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Exploring the crucial role of mask3D-induced imaging mechanisms in high- and hyper-NA EUV lithography: a study of the near- and far-field of the diffracted light

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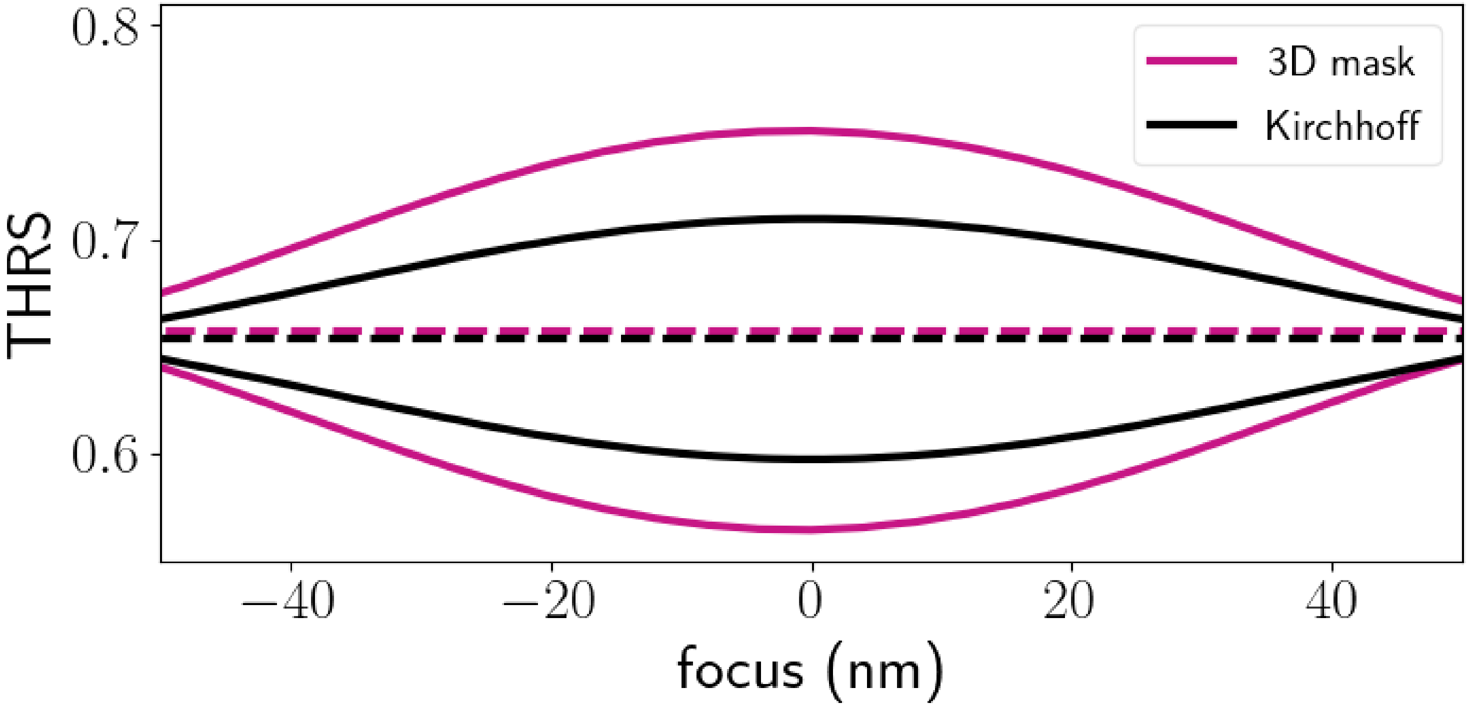
Dr. LiTHO
Lithography
Simulation

Comparison of simulated process windows

Data obtained with a Kirchhoff mask model (thin mask) and with a 3D mask

Settings:

- target: 4.5nm L/S, pitch=9nm
- NA=0.85, 4×/8×
- polarized pencil dipole at telecentric setting



- ➢ For which imaging scenario does this happen?
- ➢ Why can it happen?
- ➢ Which absorber required?

THRS: threshold-to-size

Outline

- Comparison of Kirchhoff and 3D mask performance for single source point illumination
- Investigation of root causes
- Impact of absorber shape
- Conclusions and outlook

Rules of the game: considered system and objectives

L/S imaging at the resolution limits of a fictive hyper NA system

Settings:

- **NA = 0.85**, 4×/8×, CRAO = 7.5°
- target: 4.5 nm L/S, **pitch = 9** nm (k_1 = 0.283)
- polarized illumination
  - single source point (SP) at telecentric setting
  - single pencil or dipole pencil at telecentric setting
- mask:
  - **Kirchhoff** (without double diffraction):
    - fixed clear reflectivity: $r_F = 0.7$, $\phi_F = 0°$
    - variable absorber reflectivity: $r_B = R * 0.7$ with R <= 20%, $\phi_B = 180°$

or

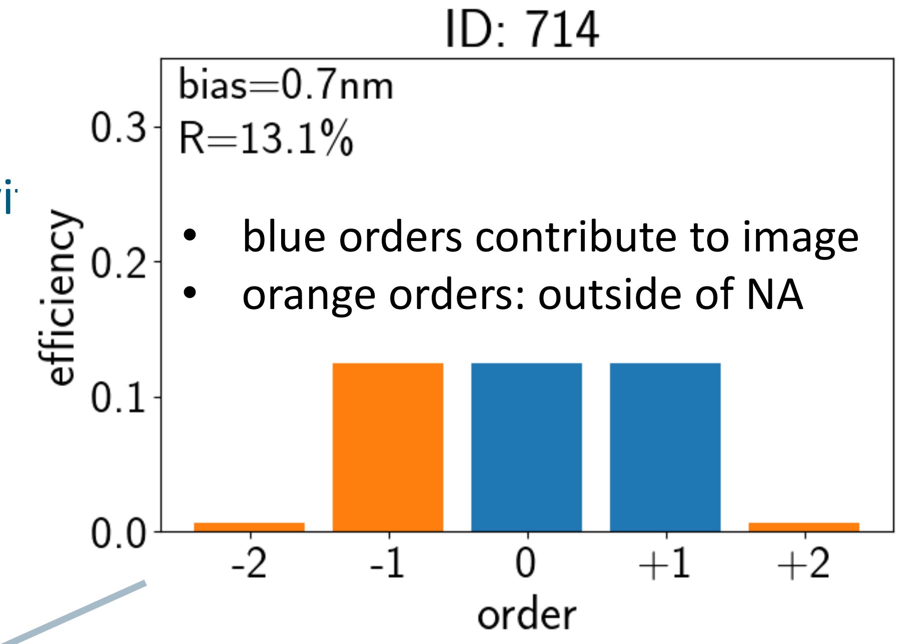
- **3D**:
  - low-n, low-k (n = 0.9, k = 0.02)
  - variable thickness in range 40 nm – 100 nm
  - basic Mo/Si: 40 bilayers of 3.31 nm Mo & 3.82 nm Si, 3.5 nm Ru capping

Objectives:

