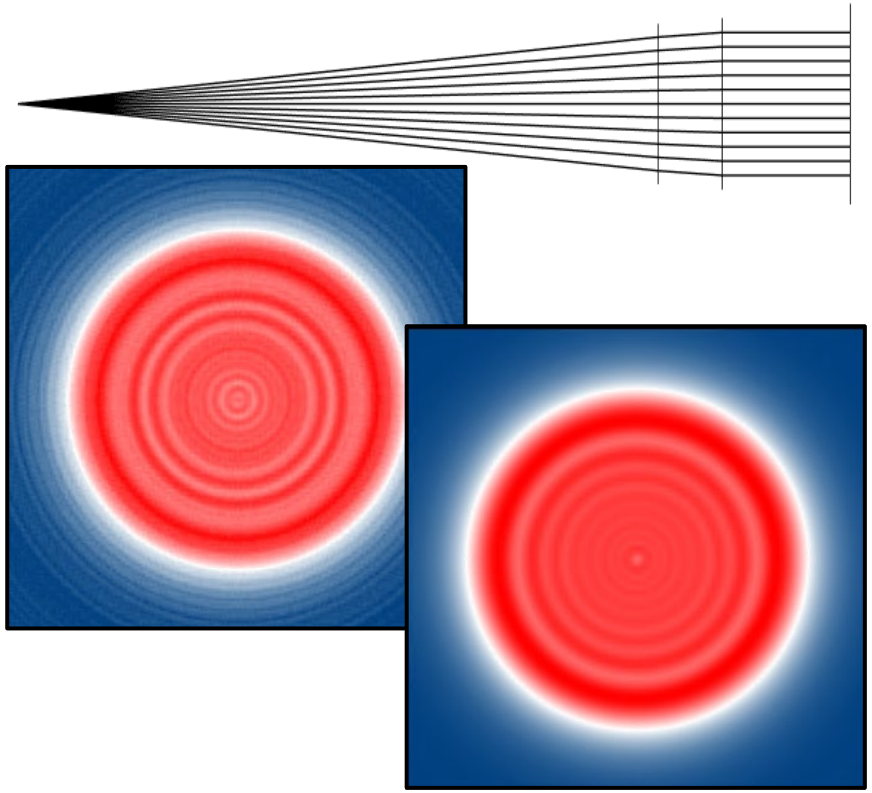
Collimation with a Metalens Based on Nanopillars

Wavefront Phase Error & Propagation Effects

Part of the Meta Optics Solution Guide

Document ID: UC-META-COLLIMATION
Version: 1.0
Date: May 18, 2026
Author: LightTrans International GmbH



Executive Summary

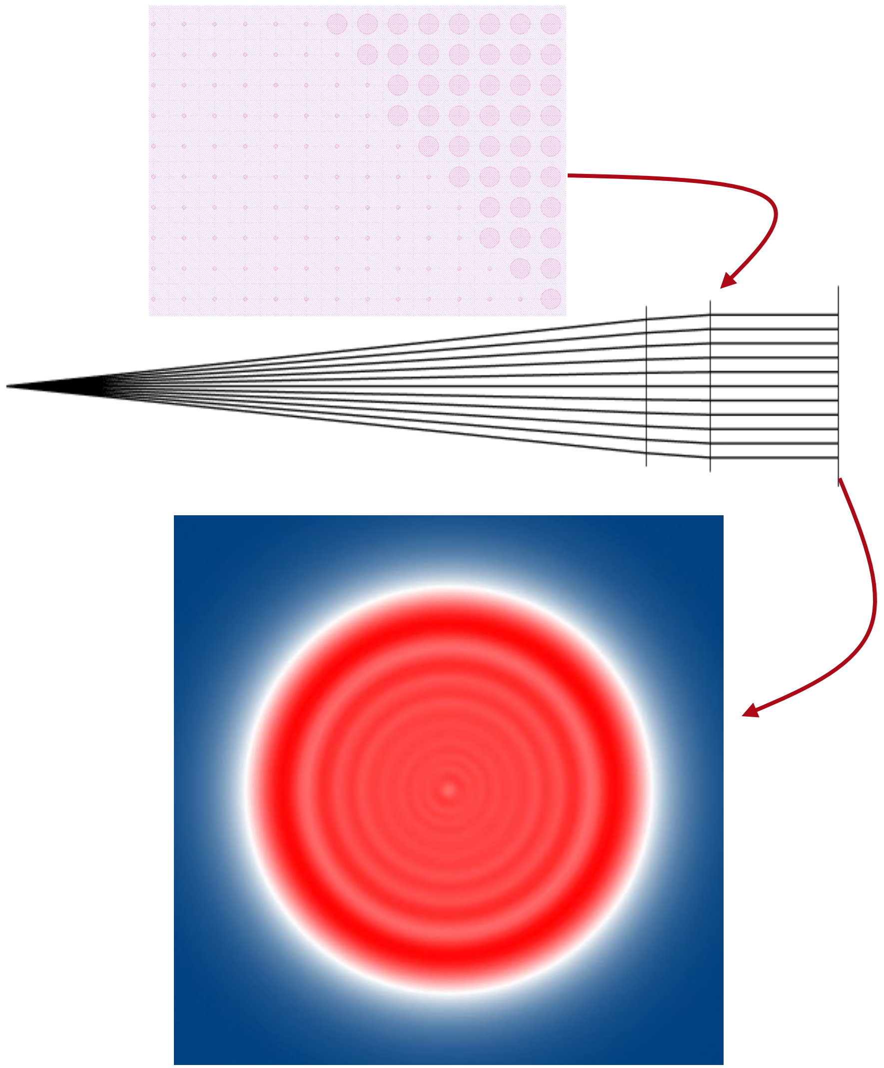
Collimation of a spherical wave using a nanopillar metalens.

Key Achievements

- Metalens negates the incident spherical wave-front to a nominal zero phase.
- RMS phase error after metalens is below 0.001 λ.
- Discretization-induced phase deviations convert into amplitude effects after propagation.

Hardware & Performance

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

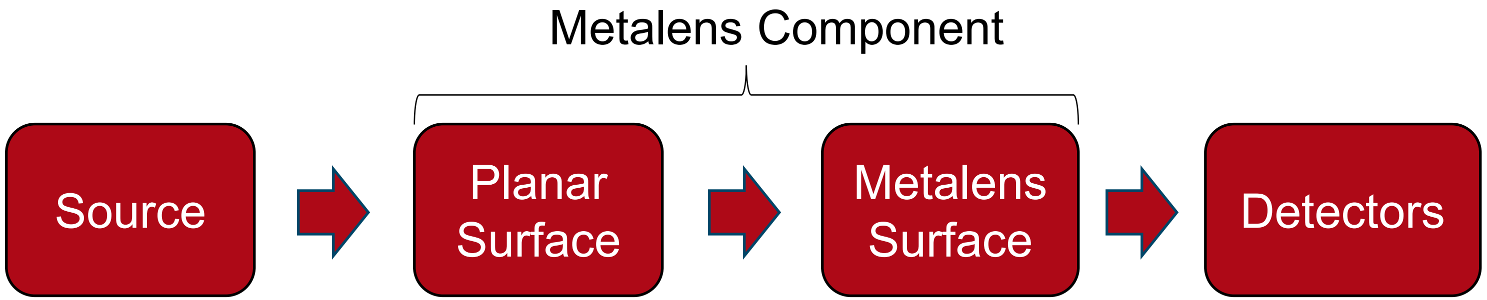


Application Scenario

The Scenario A collimating metalens was designed and its performance evaluated by analyzing the wavefront phase and phase errors after the metalens, as well as the electromagnetic field evolution at propagation distances of 0 mm and 5 mm.

