Lieven Penninck

Meta-surface design

How to catch the next wave in optics

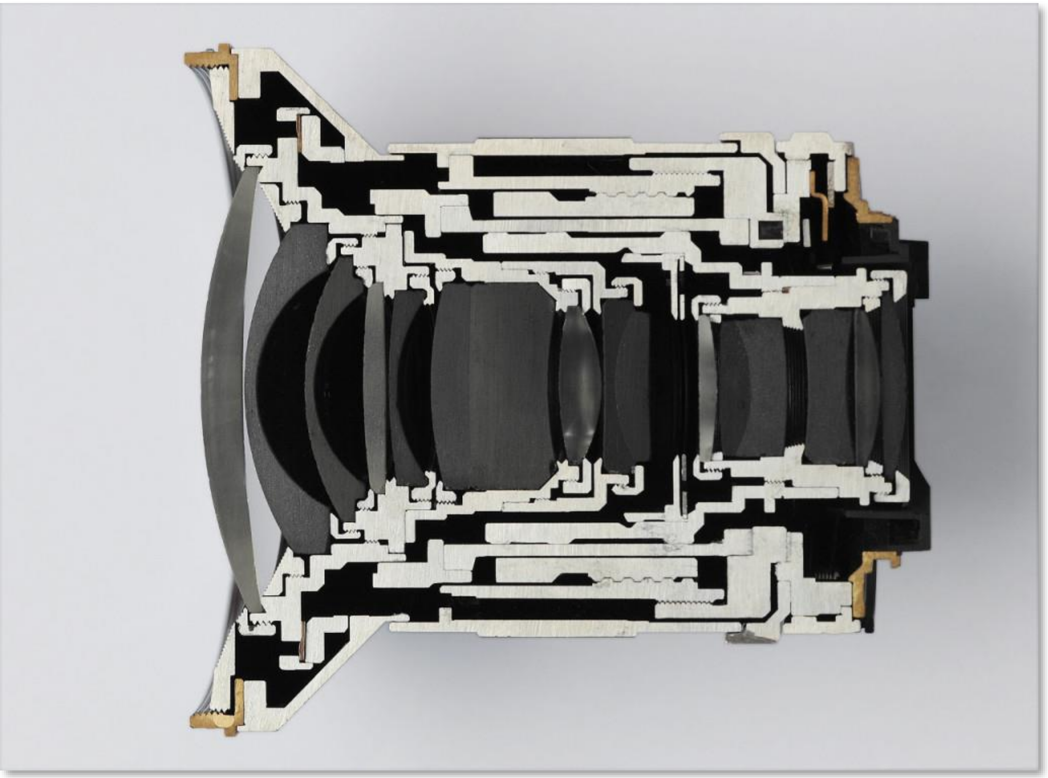
CIOE 2024, Shenzen, China

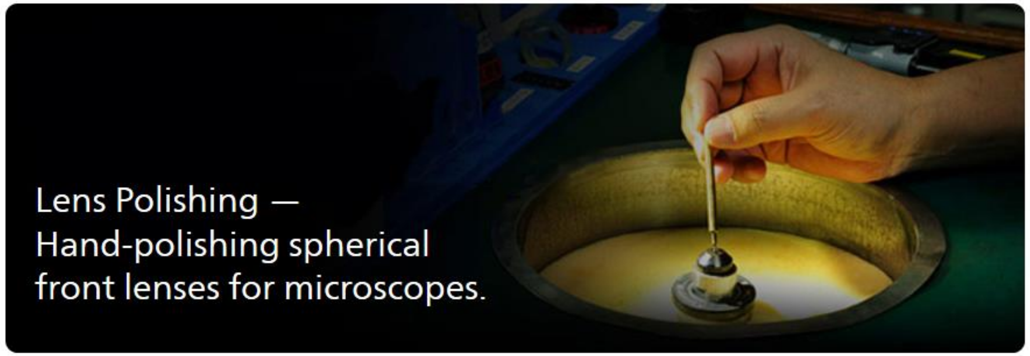
12 September 2024

PlanOpSim
Enlightened Planar Optics

Today

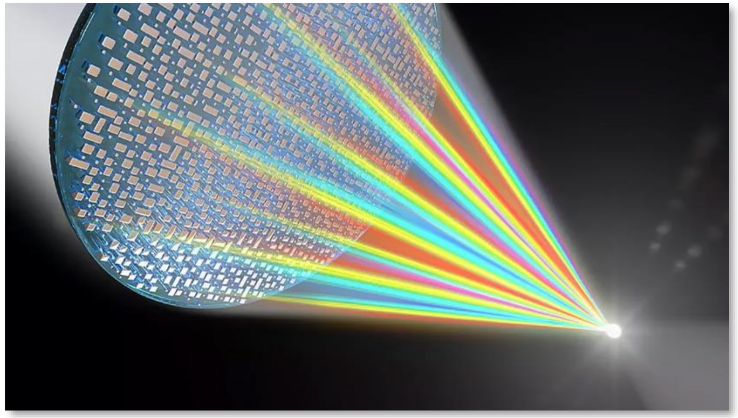
Future: Nano-enabled c

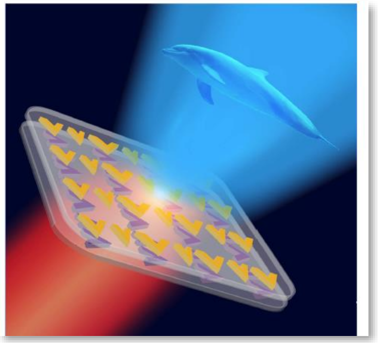


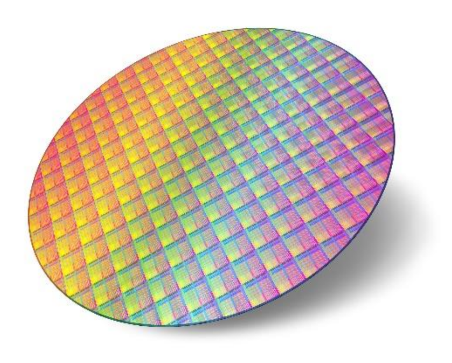


Higher Performance
Simplified
Miniaturized
New Applications

Art to Industry
Lower Cost







Why use meta-surfaces?

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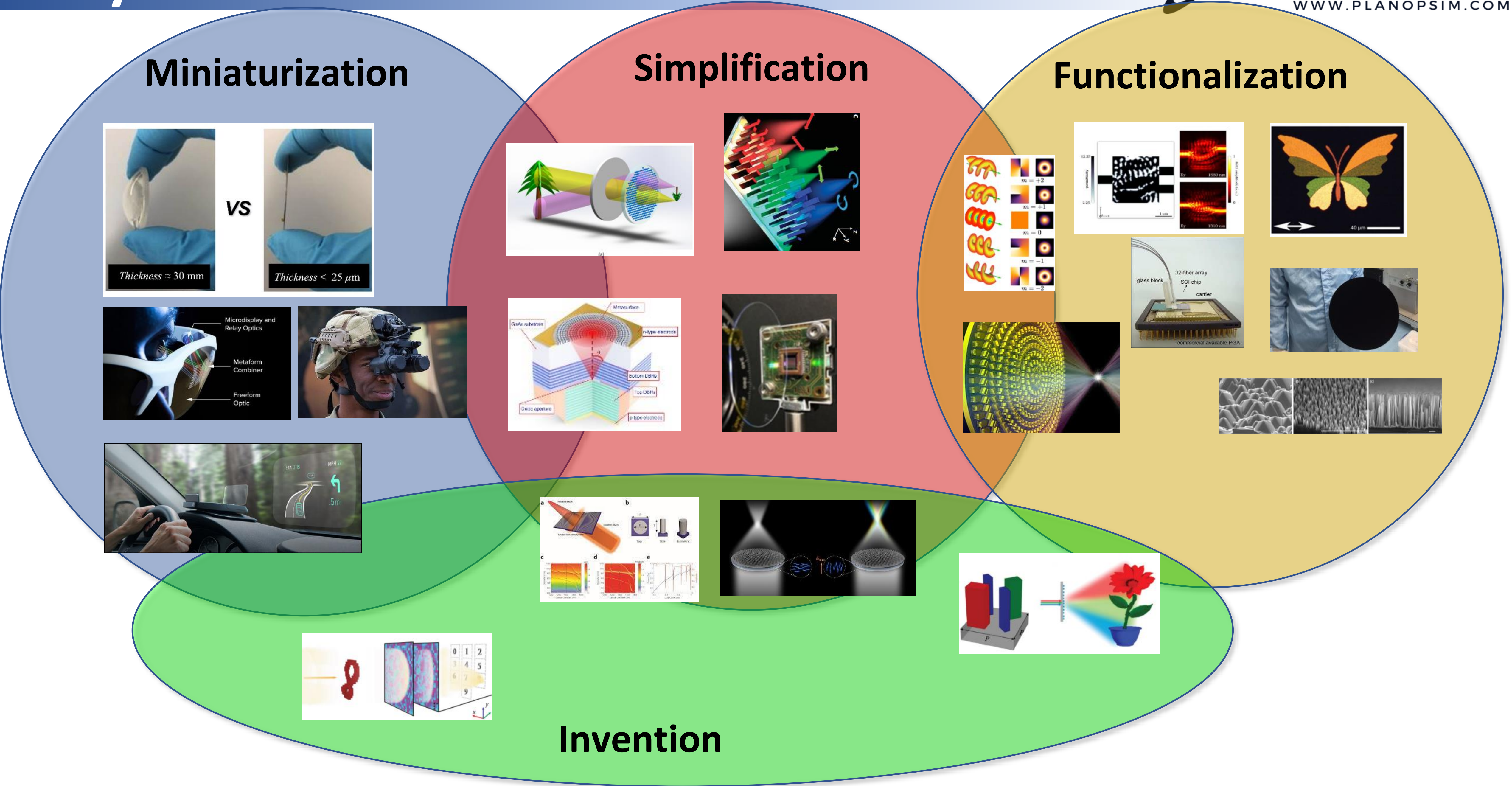

Principles of meta-surfaces

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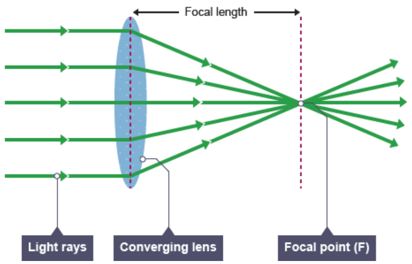
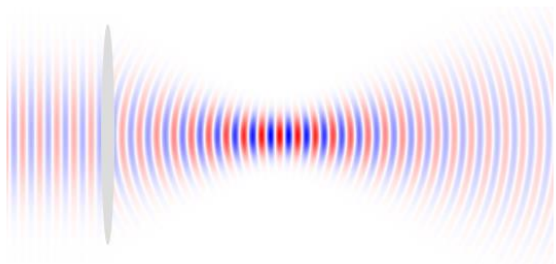
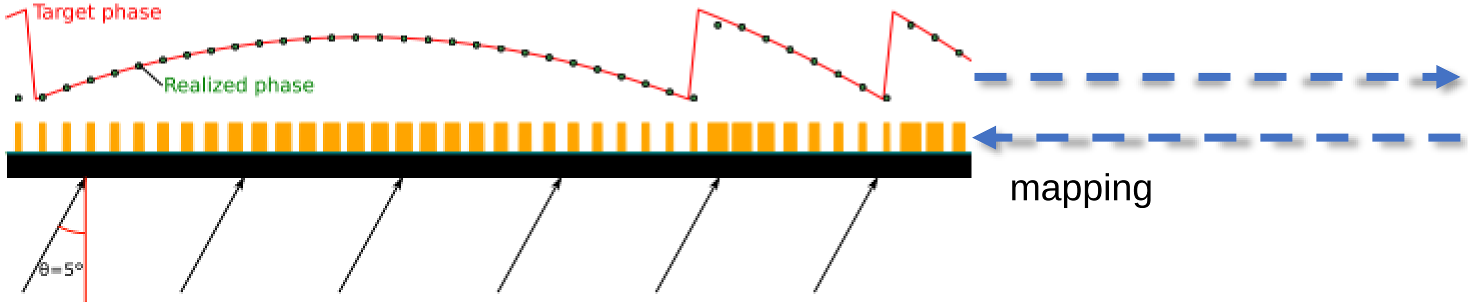
Ray picture

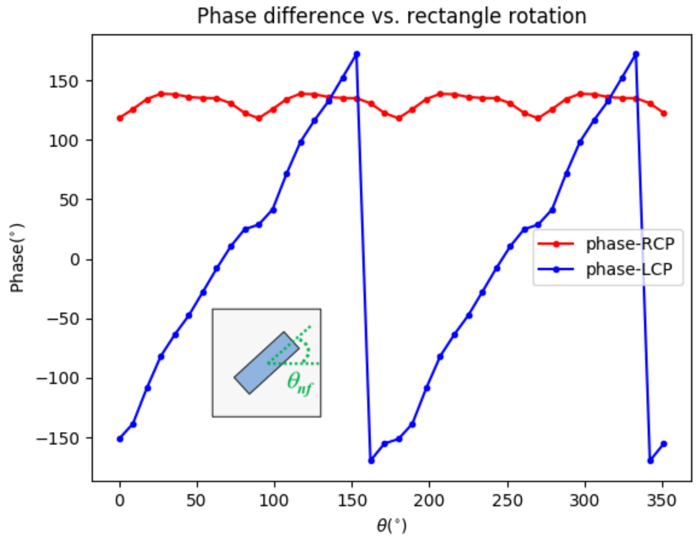


Wave picture



- 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

Why is this new?

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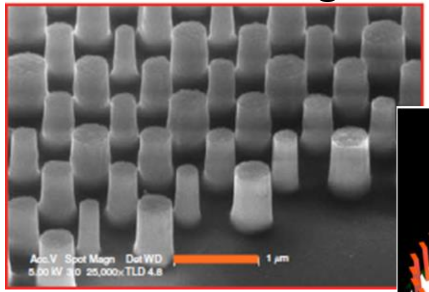
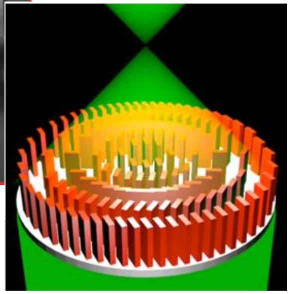
- Classical DOE:
  - Control phase by material height
- Phase sampling:
  - DOE -> greyscale or multi-layer lithography
  - Meta-surface: single lithography step
- Metasurfaces are **DOEs + extra functions**:
  - Polarization selectivity
  - Tuned spectral response: a- or hyper-chromatic
  - Combined functionalities
  - Non-linear and/or topology effects

PlanOpSim

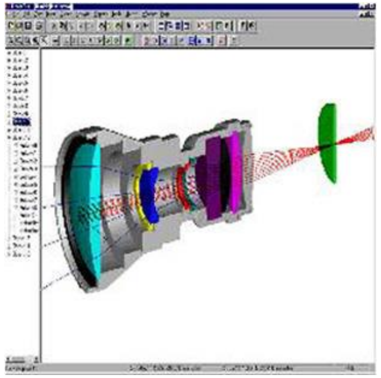
Nano-scale design



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 Planar Optics & metasurfaces
  - All-in-one design workflow
- **Design service** for metasurfaces and photonics
  - In-house and 3[d] party tools

Why use PlanOpSim

	PlanOpSim Enlightened Planar Optics	Ansys Lumerical	LightTrans	SYNOPSYS
CLOUD OR LOCAL	✓	✗	✗	✗
INTUITIVE LEARNING CURVE	✓	✗	✗	✗
LARGE AREA	✓	✗	✗	✗
INTEGRATION WITH **RAY TRACING**	✓	✓	✓	✓
SCRIPTING	✓	✓	✓	✓
EXPORT TO **MANUFCATURING**	✓	✗	✓	✓
FULL METASURFACE **WORKFLOW**	✓	✓	✗	✓
DEDICATED META-SURFACE **SUPPORT**	✓	✗	✗	✗

- Dedicated meta-surface UI and design workflow
- High speed simulation
- Multi-scale simulations from nano- to macroscale
  - Meta-atom -> full wave RCWA
  - Components -> Physical optics
  - Systems -> Integration to ray-tracing

