Hybrid meta-surface lens system for long wave infrared applications

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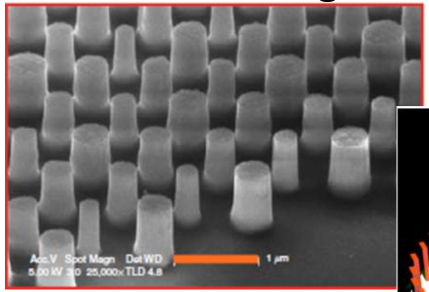
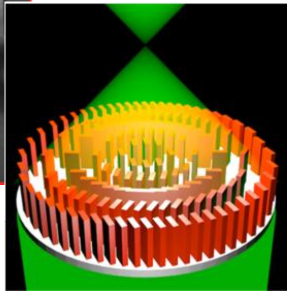
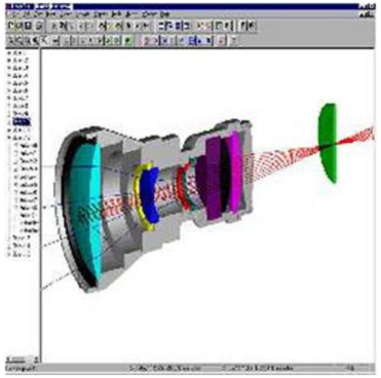
Nano-scale design



Component design



System Integration



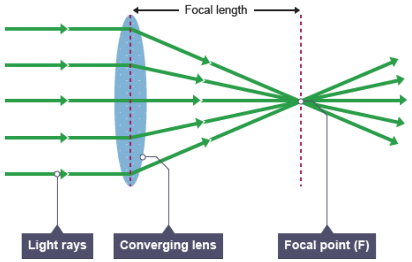
Planopsim's mission

Planopsim supplies **R&D tools** to **engineers** & **scientists** that allow to unlock the maximum benefit of **flat optics** in a **user-friendly** way.

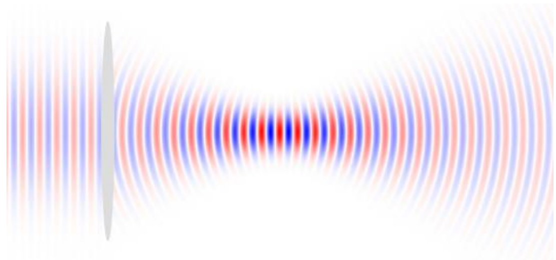
- ❖ Computer Aided Design software for Planar Optics & metasurfaces
  - ➢ All-in-one design workflow
- ❖ Design service for metasurfaces and photonics
  - ➢ In-house and 3^{d} party tools

Principles of meta-surfaces

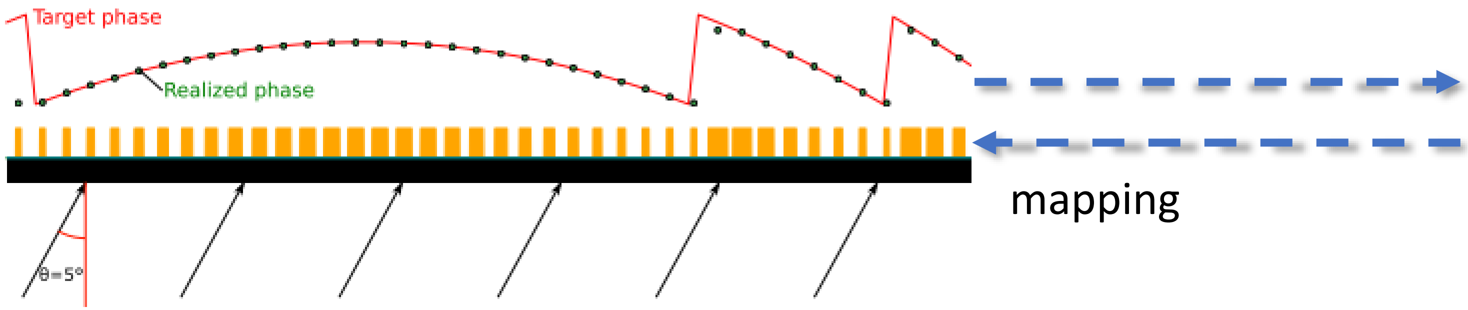
Ray picture

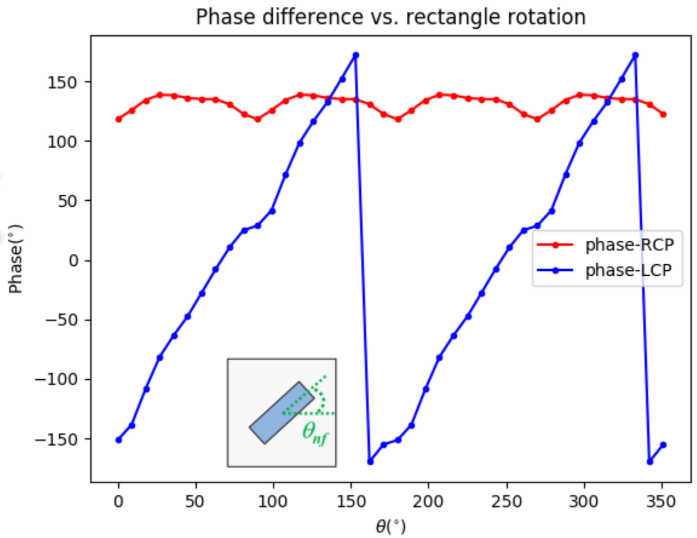


Wave picture



- Any component works by re-arranging the wavefront of the incoming waves
- Meta- atoms locally control exit phase and amplitude





- Full control of wavefront
  - Any profile can be reproduced
  - Including difficult shapes: aspheric lenses, arrays
  - Functionalize: spectral, polarization, dispersion, multiplexing

Design steps

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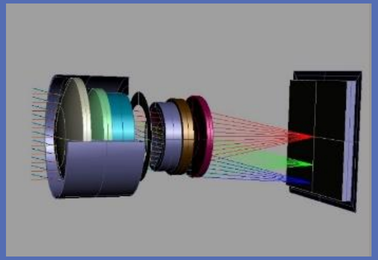
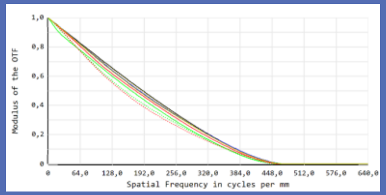
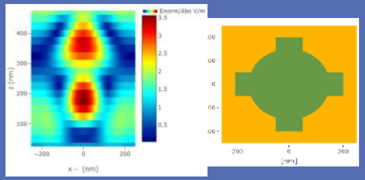
System model
- Ray tracing
- Analytical

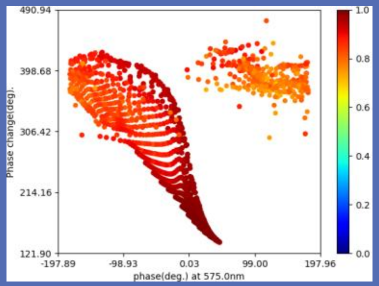




Ideal wavefront

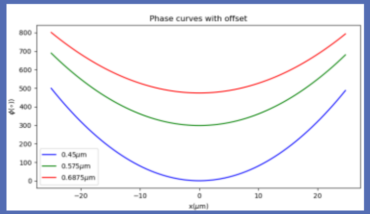
Meta-atom design
- Full wave
- nm scale

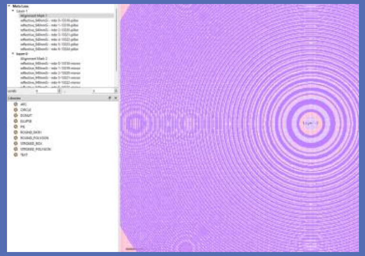




Meta-atoms

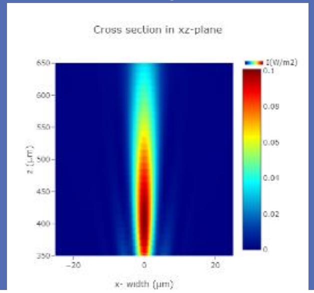
Component Design
- Target matching
- mm scale

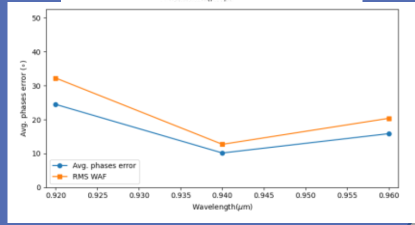




Wavefront

Analysis
- Physical Optics
- Efficiency & PSF



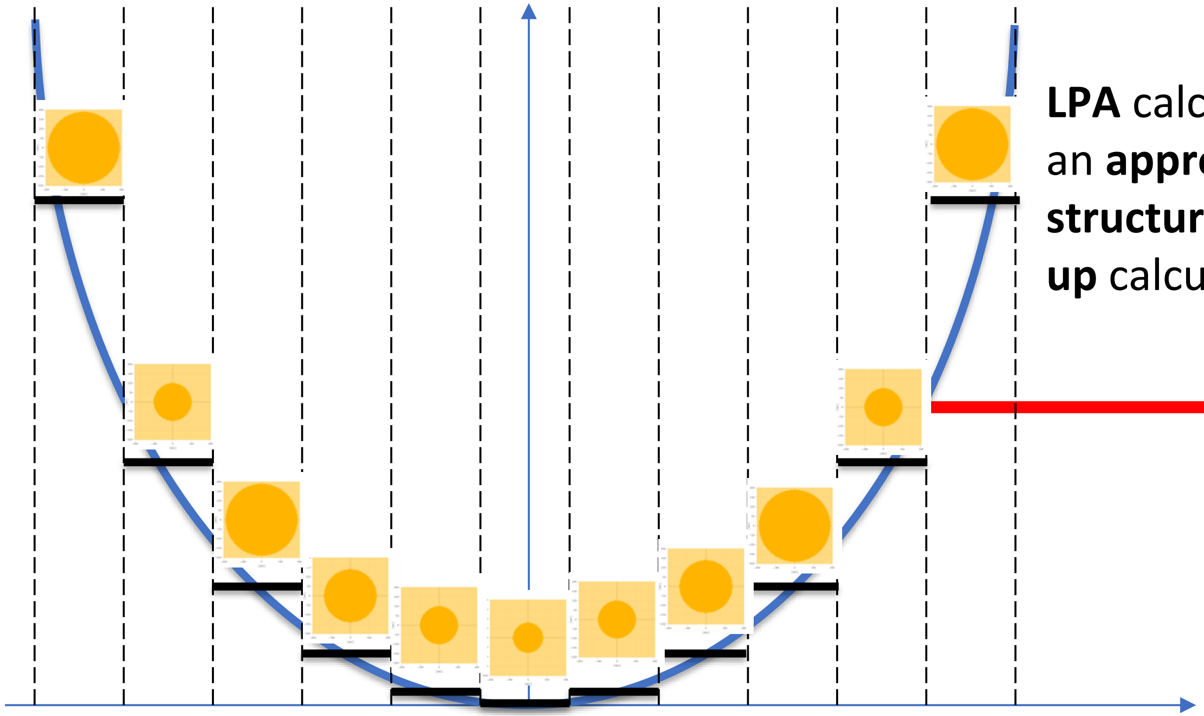


❖ Ray-tracing

❖ Full wave calculation
❖ Maxwell solver (RCWA)

