Focusing Metalens Based on Nanopillars

Part of the Meta Optics Solution Guide

SF-PLAW01 CS-MPCA01 CS-CSFP01 DF-FMON01 DK-SDKD01

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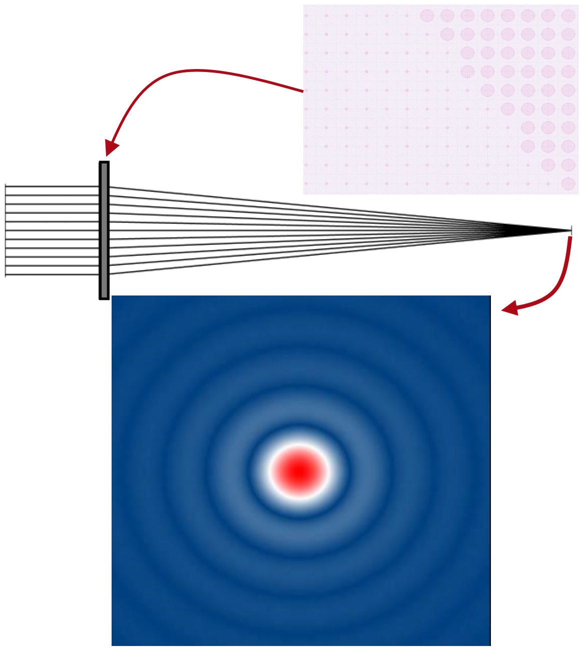
Author:	LightTrans International GmbH



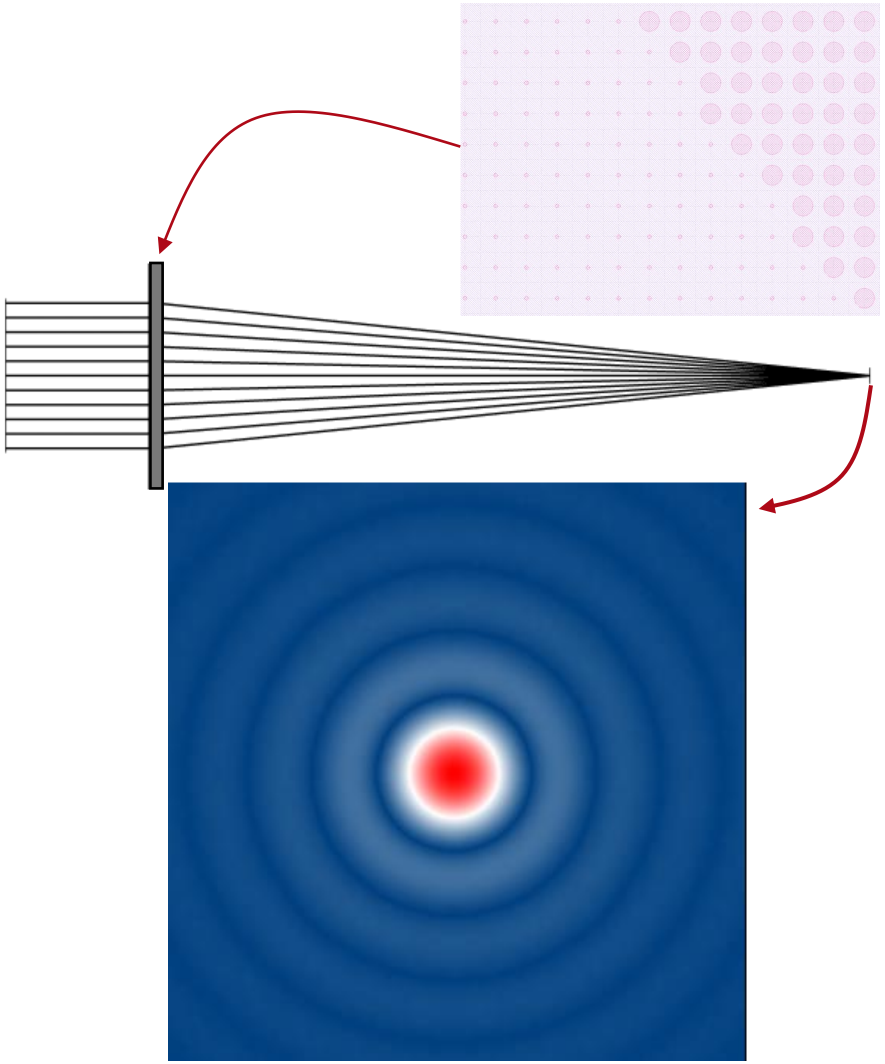
Executive Summary

Design of a focusing nanopillar metalens using a pre-trained surrogate model.

Key Achievements

- Output wavefront reproduces the target spherical phase.
- Demonstrated that despite amplitude and phase effects directly after the metalens, the focus remains diffraction-limited.

Hardware & Performance 12s Simulation time for AMD Ryzen Threadripper 3970X 32-Core Processor, 256 GB DDR4 SDRAM



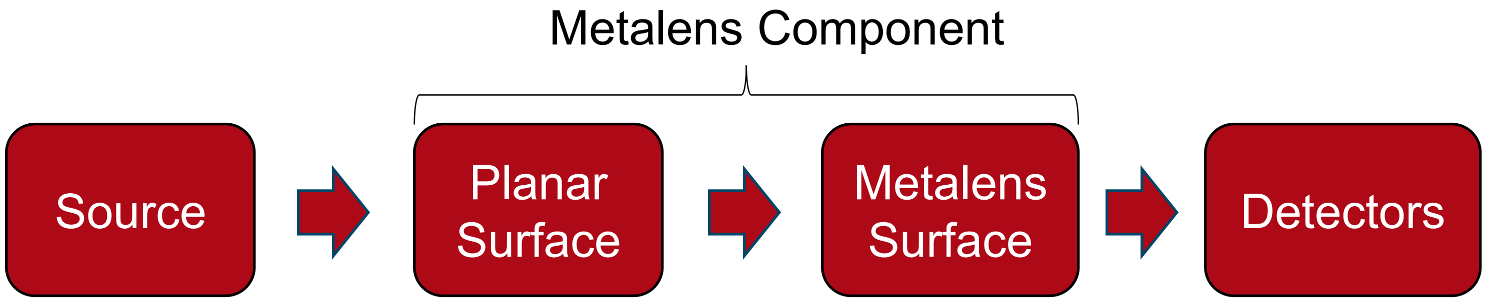
Application Scenario

The Scenario

We designed a focusing metalens and assessed its performance by analyzing amplitude and phase distributions behind the metalens and within the focal spot.