Design steps

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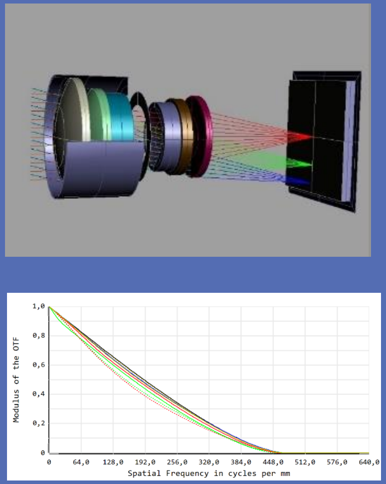
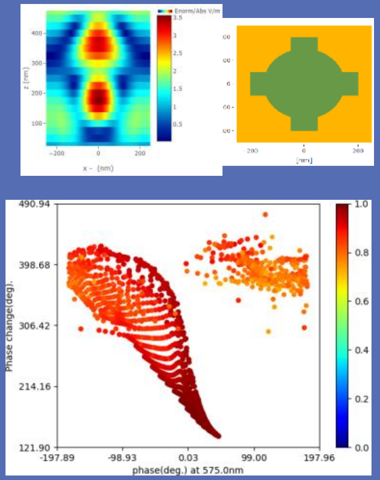
System model
- Ray tracing
- Analytical



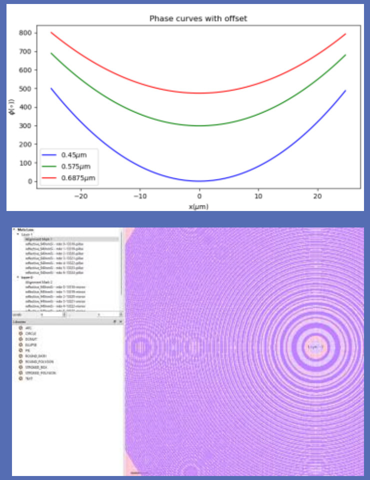
Ideal wavefront

Meta-atom design
- Full wave
- nm scale



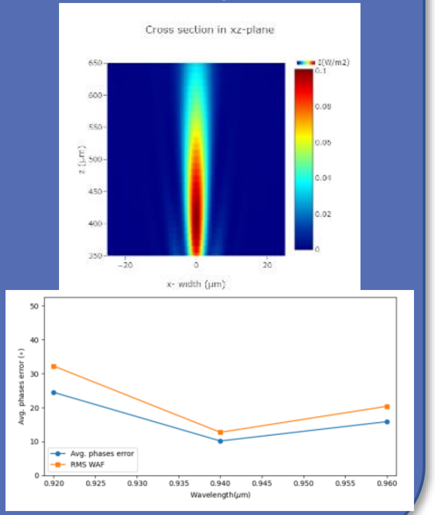
Meta-atoms

Component Design
- Target matching
- mm scale



Wavefront

Analysis
- Physical Optics
- Efficiency & PSF

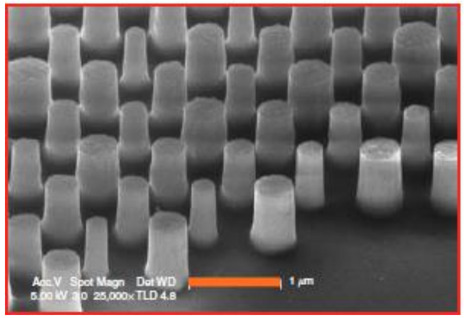


- ❖ Theory or ray-tracing
- ❖ Geometric optics
- ❖ cm-m -km

- ❖ Full wave calculation
- ❖ Maxwell solver
- ❖ nm- μm
- ❖ Very time memory intensive (RCWA, FDTD, FEM, …)

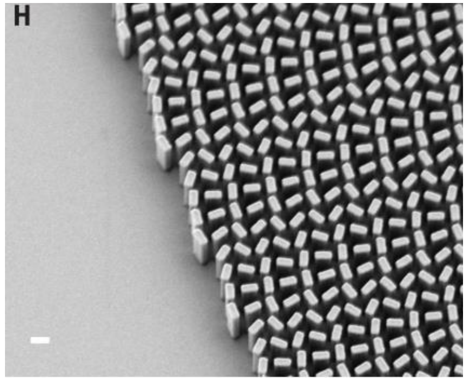
- ❖ Propagation optics
- ❖ μm-cm scale
- ❖ (Approximated) wave calculations

Nanostructure types



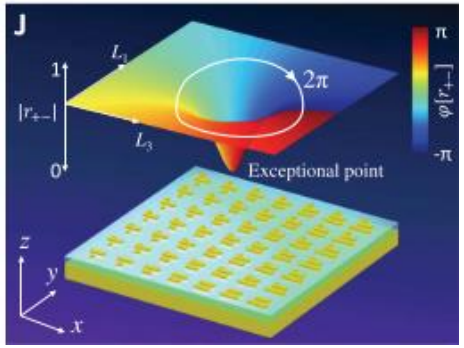
Propagation phase

- ❖ Waveguide confinement
- ❖ Phase created by optical path length $\varphi = -k_0 n_{eff} d$
- ❖ Structure change -> change n_{eff}
- ❖ Height change -> DOE



Pancharatnam-Berry phase

- ❖ Polarization conversion effect
- ❖ Phase created by rotation of wave plate
- ❖ Non-symmetric structure creates structural birefringence



Resonant phase

- ❖ Strong phase change when ‘crossing’ a resonance
- ❖ Phase control by different perturbations vs peak of resonance
- ❖ Strong selectivity
- ❖ Metal or dielectric structure

Meta-atom design

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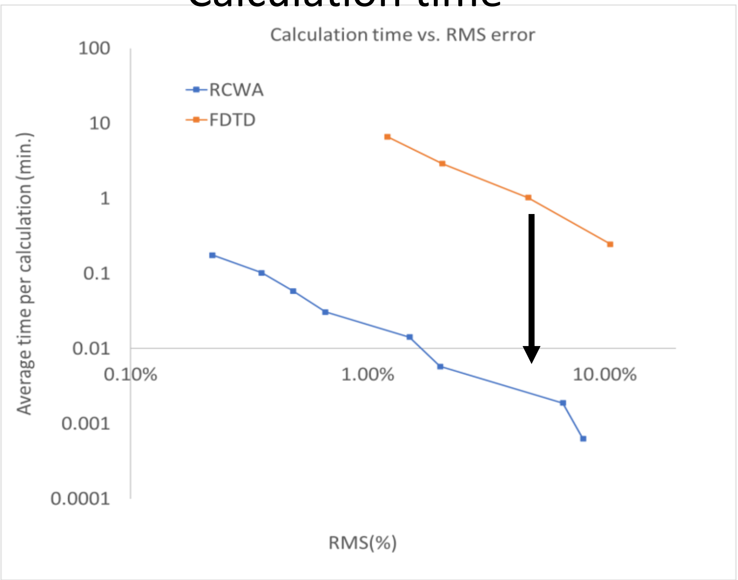
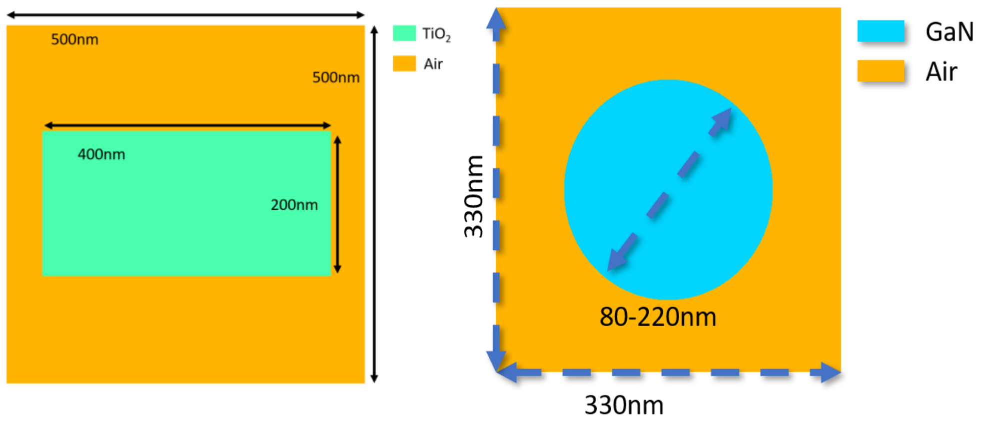
- All 3 mechanisms are present in a **full wave solver**
- Nano-structure calculation using **Rigorous Coupled Wave Analysis** (Maxwell solver)
- Thousands of nano-structures in parameter space
- Benchmark RCWA to FDTD
  - **RCWA is much faster** for meta-atom calculations
  - Meta-atom response same in RCWA and FDTD

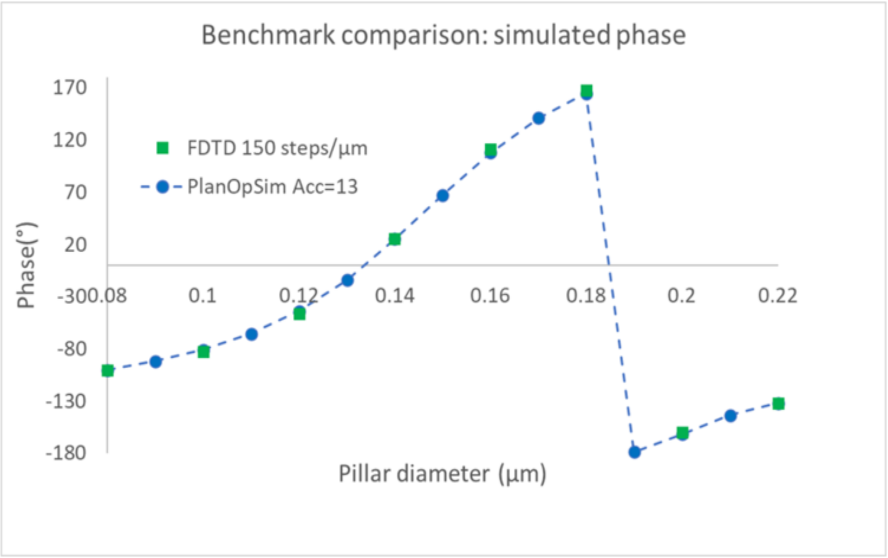
Calculation time





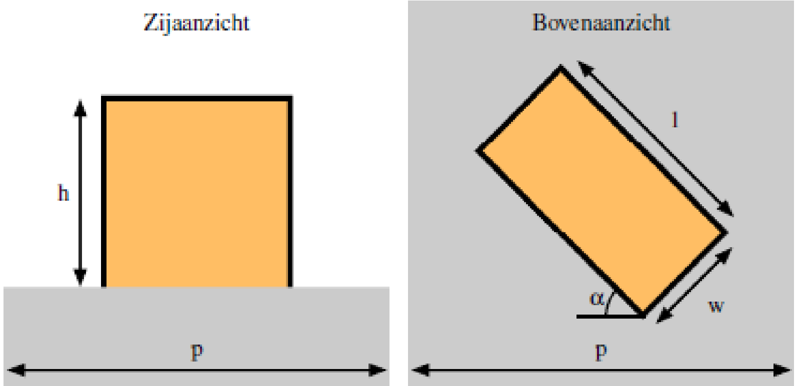
Test structures

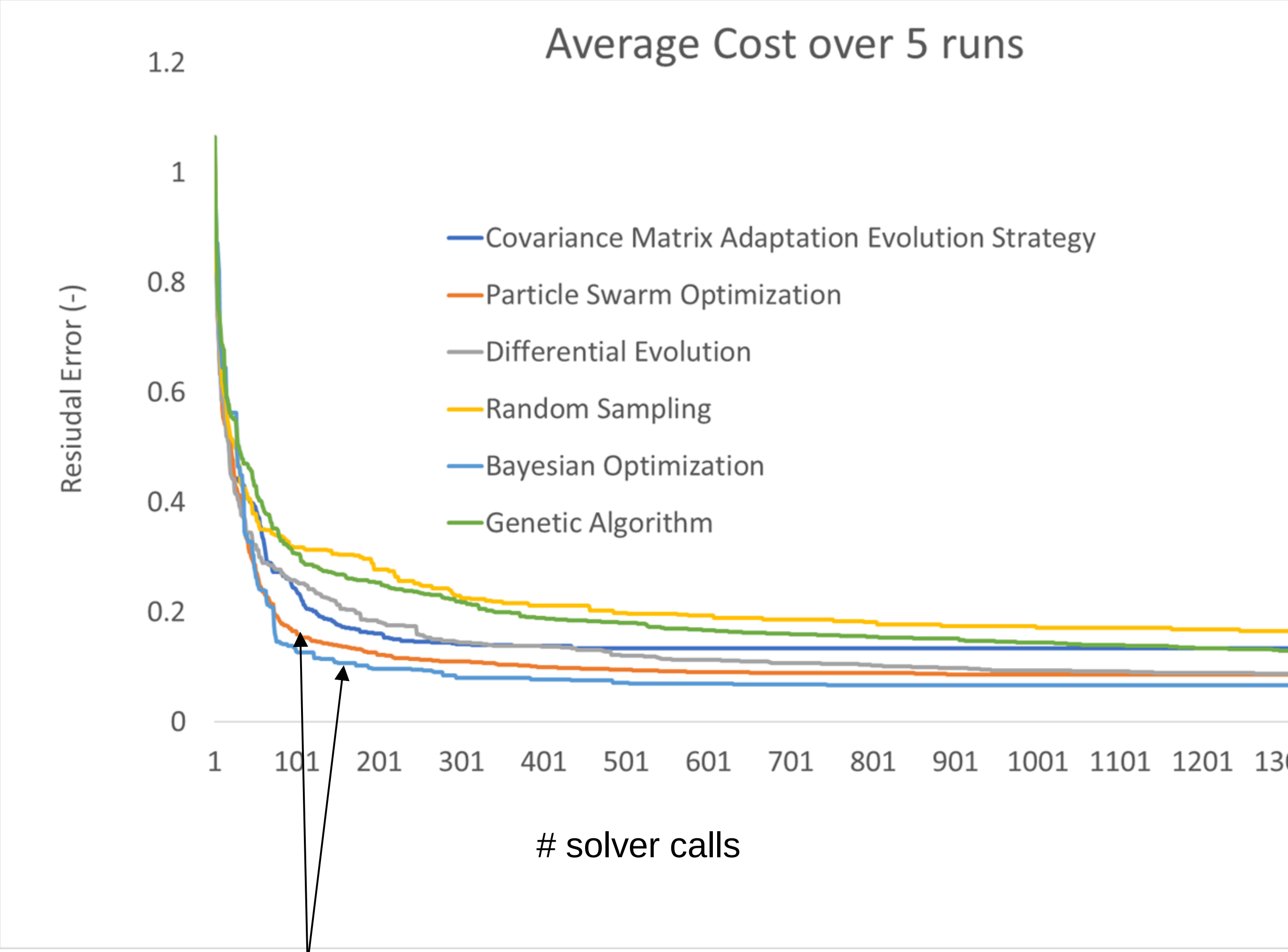
Calculated field response



Optimization/Machine learning

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





Particle swarm and Bayesian often perform best

- 7 algorithms available
  - Bayesian, Covariance Matrix, Differential Evolution, Genetic Algorithm, Gradient Descent, Particle swa[rm], Simulated Annealing

Meta-surface PDK

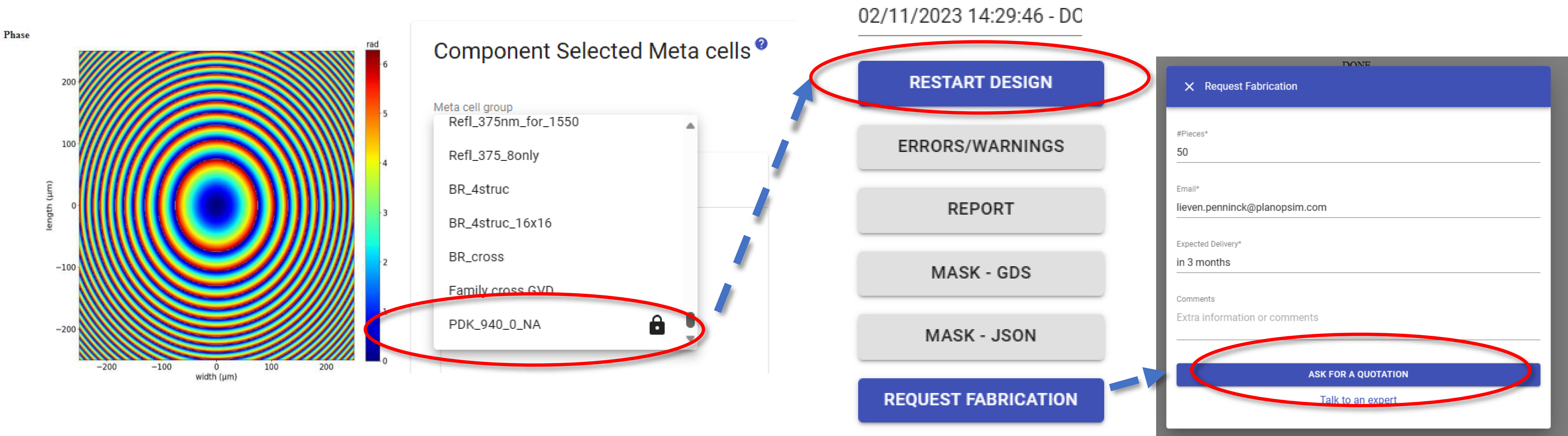
- Multi-project wafer service: **rapid prototyping**, cost effective
- Supported wavelength 940nm and size up to 5x5 mm
- **Manufacturer optimized and compatible** structure

