



Simulation of ultra-high efficiency EUV etched phase-shift mask

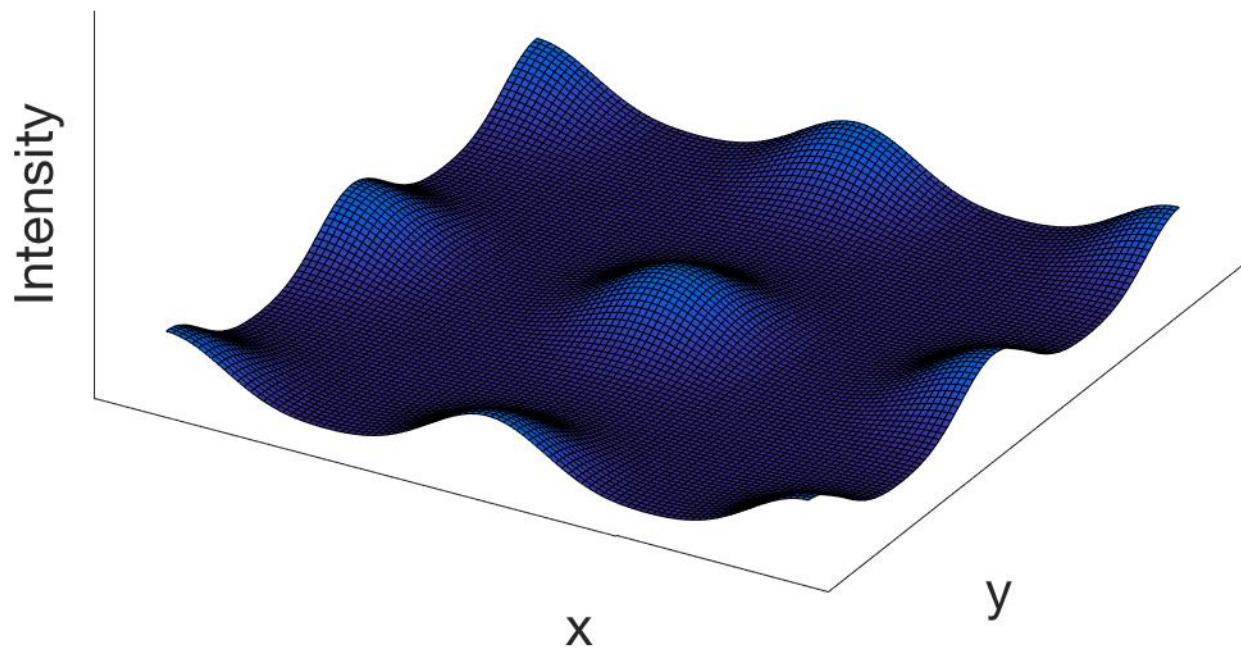
Stuart Sherwin, UC Berkeley, EECS

Center for X-Ray Optics, Lawrence Berkeley National Labs

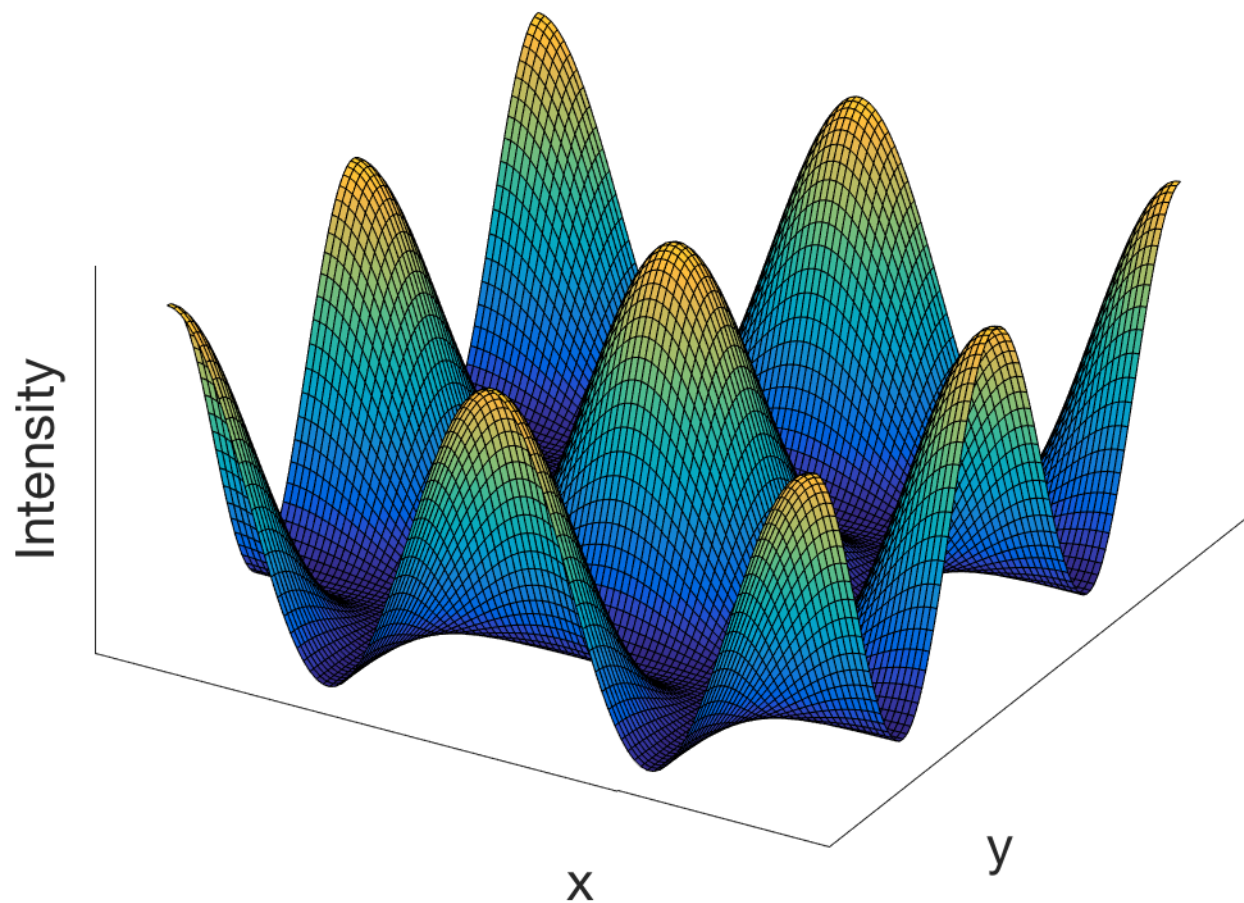
Dr. Patrick Naulleau, Prof. Andrew Neureuther, Prof. Laura Waller, Dr.
Thomas V. Pistor

EUV source power limits throughput → high-efficiency patterning

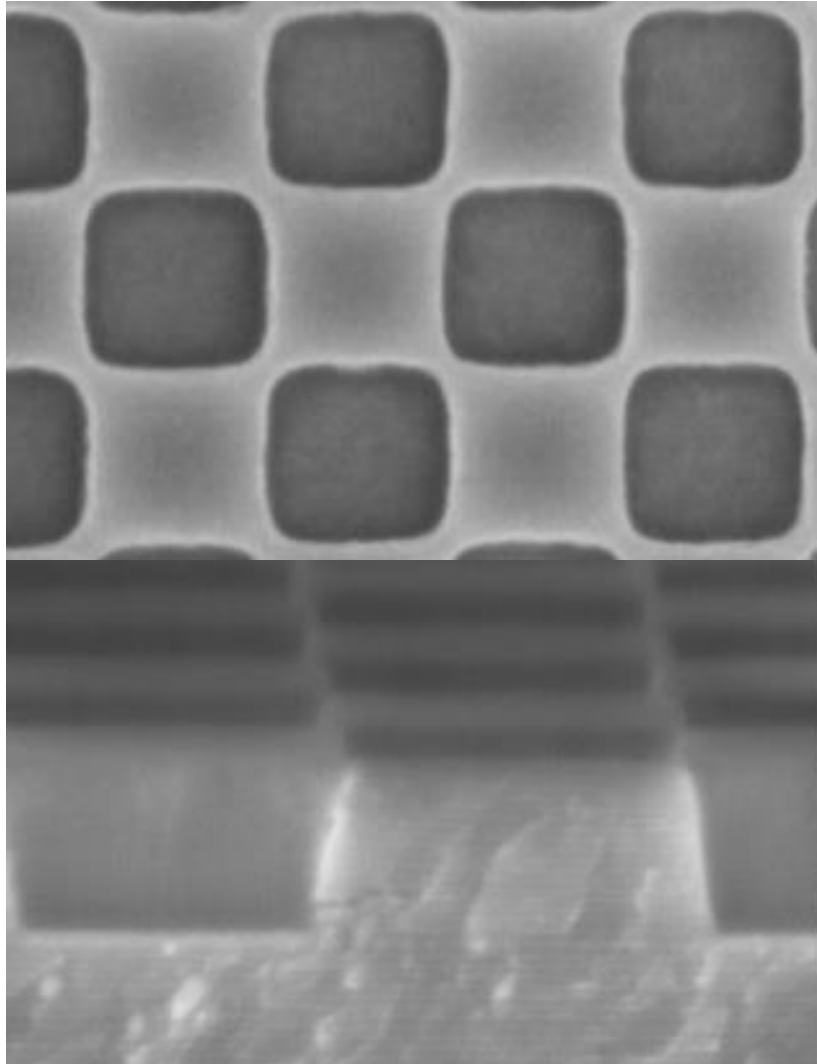
Absorber Mask



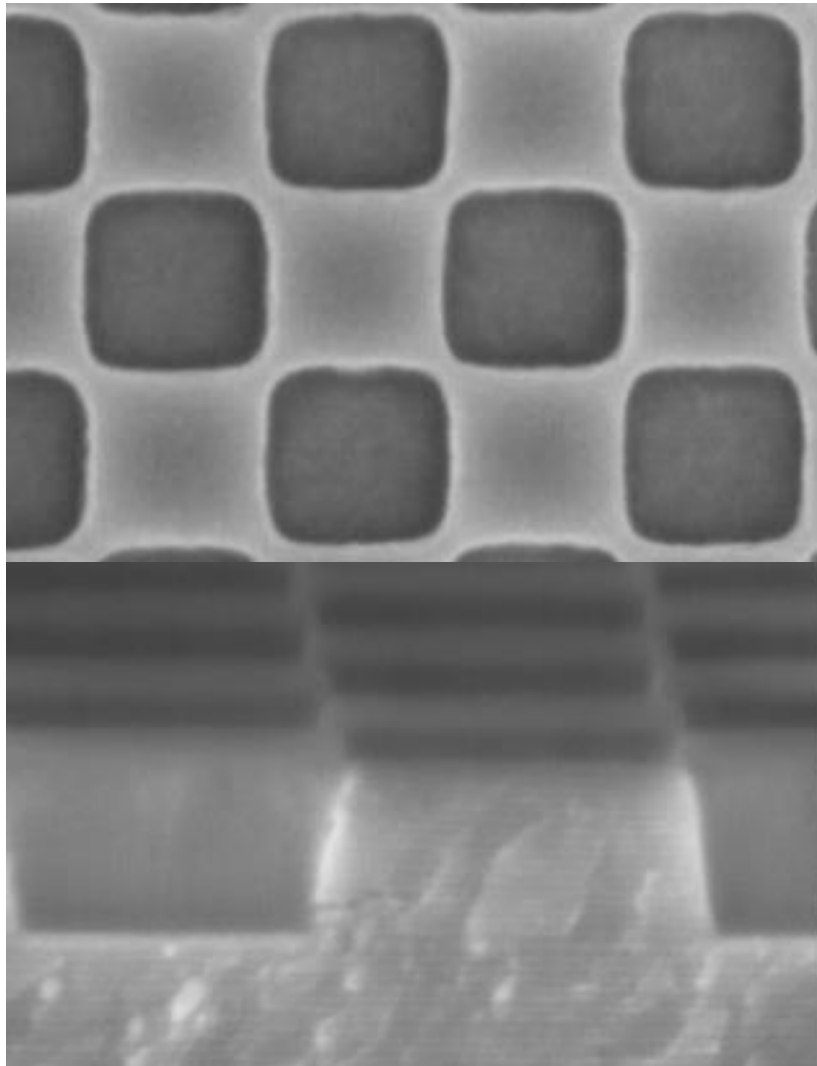
Phase-Shift Mask (PSM)



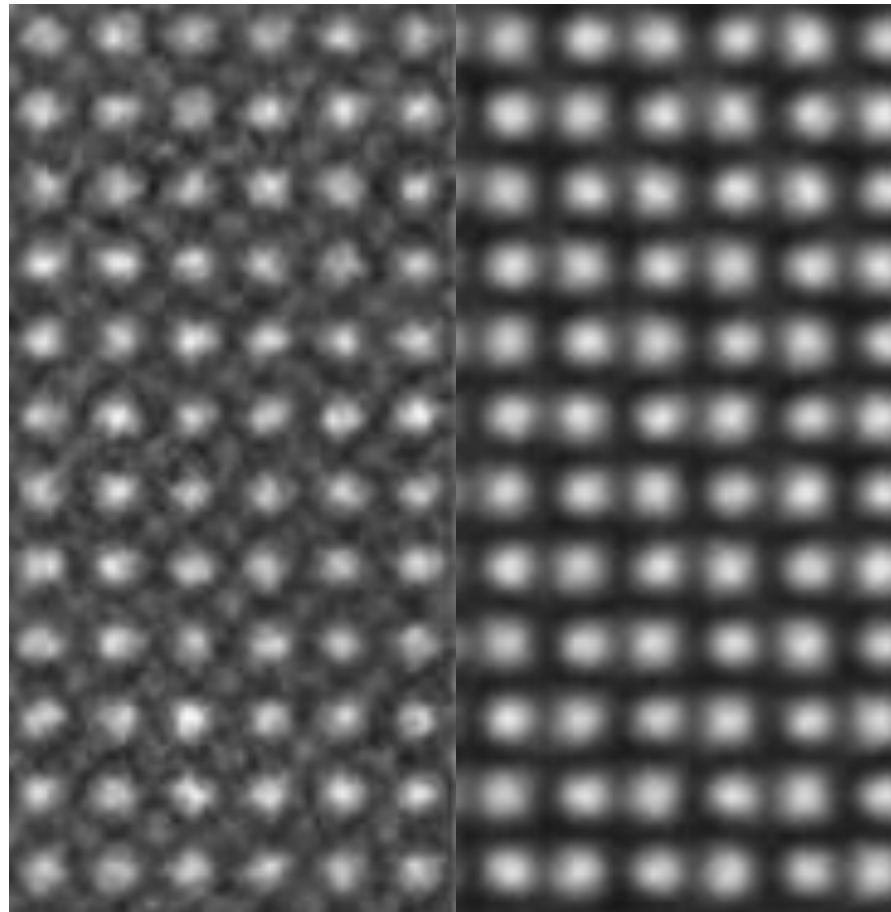
Previous work: Checker PSM fabricated, tested, works!



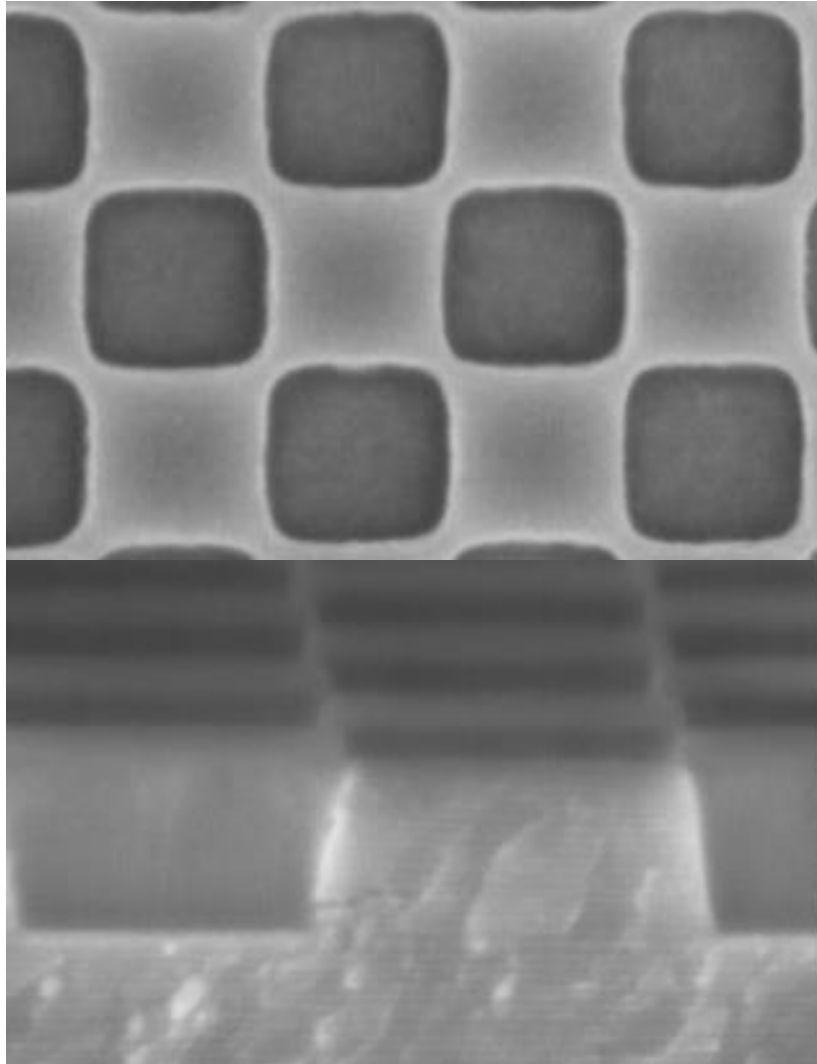
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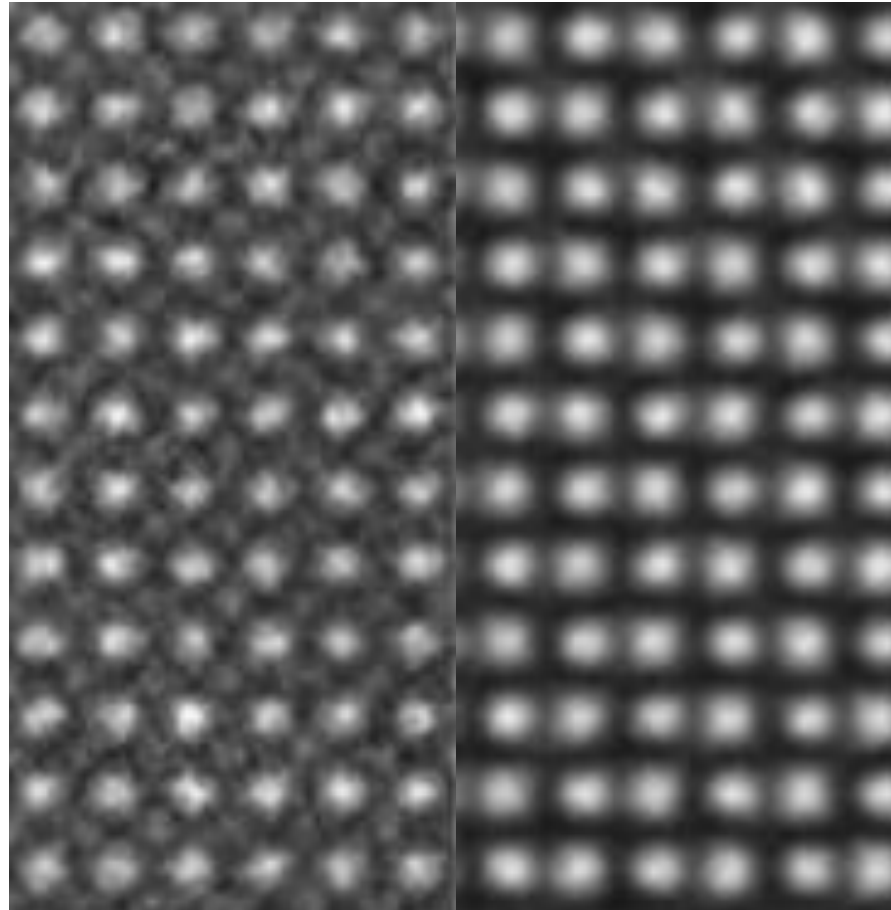
8x brighter image (SHARP)



Previous work: Checker PSM fabricated, tested, works!

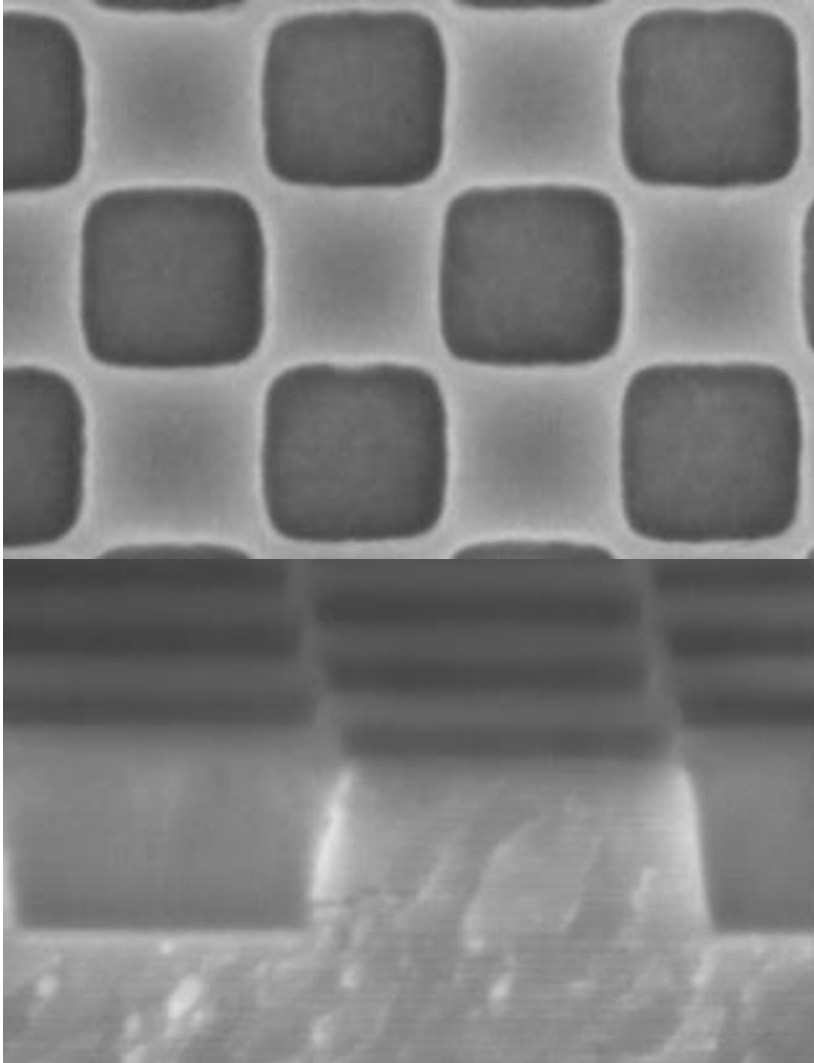


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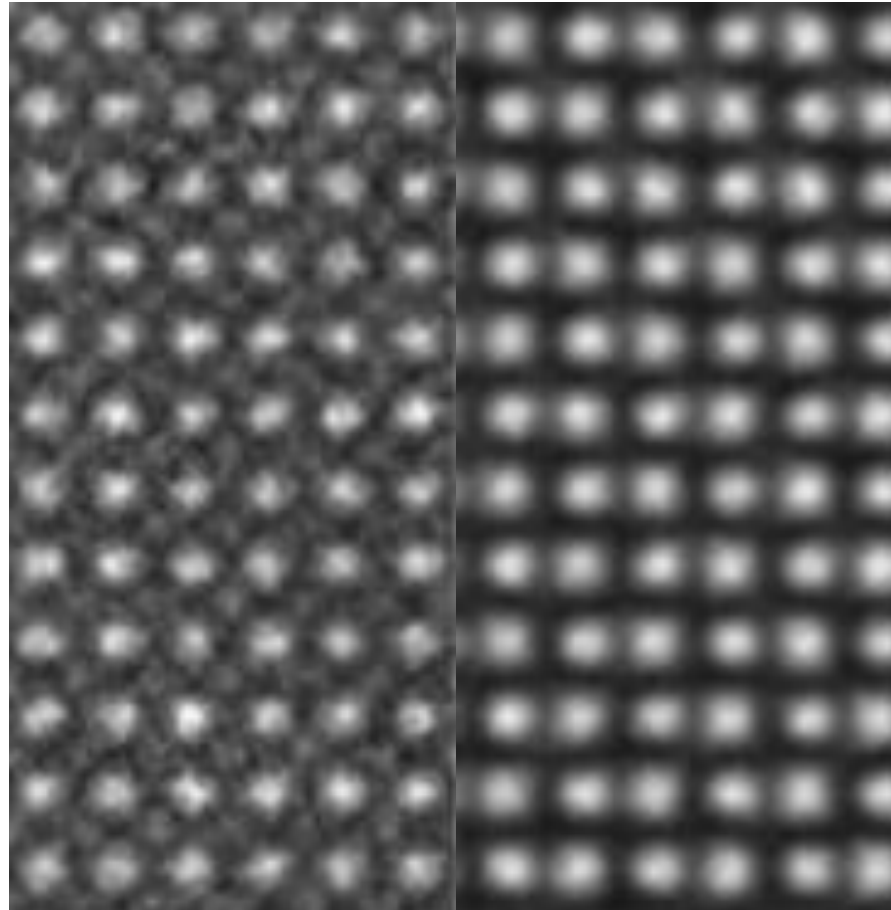