Physical Lab Setup

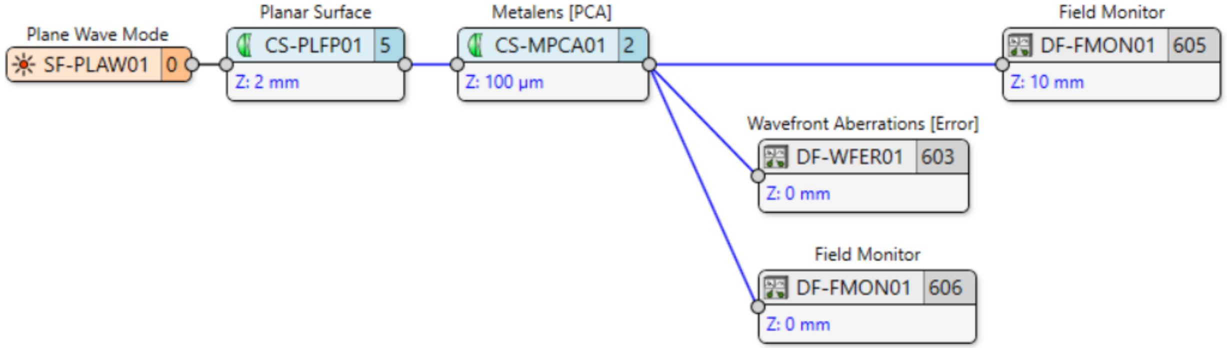
Component	Specification
Source	Plane wave, 940 nm, lin. x-polarized
Metalens	Nanopillars, n = 3.8, f = 10 mm, diameter 0.5 mm
Nanopillar meta-atom	Height 465 nm, period 400 nm × 400 nm
Detector 1	EM field & wavefront phase after metalens
Detector 2	Wavefront phase error after metalens
Detector 3	EM field at focal plane



From Real Asset to Digital Twin

Digital Twin Mapping

Real Asset	Digital Twin	Description
Laser source	SF-PLAW01	Plane wave, 940 nm, lin. x-polarization
Nanopillar metalens	CS-MPCA01	Metalens [PCA], phase profile: $\frac{2\pi}{\lambda}\sqrt{x^2+y^2-f^2}$
Substrate	CS-PLFP01	Planar surface, fused silica
Detector 1	DF-FMON01	EM field & wavefront phase
Detector 2	DF-WFER01	Wavefront phase error
Detector 3	DF-FMON01	EM field



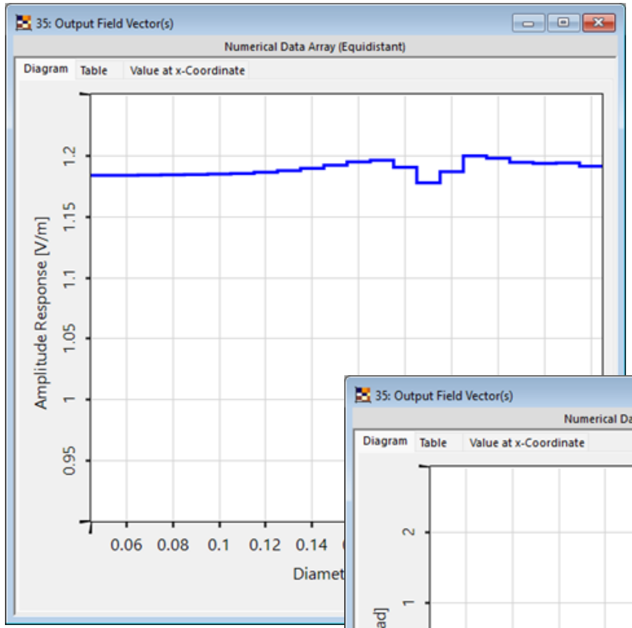
Surrogate Model Investigation

Surrogate Model Parameters

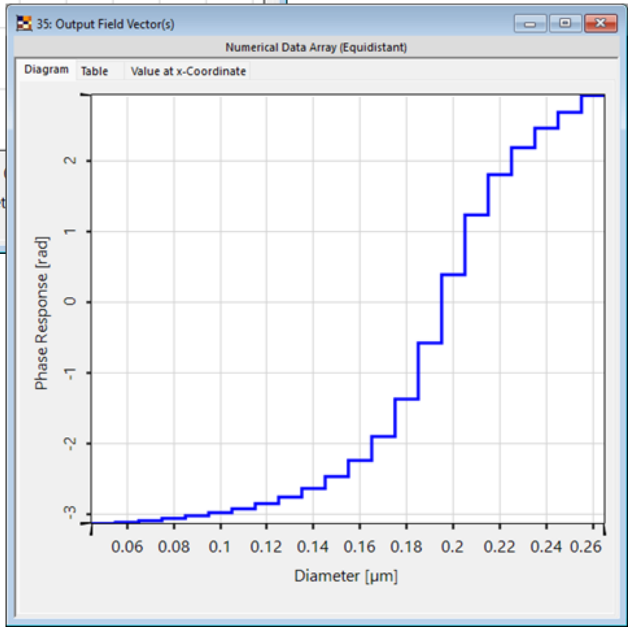
Parameter	Value
Pillar diameter range	50 nm – 260 nm (10 nm stepsize)
Wavelength	940 nm
Polarization	Linear x-polarization
Incidence angle range	-20° - 20° (11 × 11 steps)

Key Observations

- For the given parameters, the model predicts a phase range of 2π with low amplitude variation (<0.5% RMS).
- Quantization of the phase response arises from the discrete step size of the nanopillars.