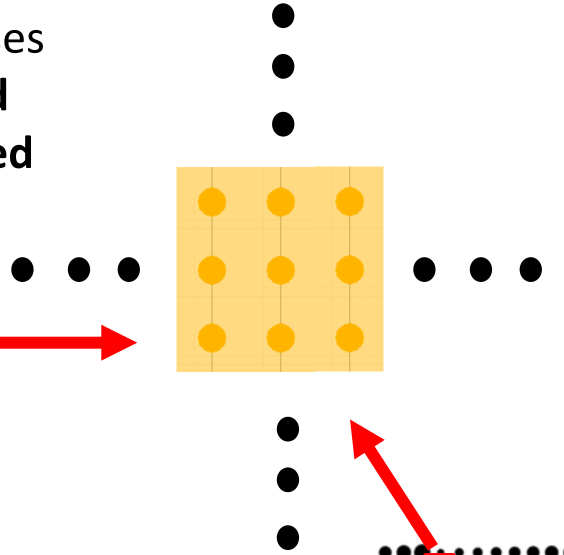
❖ Propagation optics

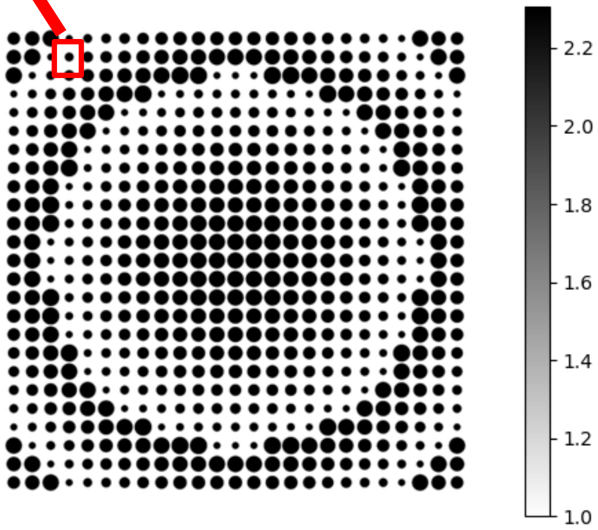
Creating wavefronts



local periodic approximation

LPA calculates uses an **approximated structure to speed up** calculation



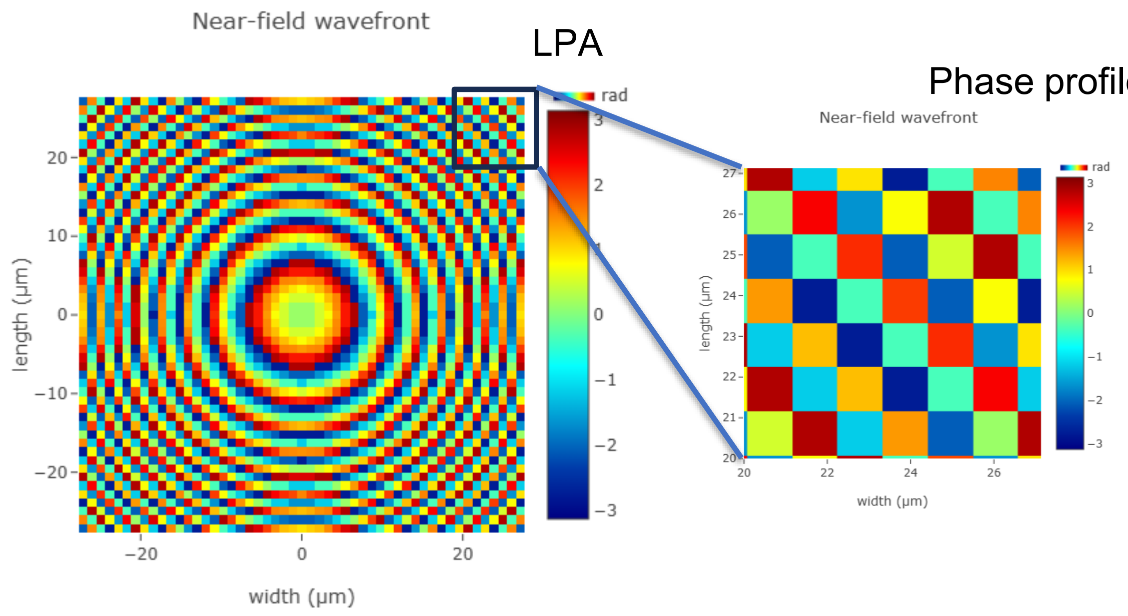


- Other aspects:
  - Pitch adjusted to Nyquist sampling
  - Phase discretization levels

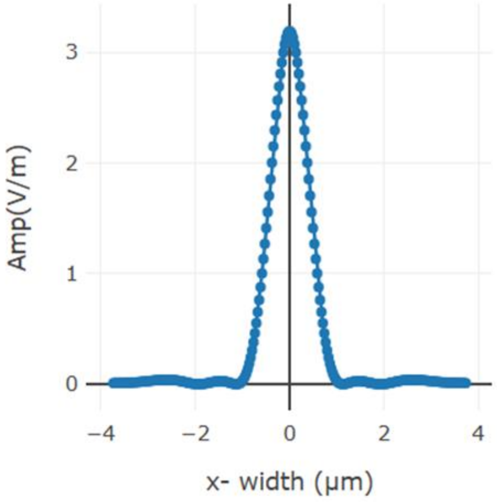
Component design: advanced methods

LPA

Phase profile

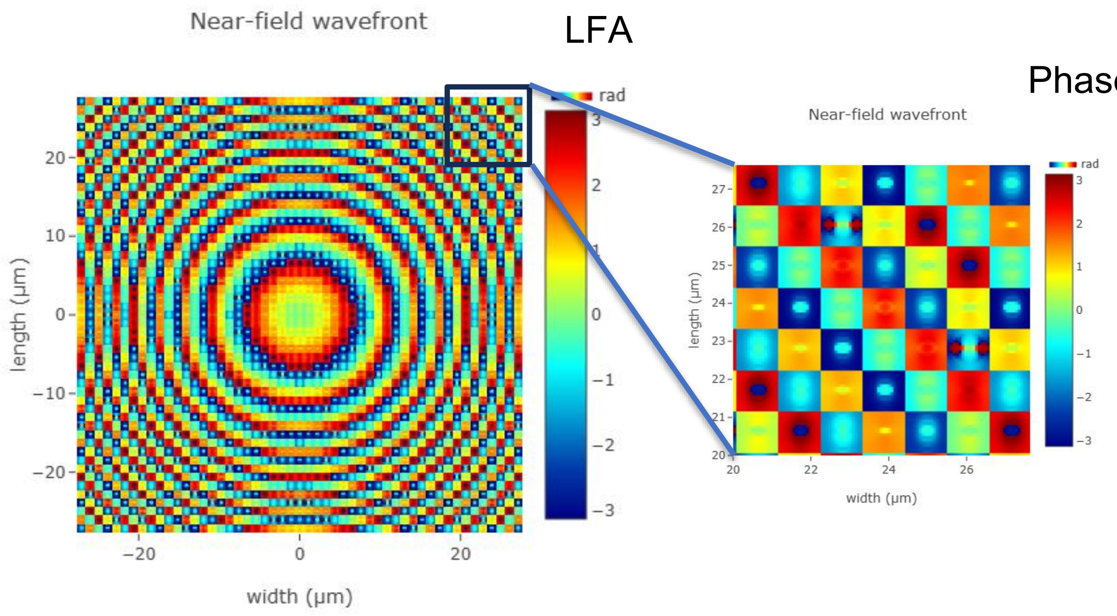


PSF section

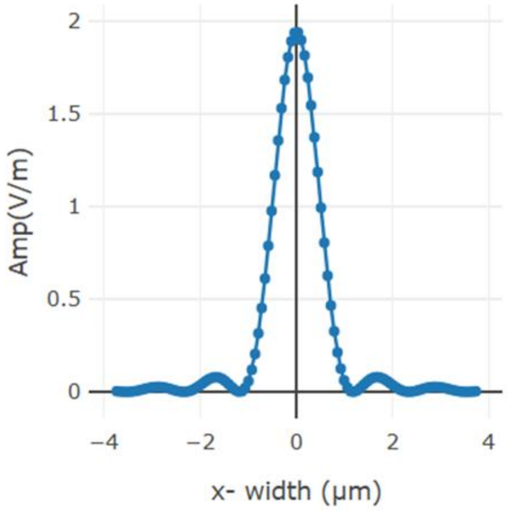


LFA

Phase profile



PSF section



Component: advanced methods

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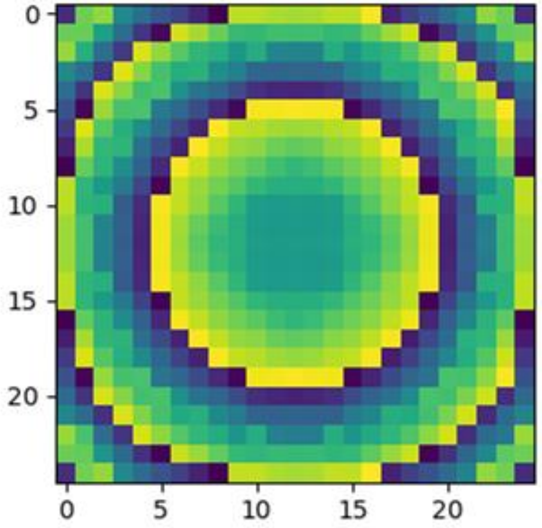
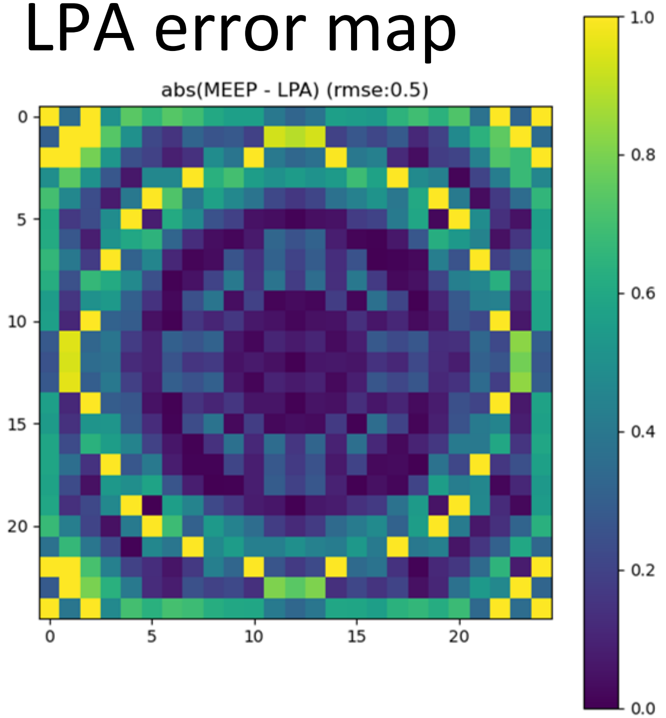
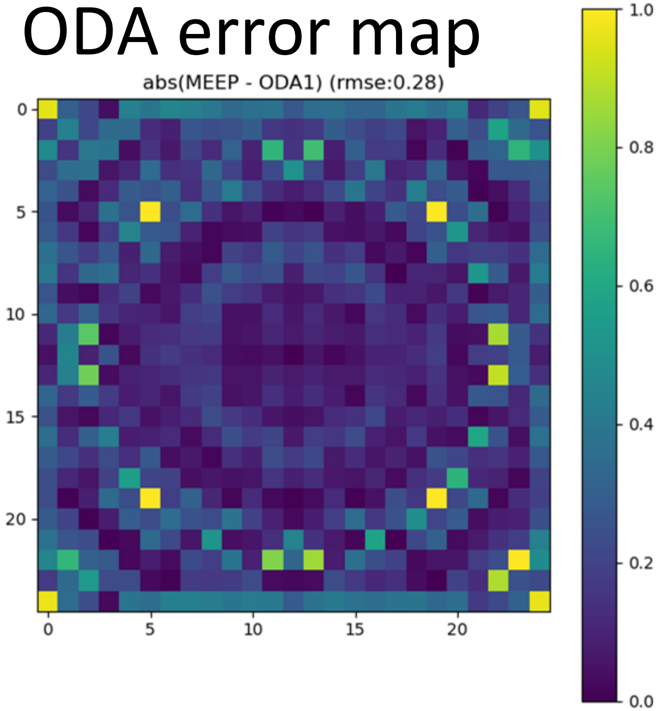
Full wave ‘ground truth’



