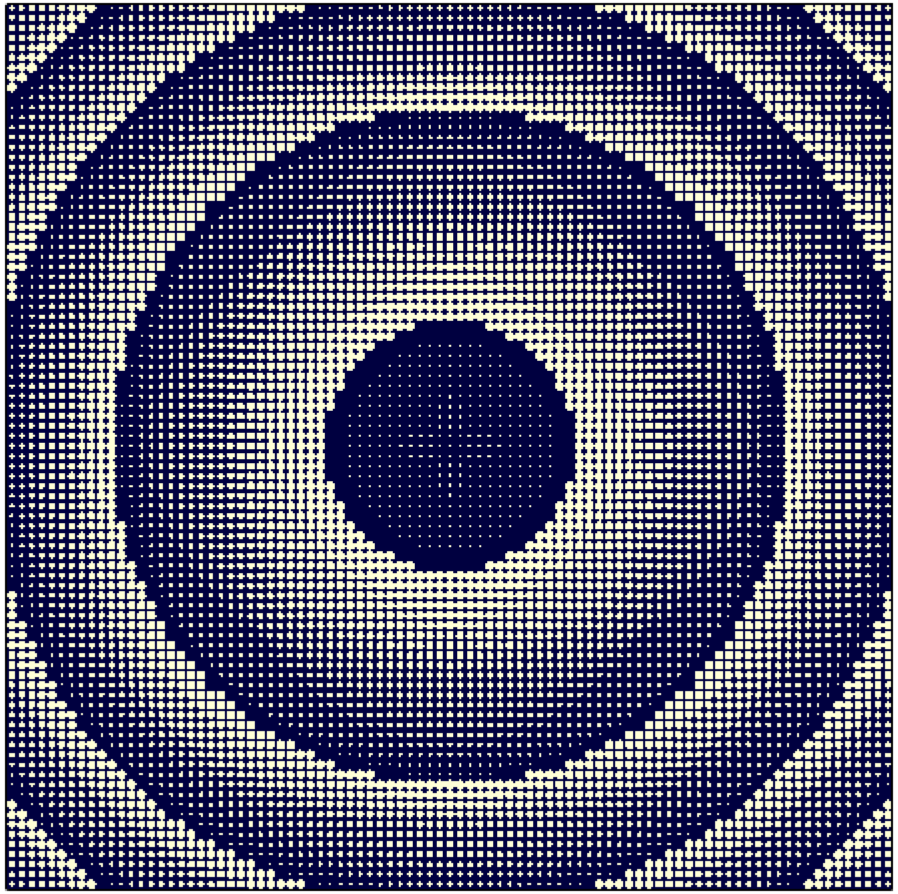
Design and Analysis of a Metalens

Abstract

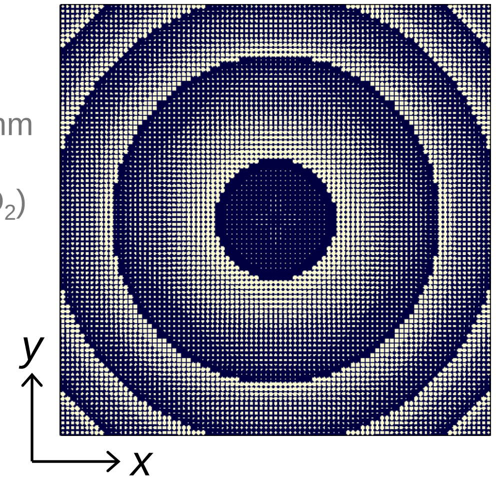


A lens is a transmissive optical device that focuses or defocuses light by changing its phase. Unlike conventional lenses, metalenses have the advantage of being able to achieve the desired phase change in a very thin layer using structures with sizes in the order of the wavelength and below, without 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.

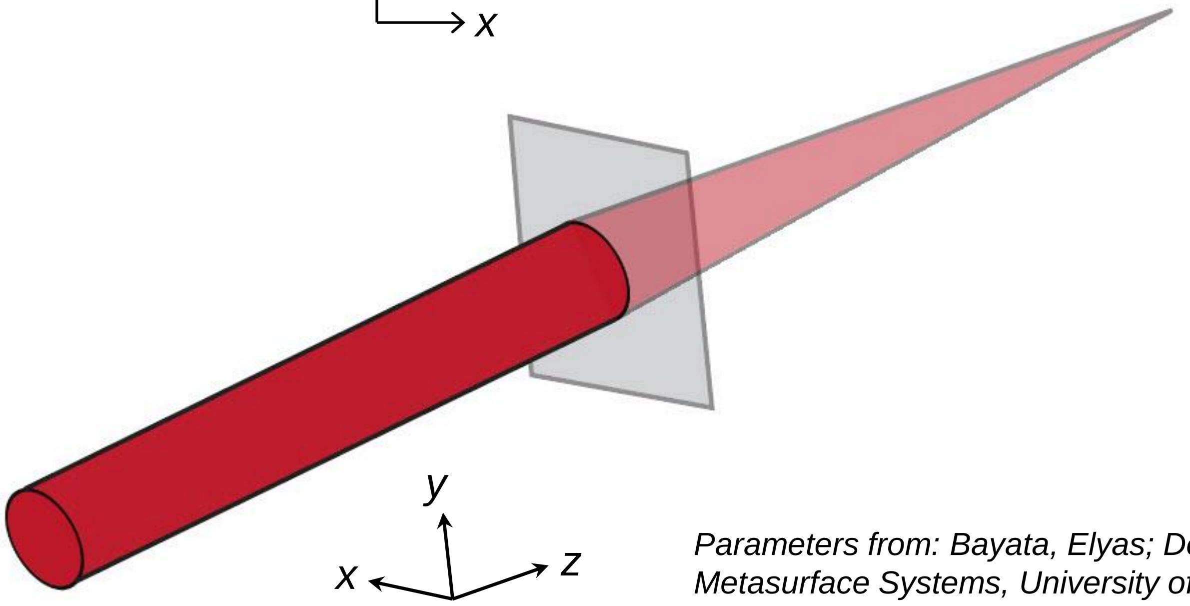
Design Task

metalens (top-view)

- extent: 70.4 µm × 70.4 µm
- size of unit cell: 790.5 nm × 790.5 nm
- substrate glass: 1.5
- refractive index of pillars: 2.4 (TiO_2)
- shape of pillars: cylindrical
- focal length: 200 µm (NA 0.175)



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



input field

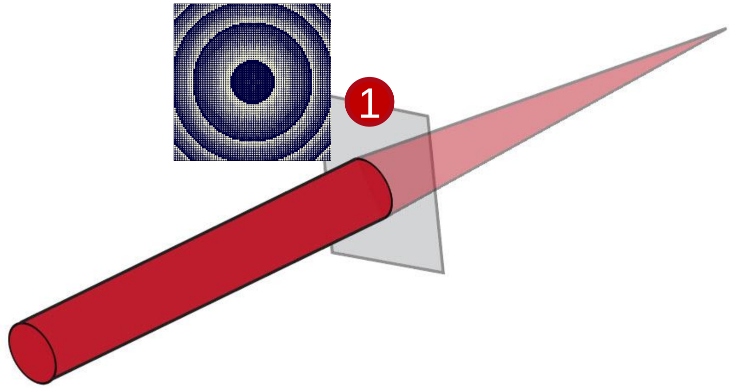
- wavelength: 1550 nm
- polarization: along x
- diameter: 70 µm × 70 µm