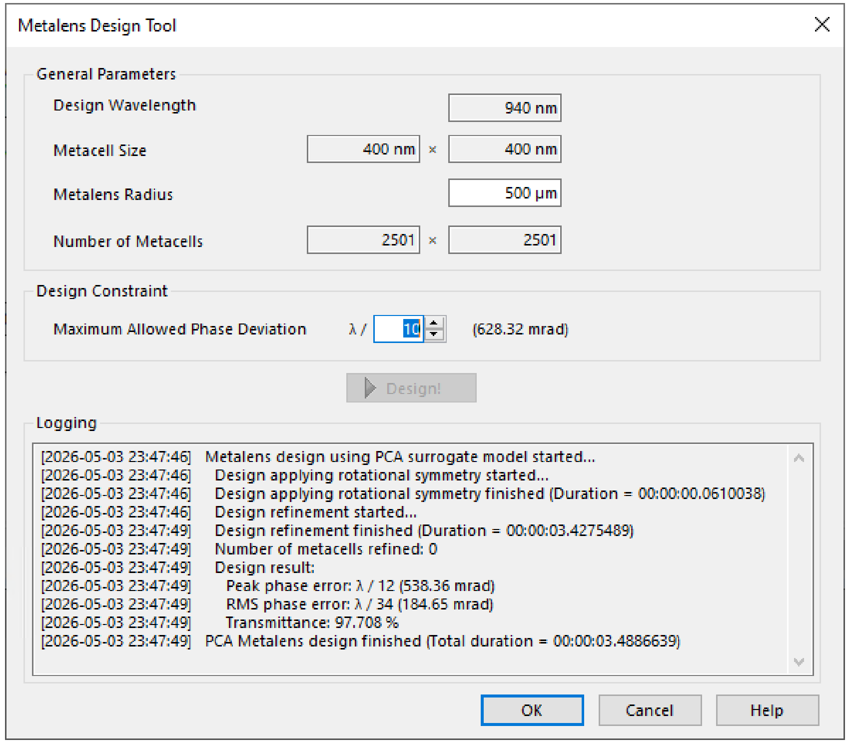


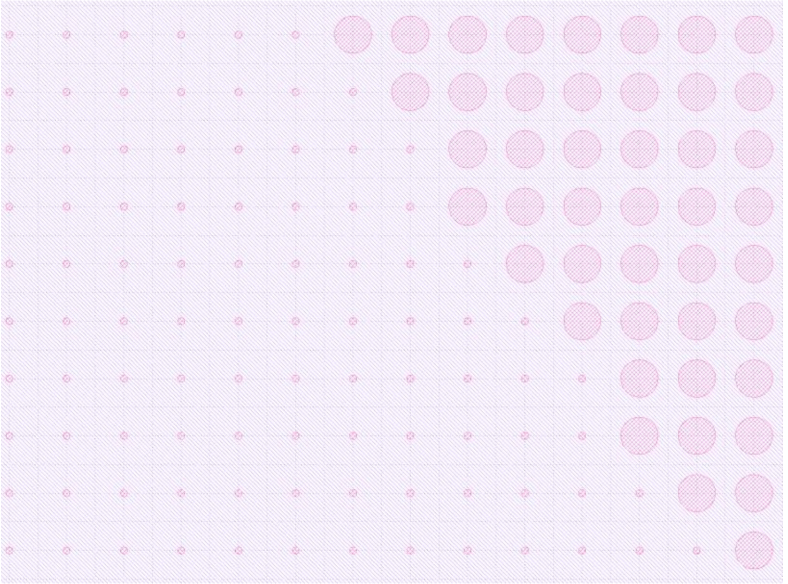
Amplitude component $|J_x^{\text{out}}|$[1]



Phase component ϕ_x[1]

Metalens Design





Detail view of designed metalens

Hardware & Performance

- Hardware: AMD Ryzen Threadripper 3970X 32-Core Processor, 256 GB DDR4 SDRAM
- Design time: 3 s for > 6.2 million meta-atoms

