Lieven Penninck

Overlapping domain analysis for large-area meta-surfaces

30 January 2024

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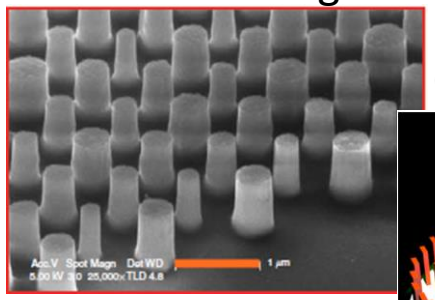
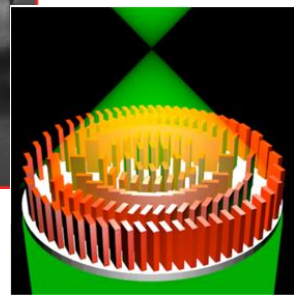
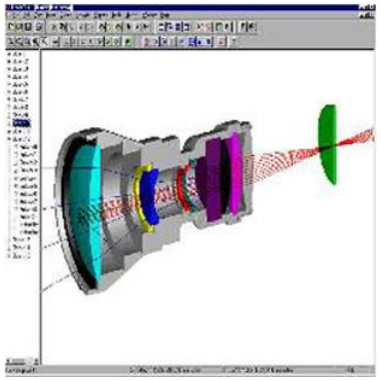
Nano-scale design



Component design



System Integration



Planopsim's mission

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

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

Metalens design workflow

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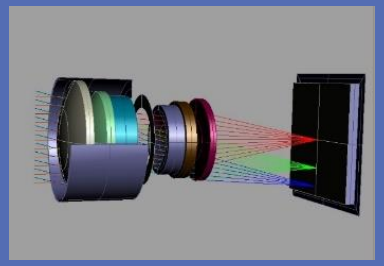
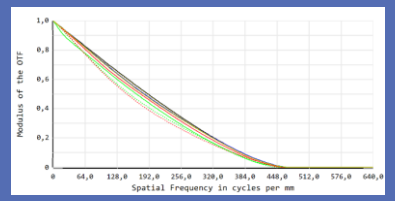
1) System model

- Ray tracing
- Analytical



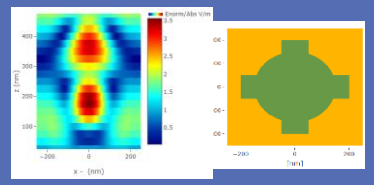


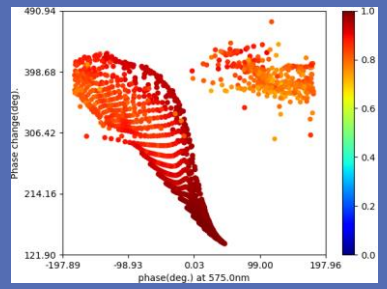
Idealized wavefront

Ideal wavefront

2) Meta-atom design

- Full wave
- Nm scale



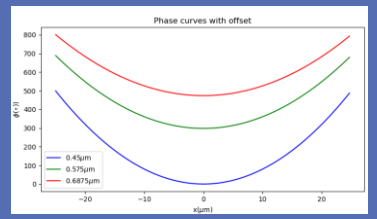


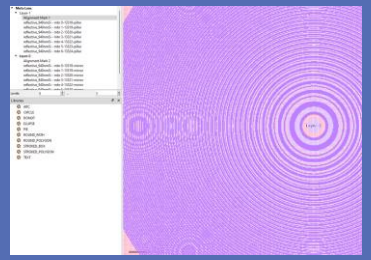
Periodic approximation

Meta-atoms

3) Component Design

- Target matching
- mm scale



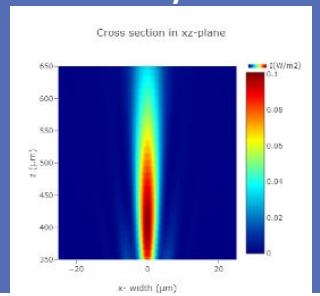


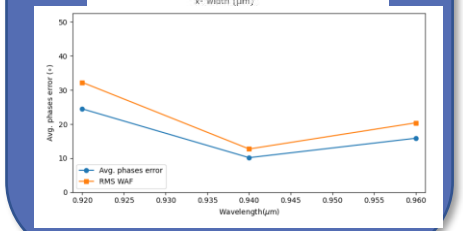
Full wave limited to small areas

Wavefront

4) Analysis

- Physical Optics
- Efficiency & PSF





- Relatively **fast and large area** calculation
- **Local periodic** approximation, **near-field coupling approximated**
- **Discrepancy** between design and actual component

Meta-atom optimization

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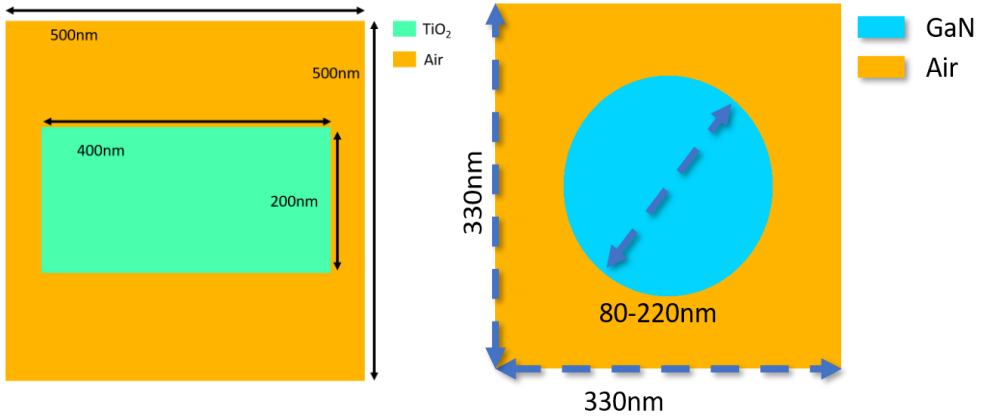
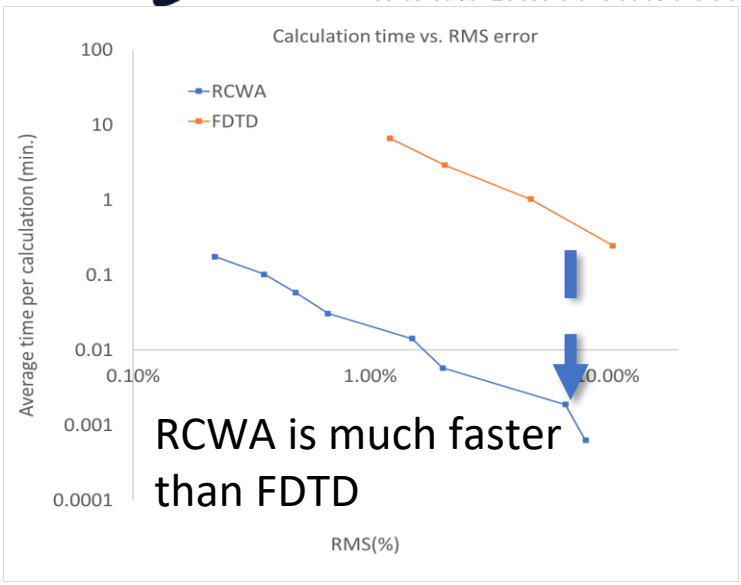
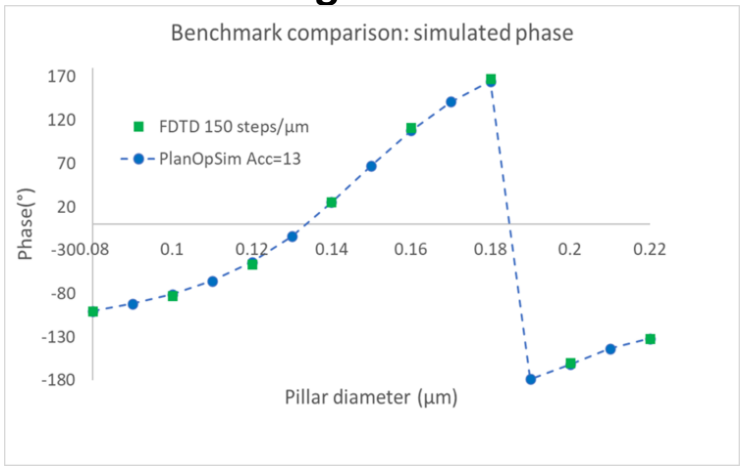
- Most commonly used full wave solver + periodic boundary condition
- Nano-structure calculation using **Rigorous Coupled Wave Analysis** (Maxwell solver)
- Thousands of nano-structures in parameter space
- Benchmark PlanOpSim (RCWA) to FDTD
  - **RCWA is much faster** for meta-atom calculations
  - Meta-atom response same in RCWA and FDTD