Acknowledgement:
Markus Benk,
Ken Goldberg,
and Antoine Wojdyla

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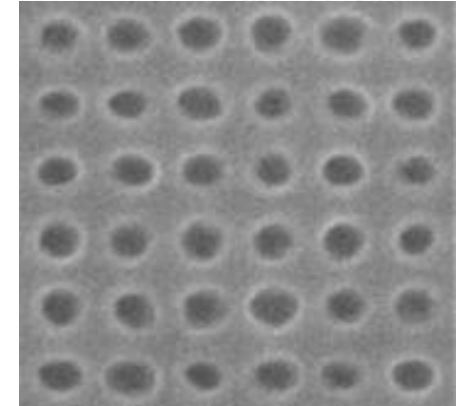


8x brighter image (SHARP)

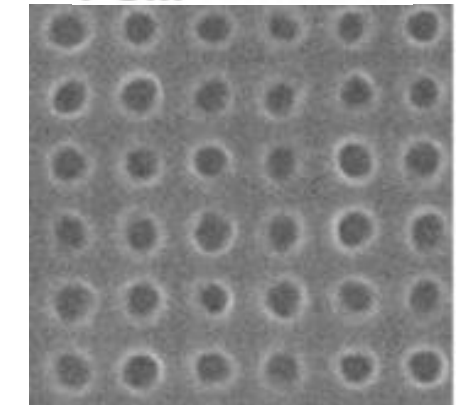


7x shorter exposure (MET)

Absorber 94 mJ/cm²

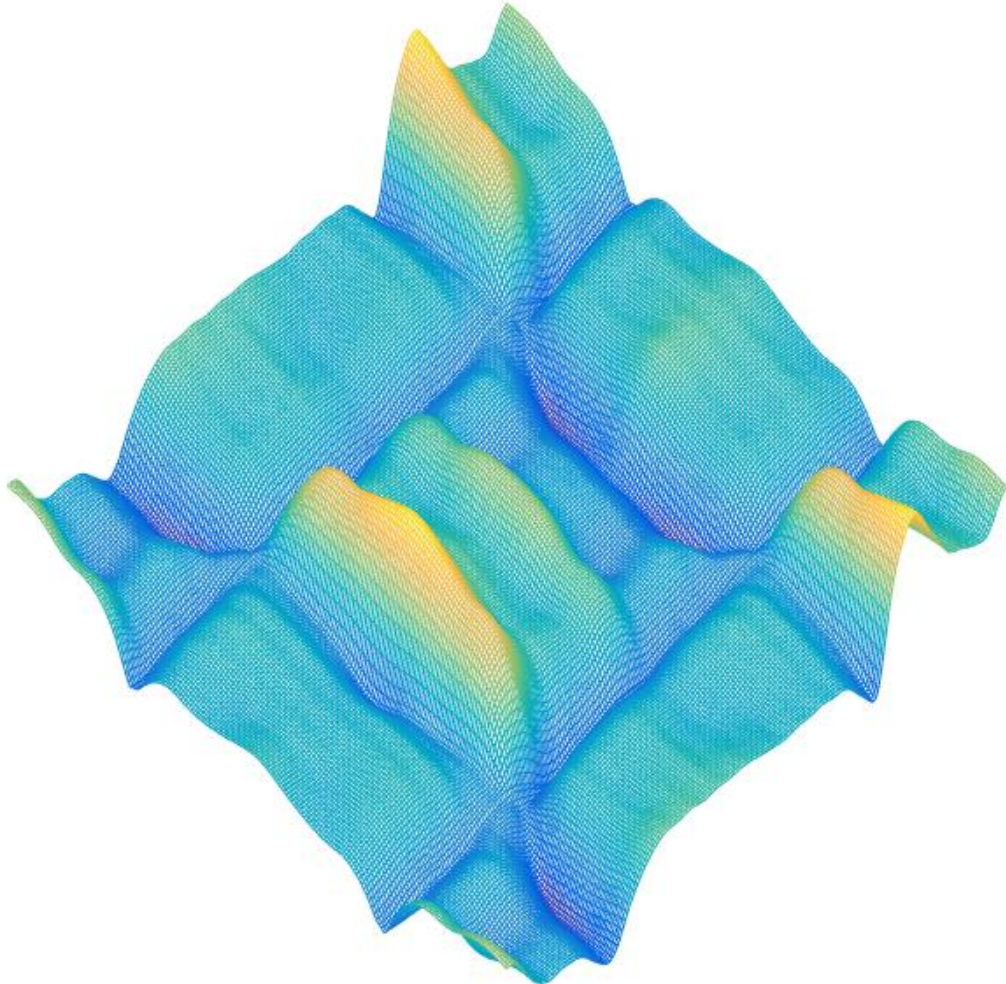


PSM 13mJ/cm²

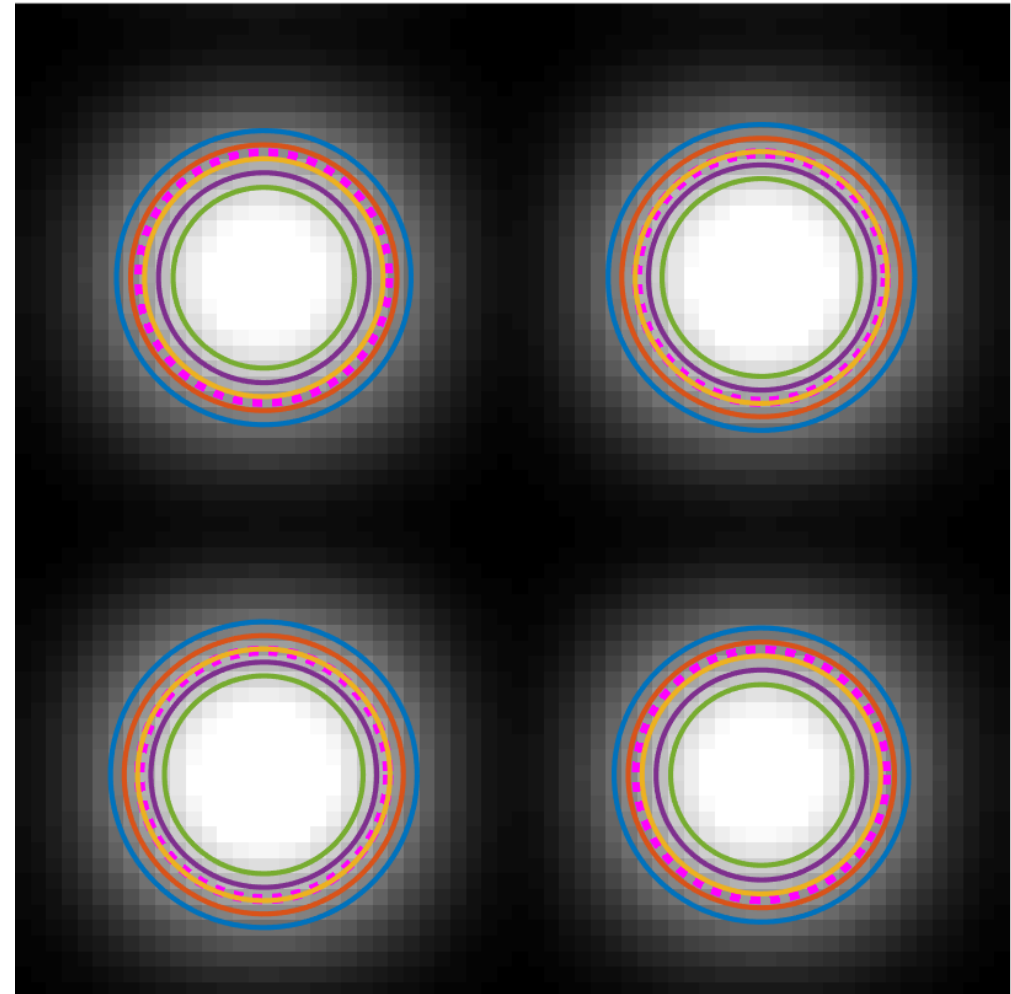


Current work: rigorous lithographic simulations of etched PSM

Near-Field

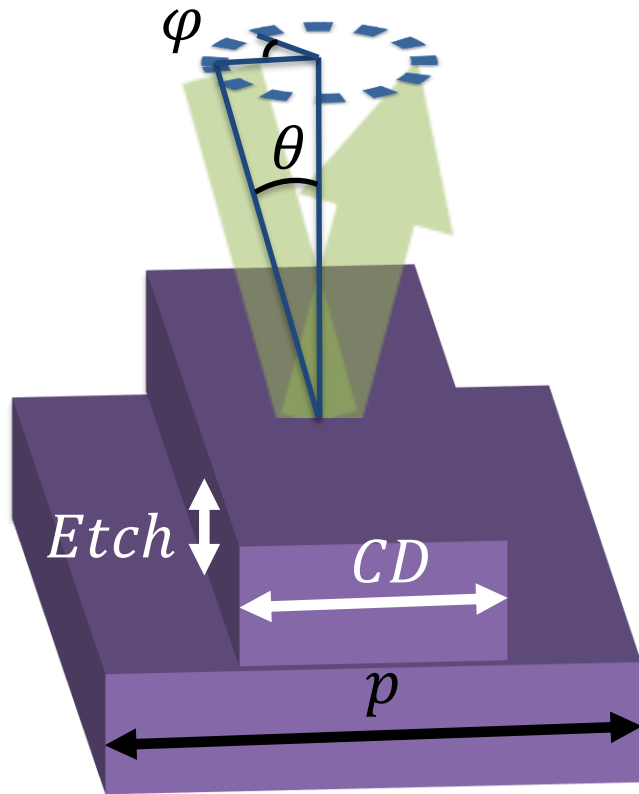


Aerial Image



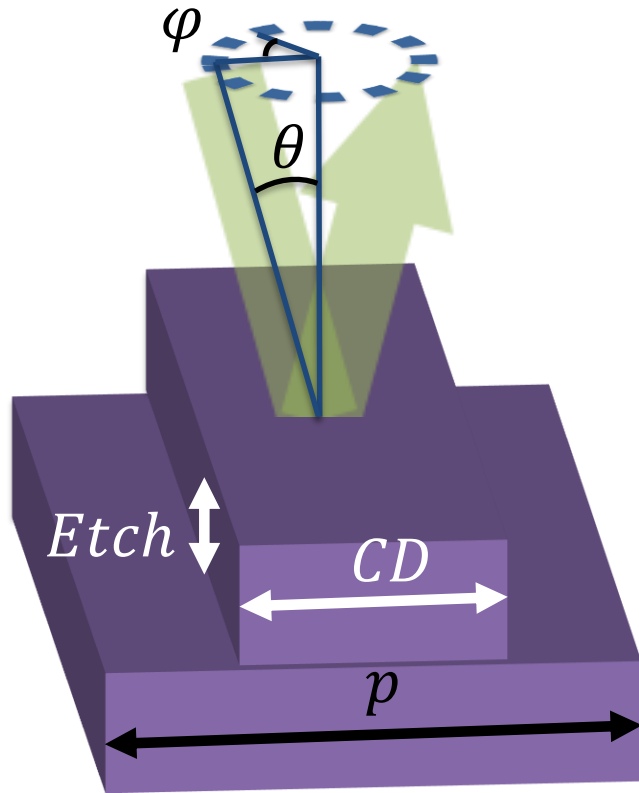
Goal: Use simulations to model EUV etched PSM design

Mask Design

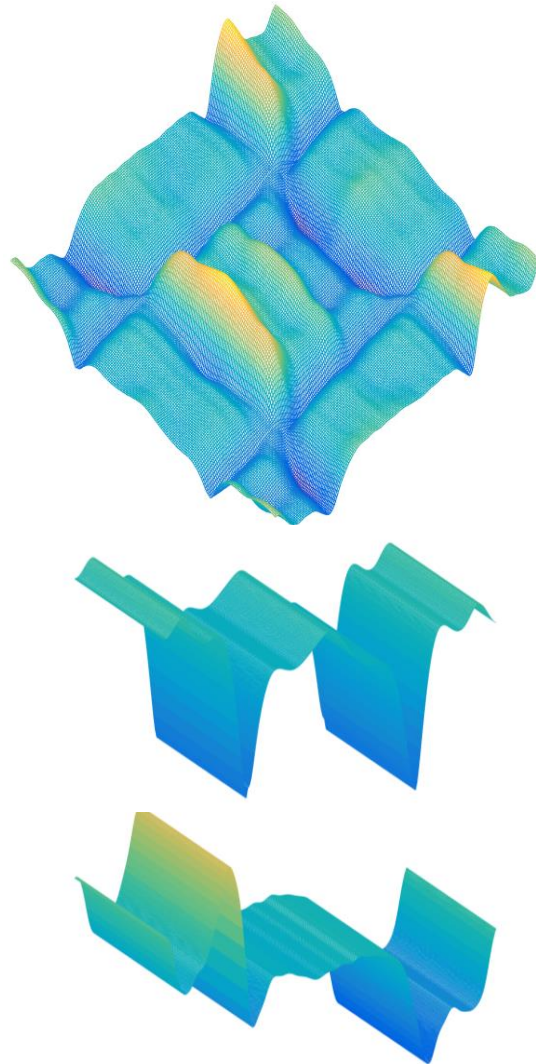


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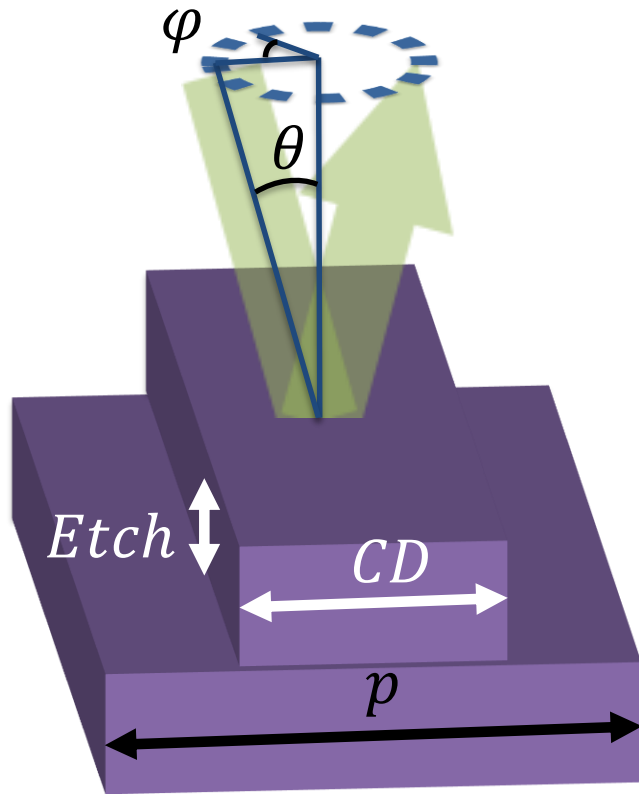


Near-Field

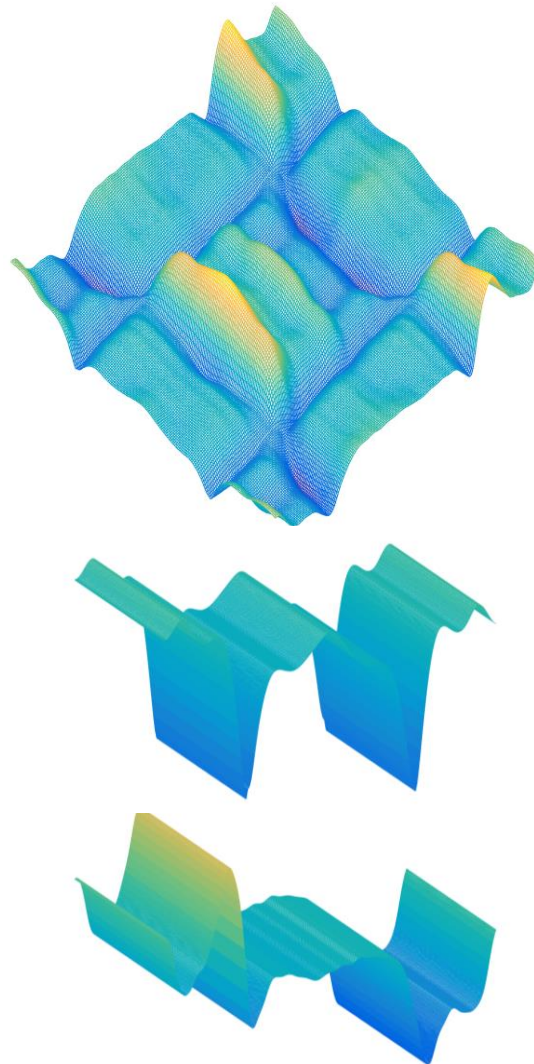


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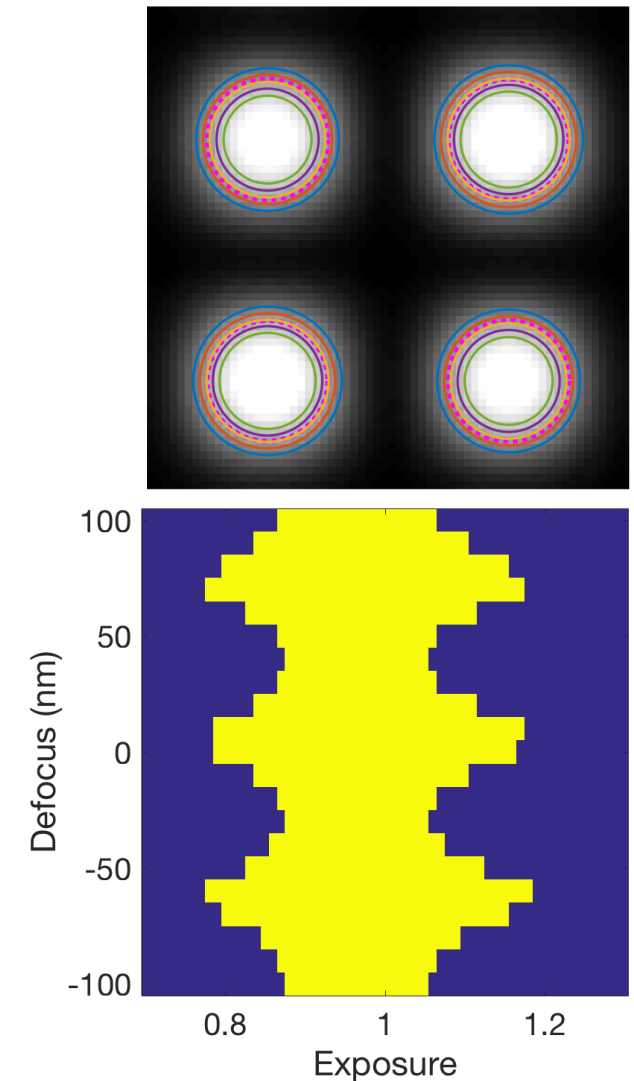
Mask Design



Near-Field

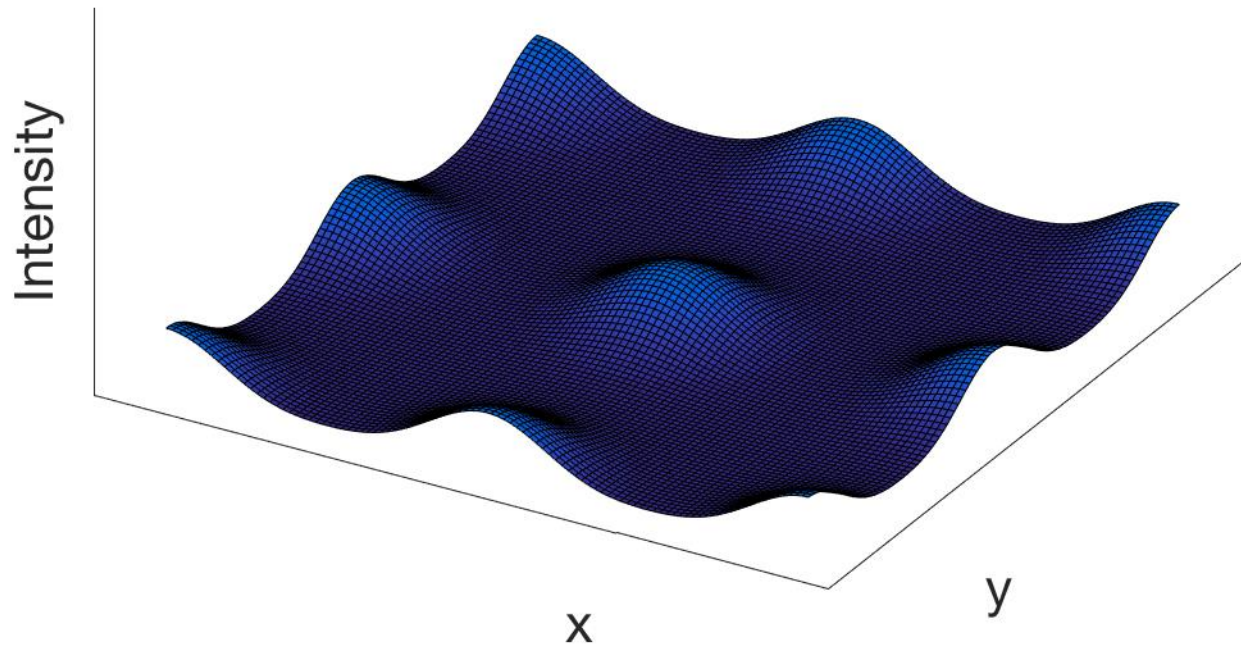


Patterning

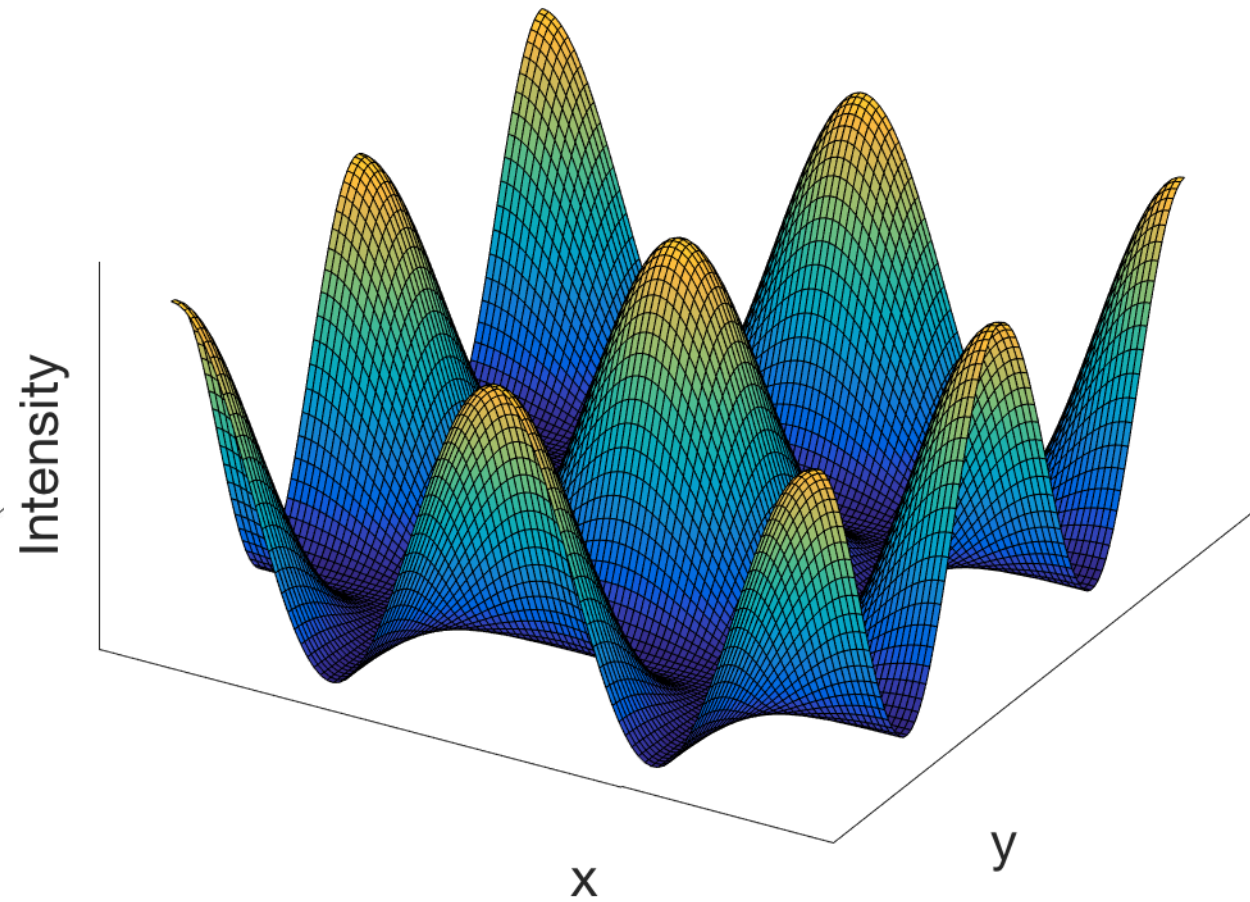


What makes phase-shift masks so efficient?

