

Lieven Penninck

Application focused meta-surface design: workflow, methods & examples

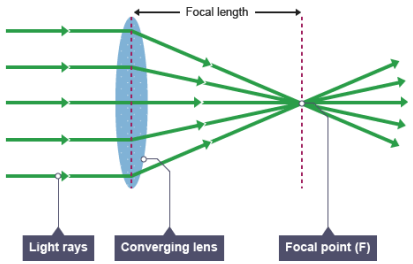
META2026
15 July 2026
Dublin, Ireland

PlanOpSim
Enlightened Planar Optics

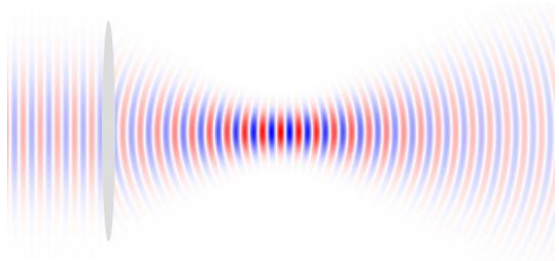
Principles of meta-surfaces

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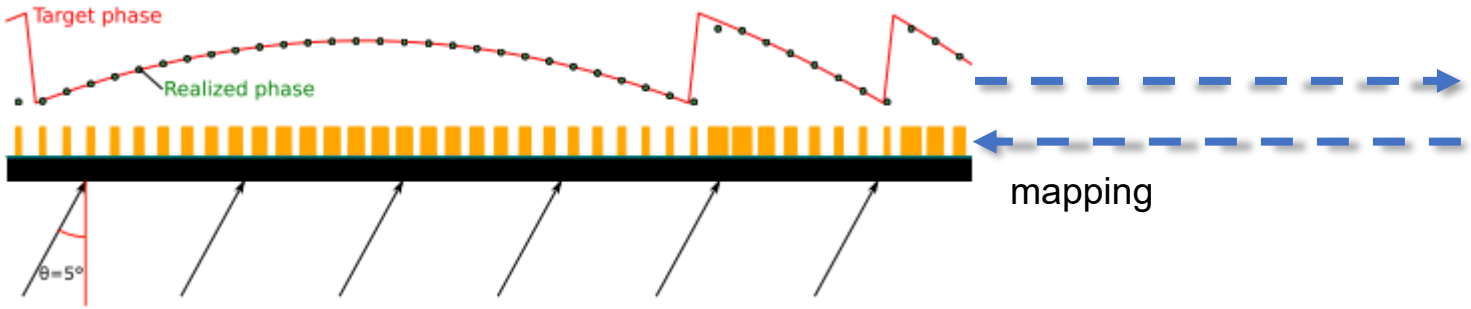
Ray picture

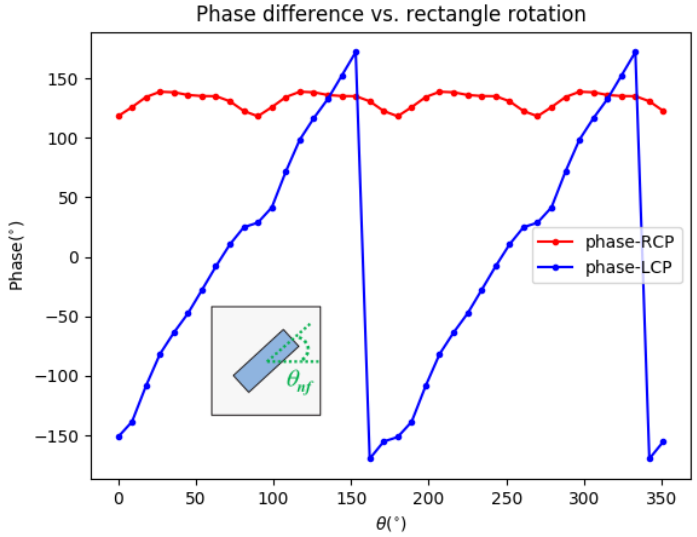


Wave picture



- Meta-surfaces work by controlling how waves propagate through them
- Meta- atoms locally control exit phase and amplitude

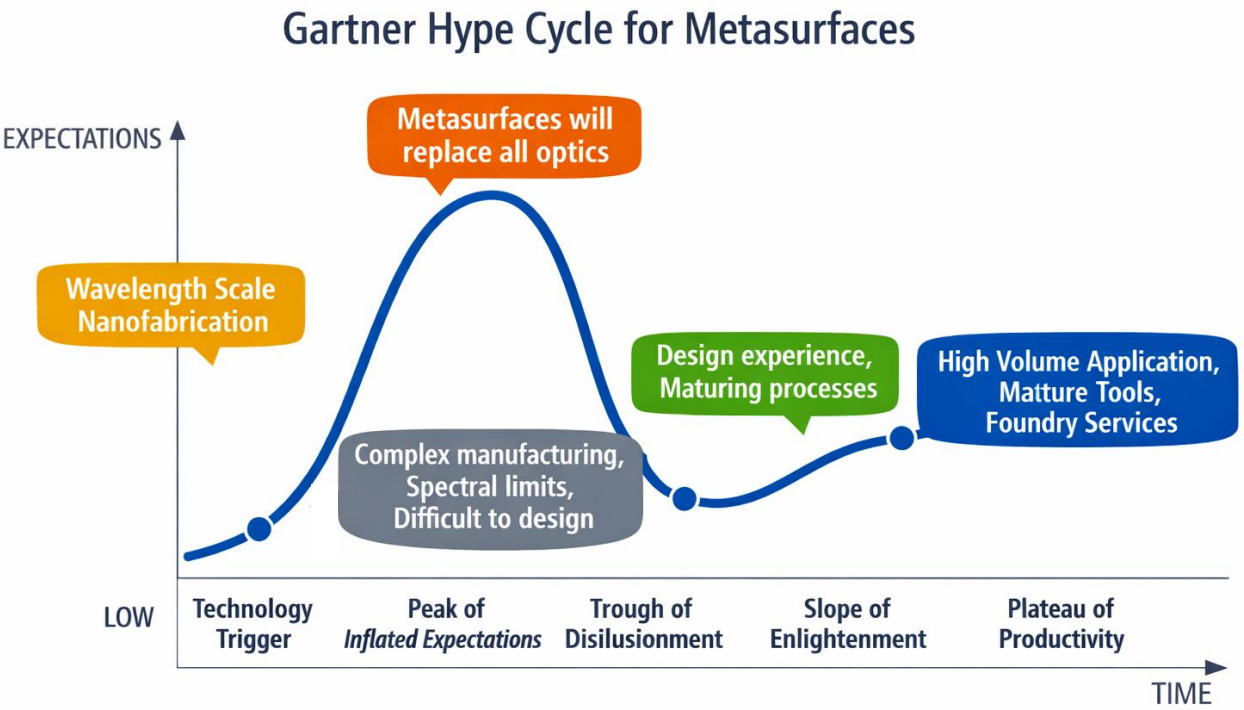




- Full control of wavefront
  - Any profile can be reproduced
  - Including difficult shapes: aspheric lenses, arrays

When to use meta-surfaces

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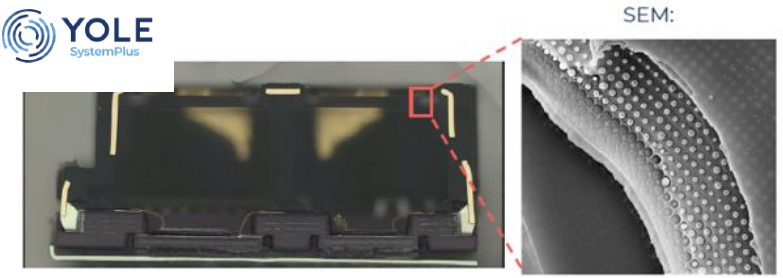
Don't:

- Replace conventional optics
- Wideband imaging
- Magic single surfaces: fundamental laws still apply

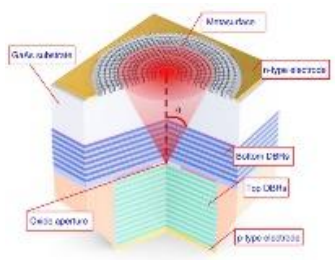
Do:

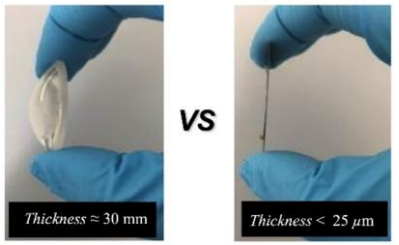
- **Miniaturized & integrated**
- Functions with **no refractive option:** polarization, complex wavefront
- Narrow band applications (laser or LED) or hybrid design