LPA error map



ODA error map



Overlapping Domain and Local Field Analysis improve meta-surface calculation accuracy and are **faster than full wave calculation**

	Calculation time*	Memory usage	Max. diameter
Standard LPA	1 minute	<1Gb	15000 µm
LFA	2 minutes	<1Gb	1363 µm
ODA	2.5 minutes	8Gb	120µm**
Benchmark (meep)	6 hours	32Gb	10µm

*10µm diameter metalens
Core i9, 64Gb RAM PC
** Time limited to 24h calculation

LWIR system

- Specific challenges of LWIR range:
  - Few transparent materials
  - Weak signal → Large aperture needed
  - Availability of raw material
  - Expensive materials

- Wavelength range 8-12μm

- Additional constraint reduce nr. of lenses

Dispersion engineering

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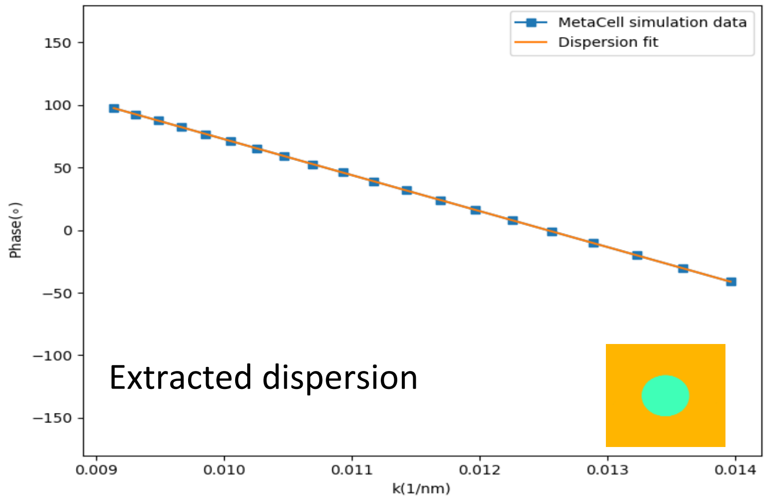
- Meta-surface offer control on material dispersion
- Dispersion engineering -> controlling phase and phase dispersion

Group delay (1st ortder)

$$\varphi(r,\lambda) = \varphi_c(r) + \frac{d\varphi(r)}{dk}\Delta k + \frac{d^2\varphi(r)}{d^2k}\Delta k^2 + \cdots$$

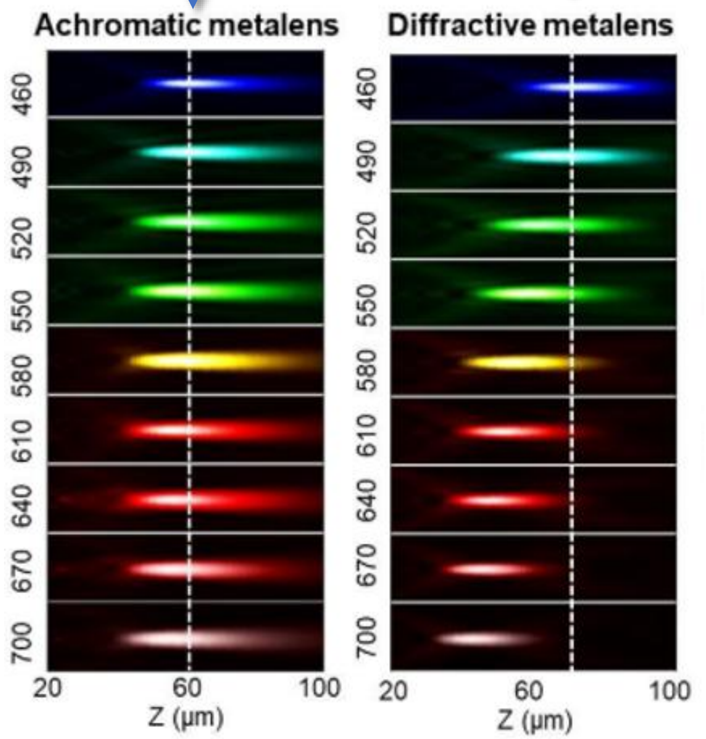
Group delay dispersion (2nd order)

- Extract phase and slope per structure



Dispersion corrected

Single wavelength design



Wang, S. *et al.* A broadband achromatic metalens in the visible. *Nat. Nanotechnol.* **13,** 227–232 (2018).

Limits of dispersion engineering

❖ Maximum dispersion in dielectric meta-atom

$$\Delta\Phi = 2\pi h\left(\frac{n_{core}}{\lambda_1} - \frac{n_{clad}}{\lambda_2}\right)$$

❖ Bandwidth, size and function are connec

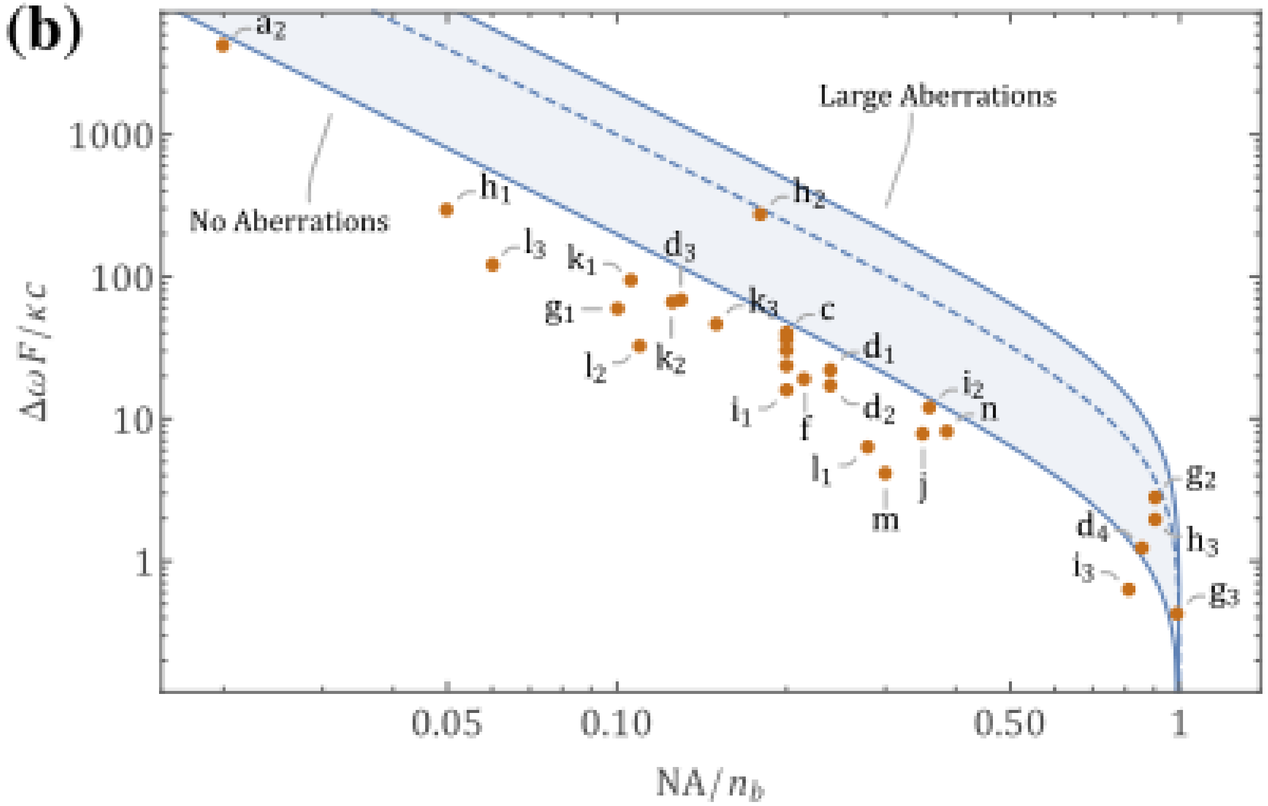
$$\varphi(\lambda, r) = \frac{2\pi}{\lambda}\left(\sqrt{r^2 + f^2} - f\right)$$

$$R_{max} \leq \frac{\Delta\Phi\, c}{\Delta\omega\left(\frac{1}{NA} - \sqrt{\frac{1}{NA^2} - 1}\right)}$$

Application parameters
- Bandwidth
- Diameter
- Spatial frequency, NA

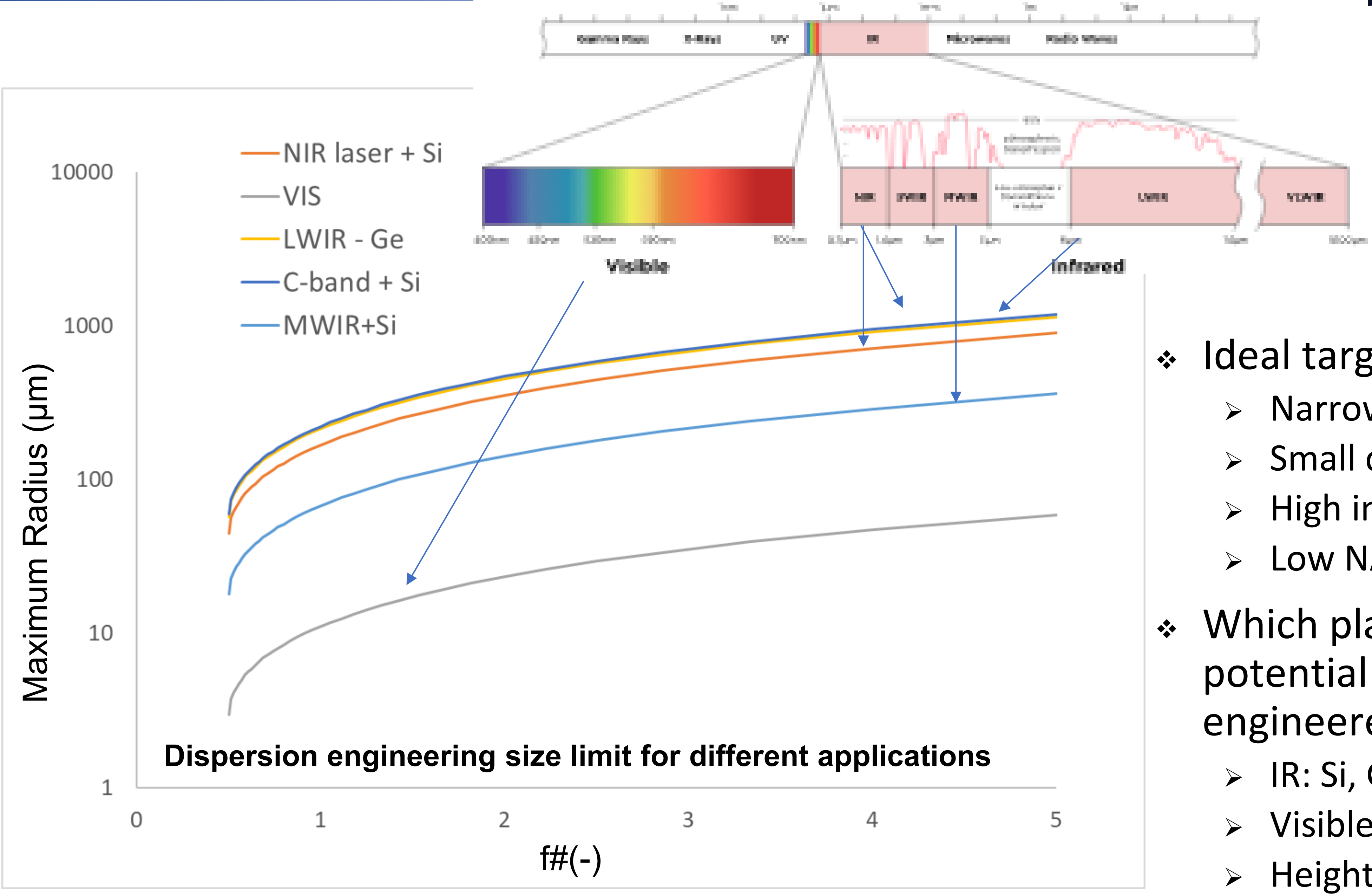
Design parameters: $\Delta\Phi$
- Materials: index contrast
- Structure: Height + aspect ratio
- Complexity: multi-layers

Literature devices within bounds of theoretical formula*



*F. Presutti and F. Monticone, "Focusing on Bandwidth: Achromatic Metalens Limits," Optica **7**, (2020).)