Absorber Mask

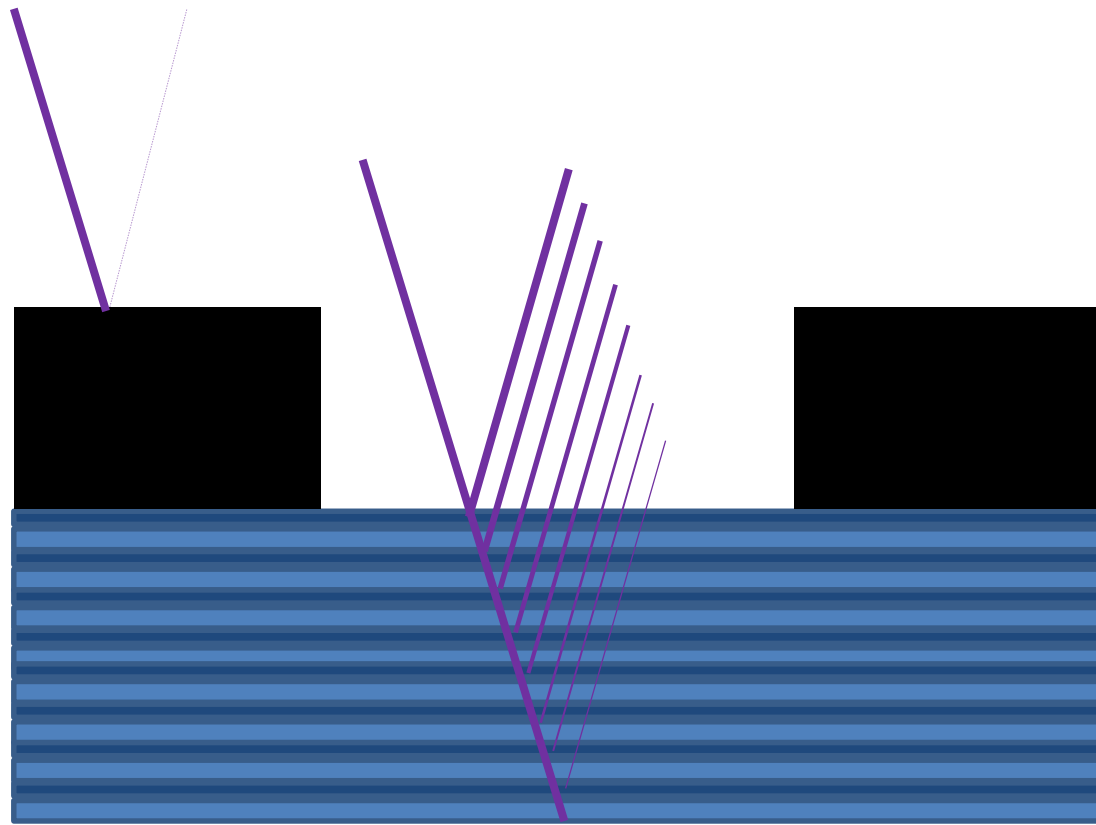


Phase-Shift Mask (PSM)



Phase shift mask: don't absorb light, delay it

Absorber Mask

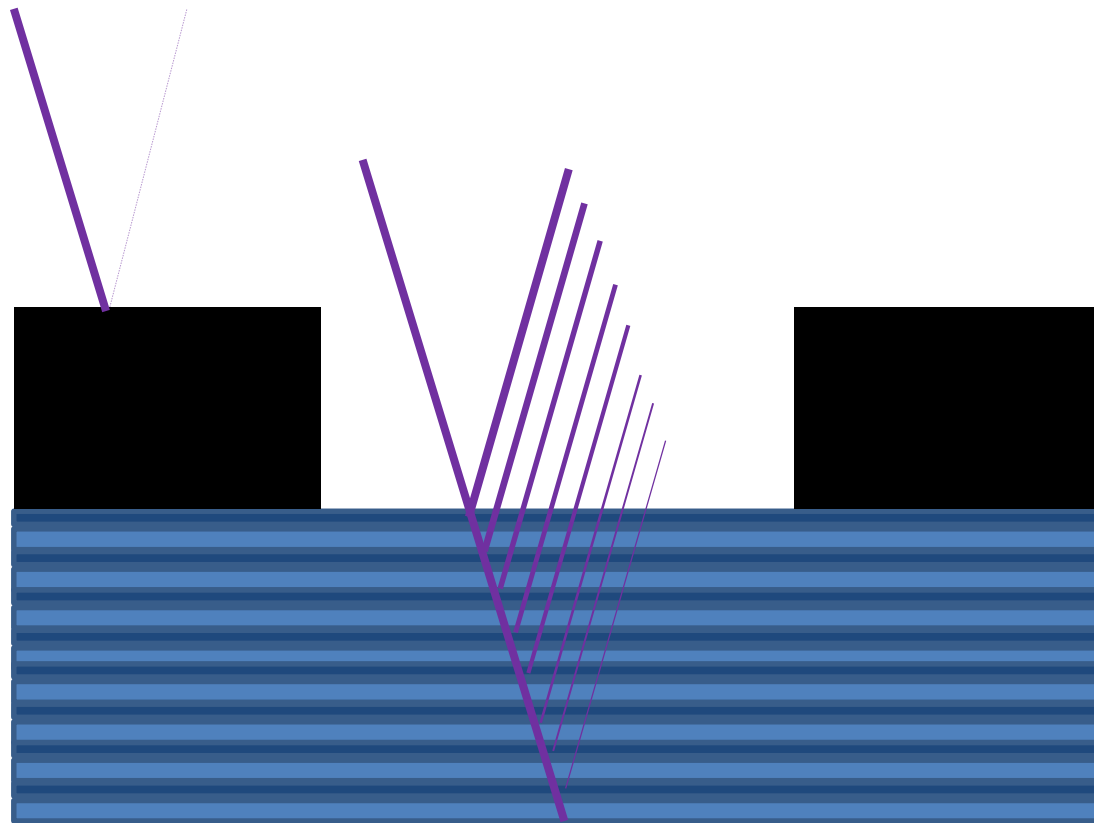


Absorber
 $R = 0$

ML Mirror
 $R = 1$

Phase shift mask: don't absorb light, delay it

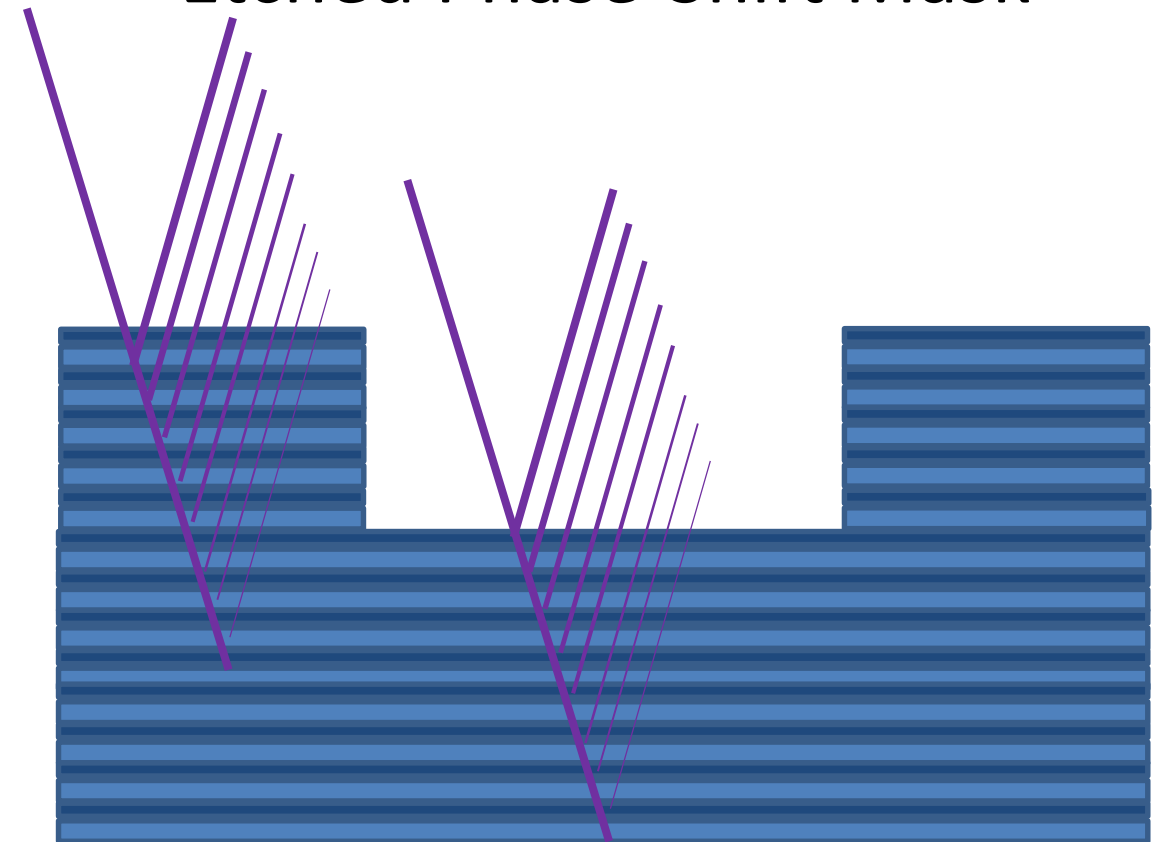
Absorber Mask



Absorber
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ML Mirror
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Etched Phase-Shift Mask



Un-etched
ML mirror
 $R = e^{i\pi} = -1$

Etched
ML mirror
 $R = 1$

Line = Space patterning with phase vs absorber (ideal thin mask)

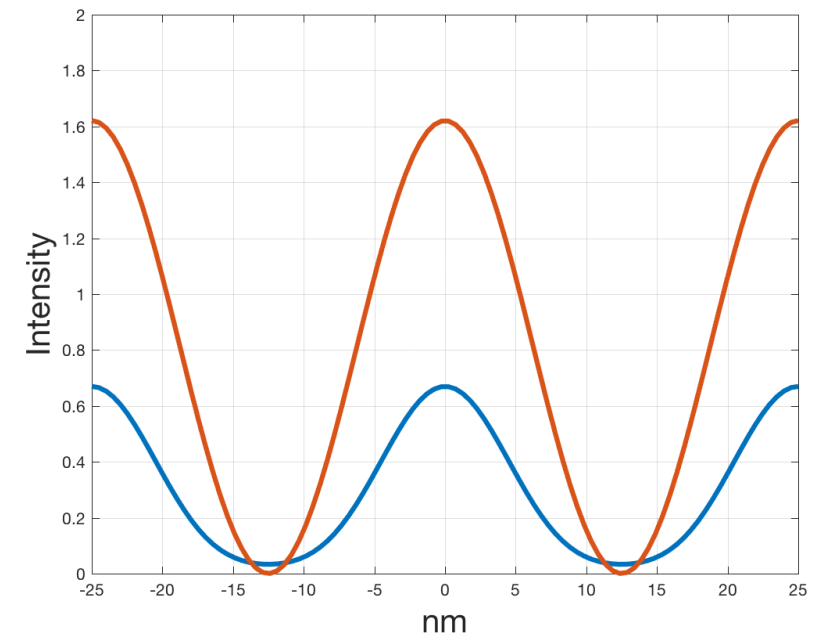
Mask Type	Illumination	CD (nm)	Mask Pitch (nm)	Peak Power	Peak Ratio
Absorber	Dipole	12.5	100	0.67	1
Phase Shift	Conventional	12.5	200	1.62	2.4

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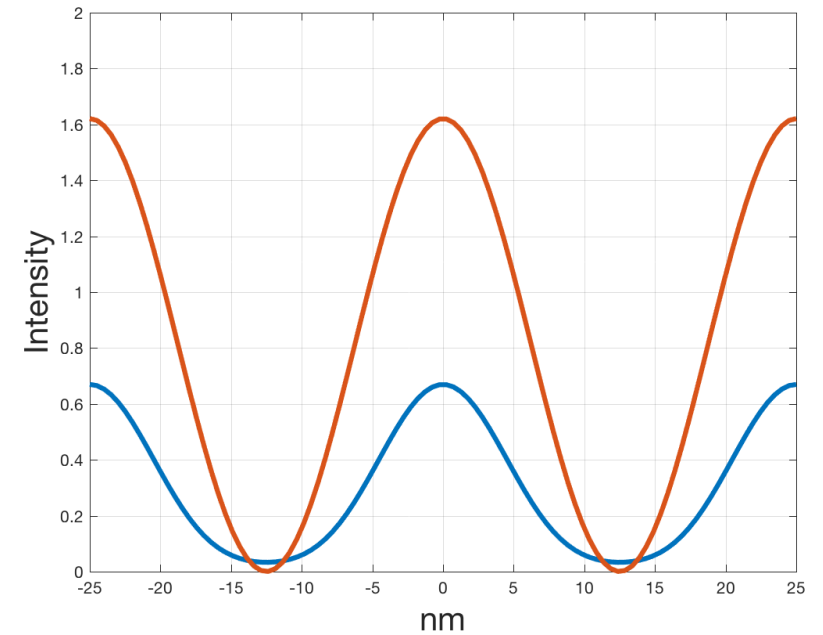
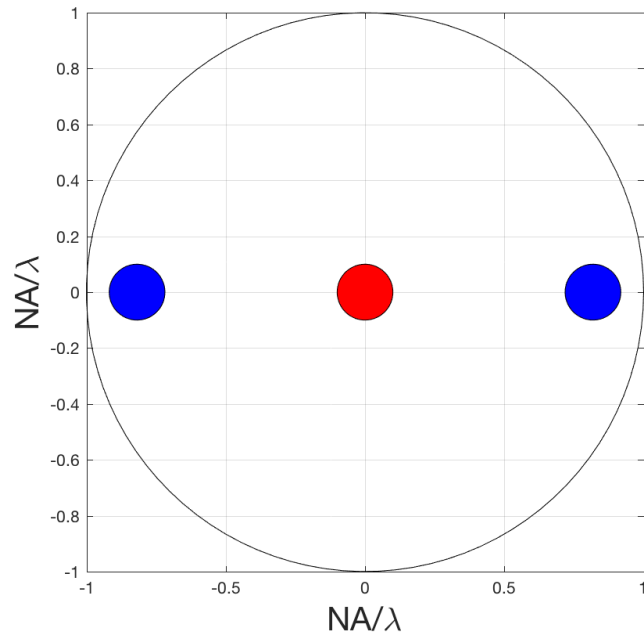
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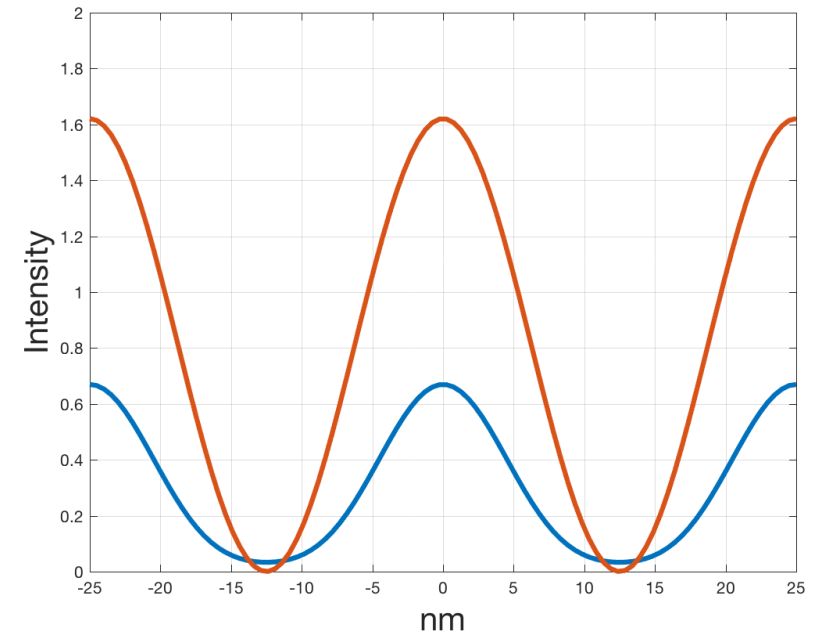
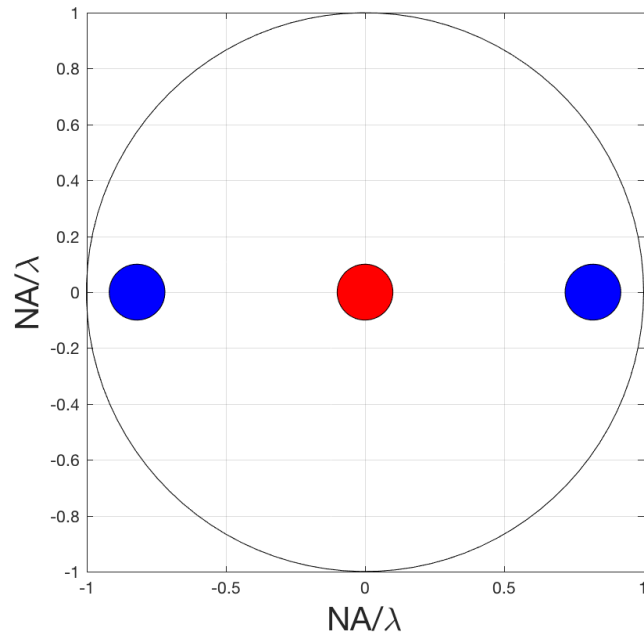
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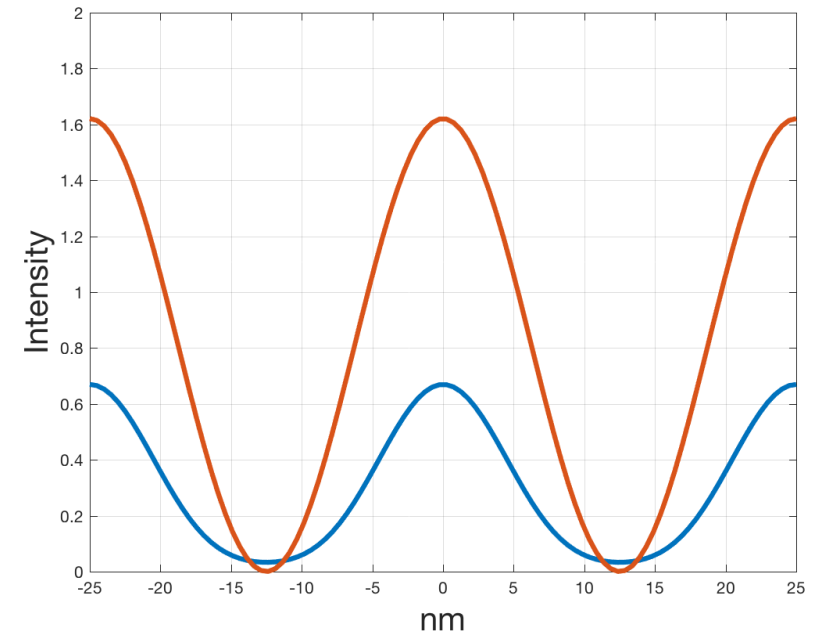
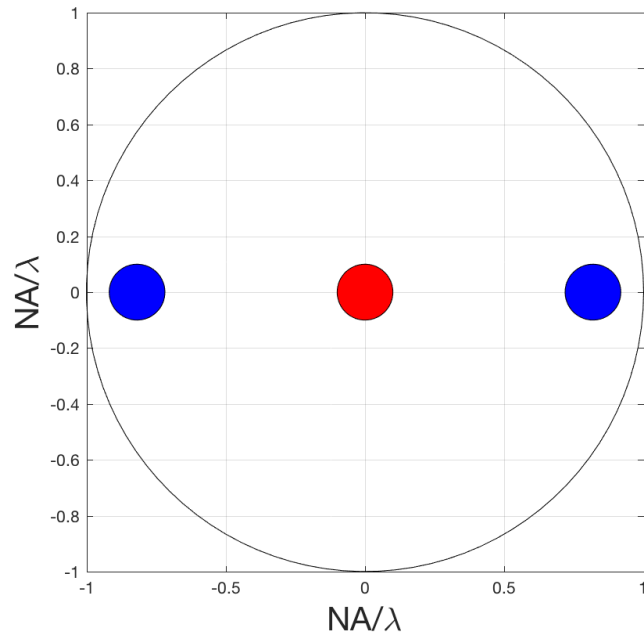
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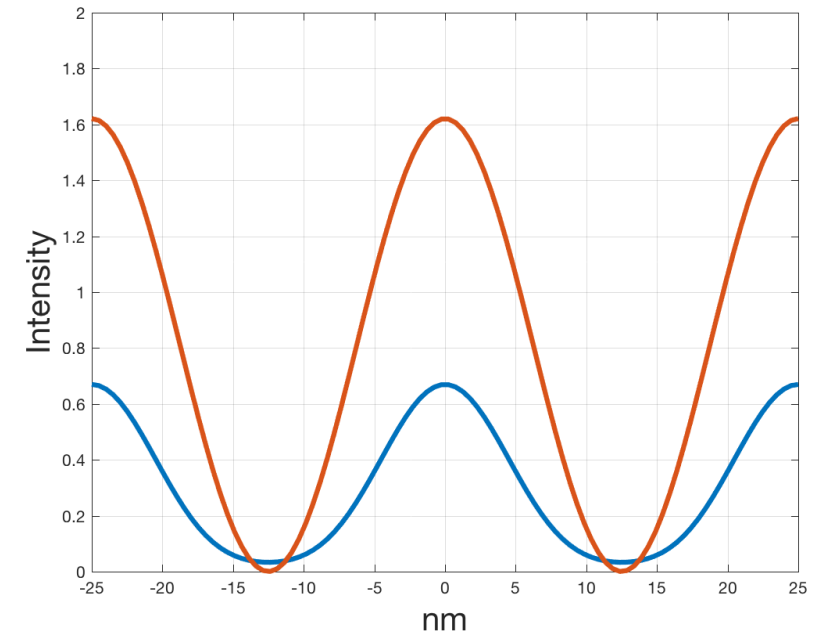
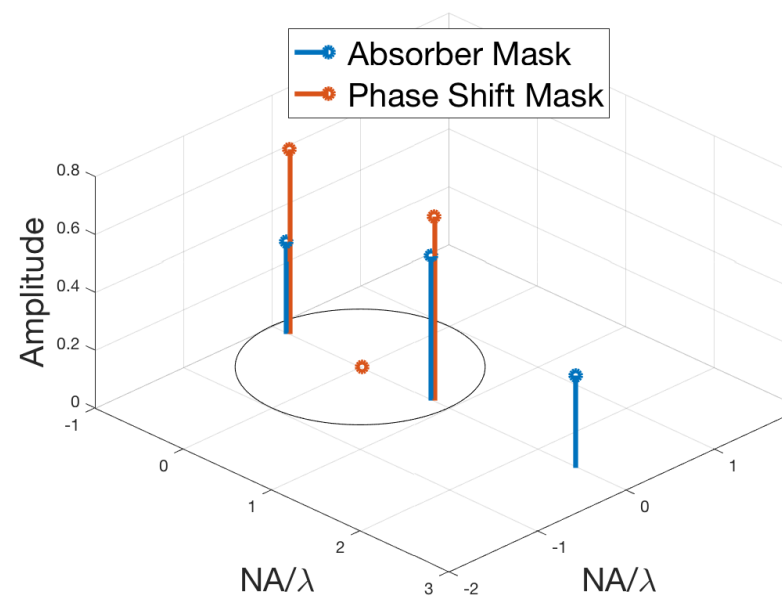
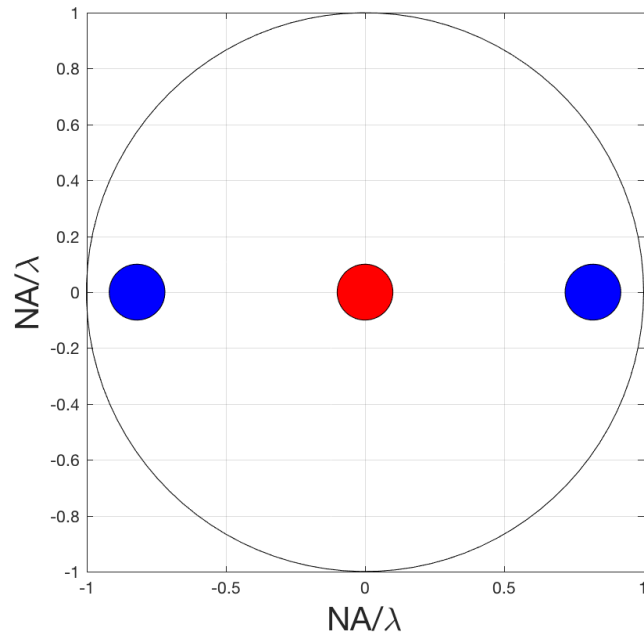
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Contact patterning with phase vs absorber (ideal thin mask)

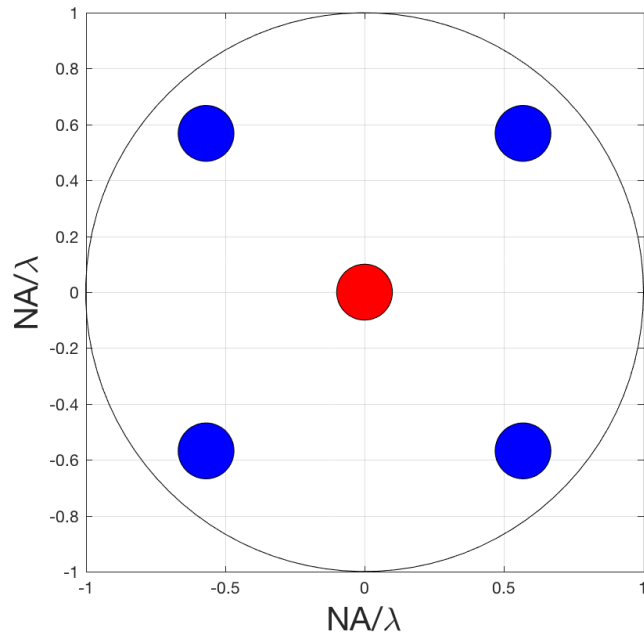
Mask Type	Illumination	CD (nm)	Mask Pitch (nm)	Peak Power	Peak Ratio
Absorber	Quadrupole	18	144	0.45	1
Phase Shift	Conventional	18	288	2.62	5.9