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



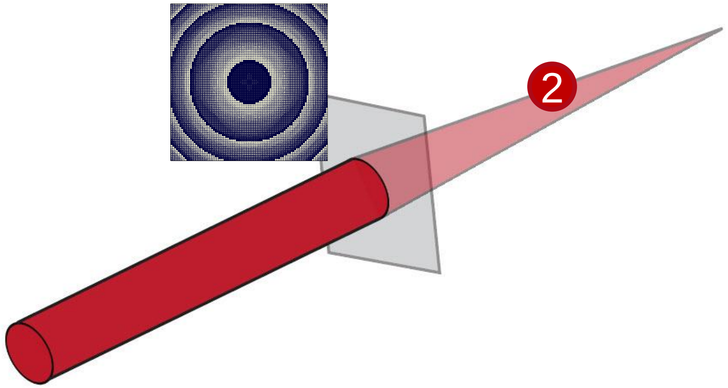
Available modeling techniques for periodic micro and nano structures:

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



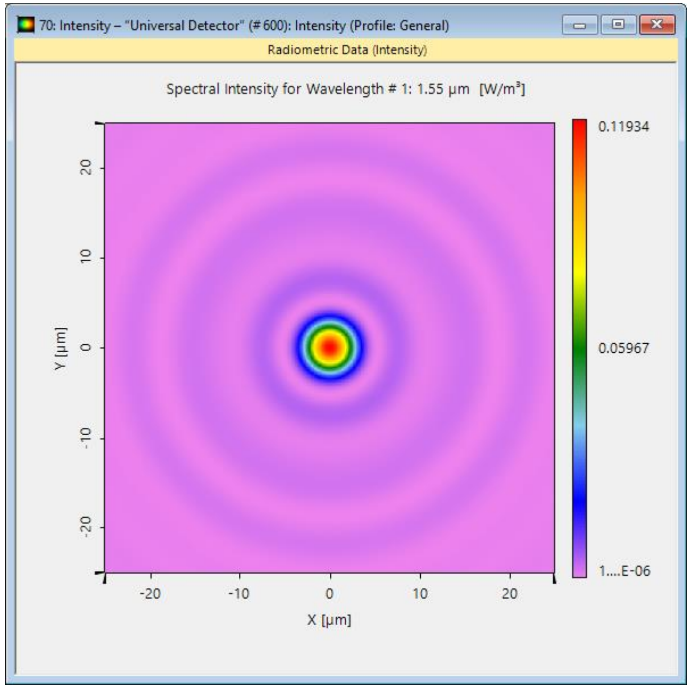
Available modeling techniques for free space propagations:

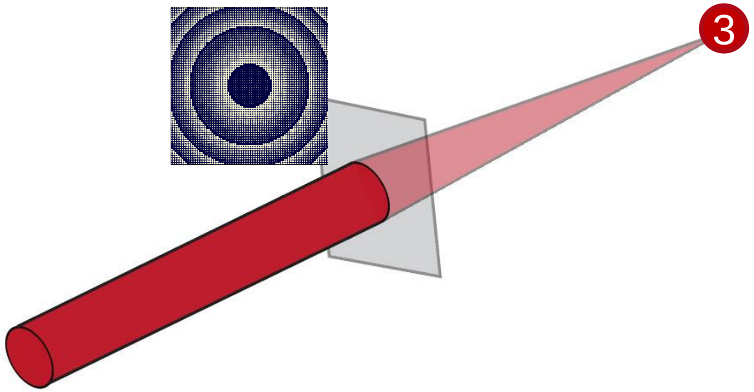
Methods	Preconditions	Accuracy	Speed	Comments
Rayleigh Sommerfeld Integral	None	High	Low	Rigorous solution
Fourier Domain Techniques	None	High	High	Rigorous mathematical reformulation of RS integral
Fresnel Integral	**Paraxial**	High	High	Assumes paraxial light; moderate speed for very short distances
	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





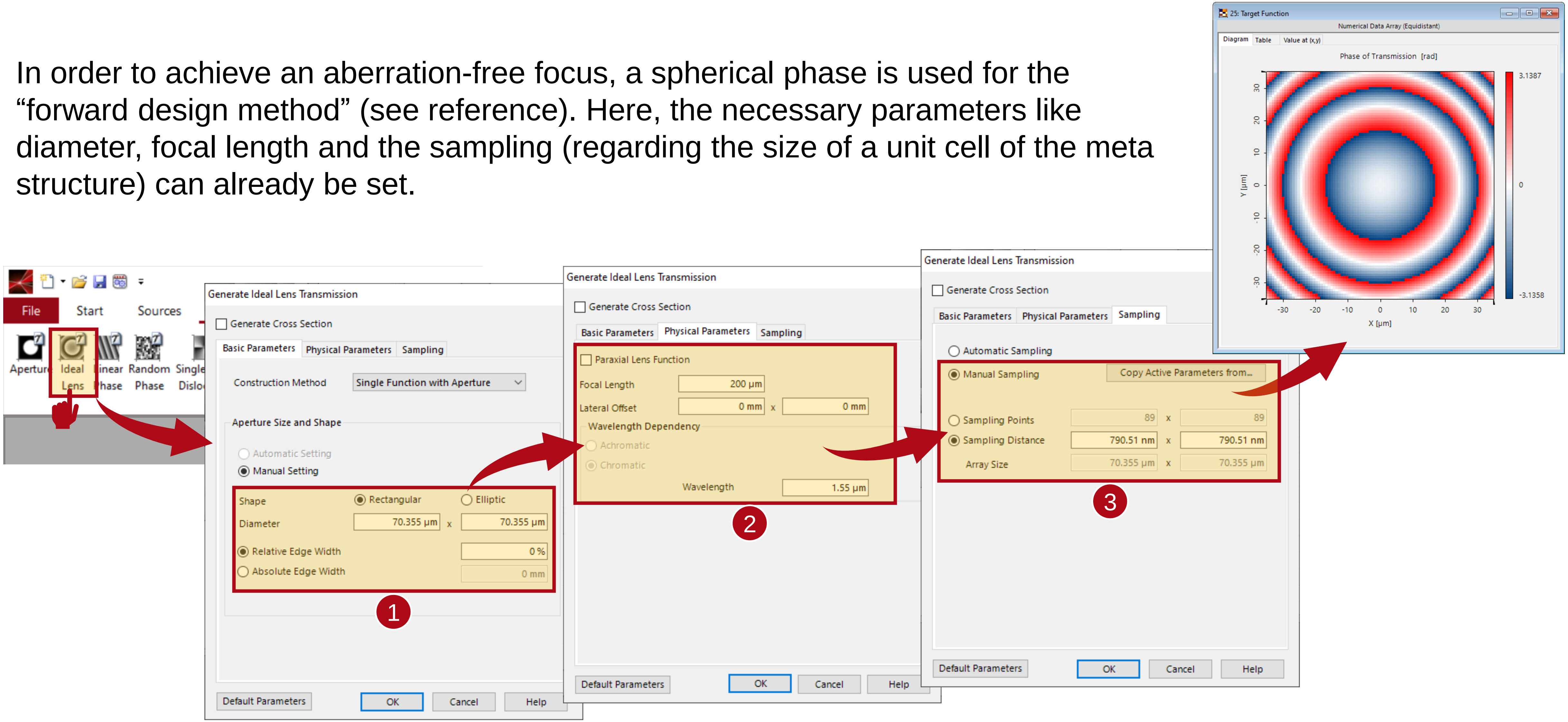
Full flexibility in detector modeling of different physical values, including:

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

Metalens Design Workflow

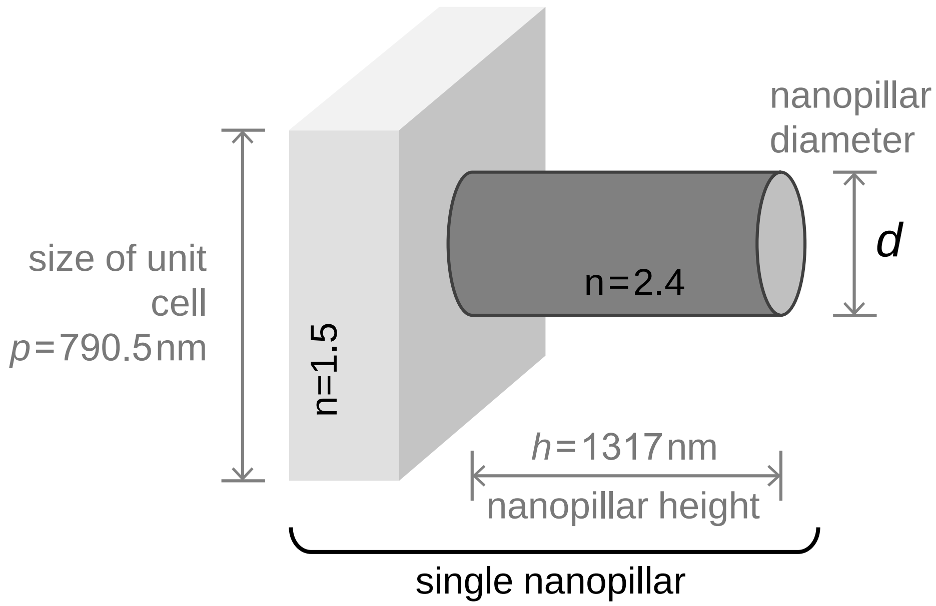
Create Ideal Phase for Design

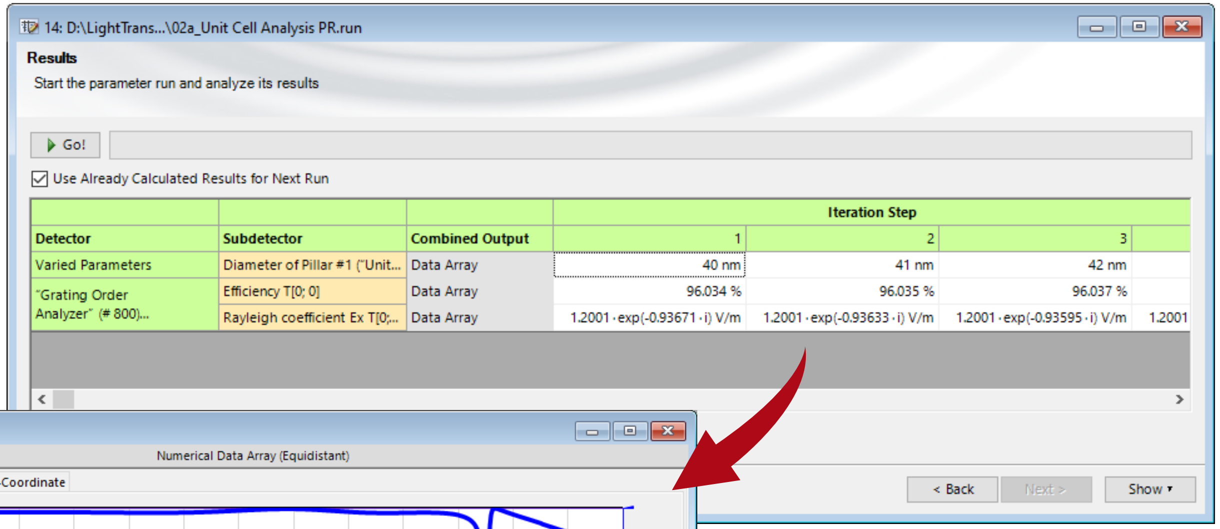
In order to achieve an aberration-free focus, a spherical phase is used for the “forward design method” (see reference). Here, the necessary parameters like diameter, focal length and the sampling (regarding the size of a unit cell of the meta structure) can already be set.

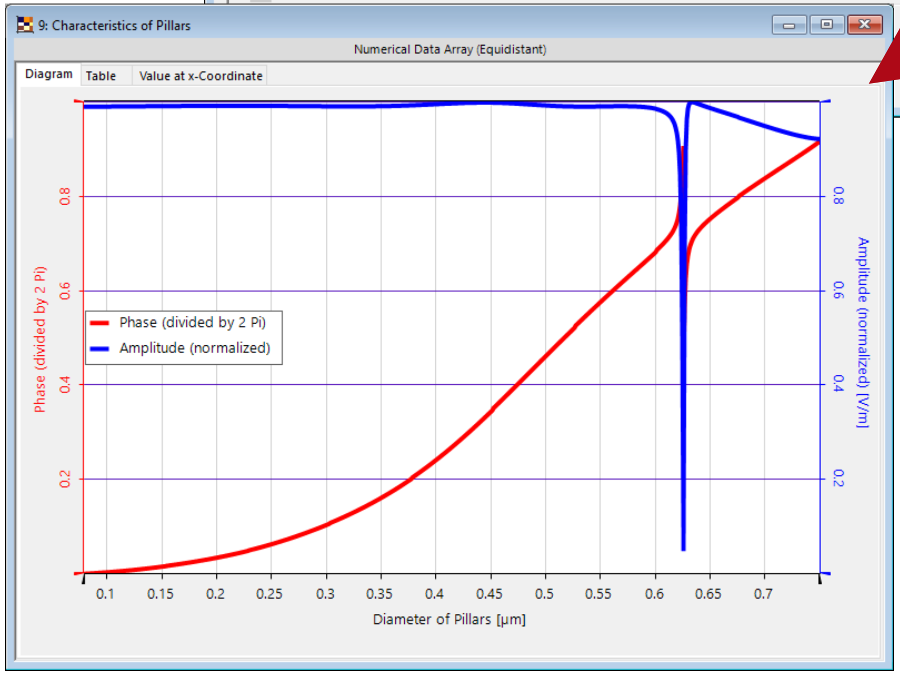


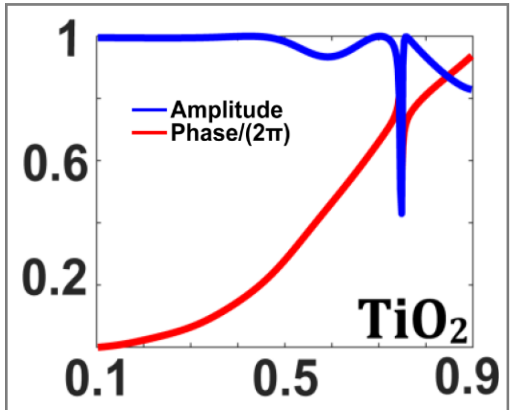
Pillar Diameter vs Phase Value

The building block of the metalens 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.





