Fast physical optics with VirtualLab Fusion optics software

Modeling and Design of Gratings, DOEs, Diffractive and Metalenses

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Jena, Germany

LightTrans International

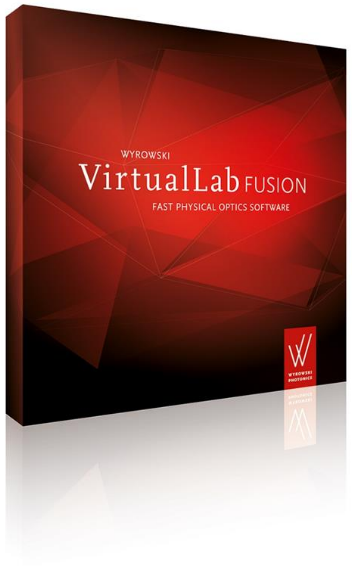
LightTrans
- Distribution of VirtualLab Fusion, together with distributors worldwide
- Technical support, seminars, and trainings
- Engineering projects

University of Jena

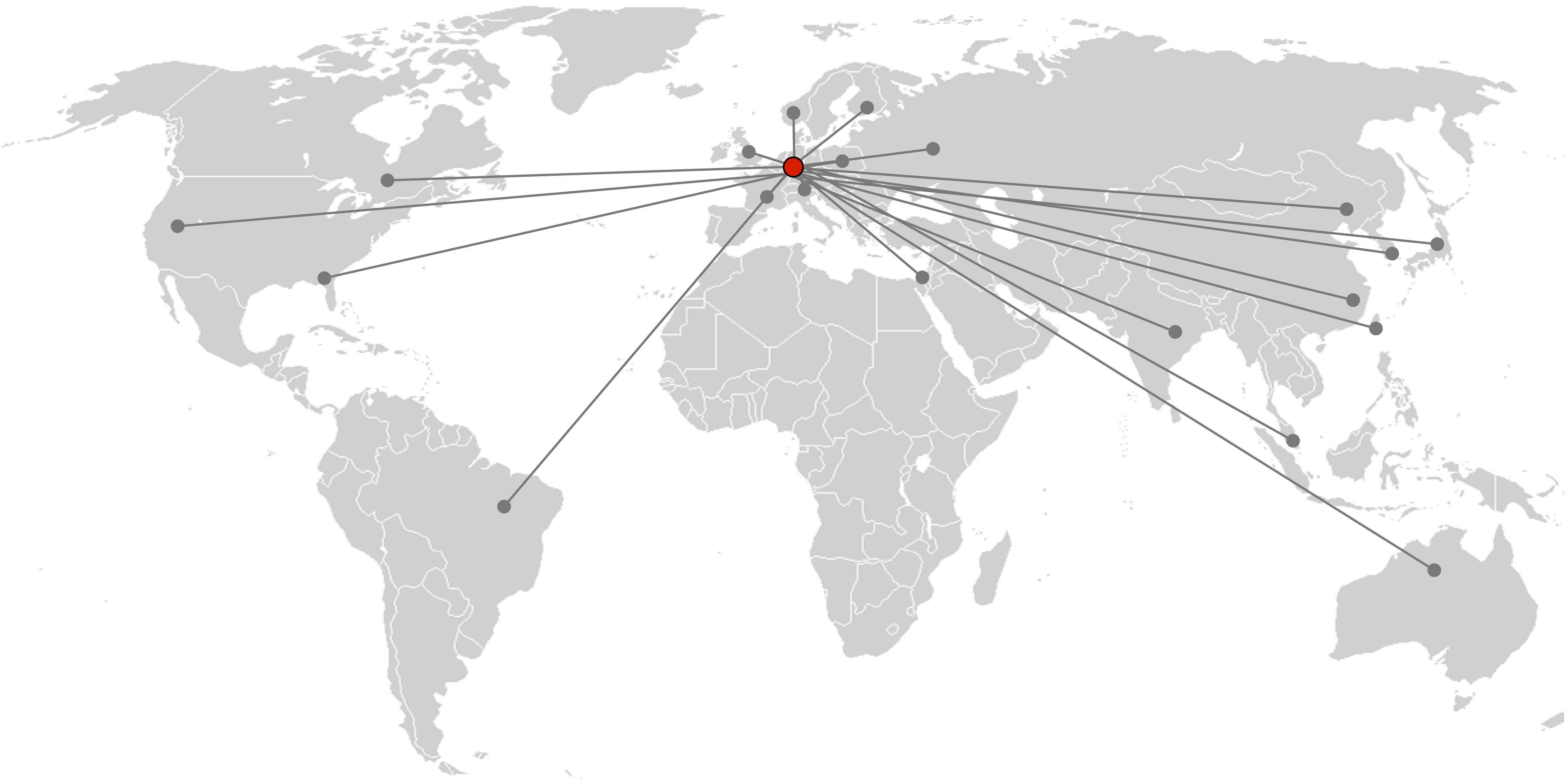
Applied Computational Optics Group R&D in optical modeling and design with emphasis on physical optics

Wyrowski Photonics

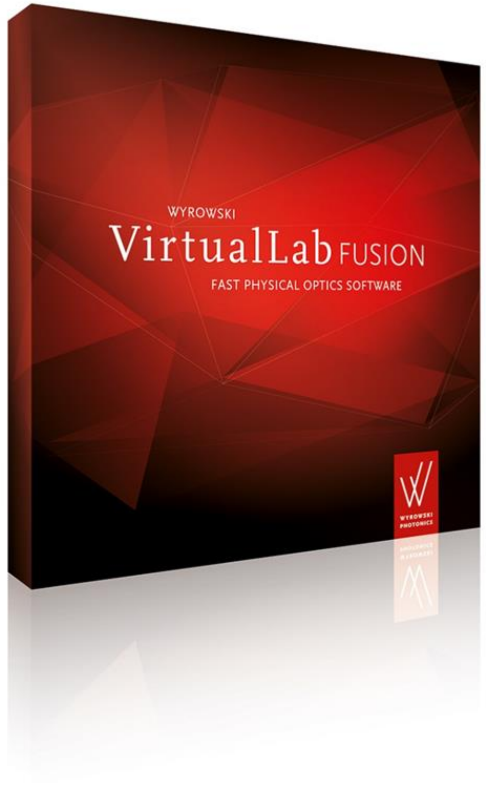
Wyrowski Photonics
Development of fast physical optics software VirtualLab Fusion



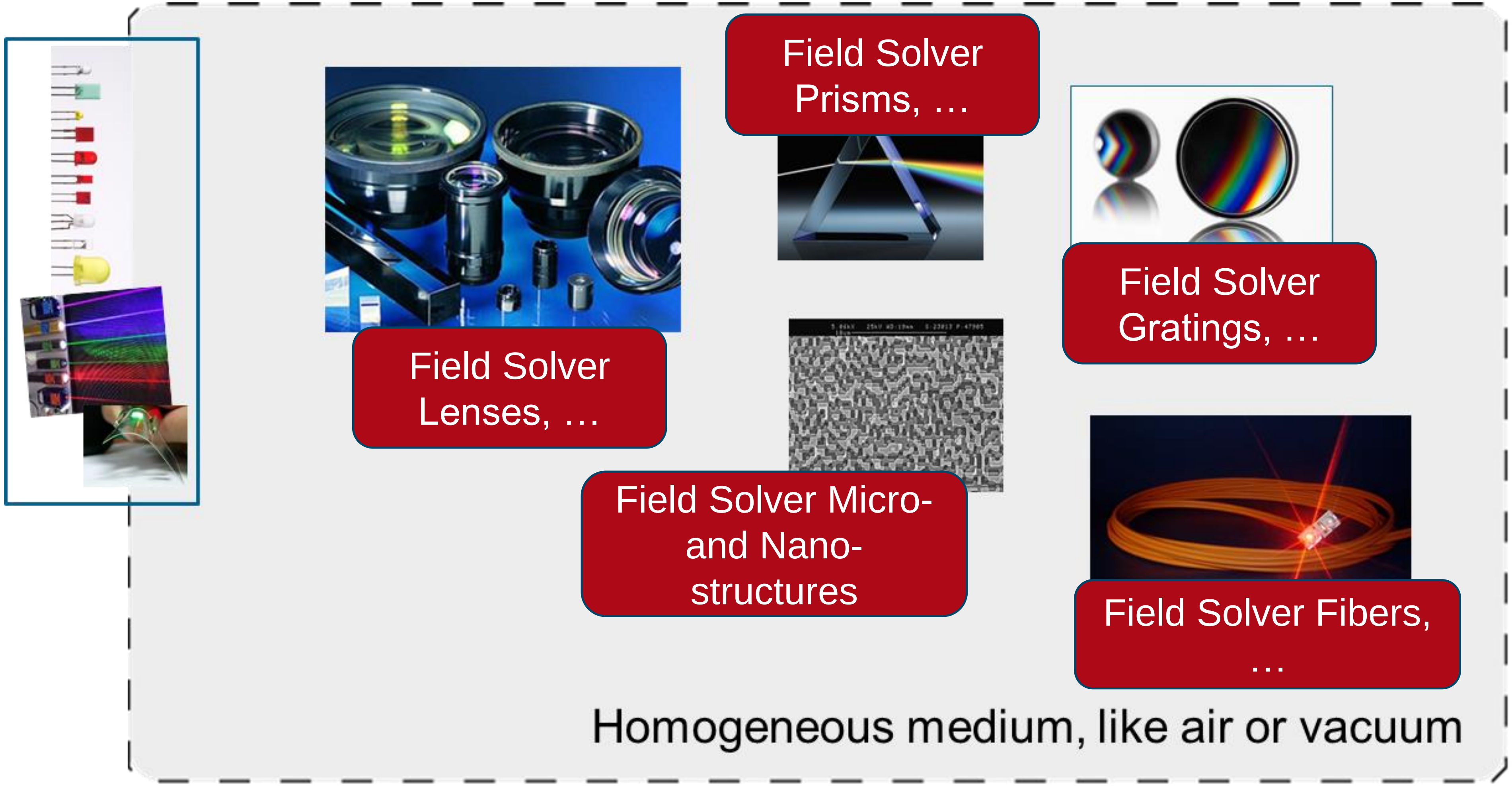
Optical Design Software and Services



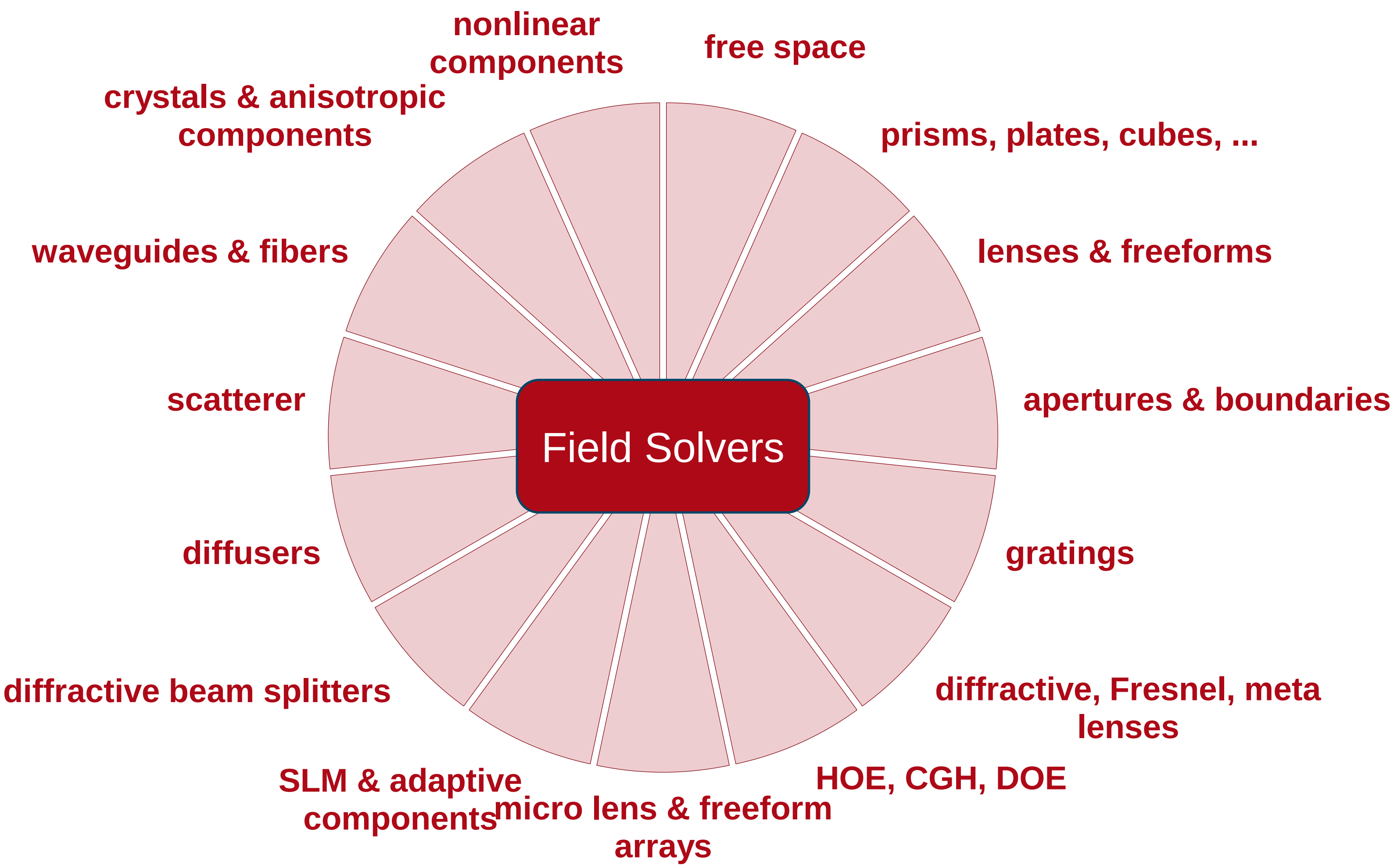
Hall B1, 209



Physical-Optics System Modeling by Connecting Field Solvers

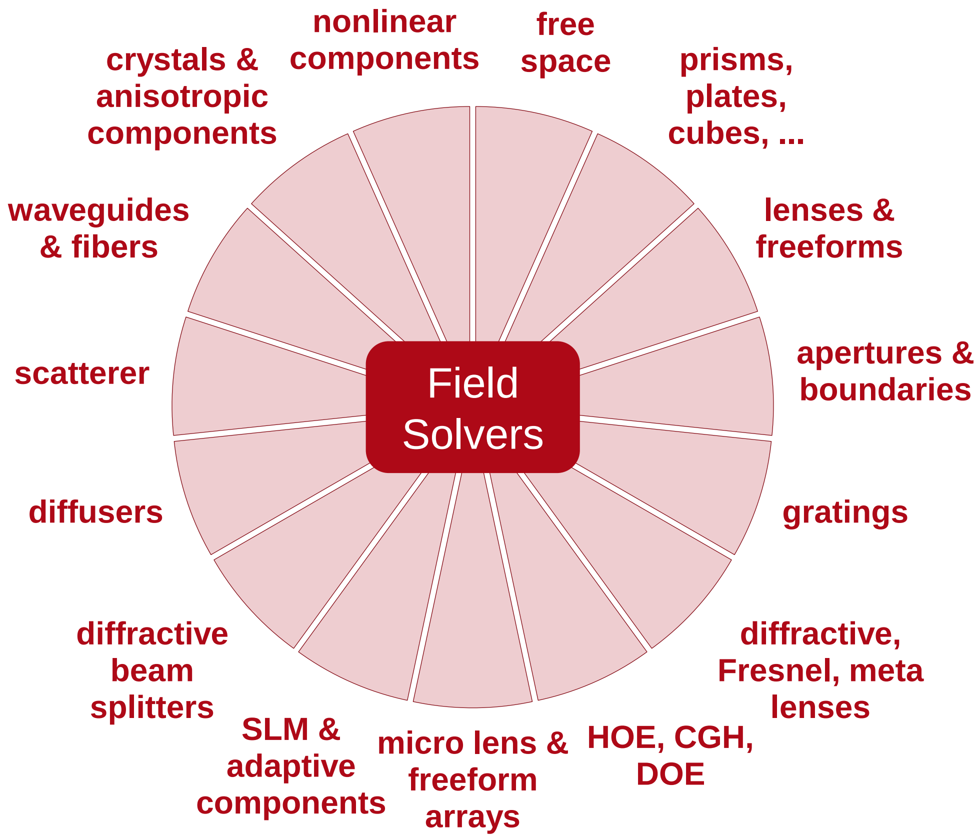


Physical-Optics System Modeling: Regional Field Solvers

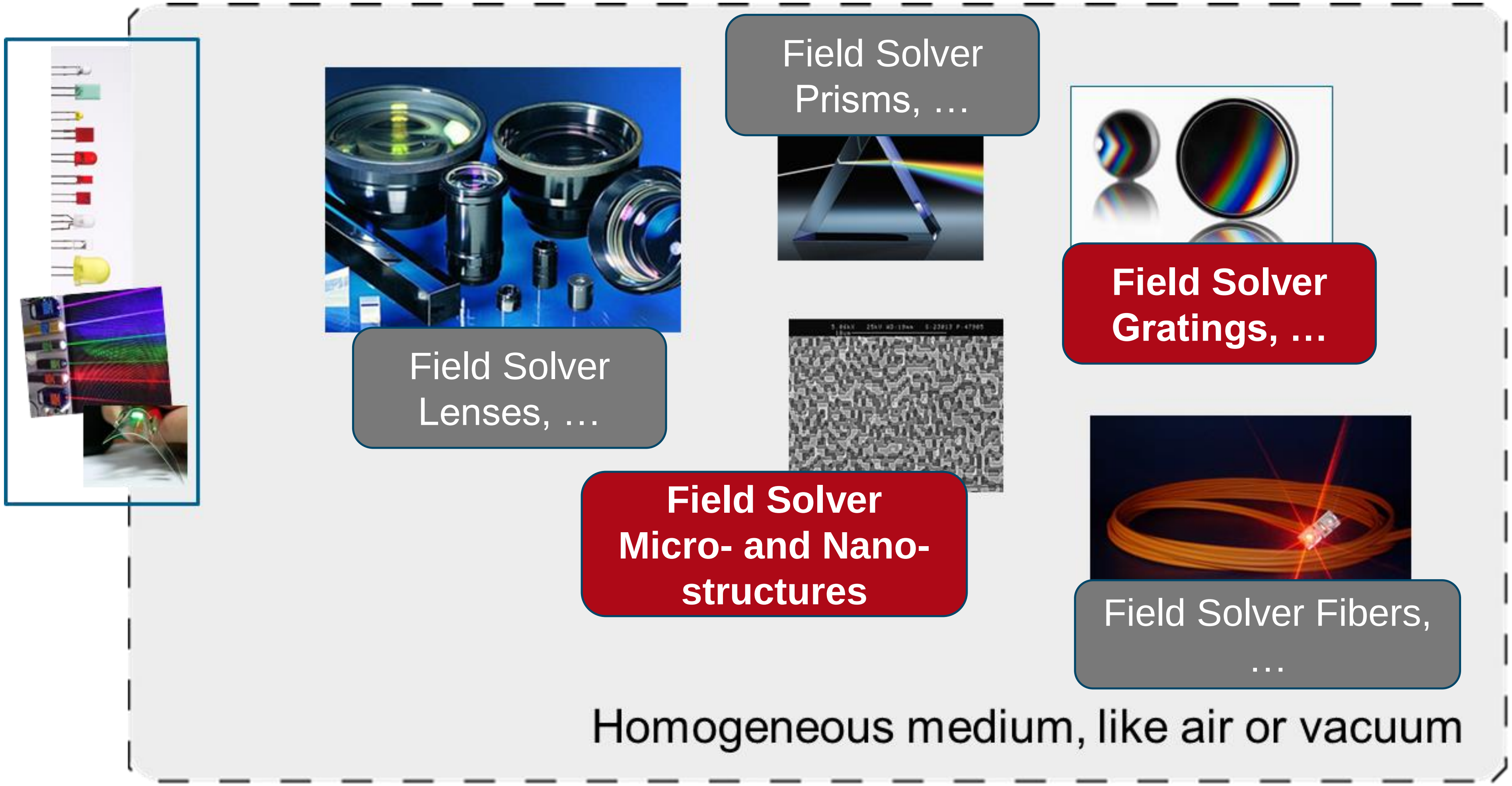


Physical-Optics System Modeling by Connecting Field Solvers

VirtualLab Fusion is a unified software platform incorporating various field solvers

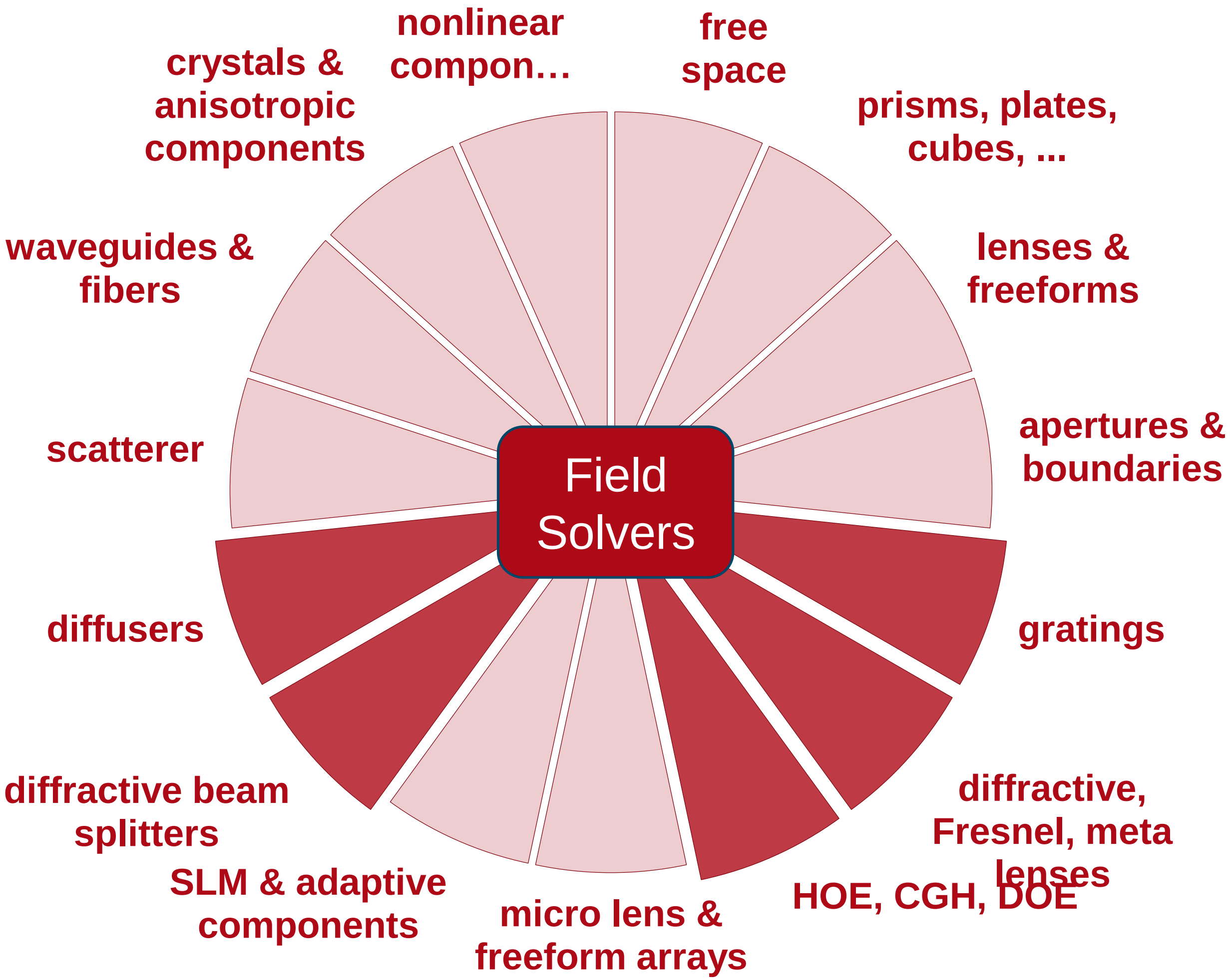


VirtualLab Fusion – Summer Release 2019



VirtualLab Fusion – Summer Release 2019

VirtualLab Fusion
Summer Release 2019



VirtualLab Fusion – Summer Release 2019

Microstructure Components Modeling

- Modeling of microstructure components beyond paraxial situtation
- Combined use with general input field
- Typical use for diffractive diffuser system modeling

Diffractive Lens

- Complementary workflow with Zemax OpticStudio
- Direct import of e.g. Binary 2 surface
- Modeling based on real diffractive lens surface structures
- Export for fabrication

Metalens

Coming in 2019

- Unified software platform with both rigorus analysis of nano structures, and also whole lens modeling
- Rigorous Fourier modal method (FMM) for unit cell modeling with friendly structure configuration

Integral Method for Grating Modeling

- In-built model for rectangular/slanted gratings with rounded edges
- Faster convergence than other techniques
- Suitable for fabrication tolerance analysis

Grating Components in General Optical Setup

- Rigorous modeling based on in-built Fourier modal method (FMM/RCWA)
- Use together with other components in general optical setups
- Arbitrary orientation

Simulation Engine Improvement

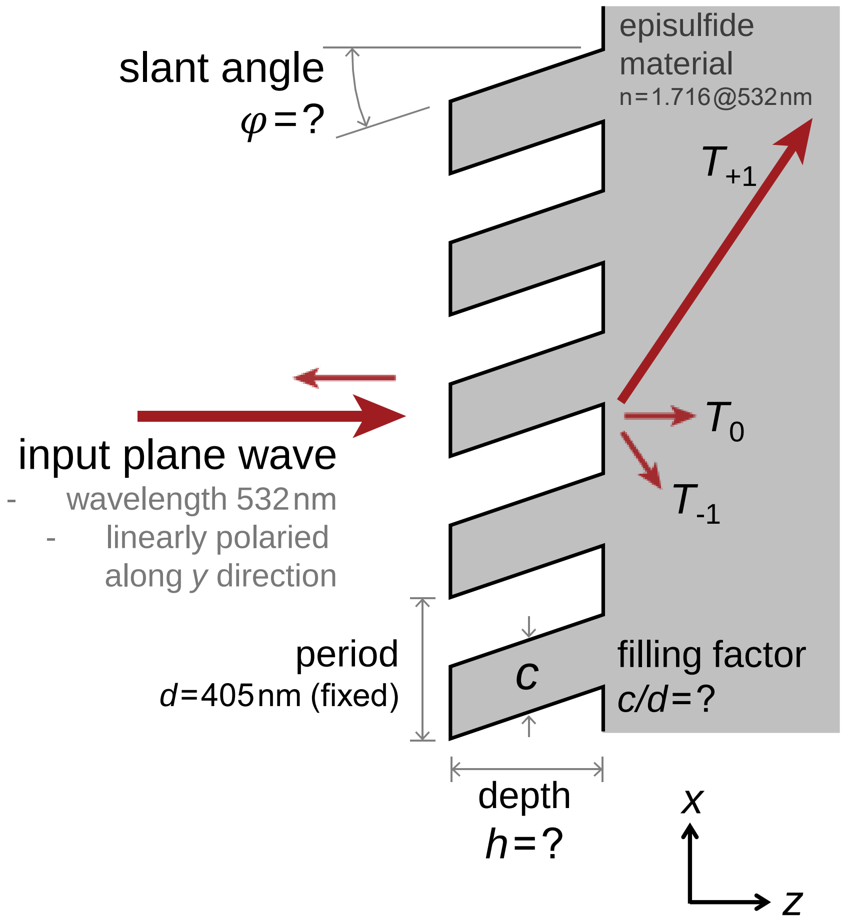
- Automatized sampling algorithm for free-space propagation
- Robust handling of aberrated wavefront phases
- Unified algorithm for propagation between tilted planes as well

… and more at our booth

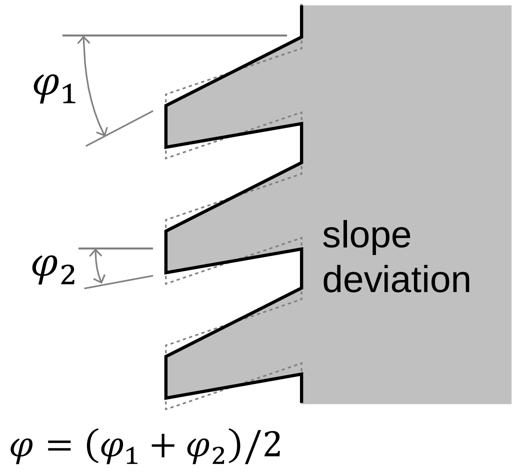
Hall B1, 209

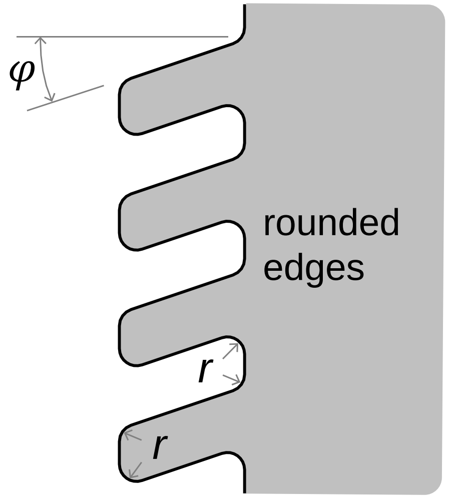
Parametric Optimization and Tolerance Analysis of Slanted Gratings

Modeling Task



How to optimize the T_{+1} order diffraction efficiency, by adjusting the slant angle φ, grating depth h, and filling factor c/d?