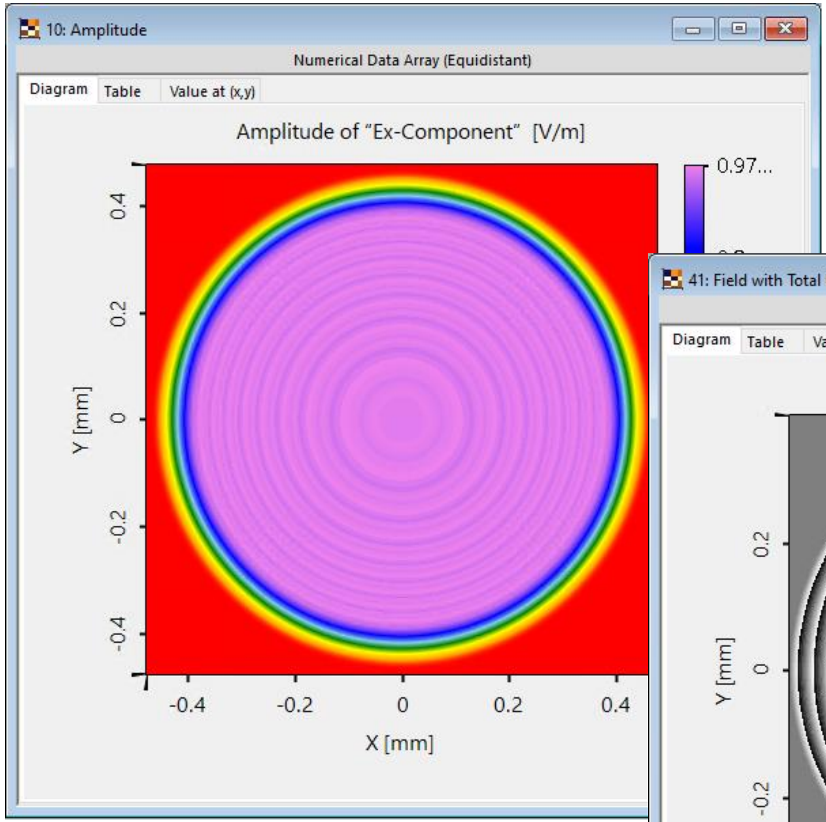
Design Results

Parameter	Value
Peak phase error	$\lambda/12$
RMS phase error	$\lambda/34$

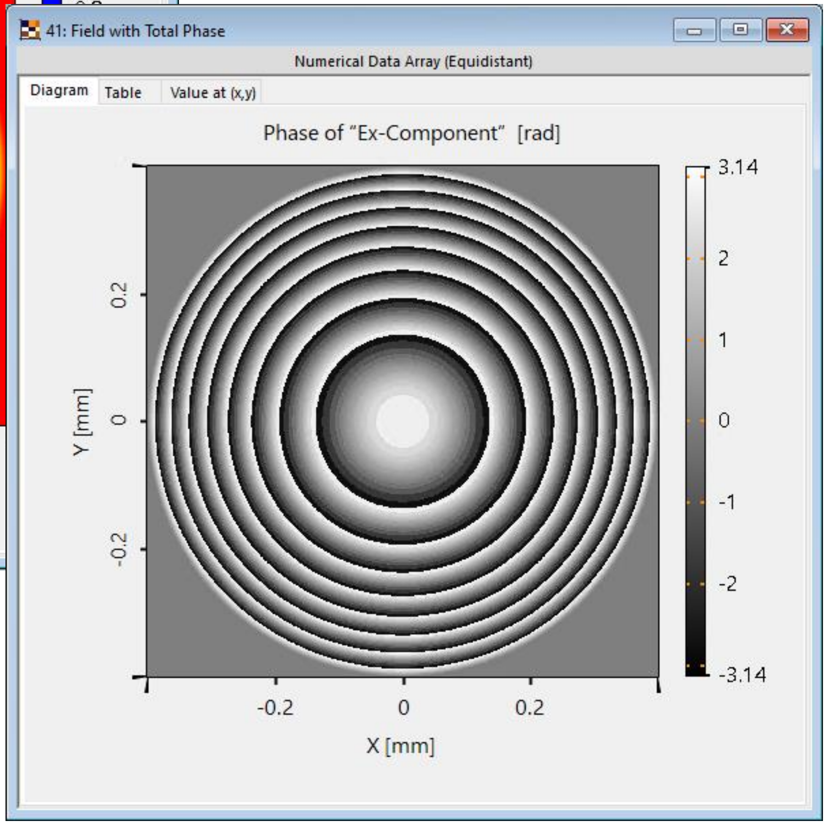
Results – Field after Metalens

Key Observation

- The metalens component was designed with a target phase profile $\Delta\psi^{\text{profile}}(\boldsymbol{\rho}) = \frac{2\pi}{\lambda}\left(\sqrt{x^2+y^2-f^2}\right)$.
- The resulting phase after propagation is spherical, as designed.
- Local deviations in amplitude and phase are present.



Amplitude after metalens



Phase after metalens

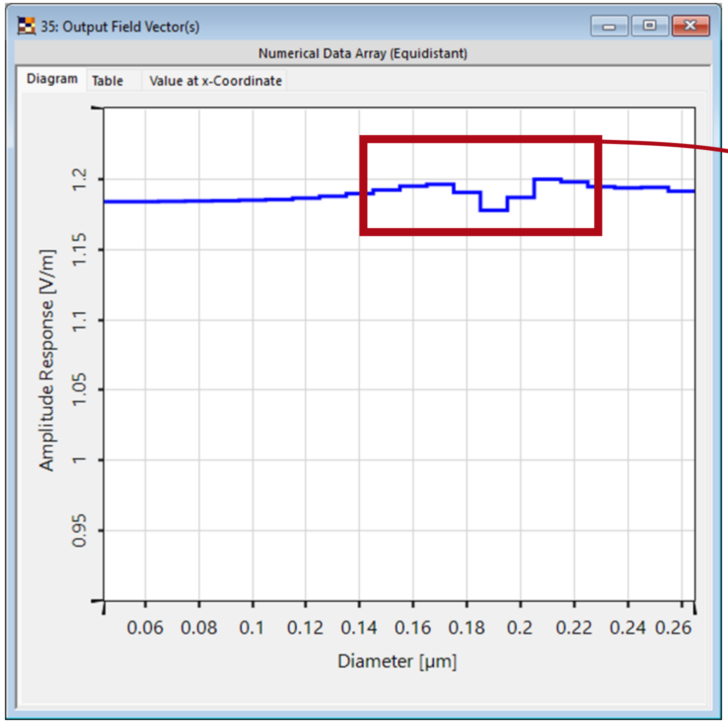
Hardware & Performance

- Hardware: AMD Ryzen Threadripper 3970X 32-Core Processor, 256 GB DDR4 SDRAM
- Simulation time: 8 s

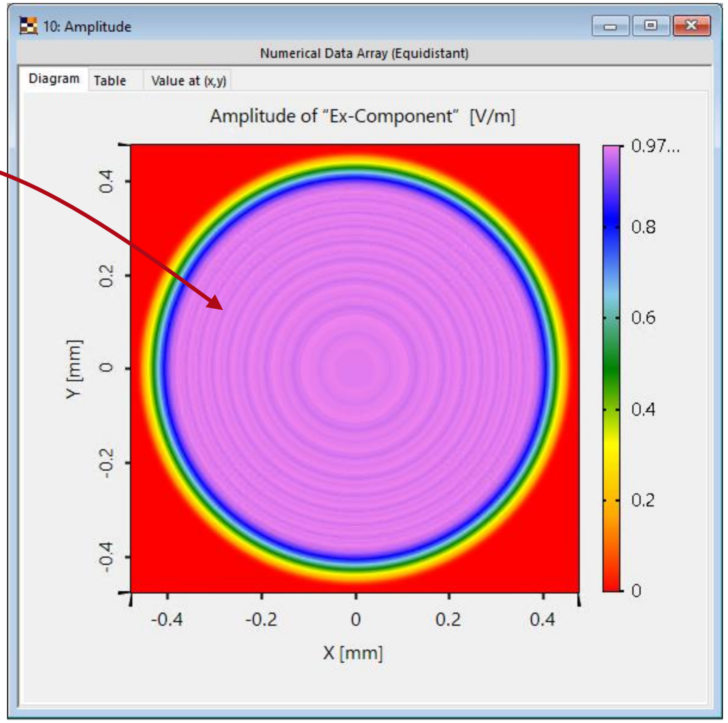
Results – Performance of Metalens (Amplitude)

Physics Insight

- The surrogate model predicts amplitude variations as a function of pillar diameter.
- These translate into concentric amplitude modulations in the field behind the metalens.