Product teardown

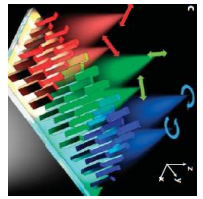


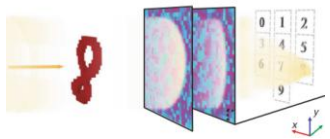
Smaller





New functionality



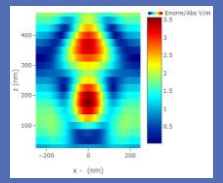


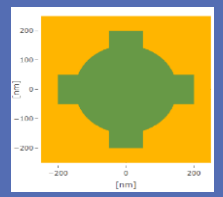
Design steps

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Meta-atom design

- Full wave
- nm scale

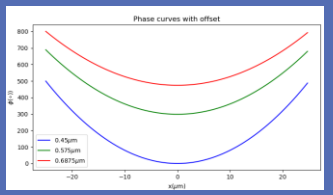


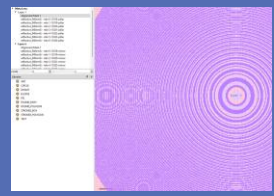


Meta-atoms

Component Design

- Target matching
- Single or multifunctional
- Wave scale

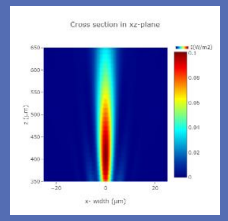


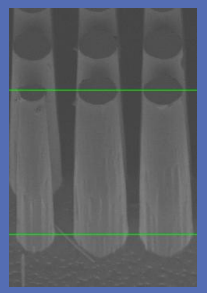


Wavefront

Validation & manufacturing

- Non-idealities
- Sensitivity & design rules
- PDKs



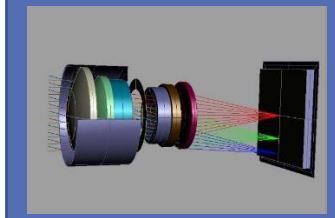


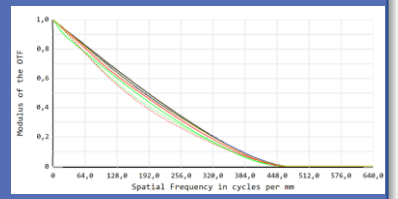
Re-iteration

Ideal wavefront

System model

- Ray & wave models
- Design to spec





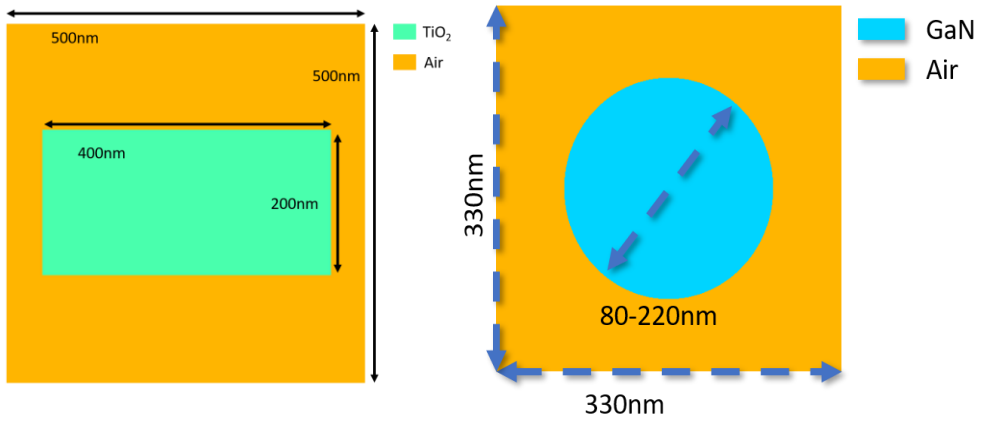
PlanOpSim

META CELL | META COMPONENT | META STACK

Meta-atom optimization

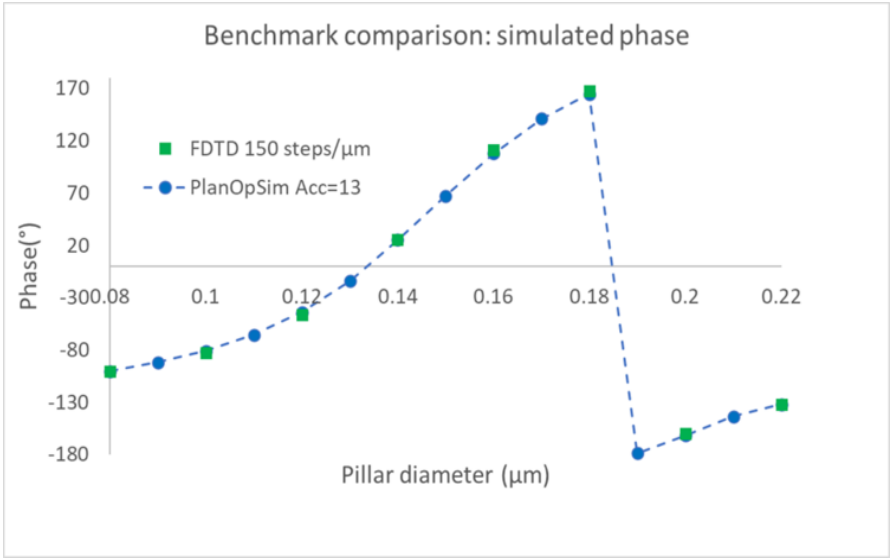
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- Nano-structure calculation using **Rigorous Coupled Wave Analysis** (Maxwell solver)
- Goal is to **fill the required** phase-amplitude response **space**
- Thousands of nano-structures in parameter space
  - **Parameter optimization needs fast solver**
  - **RCWA is much faster** for meta-atom calculations
  - Meta-atom response same in RCWA and FDTD



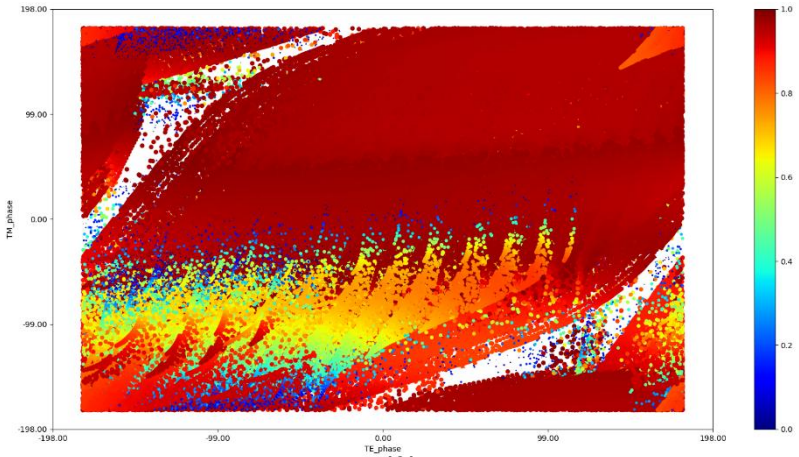
Test structures

Calculated field response



Example polzarization multiplexed space (1 dot = 1 structure = 2 calculations)

$\varphi_{TM}(°)$



$\varphi_{TE}(°)$

Meta-surface PDK

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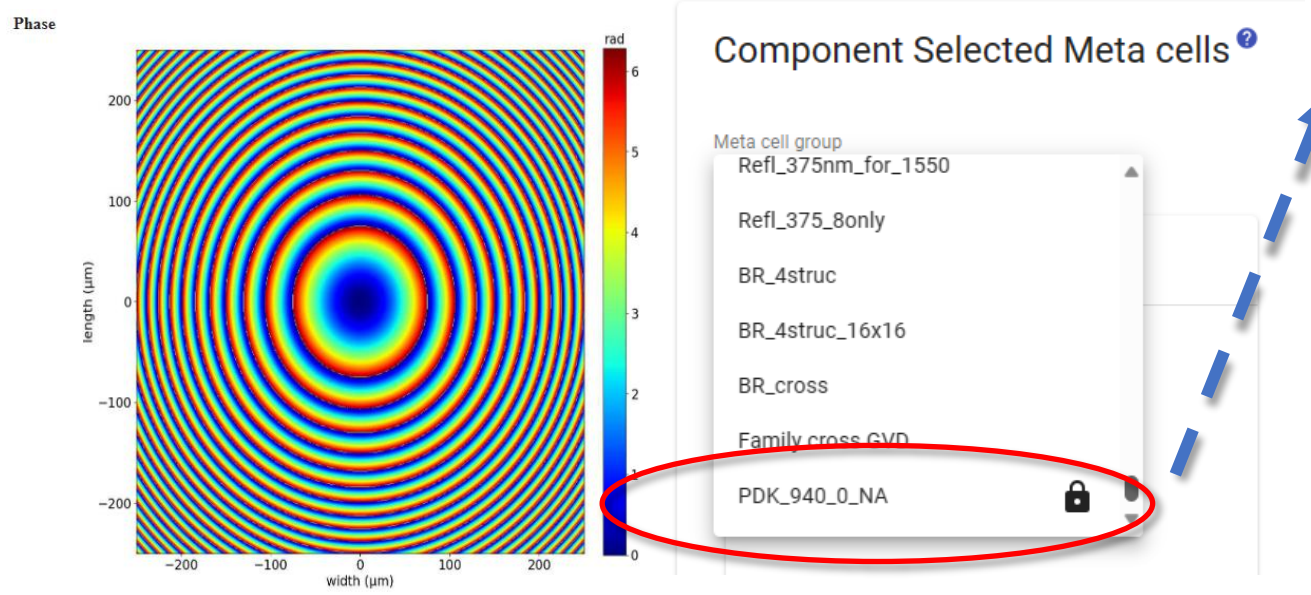
- **PDK:** Process development kit available since 2023
- **Manufacturer optimized and compatible** structure
- Multi-project wafer service: **rapid prototyping**, cost effective
- Supported wavelengths 455, 632, 532nm, 940nm

