17-19 Oct. Santa Clara, CA, USA

Analysis and Design of Diffractive and Micro-Optical Systems

Huiying Zhong (LightTrans)

Rough Overview of the 3 Training Days

Day 1

- Modeling and design of periodic structure
- Grating toolbox and Starter toolbox, maybe also part of Diffractive optic toolbox

Day 2

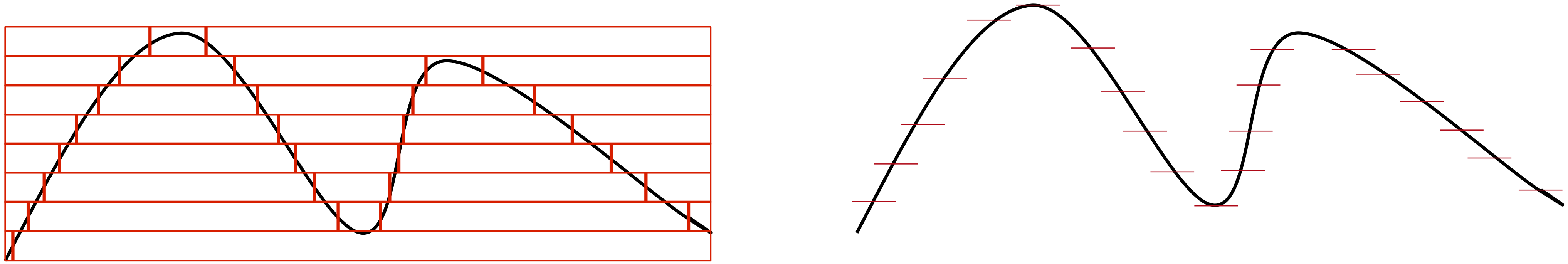
- Design and analysis tool for diffractive optical elements
- Tolerancing analysis
- Export of fabrication data

Day 3

- Beam shaper design
- General microstructure analysis

Grating Modeling

- Algorithm of grating modeling in VirtualLab
  - Fourier Modal Method (FMM)
  - Thin Element Approximation (TEA)



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Rigorous Analysis of Periodic Structures with the Fourier Modal Method (FMM)

Introduction

Fourier Modal Method

- Rigorous electromagnetic analysis of periodic 2D and 3D structures
- Numerical solution of wave equation for isotropic, linear media
- Analysis of gratings with feature sizes from sub-wavelength to several wavelength
- Includes multiple reflections and polarization effects
- Parallel computing

Fourier Modal Method

Rigorous analysis by Fourier Modal Method (FMM).

Different name: Rigorous Couple Wave Analysis (RCWA) method

Main Characteristics

- Analysis of periodic structures with infinite extension.
- Grating illumination by plane wave with infinite extension.

Name Conventions

2D gratings = so-called **linear gratings**, with a structure modulation in two directions typically X or Y and Z. Here the structure is periodic along X or Y. Sometimes also called 1D gratings if only the structure in the XY plane is regarded. → in the future we will plead for **1D periodic gratings**

3D gratings = with a structure modulation in all three directions. Then the structure is periodic along X and Y. Sometimes also called 2D gratings if only the structure in the XY plane is regarded. → **2D periodic gratings**

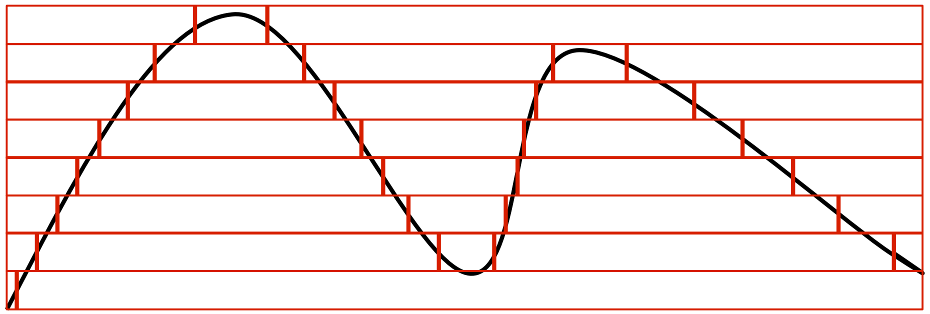
Additionally VirtualLab allows to model and analyze volumen gratings with a perodicity in Z direction.

Fourier Modal Method (VLF7.4.0.49)

- Maximum grating period ~9000 λ (2D gratings) and ~50 λ x 50 λ (3D gratings)*
- Maximum number of orders 18000 (2D gratings) and 135 x 135 (3D gratings)
- Computer requirements for grating simulation with maximum number of orders:
  - 150 GB RAM
  - ≥16 CPU cores

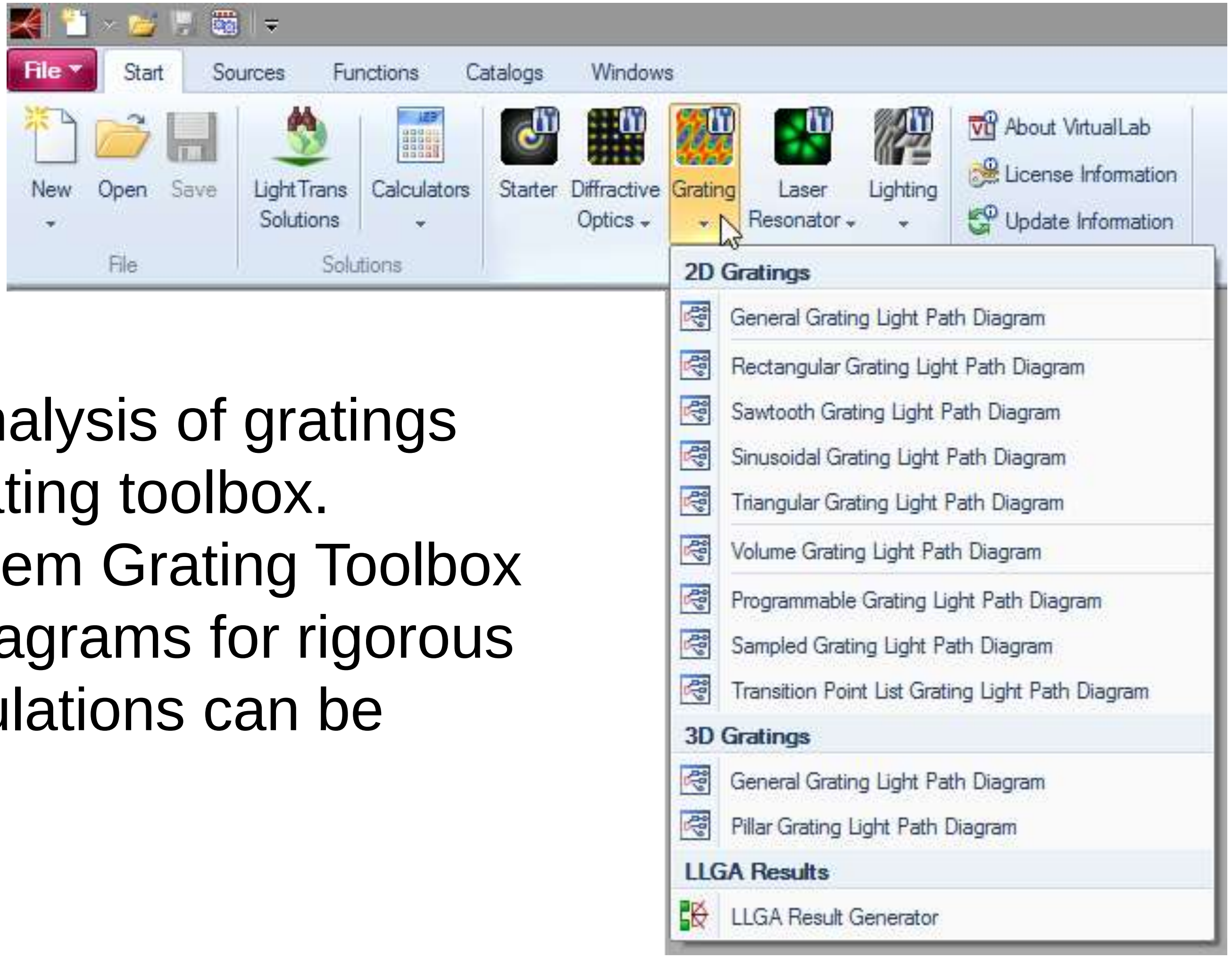
** typical maximum periods of dielectric gratings*

Fourier Modal Method



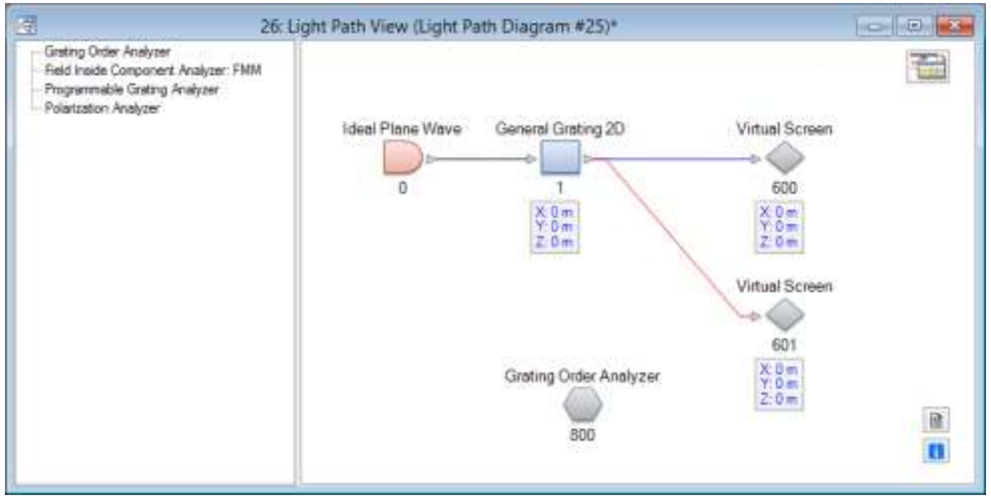
- Discretization of grating structure required for FMM.
- Surfaces and inhomogeneous media are decomposed in binary layers and transition points.
- Transition points indicate a jump of the refractive index within a layer.
- Grating structure is approximated by layers and transition points. → The more layers and transitions are used the more accurate is the modeling of the structures.
- Computational time increases linear with number of layers.

Grating Toolbox



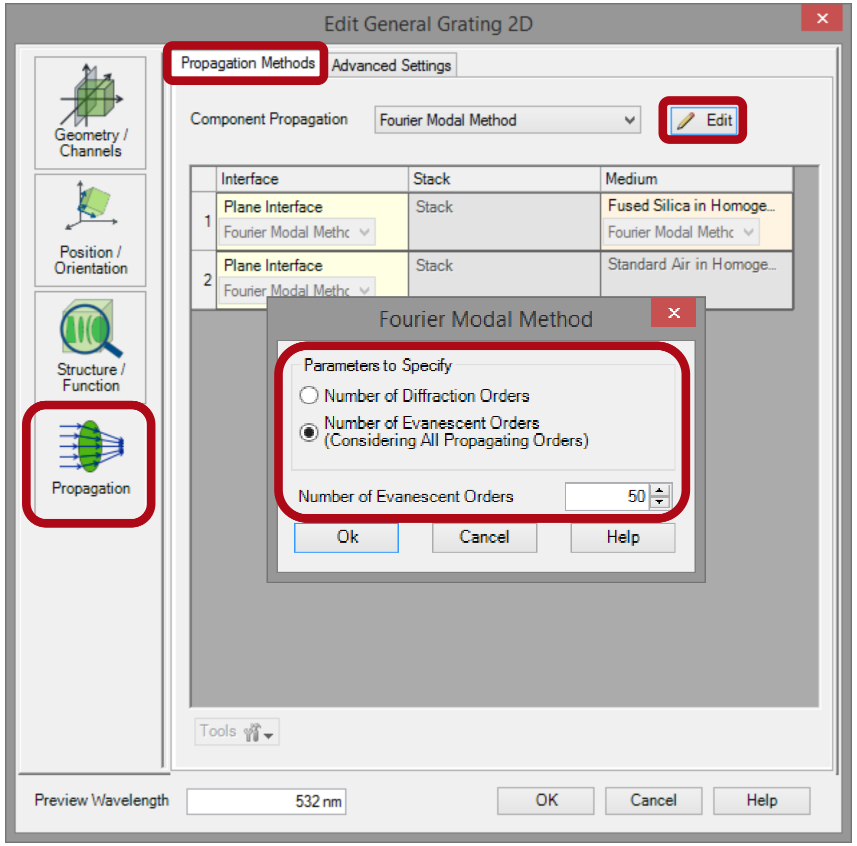
- Rigorous analysis of gratings requires grating toolbox.
- Via ribbon item Grating Toolbox light path diagrams for rigorous grating simulations can be generated.

Grating Toolbox



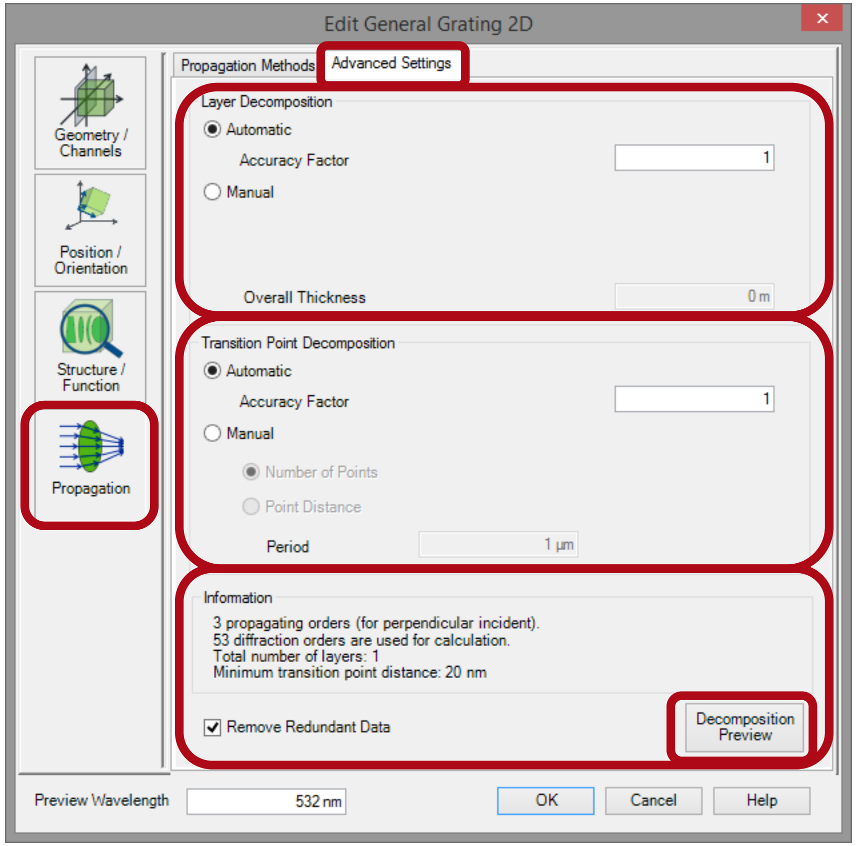
- LPD contains infinite plane wave and 2D/3D grating components.
- Virtual screens for calculation of reflected/transmitted near field.
- Grating order analyzer for calculation of diffraction efficiency.
- Field inside component analyzer calculates field distribution inside of grating structure (2D gratings only).

Fourier Modal Method



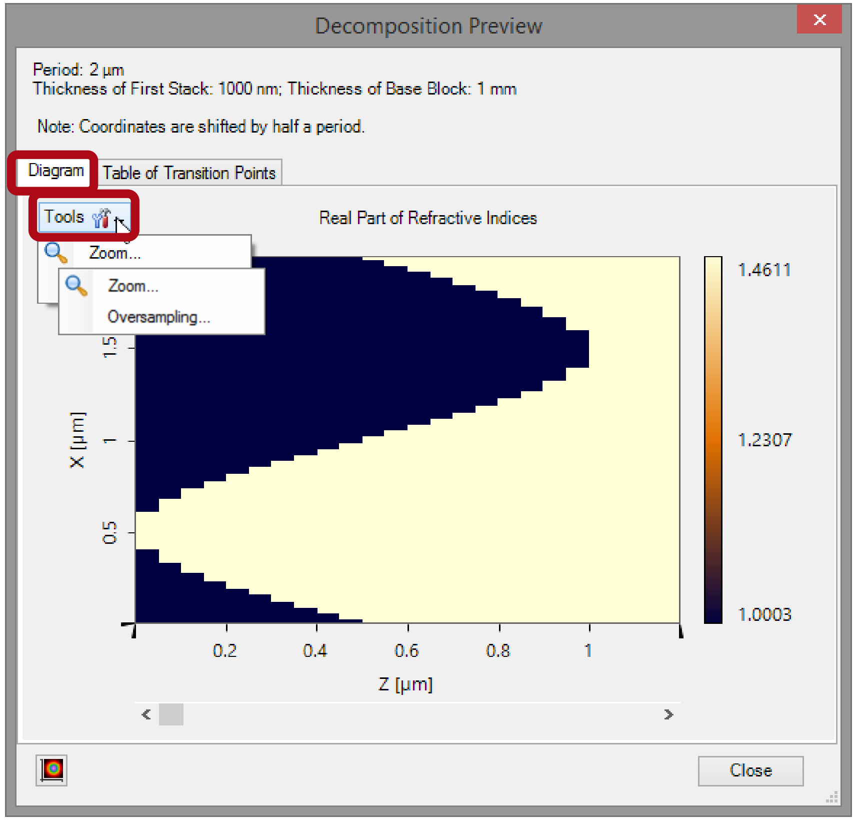
- Numerical accuracy of Fourier Modal Method (FMM) depends on number of evanescent orders.
- Number of orders must be increased until required accuracy is reached.
- Rules of thumb:
  - Dielectric gratings: >20 evanescent orders
  - Metal gratings: > 200 evanescent orders

Fourier Modal Method



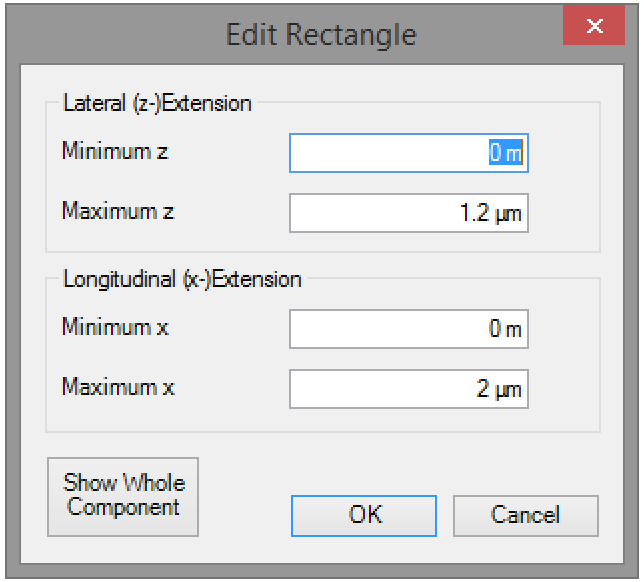
- FMM requires that the structure is decomposed in layers with binary refractive index jumps.
- Refractive index jumps are called transition points.
- Accuracy of layer decomposition.
- Accuracy of transition point decomposition.
- Summary of numerical parameters.
- Preview of structure decomposed in layers and transition points.

Fourier Modal Method



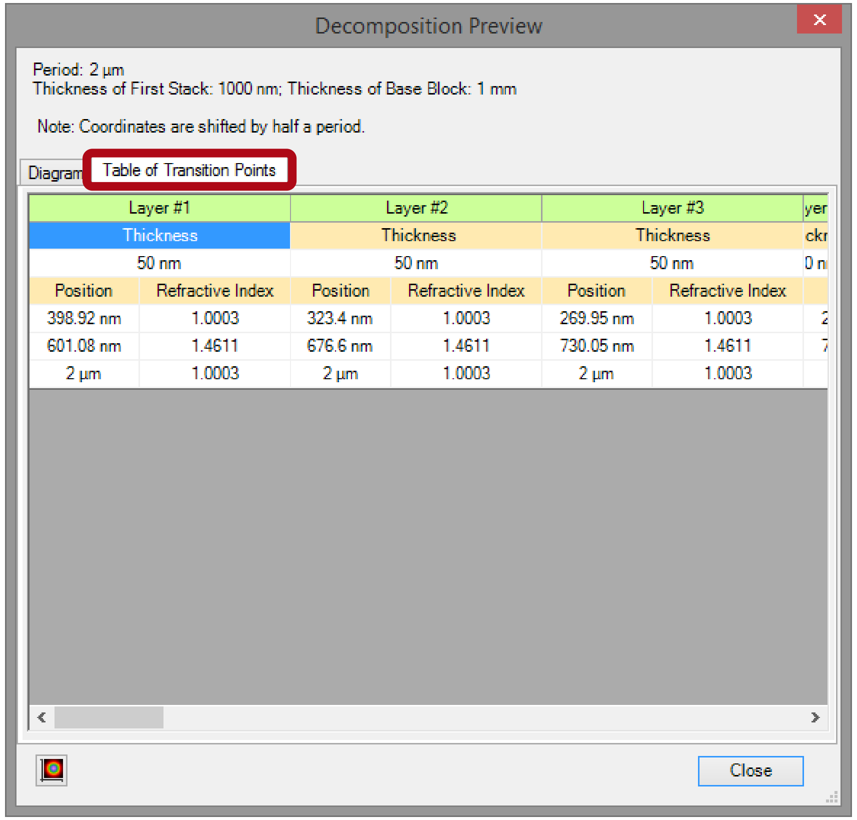
- Decomposition preview diagram shows discrete refractive index distribution of grating.
- Tools menu allows to:
  - Zoom into the region of interest
  - Increase the display resolution.

Fourier Modal Method



- Zoom dialog allows to zoom in the region of interest.
- The region of interest is typically the micro structured surface on the left or right side of the substrate.

Fourier Modal Method

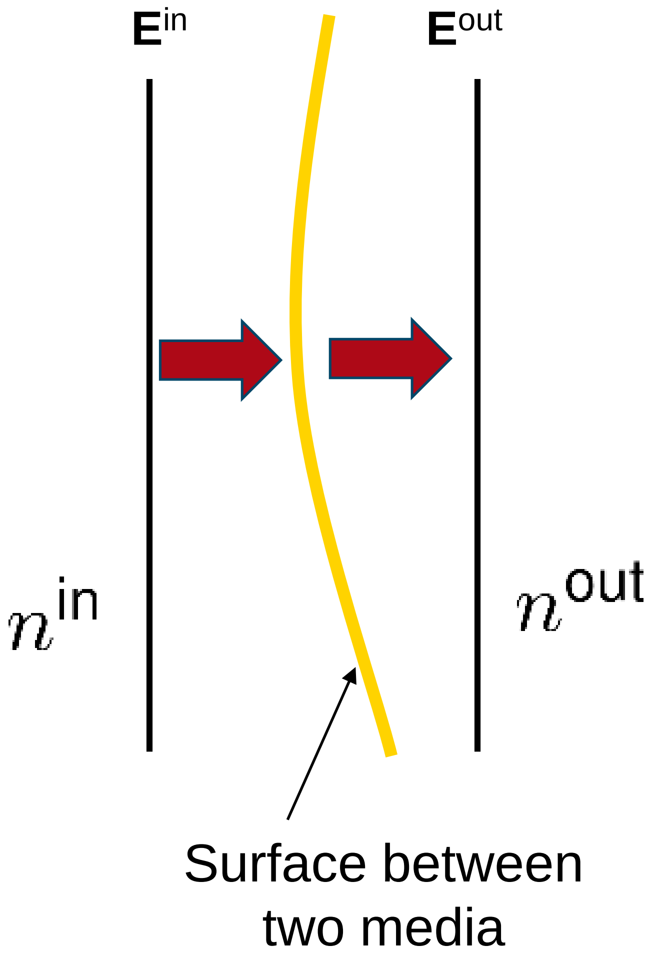


The *Table of Transition Points* shows the layers, layer thickness, transition points per layer and the refractive index.

Workflow of Modeling Grating

- Configure the grating structure by using the stack
  - Surface relief grating, both 1D periodic and 2D periodic
  - Volume grating /Holographic volume grating
- Adjust the numerical settings (FMM)
  - How many layer numbers are needed
  - How many transition points are necessary
  - How many diffraction orders are taken into calculation
- Simulation
  - Near field calculation
  - Diffraction efficiency
  - Field inside grating

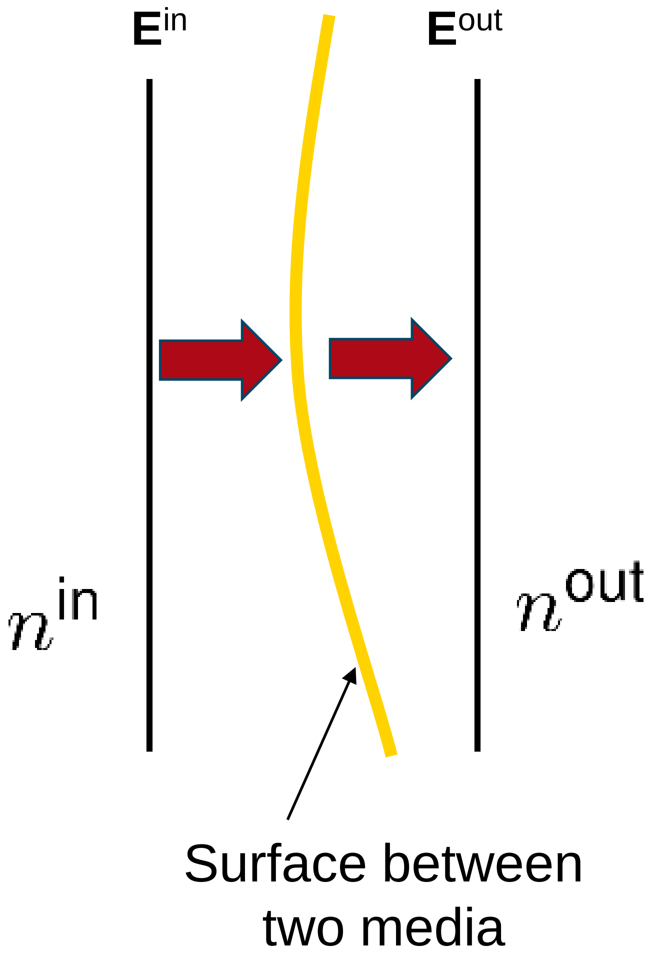
Thin Element Approximation



- In paraxial optics the local deflection at the surface by refraction is neglected.
- Then just the optical path length is considered and a phase term proportional to the height profile is obtained.

$$\Delta\phi(\boldsymbol{\rho}) = h(\boldsymbol{\rho})\frac{2\pi(n^{\text{in}} - n^{\text{out}})}{\lambda}$$

Thin Element Approximation



- In paraxial optics the local deflection at the surface by refraction is neglected.
- Then just the optical path length is considered and a phase term proportional to the height profile is obtained.
- That is the thin element approximation (TEA) frequently used in paraxial optics, e.g. Fourier and laser optics.
- Together with Fresnel integral for free-space propagation the Collins integral follows for lens systems.

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Near Field and Efficiency Analysis of Linear Sinusoidal Grating

Demonstration of basic capabilities for grating analysis with VirtualLab

Abstract

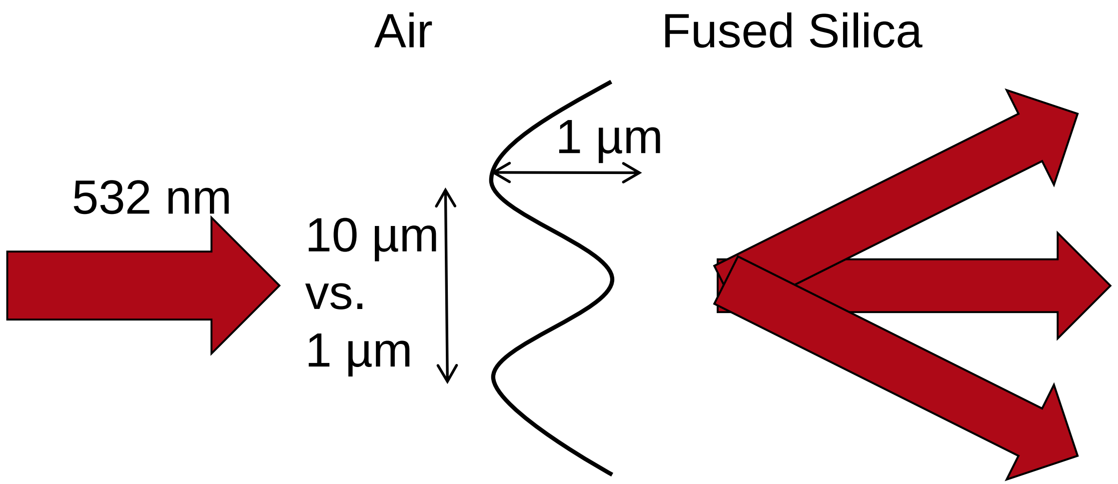
VirtualLab (VL) provides a well guided way to create an optical system for analyzing desired gratings.

This scenario demonstrates the basic investigation of the near field and the efficiencies of the transmission diffraction orders created by a linear (peridic in one direction) sinusoidal grating.

The results of two gratins are compared:

1. with a period distinctly above the wavelength
2. with a period in the range of the wavelength

Task 1 Sinusoidal Grating



Rigorous simulation of efficiency of diffraction orders and near field

Task 1: Video Part I Configure Grating

Klick the following link to watch the video:

https://youtu.be/ct9DAM8Ok58

Task 1: Video Part II TEA Modeling

Klick the following link to watch the video:

https://youtu.be/em1sLXwmvoU

Task 1: Video Part III FMM

Klick the following link to watch the video:

https://youtu.be/UvFvFEhrgjo

Task 1: Video Part IV Compare

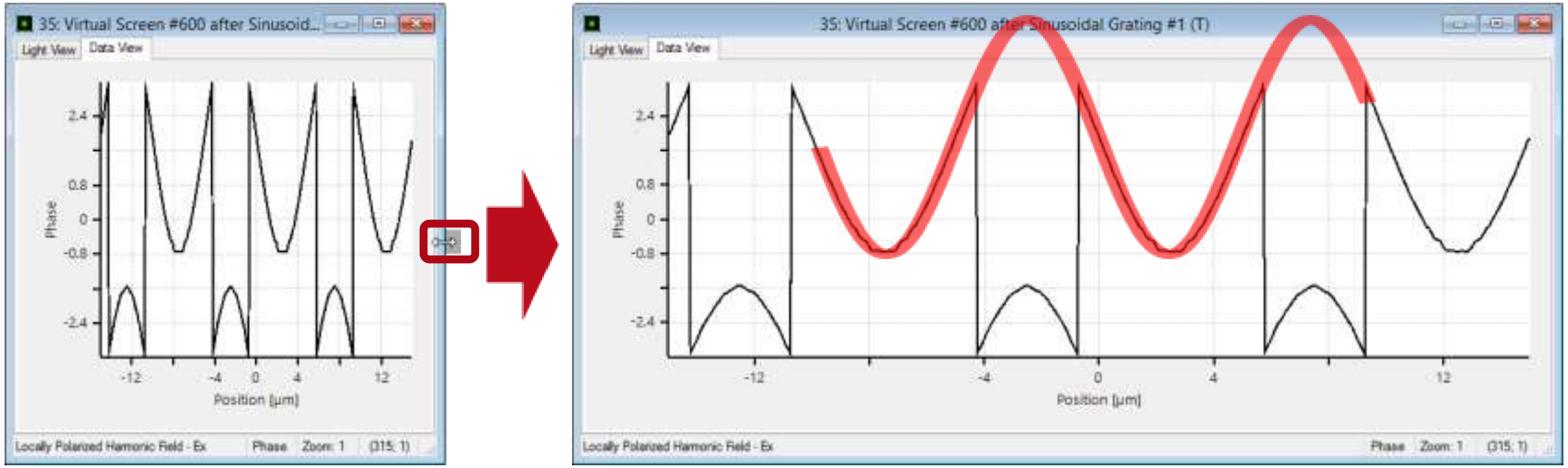
Klick the following link to watch the video:

https://youtu.be/ihPpwWWEZHA

Results from Grating with Period = 10μm

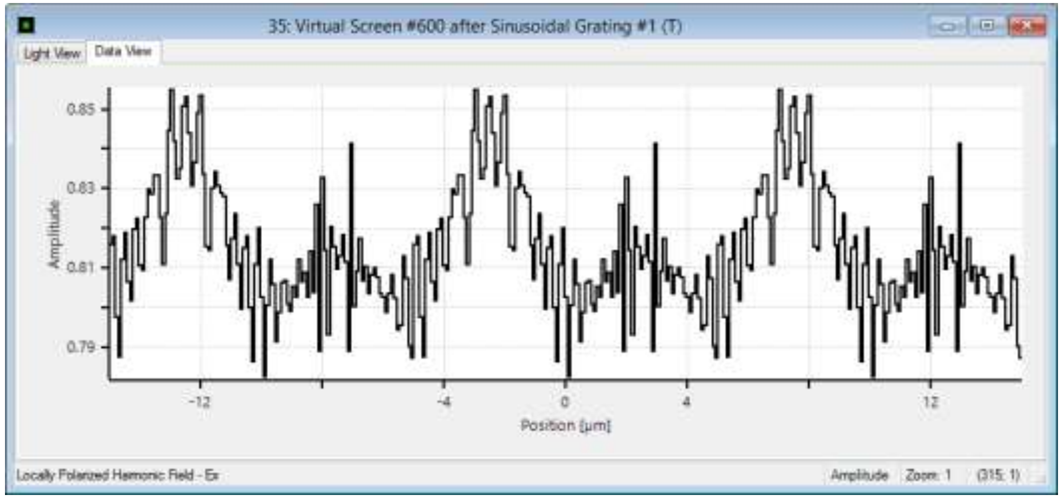
Near Field

Near Field's Phase Values (period=10µm)



3 periods of the near field's sinusoidal phase distribution with a 2Pi modulus step due to a constant phase offset.

Near Field’s Amplitude Values (period=10μm)



- The amplitude of the field varies a bit.
- In a range of about 0.78 to 0.86.

