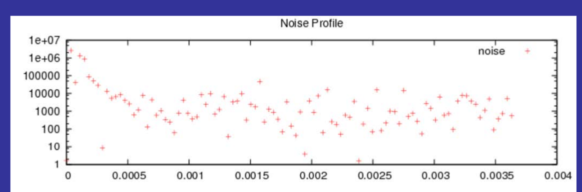
schematic

The Simulation Study

- Simulate a library of scattering profiles.
  - Angle-resolved and focus-resolved images
- Choose one in the center of the parameter space and add a systematic and random noise profile shown on the right.
  - Concatenate the data sets.
- Perform a standard regression analysis and determine uncertainties.



The noise added to simulate the experimental curves

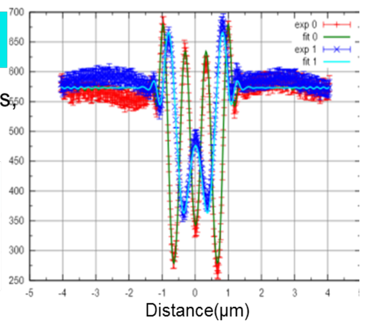


Realistic noise spectrum based on exp data.

Two simulation studies for finite gratings simulated using RCWA

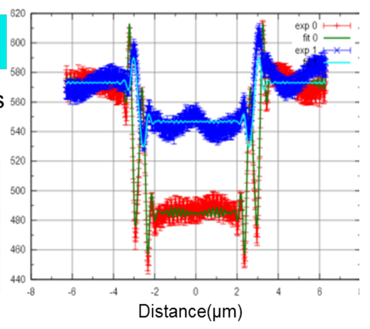
"L9P32" - 9 nm CD Si lines, 35 lines at 32 nm pitch.

	λ(nm)	top (nm)	mid (nm)	bot (nm)	height (nm)
Angle	450	1.09	1.06	1.61	0.25
TF	450	1.18	1.11	2.71	1.35



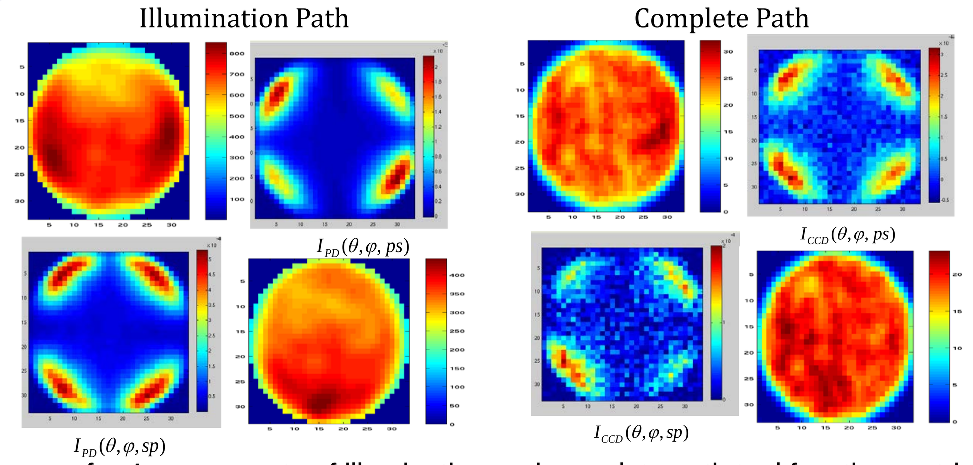
"L9P160" - 9 nm CD lines at 160 nm pitch

	λ(nm)	top (nm)	mid (nm)	bot (nm)	height (nm)
Angle	450	0.75	0.68	0.85	0.19
TF	450	0.94	0.48	0.98	0.65

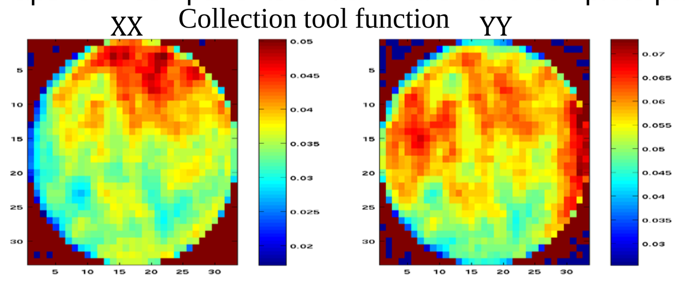


Each angle scan or through-focus scan consists of 84 concatenated profiles. The center graphics each show the best fit simulation curves for given "experimental" (noise-added simulation) curves for two polarizations at a selected focus or angle position.

