Source-mask optimization (SMO): from theory to practice

Thuc Dam*, Vikram Tolani, Peter Hu, Ki-Ho Baik,
Linyong Pang, and Bob Gleason

Luminescent Technologies Inc.

Steven D. Slonaker and Jacek K. Tyminski

Nikon Precision Inc.

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Purpose

- As total CD control and overlay requirements approach 2 nm, any unaccounted aberrations in advance projection optics would harm error budgets!
- We conducted these experiments to determine whether accounting for aberrations during SMO could help.

1. Establish theoretical baseline by conducting SMO without aberrations to determine ideal parametric source & mask for contact patterns.

2. Determine lithographic impact of vector (Jones pupil) and scalar (Zernike) aberrations applied to SMO solution that was optimized without aberrations.

3. Conduct mask optimization without source optimization to correct for aberrations.

4. Conduct SMO (mask and source optimization) with Jones pupil and Zernike aberrations.

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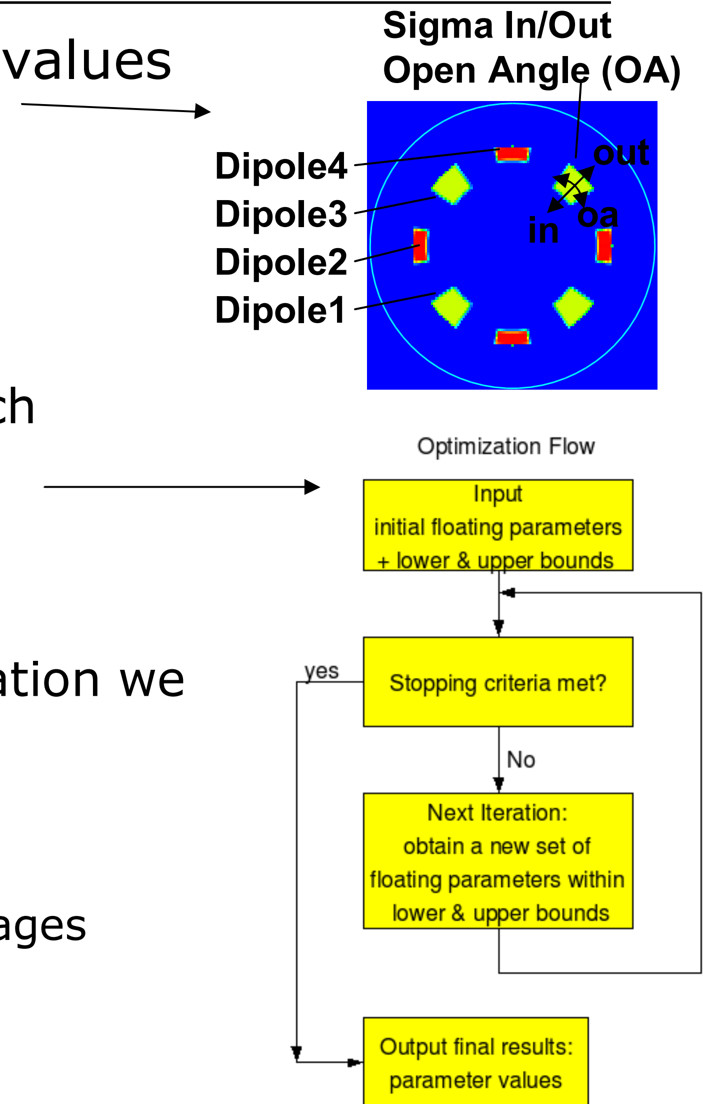
Derivative-Based Parametric Engine for Source Mask Optimization (SMO)

- User provides initial floating parameter values with lower & upper bounds
- Optimization engine Employs modified Levenberg-Marquardt method
  - Observes lower and upper bounds of each floating parameter at each iteration.
- Response Outputs:
  - For each clip's mask and source combination we computed center contact's line end
    - EPE,
    - MEEF at +/-1 nm mask bias
    - PV for nominal and +/-50 nm defocus images



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Cost Function for SMO

- Available optimize cost functions
  - Hamiltonian, ILS, MEEF, & EPE
  - Hamiltonian-based cost function was employed

$$\mathcal{H}(\varphi) = \int_{\Omega} |I^w(x,y) - T(x,y)|^2 dxdy$$

where I^w is a printed wafer image, T is the target, Ω is the wafer domain

For Mask optimization, the function φ is formulated as:

- $\{(x,y) : \varphi(x,y) > 0)\}$ region outside the mask (background or field)
- $\{(x,y) : \varphi(x,y) \leq 0)\}$ region inside the mask

For Source optimization, the function φ is formulated as:

- $\{(p,q) : \varphi(p,q) > 0)\}$ region where light pixels are OFF
- $\{(p,q) : \varphi(p,q) < 0)\}$ region where light pixels are ON

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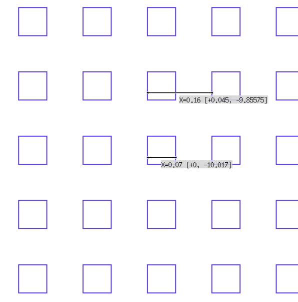
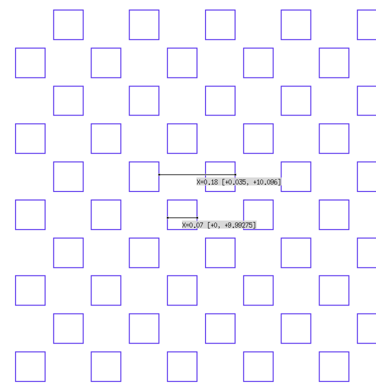
Design Patterns Used in Parametric SMO

- 2 CDs X 11 patterns = 22 total

type	target CD	pattern pitch	clip#
rect CH	70	160	1
rect CH	70	180	2
rect CH	70	200	3
rect CH	80	160	4
rect CH	80	180	5
rect CH	80	200	6
stagger CH	80	180	7
stagger CH	80	200	8
stagger CH	80	220	9
stagger CH	80	240	10
stagger CH	80	260	11
stagger CH	80	280	12
stagger CH	80	300	13
stagger CH	80	320	14
stagger CH	70	180	15
stagger CH	70	200	16
stagger CH	70	220	17
stagger CH	70	240	18
stagger CH	70	260	19
stagger CH	70	280	20
stagger CH	70	300	21
stagger CH	70	320	22



clip# 1



clip# 15

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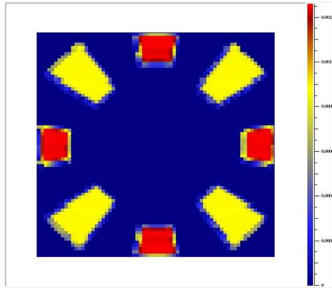
SMO Experiments with/without Aberrations

Initial Source Provided to Optimizer



Sources Obtained after Optimization

	No Aberrations	Jones Pupil	Zernike
No Polarization	SMO-NN	SMO-JN	SMO-ZN
w/XY Polarization	SMO-NP	SMO-JP	SMO-ZP

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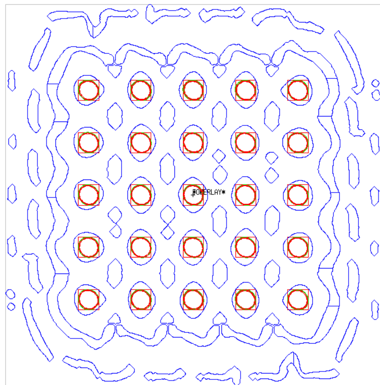
Illuminator and Mask Optimized without Aberrations



Clip2

SMO-NN mask

Fwd Imaged With:

No aberrations

100% dose & 0 nm defocus	100% dose & +/- 50 nm defocus
Mask: Clip2 SMO-NN_{msk}	Mask: Clip2 SMO-NN_{msk}
Source: SMO-NN_{src}	Source: SMO-NN_{src}

- SMO solution produces on target nominal image and defocus images that are symmetric.

