Lieven
Penninck

Meta-surface design from meta-atoms to systems

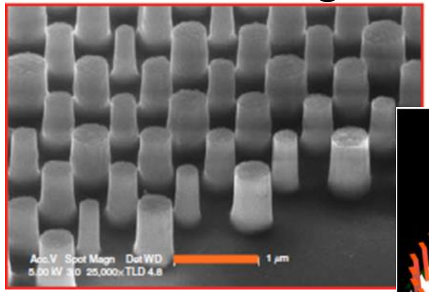
Design Seminar, San Fransico, USA

PlanOpSim
Enlightened Planar Optics

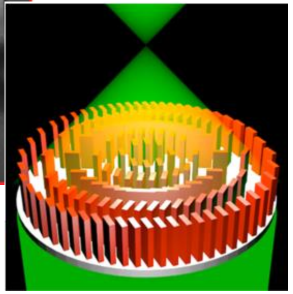
30 January 2023

PlanOpSim

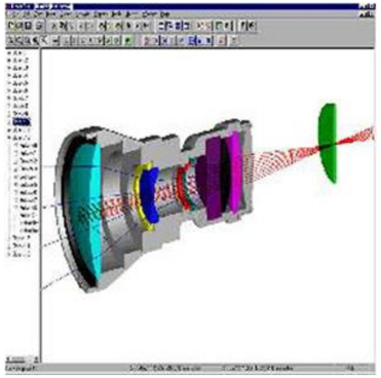
Nano-scale design



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 **metasurfaces** & planar optics
  - All-in-one design workflow
- **Design service** for metasurfaces and photonics
  - Own and 3^{d} party tools

Why use meta-surfaces?

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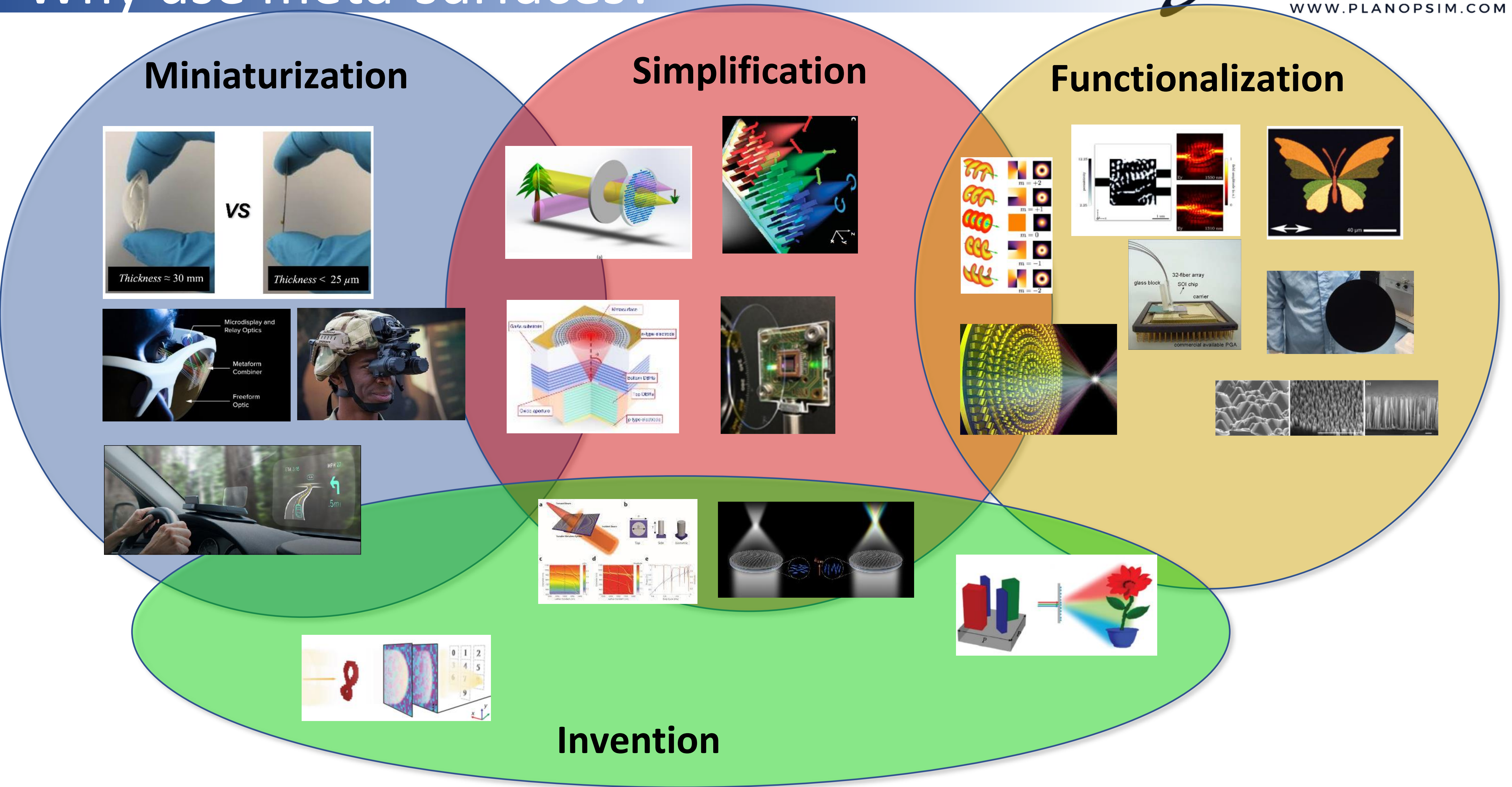

Outline

- Basics of meta-surface design
- Meta-atoms
- Meta-surfaces
- Meta-systems

Meta-optics project flow

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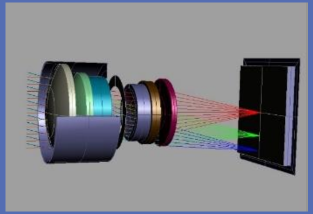
PlanOpSim Support solution

PlanOpSim Software solution

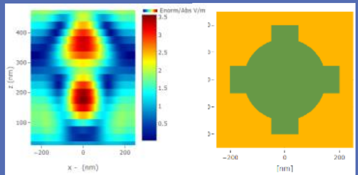
META CELL | META COMPONENT | LIBRARY | JOB OVERVIEW

Concept
- Feasibility
- Specs

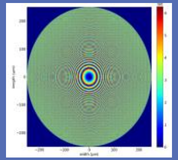
System model
- Ray tracing



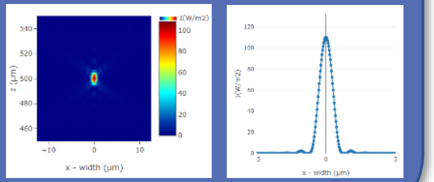
Nanostructure
- Full wave RCWA
- Structure library



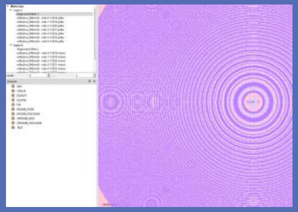
Component design
- Propagation
- Wavefront design



Validation
- Propagation
- Non-idealities



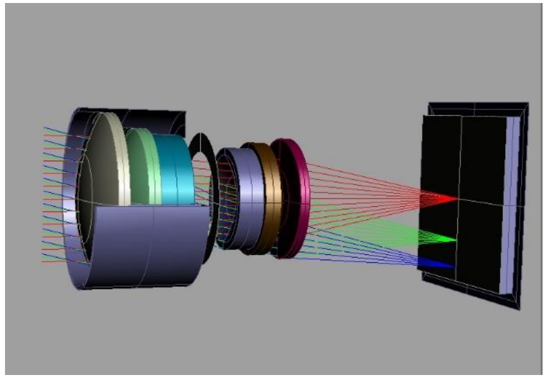
Fabrication
- gds export



REPORT

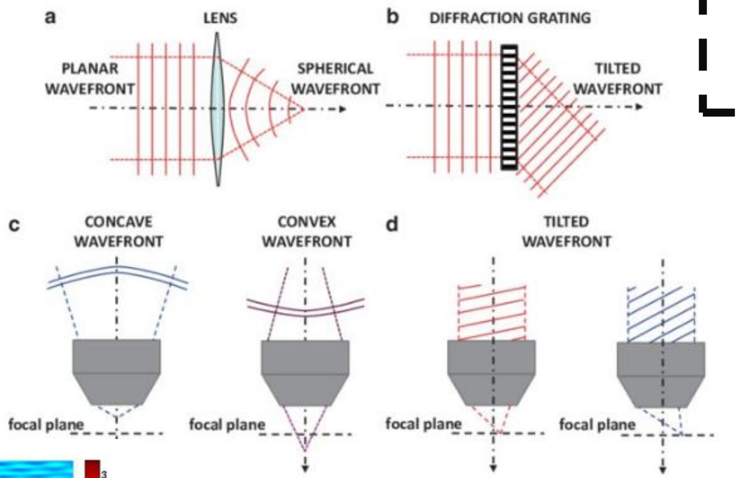
MASK

Design complexity

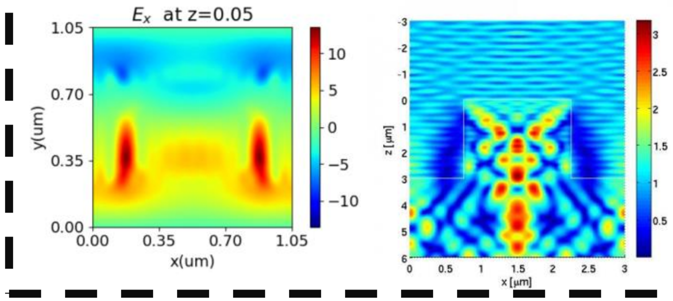


Ray tracing

Propagation optics



Full wave solvers



Large scale

100λ scale

sub-λ scale

Maxwell's equations

Waves

Geometric rays

Meta-atoms: calculation speed

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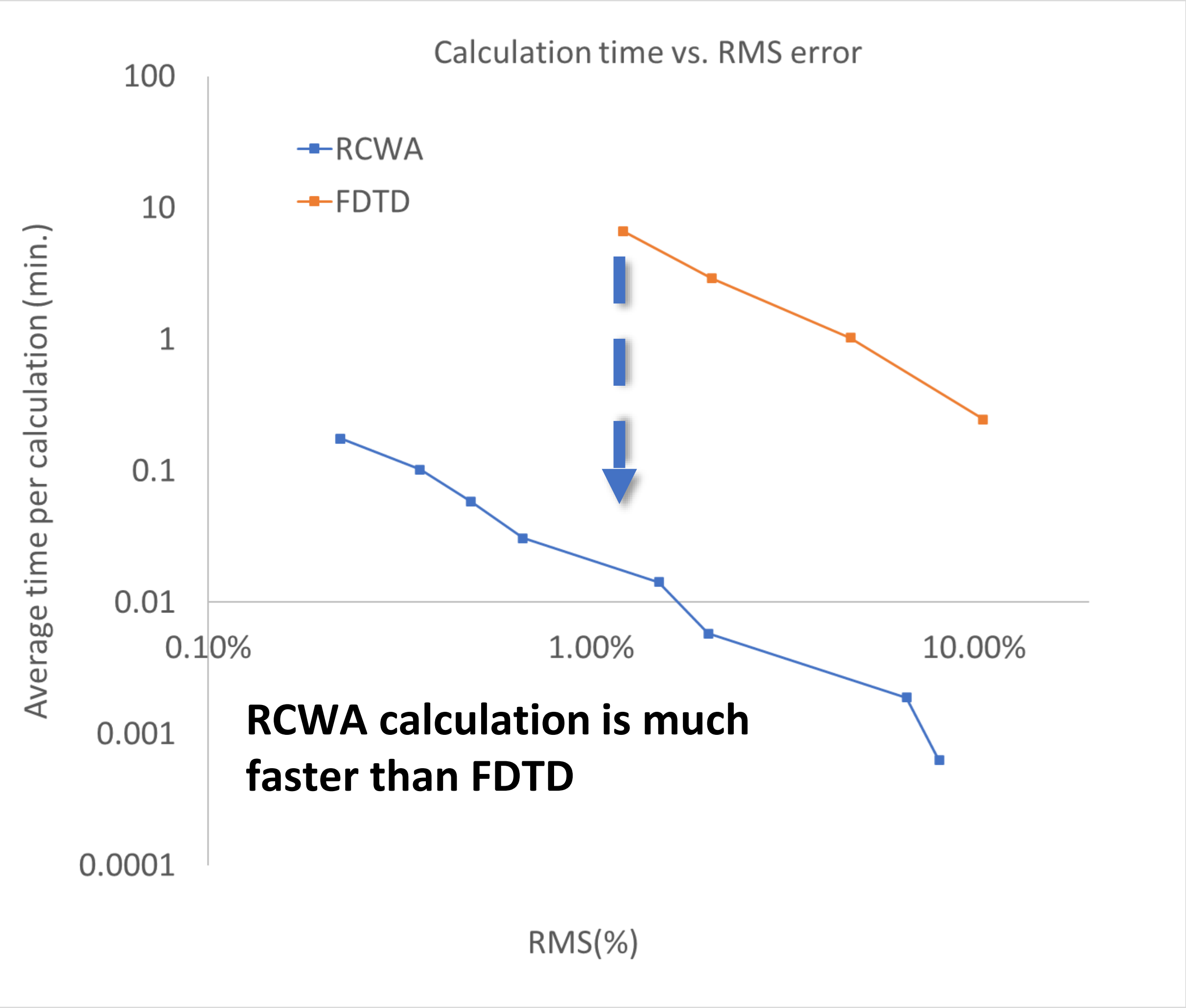
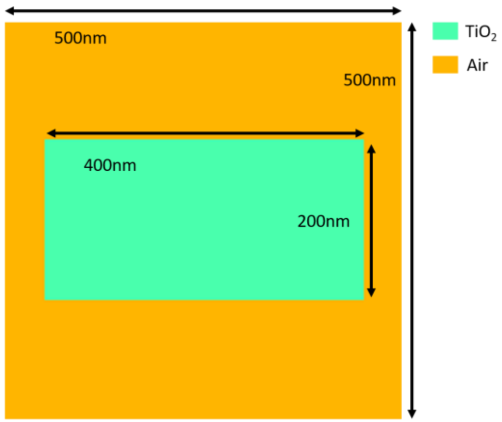
- **Benchmark**:
  - Geometric phase meta-atom
  - Calculation time vs. RMS error (at converged result)
- Full Maxwell solution is computationally intensive and limited to small areas
  - PlanOpSim (RCWA)
  - MEEP (FDTD)
- **RCWA is much faster for meta-atom calculations**
- In practical optimizations several thousand structures are calculated



Test structure



Meta atoms: method comparison

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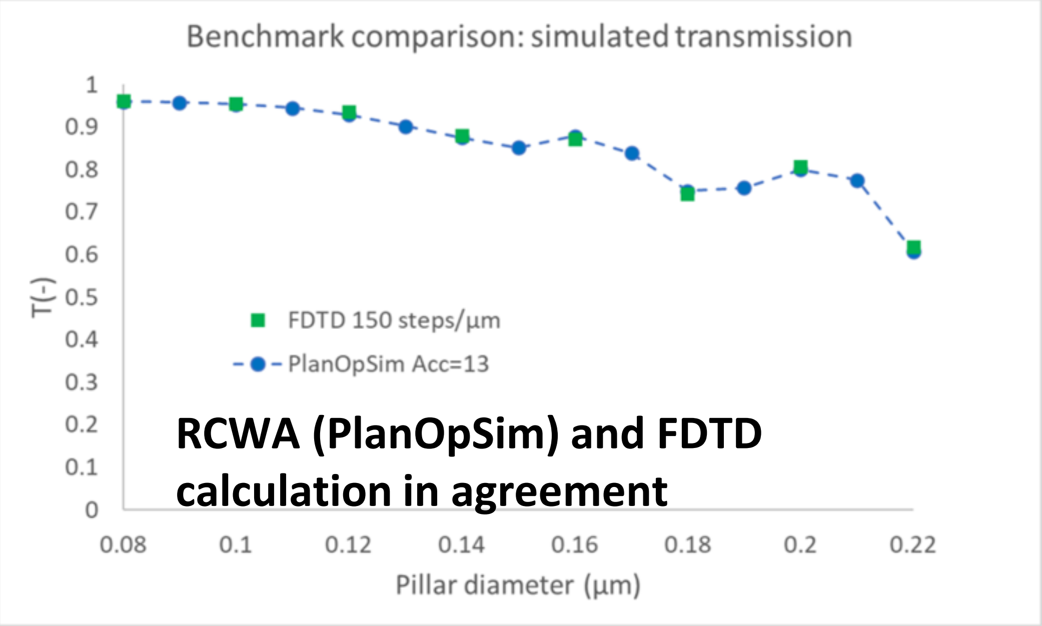
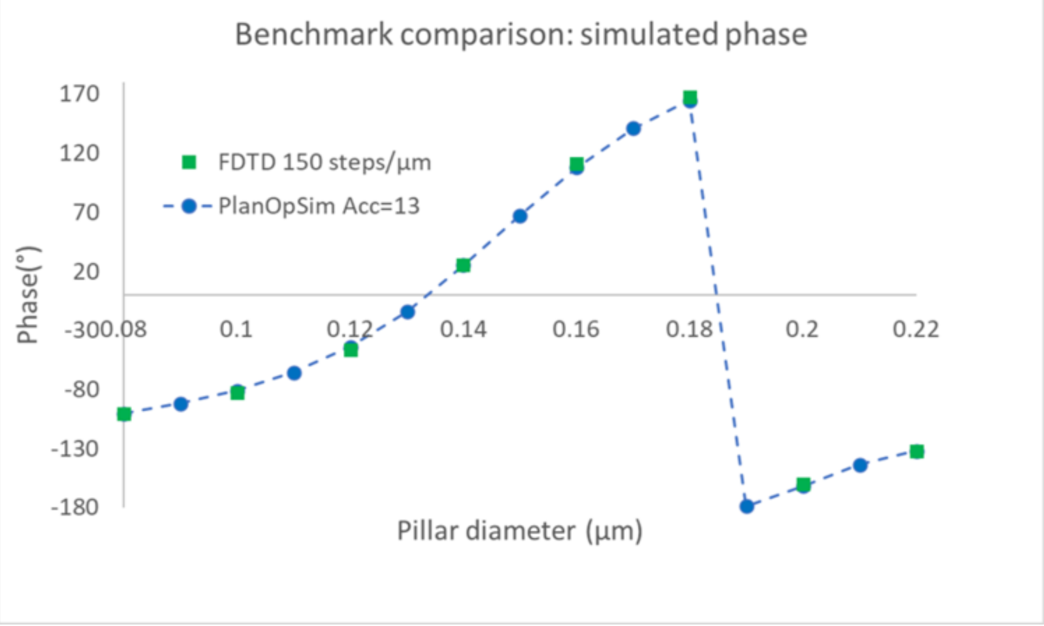
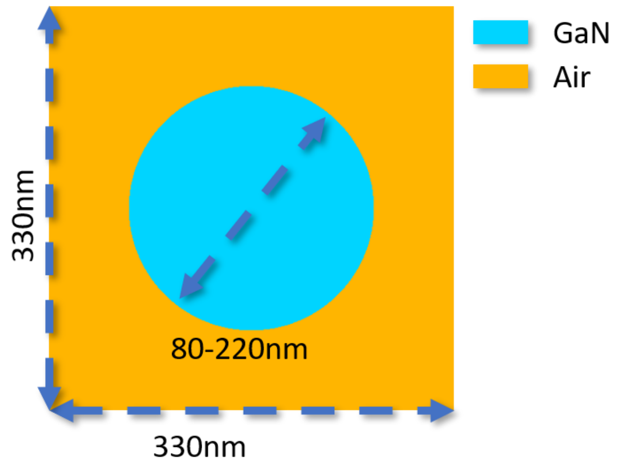
- **Benchmark**:
  - Circular pillar meta-atom
  - **Transmission and phase** for different structures
- Maxwell equations solved by different methods
  - PlanOpSim (RCWA)
  - MEEP/Lumerical (FDTD)
- Both methods give the **same results**



RCWA (PlanOpSim) and FDTD calculation in agreement



Test structure



Component level

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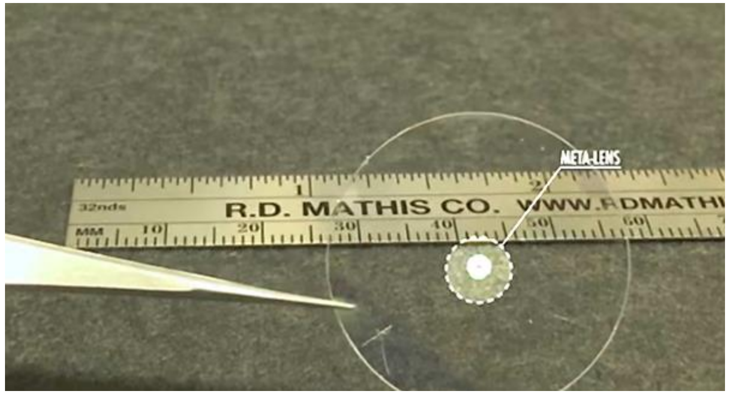
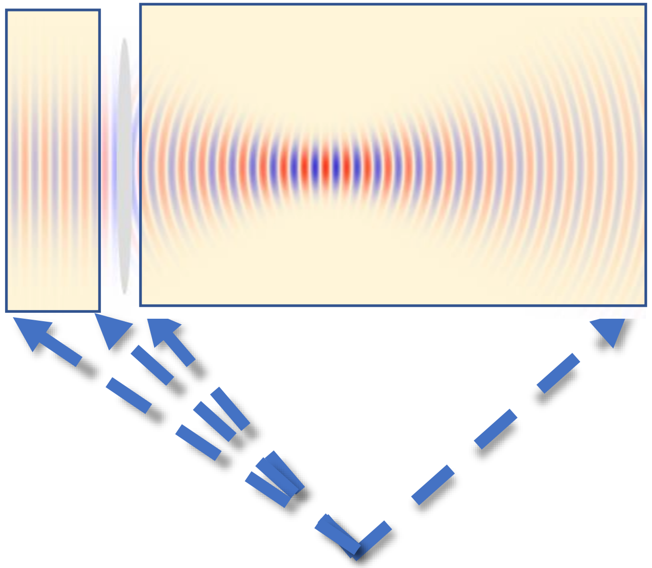
- Full wave solutions are not possible even for small components



Huge component
(for a full wave solver)

- Fourier/ physical optics
  - Field distribution
  - Transform to frequency space
  - Apply propagator
  - Inverse transform to cartesian space

From full wave solver

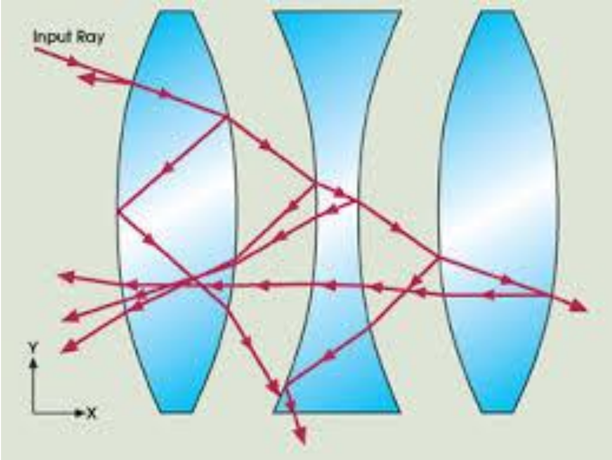


Applicable here

- Beam propagation method, Angular spectrum calculation
- Very fast, memory limit due to large number of meta-atoms
- Only in homogenous media

System level

- Macroscopic systems with many components
  - Mechanics
  - Temperature
  - Tolerances and assembly
- Monte Carlo - Ray tracing
- Sequential ray tracing: single direction
  - Imaging applications
  - Few hunderds of rays needed
- Non-sequential ray tracing: rays travel back and forth
  - Non-imaging: illumination, waveguide optics, displays, stray-light in imaging
  - typically millions of rays needed (slow)



Outline

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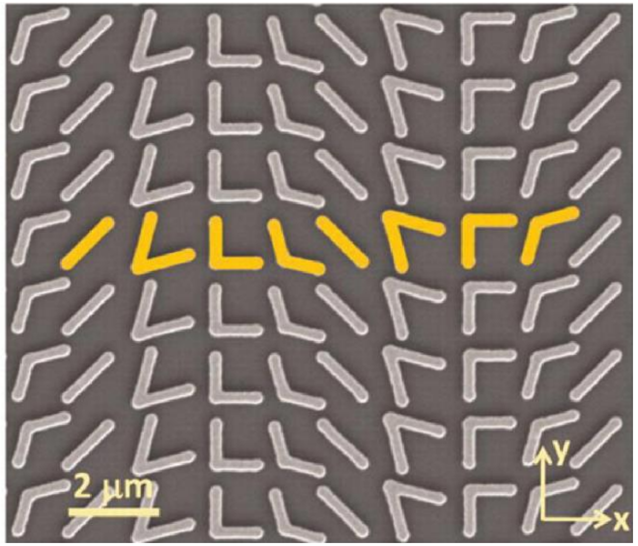
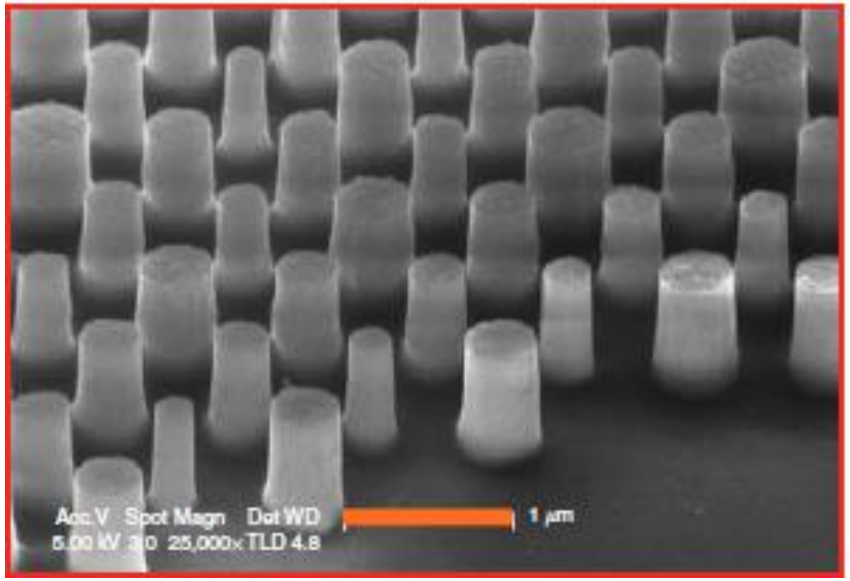
- Basics of meta-surface design
- Meta-atoms = full wave
- Meta-surfaces= propagation
- Meta-systems = ray tracing