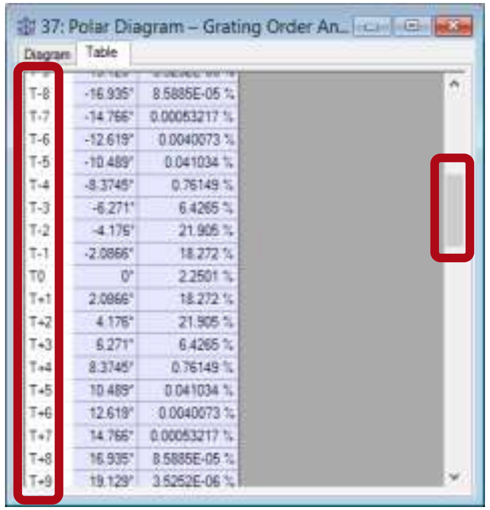
Results from Grating with Period = 10µm

Diffraction Orders‘ Efficiencies

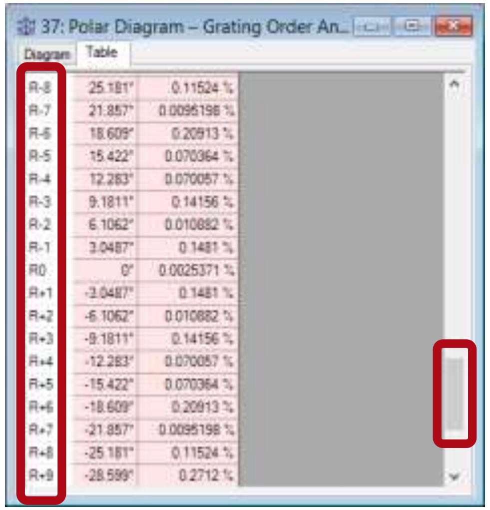
Order Efficiencies (period=10µm)

Differently Zoomed Displays

Values in Tabular Display



T-8	-16.935°	8.5885E-05 %
T-7	-14.766°	0.00053217 %
T-6	-12.619°	0.0040073 %
T-5	-10.489°	0.041034 %
T-4	-8.3745°	0.76149 %
T-3	-6.271°	6.4265 %
T-2	-4.176°	21.906 %
T-1	-2.0866°	18.272 %
T0	0°	2.2501 %
T+1	2.0866°	18.272 %
T+2	4.176°	21.905 %
T+3	6.271°	6.4265 %
T+4	8.3745°	0.76149 %
T+5	10.489°	0.041034 %
T+6	12.619°	0.0040073 %
T+7	14.766°	0.00053217 %
T+8	16.935°	8.5885E-05 %
T+9	19.129°	3.5252E-06 %



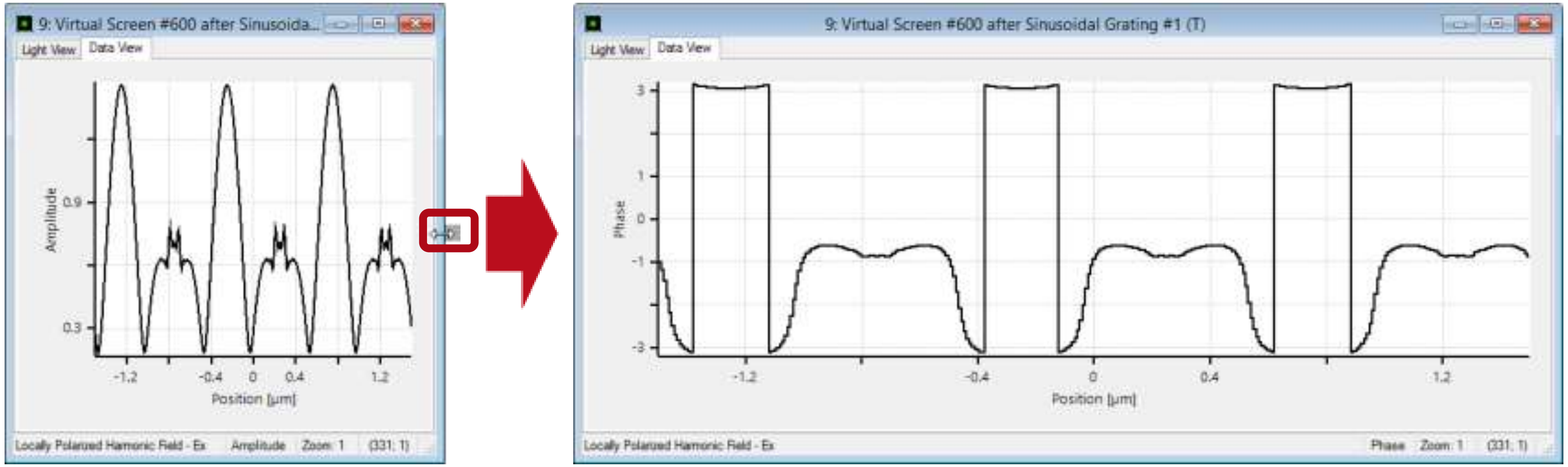
R-8	25.181°	0.11524 %
R-7	21.857°	0.0095198 %
R-6	18.609°	0.20913 %
R-5	15.422°	0.070364 %
R-4	12.283°	0.070057 %
R-3	9.1811°	0.14156 %
R-2	6.1062°	0.010882 %
R-1	3.0487°	0.1481 %
R0	0°	0.0025371 %
R+1	-3.0487°	0.1481 %
R+2	-6.1062°	0.010882 %
R+3	-9.1811°	0.14156 %
R+4	-12.283°	0.070057 %
R+5	-15.422°	0.070364 %
R+6	-18.609°	0.20913 %
R+7	-21.857°	0.0095198 %
R+8	-25.181°	0.11524 %
R+9	-28.599°	0.2712 %

Order Evaluations (period=10µm)

Results from Grating with Period = 1μm

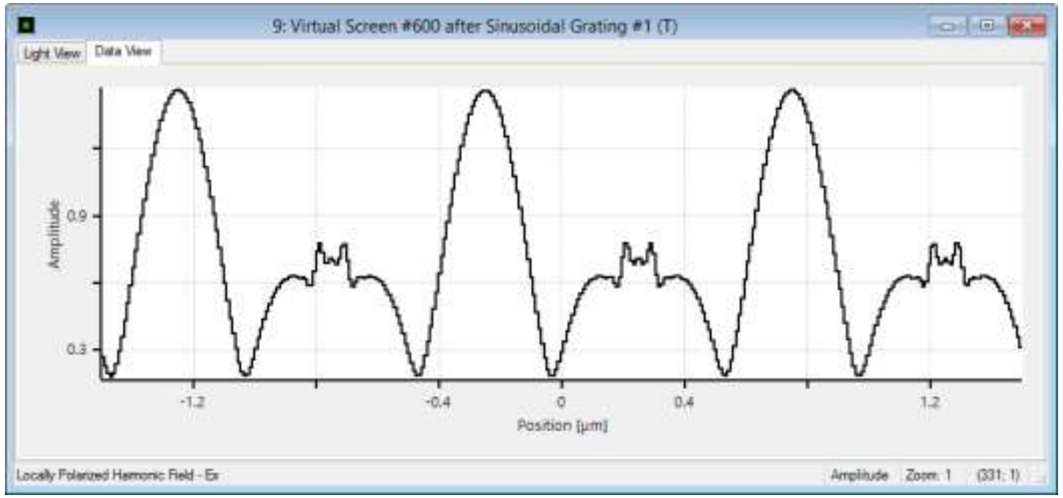
Near Field

Near Field's Phase Values (period=1µm)



- Again 3 periods are displayed.
- With these small grating structures there is no longer a sinusoidal phase distribution because of the occurring resonance effects.

Near Field's Amplitude Values (period=1µm)



- The amplitude is also dramatically changed.
- Now it varies from about 0.2 to 1.2.
- This is a typical phenomenon for gratings with a period close to the wavelength.

Results from Grating with Period = 1µm

Diffraction Orders‘ Efficiencies

Comments

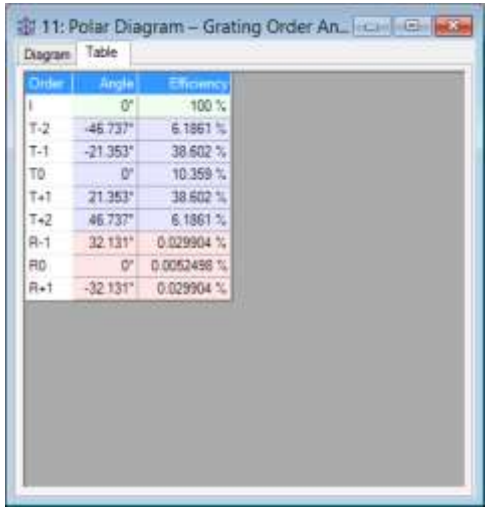
- Scenarios like this with a wavelength of 532nm and a grating period of 1µm, i.e. a structure in the range of the wavelength, typically ask for a rigorous analysis which the Fourier Modal Method offers.
- So VirtualLab is predestined for such investigations.

- This constellation results in only 3 reflecting and 5 transmitting orders. Thus the analysis is quite fast.

Order Efficiencies (period=1µm)

Differently Zoomed Displays

Values in Tabular Display



Order	Angle	Efficiency
I	0°	100 %
T-2	-46.737°	6.1861 %
T-1	-21.353°	38.602 %
T0	0°	10.359 %
T+1	21.353°	38.602 %
T+2	46.737°	6.1861 %
R-1	32.131°	0.029904 %
R0	0°	0.0052498 %
R+1	-32.131°	0.029904 %

Order Evaluations (period=1μm)

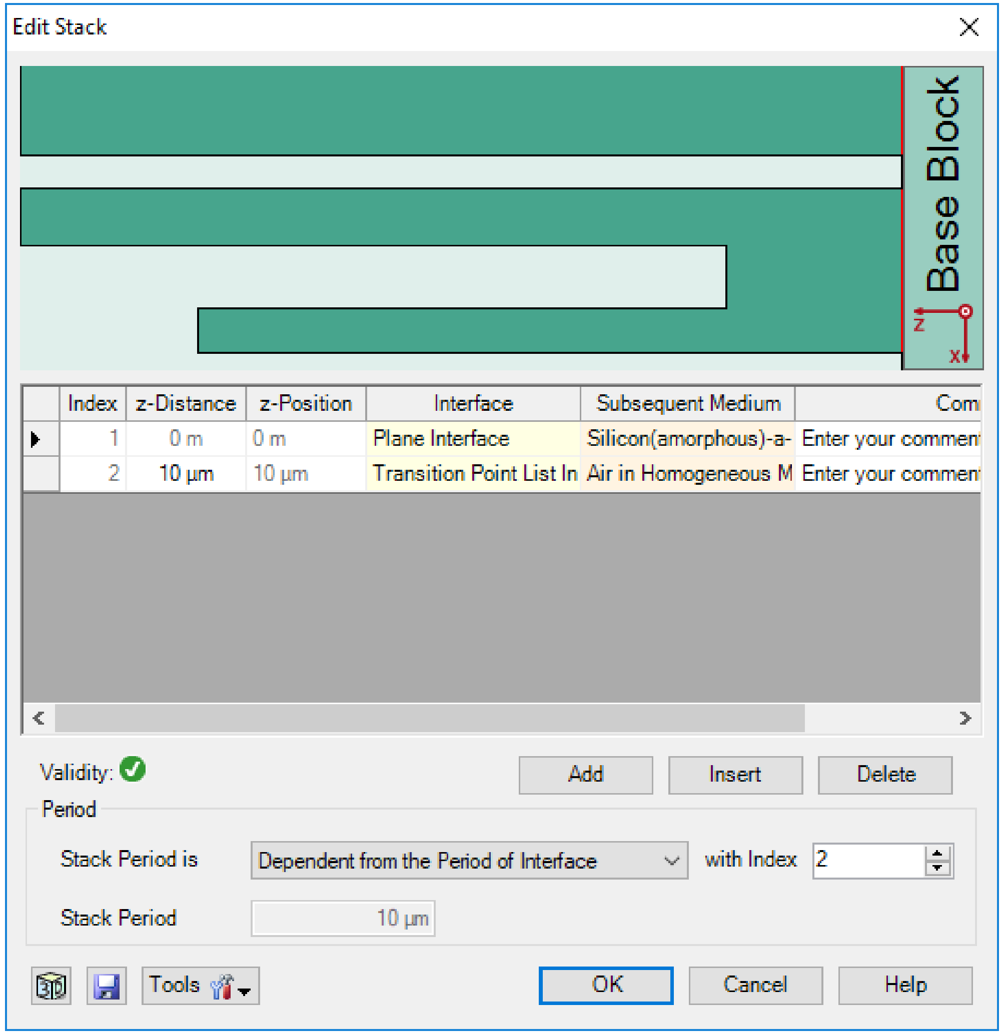
Summary

- VirtualLab allows the rigorous simulation of surface gratings.
- With the Grating Toolbox the user gets the rigorous Fourier Modal Method (FMM) as propagation technique and very powerful evaluation tools e.g. for the near field and diffraction efficiencies of the grating orders.

Configuration of Grating Structures by Using Interfaces

From this slides on, we try to give further info of configuration of surface relief gratings

Abstract



Optical grating structures are widely used for several applications such as spectrometers, near-eye display systems, etc. VirtualLab Fusion provides rigorous analysis of arbitrary grating structures in an easy way by applying the Fourier modal method (FMM). In the Grating Toolbox, the grating structure can be configured by using various interfaces or/and media within a stack. The user interface to set up the geometry of a stack is user friendly and can be used to generate even more complex grating structures. In this use case the configuration of grating structures based on interfaces is explained.

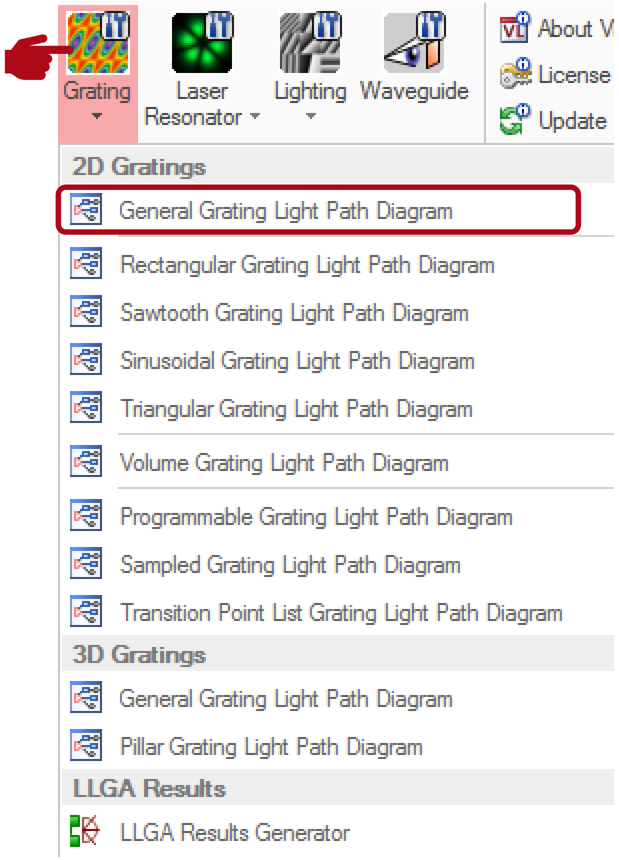
This Use Case Shows ...

- How to configure grating structures in Grating Toolbox by using interfaces, e.g.:
  - rectangular grating interface
  - transition point list interface
  - sawtooth grating interface
  - sinusoidal grating interface

- How to change advanced options & inspect defined structure before calculation.

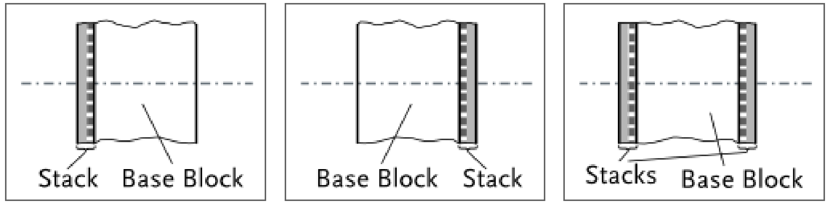
Grating Toolbox Initialization

- Initialization
  - Start ➔ Grating ➔ General Grating Light Path Diagram
- note: For usage of special type of grating, e.g. with rectangular shape, the specific light path diagram can be chosen directly.

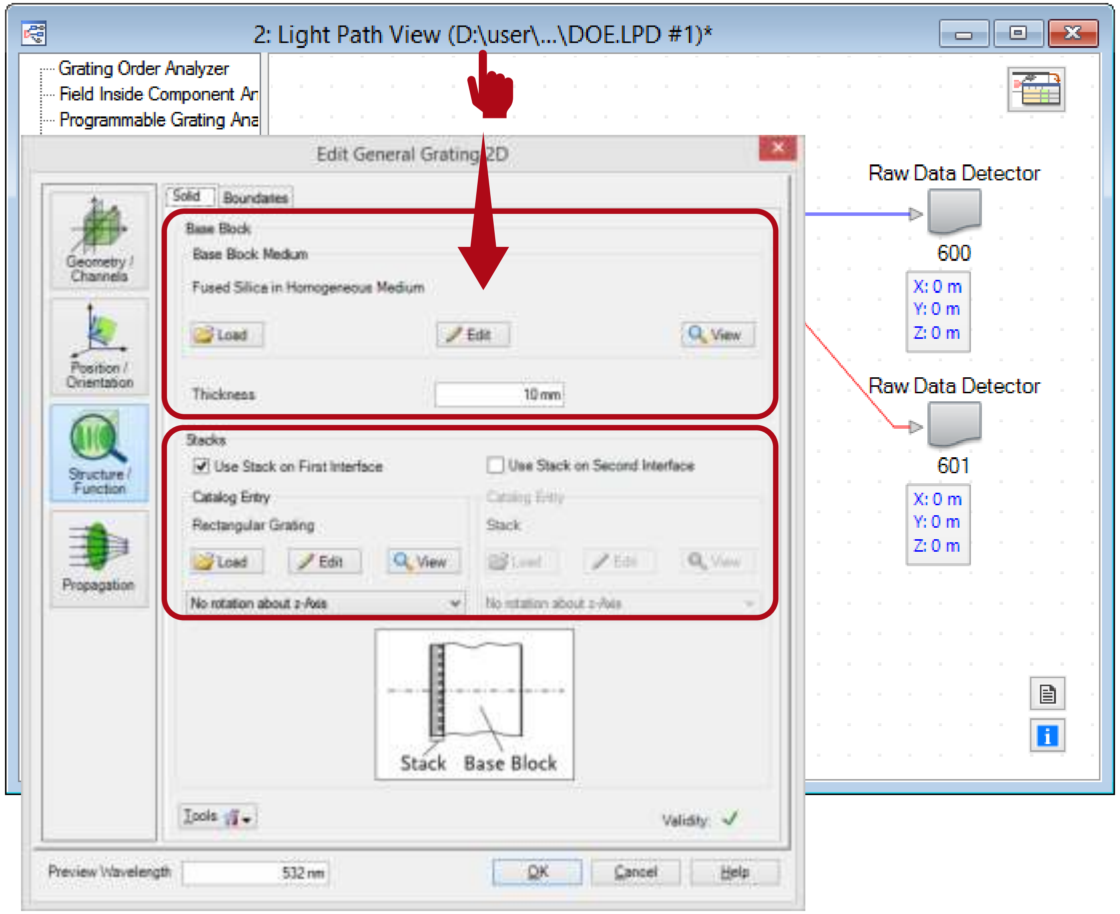


Grating Structure Settings

- First, the thickness and the material of the substrate (*Base Block*) have to be defined.
- In VirtualLab grating structures are defined in a so called stack.
- Stacks can be attached to either one or both sides of the substrate.

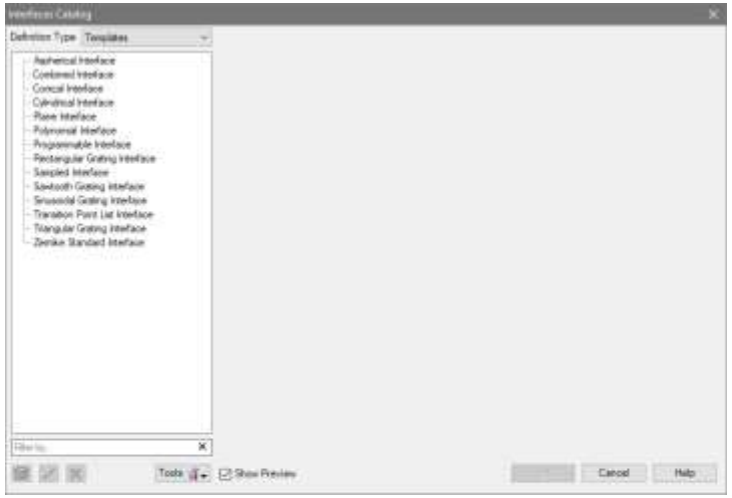


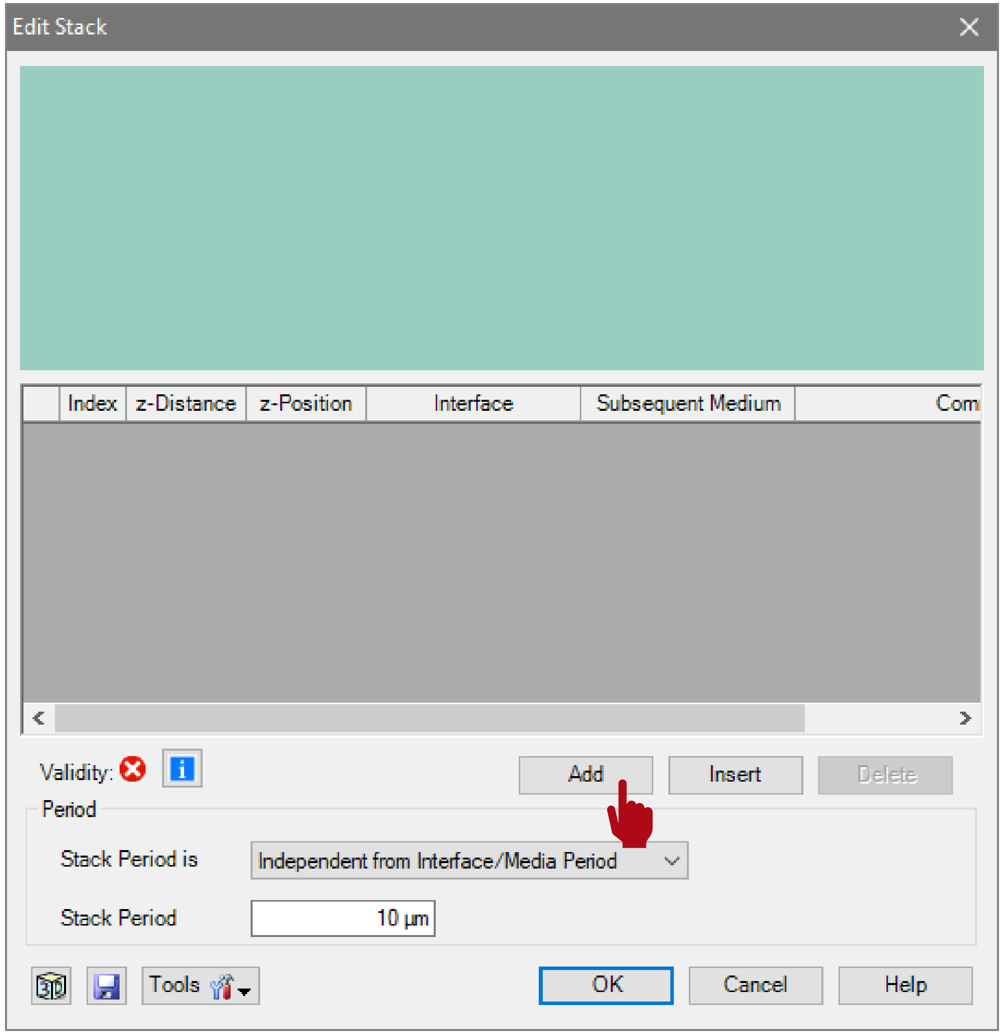
- For example, a stack on the first interface is chosen.



Stack Editor

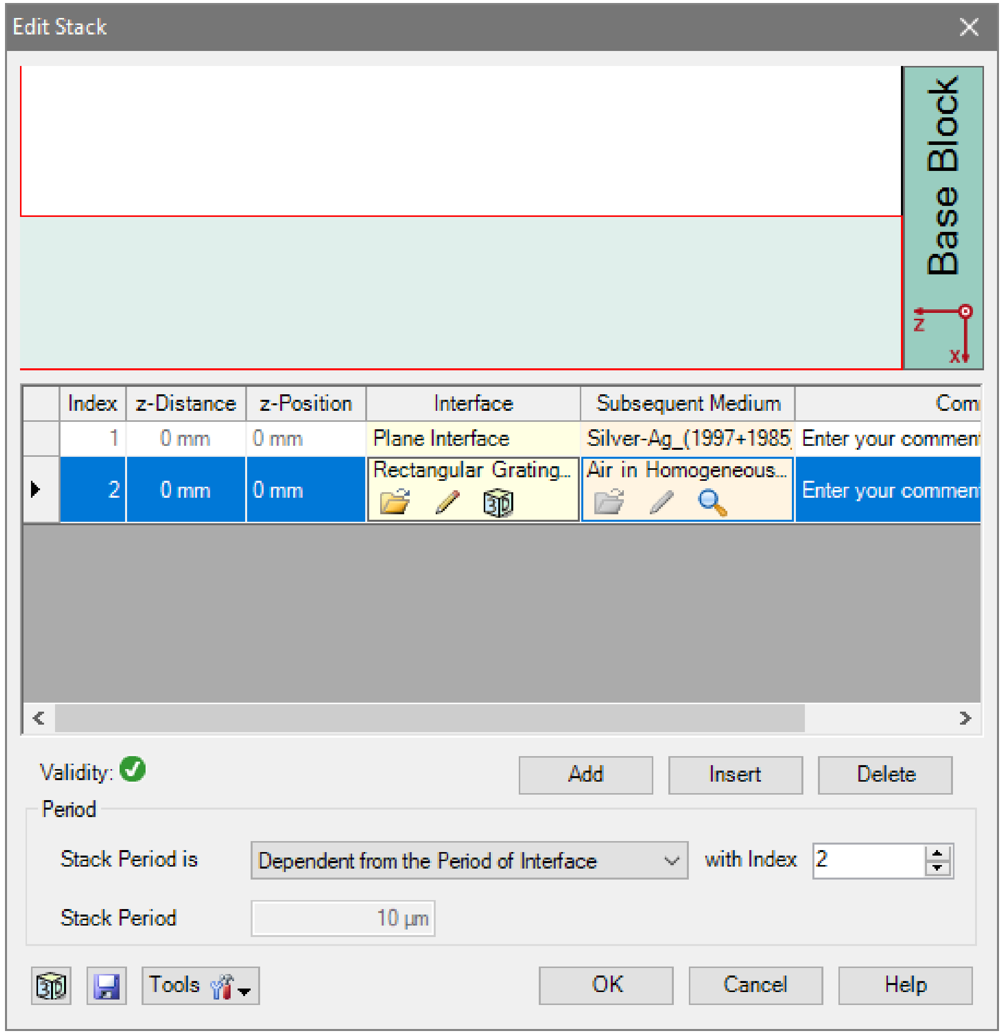
- In the *Stack Editor* interfaces can be added or inserted from catalog.
- The catalog of VirtualLab provides several types of interfaces. All of them can be used to define a grating.





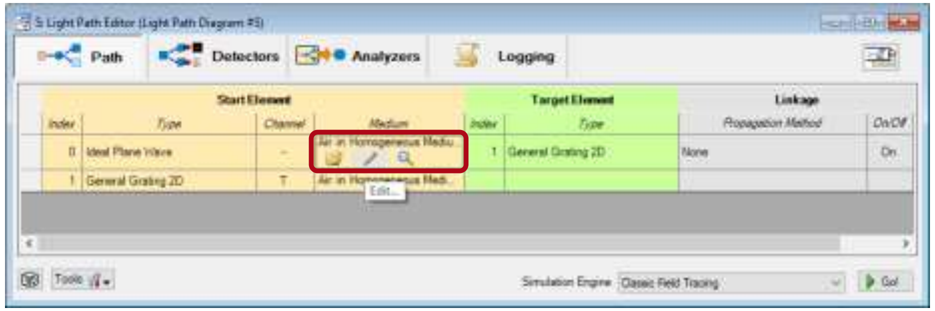
Rectangular Grating Interface

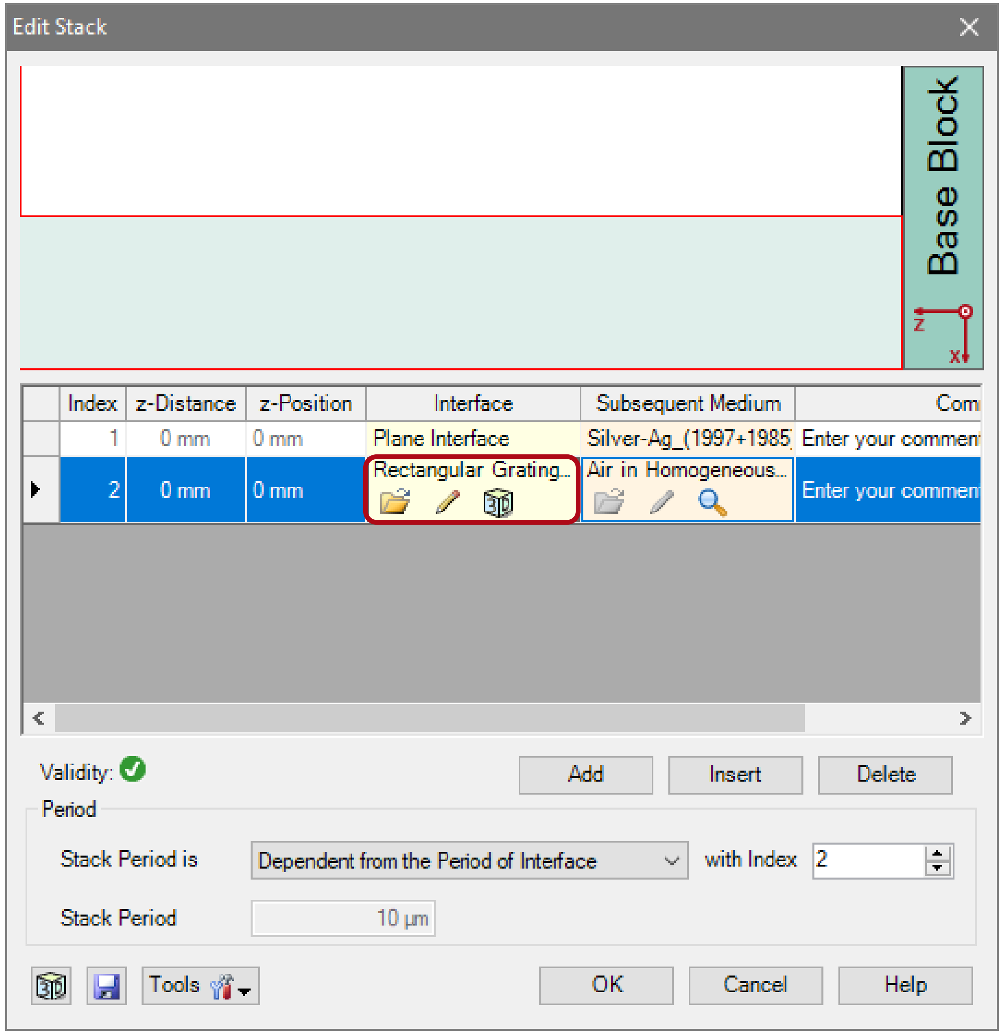
- One possible interface is the rectangular grating interface.
- This type of interface is appropriate for the configuration of simple binary structures.
- In this example, a grating made of silver is on a glass substrate.
- For this purpose, an additional plane interface was added in order to separate the grating structure from base block.
- In the view of the stack editor, different materials are indicated by other colors based on their index of refraction (dark means higher).