Physical Lab Setup

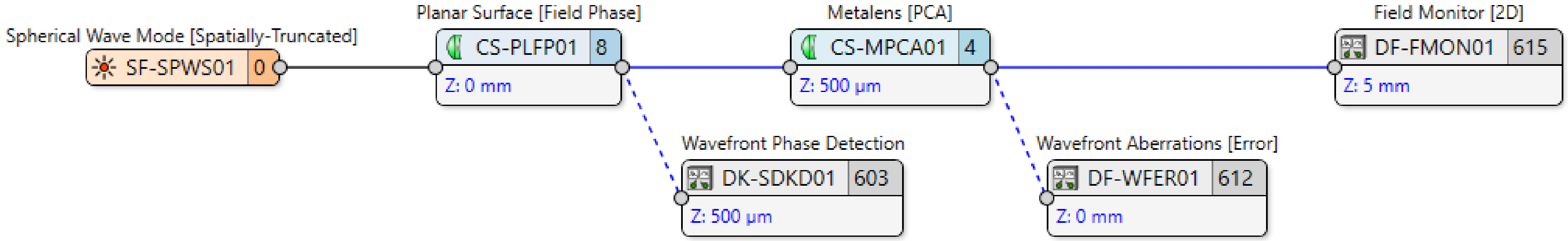
Component	Specification
Source	Plane wave, 940 nm, lin. x-polarized
Metalens	Nanopillars, n = 3.8, f = 10 mm, diameter 0.5 mm
Nanopillar meta-atom	Height 465 nm, period 400 nm × 400 nm
Detector 1	Radial wavefront phase before metalens
Detector 2	Wavefront phase error after metalens
Detector 3	EM field at (0 mm, 5 mm) behind metalens



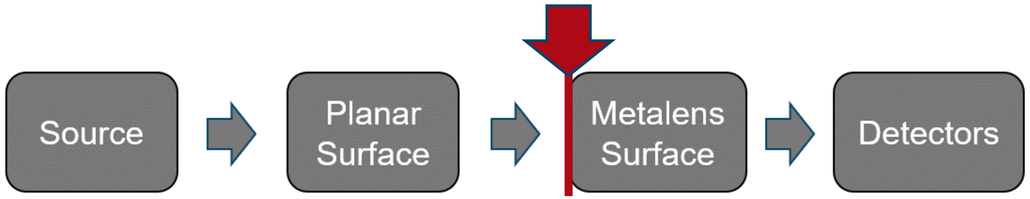
Digital Twins of the System

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: $\phi_{\text{metalens}}(r) = -\phi_{\text{input}}(r)$
Substrate	CS-PLFP01	Planar surface, fused silica
Detector 1	DF-FMON01	Radial wavefront phase
Detector 2	DF-WFER01	Wavefront phase error
Detector 3	DF-FMON01	EM field



Wavefront Phase Profile Definition



What We Did To define the wavefront phase profile of the metastructure we use the following steps:

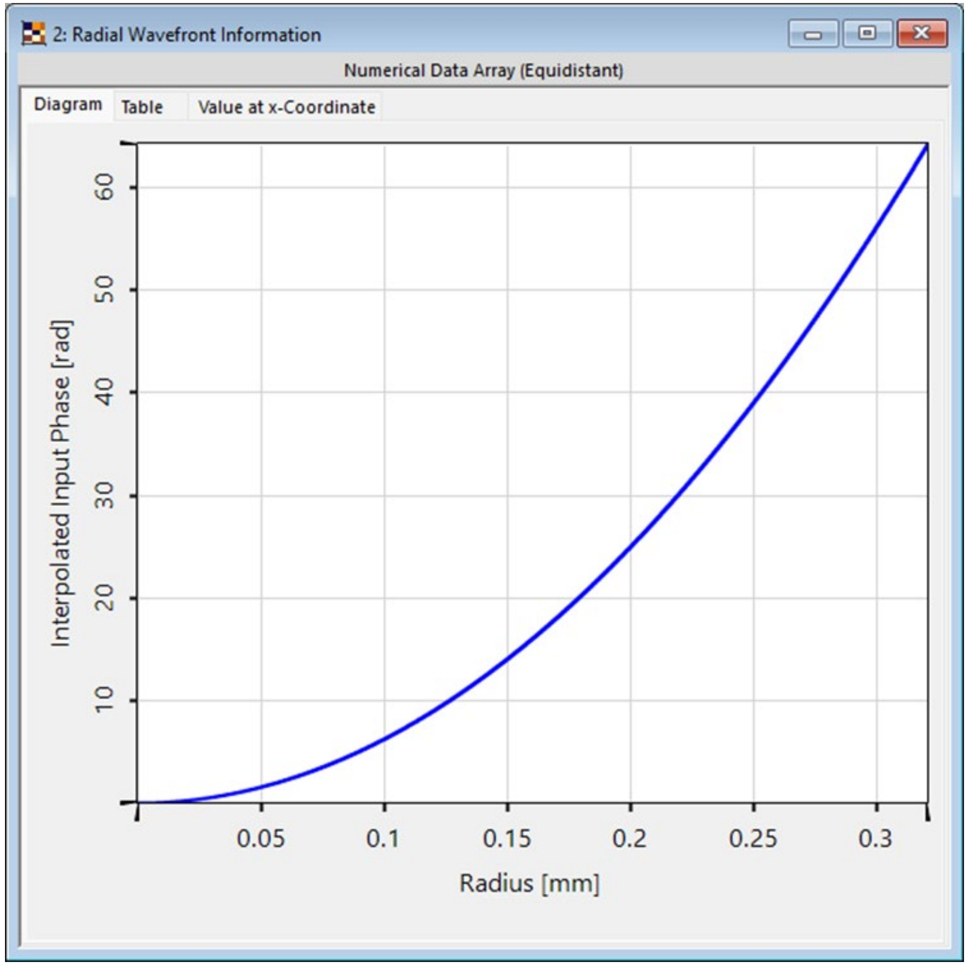
1. Calculate the incoming phase

Use *Radial Wavefront Phase Detector* to obtain $\phi_{\text{input}}(r)$ in front of the metasurface — this phase includes the lens's spherical aberration.

2. Calculate the required metalens phase via difference

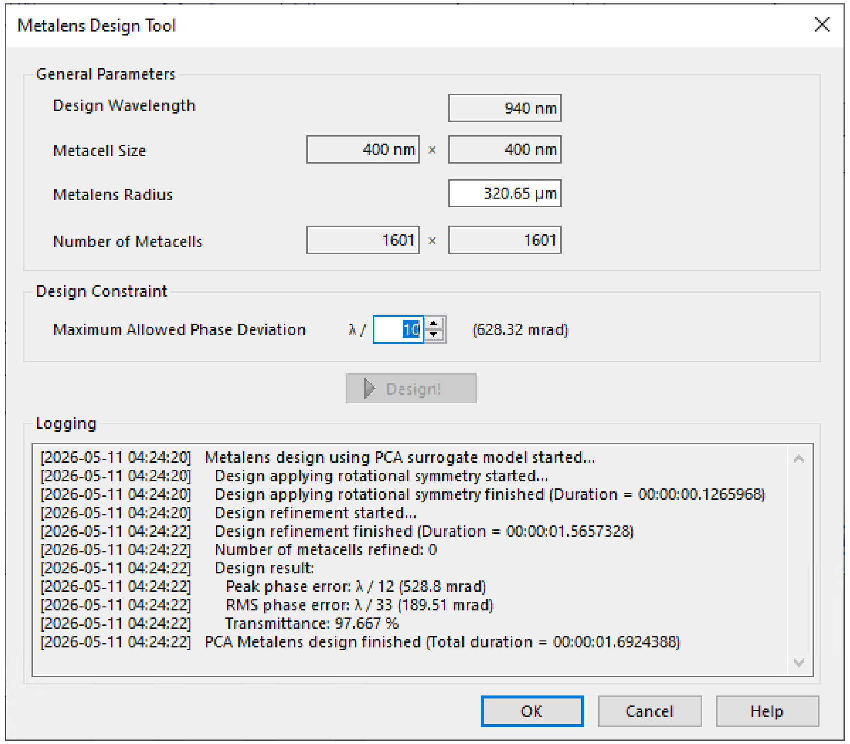
The target phase behind the lens is constant zero. The metalens must negate the input phase:

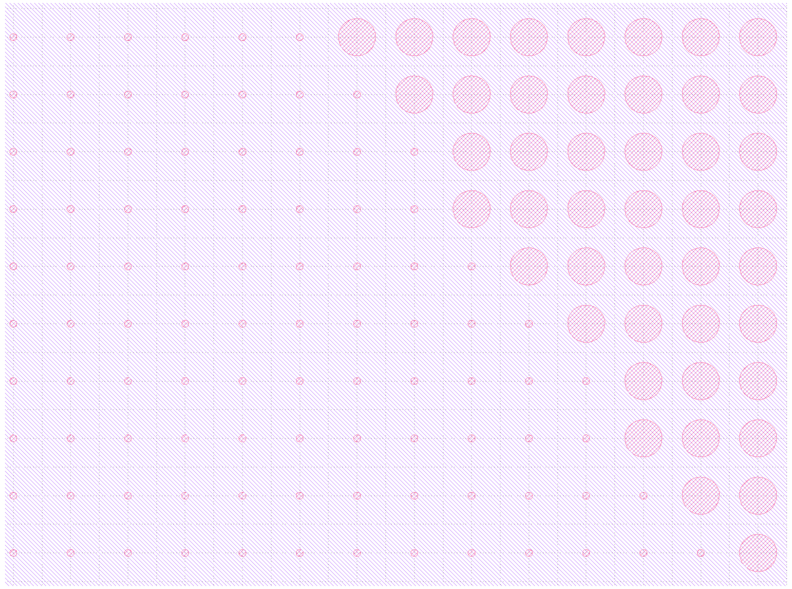
$$\phi_{\text{metalens}}(r) = -\phi_{\text{input}}(r)$$



Calculated Radial Wavefront Phase

Metalens Design





Detail view of designed metalens

Hardware & Performance

- Hardware: AMD Ryzen Threadripper 3970X 32-Core Processor, 256 GB DDR4 SDRAM
- Design time: 1.7 s for > 2.5 million meta-atoms

Design Results

Parameter	Value
Peak phase error	$\lambda/12$
RMS phase error	$\lambda/33$

Results – Wavefront Phase after Metalens

Detector Behind Metalens

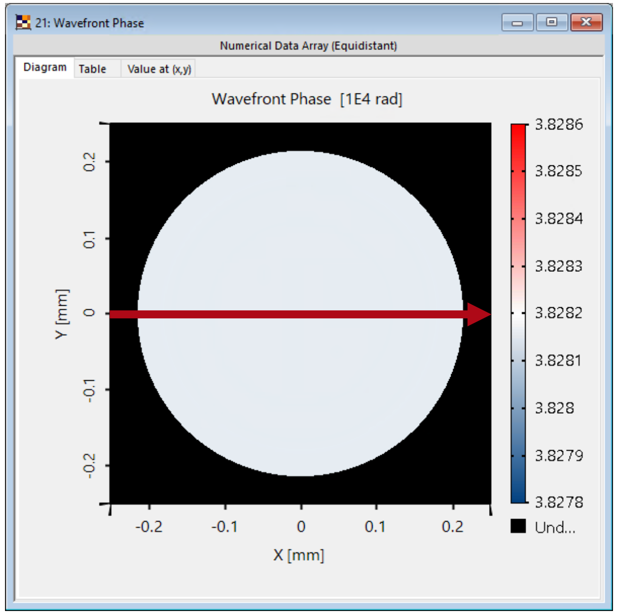
Property	Value
Wavefront	Plane
RMS	$< 10^{-3}\lambda$

Physics Insight

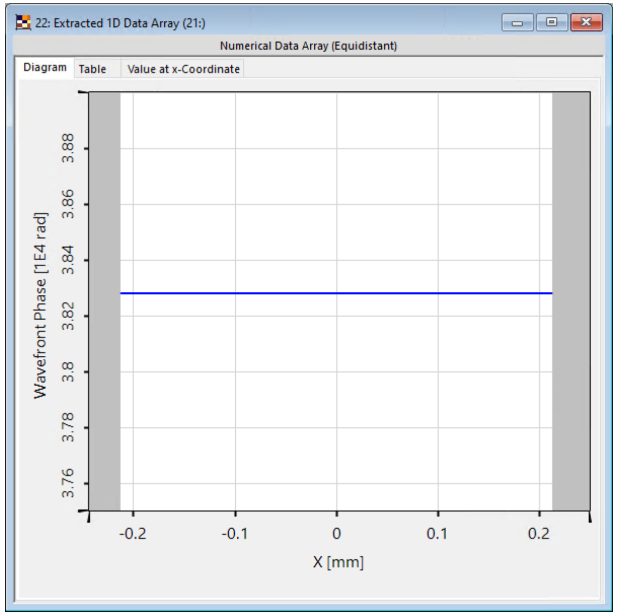
- The metalens successfully negates the incident spherical wavefront.
- The resulting total phase is nominally zero, as designed.

Hardware & Performance

- Hardware: AMD Ryzen Threadripper 3970X 32-Core Processor, 256 GB DDR4 SDRAM
- Simulation time: 4.7 s



Wavefront phase

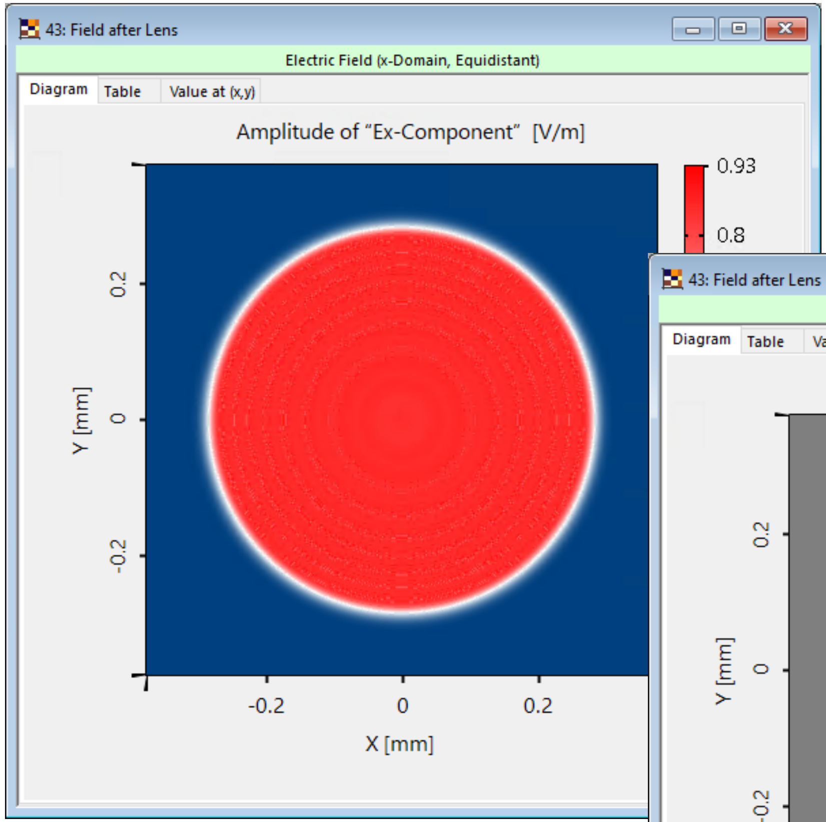


Wavefront phase (1D)