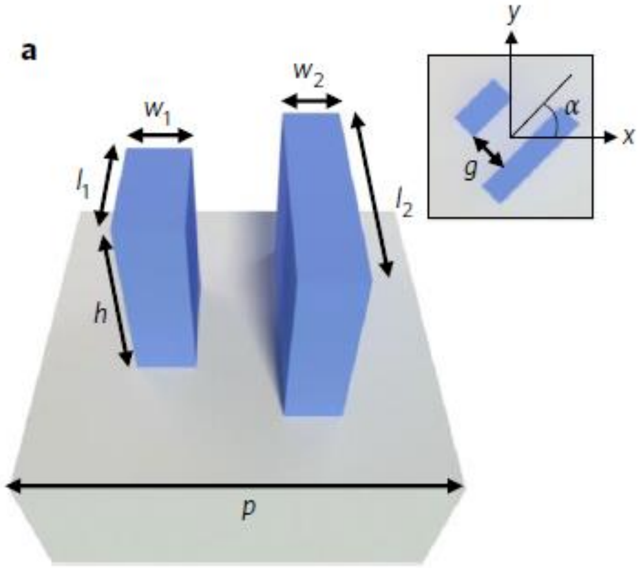
Sub-wavelength structures: 3 main types



Plasmonic structure



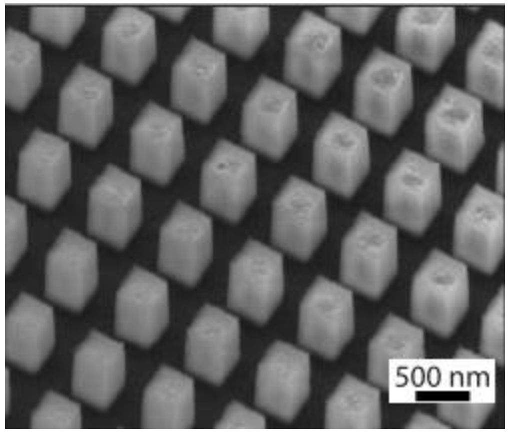
Dielectric structures

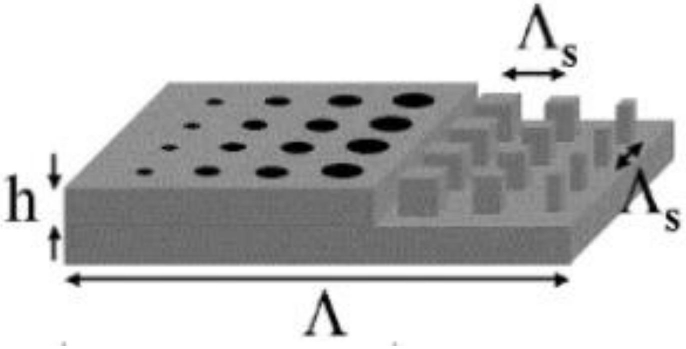


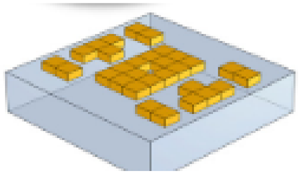
Structural birefringence

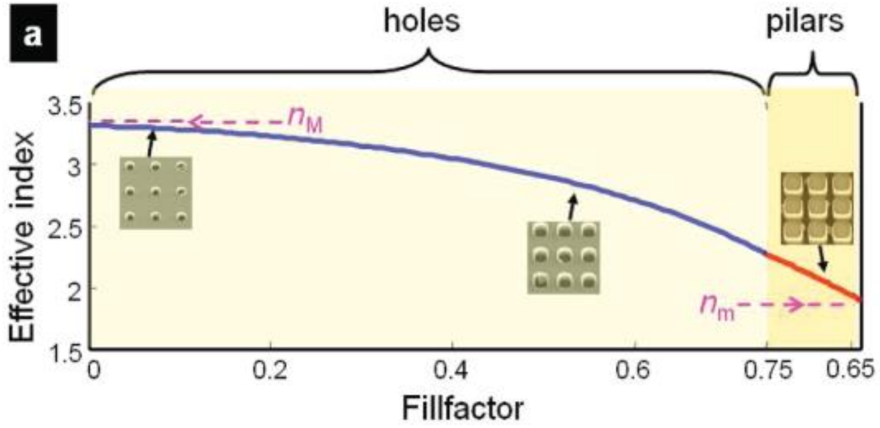
Dielectric structures

- Viewpoints on dielectric sub-wavelength structure
  - Effective medium
  - Waveguide
  - Resonator
- $n_{gap} < n_{effective} < n_{material}$
  - Δn is critical
  - High n: Si, SiN, TiO_2
  - Gap: air or low index material
- Phase & amplitude tuning:
  - Height
  - Geometry: Cylinders, Squares, Hexagon, Cross
  - Complex shapes:
    - Genetic algorithms
    - Adjoint optimization



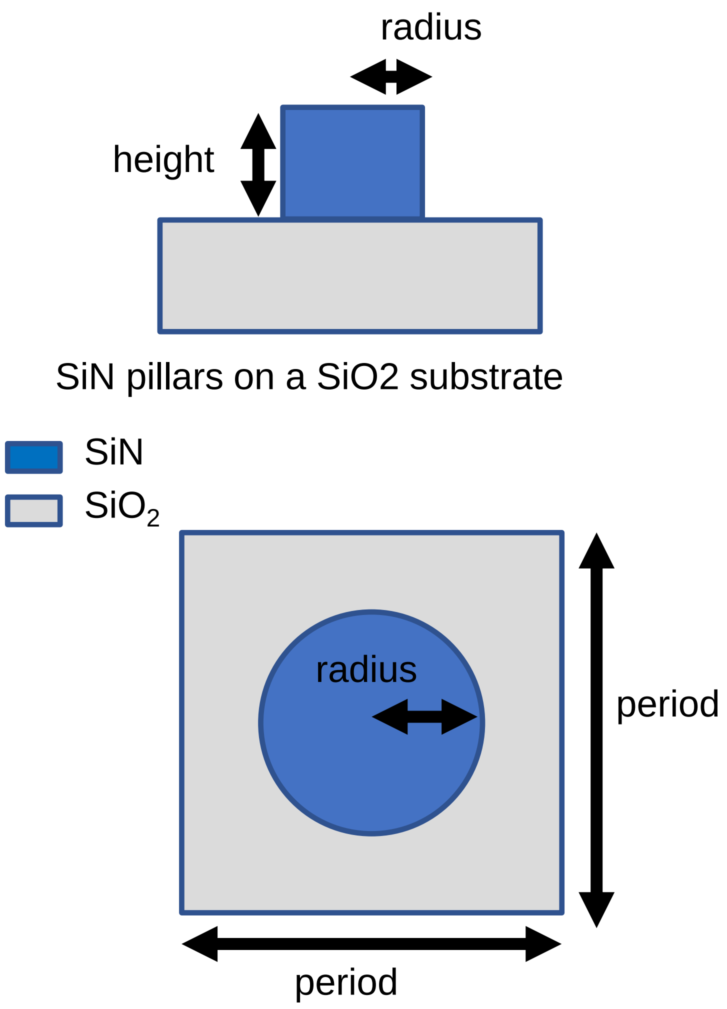


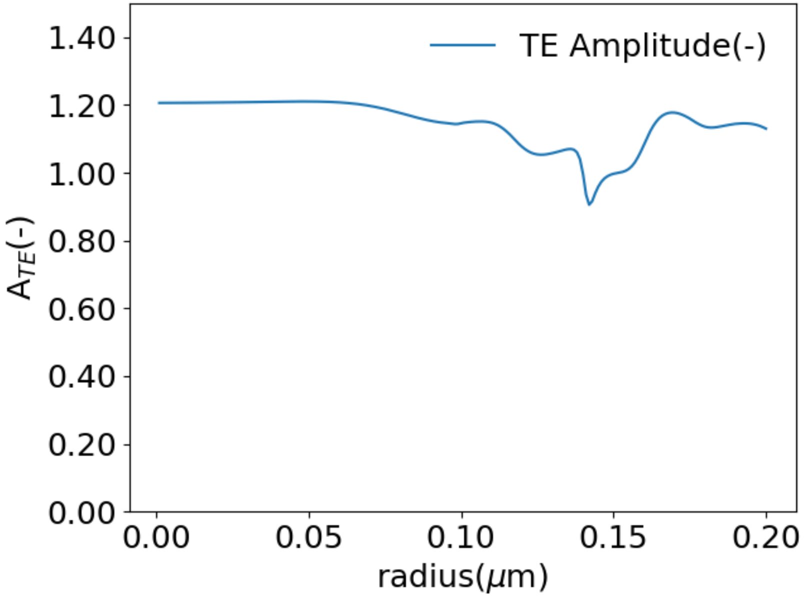


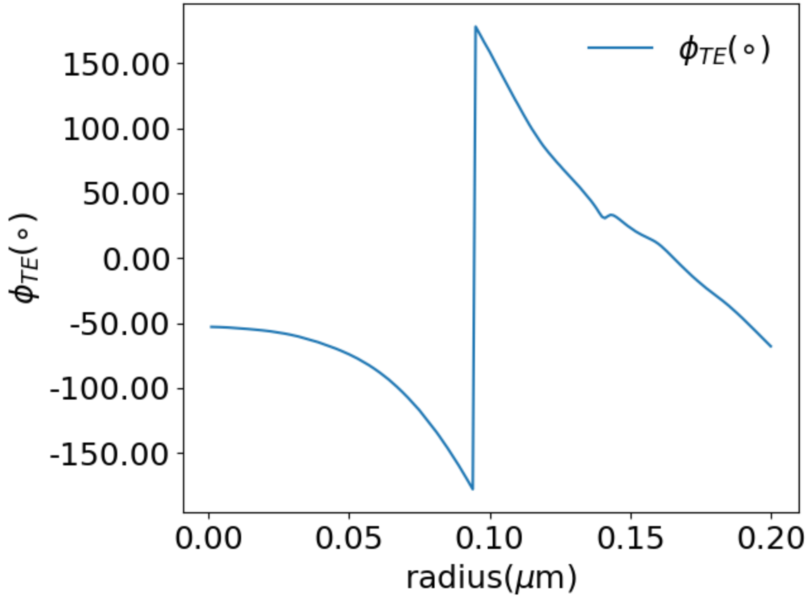


Simple example

- Meta-atom type:
  - Cylindrical pillars on glass
  - Square arrangement
  - Si_3N_4 on SiO_2
- Configurations scanned with full Maxwell solver
  - 8 meta-atoms selected for 0-2π phase coverage
  - P: 400nm
  - H: 600nm







Polarization manipulation

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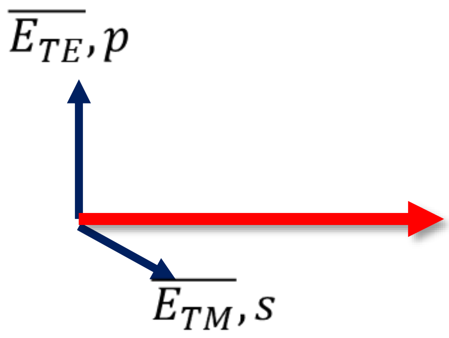
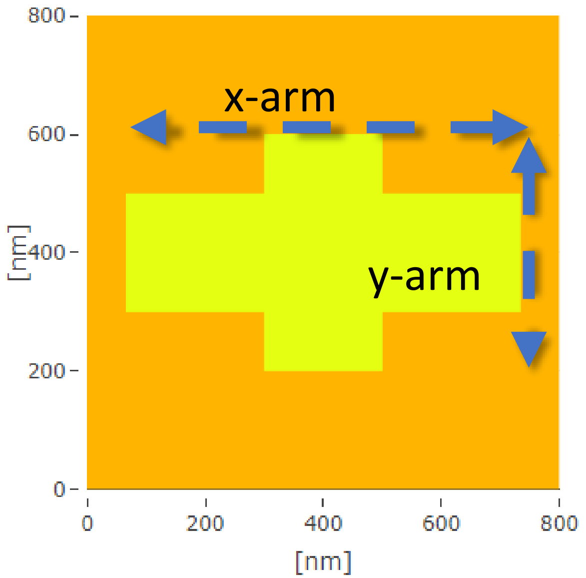
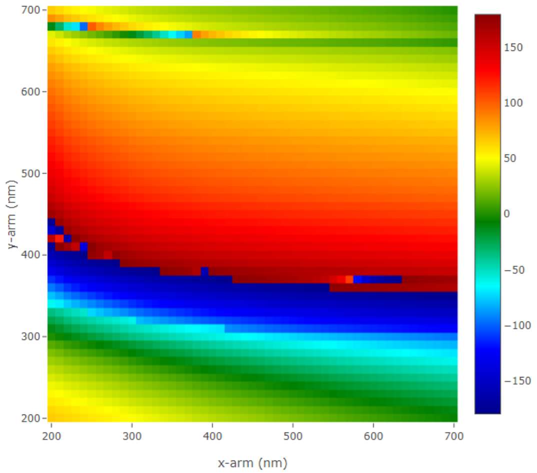
- Symmetry:
  - 90° symmetric: no change for TE/TM
  - Non-symmetric: polarization selectivity
- Structural birefringence
  - Different n_{eff} for x/y polarization
  - Acts as a an optical retarder with in plane c-axis
- Tuning the shape
  - Change Δn
  - Rotation alters phase
- Applications:
  - Polarization functionalization
  - Geometric phase



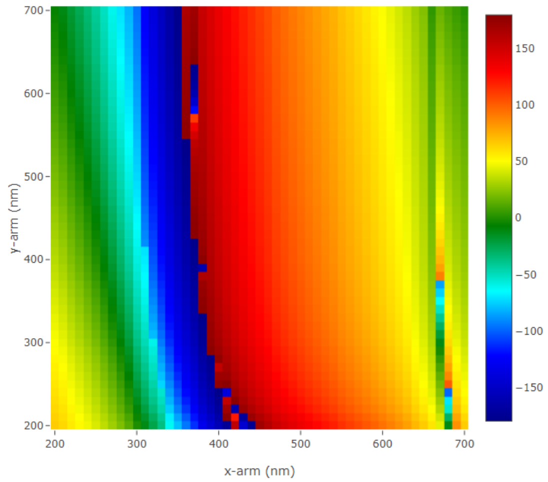


TE phase



TE, controlled by y

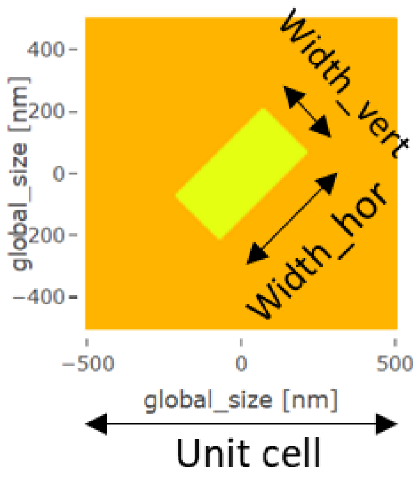
TM phase



TM, controlled by x

Half wave plate

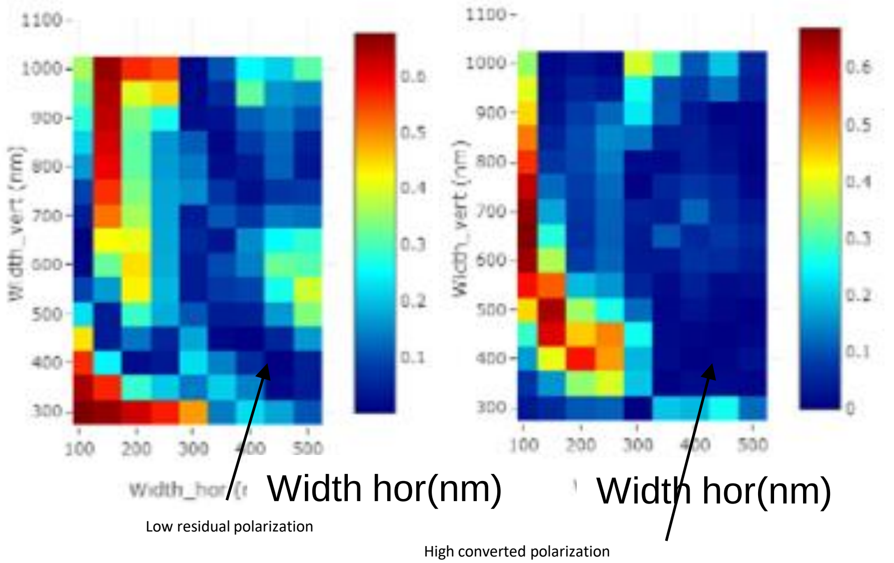
Parametrized meta-atom



- Structural birefringence
  - Extra-ordinary n_{eff}
  - Ordinary n_{eff}
- Parametrized search
  - Height, dimension, unit-cell
  - Maximize cross polarization
  - Minimize residual polarization
- Several good combinations:
  - $\Delta n_{eff}\, h = \frac{\lambda}{2}$
  - Optimize for fabrication and reflectivity

Residual polarization

PolarizationConversion



Layer Stack

index	name	Structure	Thickness	Materials
1	Incident layer	homogeneous	INF	Si
2	Birefringent	rectangle	=Height	Air, Si
3	Exit layer	homogeneous	INF	Air

Parameterized Structures

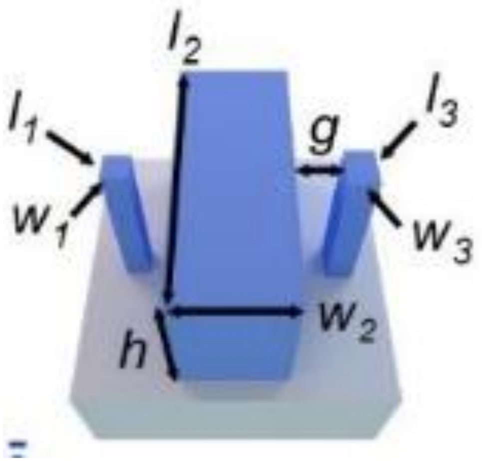
Resolution	x: 100 y: 100
Width	=Width_hor
Length	=Width_vert
Angle	45
Center Coordinate	x: 0 y: 0

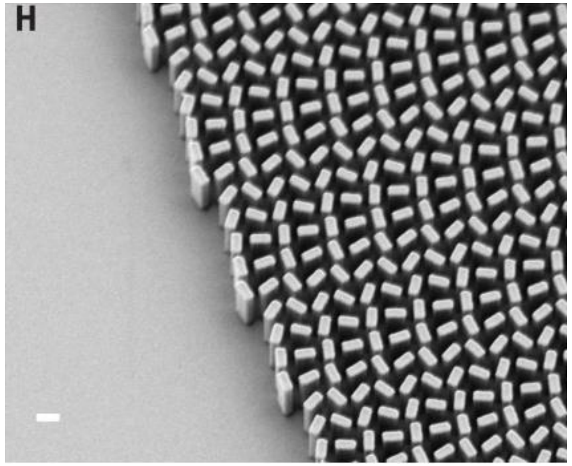
	Height	ordinary width	Extraordinary width	T(Co-pol)	T(Cross-pol)	conversion efficiency
Meta-cell 1	1345	200	400	3.7%	66.7%	94.7%
Meta-cell 1b	1345	210	400	0.4%	65.5%	99.4%
Meta-cell 2	1700	200	400	0.2%	66.5%	99.7%

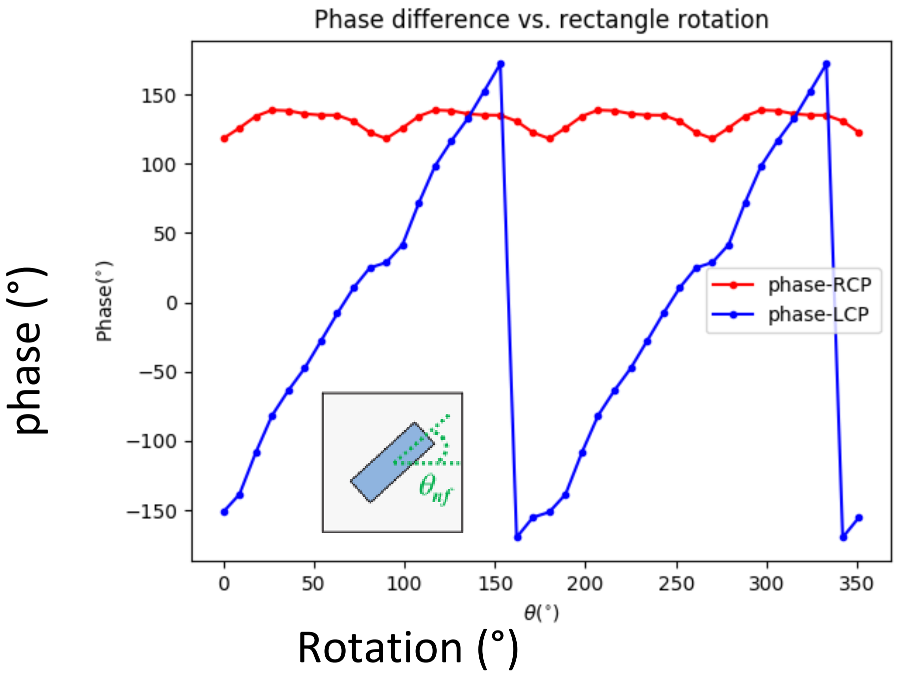
[1] Y. Dong, et al. “Si metasurface half-wave plates demonstrated on a 12-inch CMOS platform” Nanophotonics, vol. 9, no. 1, pp. 149-157, 2019.

