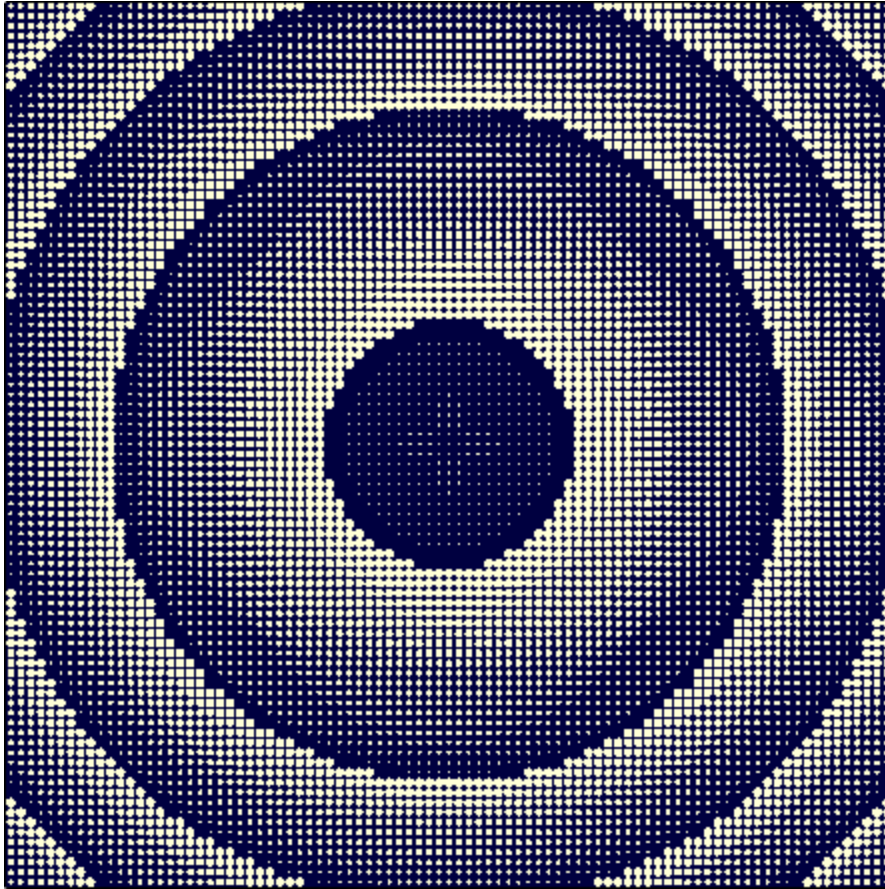


Design and Analysis of a Metalens

Abstract

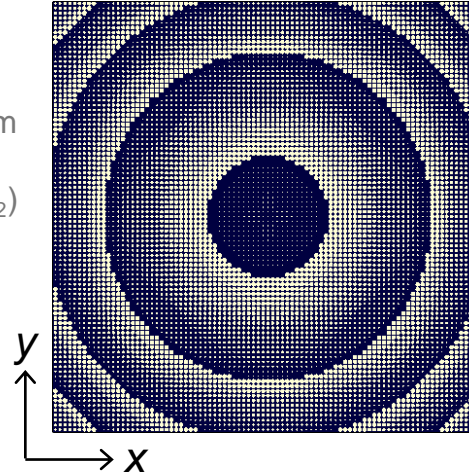


A lens is a transmissive optical device that focuses or defocuses light by changing its phase. Unlike conventional lenses, metalenses have the advantage of being able to achieve the desired phase change in a very thin layer using structures with sizes in the order of the wavelength and below, without the need for a complex and voluminous lens group. In this example, we showcase the design process of a metalens using cylindrical dielectric nanopillars. Owing to its nanoscale structure and high refractive index contrast, full vectorial modelling of the electromagnetic field is essential. For the initial configuration, parameters from E. Bayata's work are used.

Design Task

metalens (top-view)

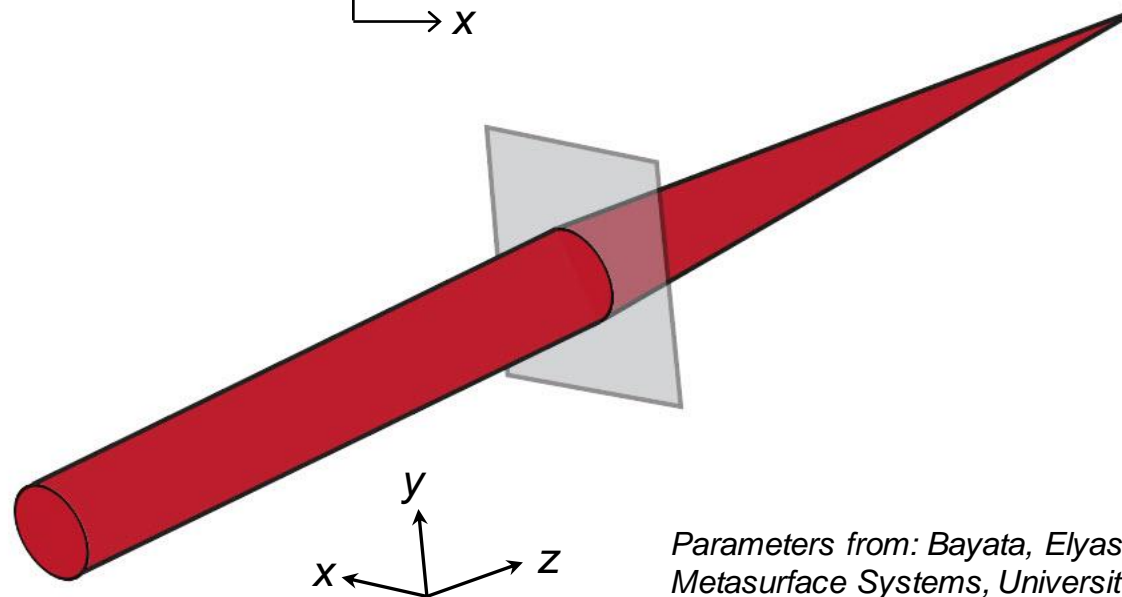
- extent: $70.4\mu\text{m} \times 70.4\mu\text{m}$
- size of unit cell: $790.5\text{nm} \times 790.5\text{nm}$
- substrate glass: 1.5
- refractive index of pillars: 2.4 (TiO_2)
- shape of pillars: cylindrical
- focal length: $200\mu\text{m}$ (NA 0.175)



How to design a meta lens to focus a plane wave?

input field

- wavelength: 1550nm
- polarization: along x
- diameter: $70\mu\text{m} \times 70\mu\text{m}$

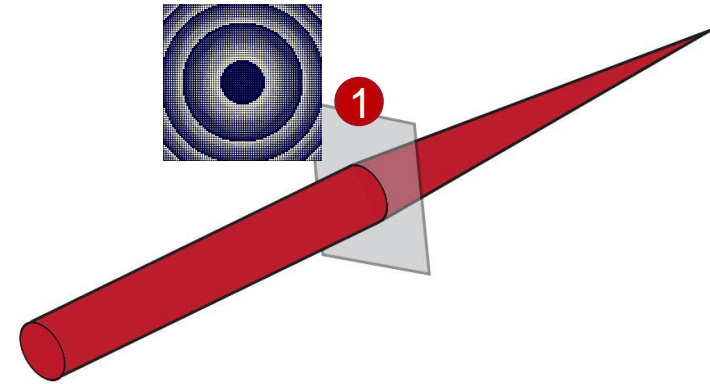


Parameters from: Bayata, Elyas; *Design and Characterization of Optical Metasurface Systems*, University of Washington, 2022.
(https://labs.ece.uw.edu/amlab/Thesis/UWPhDThesis_Elyas_Bayati_Final.pdf)