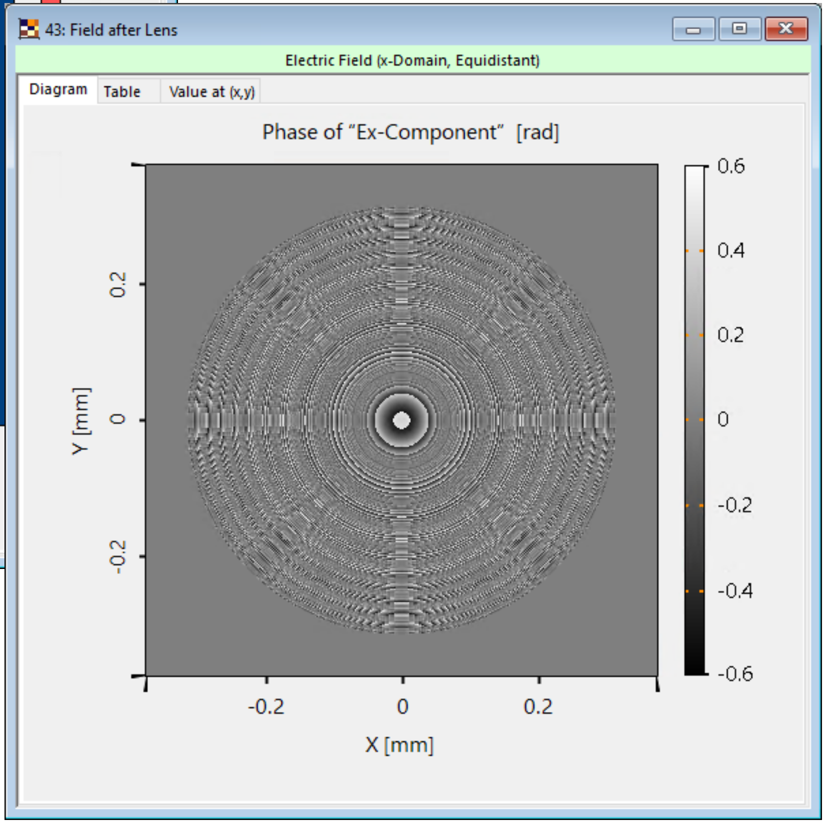
Results – Field after Metalens (0 mm)

Key Observations

- The field directly after the lens resembles a plane wave.
- The phase, however, exhibits structured deviations.



Amplitude after metalens



Phase after metalens

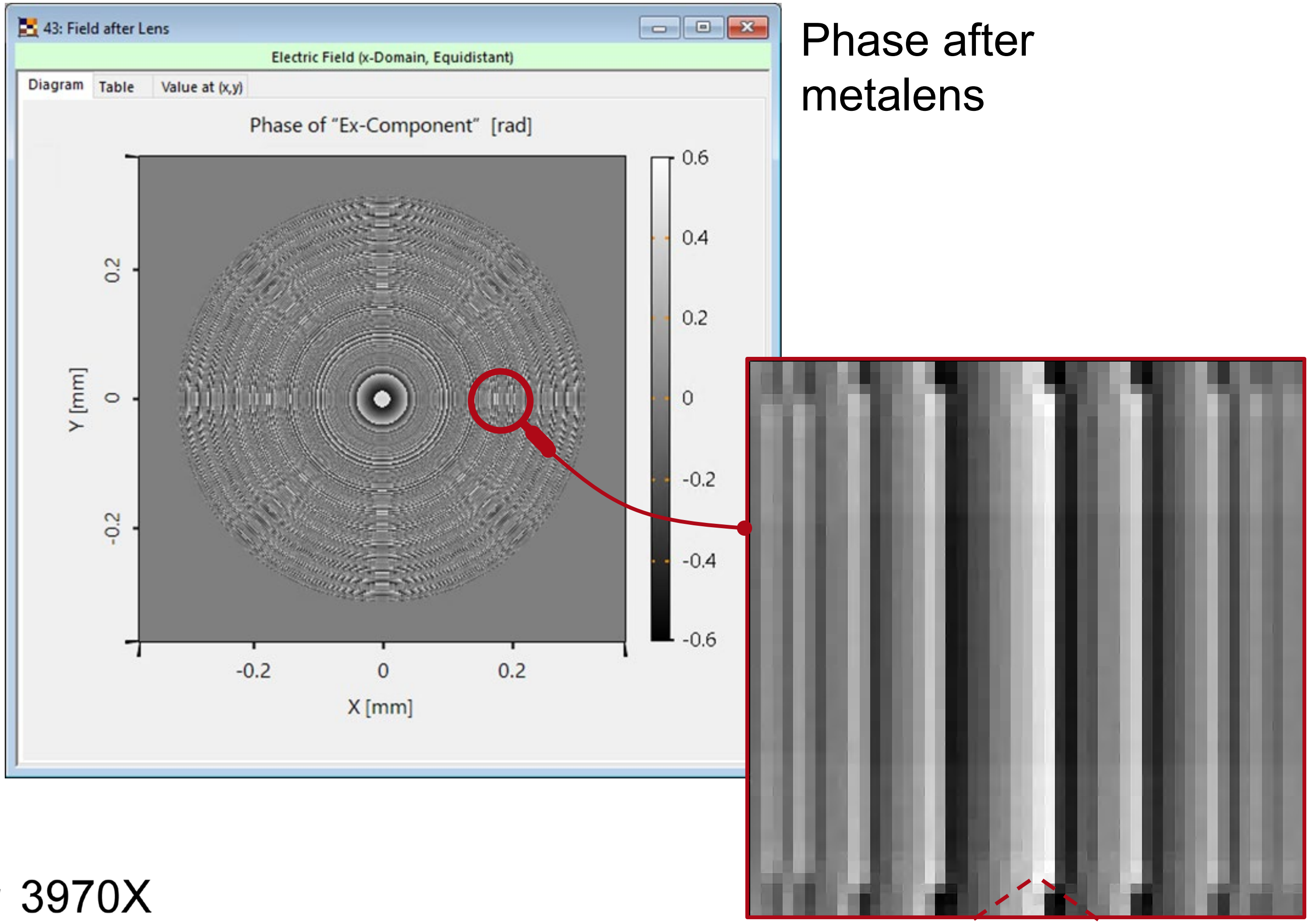
Hardware & Performance

- Hardware: AMD Ryzen Threadripper 3970X 32-Core Processor, 256 GB DDR4 SDRAM
- Simulation time: 5 s

Results – Field after Metalens (0 mm)

Physical Interpretation

- Detailed analysis indicates that the phase deviations exhibit the same feature size as the meta-atom period.
- These deviations likely originate from discretization of the pillar diameter.