MOXTEK

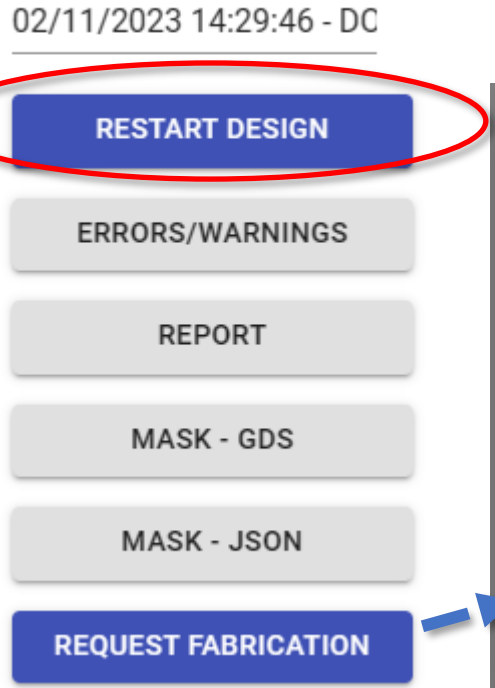
Phaseshift

10.6µm coming soon

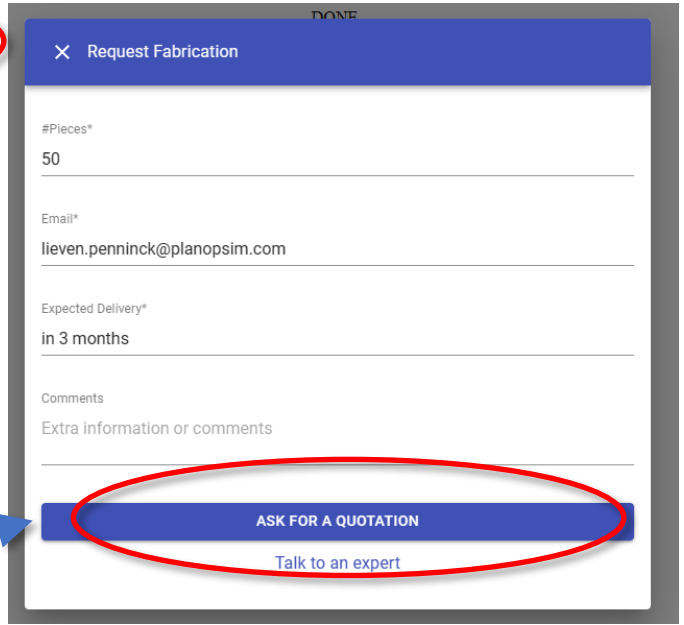
Step 1: select PDK and optical target



Step 2: run design

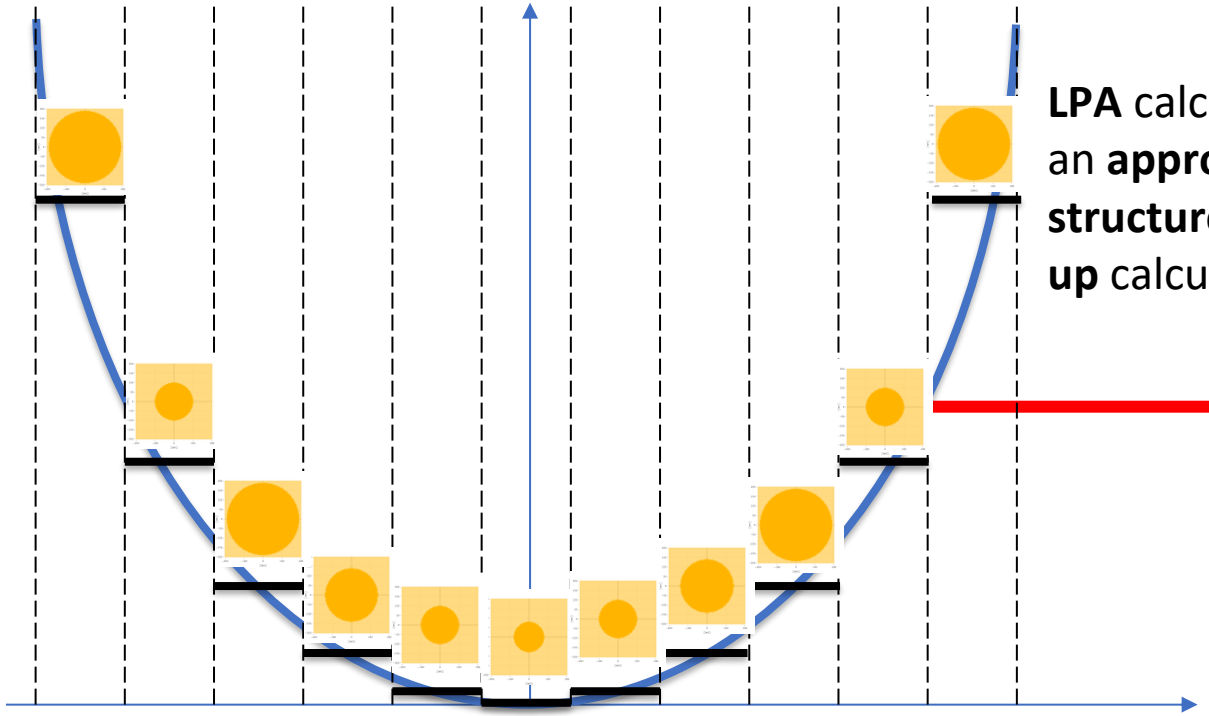


Step 3: submit design



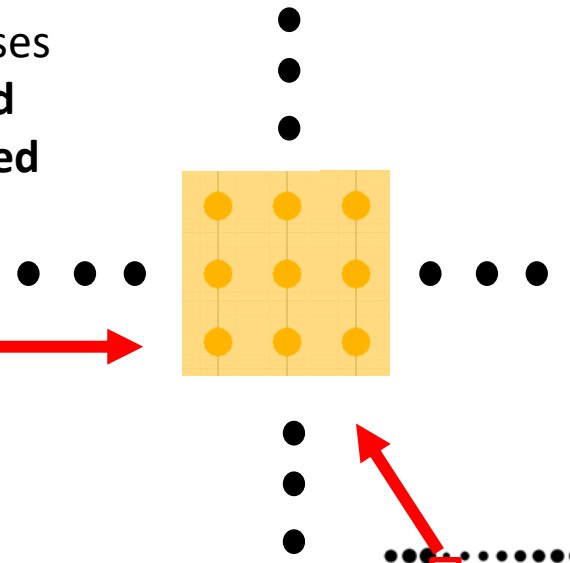
Component design

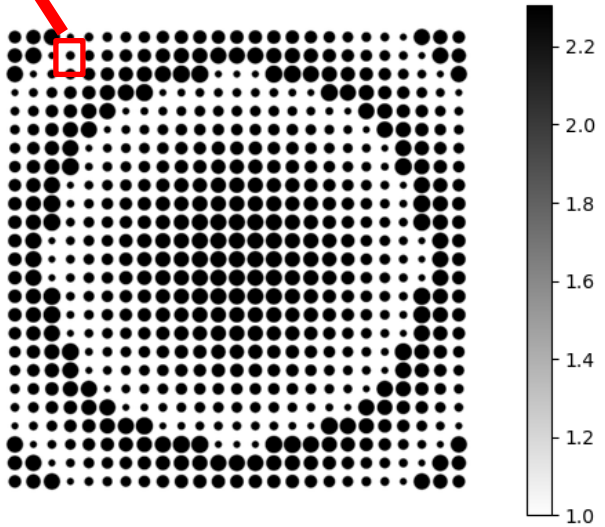
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LPA calculates uses an **approximated structure to speed up** calculation

local periodic approximation



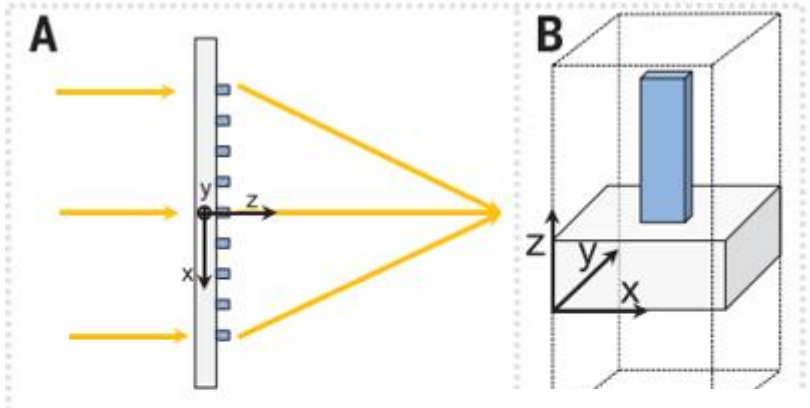


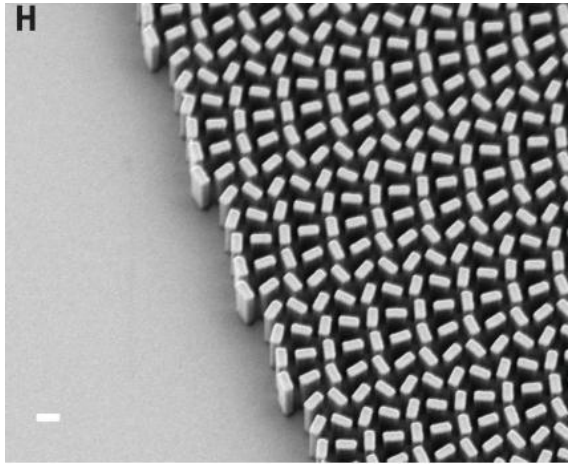
- More refined models: LFA, ODA
- Other aspects:
  - Pitch adjusted to Nyquist sampling
  - Phase discretization levels

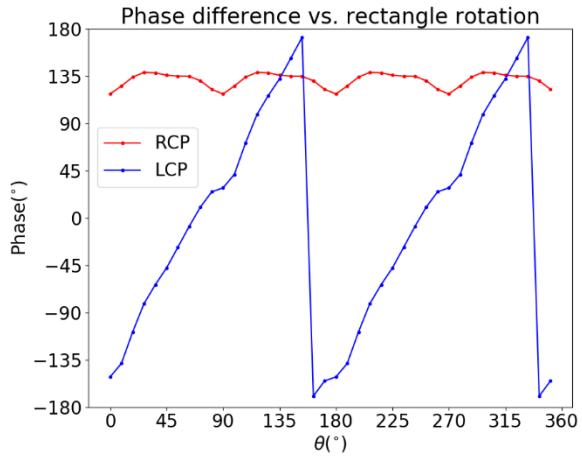
Component design

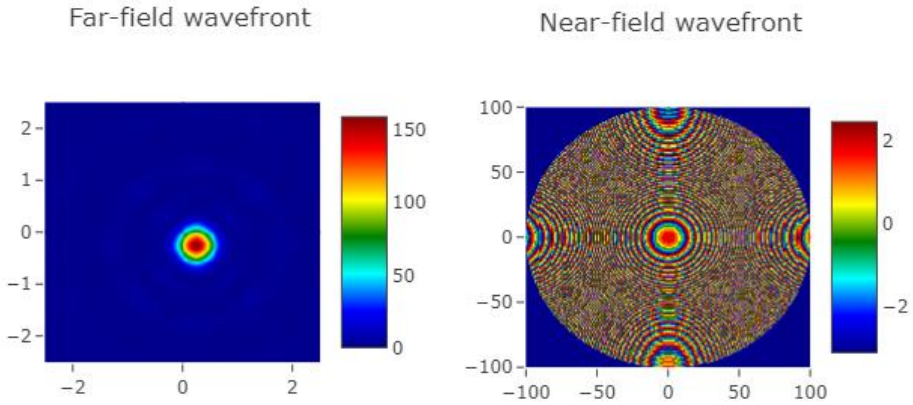
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- Design of a metalens with diffraction limited focusing and NA 0.55 for 632nm
- Integrated workflow:
  - Tuning of nano-pillars
  - Design of full metalens