Geometric phase

- Geometric phase structures
  - Elegant phase control
  - Not limited to shapes or nano-structures
- Tuning the shape
  - Dispersion corrections
  - Amplitude corrections (conversion efficiency)
- Applications:
  - **Polarization selective but not polarization controlling**
  - $\varphi_{LCP}(x,y) = -\varphi_{RCP}(x,y)$







Library building

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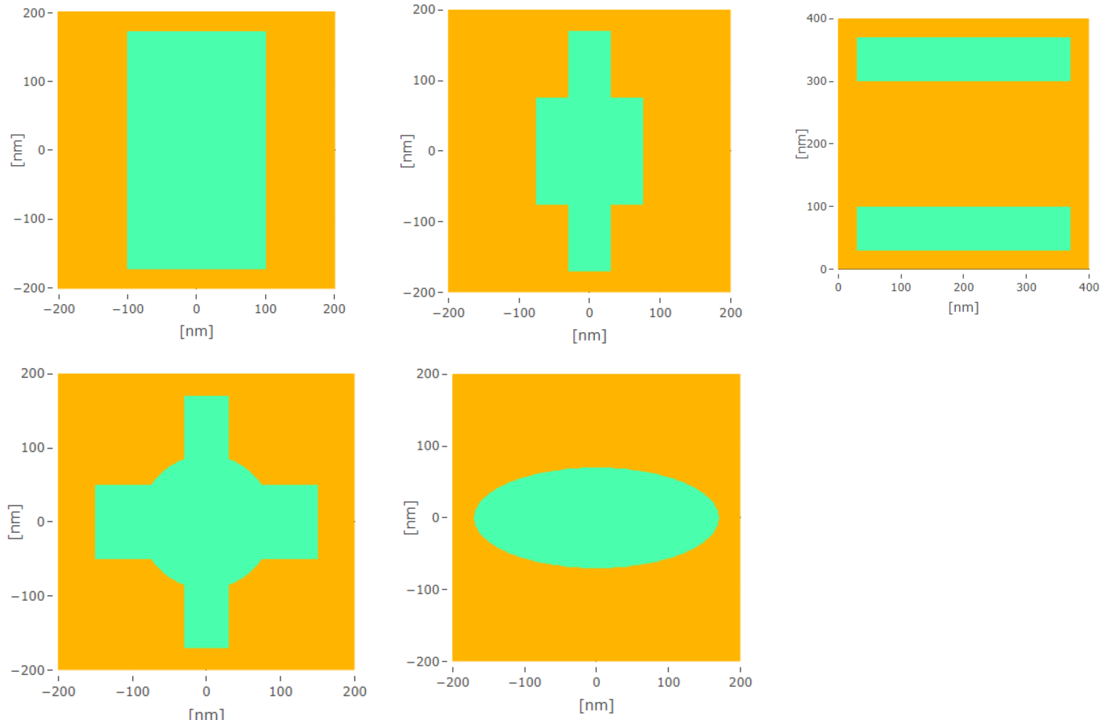
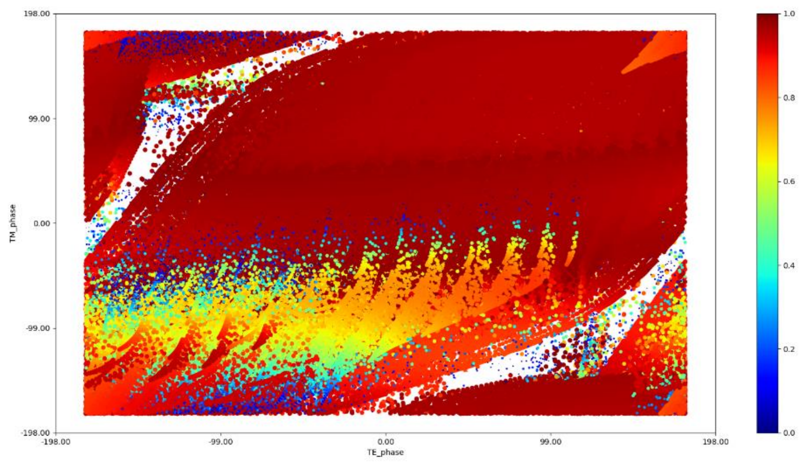
- Example library for polarization multiplexing
- Fast simulation is needed to construct large libraries:
  - Calculation time ~1-2 days
- Polarization effect-> symmetry breaking
- Criteria T, φ , dφ/dλ, …
- 1 dot = 1 structure



58 k structures T(-)

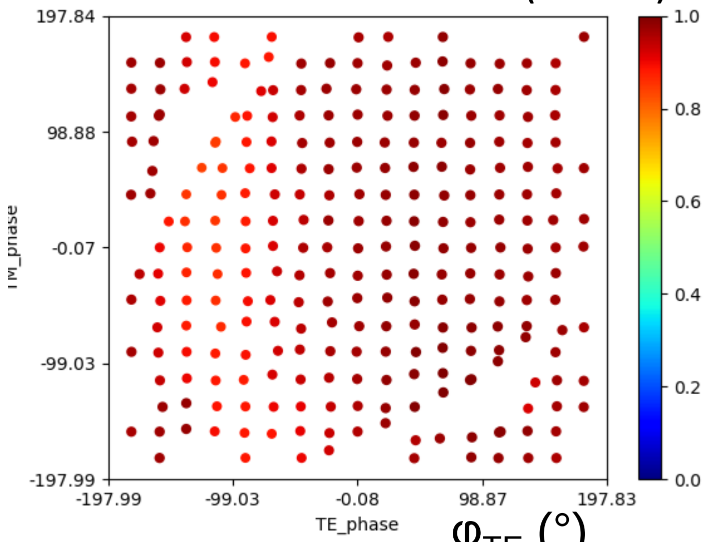
$\varphi_{TM}(°)$



φ_{TE} (°)

Selected structures (16x16) T(-)

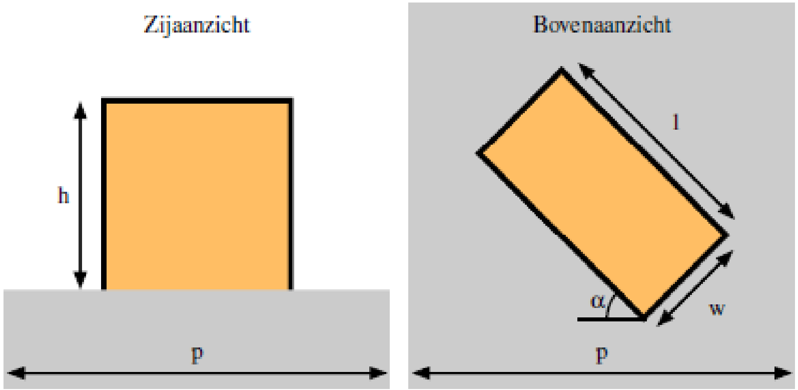
$\varphi_{TM}(°)$

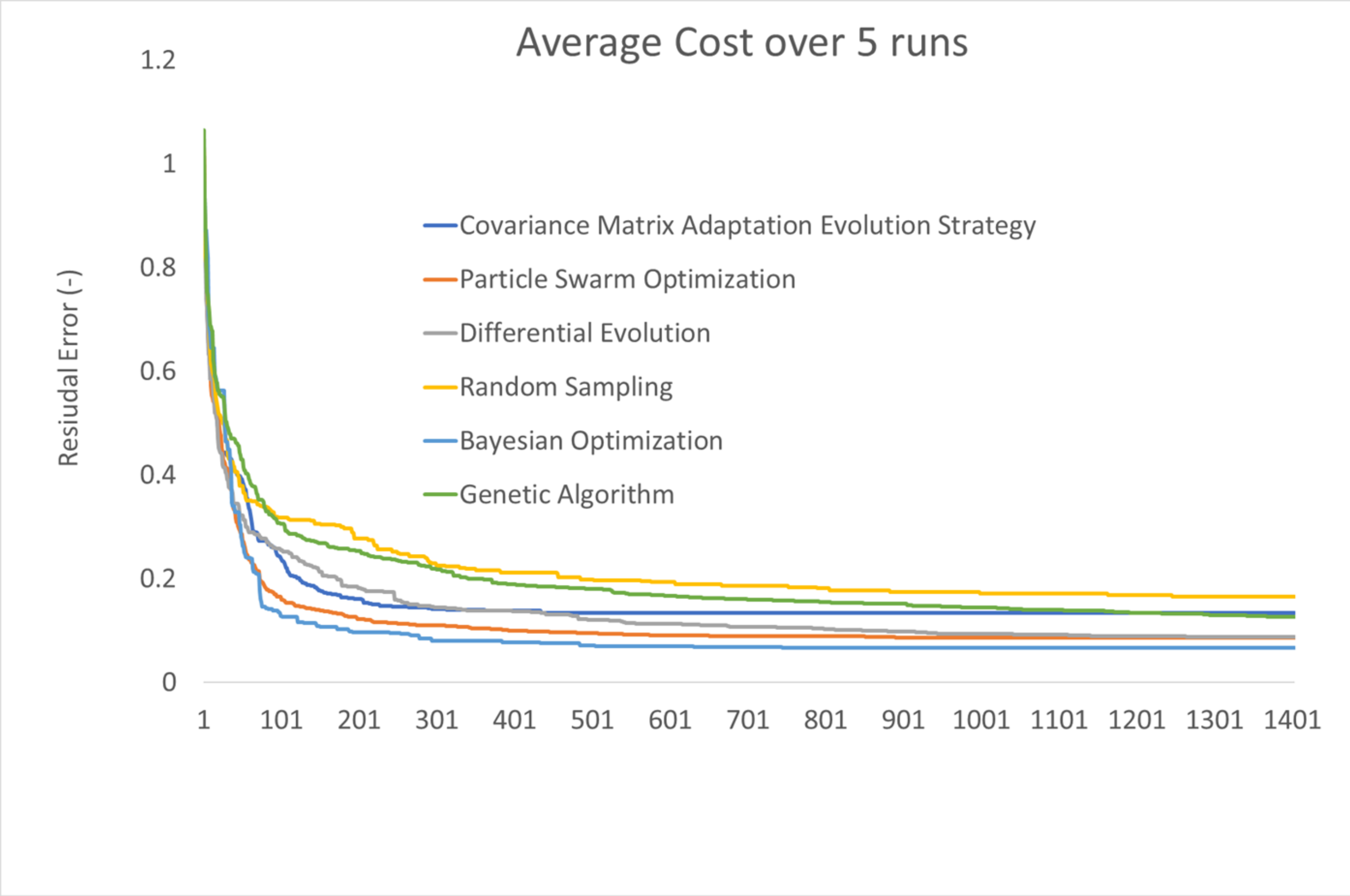


φ_{TE} (°)

Optimization

- Comparison of 5 algorithms
- Benchmark problem (shown):
  - Optimization of 8 elements with 3 parameters: W, L, alpha





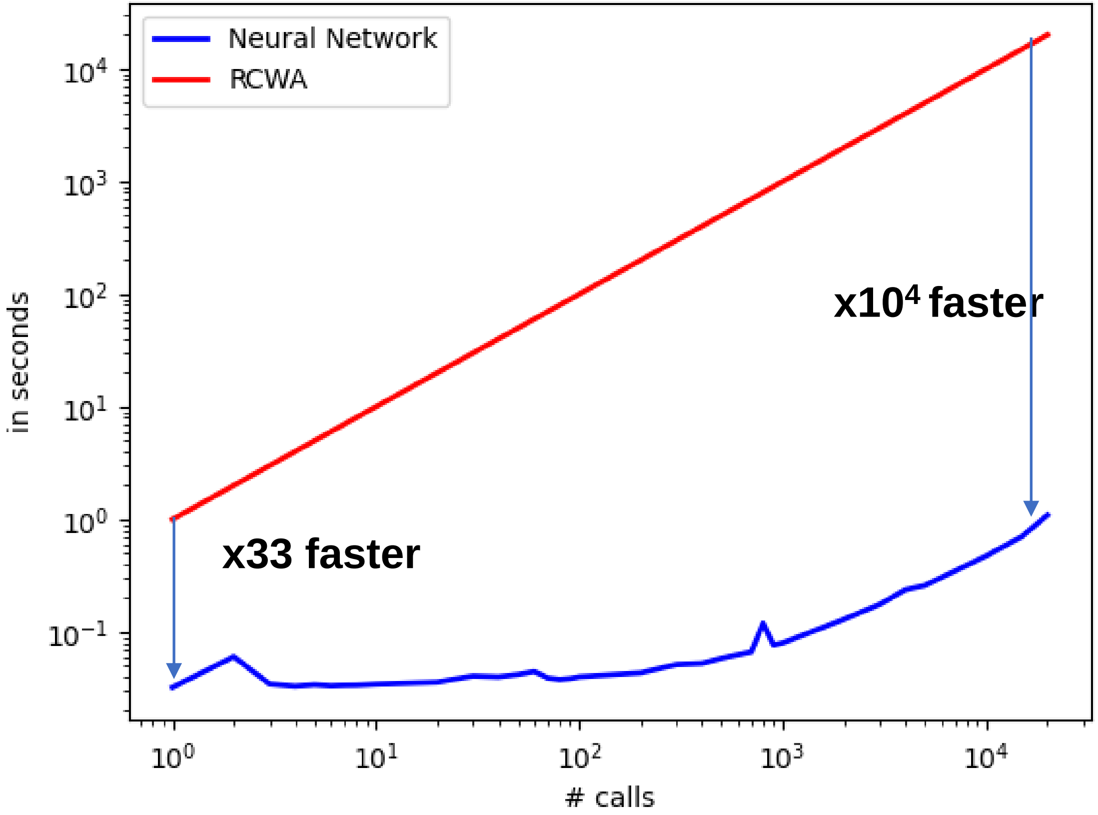
- Best algorithms: lowest error and good convergence time
  - Particle swarm
  - Bayesian optimization

Acceleration options

- **Surrogate solver** and **optimization methods** can **speed up** meta-atom design **up to 500 fold**
- **PSO, Bayesian** and **adjoint** method are **most performant optimization** algorithms
- **Training takes more time** than a **classical design**
- Future work:
  - Wide applicapility
  - Larger area

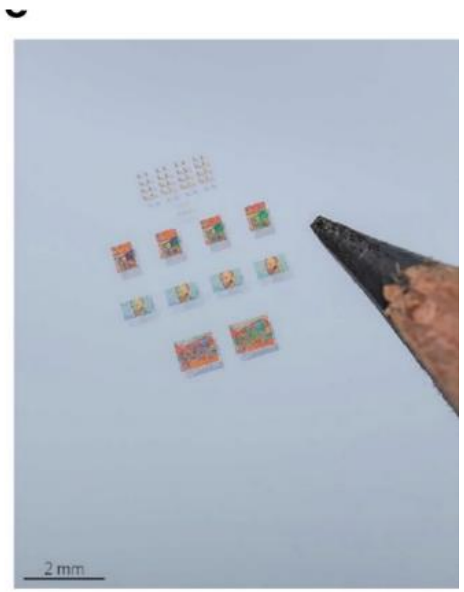
	Total calculation time	Acceleration factor
Brute force sweep	**19.55hr**	1 (baseline)
Inverse design	8.9hrs	2
Neural network	0.53hrs	37
Genetic Algorithm + Neural netowrk	**0,04hrs (3mins)**	**488**

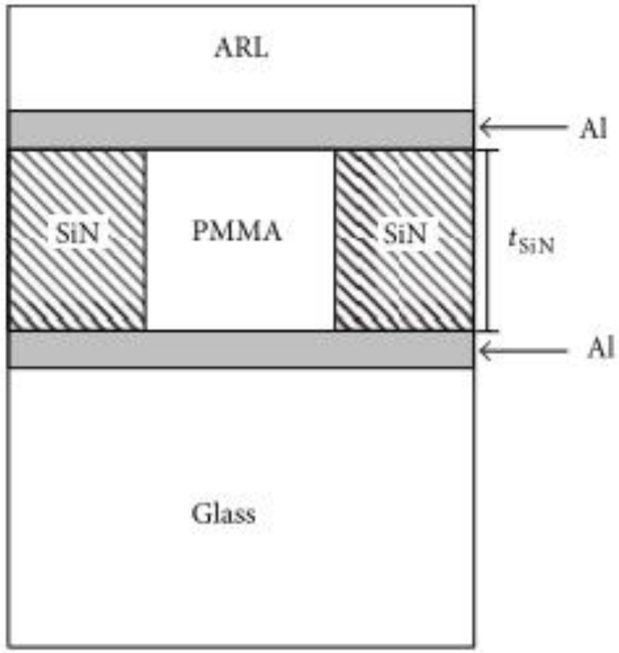
Time benchmark

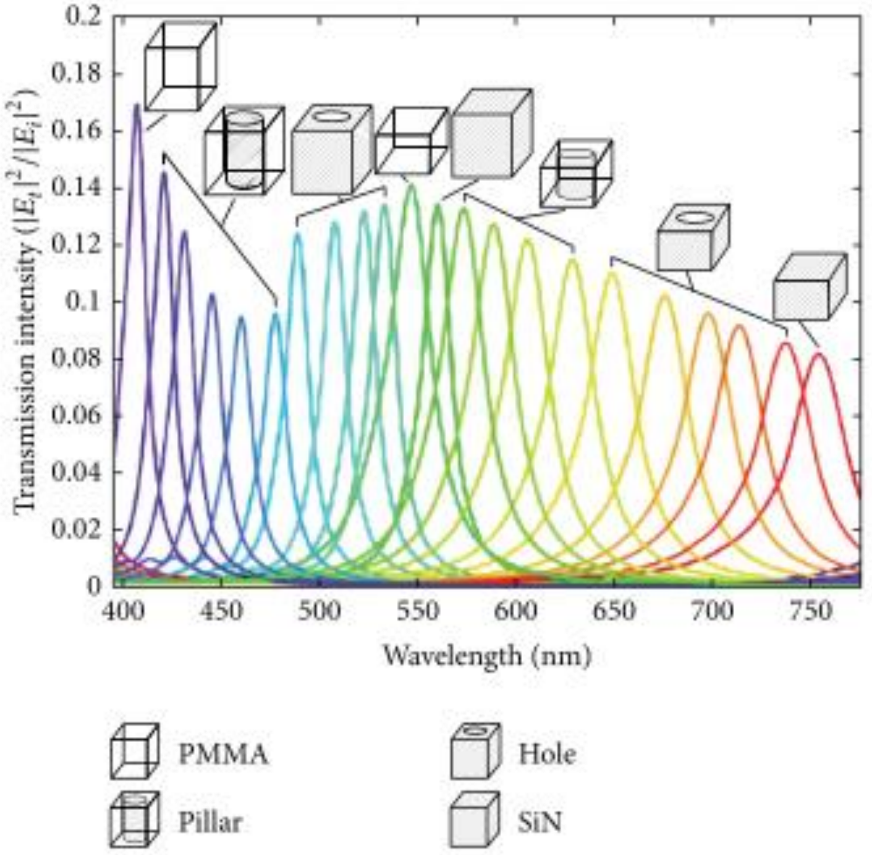


Structural colour

- Tuning effective path length
- Reflective & transmissive configurations
- Conventional thin film filters limited by materials





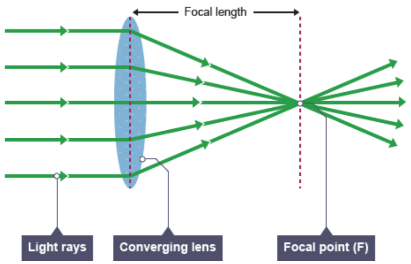


Outline

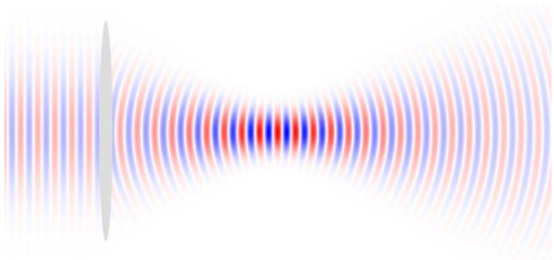
- Basics of meta-surface design
- Meta-atoms = full wave
- Meta-surfaces= propagation
- Meta-systems = ray tracing

Principles of meta-surfaces

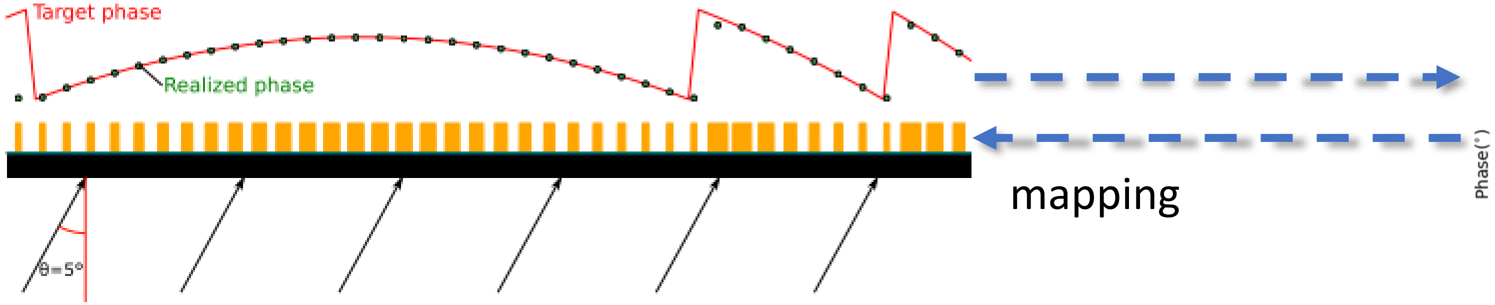
Ray picture

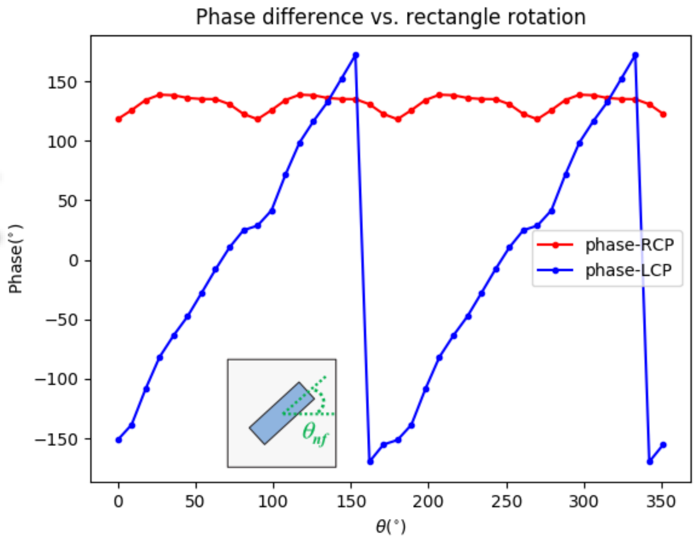


Wave picture



- ❖ 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

Pitch requirments

- Why sub-wavelength?
- Suppress diffraction:

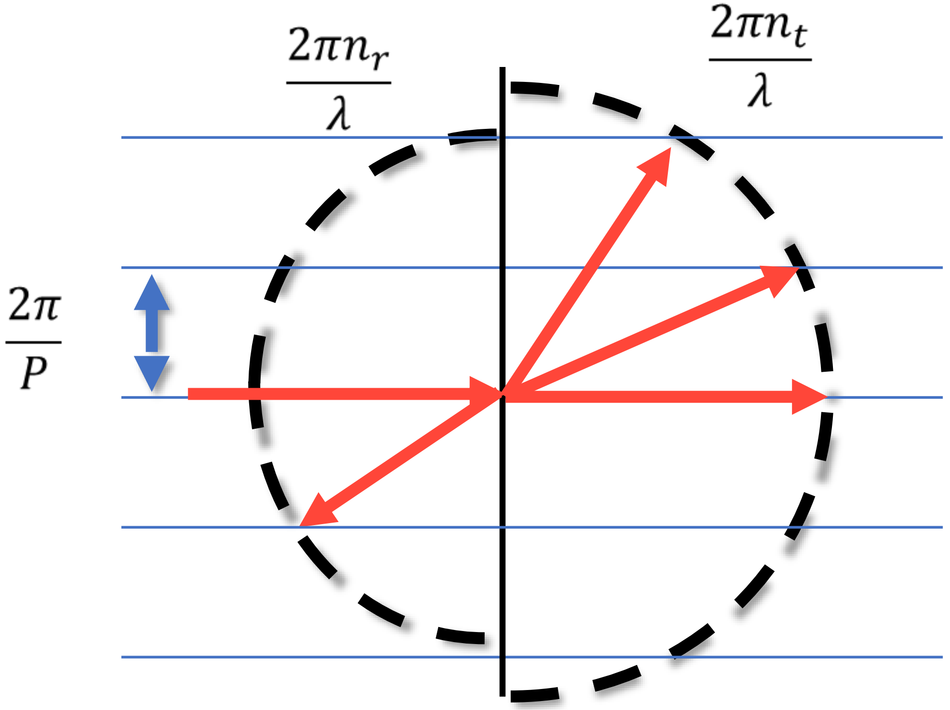
$$\frac{2\pi n_t}{\lambda} < \frac{-2\pi\, n_r \sin(\theta_{in})}{\lambda} + 1\,\frac{2\pi}{P}$$

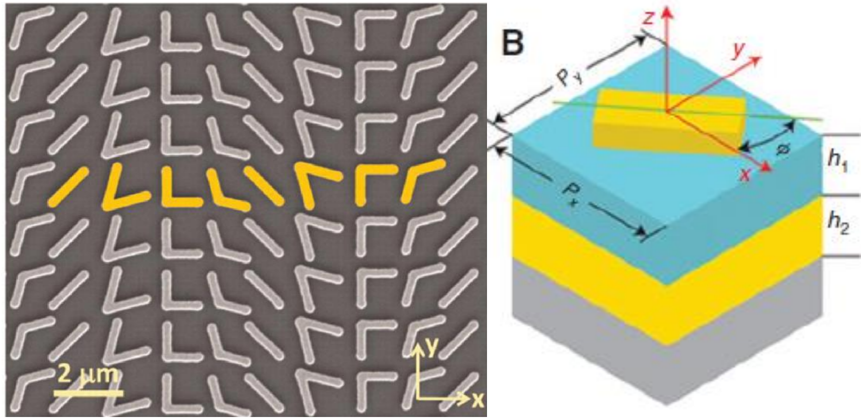
- P < λ/n only 0-order diffraction possible

$$P < \frac{\lambda}{n_{r/t} + n_r \sin(\theta_{in})}$$

- Normal incidence into air:

$$P < \frac{\lambda}{n_r}$$





Sampling

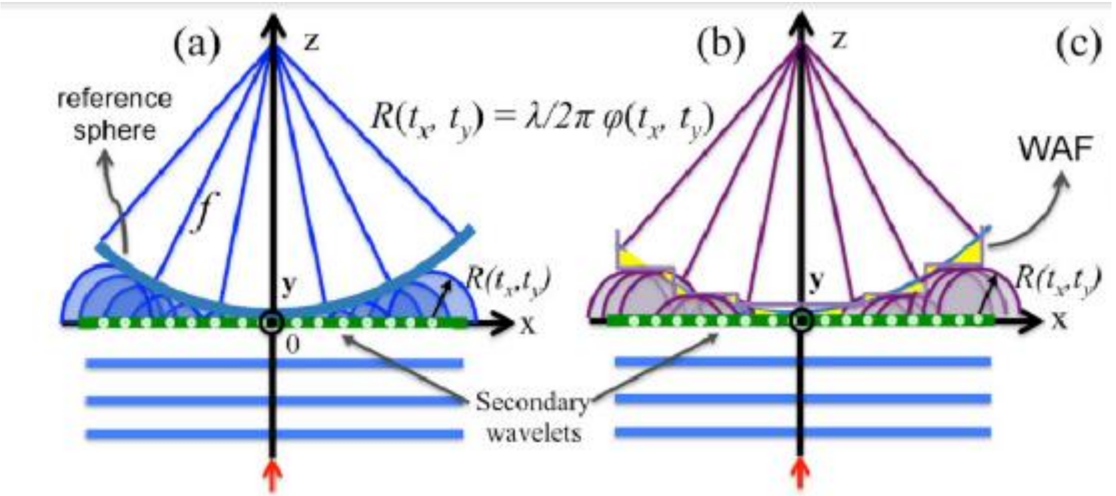
Spatial sampling

- Nyquist theorem: 2 samples per period
- $\frac{2\pi}{P} > 2\frac{\delta\varphi}{\delta x}$ $\Rightarrow$ $P < \frac{\lambda}{2n\frac{\delta f}{\delta x}}$ Normalized gradient
- Implications:
  - Focal distance: short is more difficult
  - Beam steering: large deflection angle is more difficult