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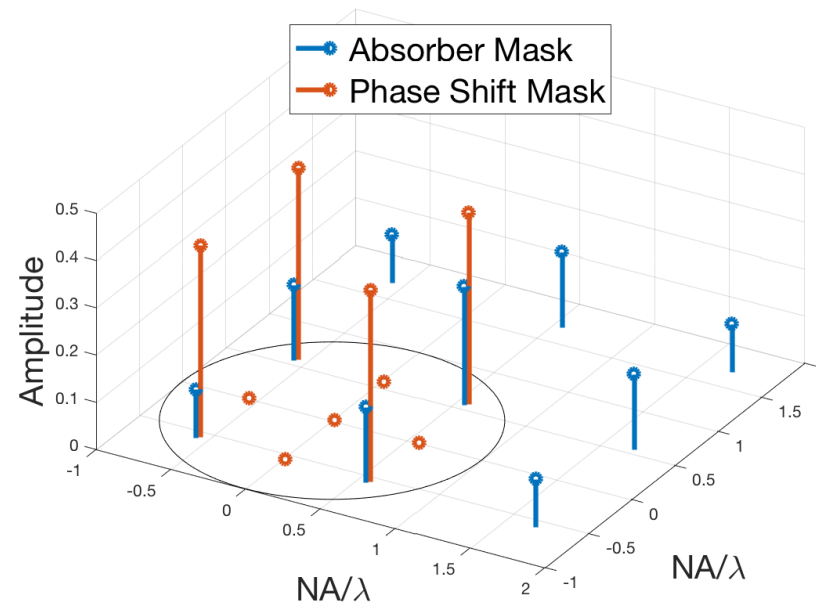
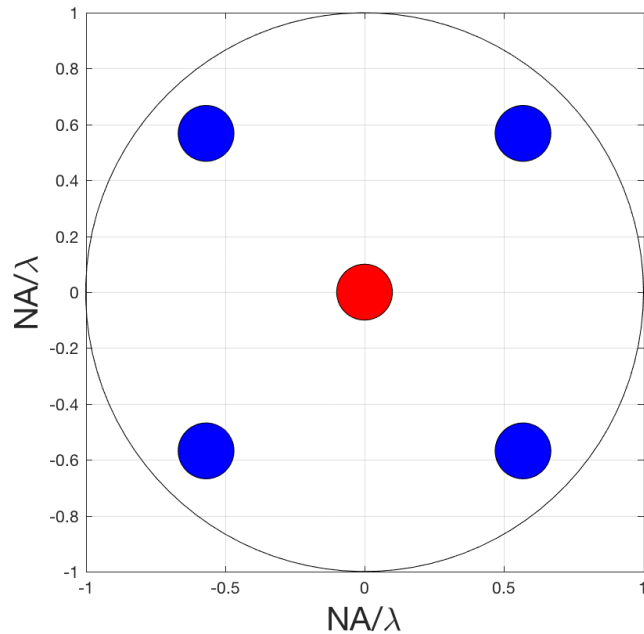
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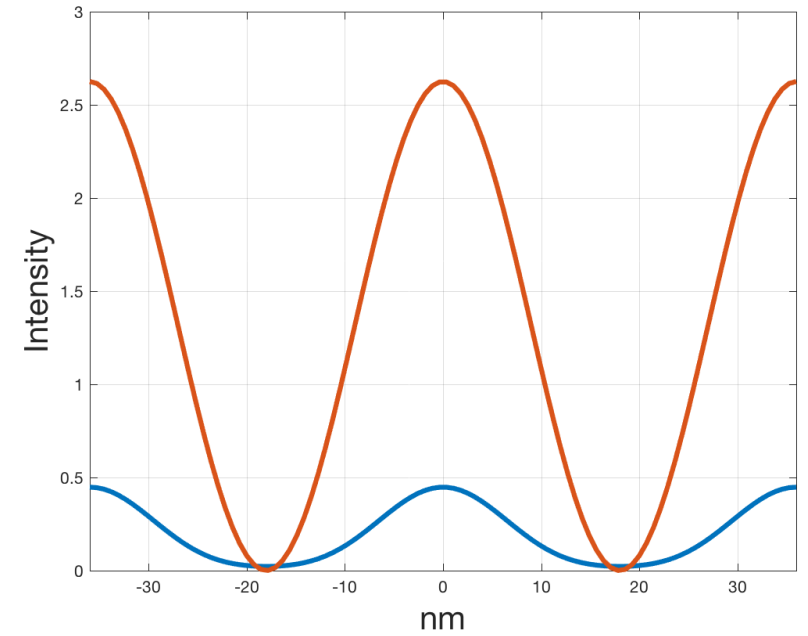
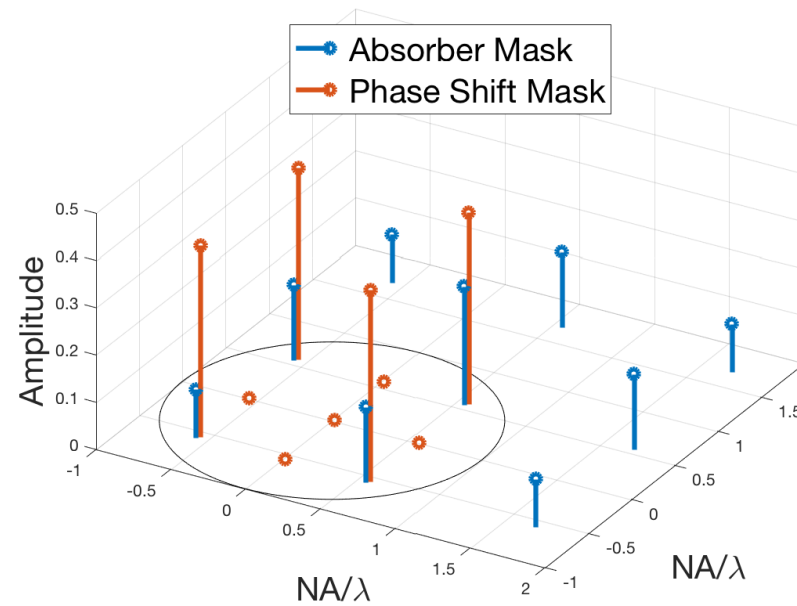
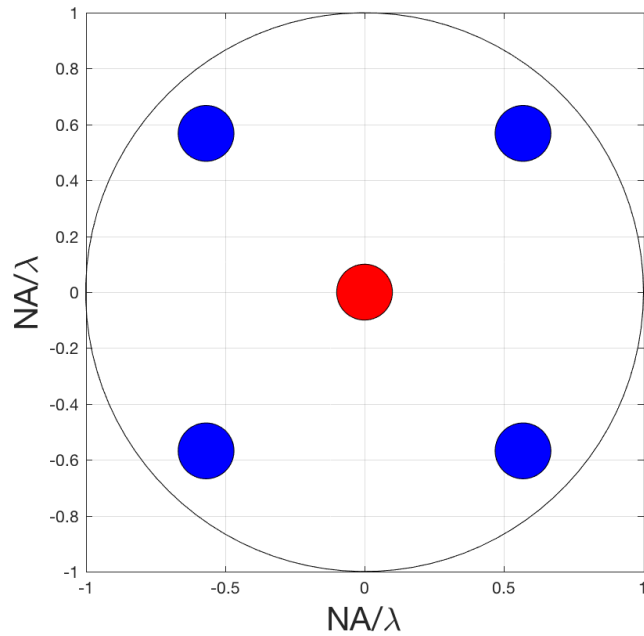
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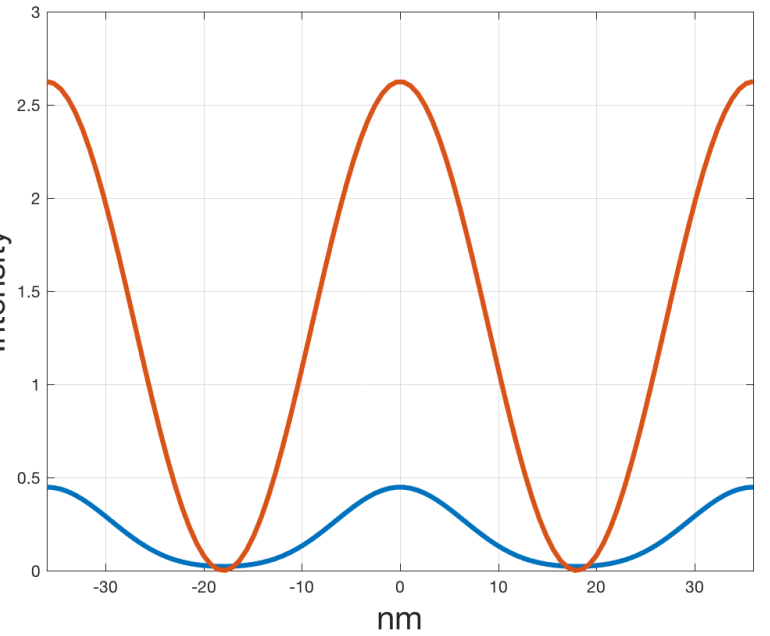
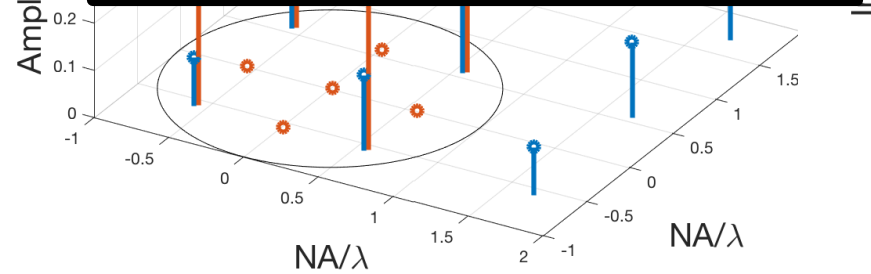
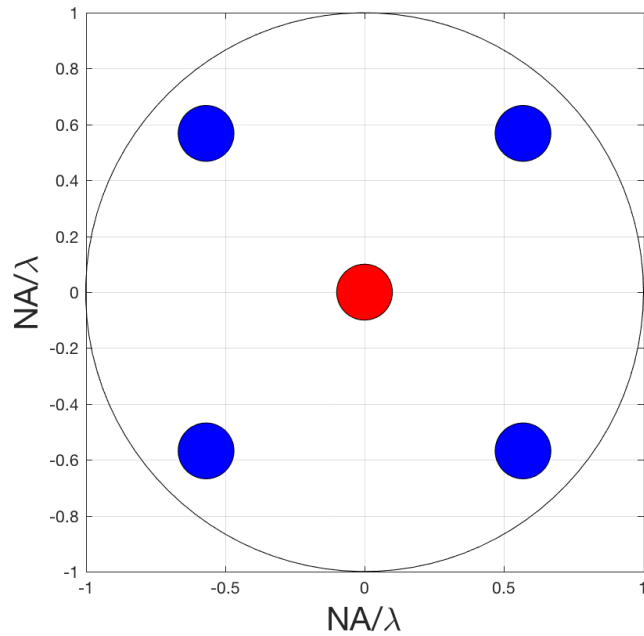
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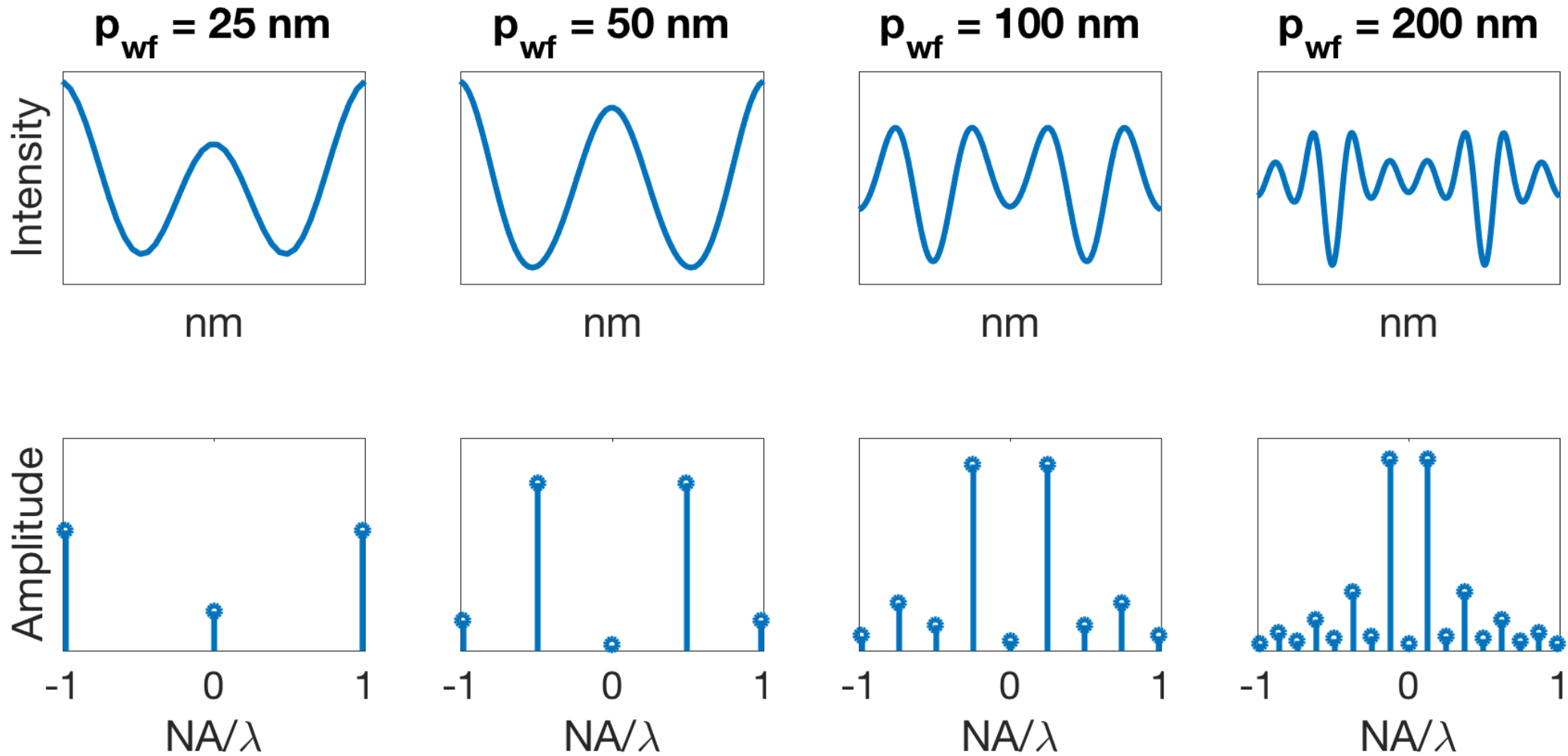
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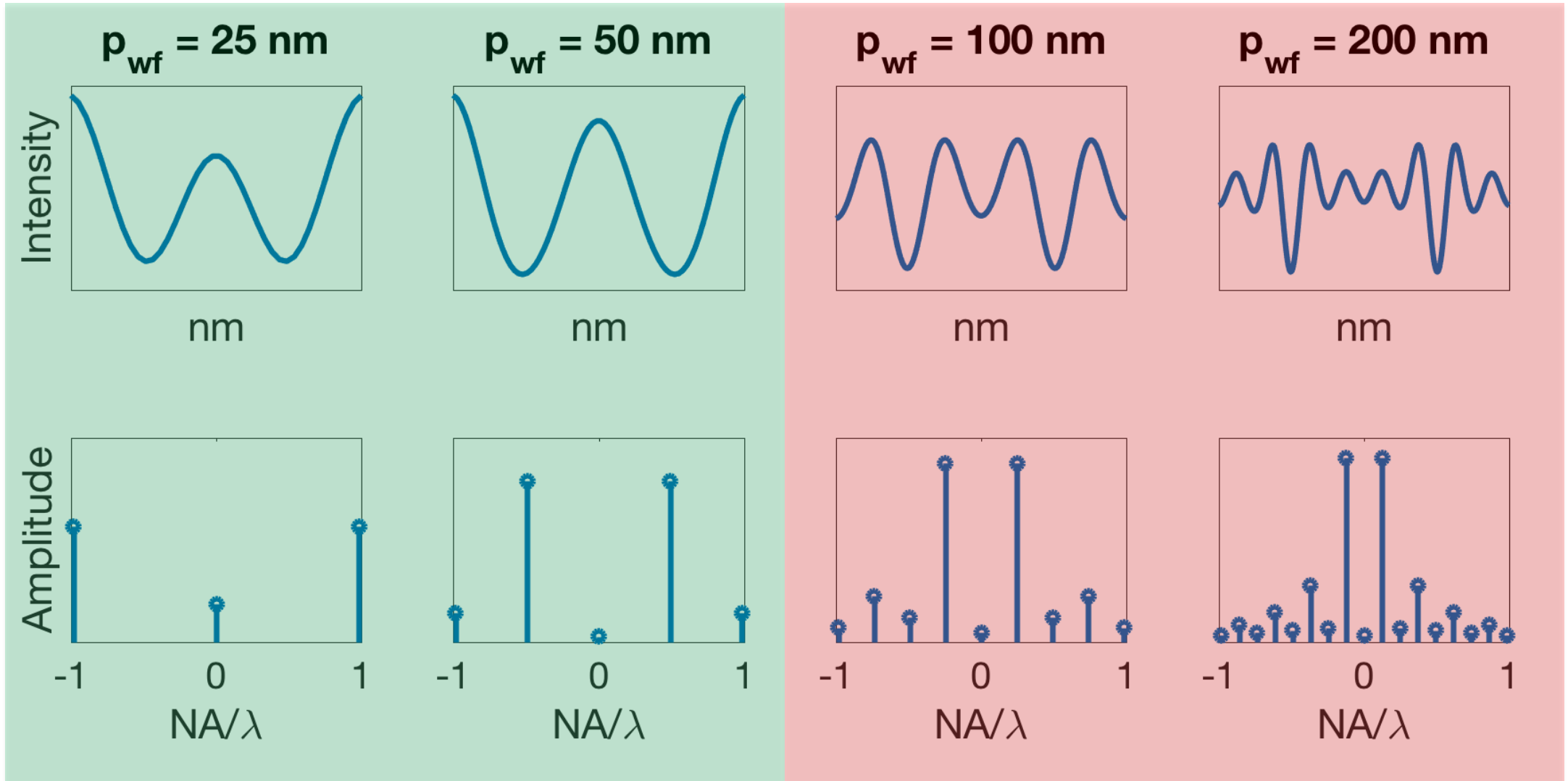
So phase-shift masks are more efficient. Are they practical?



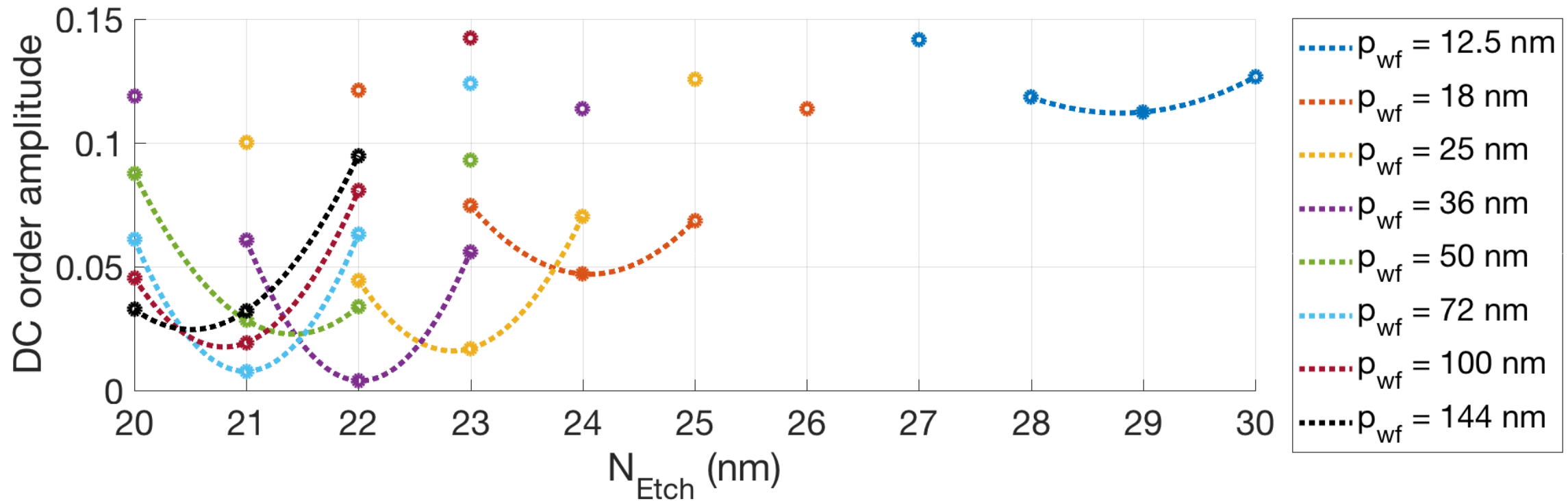
Not all pitches can be printed with alternating PSM