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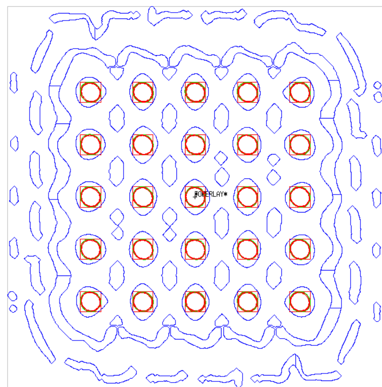
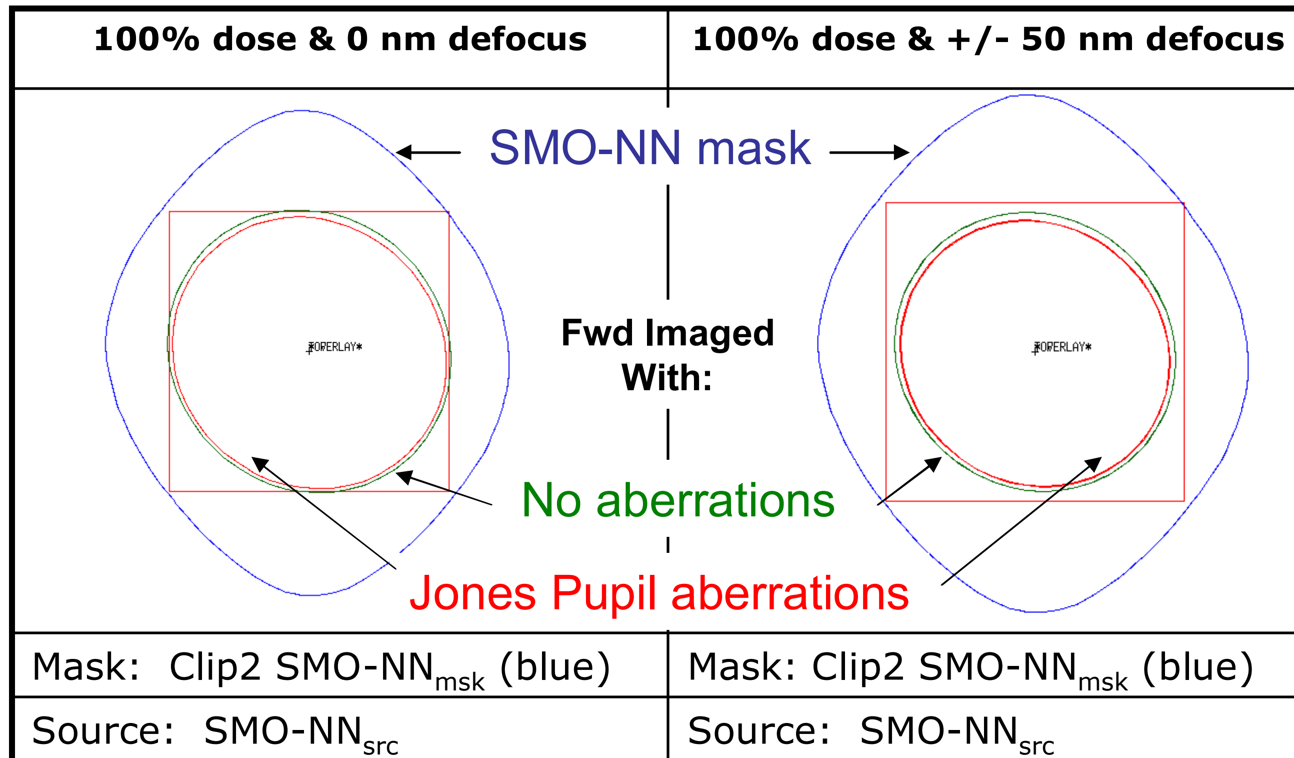
Images with Jones Pupil Aberrations not Included During Optimization



Clip2



- Adding Jones Pupil aberration during forward simulation of a fixed mask & source obtained from SMO with unaberrated unpolarized light can lead to image shrinkage at both nominal and defocus conditions.

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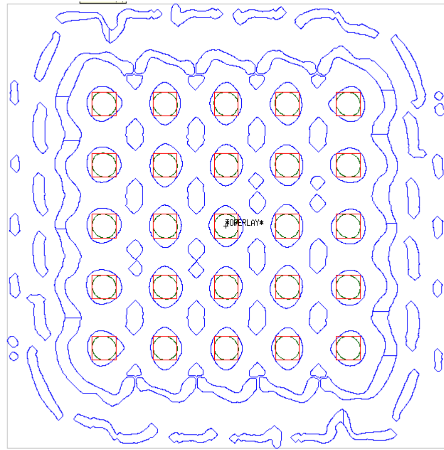
Images with Zernike Aberrations not Included During Optimization



Clip2

100% dose & 0 nm defocus	100% dose & +/- 50 nm defocus
Mask: Clip2 SMO-NN_{msk} (blue)	Mask: Clip2 SMO-NN_{msk} (blue)
Source: SMO-NN_{src}	Source: SMO-NN_{src}

SMO-NN mask

Fwd Imaged With:

No aberrations

Zernike aberrations

- Adding Zernike aberration during forward simulation of a fixed mask & source obtained from SMO with unaberrated unpolarized light can lead to image shift at both nominal and defocus conditions. At defocus, it can also introduce defocus asymmetry