Phase sampling

- In reality phase is continuous
- In a metasurface we sample the phase
- Wavefront aberration function

  $WAF_{RMS} < \lambda/14$



1) US 2018 / 0246262 A1, low – contrast Silicon Nitride based metasurfaces

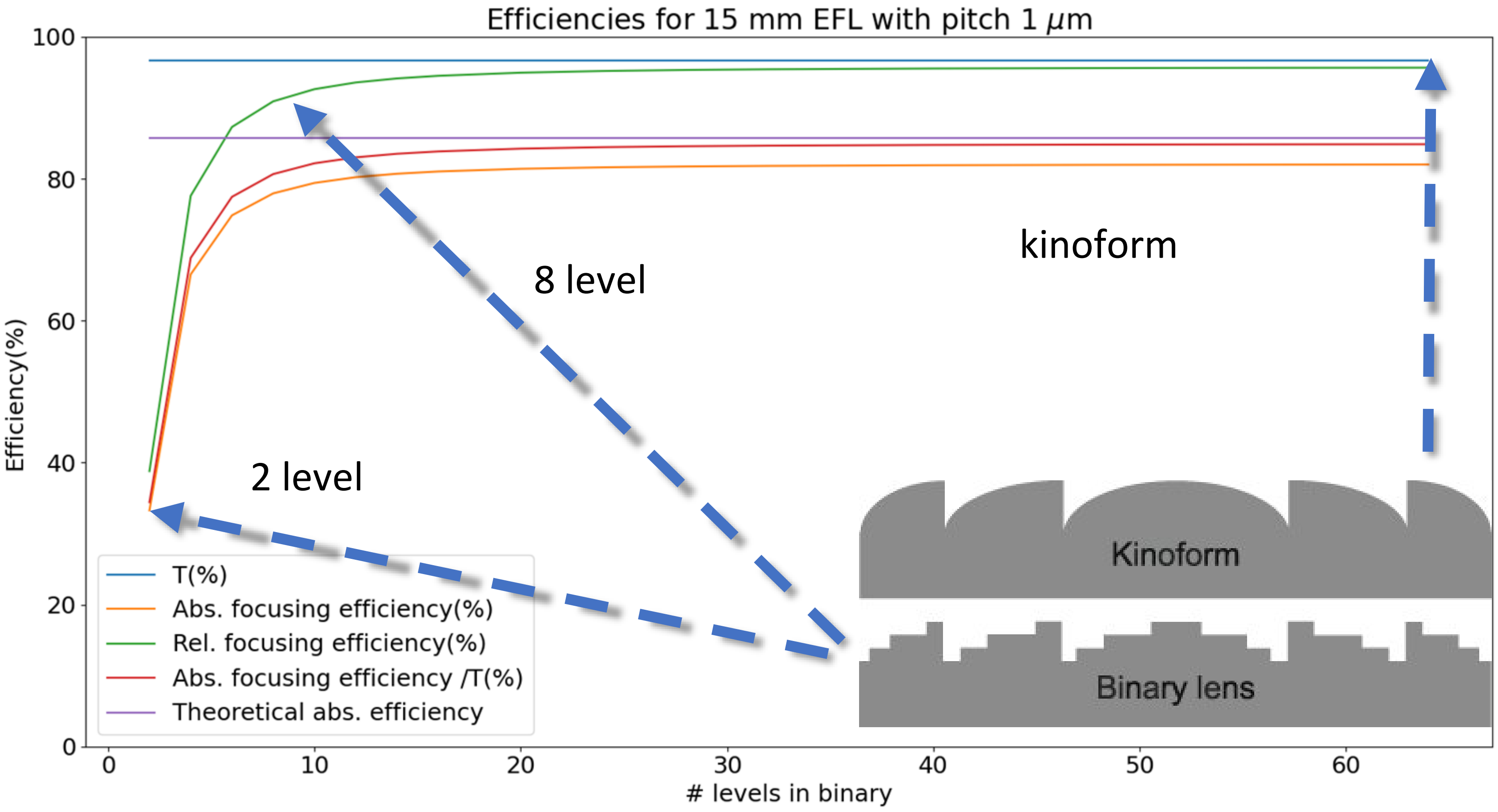
2) F. Aieta, et. al, “Aberrations of flat lenses and aplanatic metasurfaces,” *Opt. Express*, vol. 21, no. 25, p. 31530, 2013.

3) Huang, K. *et al.* Planar Diffractive Lenses: Fundamentals, Functionalities, and Applications. *Adv. Mater.* **30,** 1–22 (2018).

Practical effect

- Equal wavefront, changed phase sampling
- Diffraction limited lens for 1064nm

  NA= 0.164
- Better sampling = higher efficiency
- Saturation from 16 levels

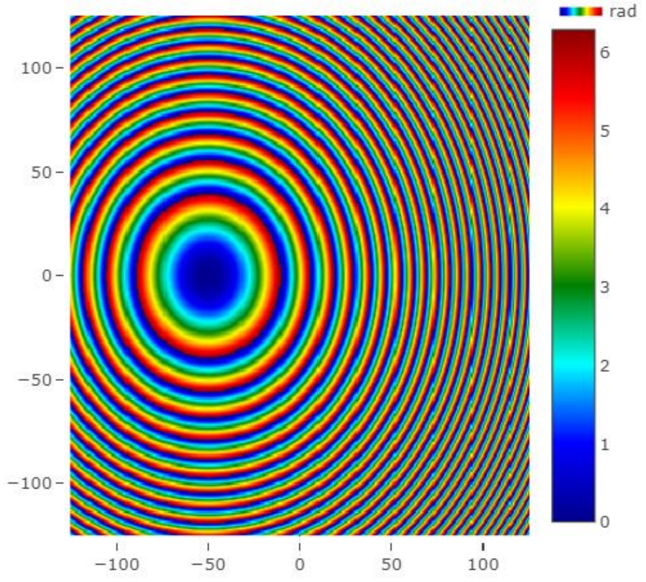


Focusing polarizing beamsplitter

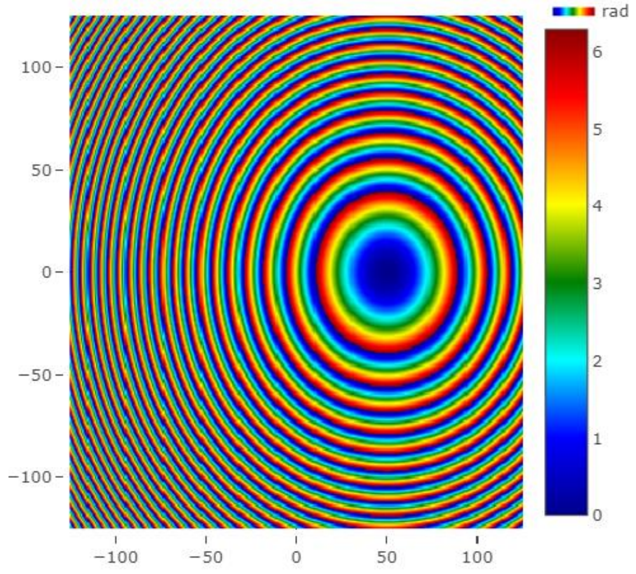
- Analytical phase profile: aplanatic/diffraction limited lens
- Independent targets
  - TE: focal distance 500µmand **shifted left 50µm**
  - TM: focal distance 500µm and **shifted right 50µm**

$$\varphi_{TE} = \frac{2\pi}{\lambda}\left(-f + \sqrt{f^2 + y^2 + (\boldsymbol{x} \boldsymbol{+} \mathbf{50})^2}\right)$$
$$\varphi_{TM} = \frac{2\pi}{\lambda}\left(-f + \sqrt{f^2 + y^2 + (\boldsymbol{x} \boldsymbol{-} \mathbf{50})^2}\right)$$

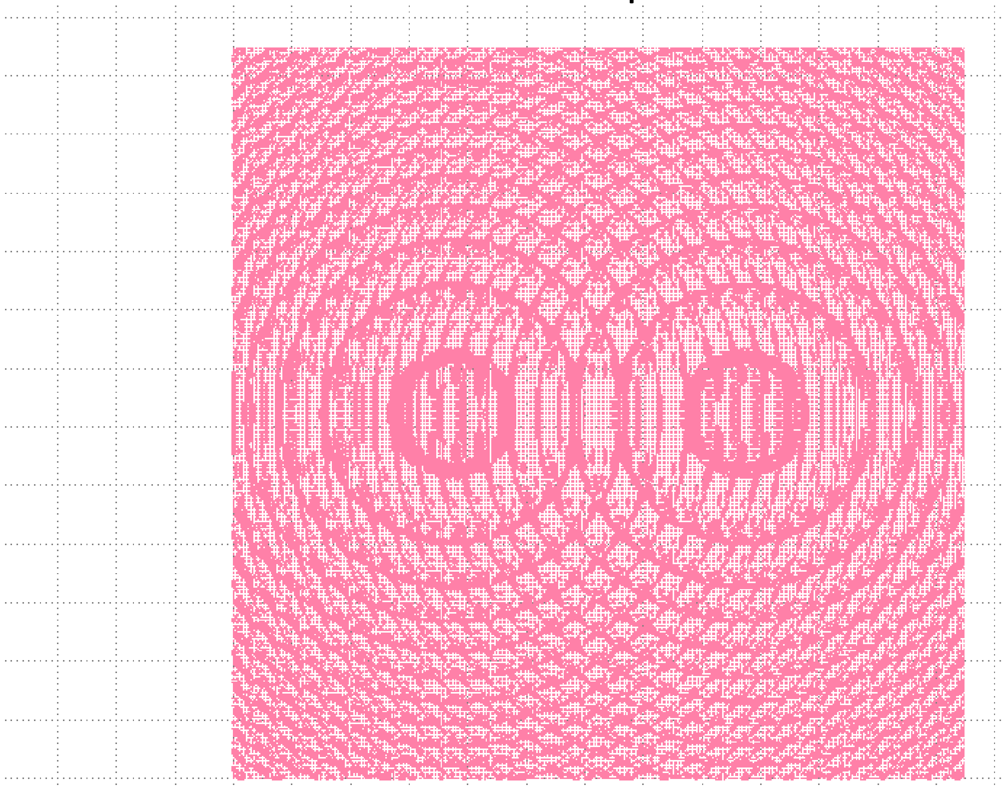
TE target



TM target



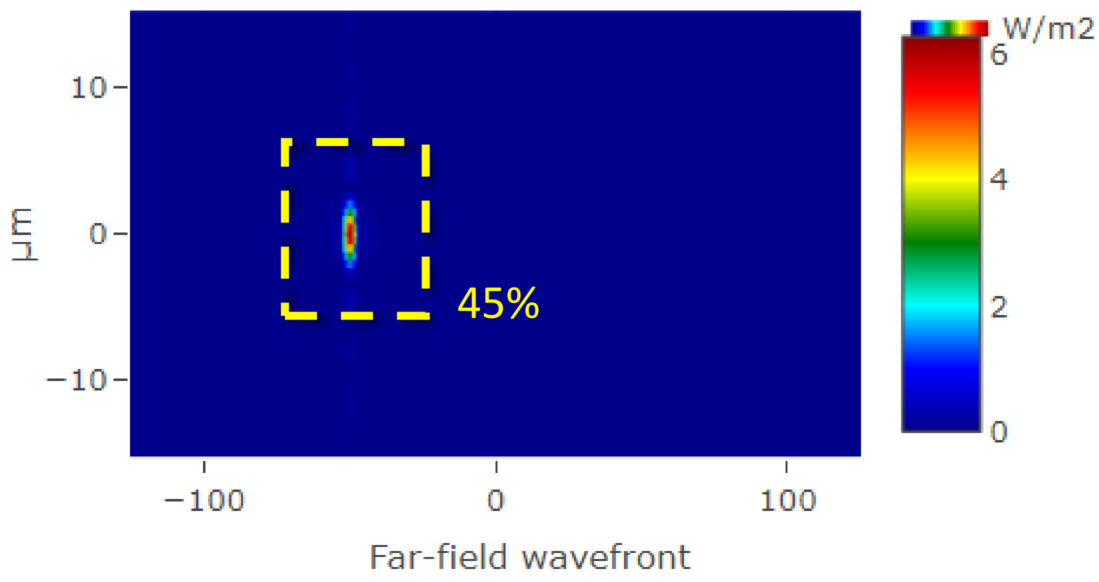
GDS output



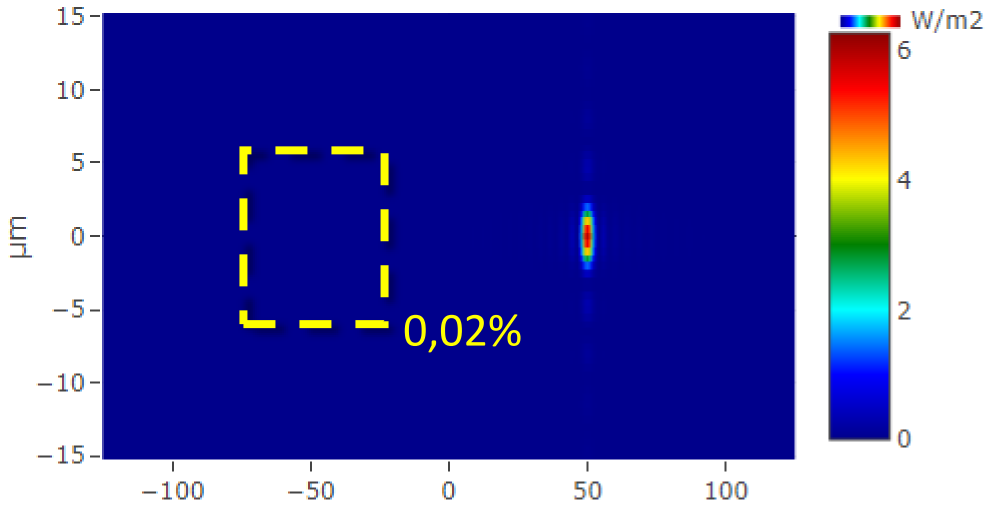
Focusing polarizing beamsplitter

- Simulated Intensity profile **at f** (500µm)
- **TE and TM** polarization **separately focused**
- Transmission efficiency: 89.2%
- Spot efficiency: 65.1%
- Ratio TE/TM 2250:1 in focal point
  - Commercial polarizing beamsplitter cube >1000:1

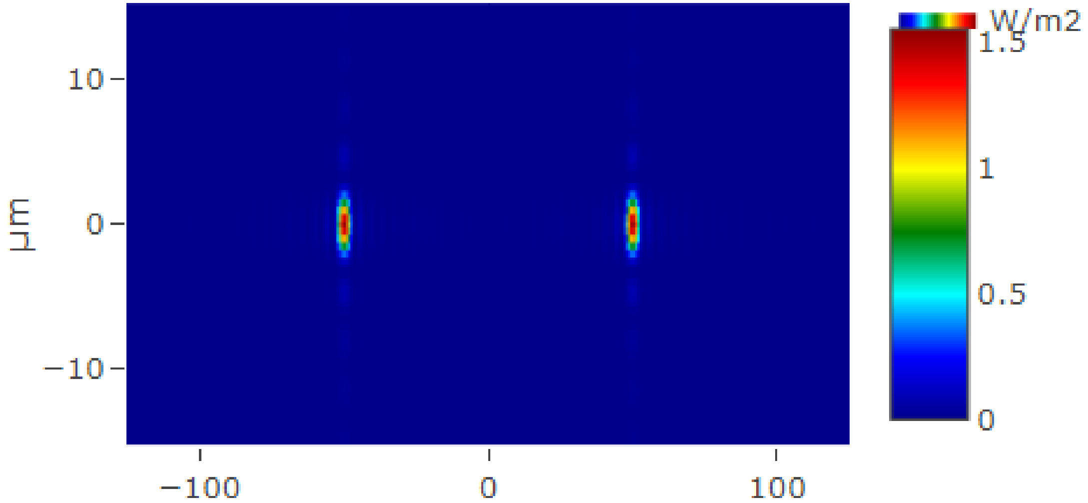
TE incidence



TM incidence



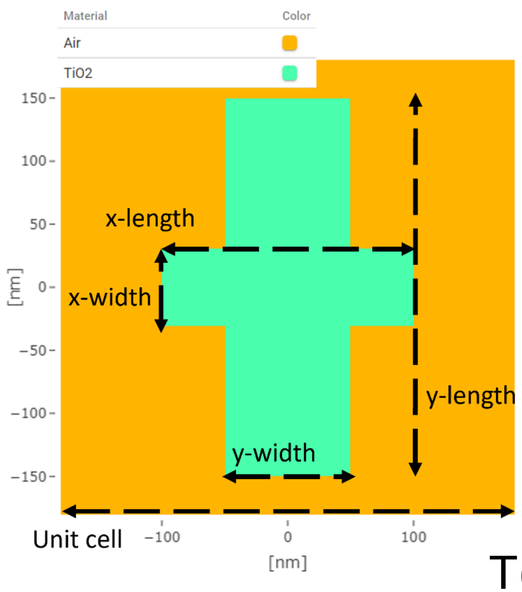
Circular Polarization (R) incidence



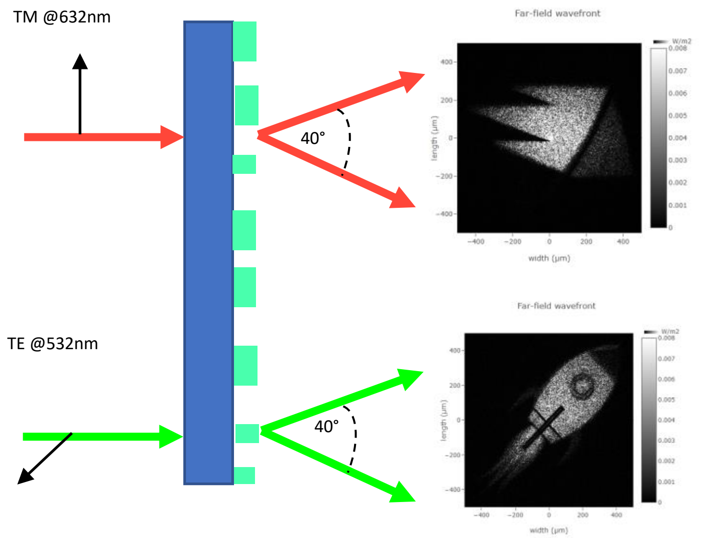
Multi-wavelength hologram

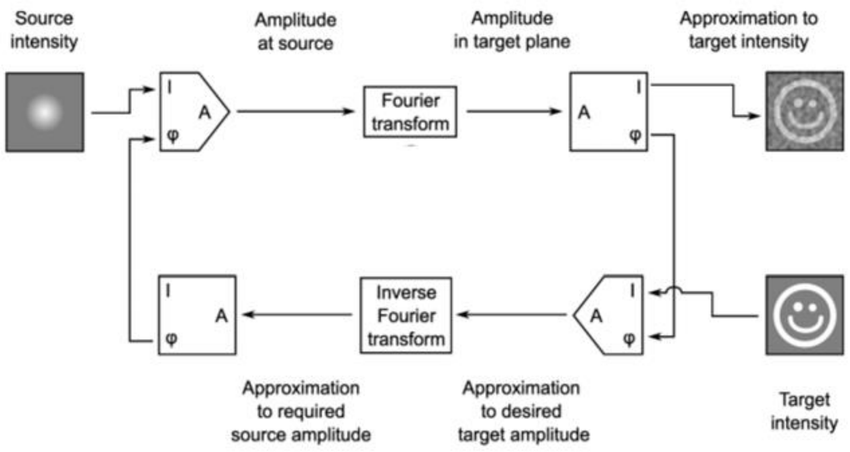
- Phase only hologram calculated using IFTA
  - Separate optimization for 632 and 532 nm
- Joint reproduction of phase profiles
  - Independent control of 532 and 632nm phase via polarization decoupling
  - Alternative: higher order tuning of d * n_{eff}
  - 64k structures
- Straight forward design of multi-functional metasurfaces

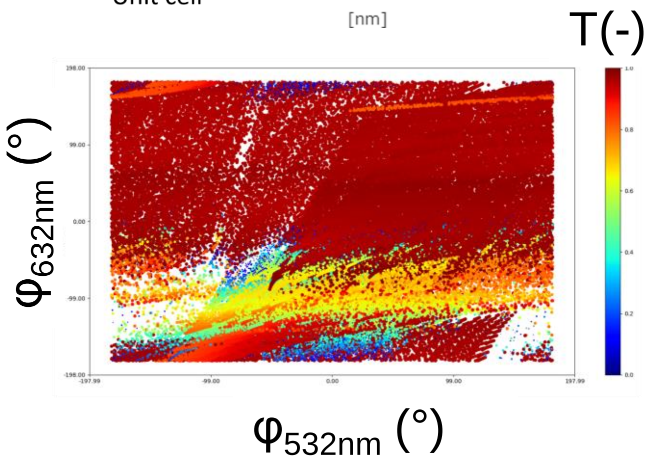
Parametrized meta-atom



Simulated projection







Nano-structure library

Dispersion engineering

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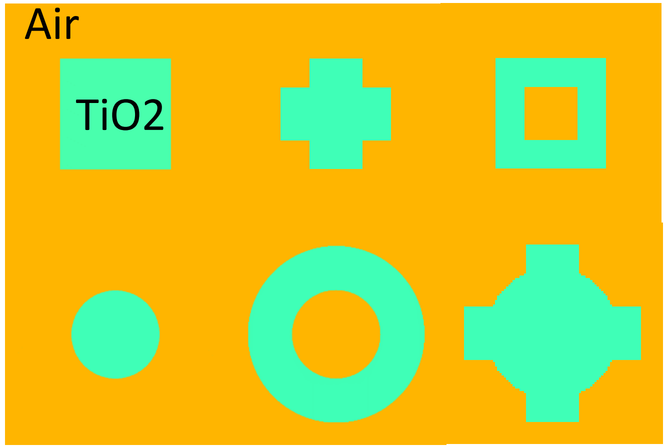
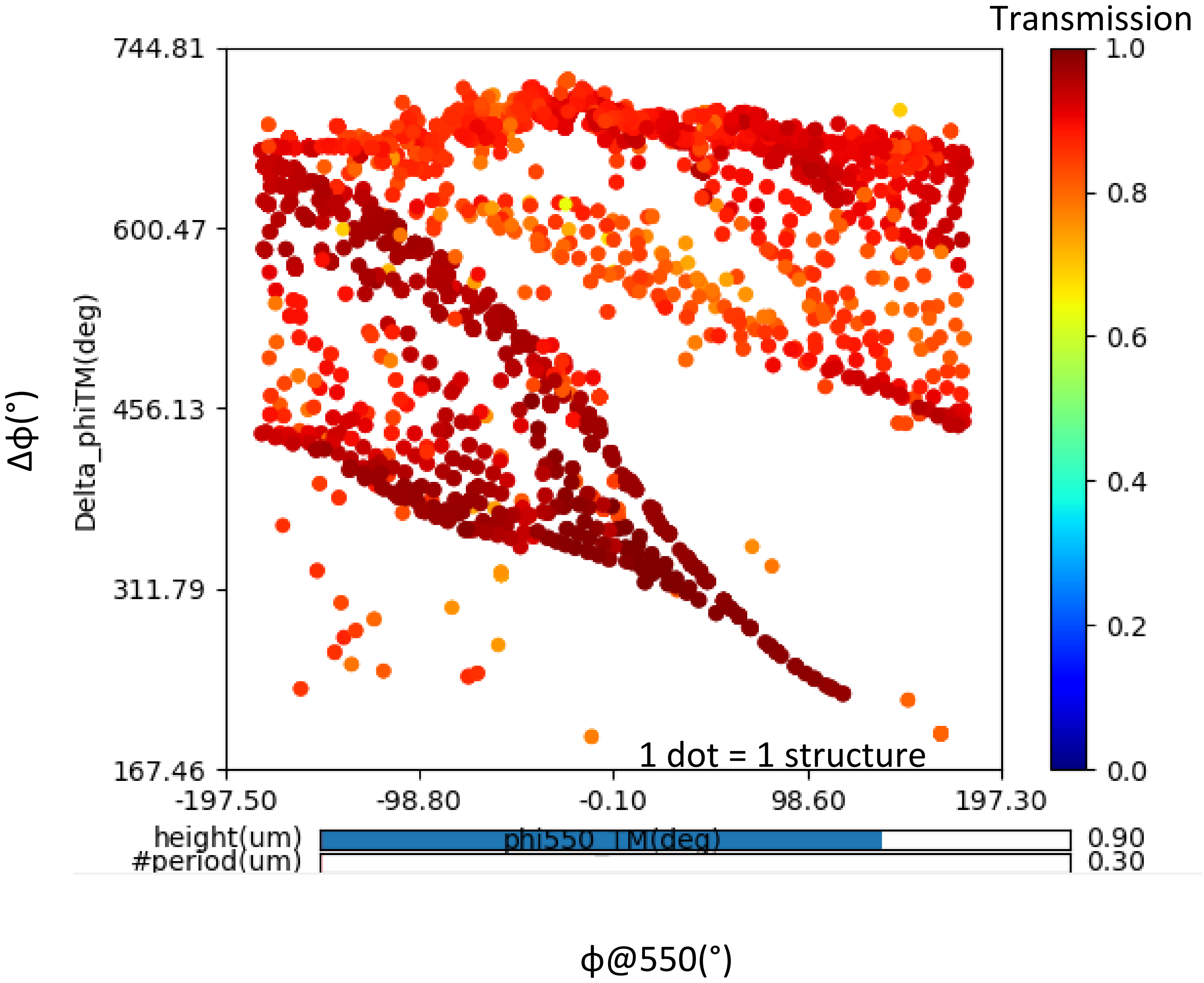
- From **discrete wavelengths to** broader **bands**
- Mapping:
  - phase Φ
  - phase dispersion ΔΦ over spectral band
  - Transmission in band
- Structures in library