Tool Functions

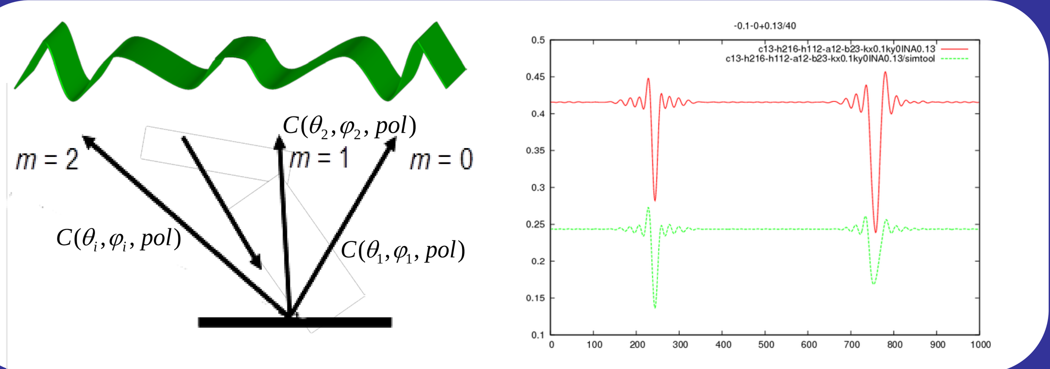


maps for 4 components of illumination and complete path tool function matrix



The color bars for the illumination and complete path are intensities with CCD units, and the color scales on the cross terms (XY and YX) are much less than those for the other plots.

Fourier Domain Normalization



- The incident illumination is independently normalized.
- Then the simulated data used to fit the experimental data are normalized in the frequency domain.
- The red curve shows uncorrected simulation data and the green shows the reconstructed image following Fourier normalization.

Linear Regression Model

With a Taylor expansion the nonlinear regression becomes

$$y_i=y(x_i;\vec{a}(0))+\sum_{k=1}^{K}\left[\frac{\partial y(x_i;\vec{a})}{\partial a_k}\right]_{\vec{a}=\vec{a}(0)}(a_k-a_k(0))+\varepsilon_i(0)$$

With initial set of floating parameters $\vec{a}(0)=\{a_1(0),\ldots,a_K(0)\}$

By re-parameterization, the model is expressed as

$$y_i(0)=\sum_{k=1}^{K}D_{ik}(0)\beta_k(0)+\varepsilon_i(0)$$

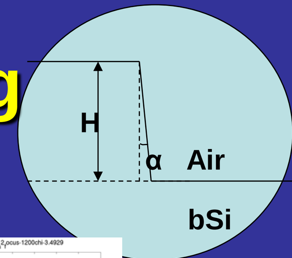
With $\beta_k(0)=a_k-a_k(0)$ and $D_{ik}(0)=\left[\frac{\partial y(x_i;\vec{a})}{\partial a_k}\right]_{\vec{a}=\vec{a}(0)}$

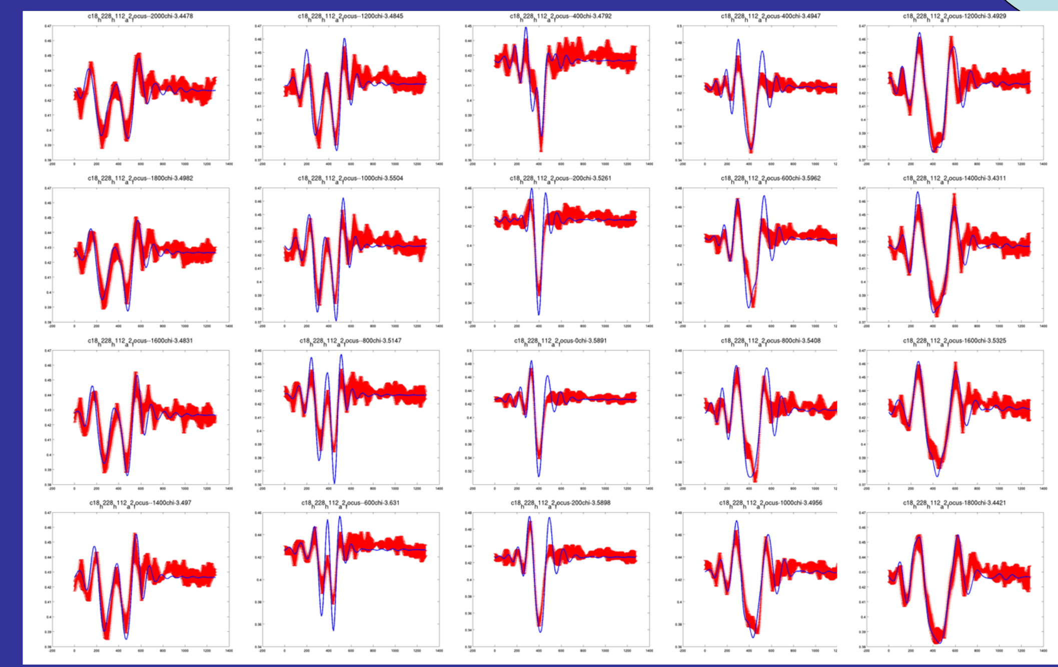
It can be shown that the generalized least squares estimator of $\beta(0)$ is now given by