Promising configurations



- Ideal target application
  - Narrow spectrum
  - Small diameters
  - High index contrast
  - Low NA / high F#
- Which platforms have highest potential for dispersion engineered design?
  - IR: Si, Ge
  - Visible: TiO2, SiN, GaN
  - Height assumed = λ

Limits of dispersion engineering

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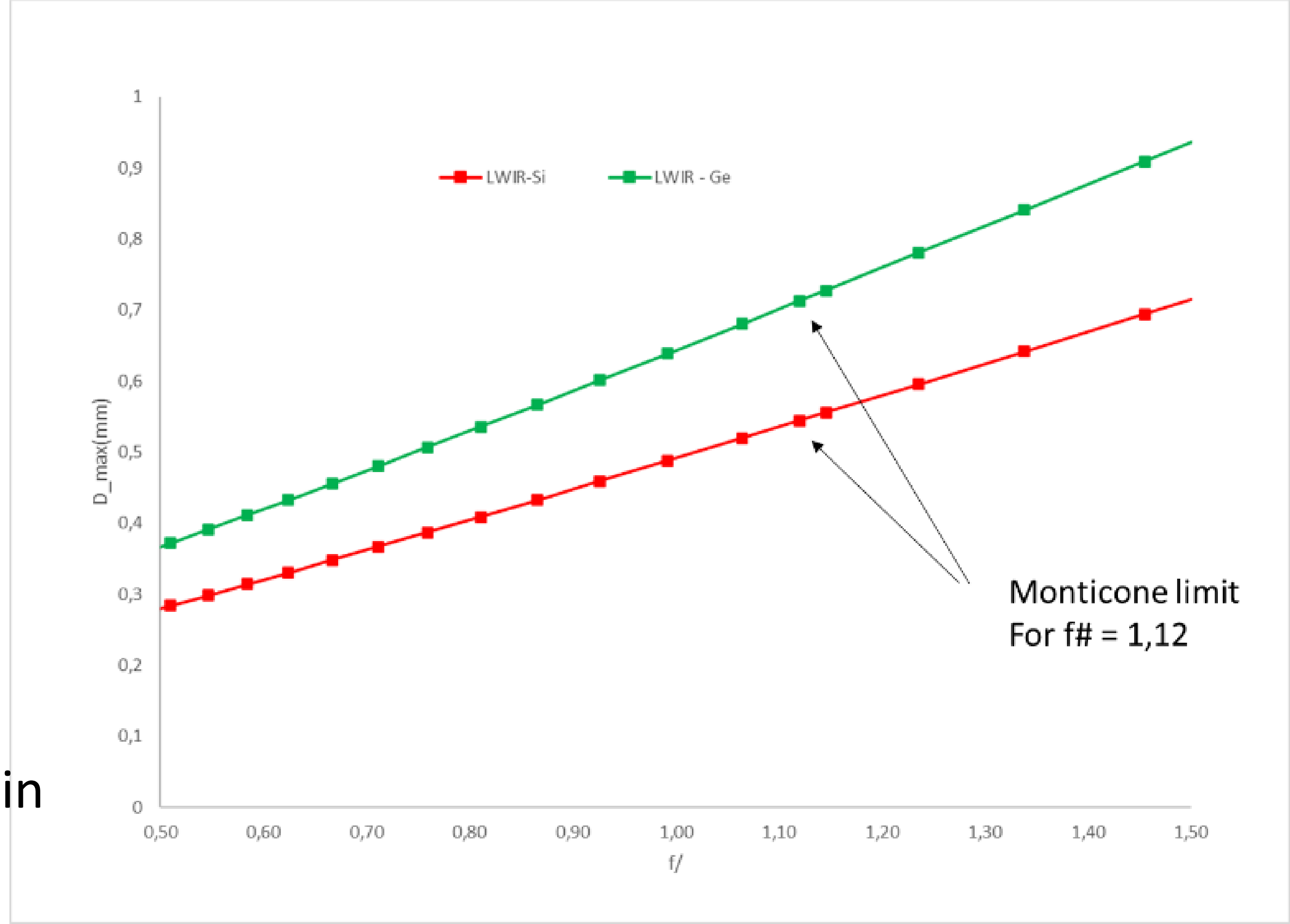
- Maximum dispersion in dielectric meta-atom

$$\Delta\Phi = 2\pi h\left(\frac{n_{core}}{\lambda_1} - \frac{n_{clad}}{\lambda_2}\right)$$

- Bandwidth, size and function are connected*

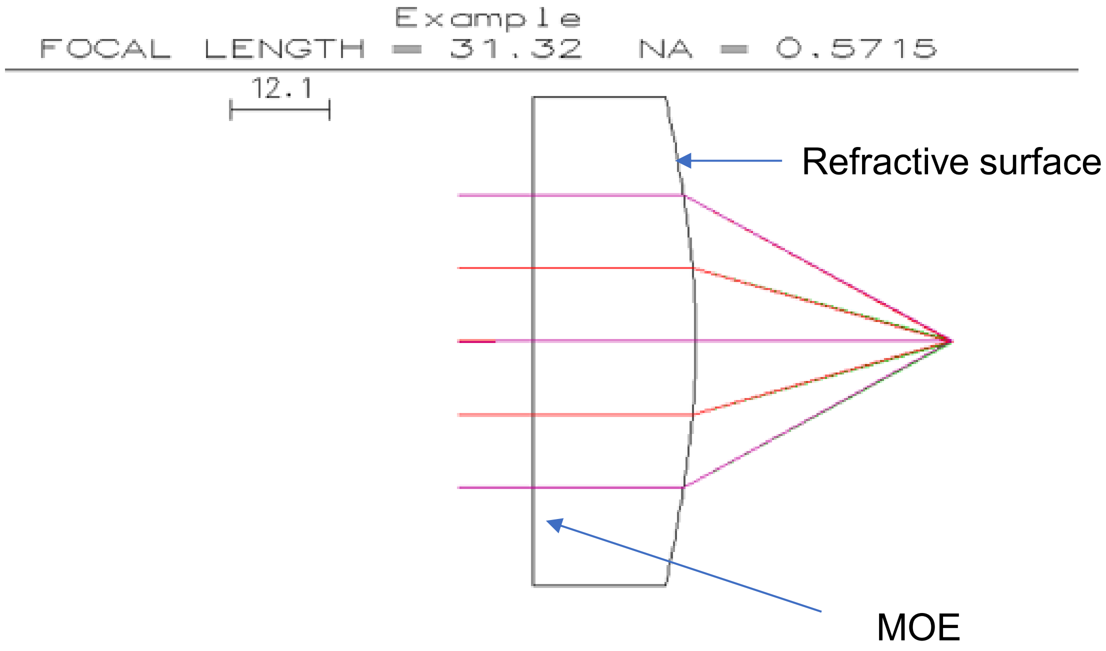
$$R_{max} \leq \frac{\Delta\Phi\, c}{\Delta\omega\left(\frac{1}{NA} - \sqrt{\frac{1}{NA^2} - 1}\right)}$$

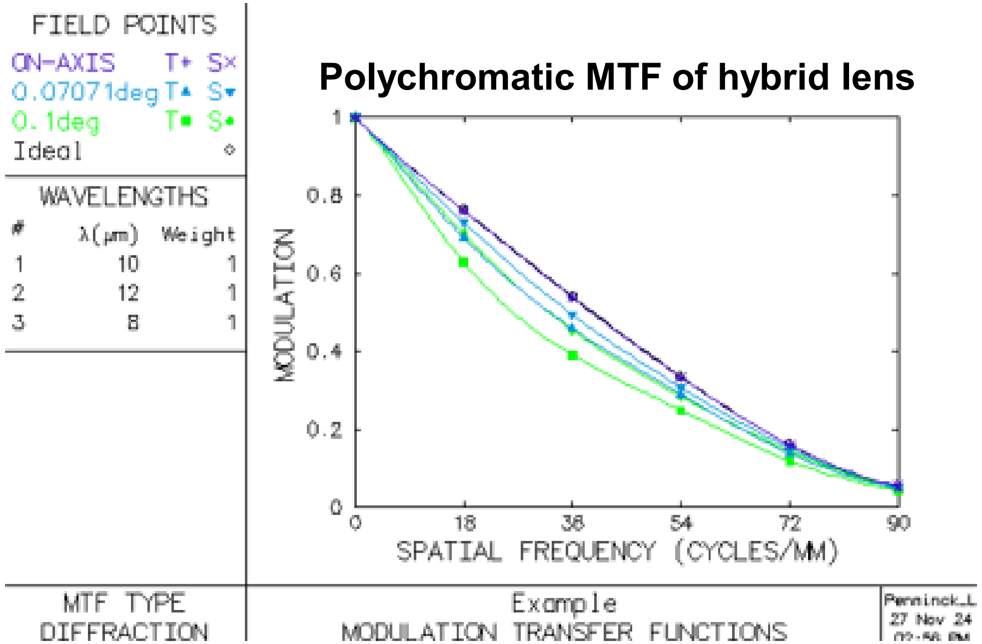
- Achromatic flat surfaces have a limit in diameter
  - Only small sizes <1mm can be achieved



*F. Presutti and F. Monticone, "Focusing on Bandwidth: Achromatic Metalens Limits," Optica **7**, (2020).)