Test structures



RCWA (PlanOpSim) and FDTD calculation in agreement



Meta-atoms in example lens

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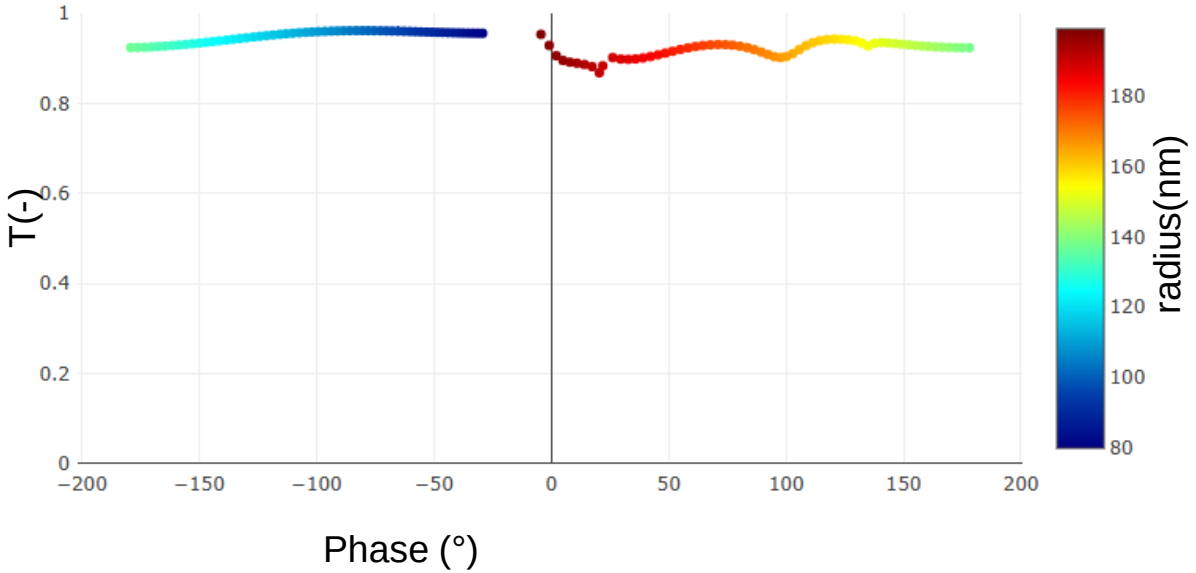
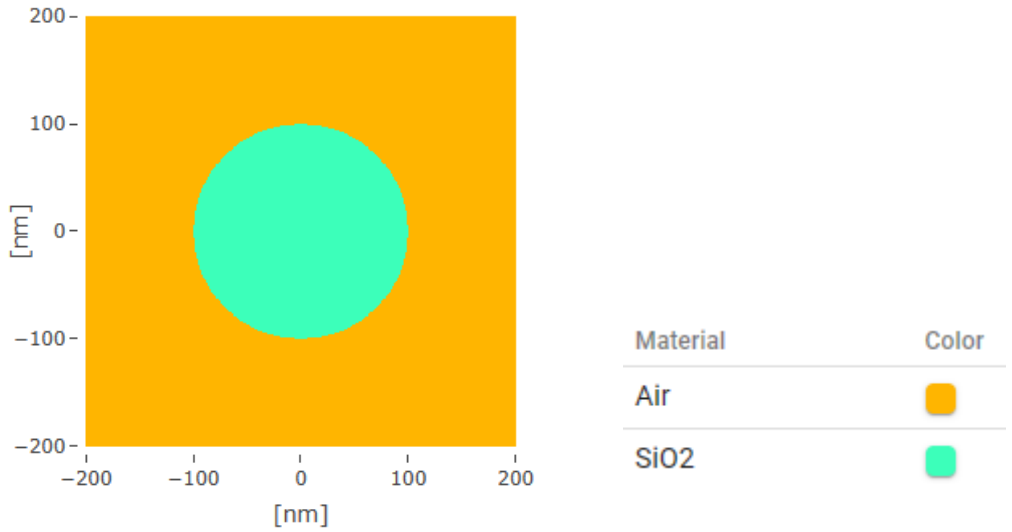
- Meta-atom library for demonstration
- Radius 80 – 200nm
- Optimized via RCWA (PlanOpSim Meta-Cell)
- Selected for 360° phase coverage



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



LPA phase matching

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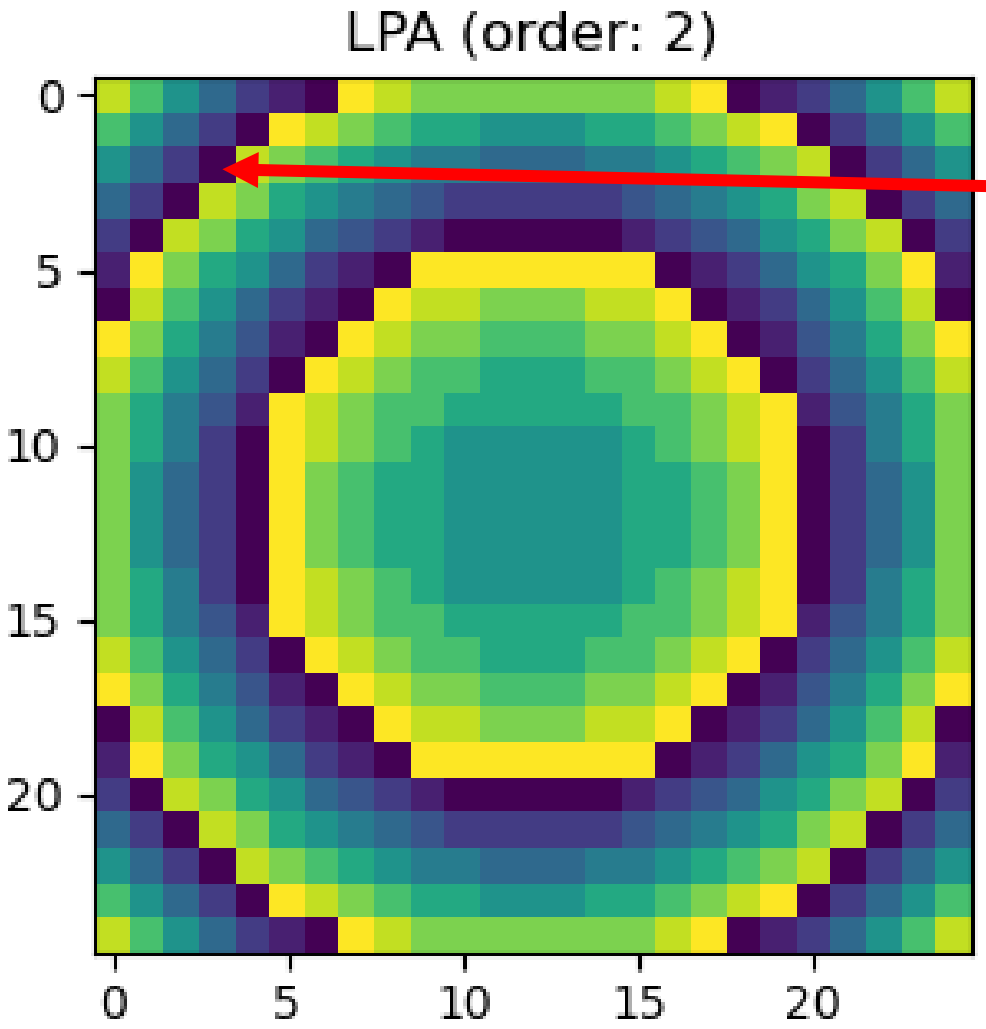
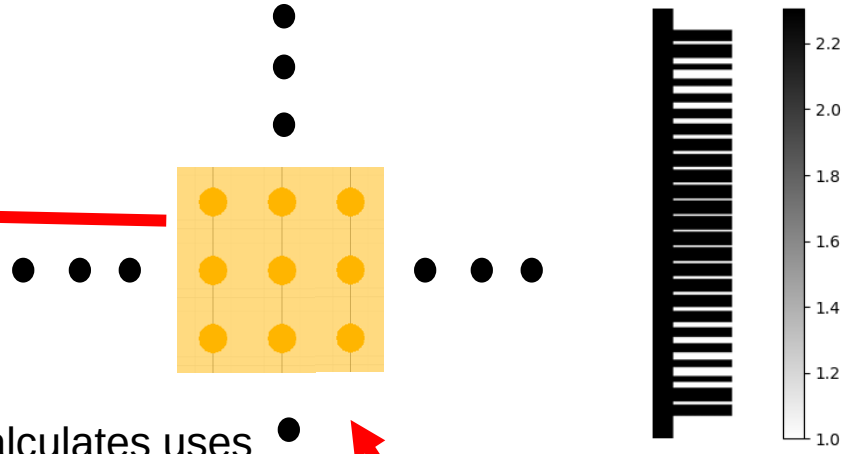
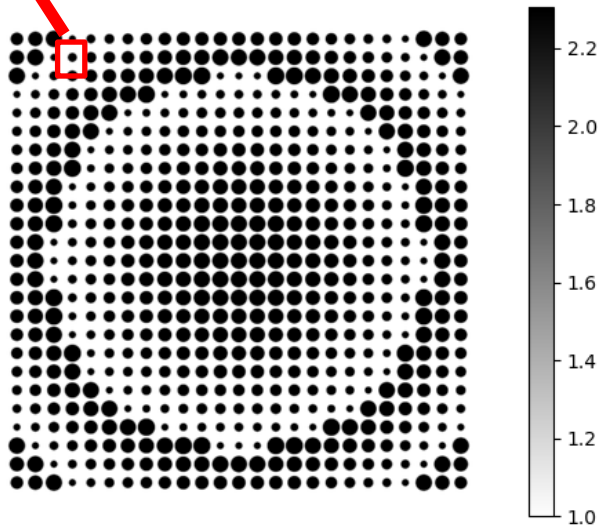


local periodic approximation



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

Periodic approximation



	Calculation time	Memory usage
LPA	1 minute	<1Gb

Full wave calculations

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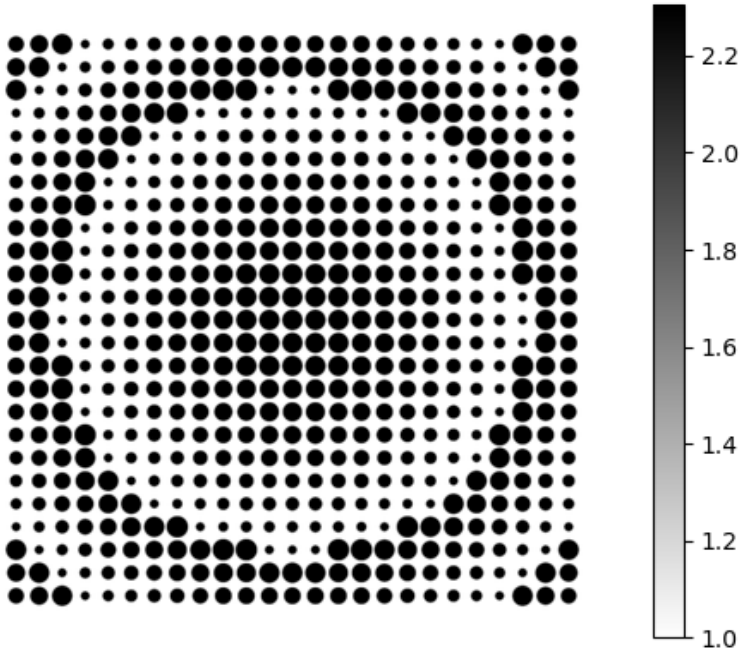
Full wave calculations are accurate but **very slow and memory consuming**. In practice limites to ~100λ