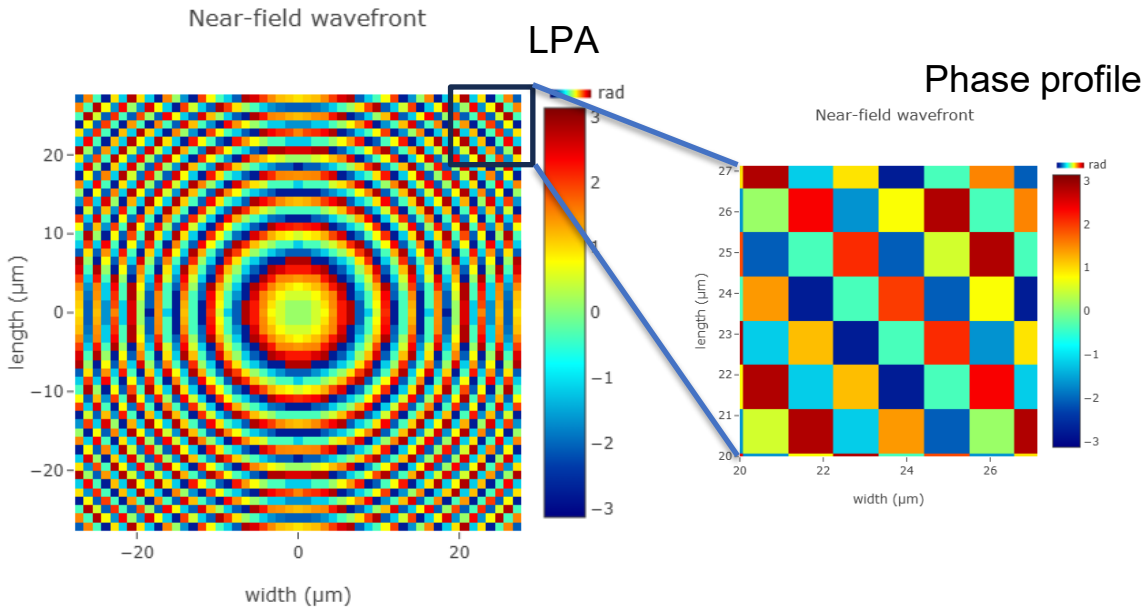


Focal spot and phasefront

Component design: advanced methods

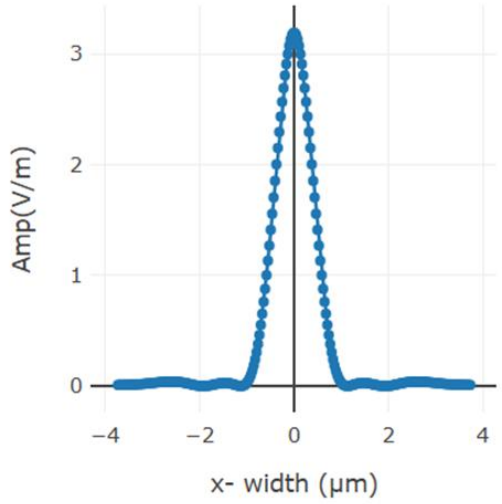
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LPA

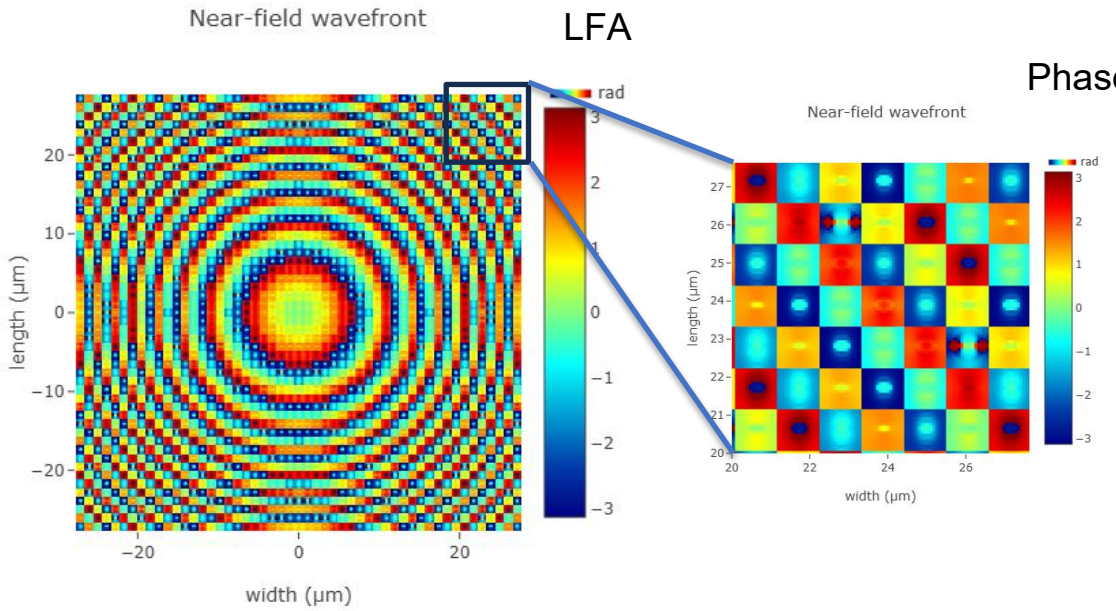


Phase profile

PSF section

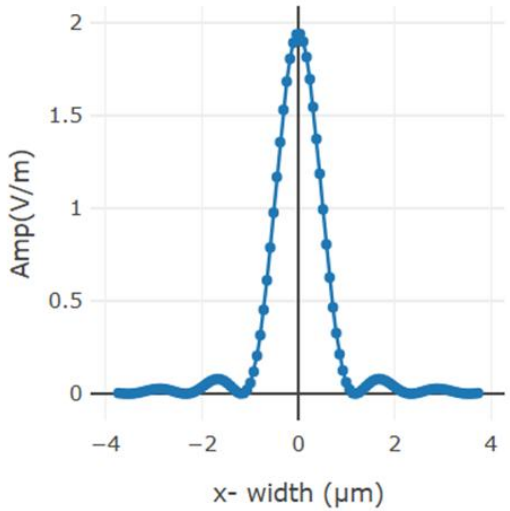


LFA



Phase profile

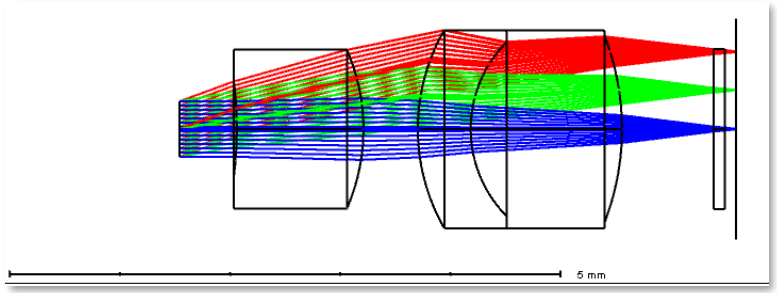
PSF section



Ray tracing meta-surfaces

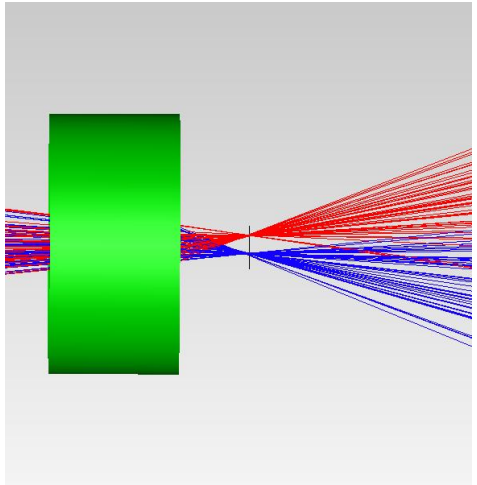
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- Example: **Pixel level colour routing in system**
  Reference design: imaging system. Meta-surface provides colour routing



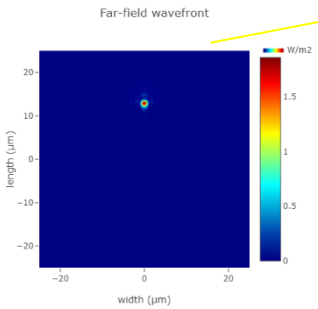
PlanOpSim
Ray Tracing Link
Ansys part of SYNOPSYS® TECHNOLOGY PARTNER
TracePro

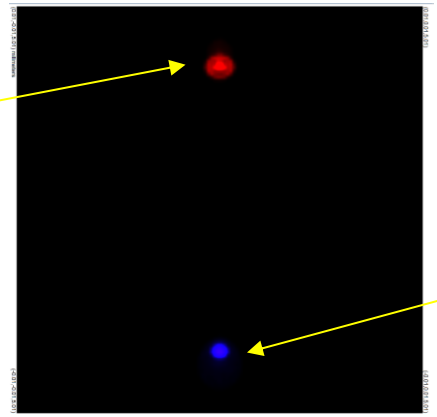
- Colour multiplexing meta-lens **designed and exported from PlanOpSim***
- Open interface



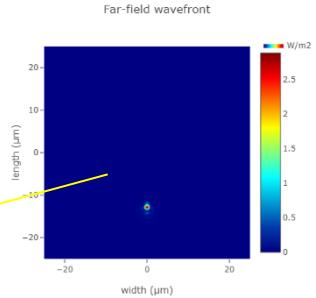
*Chen et. Al. (2017). GaN Metalens for Pixel-Level Full-Color Routing at Visible Light.. https://doi.org/10.1021/acs.nanolett.7b03135

Wave simulation 630nm





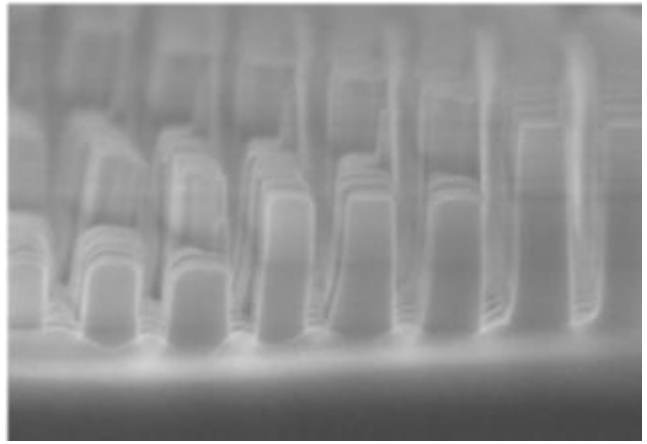
Wave simulation 450nm



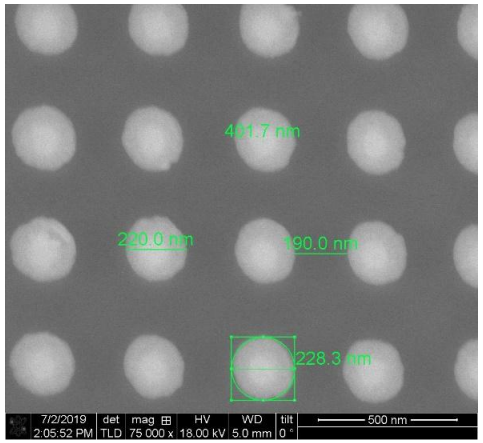
Design for manufacture

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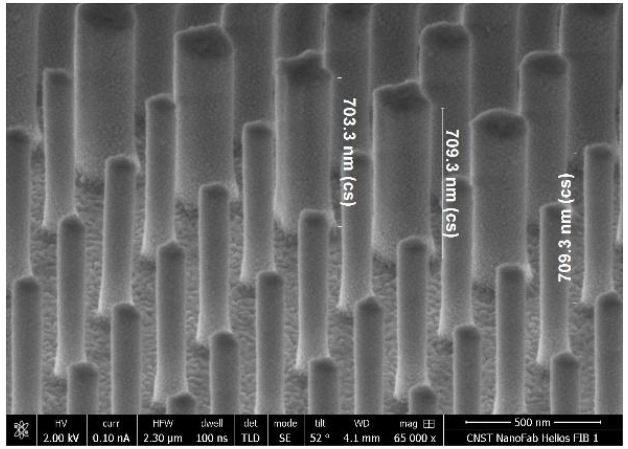
Sidewall not vertical, not linear