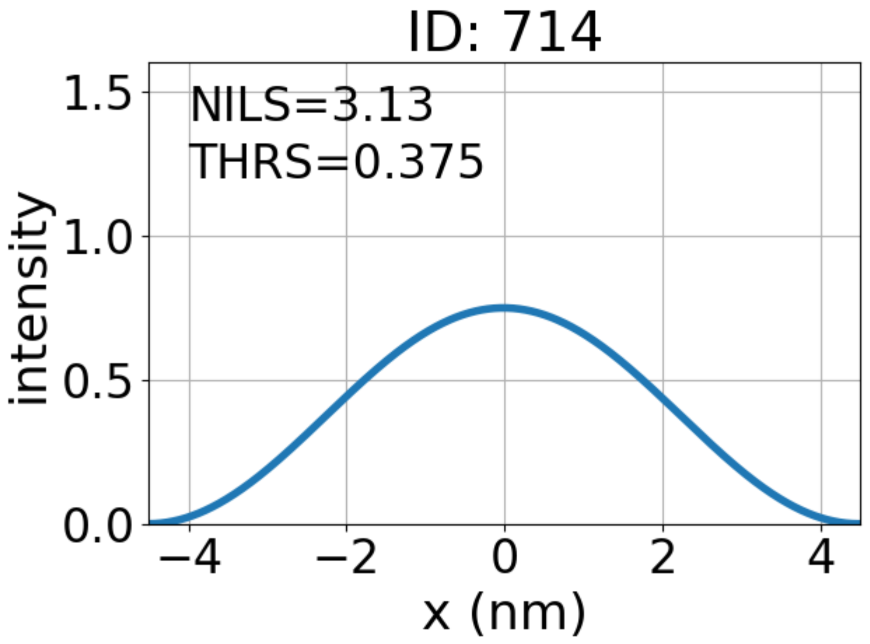
- print features with highest contrast / normalized-image-log-slope (NILS) **and** threshold-to-size (THRS)
- compare achievable performance for different assumptions on mask

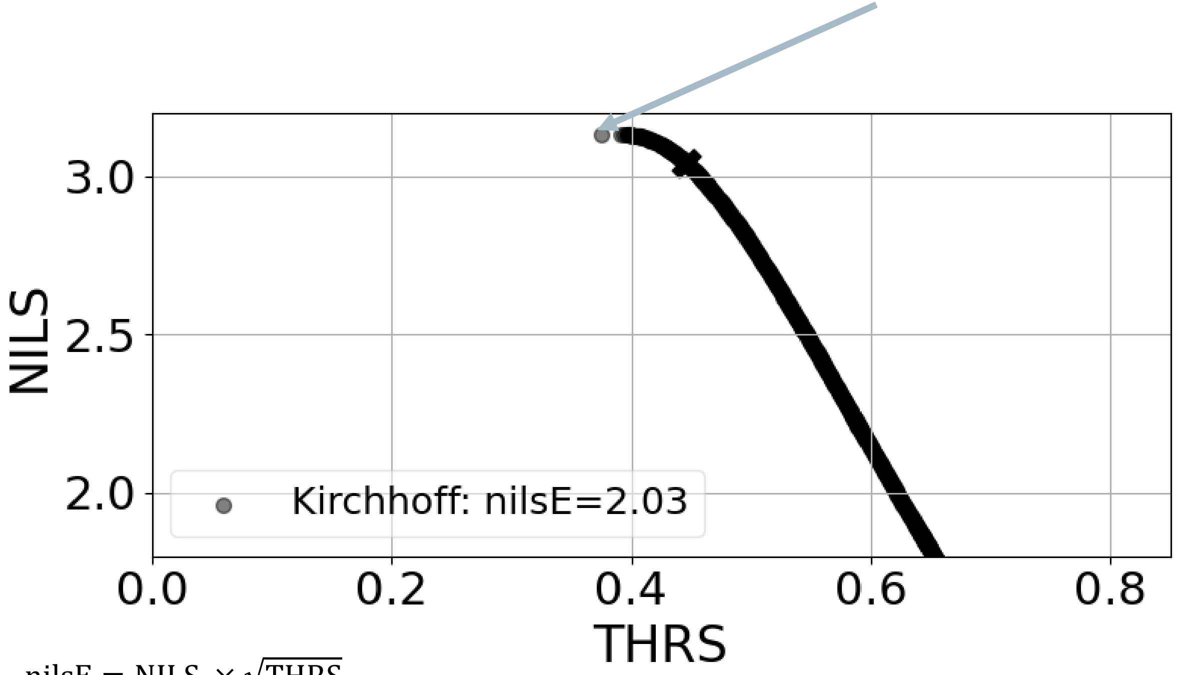
Kirchhoff mask: HOR L/S

Variation of bias and reflectivi



- blue orders contribute to image
- orange orders: outside of NA



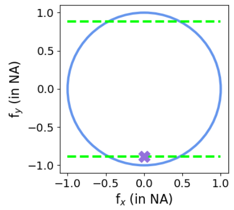


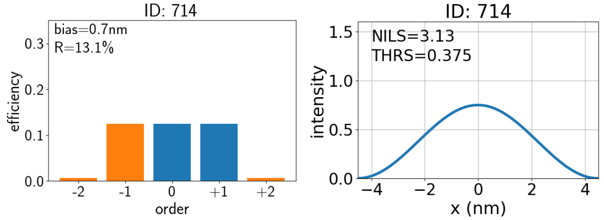
$$\text{nilsE} = \text{NILS} \times \sqrt{\text{THRS}}$$

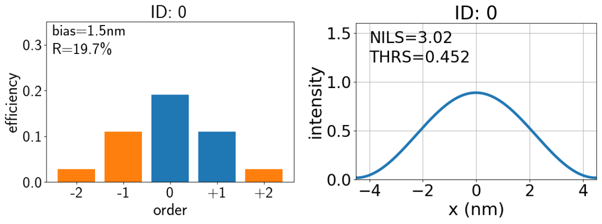
Kirchhoff mask: single source point

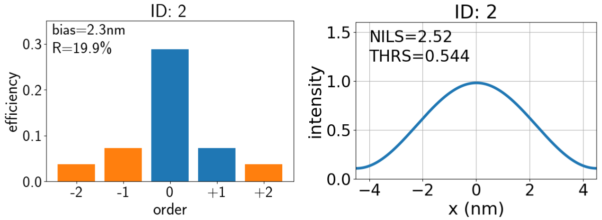
Variation of bias and reflectivity (R<=20%)