Simulation & Setup: Single-Platform Interoperability

Connected Modeling Techniques: Metalens

- ① metalens (analysis of pillar structure)
- ② propagation to focus
- ③ detector



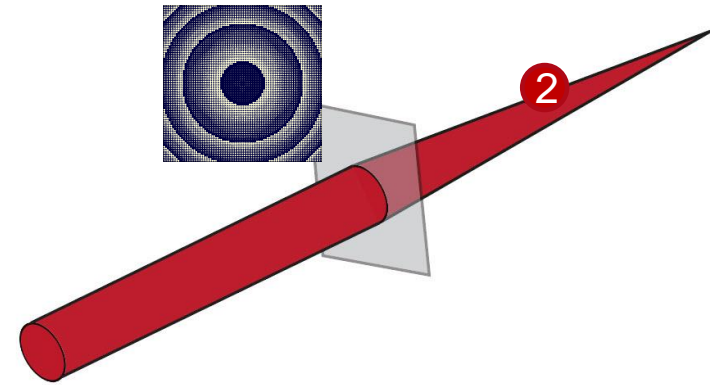
Available modeling techniques for periodic micro and nano structures:

Methods	Preconditions	Accuracy	Speed	Comments
Fourier Modal Method (FMM)	None	High	Low	-
Thin Element Approximation	Large periods & features, thin	High	High	Thickness about wavelength; period & features larger than about ten wavelengths
	Otherwise	Low	High	
FMM in Kogelnik Approximation	Thick volume gratings; Bragg condition	High	Very high	Method is electromagnetic formulation of Kogelnik's approach
	No Bragg condition	Low	Very high	

← As a rigorous eigenmode solver, the Fourier modal method (also known as rigorous coupled wave analysis, RCWA) provides a very high accuracy. While calculation may take a while, for complex systems like this, the high accuracy is absolutely necessary.

Connected Modeling Techniques: Free-Space Propagation

- ① metalens
- ② propagation to focus
- ③ detector



Available modeling techniques for free space propagations:

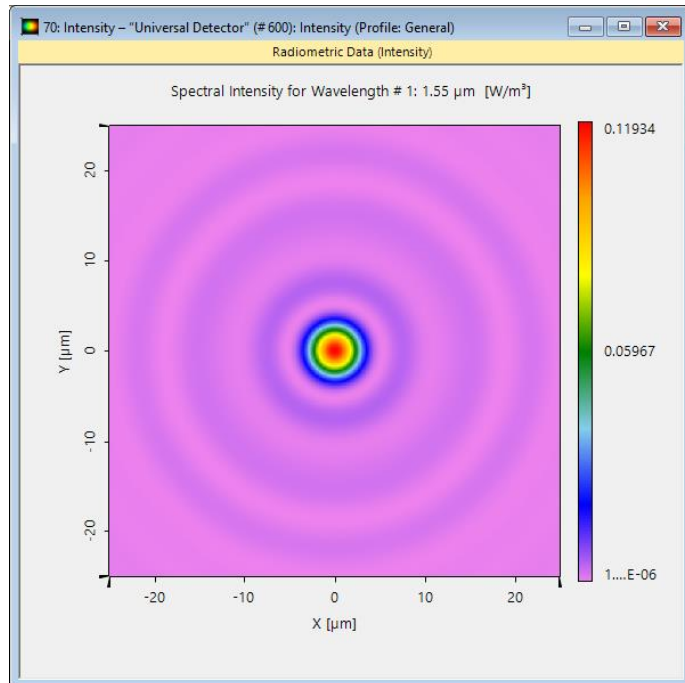
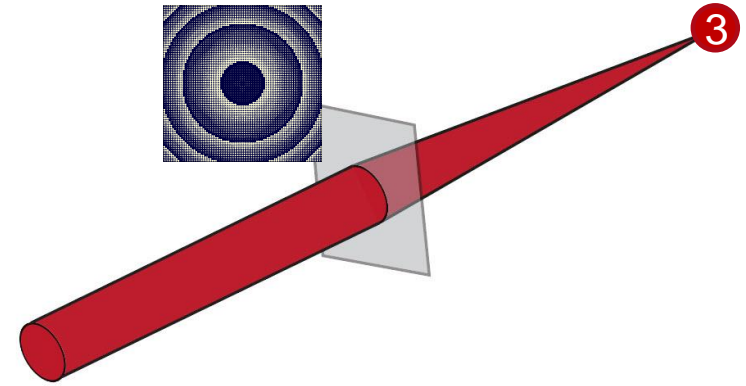
Methods	Preconditions	Accuracy	Speed	Comments
Rayleigh Sommerfeld Integral	None	High	Low	Rigorous solution
Fourier Domain Techniques	None	High	High	Rigorous mathematical reformulation of RS integral
Fresnel Integral	Paraxial	High	High	Assumes paraxial light; moderate speed for very short distances
	Non-paraxial	Low	High	
Geometric Propagation	Low diffraction	High	Very high	Neglects diffraction effects
	Otherwise	Low	Very high	



As we propagate the field into the focus, we expect diffraction effects to play a role. For this purpose, **Fourier Domain Techniques** were chosen for the simulation of this free-space propagation step, as they provide a good compromise between speed and accuracy.

Connected Modeling Techniques: Detectors

- ① metalens
- ② propagation to focus
- ③ detector



Full flexibility in detector modeling of different physical values, including:

- Radiometry, e.g., irradiance, intensity
- Photometry, e.g., illuminance, luminance
- Measurement of lateral extent (e.g. FWHM)

Metalens Design Workflow

Create Ideal Phase for Design

In order to achieve an aberration-free focus, a spherical phase is used for the “forward design method” (see reference). Here, the necessary parameters like diameter, focal length and the sampling (regarding the size of a unit cell of the meta structure) can already be set.

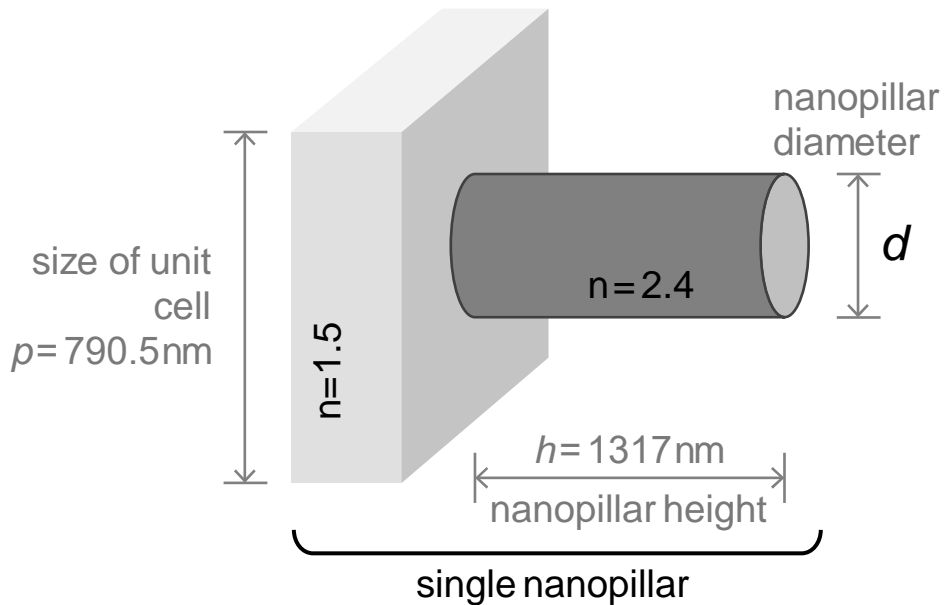
The image displays the 'Generate Ideal Lens Transmission' software interface, showing three panels with red boxes and arrows indicating key parameters:

- Panel 1:** Aperture Size and Shape settings. Shape: Rectangular, Elliptic. Diameter: 70.355 μm x 70.355 μm . Relative Edge Width: 0%. Absolute Edge Width: 0 mm.
- Panel 2:** Basic Parameters settings. Focal Length: 200 μm . Lateral Offset: 0 mm x 0 mm. Wavelength Dependency: Achromatic, Chromatic. Wavelength: 1.55 μm .
- Panel 3:** Sampling settings. Manual Sampling. Sampling Points: 89 x 89. Sampling Distance: 790.51 nm x 790.51 nm. Array Size: 70.355 μm x 70.355 μm .

The 'Target Function' plot in the top right shows the Phase of Transmission [rad] as a function of X [μm] and Y [μm]. The plot displays concentric rings of red and blue, indicating a spherical phase distribution. The color scale ranges from -3.1358 to 3.1387 rad.

Pillar Diameter vs Phase Value

The building block of the metasurfaces in this use case is a cylindrical dielectric nanopillar. Since the size of the unit cell and height of the pillars are already selected according to the reference, the phase provided by the pillar can be calculated as a function of its diameter, using a *Parameter Run*. The diagram on the right illustrates the relationship between the pillar diameter and phase value.



14: D:\LightTrans...\02a_Unit Cell Analysis PR.run

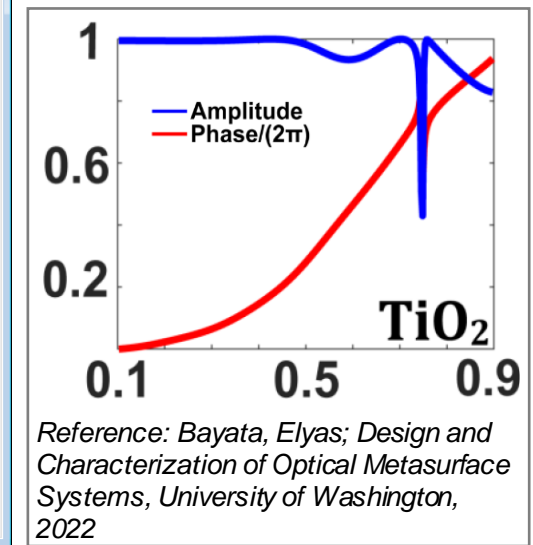
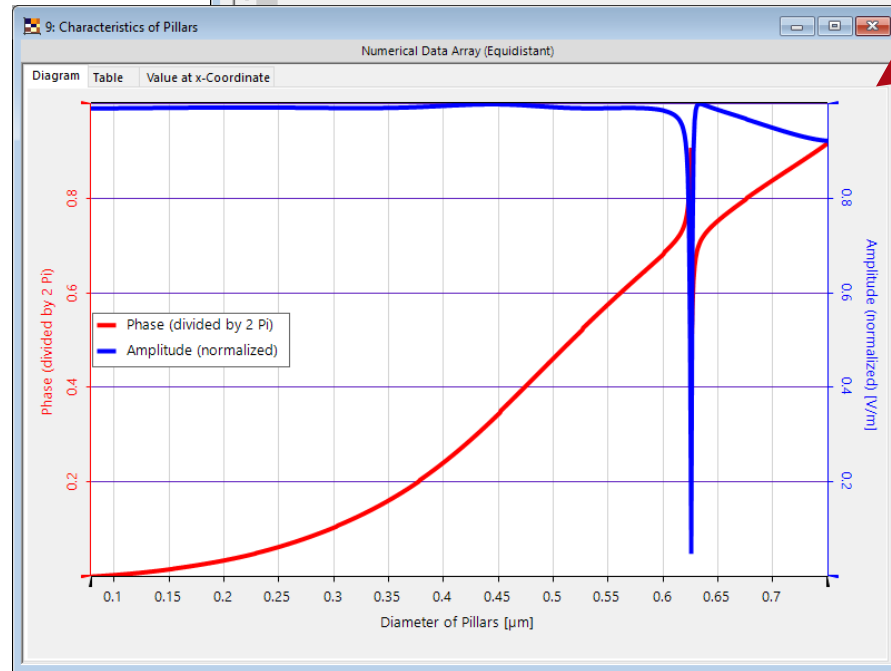
Results

Start the parameter run and analyze its results

Go!

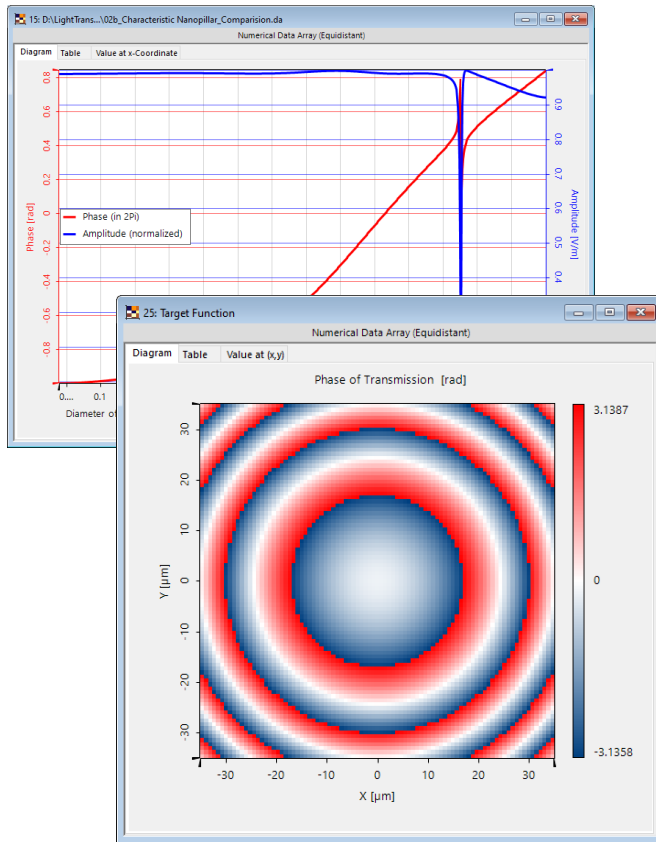
Use Already Calculated Results for Next Run

Detector	Subdetector	Combined Output	Iteration Step		
			1	2	3
Varied Parameters	Diameter of Pillar #1 ("Unit...	Data Array	40 nm	41 nm	42 nm
"Grating Order Analyzer" (# 800)...	Efficiency T[0; 0]	Data Array	96.034 %	96.035 %	96.037 %
	Rayleigh coefficient Ex T[0;...	Data Array	$1.2001 \cdot \exp(-0.93671 \cdot i) \text{ V/m}$	$1.2001 \cdot \exp(-0.93633 \cdot i) \text{ V/m}$	$1.2001 \cdot \exp(-0.93595 \cdot i) \text{ V/m}$



Design of Pillar Distribution

With the desired optical function and the phase values provided by the chosen type of meta-atoms, the lateral distribution can be designed. For this step, a module is used, which chooses the proper diameter of pillar to generate the lateral distribution of the desired phase.