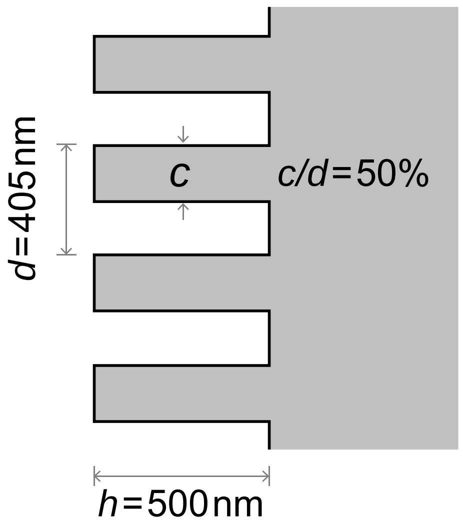




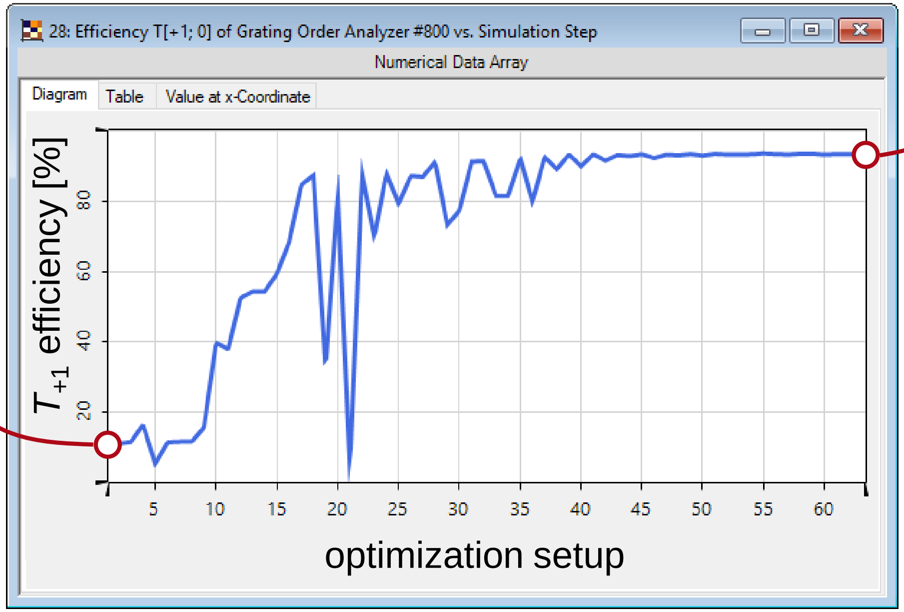
In addition, how to evaluate the grating performance with the slope deviation and the rounded edges due to the fabrication technique taken into account?

Parametric Optimization for 1st Order

initial structure

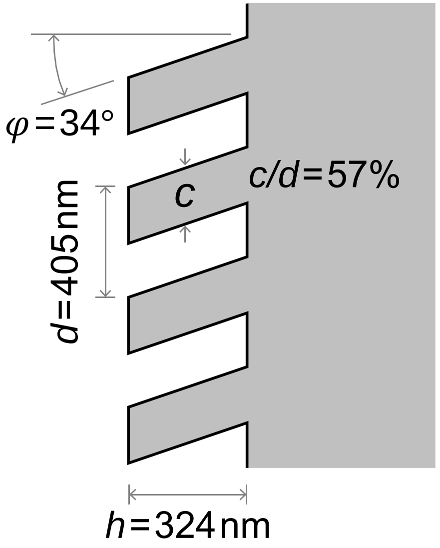


Order	Efficiency
-1	11.551%
0	72.795%
+1	11.551%



parametric optimization – downhill simplex method – with rigorous Fourier modal method (FMM) used for grating efficiency calculation

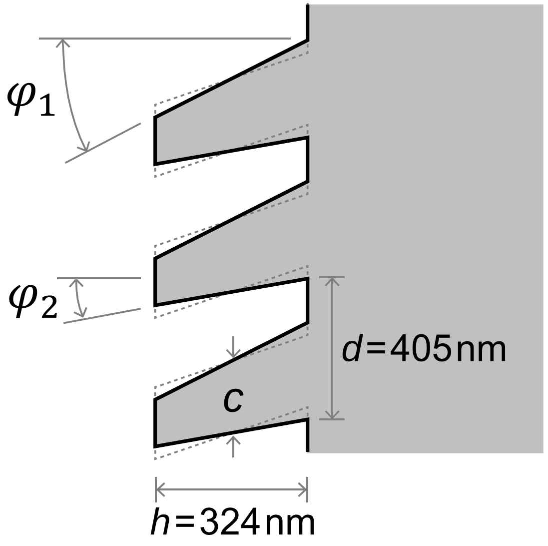
optimized structure



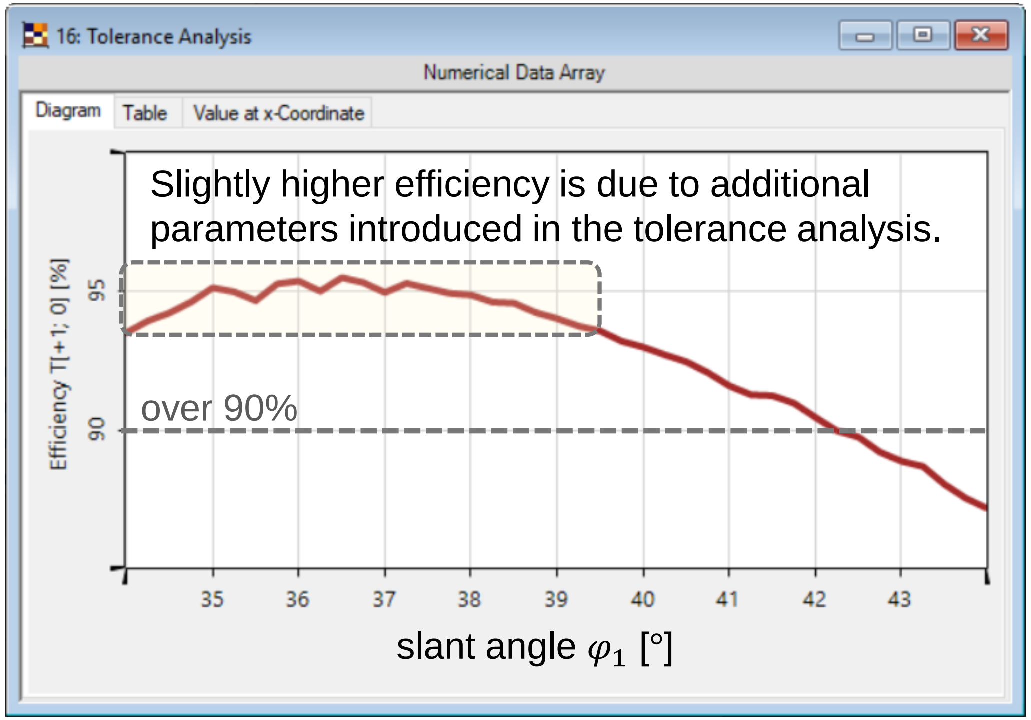
Order	Efficiency
-1	3.257%
0	0.365%
+1	**93.659%**

Results – Tolerance Analysis

The fabricated slanted gratings often shows a deviation from the perfect parallel grating lines. Such slope deviations should be taken into account for the tolerance analysis.



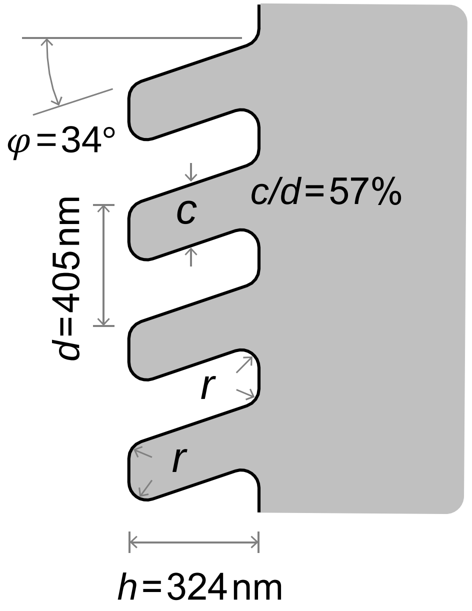
- fixed average slant angle $\varphi = (\varphi_1 + \varphi_2)/2 = 34°$
- fixed filling factor (average) c/d=57%
- varying φ_1 from 34 to 44°



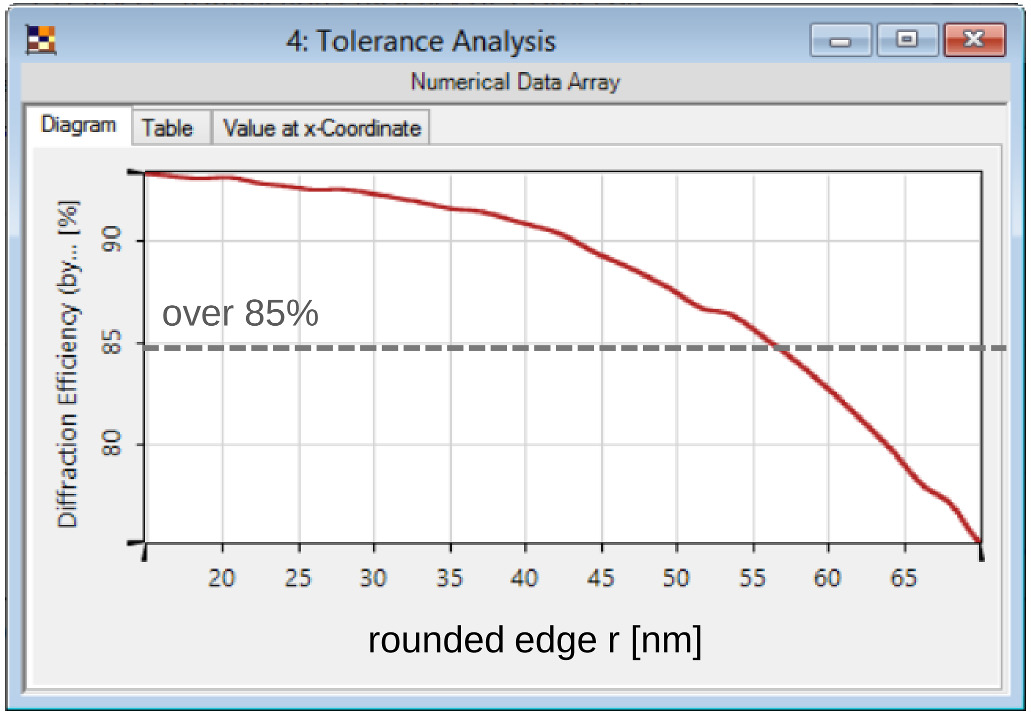
Rigorous simulation with Fourier modal method (FMM), for tolerance analysis over 50 steps, takes 30 seconds.

Results – Tolerance Analysis

The fabricated slanted gratings often shows a deviation from the perfect parallel grating lines. The rounded edges should be taken into account for the tolerance analysis.



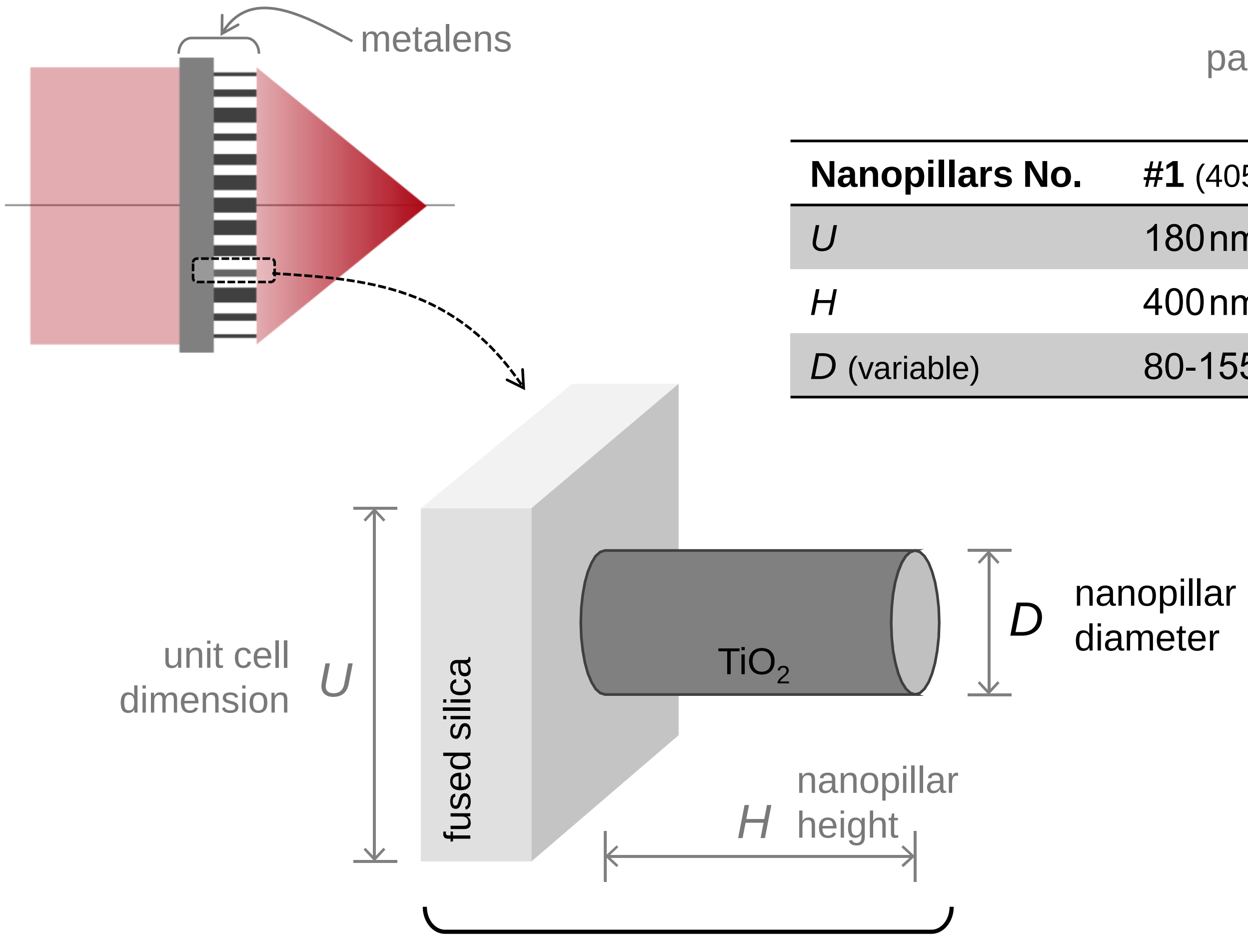
- fixed average slant angle $\varphi = 34°$
- fixed filling factor c/d=57%
- varying *r* from 15nm 70nm



Rigorous simulation with **Integral Method** (IM), for tolerance analysis over 30 steps, takes 9 seconds.

Rigorous Analysis of Nanopillar Metasurface Building Block

Modeling Task



single nanopillar as the building block of the metasurface

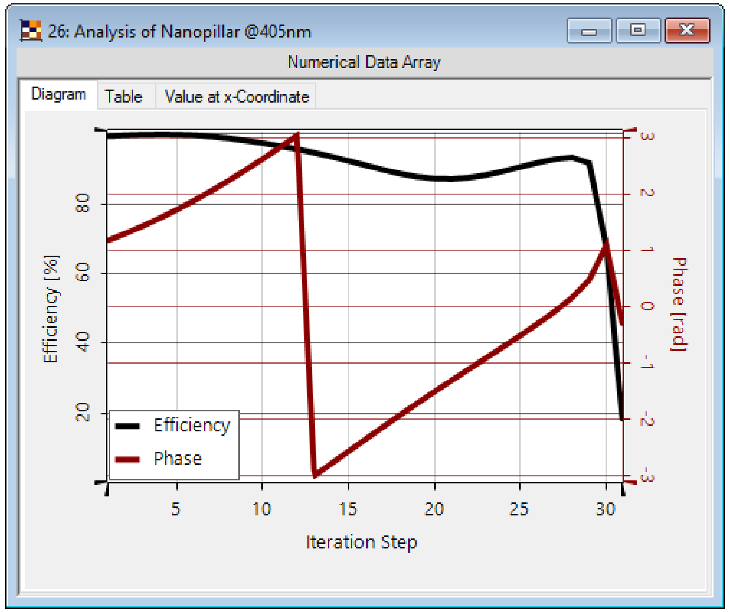
parameters from M. Khorasaninejad, *Nano Lett*. 2016, 16, 7229-7234

Nanopillars No.	**#1** (405 nm)	**#2** (532 nm)	**#3** (660 nm)
U	180 nm	250 nm	350 nm
H	400 nm	600 nm	600 nm
D (variable)	80-155 nm	100-220 nm	100-320 nm

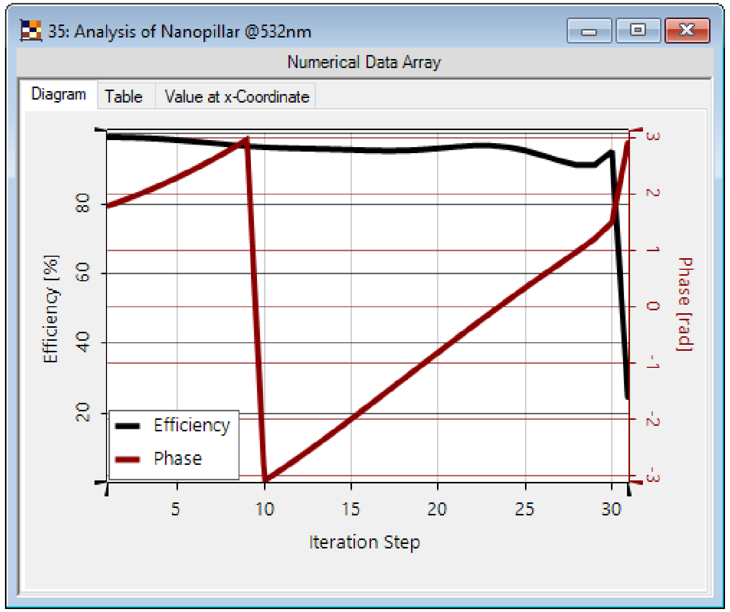
By varying the nanopillar diameter, the metasurface building block is supposed to have phase modulation covering 2π. How to evaluate such nanopillar structure rigorously?

Nanopillar Analysis vs. Pillar Diameter

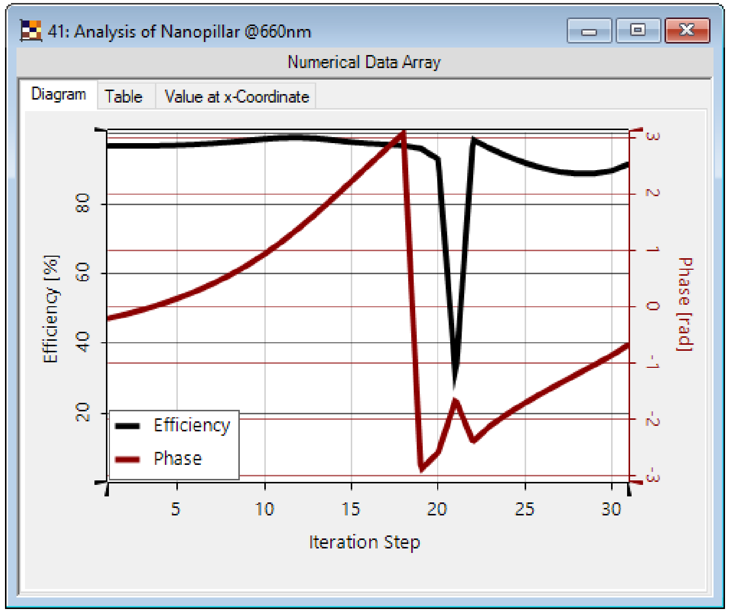
nanopillar #1



nanopillar #2



nanopillar #3



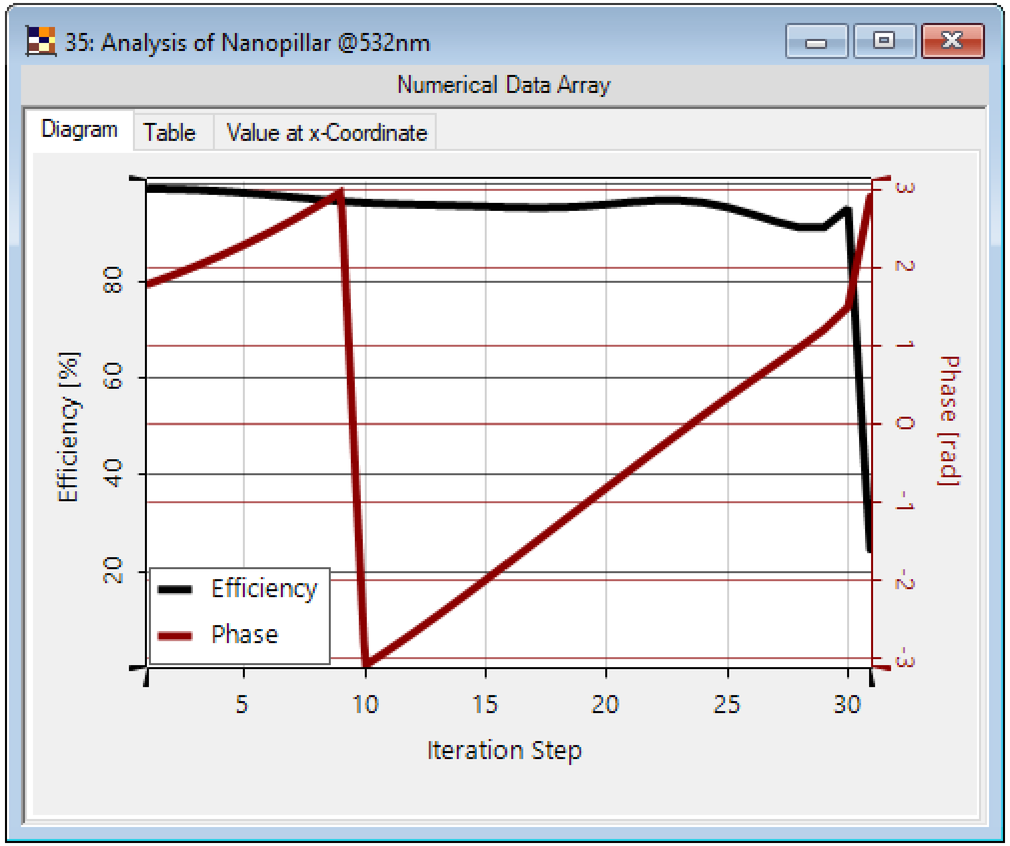
Nanopillars No.	**#1** (405nm)	**#2** (532nm)	**#3** (660nm)
U	180nm	250nm	350nm
H	400nm	600nm	600nm
D (variable)	80-155nm	100-220nm	100-320nm

Nanopillar Analysis vs. Pillar Diameter

- The phase modulation covers 2π range, and it changes almost linearly with pillar diameter, which enables convenient phase control.
- The transmission efficiency remains above 90% for varying pillar diameter over the design range.