0-order loss measurement

Step 1: select PDK and optical target

Step 2: run design

Step 3: submit design



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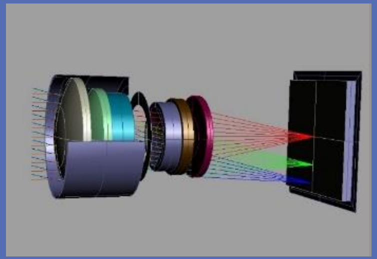
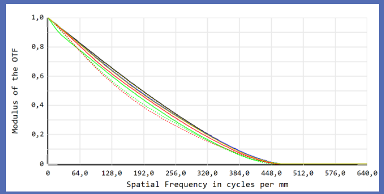
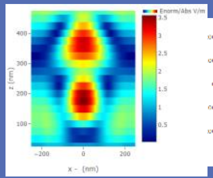
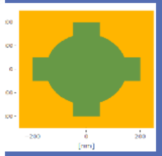


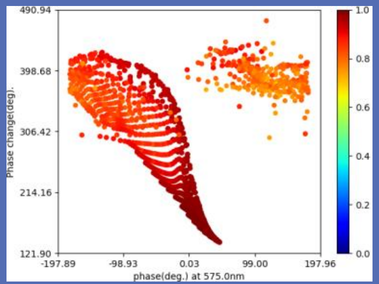


Ideal wavefront

Meta-atom design
- Full wave
- nm scale

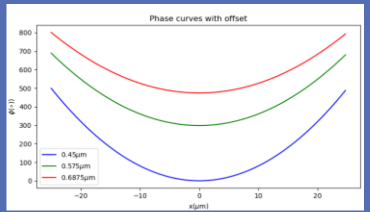


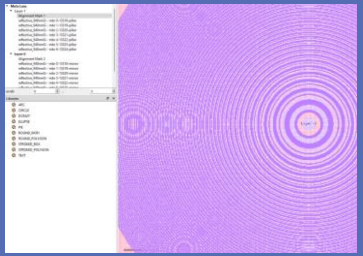




Meta-atoms

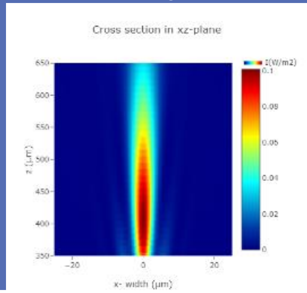
Component Design
- Target matching
- mm scale

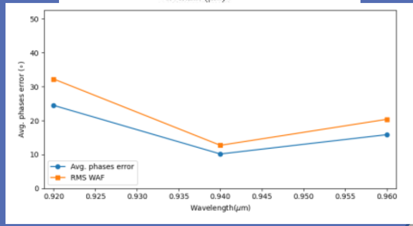




Wavefront

4) Analysis
- Physical Optics
- Efficiency & PSF





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- ❖ µm-cm scale
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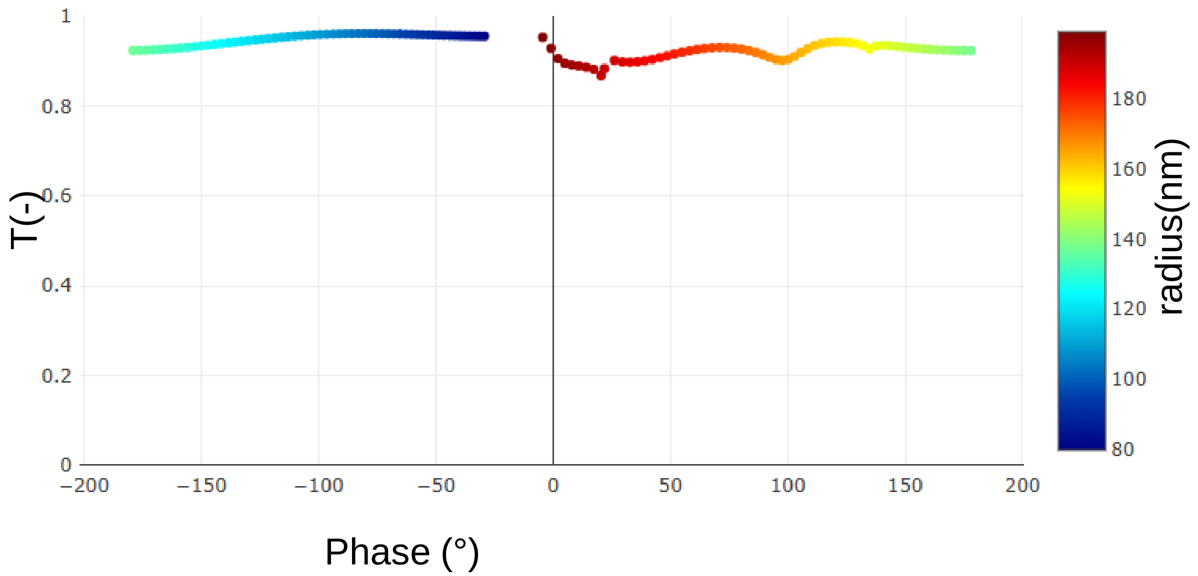
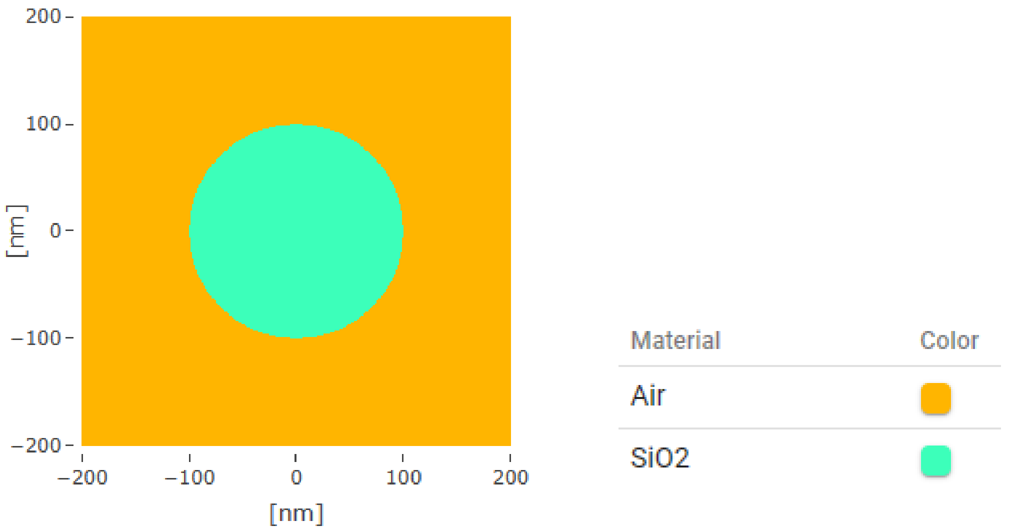
Meta-atoms in example lens

- Meta-atom library for demonstration
- Radius 80 – 200nm
- Optimized via RCWA (PlanOpSim Meta-Cell)
- Selected for 360° phase coverage



Parameter	Value
Unit cell	400 x 400nm
Wavelength	520nm
Angle of incidence	0°
Polarization	TE
Substrate	SiO_2
Height	1500nm



Reference design

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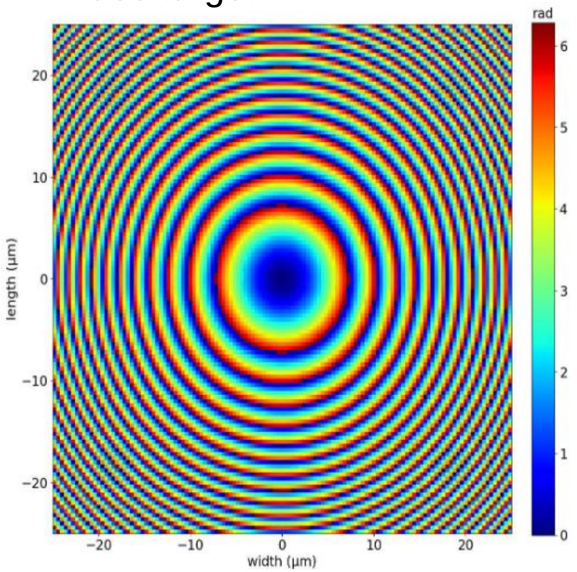
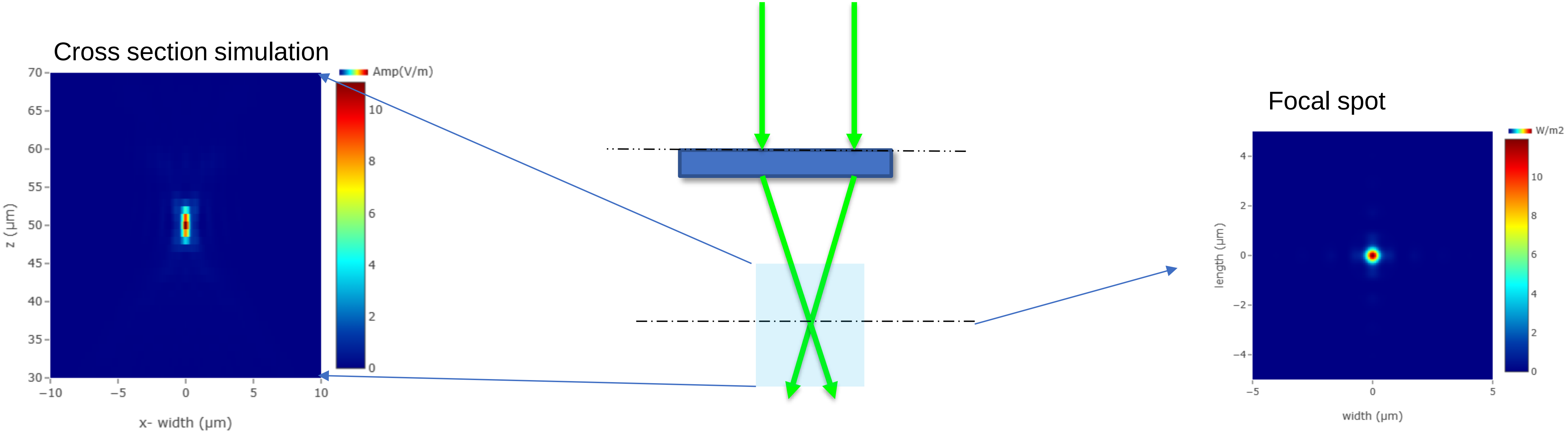
- Meta-lens target wavefront:

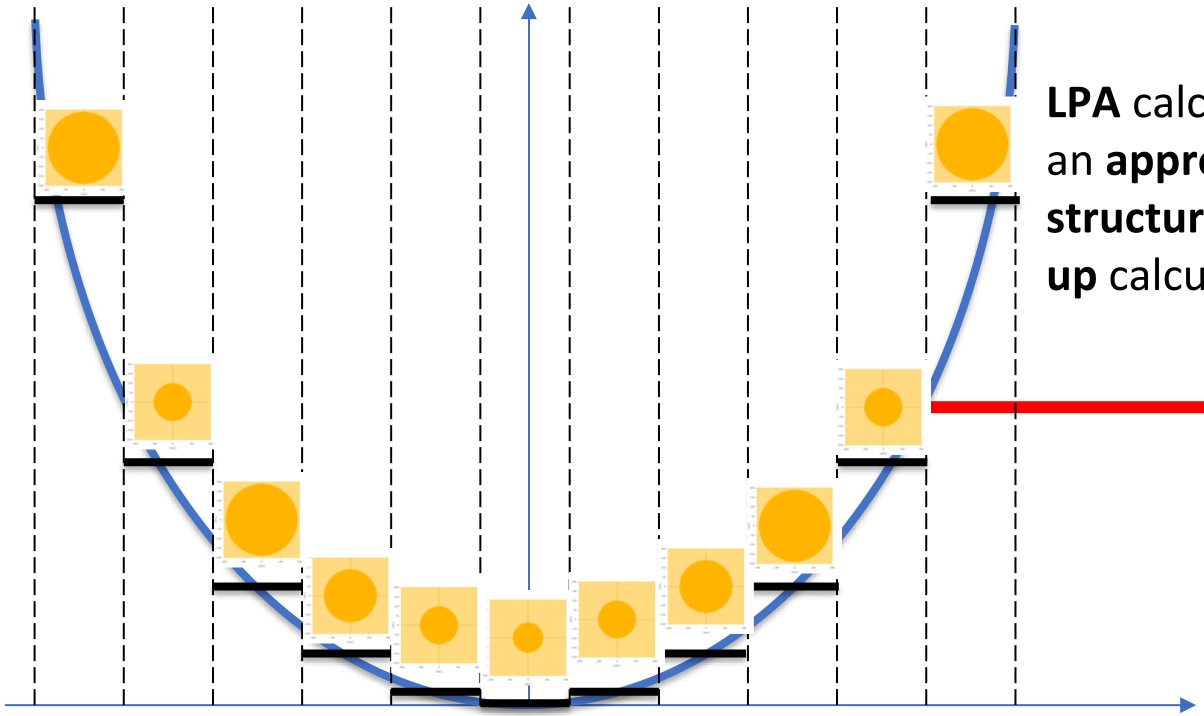
$$\varphi = \frac{2\pi}{\lambda}\left(\sqrt{r^2 + f^2} - f\right)$$

- Library phase placement
- Angular spectrum method simulation of focal spot
  - Transmission efficiency: 93,6%
  - Focusing efficiency: 80,6%