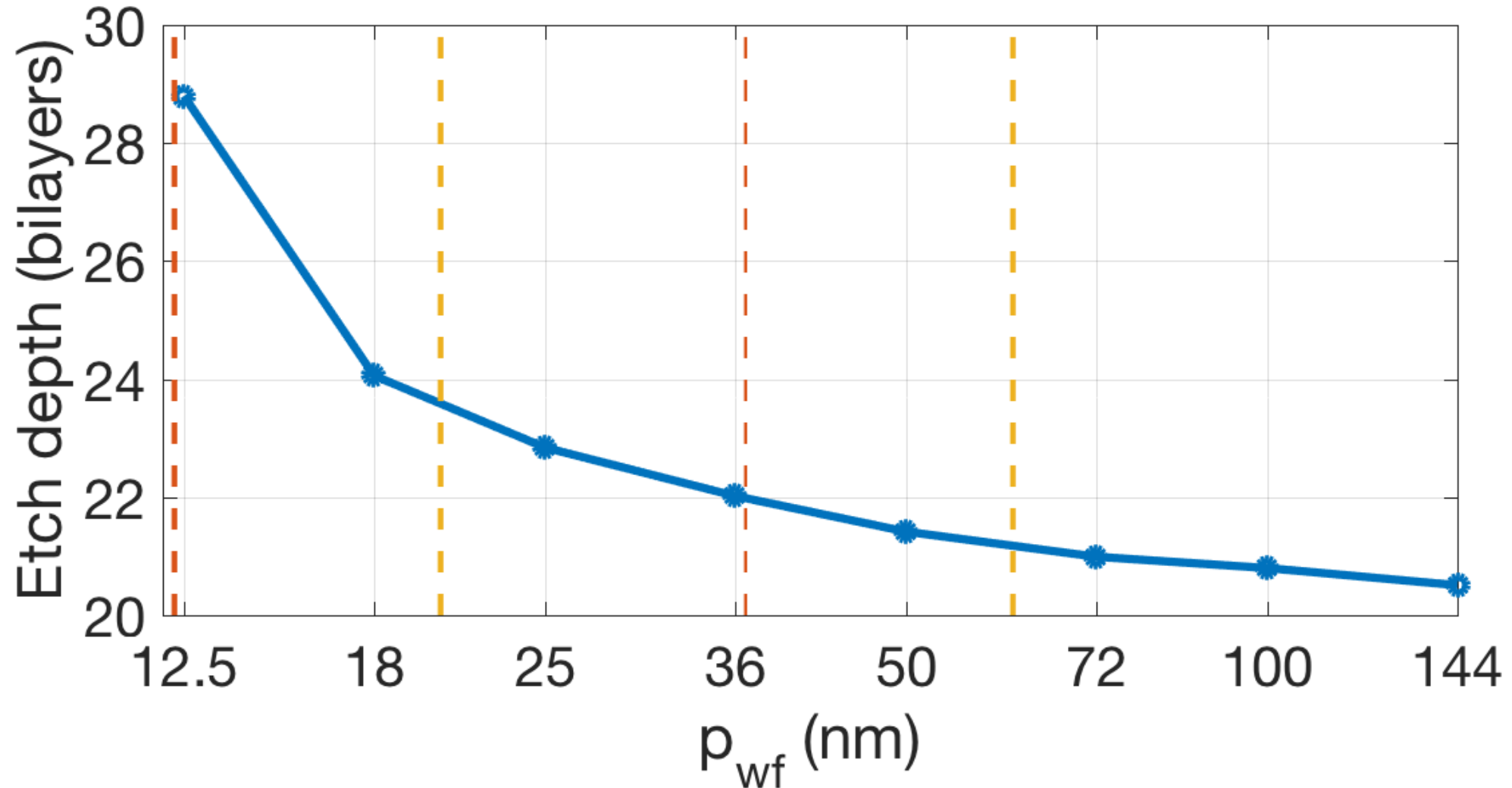
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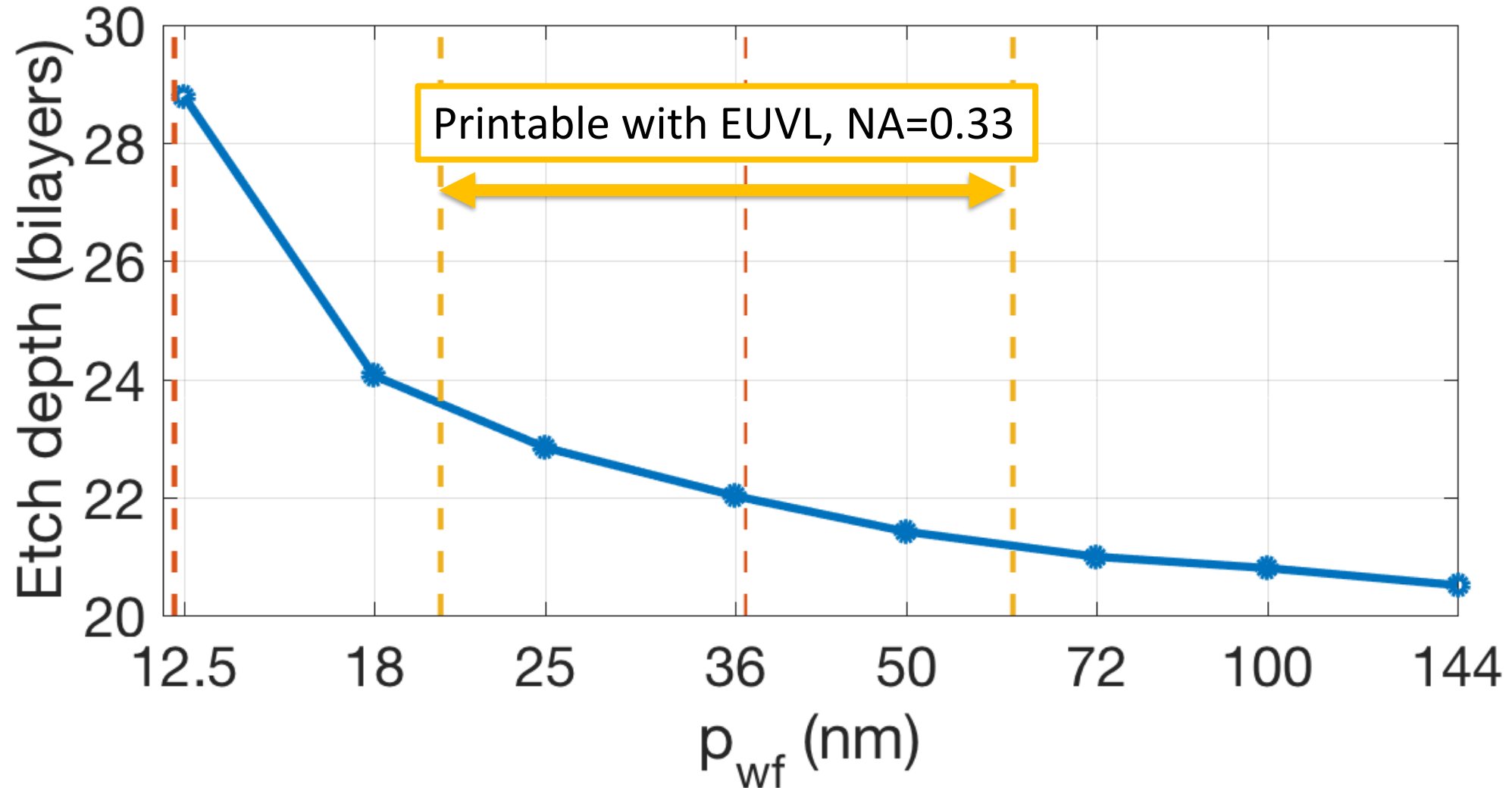
3D Geometry $\rightarrow \pi$ phase shift etch depth depends on pitch



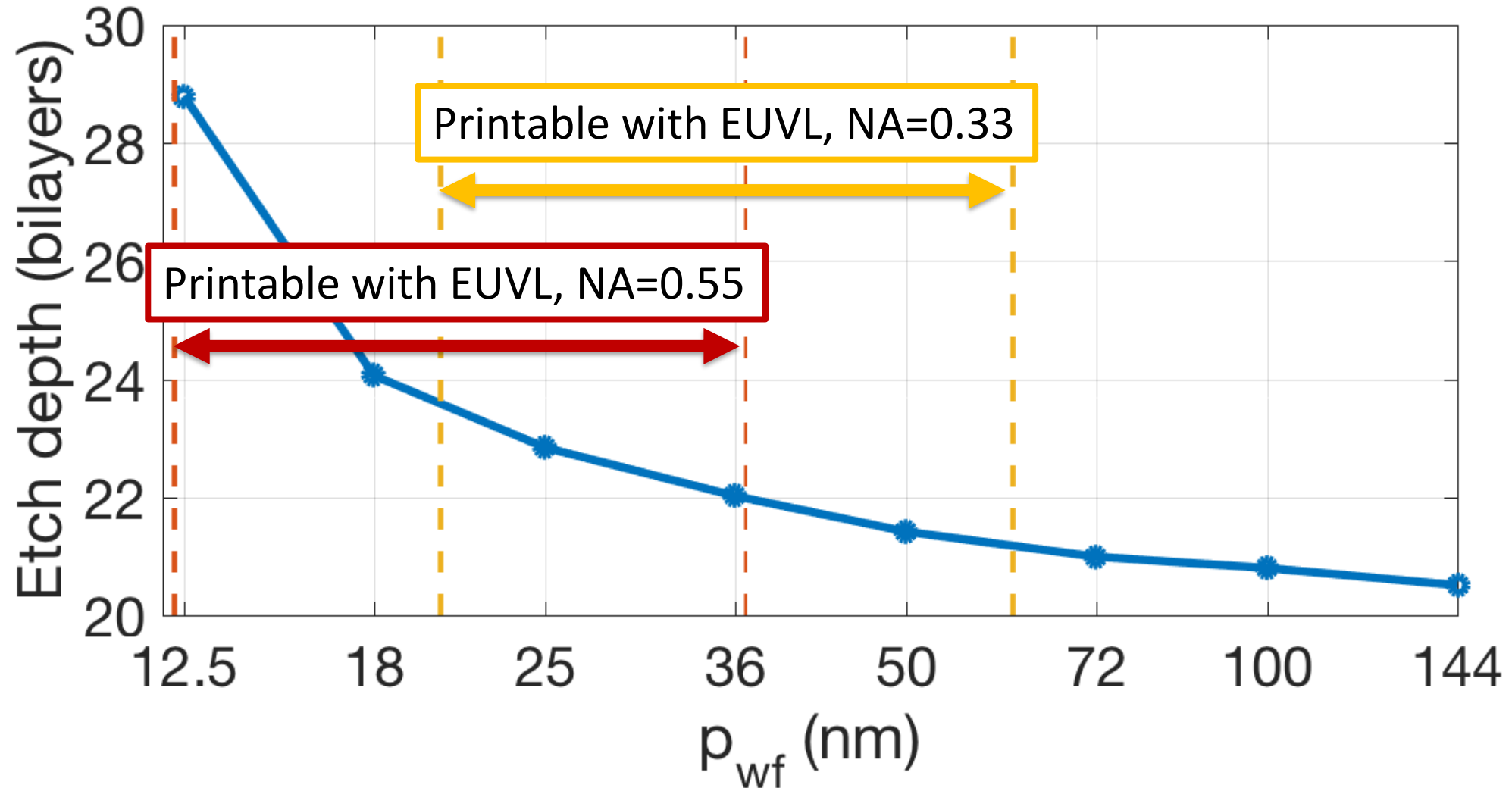
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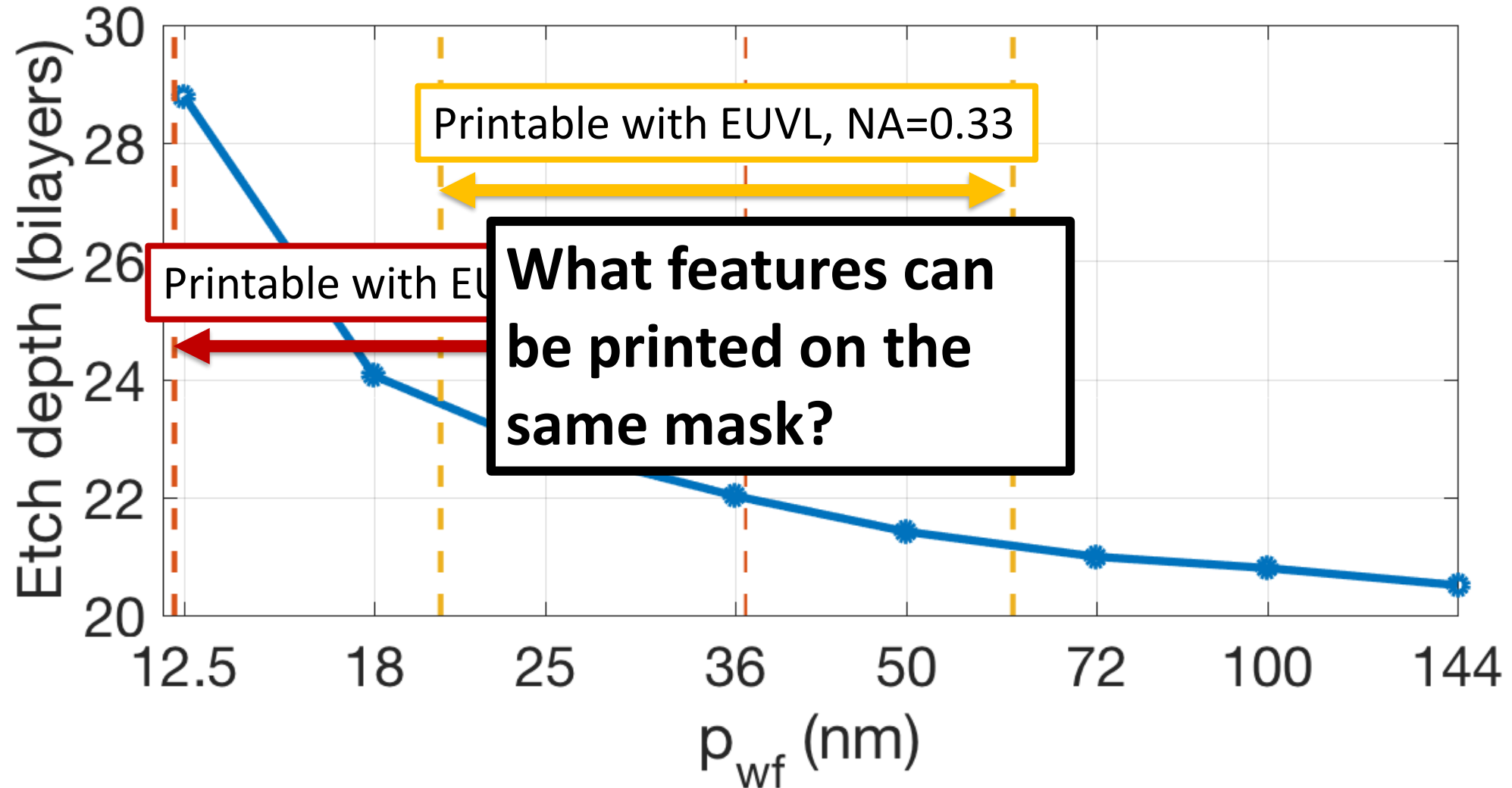
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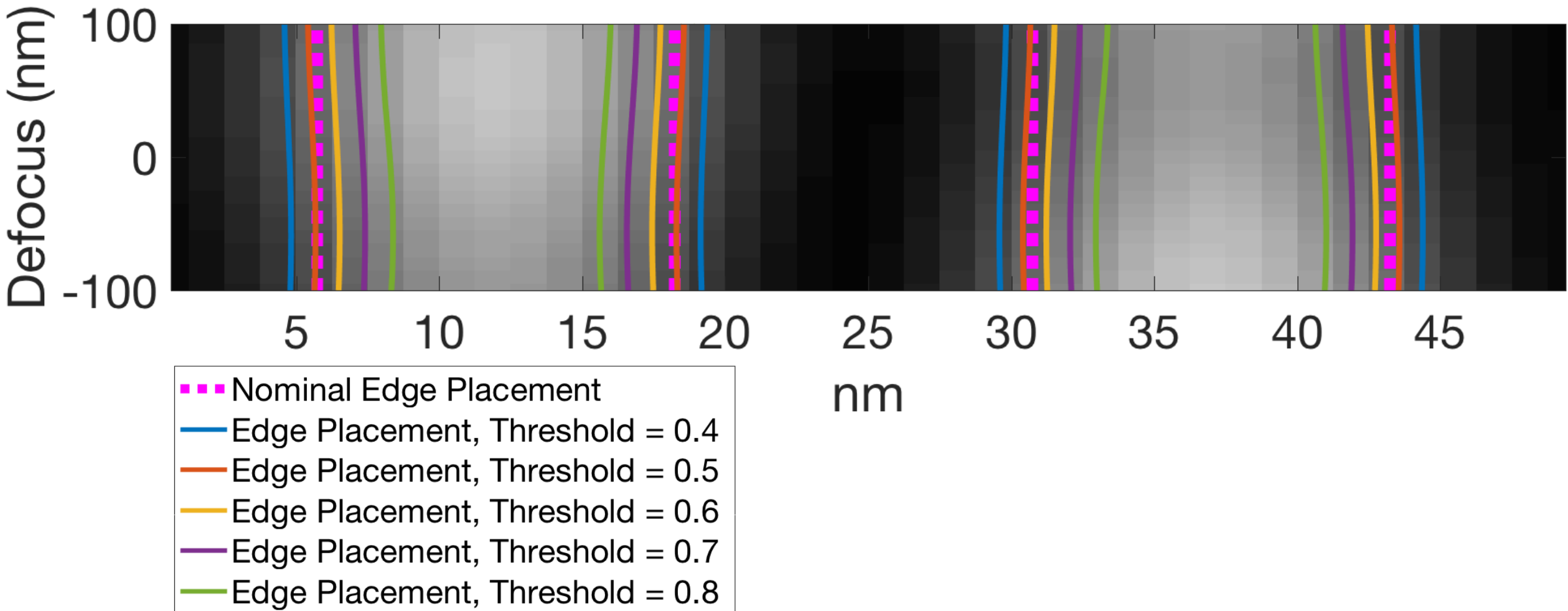
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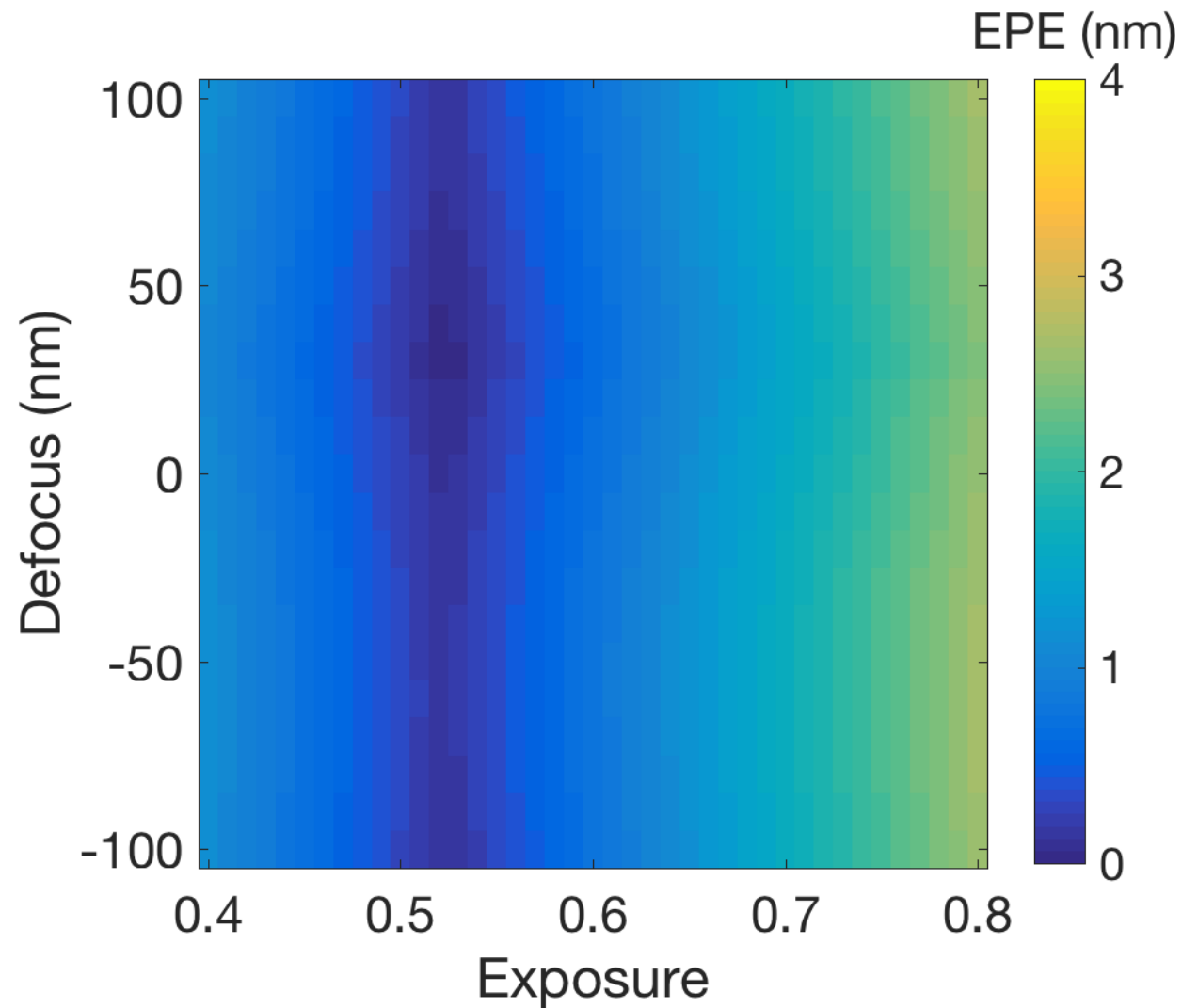
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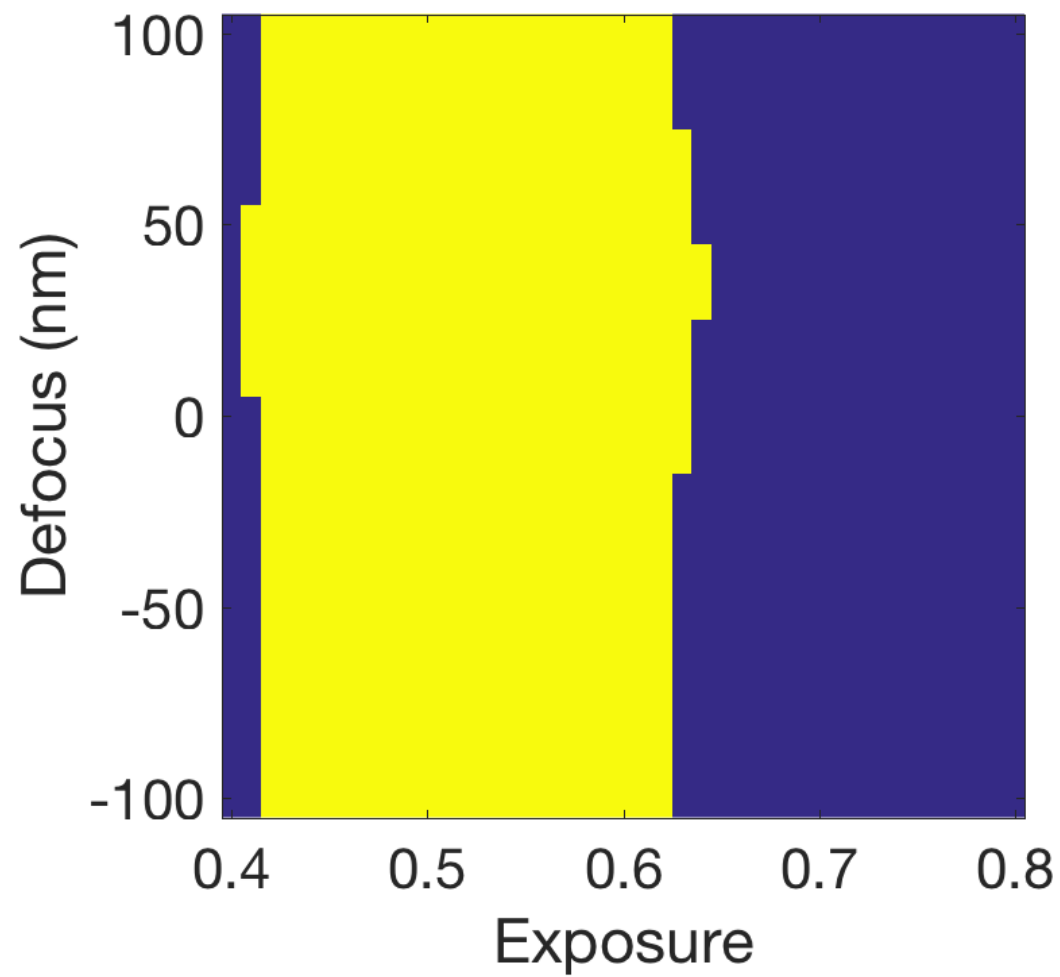
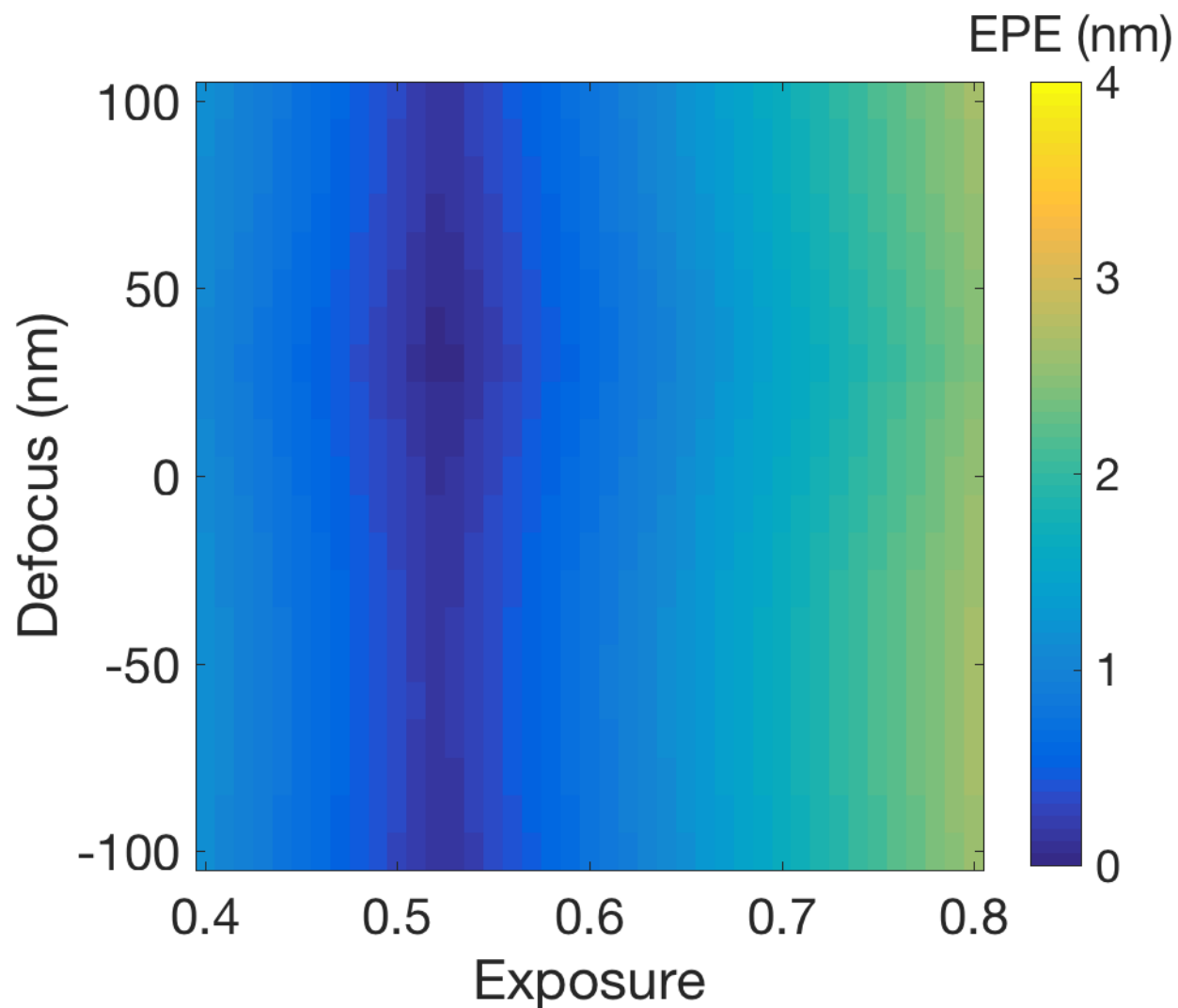
Edge placement error (EPE) through focus and exposure