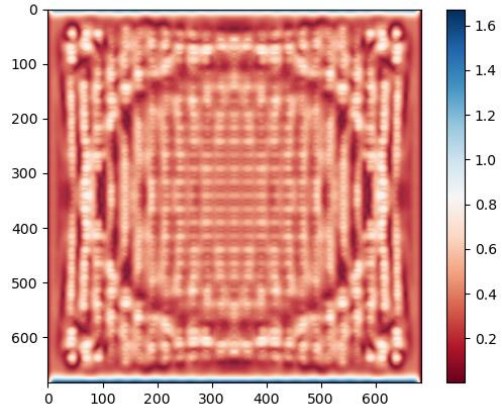


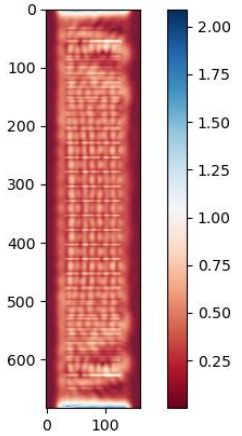
Full wave solution*

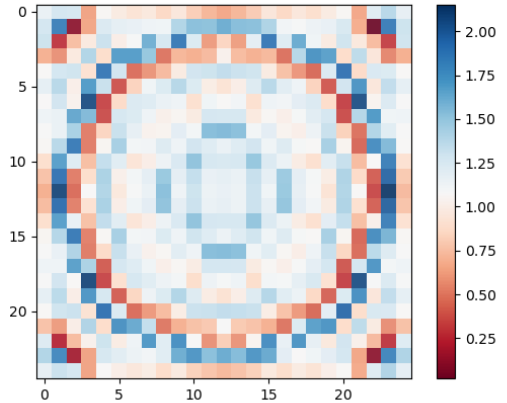
Side view

Full wave solution local zeroth order

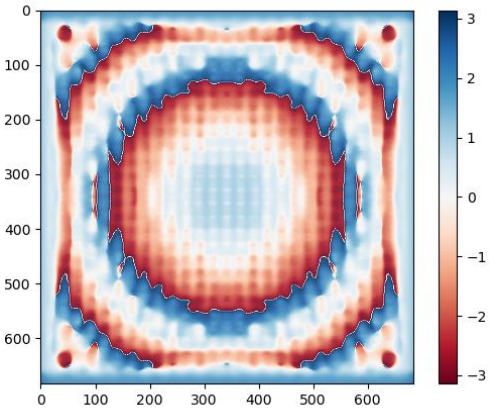
Amplitude

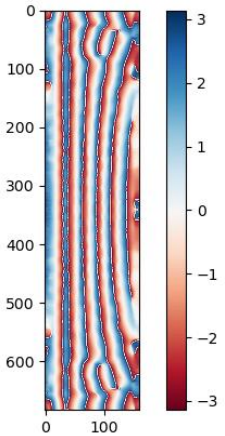


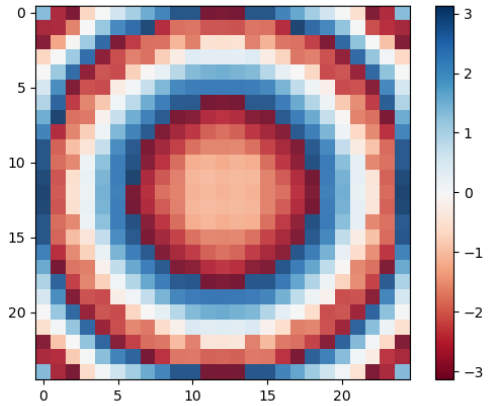




Phase







	Calculation time	Memory usage
Full wave (meep)	6 hours	32Gb

* 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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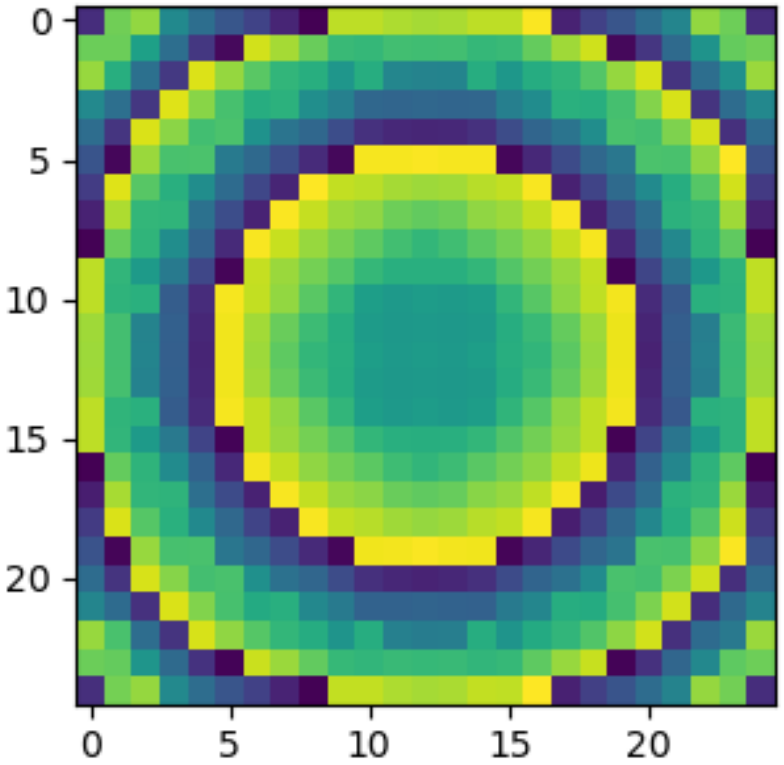
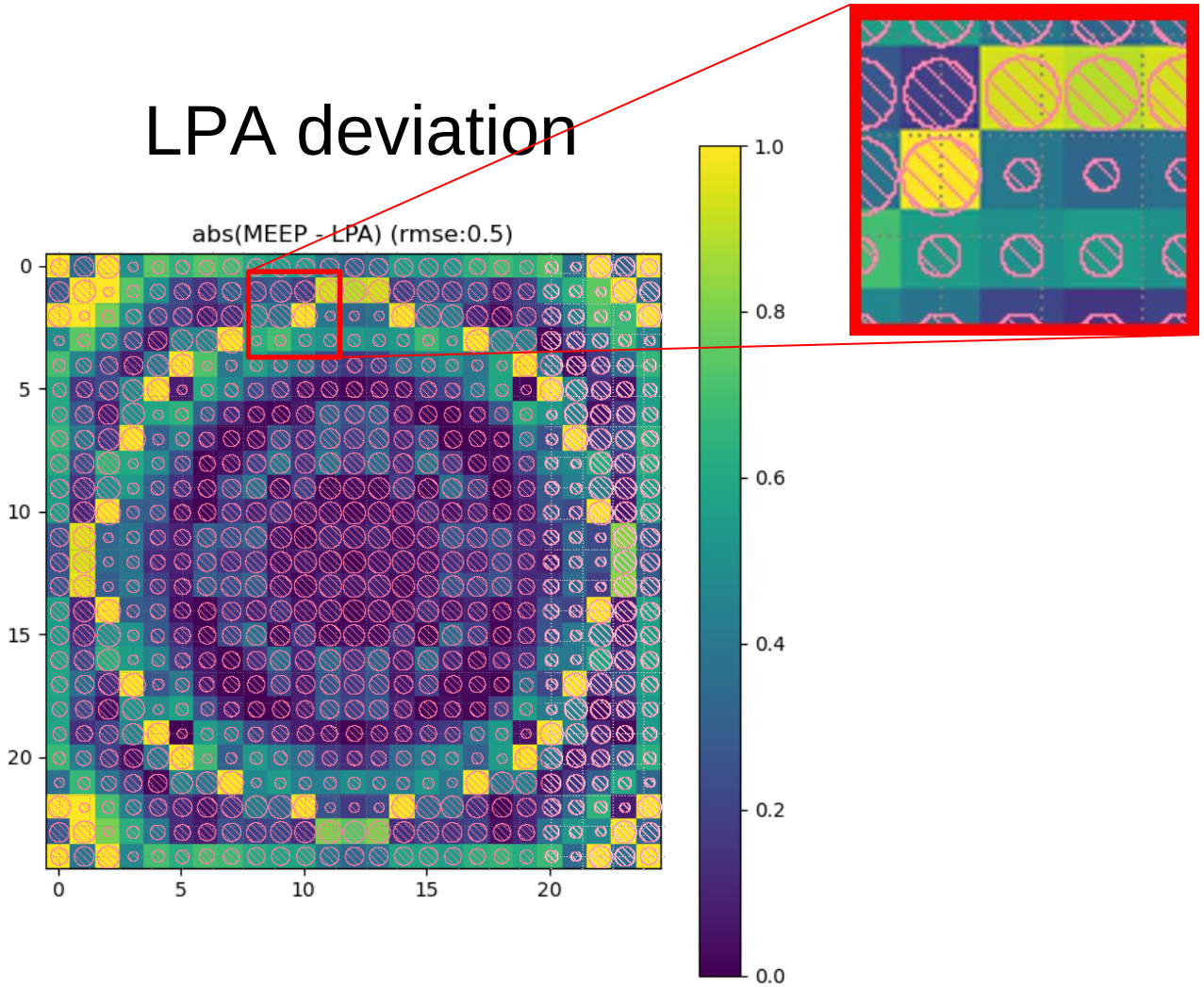
Full wave ‘ground truth’