Phase target

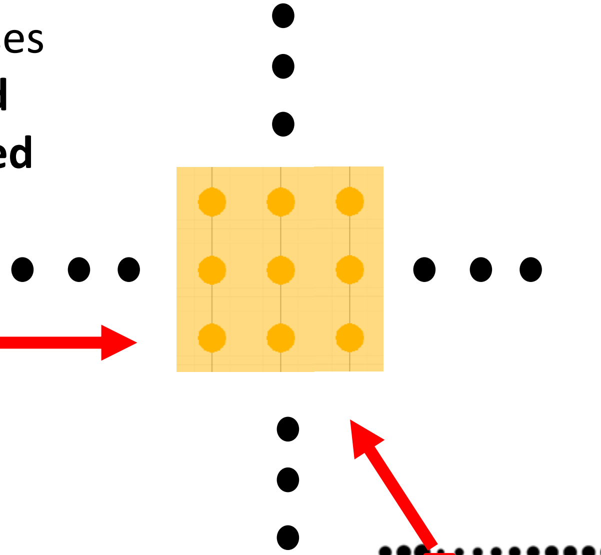


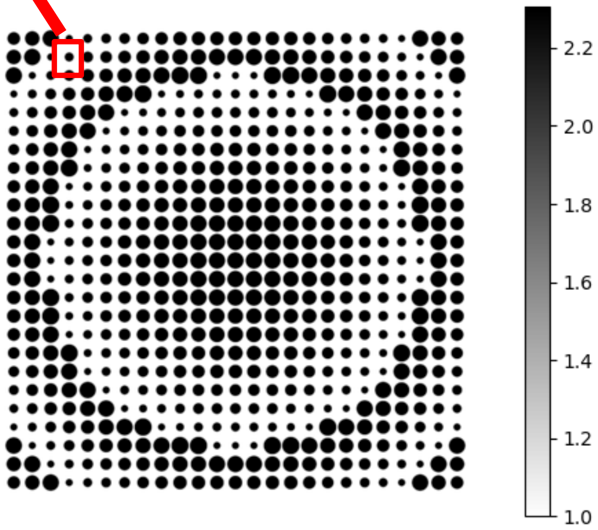




local periodic approximation

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

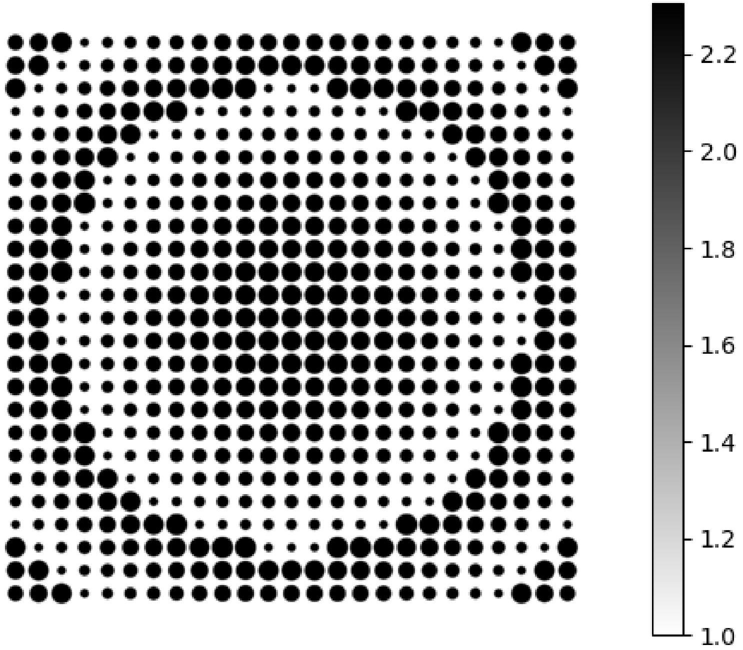


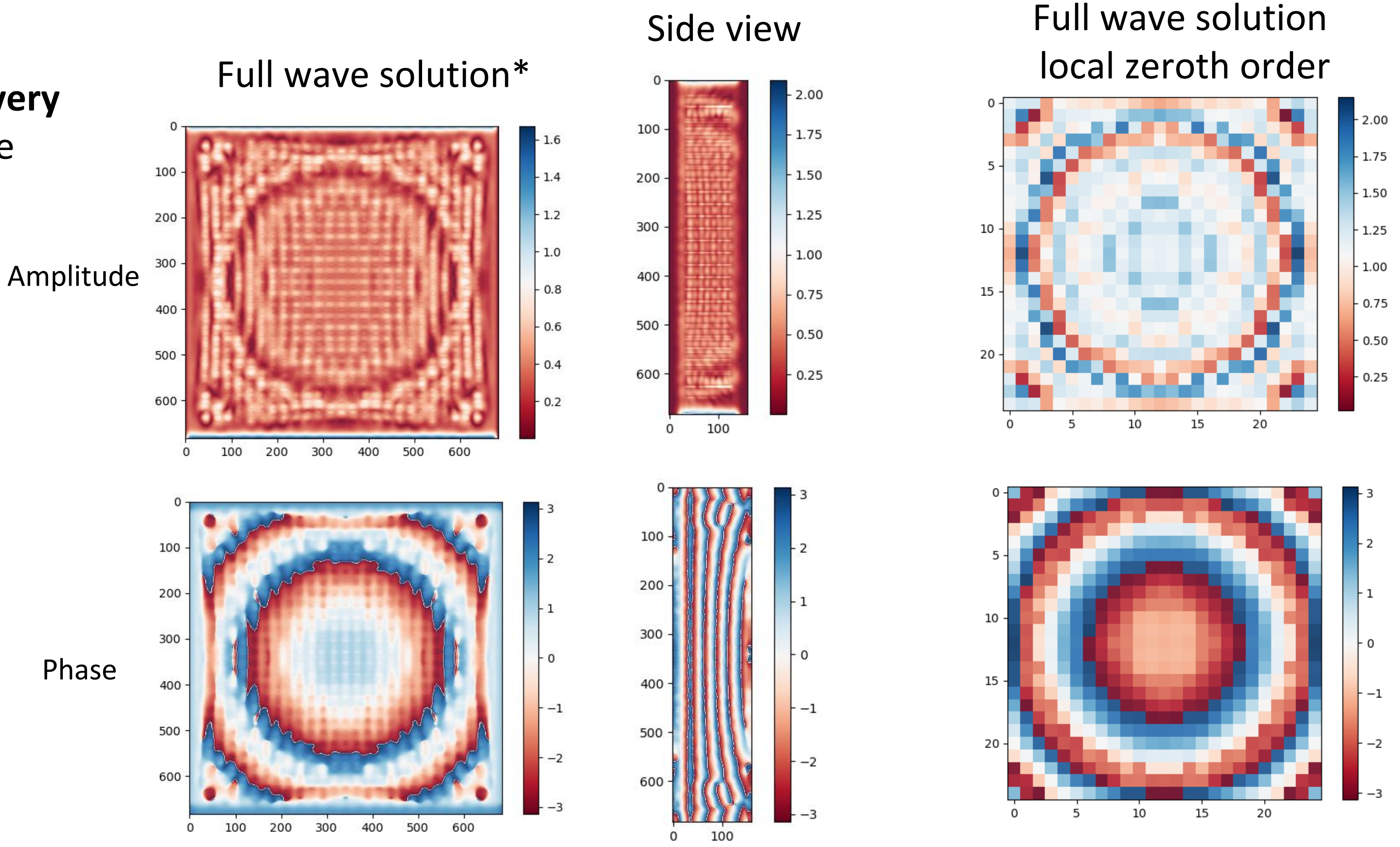


- Other aspects:
  - Pitch adjusted to Nyquist sampling
  - Phase discretization levels

Full wave calculations

Full wave calculations are accurate but **very slow and memory consuming**. In practice limited to ~100λ





* Simulations were performed with the finite-difference time-domain (FDTD) method, using an open-source software package MEEP
A. Oskooi, D. Roundy, M. Ibanescu, P. Bermel, J.D. Joannopoulos, and S.G. Johnson, "[MEEP: A flexible free-software package for electromagnetic simulations by the FDTD method](#)," *Computer Physics Communications*, Vol. 181, pp. 687-702 (2010) ([pdf](#))

Comparison

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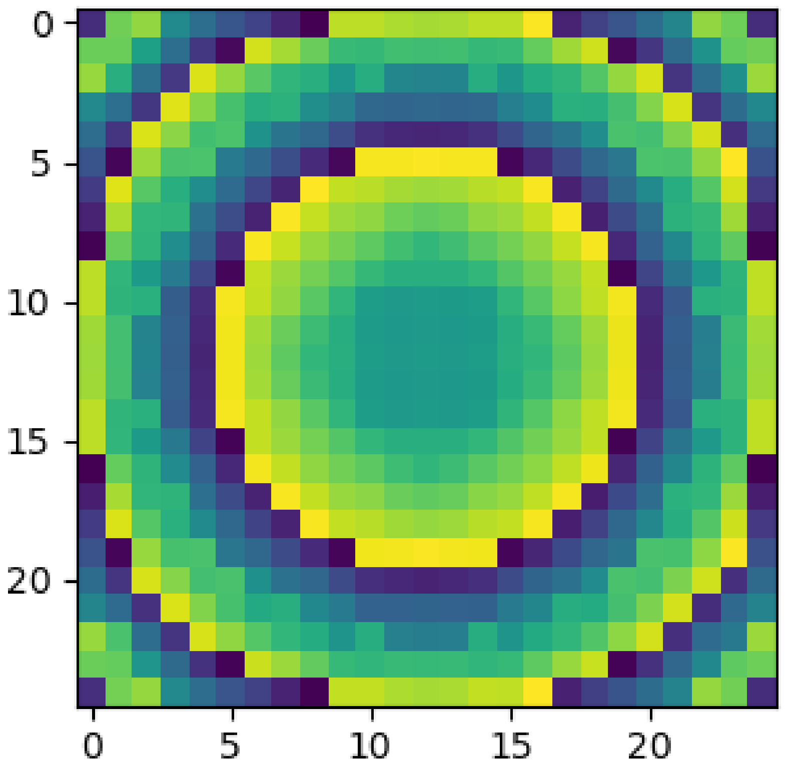
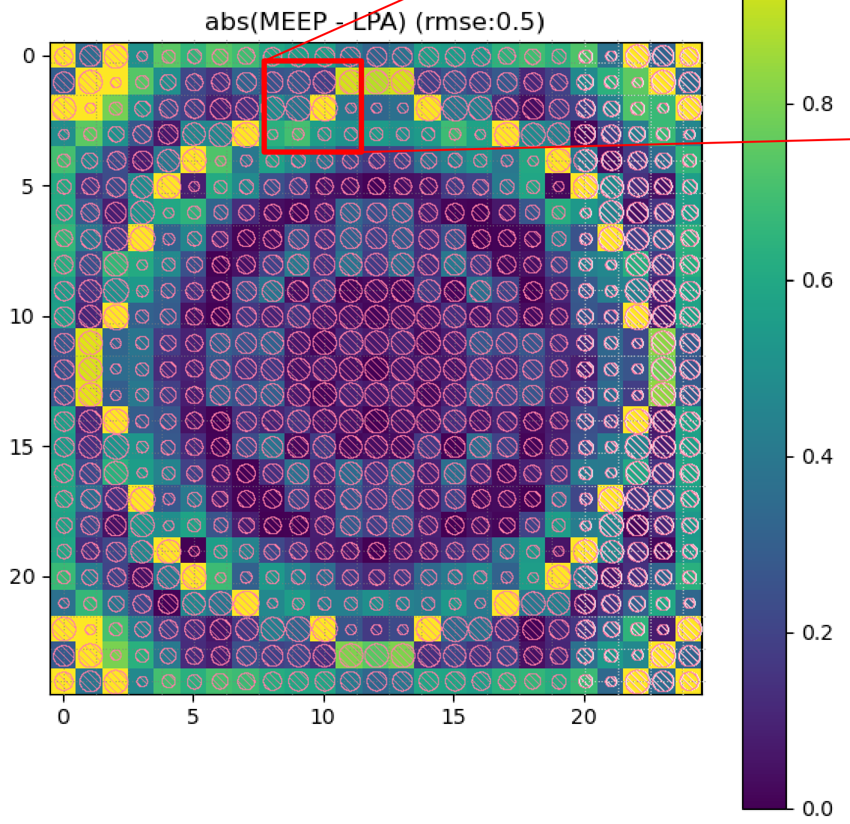
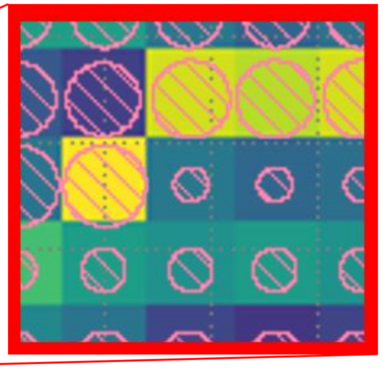
Full wave 'ground truth'



LPA deviation





ODA vs. LPA

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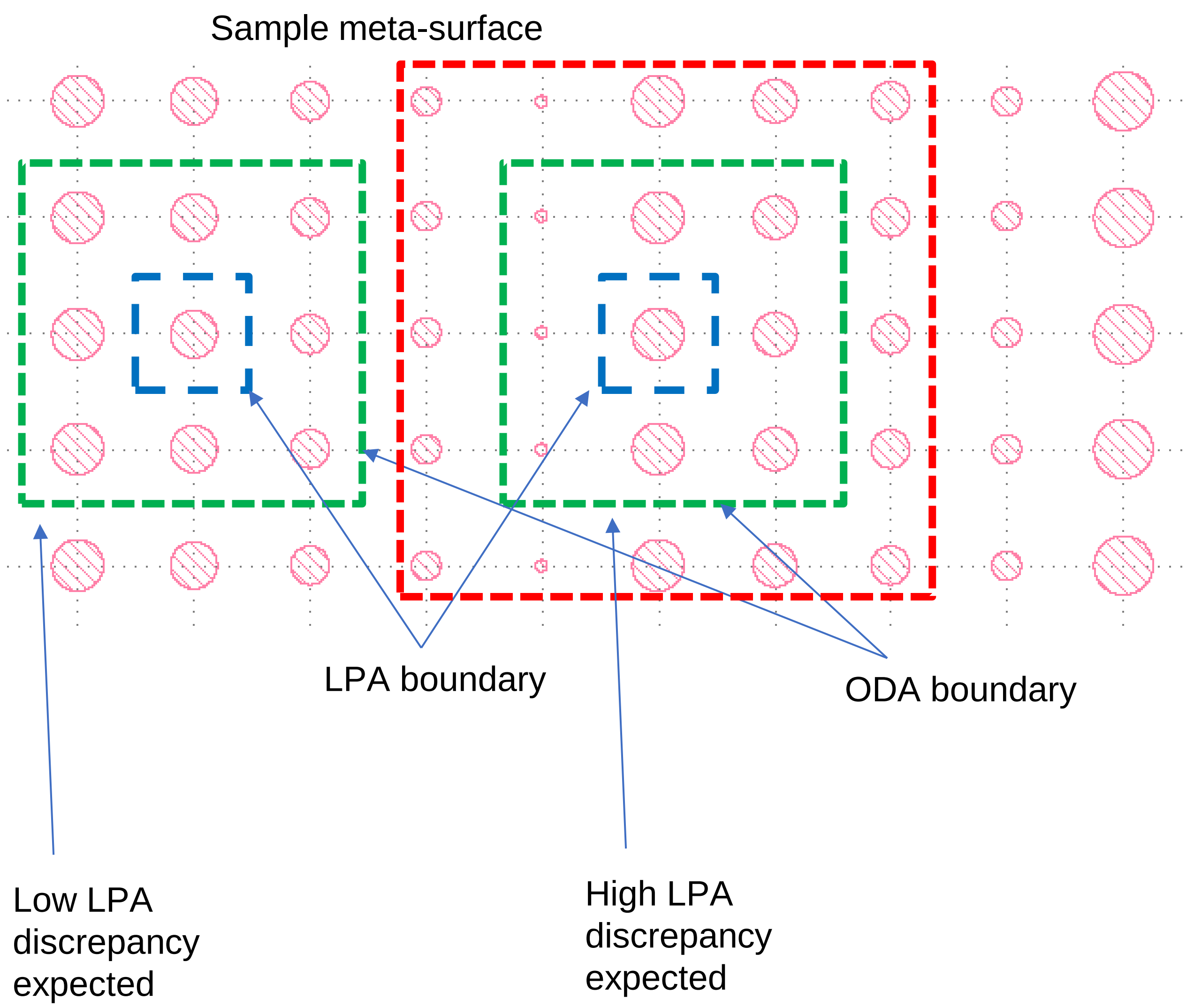
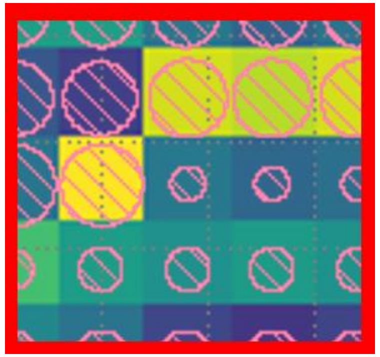
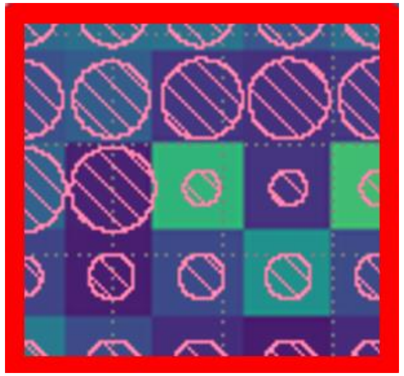
- Standard meta-surface design flow:
  - Meta-atom: periodic boundary
  - Meta-surface: phase mapping, implicit local periodic approximation (LPA)
- Overlapping Domain Approximation (ODA)
  - Expand simulation area per met-atom
  - Choice of #neighbours 0, 1, 2, ...
  - Calculate with RCWA
  - Extract field amplitude and phase for central meta-atom
- Computational implications:
  - Library (8 values) -> scanning (1.3^{e}+8)