$$\hat{\beta}(0)=\left(D(0)^T V^{-1}D(0)\right)^{-1}D(0)^T V^{-1}Y(0)$$

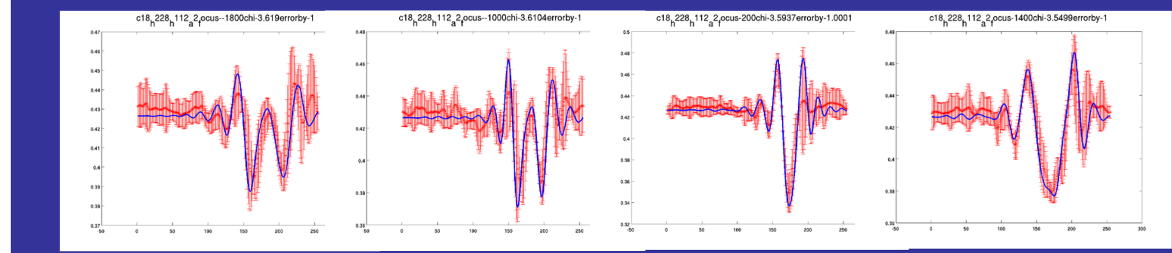
for the best K parameter estimates $\hat{\beta}(0)=\{\hat{\beta}_1(0),\ldots,\hat{\beta}_K(0)\}$

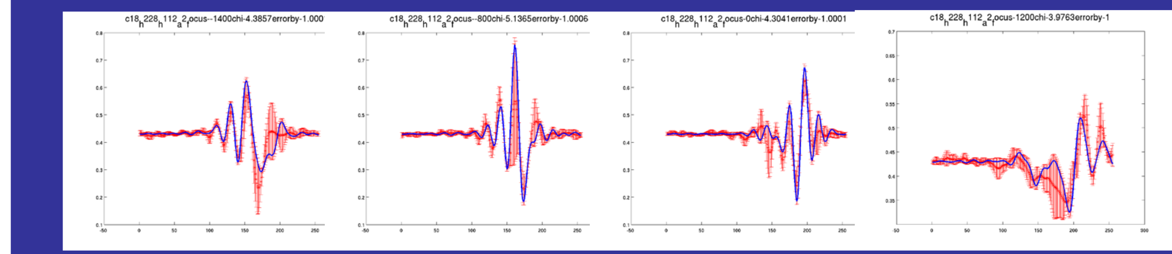
Simulation/Experiment Fitting Results of a Si Edge





These data show consistent theory to experiment agreement as a function of focus height throughout a 4 μm range using the full frequency domain normalization.





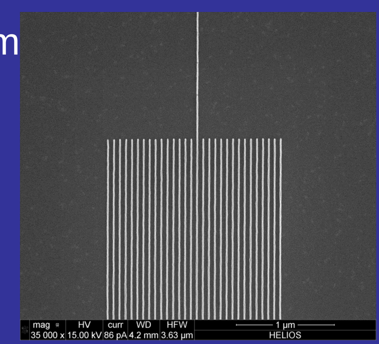
-2000nm -1000nm 200nm 1400nm

Best estimates for height and sidewall angle are (228 nm, 2°) with uncertainties of (0.08 nm, 0.03°)

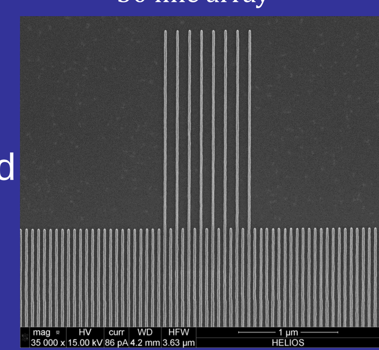
Note: Only two parameters floated, Figures in upper and lower rows are plotted using different scales.