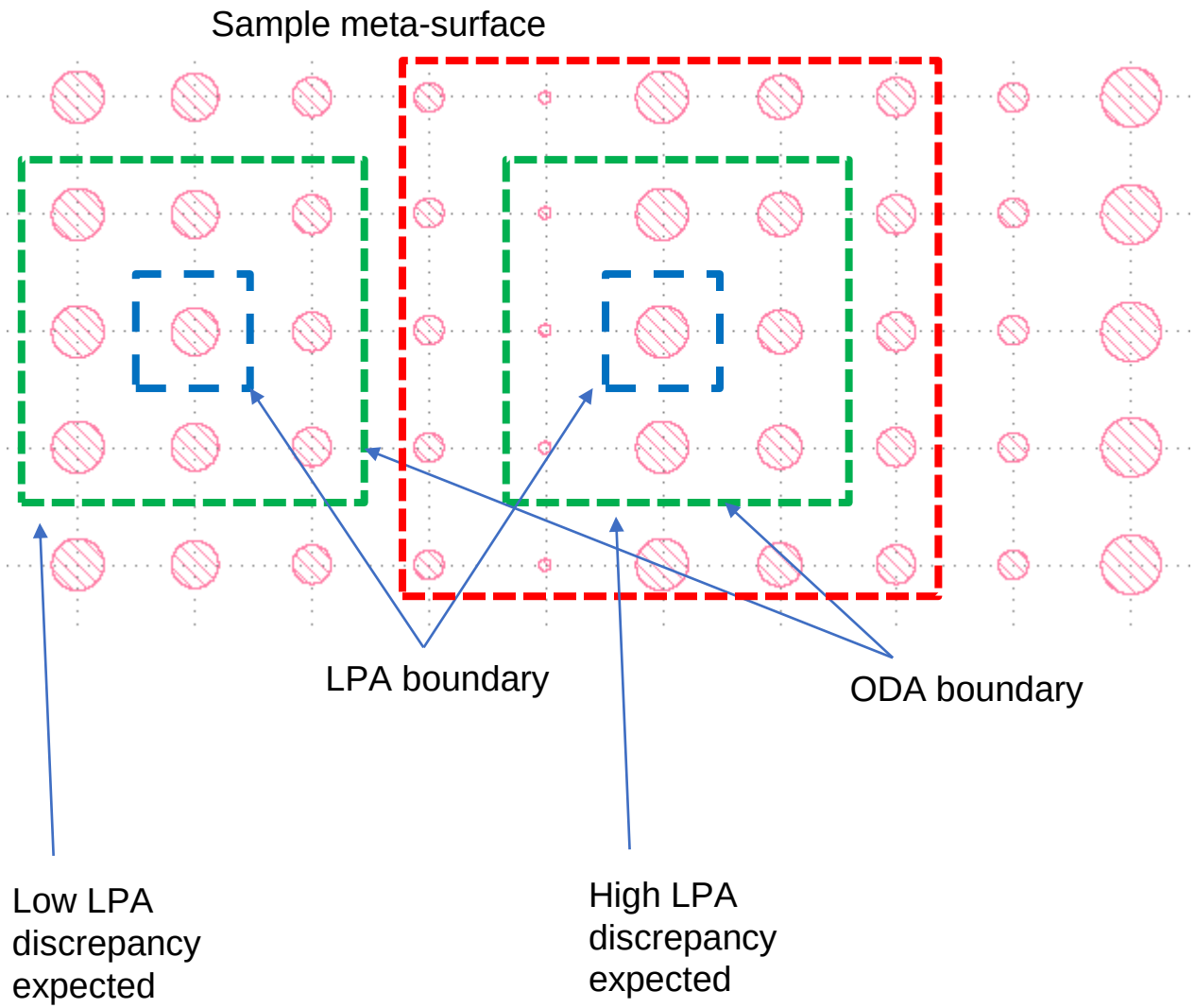


LPA deviation



ODA vs. LPA

- 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 ($1.3^{e}+8$)



ODA calculations

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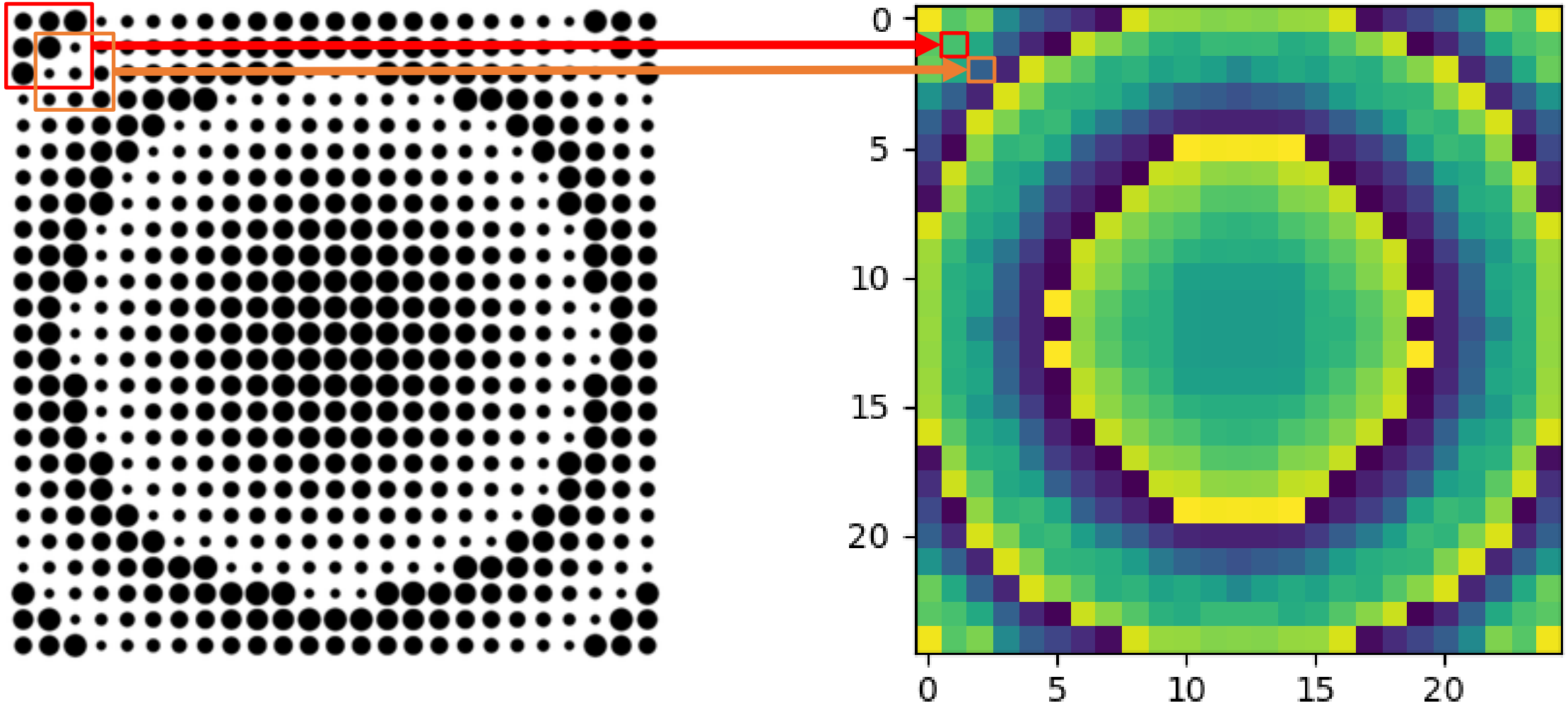
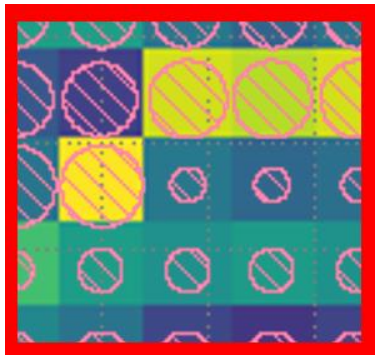
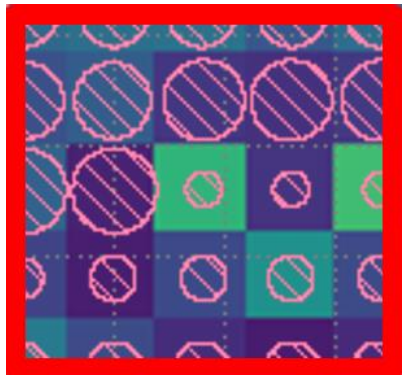
Beta release November 2023

Overlapping Domain Analysis accounts for **interaction of meta-atom with neighbouring structures**.
Local calculation **avoids memory restriction** of full wave calculation.