Pillar size and shape modified



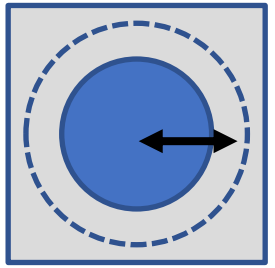
Evaporation thickness variation



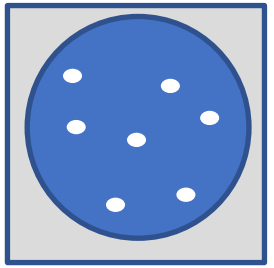
- As designed ≠ as manufactured
- How does manufacturing tolerance influence optical performance?
- Sensitivity simulation:

1. Nominal design
2. Change meta-atoms: uniform, proportional or random
3. Resimulate performance

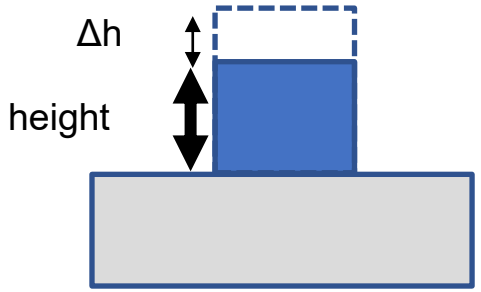
shape modified



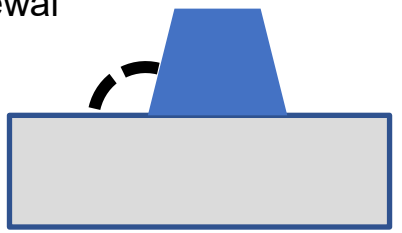
Film density changes



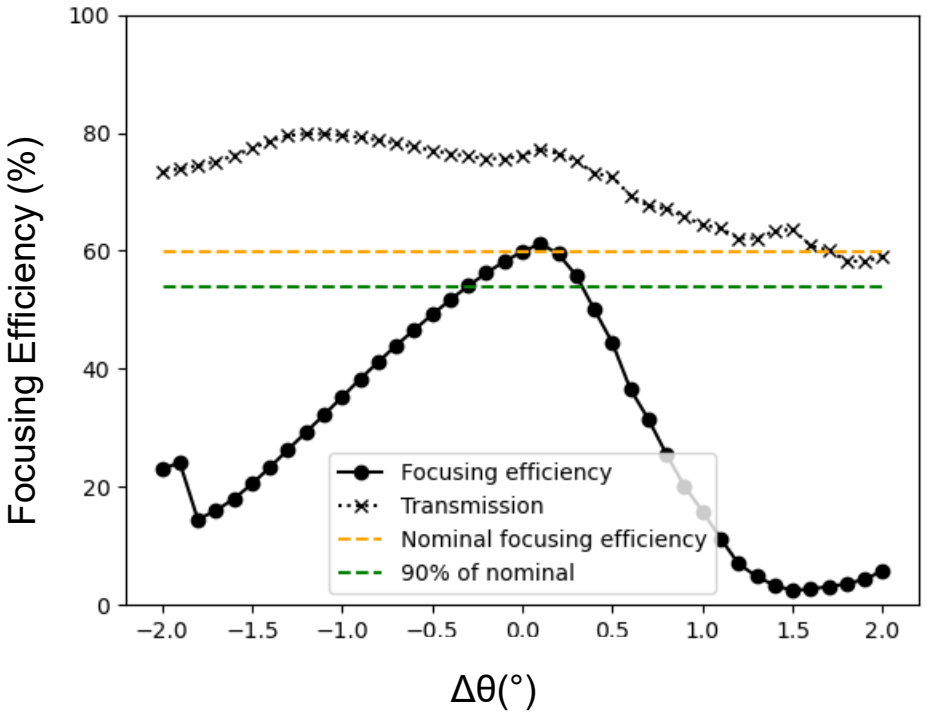
Height modified



Sidewal



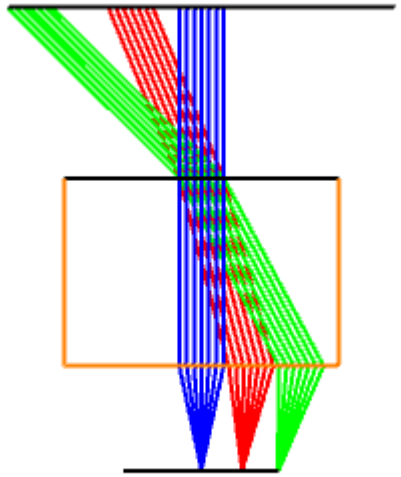
Example: sidewall angle



- Sample design for MWIR 4µm
- Δθ = ±2°
- Most sensitive parameter
- Transmission 76-> 58.2%
- Focussing efficiency 59,9->2.4%
- Focussing reduces more quickly than transmission
- Threshold 90% of nominal focussing efficiency:
  - ±0,3°

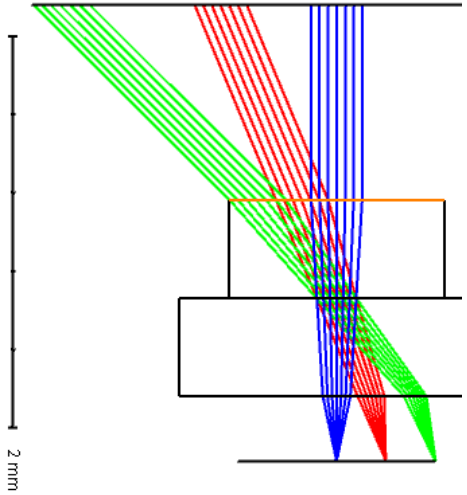
Sidewall angle	Transmission	Focussing efficiency	F/T
90° (nominal)	**76%**	**59.9%**	**0,76**
88,5° (uncompensated)	63,7%	2,4%	0,04
88,5° (compensated)	**76,7%**	**60,9%**	**0,79**

Highly compact designs



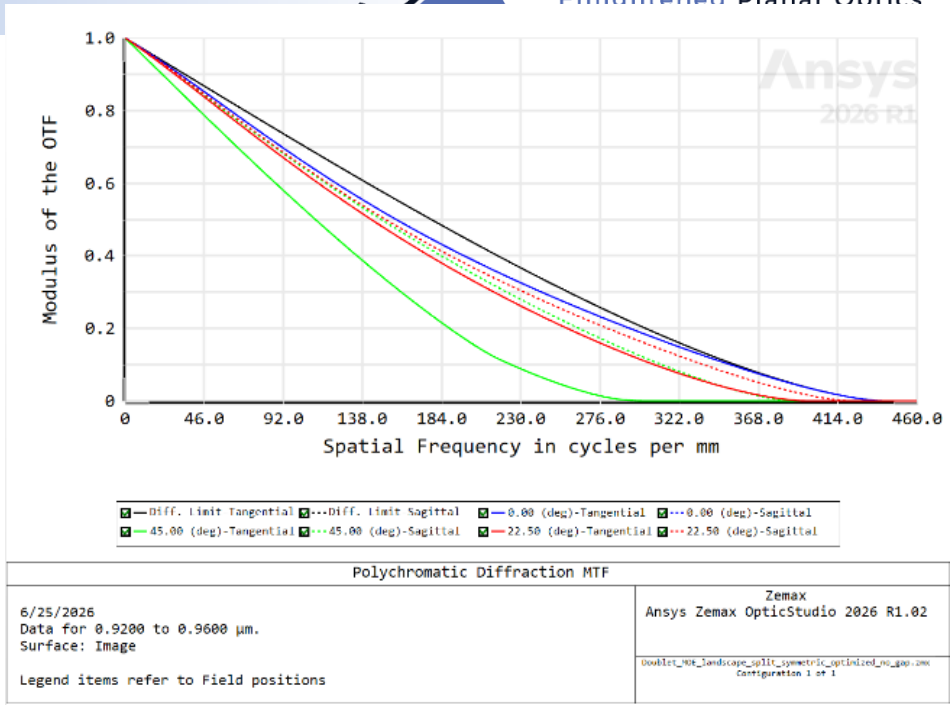
Single metalens design

- FOV 90°, f # 2.4
- Narrowband 940 +-2nm
- Total length 1.72 mm



Doublet metalens design

- Wider band 940 +-20nm
- FOV 90°, f # 2.4
- Total length 1.34 mm



Nice ray trace but :

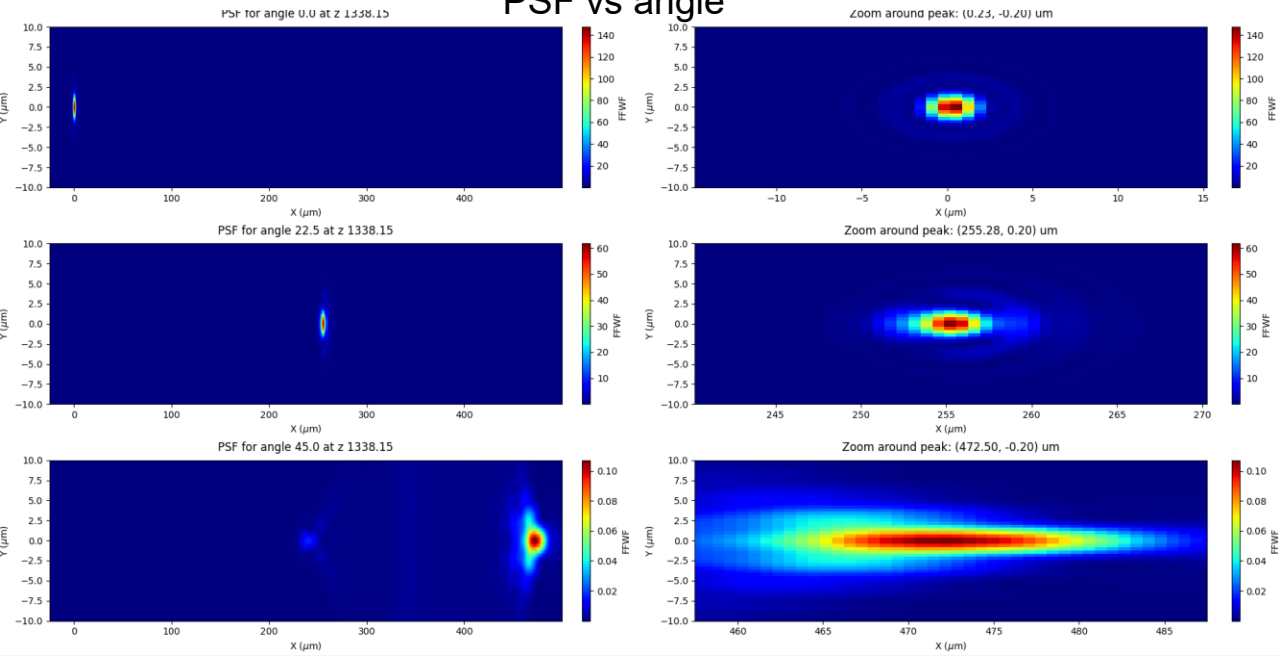
- Meta-atom under angle
- 0 and high order diffraction
- Fabrication defects vs. imaging