Rectangular Grating Interface

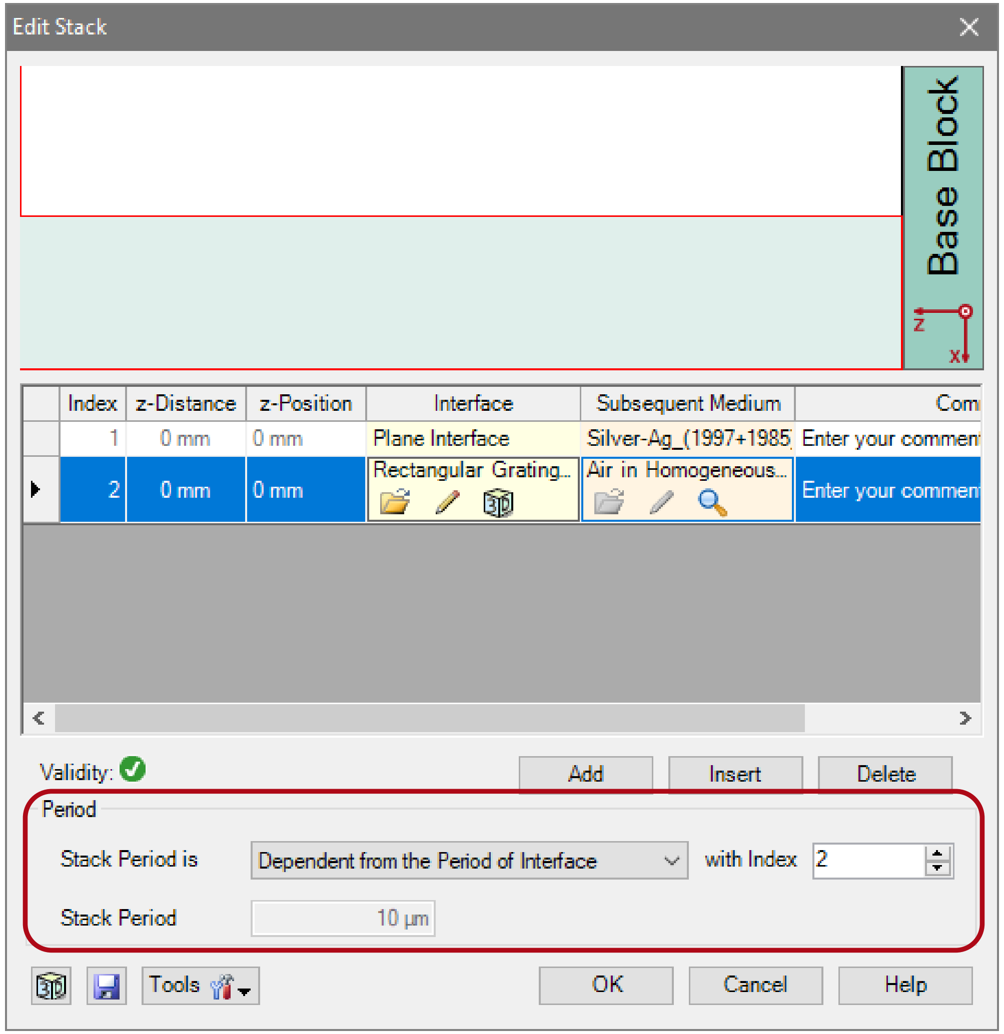
- Please note: the order of the interfaces is always counted from the surface of the substrate.
- The selected interface is highlighted red in the view.
- Further, the medium in front of the grating (means behind last interface) can not be defined here. It is automatically taken from the material in front of the grating component.
- This material can be changed in the *Optical Setup Editor*





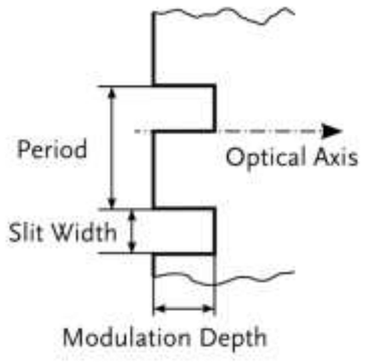
Rectangular Grating Interface

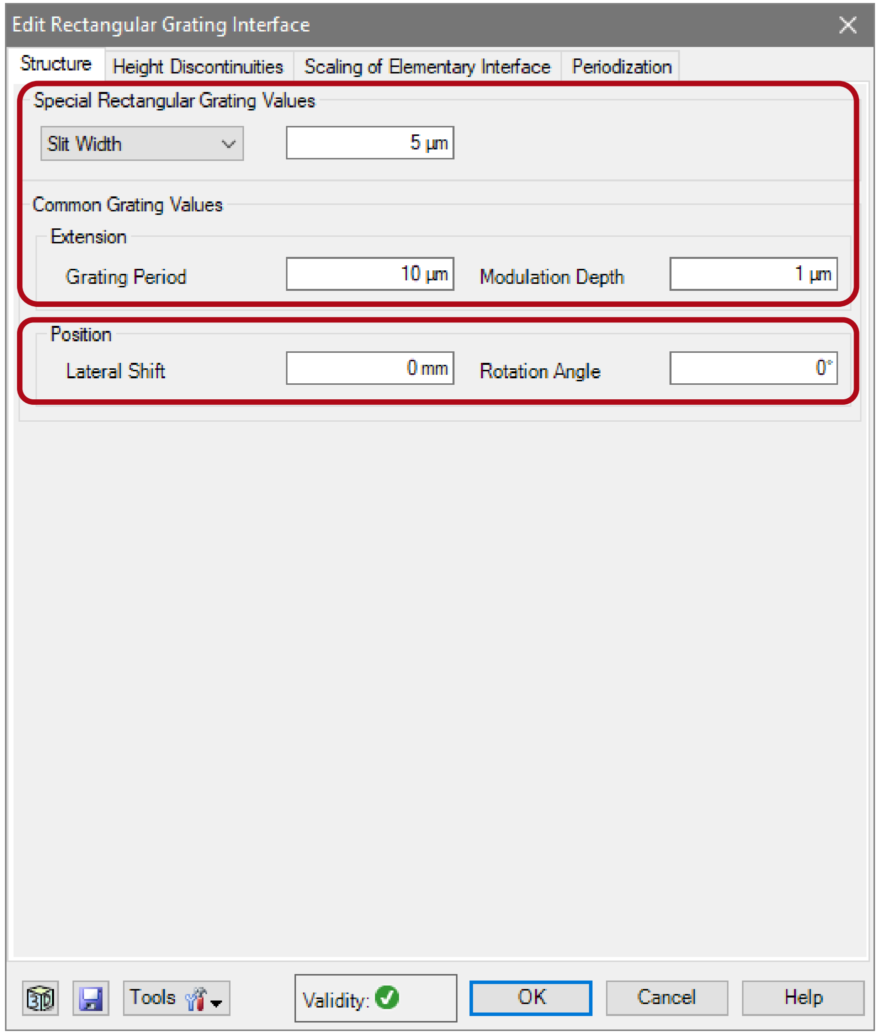
- The *Stack Period* allows to control the period of the whole configuration.
- This period is also taken for the periodic boundary conditions of the FMM algorithm.
- In case of simple grating structures, it is recommended to choose the option *Dependent from Period of Interface* and select the proper index of the periodic interface.



Rectangular Grating Interface Parameters

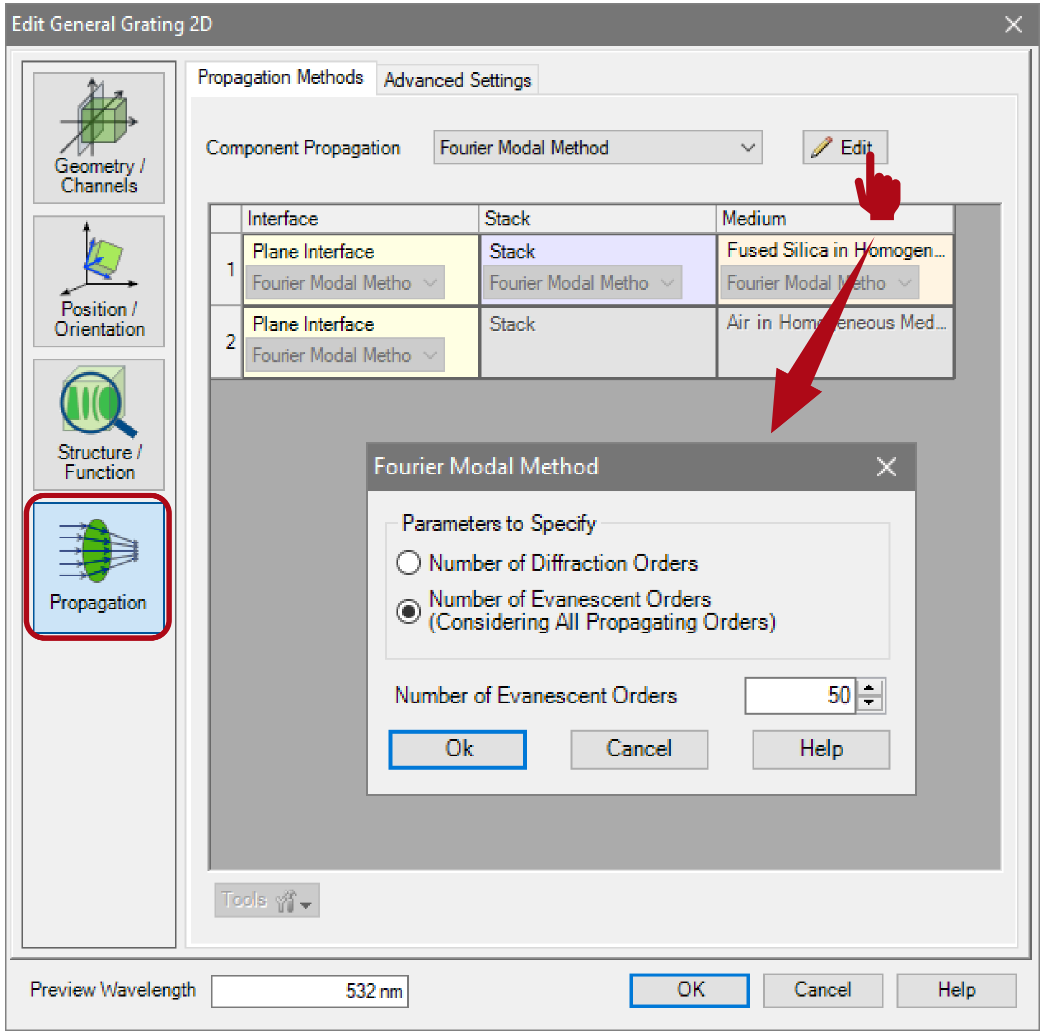
- The rectangular grating interface is defined by the following parameters
  - slit width (absolute or relative)
  - grating period
  - modulation depth
- A lateral shift and rotation can be set optionally.





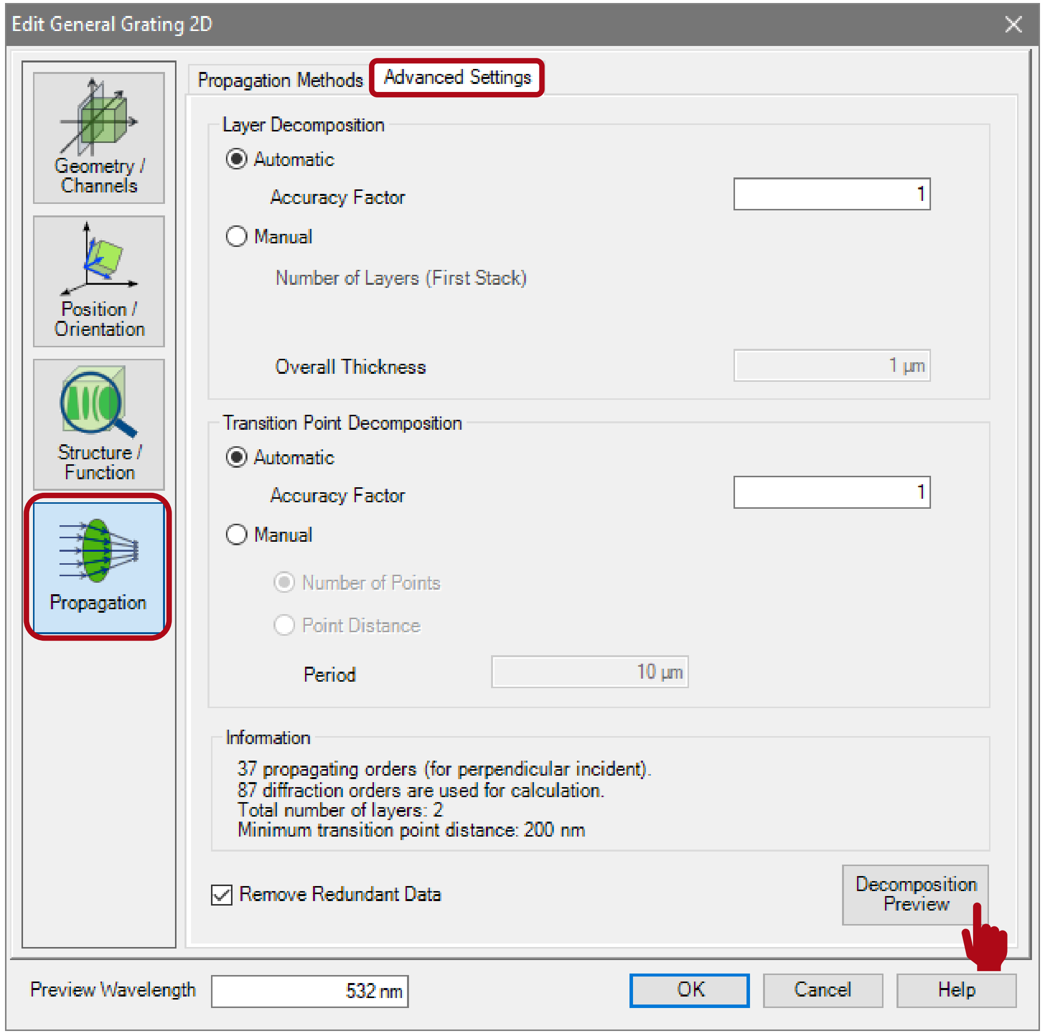
Advanced Options & Information

- In the propagation menu several advanced options are available.
- The propagation method tab allows to edit the accuracy settings of the FMM algorithm.
- Either the numbers of considered total orders or evanescent orders can be set.
- This might be useful, if metallic gratings are considered.
- In contrast, in case of dielectric gratings, the default setting will be sufficient.



Advanced Options & Information

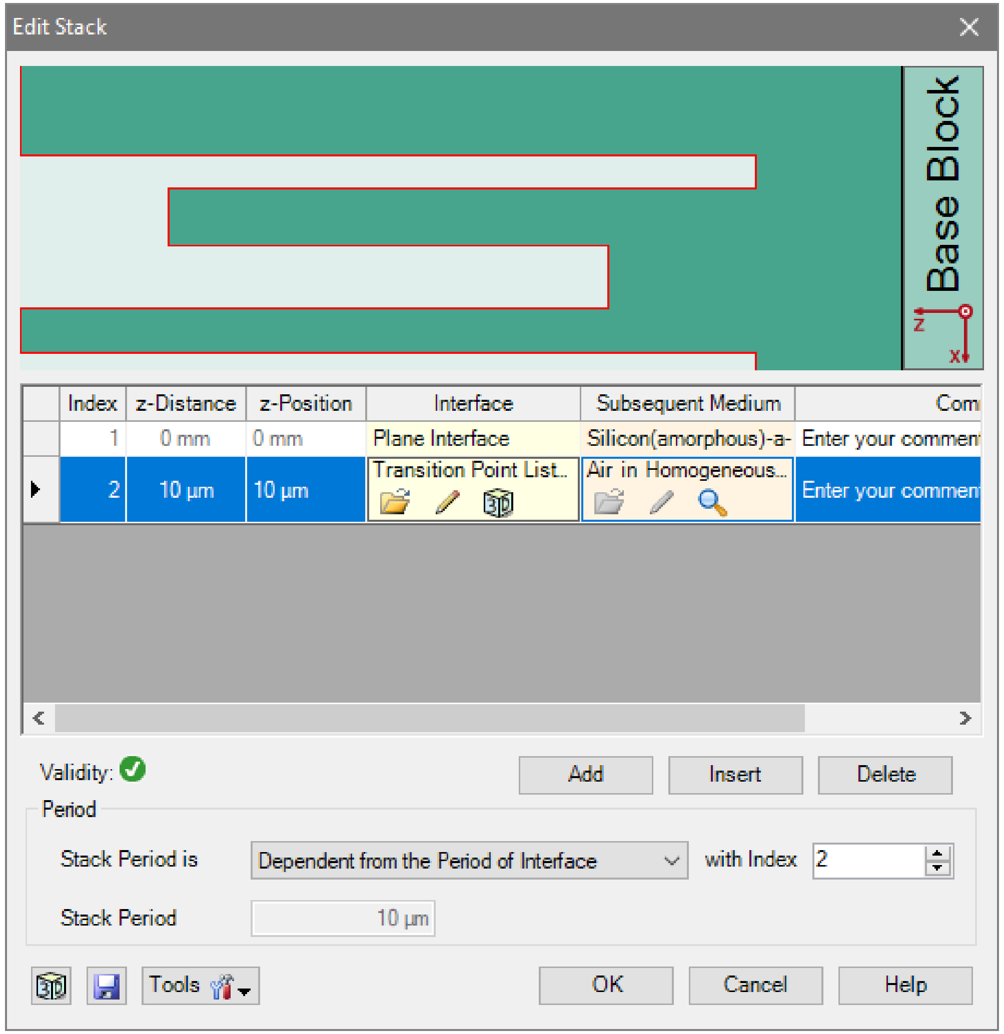
- The *Advanced Settings* tab provides information about the decomposition of the structure.
- The *Layer Decomposition* and *Transition Point Decomposition* settings can be used to adjust the discretization of the structure. The default settings are appropriate for nearly all grating structures.
- Further, information about the number of layers and transition points are provided.
- The *Decomposition Preview* button provides a depiction of the structure data which are used for the FMM calculation. The refractive index is illustrated by a color scale.



Transition Point List Interface

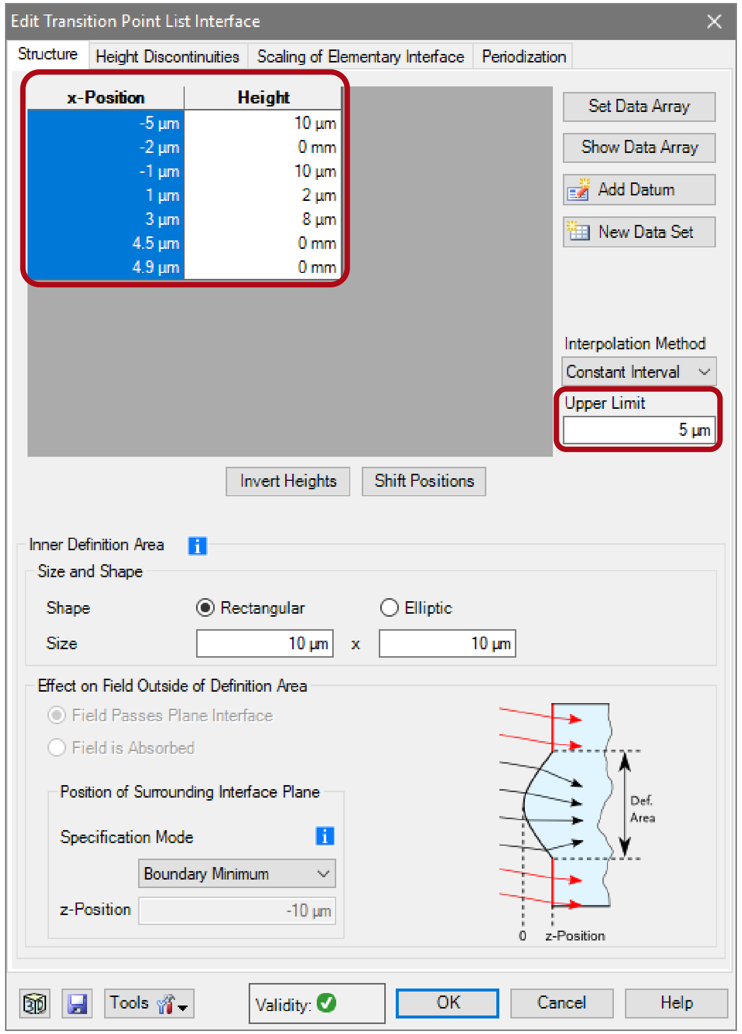
Transition Point List Interface

- Another type of interface which can be used for the configuration of gratings is the transition point list interface.
- This interface allows to configure a structure based on height values for different positions inside the period.
- Again, a plane interface is used to separate the grating material or medium from the one of the substrate.



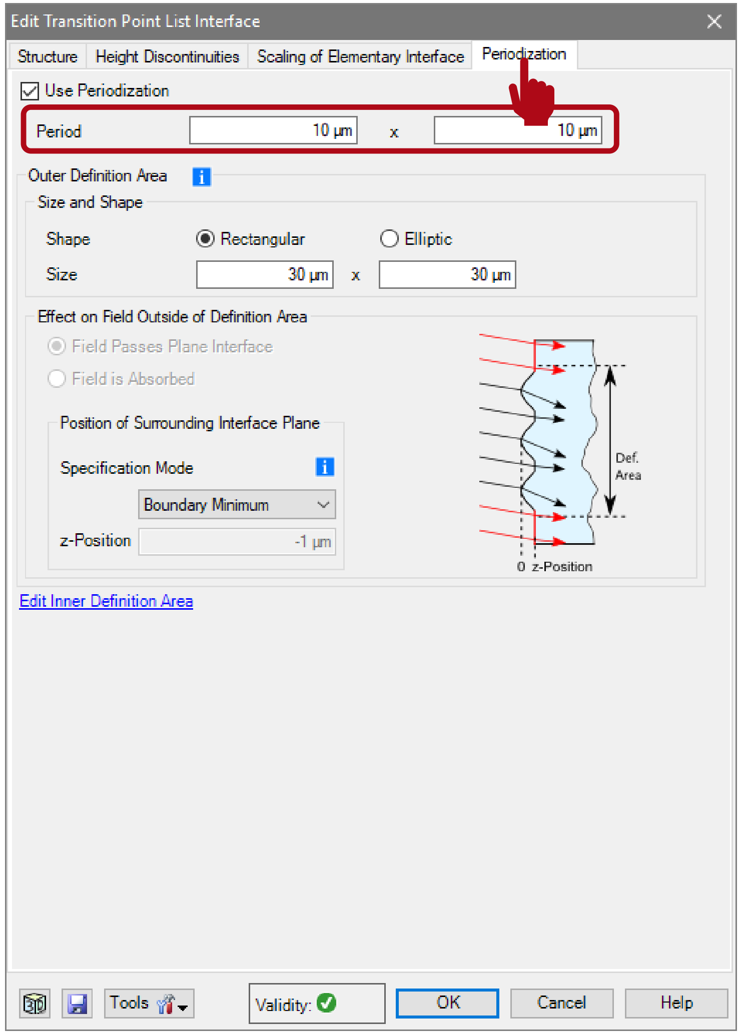
Transition Point List Parameters

- The transition point list interface is defined by a list which contains the data of x-positions and heights.
- The *Upper Limit* has to be set to a value larger than half of the desired grating period, but is set automatically in case of periodic structures.



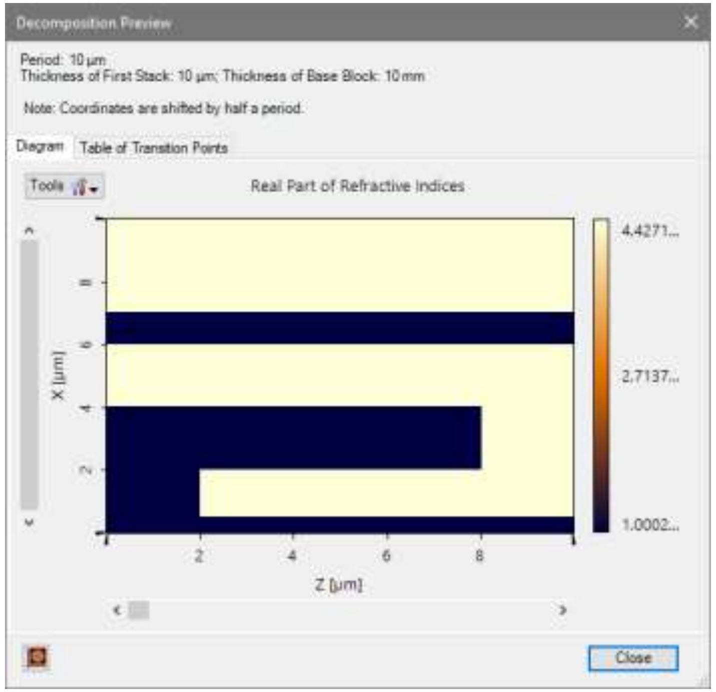
Transition Point List Parameters

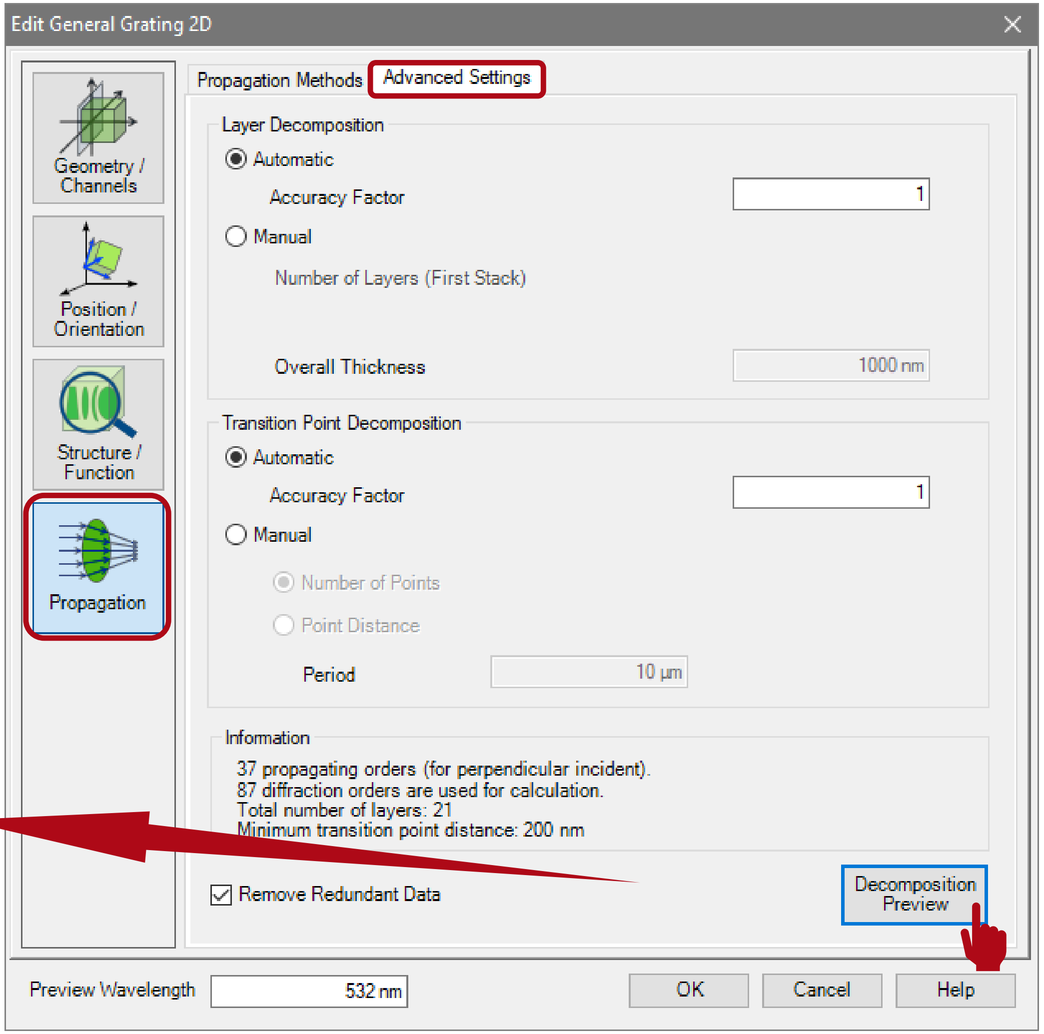
- The period of this interface has to be set in the *Periodization* tab.
- Here, the periods in x- and y-direction can be defined.
- The settings of the inner and outer definition area can be neglected in this case, because the extension of the interface is already truncated by the periodic boundary conditions.



Advanced Options & Information

- Again, the data of the decomposed structure can be adjusted and investigated on the advanced settings tab page.

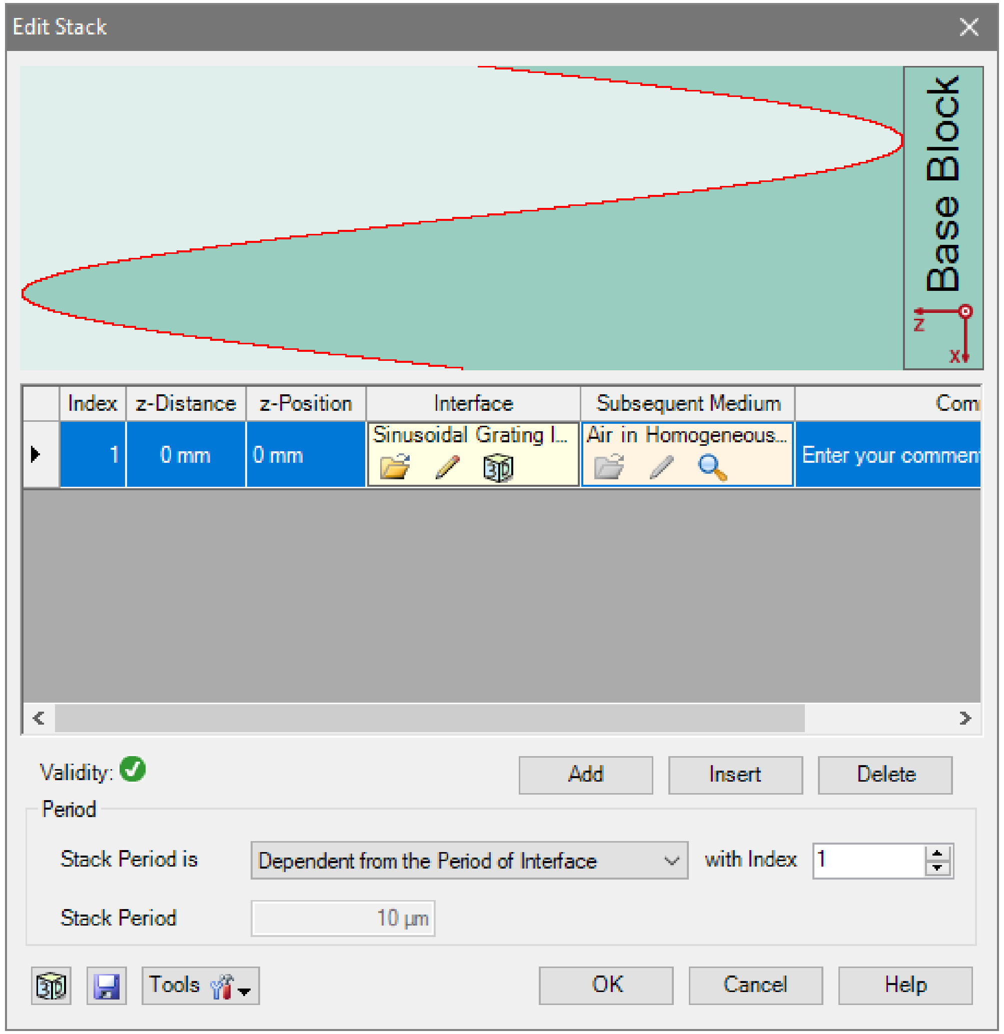




Sinusoidal Grating Interface

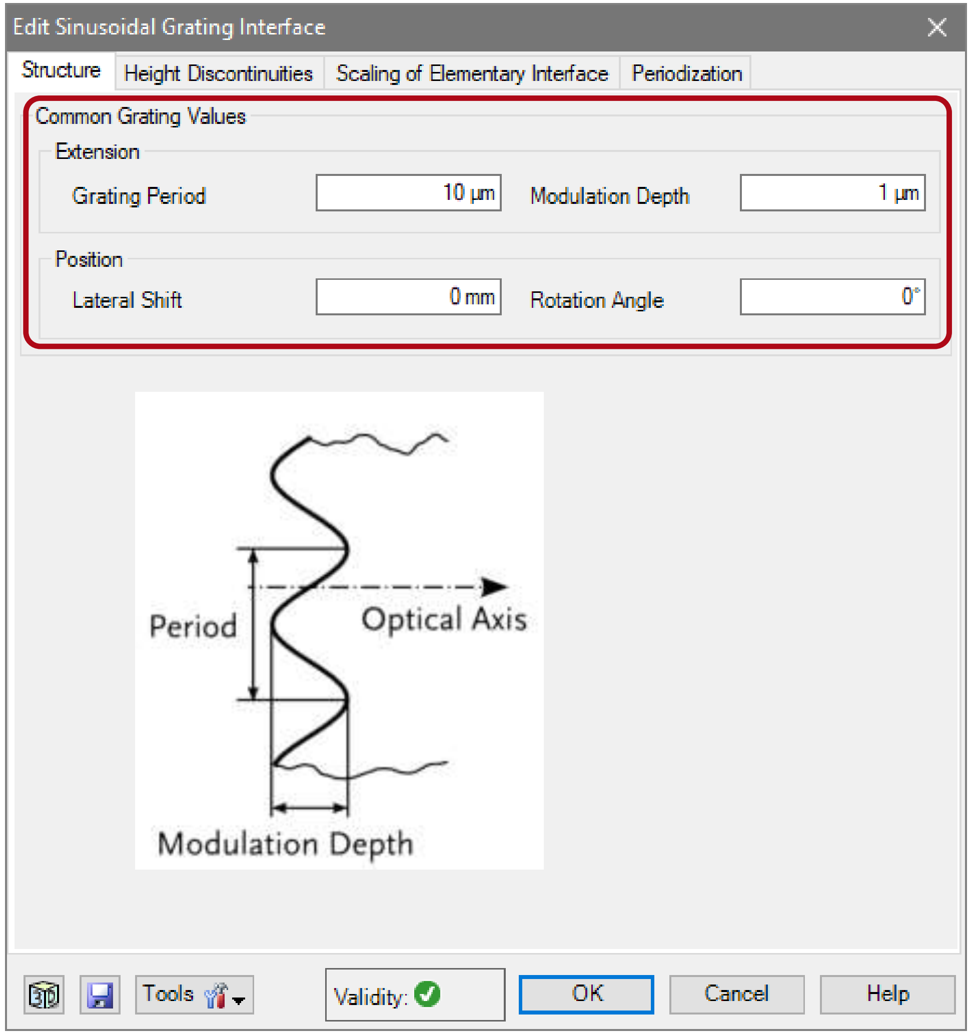
Sinusoidal Grating Interface

- Another type of interface which can be used for the configuration of gratings is the sinusoidal grating interface.
- This interface allows to configure gratings with a smooth shape of a sinusoidal function.
- If a single interface is used to describe the grating structure, the materials are chosen automatically:
  - material of ridges: material of substrate
  - material of grooves: material in front of grating



Sinusoidal Grating Interface Parameters

- The sinusoidal grating interface is also defined by the following parameters:
  - grating period
  - modulation depth
- A lateral shift and rotation can be set optionally.
- As this is a grating interface (likewise to the rectangular and sawtooth one) no periodization has to be chosen.