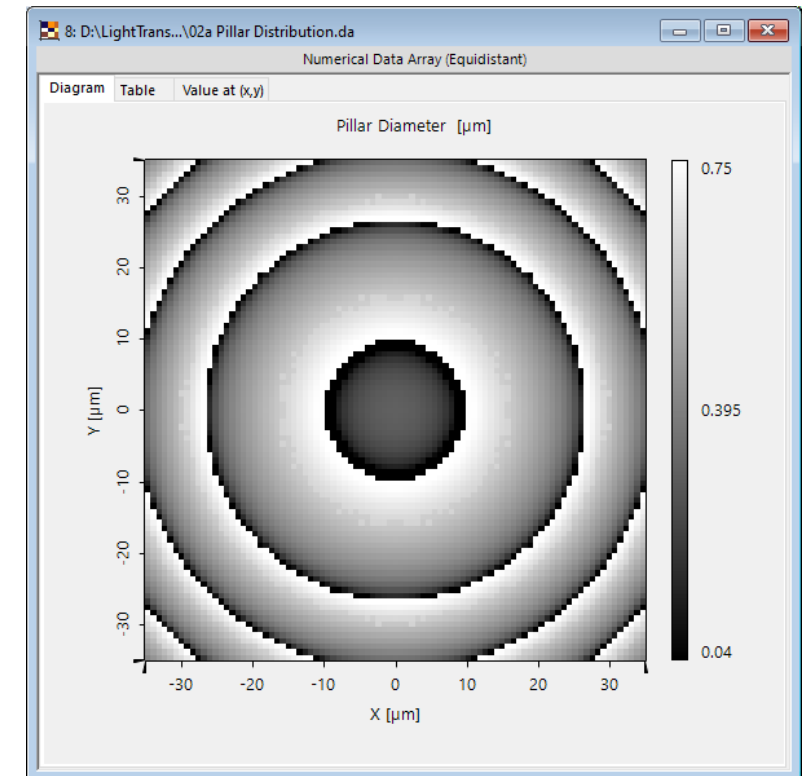


```
4: Design Pillar Distribution
Source Code  Advanced Settings
1  Preset using directive
26
27 namespace OwnCode {
28     public class VLModule {
29         //define amplitude threshold which shall be u
30         //value is given as multiple of the maximum a
31         //if the amplitude value is smaller than three
32         double amplitudeThreshold = 0.9;
33     }
34 }
Code  Description  Line
Thread finished normally  Ln 1  Ch 1
```



The module “*DesignMetaStructure FromTargetFunctionAndLUT.cs*” is used. This module allows us to exclude pillar diameters if the amplitude is below a given threshold (here: 0.9). This helps exclude jumps (e.g. caused by mode resonances).

Resulting distribution of pillars

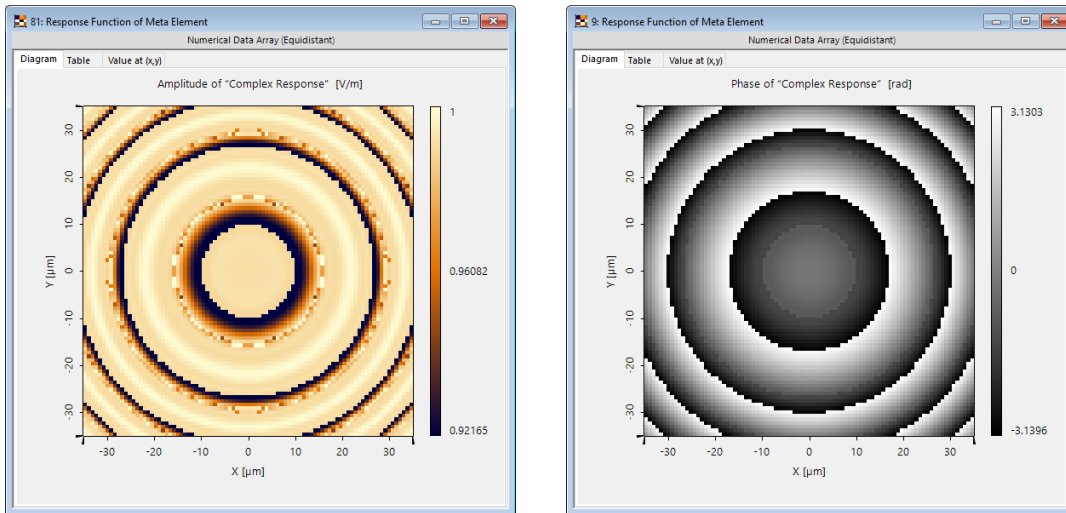


(absolute phase is a free parameter)

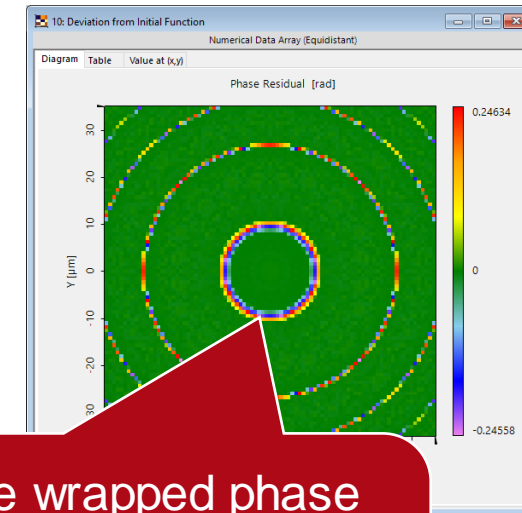
Design of Pillar Distribution

During the design of the pillar distribution, the expected response of the metalens and the deviation from the initially desired function are delivered as outputs as well:

Response function of the designed pillar distribution
(amplitude and phase)



Deviation from initially desired function
(phase)



At the jumps of the wrapped phase differences are noticeable, because the chosen pillars do not provide a full 2π phase in the range of diameters.

Setting Up the Metalens

In order to set up the meta lens, the distribution of the pillar diameters is imported into a *Pillar Medium* in a *General Grating Component (Grating Specific Optical Setup)*.

The image shows a multi-step process in a software application:

- 1:** In the **Edit General Grating Component (Metalens)** dialog, the **Metagrating** section is selected, and the **Edit** button is highlighted.
- 2:** In the **Edit Stack** dialog, the **Pillar Medium (General)** component is selected, and the **Edit...** button is highlighted.
- 3:** In the **Edit Pillar Medium (General)** dialog, the **Pillar Geometry** section is expanded, and **Pillar Distribution** is selected.
- 4:** In the **Edit Pillar Medium (General)** dialog, the **Import Diameter Data** button is highlighted.