Dispersion engineering

- Phase is determined up to a constant

$$\varphi(\lambda) = \frac{2\pi}{\lambda} * \sin(\theta) * x + C(\lambda)$$

$$\varphi(\lambda) = \varphi_{lens}(\lambda, x) + C(\lambda)$$

Functional requirement

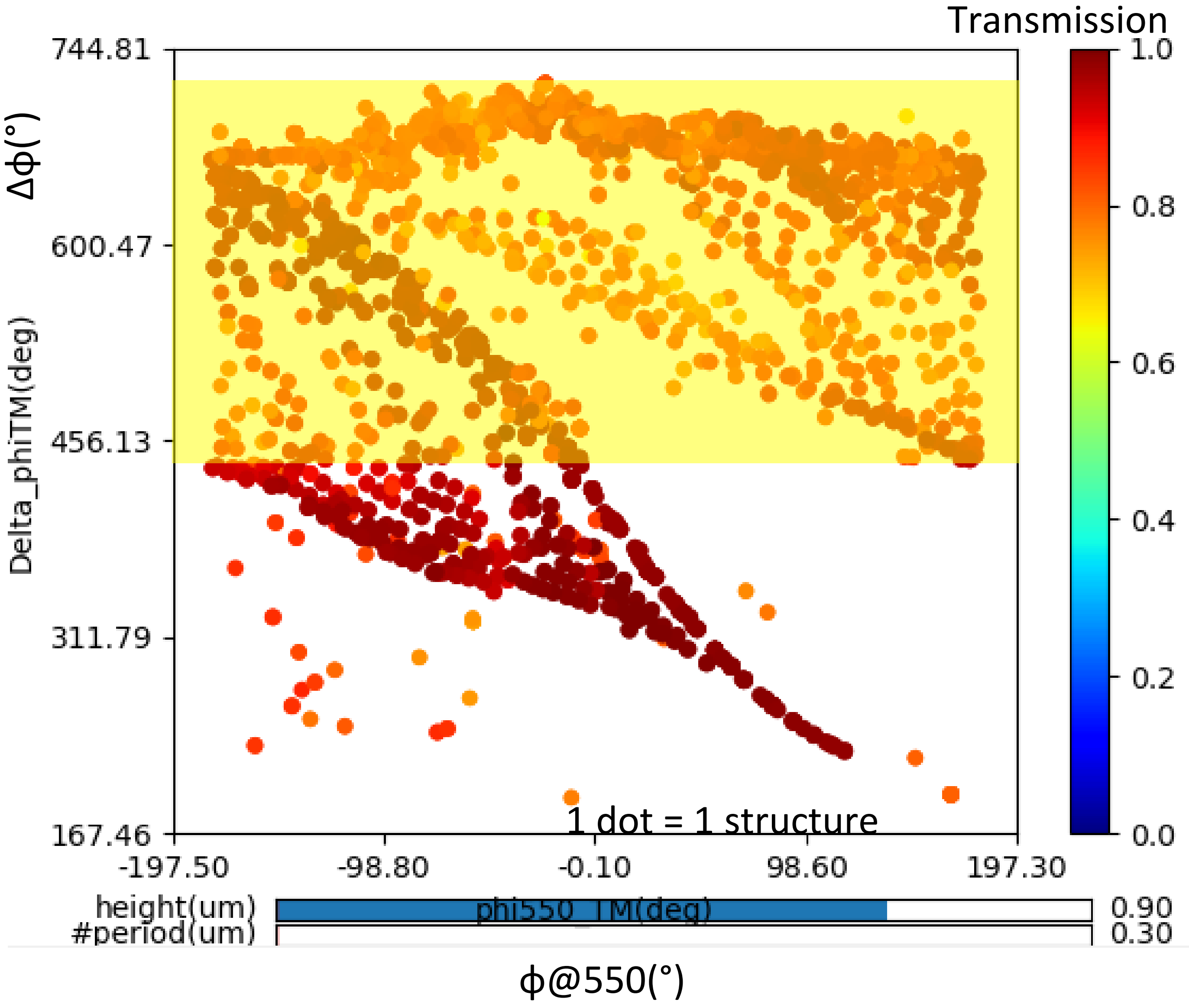
Design freedom

$$\Delta\phi(x) = \varphi_{lens}(\lambda_2, x) - \varphi_{lens}(\lambda_1, x) + C(\lambda_2) - C(\lambda_1)$$

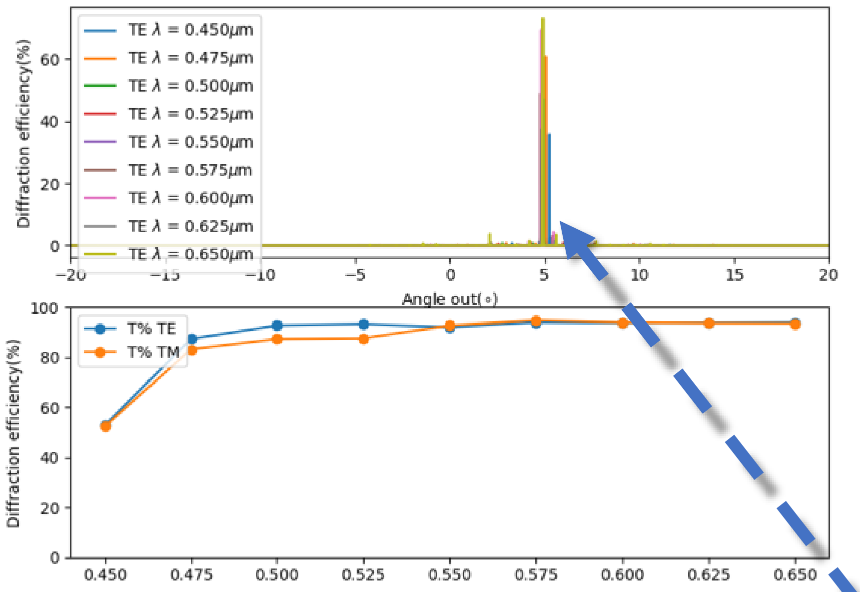
- **Functionality** determines **ΔΦ needed**
- Choice of **material and fabrication limits ΔΦ possible**

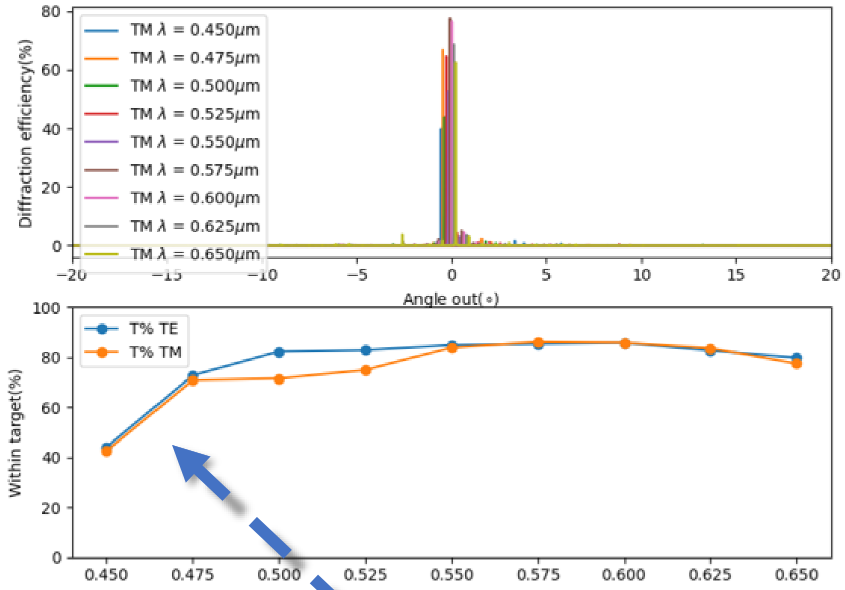
$$\Delta\phi = 2\pi h \left(\frac{n_{max} - n_{min}}{\lambda_c}\right)$$

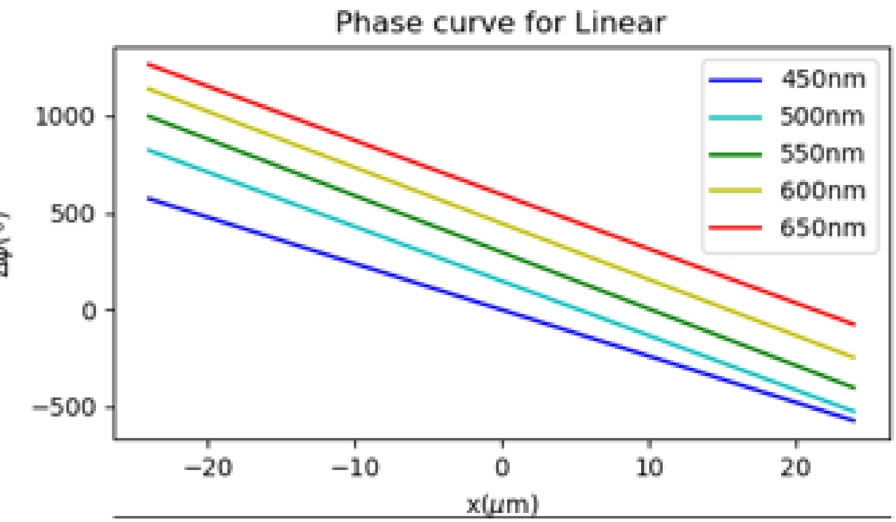
- **Component optimization needs to account for nano-structure possibilities and limitations**



Example: achromatized grating







Narrow angle, wide spectrum diffraction

Diffraction loss

- Dispersion engineered blazed grating:
- Spectral range 500 - 650nm
- Angle spread : 0,4° (4,8-5,2°)
  - Classical grating: 1,3° (4,35°-5,65°)

Outline

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- Basics of meta-surface design
- Meta-atoms = full wave
- Meta-surfaces= propagation
- Meta-systems = ray tracing

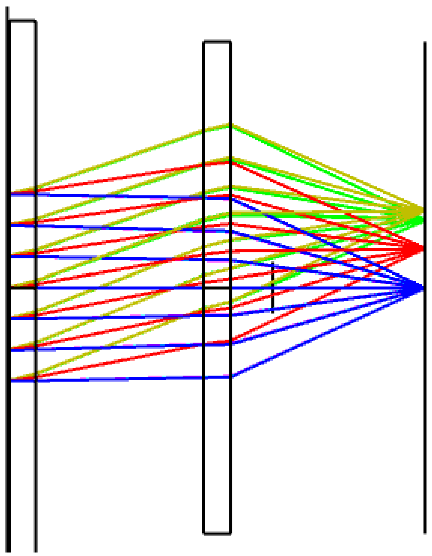
Ray tracing

- Analytical calculation only possible in simple systems
- Realistic situations:
  - Multiple specifications
  - Multiple components
- **Optimize** wavefront **in ray tracing**
  - Parametrized wavefront description
  - E.g. polynomial series

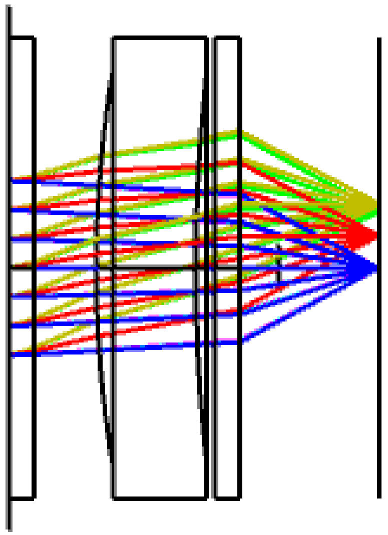
$$\Phi = M \sum_{i=1}^{N} A_i \rho^{2i}$$

- Advantages:
  - **Co-optimization** of multiple metasurfaces
  - Hybrid systems can be designed
  - Investigate complex performance trade-offs
- Disadvantage:
  - Idealized wavefront

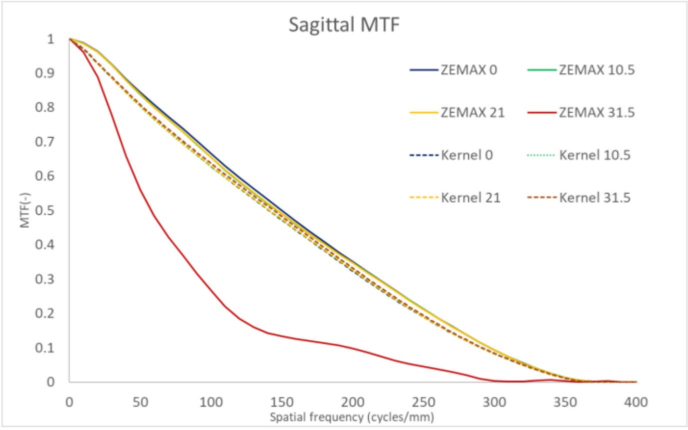
2 meta-surface system



Hybrid meta-surface + refractivesystem



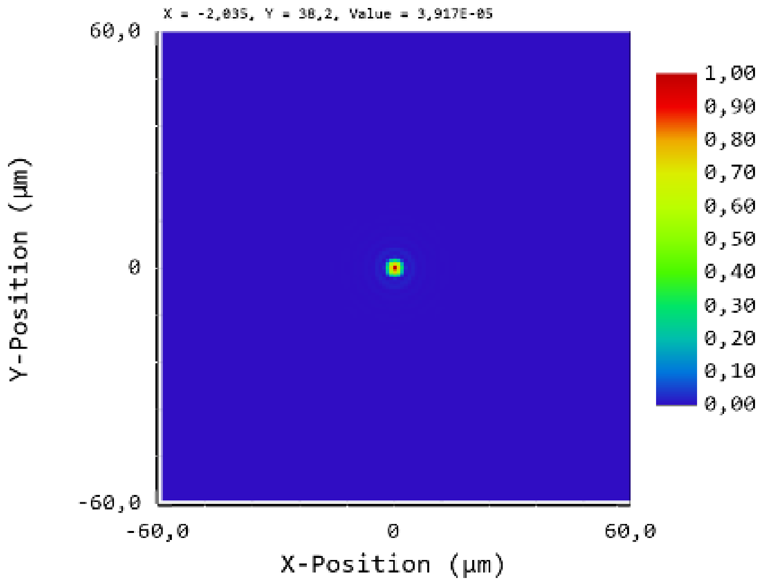
System MTF vs. field angle



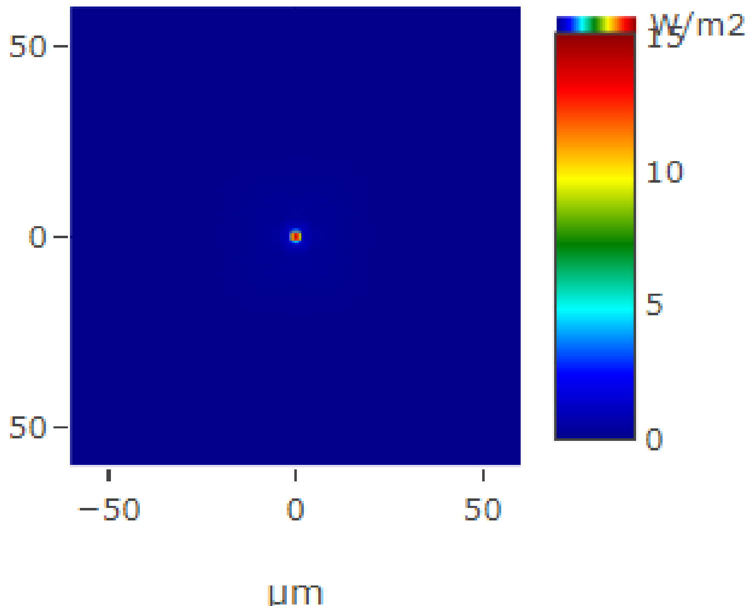
From wavefront to meta-surface

- Wavefront optimized in ray-tracing
- Reproduce as meta-surface
- Example for Si pillars @940nm
  - Nanostructure Transmission efficiency 76% (NFWF efficiency)
  - Focusing Efficiency 57% (FFWF Efficiency)

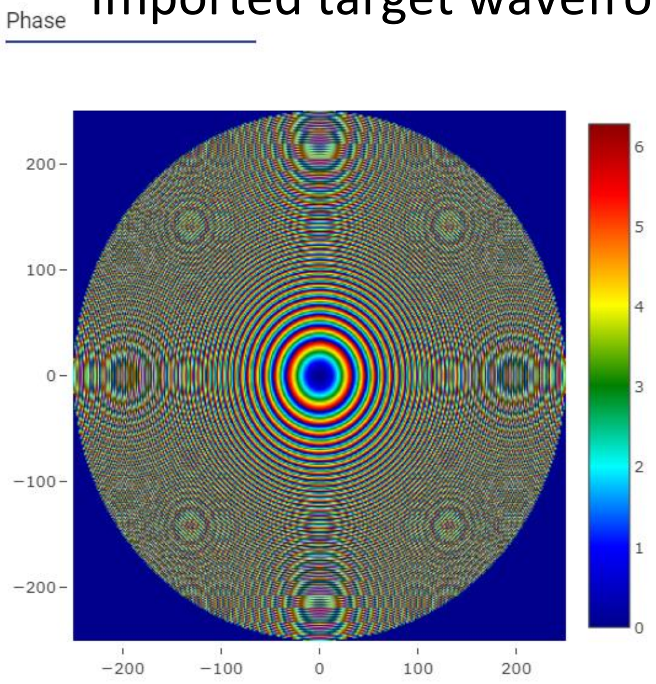
Ray tracing



Meta-component simulation

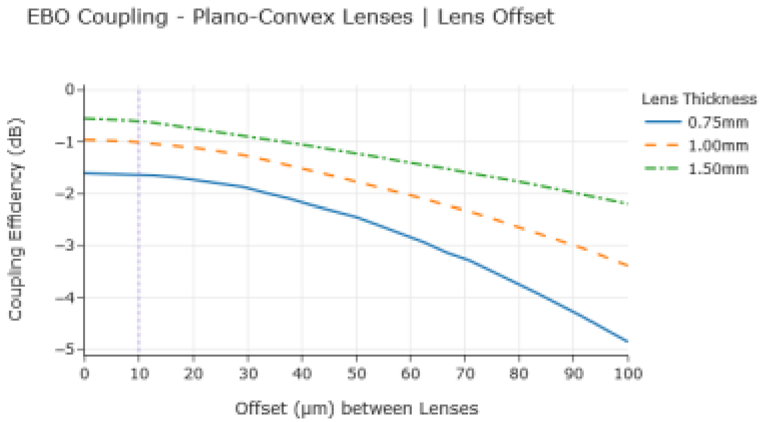


Imported target wavefront



Design example

- Example fiber to fiber coupling
  - Multimode fiber 50µm
  - NA : 0,4
  - Spectrum: 1530 – 1625nm (C+L band)
- Goal of example:
  - Design a metalens fiber coupler
  - Minimize coupling loss over spectrum using dispersion engineering
  - Minimize system volume



Data from (NA 0,2 , wl 850nm): https://www.ieee802.org/3/OMEGA/public/12_may_2020/plinio_OMEGA_01_120520_EBOandBCFeasibility.pdf

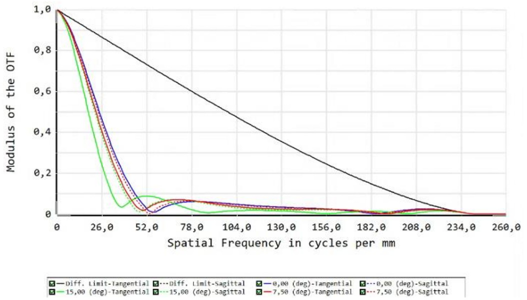
Dispersion engineering in a system

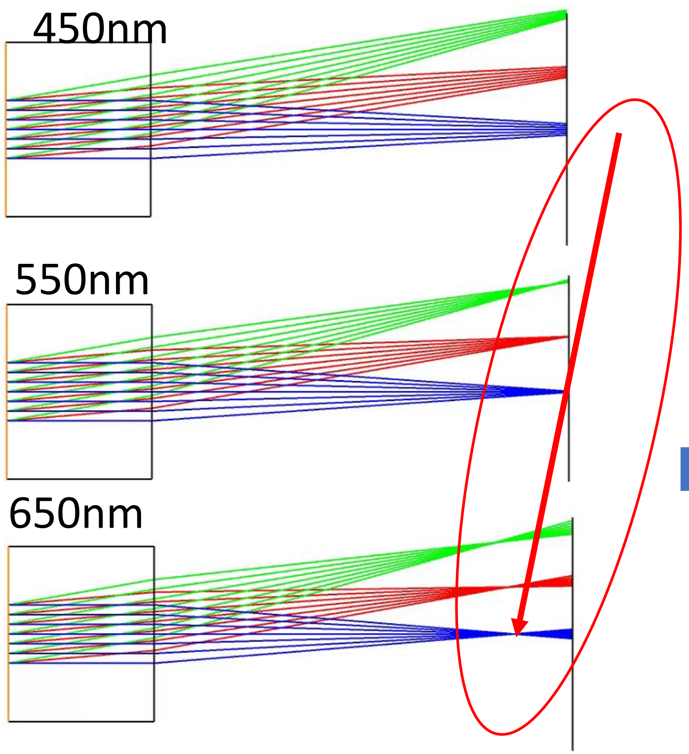
- Binary phase profiles is by default constant vs. Wavelength
- **Achromatization of meta-lenses requires a different wavefront shape for each wavelength**
- Parameter optimization per wavelength

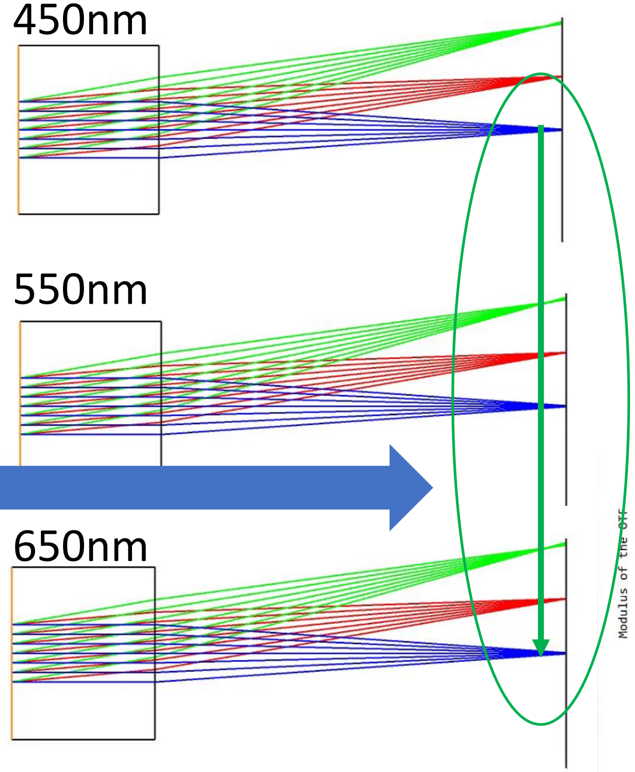
Standard optimization:
Fixed parameters for 450,550, 650nm
diffractive lens $f * \lambda = c$

Optimization for dispersion engineering:
Separate parameters for 450,550, 650nm
Chromatic focal length shift strongly reduced