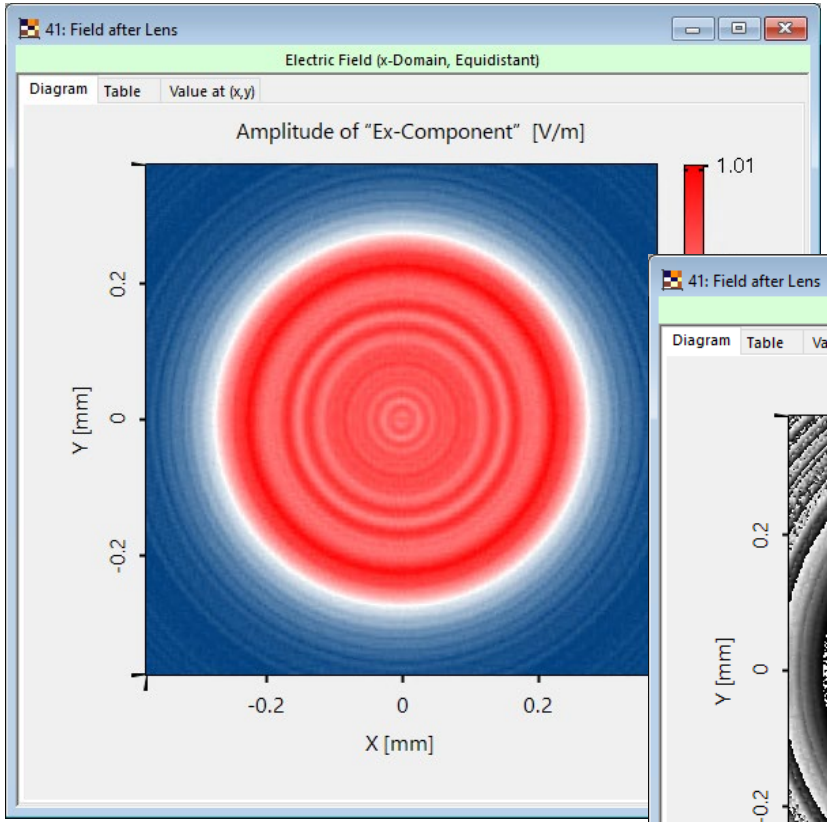
Hardware & Performance

- Hardware: AMD Ryzen Threadripper 3970X 32-Core Processor, 256 GB DDR4 SDRAM
- Simulation time: 5 s

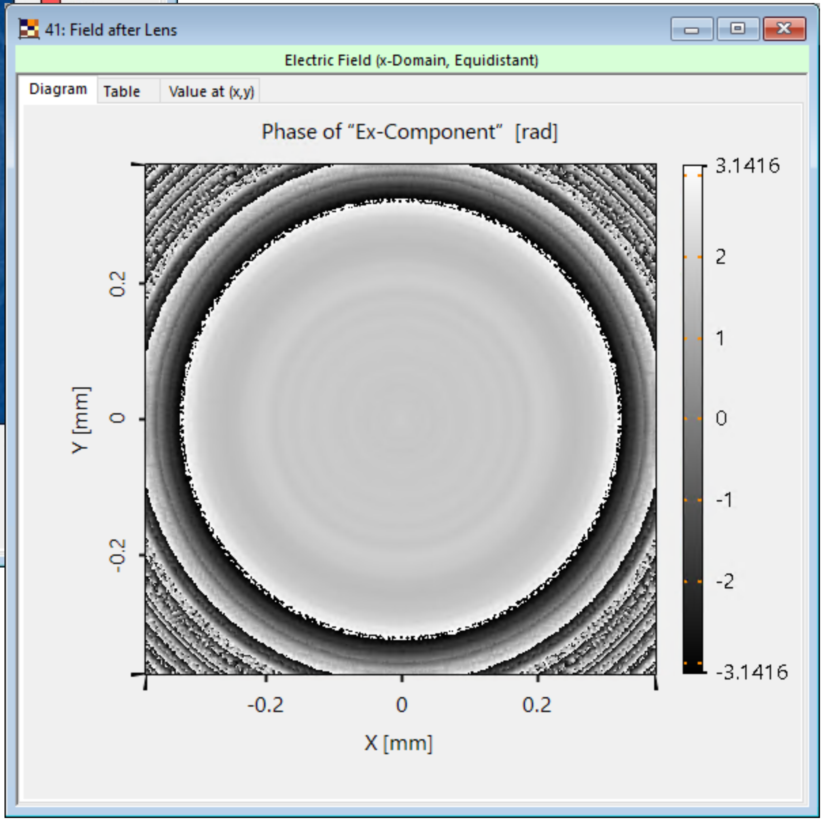
Results – Field after Metalens (5 mm)

Key Observations

- After 5 mm propagation, the amplitude pattern shows a superposition of Fresnel diffraction from the aperture and stray light generated by pillar diameter discretization.



Amplitude after metalens



Phase after metalens

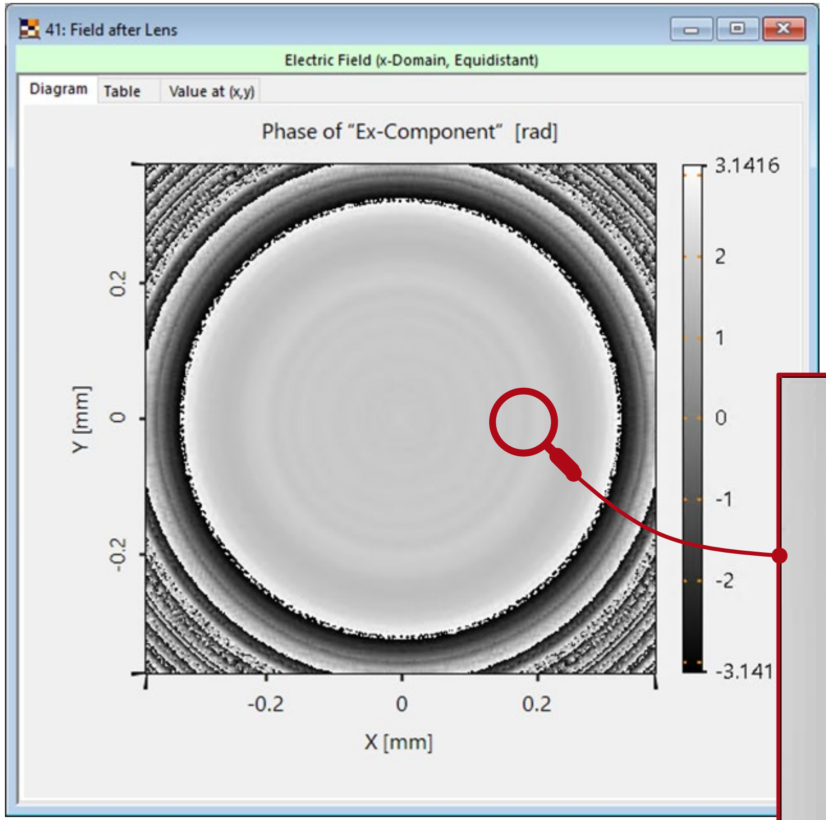
Hardware & Performance

- Hardware: AMD Ryzen Threadripper 3970X 32-Core Processor, 256 GB DDR4 SDRAM
- Simulation time: 1 min

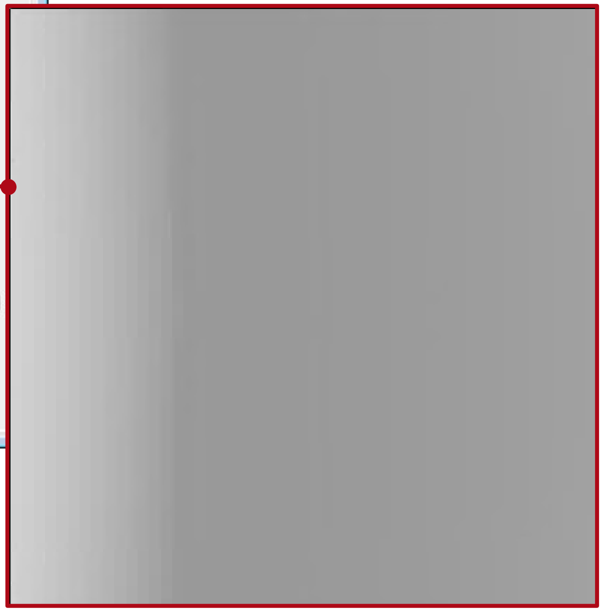
Results – Field after Metalens (5 mm)

Physics Insight

- Since the effect caused by pillar diameter discretization is evanescent, a smooth phase is recovered after propagation.