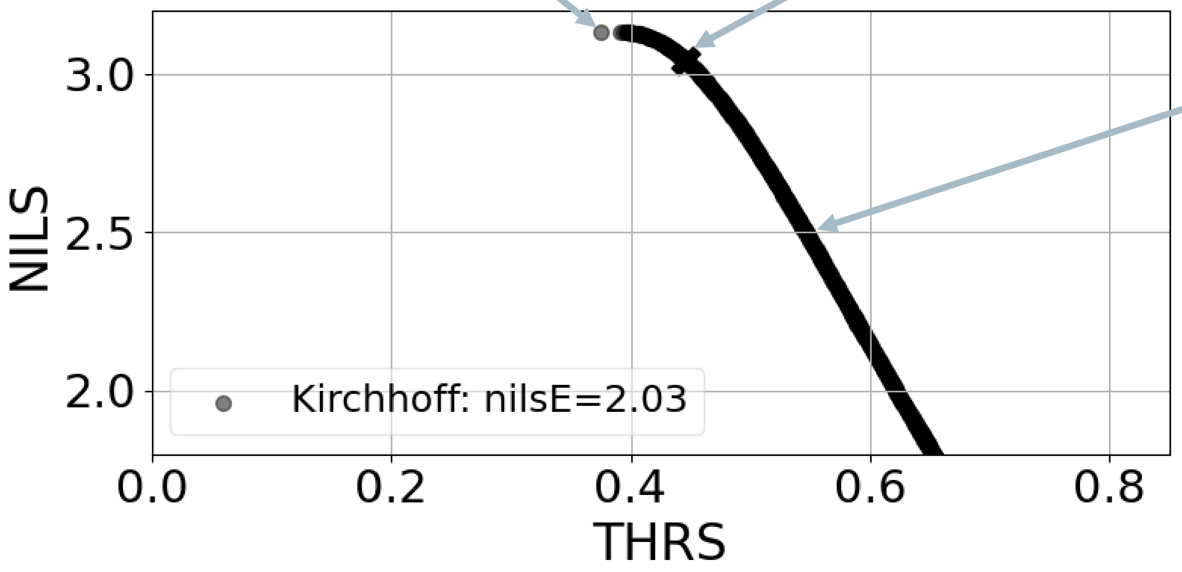
illumination:
single source point







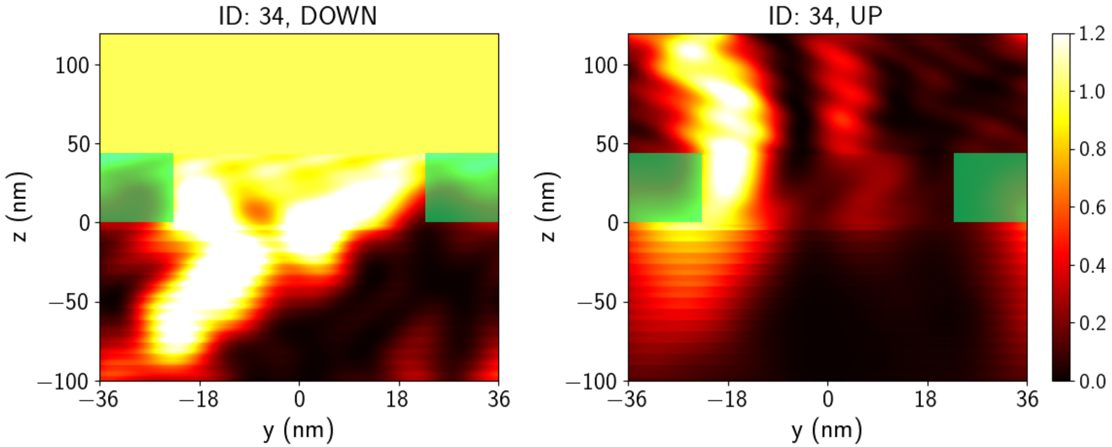


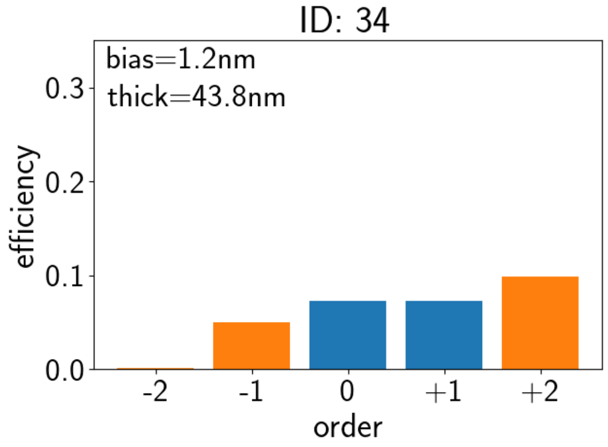


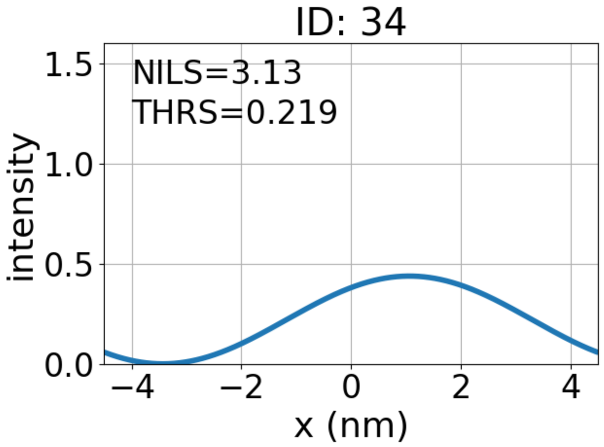
- ➢ Tradeoff between NILS and THRS is limited by
  - symmetric distribution to orders
  - coupling of light to orders outside projector NA
- ➢ Pareto exhibits best tradeoff, but not unique solution

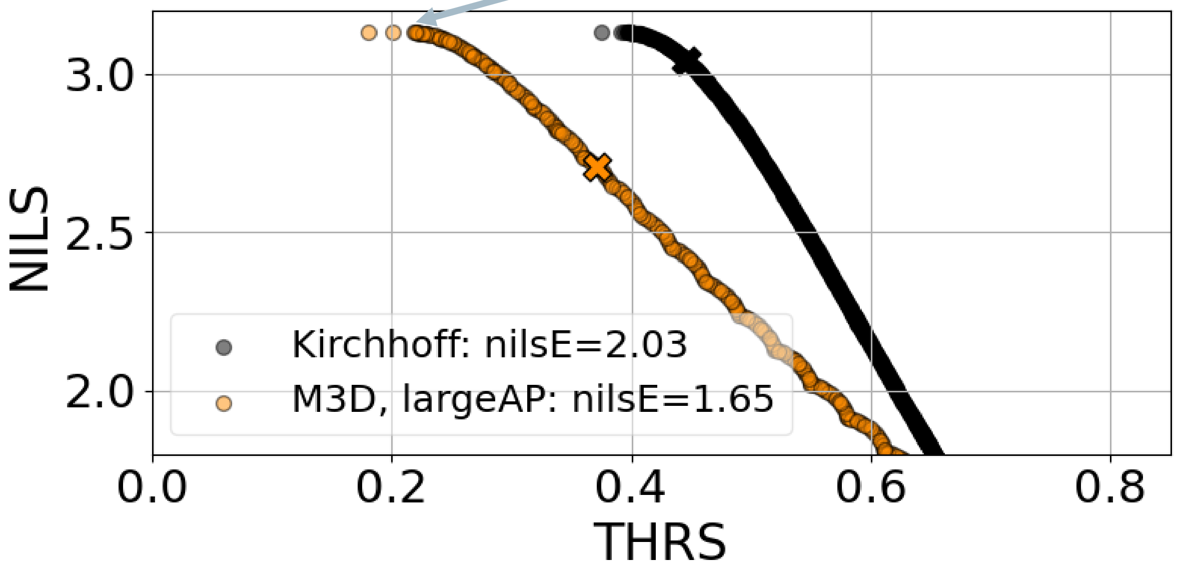
3D

Va


ID: 34, DOWN
ID: 34, UP
z (nm)
y (nm)
100
50
0
−50
−100
−36
−18
0
18
36
1.2
1.0
0.8
0.6
0.4
0.2
0.0


ID: 34
bias=1.2nm
thick=43.8nm
efficiency
0.3
0.2
0.1
0.0
-2
-1
0
+1
+2
order

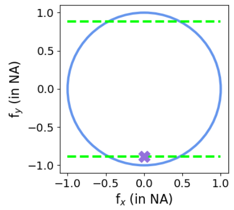

ID: 34
NILS=3.13
THRS=0.219
intensity
1.5
1.0
0.5
0.0
−4
−2
0
2
4
x (nm)

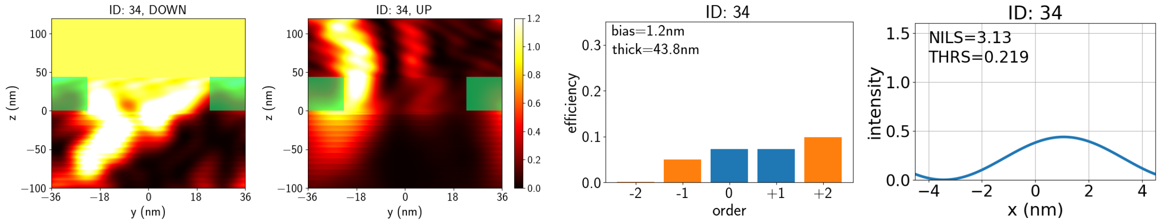

NILS
3.0
2.5
2.0
0.0
0.2
0.4
0.6
0.8
THRS
Kirchhoff: nilsE=2.03
M3D, largeAP: nilsE=1.65