Amplitude component $|J_x^{\mathrm{out}}|$

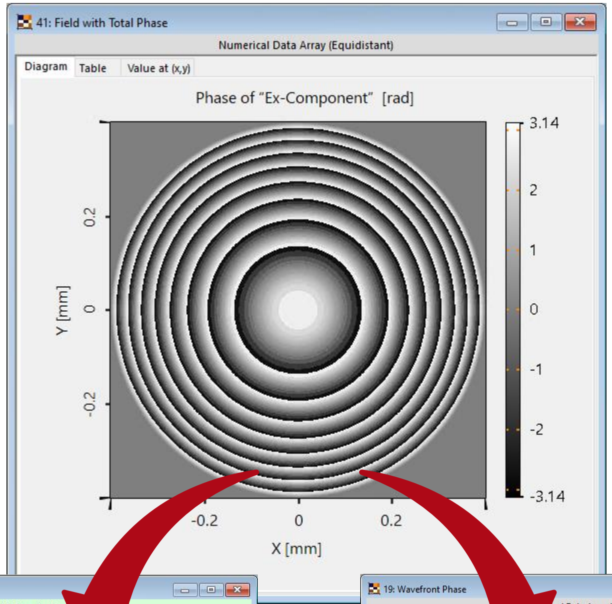


Field after metalens

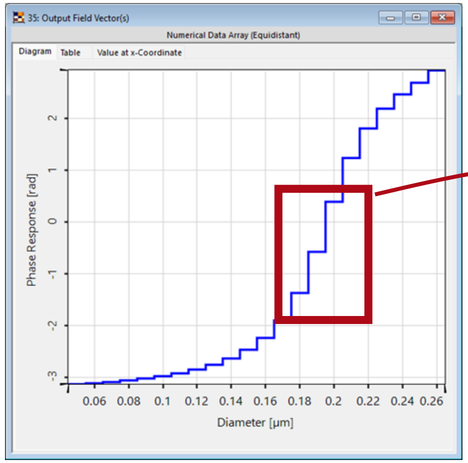
Results – Performance of Metalens (Phase)

Physical Insight

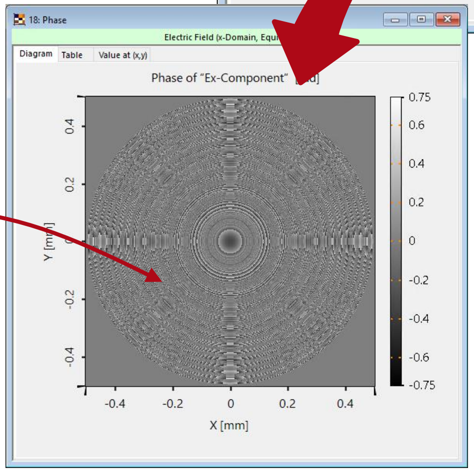
- The phase behind the metalens can be decomposed into a smooth wavefront phase and a residual phase.
- The smooth component matches the designed profile.
- The residual phase originates from the pillar diameter discretization of the metalens.



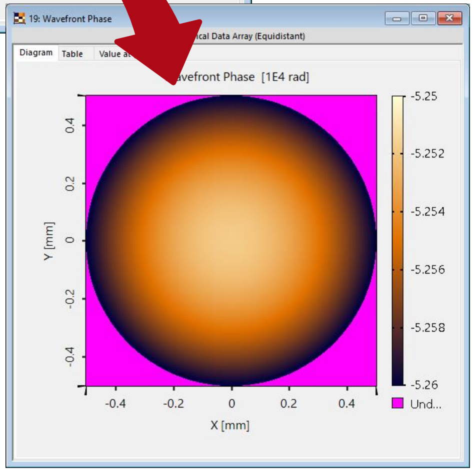
Field with total phase



Phase component $\phi_x^{[1]}$



Residual phase



Wavefront phase

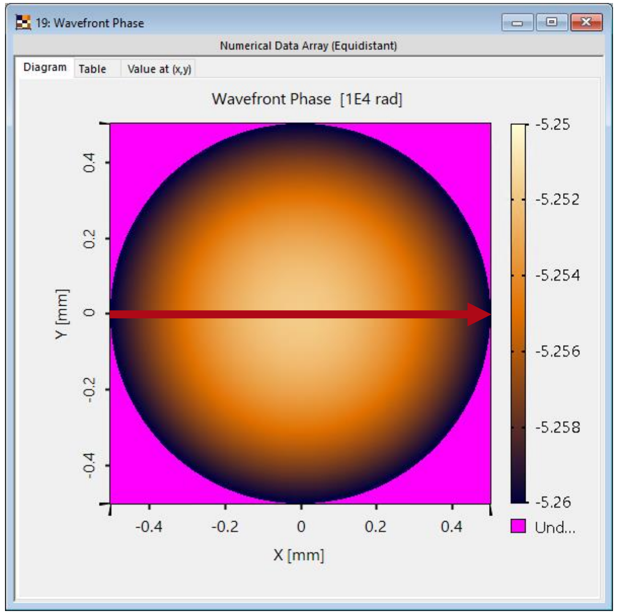
Results – Performance of Metalens (Wavefront Phase)