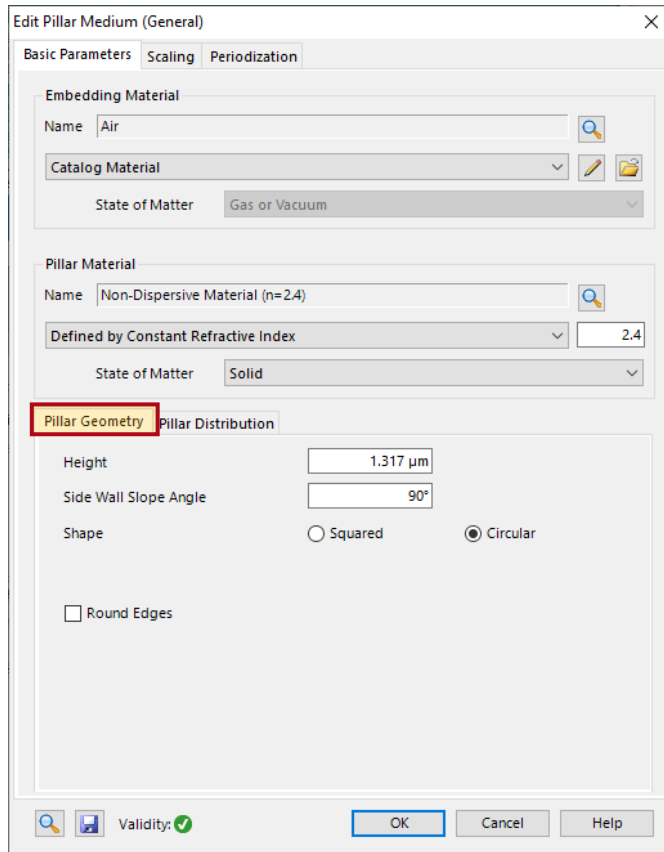
The **Edit Pillar Medium (General)** dialog also shows the following configuration:

- Basic Parameters:** Name: Air, State of Matter: Gas or Vacuum.
- Pillar Material:** Name: Non-Dispersive Material (n=2.4), Defined by Constant Refractive Index: 2.4, State of Matter: Solid.
- Pillar Geometry Table:**

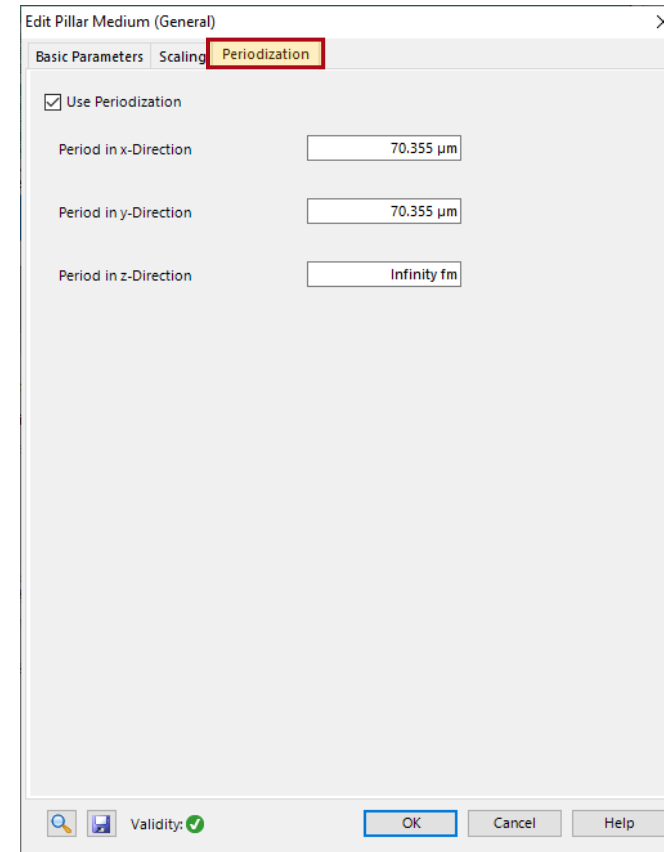
	x-Position	y-Position	Diameter
1	-34.782 μm	-34.782 μm	414 nm
2	-34.782 μm	-33.992 μm	454 nm
3	-34.782 μm	-33.201 μm	489 nm
4	-34.782 μm	-32.411 μm	524 nm
5	-34.782 μm	-31.62 μm	560 nm
6	-34.782 μm	-30.83 μm	630 nm
7	-34.782 μm	-30.039 μm	649 nm
8	-34.782 μm	-29.249 μm	691 nm
9	-34.782 μm	-28.458 μm	737 nm
10	-34.782 μm	-27.668 μm	40 nm
11	-34.782 μm	-26.877 μm	198 nm

Setting Up the Metalens

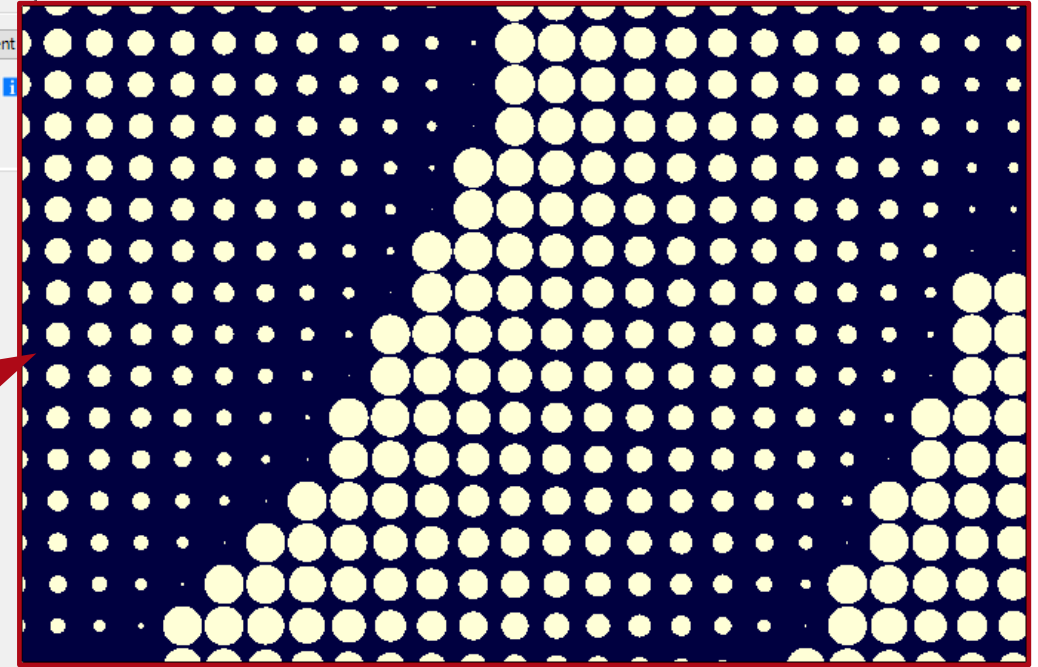
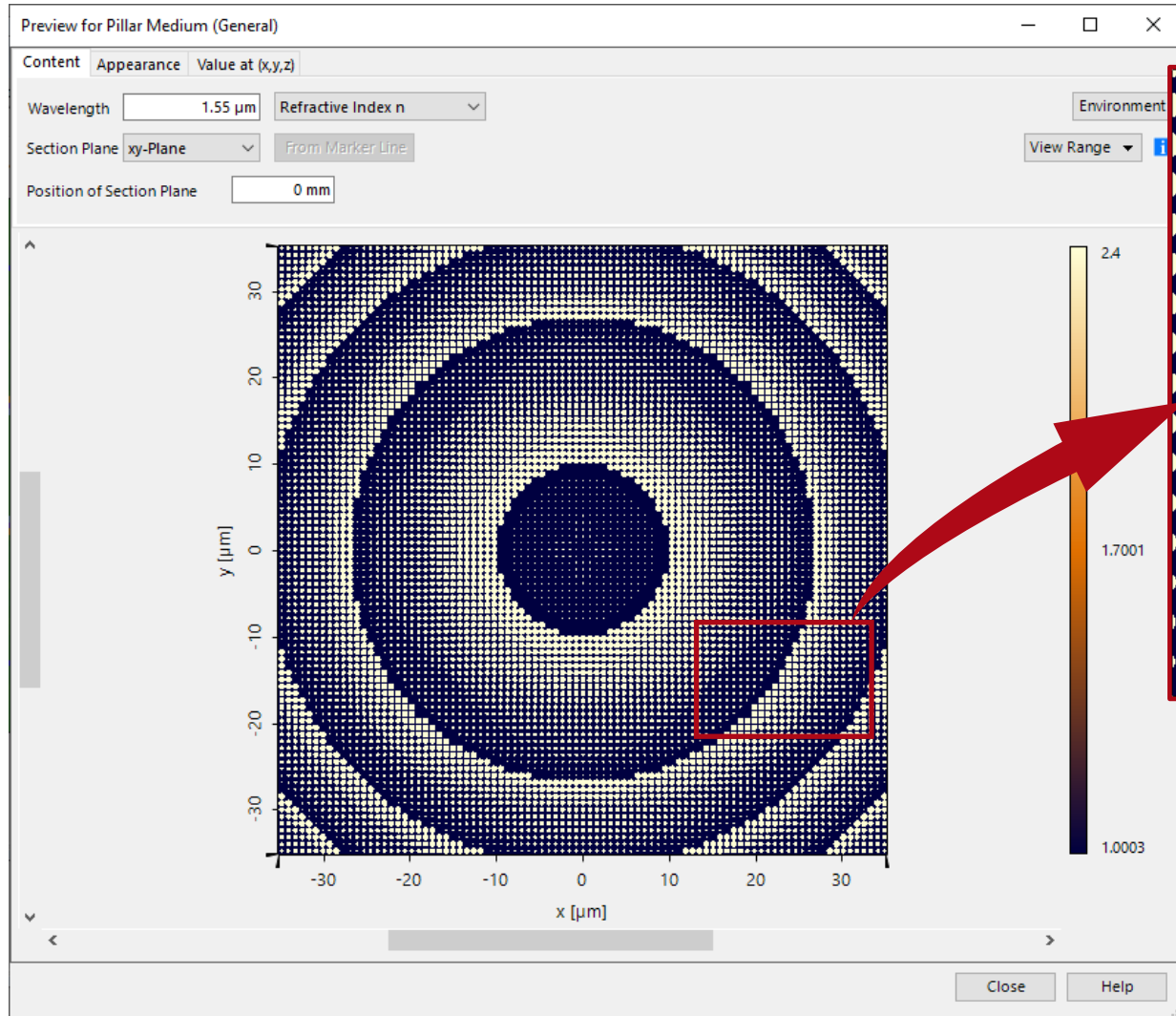
In addition, the height and shape of the pillar, as well as the material, must be configured properly in the *Pillar Geometry* tab:



The lateral extension of the metalens is configured in the Periodization tab:



Resulting Metastructure



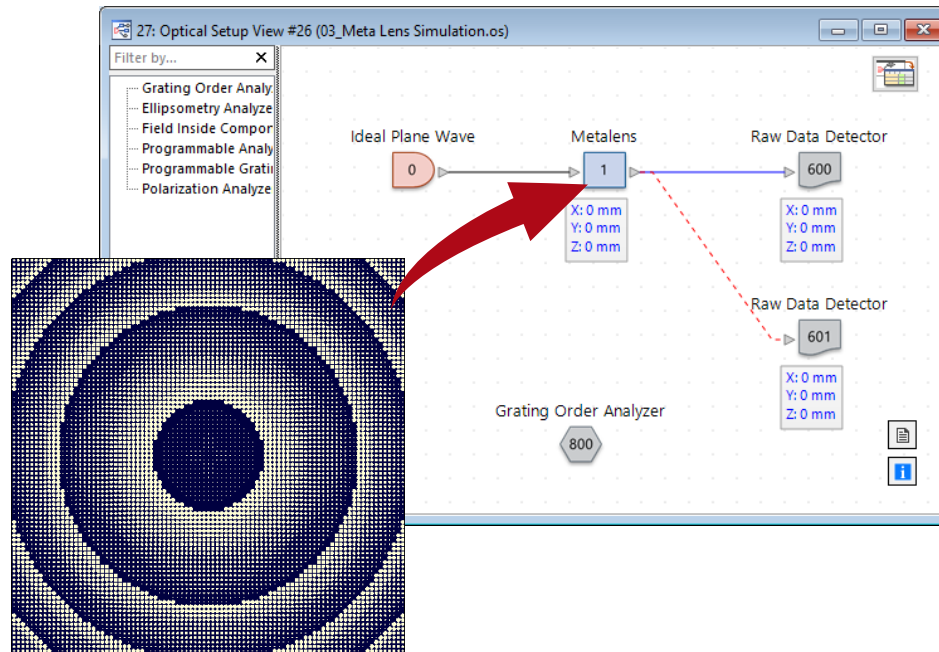
In the preview window of the pillar medium, the pillar distribution is shown. The color scale represents the refractive index (real part).

Simulation Workflow Step #1

In order to model the function of the pillar structure, the *Fourier Modal Method* (FMM, also known as RCWA) is applied. For this purpose, a *Grating Specific Optical Setup* with a *General Grating Component* is used. In contrast to the method used in the design stage, the resulting phase now includes the interactions of different pillars in close vicinity.

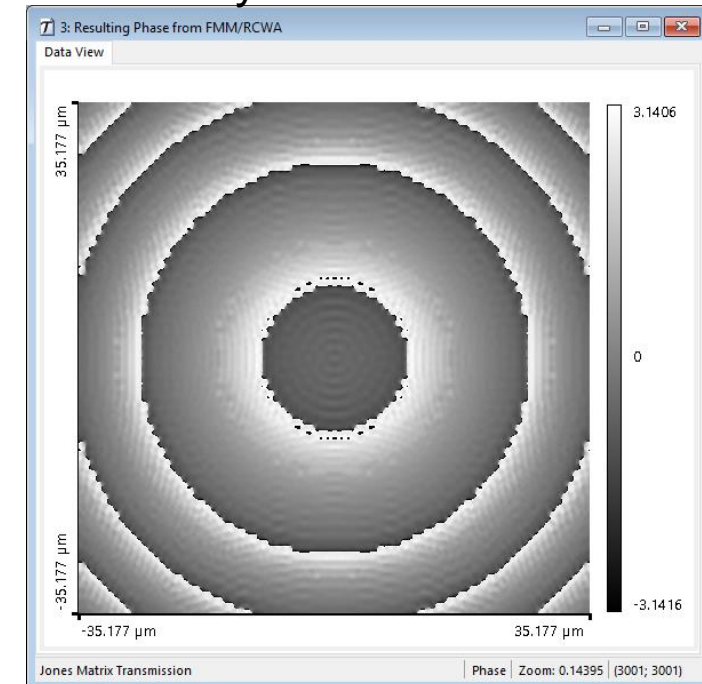
Step #1:

Grating Specific Optical Setup



pillar structure

Result: phase (and amplitude, not shown) directly behind meta lens



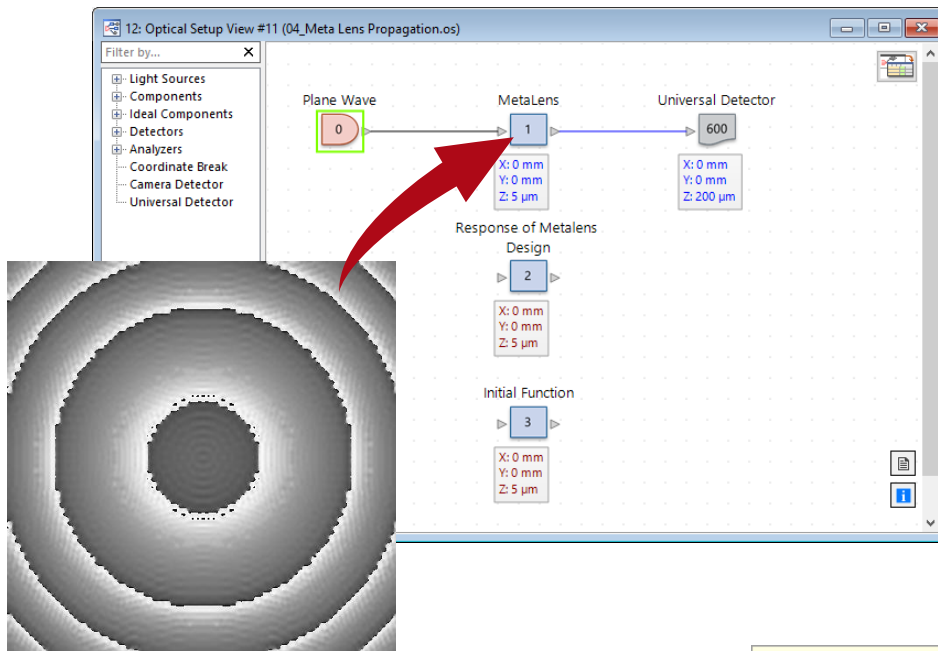
(complex transmission function of the metalens)

Simulation Workflow Step #2

In a second step, the calculated function of the real structure is further propagated in a *General Optical Setup* using a *Stored Function Component*.

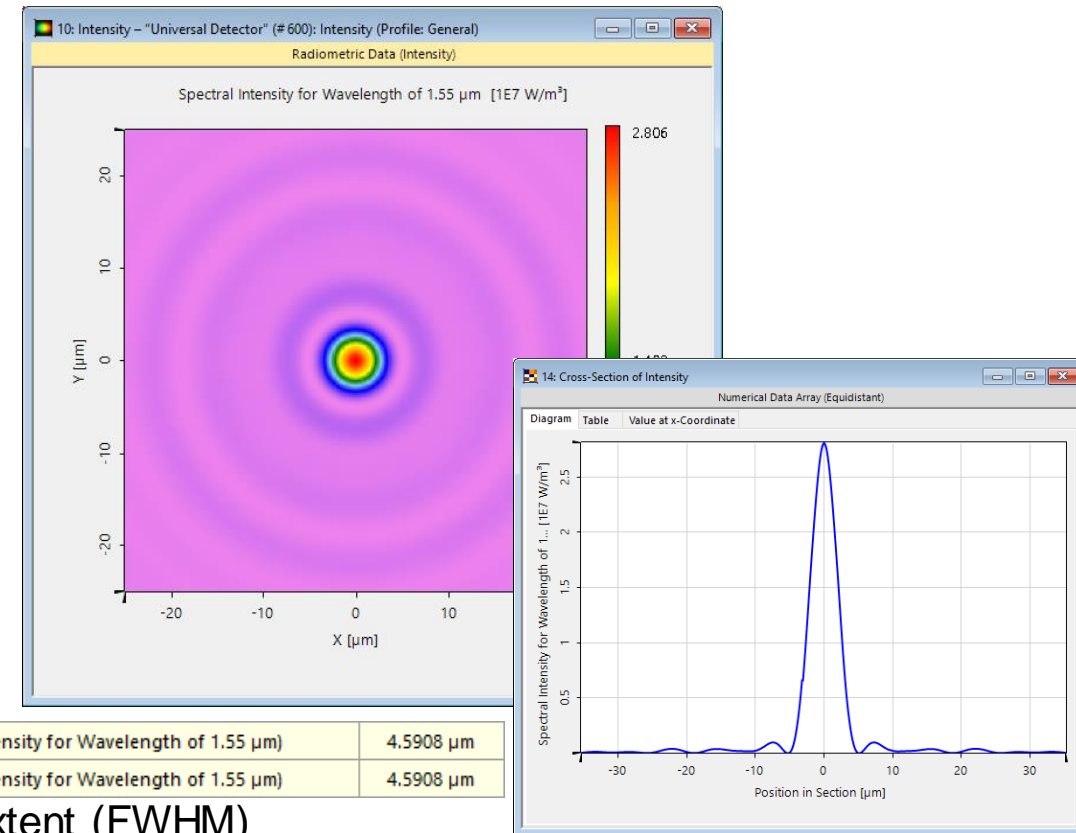
Step #2:

Optical Setup with Metalens (designed and initial)



calculated complex transmission

Result: focal spot (intensity)

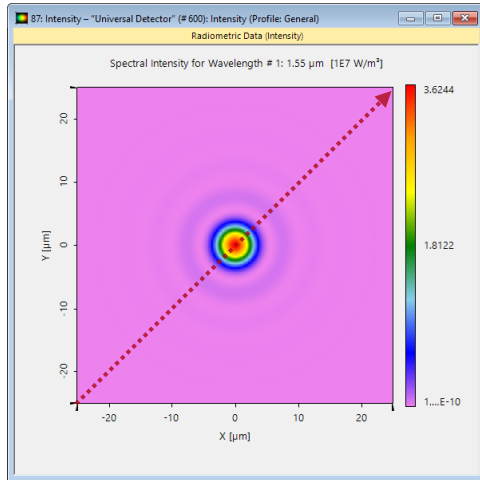


lateral extent (FWHM)

Comparison

While the focal spot of the initial function and the response of the designed pillar structure provide identical spots, the propagation through the pillar structure causes some aberrations. However, the designed metalens still provides a focal spot of similar size and structure as the original phase function. This result could then be the starting point for further optimization.

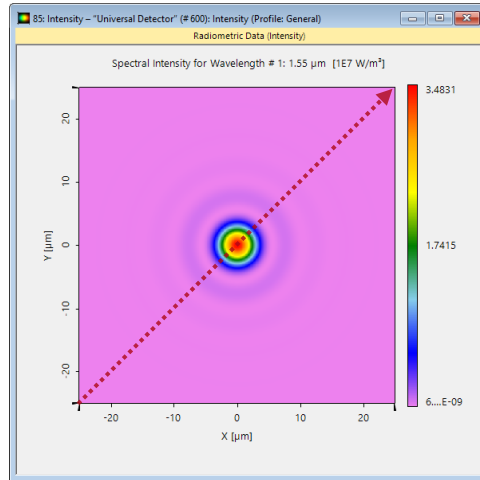
initial function



FWHM

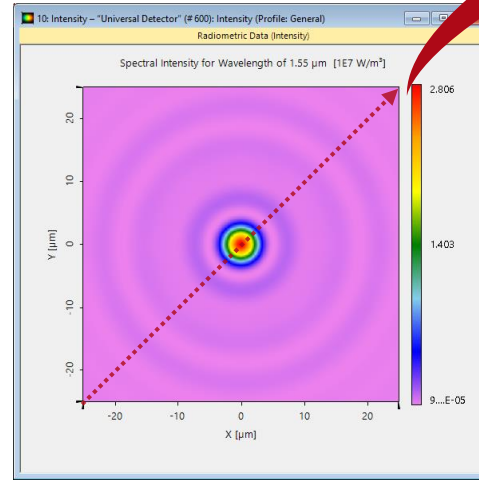
Size X (Intensity; [1] → Spectral Intensity...	4.8828 μm
Size Y (Intensity; [1] → Spectral Intensity...	4.8828 μm