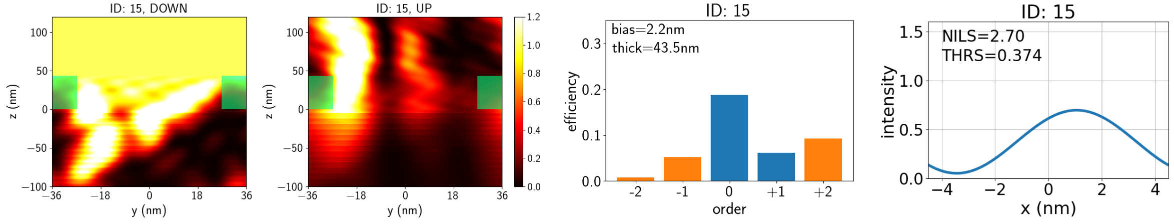
3D mask: HOR L/S

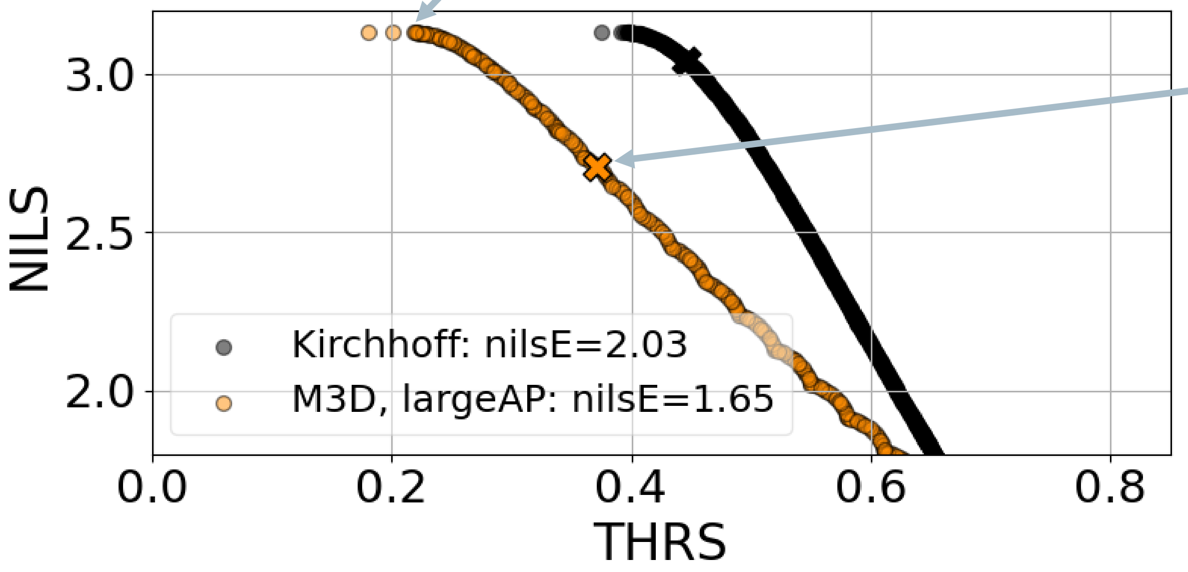
Variation of bias and absorber thickness (40nm – 100nm)

illumination:
single source point
large angle pole (largeAP)







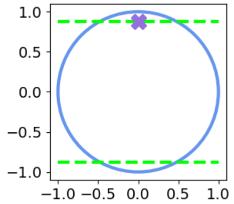


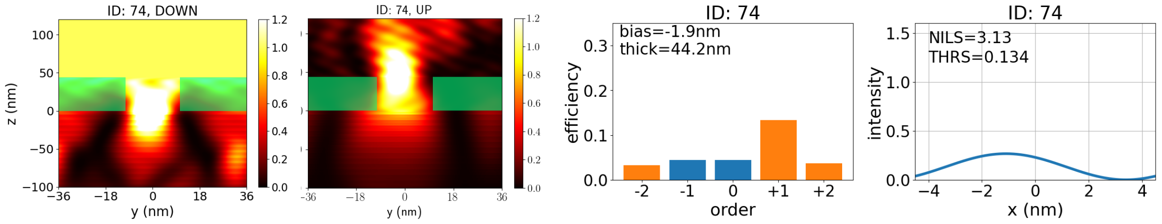
- Worse tradeoff compared to Kirchhoff
- Balancing of orders requires attenuation of zero order
- Reflected light only from the left part of opening
- Large image shifts

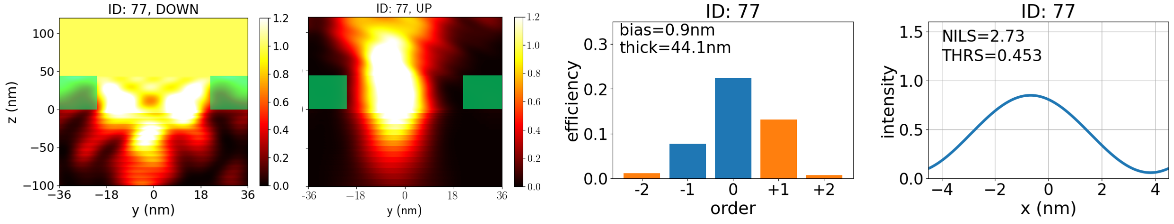
3D mask: HOR L/S

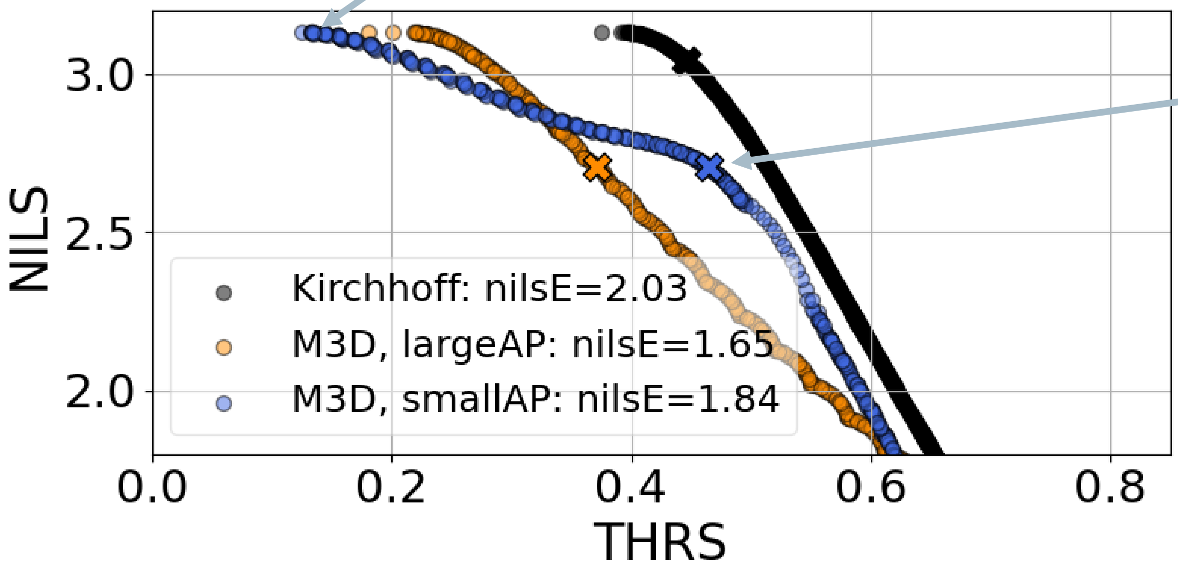
Variation of bias and absorber thickness (40nm – 100nm)

illumination:
single source point
small angle pole (smallAP)