Detector Behind Metalens

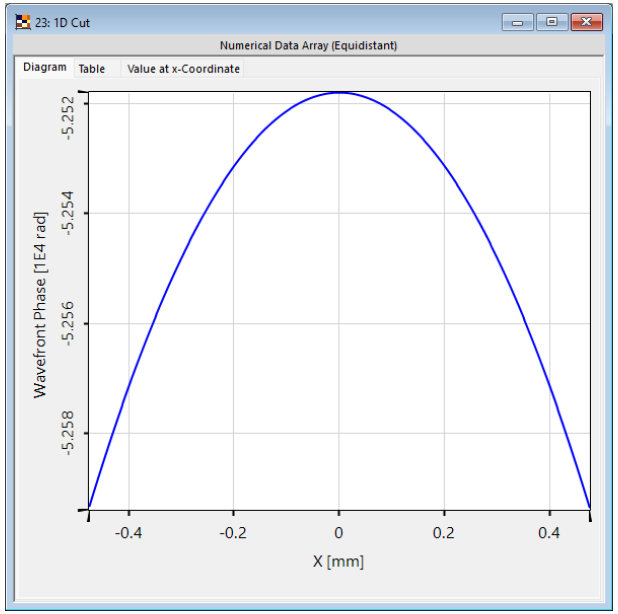
Property	Value
Wavefront	Spherical (focusing to 10 mm)
RMS	$< 10^{-10}\lambda$

Key Observations

- The target wavefront phase after the metalens was defined as $\phi(r) = \frac{2\pi}{\lambda}\left(\sqrt{x^2+y^2-f^2}\right)$.
- The Metalens [PCA] component accurately reproduces this target wavefront.



Wavefront phase

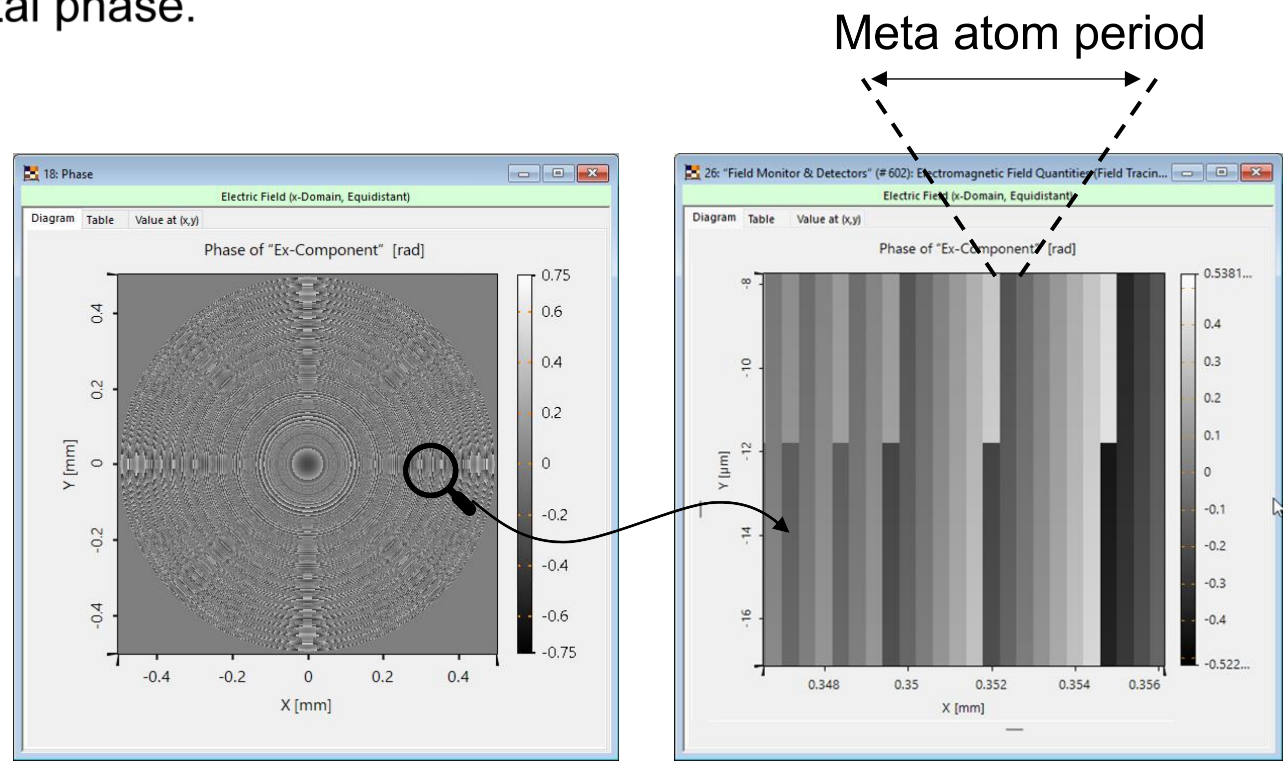


Wavefront phase (1D)

Results – Performance of Metalens (Residual Phase)

Physics Insight

- Discretization of nanopillar diameters introduces small phase errors.
- These residuals are shown after subtracting the smooth wavefront from the total phase.