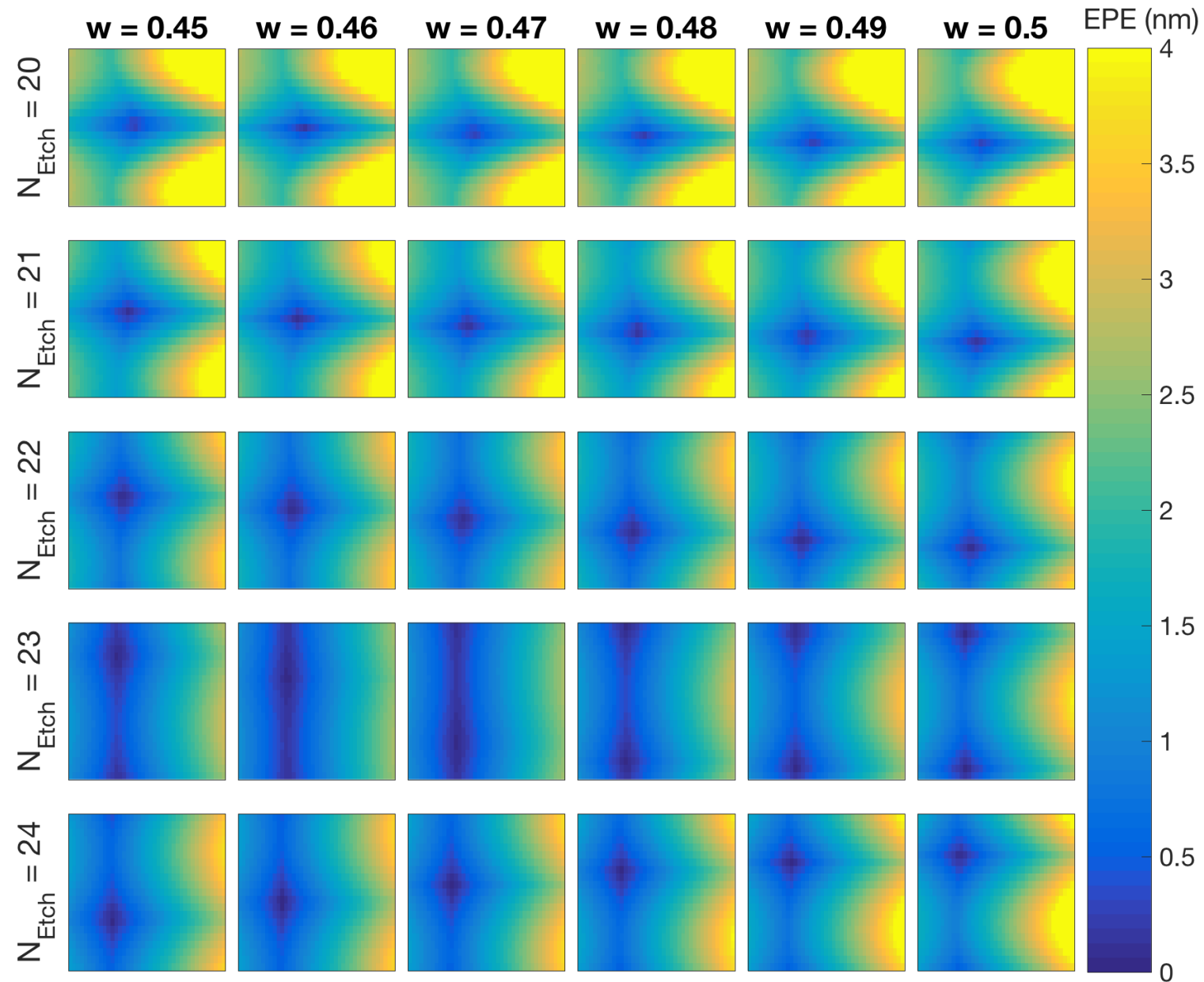
Calculate focus-exposure process window from EPE spec



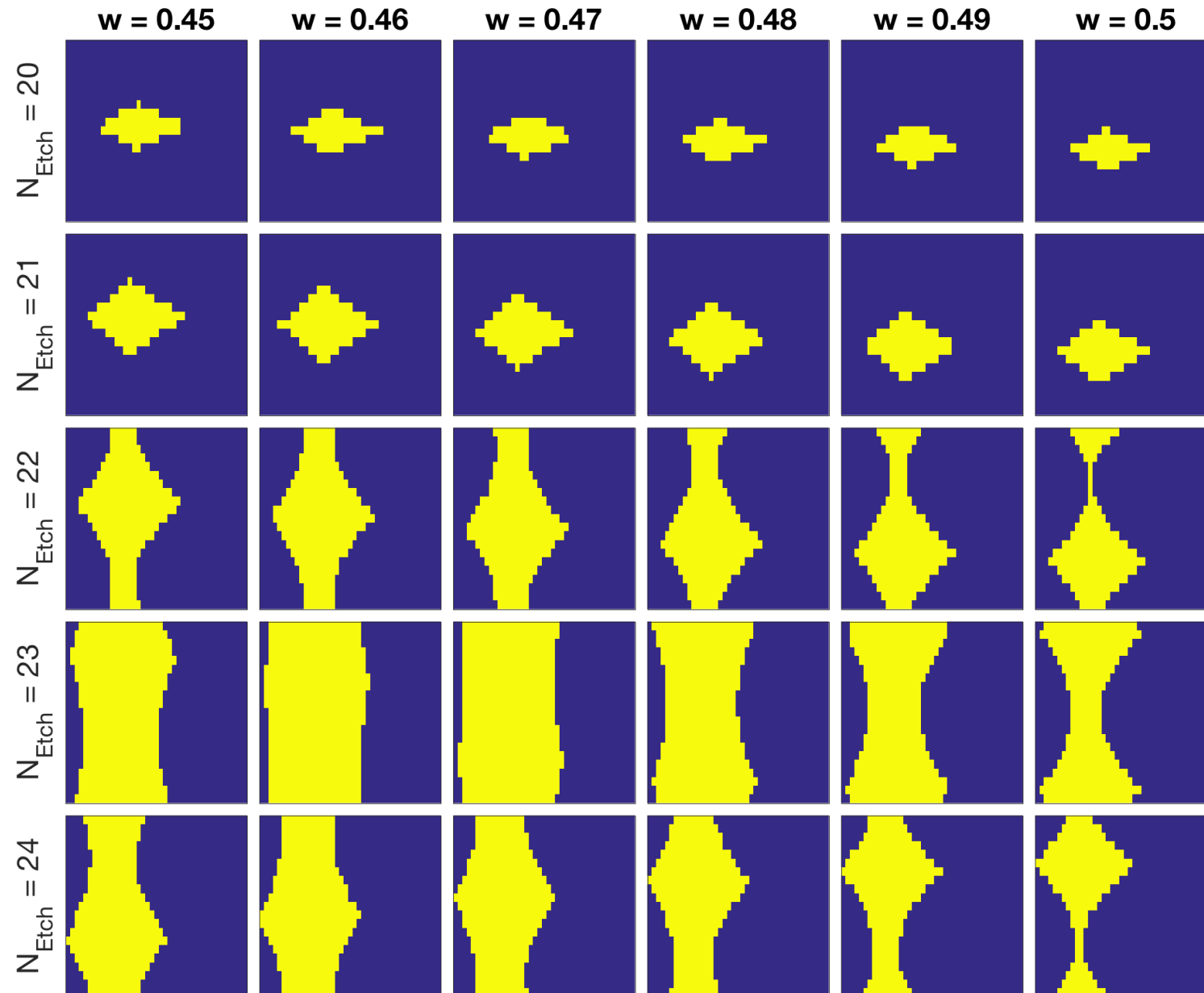
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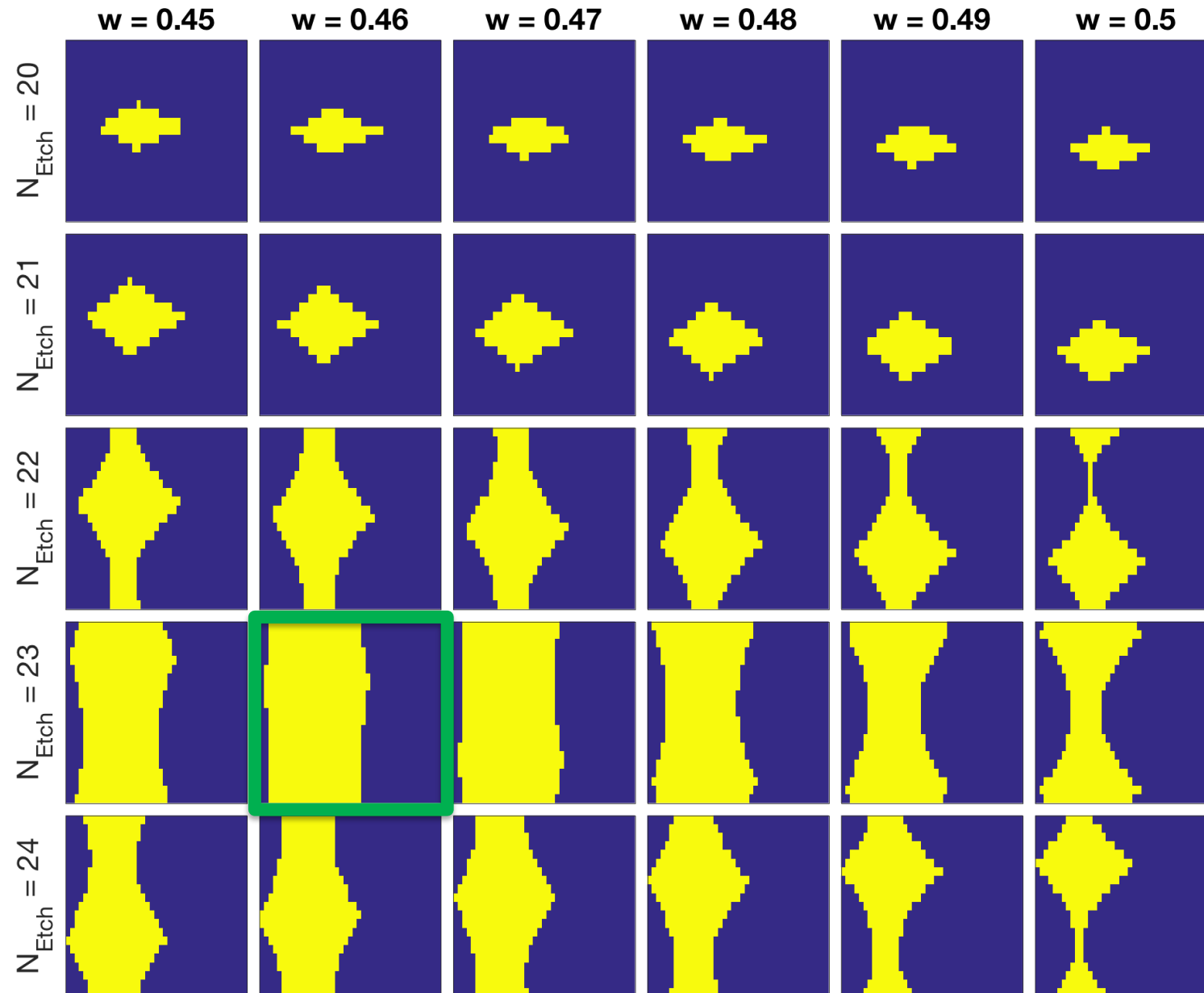
Calculate EPE for different mask designs



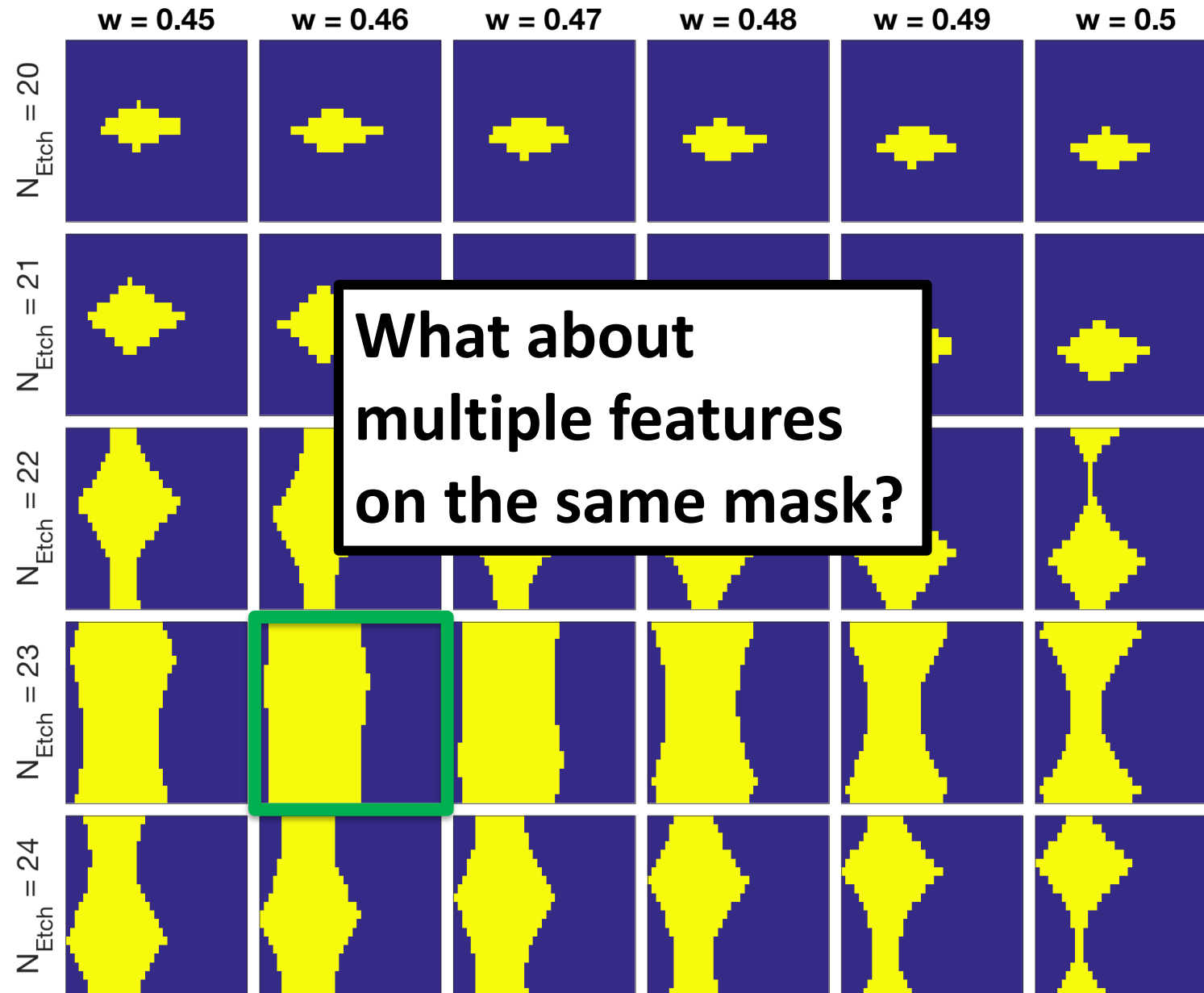
Choose design with largest process window



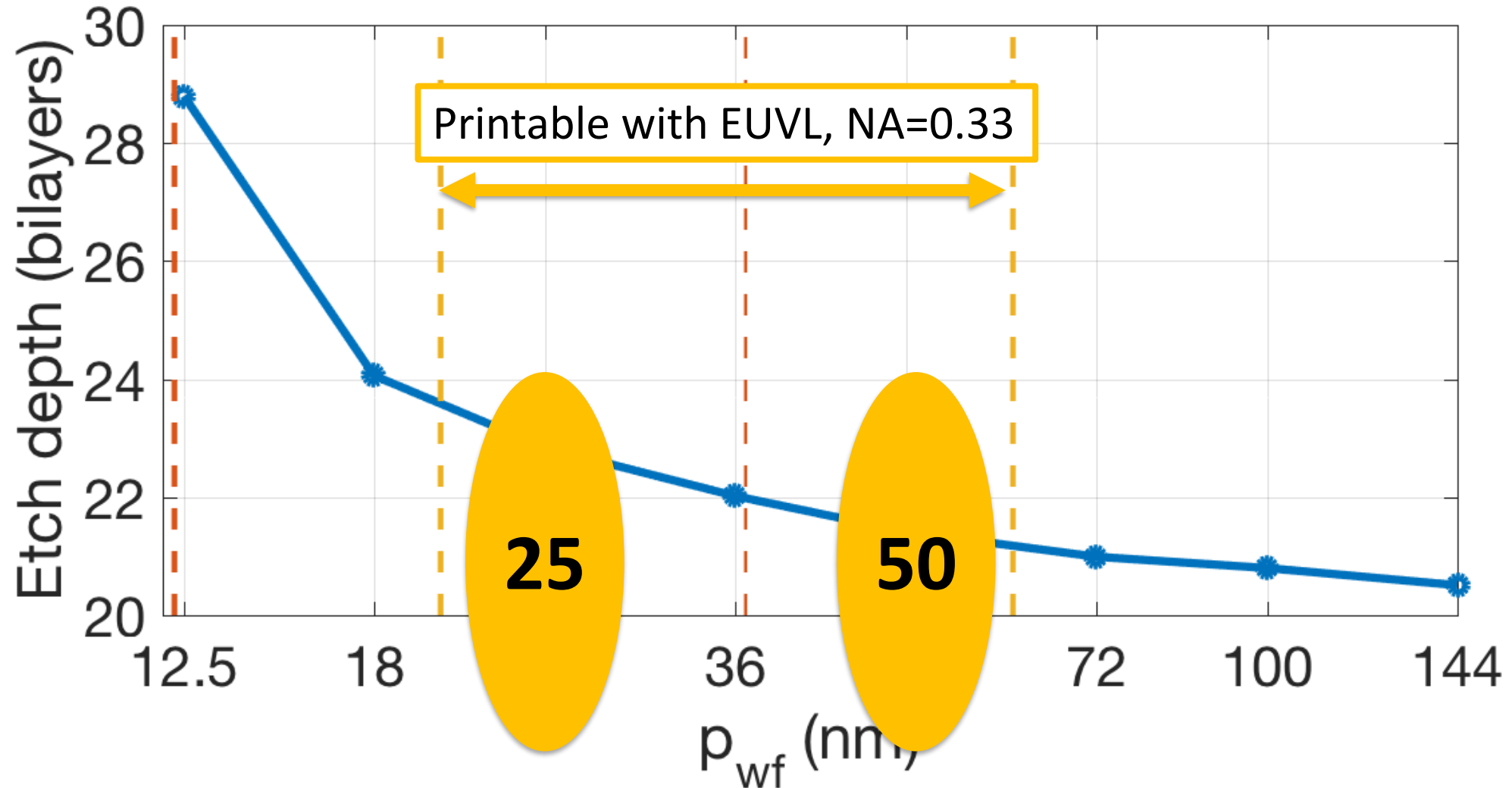
Choose design with largest process window



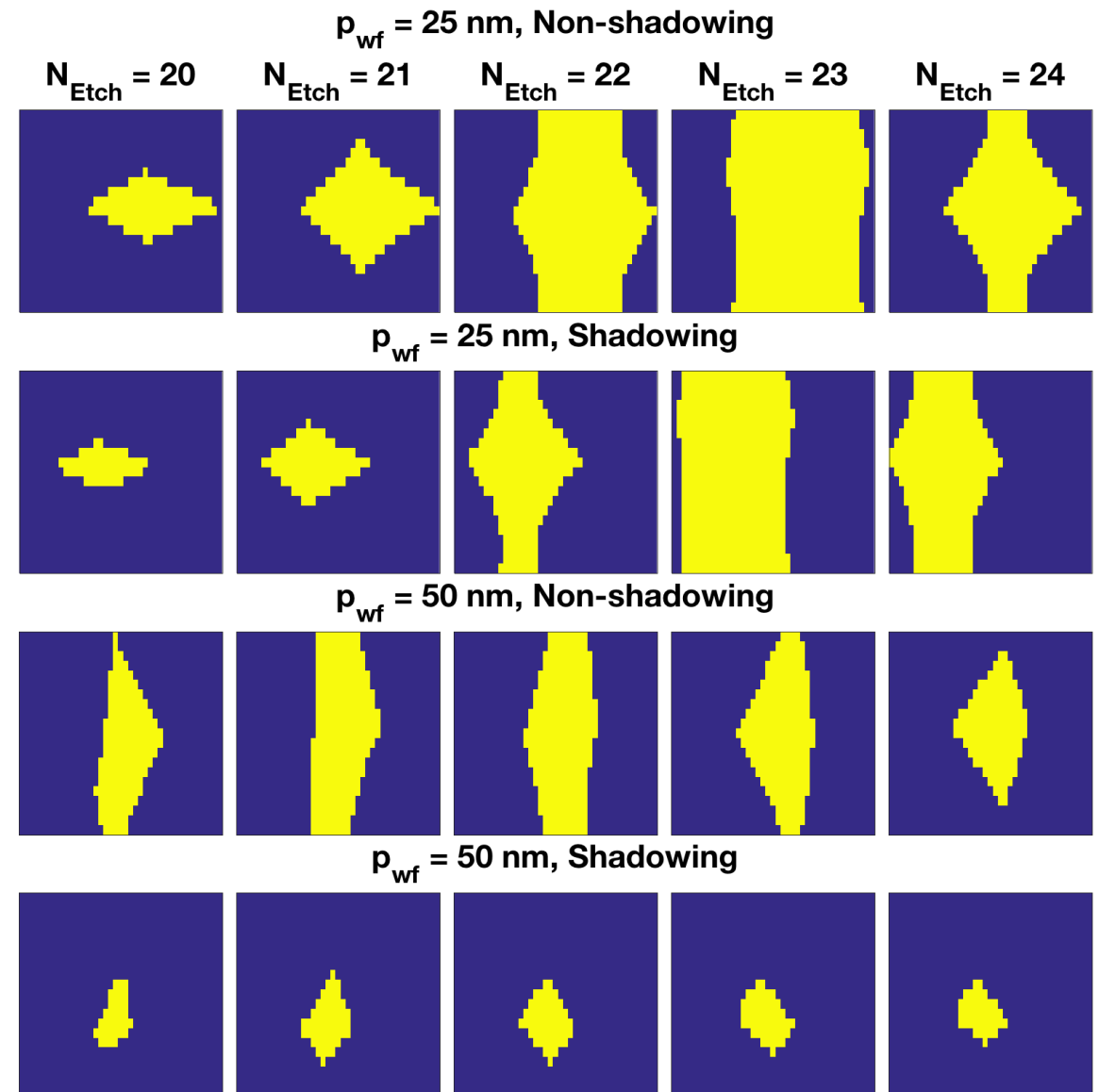
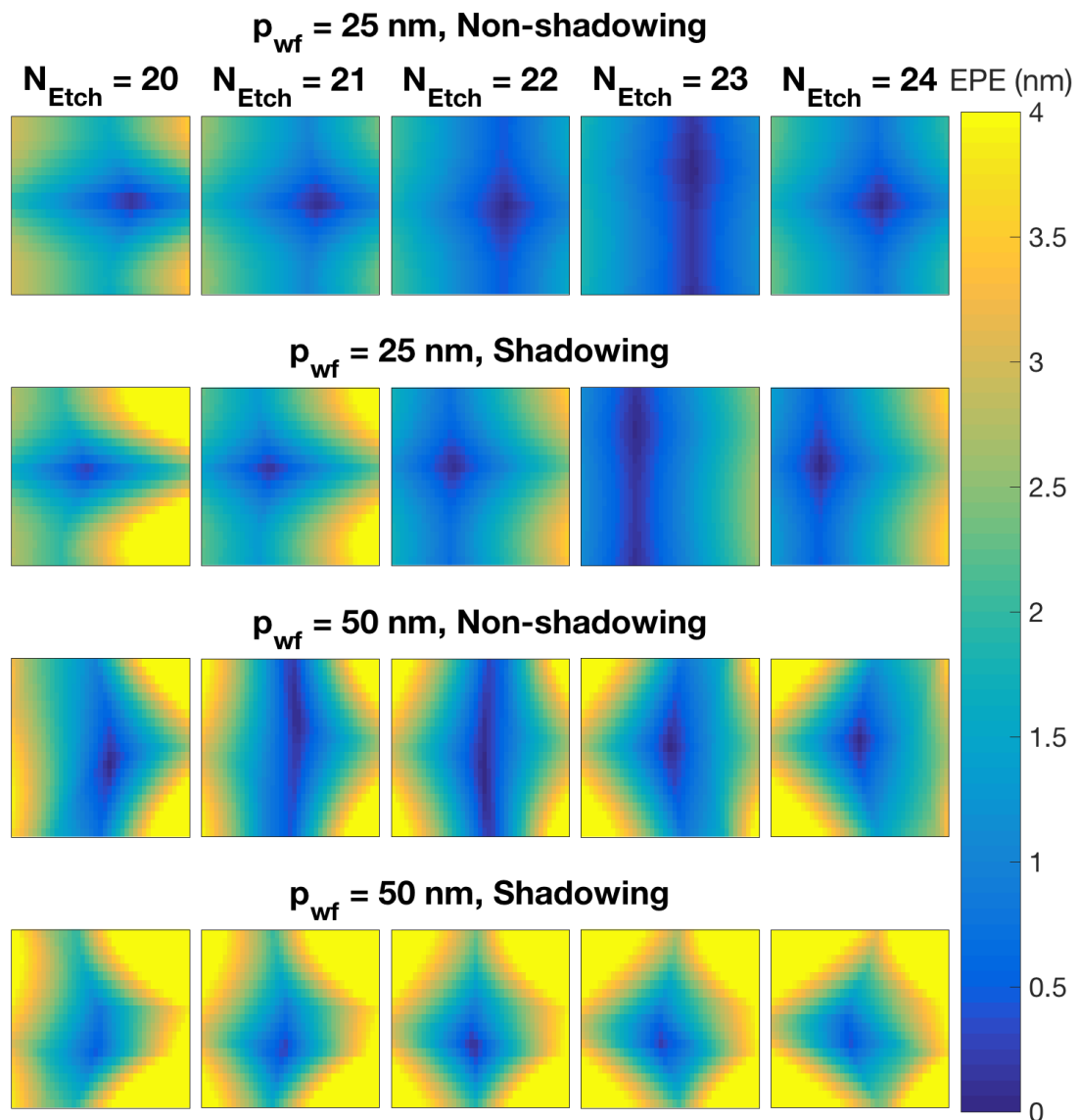
Choose design with largest process window