Sinusoidal Grating Interface Parameters

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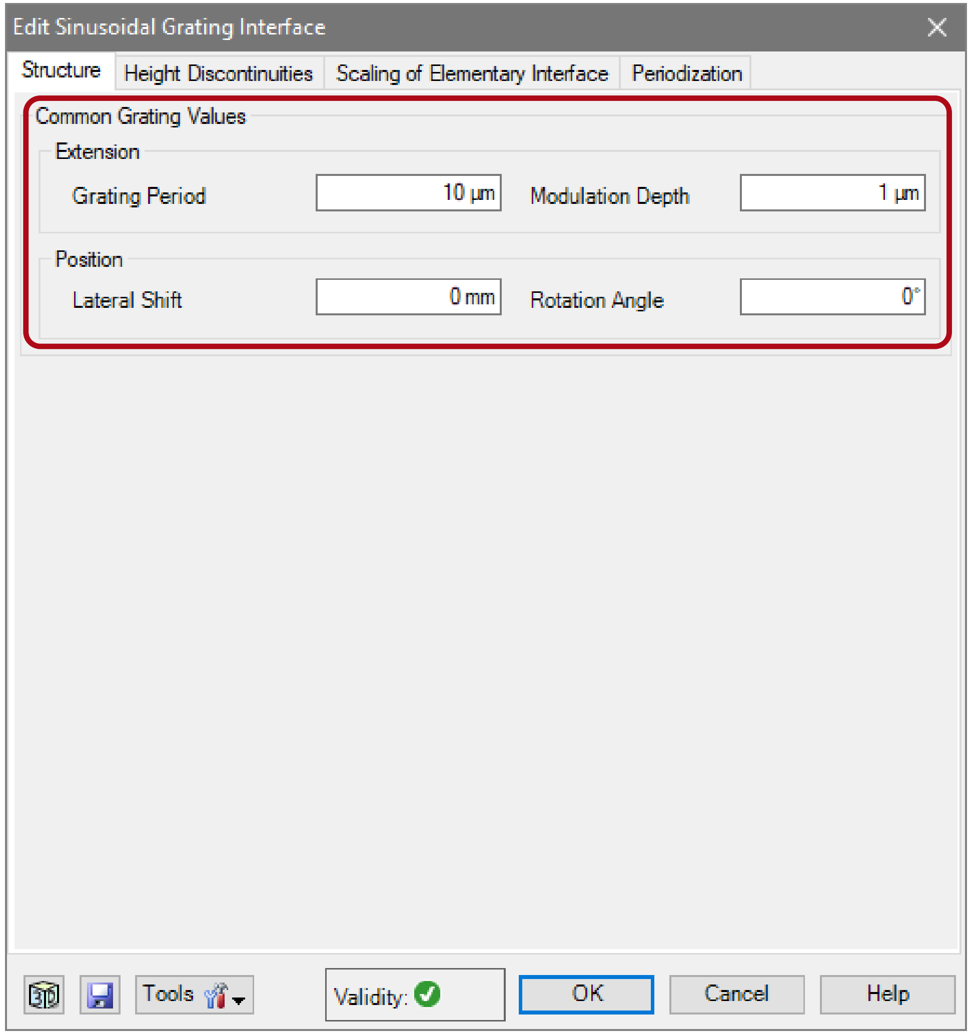
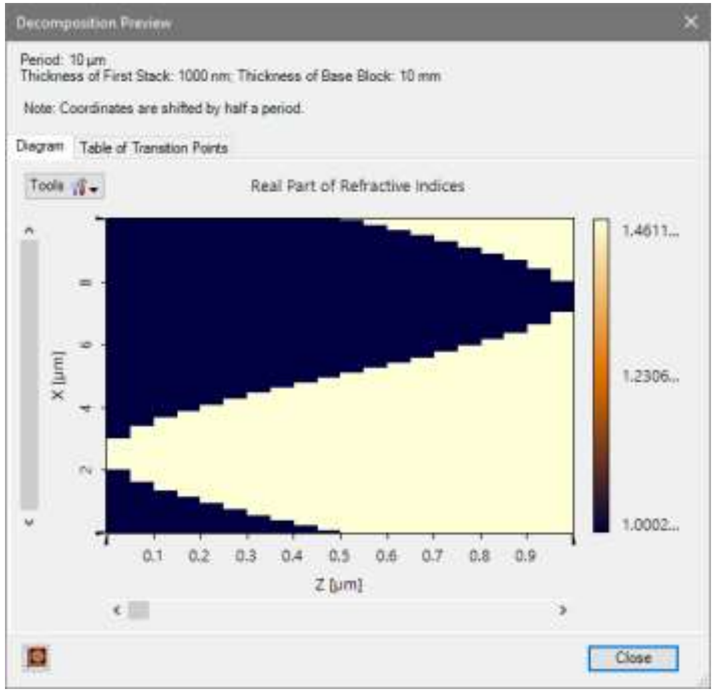
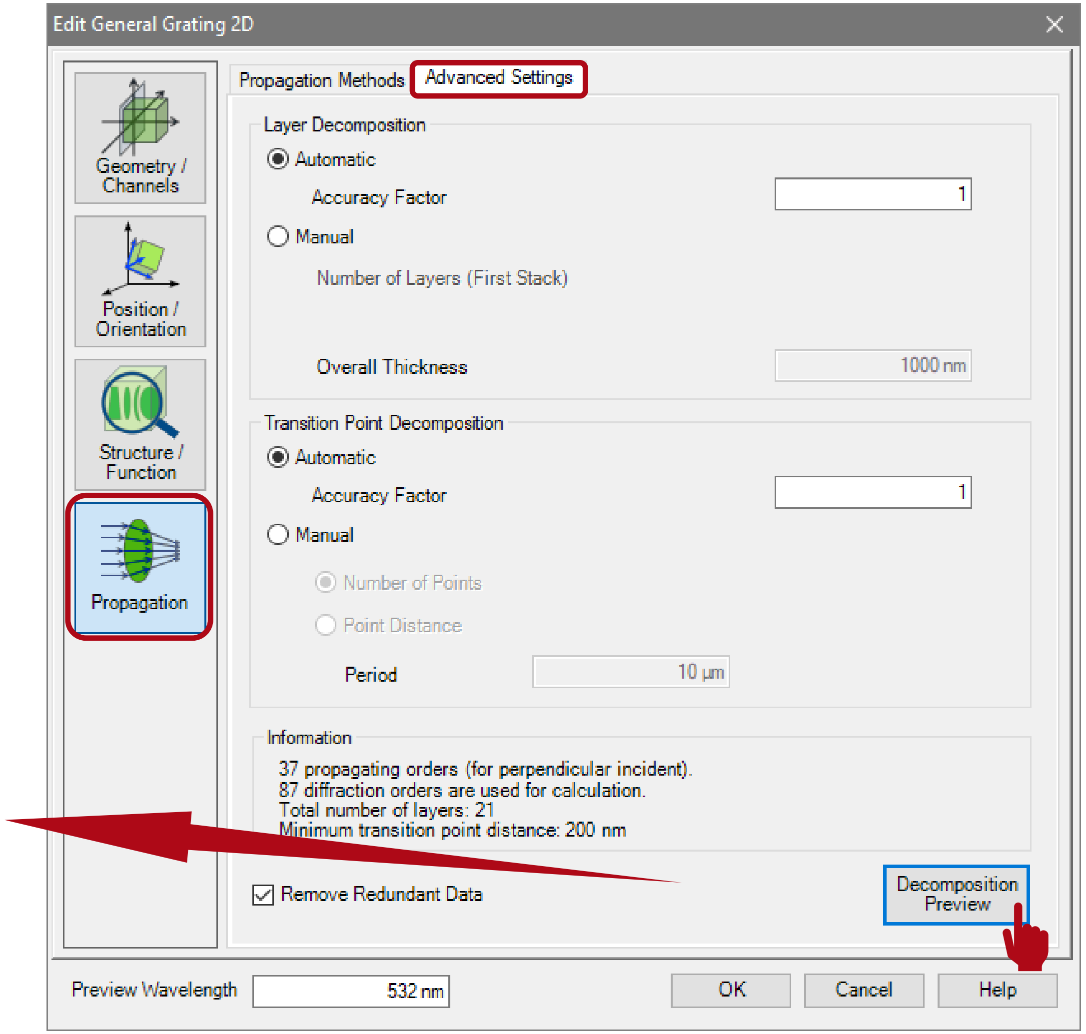


Advanced Options & Information

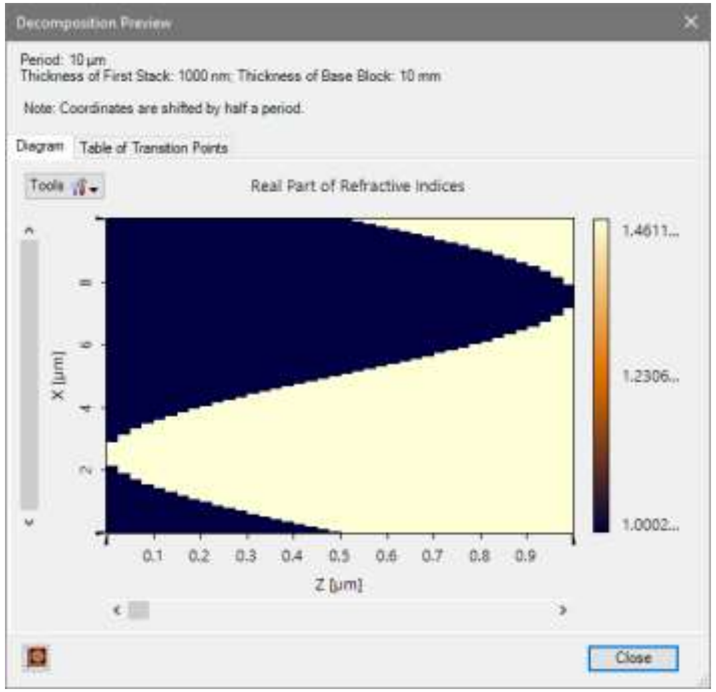
- Again, the data of the decomposed structure can be adjusted and investigated in the advanced settings tab.

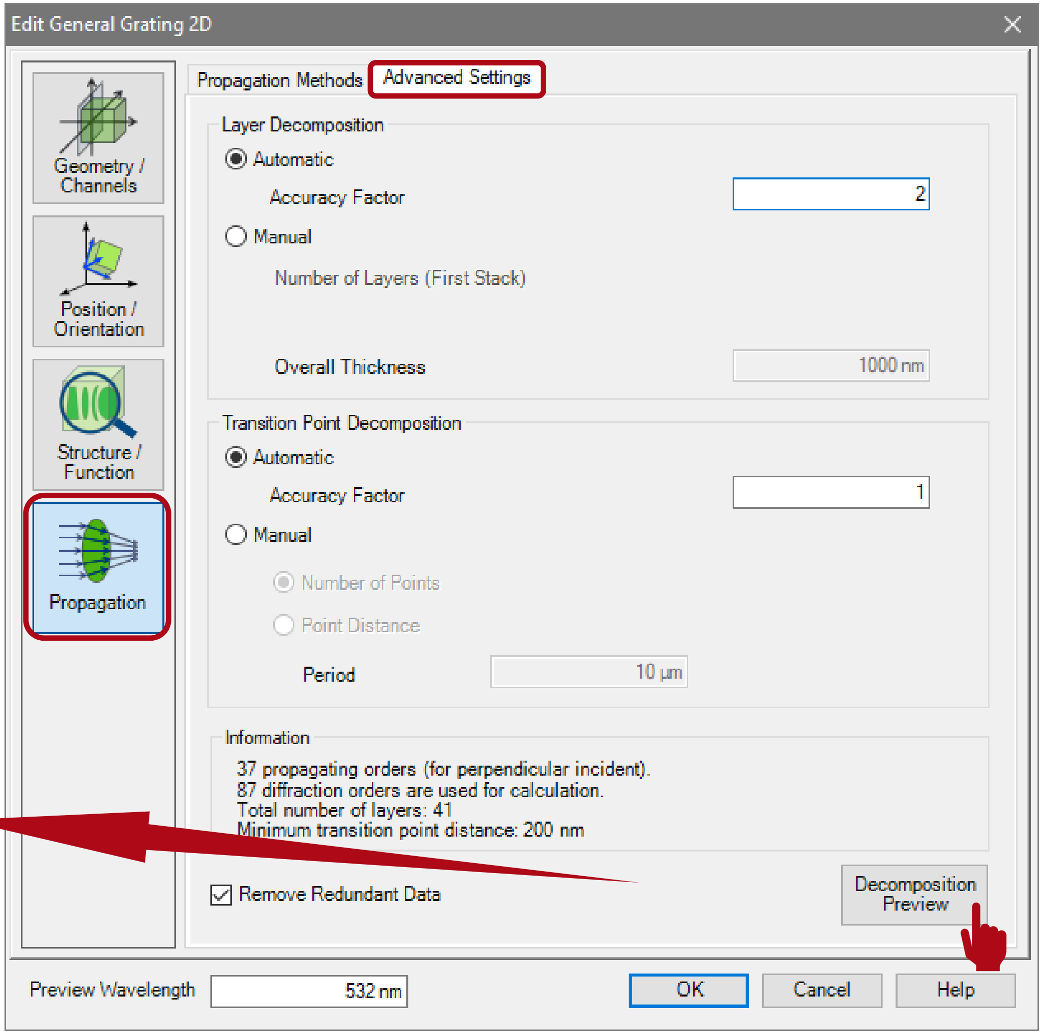




Advanced Options & Information

- If the number of layers is increased (e.g. by a factor of 2), the discretization becomes less rough.

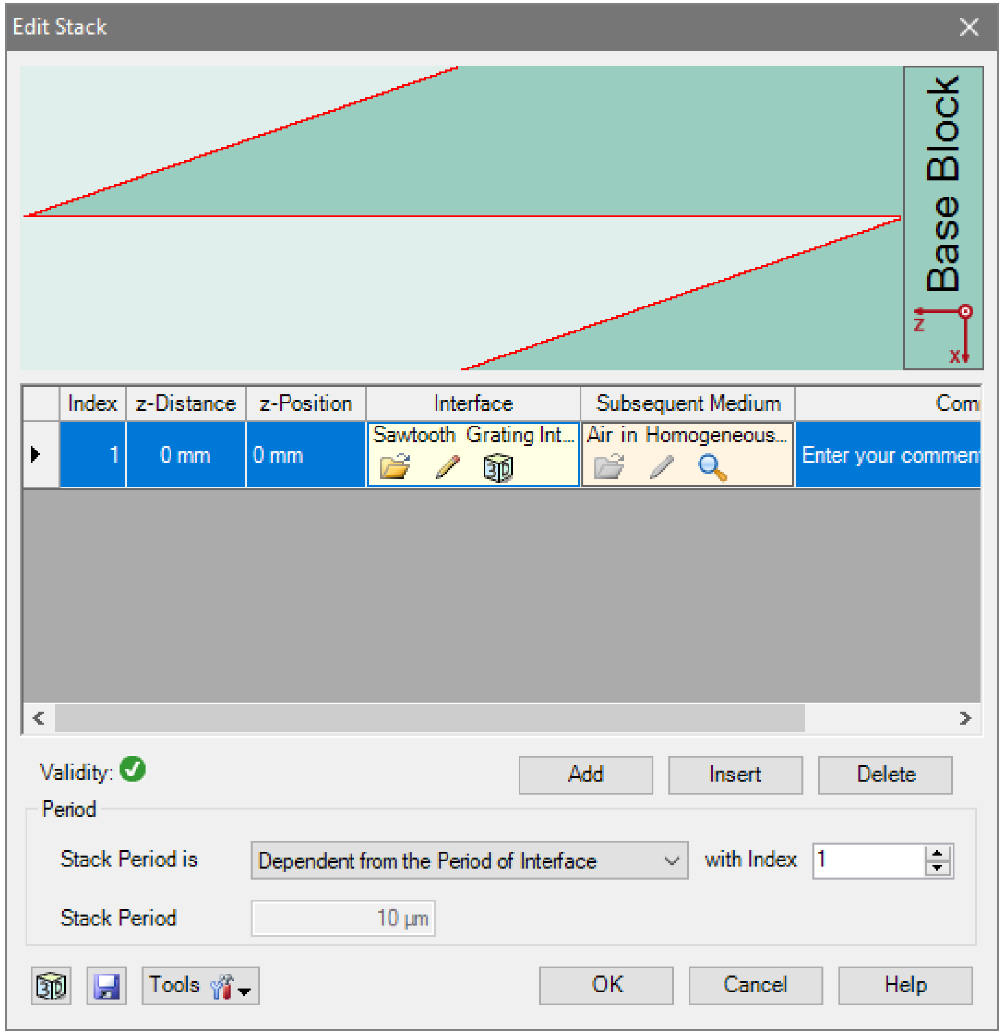




Sawtooth Grating Interface

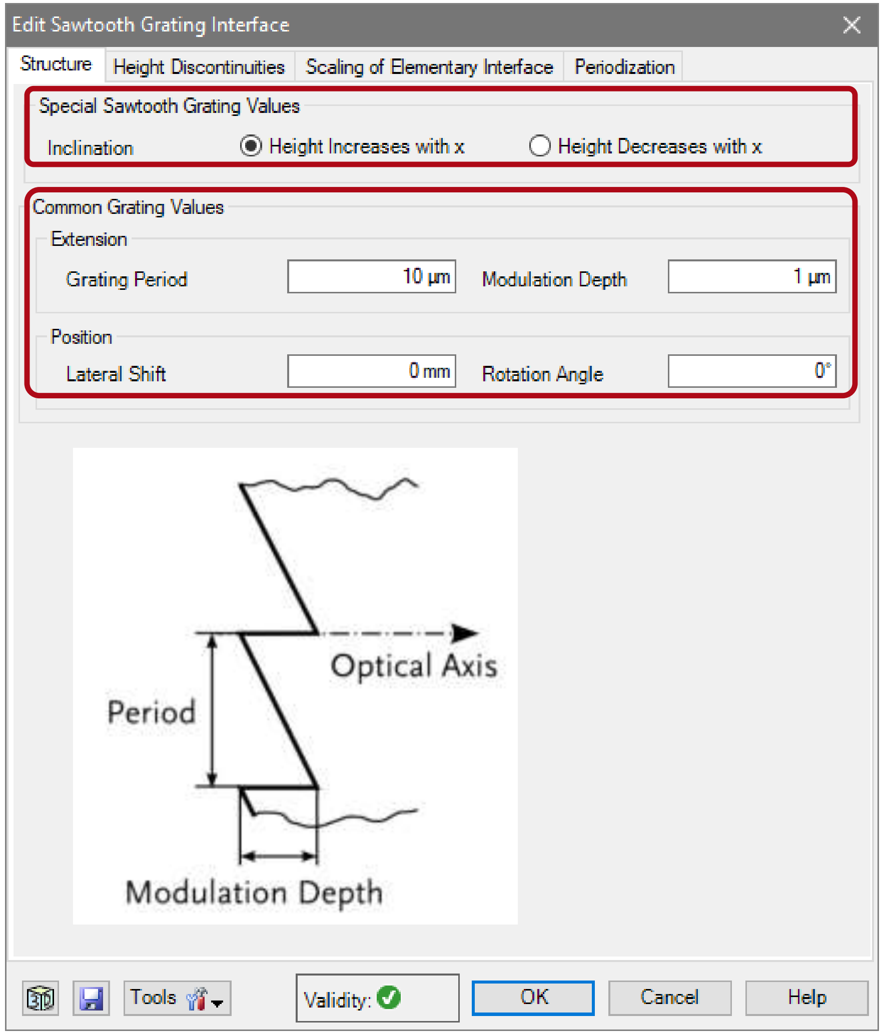
Sawtooth Grating Interface

- Another type of interface which can be used for the configuration of gratings is the sawtooth grating interface.
- This interface allows to configure gratings with blazed structure.
- If a single interface is used to describe the grating structure, the materials are chosen automatically:
  - material of ridges: material of substrate
  - material of grooves: material in front of grating



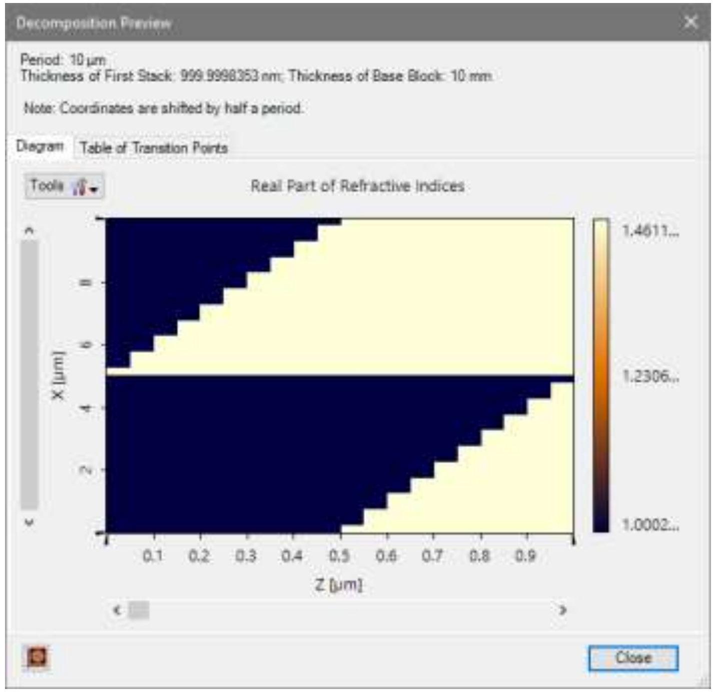
Sawtooth Grating Interface Parameters

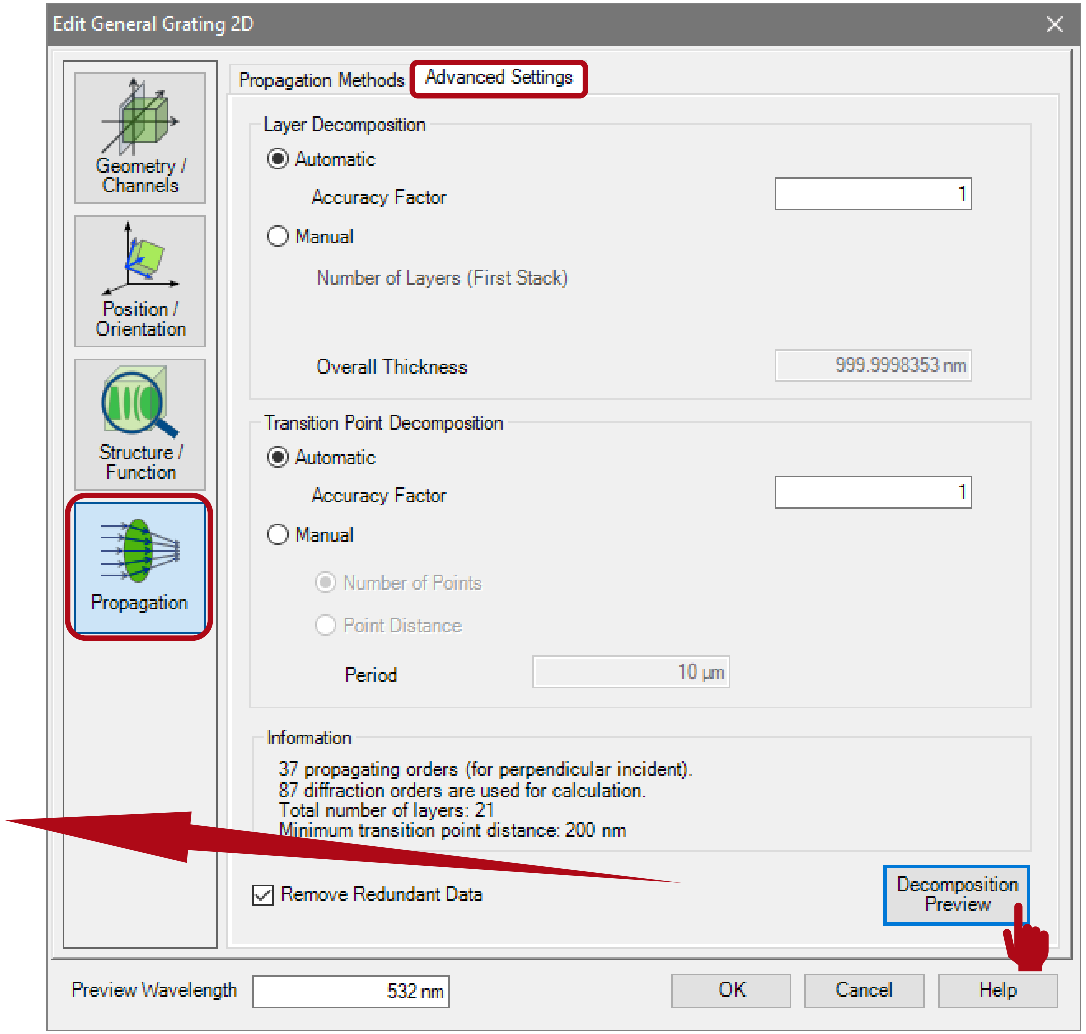
- The sawtooth grating interface is also defined by the following parameters:
  - grating period
  - modulation depth
- Further, the direction of the blaze can be adjusted by setting the inclination.
- A lateral shift and rotation can be set optionally.
- As this is a grating interface (likewise to the rectangular and sinusoidal one) no periodization has to be chosen.



Advanced Options & Information

- Again, the data of the decomposed structure can be adjusted and investigated in the advanced settings.

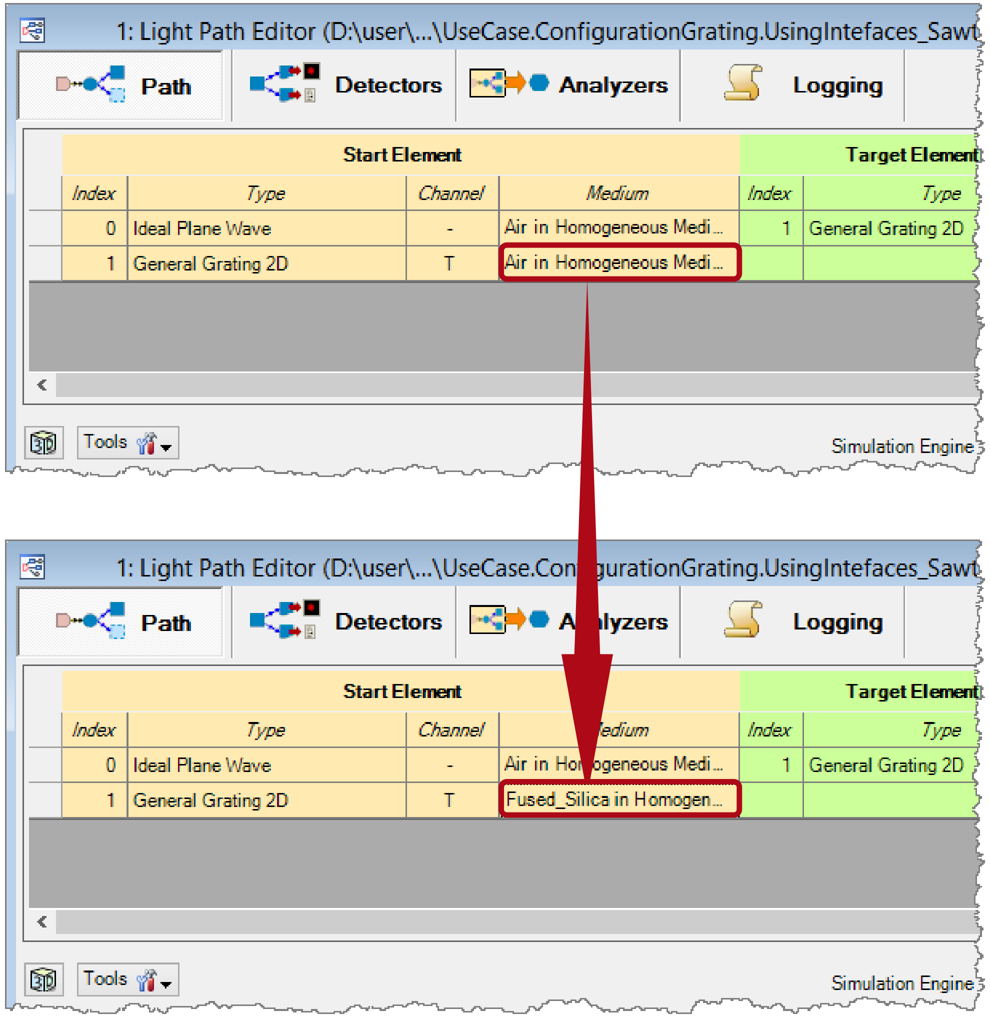




Remark on the Position of the Detector

Remark on the Detector Position

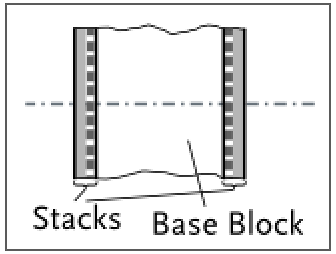
- In VirtualLab the detector is located subsequent to the substrate in air by default.
- This is necessary if the grating is included in a complex optical setup.
- However, the perfect plane and parallel substrate may cause some interference effects, which not occur in reality.
- Thus, for calculation of just grating efficiencies it is appropriate to set the detector inside the substrate material (likewise to most of grating evaluation software).
- This avoids the undesired influence of those interference effects.



(v0.9)

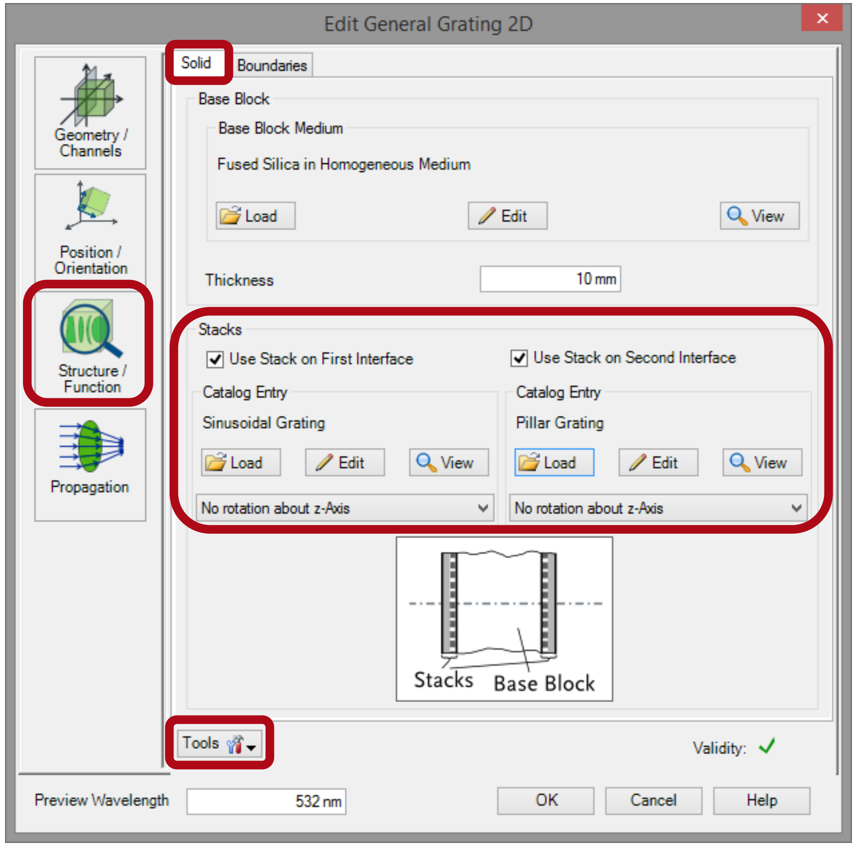
Definition of Customized 2D and 3D Grating Structures by Stack Concept

Baseblock and Stacks



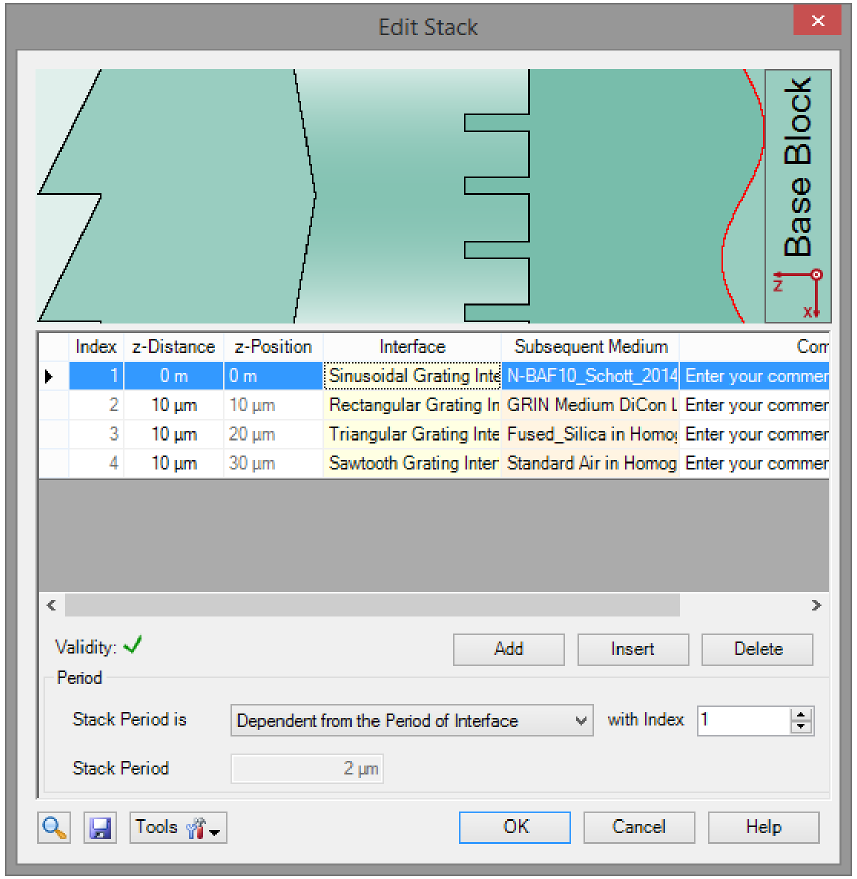
- A base block of a homogeneous medium (substrate) can have a stack of micro structured layers on each side.
- The stacks consists of a sequence of optical interfaces and homogeneous as well as inhomogeneous media.