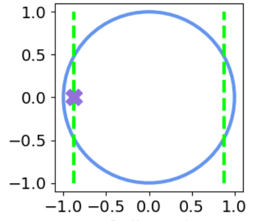


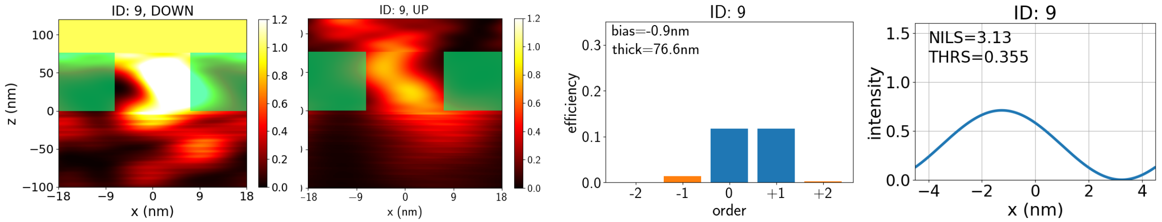
- ➢ Slightly worse tradeoff compared to Kirchhoff
- ➢ Balancing of orders requires attenuation of zero order
- ➢ Reflected light almost symmetric inside opening
- ➢ Small or no image shifts

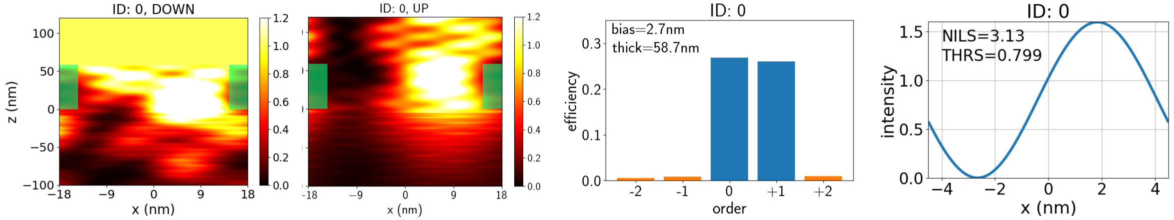
3D mask: VER L/S

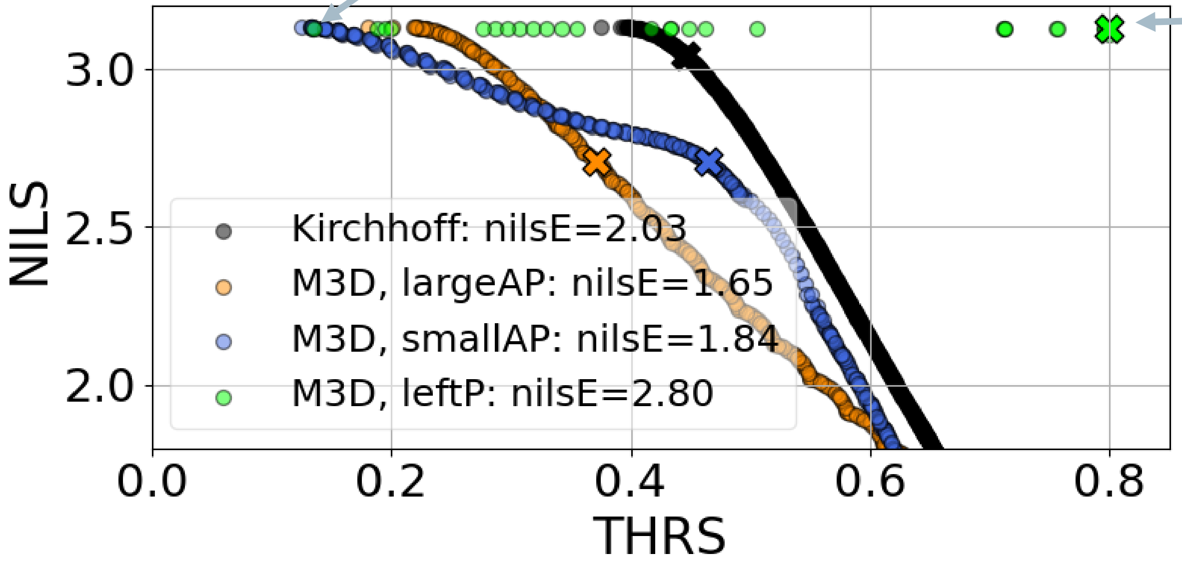
Variation of bias and absorber thickness (40nm – 100nm)

illumination:
single source point
left pole (leftP)*









- Almost no tradeoff between NILS and THRS
- Balancing of orders without attenuation of zero order
- Thick absorbers with large NILS and THRS on Pareto, large to very large positive bias
- Reflected light asymmetric inside absorber opening

**right pole provides identical results for -1st and 0th order with opposite image shift*

Comparison of Kirchhoff and 3D mask performance for single source point illumination

Summary of observations

- Very strong impact of feature orientation

- 3D mask for VER L/S can perform significantly better than Kirchhoff mask
  - Almost no tradeoff between achievable NILS and THRS
  - Balancing of orders achievable for absorbers with thickness > 50nm
  - Coupling of light to orders outside projector NA can be (almost) suppressed
  - Potential issue: significant opposite image shifts for left/right poles

- 3D mask for HOR L/S perform worse than Kirchhoff mask
  - Significant tradeoff between achievable NILS and THRS
  - Balancing of orders requires attenuation of zero order and comes with low THRS
  - Best performance for absorbers with thickness < 45nm

➢ What causes this different behavior of VER and HOR L/S?
➢ Can we do something to improve the performance of HOR L/S?

Outline

- Comparison of Kirchhoff and 3D mask performance for single source point illumination
- Investigation of root causes
- Impact of absorber shape
- Conclusions and outlook

Why do ver/hor features behave differently?