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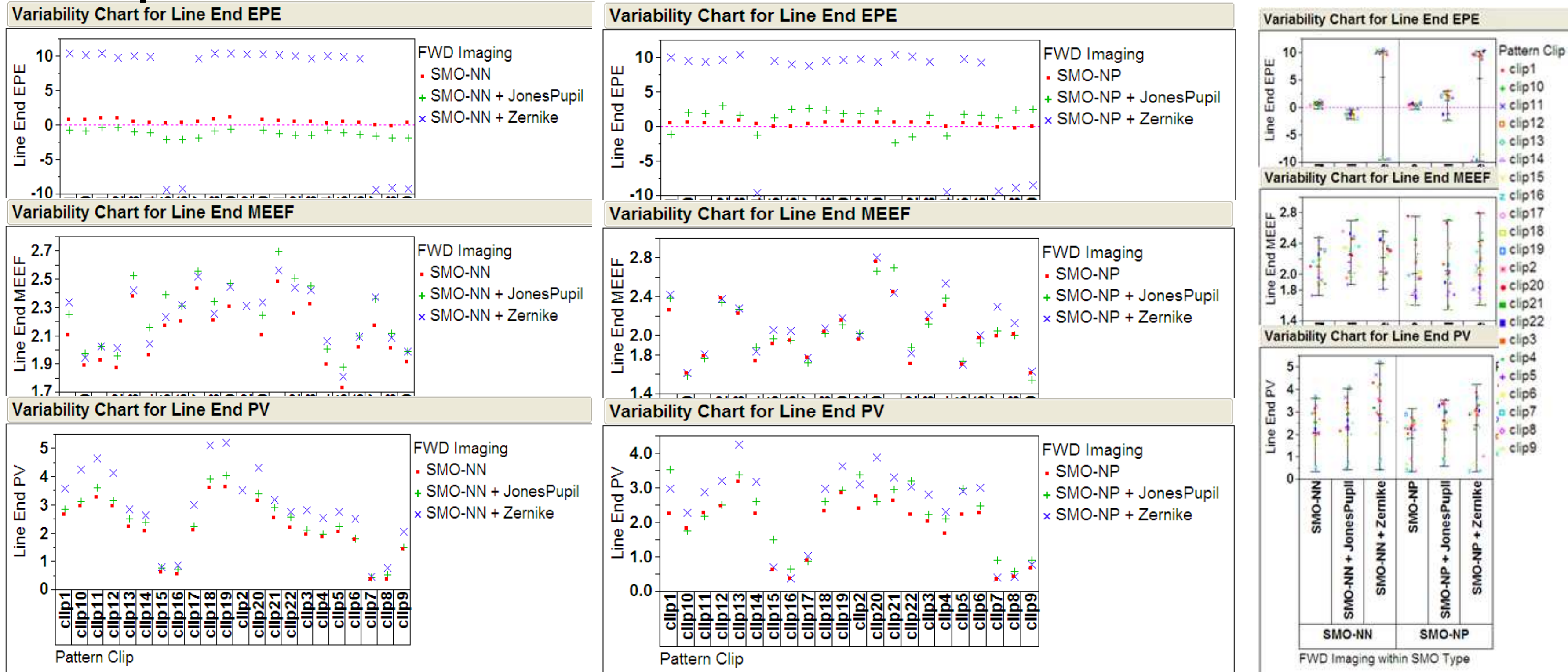
Image Statistics Using SMO Solution Computed without Aberrations



- Assess of 22 clips showed Zernike aberration manifest in significant EPE deviation as well as larger PV band.
- Jones Pupil aberrations do show minor EPE & PV shift.
- Aberrations do not seem to affect MEEF.
- XY polarized light do contribute to PV band improvements.