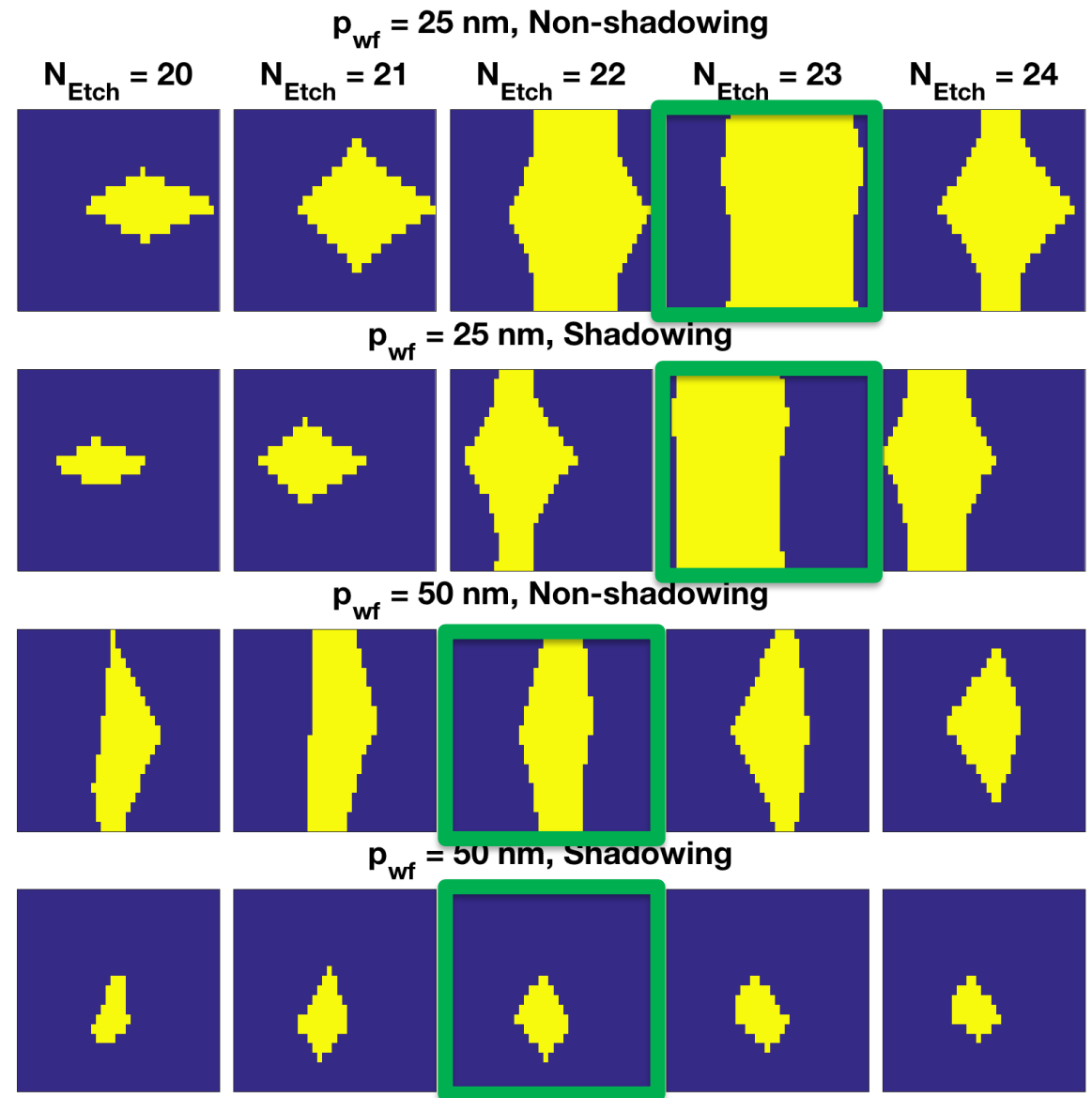
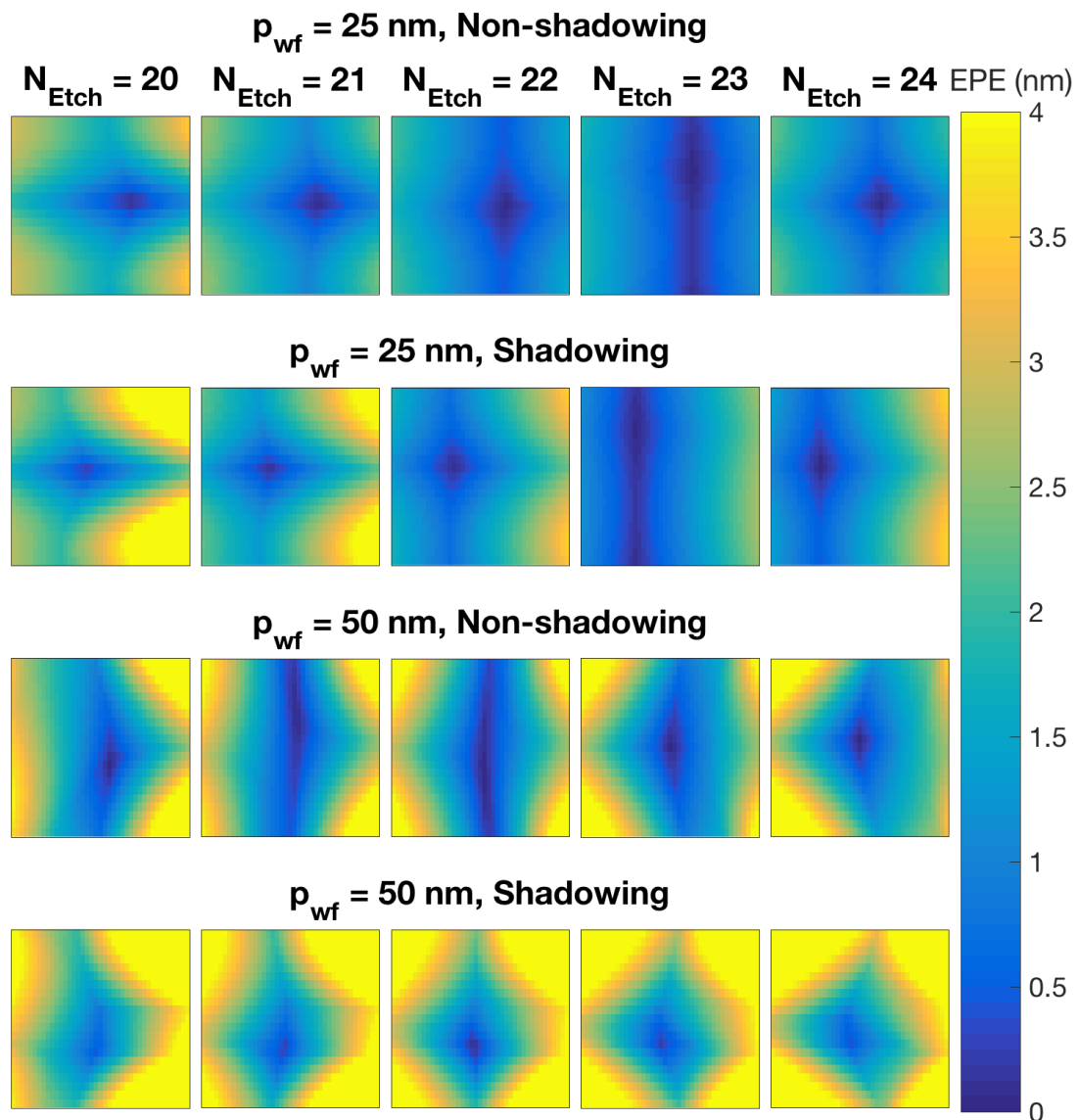
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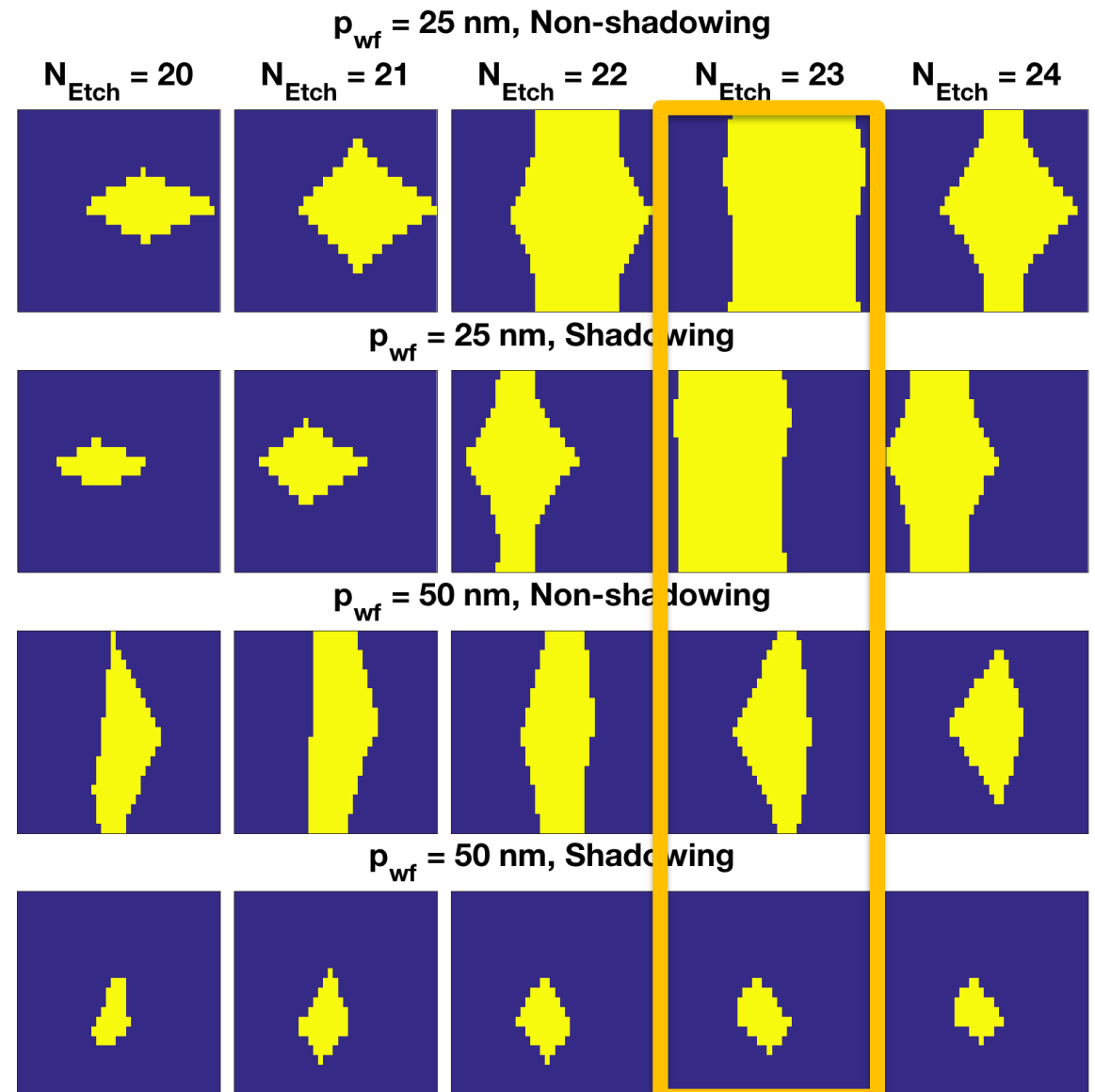
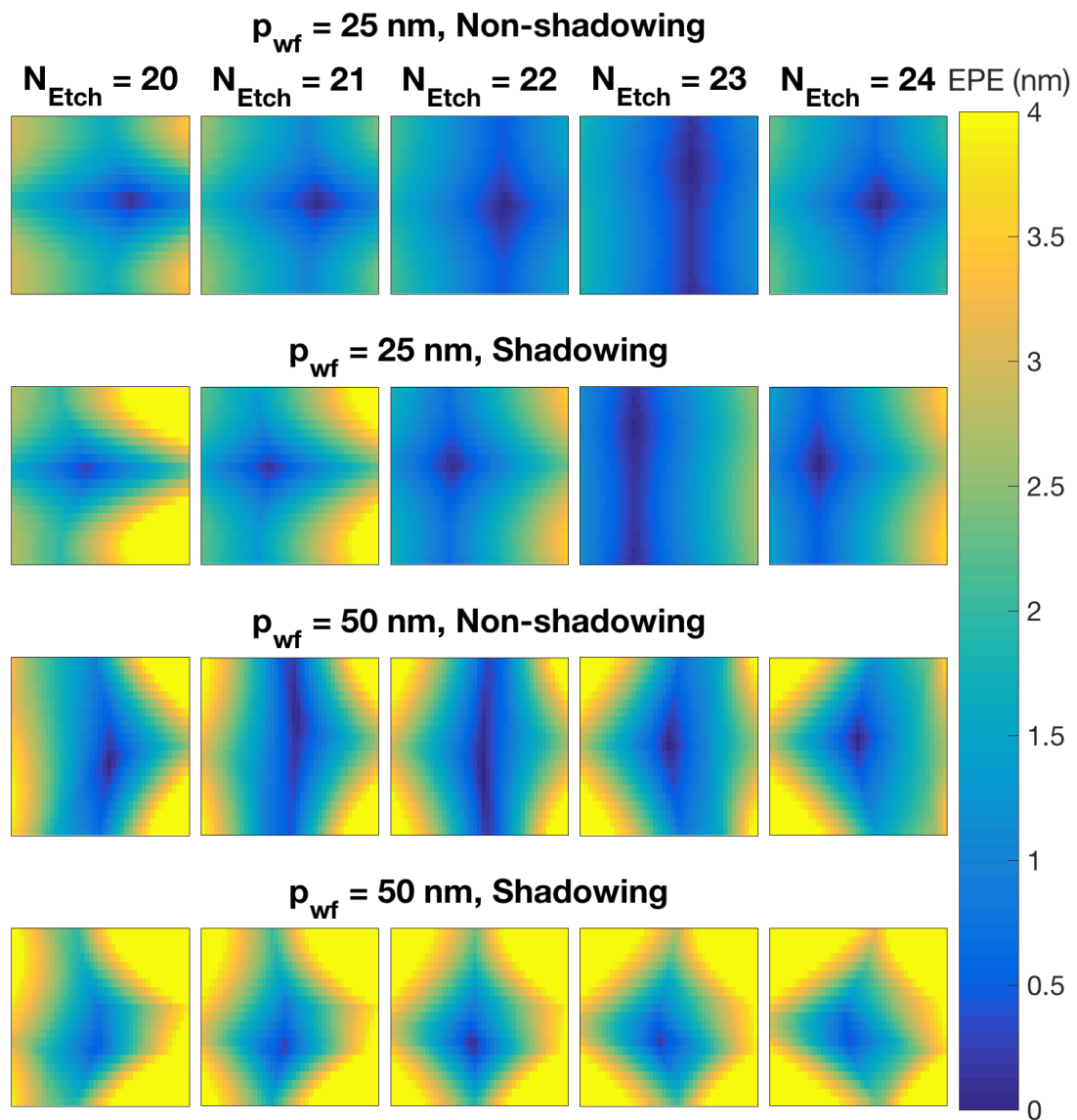
Optimizing design for different features, NA = 0.33



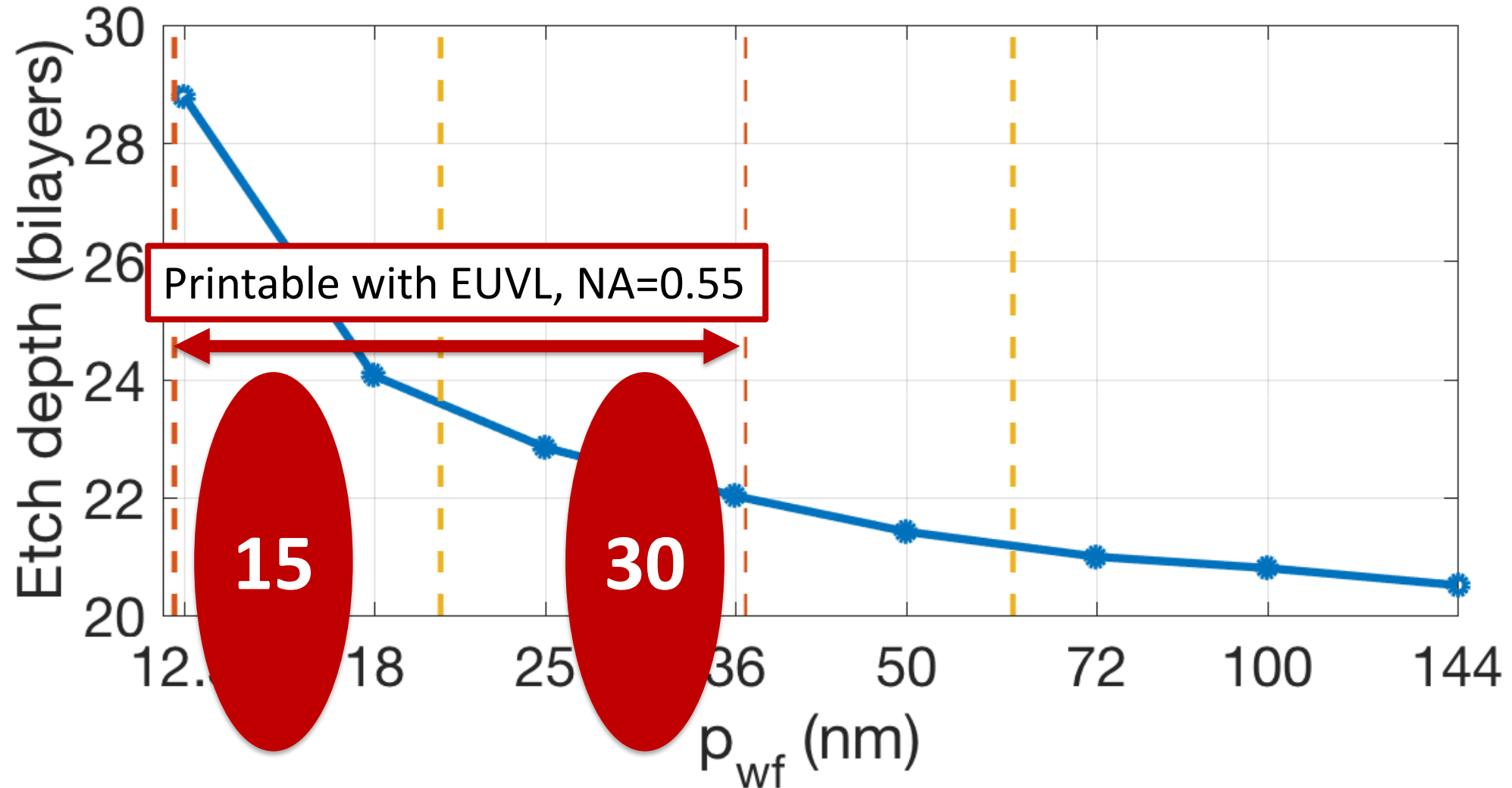
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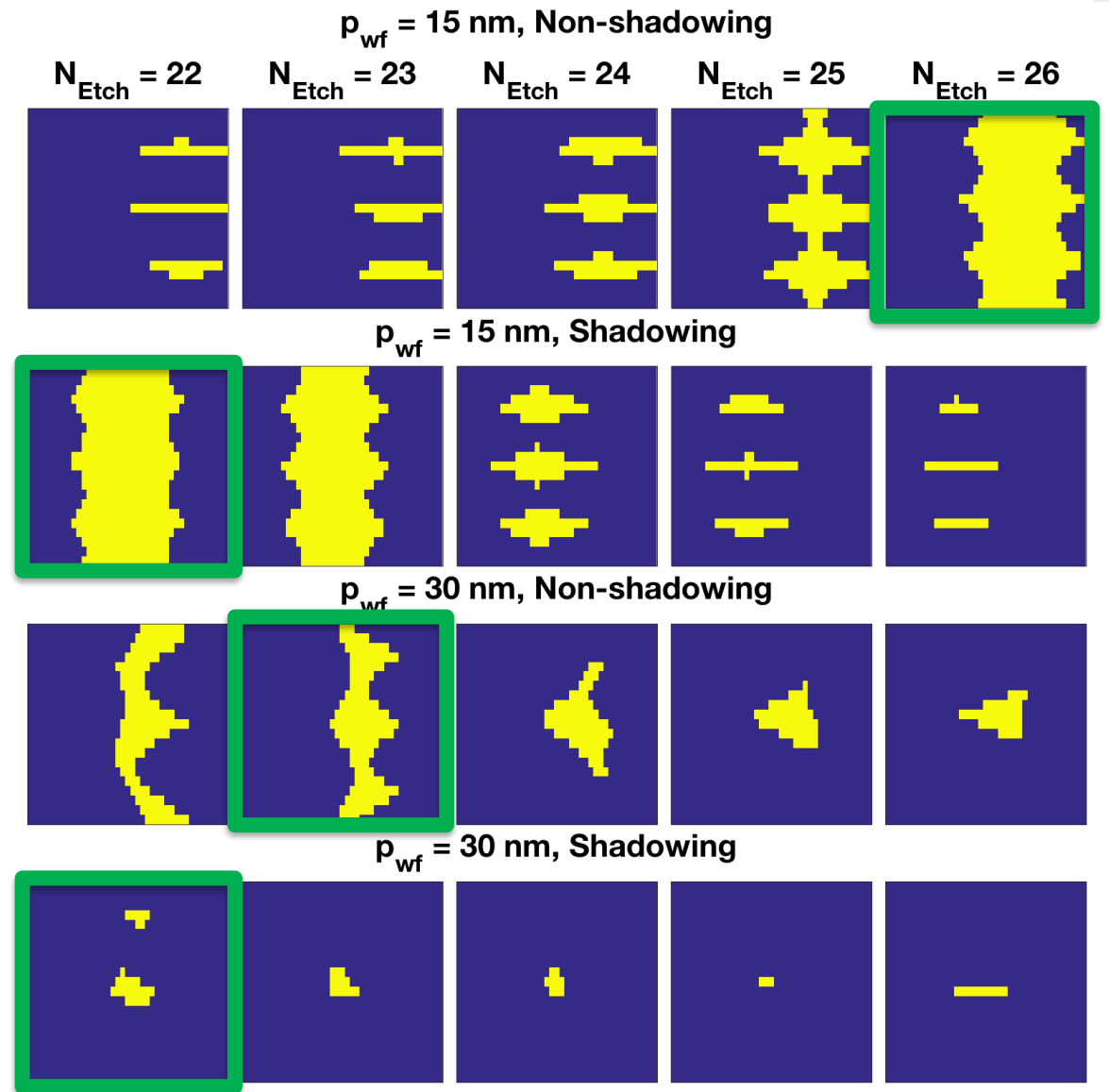
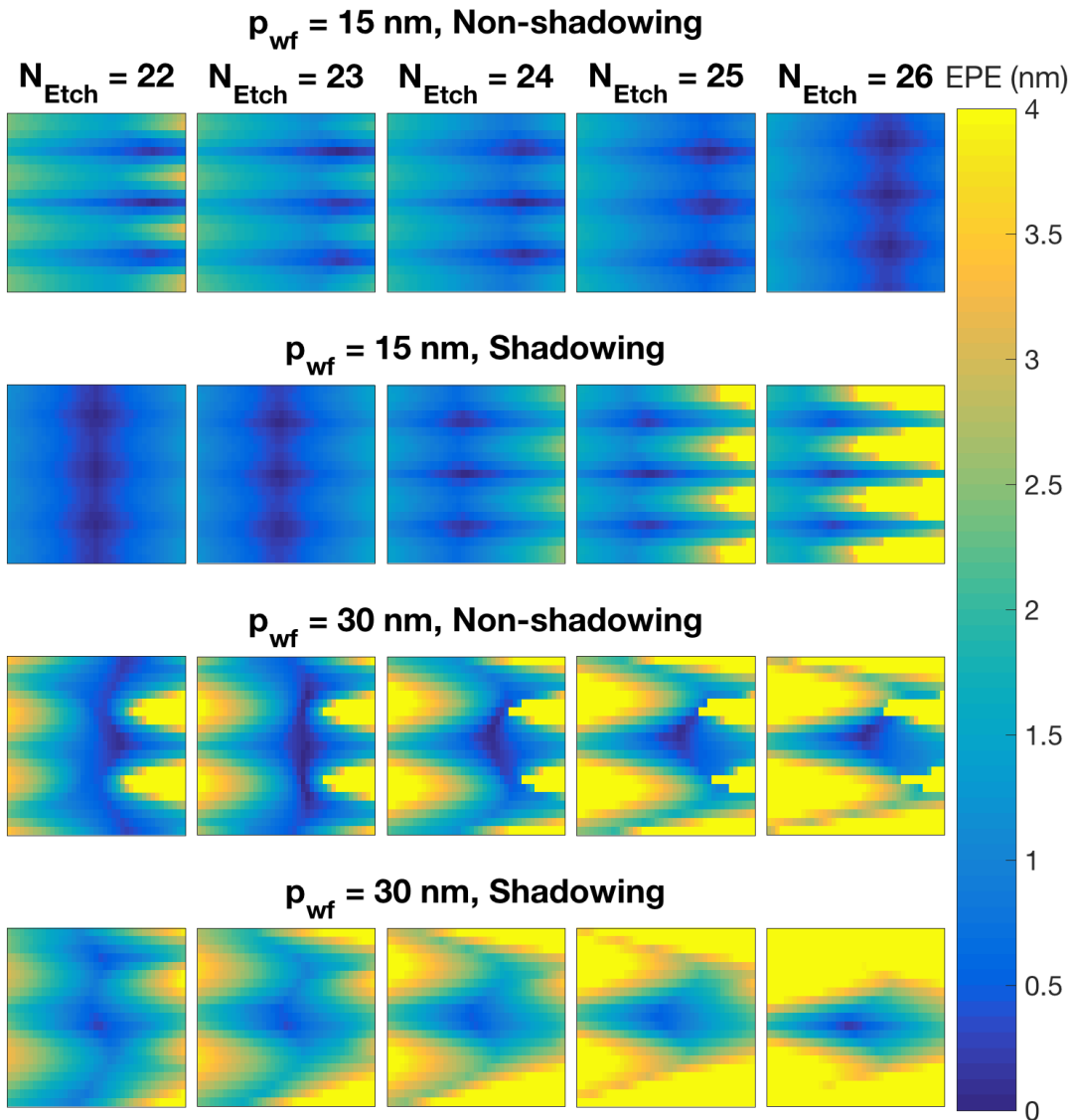
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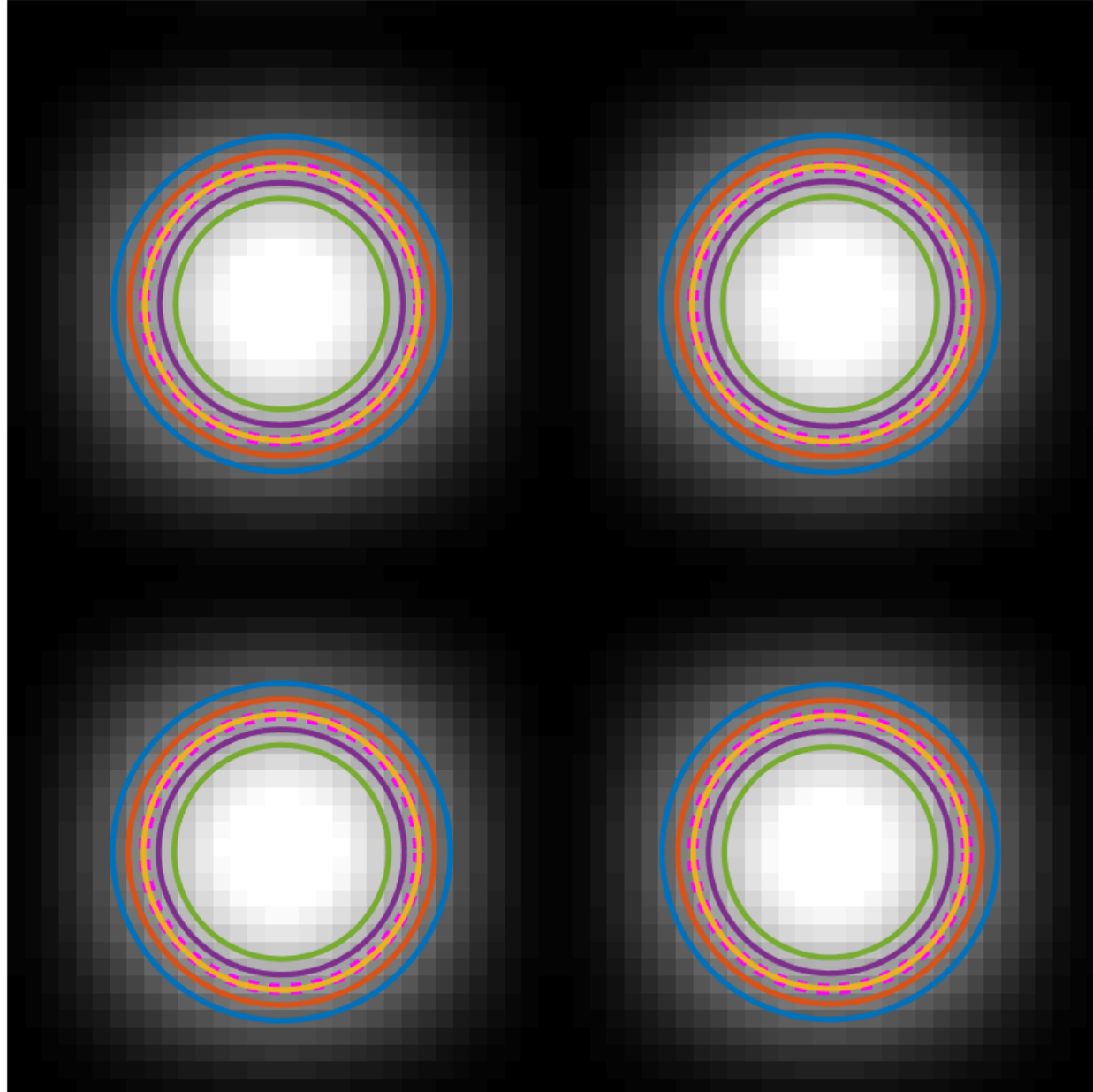
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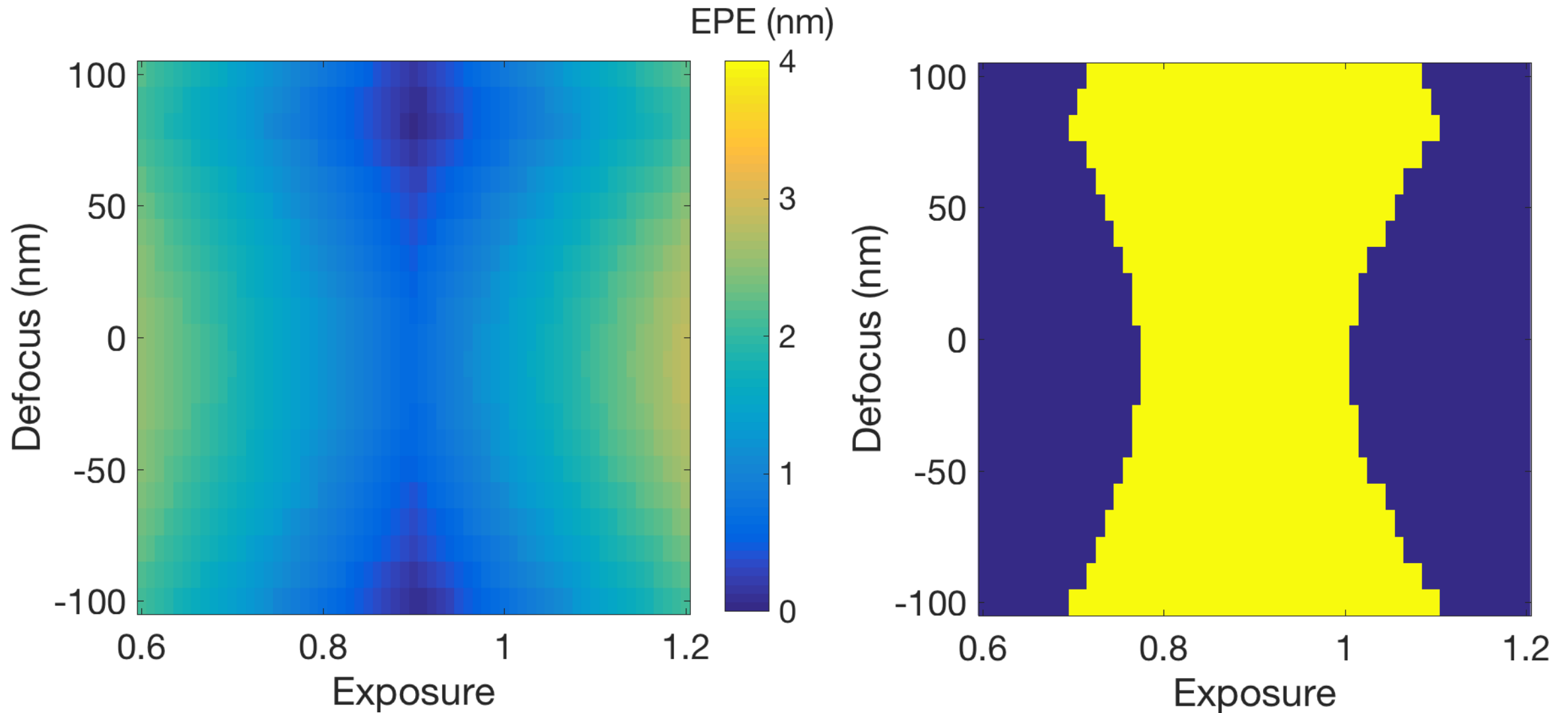
Optimizing design for different features, NA = 0.55