A mode coupling perspective for telecentric illumination

● vertical incidence

telecentric illumination

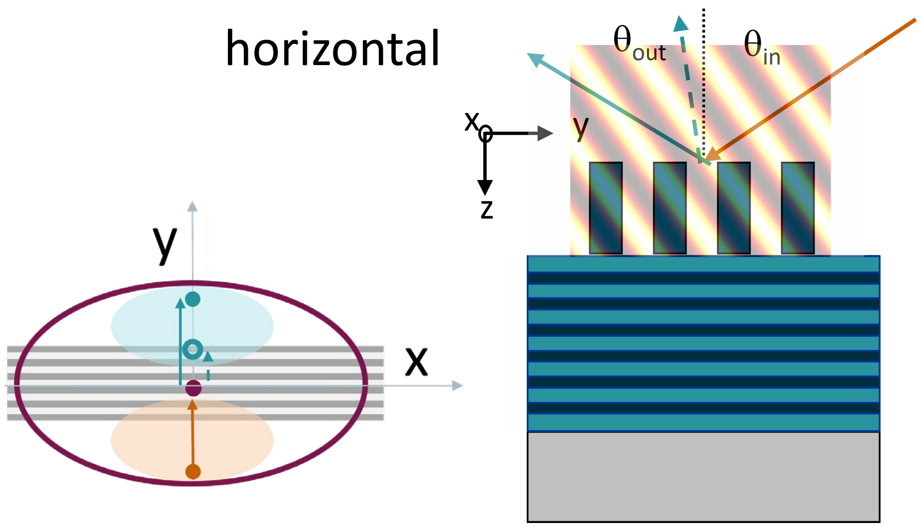
0th order

1st order

projection

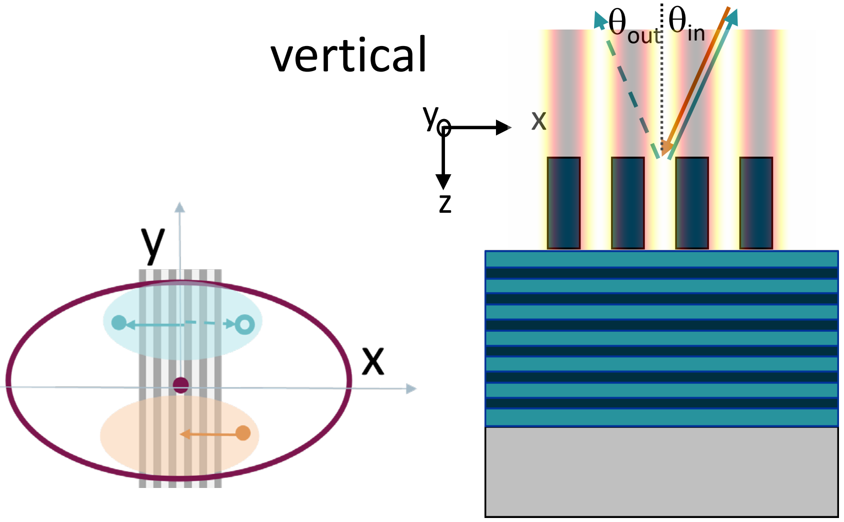
illumination

interference pattern created by 0th and 1st order



Tilt between interference pattern and absorber lines

- ➢ mismatch with waveguide modes



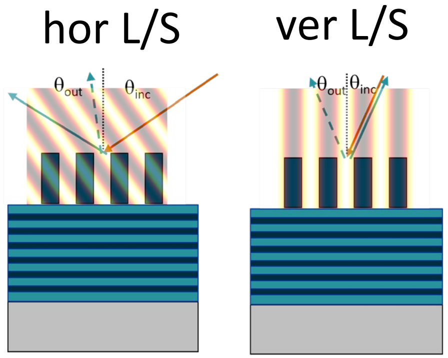
Interference of 0th and -1st order parallel wrt. absorber lines:

- ➢ perfect phase match with waveguide modes*

Why do vertical and horizontal features behave differently?

Thick EUV absorbers behave similar to volume holograms

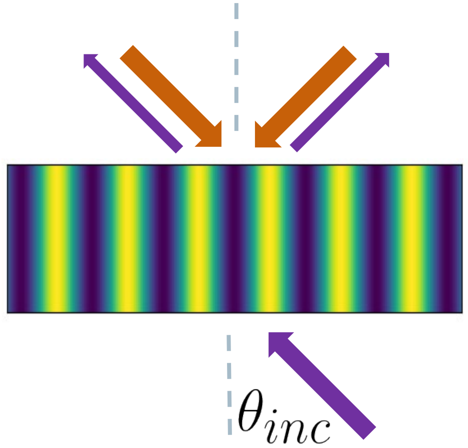
EUV mask



- low- masks provid arge mod ation of n
- smal r pitches incr se aspe ratio d / pitc

$$\zeta_{HOR}>0 \qquad \zeta_{VER}=0$$

“Perfect” volume grating



- grating obtained by recording of the interference between two plane waves
- sinusoidal modulation of the refractive index
- thickness / period > 1

Kogelnik coupled wave theory

analytical expression for diffraction efficiency

$$\eta = \frac{\left(\sin\sqrt{\frac{\kappa^2 d^2}{c_R \cdot c_S} + \frac{d^2\zeta^2}{4c_S^2}}\right)^2}{1 + \frac{\zeta^2 c_R}{4c_S\kappa^2}}$$

depends on

- coupling coefficient

$$\kappa = \frac{4(1-n_{absorber})}{\lambda}$$

- off-Bragg dephasing parameter

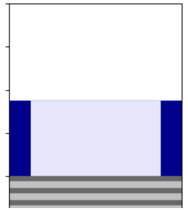
$$\zeta = \frac{2\pi}{pitch}\left(\sin\theta_{inc} - \frac{\lambda}{2pitch}\right)$$

- absorber thickness *d*

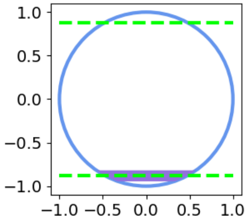
[*] *H. Kogelnik; Bell Syst. J 1969, DOI: 10.1002/j.1538-7305.1969.tb01198.x*

Outline

- Comparison of Kirchhoff and 3D mask performance for single source point illumination
- Investigation of root causes
- Impact of absorber shape
- Conclusions and outlook

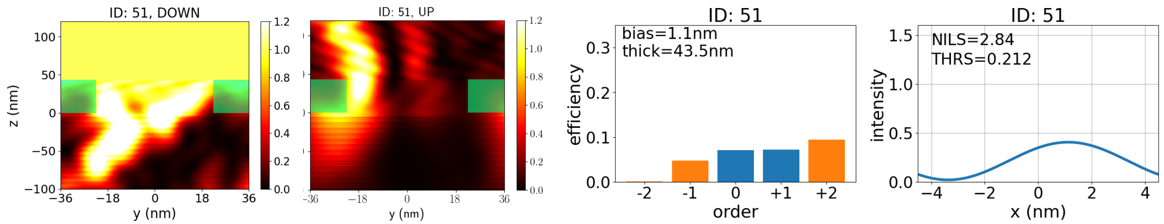


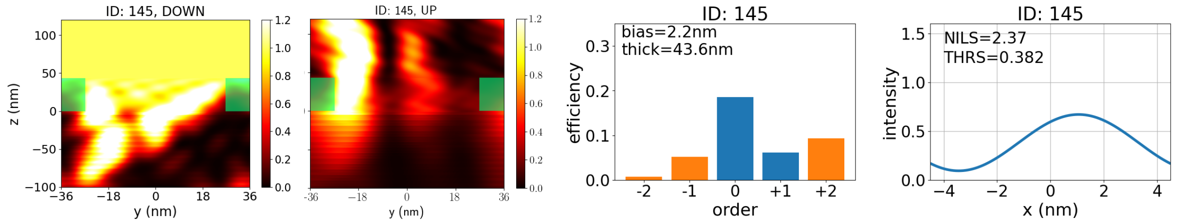
illumination:
pencil (source fill 7.5%/2)
large angle pole (largeAP)

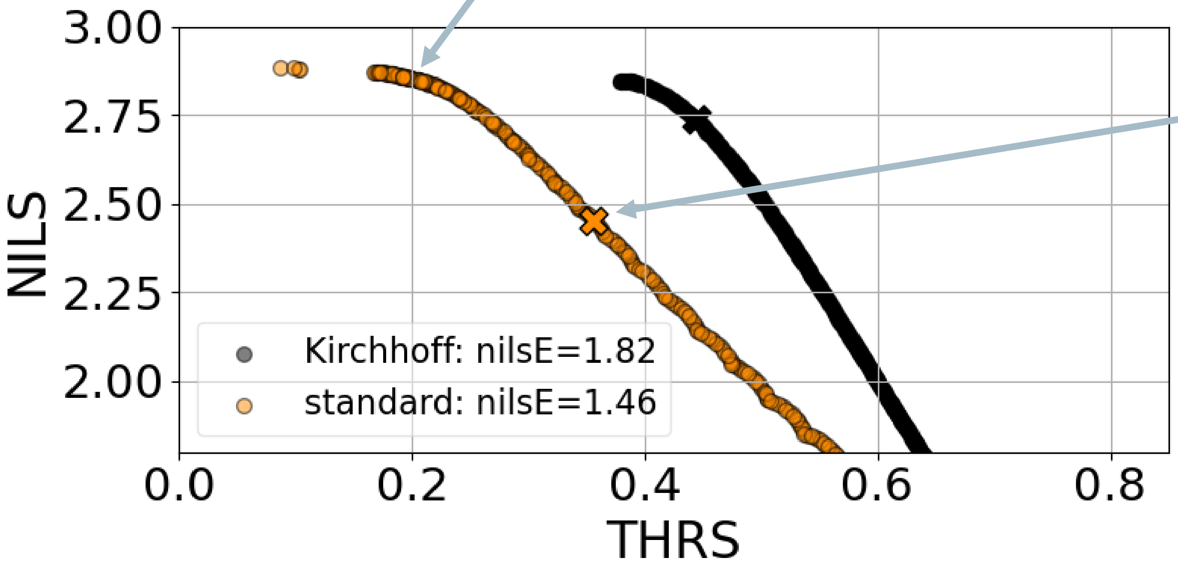


Can we improve performance of HOR L/S at largeAP?