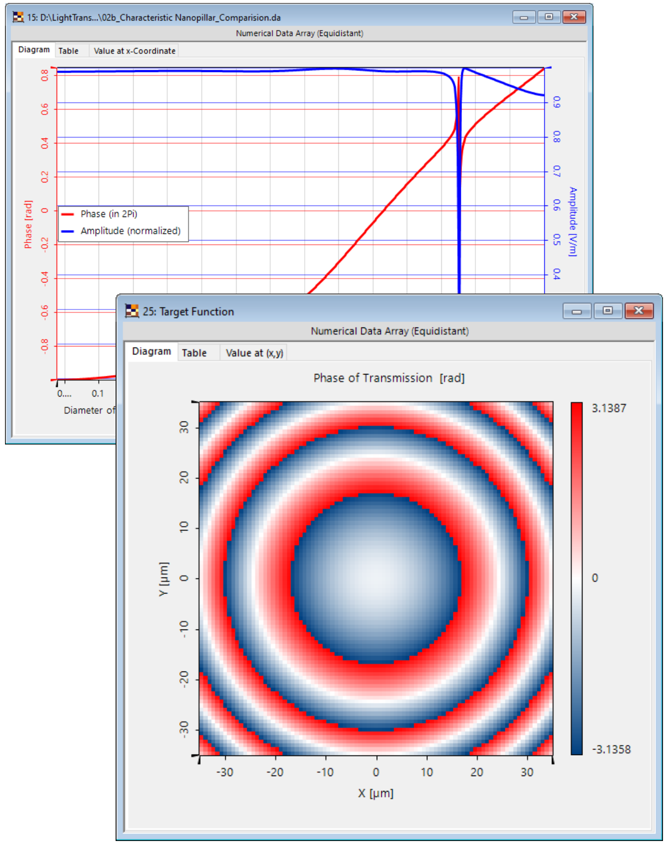


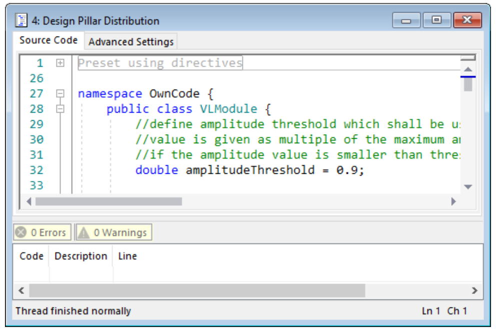


Reference: Bayata, Elyas; Design and Characterization of Optical Metasurface Systems, University of Washington, 2022

Design of Pillar Distribution

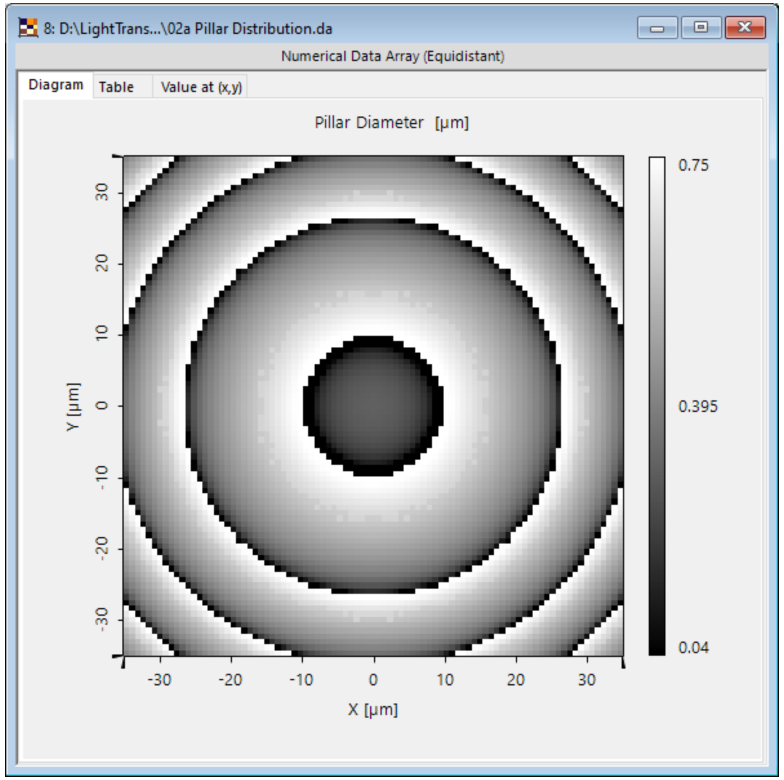
With the desired optical function and the phase values provided by the chosen type of meta-atoms, the lateral distribution can be designed. For this step, a module is used, which chooses the proper diameter of pillar to generate the lateral distribution of the desired phase.





The module *"Design Pillar Distribution.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

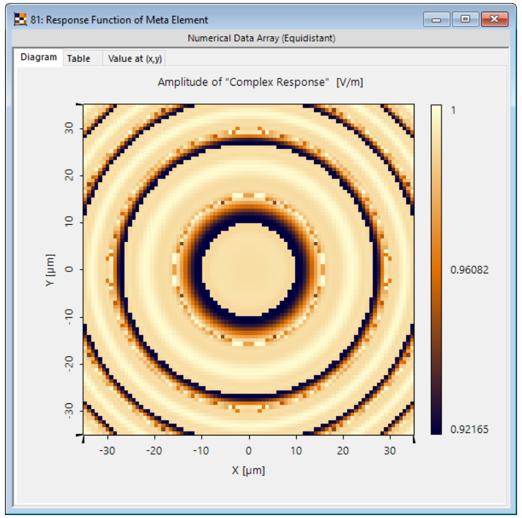


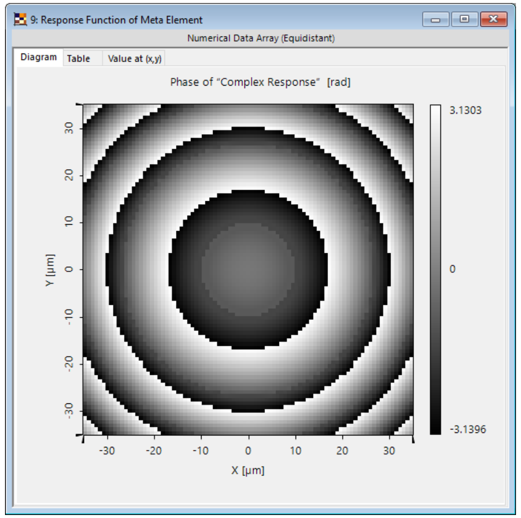
(absolute phase is a free parameter)

Design of Pillar Distribution

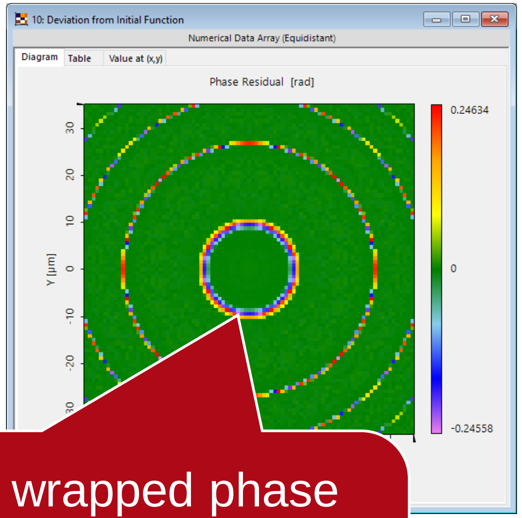
During the design of the pillar distribution, the expected response of the metalens and the deviation from the initially desired function are delivered as outputs as well:

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





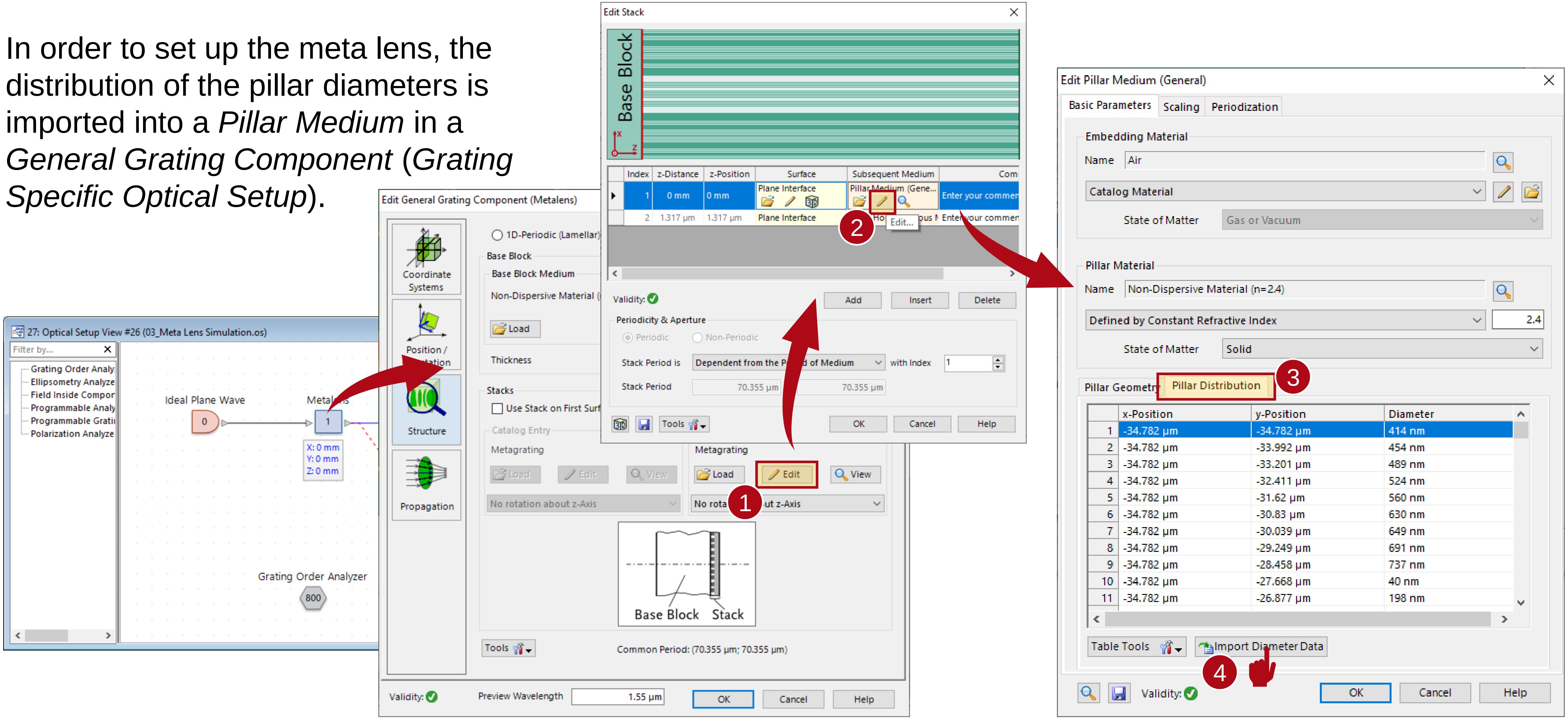
Deviation from initially desired function (phase)



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.

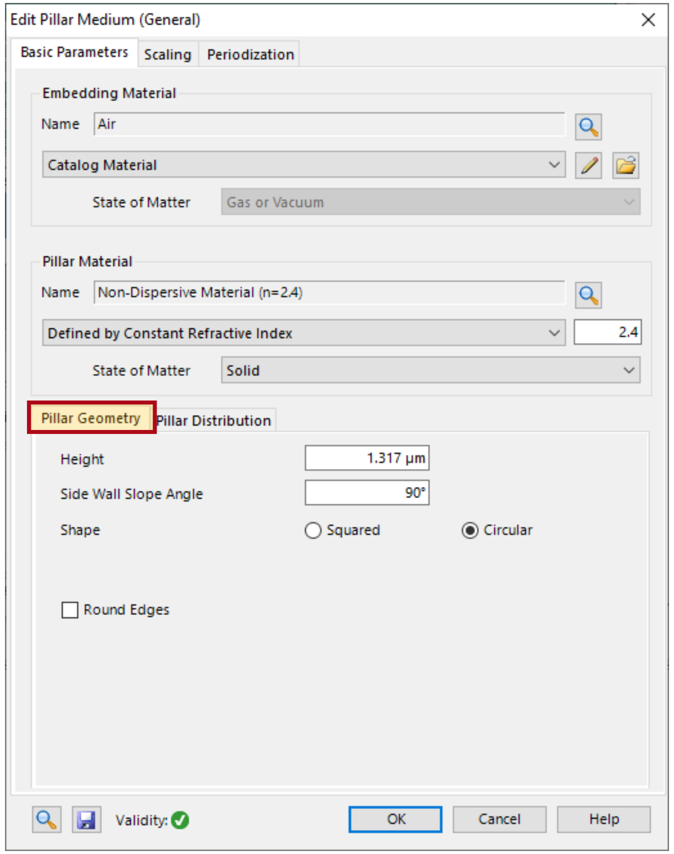
Setting Up the Metalens

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*).