Meta-stack wave model

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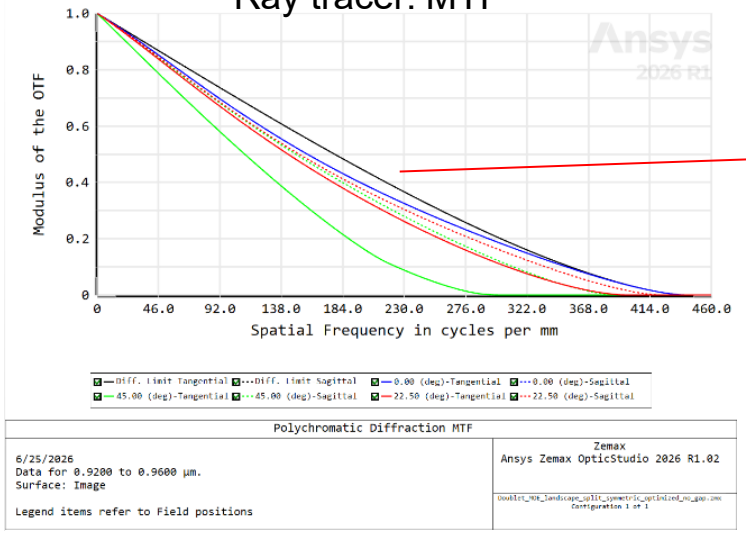
META CELL | META COMPONENT | META STACK

PSF vs angle



- 3 surface meta-lens (2 lenses + aperture)
- Accounts for:
  - Phase sampling
  - Diffraction
  - Phase & transmission under angle
- First commercial model to handle wave effects in >mm scale meta-surface systems

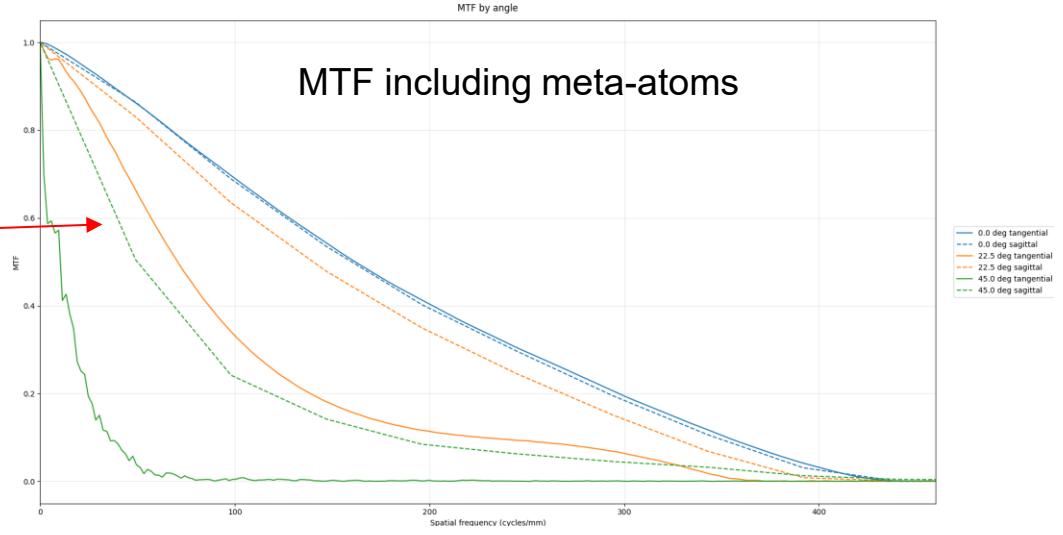
Ray tracer: MTF



Ray traced MTF is overestimated

Wave model accounts for diffractive loss of contrast

MTF including meta-atoms

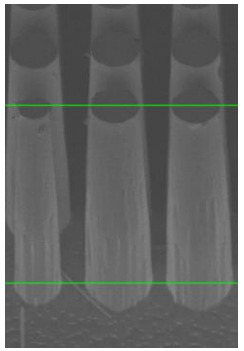


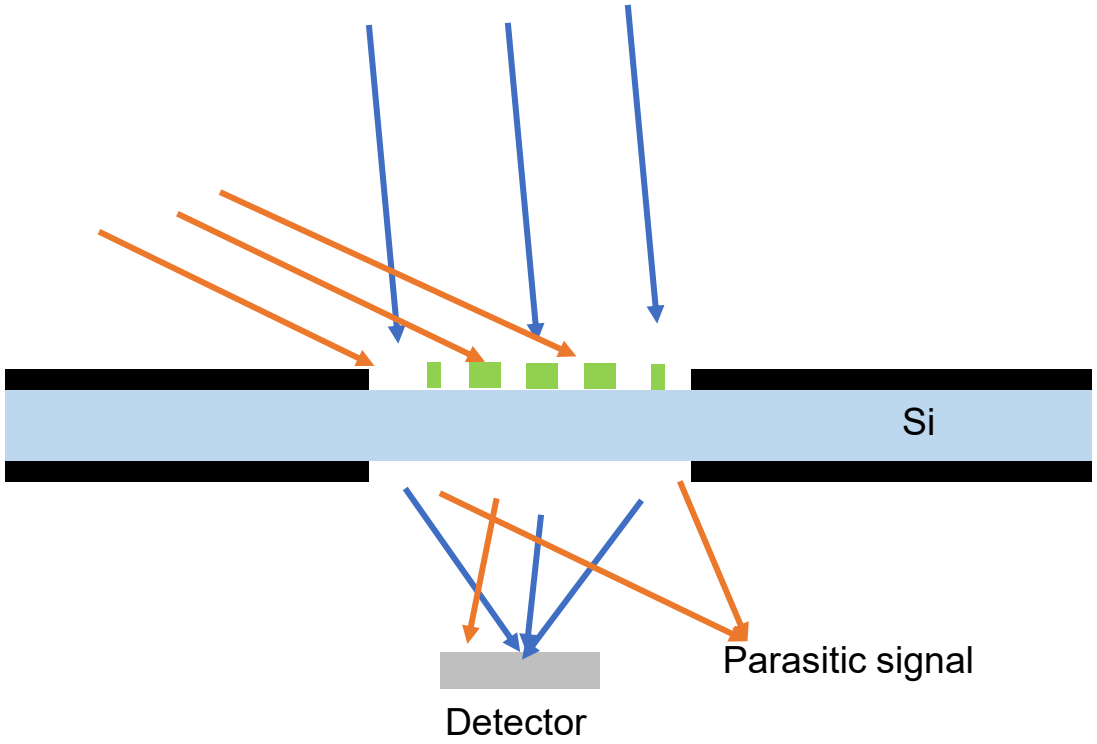
System sensitivity

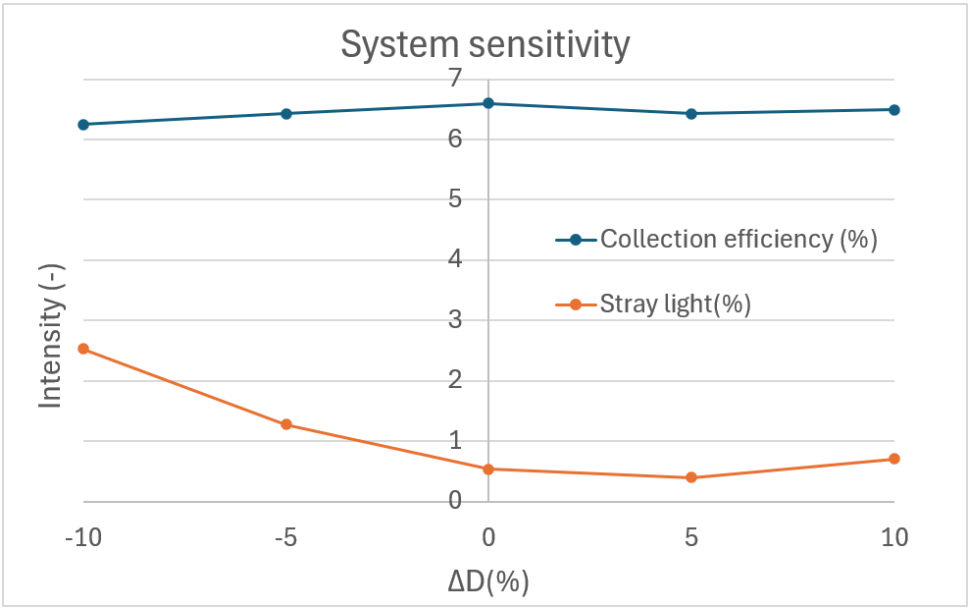
PlanOpSim release Q3 2026

META CELL | META COMPONENT | META STACK

- Imperfections in meta-surfaces cannot be ray-traced effectively
- **Meta-stack: wave model of multi-surface systems**
- Translate structural effect to system performance
- **Example: sensitivity of LWIR detector**
  - Manufacturing tolerance influences stray light collection