Result for standard absorber with vertical sidewalls



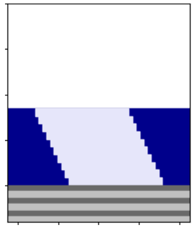




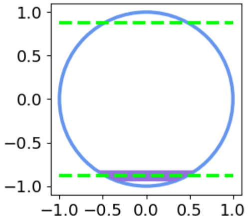
- The extended source gives very similar result to point pole

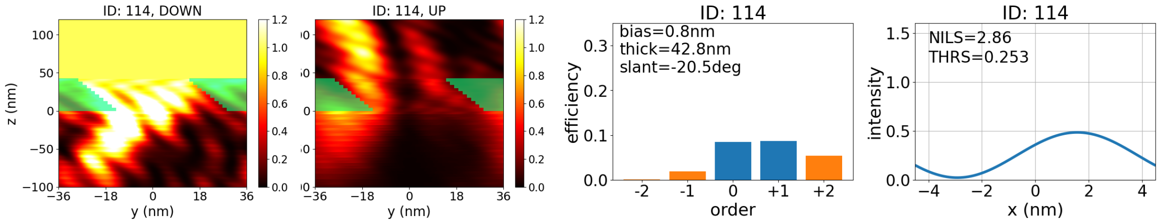
Can we improve performance of HOR L/S at largeAP?

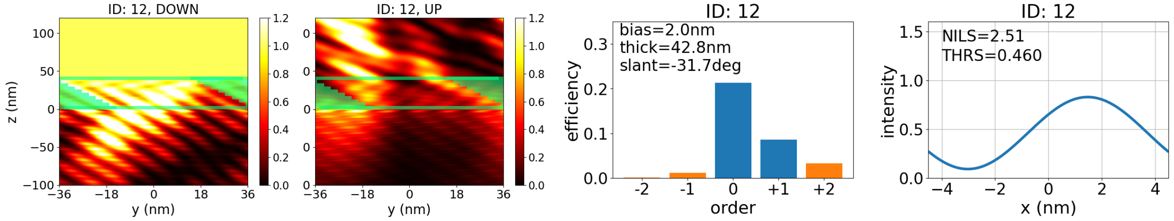
Result for slanted absorber

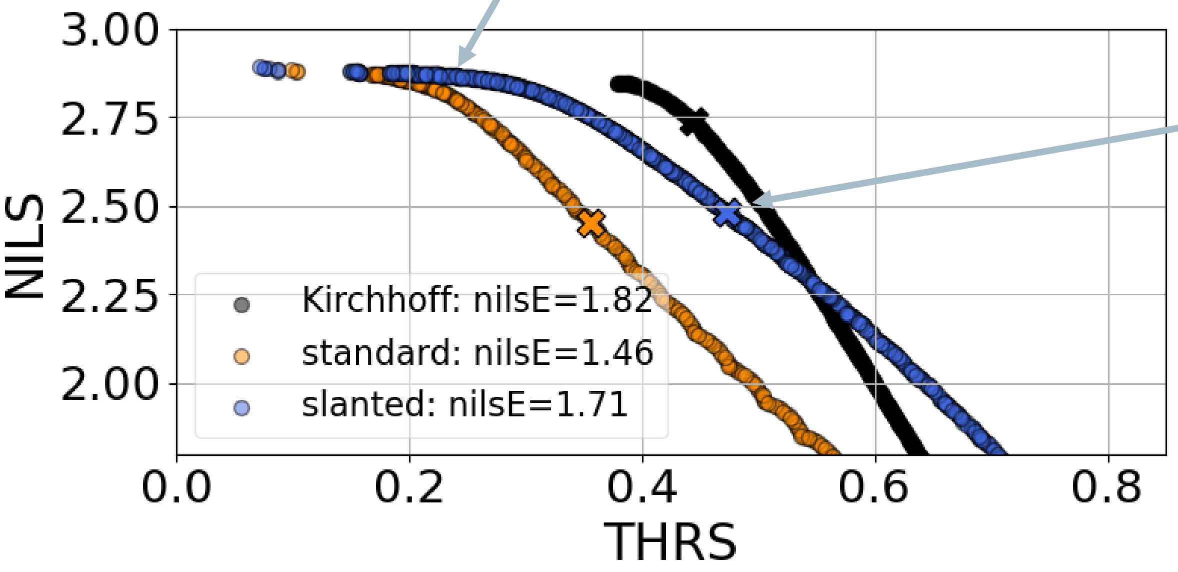


illumination:
pencil (source fill 7.5%/2)
large angle pole (largeAP)







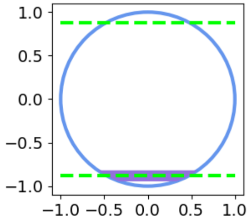


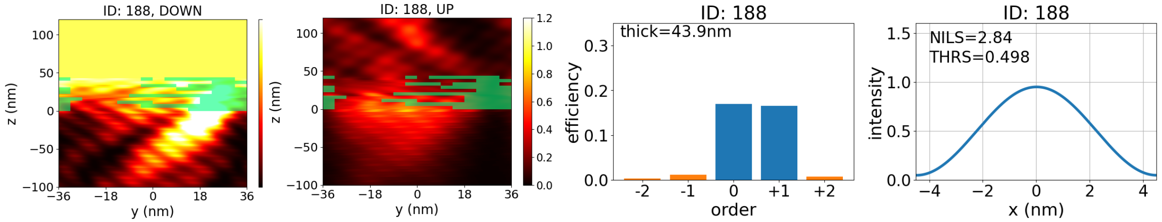
- Distinct improvement compared to vertical sidewalls
- Performance closer to Kirchhoff mask
- Slant attenuates coupling to orders outside NA

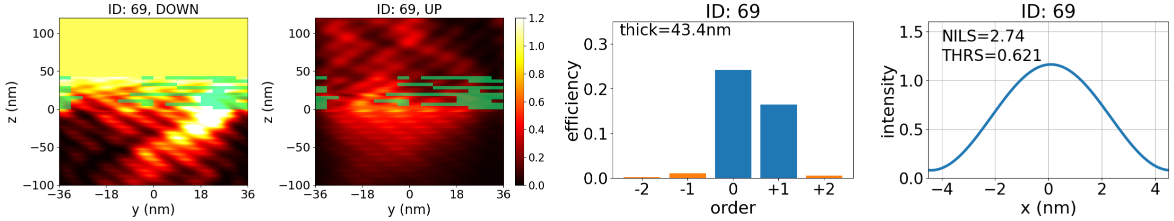
Can we improve performance of HOR L/S at largeAP?