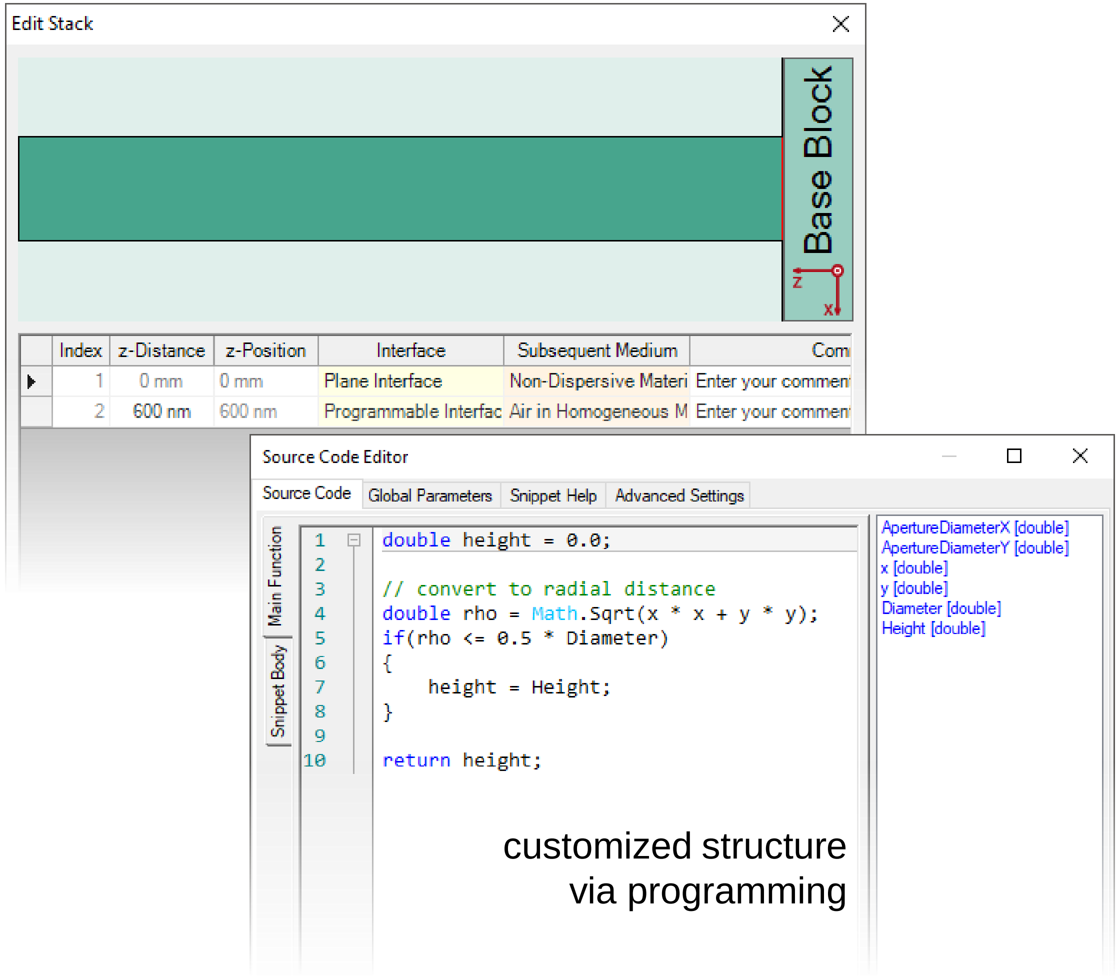
Nanopillars No.	**#1** (405nm)	**#2** (532nm)	**#3** (660nm)
U	180nm	250nm	350nm
H	400nm	600nm	600nm
D (variable)	80-155nm	100-220nm	100-320nm

nanopillar #2

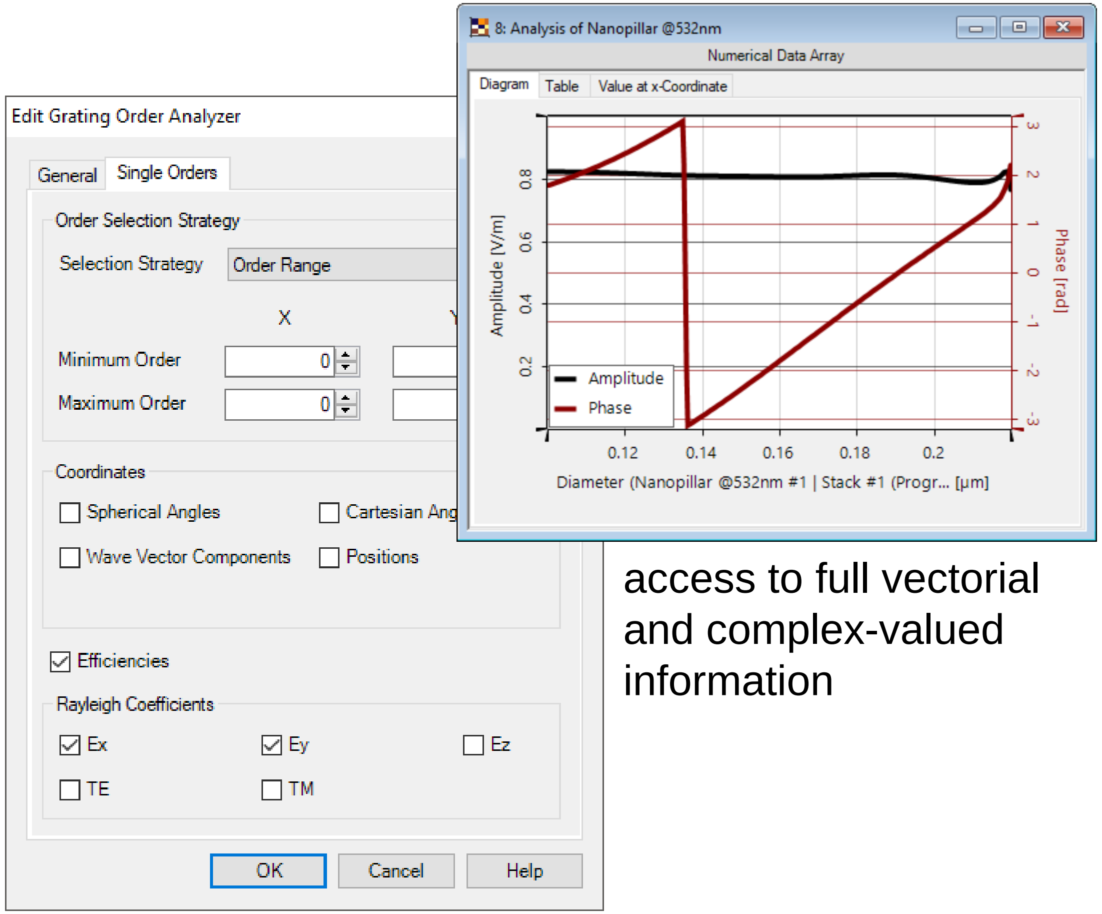


Peek into VirtualLab Fusion

flexible pillar structure definition



customized structure
via programming

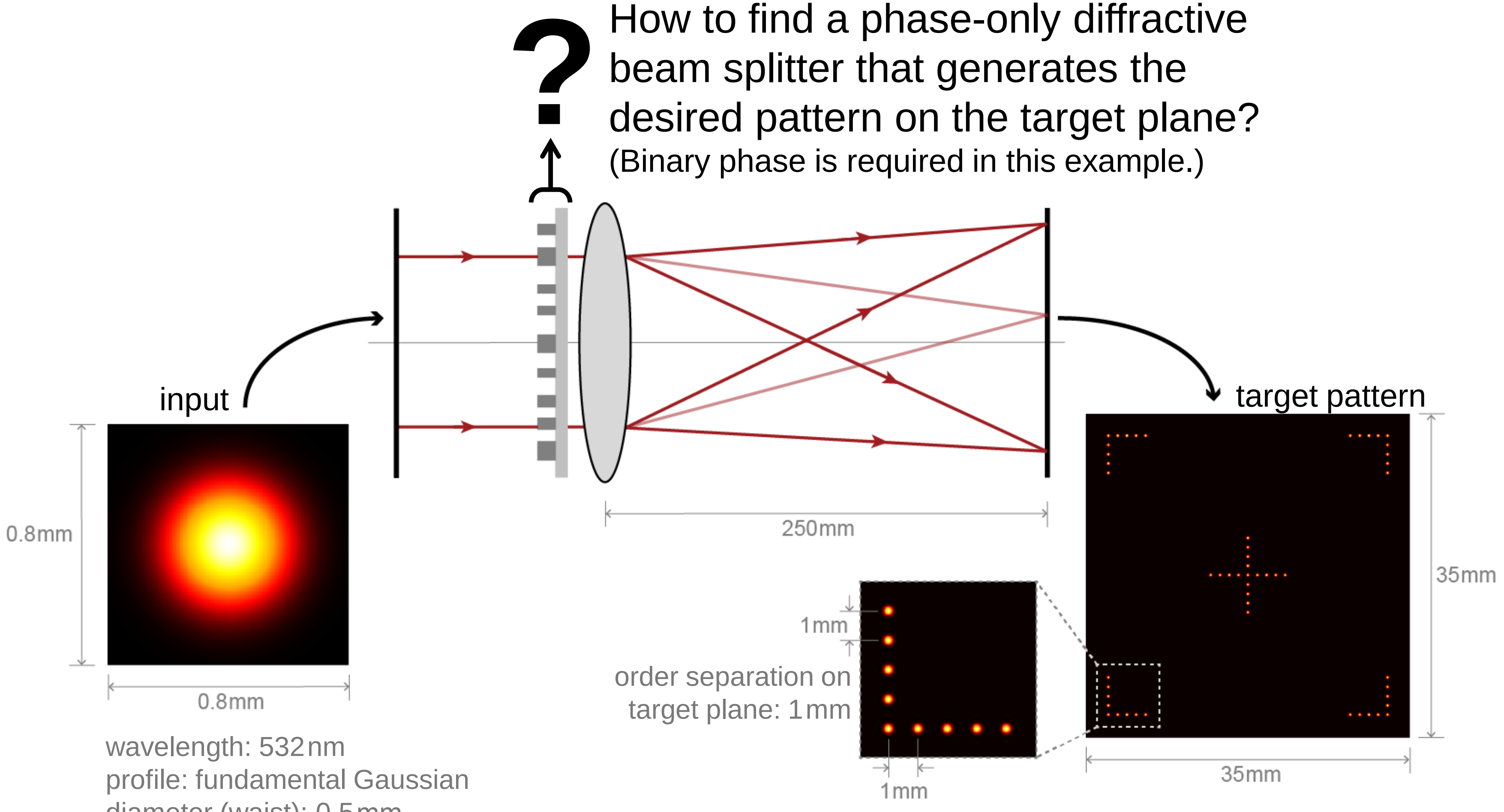


access to full vectorial and complex-valued information

Design of Diffractive Beam Splitters for Generating a 2D Light Mark

Design Task

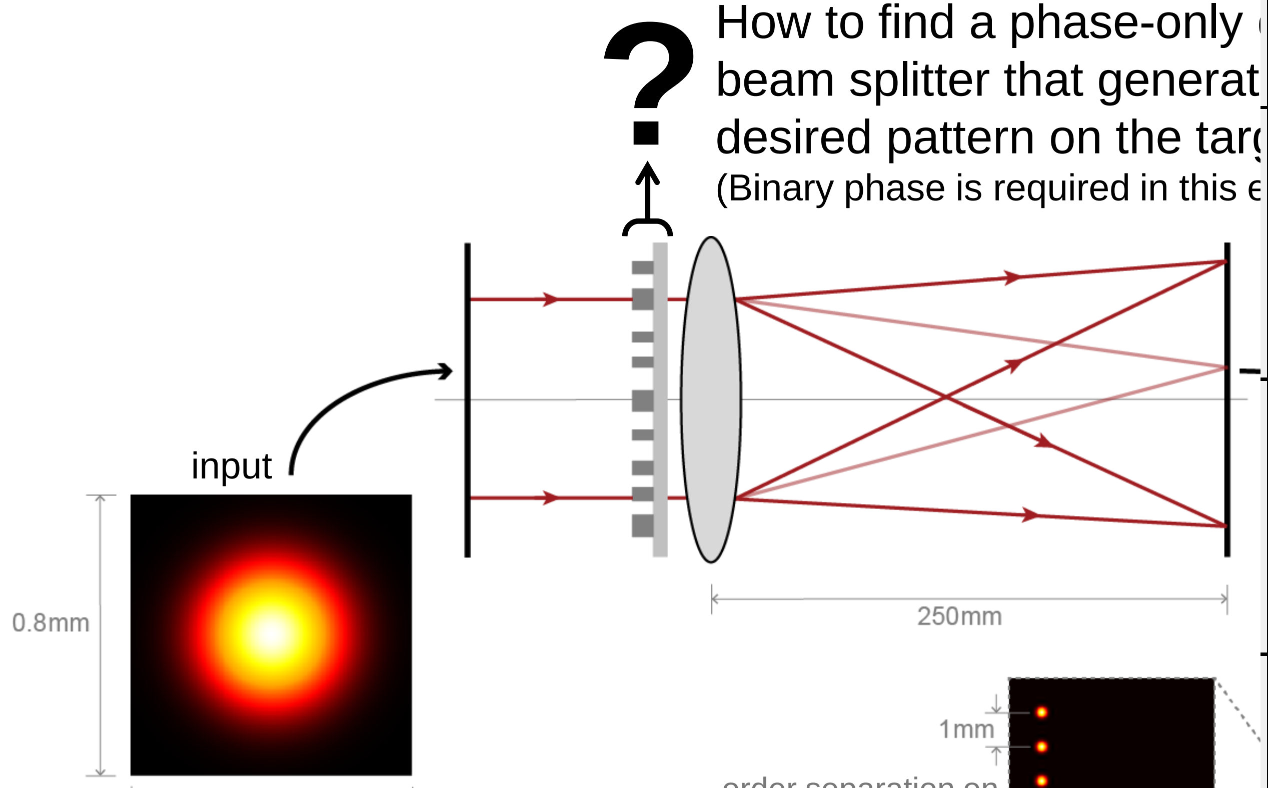
How to find a phase-only diffractive beam splitter that generates the desired pattern on the target plane?
(Binary phase is required in this example.)



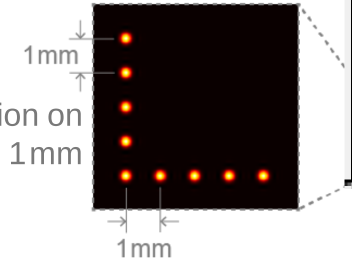
wavelength: 532 nm
profile: fundamental Gaussian
diameter (waist): 0.5 mm

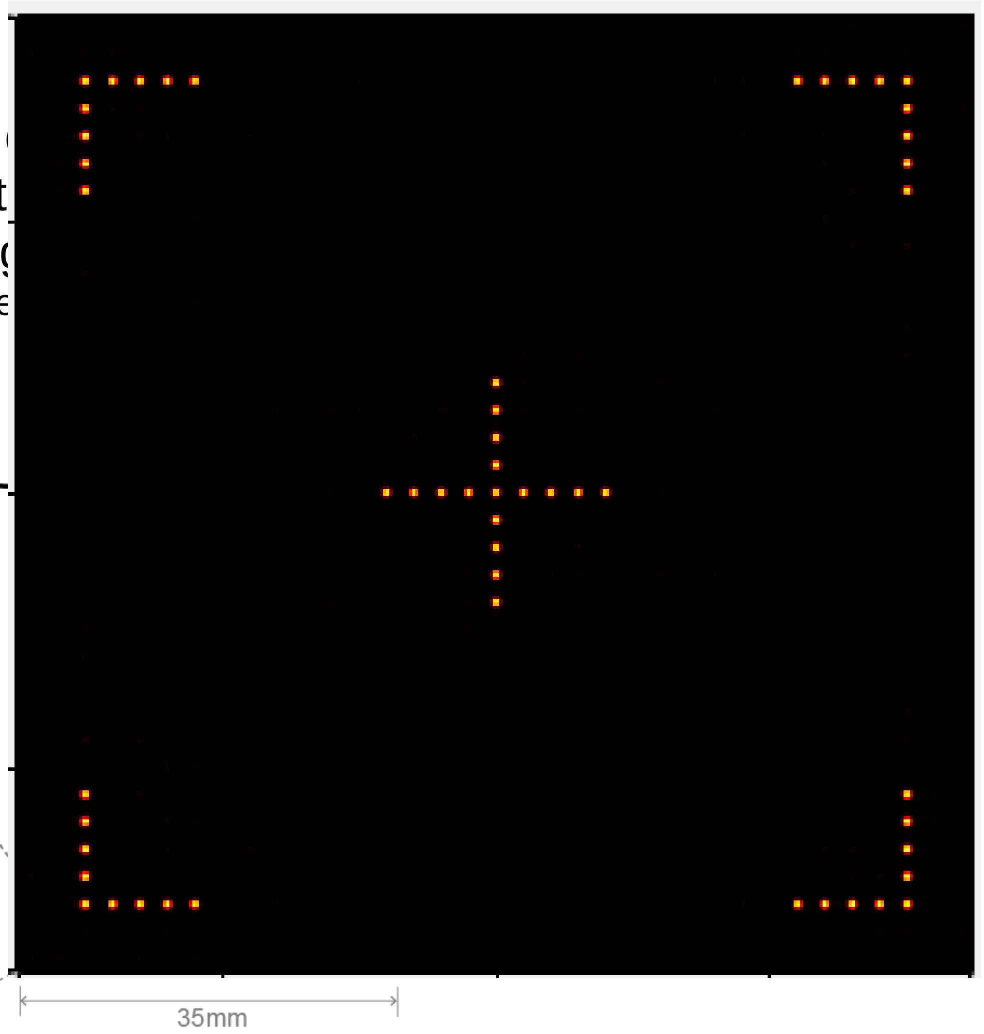
Design Task

How to find a phase-only
beam splitter that generat
desired pattern on the targ
(Binary phase is required in this e



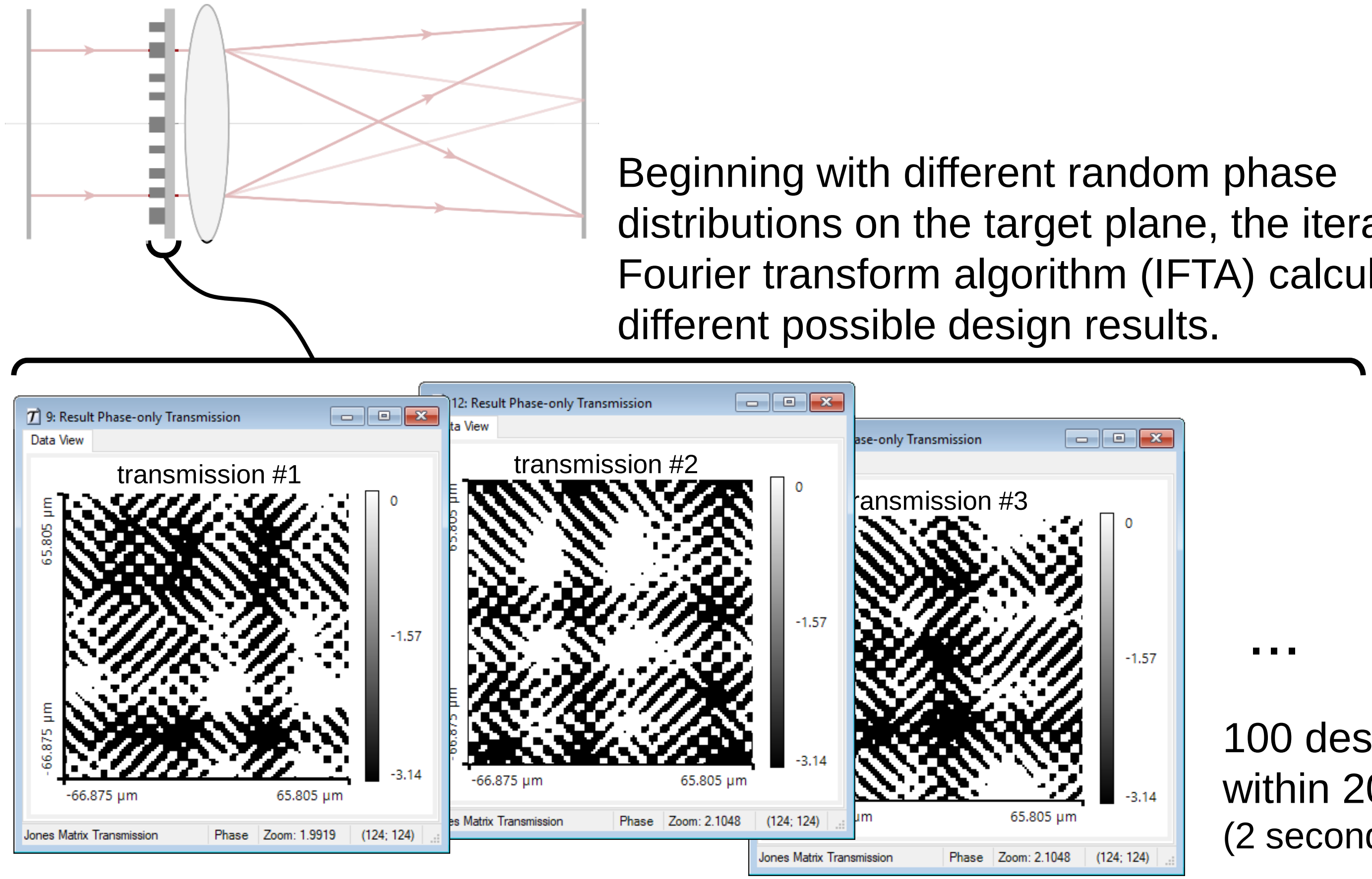
wavelength: 532 nm
profile: fundamental Gaussian
diameter (waist): 0.5 mm





Results

- Designed binary-phase for beam splitter



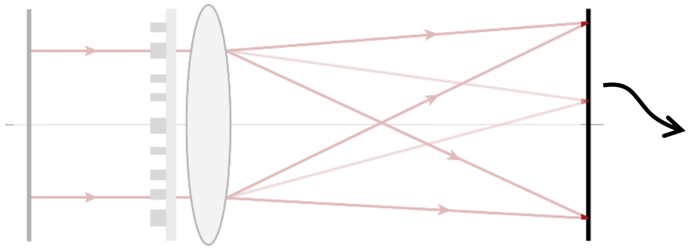
Beginning with different random phase distributions on the target plane, the iterative Fourier transform algorithm (IFTA) calculates different possible design results.

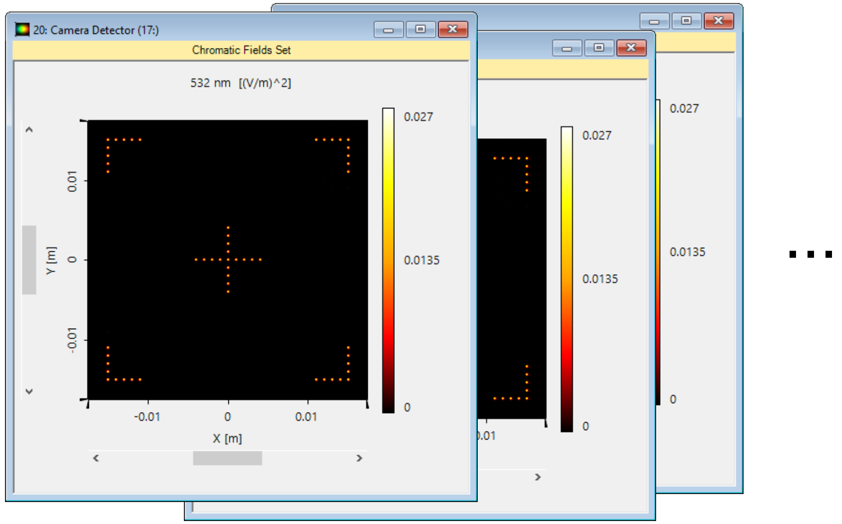
…

100 designs delivered within 200 seconds!
(2 seconds per design)

Results

- Performance evaluation



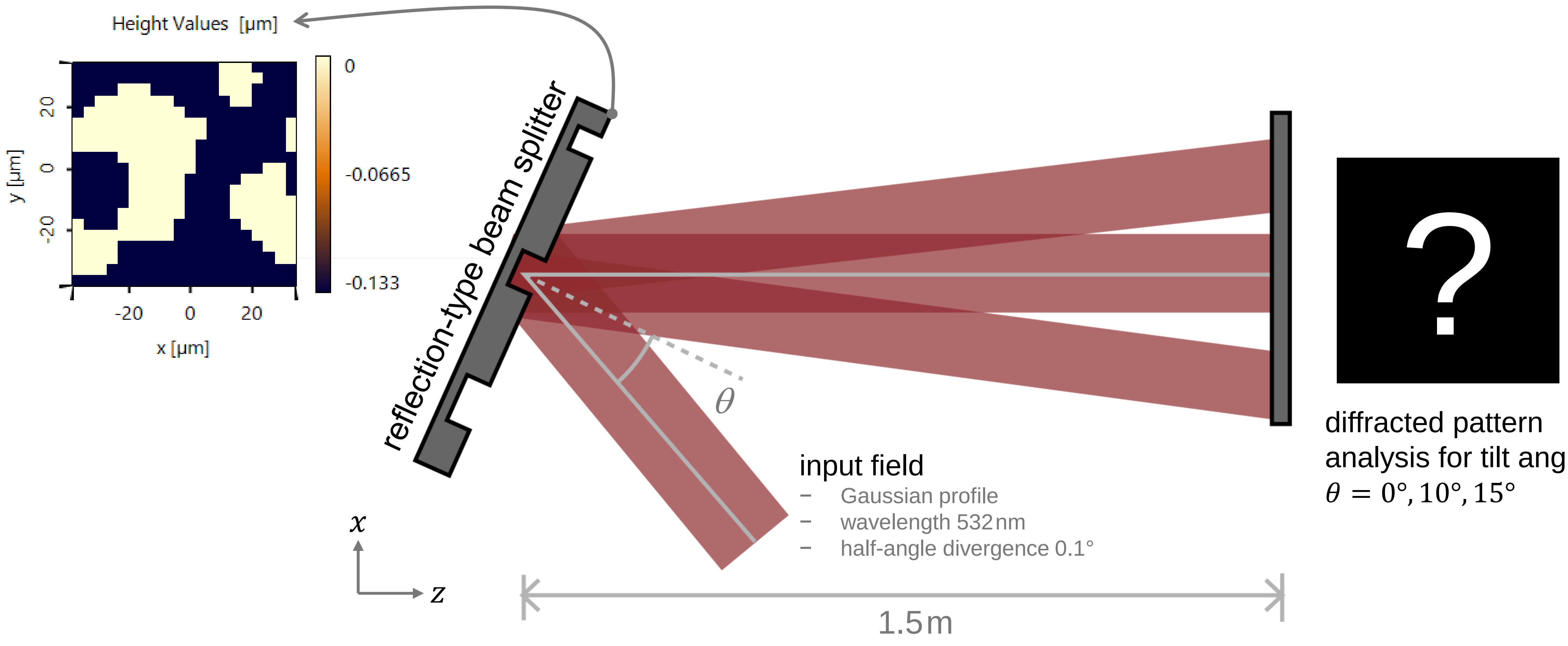


Fast physical-optics simulation of the complete optical system gives access to multiple merit functions at once.