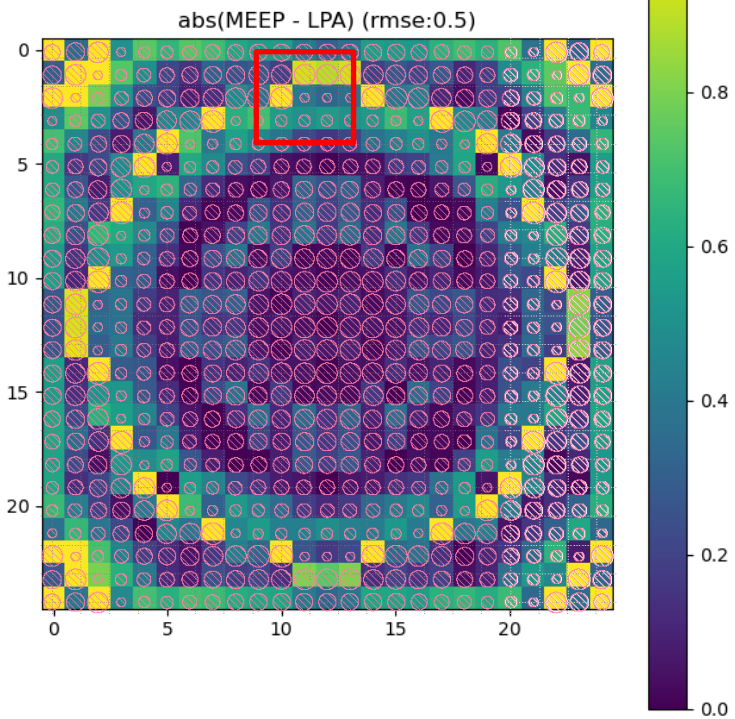


Phase error

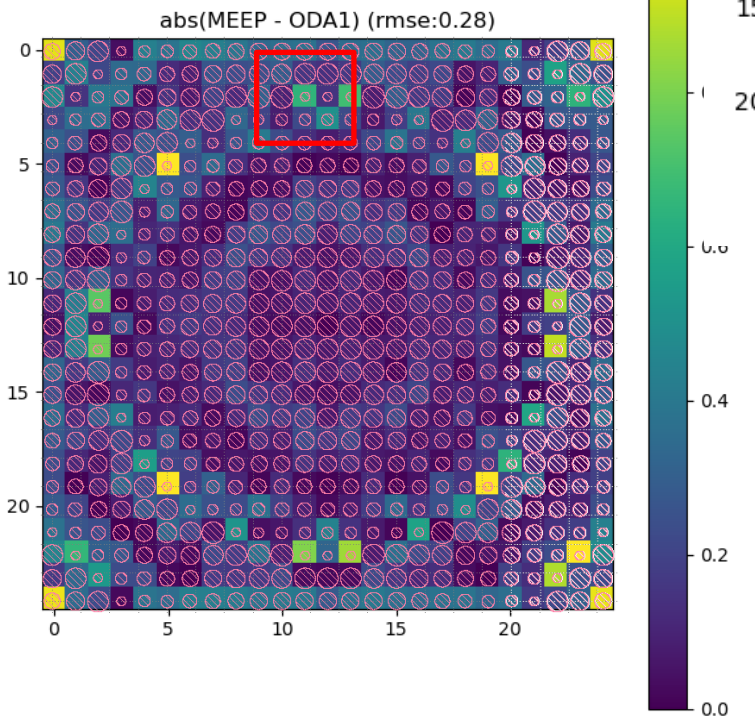


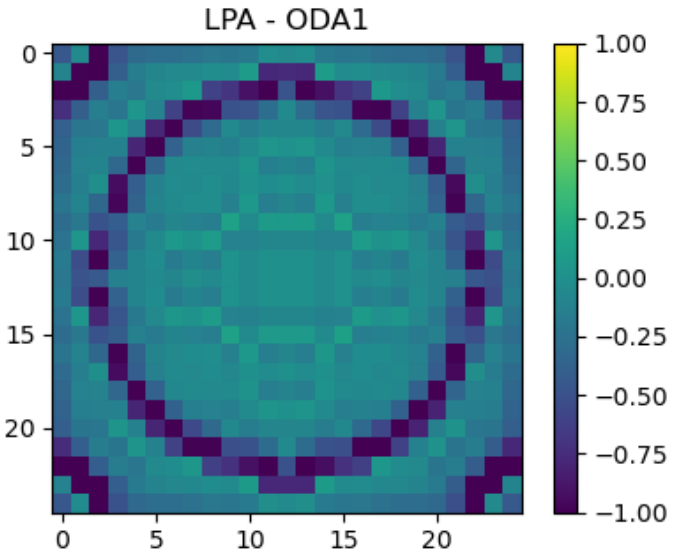


LPA deviation



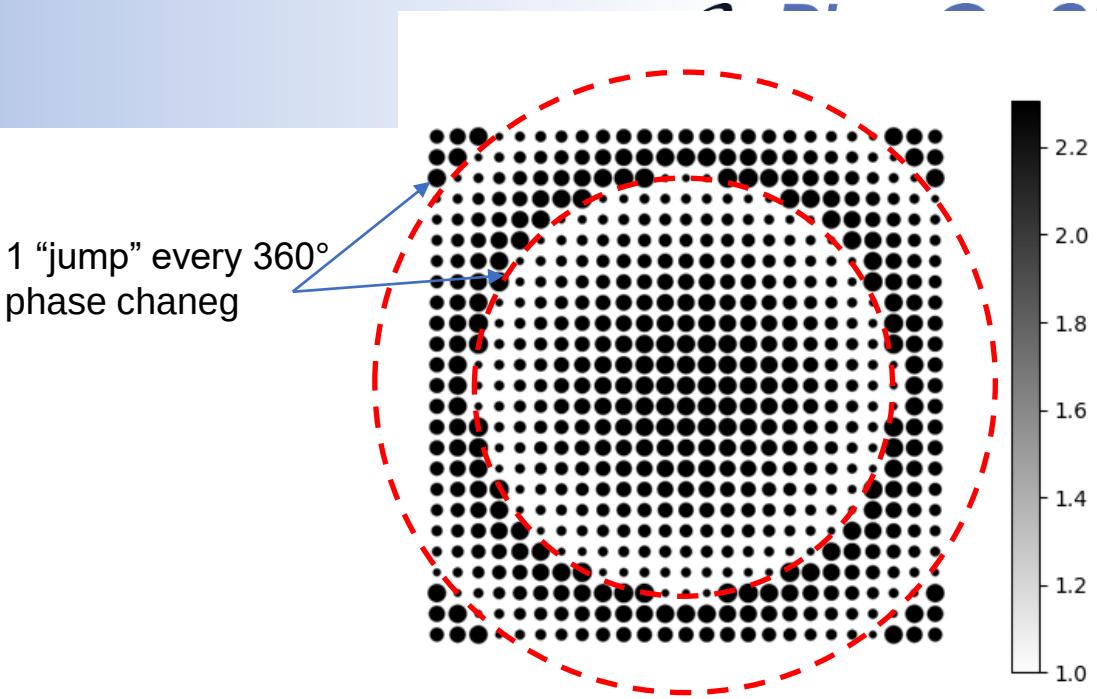
ODA deviation



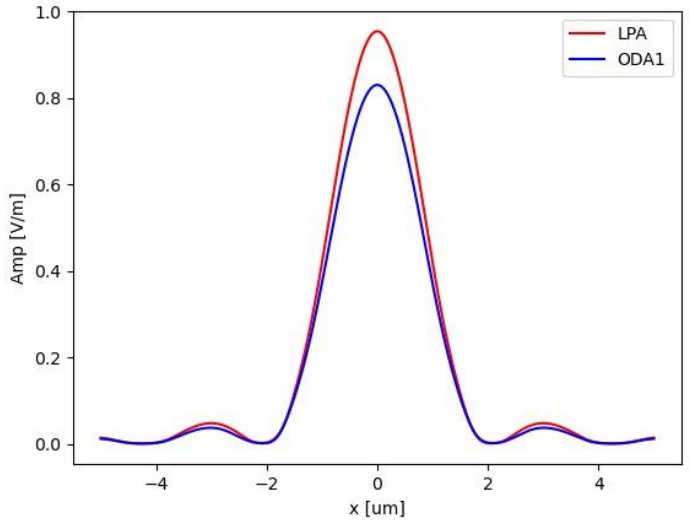


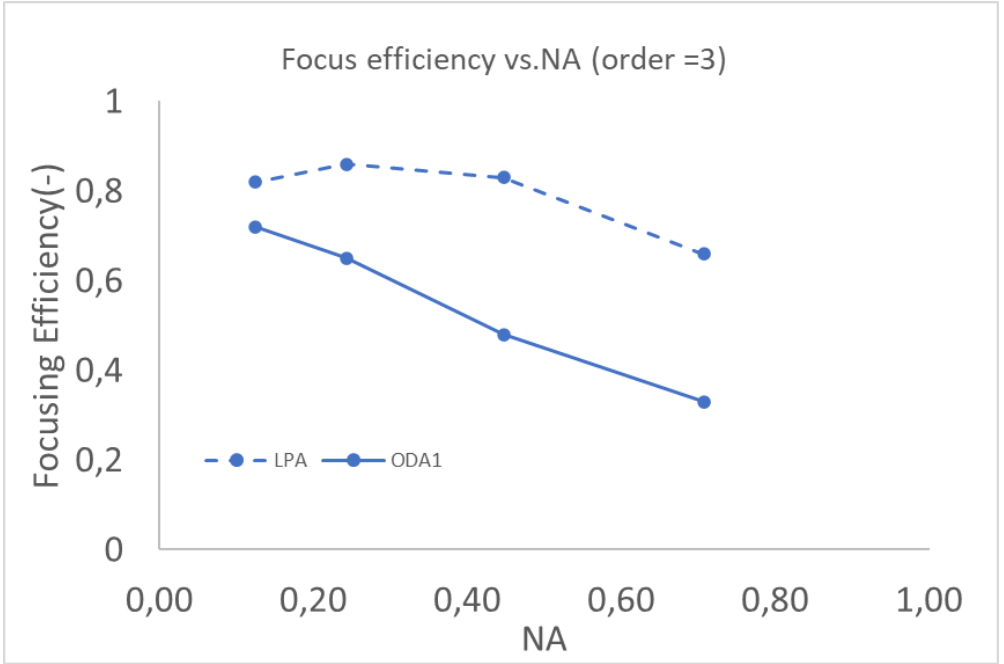
Focusing efficiency

- Example lens:
  - 50x50µm^2, 8 pillars, λ=520nm
  - Intensity recorded in 10x10 µm^2 area
  - Focal distance swept from 25-200µm
- Size discrepancies “rings” occur more for high deflection angles
- Focal spot simulated by angular spectrum method
- For **low NA** the **LPA** approximation has **lower error** than for high NA