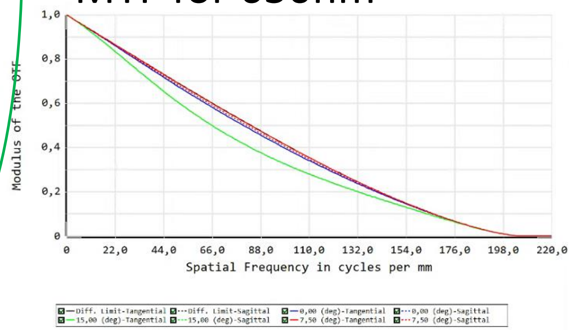
MTF for 650nm







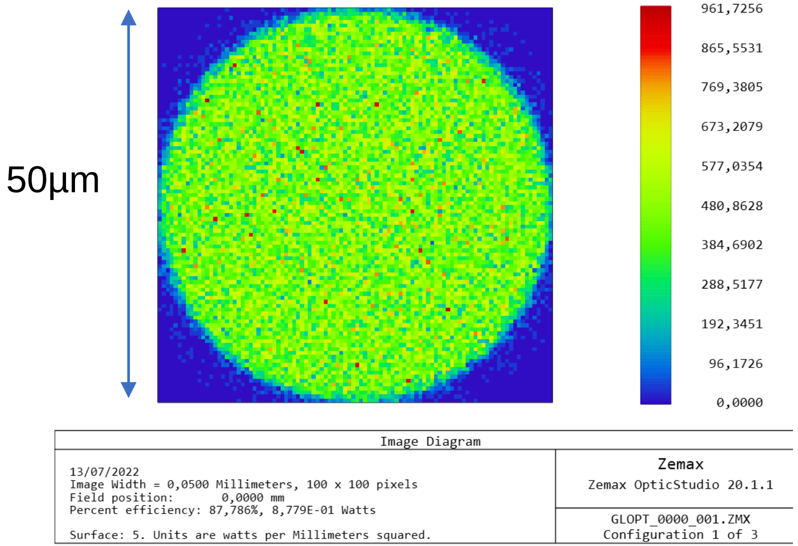
MTF for 650nm

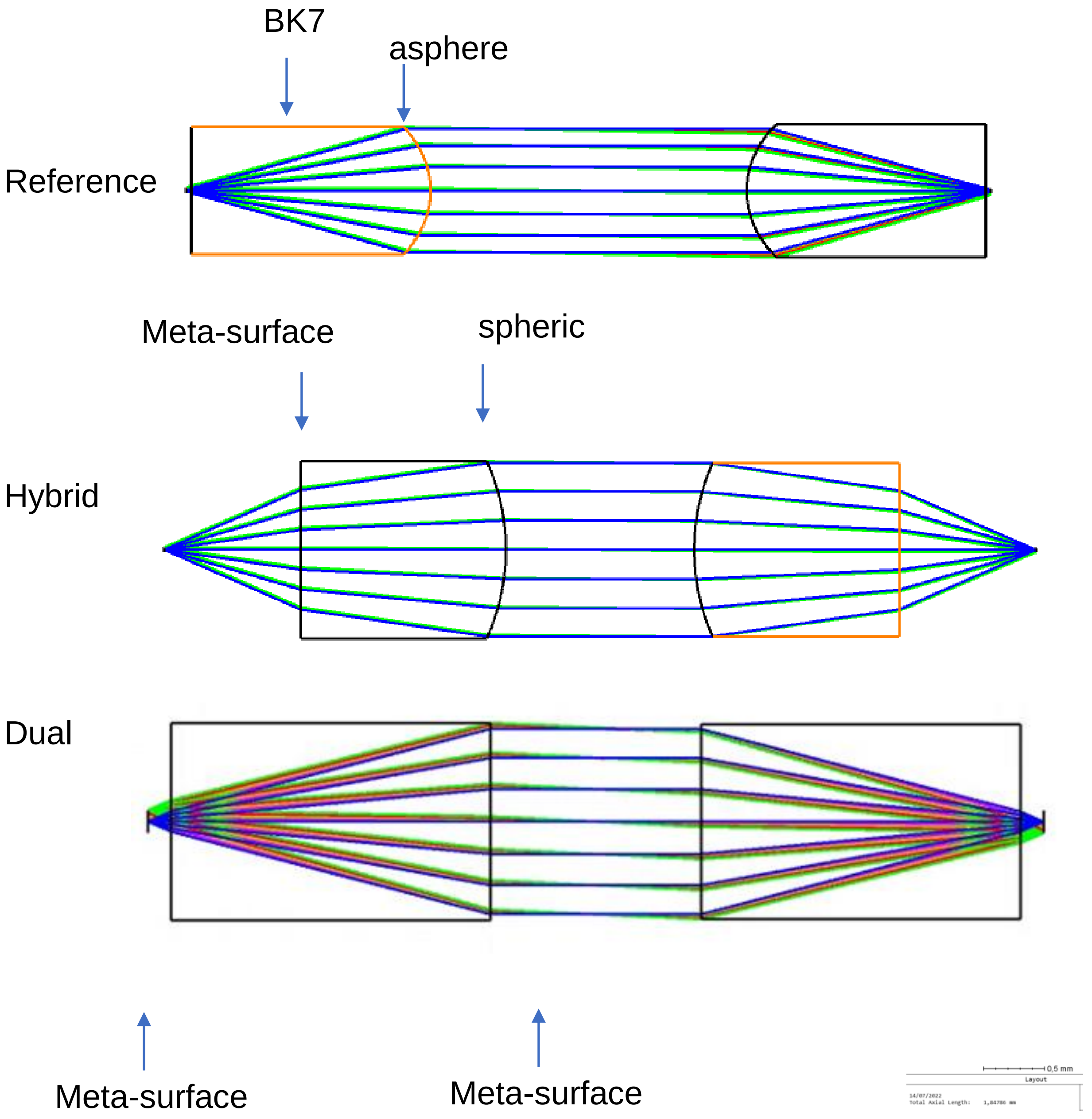


Phase profile determination

- Ray tracing model set up:
  - Reference: aspheric lens coupler
  - Design candidates
  - All surfaces AR coated
- Meta-surfaces:
  - Wavelength specific phase profiles
  - Phase dispersion limit enforced per metasurface
- All systems separately optimized:
  - Wavelengths: 1530, 1555, 1625

Intensity at 2nd fiber



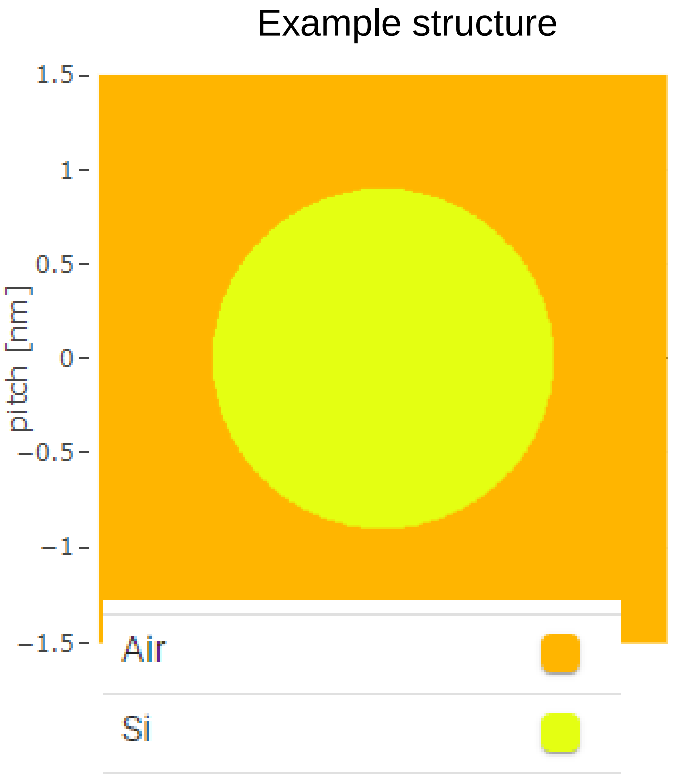


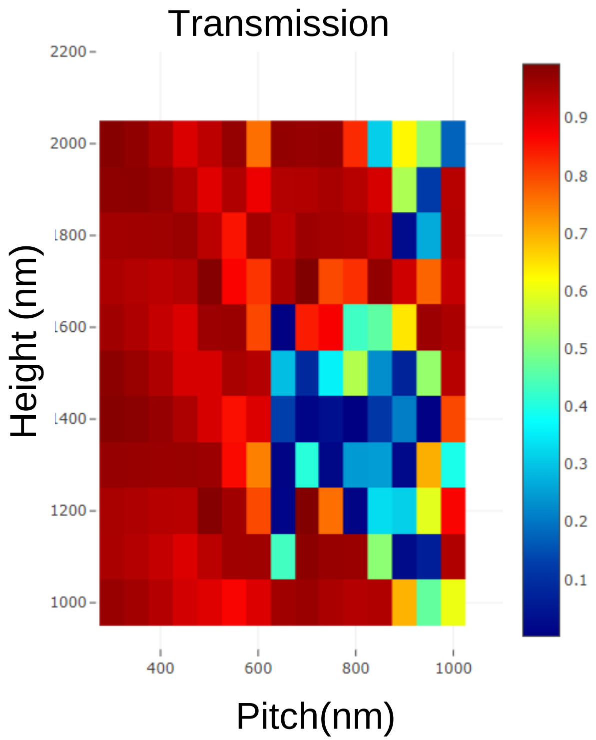
Nano-structure design

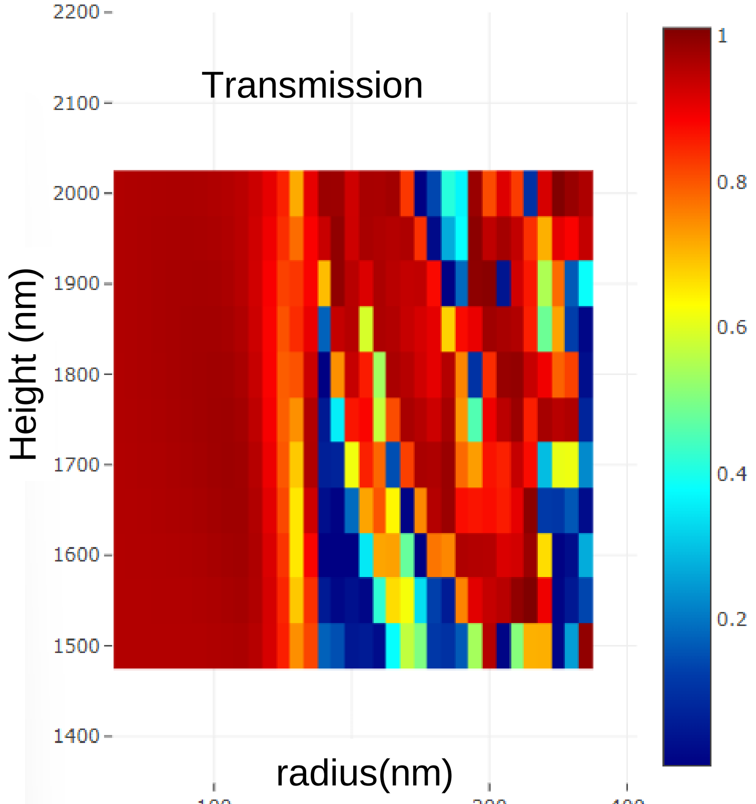
- [redacted]
  - [redacted]
  - [redacted]
- [redacted]
- [redacted]

$$P < \frac{\pi}{\frac{\delta\varphi}{\delta x}}$$

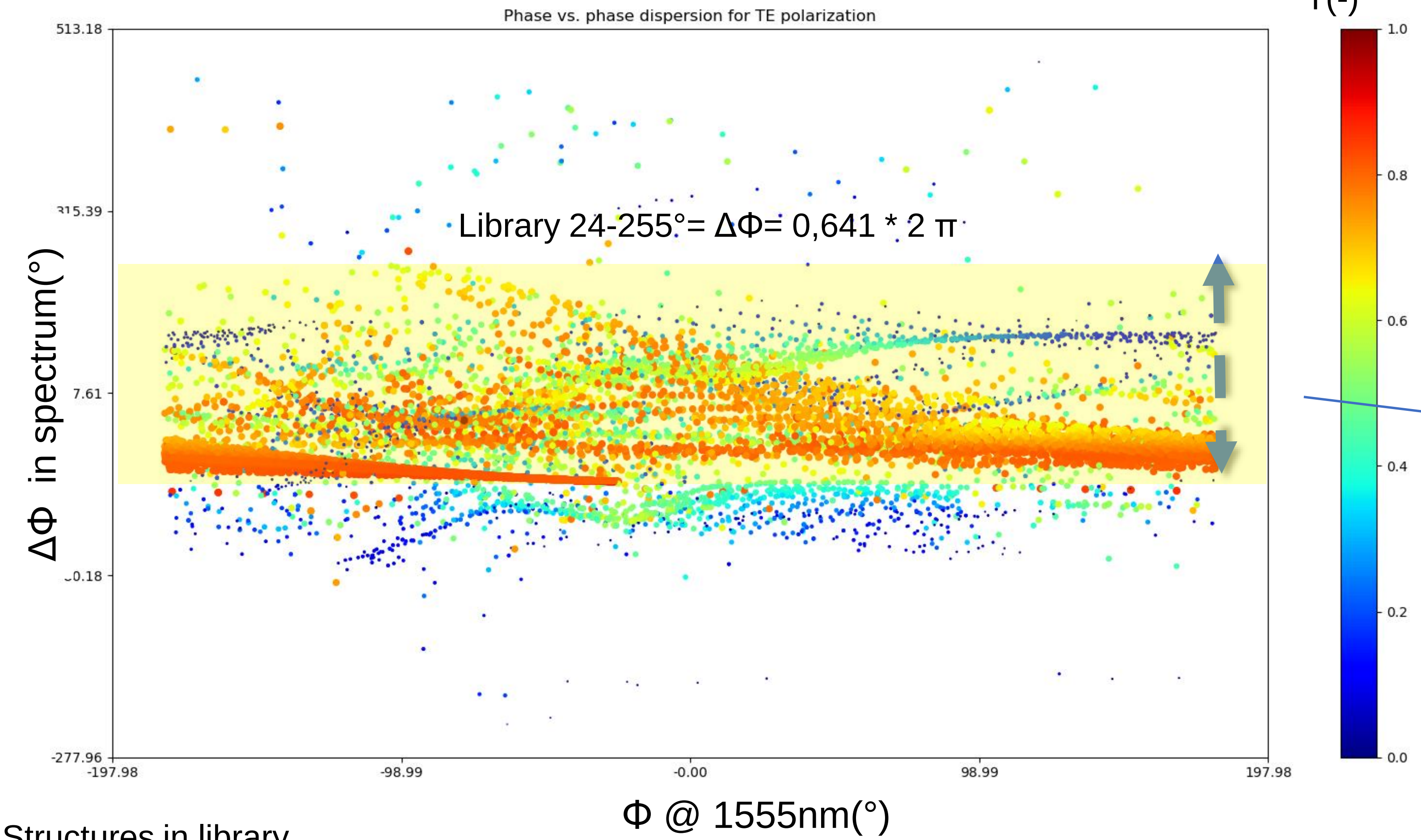
$$P < \frac{\lambda}{n_{r/t} + n_r \sin(\theta_{in})}$$

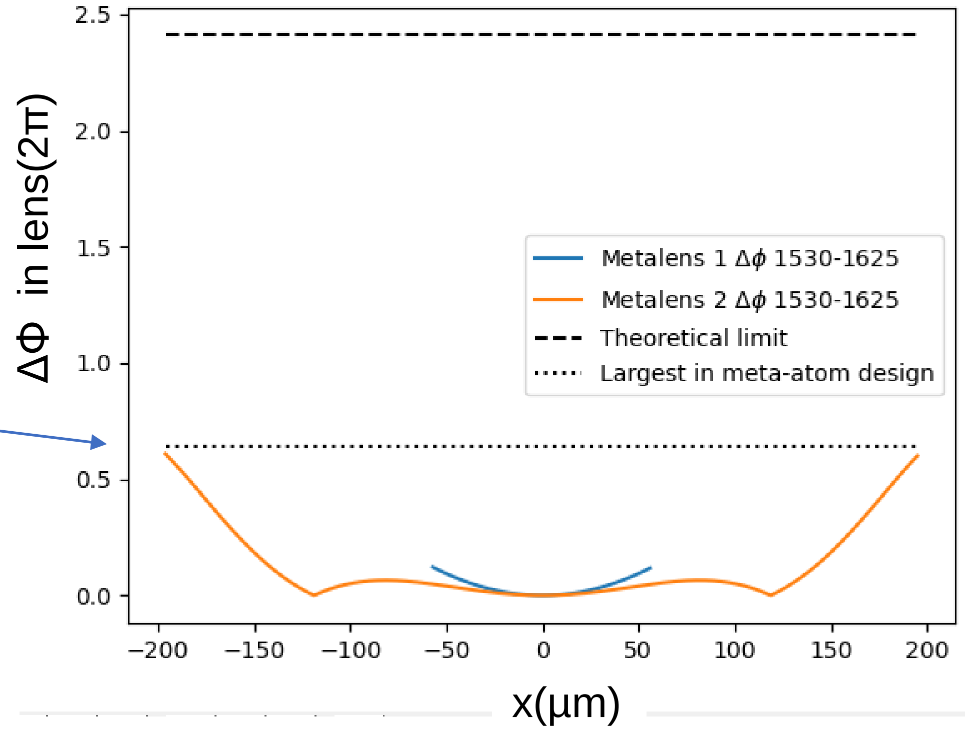






Dispersion library





Structures in library

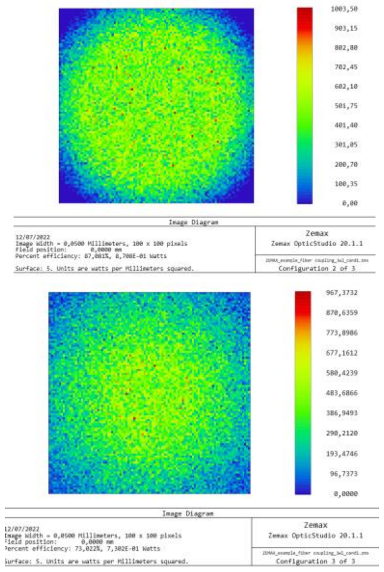
- ❖ Extensive parameter search
- ❖ Critieria: avg. Transmission, phase coverage, phase difference coverage
- ❖ Available phase dispersion is an optimization limit for rat-tracing design

Ray tracing outcome

Single wavelength metalenses

1530nm

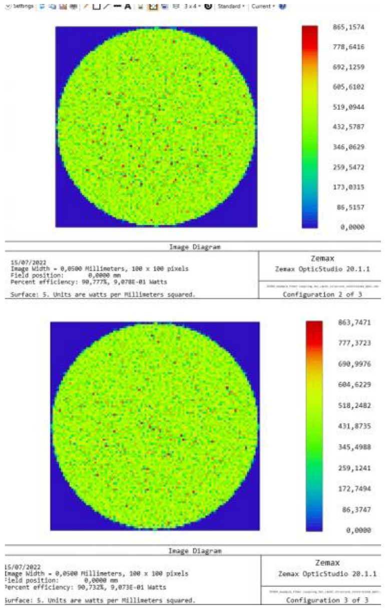
1625nm



87% coupling

73% coupling

Dispersion engineered



91% coupling

91% coupling

- The system has been **reduced in volume** by factor 31
- Dispersion engineering needed for non-monochromatic designs

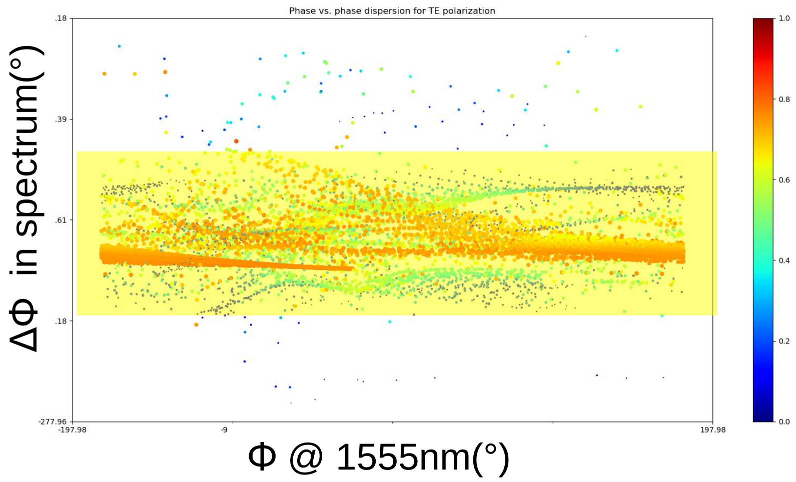
Case	Avg . Coupling loss	Diameter	System length	Volume
Asphere	-0,57dB	1,2 mm	7,6 mm	34,4 mm^3
Spheric + metalens	-0,45dB	1,8mm	8,9 mm	90 mm^3
2 metalens (single wavelength)	-0,79dB	0,43mm	1,96mm	1,1 mm^3
2 metalens (dispersion engineered)	**-0,42dB**	0,43mm	1,96mm	**1,1 mm^3**

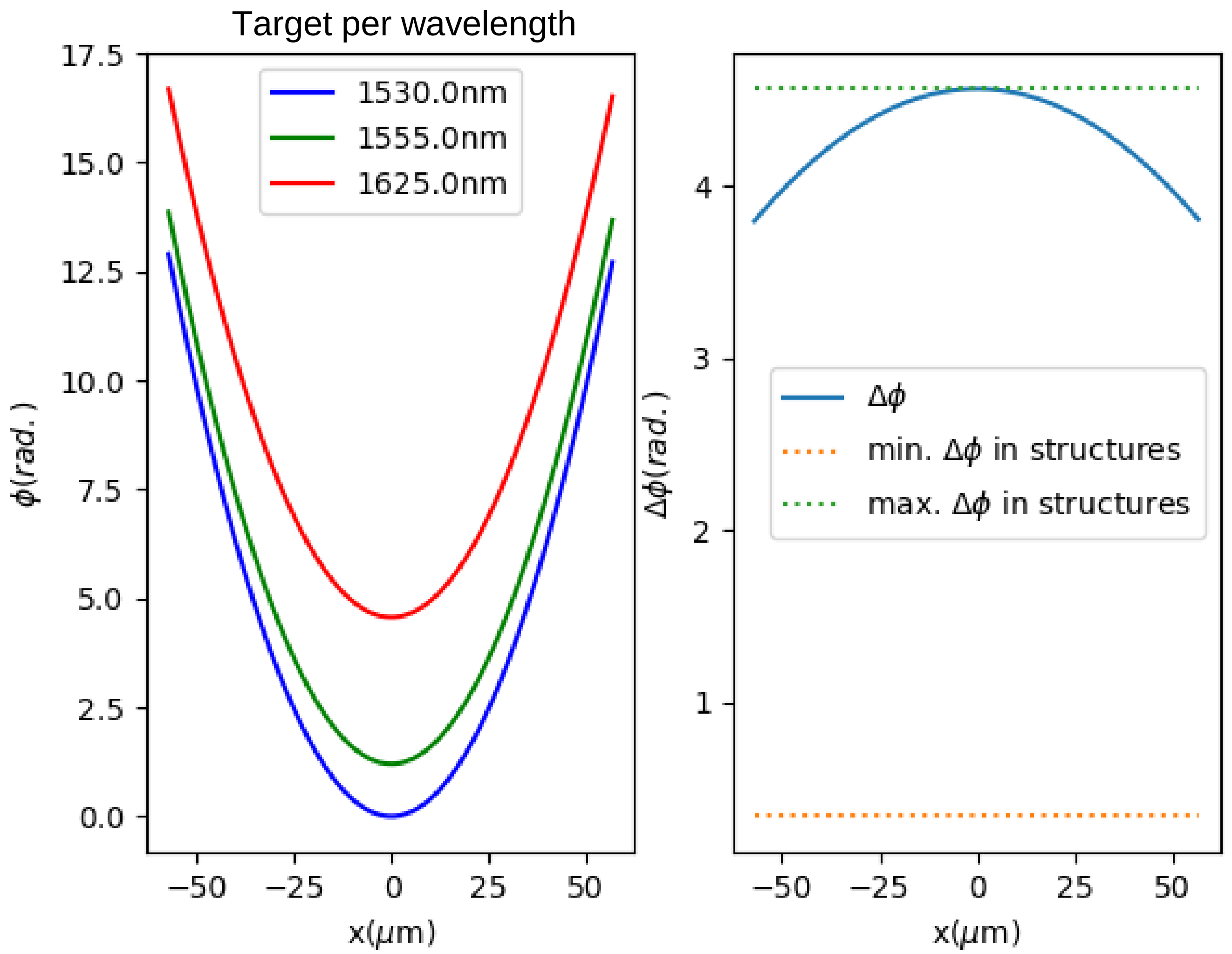
Metalens definition

- Phase fronts from ray tracing
- Meta-cell from library
- Offset application
  - Offset per wavelength
  - Shifts required $\Delta\Phi(x)$ into available range for all positions

$$\Delta\phi(x) = \varphi_{lens}(\lambda_1, x) - \varphi_{lens}(\lambda_2, x) + \mathrm{C}(\lambda_1) - \mathrm{C}(\lambda_2)$$