Merit functions	Design #1	Design #2	Design #3	...
conversion efficiency	65.92%	66.38%	64.71%	
uniformity error	4.31%	3.69%	6.76%	
stray light	3.99%	5.17%	3.11%	

Diffraction Pattern Calculation from a Reflection-Type Diffractive Beam Splitter

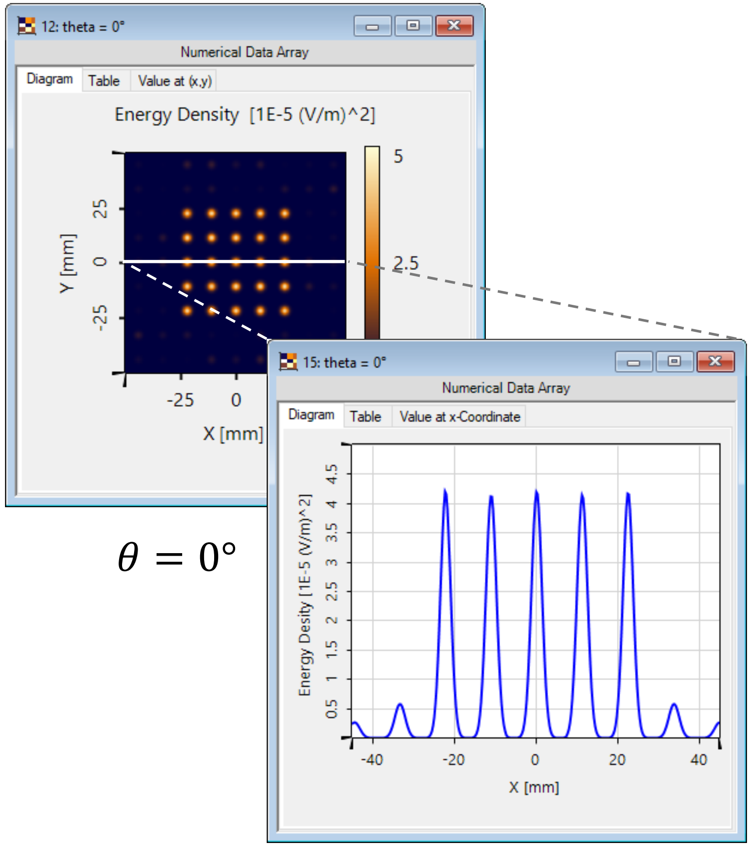
Modeling Task



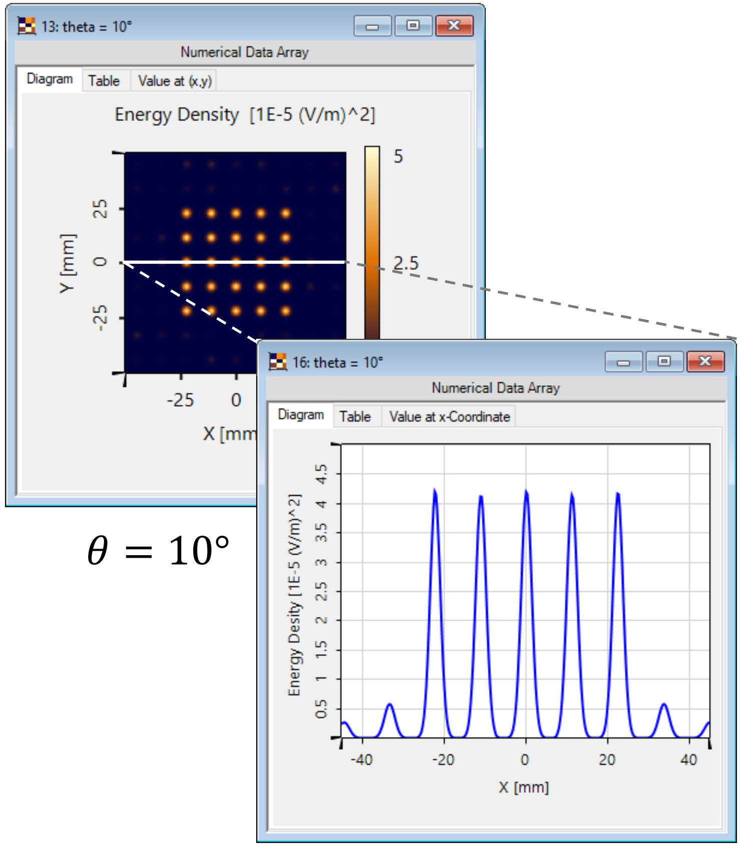
input field
- Gaussian profile
- wavelength 532 nm
- half-angle divergence 0.1°

diffracted pattern analysis for tilt angles $\theta = 0°, 10°, 15°$

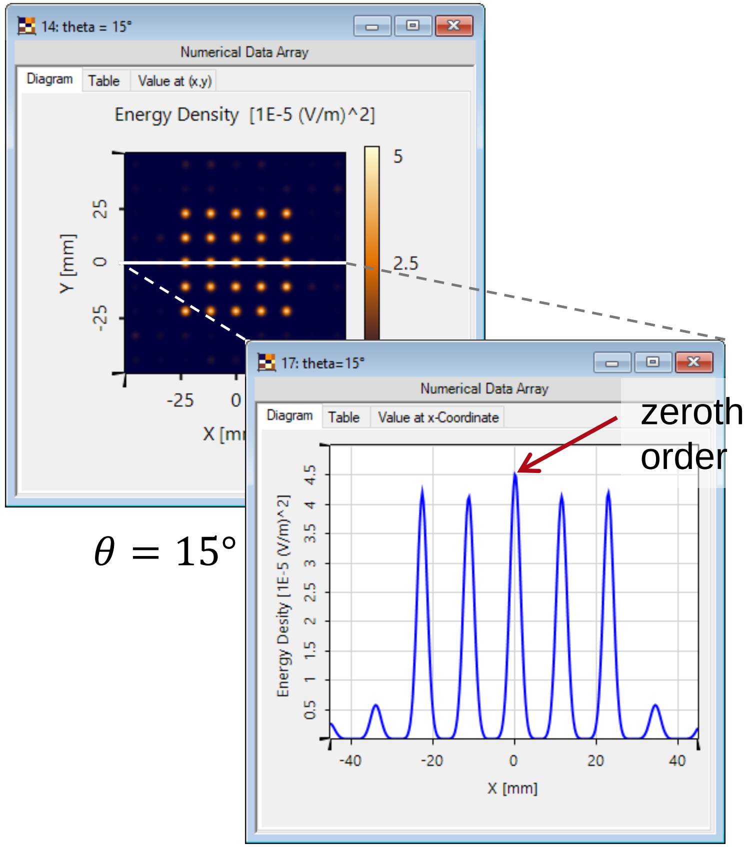
Diffracted Pattern in Detector Plane



$\theta = 0°$



$\theta = 10°$

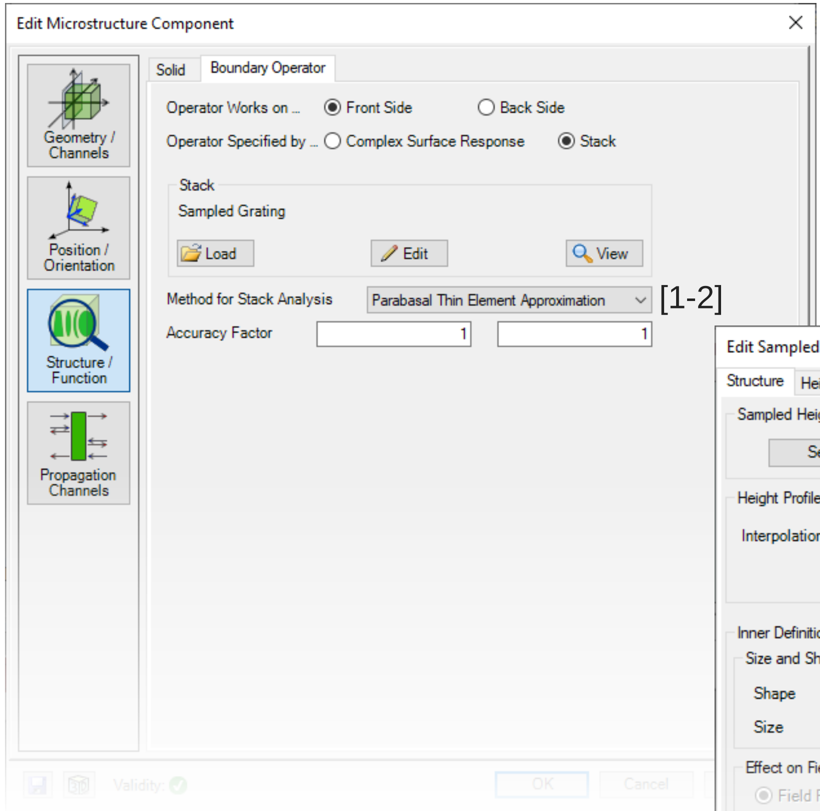


$\theta = 15°$

The beam splitter is designed under normal incidence, and for small angle (< 10°) it delivers uniformly split diffraction orders.

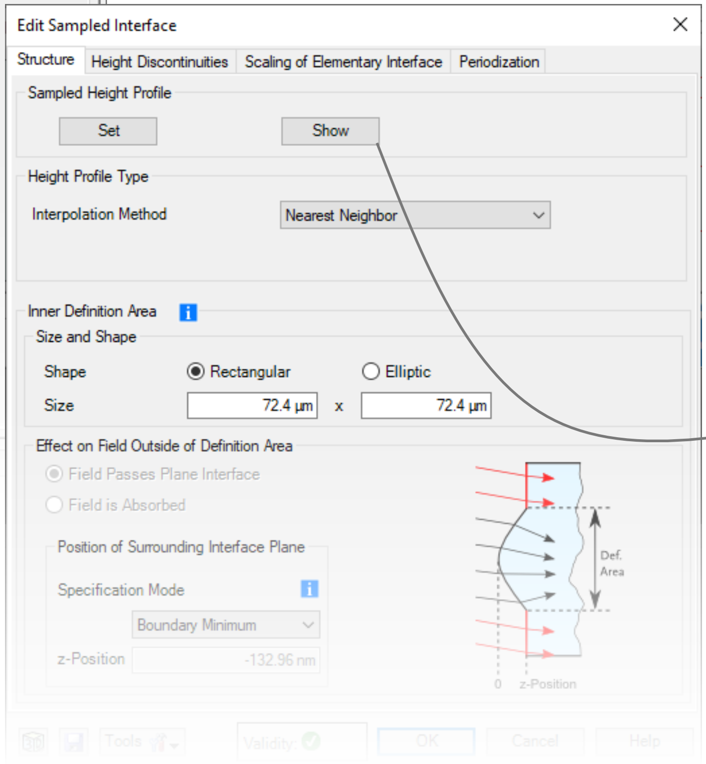
The efficiency of zeroth order exceeds other orders, when θ increases to 15°. Such situation shall be avoided in practice.

Peek into VirtualLab Fusion

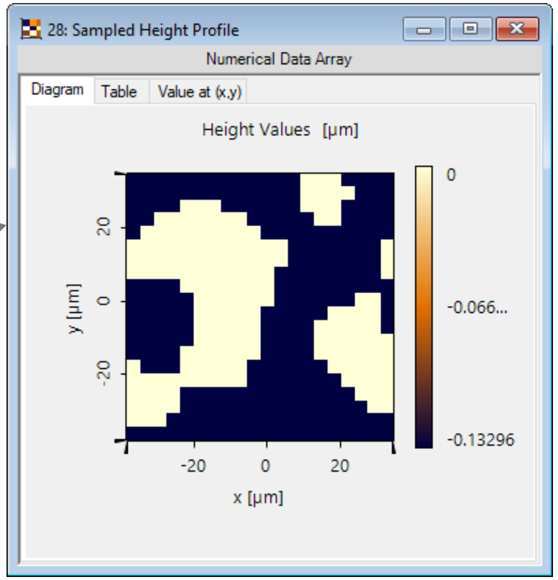


[1-2]

Microstructure Component is used to configure the diffractive beam splitter.



The microstructure can be defined by an imported data matrix.

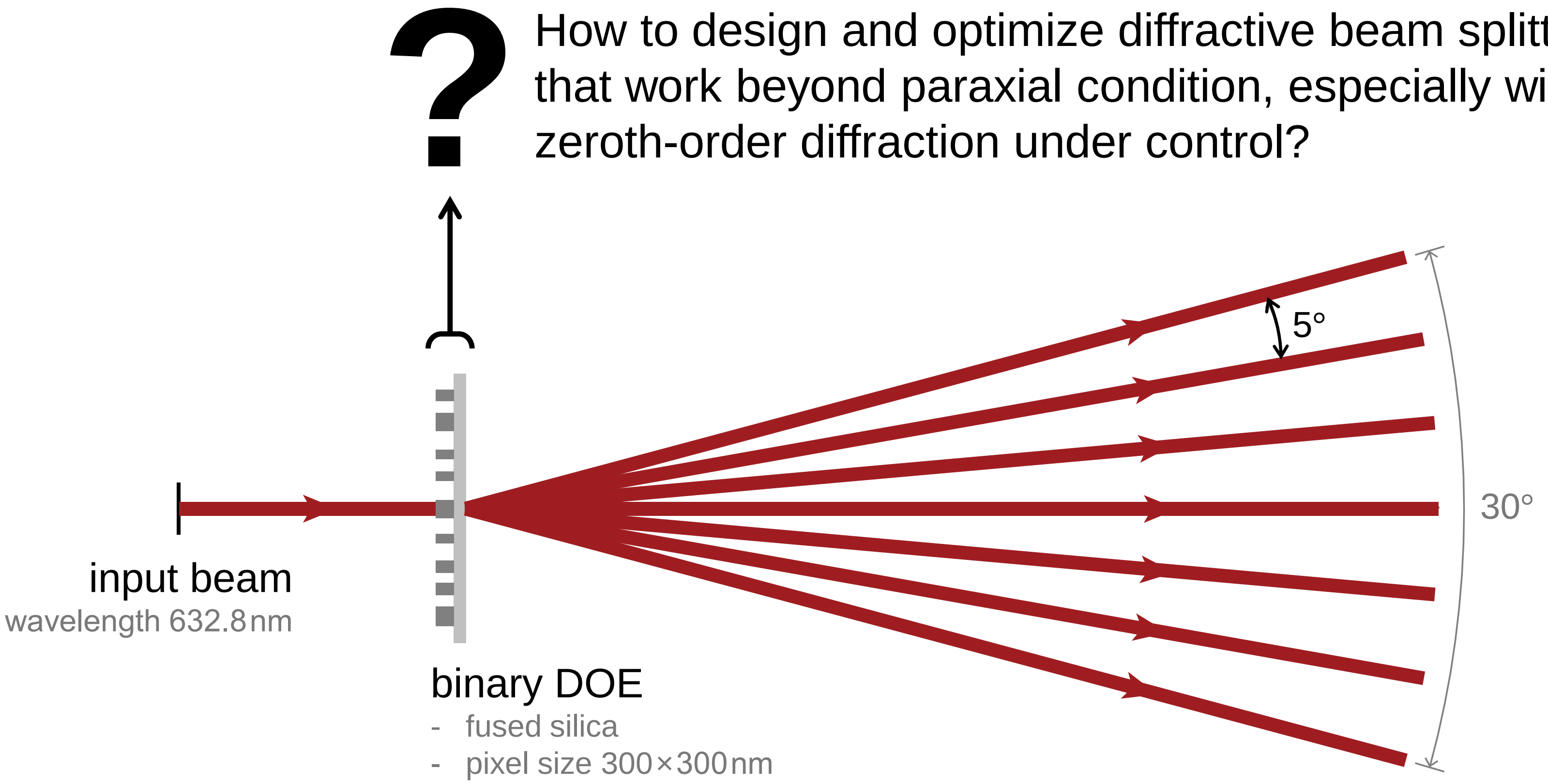


[1] Jari Turunen *et al*., "Storage of multiple images in a thin synthetic Fourier hologram," Optics Communications, **84**(5-6), 383-392 (1991)
[2]Huiying Zhong *et al*., "**Parabasal thin-element approximation approach** for the analysis of microstructured interfaces and freeform surfaces," J. Opt. Soc. Am. A **32**, 124-129 (2015)

Design and Rigorous Analysis of Non-Paraxial Diffractive Beam Splitter

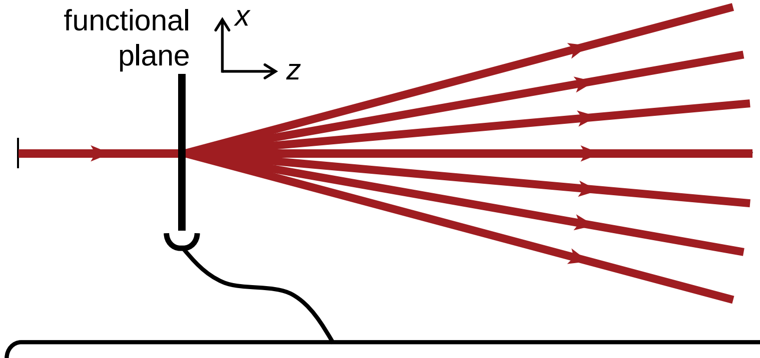
Design Task

How to design and optimize diffractive beam splitters that work beyond paraxial condition, especially with zeroth-order diffraction under control?

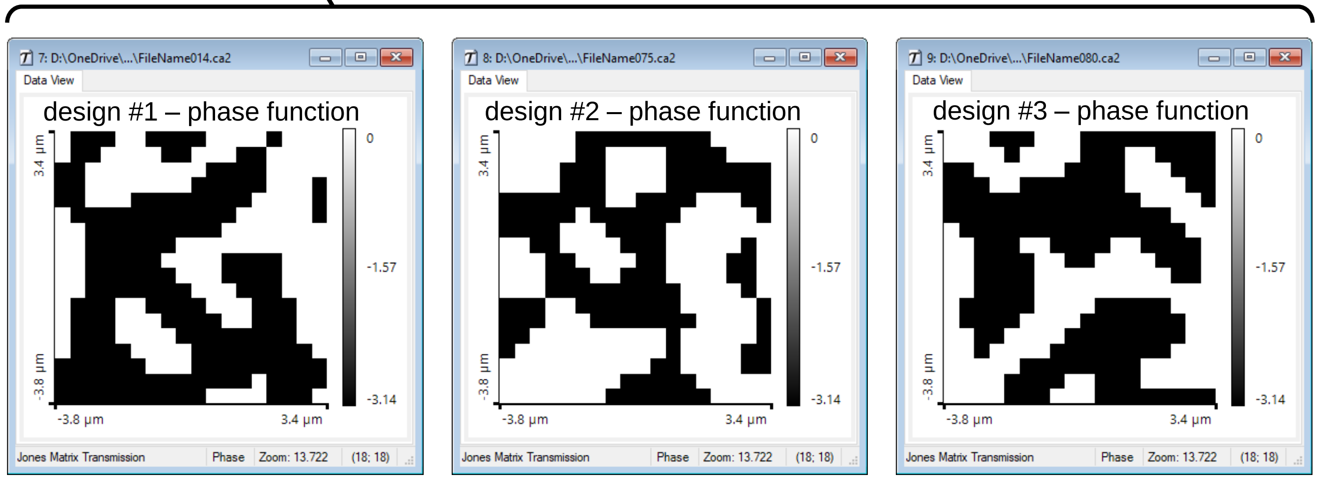


Results

- Phase-only transmission design
  [with iterative Fourier transform algorithm (IFTA)]



With differently random phase distributions as starting points, IFTA calculates different possible design results. 3 designs are selected out of 100 according to customized criteria.

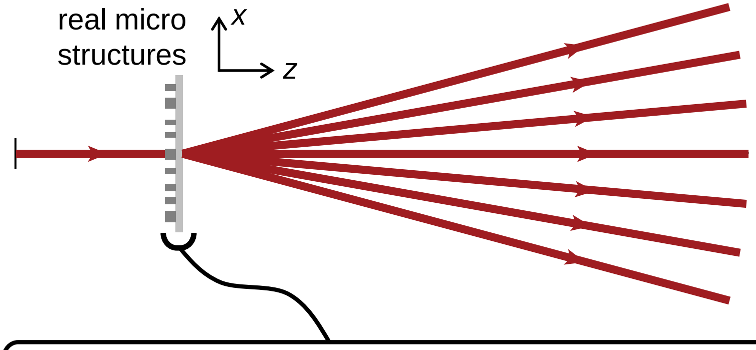


...

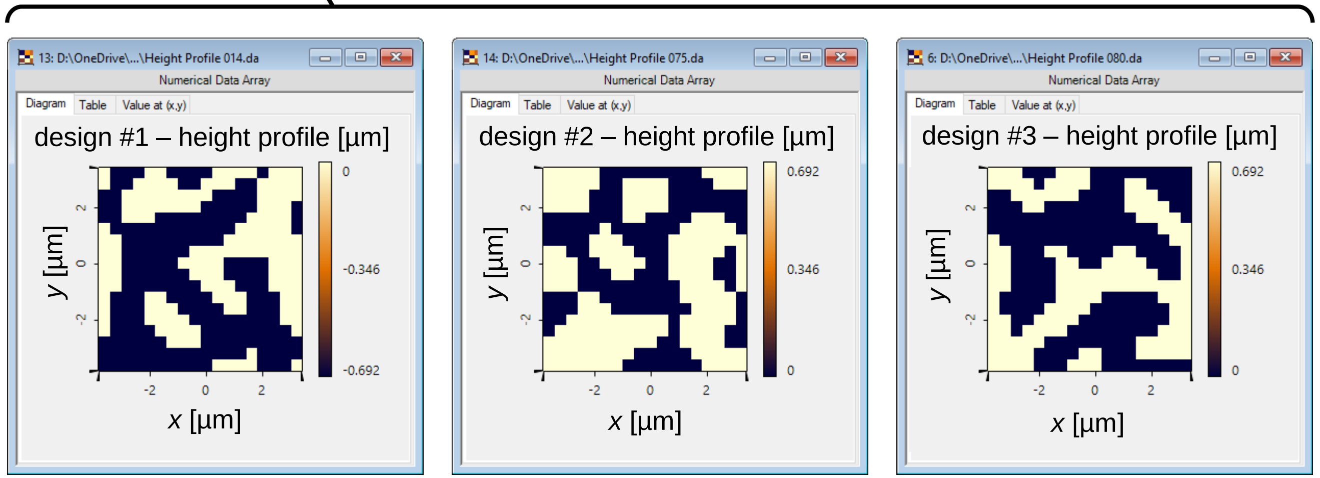
delivery of 100 designs within 20 seconds!

Results

- Structure design
  [with thin-element approximation (TEA)]

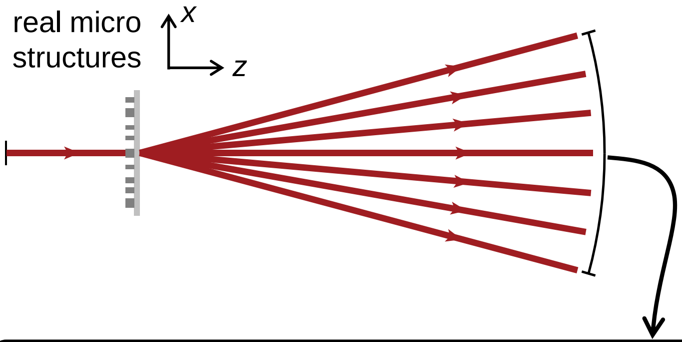


Automatic conversion from phase-only transmission to structure height profile, according to given wavelength and material.

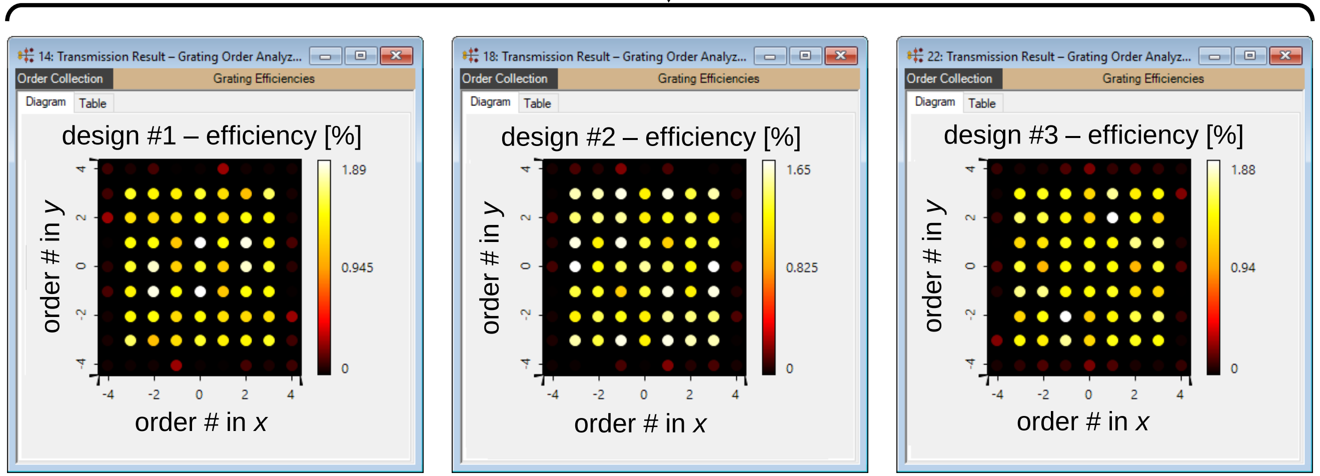


Results

- Performance evaluation with TEA



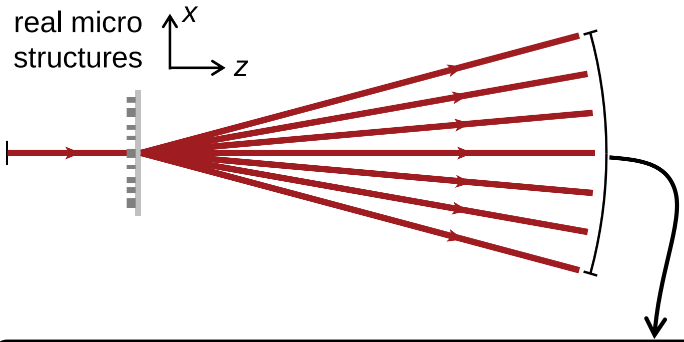
Merit functions	Design #1	Design #2	Design #3
total efficiency	69.057%	68.068%	69.613%
average efficiency	1.4093%	1.3892%	1.4207%
zeroth efficiency (zeroth order error)	1.4888% (5.6374%)	1.4888% (7.1723%)	1.4704% (3.5%)
uniformity error	14.422%	**12.266%**	12.989%



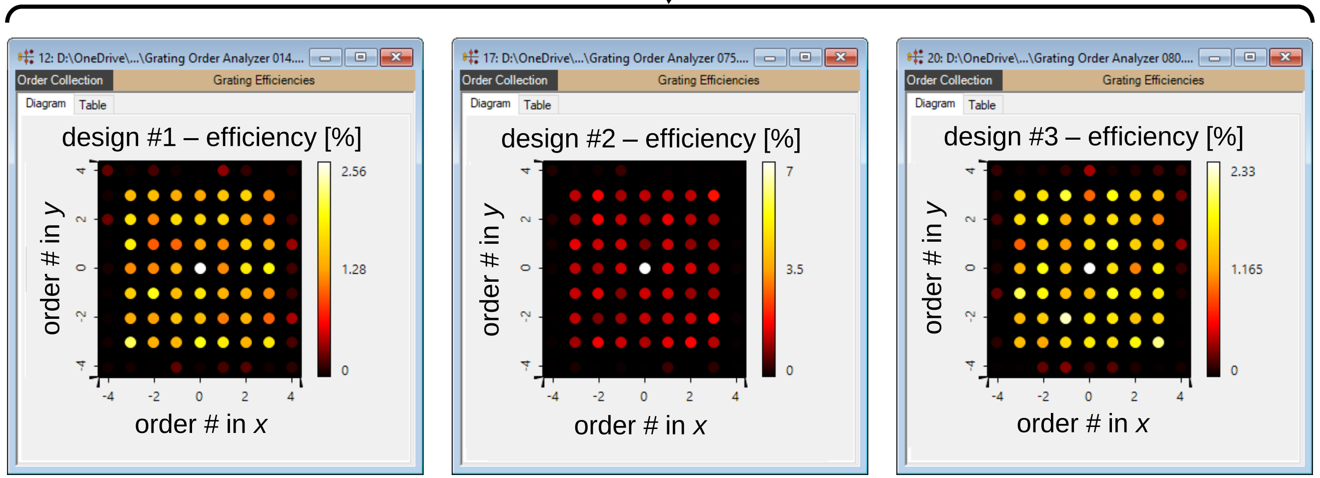
Design #2 seems to give the best uniformity, based on the evaluation results from thin-element approximation. But, is it still true for the non-paraxial situation?