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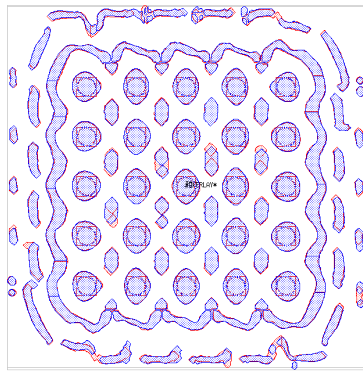
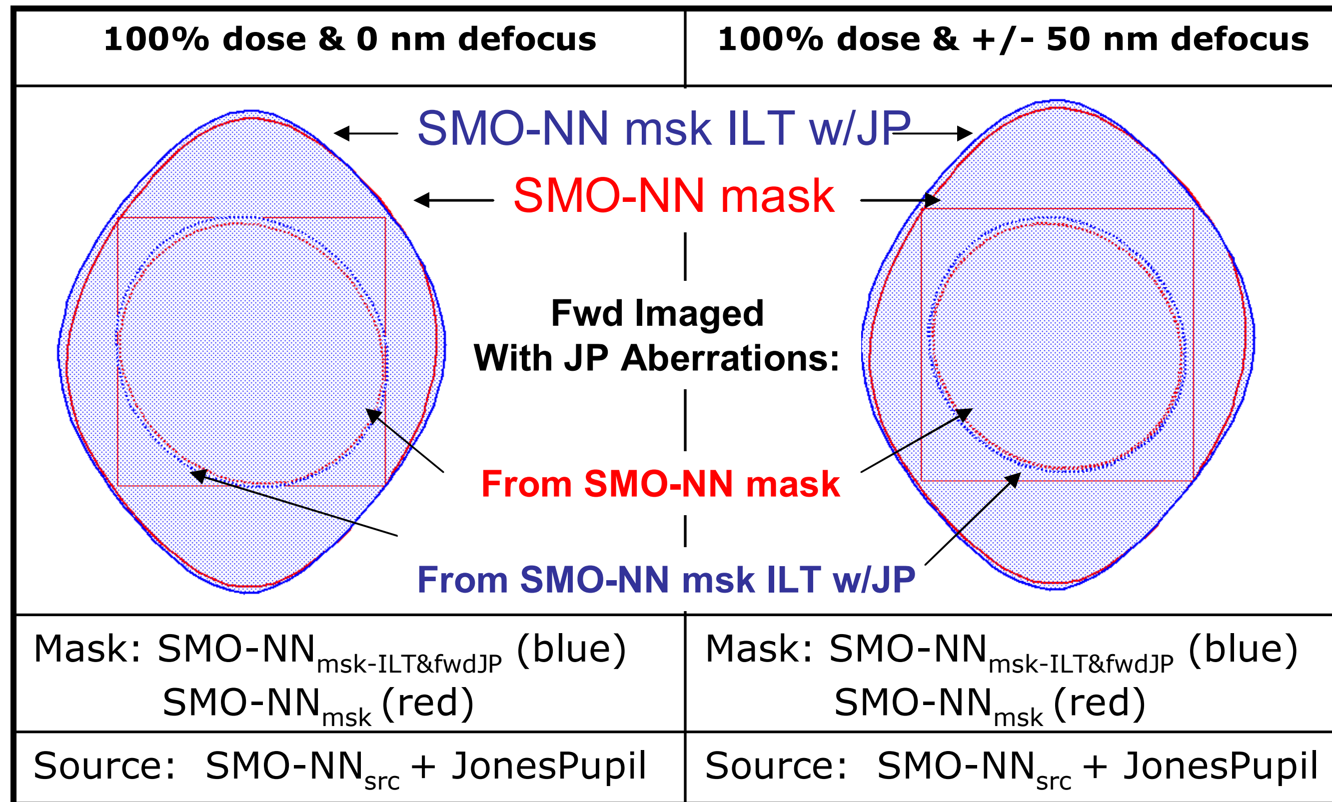
Illuminator Optimized without Aberrations, Mask Optimized with Jones Pupil Aberrations



Clip2



- Mask inversion with Jones Pupil in forward simulation engine can correct for image shrinkage.
- Blue mask grows larger to compensate for Jones Pupil effect of image shrinkage.

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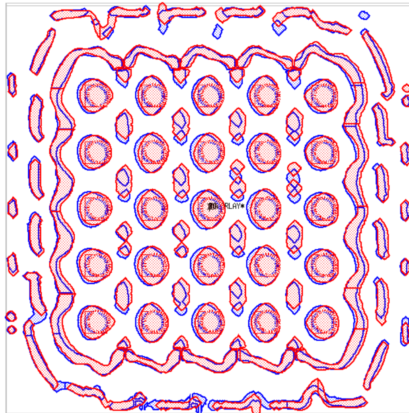
Illuminator Optimized without Aberrations, Mask Optimized with Zernike Aberrations



Clip2

SMO-NN msk ILT w/Zern

SMO-NN mask

Fwd Imaged With Zernike Aberrations:

From SMO-NN mask

From SMO-NN msk ILT w/JP

100% dose & 0 nm defocus	100% dose & +/- 50 nm defocus
Mask: $\text{SMO-NN}_{\text{msk-ILT\&fwdZern}}$ (blue) $\text{SMO-NN}_{\text{msk}}$ (red)	Mask: $\text{SMO-NN}_{\text{msk-ILT\&fwdZern}}$ (blue) $\text{SMO-NN}_{\text{msk}}$ (red)
Source: $\text{SMO-NN}_{\text{src}}$ + Zernike	Source: $\text{SMO-NN}_{\text{src}}$ + Zernike

- Mask inversion with Zernike in forward simulation engine can correct for lateral image shift, but not defocus asymmetry.
- Blue mask shifted to left to correct for Zernike effect of shifting image to the right.