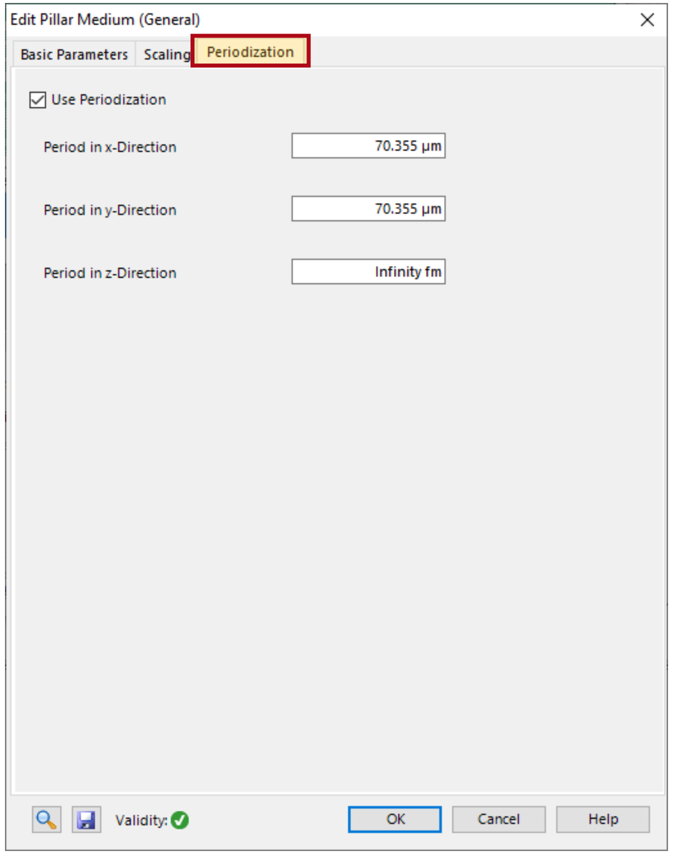


Setting Up the Metalens

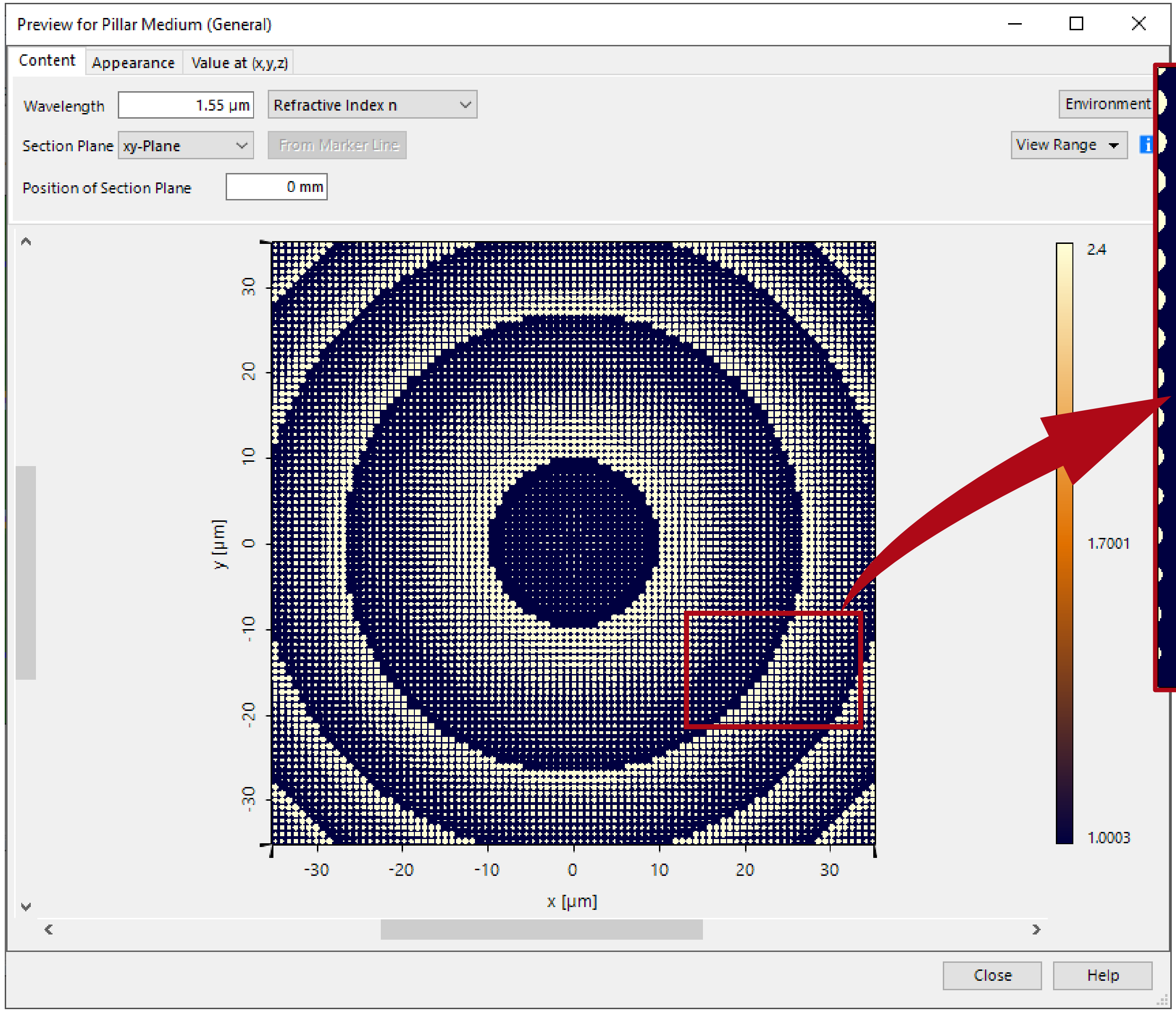
In addition, the height and shape of the pillar, as well as the material, must be configured properly in the *Pillar Geometry* tab:

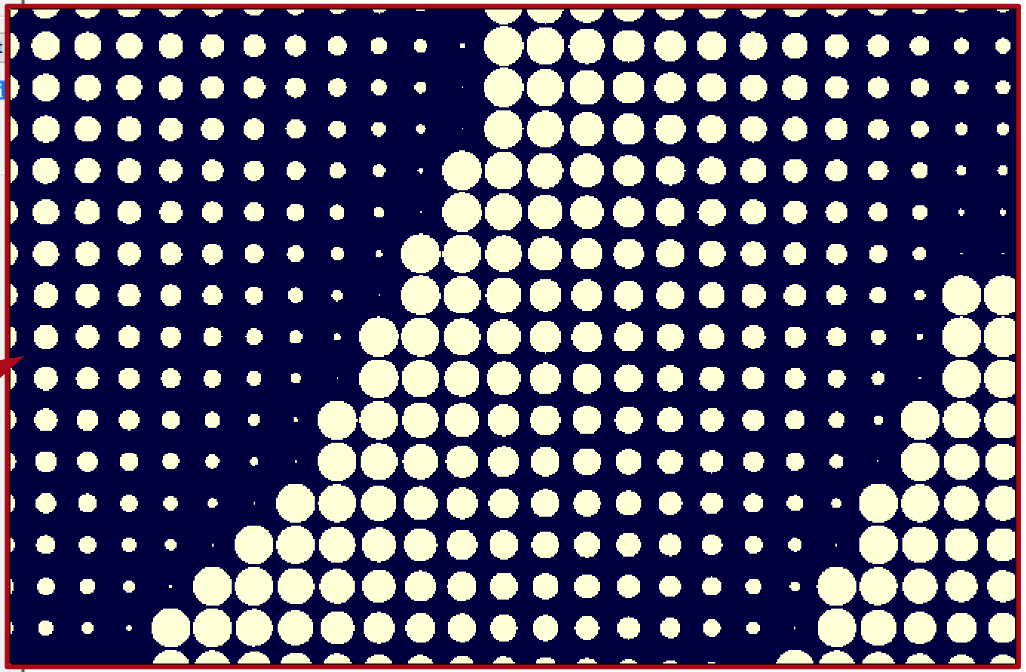


The lateral extension of the metalens is configured in the Periodization tab:



Resulting Metastructure





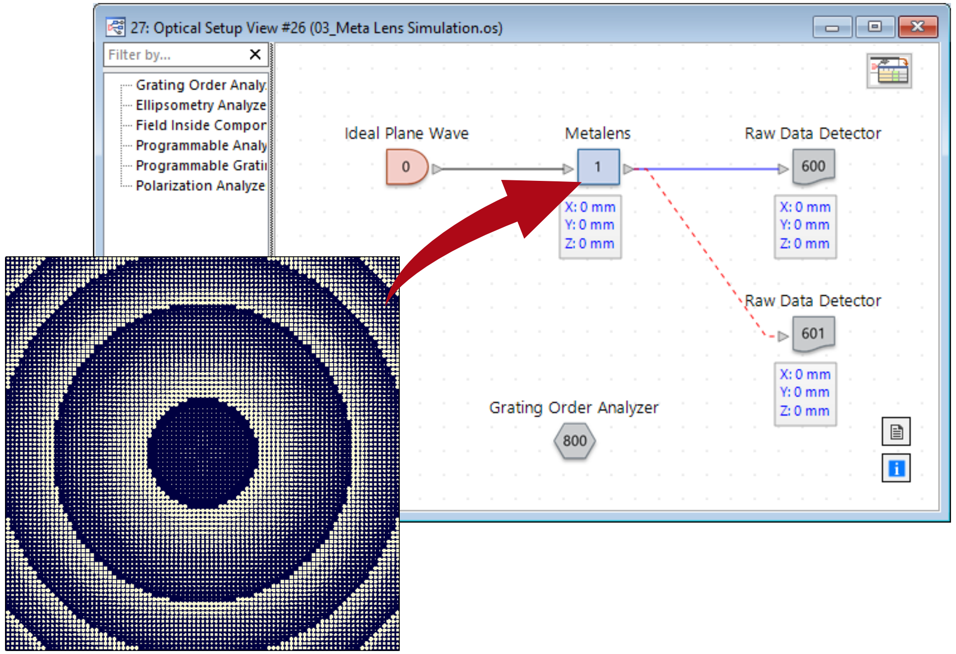
In the preview window of the pillar medium, the pillar distribution is shown. The color scale represents the refractive index (real part).

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.