Results

- Performance evaluation with Fourier modal method



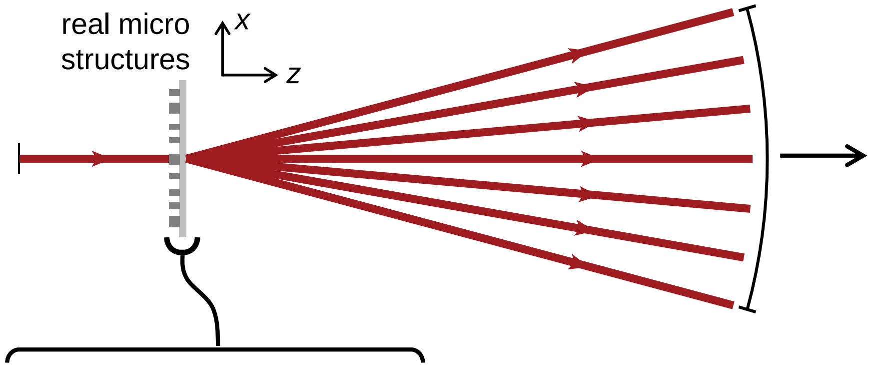
Merit functions	Design #1	Design #2	Design #3
total efficiency	72.122%	70.619%	74.311%
average efficiency	1.4719%	1.4412%	1.5165%
zeroth efficiency (zeroth order error)	2.5574% (73.753%)	7.011% (386.47%)	2.3324% (53.799%)
uniformity error	21.064%	**58.431%**	18.946%

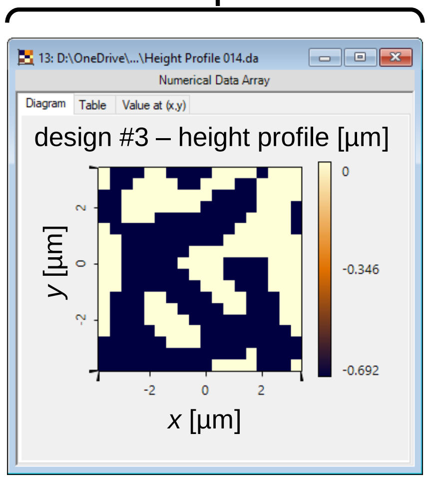


With the rigorous Fourier modal method (FMM), it turns out that design #2 produces strong zeroth diffraction order, resulting in very poor uniformity in fact.

Results

- Further optimization – zeroth order tuning



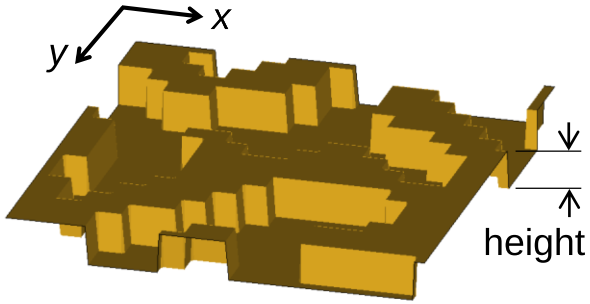


FMM evaluation results

Merit functions	Design #3
total efficiency	74.311%
average efficiency	1.5165%
zeroth efficiency (zeroth order error*)	**2.3324% (53.799%)**
uniformity error	18.946%

Design #3 gives good overall performance but still produces undesired zeroth order error.

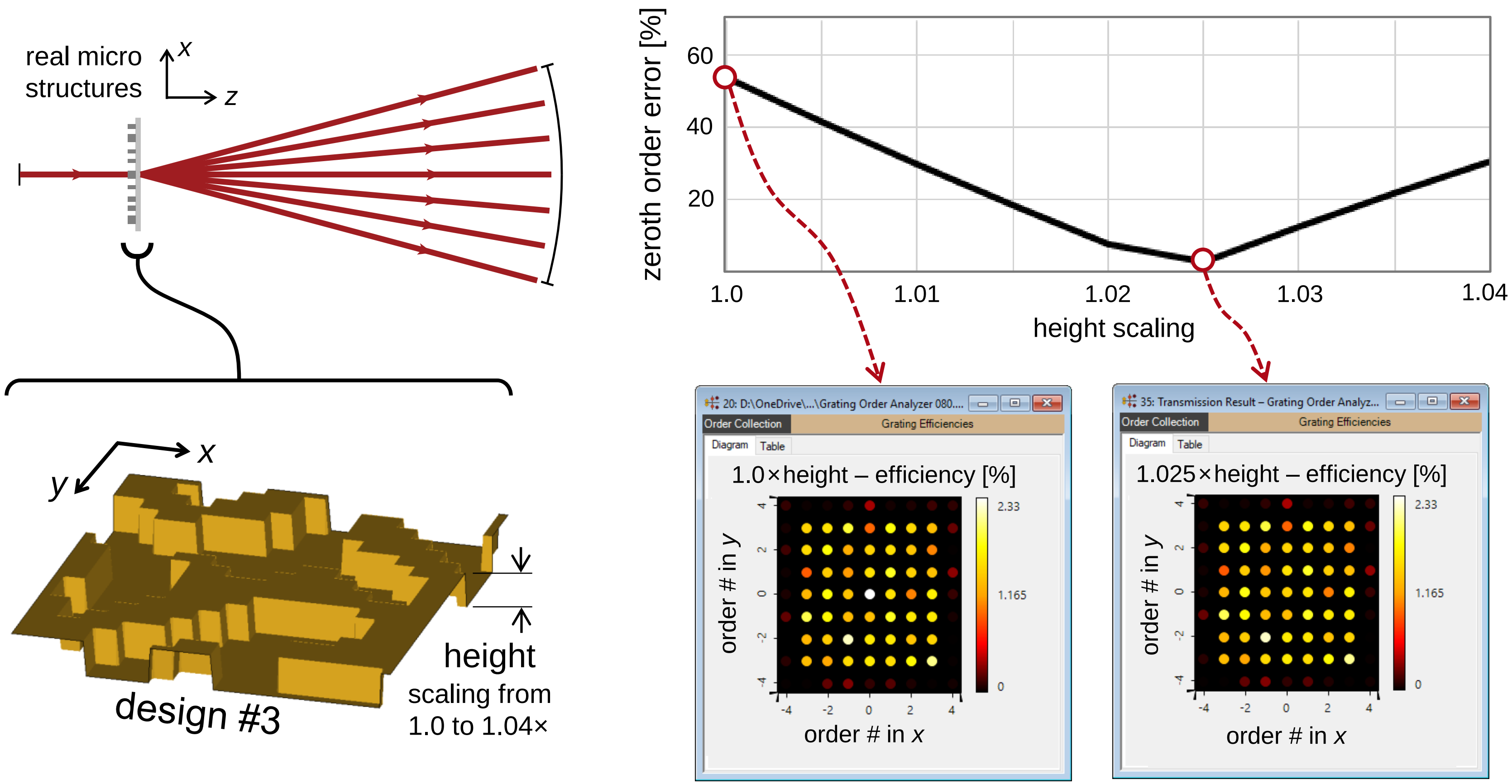
$$*\text{zeroth order error} = \frac{\text{zeroth efficiency} - \text{average efficiency}}{\text{average efficiency}}$$



Sometimes, the zeroth order error can be reduced by tuning the height of the binary structure.

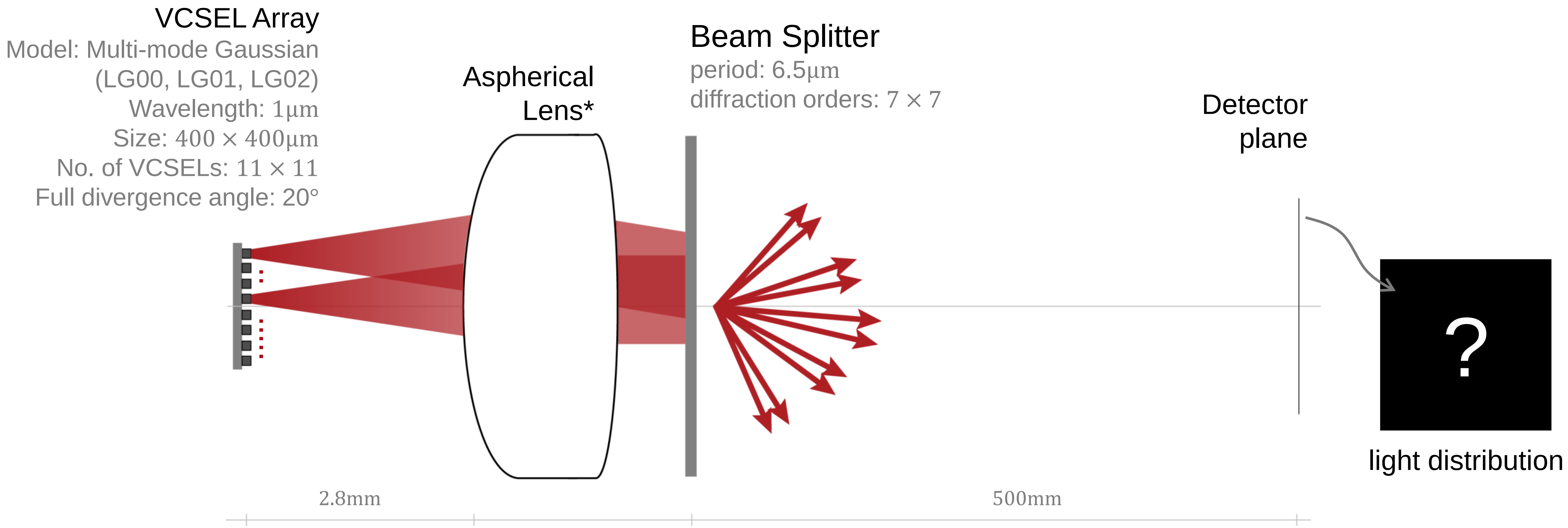
Results

- Further optimization – zeroth order tuning



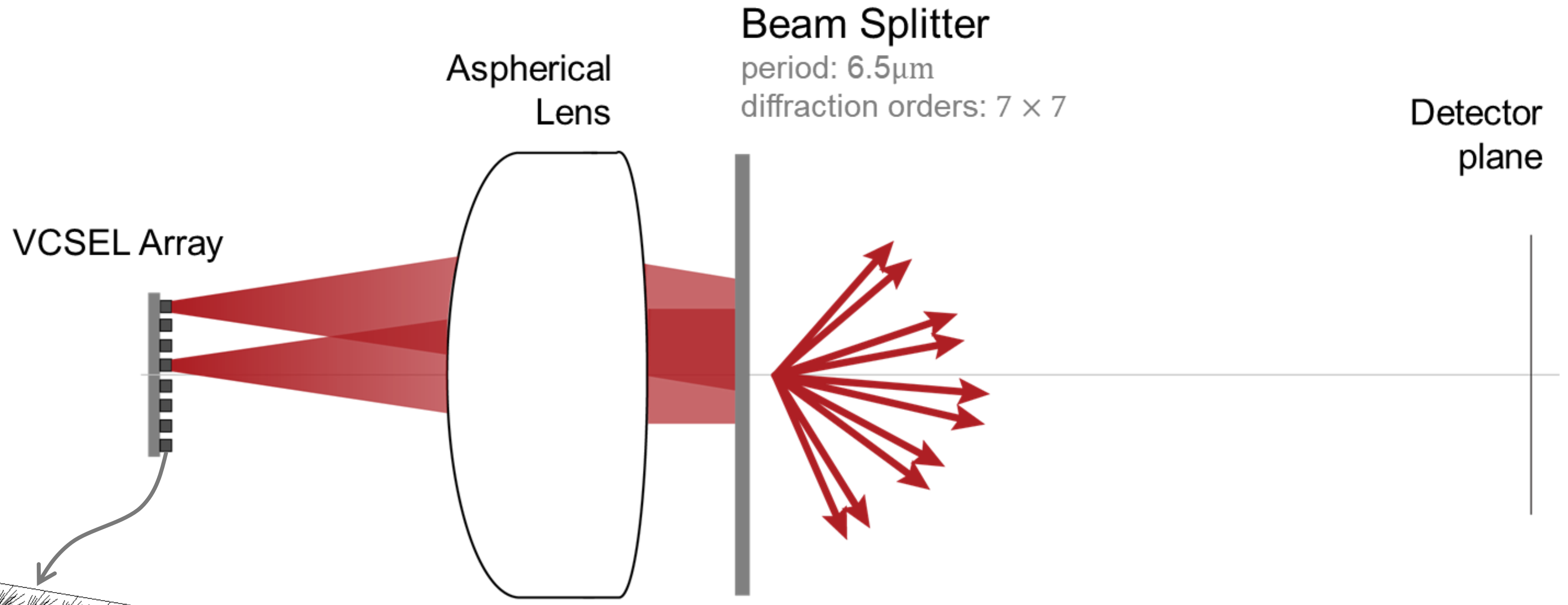
Working Principle Demonstration of the Dot Projector with Physical Optics Modeling

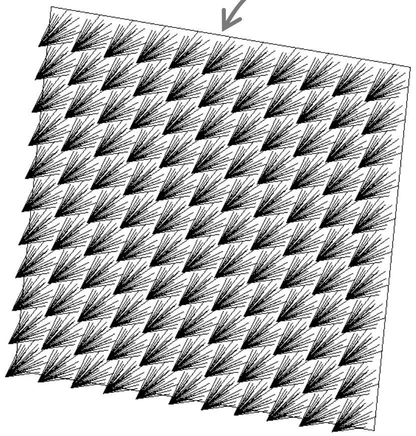
Modeling Task



* The aspherical lens in the document is designed with OpticStudio

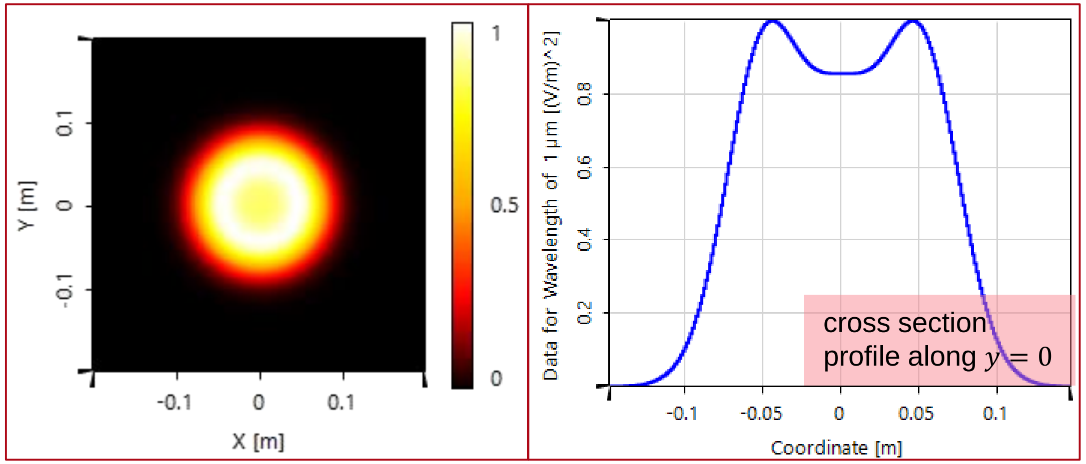
Source Modeling



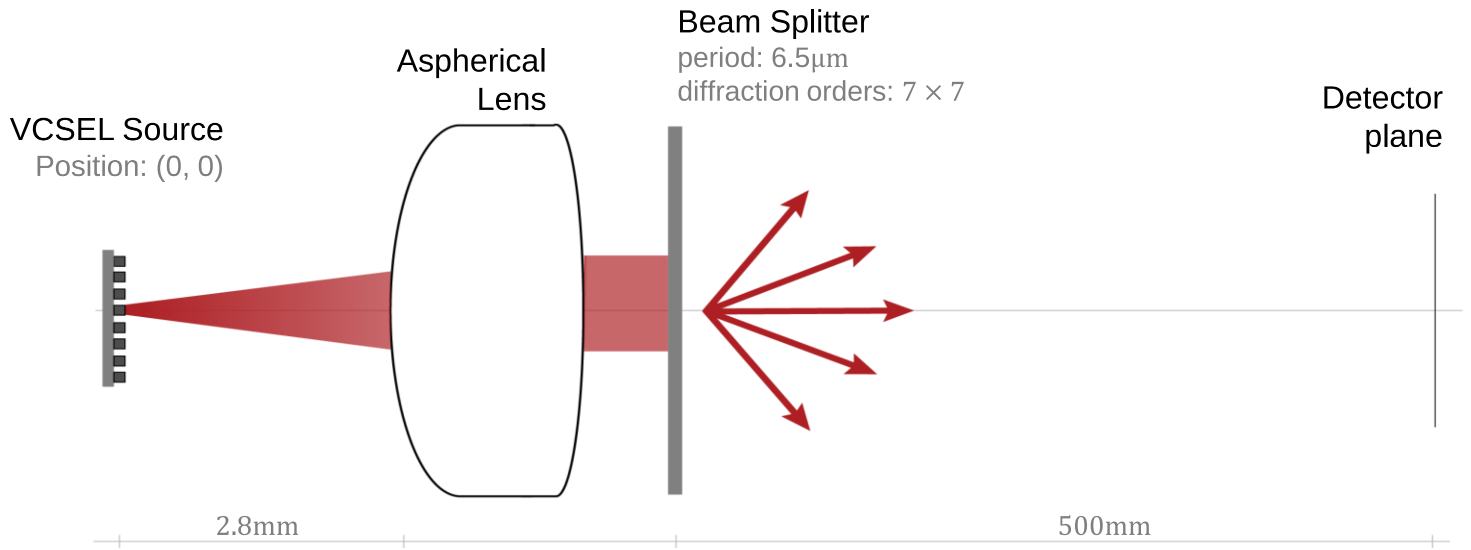


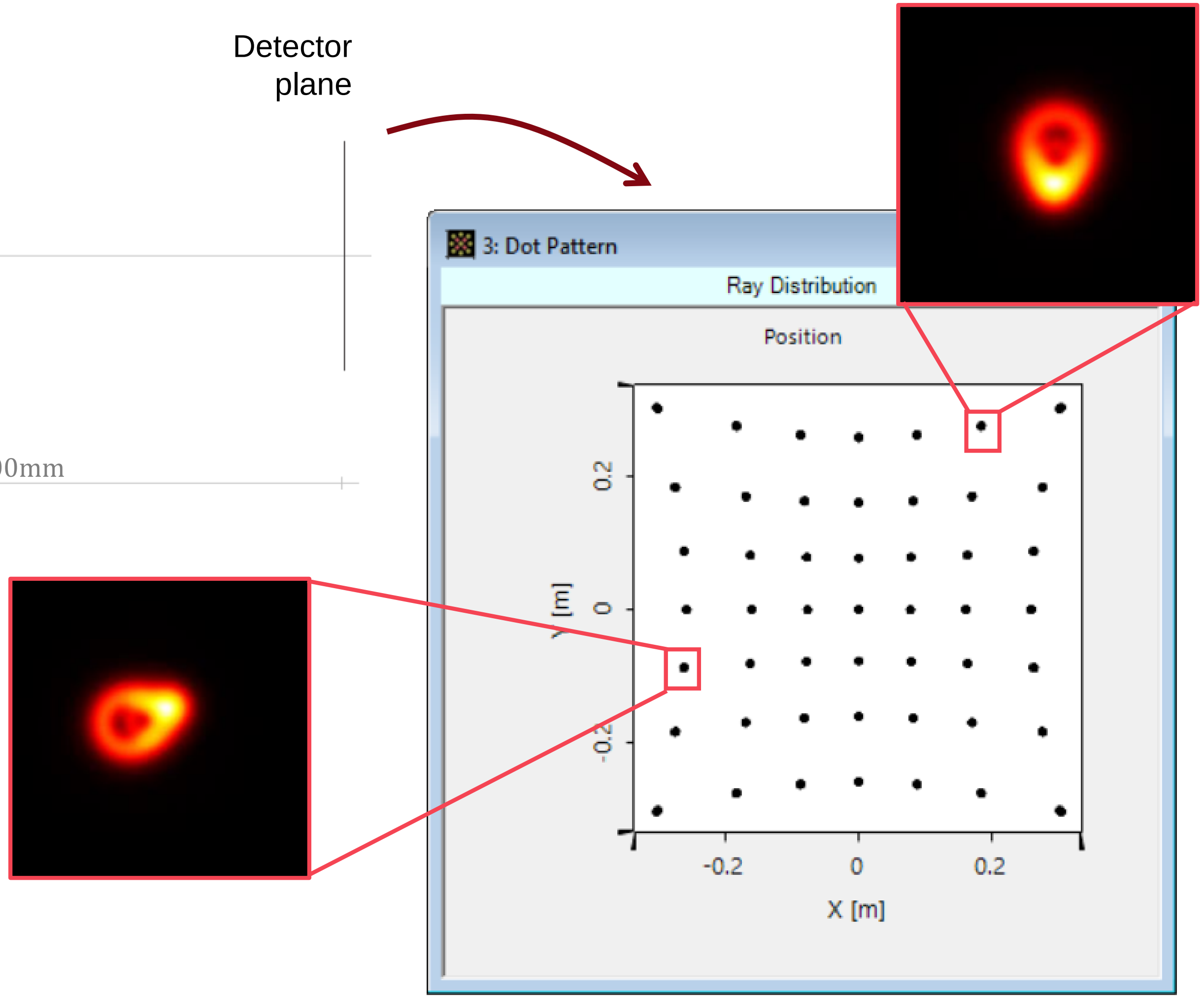
sketch of the arranged VCSEL array

Far field pattern of a single VCSEL



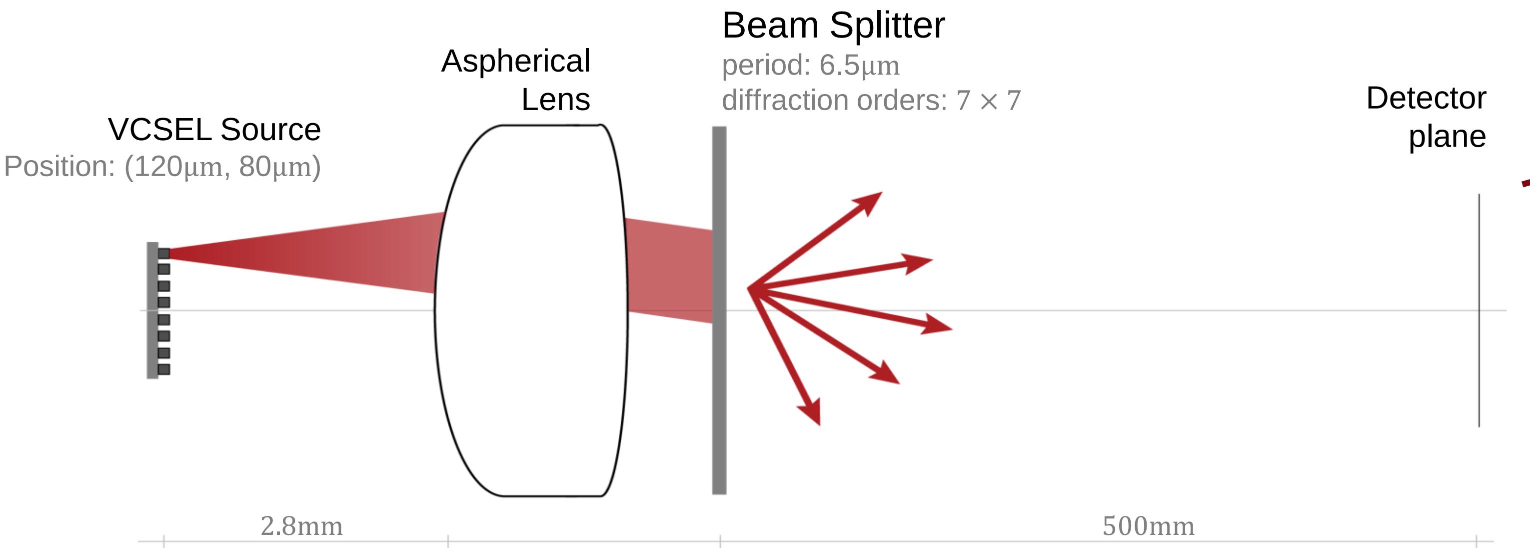
Simulation with the On-axis VCSEL

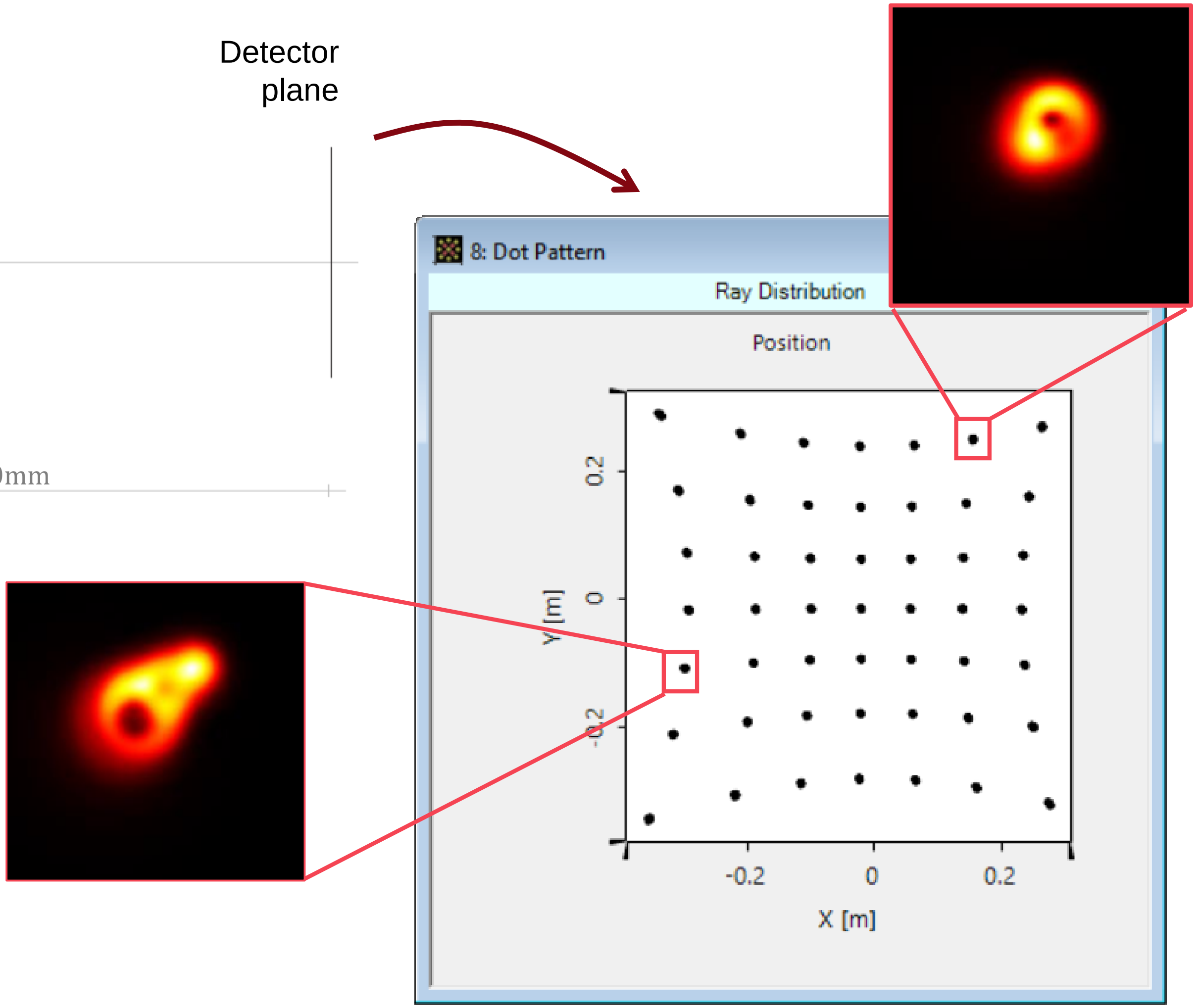




- The lens is applied to collimating the input beam
- The beam splitter diffracts the beam into different orders, and irradiance pattern of the orders is obtained on detector plane

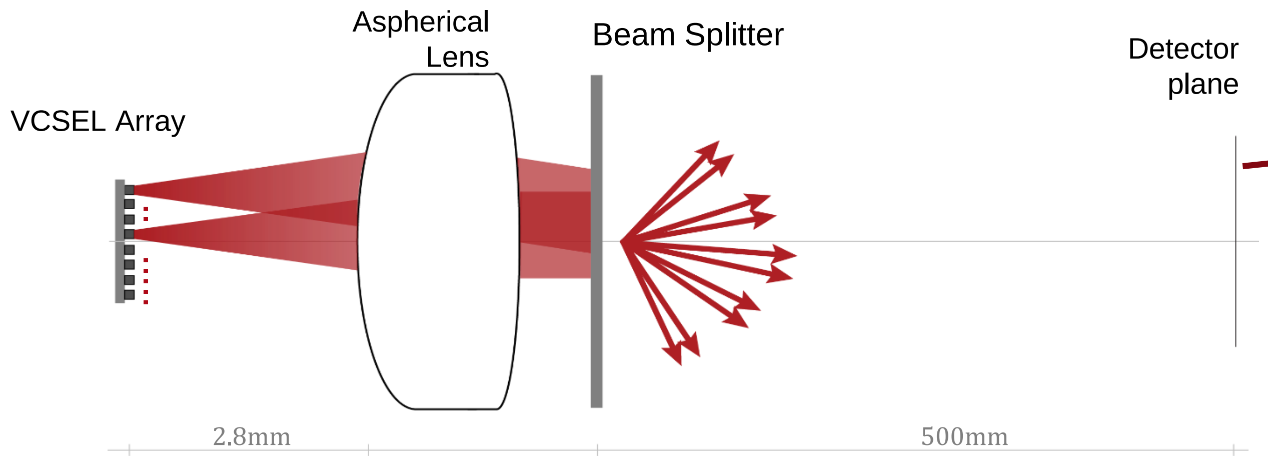
Simulation with an Off-axis VCSEL





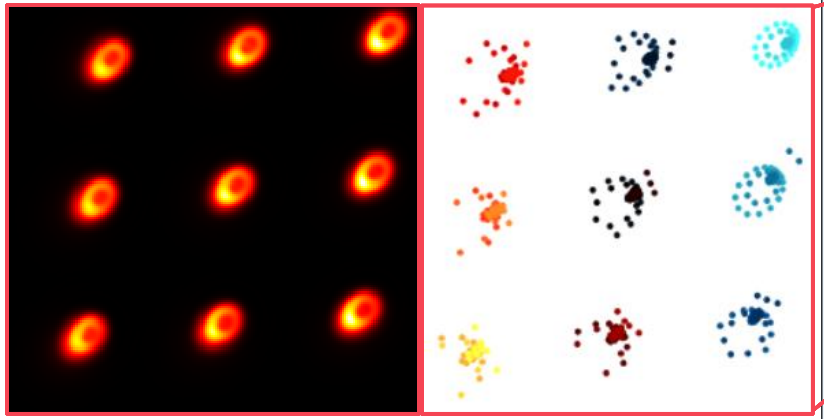
- For off-axis VCSEL, the lens collimates the input beam with an angle regarding to the mode's position
- The irradiance pattern is shifted from the on-axis case, with respect to the collimated angle of the beam.