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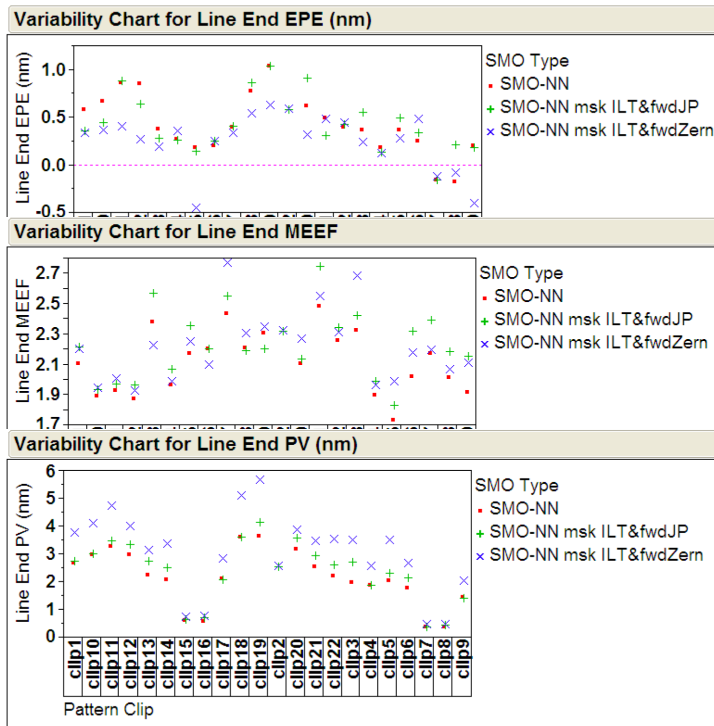
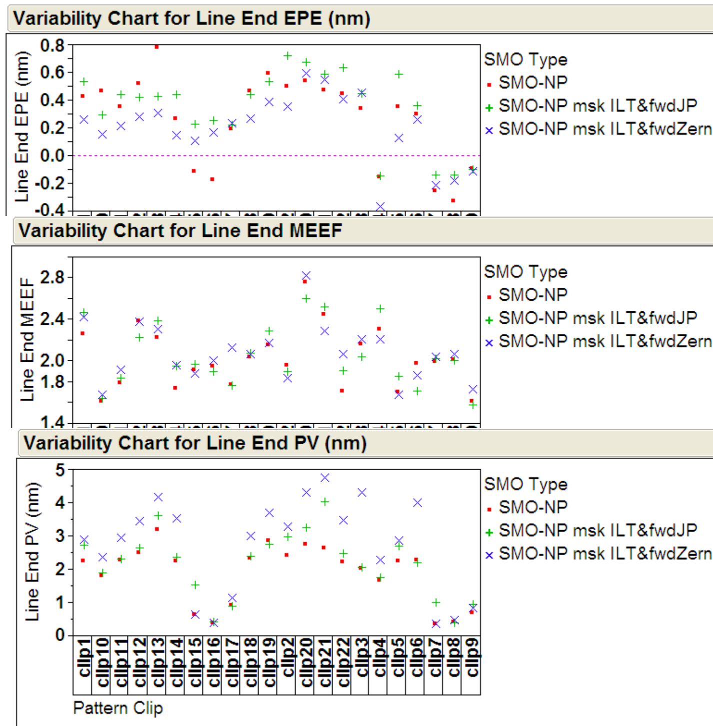
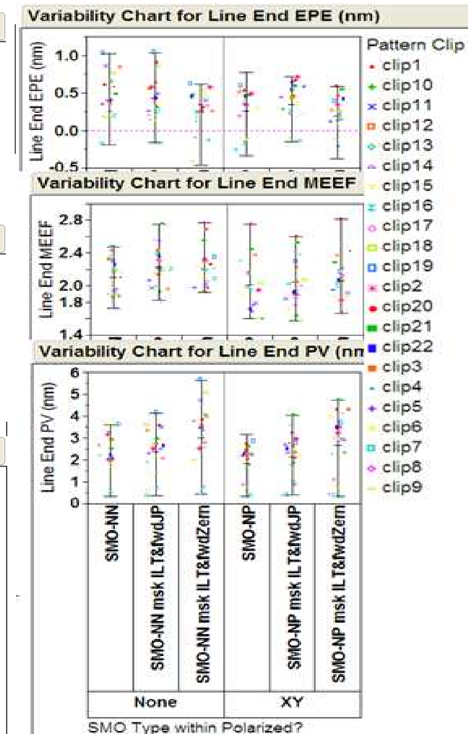
Image Statistics Using Aberrations Only for Mask Optimization

Unpolarized | XY Polarized | Distribtion Plots







- Mask inversion with aberrations can correct for the image shift and shrinkage caused by Zernike and Jones pupil without any impact on MEEF.
- PV band performance cannot be recovered by mask inversion alone with the Zernike aberrations.
- XY polarized light can improve PV band performance when Zernike aberrations are present