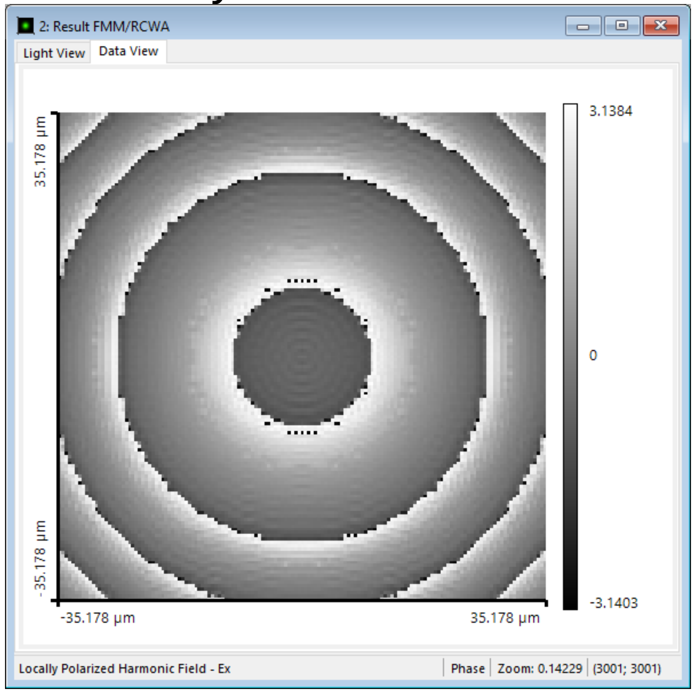
Step #1:

Grating Specific Optical Setup



pillar structure

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



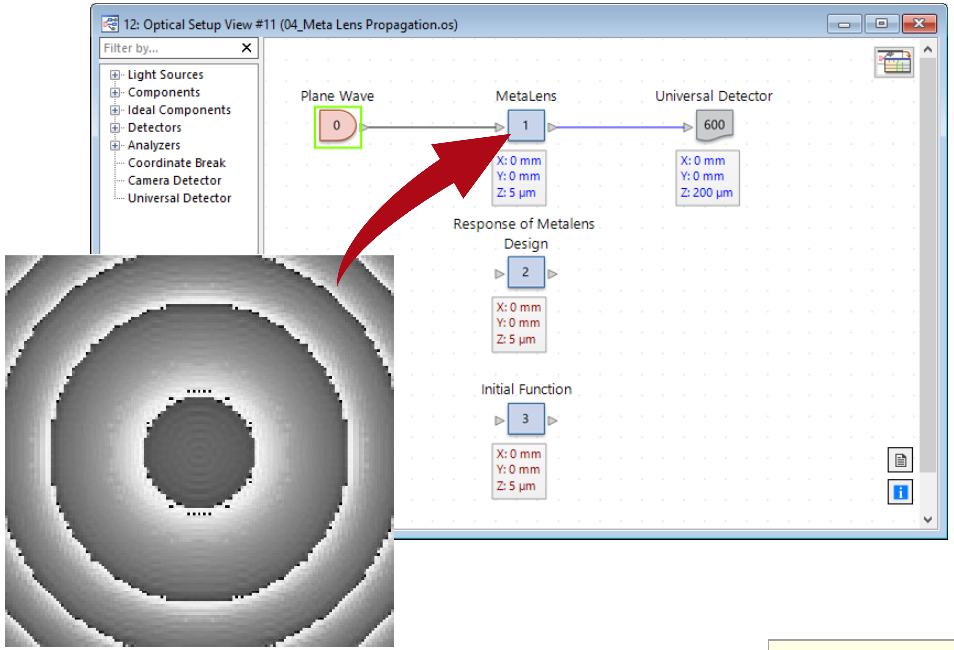
(complex transmission function of the metalens)

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.*

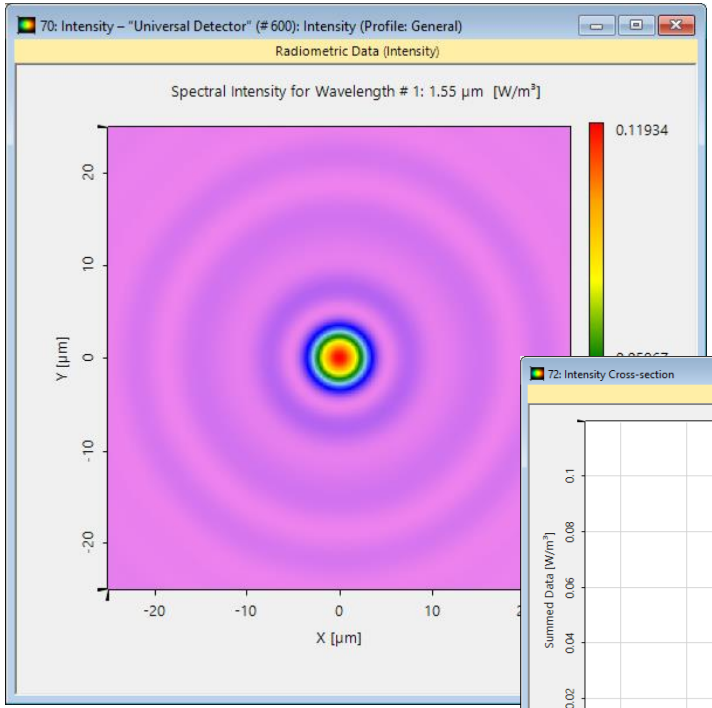
Step #2:

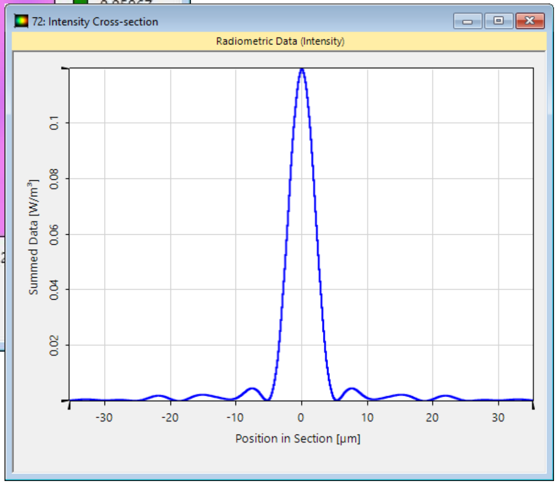
Optical Setup with Metalens (designed and initial)



calculated complex transmission

Result: focal spot (intensity)



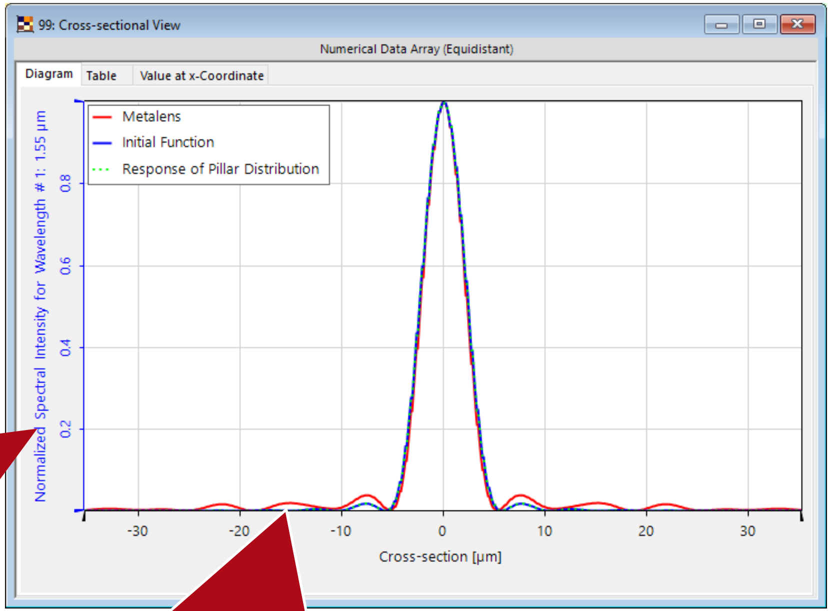


Size X (Intensity; [1] ➔ Spectral Intensity for Wavelength # 1: 1.55 µm)	4.6875 µm
Size Y (Intensity; [1] ➔ Spectral Intensity for Wavelength # 1: 1.55 µm)	4.6875 µm

lateral extent (FWHM)

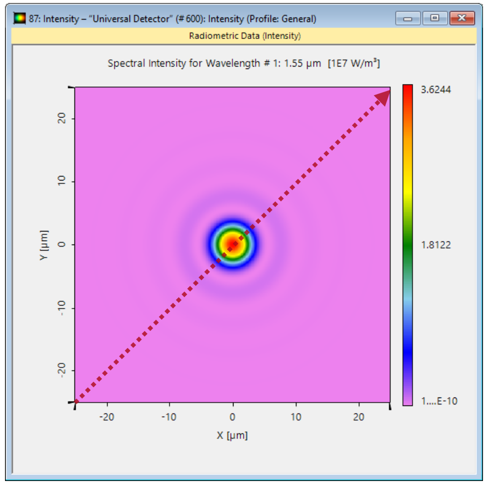
Comparison

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.