Meta + Refractive hybrids





- Classical hybrid solution
  - Combine meta/diffractive lens with refractive

$$Pt = \frac{1}{f_t} = \frac{1}{f_R} + \frac{1}{f_M}$$

$$\Delta P = P(\lambda 1) - P(\lambda 2) = \frac{n2 - n1}{R} + \frac{\lambda 1 - \lambda 2}{f_0 \lambda_0} = 0$$

- Achromatic hybrid when

$$f_0 \lambda_0 = -\frac{\Delta \lambda}{\Delta n} R$$

- Hybrid design chromatic correction over wide spectrum
  - Example LWIR 8-12 um

System design result

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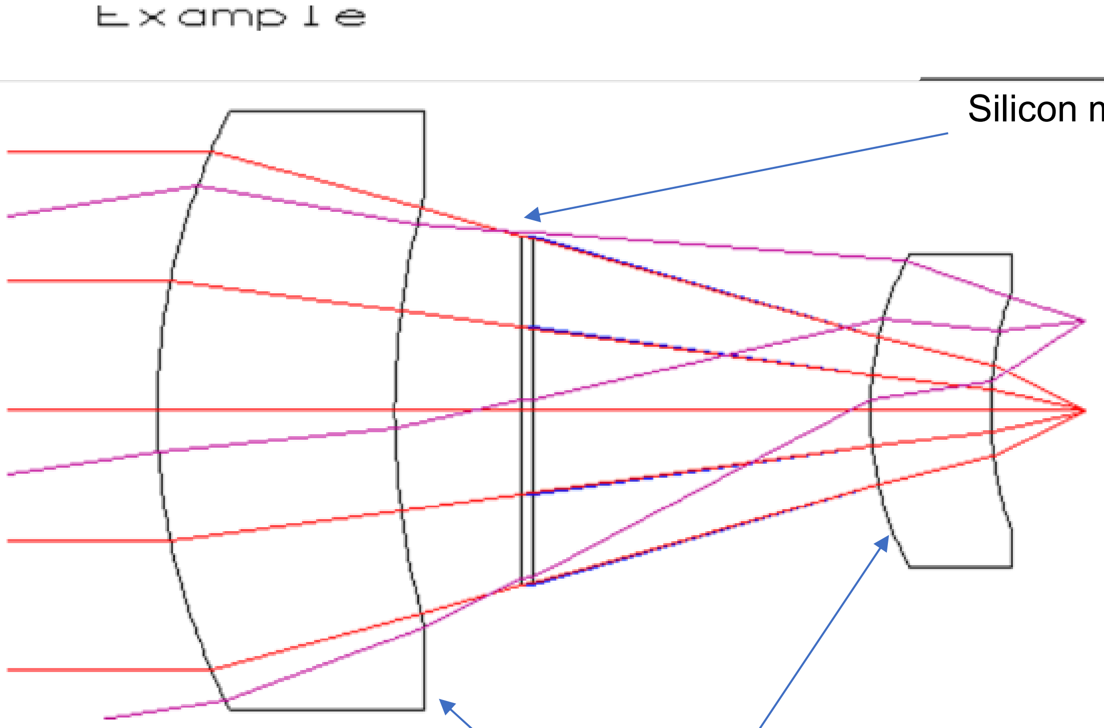
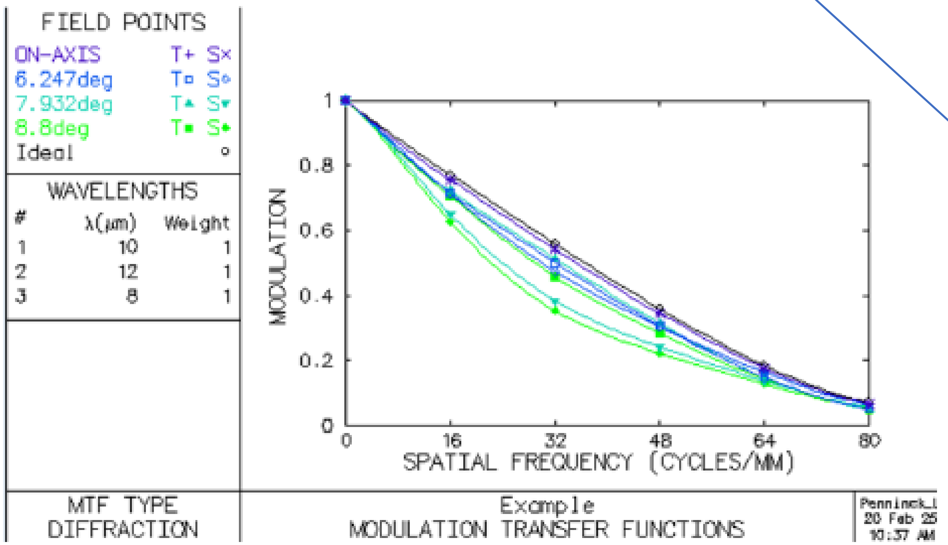
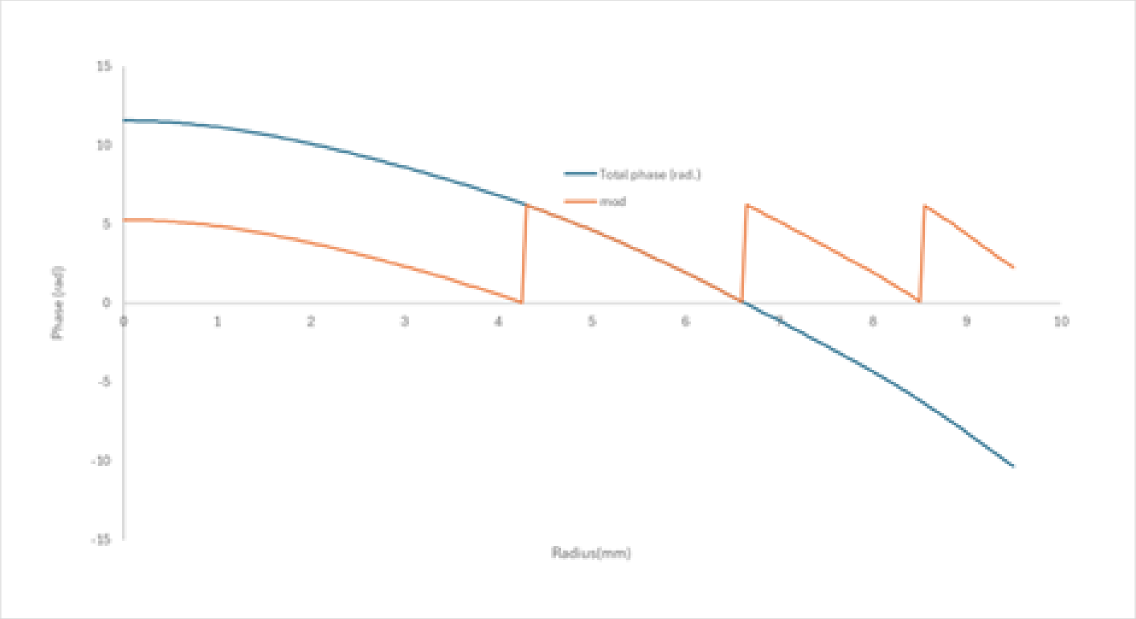




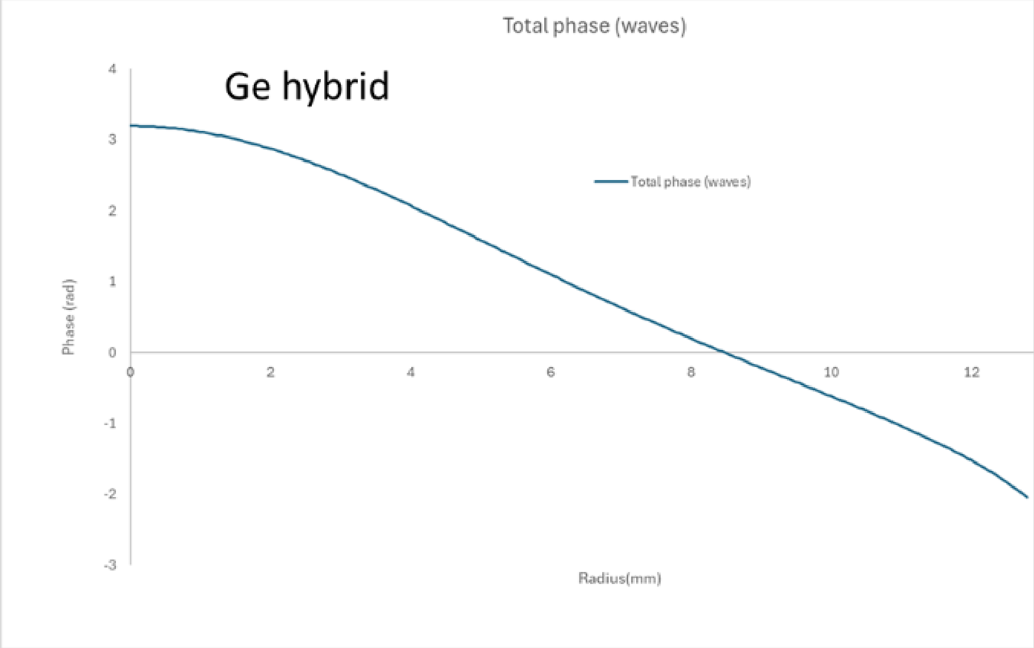
- ❖ Configuration meets specification in multiple iterations
  - ➢ Several lens materials
  - ➢ Germanium and Silicon metasurface
- ❖ Performance near diffraction limit
- ❖ Optimized via ray tracing
  - ➢ Meta-surface as polynomial
  - ➢ Constant phase vs. Wavelength

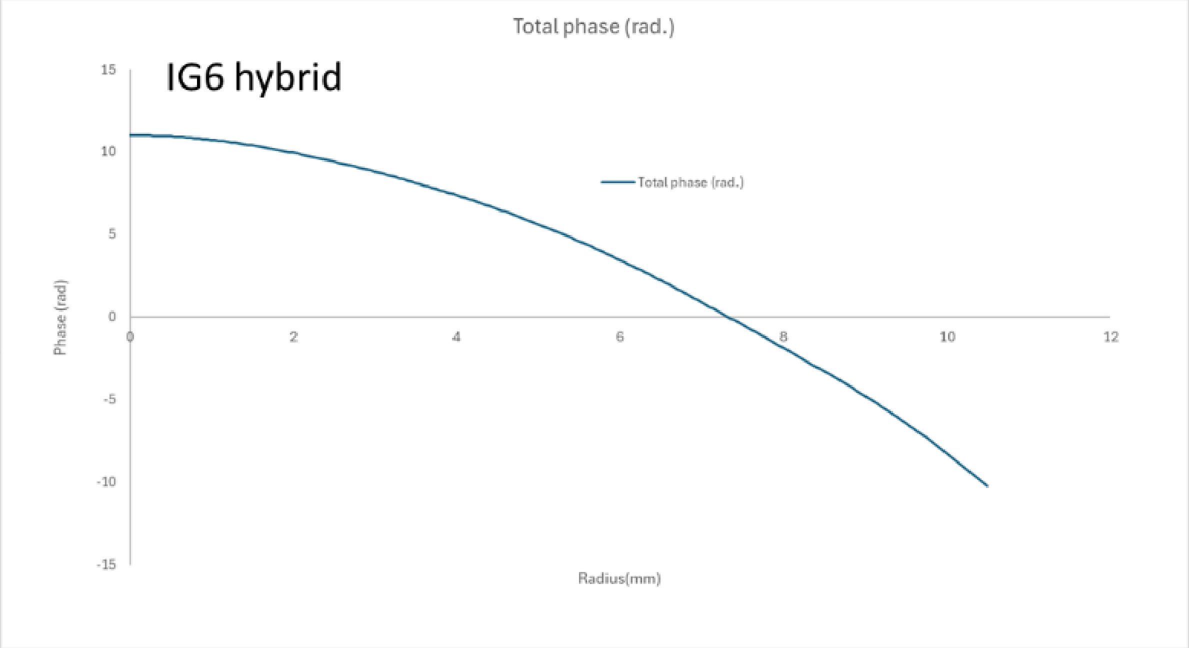
Common assumption in ray tracing but not accurate in meta-surfaces or diffractive optical elements