Stack Configuration



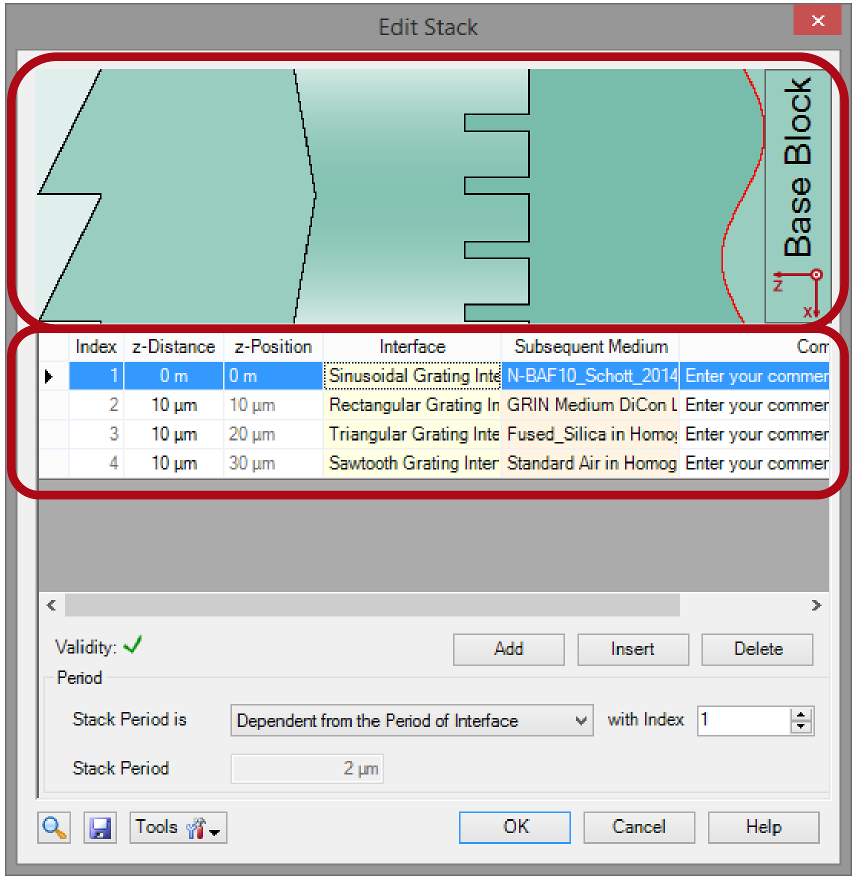
- Stacks can be added for the front and back surface of the base block.
- Stacks can be loaded from the stack catalog.
- Rotation of stack by 180° possible.
- Tools menu allows to
  - Swap stacks of front and back surface
  - Disable second stack

Stack Configuration



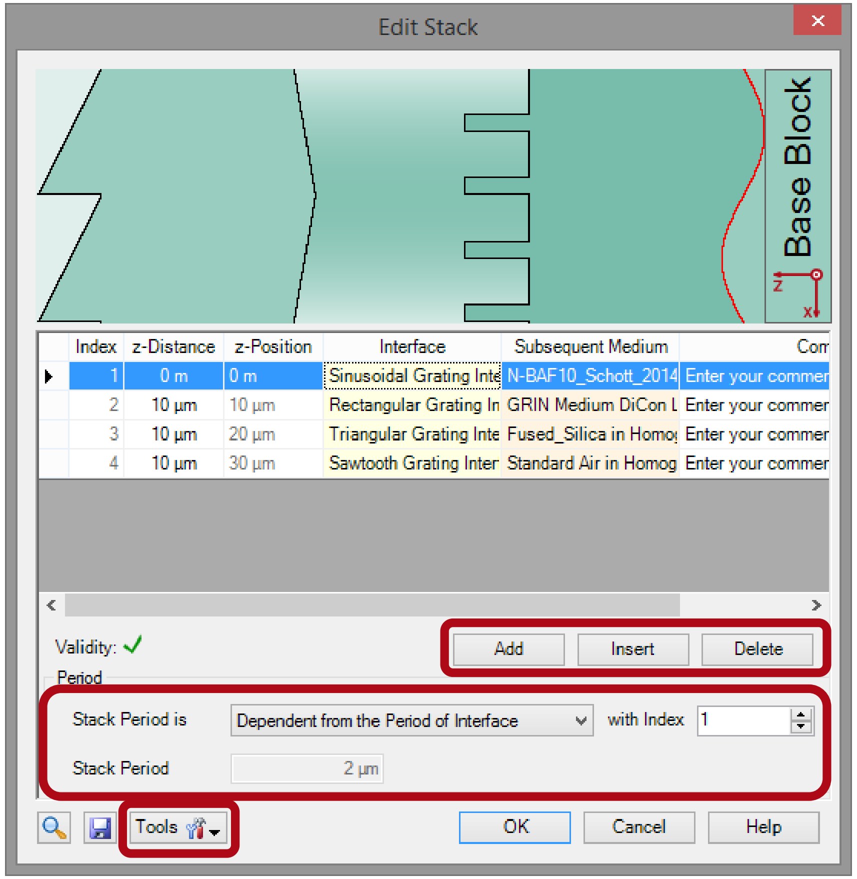
- A stack is constructed by a sequence of predefined or user defined optical interfaces and media.
- Homogeneous and inhomogeneous media can be between the optical interfaces.

Stack Configuration



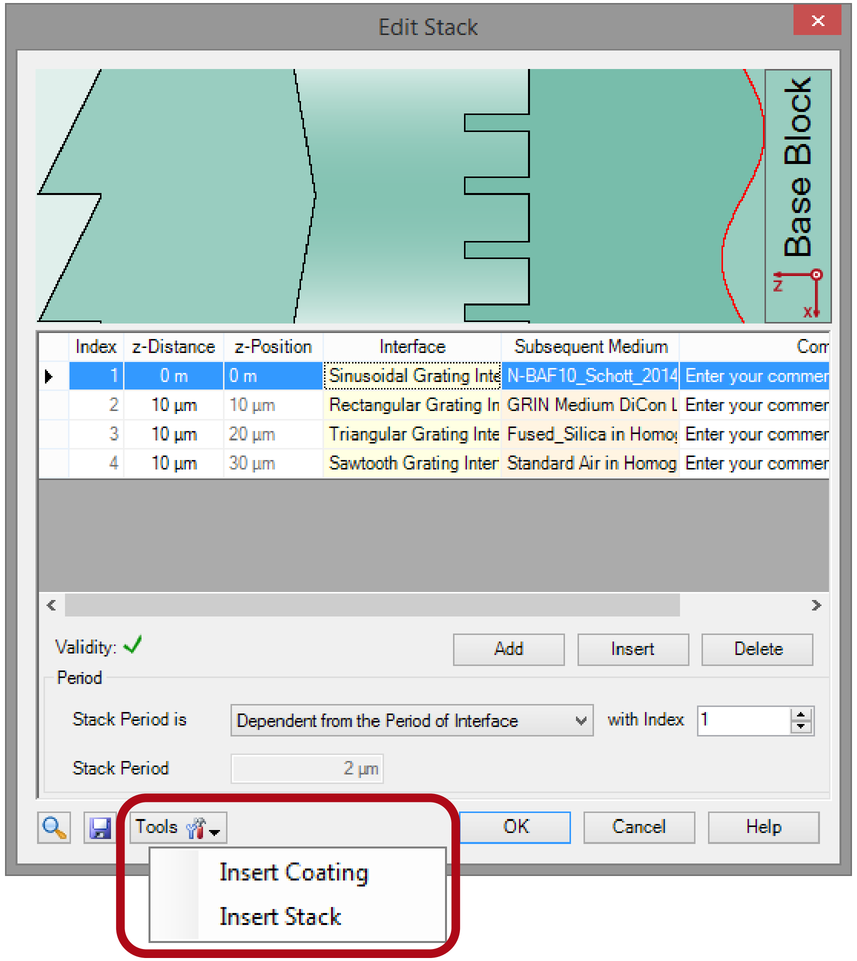
- 2D view of Stack.
- Table contains the sequence of interfaces.
- The distances are measured to the previous interface on the optical axis.
- All VirtualLab surfaces can be used, such as:
  - Plane interface
  - Conical interface
  - Aspherical interface
  - Cylindrical interface
  - Polynomial interface
  - Programmable interface
  - Sampled interface
  - Combined interface
  - Grating interfaces
  - Zernike Standard interface

Stack Configuration



- Buttons allow to add, insert and delete surfaces.
- Surfaces are add or inserted from interface catalog.
- Different option for a common stack period.
- Additional tools for manipulation of stacks.

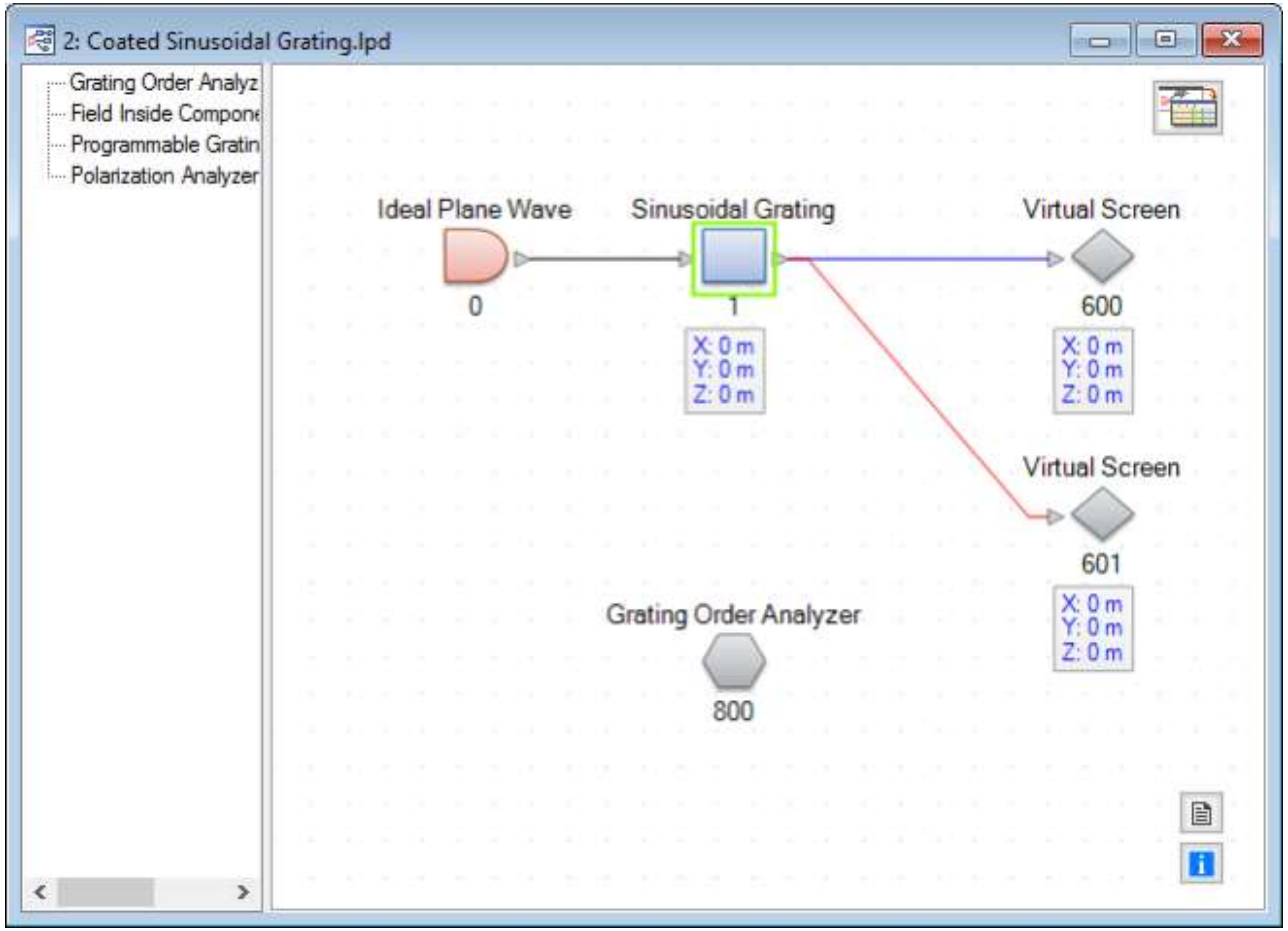
General 2D/3D Gratings



- Insert coating as a sequence of surfaces.
- Coating thickness varies depending on surface gradient.
- Inserts a stack from stack catalog.

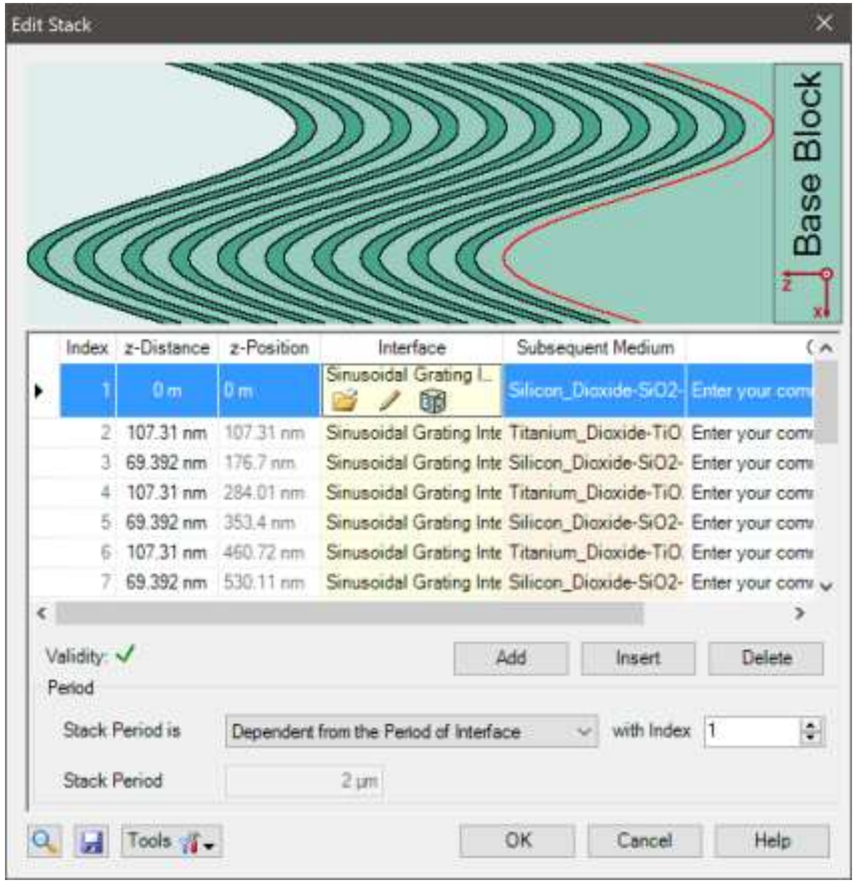
Applied VirtualLab Techniques and Tools

Sample File



Filename: Coated Sinusoidal Grating.lpd

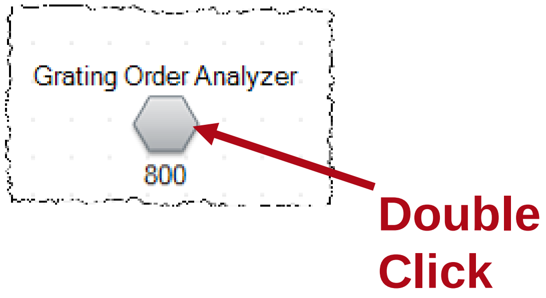
Grating Specification



- For the demonstration of the Grating Order Analyzer for 1D gratings we use a coated sinusoidal grating.
- The grating parameters can be specified within the stack that can be accessed in the edit dialog of the grating component.

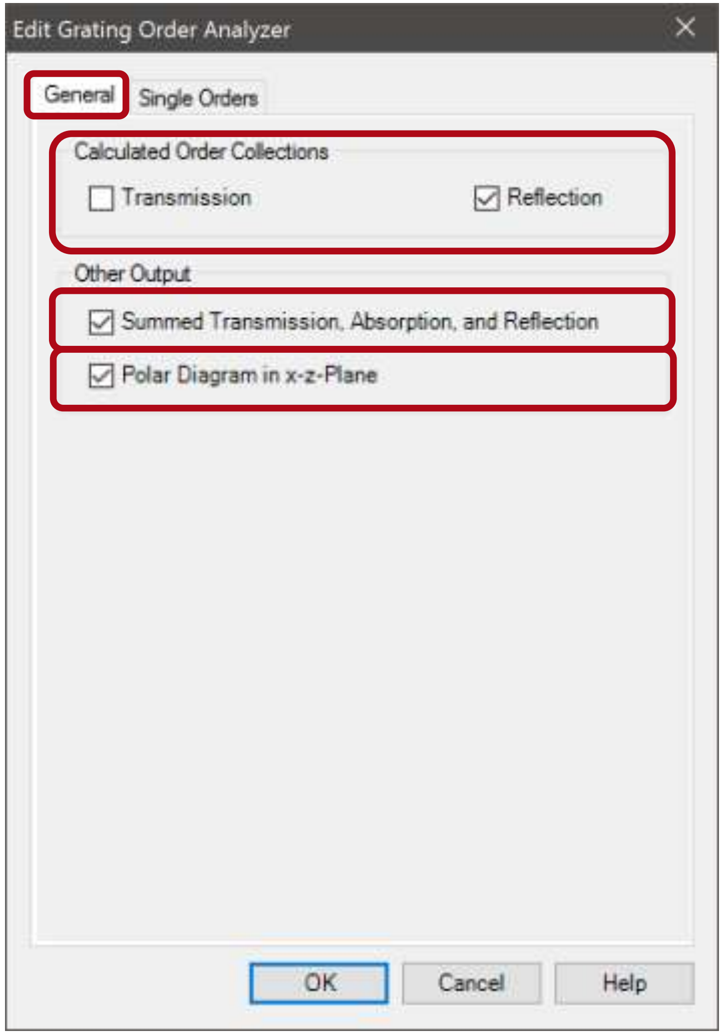
Grating Order Analyzer

- After the grating structure has been defined you can configure the grating order analyzer.
- Various output options can be specified.
- This is done through the edit dialog of the analyzer which is opened by double clicking on the light path element in the light path view.



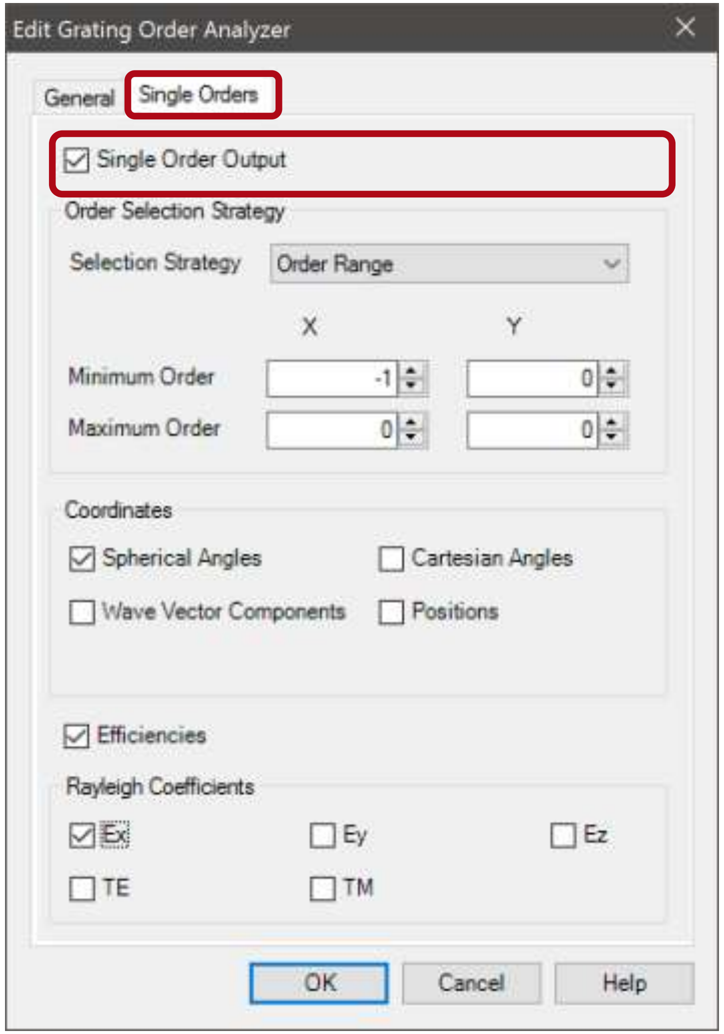
- The options of the analyzer will be explained in the following slides.

Grating Order Analyzer



- In the *General* tab page you can select whether transmission and/or reflection shall be analyzed.
- In addition you can specify whether you would like to evaluate the summed transmission, absorbtion and reflection values and whether you would like to show a polar diagram.

Grating Order Analyzer

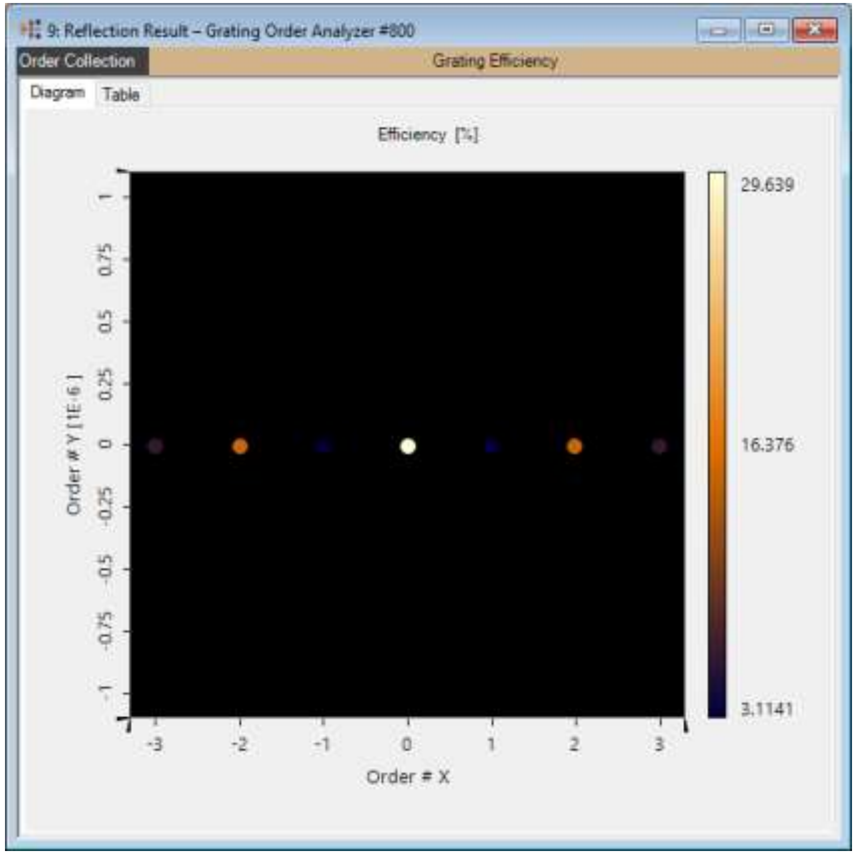


- In the *Single Orders* tab you can select whether information for single orders shall be logged.
- This option is very helpful if you would like to use the parameter run or the parametric optimization of VirtualLab to analyze and optimize specific orders of a grating.

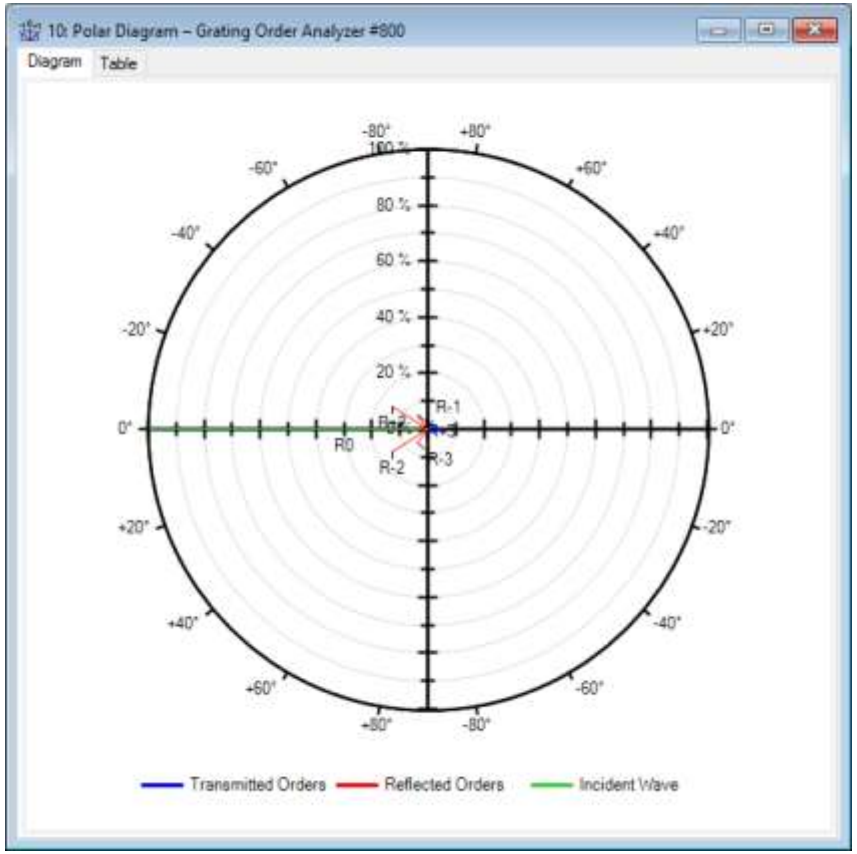
Options for Single Order Output

Parameter	Description
Order Selection Strategy	The user can define which order shall be evaluated. The user can define whether to analyze **All** orders, analyze only those orders which have an efficiency **Above a Given Threshold** or calculate only orders in a manually defined **Order Range**. Depending on the selection strategy the user has to define additional parameters.
Coordinates	Logging of the coordinates of the orders is also supported. The user can specify whether to show the coordinates in **Spherical Angles**, **Cartesian Angles**, **Wave Vector Components** or **Positions**. For the Position calculation a z-distance between the grating and the screen has to be specified.
Efficiencies	The user can select whether efficiencies shall be logged.
Rayleigh Coefficients	In addition it is possible to log the Rayleigh coefficients. The user can select to show the coeffient $\mathbf{E_x}$, $\mathbf{E_y}$, $\mathbf{E_z}$, **TE** or **TM**.

Grating Order Analyzer – Outputs

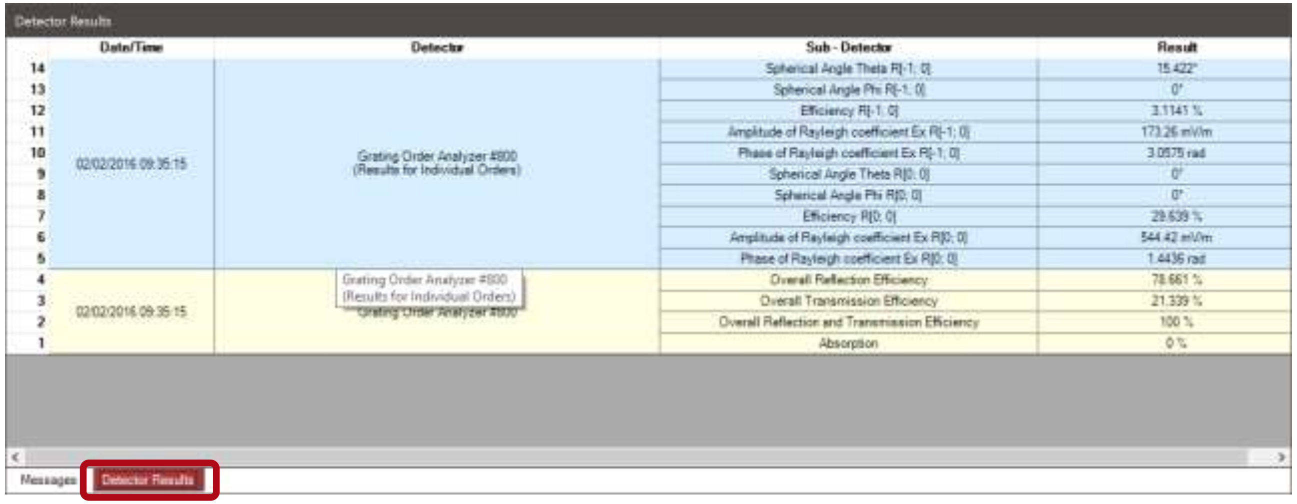


Grating Order Collection



Polar Diagram

Grating Order Analyzer – Outputs



Detector Results

	Date/Time	Detector	Sub - Detector	Result
14	02/02/2016 09:35:15	Grating Order Analyzer #800 (Results for Individual Orders)	Spherical Angle Theta R[-1; 0]	15.422°
13			Spherical Angle Phi R[-1; 0]	0°
12			Efficiency R[-1; 0]	3.1141 %
11			Amplitude of Rayleigh coefficient Ex R[-1; 0]	173.26 mV/m
10			Phase of Rayleigh coefficient Ex R[-1; 0]	3.0575 rad
9			Spherical Angle Theta R[0; 0]	0°
8			Spherical Angle Phi R[0; 0]	0°
7			Efficiency R[0; 0]	28.639 %
6			Amplitude of Rayleigh coefficient Ex R[0; 0]	544.42 mV/m
5			Phase of Rayleigh coefficient Ex R[0; 0]	1.4436 rad
4	02/02/2016 09:35:15	Grating Order Analyzer #800	Overall Reflection Efficiency	78.661 %
3			Overall Transmission Efficiency	21.339 %
2			Overall Reflection and Transmission Efficiency	100 %
1			Absorption	0 %

Messages | Detector Results

- If the Grating Order analyzer is processed within the Light Path diagram the single order output values are logged into the detector results tab.
- These values are also available in the parameter run and the parametric optimization.

Grating Order Output: Polar Diagram

Polar Diagram

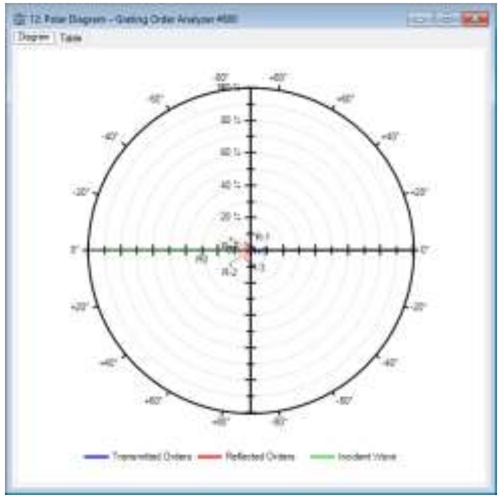


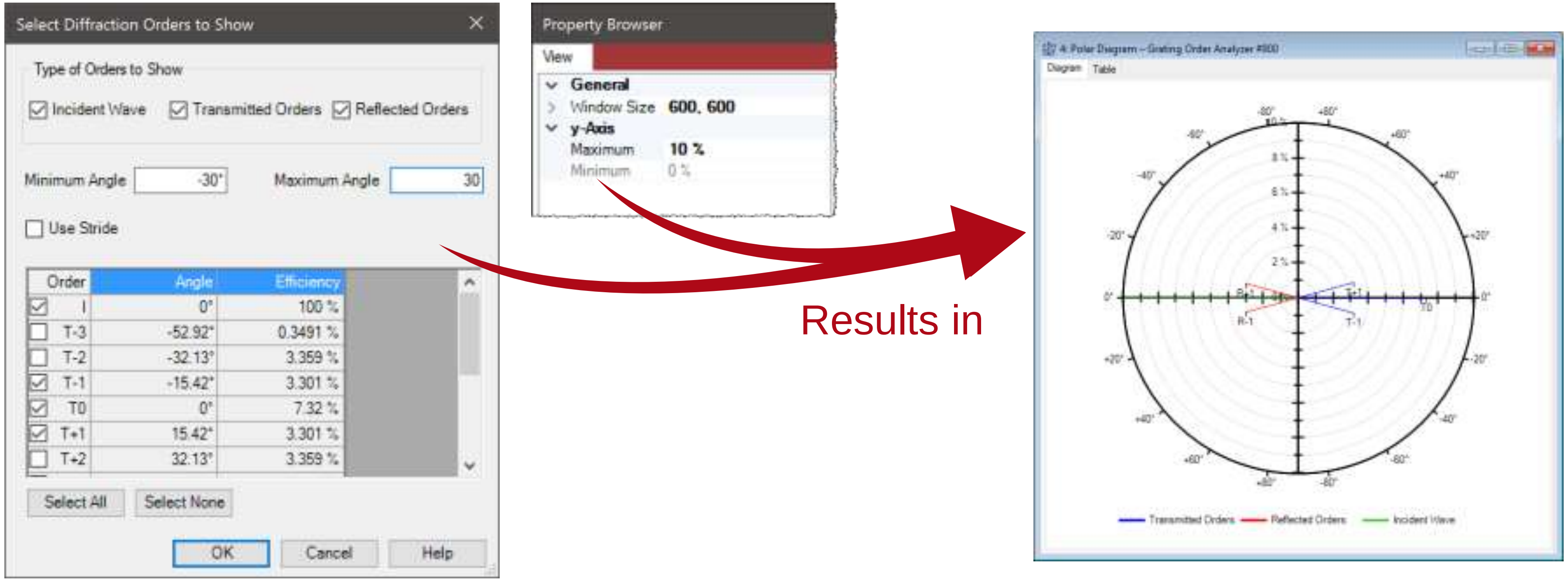
Diagram | Table

Order	Angle	Efficiency
I	0°	100 %
T-3	-52.919°	0.34913 %
T-2	-32.131°	3.3594 %
T-1	-15.422°	3.3009 %
T0	0°	7.3204 %
T+1	15.422°	3.3009 %
T+2	32.131°	3.3594 %
T+3	52.919°	0.34913 %
R-3	52.919°	6.2033 %
R-2	32.131°	15.194 %
R-1	15.422°	3.1141 %
R0	0°	29.639 %
R+1	-15.422°	3.1141 %
R+2	-32.131°	15.194 %
R+3	-52.919°	6.2033 %

- The polar diagram output of the Grating Order Analyzer plots the efficiencies of both the reflected and the transmitted orders versus the angles in the x-z-plane.
- It also provides a table of all angles and efficiencies of the displayed orders.