Free design parameter

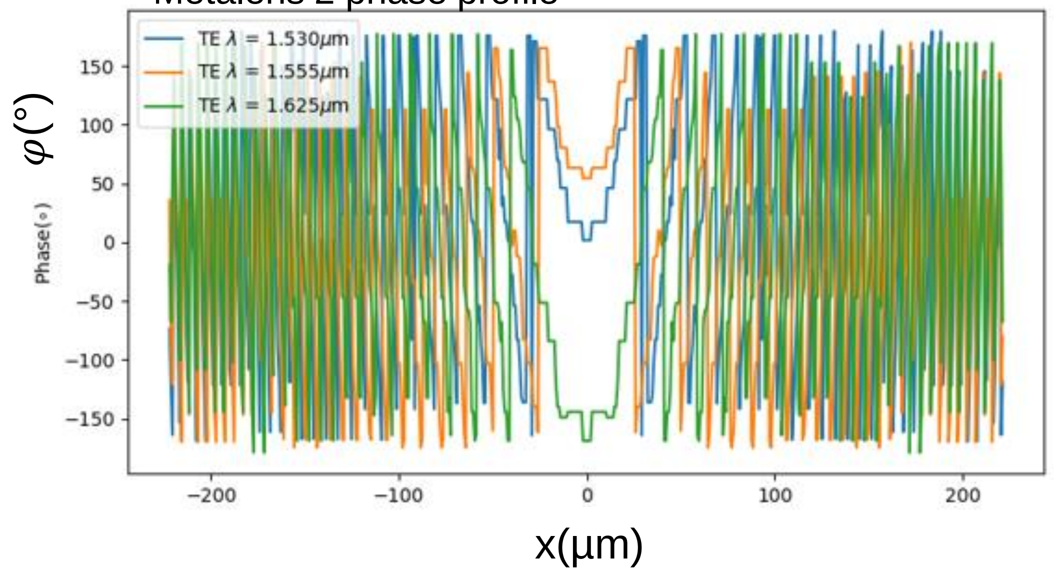




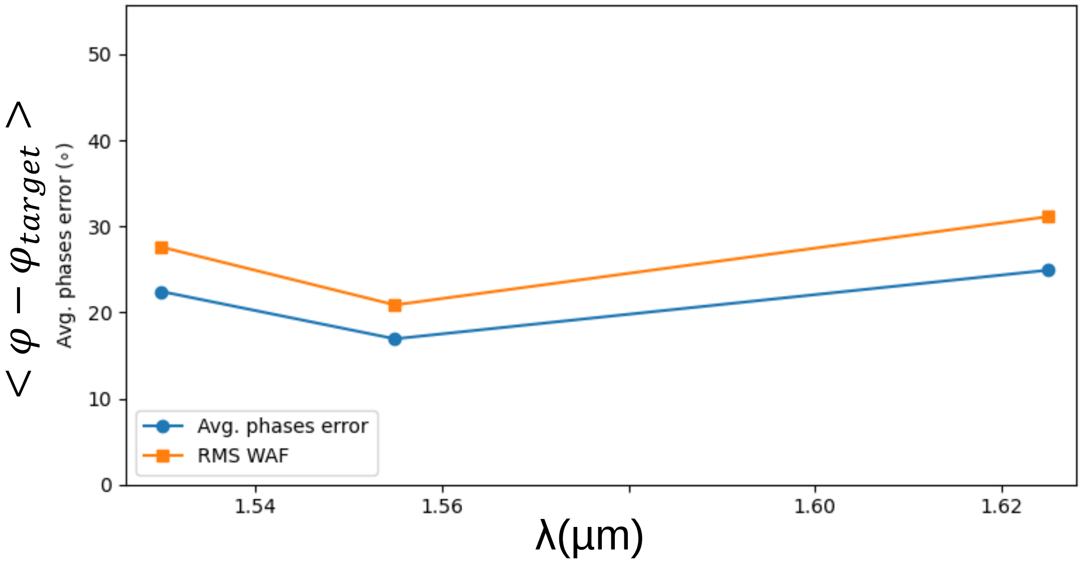
Metalens generated

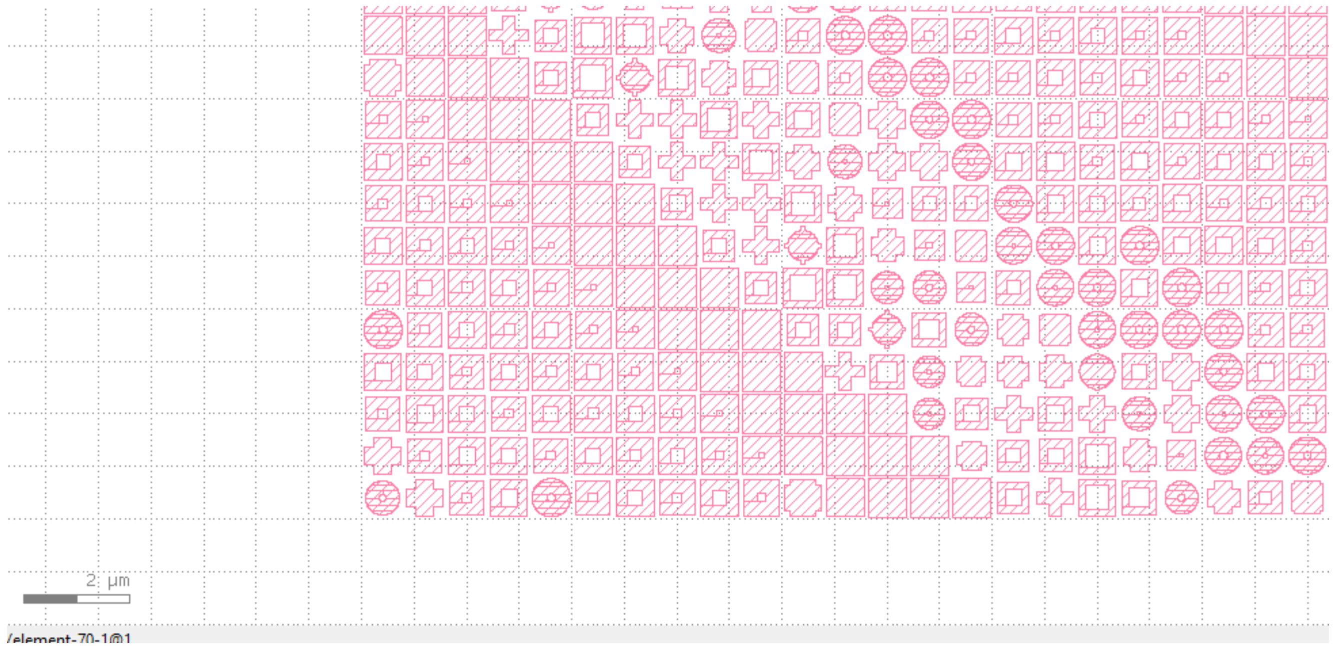
- Phase error low (<20°) for all 3 design wavelengths in both metalense
- Structure usage across available dispersion range
- Further improvements require:
  - Denser population of library
  - Increased transmission across spectrum

Metalens 2 phase profile



Metalens 2 phase error





Example 2: NIR imager

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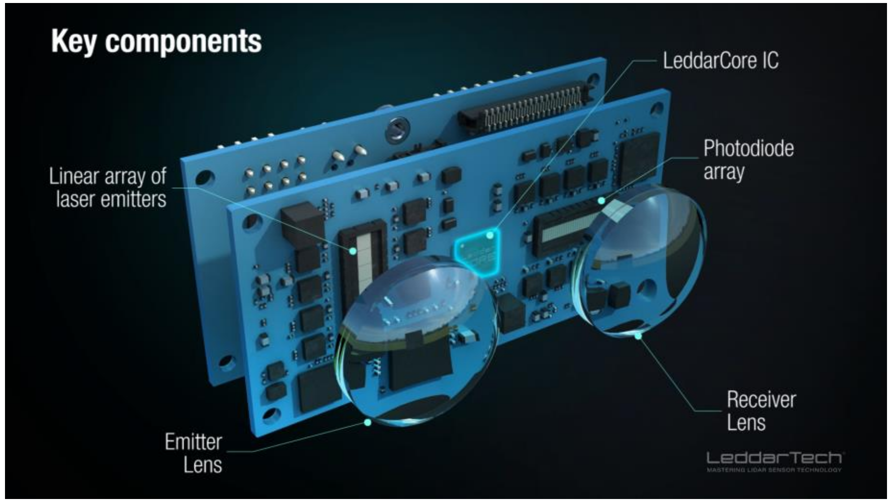
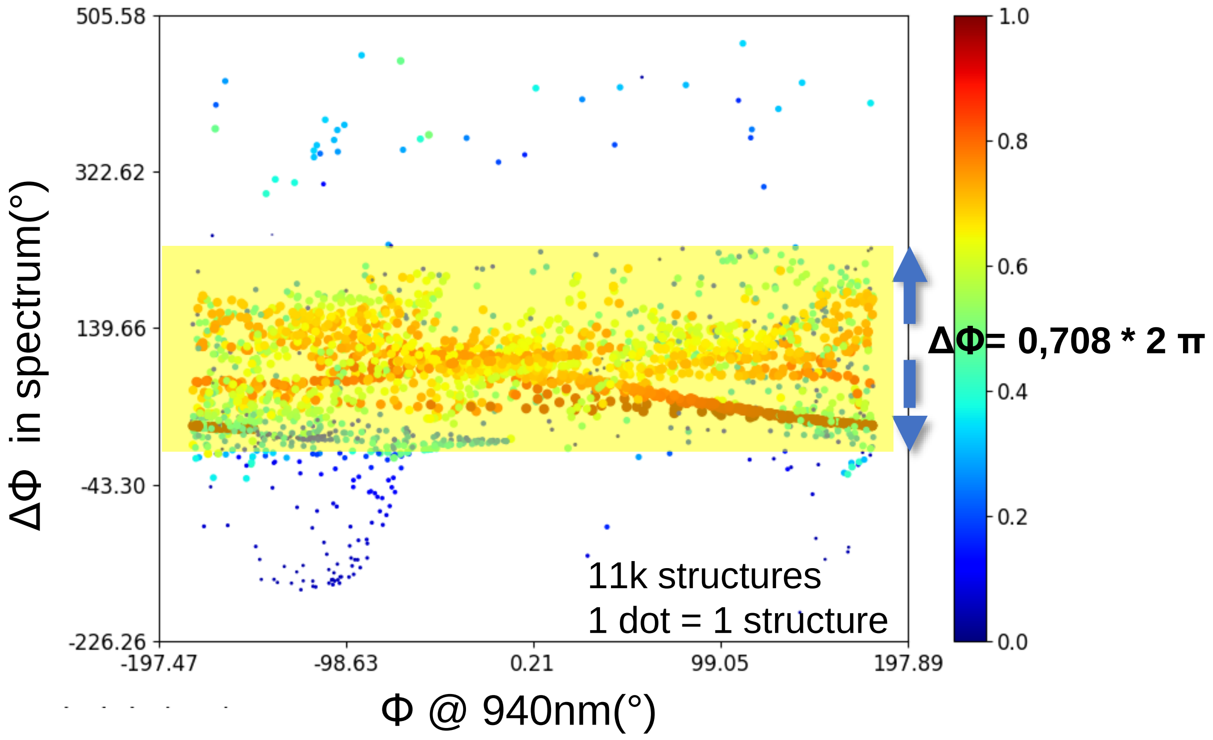
- Use in sensing application: LIDAR, facial recognition …
- Dot pattern generation emitter + receiver
- Imaging system
- Specifications

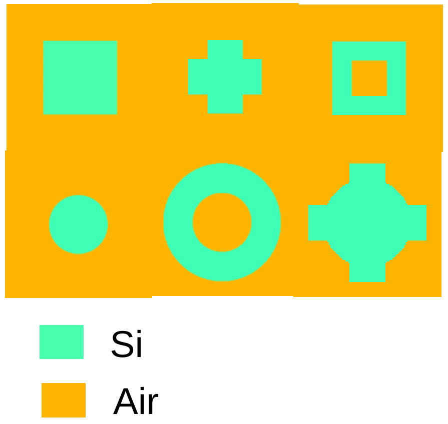
Quantity	Specification
Field of view	HFOV 30°
Imaging performance	MTF >70% @100lp/mm Diffraction limited
Telecentric	CRA <3°
Back Focal Length	5mm
Design Wavelength	920-960nm
Numerical aperture	0,276
F-number	1,74
Image Size	6,4x4mm
Distortion	<10%



Dispersion extraction



Structures in library



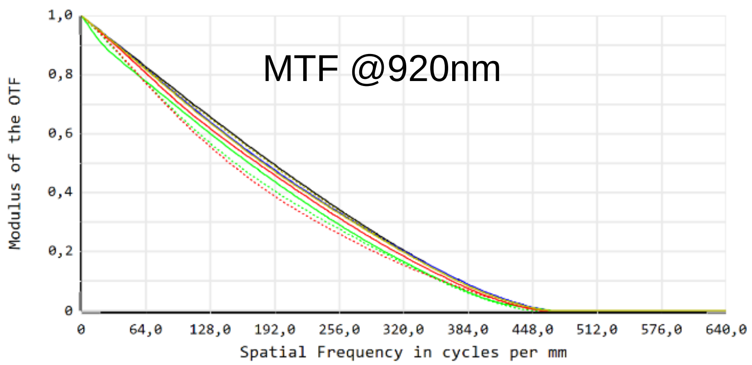
- ❖ Critieria: avg. Transmission, phase coverage, phase dispersion coverage
- ❖ Meta-atom simulation using PlanOpSim MetaCell (RCWA)

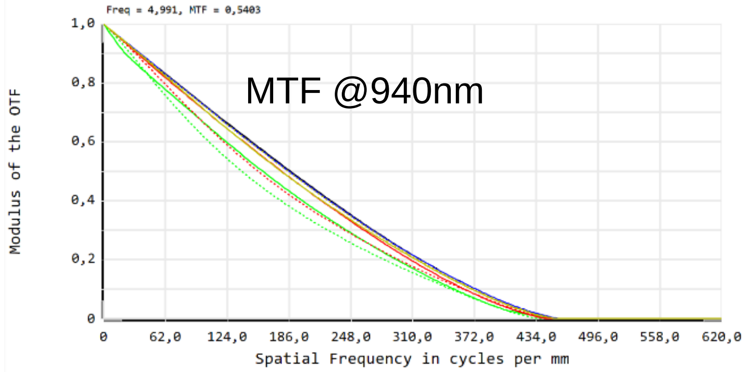
Parameter	Value
P	450nm
Height	1300nm
Spectrum	920-960nm
Incidence	0°
Polarization	TE
Substrate	SiO_2

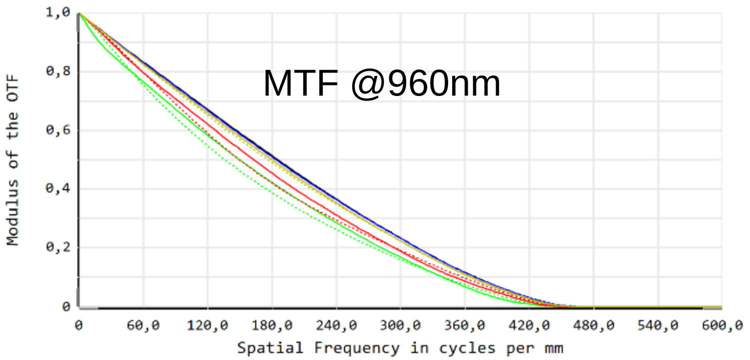
System design

❖ Dispersion contrained optical system

Quantity	Specification	Hybrid 2 MOE + 2 Spherical			
Field of view	HFOV 30°	30°			
Imaging performance	MTF >70% @100lp/mm Diffraction limited	0°	5°	10°	15°
		72,6%	71,3%	71%	66,7%
Telecentric	CRA <3°	0,8°			
Back Focal Length	5mm	5mm			
Design Wavelength	920-960nm	920-960			
Numerical aperture	0,276	0,276			
F-number	1,74	1,7474			
Image Size	6,4x4mm	3,2 (lateral colour)			
Distortion	<10%	1,5%			
Total volume		1311,6 mm³			







Optical performance

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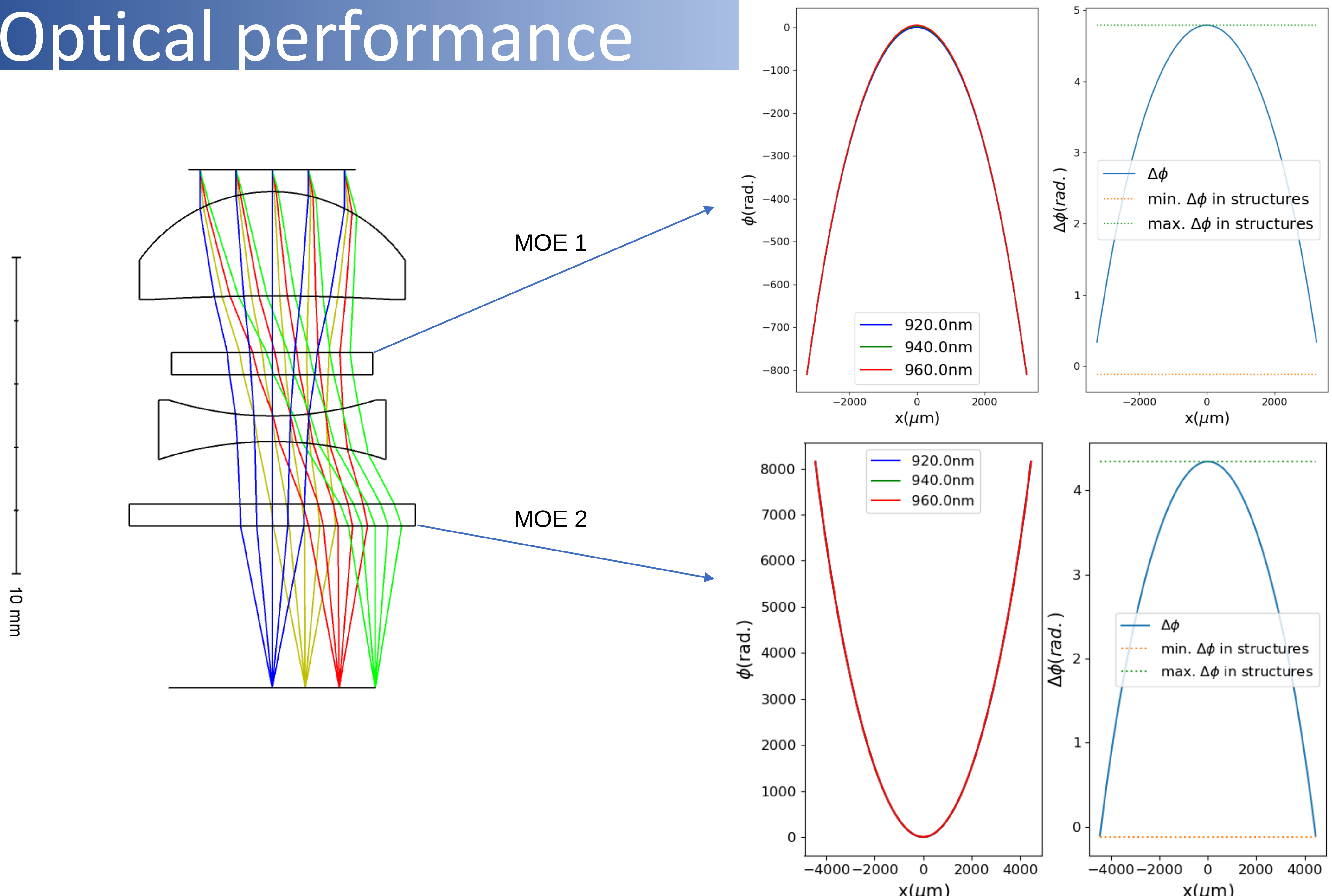

Target error MOE1

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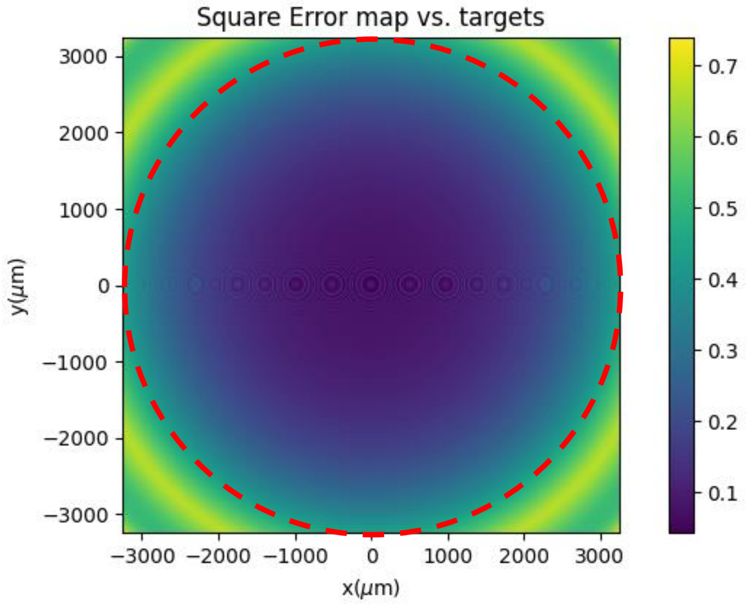
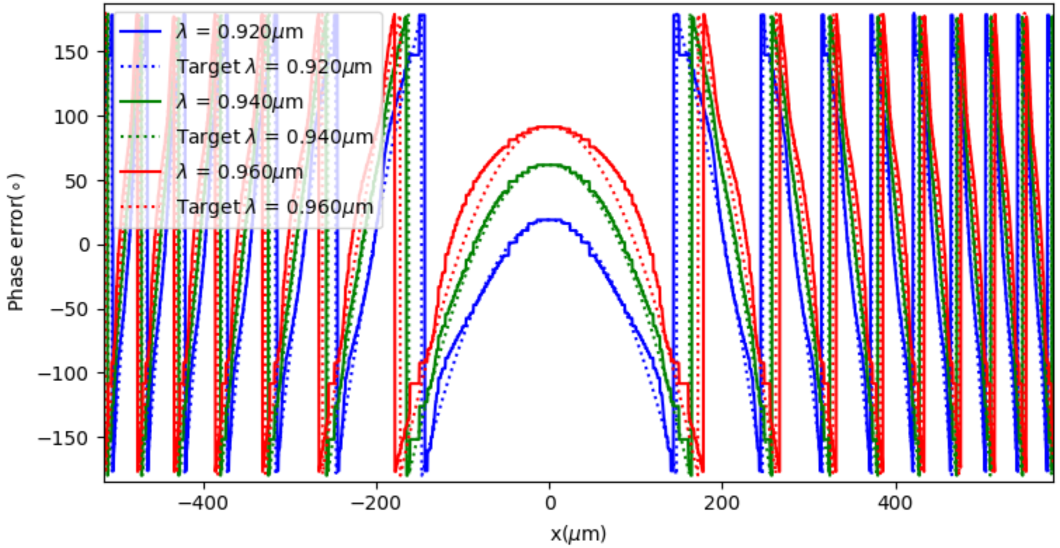
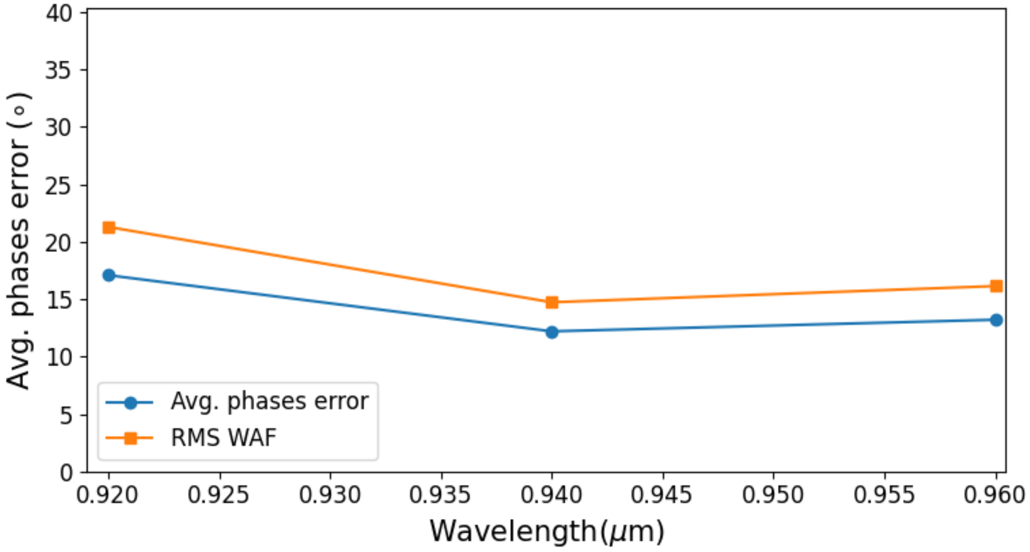
- ❖ Target well reproduced in active area
- ❖ Corners exceed dispersion range -> poor target reproduction
- ❖ RMS Waverfront aberration <21°(= λ/17)



Target vs. Meta-surface phase



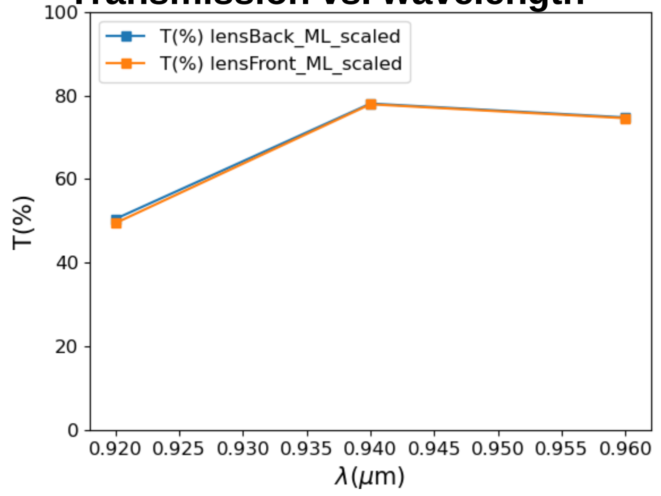
Phase error vs. wavelength



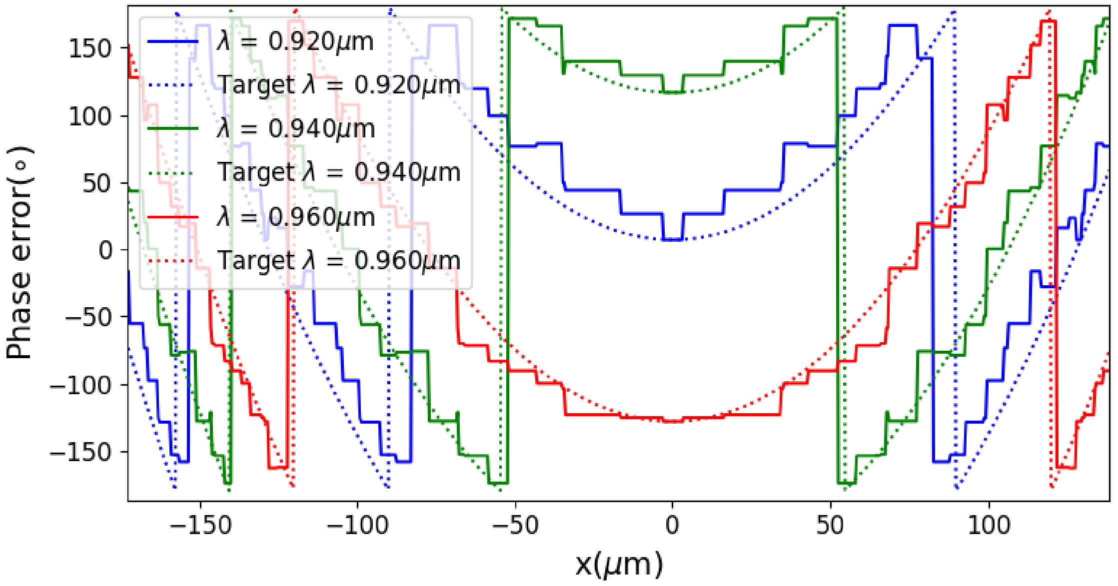
Target error MOE2

- ❖ Corners exceed dispersion range -> poor target reproduction
- ❖ RMS Waverfront aberration <22°(= λ/16)
- ❖ Transmited light ~49-75%