Wavefront profiles



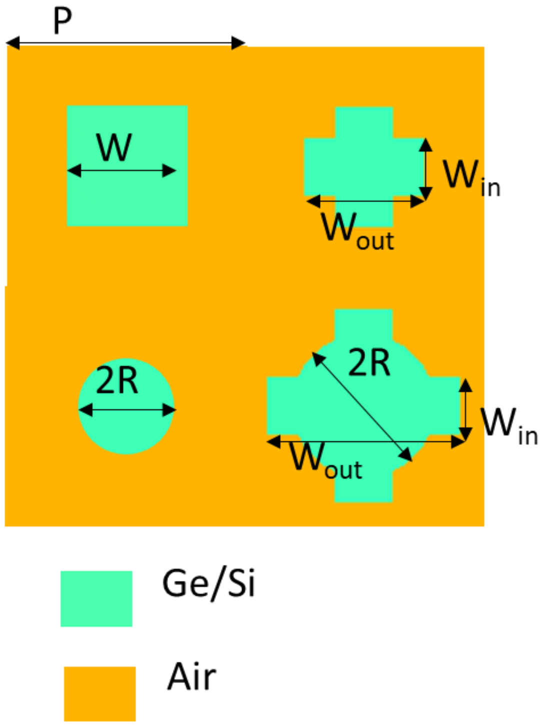
- Phase vs. radius for various configurations
- Meta-surface acts as a corrector with limited optical power





Meta-atom design

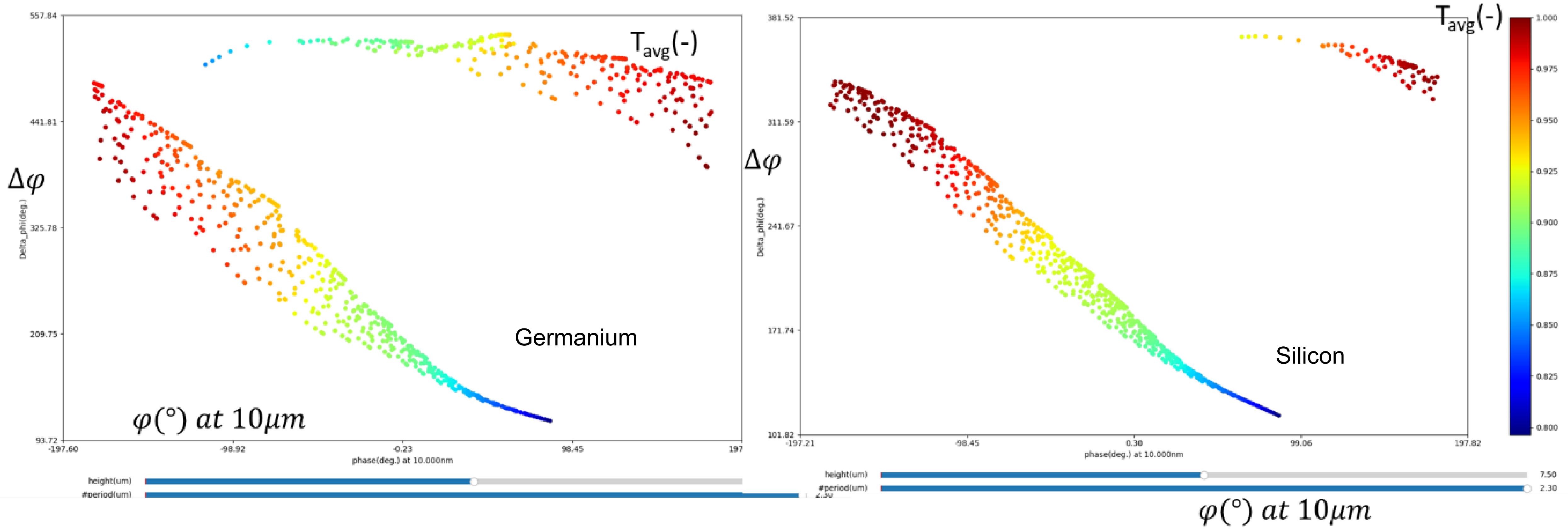
Structures in library



- Meta-atom shapes for LWIR library
- Simualtion in PlanOpSim Meta-cell (RCWA)
- Large parameter sweep
  - Several weeks to perform sweep

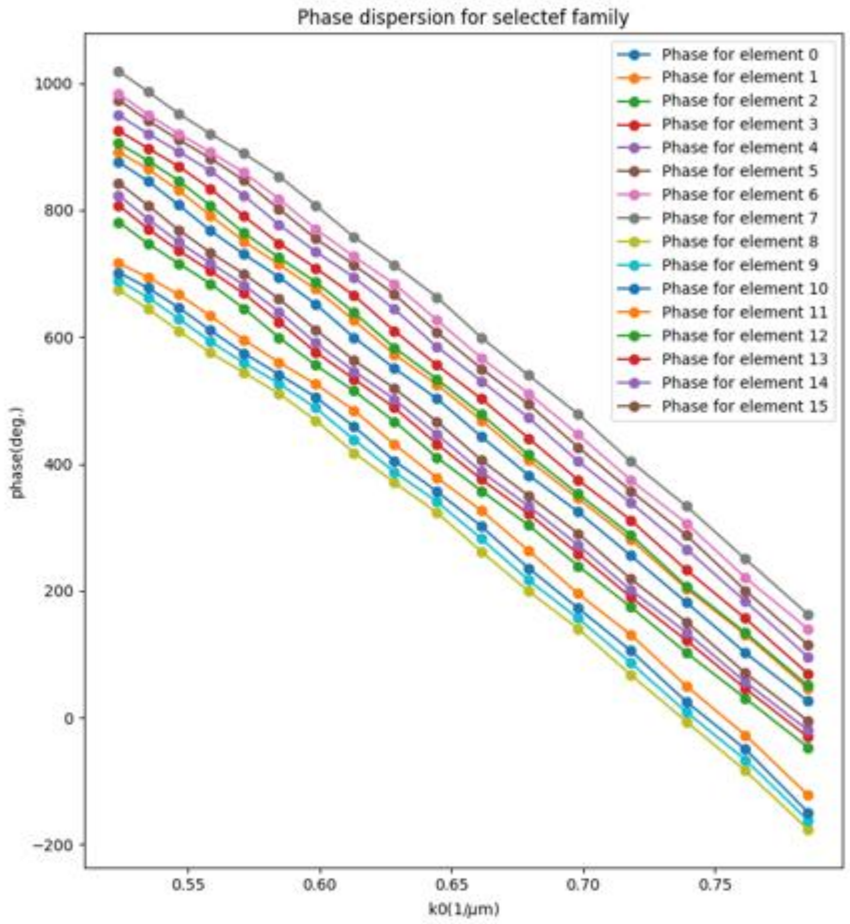
Parameter	Values
Material	Si +Ge
Unit Cell P	1-3um
Shape parameters	4 shapes
Height	3-12um
Wavelngth	8-12um

Sample result



- Phase and phase dispersion
- Sample for H = 10, P=2.3um
- Si and Ge produce 0-360° phase coverage
- Ge library allows phase coverage at constant dispersion

Meta-atom selection



- Selected meta-atoms

$$\varphi \approx \frac{2\pi}{\lambda} n_{eff} d$$

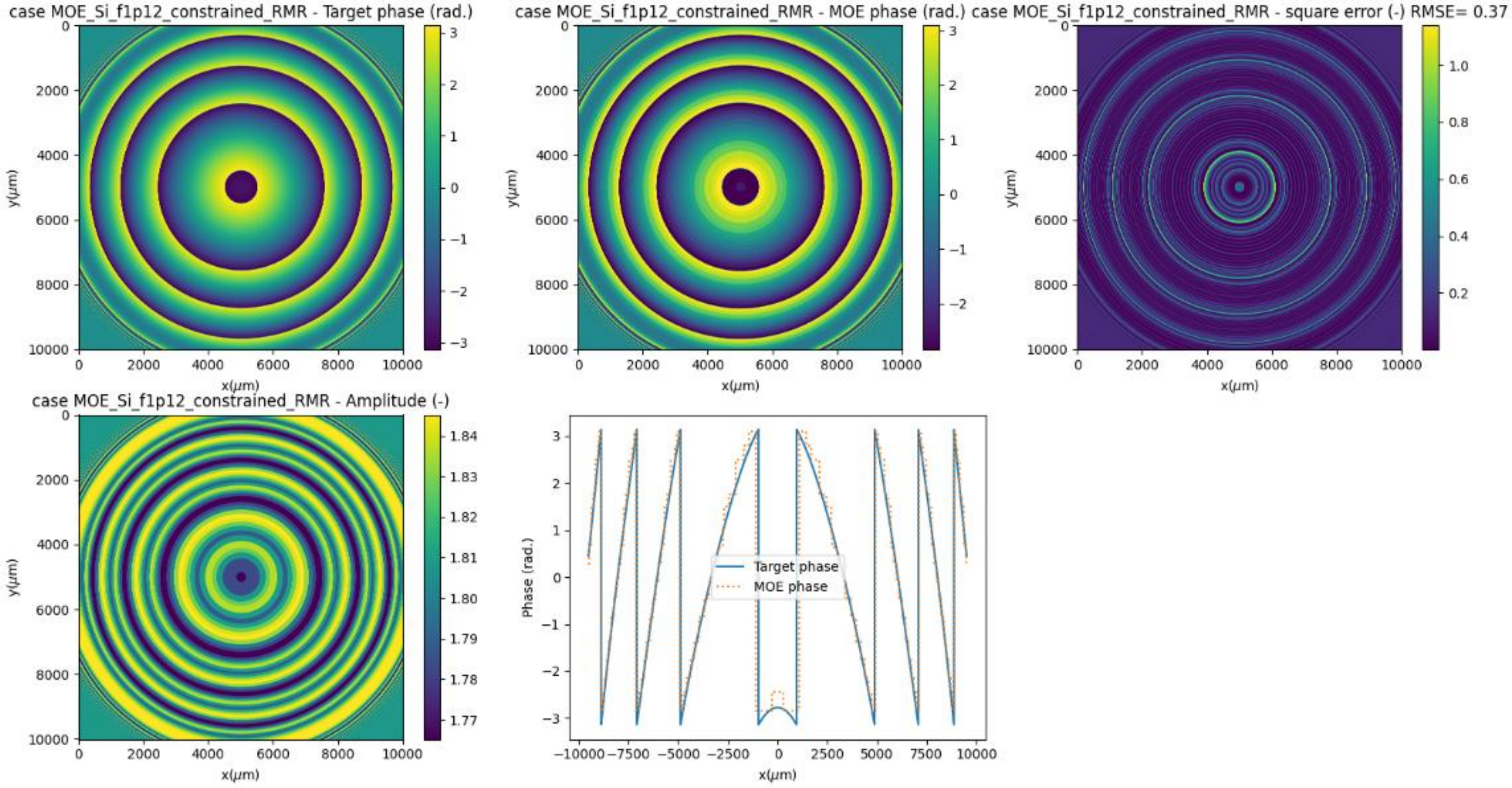
- Wavefront requirement (from ray -tracing)

$$\varphi(\lambda) = \sum_n A_n r^{2n} + C(\lambda)$$

Choosing C so that it matches the slope present in our meta-atoms

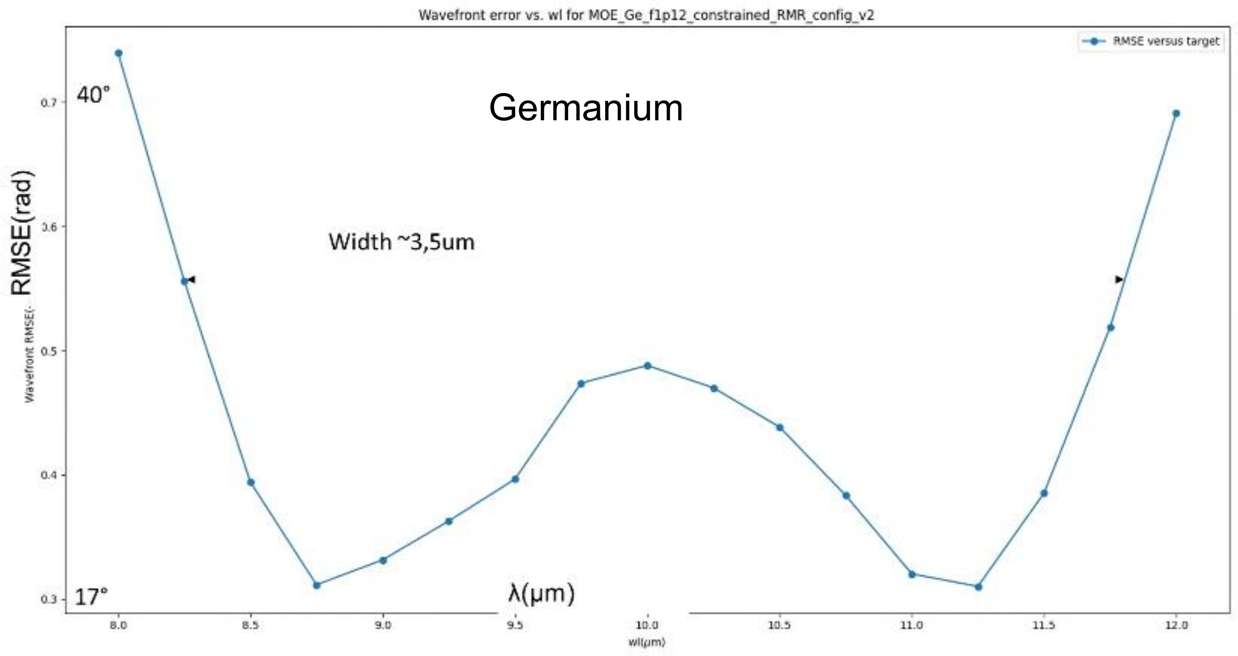
- Similar performance possible with lower n metarials if height is increased