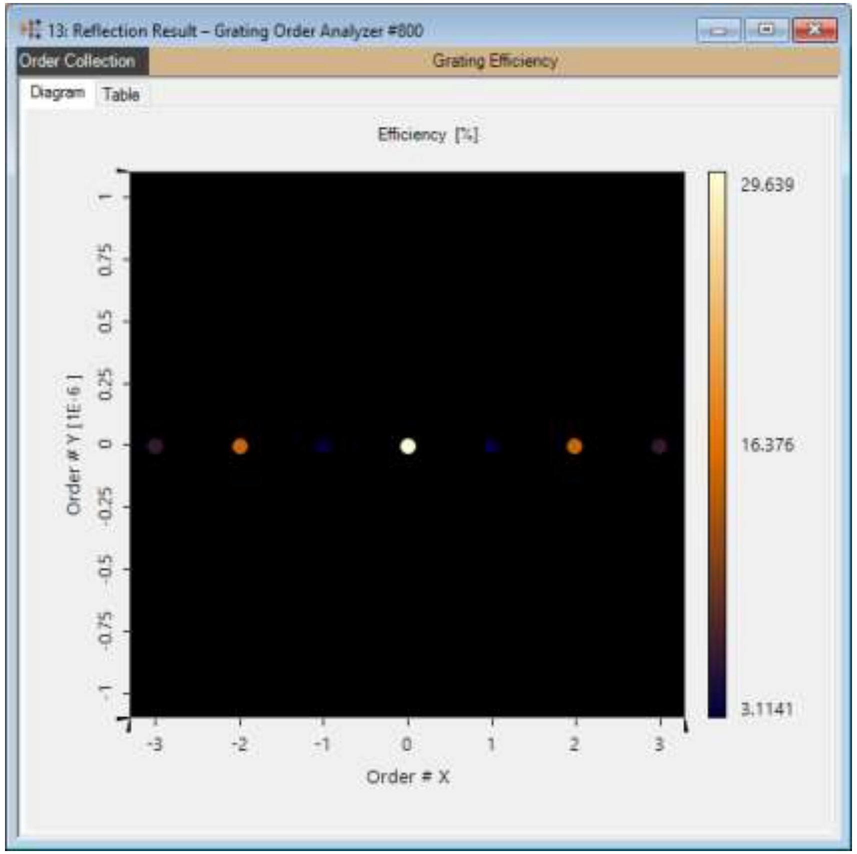
Configuring the Polar Diagram

- You can zoom into the polar diagram via the mouse wheel, the property browser and ribbon item.
- You can configure which orders are shown by right-clicking on the diagram.



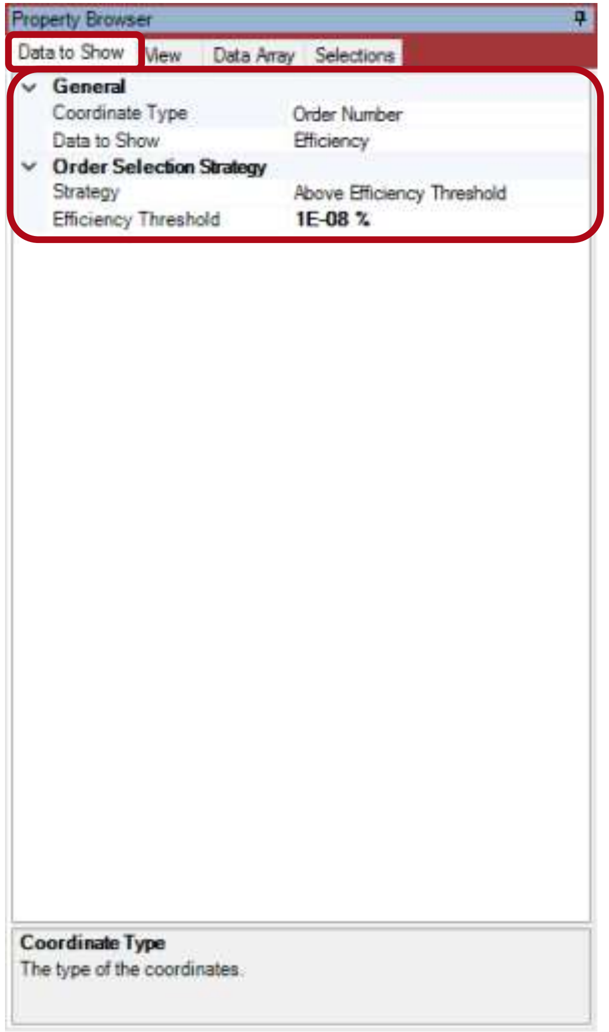
Grating Order Output: Order Collection

Grating Order Collection



- The Grating Order Collection object is used to visualize the calculated grating efficiencies or the Rayleigh coefficients over different coordinates.
- The user can configure the data that shall be shown by setting diverse options via the property browser.

Setup of Data to Show

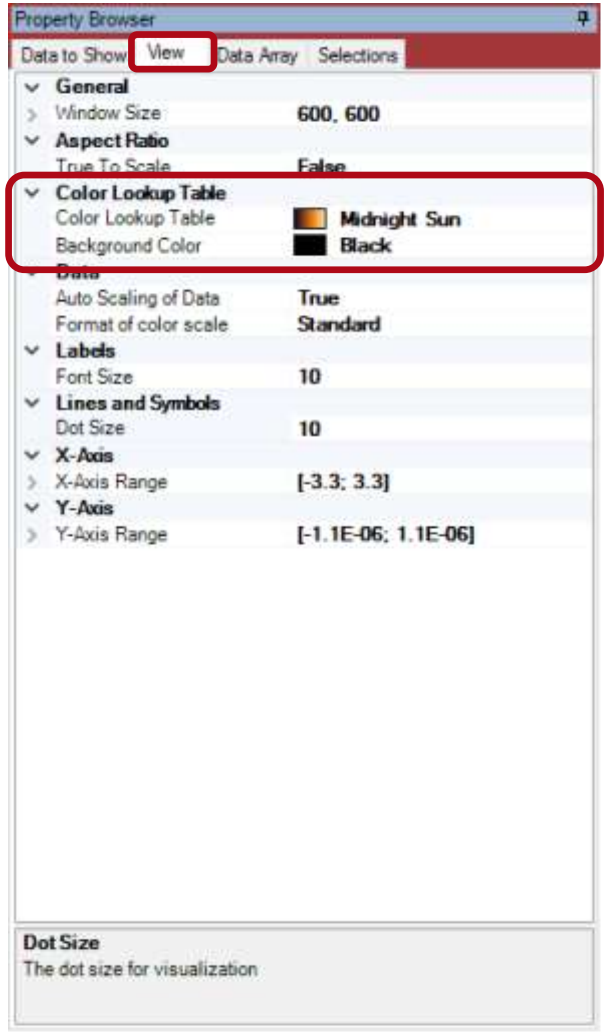


- You can specify via the property browser which data shall be shown over which coordinates.
- In addition the user can select the order to be shown in the diagram.
- These settings are done on the **Data to Show** tab page of the property browser.

Setup of Data to Show

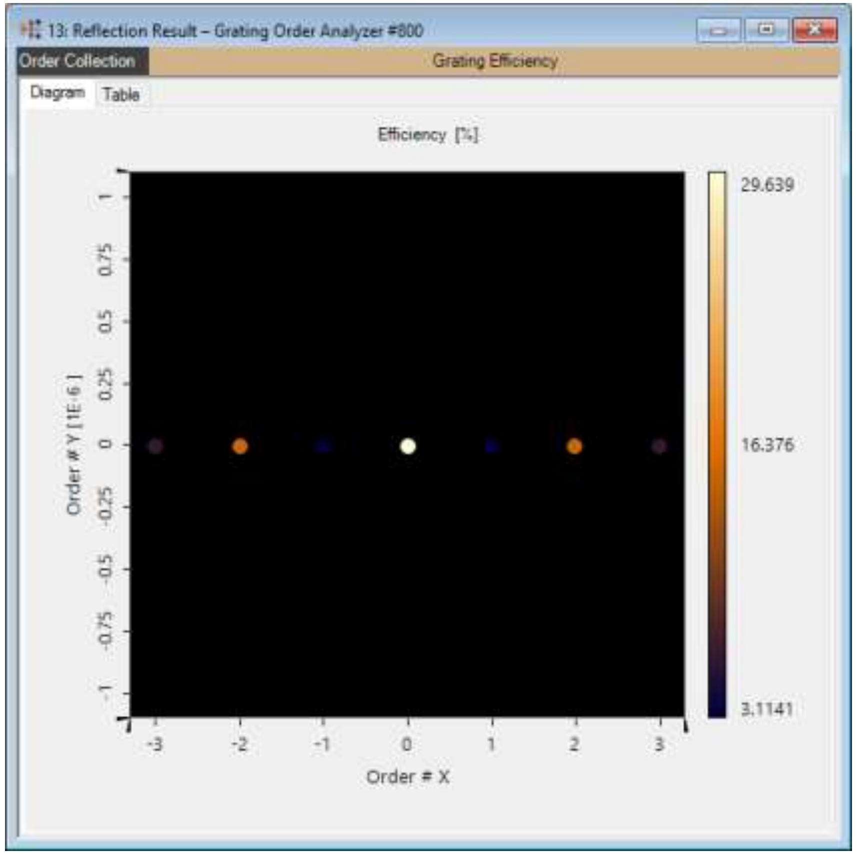
Option	Description
Coordinate Type	This property can be used to define the coordinates over which the data shall be visualized. Currently the order collection supports the visualization over **Cartesian Angles**, **Spherical Angles**, **Wave Number Vectors** and **Positions**.
Data to Show	It is possible to select the different data values that should be shown. The user can select to display the efficiency or the Rayleigh coefficient over the selected coordiante type. For Rayleigh coefficents $\mathbf{E_x}$, $\mathbf{E_y}$, $\mathbf{E_z}$, **TM** and **TE** are supported.
Order Selection Strategy	The user can define which order shall be displayed. The user can define whether to show **All**, show only orders which have an efficiency **Above a Given Threshold** or show only orders for a manually defined **Order Range**. Depending on the selection strategy the user has to define additional parameters.

Setup of Additional View Settings

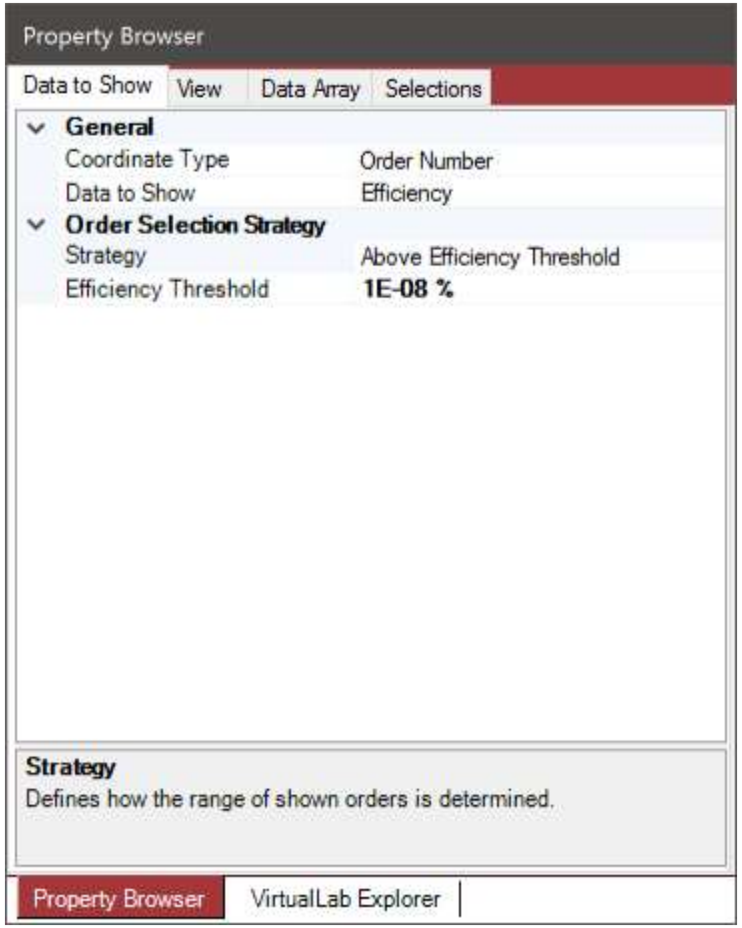


- In the **View** tab page of the property browser the user can set up additional view parameters.
- Most important for the customization of the view are the color settings.
- The user can select the background color for the view as well as the color lookup table that shall be used to define the colors for the displayed data values.

Example of View Customization

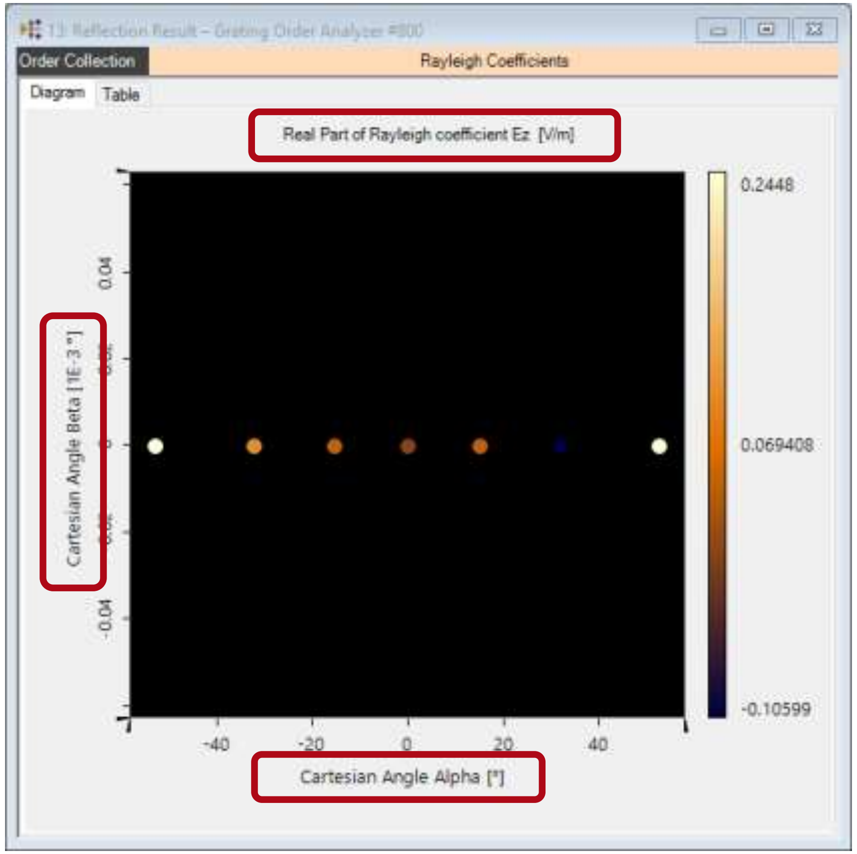


Visualization

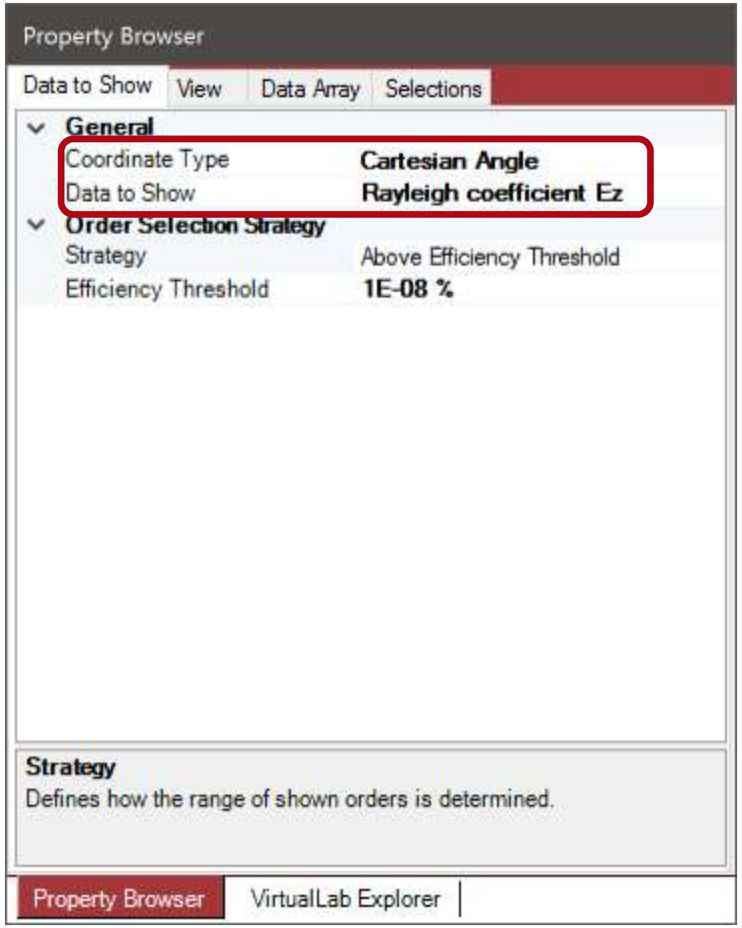


View Settings

Example of View Customization

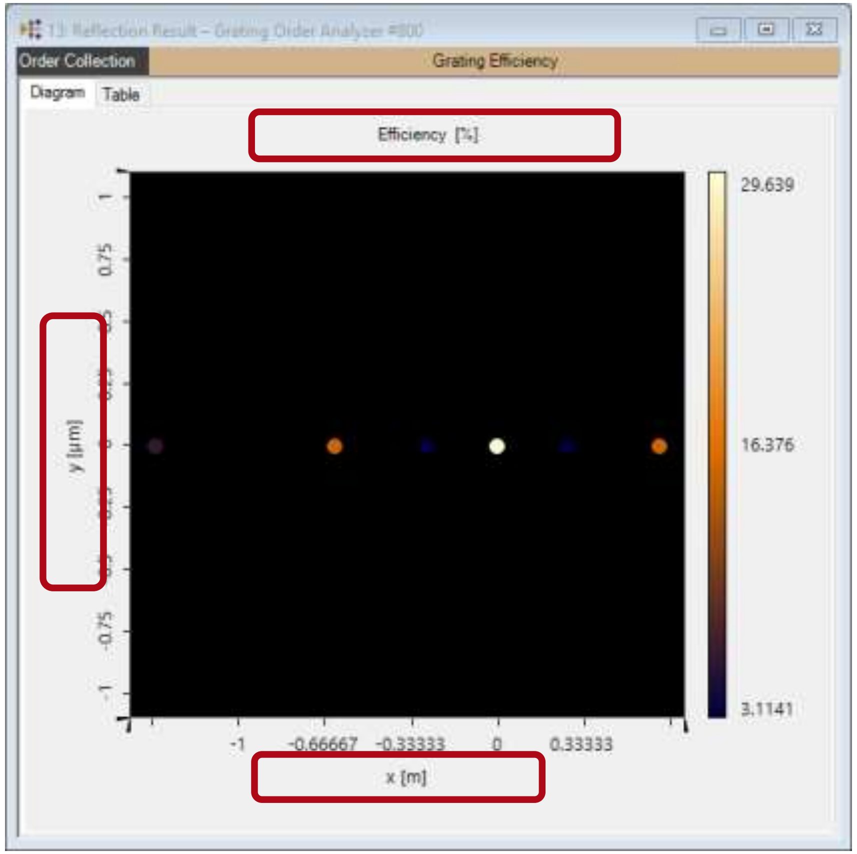


Visualization

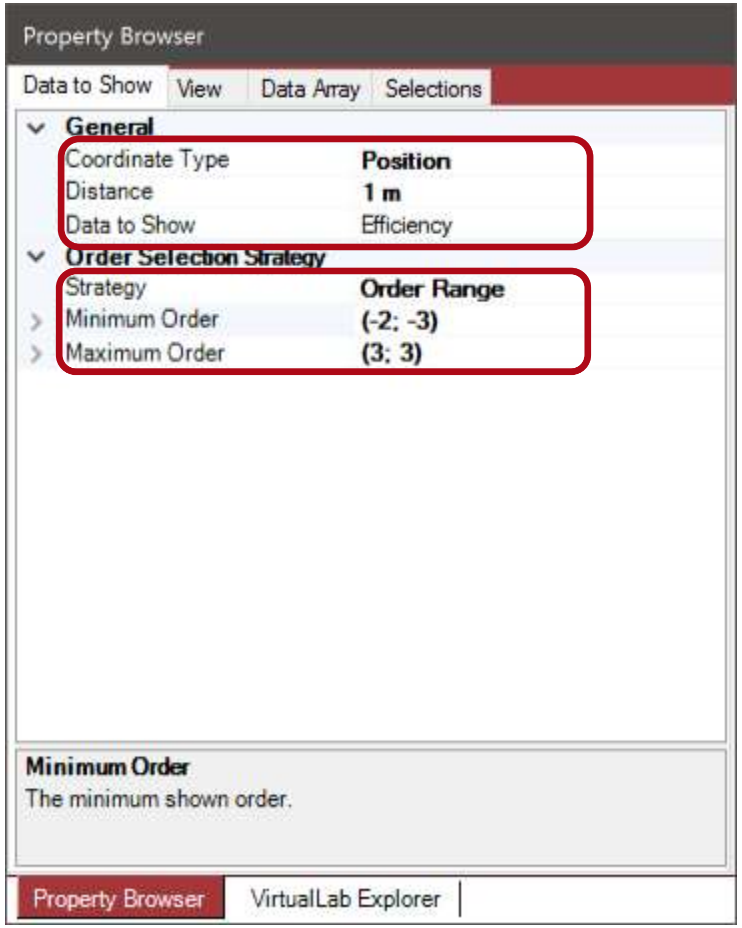


View Settings

Example of View Customization



Visualization



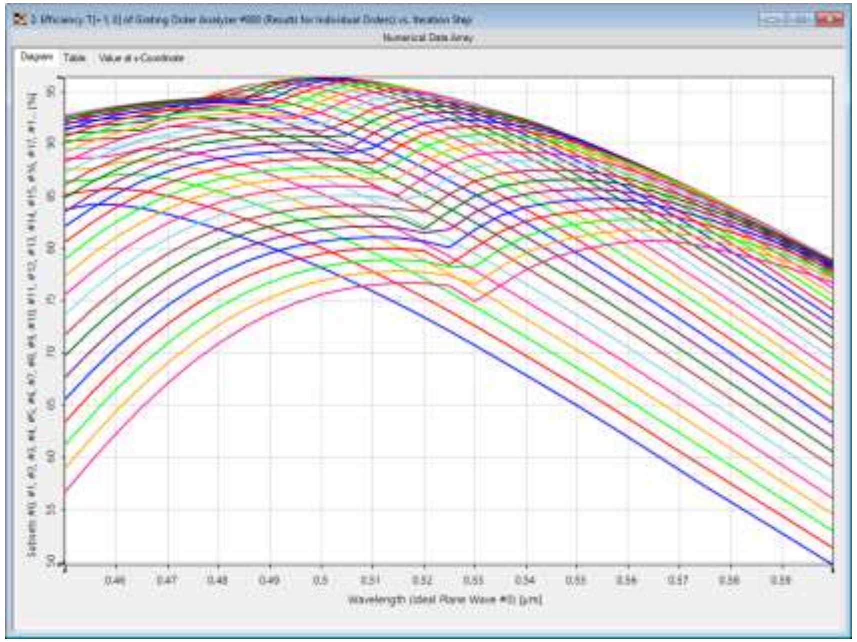
View Settings

Task 2

Analysis of Blazed Grating by Fourier Modal Method

This task helps us to review the workflow of using FMM to simulate field propagation through a grating.

Abstract

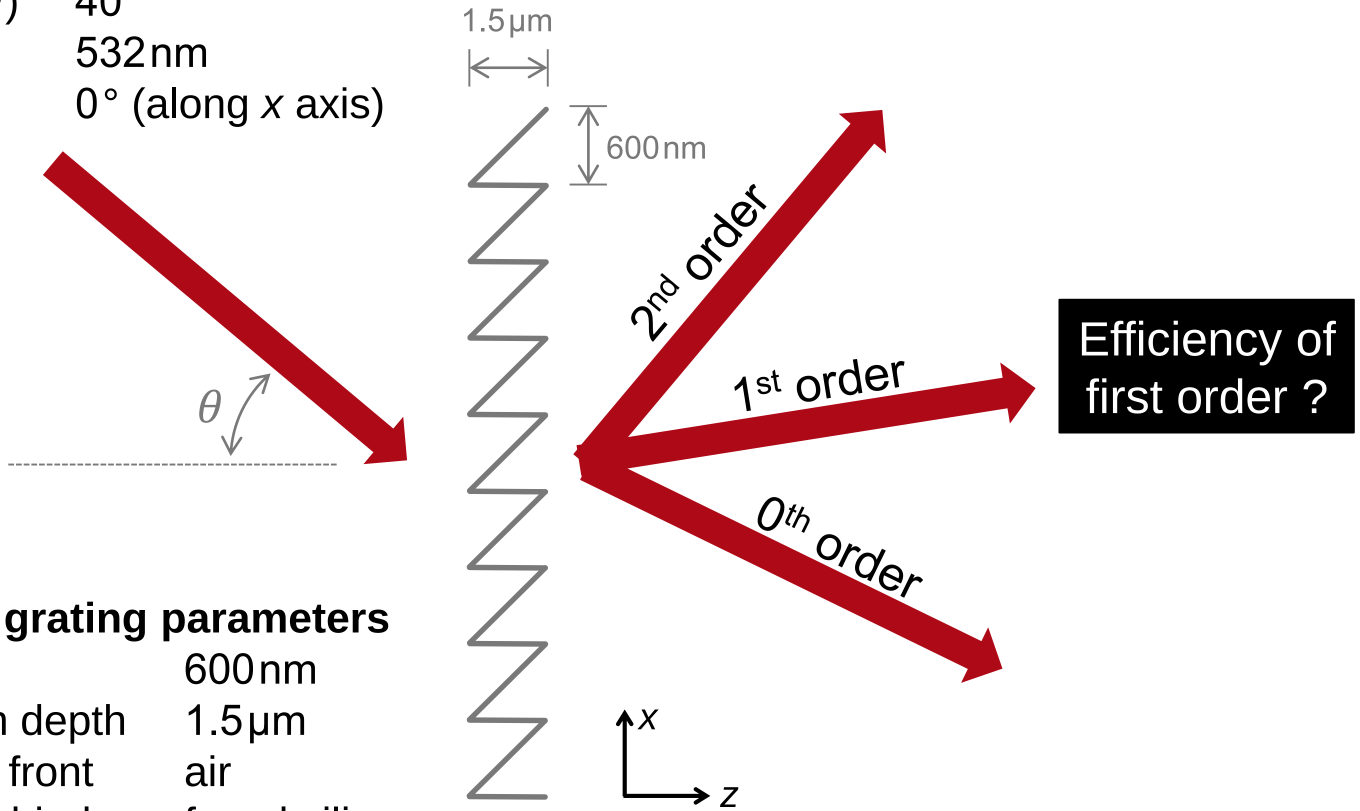


The Fourier modal method (FMM) can be used to analyze grating efficiencies rigorously. In VirtualLab you can setup your grating system, perform the rigorous analysis, and present the results in different format (e.g. grating order collection, single values, …). In combination with the parameter run you can also scan a given parameter space to investigate the performance of the specified structure for different configurations. For the evaluation of the results of the parameter run, several evaluation tools are available to give you the best insight in your optical setup.

Modeling Task

Incident plane wave

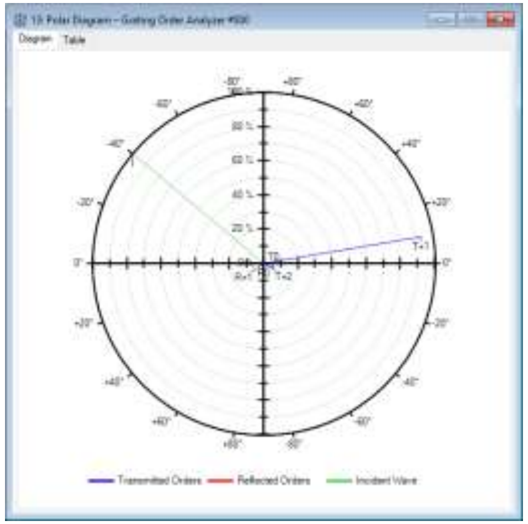
incident angle (θ)	40°
wavelength (λ)	532 nm
polarization	0° (along x axis)

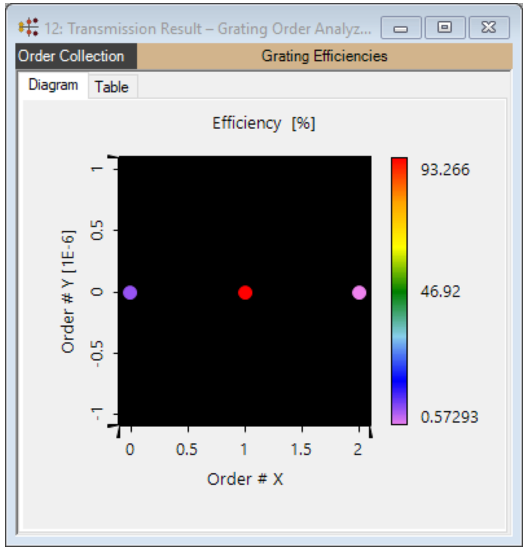


Sawtooth grating parameters

period	600 nm
modulation depth	1.5 µm
material in front	air
material behind	fused silica

Results





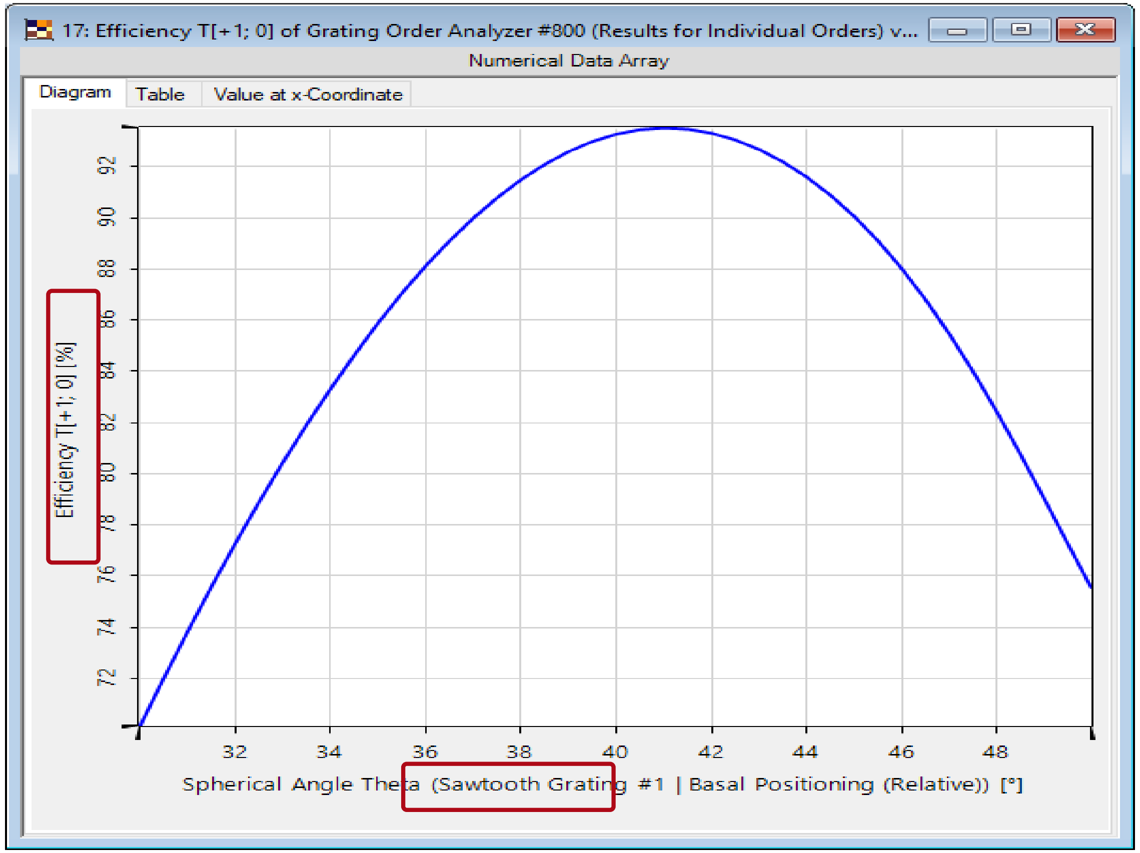
Polar diagram
used for projected visualization of grating efficiencies for transmission and reflection

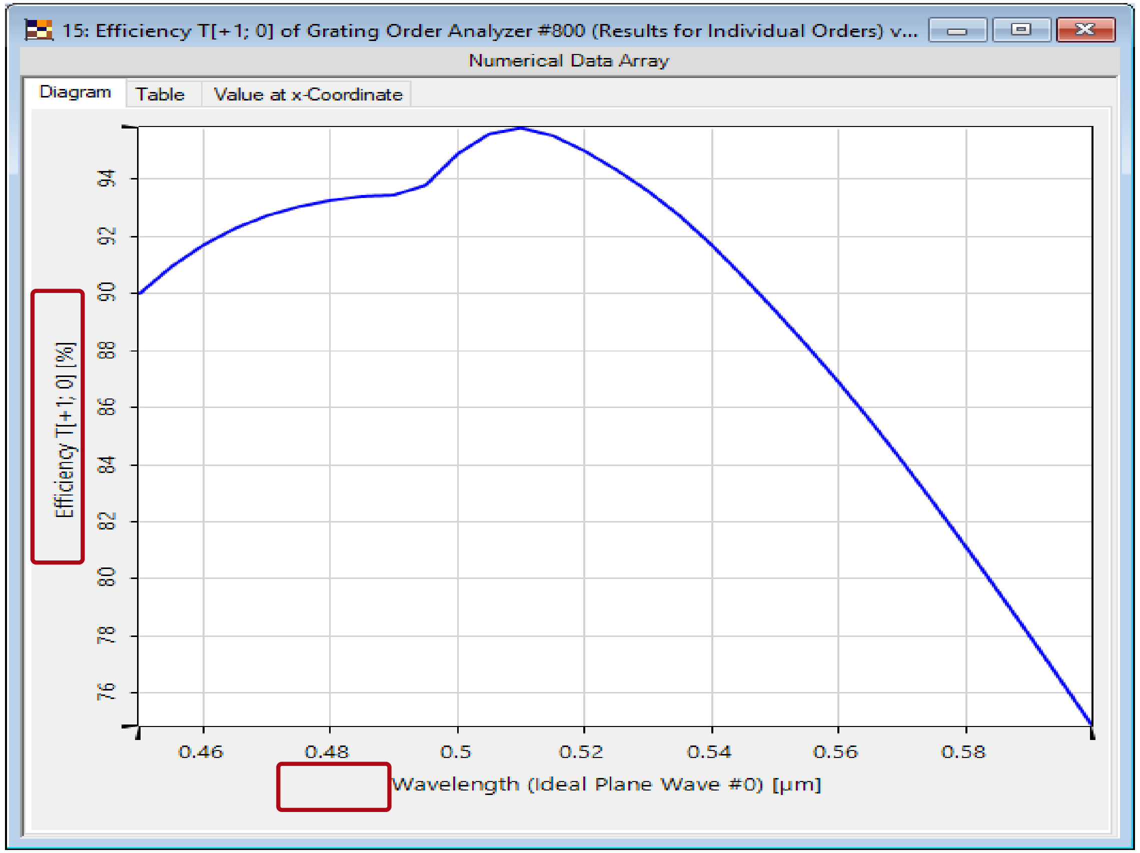
Results in transmission:

	Angle	Efficiency
0th order	-26.107°	6.1579%
1st order	9.6014°	93.266%
2nd order	50.682°	0.57293%

Order collection
display of efficiency or other quantity with respect to e.g. diffraction order, angle, etc.