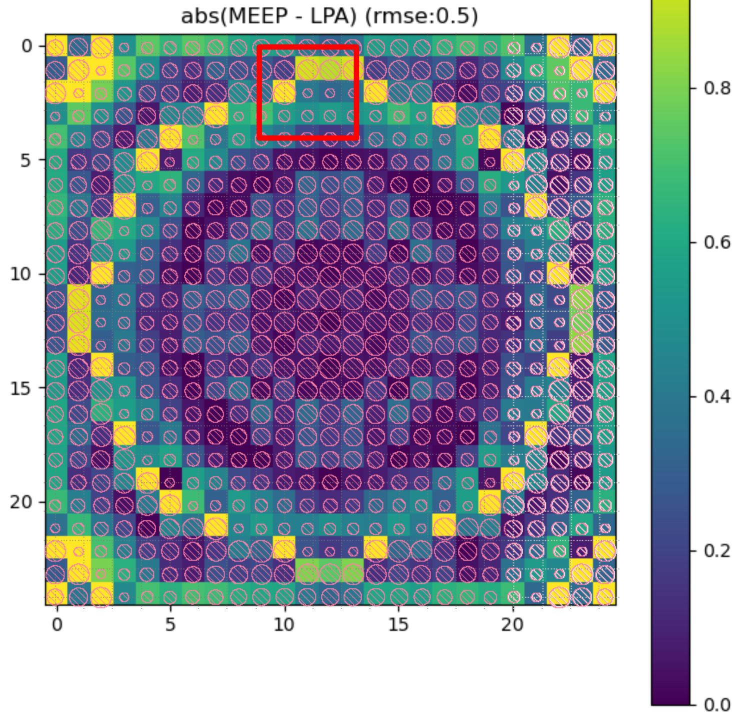


Phase error

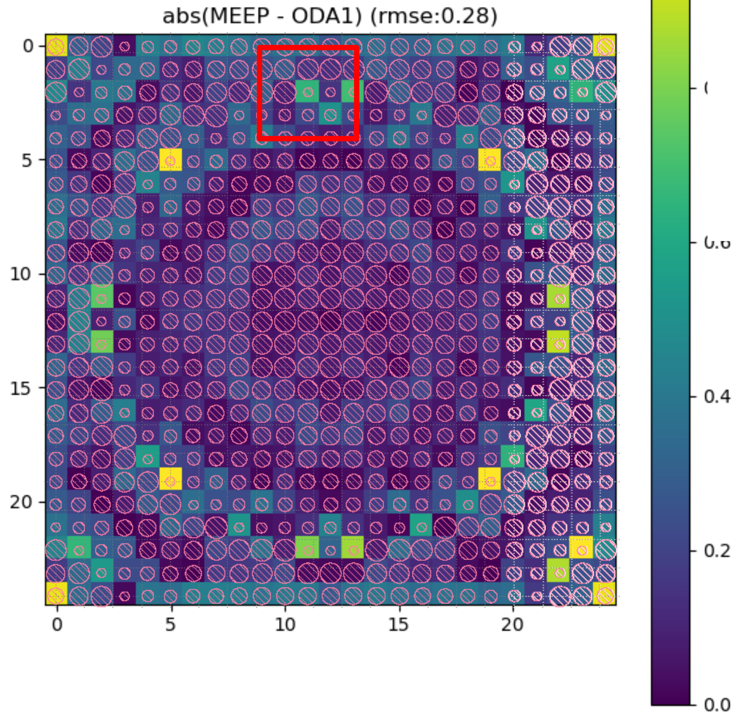


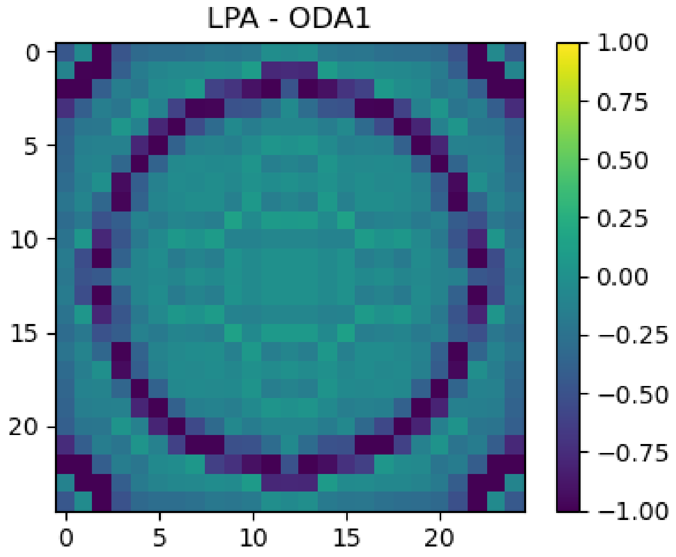


LPA deviation



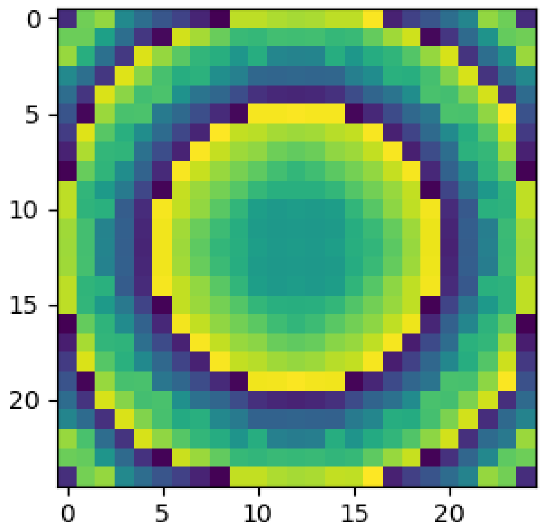
ODA deviation



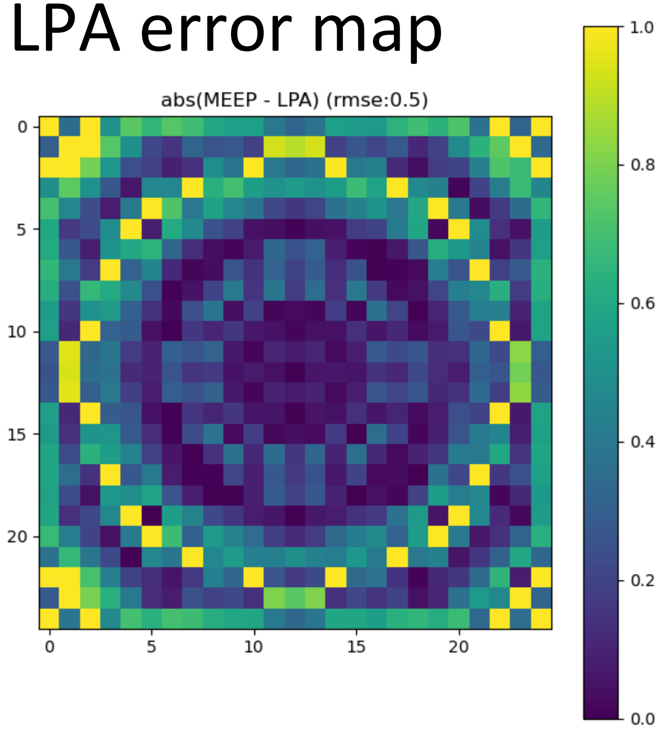


Comparison

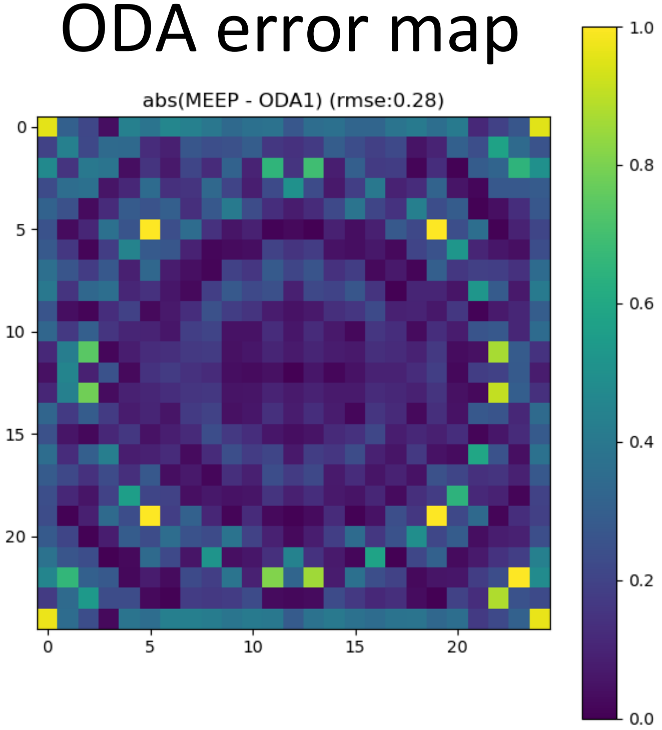
Full wave ‘ground truth’



LPA error map



ODA error map



Overlapping Domain Analysis improves meta-surface calculation accuracy and is **18x faster than full wave calculation**

	Calculation time*	Memory usage	rmse	Max. diameter*
LPA	1 minute	<1Gb	0,5	6000 µm
ODA	20 minutes	8Gb	0,28	120µm**
Full wave (meep)	6 hours	32Gb		10µm

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

Design steps

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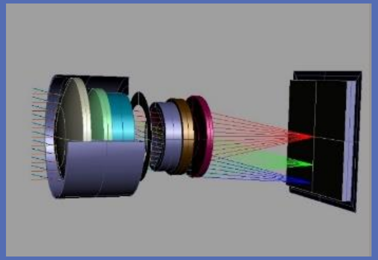
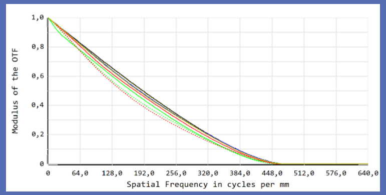
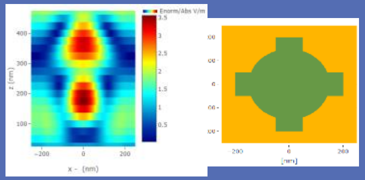
System model
- Ray tracing
- Analytical

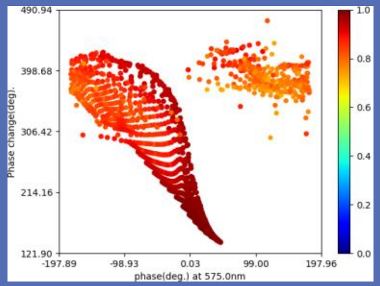




Ideal wavefront

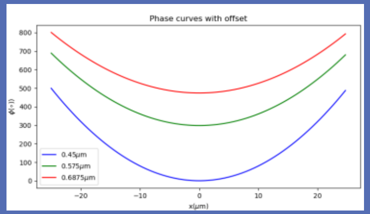
Meta-atom design
- Full wave
- nm scale

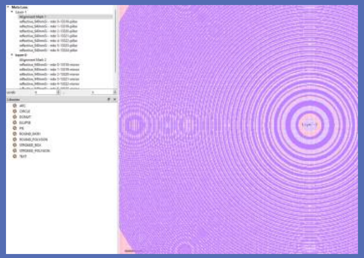




Meta-atoms

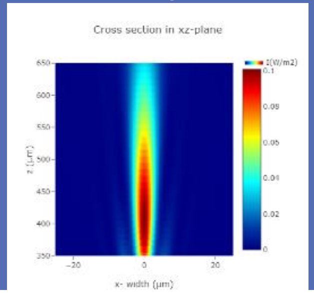
Component Design
- Target matching
- mm scale

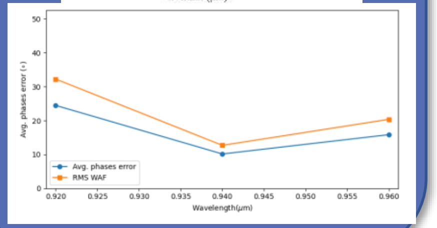




Wavefront

Analysis
- Physical Optics
- Efficiency & PSF





- ❖ Theory or ray-tracing
- ❖ Geometric optics
- ❖ cm-m -km

- ❖ Full wave calculation
- ❖ Maxwell solver
- ❖ nm- µm
- ❖ Very time memory intensive (RCWA, FDTD, FEM, …)

- ❖ Propagation optics
- ❖ µm-cm scale
- ❖ (Approximated) wave calculations

Ray tracing

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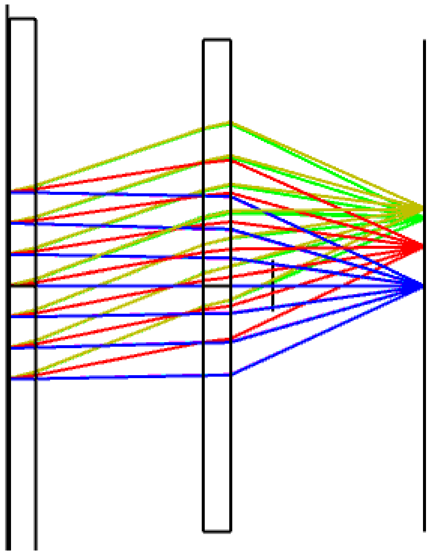
- Analytical calculation only possible in simple systems
- Realistic situations:
  - Multiple specifications
  - Multiple components
- **Optimize** wavefront **in ray tracing**
  - Parametrized wavefront description
  - E.g. polynomial series

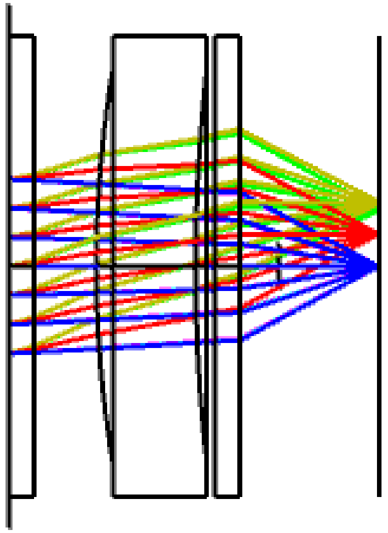
$$\Phi = M \sum_{i=1}^{N} A_i \rho^{2i}$$

- Advantages:
  - **Co-optimization** of multiple metasurfaces
  - Hybrid systems can be designed
  - Investigate complex performance trade-offs
- Disadvantage:
  - Idealized wavefront
  - Doesn’t account for meta-surface design options

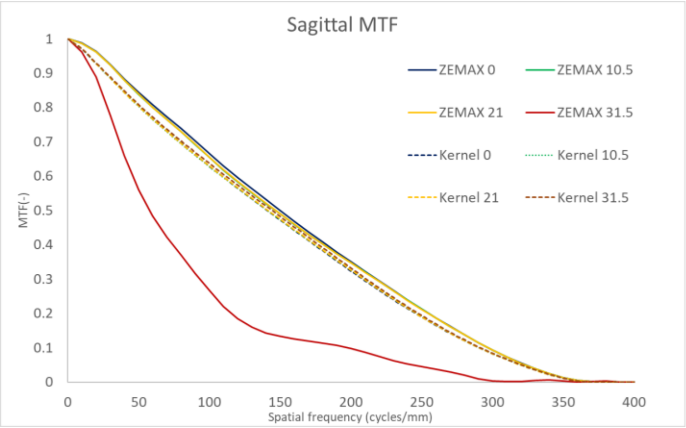
2 meta-surface system



Hybrid meta-surface + refractivesystem



System MTF vs. field angle



Dispersion engineering

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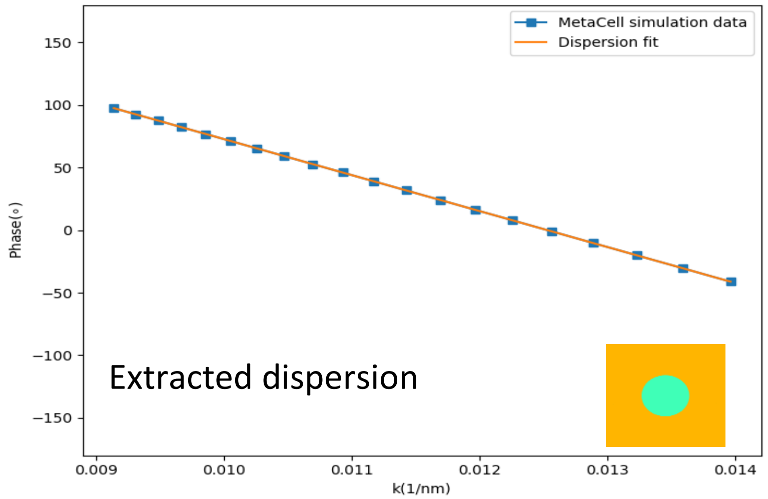
- Meta-surface offer control on material dispersion
- Dispersion engineering -> controlling phase and phase dispersion

Group delay (1st ortder)

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

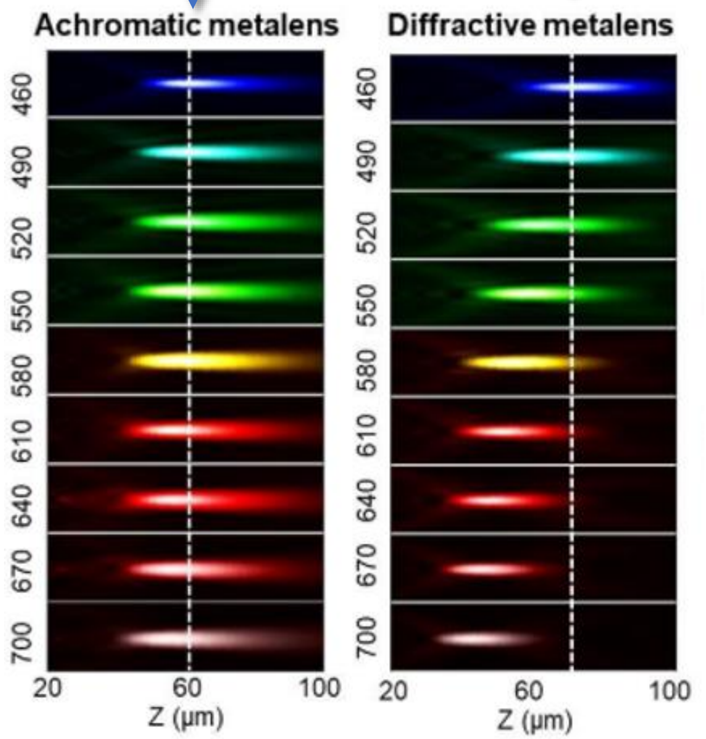
Group delay dispersion (2nd order)