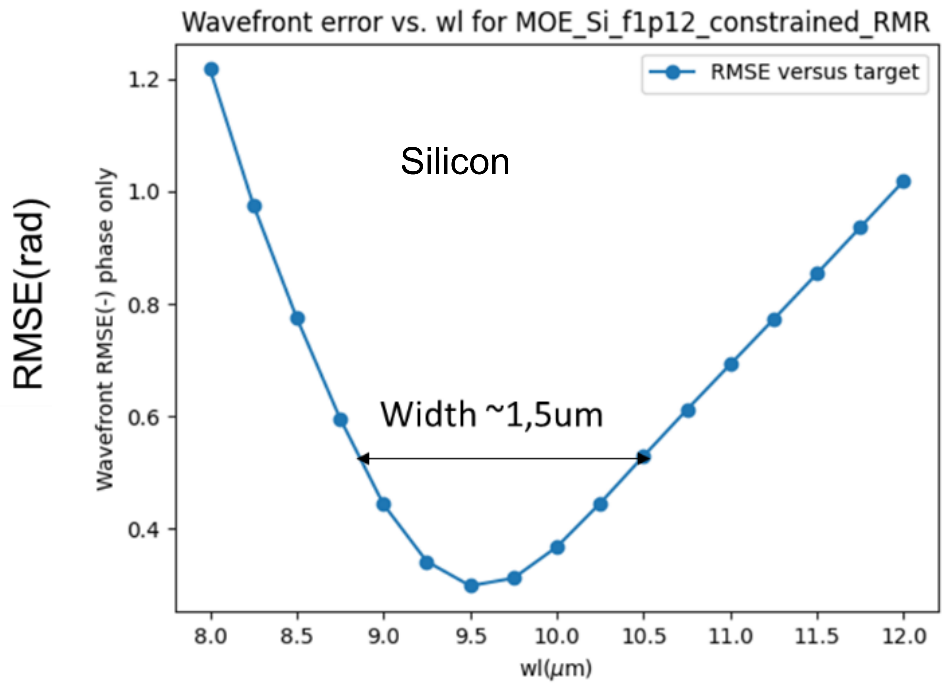
Wavefront matching



- Meta-atom position matched to waveprofile
- Least squares match to multi-wavelength profiles

Spectral wavefront error





- ❖ Meta-atoms with dispersion control result in a lower error vs. Wavelength
- ❖ Withoot dispersion control the error rises from the design wavelength towards the edge of the spectrum

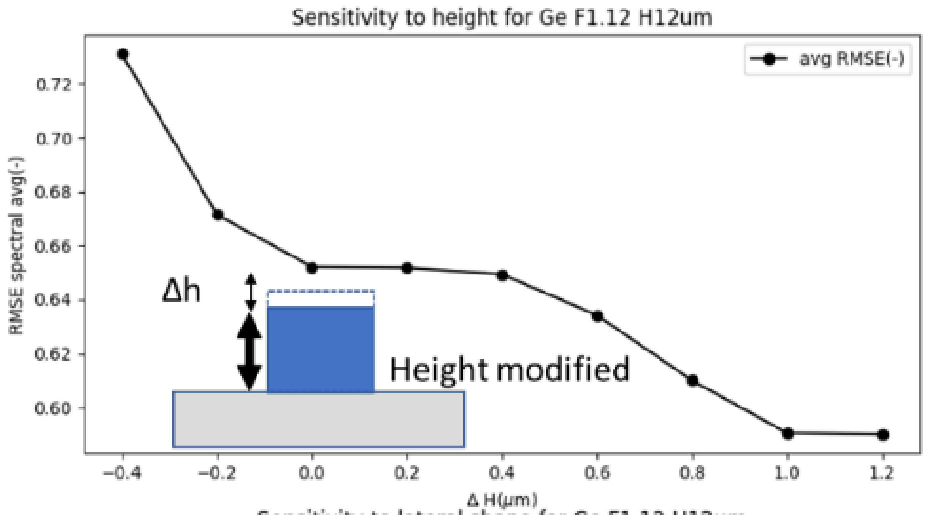
How does it compare to DOE?

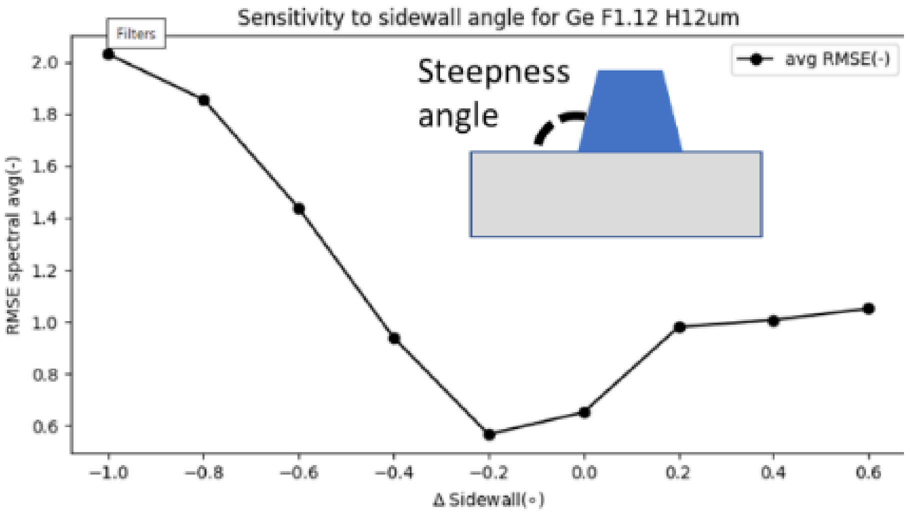
- Phasefront replication also possible with a Diffractive optical element
- Comparison of wavefront error over spectrum

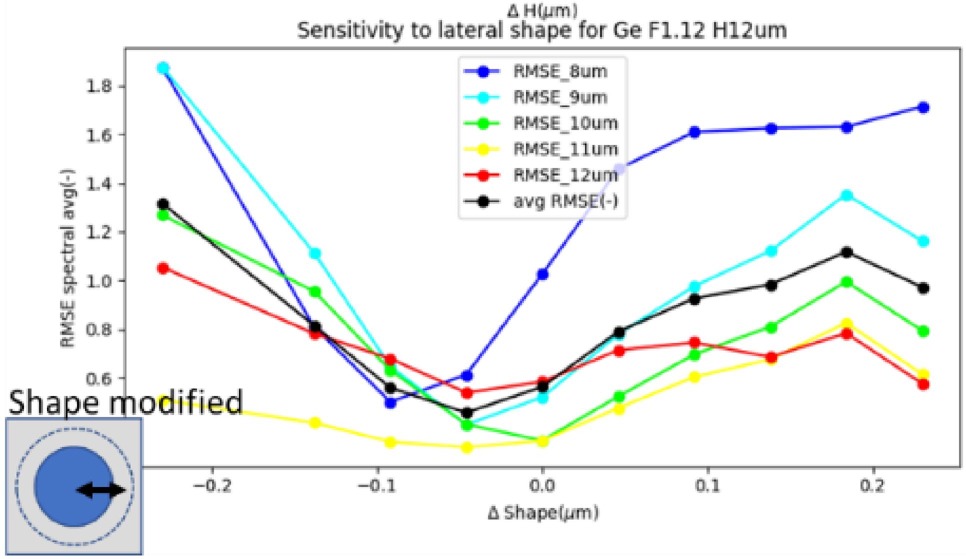
Design	Average wavefront error RMSE (-)
Ge	0,66
Si 12µm	1,02
DOE (16 level)	0,703

- Lens system and wavefront re-optimized for each case
- Dispersion controlled library results in a lower error over spectrum, single wavelength design results in worse average error