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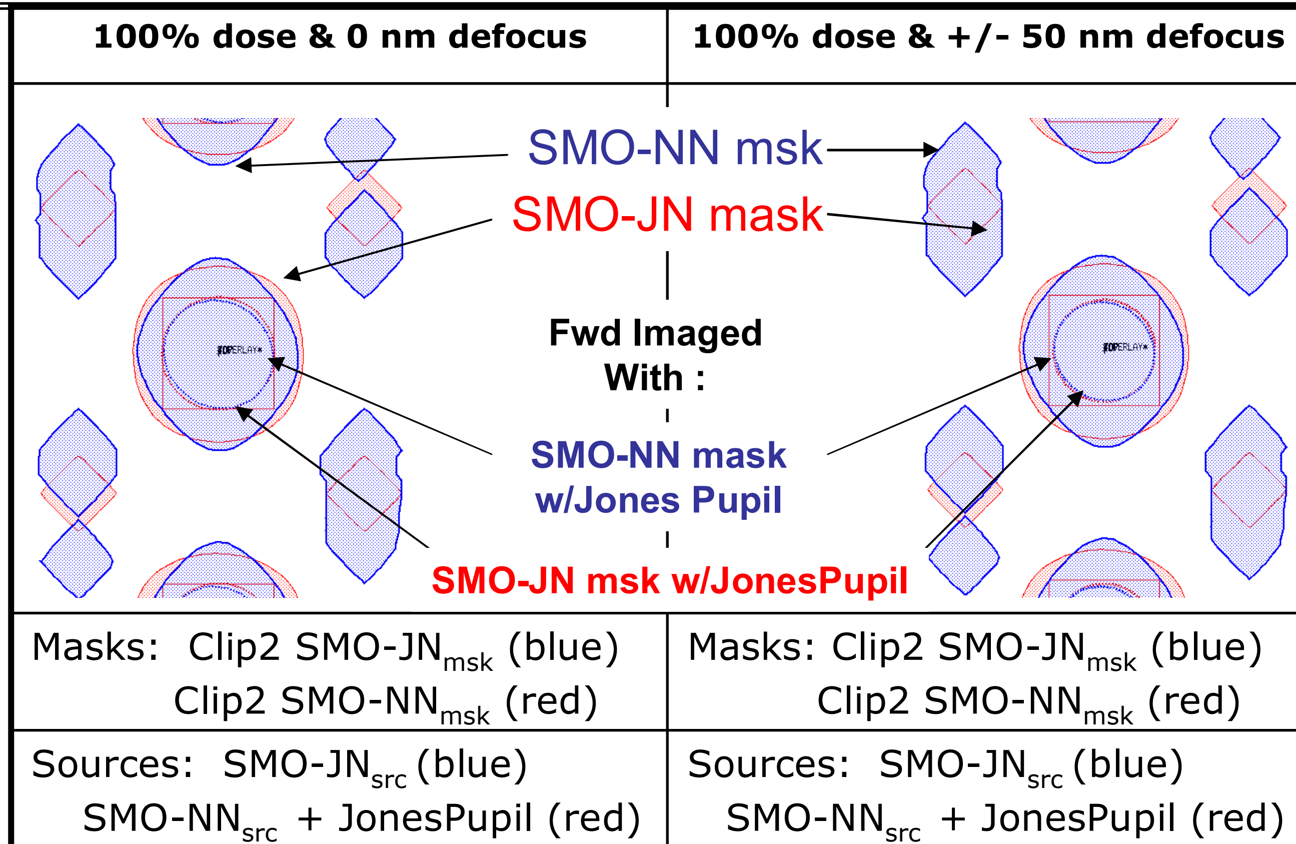
Jones Pupil Aberrations Used to Optimize both Illuminator and Mask



- Including Jones Pupil aberration in SMO can generate source & mask that can correct for image shrinkage.
- Both nominal and defocus images can be corrected.
- SMO-JN masks is larger to compensate image shrinkage from Jones Pupil effects.

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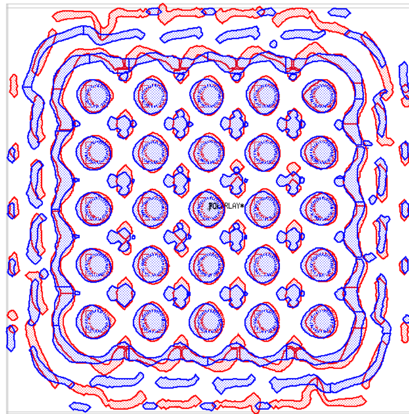
Zernike Aberrations Used to Optimize both Illuminator and Mask



Clip2

100% dose & 0 nm defocus	100% dose & +/- 50 nm defocus
SMO-ZN msk; SMO-NN mask; Fwd Imaged With :; SMO-NN mask w/Zernike; SMO-ZN msk w/Zernike	
Mask: Clip2 SMO-ZN_{msk} (blue) Clip2 SMO-NN_{msk} (red)	Mask: Clip2 SMO-ZN_{msk} (blue) Clip2 SMO-NN_{msk} (red)
Source: SMO-ZN_{src} (blue) SMO-NN_{src} + Zernike (red)	Source: SMO-ZN_{src} (blue) SMO-NN_{src} + Zernike (red)

- Including Zernike aberration in SMO can generate source & mask that can correct for image shift.
- Defocus asymmetry remains. May possibly be corrected by focal plane adjustment.