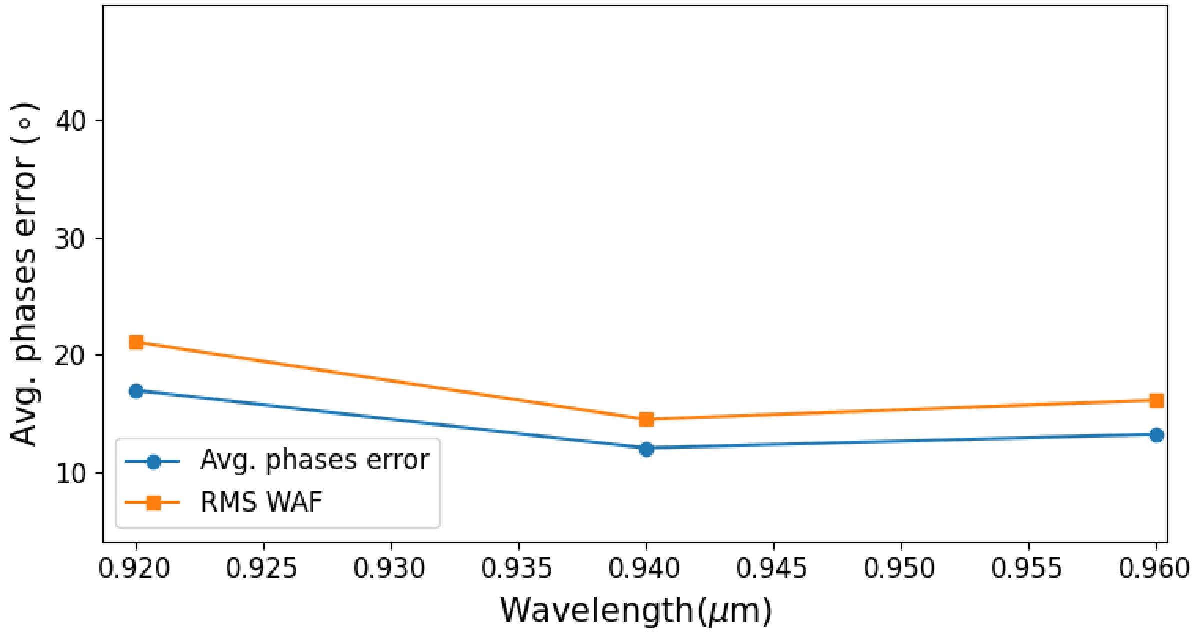
Transmission vs. wavelength



Target vs. Meta-surface phase



Phase error vs. wavelength



Conclusion

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- Meta surface applications require an **integrated design workflow** from **nano- to system scale**

- Multi-scale simulations allow efficient design by combining
  - **Full wave** calculation : **PlanOpSim Meta-Cell**
  - **Propogation** calcultions: **PlanOpSim Meta-Component**
  - **Ray tracing**: **nano-structure informed optimization**

- Software tools allow fast and efficient design

- Meta-surface systems require multi-domain expertise.

Contact info!

www.planopsim.com
info@planopsim.com

Supported by:

Outline

- ❖ Basics of meta-surface design
- ❖ Meta-atoms = full wave
- ❖ Meta-surfaces= propagation
- ❖ Meta-systems = ray tracing

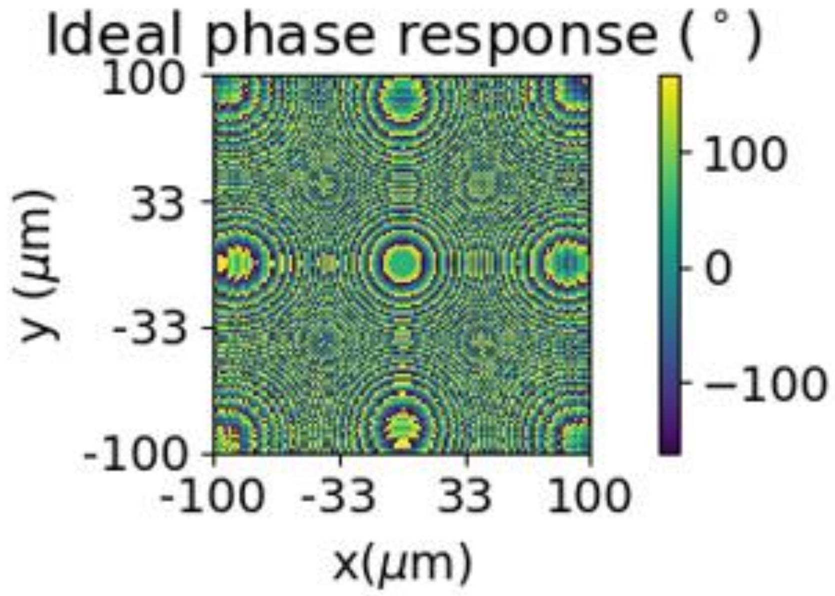
- ❖ BONUS: design for manufacture

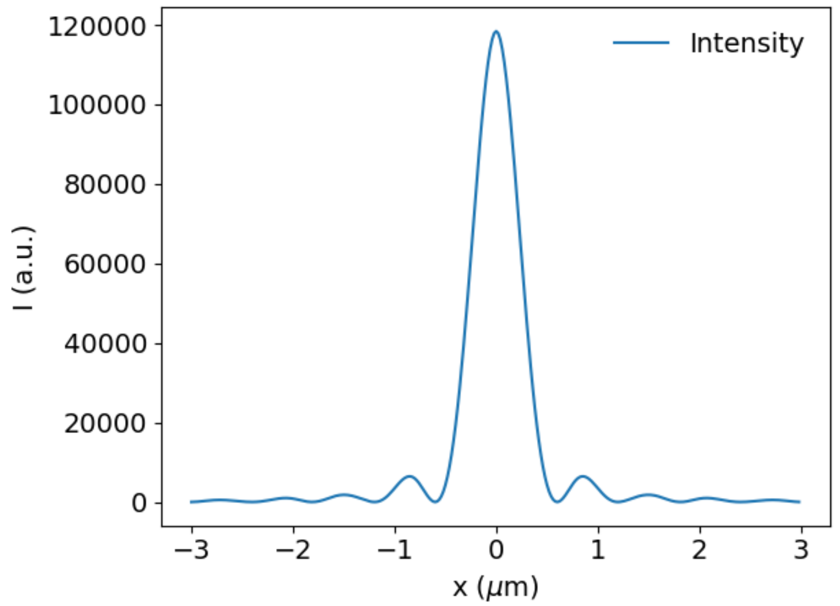
Example: metalens

- Reference lens parameters:
  - Size: 200 x 200um
  - Focal distance *f:* 200µm
  - Design wavelength: 523nm
  - Corresponding NA: 0.45
- Analytical spherical phasefront:

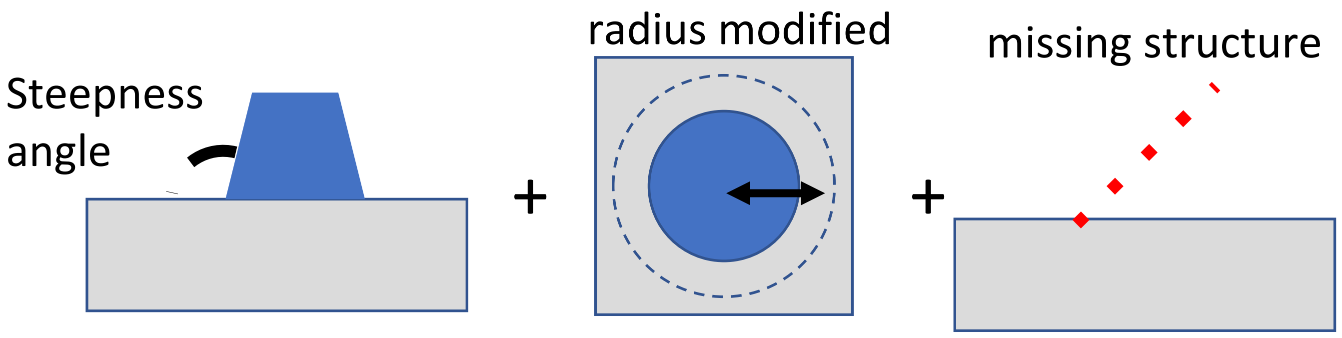
$$\varphi(\lambda) = \frac{2\pi}{\lambda}\left[\sqrt{x^2 + y^2 + f^2} - f\right]$$

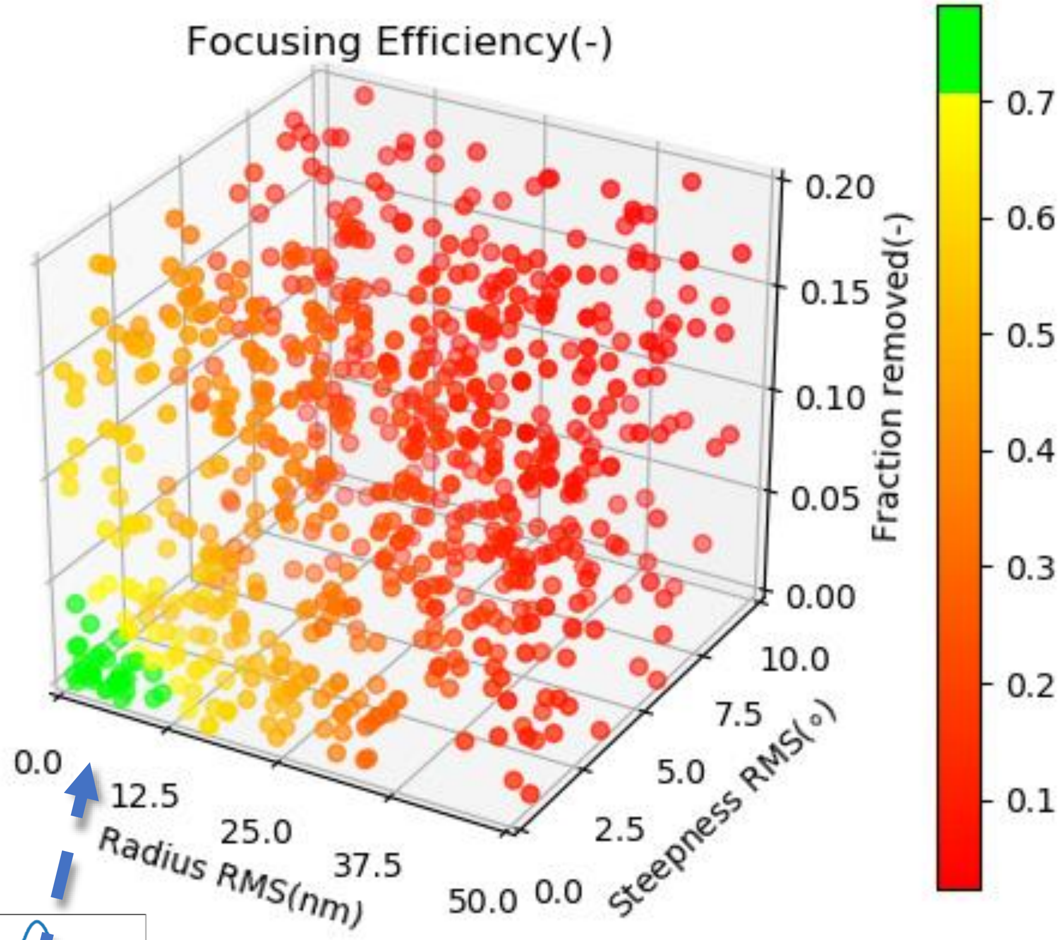
- Simulated using physical optics propagatic
- Nominal spot characteristics:
  - FWHM: 0.516 µm
  - Focussing efficiency: 78.6%
  - Strehl ratio: 88.8%

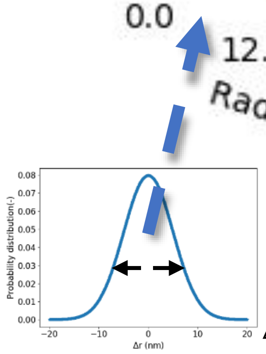




Yield and tolerancing example





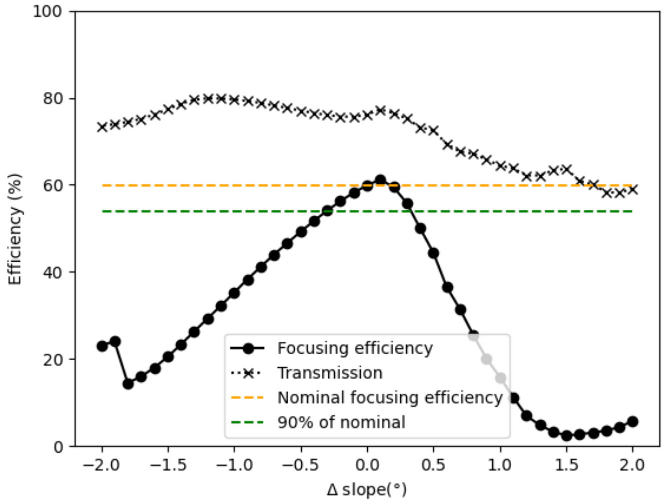

Δr (nm)

- Monte carlo study for error tolerancing
- 25’230 metalenses simulated in this plot

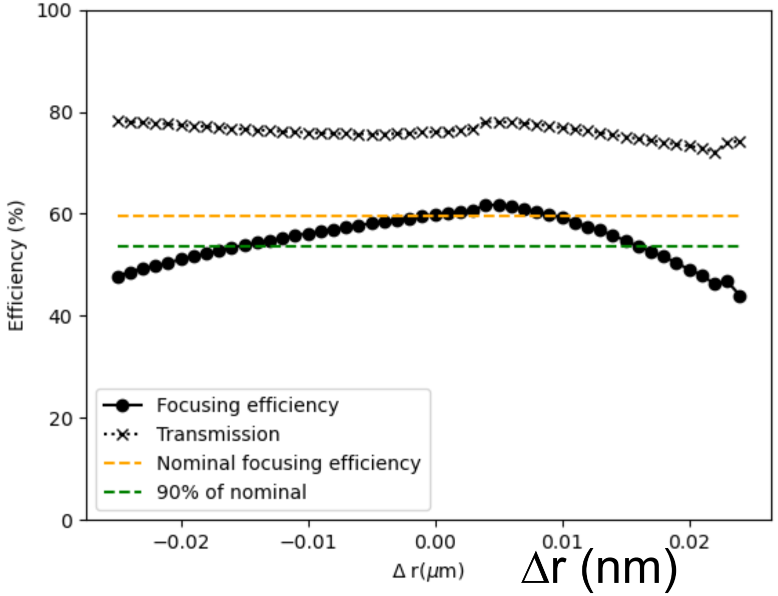
Comparison systematic to random error

- **Systematic errors** have a **stronger impact than random errors** on focussing efficiency
- Monte carlo results for meta-lens for 532nm

Systematic errors

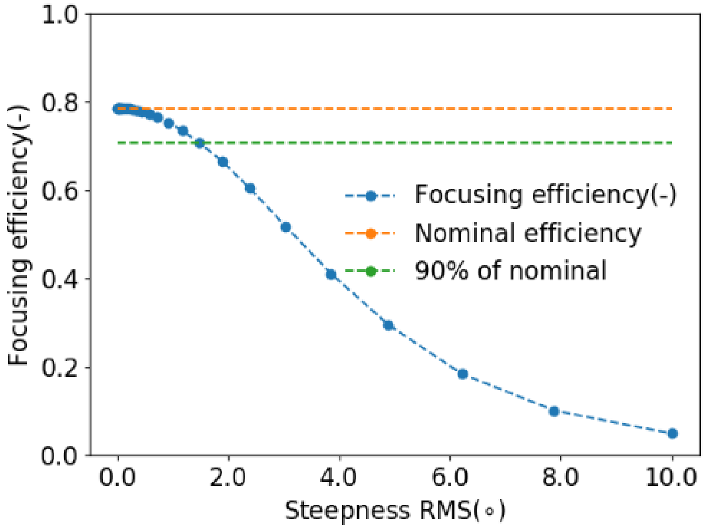


Δθ (°)

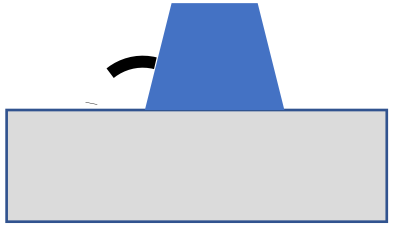


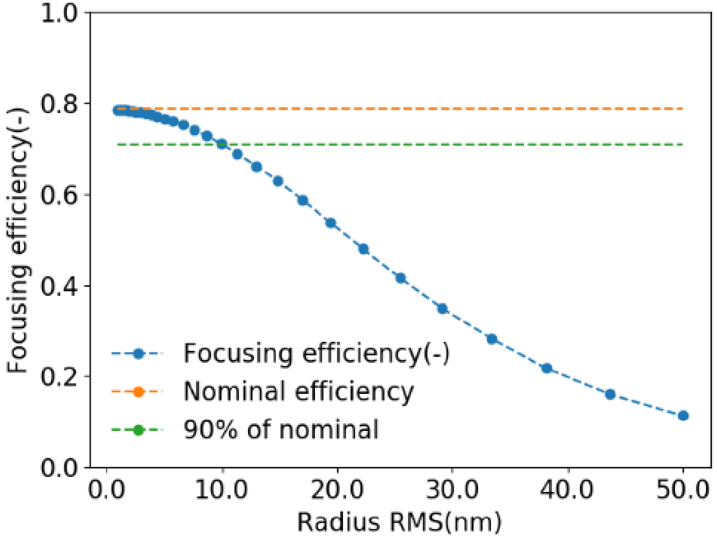
Δr (nm)

Random errors (Monte Carlo)

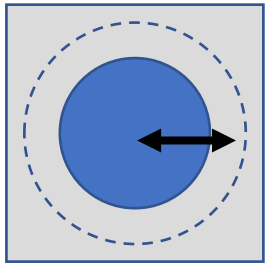


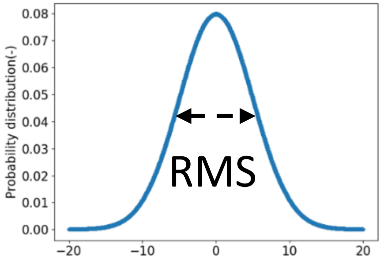
Steepness angle



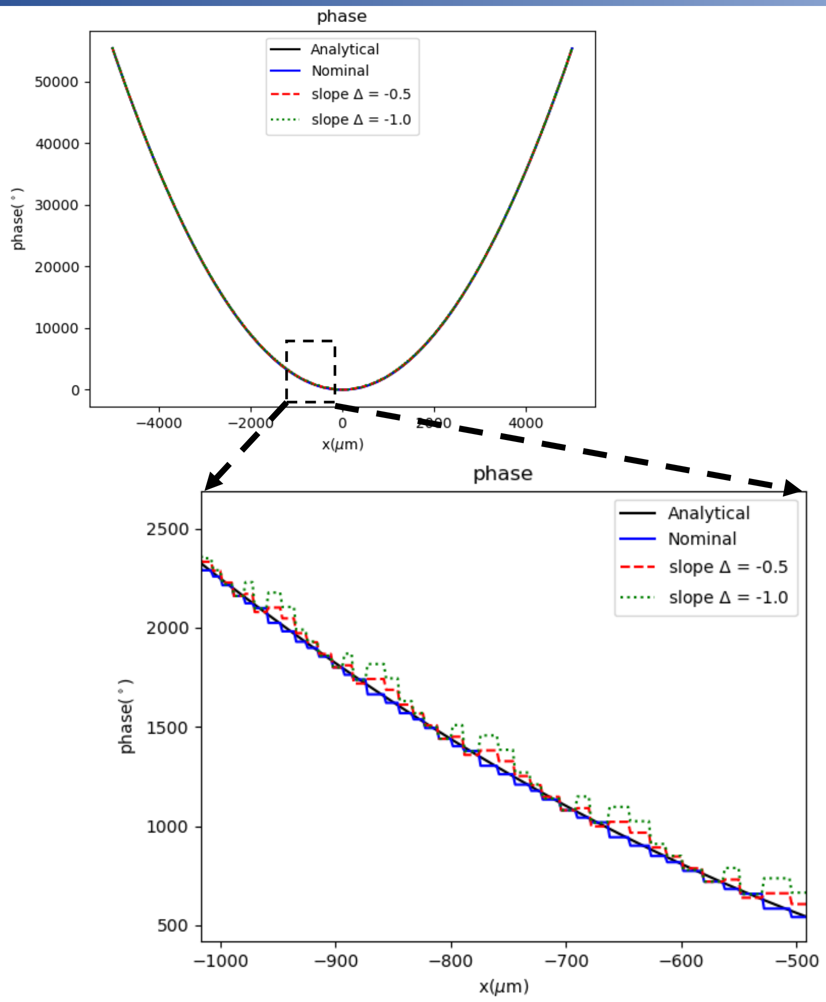


radius modified



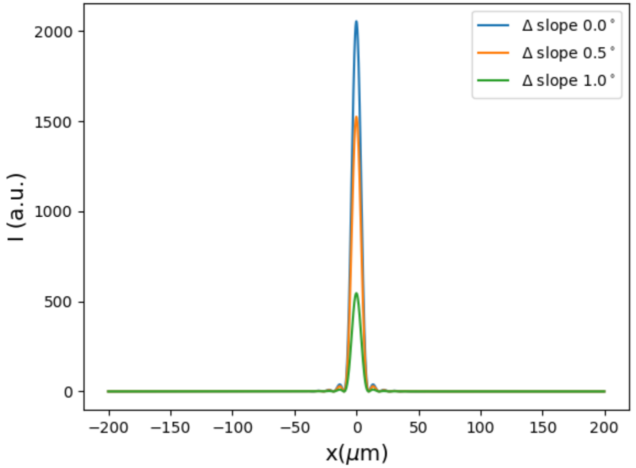


What effects do errors have?



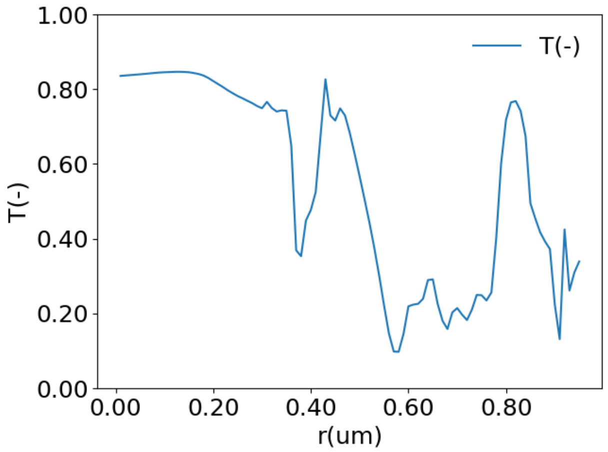
- Wavefront phase for nominal and aberrated cases
  - Example: sidewall angle
- Overall wavefront shape remains the same
- Aberrated wavefront -> perturbation on ideal wavefront
  - Focal distance remains the same
  - Spot width remains the same
  - Loss of efficiency to scattering and higher diffraction orders
- Transmission: additional loss

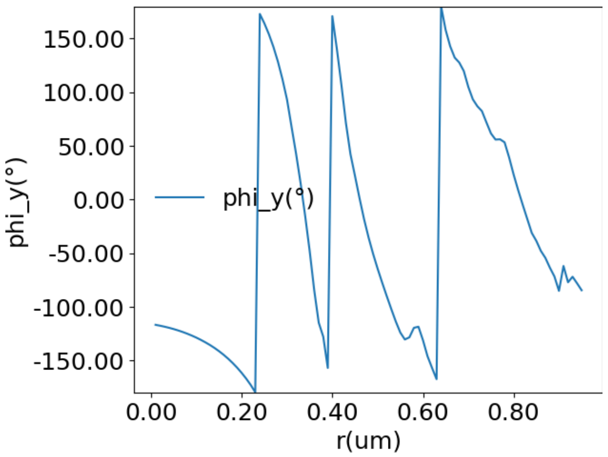
Intensity at z =20mm



Sidewall angle	Phase error (RMS)	Amplitude error (RMS)
90° (nominal)	16,2°	0,19
89,5°	34,2°	0,23
89°	68,5°	0,35

Compensating known errors





- Known sidewall steepness 88,5° (worst case)
- Meta-atoms resimulated and selected
  - P = 2µm
  - H = 5,25µm
- Meta-atoms placement repeated using new meta-atom results
- A **known and constant error can be compensated**

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**