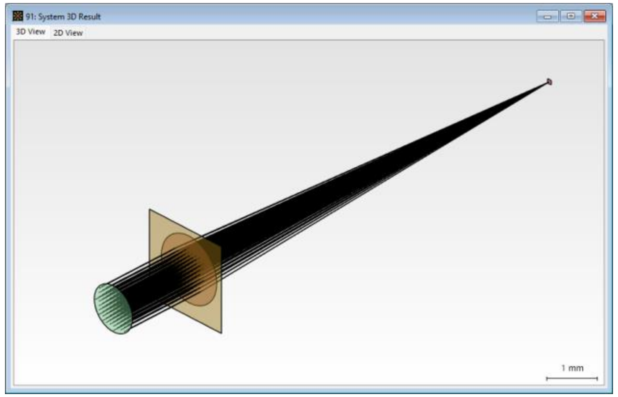


Residual phase after metalens

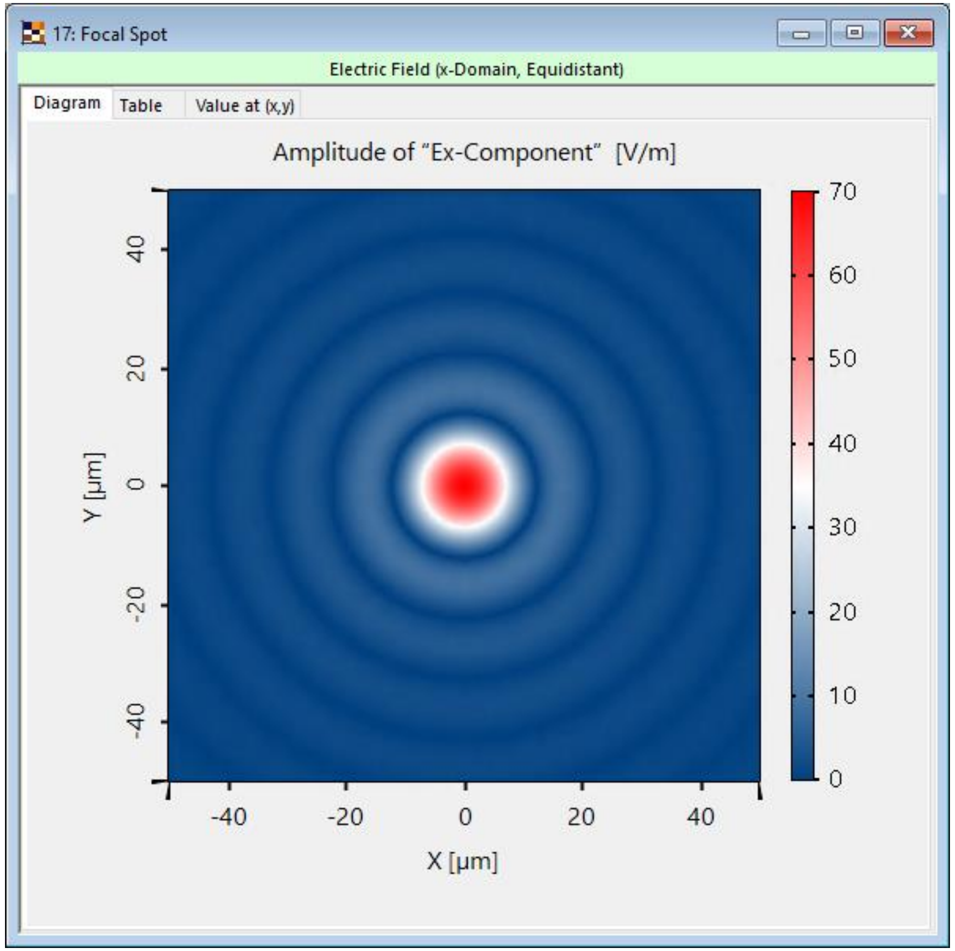
Detailed look on the residual phase after metalens

Results – Focal Spot

Key Observation Despite observable amplitude and phase imperfections immediately after the metalens, the metalens still forms a diffraction-limited focal spot.



3D System View



Focal spot

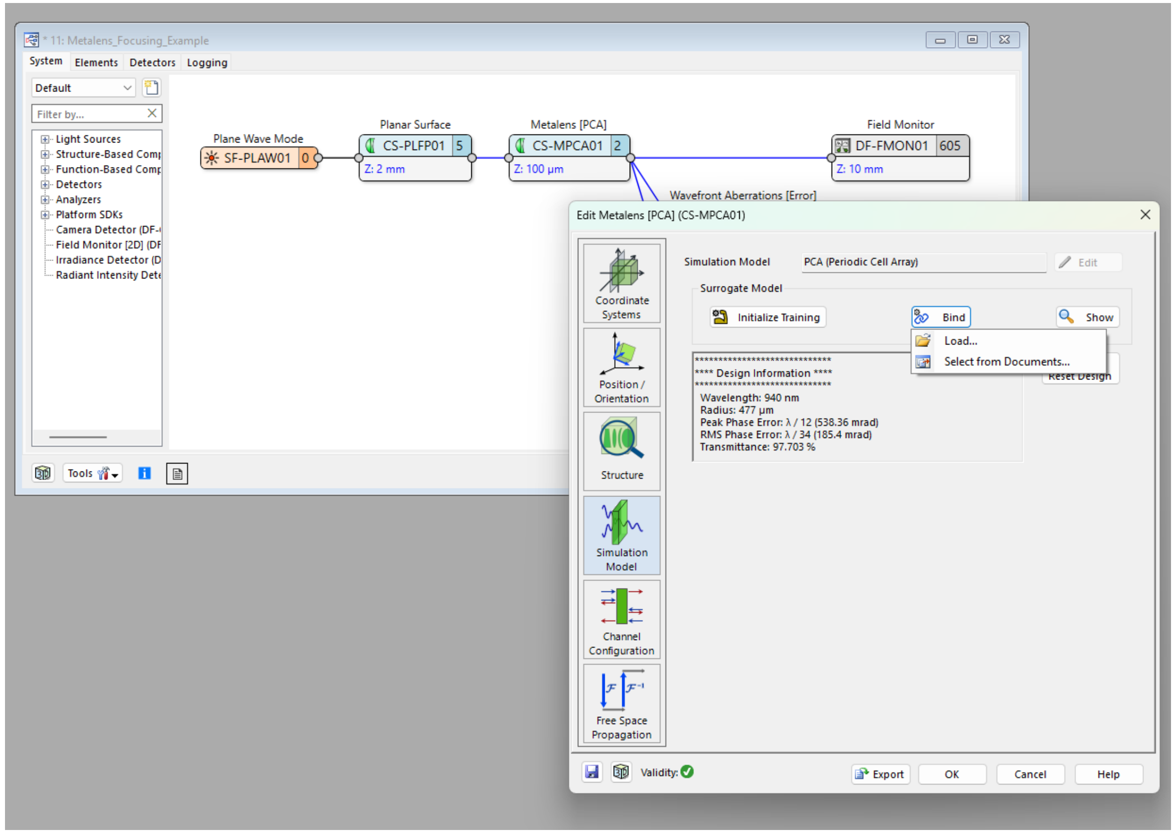
Hardware & Performance

- Hardware: AMD Ryzen Threadripper 3970X 32-Core Processor, 256 GB DDR4 SDRAM
- Simulation time: 12 s for focal spot, <1s for 3D system view