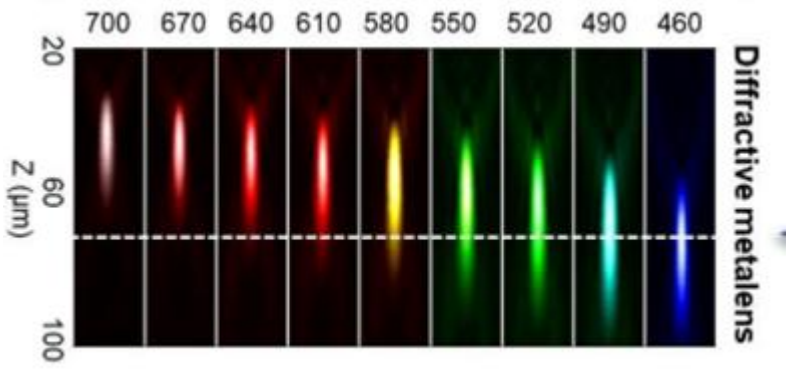


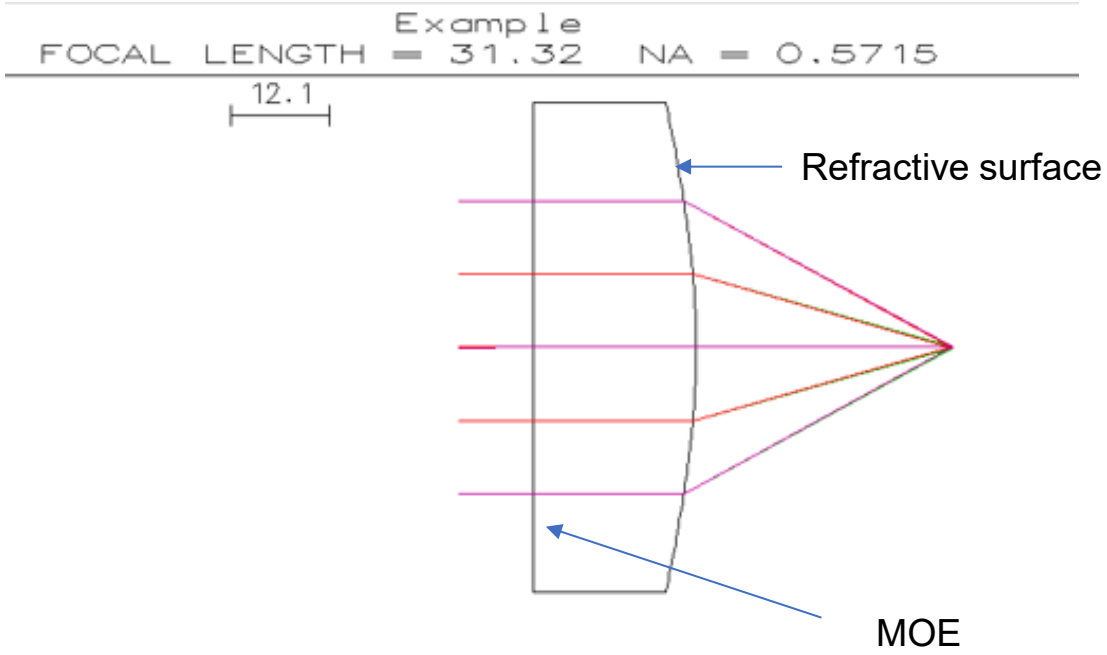




Meta + Refractive hybrids

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- Meta-lenses have strong chromatic focal shift

$$f(\lambda) = \frac{f_0 \lambda_0}{\lambda}$$

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

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

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

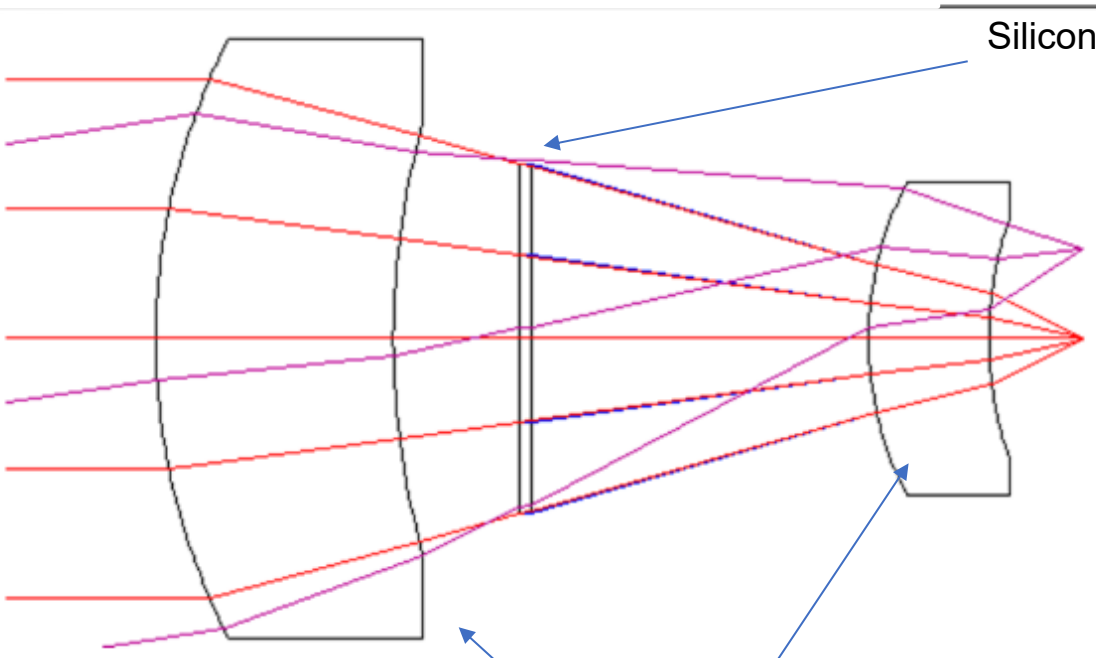
- Achromatic hybrid when

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

System design result

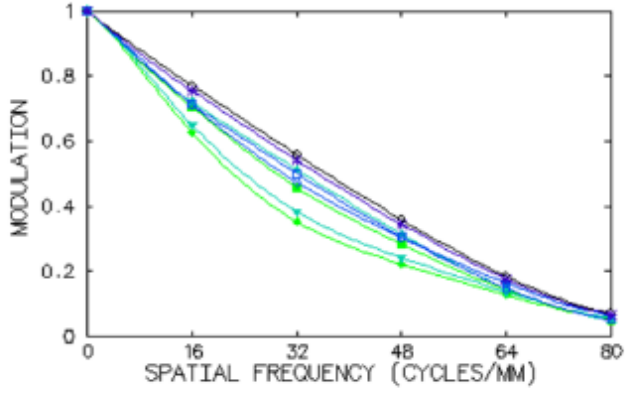
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Example



FIELD POINTS

Polychromatic MTF of hybrid lens

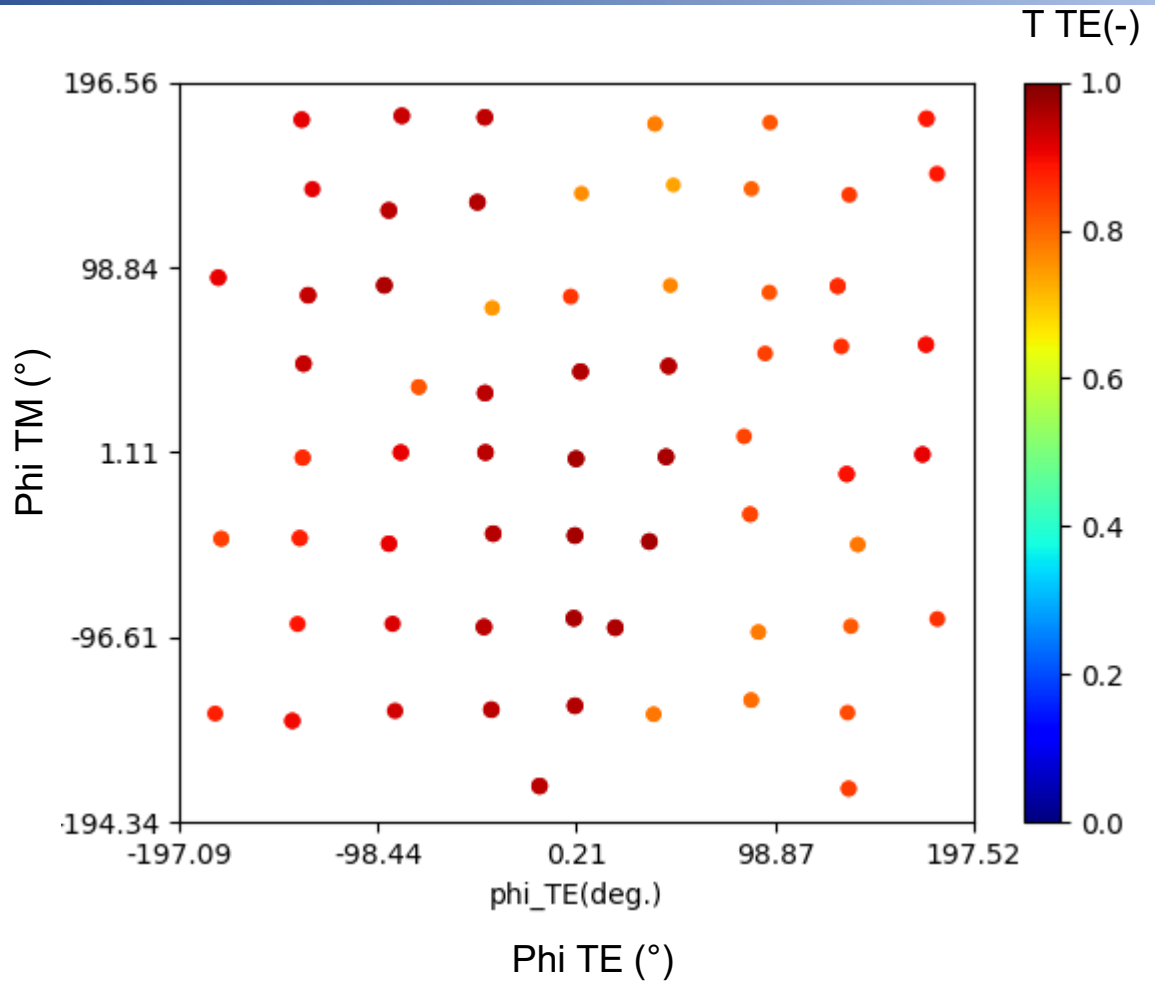


WAVELENGTHS		
#	λ(μm)	Weight
1	10	1
2	12	1
3	8	1

MTF TYPE	Example	Penninck_L
DIFFRACTION	MODULATION TRANSFER FUNCTIONS	20 Feb 25 10:37 AM