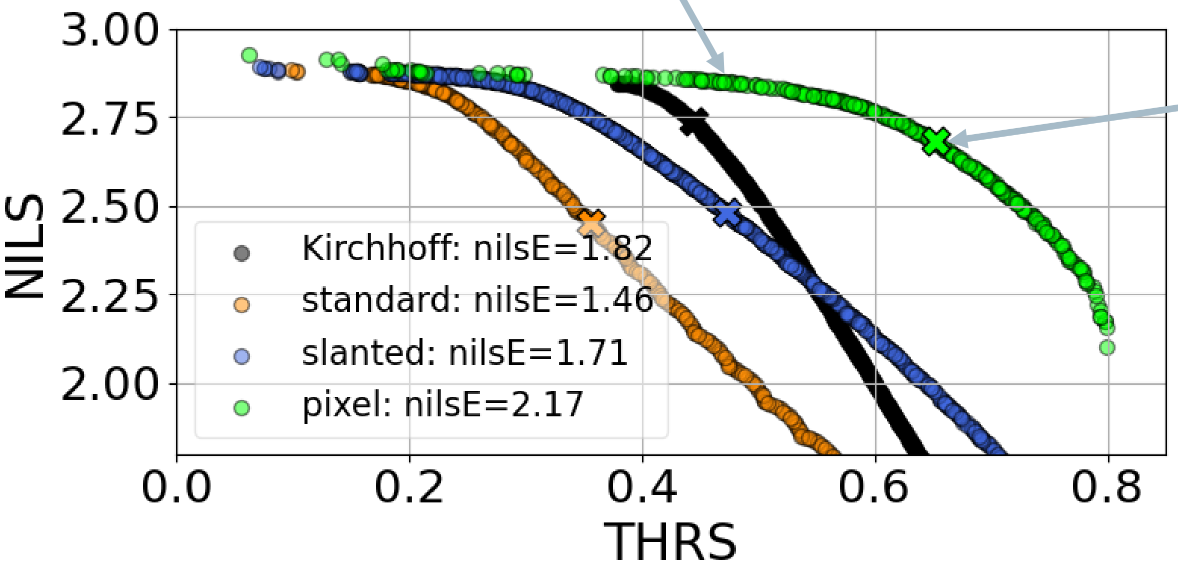
Result for pixel absorber

illumination:
pencil (source fill 7.5%/2)
large angle pole (largeAP)







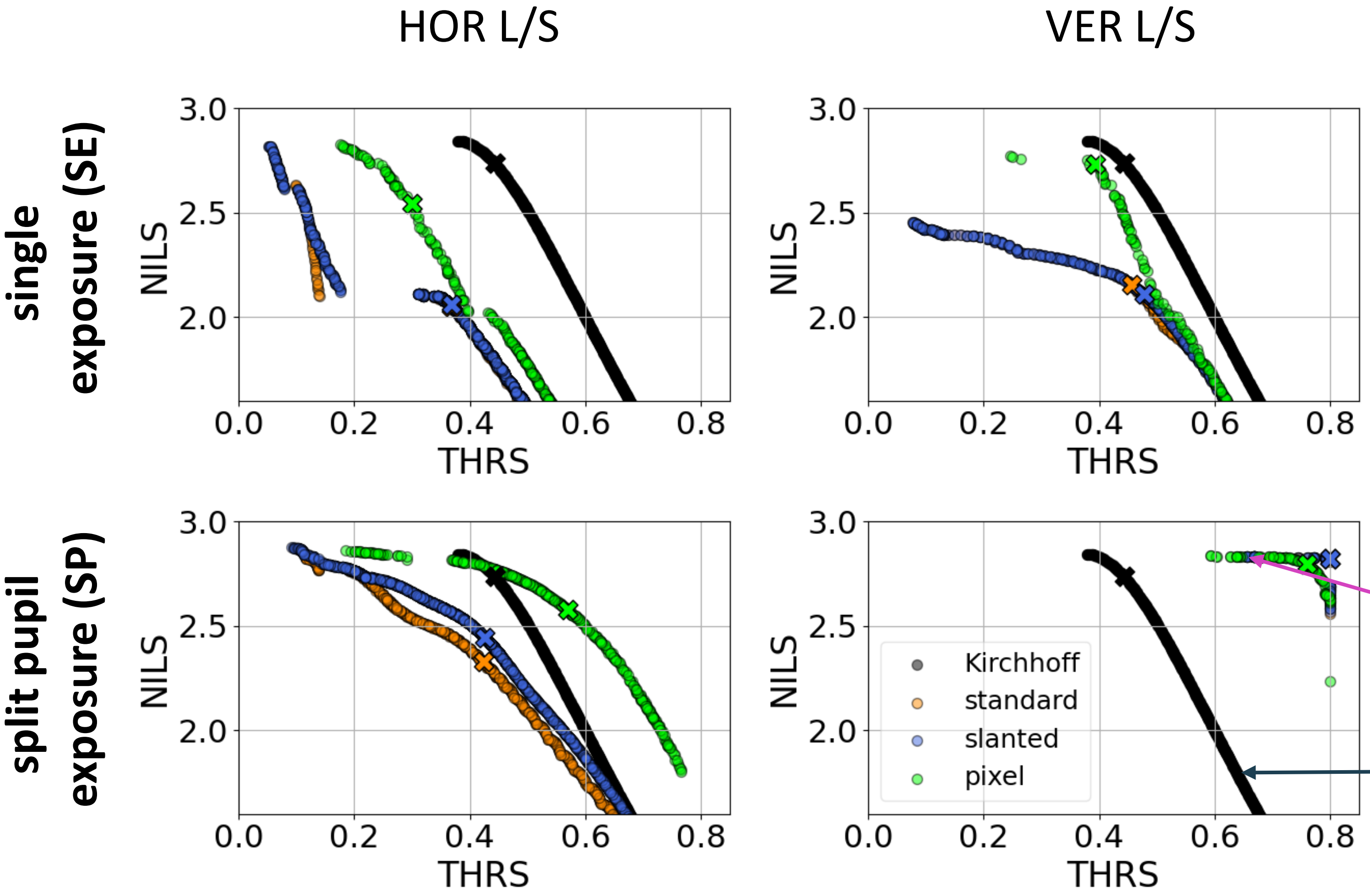


- Significant improvement compared to vertical and slanted sidewalls; better than Kirchhoff
- Coupling to orders outside NA further attenuated
- Advantage of solution with largest nilsE value hard to see in near field

- sFill=7.5%
- plot_paretoComparison-ls-315.py

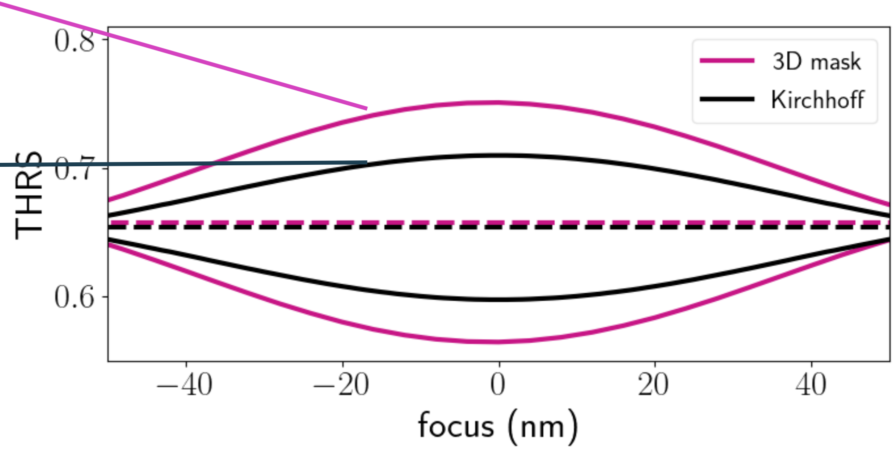
Performance for dipole pencil

Comparison of different absorber geometry options



- SE for vertical absorber (standard) suffers from strong image blur (shift between images for two poles)
- Pixel mask helps to address this image shift
- SP provides more significant improvement compared to SE for VER L/S (compensation of image shift)

- Pixel mask performs better than Kirchhoff



Summary

- Benefits of M3D effects: can enable larger bias and better tradeoff between NILS and THRS
- These benefits are more pronounced for VER L/S:
  - almost no tradeoff between NILS and THRS
  - different combinations of mask bias and absorber thickness
  - risk: large image shifts and blur for dipole exposures (can be compensated by split pupil exposures or other techniques)
- Non-standard absorber shapes, e.g. slanted absorber shapes and pixel type absorbers, can (partly) address reduced performance of HOR L/S
- Physics of underlying imaging mechanisms understood in terms of waveguide effects and Kogelnik theory

- M3D effects do not limit the performance of high NA and hyper NA systems
- Future innovations in mask technology can unleash the benefits of mask 3D effects