Demonstrated Workflow

Step-by-Step Workflow

1. **Train surrogate model:** Load the provided sample file — preset parameters are included and training has been performed.
2. **System setup:** Add digital twins — *Plane Wave Mode*, *Metalens [PCA]*, *Planar Surface*, *Field Monitor [2D]*, *Wavefront Aberrations [Error]*. Set parameters and connect them according to the *Application Scenario* page.
3. **Add detector add-ons:** Add *Field with Total Phase* add-on to the detector behind the metalens.
4. **Bind surrogate model:** In the *Metalens [PCA]* component, navigate to the *Simulation Model* page and click *Bind*. Select the trained surrogate
5. **Show Ray Tracing:** Simulate the system using Ray Tracing engine.
6. **Investigate performance:** Simulate the system using Field Tracing engine to calculate focal spot and wavefront error.



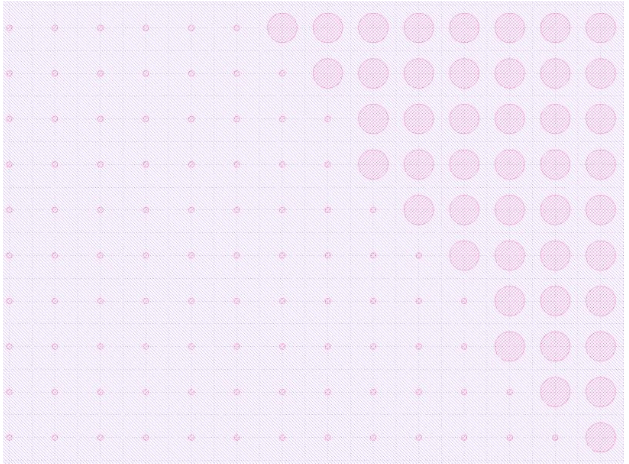
Conclusion

Key Takeaways

- VirtualLab Fusion provides a complete work-flow to design, simulate, and analyze focusing metalenses.
- Amplitude and phase effects due to pillar diameter discretization are directly observable behind the metalens.
- Nevertheless, the focal spot remains diffraction-limited (Airy pattern).

Next Steps

- Download the sample files and reproduce the results.
- Export the designed metastructure for manufacturing.



Detail of exported metastructure

Resources Used

White Papers

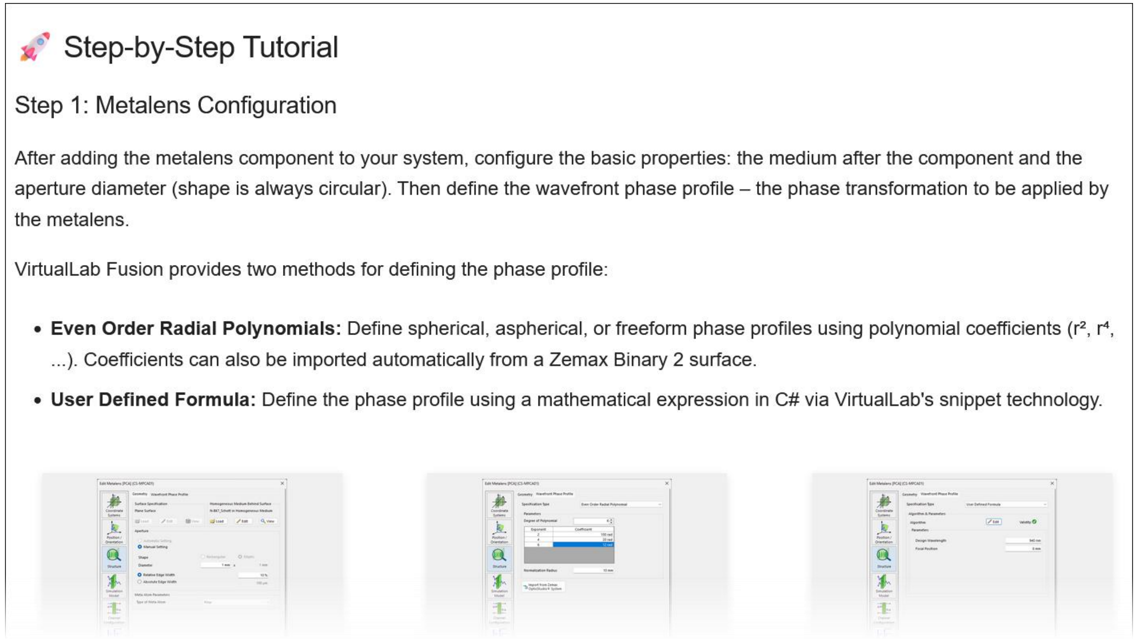
- WP-META-SURROGATE — Surrogate Modeling: Enabling Practical Metalens Design and Simulation
- WP-META-PHASE — Designing and Analyzing the Phase Response of Metasurfaces

Tutorials

- Initialization and Training of a Surrogate Model
- Designing a Metalens in VirtualLab Fusion

Related Use Cases

- Surrogate Model Training for Nanopillars
- Aberration Control via Metalens



🚀 Step-by-Step Tutorial

Step 1: Metalens Configuration

After adding the metalens component to your system, configure the basic properties: the medium after the component and the aperture diameter (shape is always circular). Then define the wavefront phase profile – the phase transformation to be applied by the metalens.

VirtualLab Fusion provides two methods for defining the phase profile:

- **Even Order Radial Polynomials:** Define spherical, aspherical, or freeform phase profiles using polynomial coefficients (r^2, r^4, ...). Coefficients can also be imported automatically from a Zemax Binary 2 surface.
- **User Defined Formula:** Define the phase profile using a mathematical expression in C# via VirtualLab's snippet technology.