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

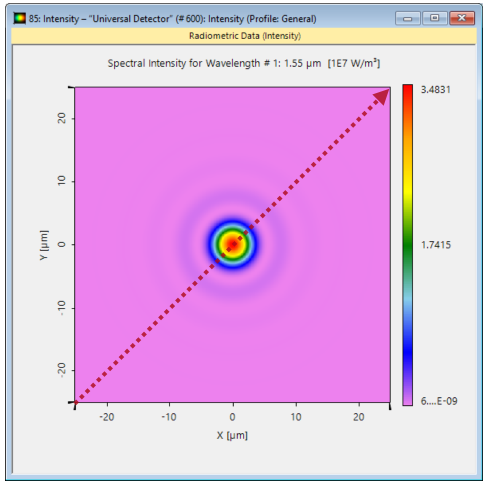
initial function



FWHM

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

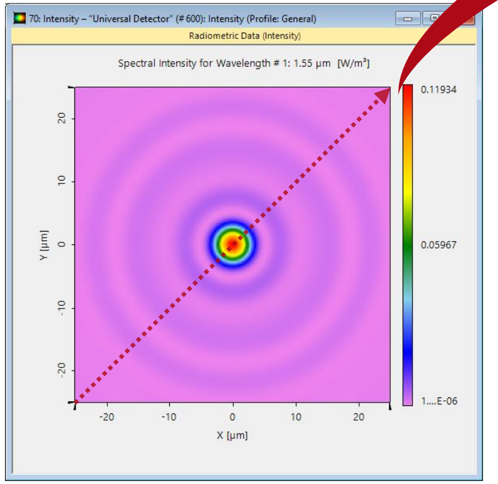
response of pillar design



FWHM

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

meta lens

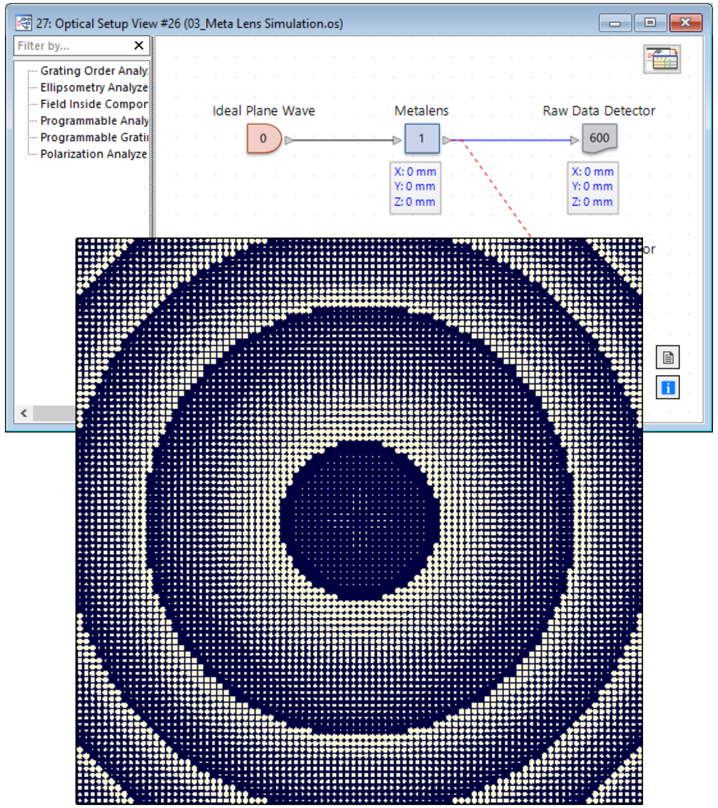


FWHM

Size X (Intensity; [1] ➔ Spectral Intensity...	4.6875 µm
Size Y (Intensity; [1] ➔ Spectral Intensity...	4.6875 µm

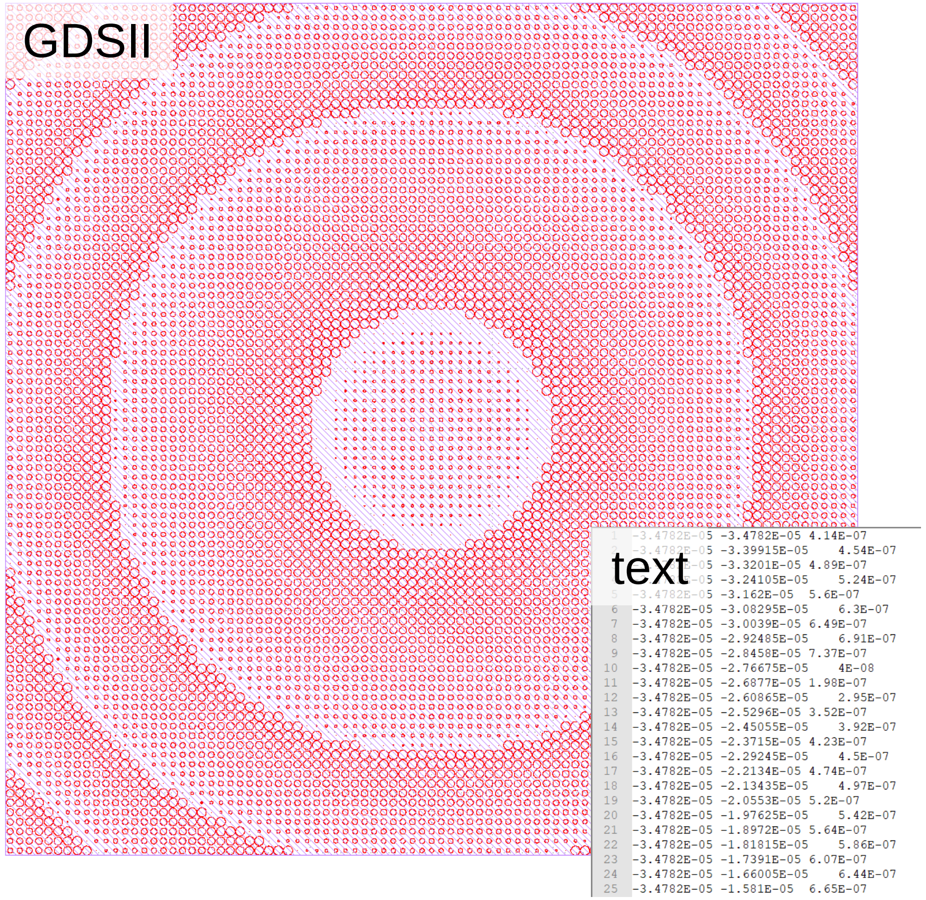
Export of Pillar Structure

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



pillar structure (configured in the *Pillar Medium*)

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).



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