Phase after metalens



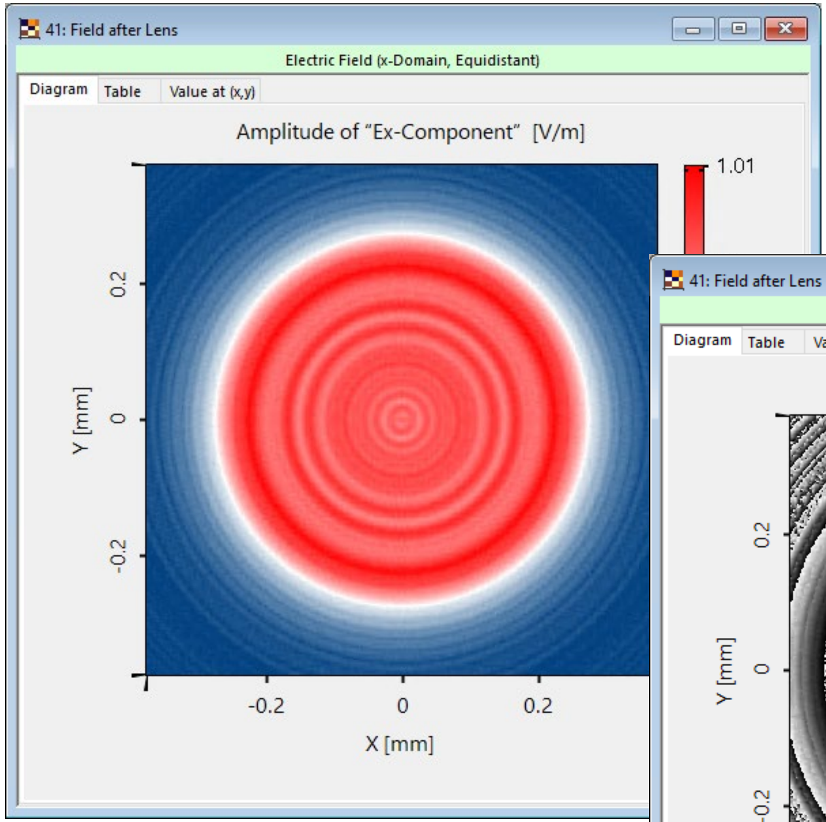
Phase after metalens

Hardware & Performance

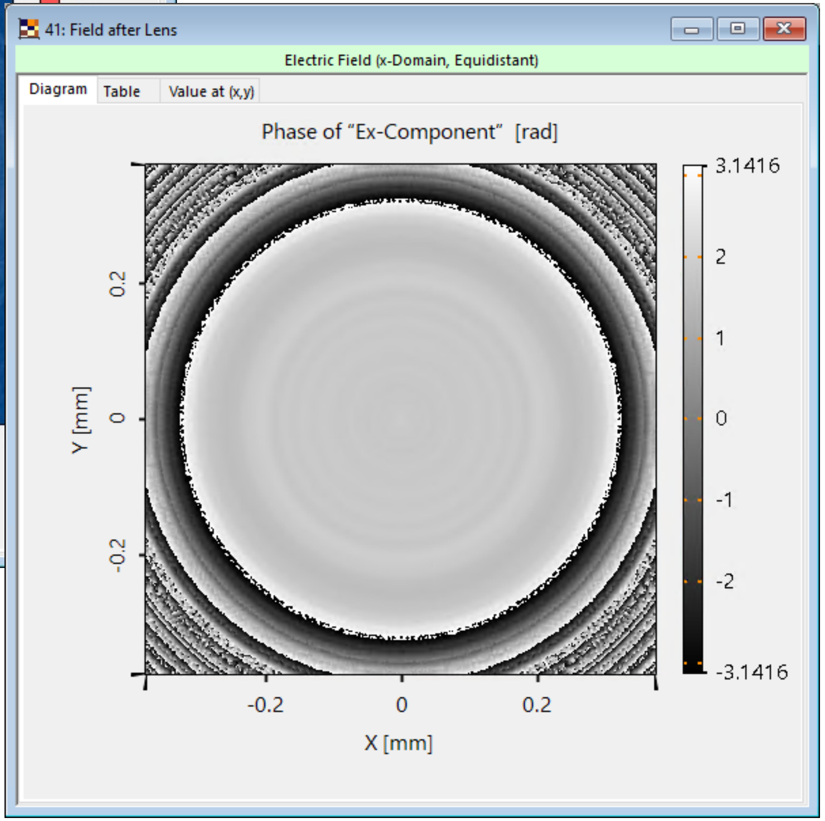
- Hardware: AMD Ryzen Threadripper 3970X 32-Core Processor, 256 GB DDR4 SDRAM
- Simulation time: 1 min

Results – Field after Metalens (5 mm)

❓ What is the magnitude of the effect of phase deviations caused by pillar diameter discretization on the field?