- Extract phase and slope per structure



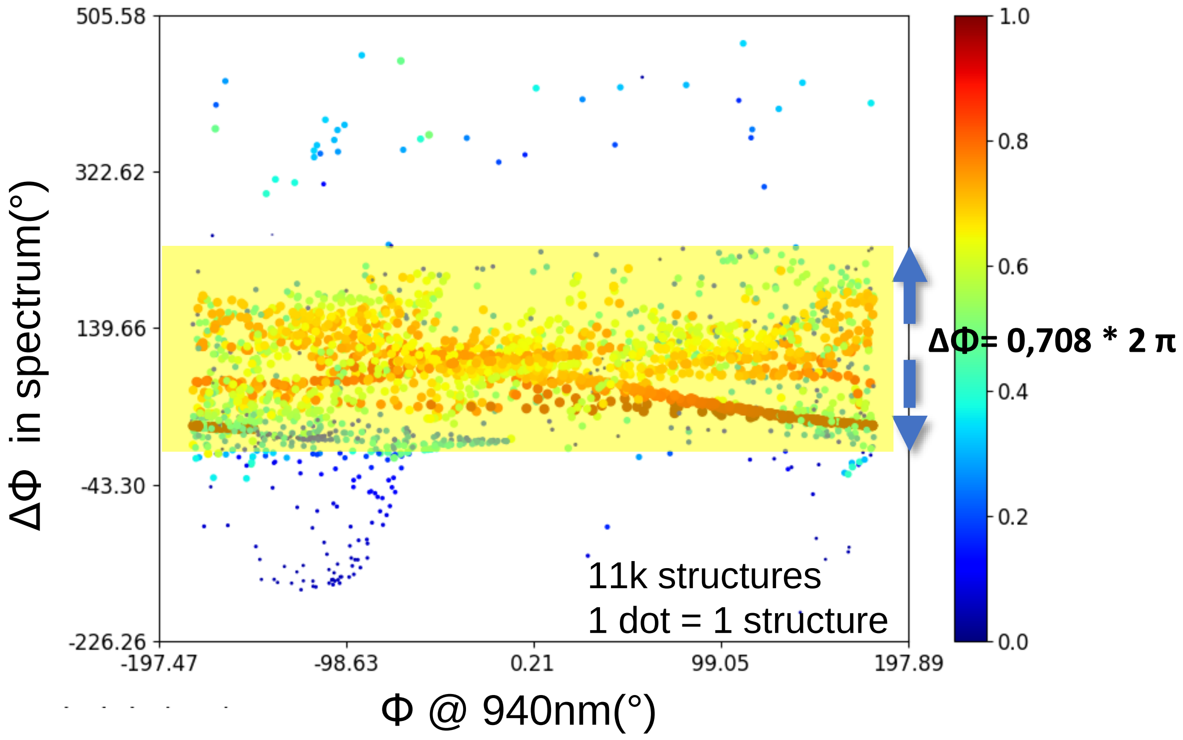
Dispersion corrected

Single wavelength design



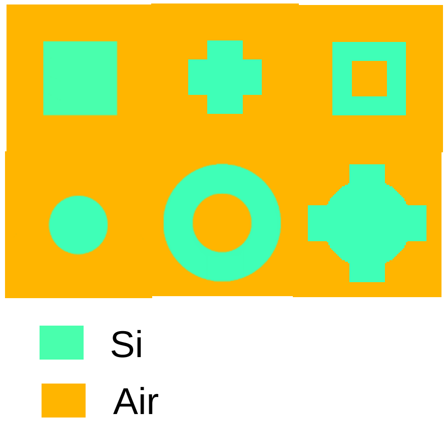
Wang, S. *et al.* A broadband achromatic metalens in the visible. *Nat. Nanotechnol.* **13,** 227–232 (2018).

Dispersion extraction



- Phase + phase dispersion library
- Mapping:
  - phase Φ
  - phase dispersion ΔΦ over spectral band
  - Transmission in band
- Structures in library

Structures in library



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

Example: hybrid design

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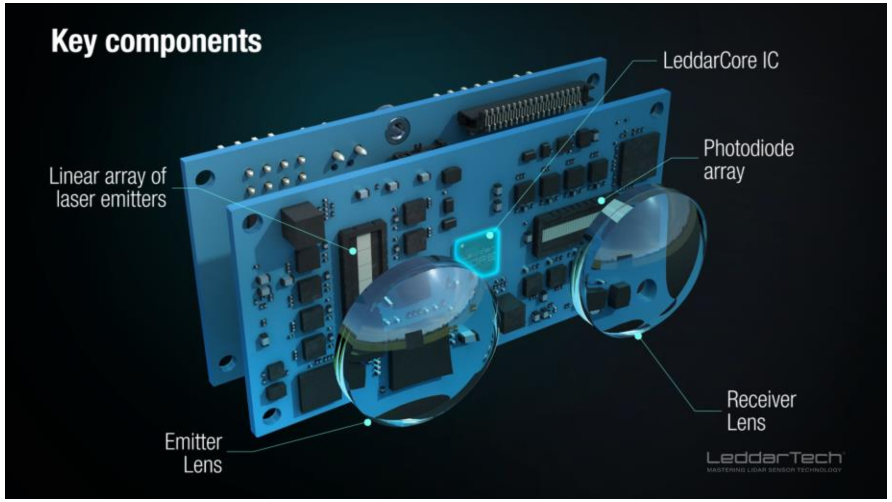
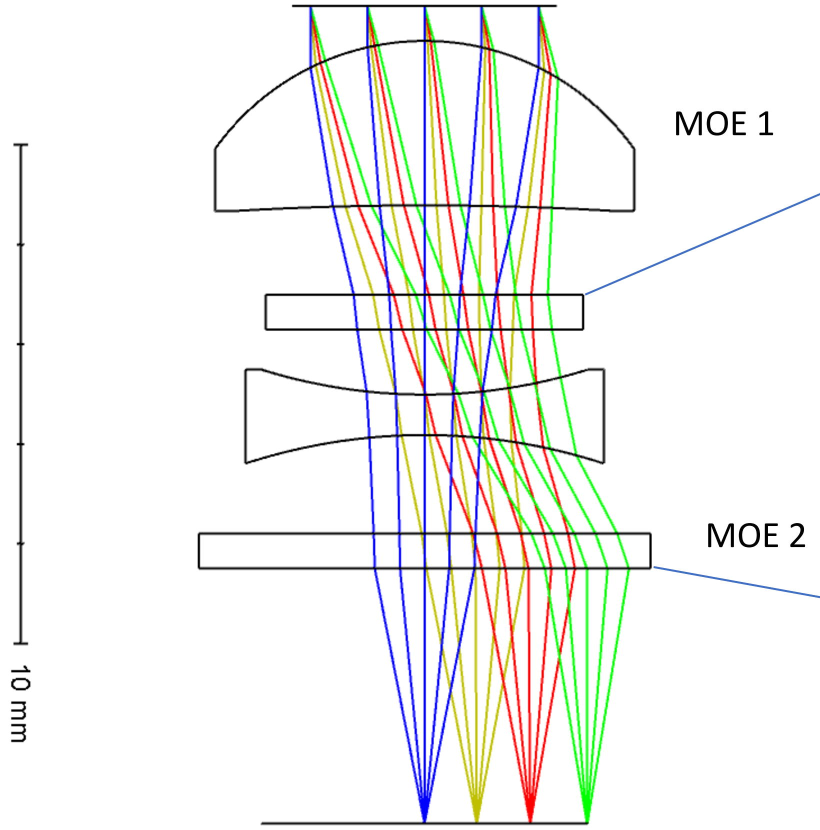
- Apply meta-surface capability in a system
- Include meta-atom behaviour in the optimizers merit function
- **Hybrid** meta-surface + refractive lenses

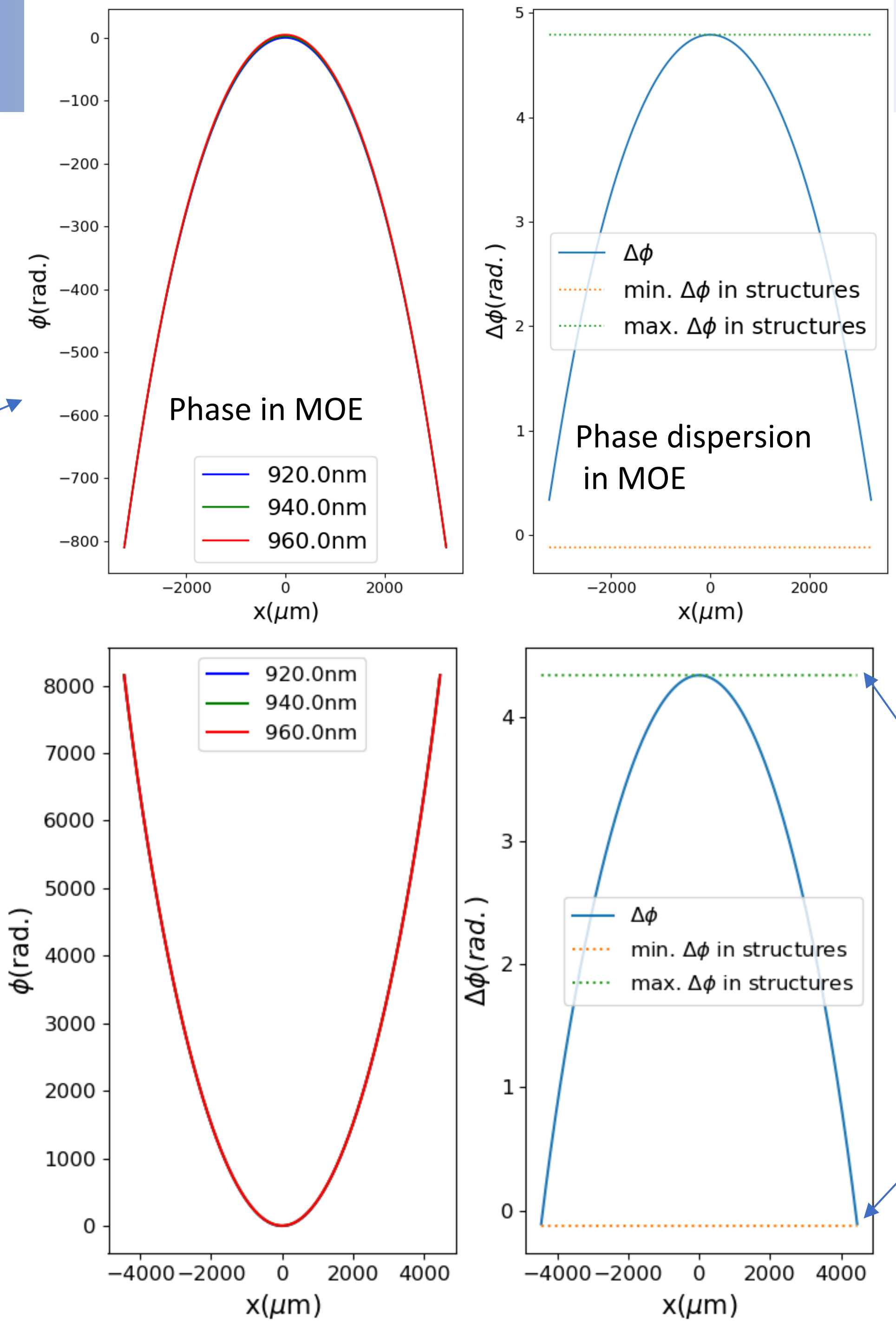
Example application: depth sensor

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%

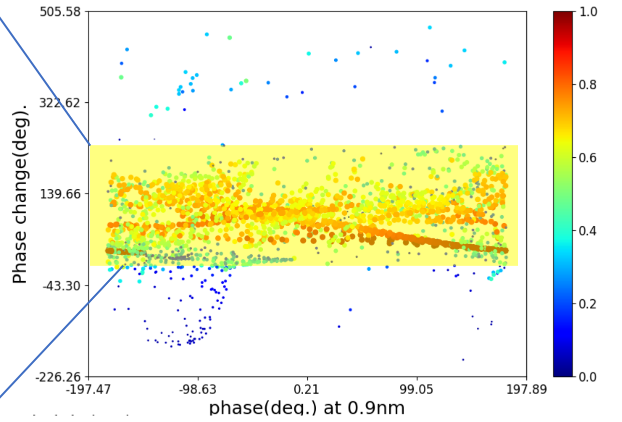


Design result





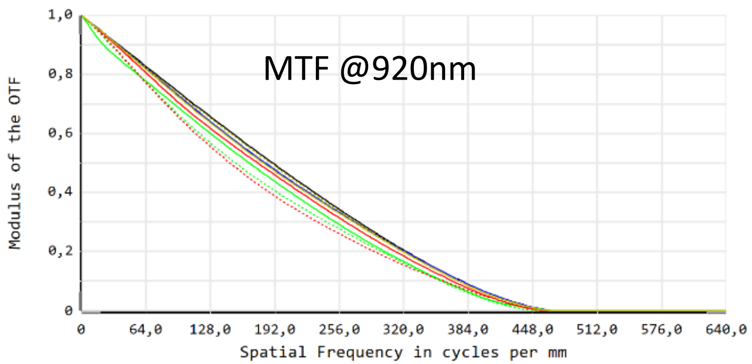
- Co-optimized meta + refractive design
- Optimization within boundary of library structures