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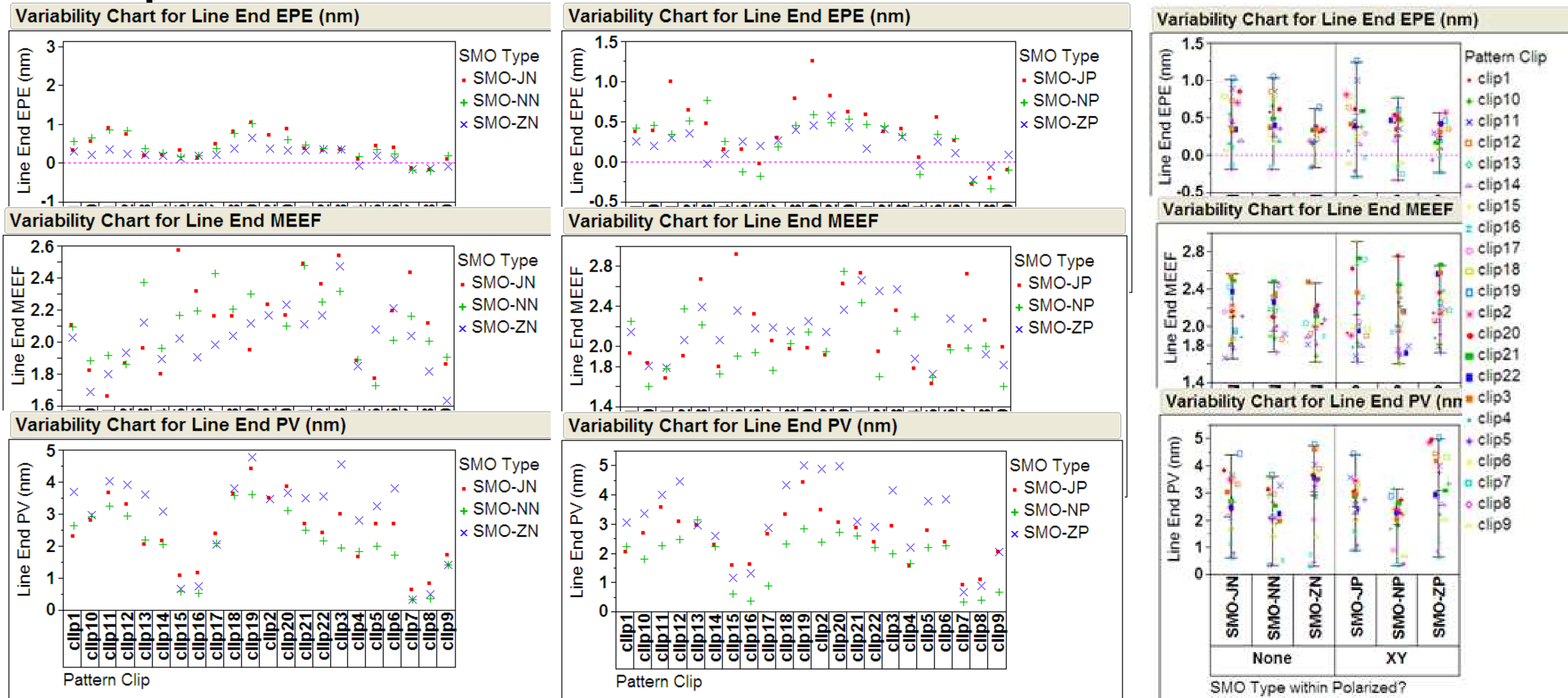
Image Statistics Using Aberrations to Optimize Both Illuminator and Mask



- SMO with aberrations can lead to converged images, and very little impact on MEEF.
- PV is best for the unaberrated case, while the Zernike aberrations appear difficult to correct.
- XY polarization had little effect on SMO conducted with aberrations

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Conclusions

- Accounting for aberrations during SMO process can produce solutions whose lithographic performance is close to that of the ideal unaberrated case.
- Even with such large aberrations, which shift and distort the nominal image contour up to 10 nm, we obtain good solutions both in and out of focus by properly accounting for the aberrations during source and mask co-optimization (SMO).
- Some aberrations effects such as image shrinkage and shifts can be mitigated with mask optimization alone as well.

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