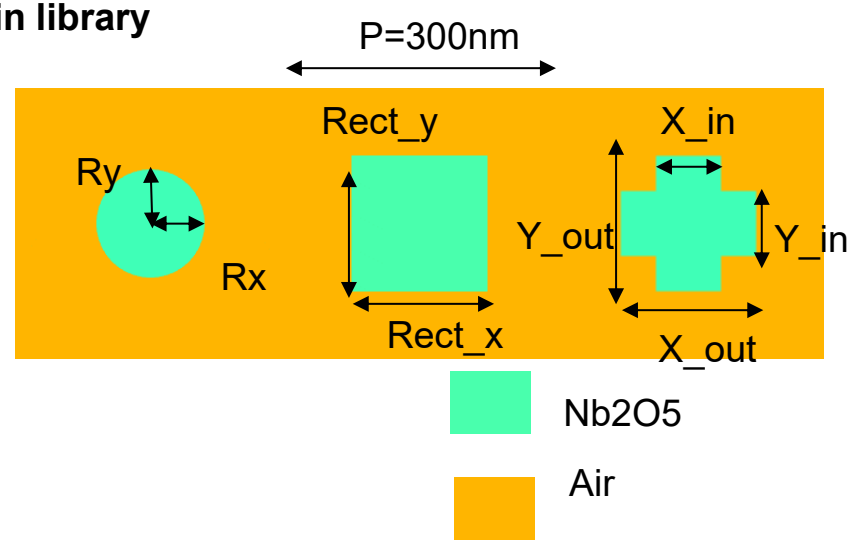
- Hybrid design allow to reach compact and wideband systems
- Hybrid design chromatic correction over wide spectrum
  - Example LWIR 8-12 um
- Optimized via ray tracing
  - Meta-surface as polynomial
  - Constant phase vs. Wavelength

Meta-surface design



- Functions with no refractive analogue
- Polarization multiplexed designs
- 8x8 phase sampling levels for phi TE/phi TM pairs

Structures in library

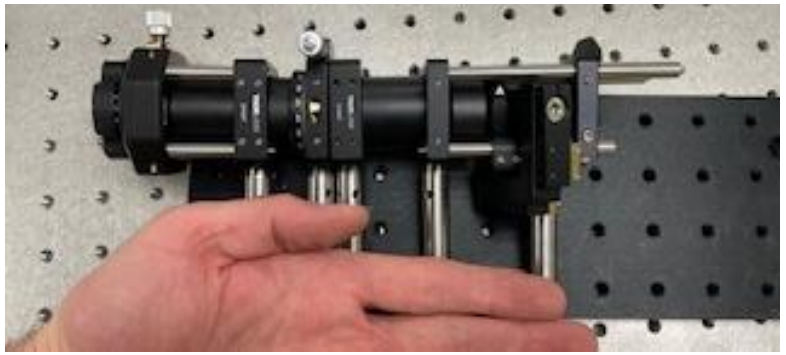


Application examples

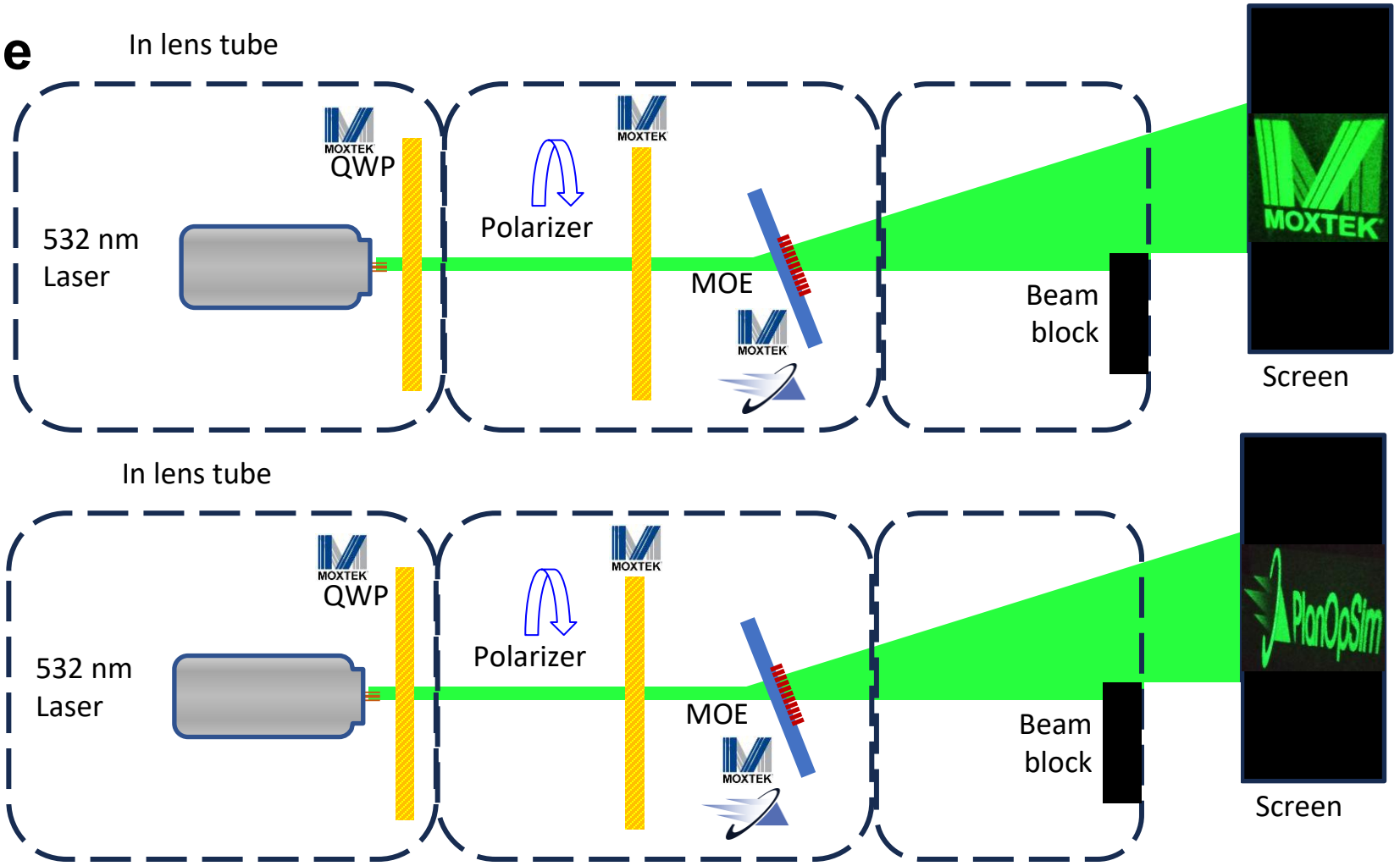
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Single meta-components replace function of multiple traditional optics

TM mode



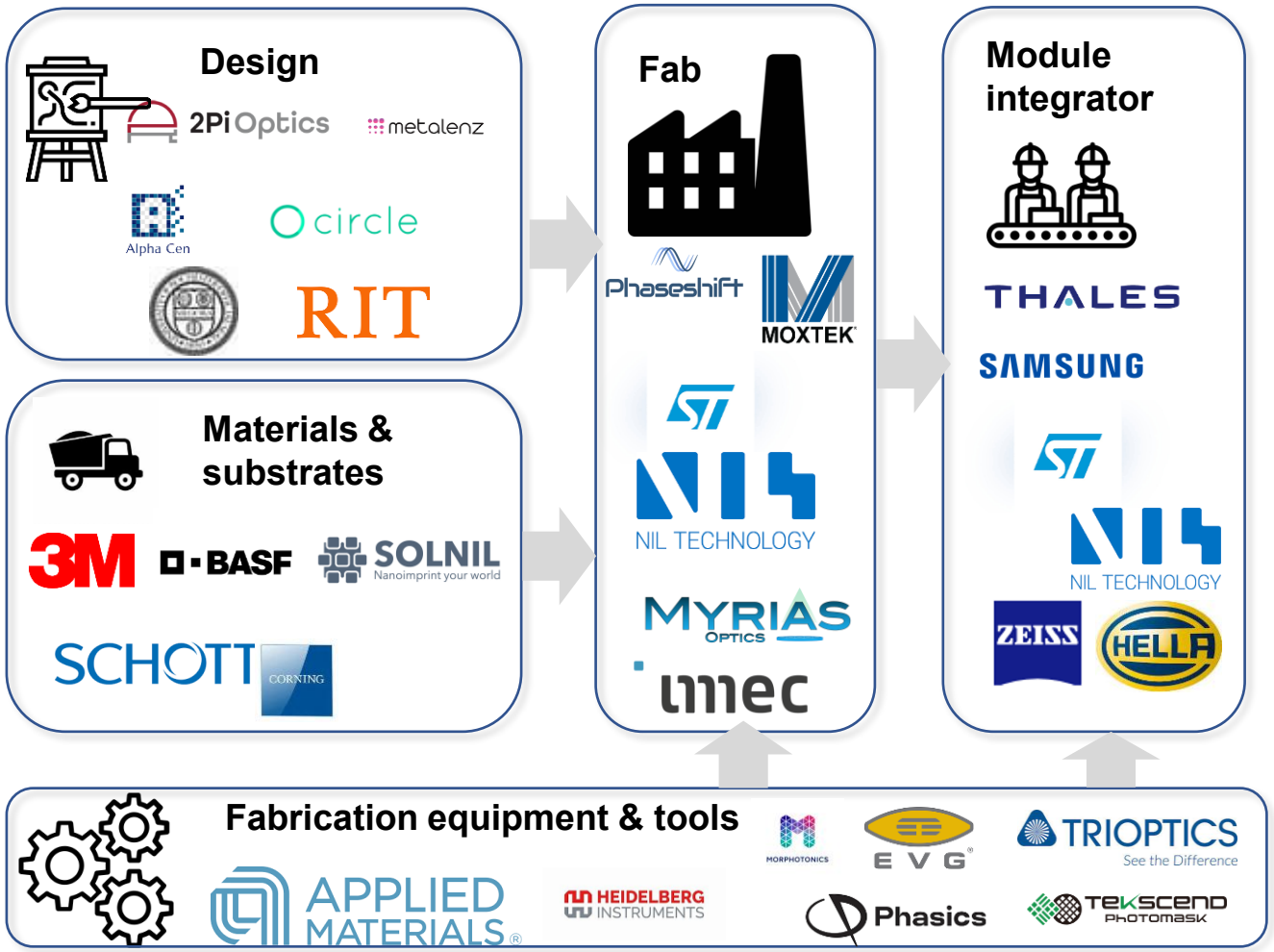
TE mode



Conclusion

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PlanOpSim The tool for meta-optics development



- Meta-surfaces are in high volume production today
- Miniature and new optics is the key to successful use cases
- **Powerful design tools** are needed for commerical application development
  - System & component design
  - Integrated value chain of design & manufacturing
  - Rapid iteration
- Design tools have matured to meet these needs

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Formerly OSA

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