Simulated focal spot (NA 0,12)





Convergence

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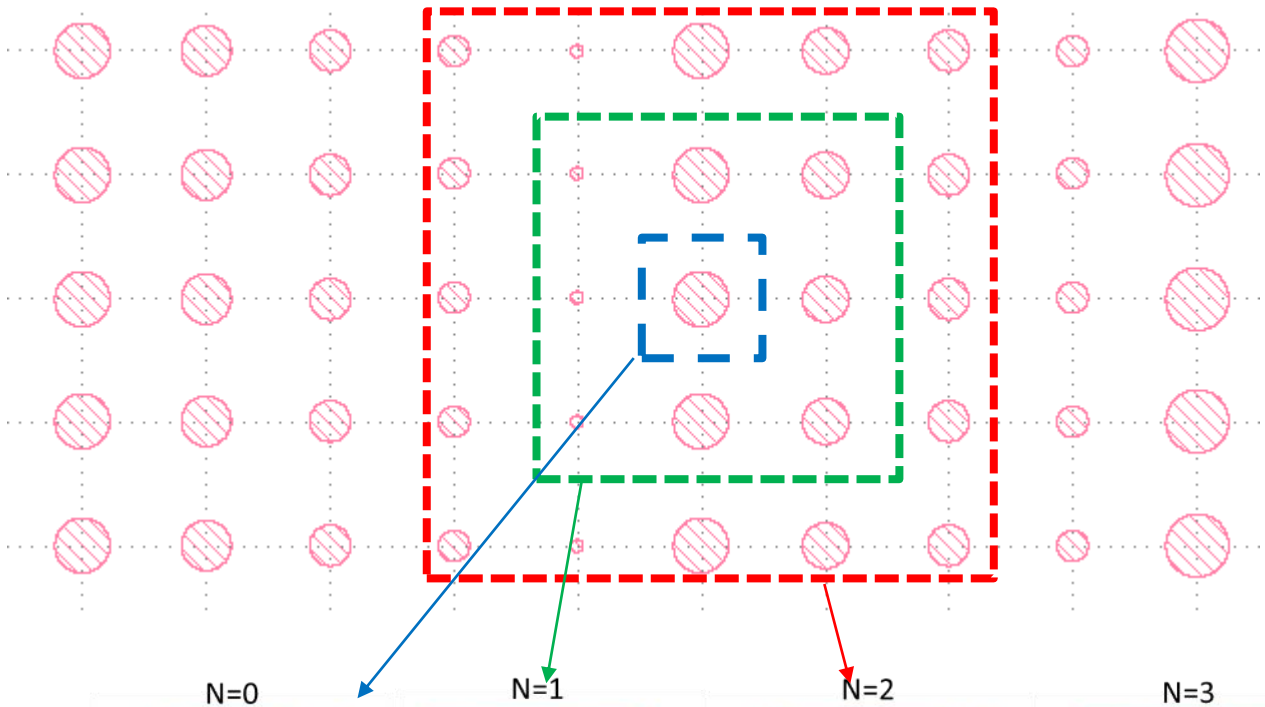
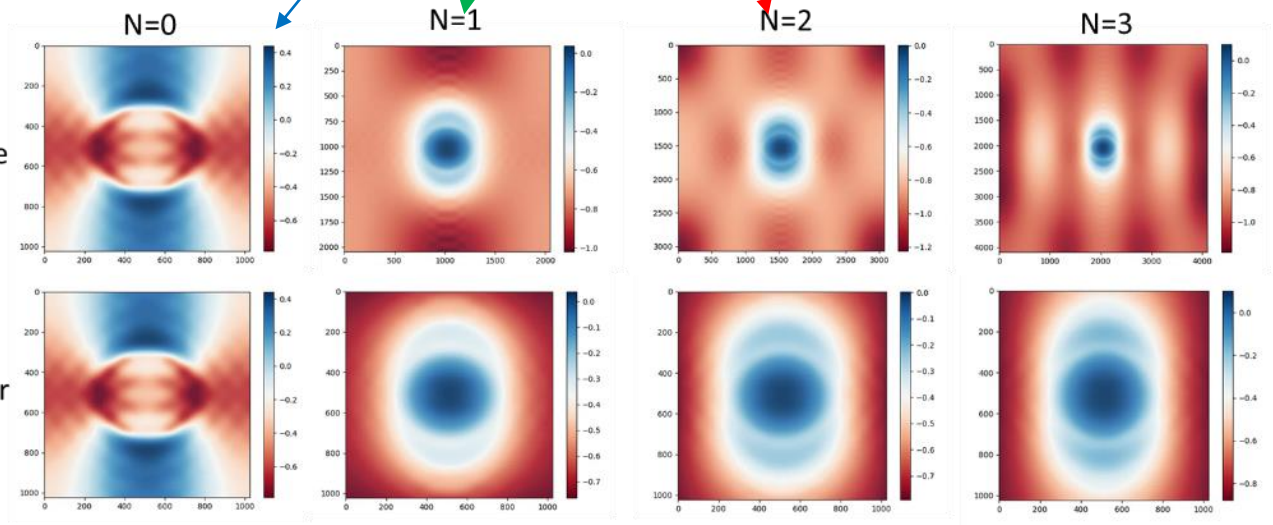
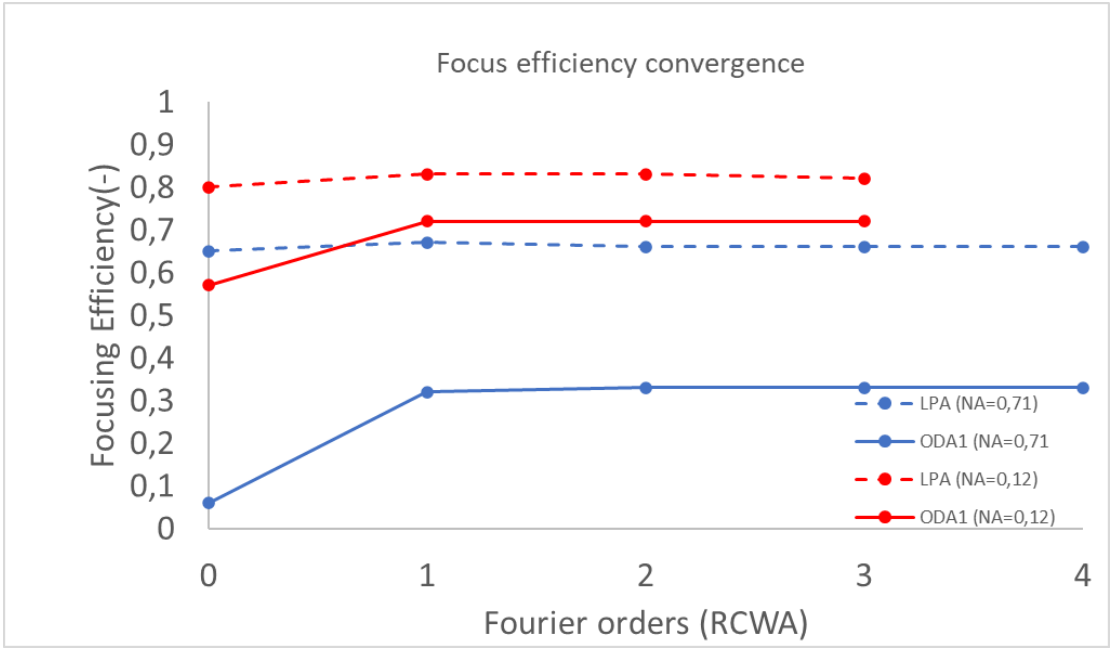
Sample meta-surface







- Strong change from 0-1 neighbour, smaller changes from 1-3
- 2 or 3 order decomposition produces stable result for single structure
- 6-9 order decomposition for structure + nearest neighbours
- Similar convergence for low and high NA lens