Sub-20 nm CD Metrology Target

- Sets of nominally 14nm, 16 nm, and 18 nm lines were fabricated by SEMATECH based on NIST designs.
- Targets are Si on Si with a thin conformal oxide. Two wafers were fabricated using e-beam litho. One was cleaned and the other has residual SiOx ~ 2-3 nm.
- Line extensions were included to facilitate AFM measurements. Note AFM measurements may have a bias compared to dense area optical measurements.
- Current target sizes as small as 1.75 μm x 6 μm.

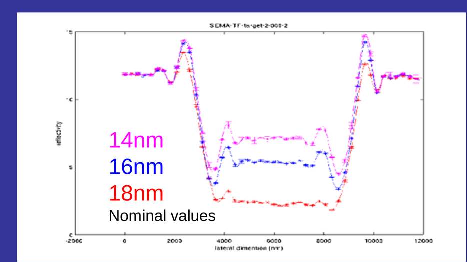


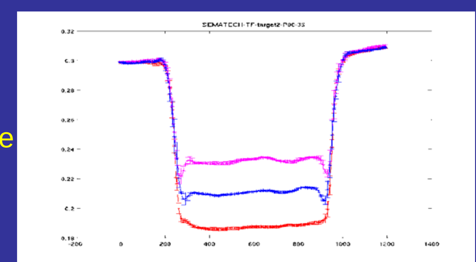
30 line array



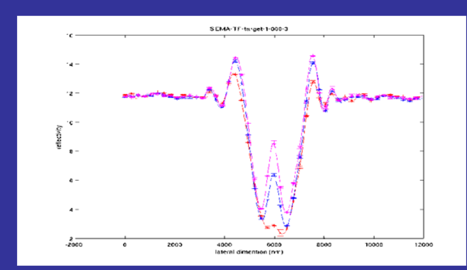
100 line array

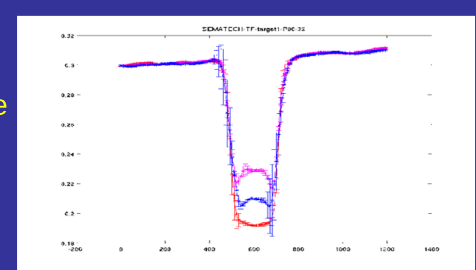
Experimental Sensitivity





100 line array





30 line array

450 tool x pol (along the lines) **193 tool x pol (along the lines)**

Type B Uncertainty Estimates

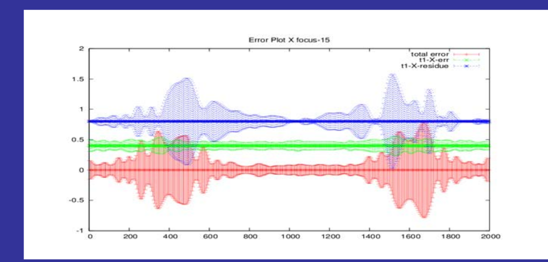
1. CCD pixel pitch uncertainty mapped into intensity variation
2. SiOx thickness uncertainty
3. Numerical Aperture size uncertainty 0.12~0.14
4. CBFP Aperture position uncertainty (incidence angle uncertainty)
5. Intensity variation due to through focus increment (4nm)
6. λ/10 random phase error with systematic phase errors mapped into intensity variation
7. Tool function repeatability error
8. Parametric modeling errors, physical parameterization

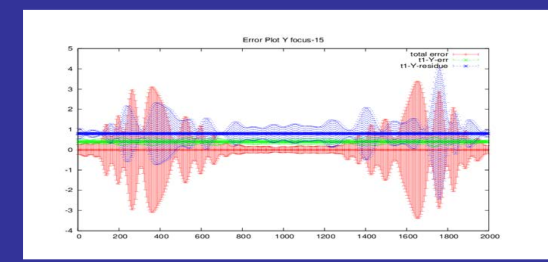
Type B errors are combined with experimental repeatability uncertainties