Simulation with All Modes of the VCSEL Array



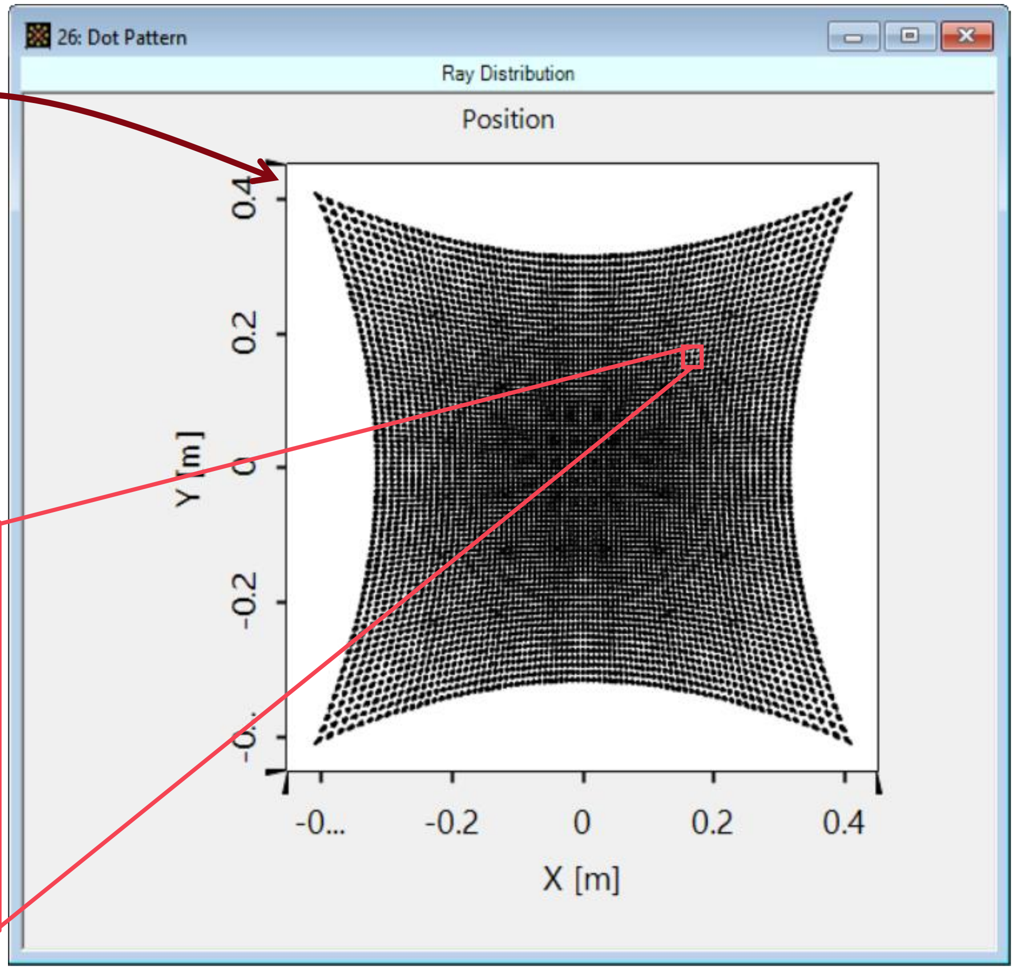
Simulation results

The beam splitter duplicates the irradiance pattern of different VCSELs with a lateral shifted on detector plane, and the whole dot pattern is generated.



Field Tracing

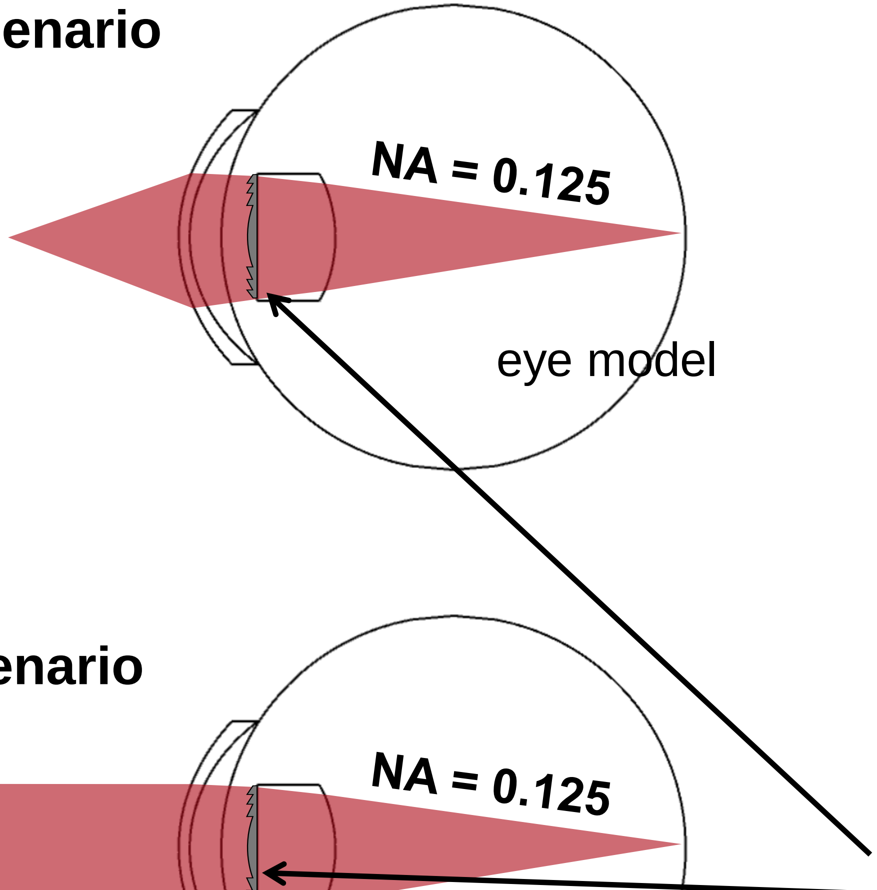
Ray Tracing



Design and Analysis of Intraocular Diffractive Lens

Design Task for a Diffractive Lens

Near View Scenario

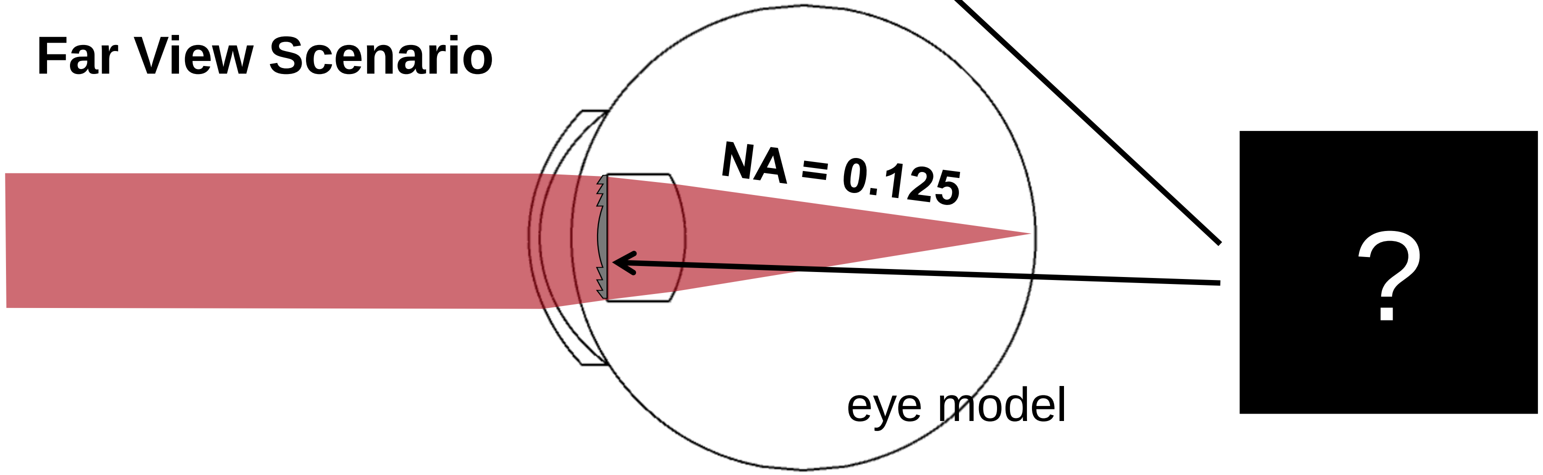


Each configuration of the two intraocular lens requires a certain wavefront surface response function.

$$\Delta\psi(\rho) = m\Delta\psi(\rho)$$

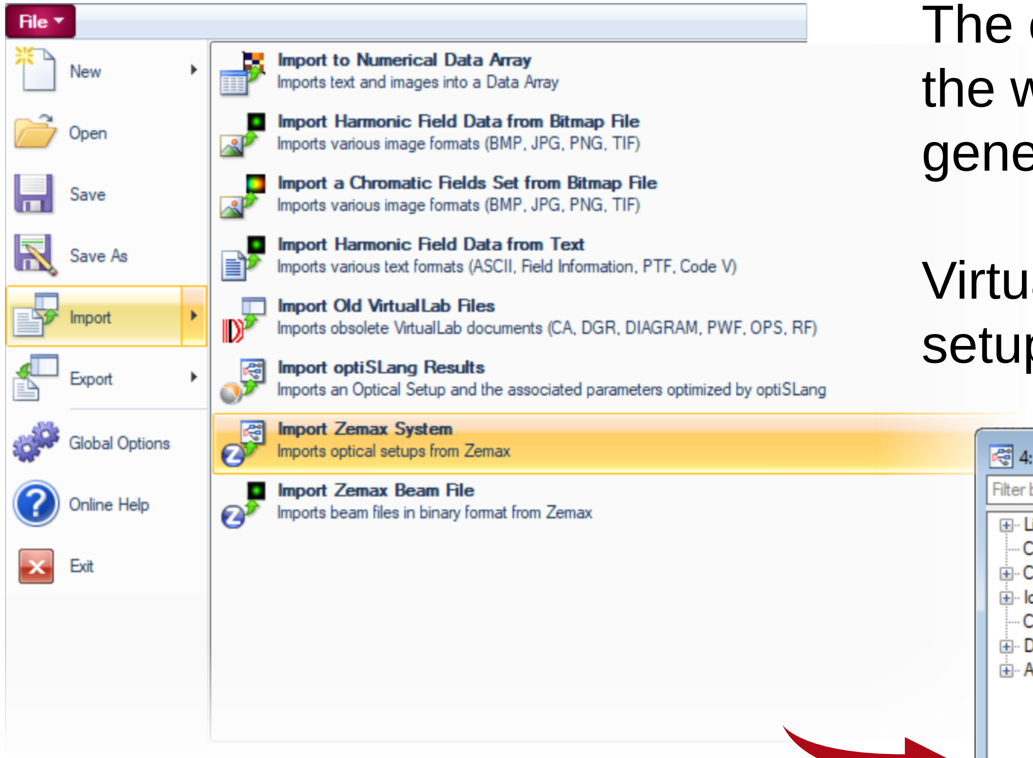
Where $m = 0$ for the far view scenario and $m = 1$ for the near view scenario

Far View Scenario



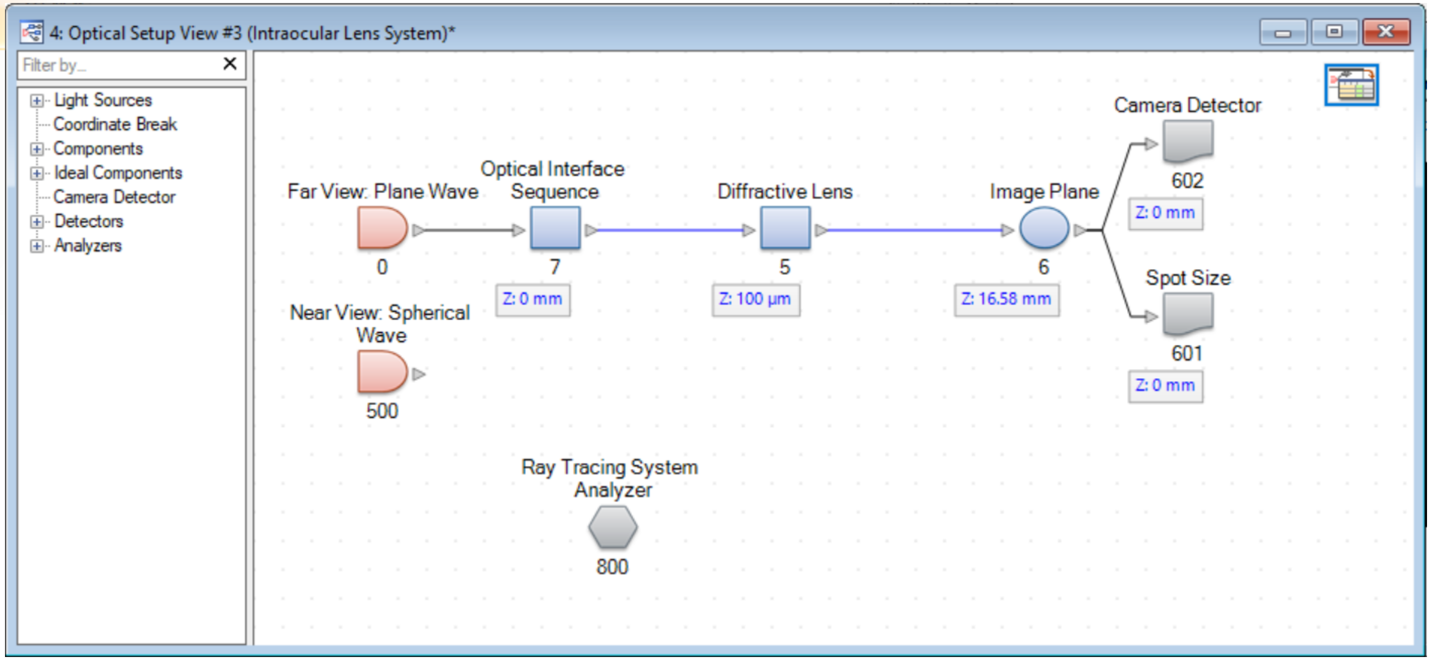
How to design a diffractive lens to achieve different wavefront effects for the two configurations?

Import of Optical System from OpticStudio



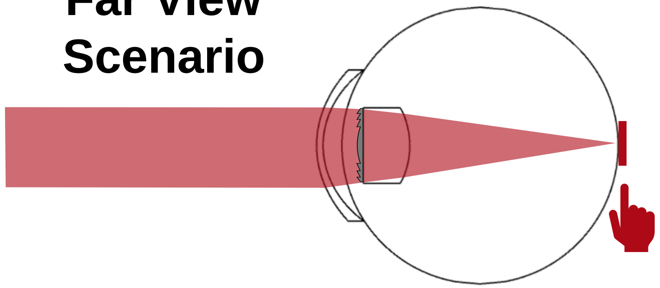
The configuration of the optical setup as well as the design of the wavefront surface response by a Binary-2 surface was generated in OpticSudio.

VirtualLab Fusion provides the capability to import the optical setups and merge them in a single optical setup configuration.

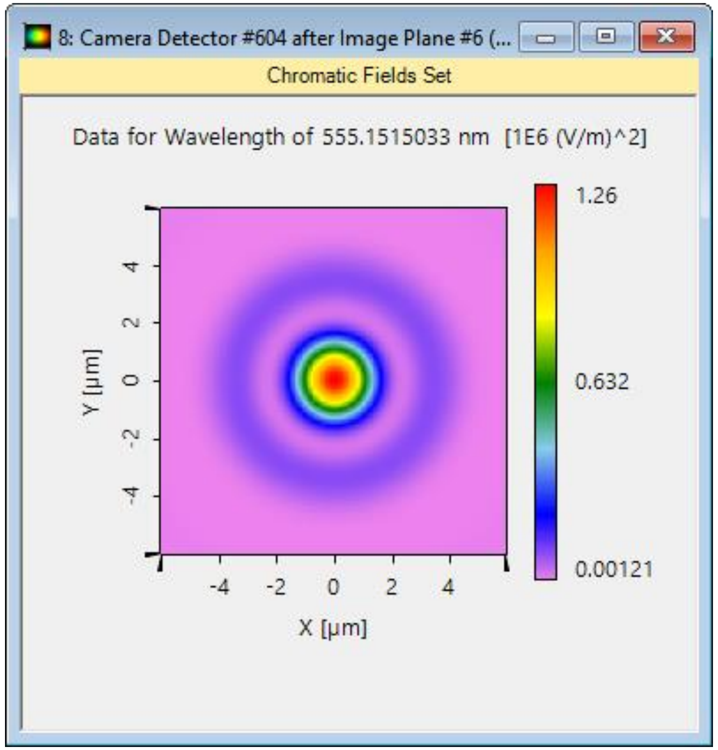


Far View: Conformity of OpticStudio Import

Far View Scenario

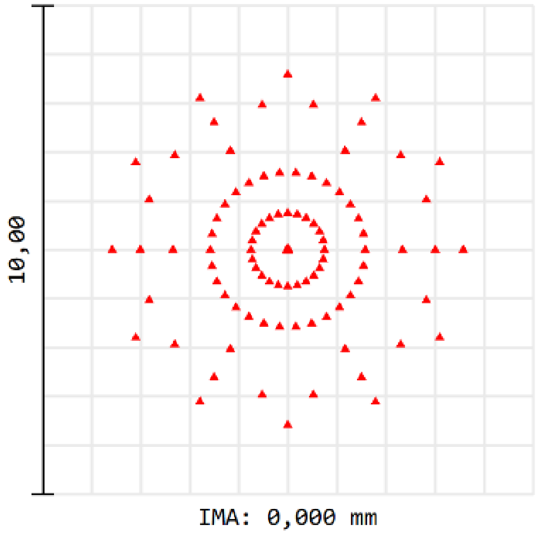


PSF calculation with the wavefront surface response by **VirtualLab Fusion**

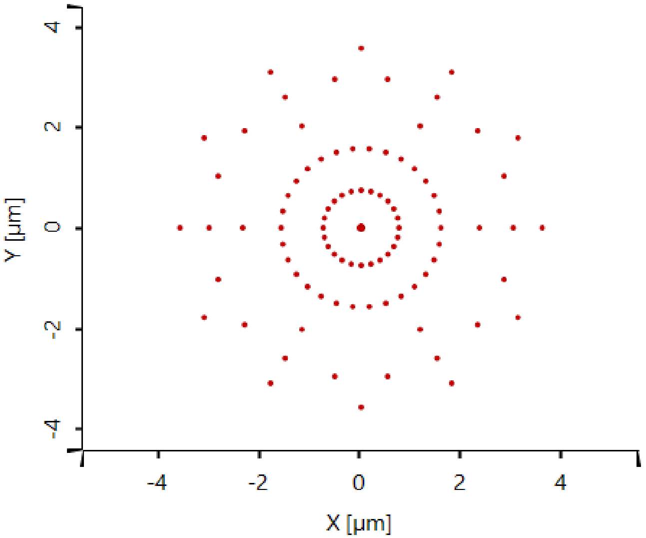


spot diagram of central wavelength (555 nm) calculated by:

OpticStudio

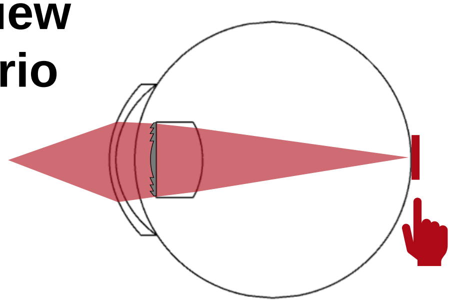


VirtualLab Fusion

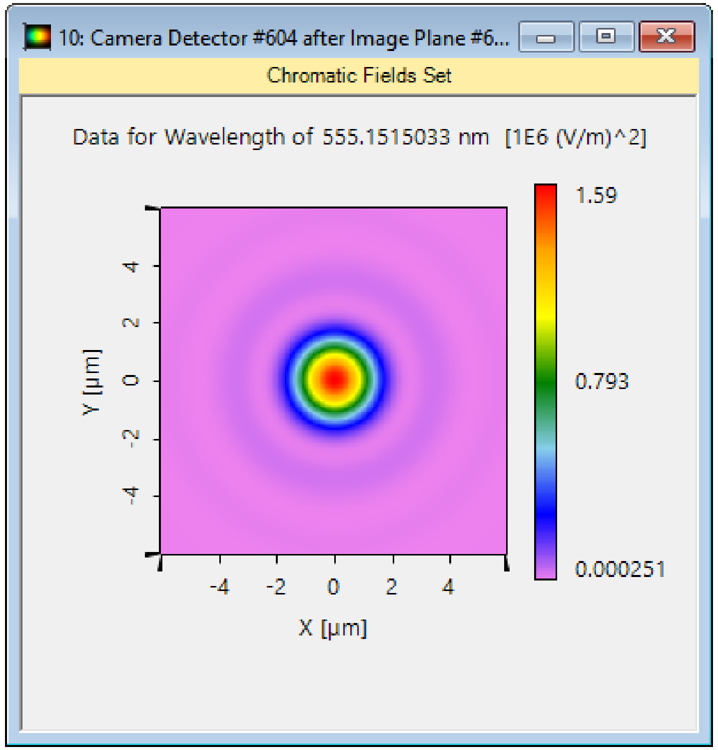


Near View: Conformity of OpticStudio Import

Near View Scenario

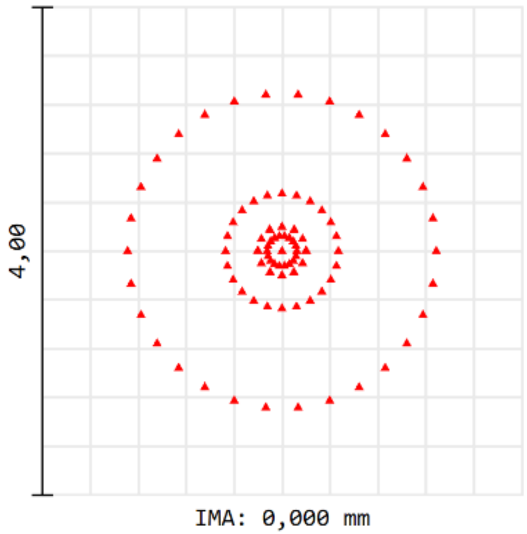


PSF calculation with the wavefront surface response by **VirtualLab Fusion**

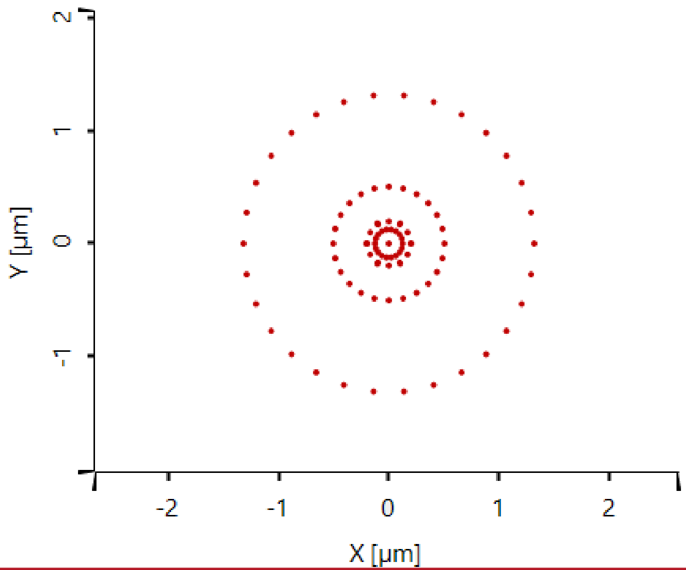


spot diagram of central wavelength (555 nm) calculated by:

OpticStudio



VirtualLab Fusion



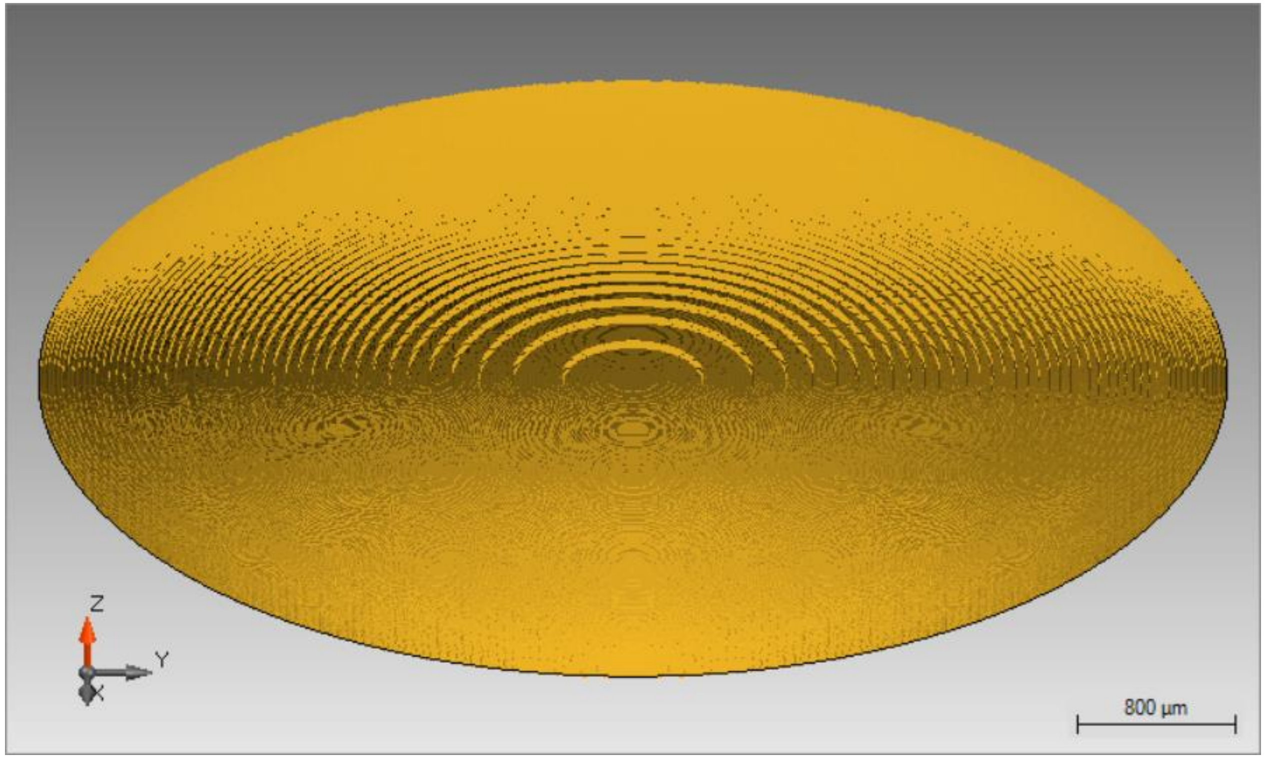
Structure Design: Diffractive Lens Profile Height

- The structure profile of the diffractive lens is calculated by Thin Element Approximation (TEA) according to the wavefront surface response:

$$h^{\mathrm{DOE}}(\rho) = \beta \frac{\lambda}{2\pi\Delta n} \Delta\psi(\rho)^{\mathrm{DOE}}$$

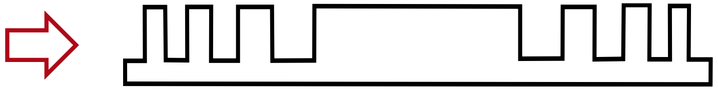
  with a scaling factor β to modulate the height and control the efficiency of the diffraction orders

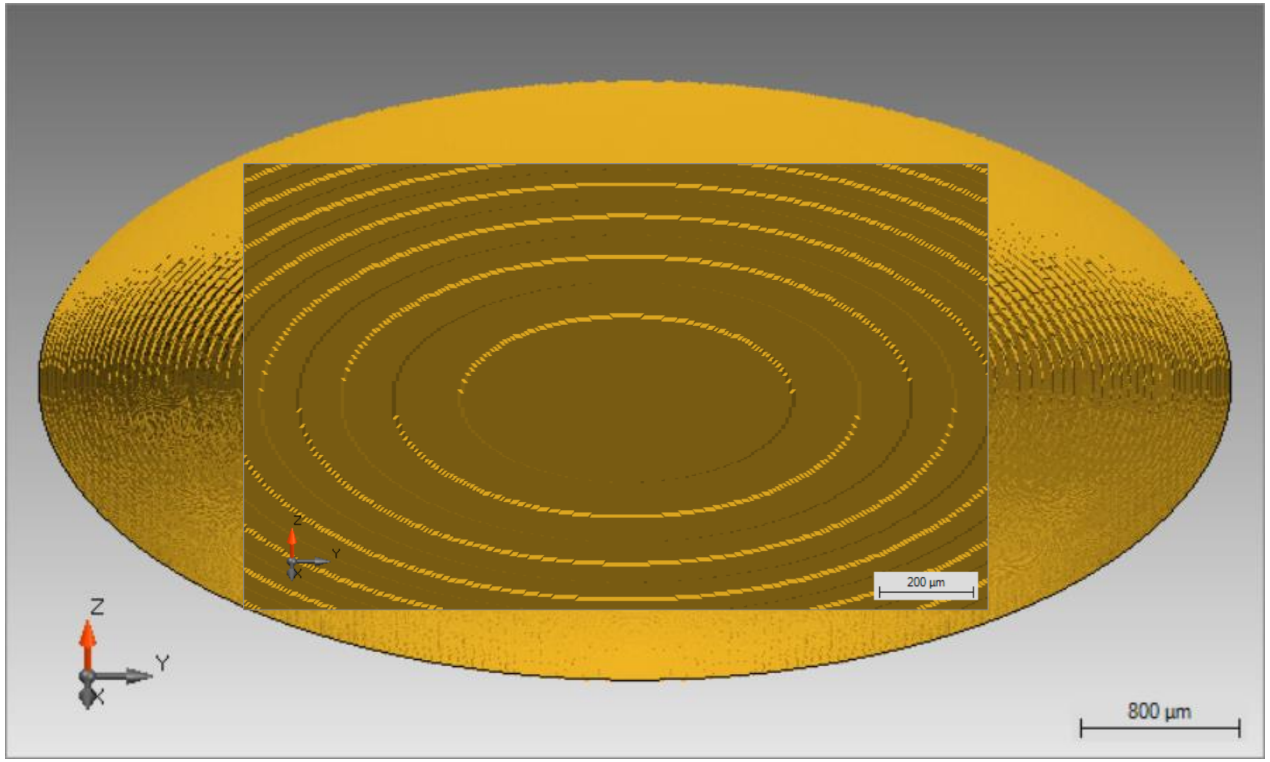
TEA provides directly a very high efficiency for the 1^{st} order



Structure Design: Diffractive Lens Profile Height

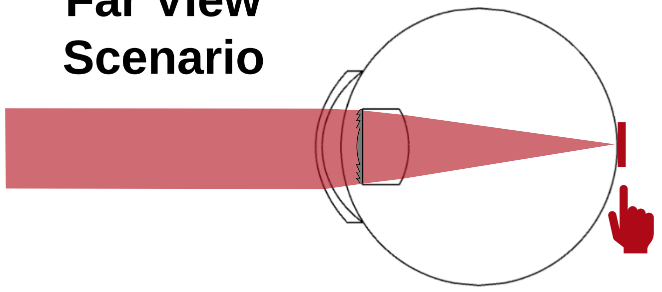
- A quantization of the structure with 2 height levels is chosen because the binary diffractive lens
  - is beneficial for manufacturing (cost, easier to fabricate)
  - gives a better control of the efficiencies especially for the 0th and 1st order using the height modulation approach



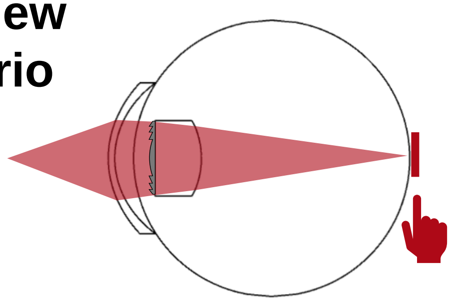


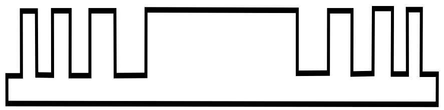
Structure Design: Height Modulation of 1.00

Far View Scenario



Near View Scenario

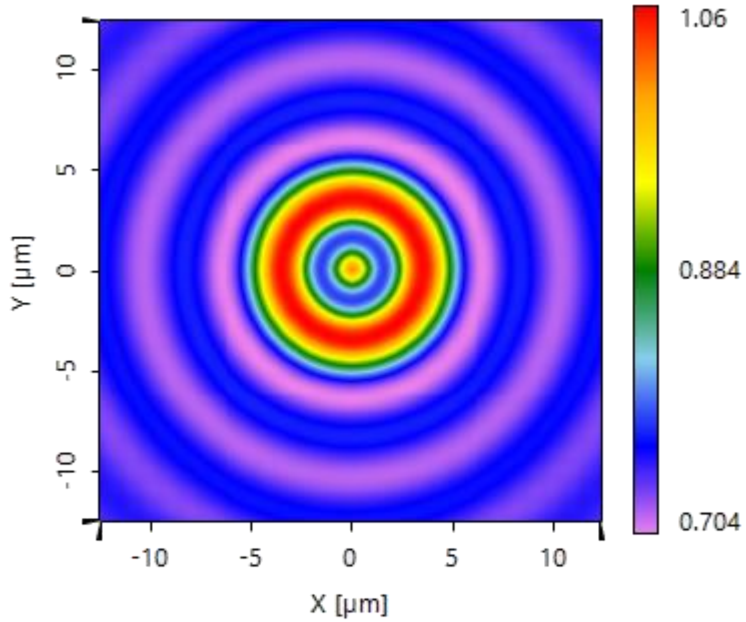




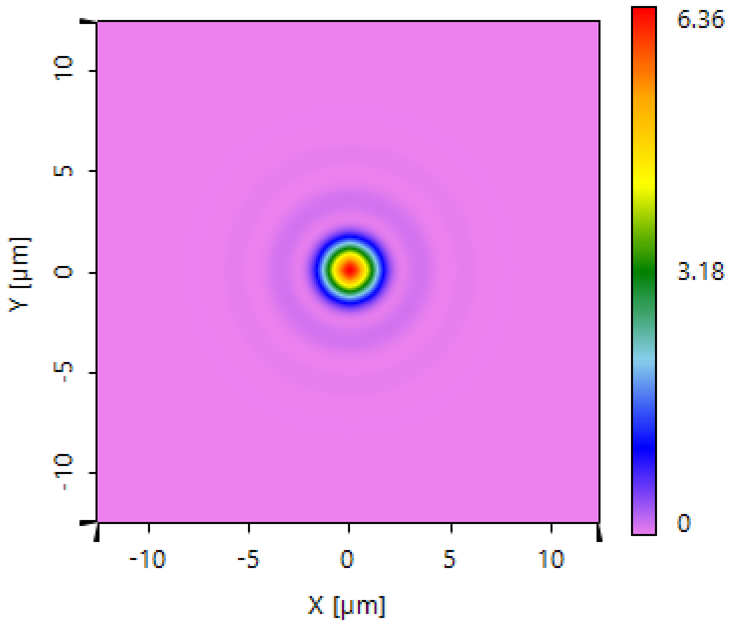
scaling of modulation height by

$\boldsymbol{\beta = 1.00}$

$\propto$ Electric Energy Density $[1E2\,(V/m)^2]$

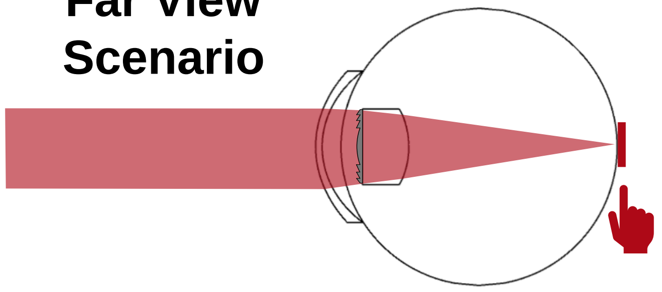


$\propto$ Electric Energy Density $[1E5\,(V/m)^2]$

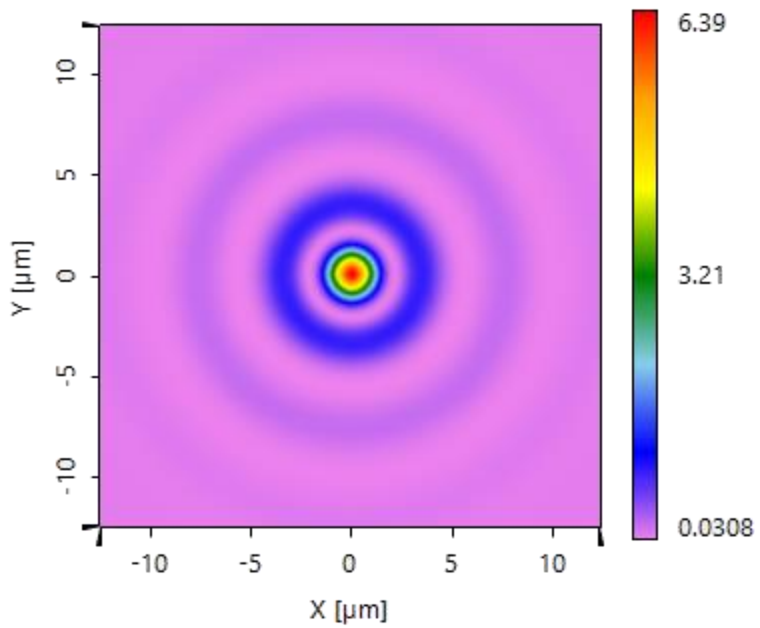


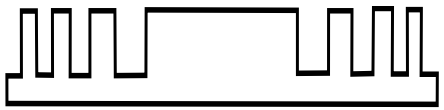
Structure Design: Height Modulation of 0.95

Far View Scenario



$\propto$ Electric Energy Density [1E3 $(V/m)^2$]

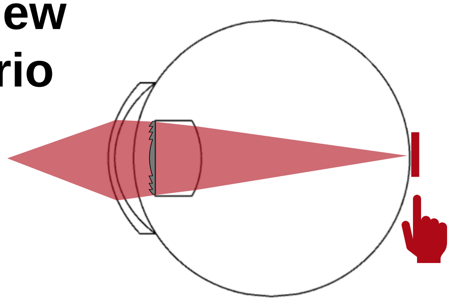




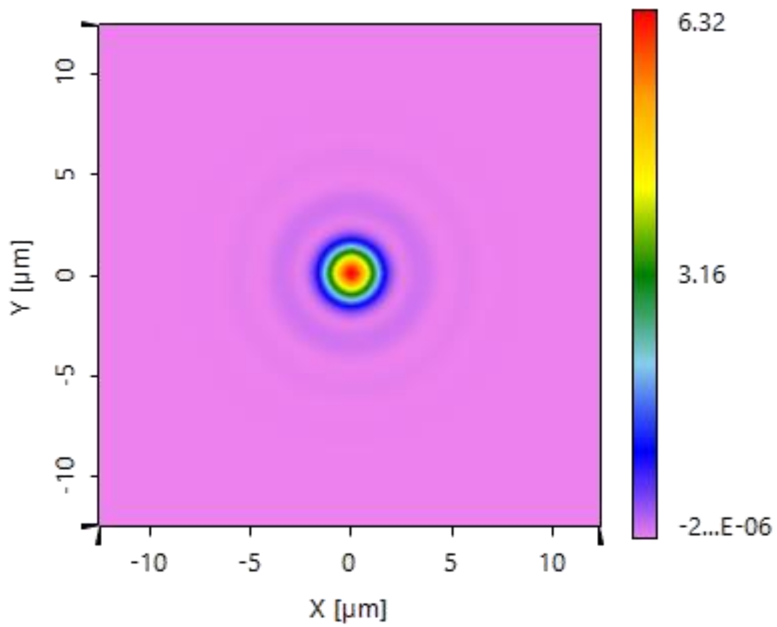
scaling of modulation height by

$\boldsymbol{\beta = 0.95}$

Near View Scenario

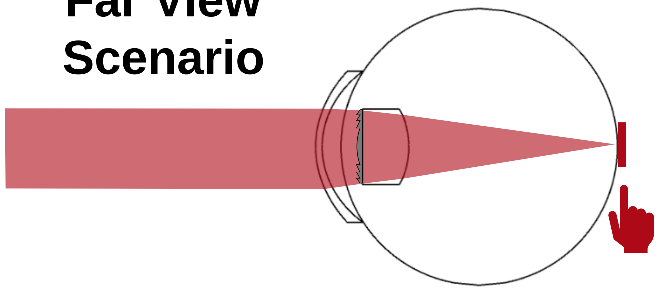


$\propto$ Electric Energy Density [1E5 $(V/m)^2$]

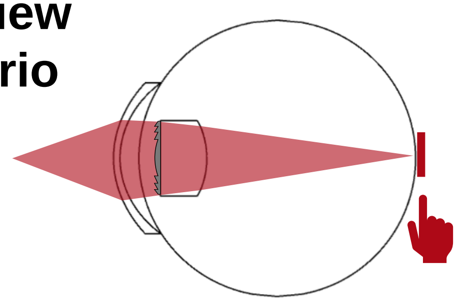


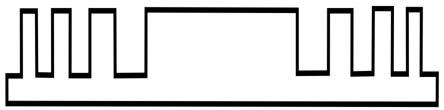
Structure Design: Height Modulation of 0.90

Far View Scenario



Near View Scenario

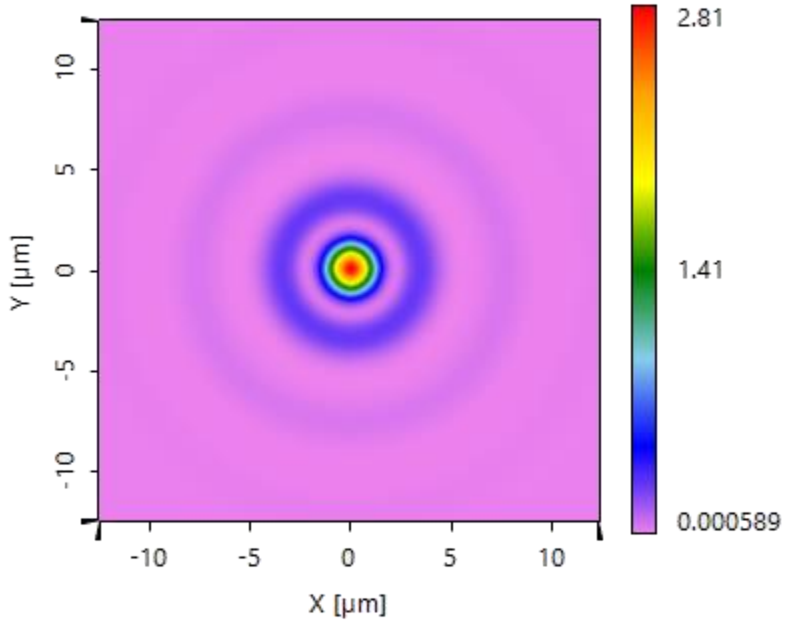




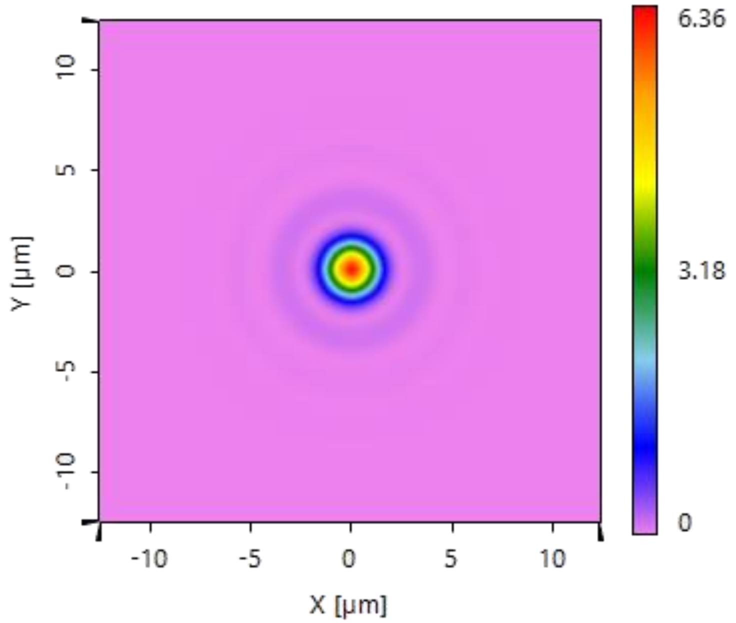
scaling of modulation height by

$\boldsymbol{\beta = 0.90}$

$\propto$ Electric Energy Density $[1E4\,(V/m)^2]$



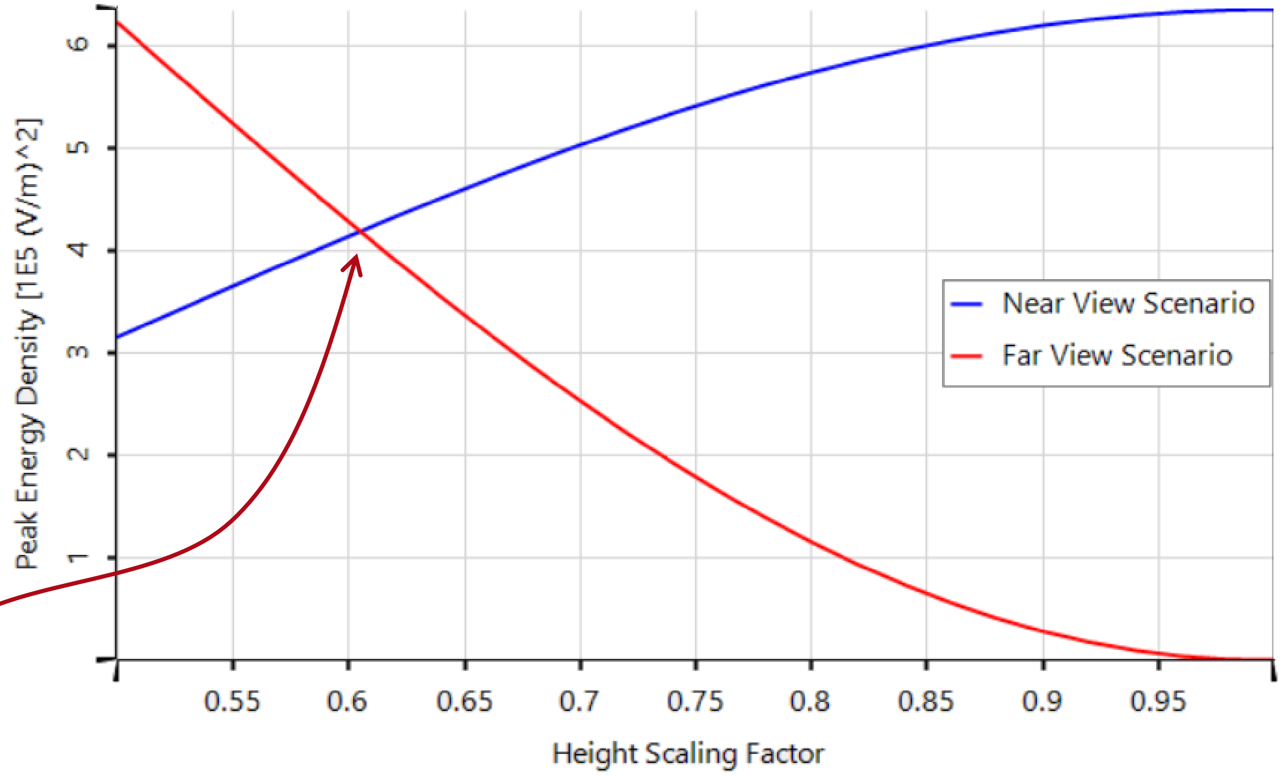
$\propto$ Electric Energy Density $[1E5\,(V/m)^2]$



Structure Design: Find the Optimum Scaling Factor

- As a goal, the peak energy density of the foci for both far view and near view scenario shall be the same.

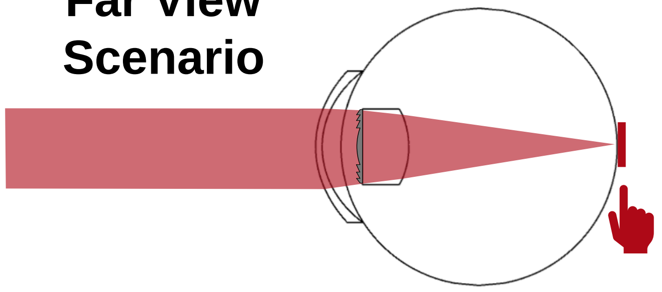
- Therefore, the peak energy density is calculated with respect to the height scaling factor for both scenarios.



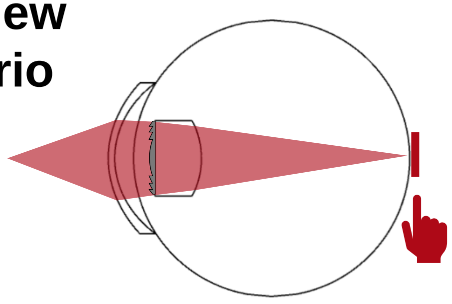
Optimum of the scaling factor for equivalent peak energy density for both foci (near and far view)

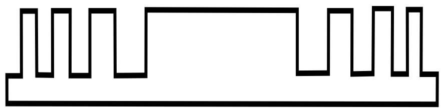
Structure Design: Optimum Height Modulation of 0.605

Far View Scenario



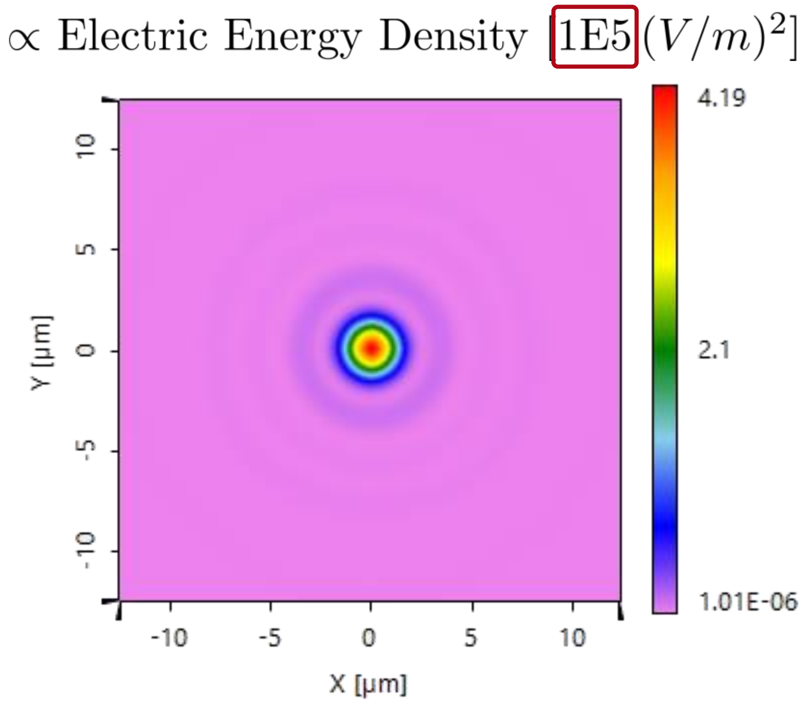
Near View Scenario





scaling of modulation height by

$\boldsymbol{\beta = 0.605}$



Goal of equivalent maximum energy density for both foci achieved!