Sensitivity analysis

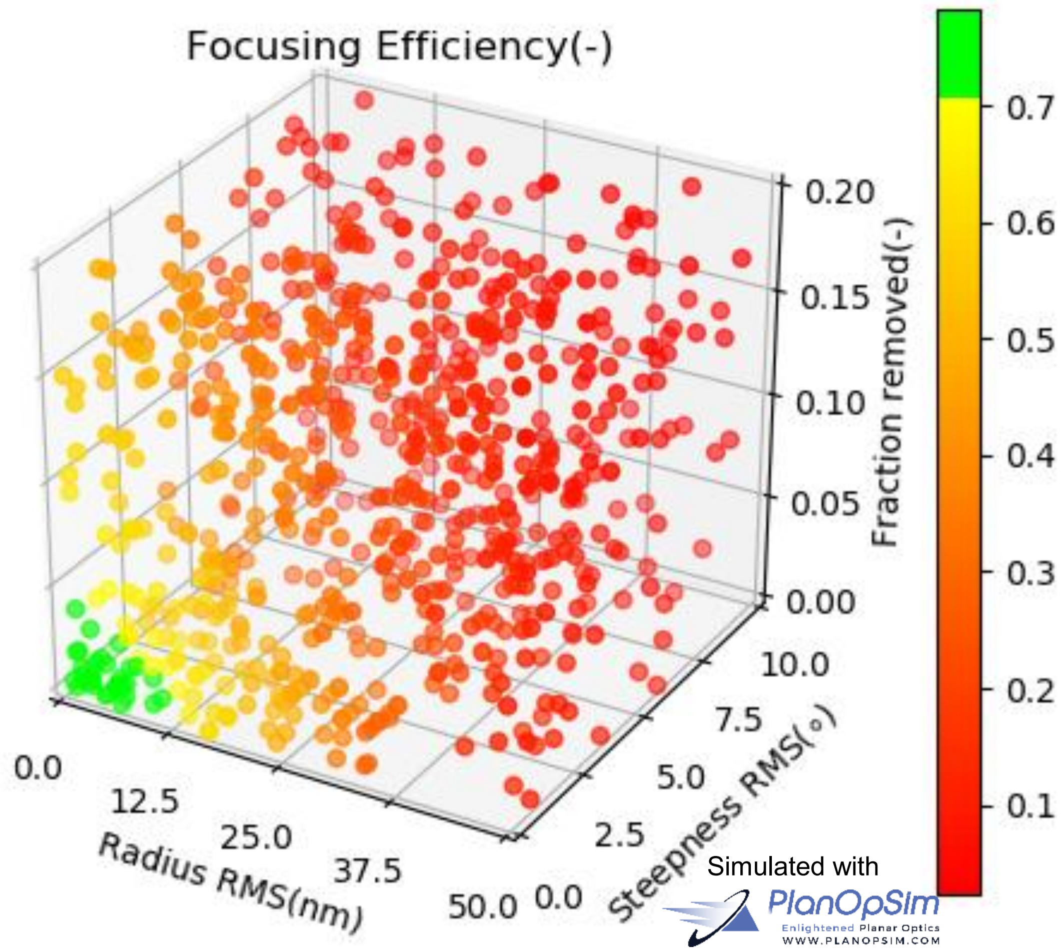


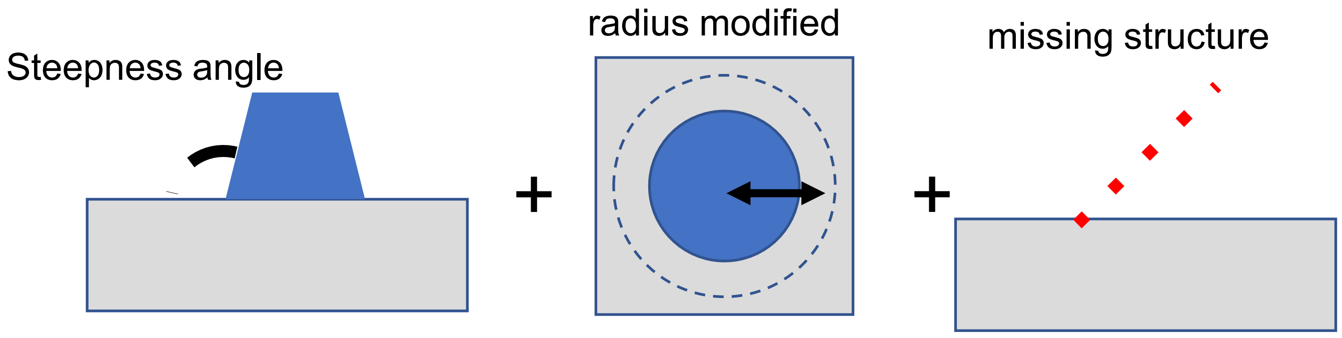




- ❖ Sensitivity analysis versus sidewall, lateral size and height
- ❖ Sidewall angle is the most critical parameter
  - ➢ Overetch is worse than underetch

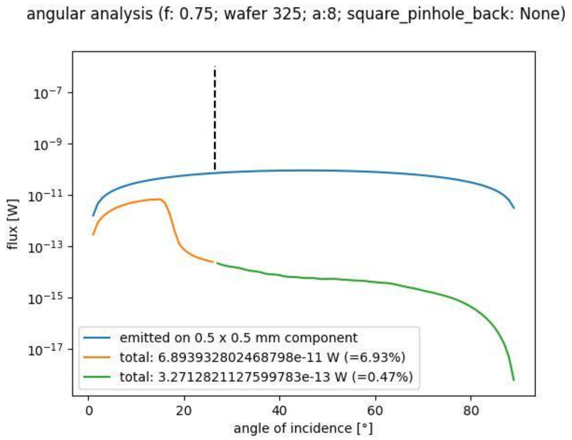
Tolerancing





- Most designs work with nominal structure
- Effect of manufacturing error
  - **Monte Carlo 25’230 metalenses simulated in this plot**
  - **Systematic errors can be compensated in design**
- Integrate DFM into design process
  - Needs to be integrated into an out-of-the box solution

Preview: multiple meta-surfaces

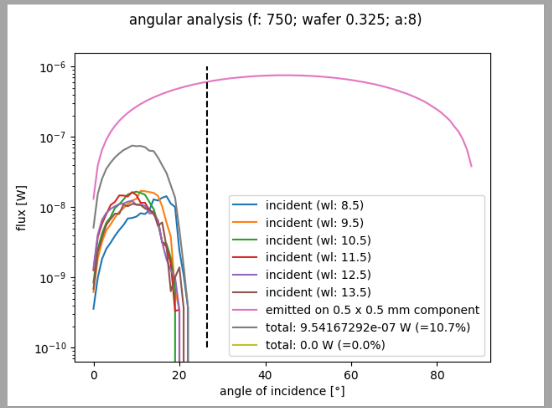


Wave calculation

0,47% stray light / signal

Raytrace calculation

0,0% stray light / signal

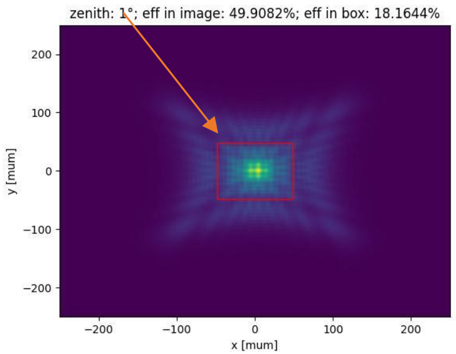


- ❖ Diffractive effects are one of the main loss and aberation mechanisms in metasurfaces
- ❖ Impact is application specific
- ❖ Wave based calculation of multiple meta-surface systems
- ➢ Higher order diffraction
- ➢ Aperture diffraction

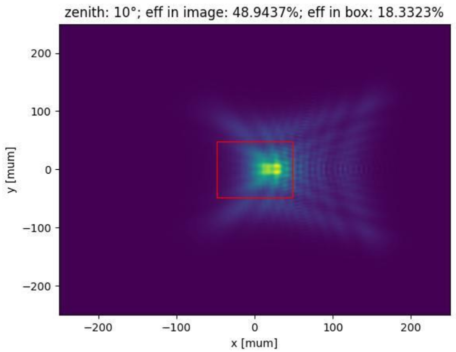
release expected Q2 2026

Plane wave incidence vs. incidence angle

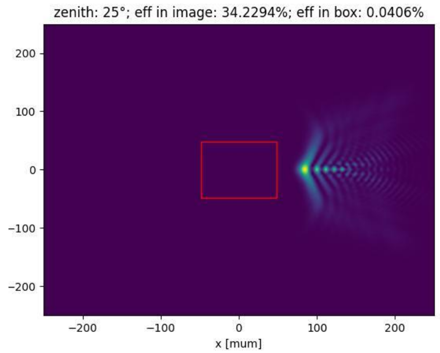
0°



10°

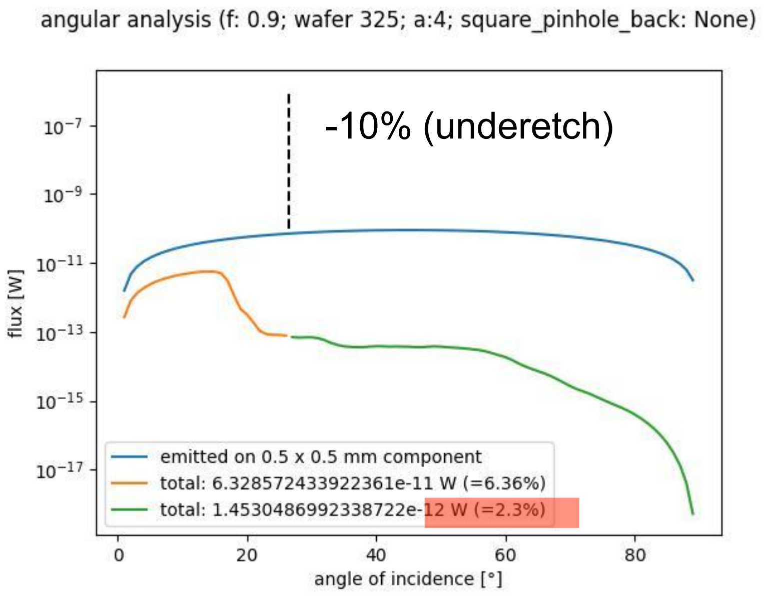


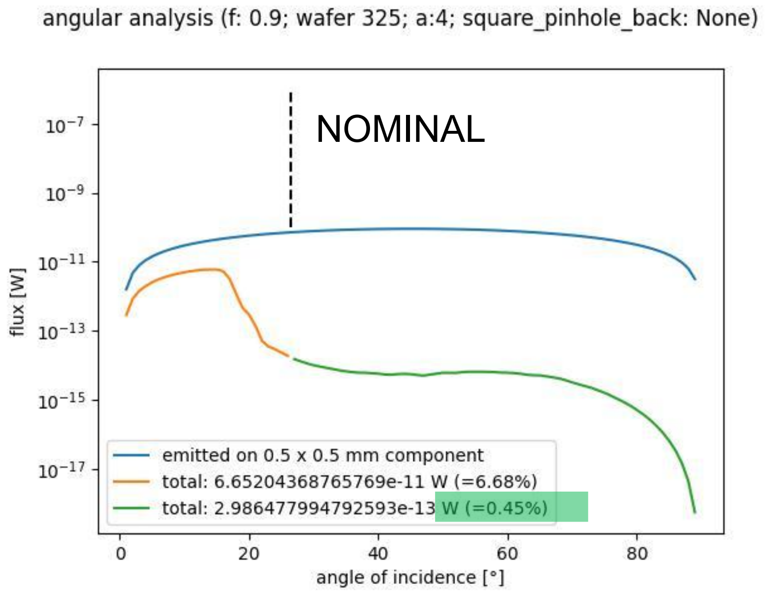
25°

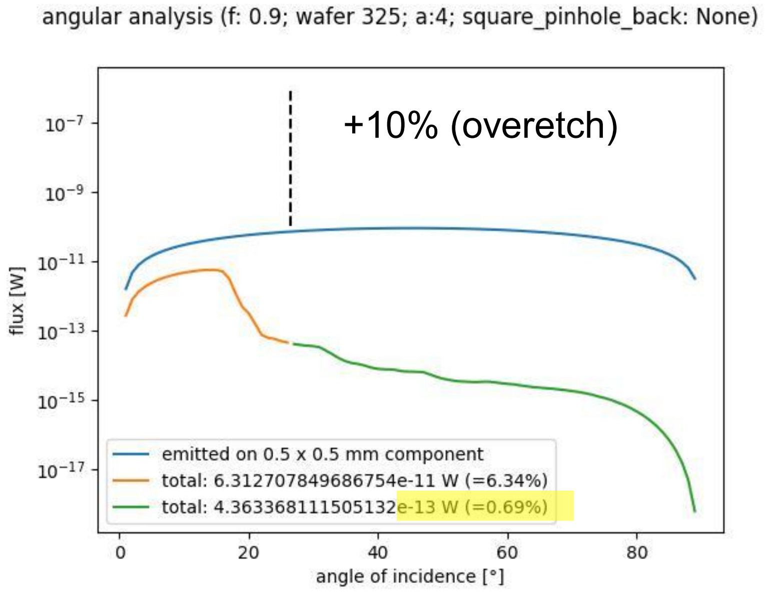


confidential

Preview: system sensitivity







- Combination: multi-surface + nano-structure tolerancing
- Guides fabircation process to higher robustness
- Stray light/signal

Nominal	0.45% (x 1.00)
+10% height	0.69% (x 1.53)
-10% height	2.3% (x 5.11)

Conclusion

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- Hybrid meta-lens system deisgn for LWIR
- Meta-surfaces for 8-12um range in Silicon and Germanium
- Wavefront error over spectrum below equivalent DOE design
- Meta-atoms are most sensitive to sidewall angle in microfabrication

- Future work: quantifying effect of wavefront error on system performance

Visit us at booth #130S

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