response of pillar design

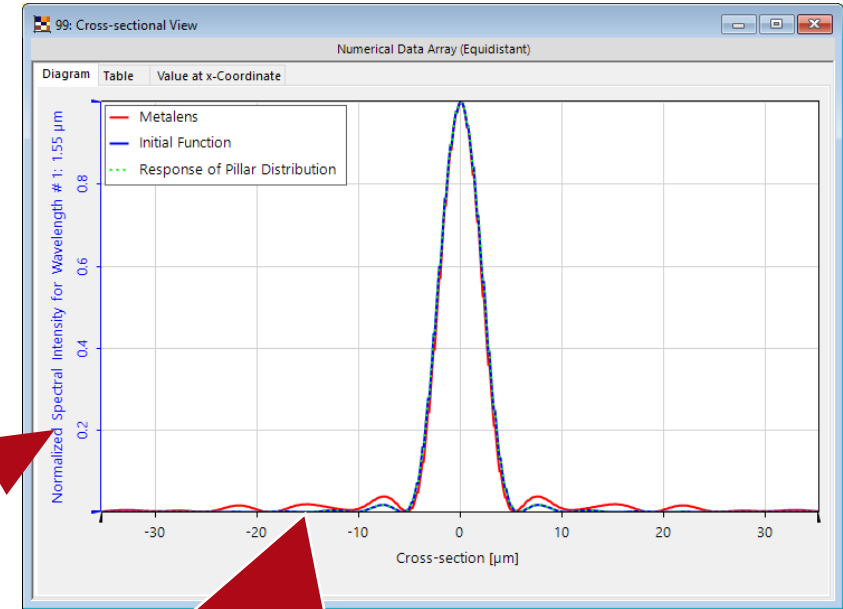


FWHM

Size X (Intensity; [1] → Spectral Intensity...	4.8828 μm
Size Y (Intensity; [1] → Spectral Intensity...	4.8828 μm



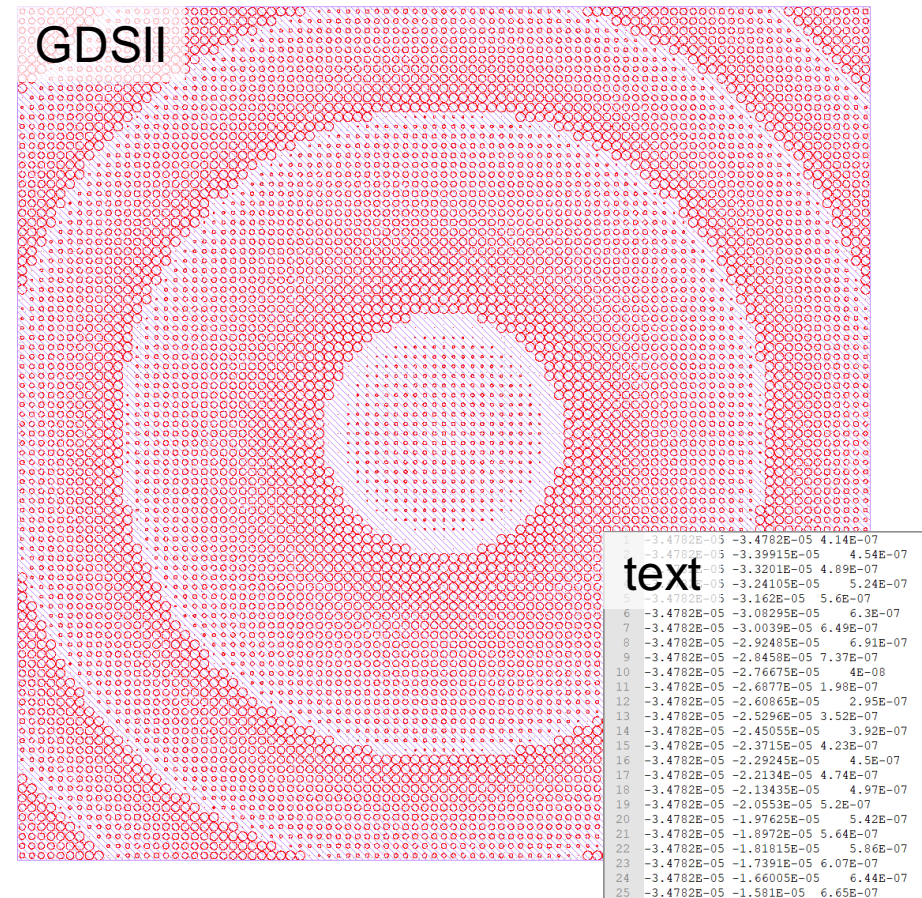
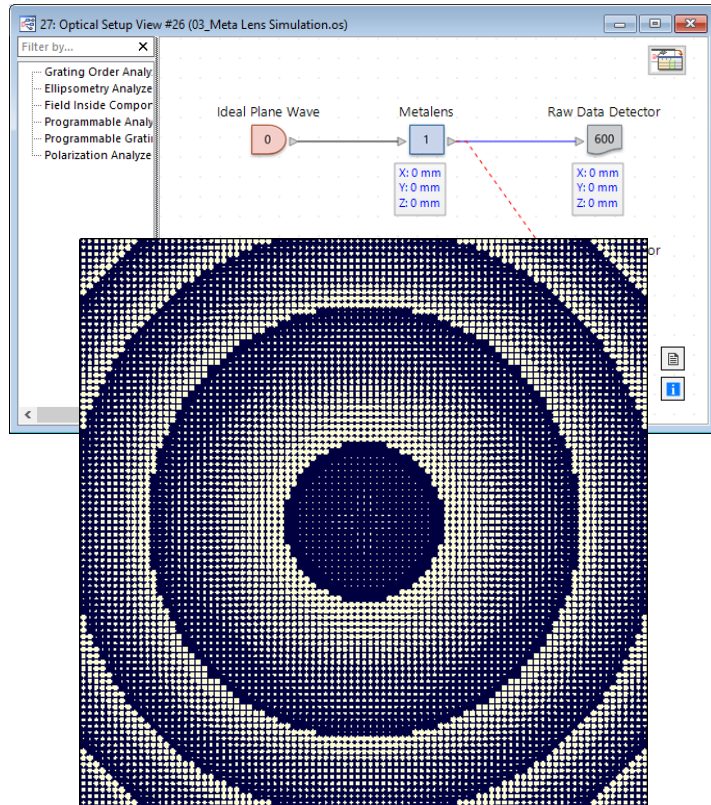
Size X (Intensity; [1] → Spectral Intensity...	4.5908 μm
Size Y (Intensity; [1] → Spectral Intensity...	4.5908 μm



Slightly stronger secondary maxima are obtained for the focus of the metalens.

Export of Pillar Structure

In order to export the designed pillar structure, a GDSII and text-based export are supported via a module.



The module "06_ExportMetaGratingToGDSIIAndText.cs" exports the pillar configuration of a Pillar Medium inside an optical setup to a GDSII and text-based table (containing pillar positions and diameters).

pillar structure (configured in the *Pillar Medium*)

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further reading	<ul style="list-style-type: none">• <u>Design of 2D Non-Paraxial Beam-Splitting Metagrating</u>• <u>VirtualLab Fusion Technology – FMM / RCWA [S-Matrix]</u>• <u>Configuration of Grating Structures by Using Special Media</u>