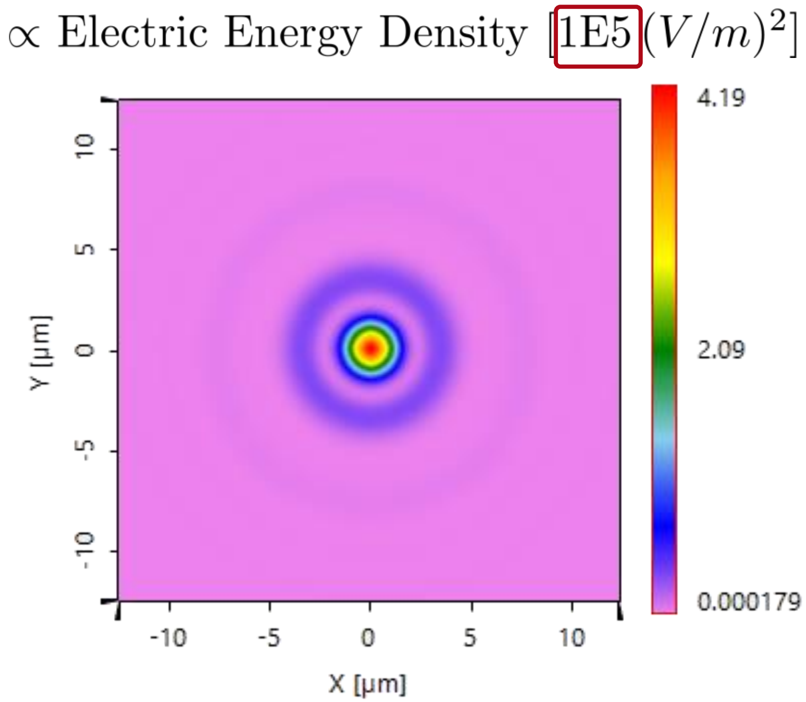
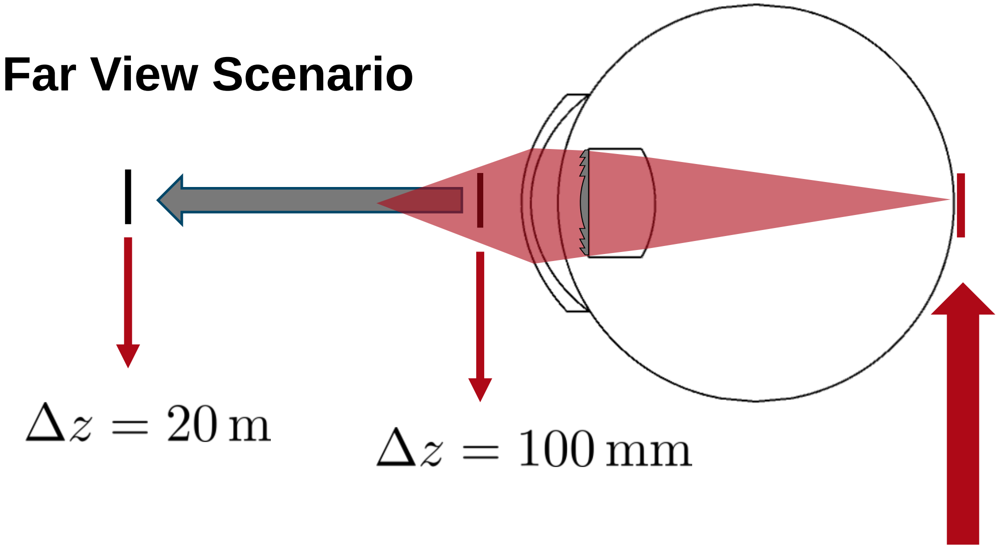
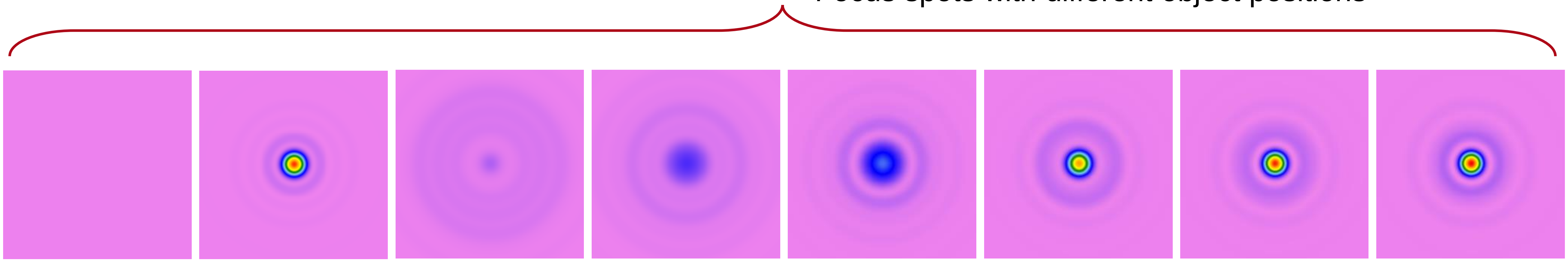


Illustration of Focus Development from Near to Far Region

Near to Far View Scenario



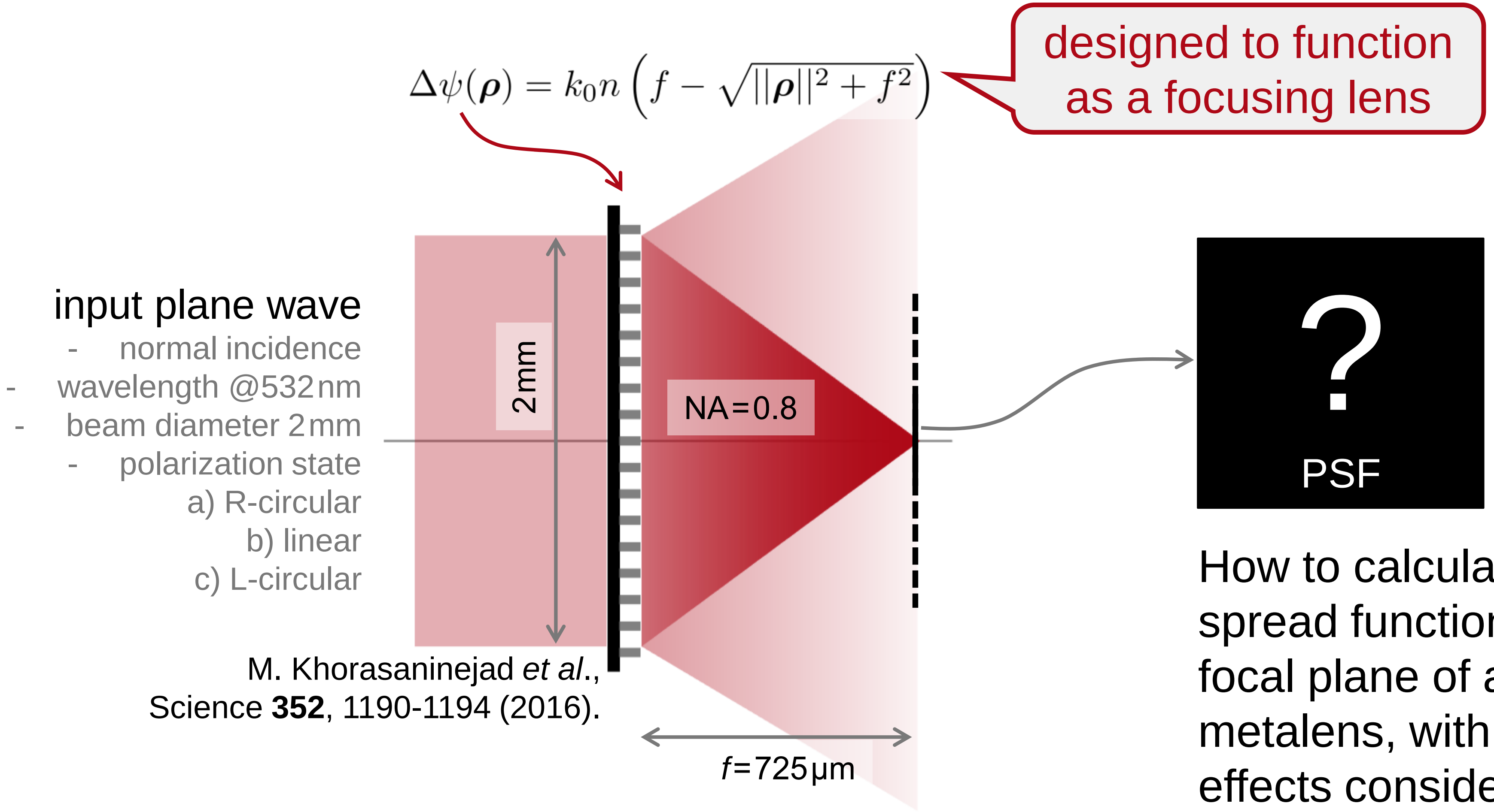
Focus spots with different object positions



$\Delta z = 100\mathrm{mm}$ 250mm 500mm 3m 5m 10m 15m 20m

Modeling of a Metalens Singlet Based on Half-Wave Plate Model

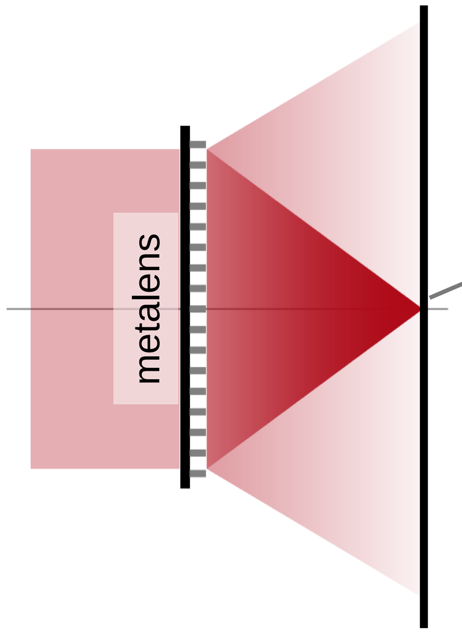
Modeling Task



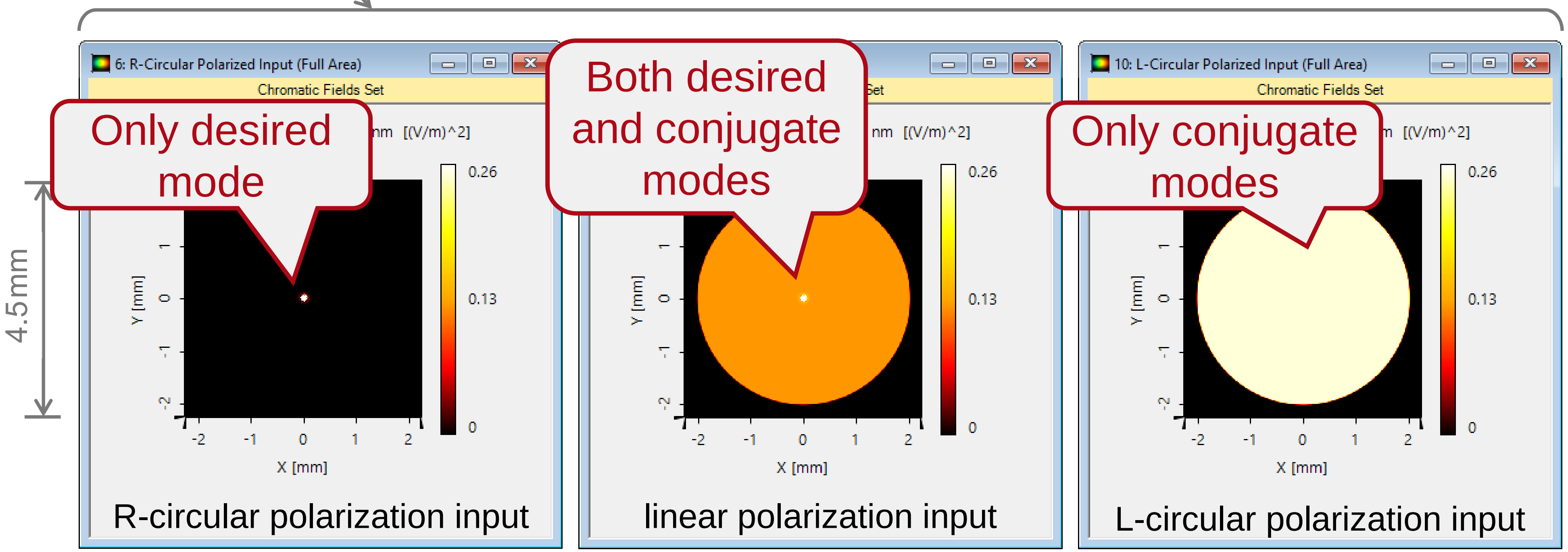
M. Khorasaninejad *et al.*, Science **352**, 1190-1194 (2016).

How to calculate the point spread function (PSF) at the focal plane of a nano-fin type metalens, with polarization effects considered?

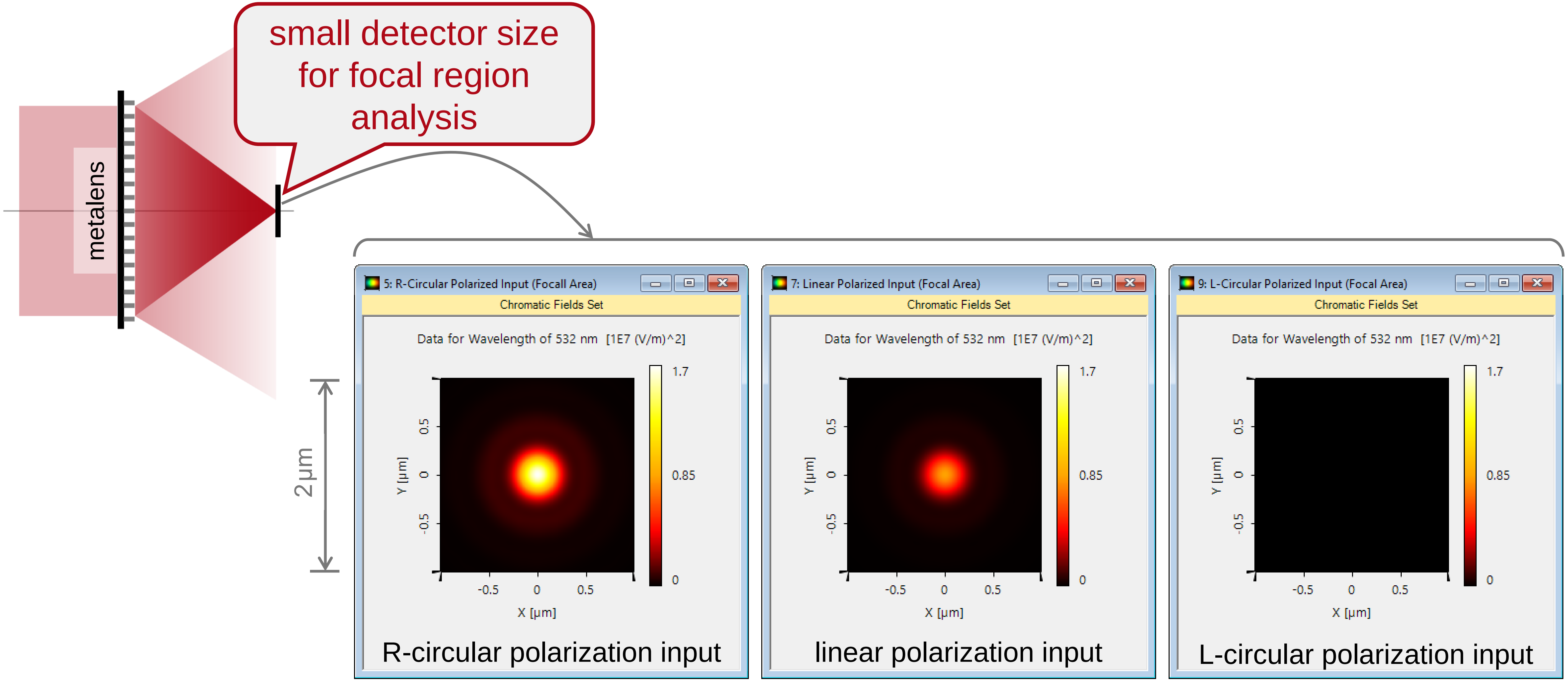
Simulation Results on Whole Detector Plane



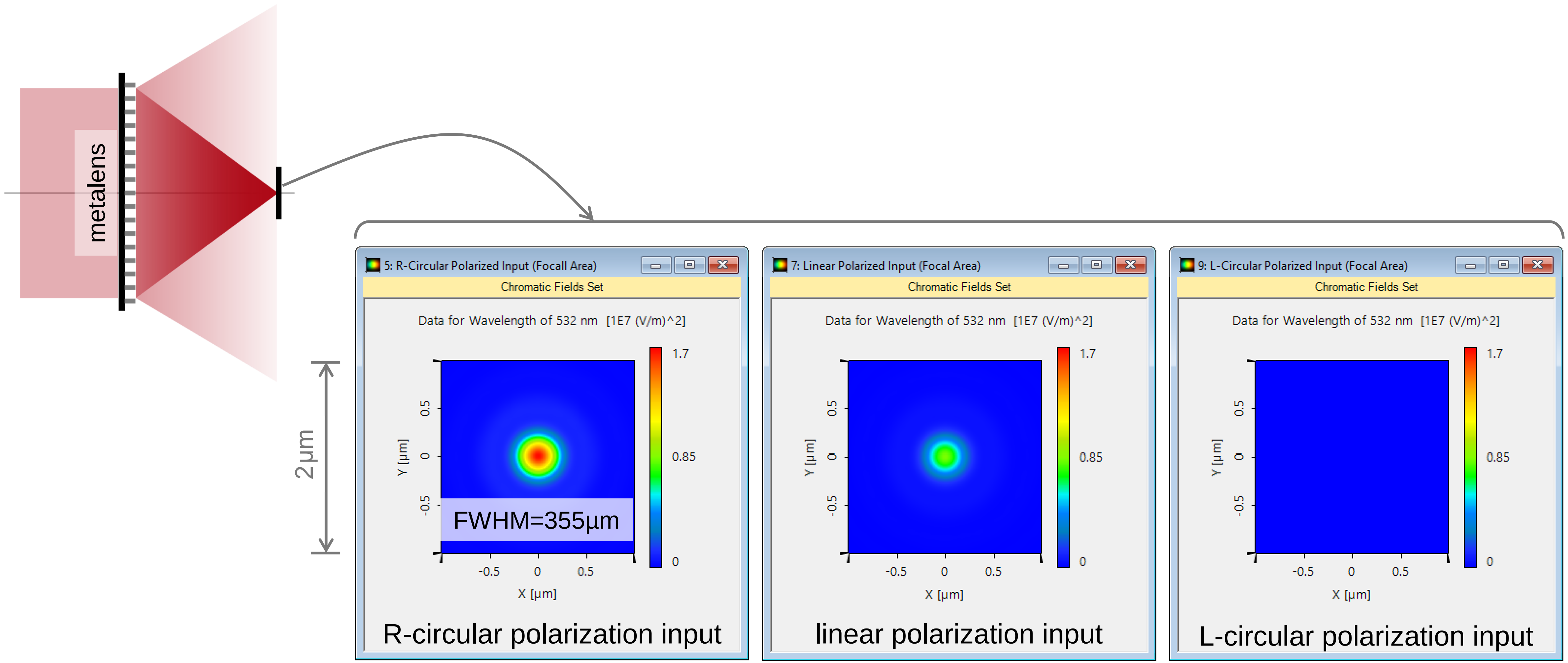
Behavior of the metalens obviously depends on the polarization states of the input fields.



Focal Area Analysis

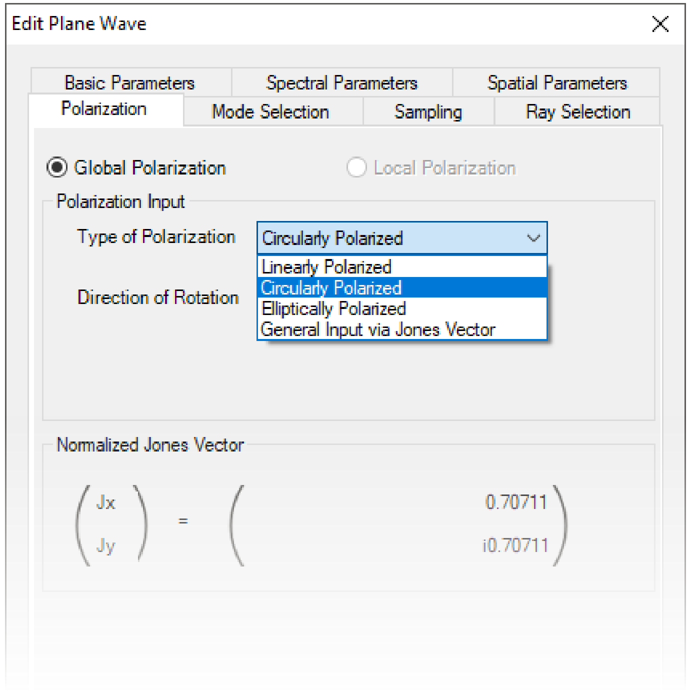


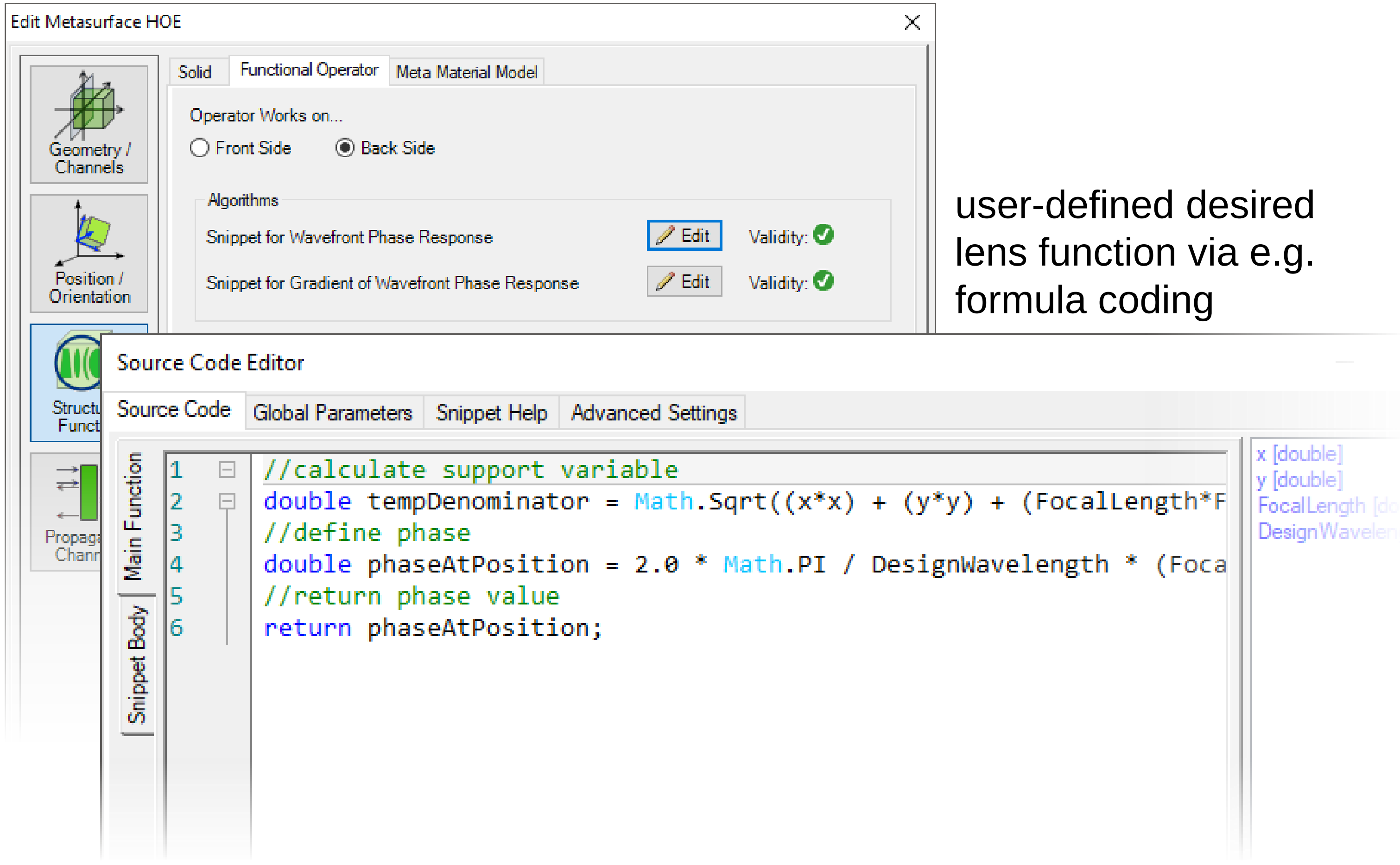
Focal Area Analysis



Peek into VirtualLab Fusion

polarization definition via pre-defined or customized Jones vectors





user-defined desired lens function via e.g. formula coding

VirtualLab Fusion – Summer Release 2019

Microstructure Components Modeling

- Modeling of microstructure components beyond paraxial situtation
- Combined use with general input field
- Typical use for diffractive diffuser system modeling

Diffractive Lens

- Complementary workflow with Zemax OpticStudio
- Direct import of e. g. Binary 2 surface
- Modeling based on real diffractive lens surface structures
- Export for fabrication

Coming in 2019

Metalens

- Unified software platform with both rigorus analysis of nano structures, and also whole lens modeling
- Rigorous Fourier modal method (FMM) for unit cell modeling with friendly structure configuration

Integral Method for Grating Modeling

- In-built model for rectangular/slanted gratings with rounded edges
- Faster convergence than other techniques
- Suitable for fabrication tolerance analysis

Grating Components in General Optical Setup

- Rigorous modeling based on in-built Fourier modal method (FMM/RCWA)
- Use together with other components in general optical setups
- Arbitrary orientation

Simulation Engine Improvement

- Automatized sampling algorithm for free-space propagation
- Robust handling of aber-rated wavefront phases
- Unified algorithm for propagation between tilted planes as well

… and more at our booth

Hall B1, 209