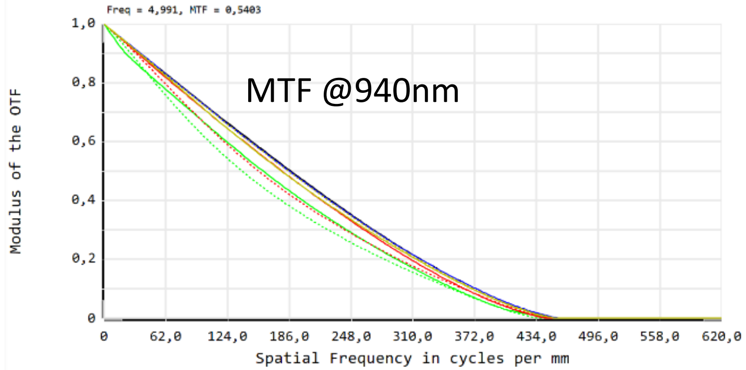


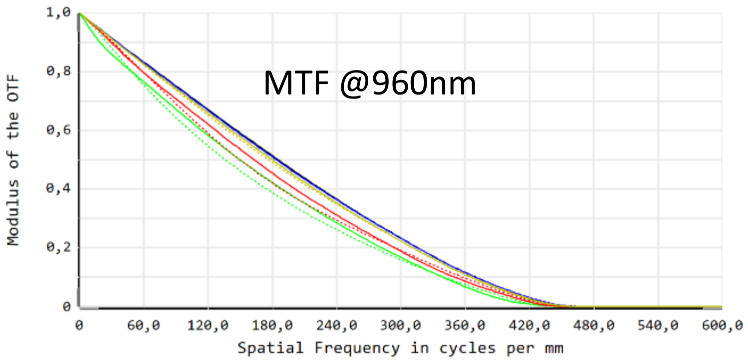
System design

❖ 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			

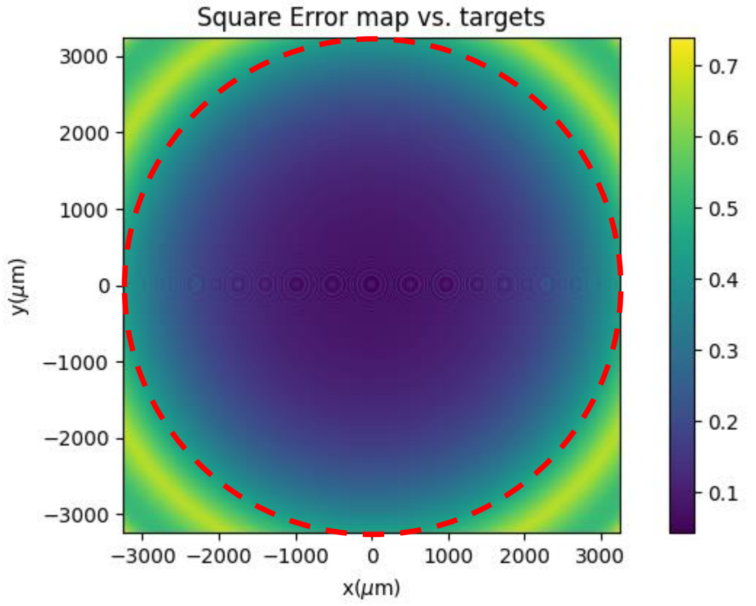




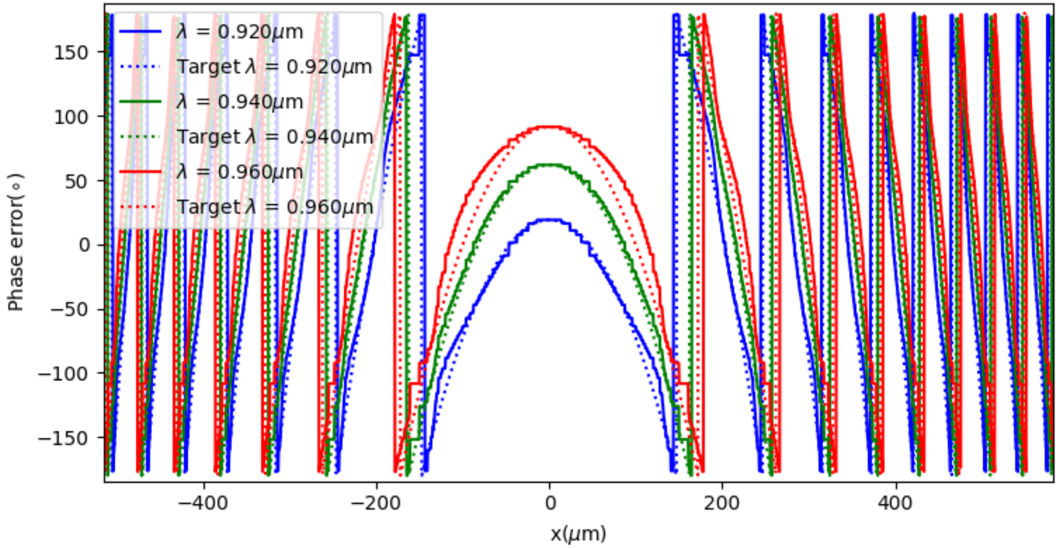


Target error MOE1

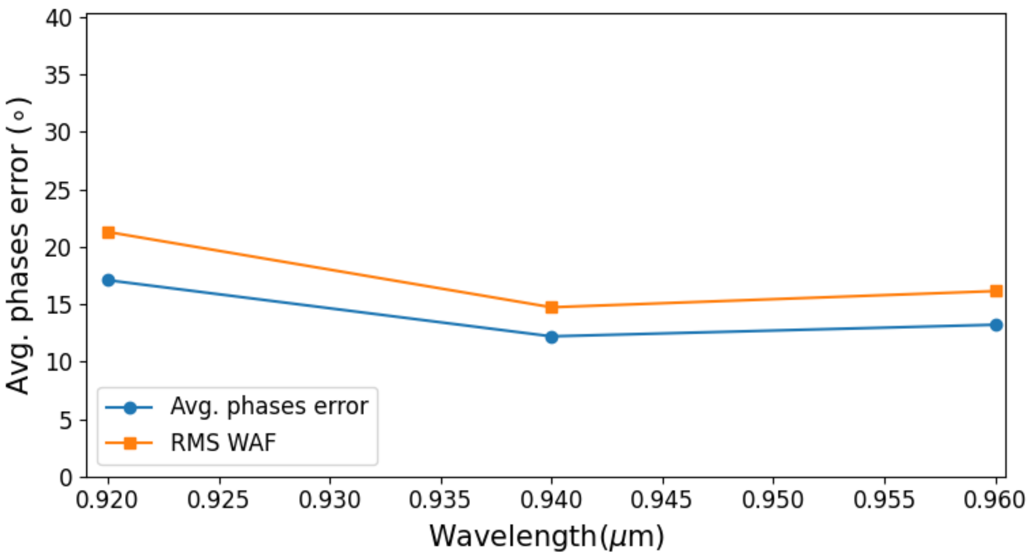
- ❖ Target well reproduced in active area
- ❖ Corners exceed dispersion range -> poor target reproduction
- ❖ RMS Waverfront aberration <21°(= λ/17)



Target vs. Meta-surface phase



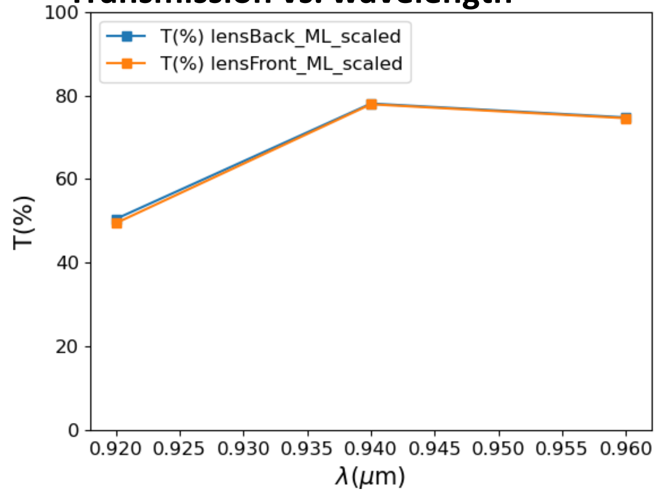
Phase error vs. wavelength



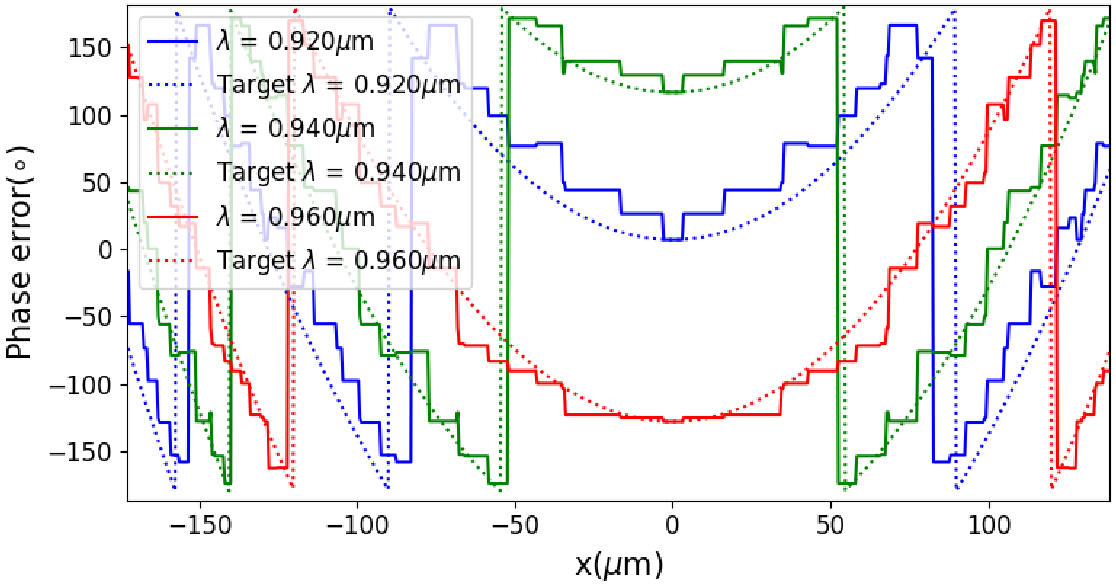
Target error MOE2

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

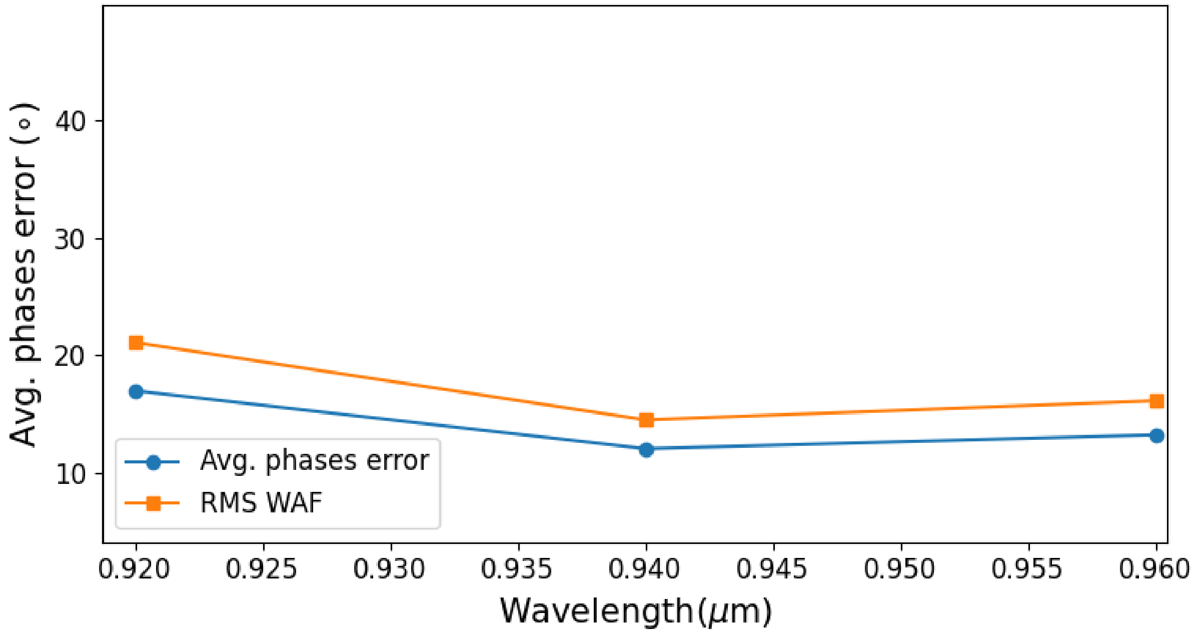
Transmission vs. wavelength



Target vs. Meta-surface phase

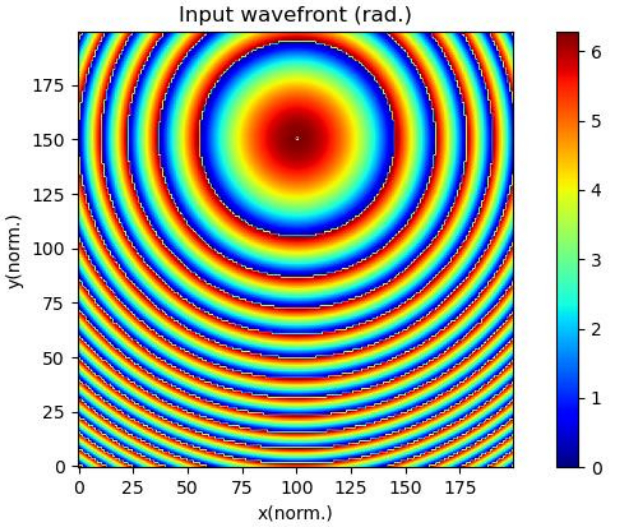


Phase error vs. wavelength

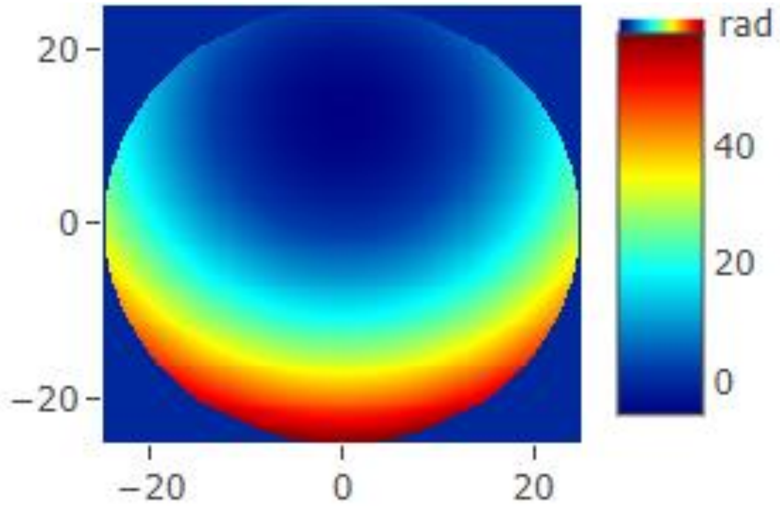


Ray tracing meta-surfaces

NFWF

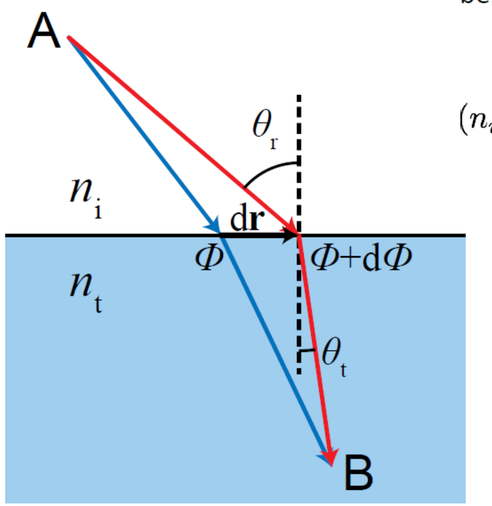


Restored NFWF



generalized law of refraction

Principle of least action → The difference between blue and red path is zero



$$(n_i k_0 sin\theta_i + \nabla\Phi)dr - (n_t k_0 sin\theta_t)dr = 0$$

For reflection

$$sin\theta_r - sin\theta_i = n_i^{-1} k_0^{-1} \nabla\Phi$$

For refraction

$$n_t sin\theta_t - n_i sin\theta_i = k_0^{-1} \nabla\Phi$$

- Metasurface wavefronts in ray tracing
- Millions of meta-atoms: too slow for propagation calculations
- Wave calculation has 2π wrapped phase
- Dependent on wavelength, incident angle, polarization
- To trace any ray **we need a differentiable description**

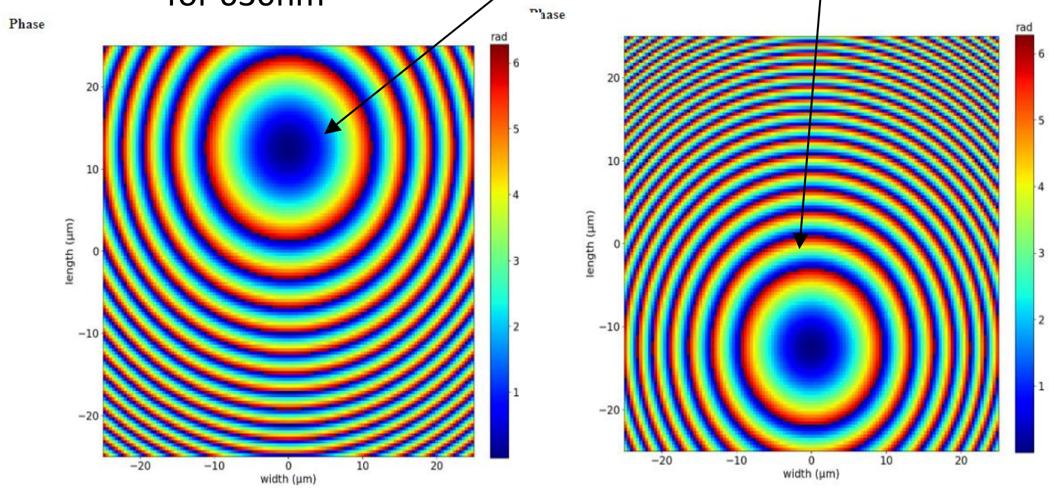
Ray tracing meta-surfaces

- **Meta-surface has a wavelength, polarization and angle dependant wavefront**
- **Separate target** nearfield wavefront **for 450 and 630nm**
- Lens profile:

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

for 630nm

for 450nm

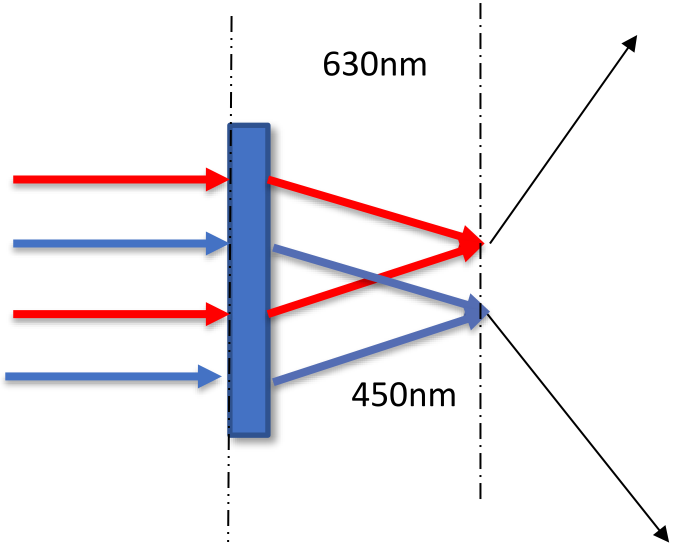


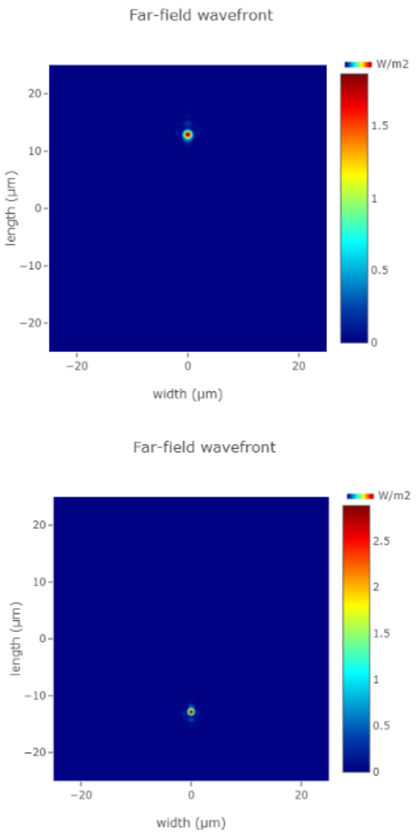
In this example

Quantity	Value
Dimensions	50µm x 50µm
Wavefront	100µm focal length with ±12,5 um shift in the y direction for
Wavelength	450nm & 630nm
Meta-atom library	From step 1
Decentering y_c	±12,5 µm for blue and red

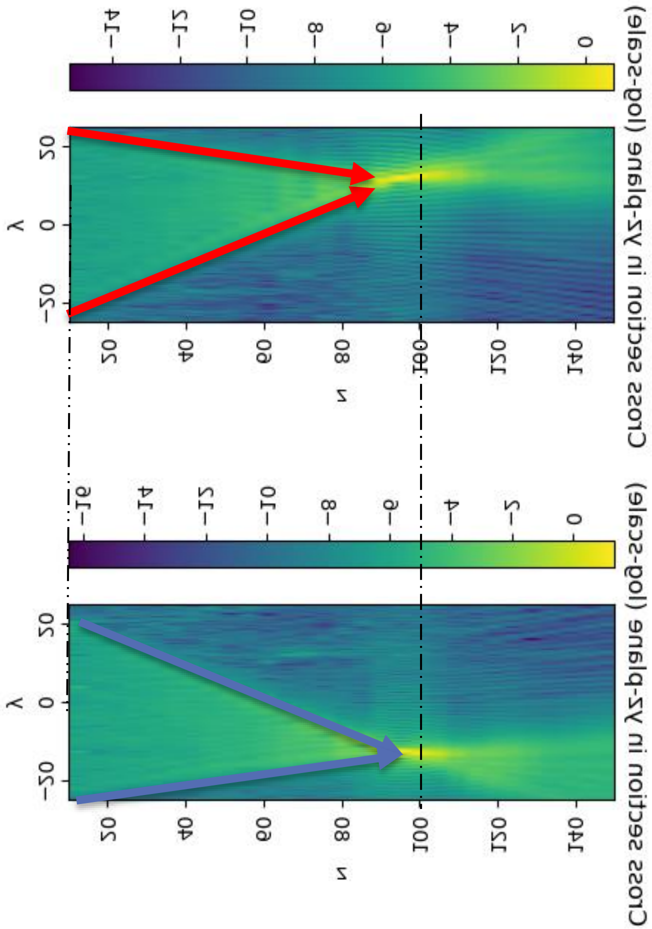
*Based on: GaN Metalens for Pixel-Level Full-Color Routing at Visible Light. *Nano Letters*, *17*(10), 6345–6352.

Ray tracing meta-surfaces





Cross section



- ❖ **Wave based simulation** in meta-component analysis
- ❖ Meta-lens focuses at designed position
- ❖ 450 and 630nm focal spot on designed position

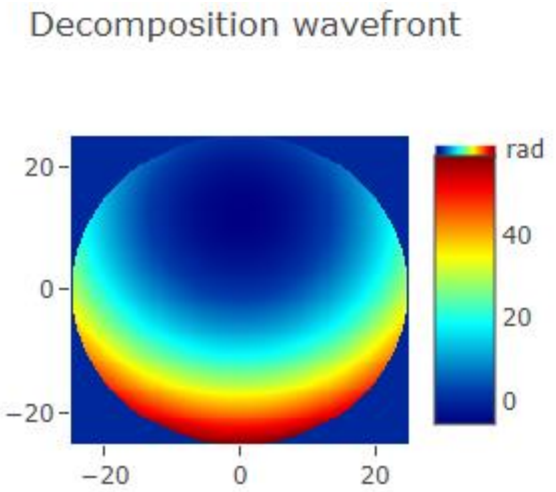
Wavelength	Shift	Transmission	Focusing efficiency
450nm	-12,8 µm	93,7%	87,1%
630nm	+12,8 µm	97,3%	89%

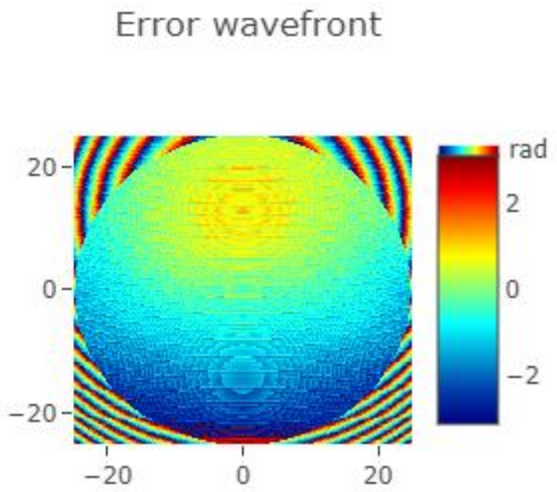
Ray tracing meta-surfaces

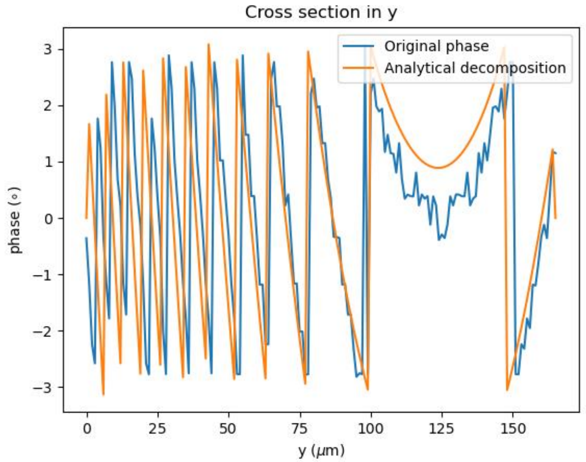
- Decomposition is fit to meta-surface phase
- 1st order model: 1 analytical decomposition per wavefrontµ
- Independent decomposition models multiplexed wavelength effect

Decomposition for 630 nm

RMSE: 0.071

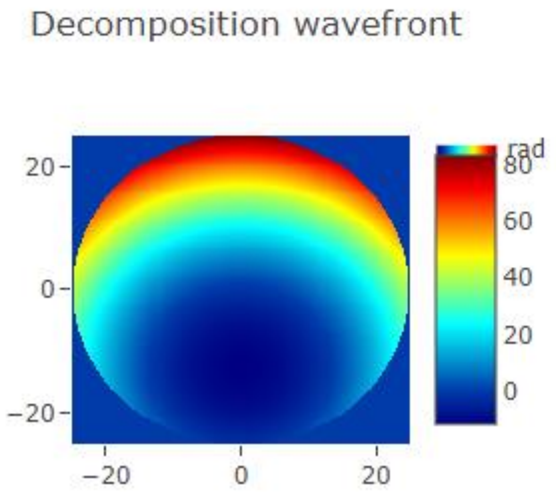


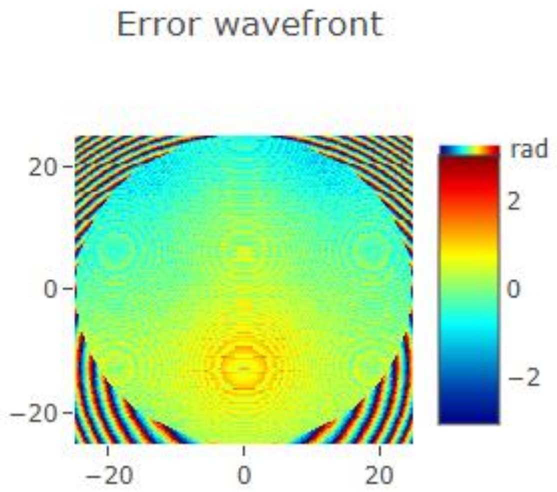


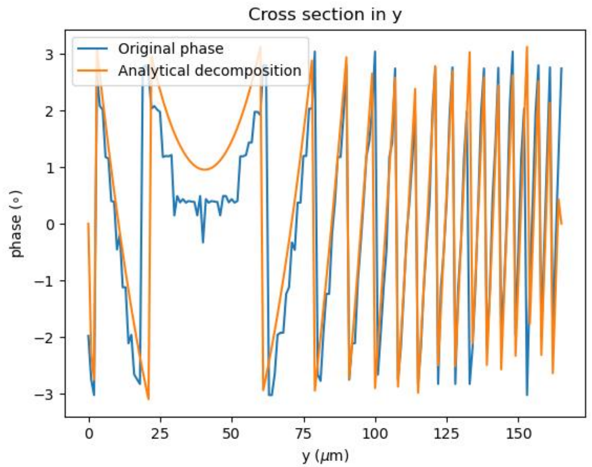


Decomposition for 450nm

RMSE: 0.085

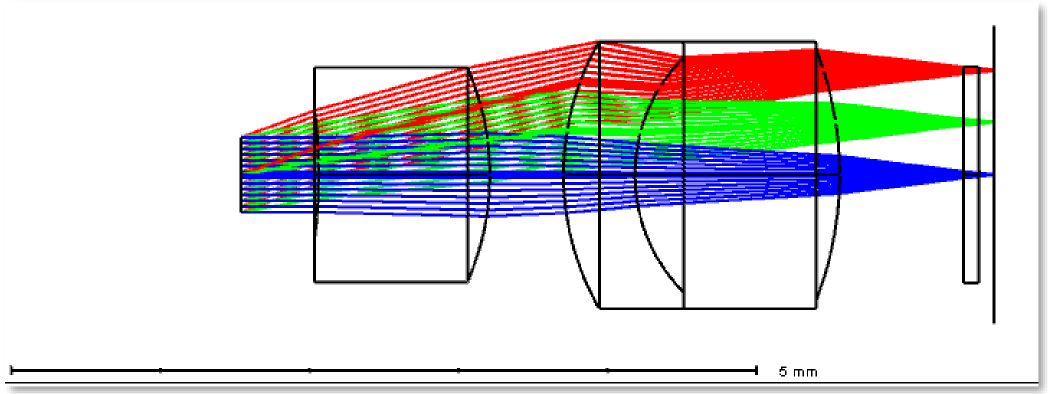






Ray tracing meta-surfaces

- Example: **Pixel level colour routing in system**
  Reference design: telecentric imaging system. Dummy window as place holder for meta-surface substrate



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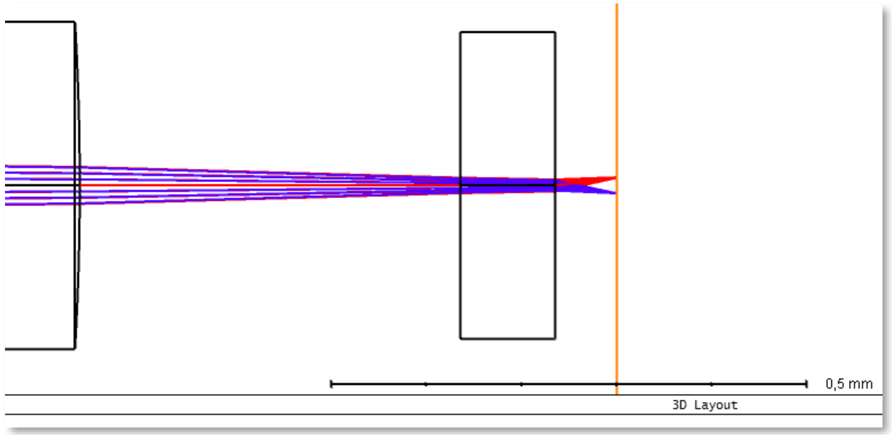
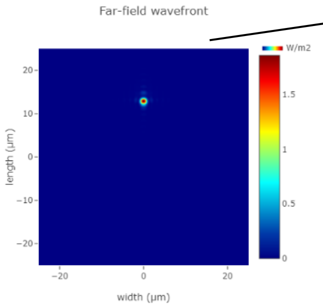
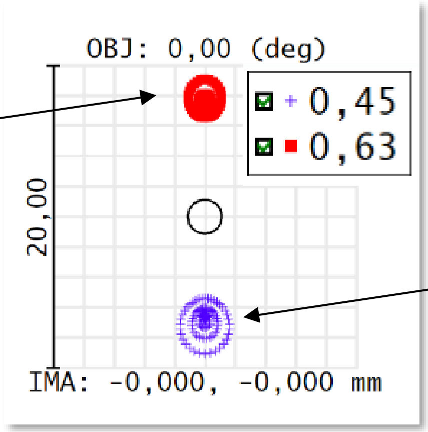
Ray Tracing Link

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

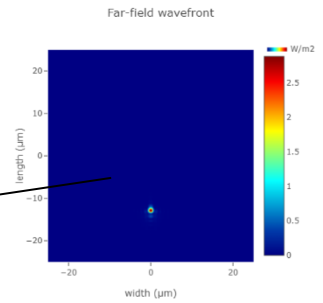


Wave simulation 630nm





Wave simulation 450nm



Nano- to macro design

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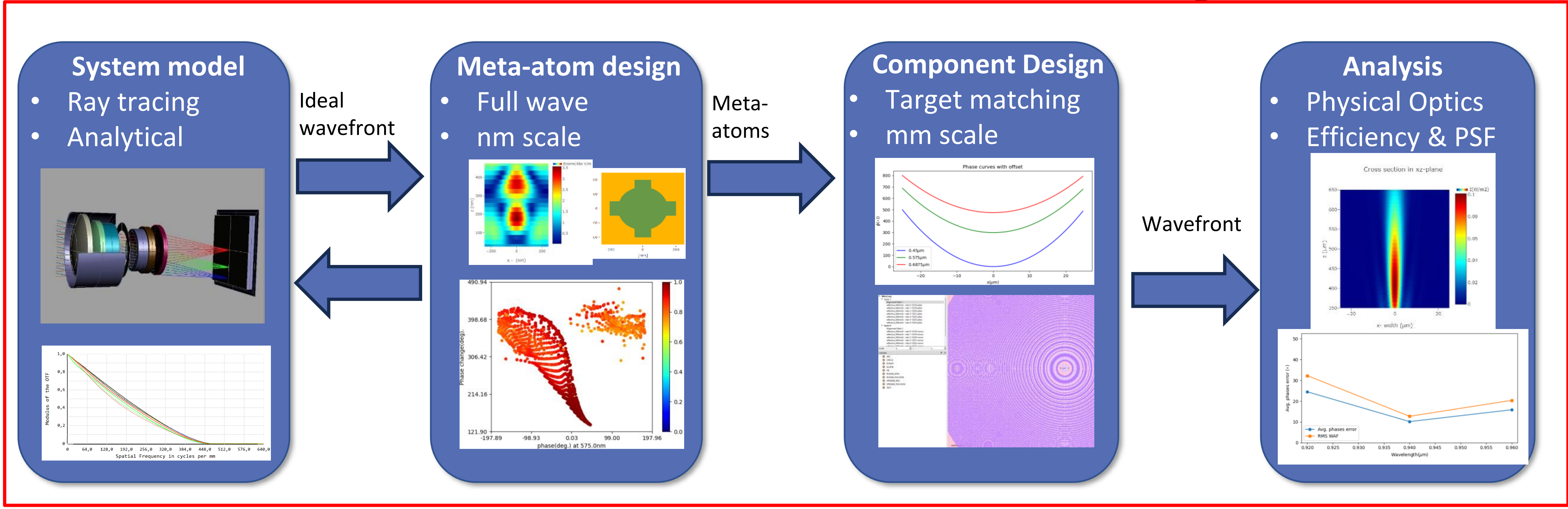

- ❖ Multiscale model to design from nano-structure to system
- ❖ Levels of approximation allow reaching practical sizes for meta-surfaces
- ❖ Co-optimization of system
  - ➢ Inform nano and macro level of constraints
  - ➢ Hybrid systems combine stengths of conventional optics and meta-surface

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