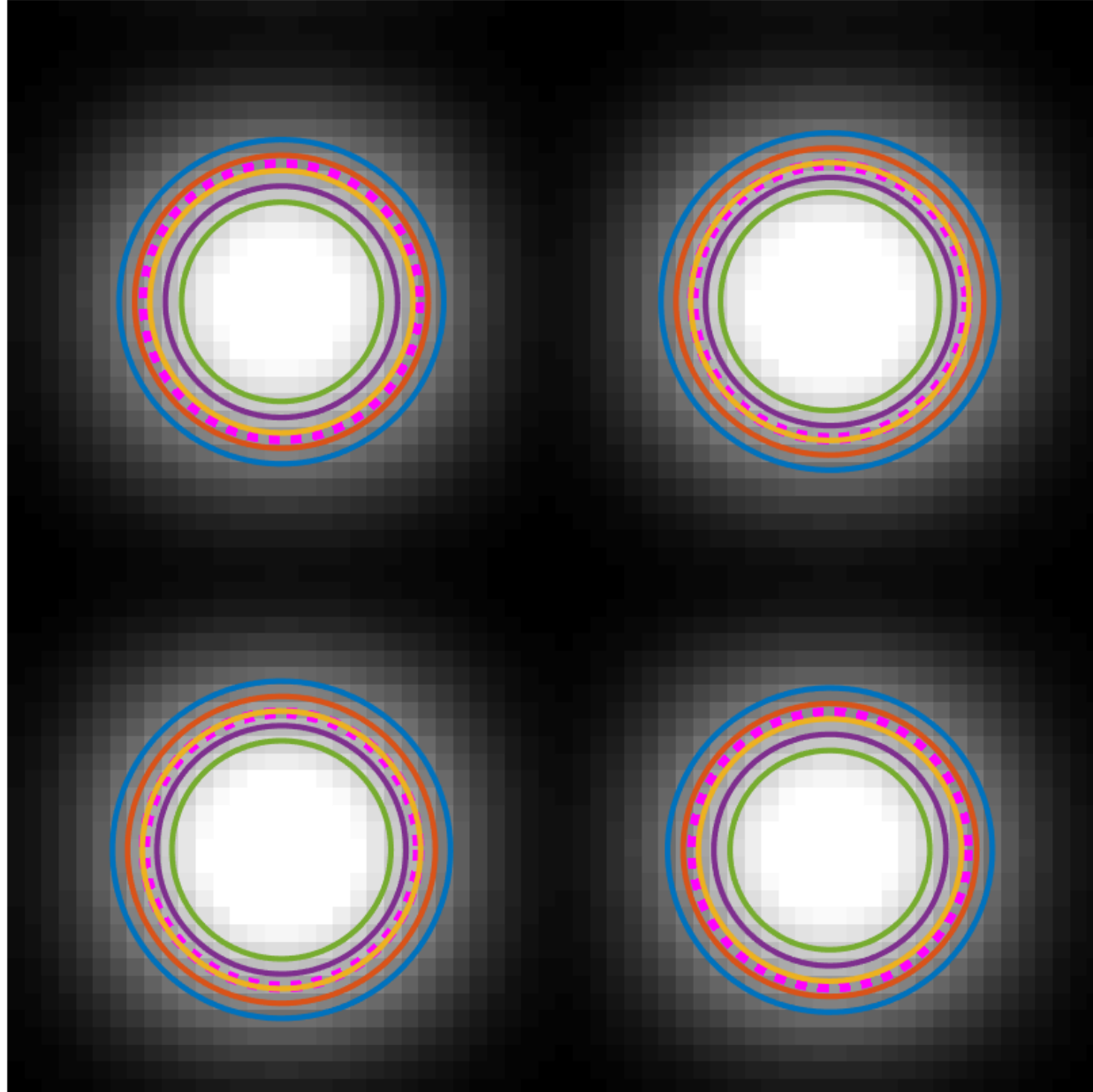
Contact array: $NA = 0.33$, $p_{wf} = 36\text{nm}$



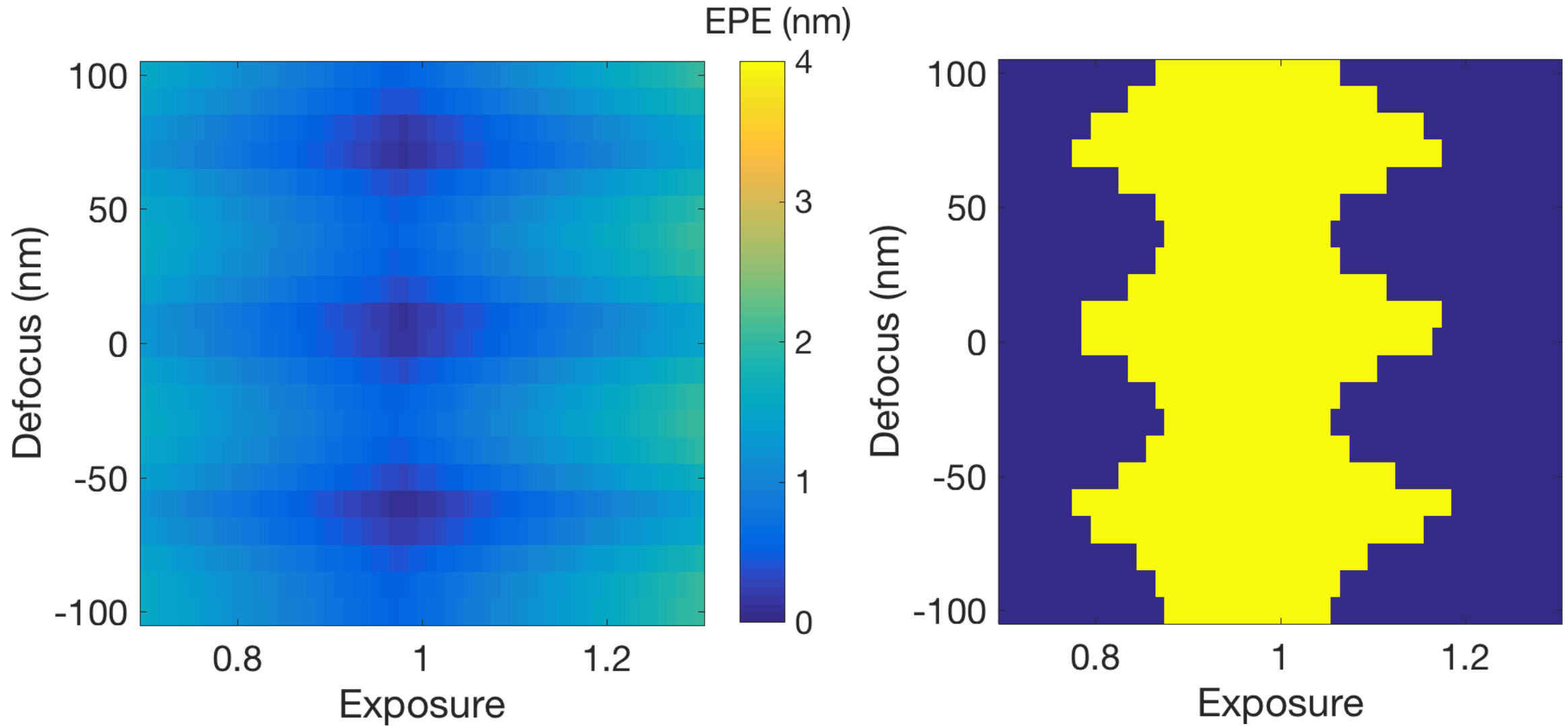
Contact array: $NA = 0.33$, $p_{wf} = 36\text{nm}$



Contact array: $NA = 0.55$, $p_{wf} = 22\text{nm}$



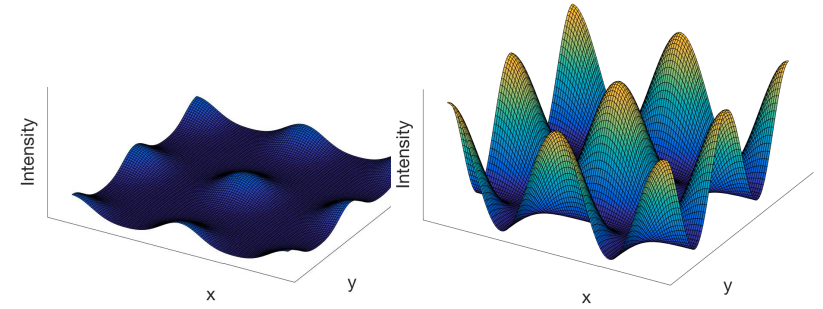
Contact array: $NA = 0.55$, $p_{wf} = 22\text{nm}$



Summary

Phase is **much** more efficient than
amplitude

6-8x for contact array

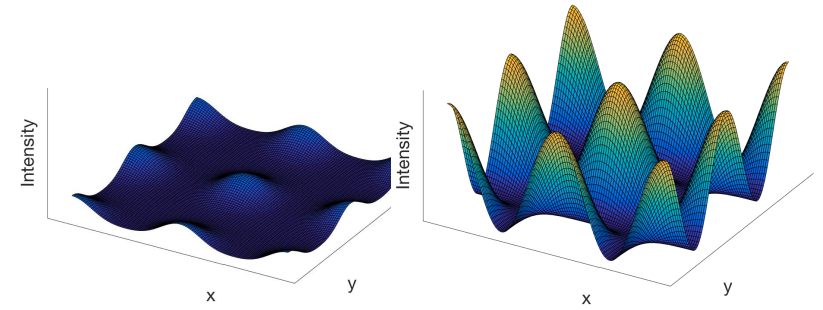
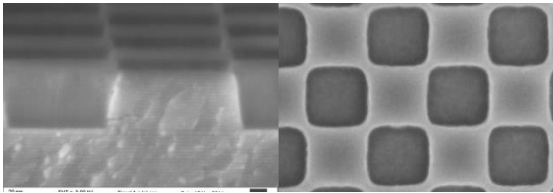


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Etched multilayer EUV mask works in theory and experiment



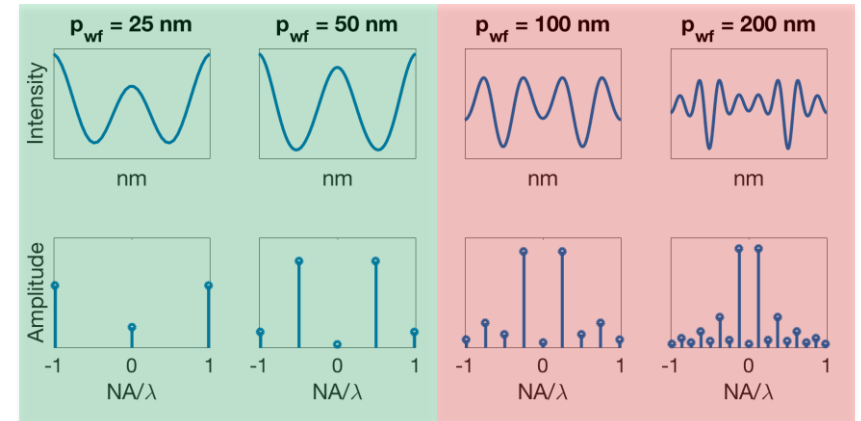
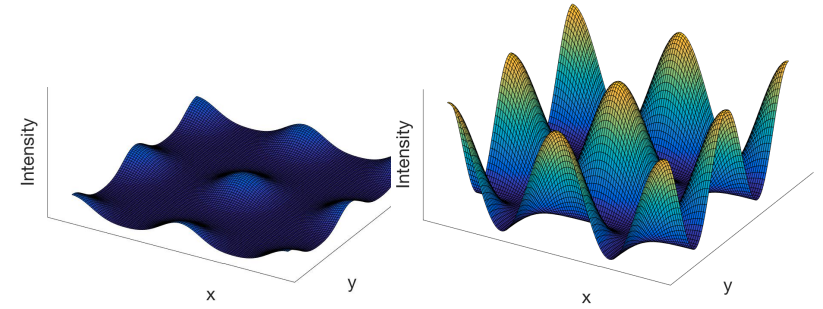
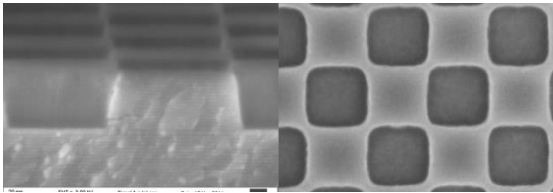
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Alternating phase-shift masks can only print certain patterns



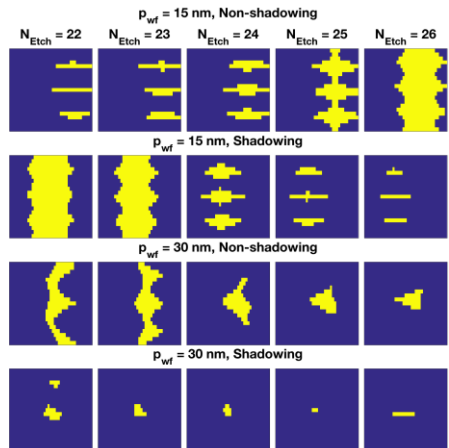
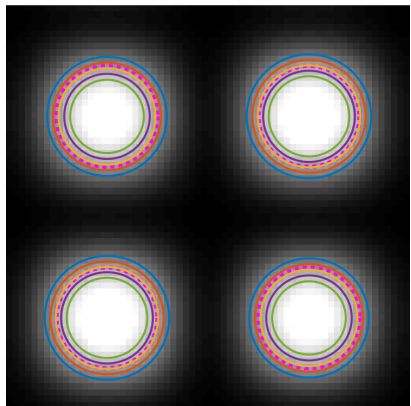
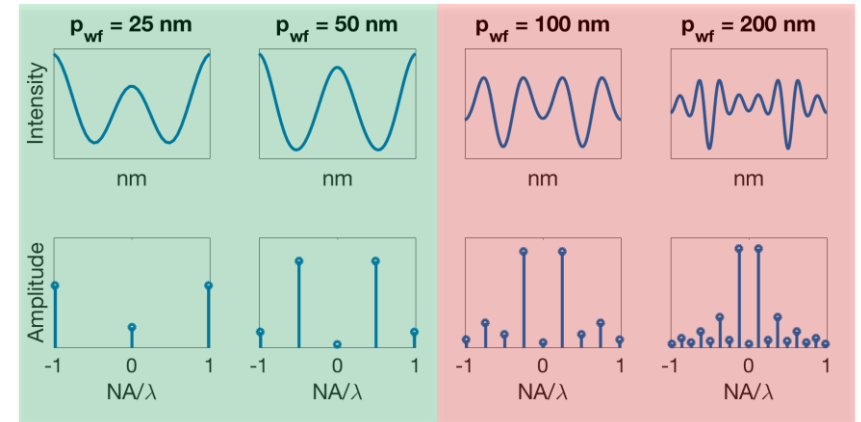
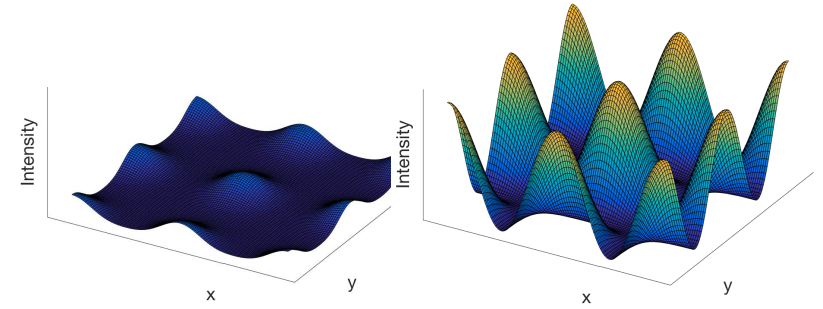
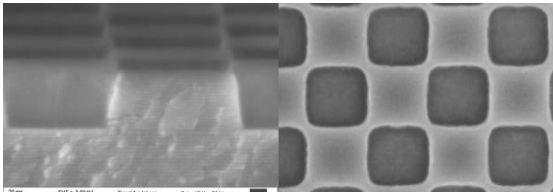
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Need rigorous simulation to accurately design mask
Optimal design varies with pitch, pattern, and orientation

Thanks for your attention!