Comparison

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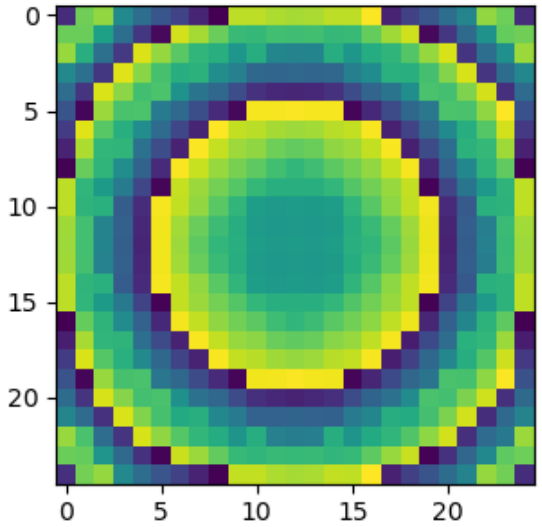
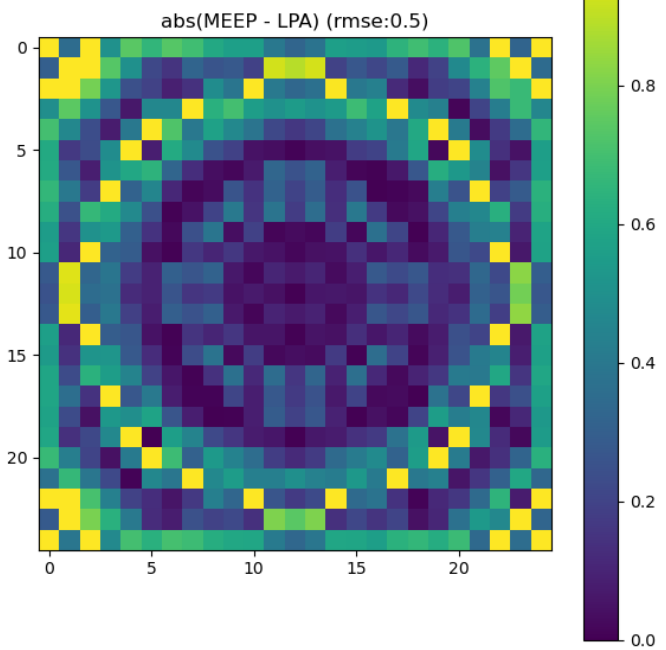
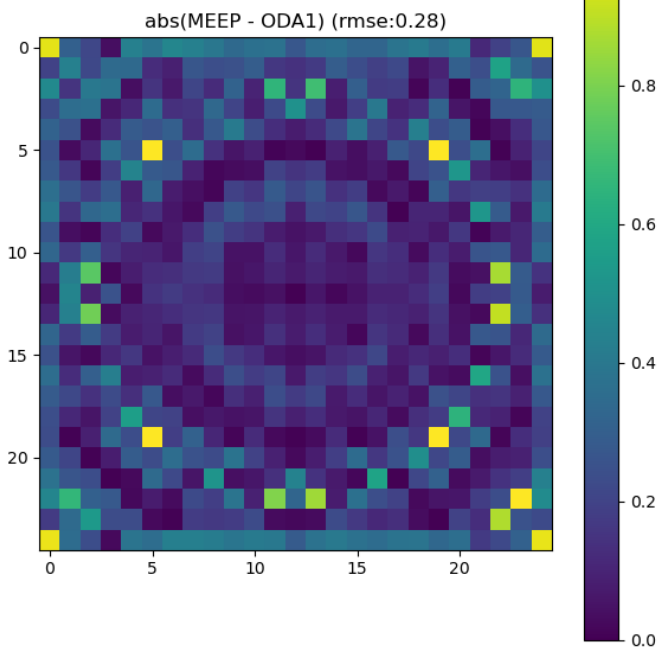
Full wave ‘ground truth’



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	23 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

Summary

- Local Periodic Approximation is required to calculate large metasurfaces but introduces approximation errors
- The LPA becomes less accurate at high NA
- Overlapping Domain Analysis can be used to calculate a more accurate wavefront
- **Overlapping Domain Analysis** is a useful **compromise between full wave** simulation **and LPA**
- Full wave calculation area is limited by memory, ODA calculation area is limited by time

Ray tracing meta-surfaces

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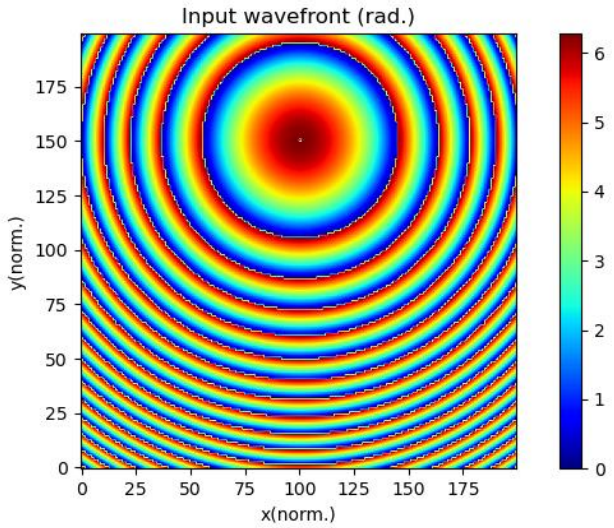
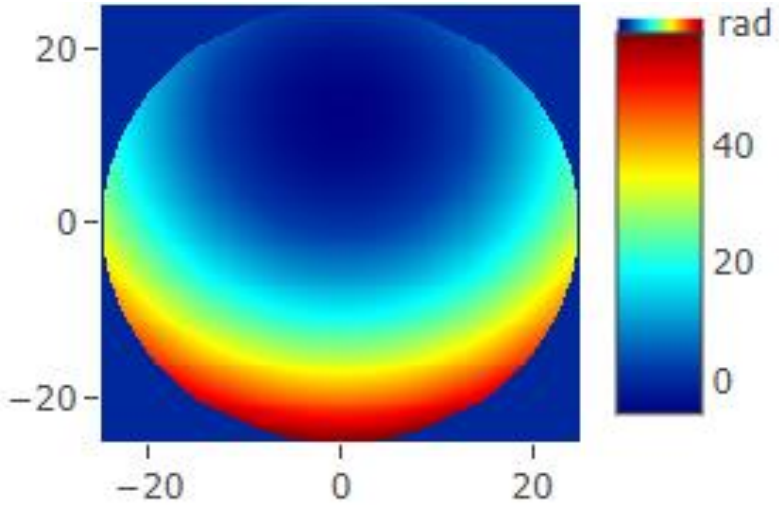
NFWF

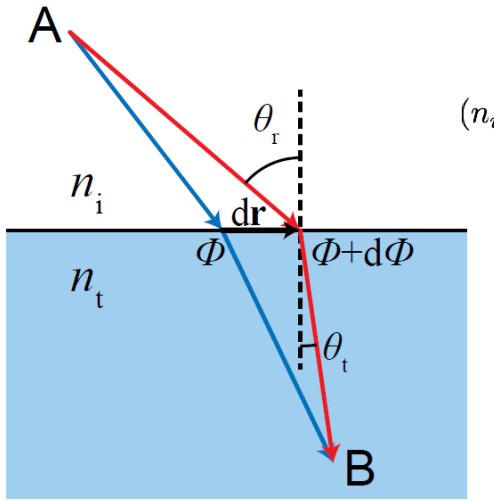


Restored NFWF



generalized law of diffraction

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
- High resolution: too slow for propagation calculations (POP)
- Wave calculation has 2π wrapped phase
- Dependent on wavelength, incident angle, polarization

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Ray Tracing Link

Ray tracing meta-surfaces

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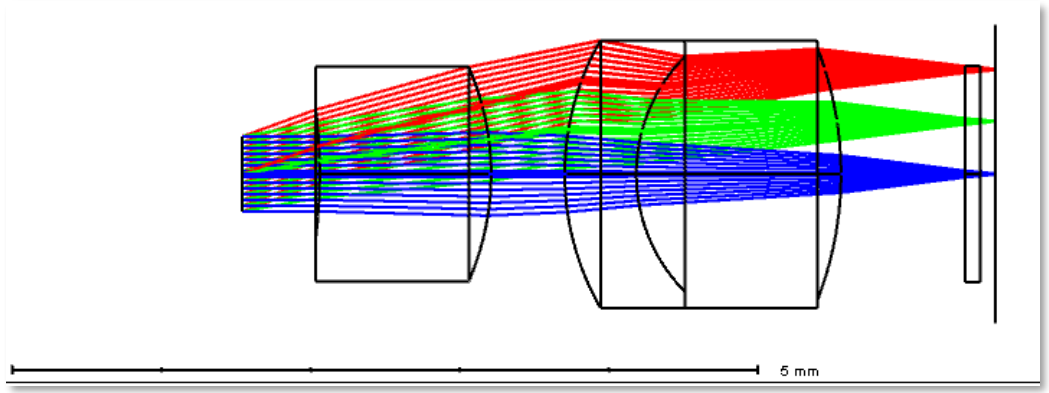
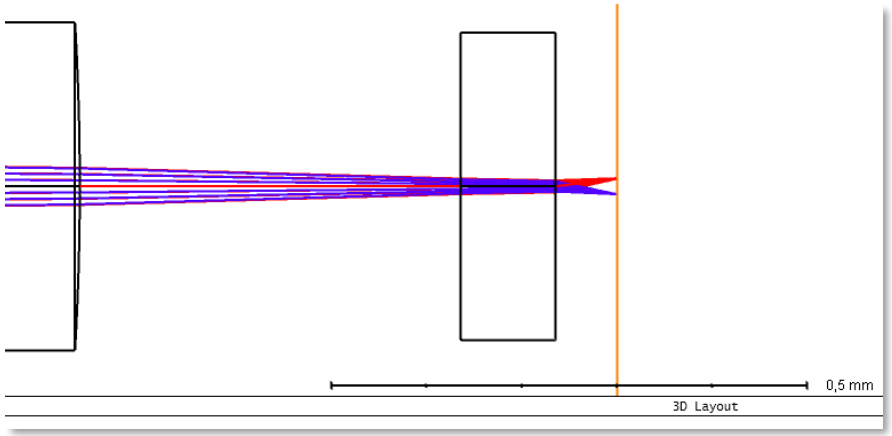
- Example: **Pixel level colour routing in system**
  Reference design: telecentric imaging system. Dummy window as place holder for meta-surface substrate