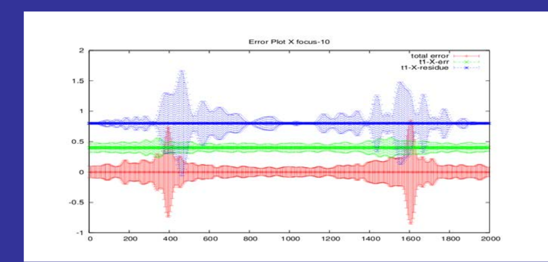
Uncertainties vs. Fitting Residuals

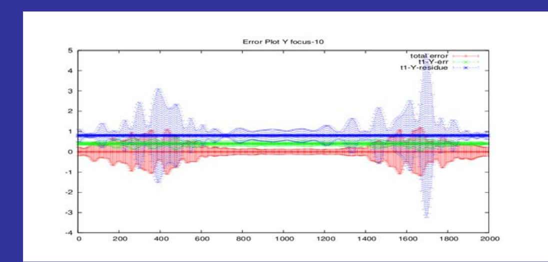
X polarization, z = 0, -1 mm

Y polarization, z = 0, -1 mm

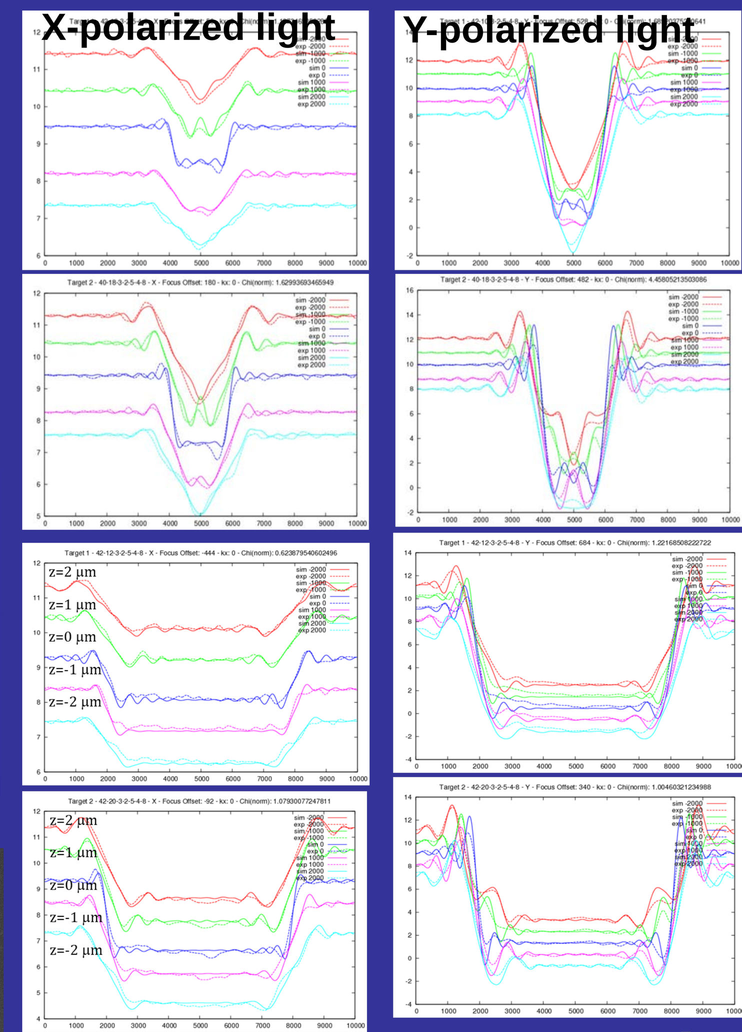








Fitting Results



30-line Dense Array

	Target 1	Target 2
Height (nm)	45 ± 0.180	43 ± 0.112
CD [1.0 h] (nm)	7	15
[0.8 h](nm)	11	19
[0.5 h] (nm)	14 ± 0.085	22 ± 0.043
[0.3 h] (nm)	16	24
[0.0 h] (nm)	24	32

100-line Dense Array

	Target 1	Target 2
Height (nm)	42 ± 0.024	45 ± 0.123
CD [1.0 h] (nm)	9	17
[0.8 h](nm)	13	21 ± 0.047
[0.5 h] (nm)	16 ± 0.017	24 ± 0.210
[0.3 h] (nm)	18	26
[0.0 h] (nm)	26	34

Conclusions

- **We have rigorously fit complex targets that scatter a broad range of frequencies using focus-resolved scatterfield microscopy.**
- **A comprehensive approach using Fourier normalization and field corrections was used to rigorously fit the data with no tunable parameters.**
- **Excellent uncertainties were obtained for the parameter fits shown here by using all of the phase and frequency information.**
- **This technique was validated for micrometer-sized dense targets.**
- **Microscope phase errors are embedded in the normalization.**
- **Next, we will compare with SEM and then use a Bayesian hybrid metrology formulation to optimize the measurements.**

Acknowledgements

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