Amplitude after metalens

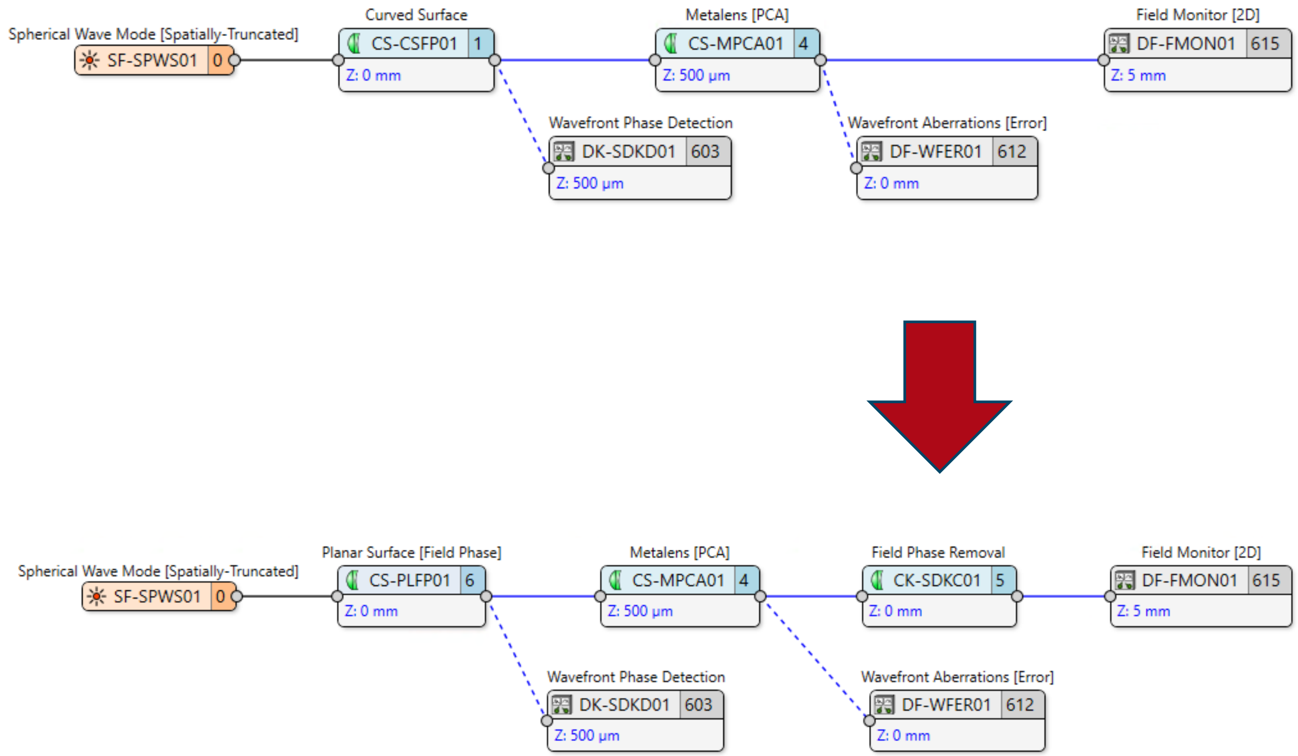


Phase after metalens

Validation – Field Phase Removal

Physics Insight

- To isolate the effect of phase residuals, a *Field Phase Removal* component was inserted after the metalens.
- This component calculates the residual phase (deviation from the smooth wave-front) and numerically compensates it.



From Real Asset to Digital Twin

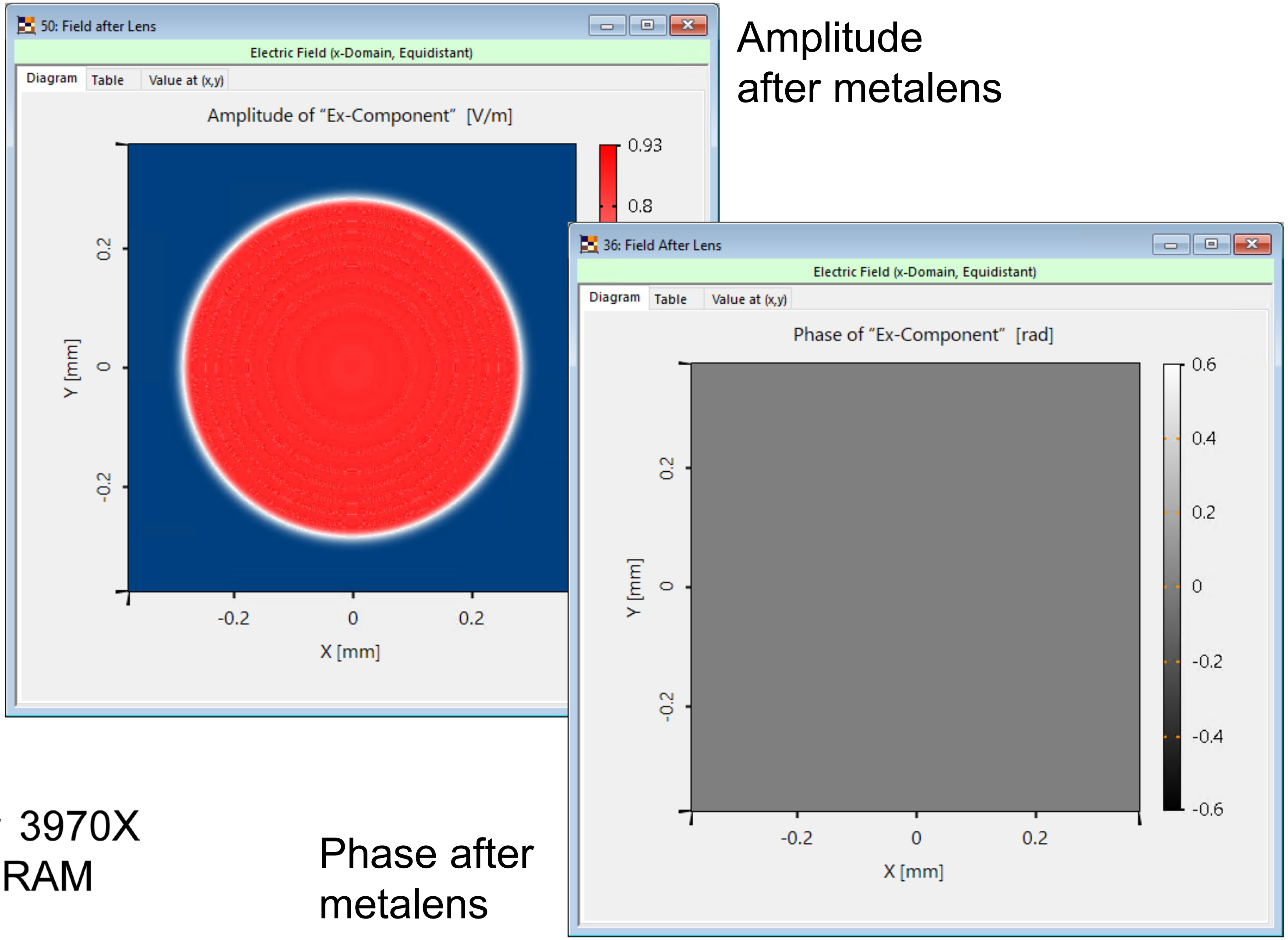
Digital Twin Mapping

Real Asset	Digital Twin	Description
Laser source	SF-PLAW01	Plane wave, 940 nm, lin. x-polarization
Nanopillar metalens	CS-MPCA01	Metalens [PCA], phase profile: $\phi_{\text{metalens}}(r) = -\phi_{\text{input}}(r)$
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
Field Phase Removal	CK-SDKC01	Removal of field phase

Results – Field after Metalens with Phase Filter (0 mm)

Key Observations

- As intended the phase effect after the lens is eliminated.