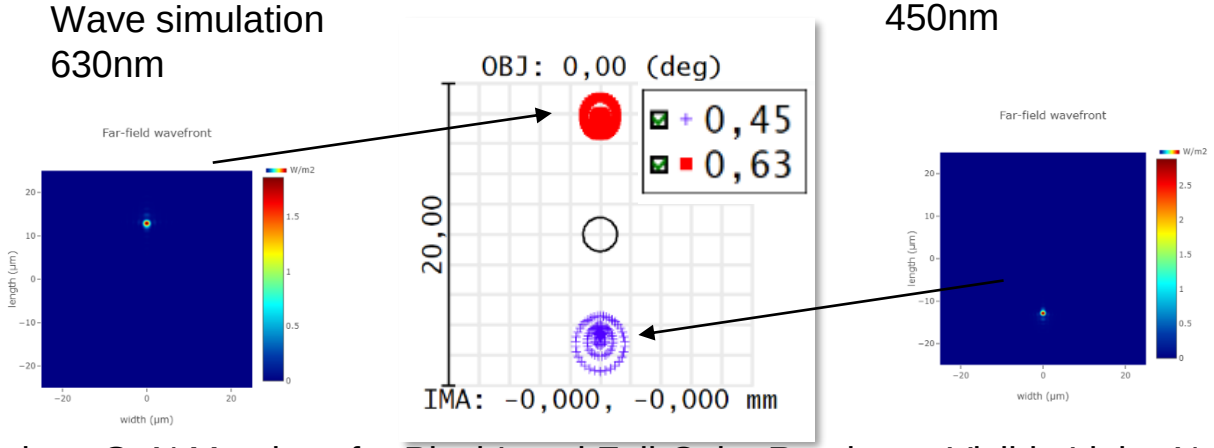
PlanOpSim
Ray Tracing Link

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



Wave simulation
630nm

Wave simulation
450nm



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

Metalens design workflow

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Enlightened Planar Optics
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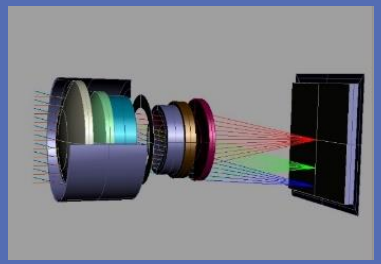
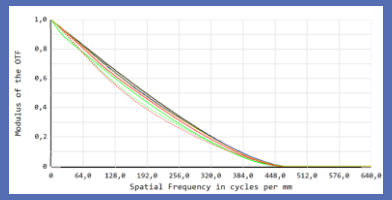
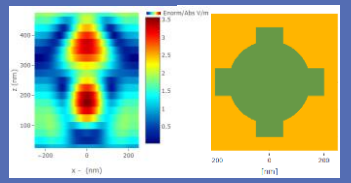
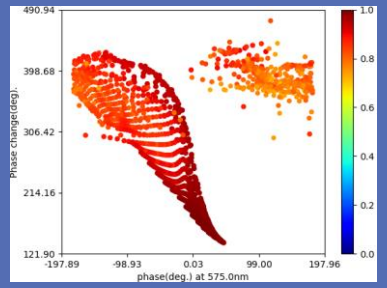
System model
- Ray tracing
- Hybrid Design



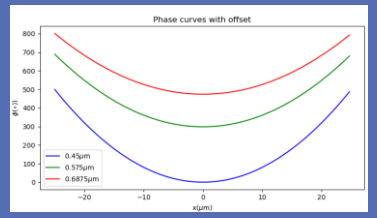


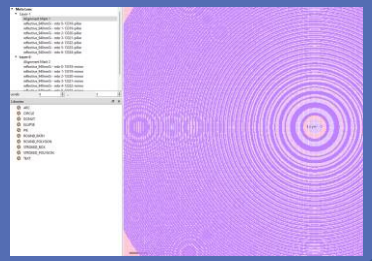
Library building
- Structure library
- Extract dispersion



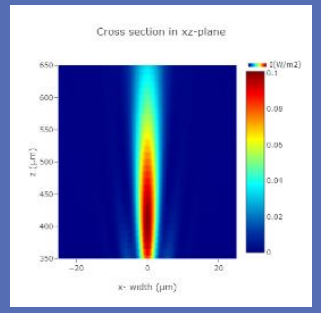


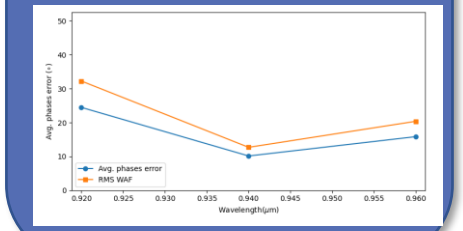
Component Design
- Phase offset
- Target matching
- Mask generation





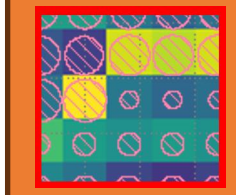
Analysis
- Chromatic focal shift
- Efficiency & PSF



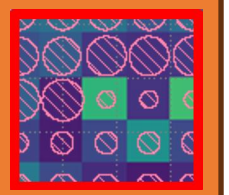


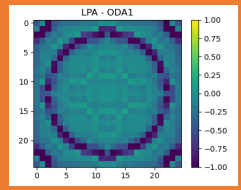
ODA analysis
- Verify if the local periodic approximation is sufficient

LPA



ODA





System analysis
- Actual metalens back in raytracing

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Meta-surface PDK

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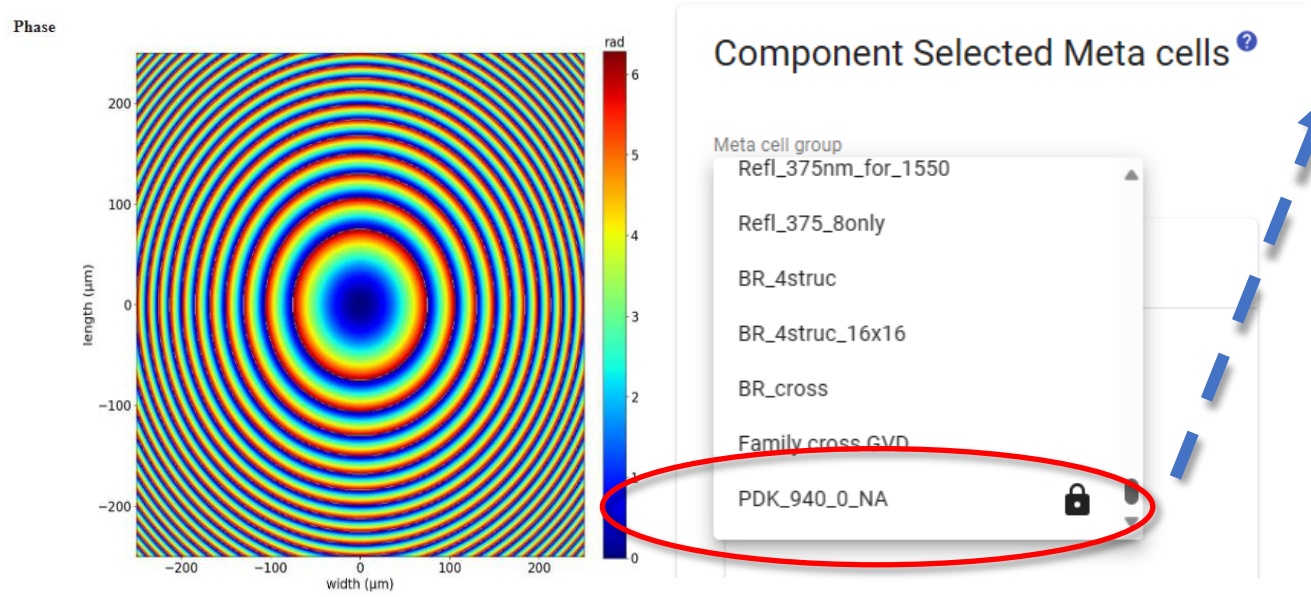
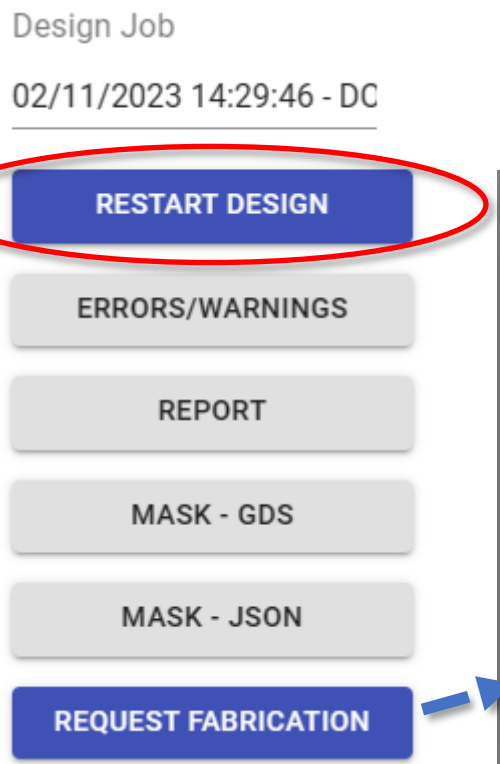
- **Multi-project wafer** service
- **Submit** meta-surface designs **to manufacturing partner from PlanOpSim software**
- Supported wavelength 940nm and size up to 5x5 mm

Step 1: select PDK and optical target



Step 2: run design



Step 3: submit design