Amplitude after metalens

Phase after metalens

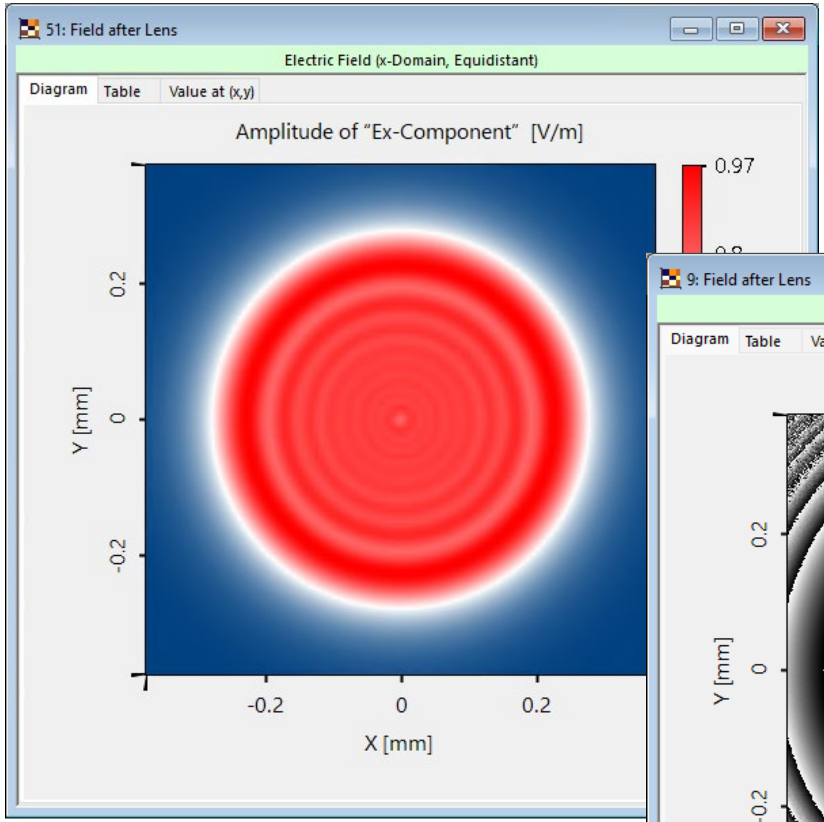
Hardware & Performance

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

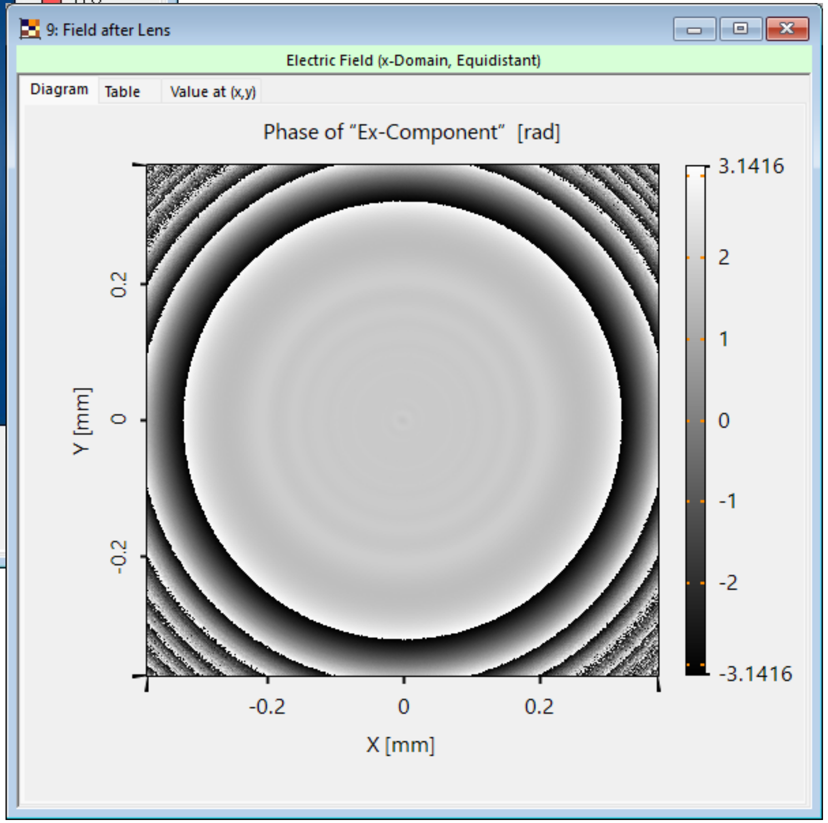
Results – Field after Metalens with Phase Filter (5 mm)

Key Observations

- The field after propagation now exhibits clear diffraction rings caused by the aperture of the metalens.



Amplitude after metalens



Phase after metalens

Hardware & Performance

- Hardware: AMD Ryzen Threadripper 3970X 32-Core Processor, 256 GB DDR4 SDRAM
- Simulation time: 13 s

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 — *Spherical Wave Mode*, *Metalens [PCA]*, *Planar Surface*, *Field Monitor [2D]*, *Wavefront Aberrations [Error]*, *Field Phase Removal* and *Radial Wavefront Phase*. Set parameters and connect them according to the *Application Scenario* page.
3. **Bind surrogate model:** In the *Metalens [PCA]* component, navigate to the *Simulation Model* page and click *Bind*. Select the trained surrogate model.
4. **Calculate 1D radial wavefront phase:** Calculate the result of the *Radial Wavefront Phase* detector.
5. **Define wavefront phase profile:** Import *Negate Incident Phase* snippet from sample files into *Metalens [PCA]* component. Use the calculated 1D radial wavefront profile as *Input Wavefront Data*.
6. **Field tracing:** On first use, the metalens design process starts automatically. Change Maximum Allowed Phase Deviation to $\lambda/10$. Click *Design*, then *OK* after completion — field tracing proceeds automatically.

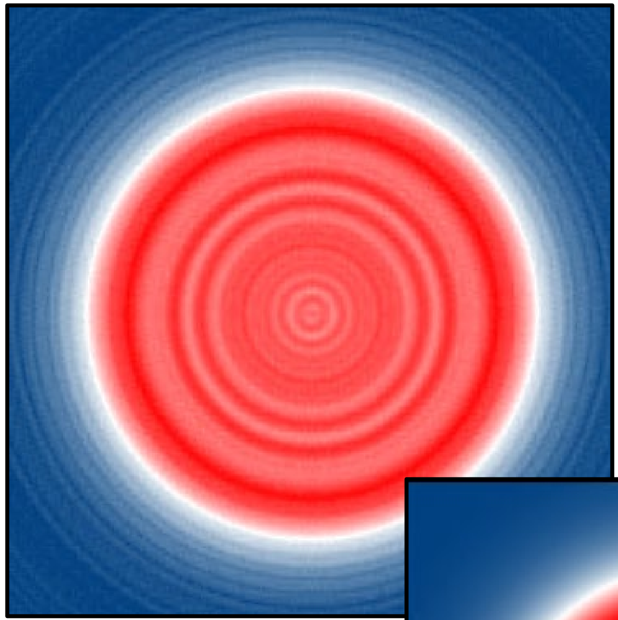
Conclusion

Key Takeaways

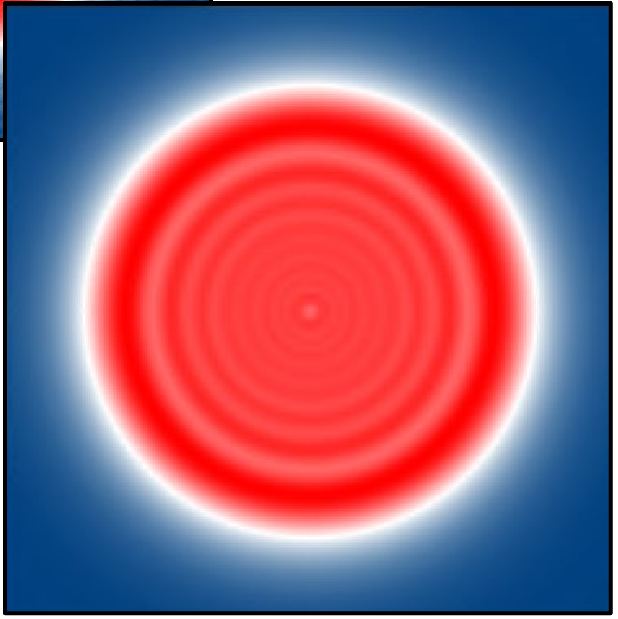
- The nanopillar metalens successfully negates the incident spherical wavefront, achieving a nominal zero phase after the metalens.
- Discretization-induced phase deviations smear out upon propagation — no lasting phase artifacts remain.
- Amplitude modulations caused by pillar discretization persist and overlay with Fresnel diffraction features from the finite aperture.

Next Steps

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



Field after 5 mm without filter



Field after 5 mm with filter

Resources Used

White Papers

- WP-META-PCA - PCA: The Foundation for Metalens Design
- WP-META-PHASE - Designing and Analyzing the Phase Response of Metasurfaces

Tutorials

- Define Metalens Functionality
- Designing a Metalens in VirtualLab Fusion

Related Use Cases

- Surrogate Model Training for Nanopillars
- Focusing Metalens Based on Nanopillars

🚀 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.