Results





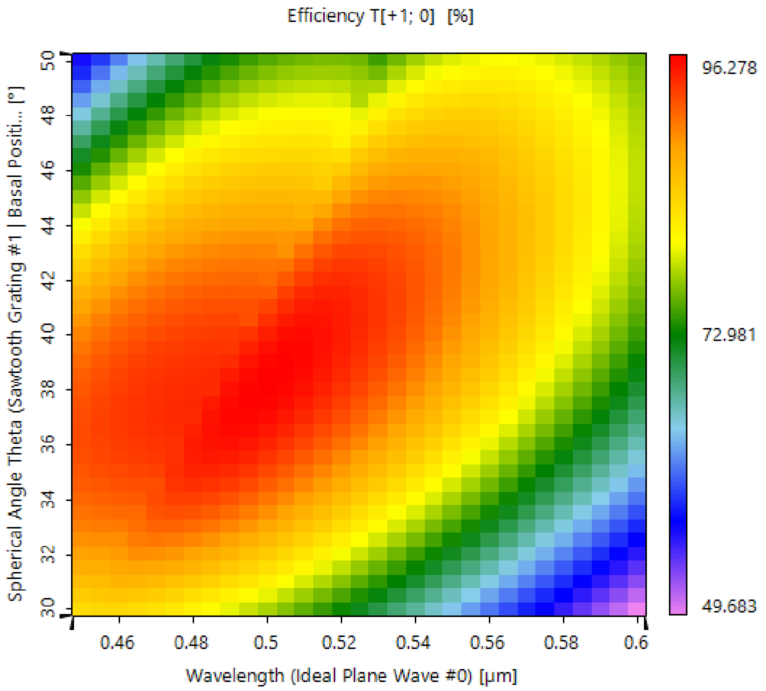
Parameter variation (fixed $\lambda = 532\,nm$)

theta 30° - 50°

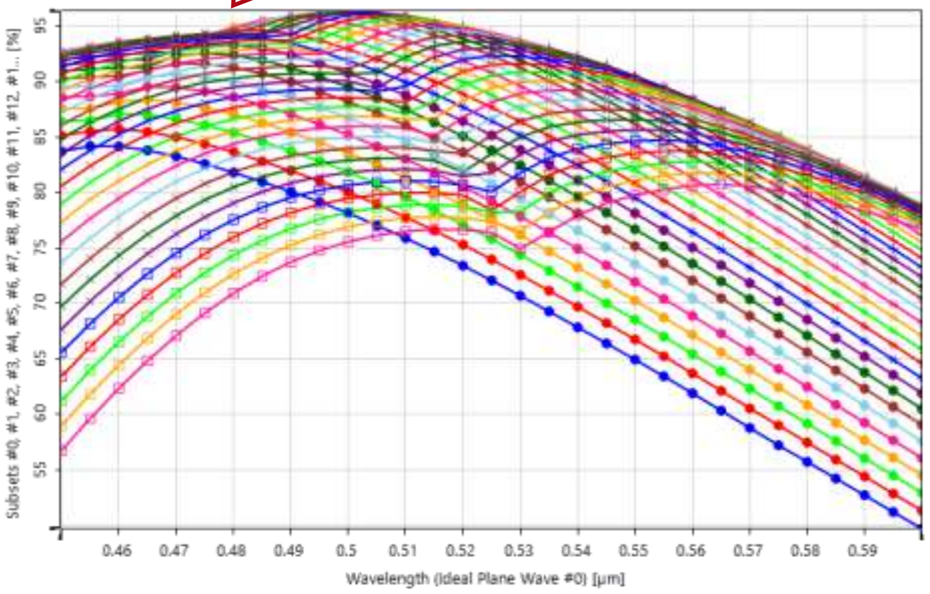
Parameter variation (fixed $\theta = 40°$)

wavelength 450 nm - 600 nm

Results



VirtualLab allows to plot the efficiencies also as 1D multigraphs. Each curve is associated with one incident angle.



Parameter Variation

theta	30° - 50°
wavelength	450 nm - 600 nm

Step 1: Configure a Grating (Video)

Klick the following link to watch the video:

https://youtu.be/bOU5wM-kQPE

Step 2: Check the Convergence

Klick the following link to watch the video:

https://youtu.be/a-9u9ttzRLA

Step 3: Simulation of Grating Properties

Klick the following link to watch the video:

https://youtu.be/WGHtnCTWuzk

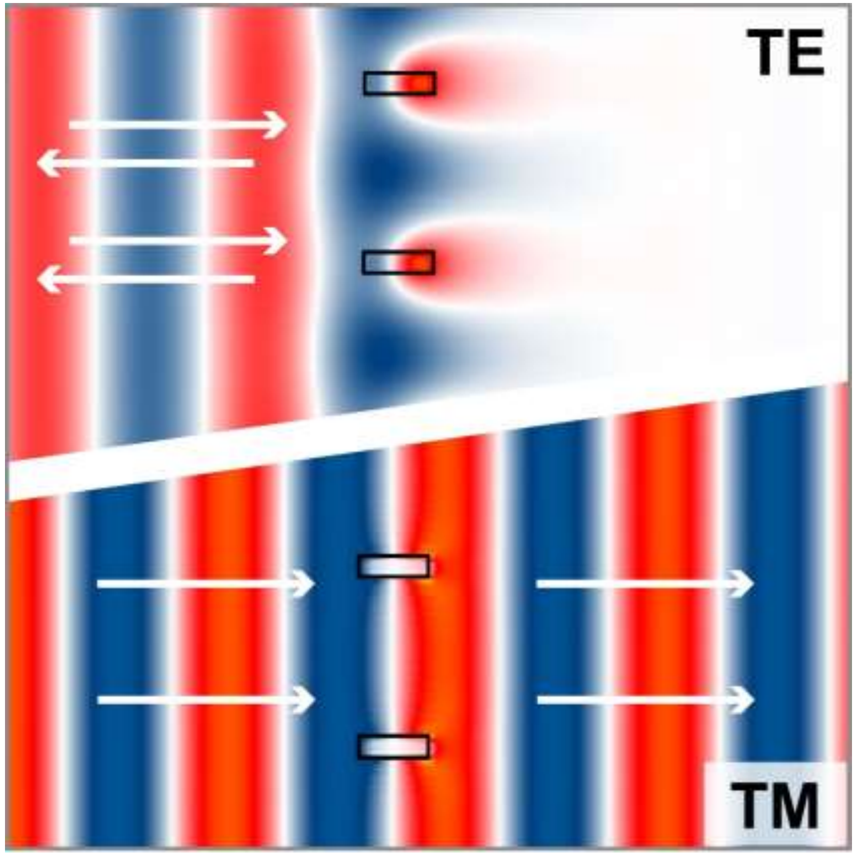
Task 3

Ultra-Sparse Dielectric Nano-Wire Grid Polarizers

This task is used to review the feature how to show the field inside grating region.

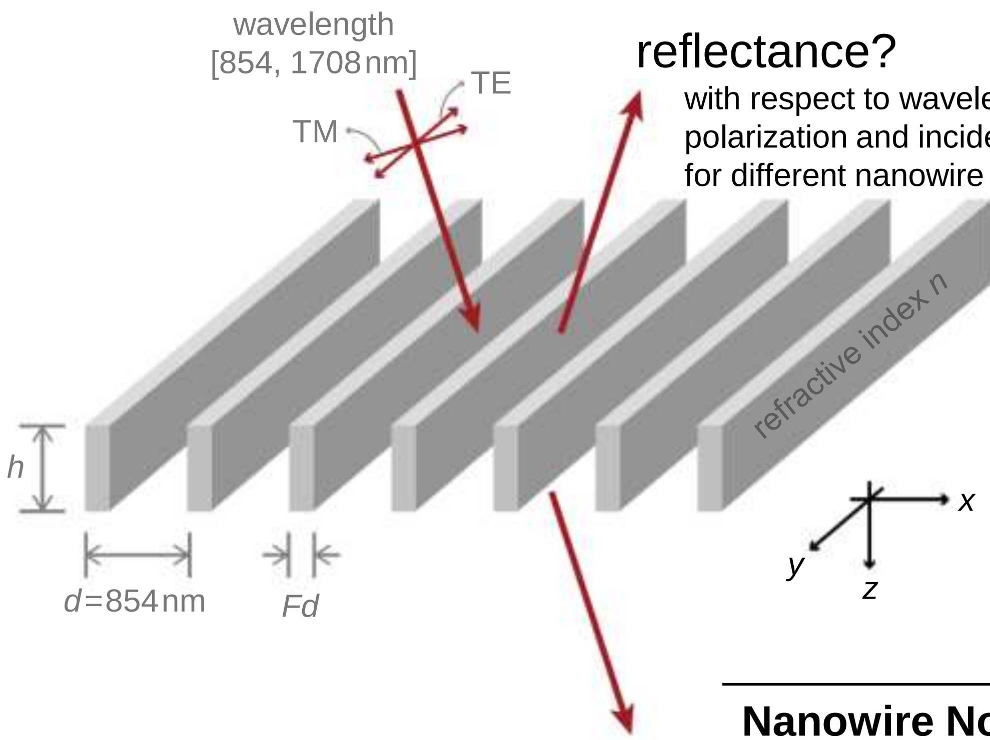
(0.2h)

Abstract



Ultra-sparse dielectric nanowire grids show strongly polarization-dependent properties and they can be employed as wideband reflectors [J. W. Yoon *et al*., Opt. Express **23**, 28849-28856 (2015)]. The polarization-, wavelength-, and angle-dependent properties of selected nanowire grids are investigated by using the Fourier modal method (FMM). Visualization of the interaction between electric field and the nanowire grids are presented.

Modeling Task



reflectance?

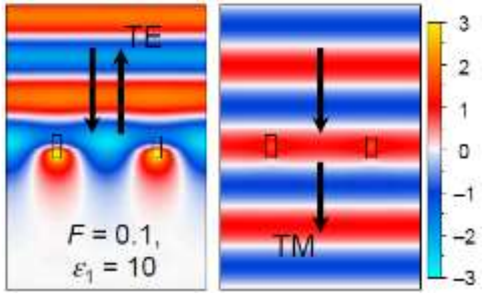
with respect to wavelength, polarization and incident angle, for different nanowire structures

Wavelength 1.045 µm

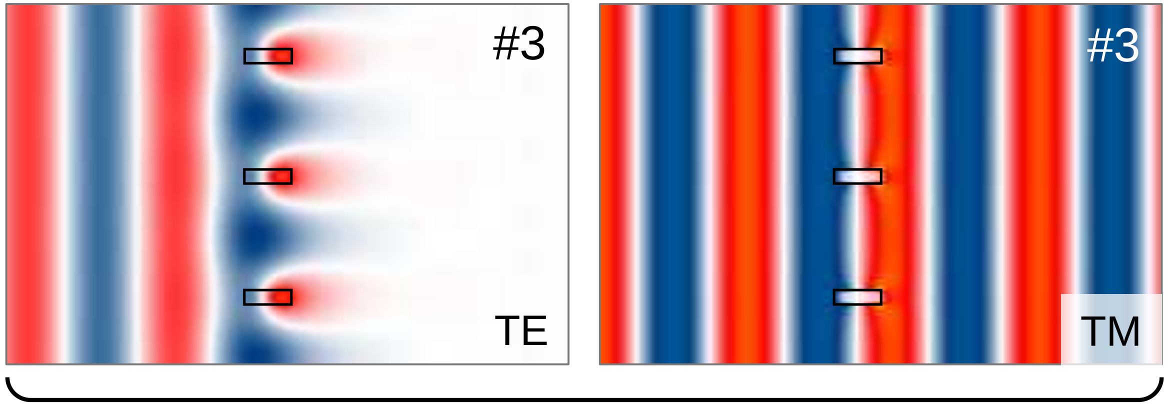
Nanowire No.	**#1**	**#2**	**#3**
refractive index *n*	10	7.07	3.16
height *h*	269 nm	270 nm	292 nm
filling factor *F*	0.01	0.02	0.1

Results

- Visualization of fields inside a nanowire grid



reference results from J. W. Yoon *et al.*, Opt. Express **23**, 28849-28856 (2015)



FMM simulation in VirtualLab (animation)

Nanowire No.	**#1**	**#2**	**#3**
refractive index *n*	10	7.07	3.16
height *h*	269 nm	270 nm	292 nm
filling factor *F*	0.01	0.02	0.1

Task 3: Video

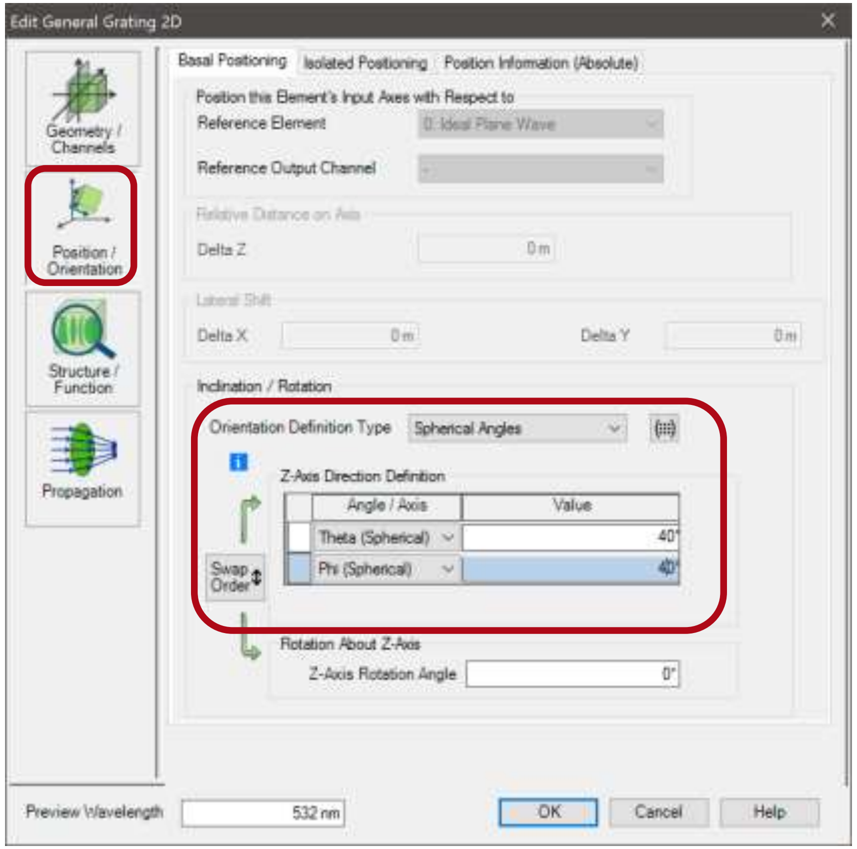
Klick the following link to watch the video:

https://youtu.be/_LfO7443a4c

Visualization of Conical Incidence

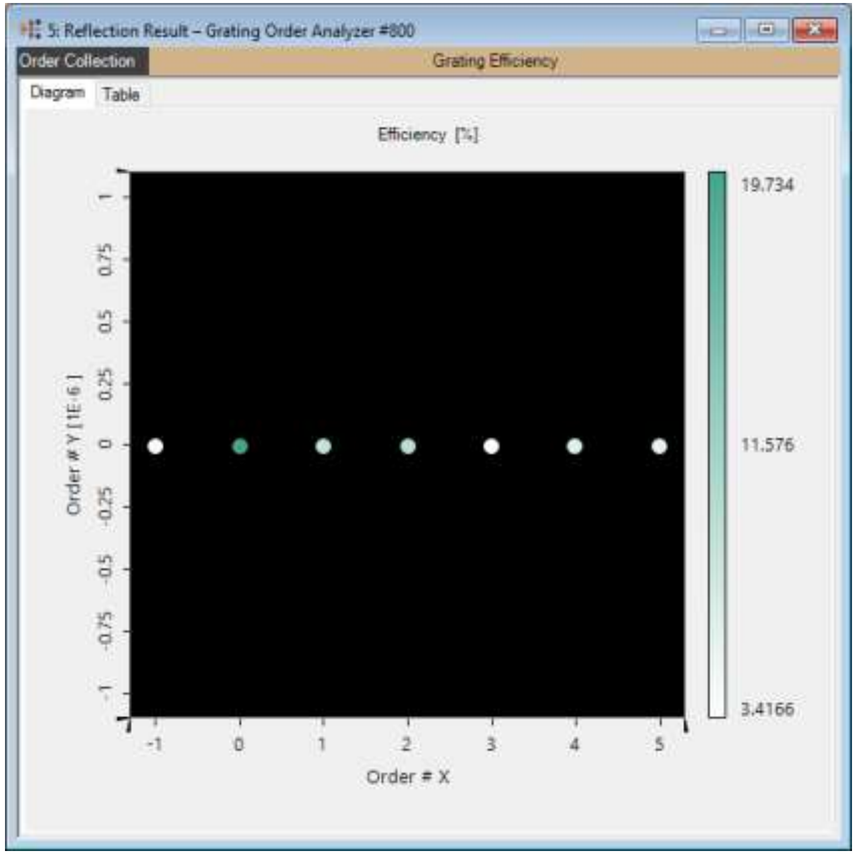
This is a feature which is shown shortly when we simulate task 1 to 3. Here I give some slides to emphasis that FMM is rigorous. Any incident direction of input plane wave can be considered.

Define Conical Incidence

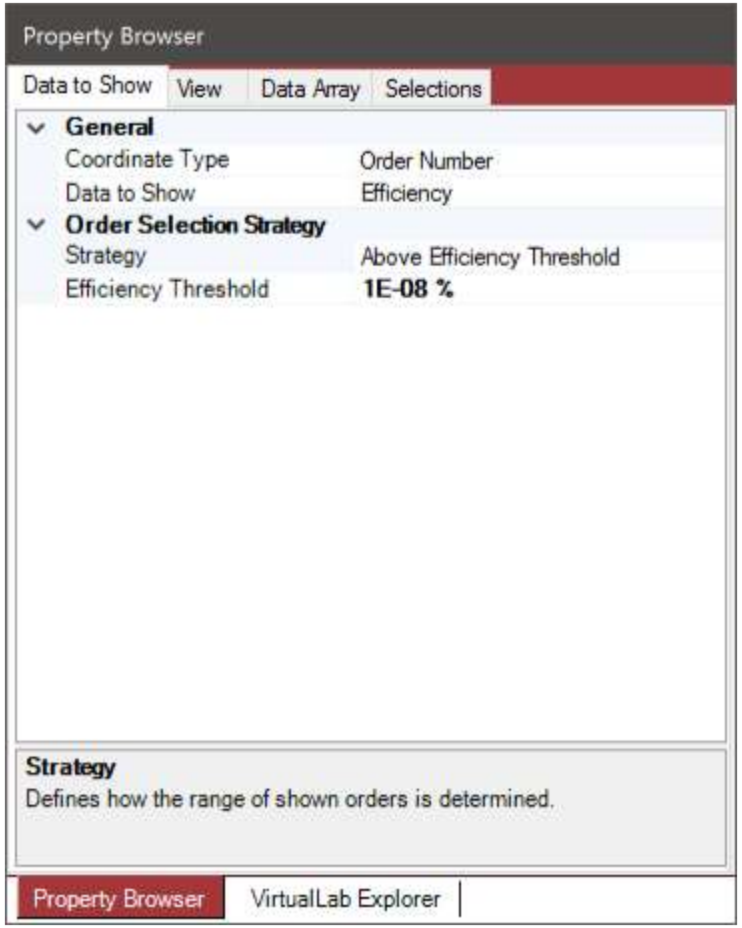


- On the *Position/ Orientation* page of the grating component‘s edit dialog the user can define an arbitrary orientation of the element. This way different incident angles can be simulated.
- For this use case we use *Theta* = 40° and *Phi* = 40°.

Result – Grating Efficiencies over Order Number

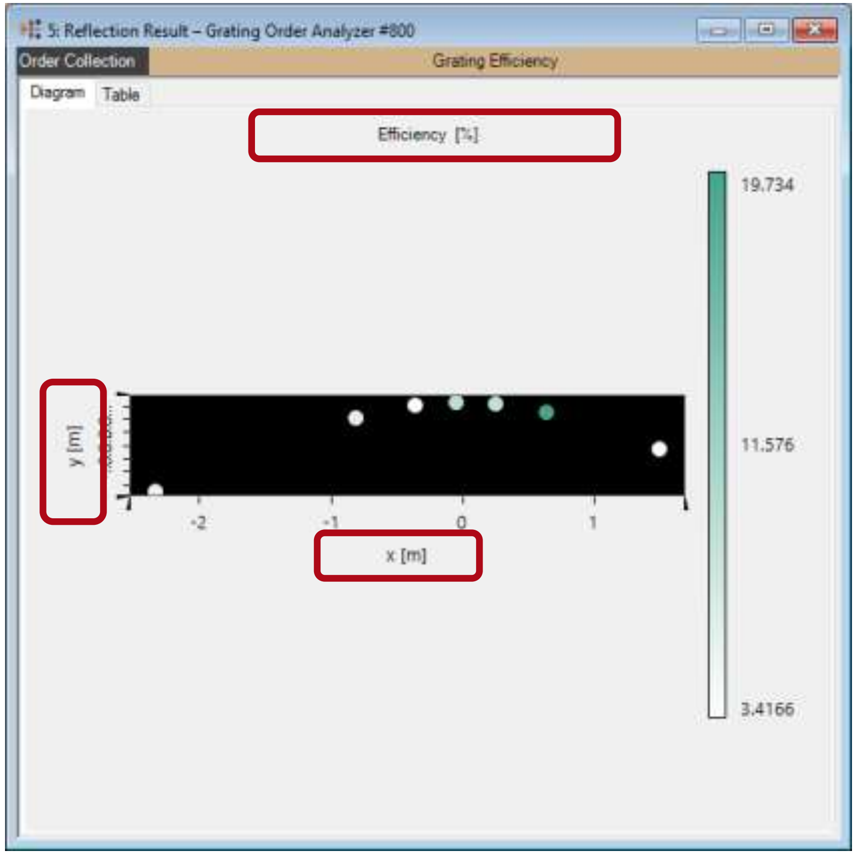


Visualization

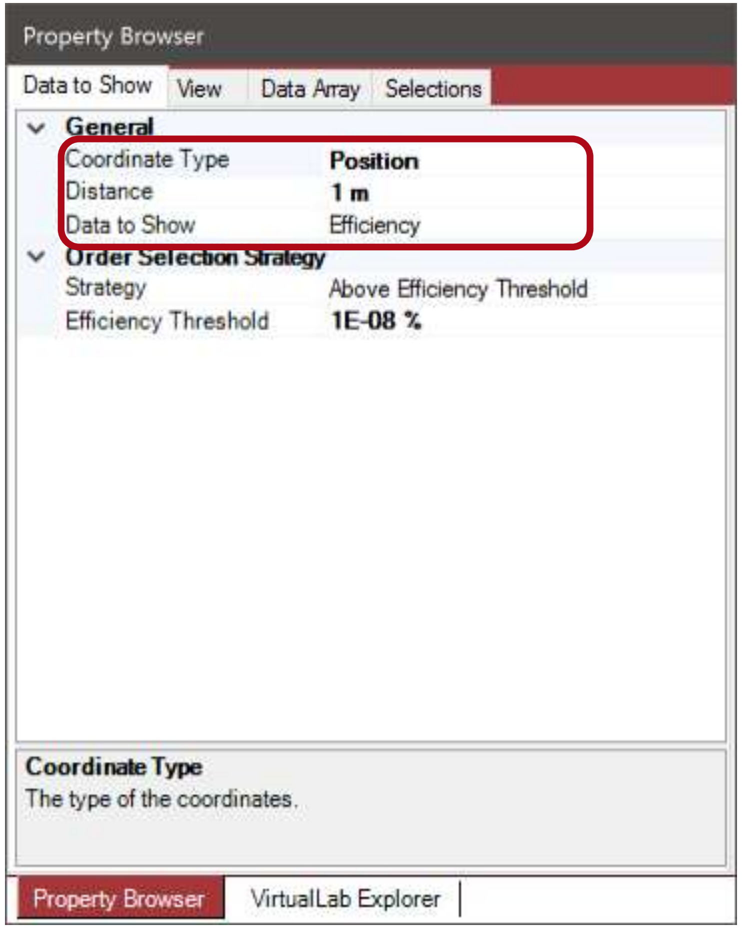


View Settings

Result – Grating Efficiencies over Order Position

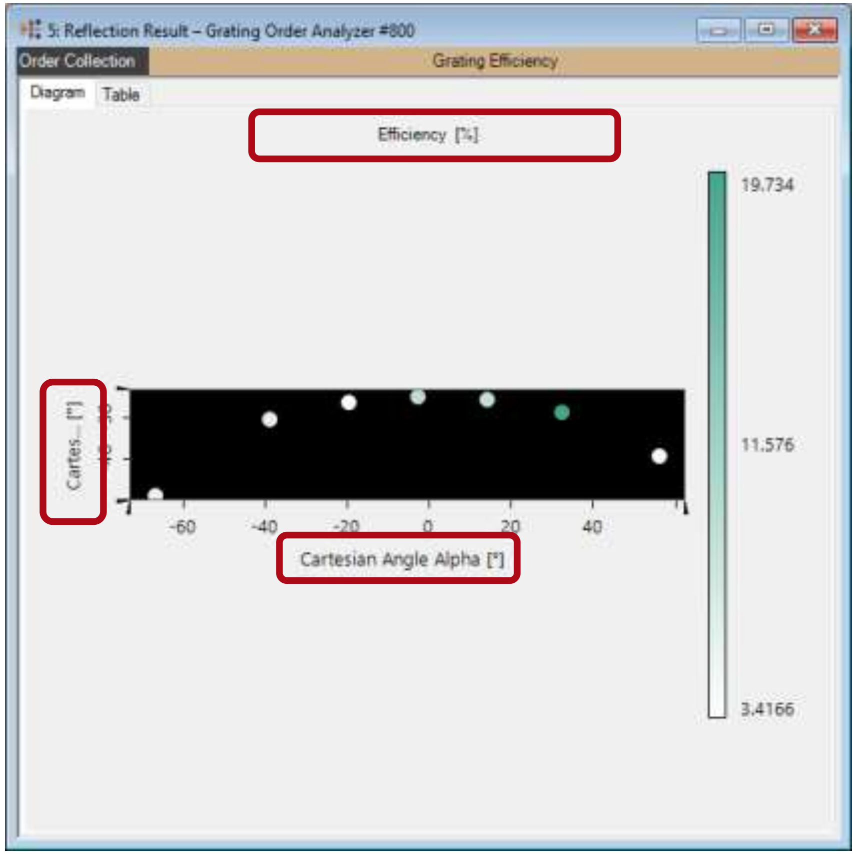


Visualization

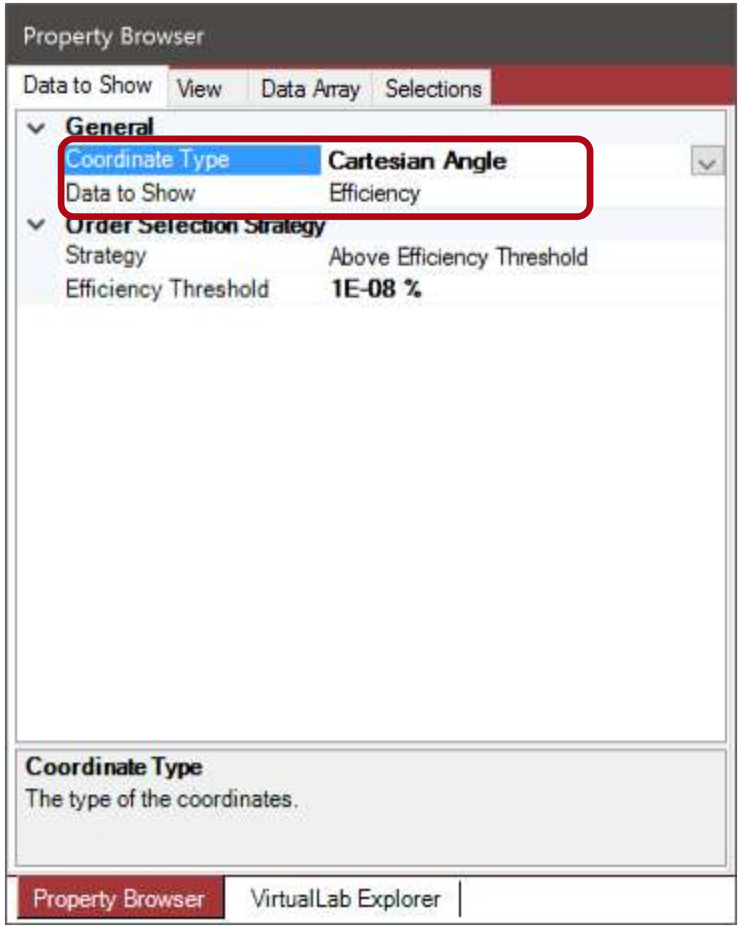


View Settings

Result – Grating Efficiencies over Cartesian Angles

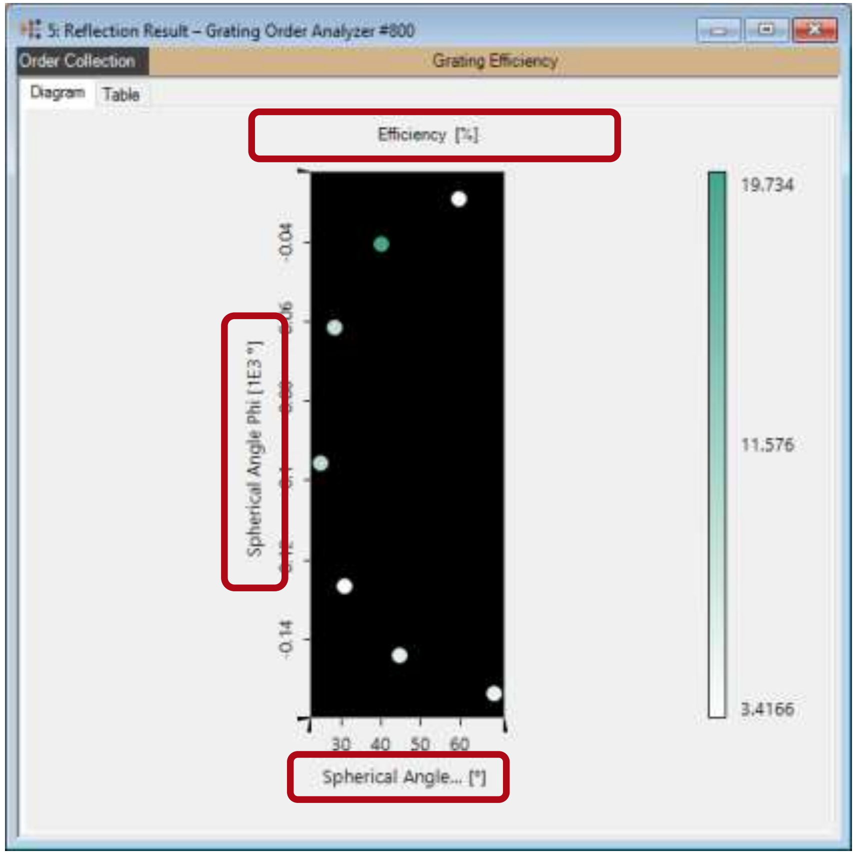


Visualization

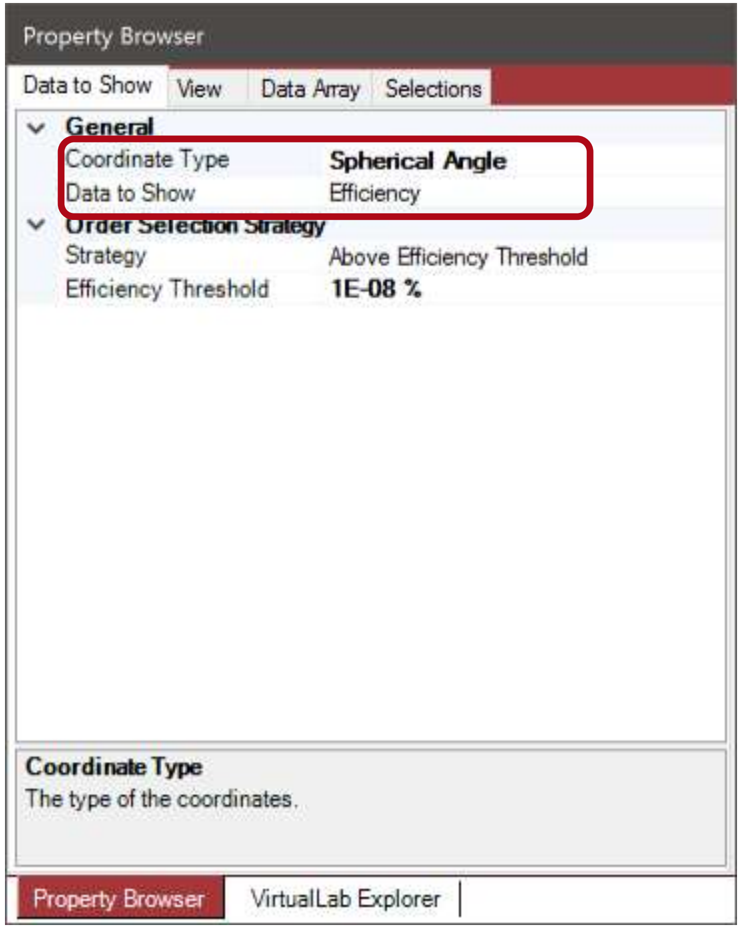


View Settings

Result – Grating Efficiencies over Spherical Angles

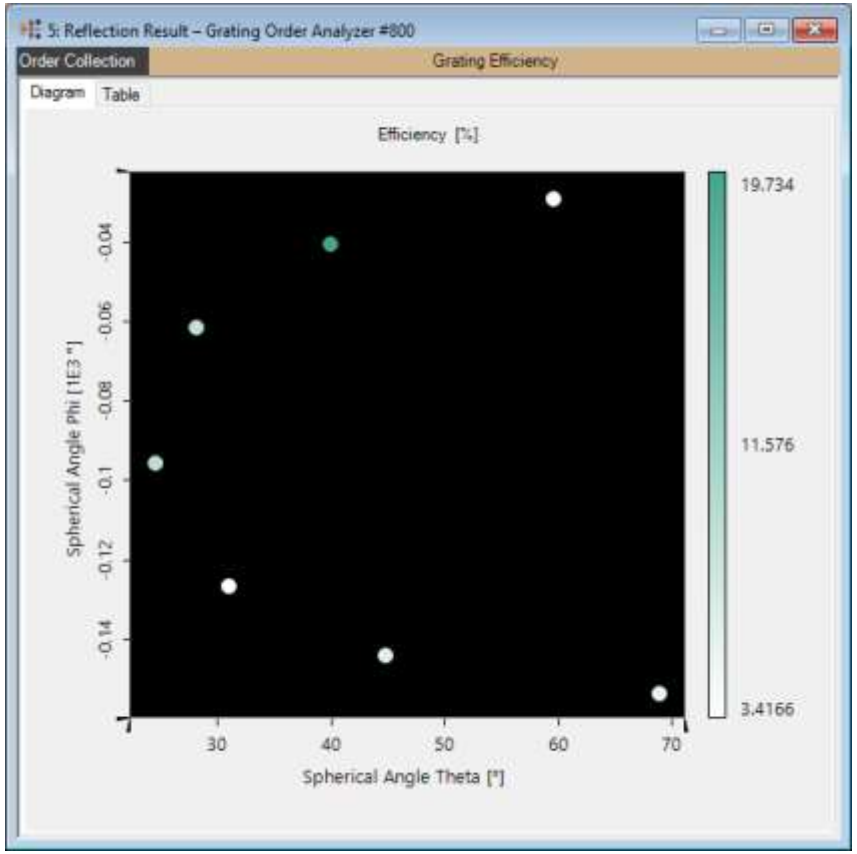


Visualization



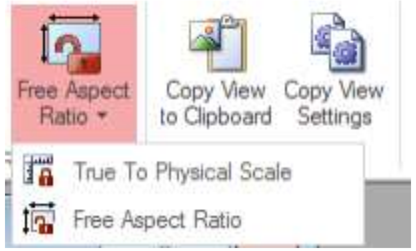
View Settings

Tips & Tricks: Aspect Ratio



Free Aspect Ratio

- Depending on the coordinate range which is displayed it could be helpful to change the aspect ratio of the data.
- The aspect ratio can be adapted via the property browser or via the corresponding ribbon entry:

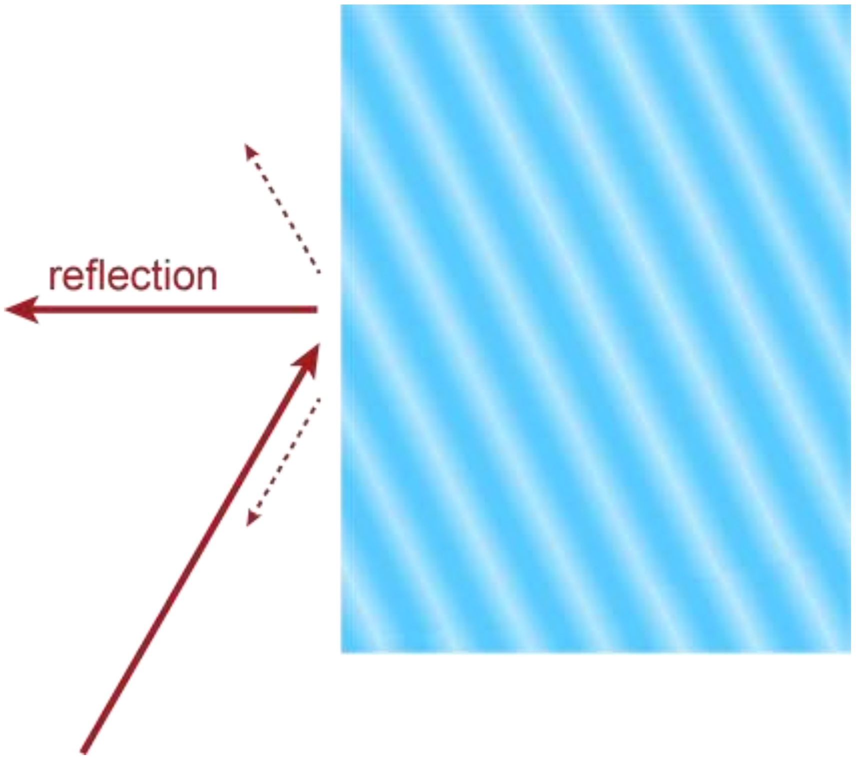


Task 4

Rigorous Simulation of Holographic Generated Volume Grating

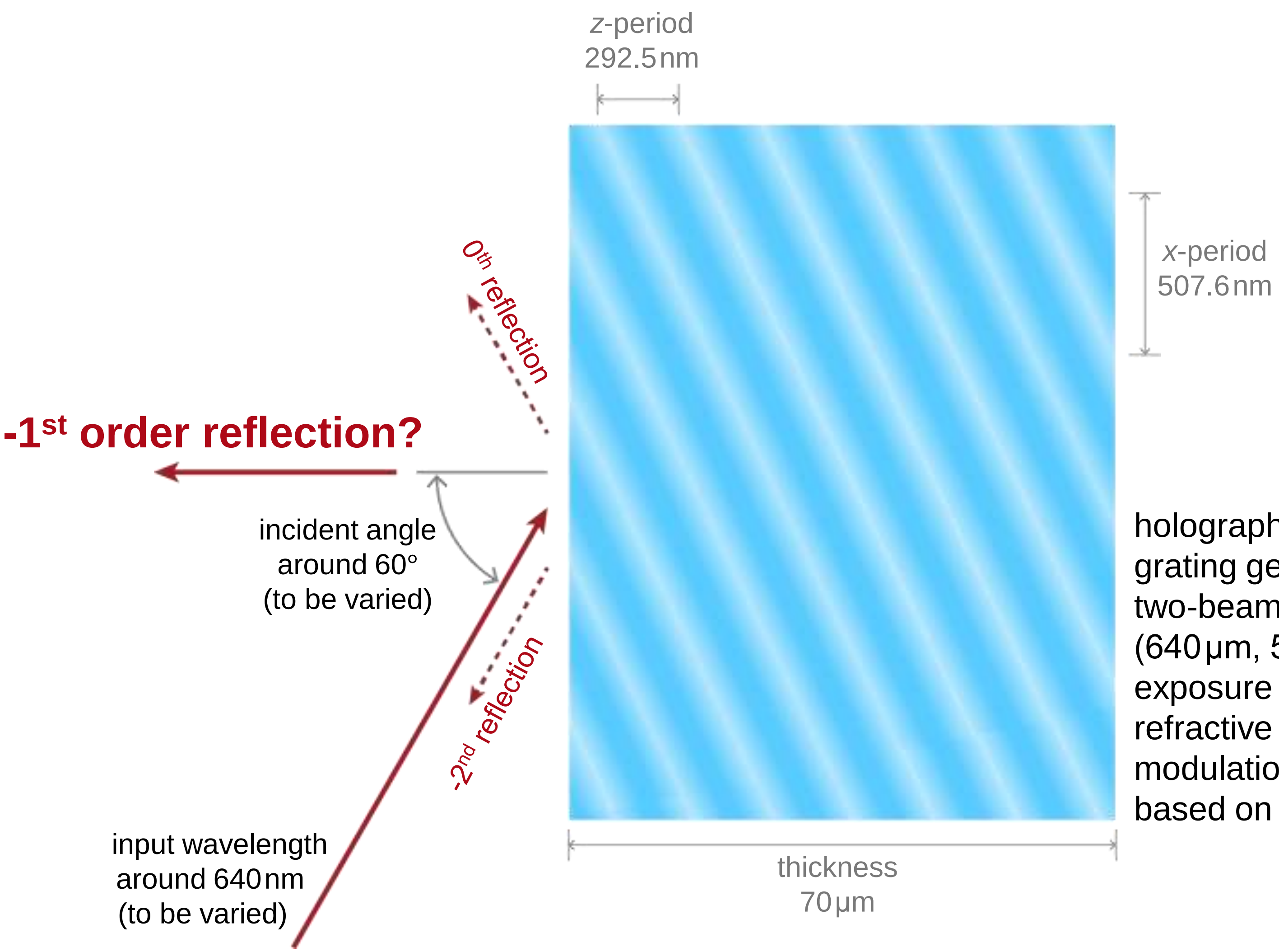
This task is used to show how to configure a holographc media, created by two plane wave.

Abstract



Holographic generated volume gratings, with a thickness much larger than the wavelength, often shows a narrow bandwidth around particular wavelength and angle. Following the two-beam interference exposure process, a volume grating inside fused silica is generated and simulated with the rigorous Fourier modal method (FMM) in VirtualLab. Both the spectral and angular dependent reflection property of the grating are analyzed.

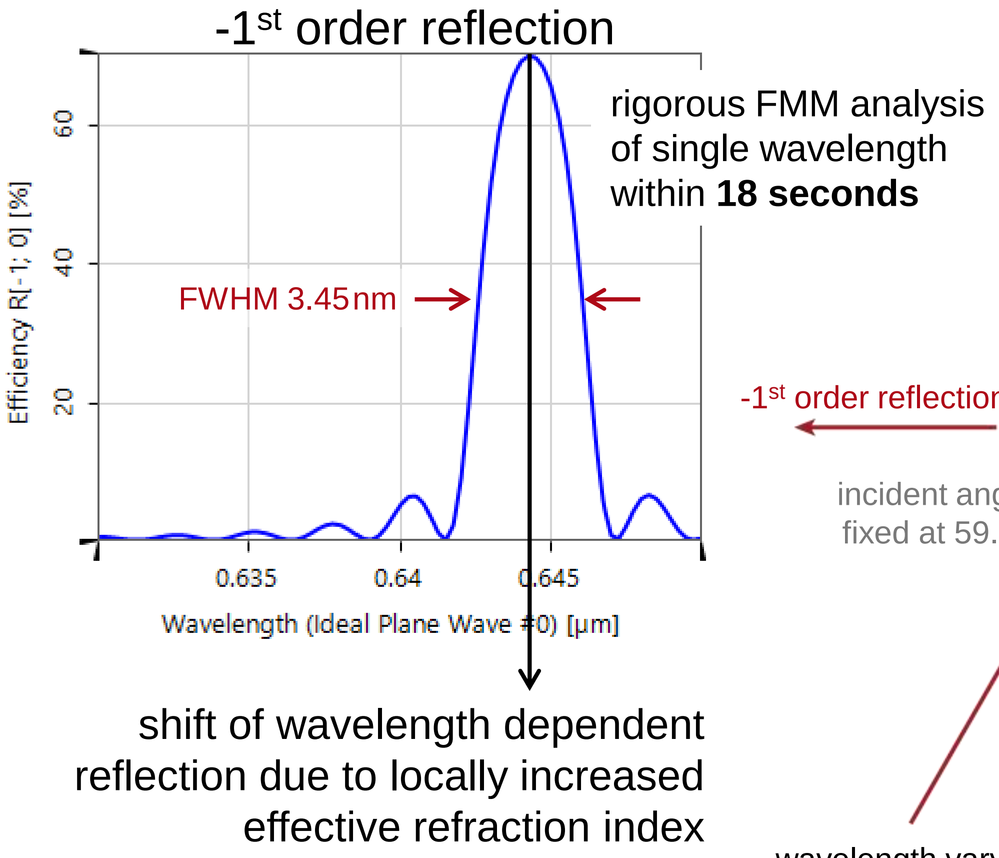
Modeling Task

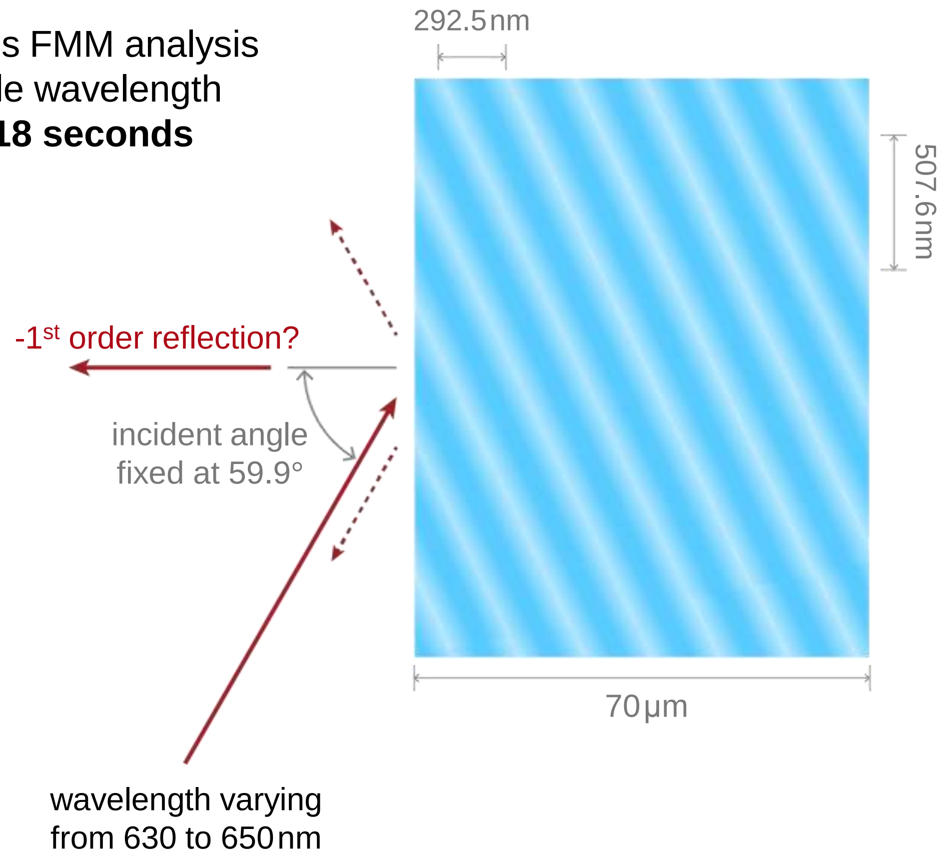


holographic volume grating generated by two-beam interference (640 µm, 59.9° angle) exposure process, with refractive index modulation of 0.01 based on fused silica

Results

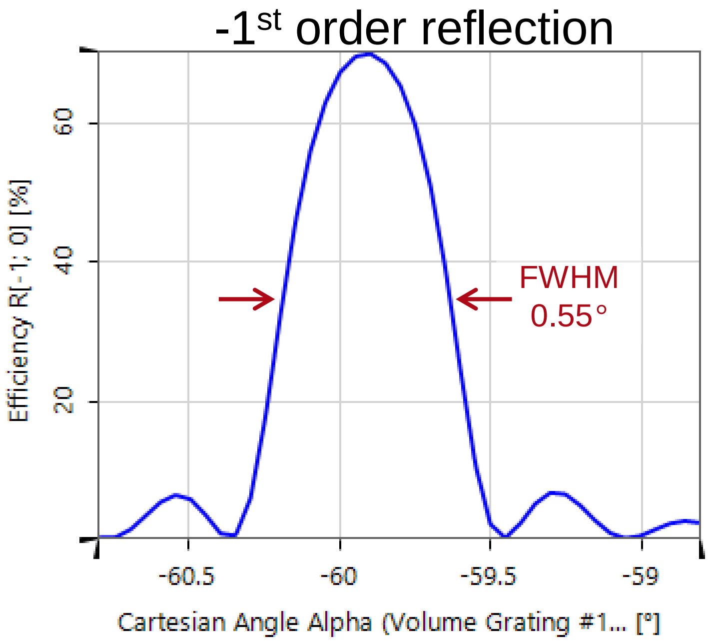
- Wavelength scanning

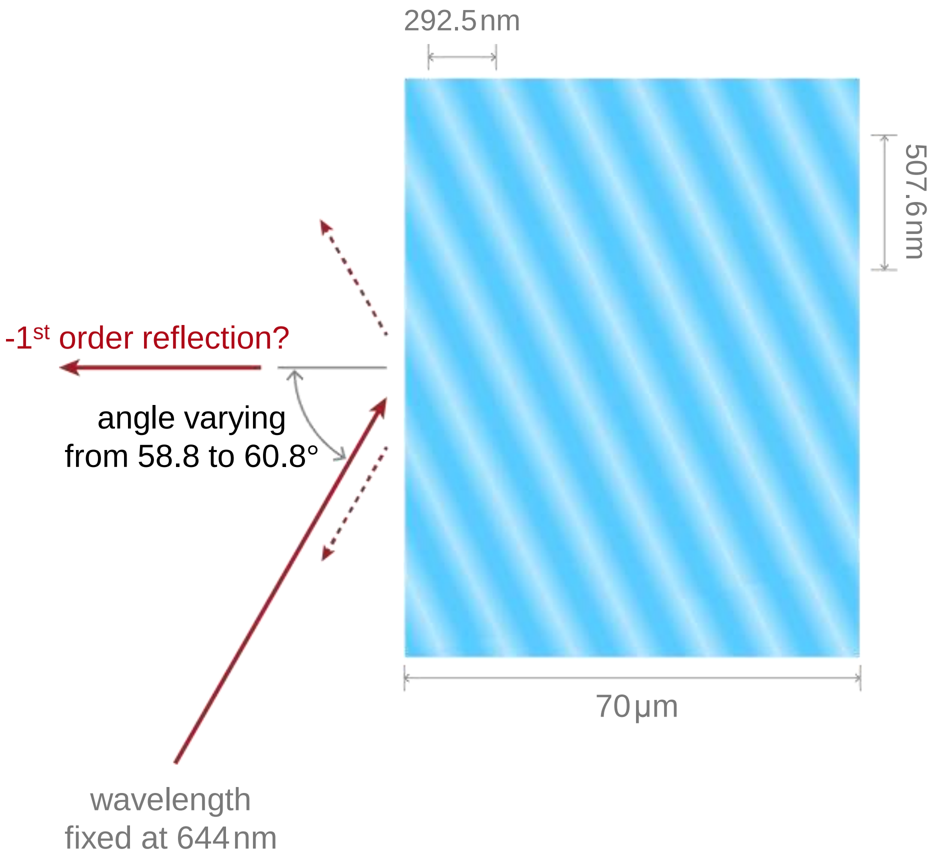




Results

- Angle scanning

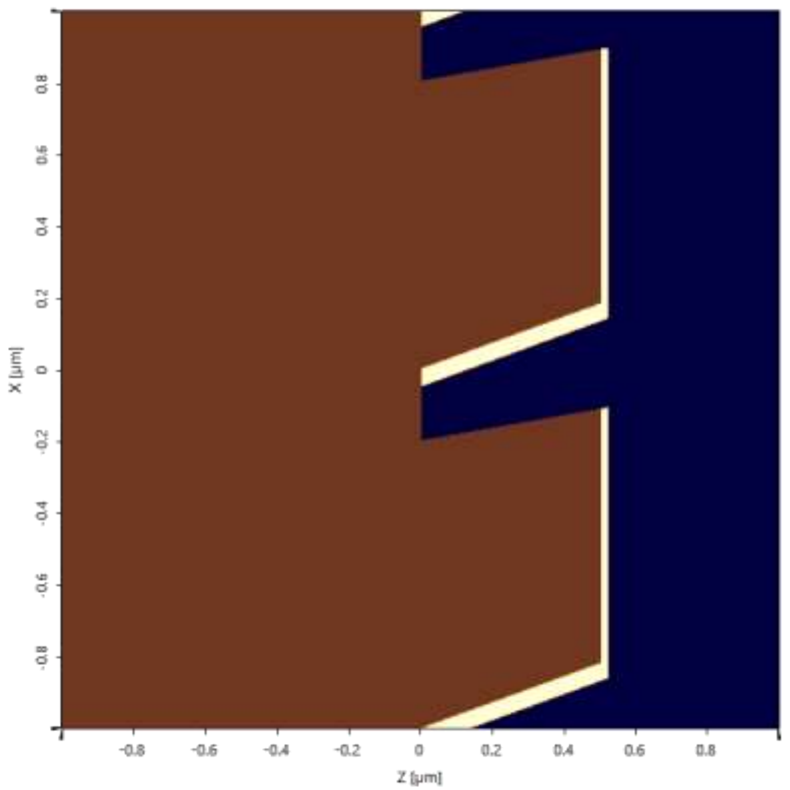




From now on, we start to configure gratings defined by periodic media...

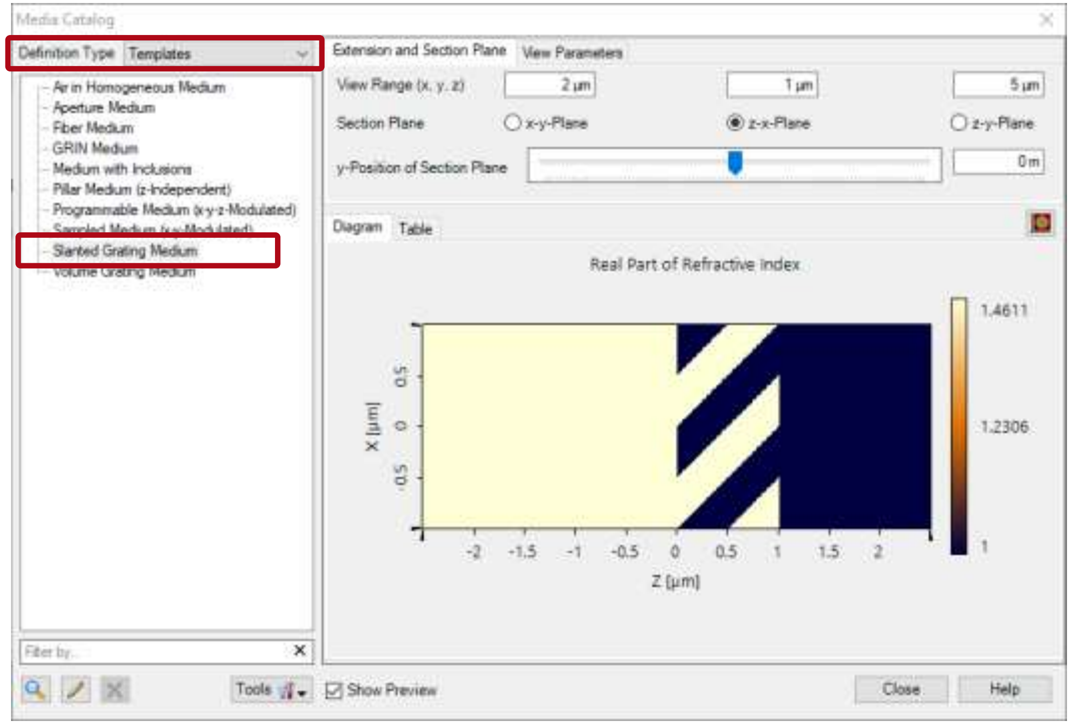
Advanced Configuration of Slanted Gratings

Abstract



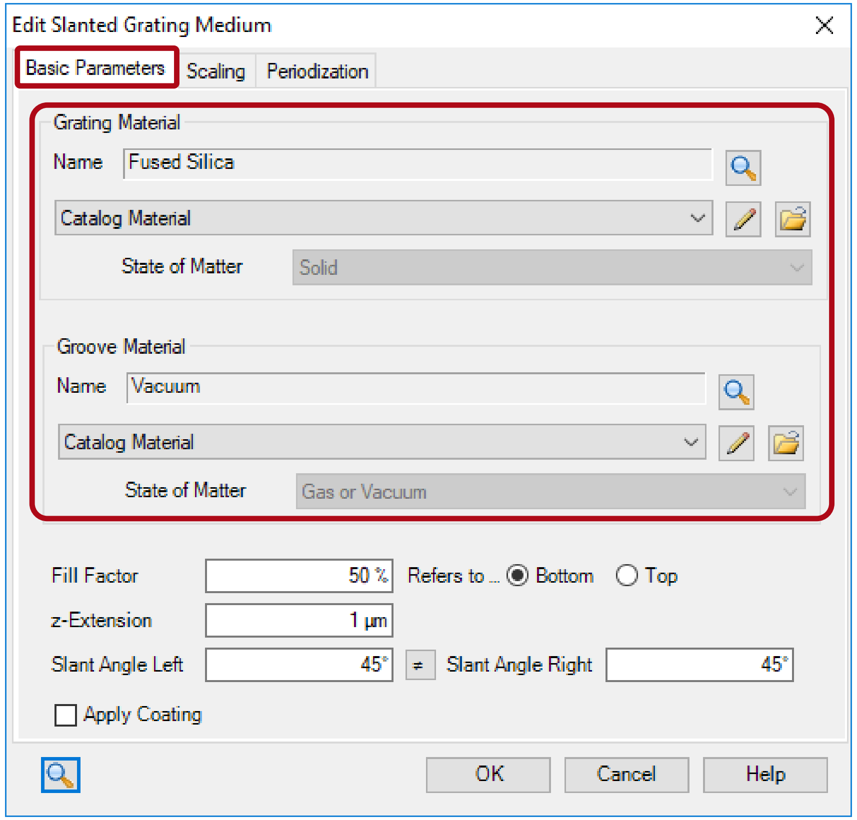
VirtualLab can be used to analyze arbitrary types of gratings. Due to the raising importance of gratings which exhibit slanted structures within complex optical setups also slanted gratings are available. The slanted grating is realized by an special optical medium, where the geometry can be defined, versatilely. Moreover, several advanced specification options are available, e.g. adding a full and partially coating layer. In this use case the available options for configuration are explained and their influence on the geometry of the grating are discussed.

Slanted Grating Medium in Media Catalog



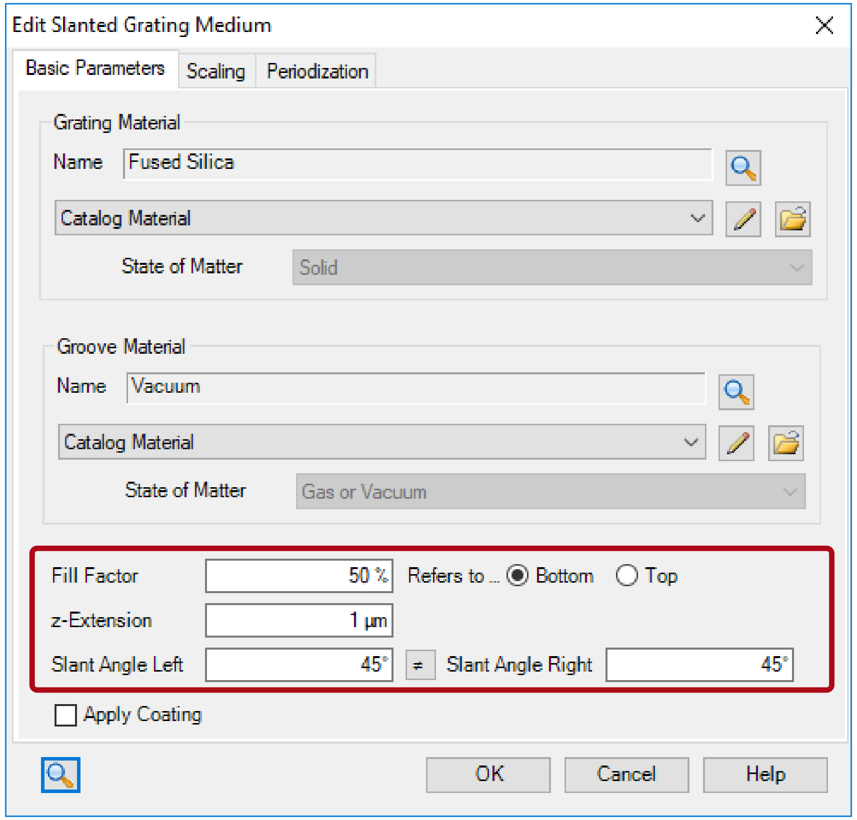
- The build-in slanted grating medium can be found in the embedded media catalog of VirtualLab.
- It can be used in order to set up complex optical grating structures (so-called stacks) and analyzed by applying the Fourier Modal method.

Edit Dialog of the Slanted Grating Medium



- The slanted grating medium provides numerous options for customization of the periodic structure.
- First, the material of the grating ridges and of the grooves have to be defined inside the basic parameters tab.
- These materials can either be chosen from the material catalog, or defined by a constant index of refraction.

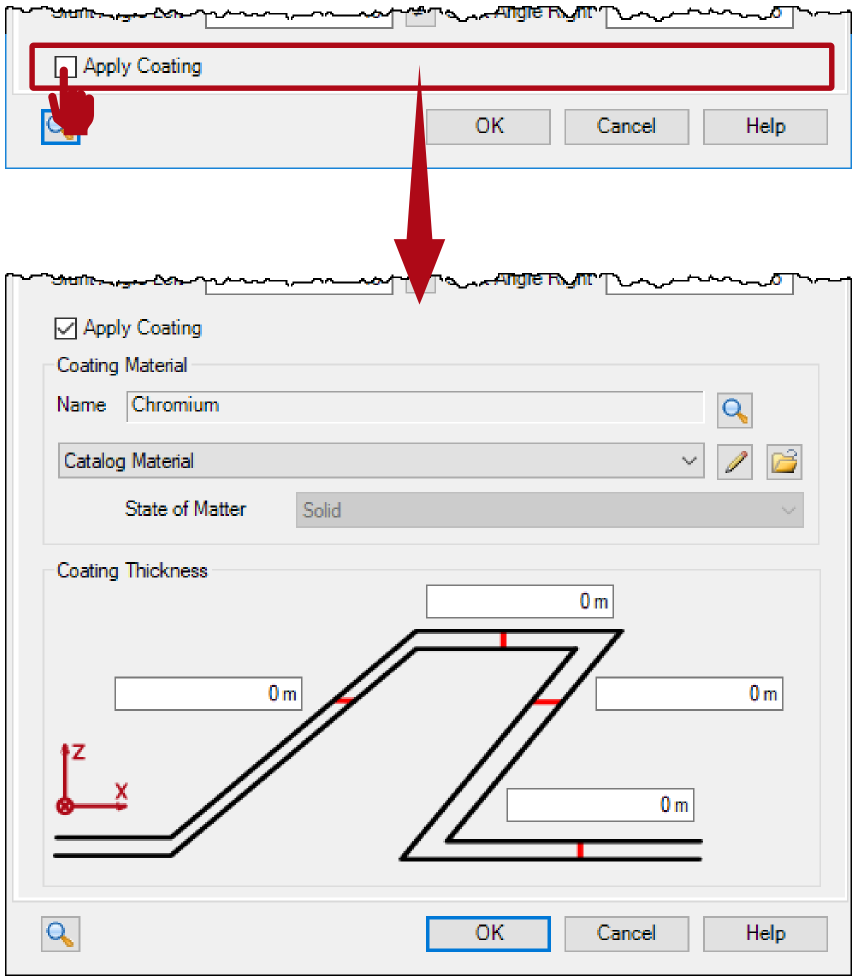
Edit Dialog of the Slanted Grating Medium



- Below the material settings, the geometrical parameters of the grating can be defined.
- The following parameters are available:
  - fill factor (defined either at top or bottom of the grating)
  - z-extension (grating height measured along z-direction)
  - slant angle left (slant angle of the left sidewall of the ridge)
  - slant angle right (slant angle of the right sidewall of the ridge)

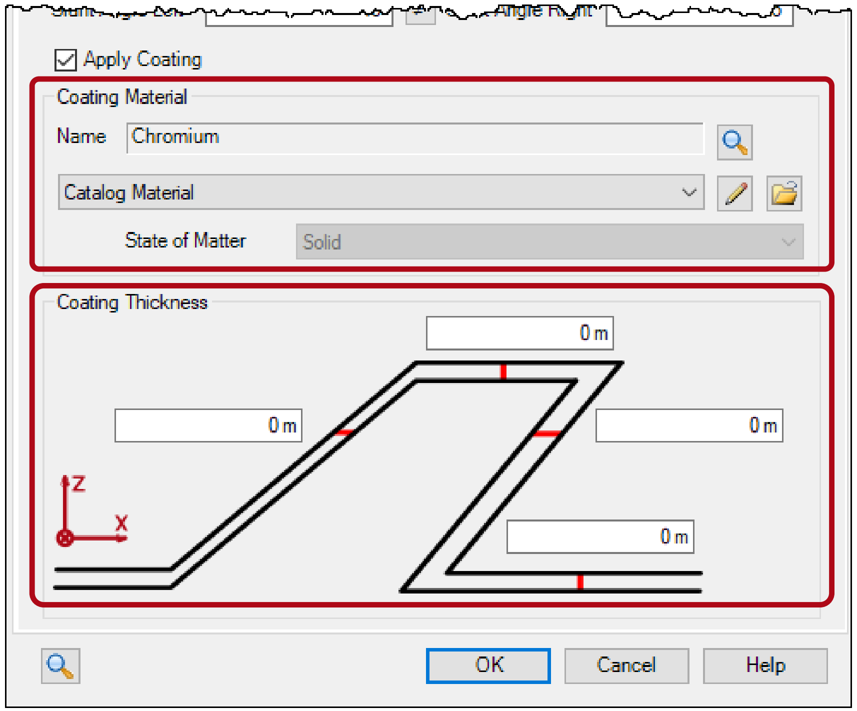
(in case of equal slant angles, the settings can be linked, by clicking the (un-)equal sign)

Edit Dialog of the Slanted Grating Medium



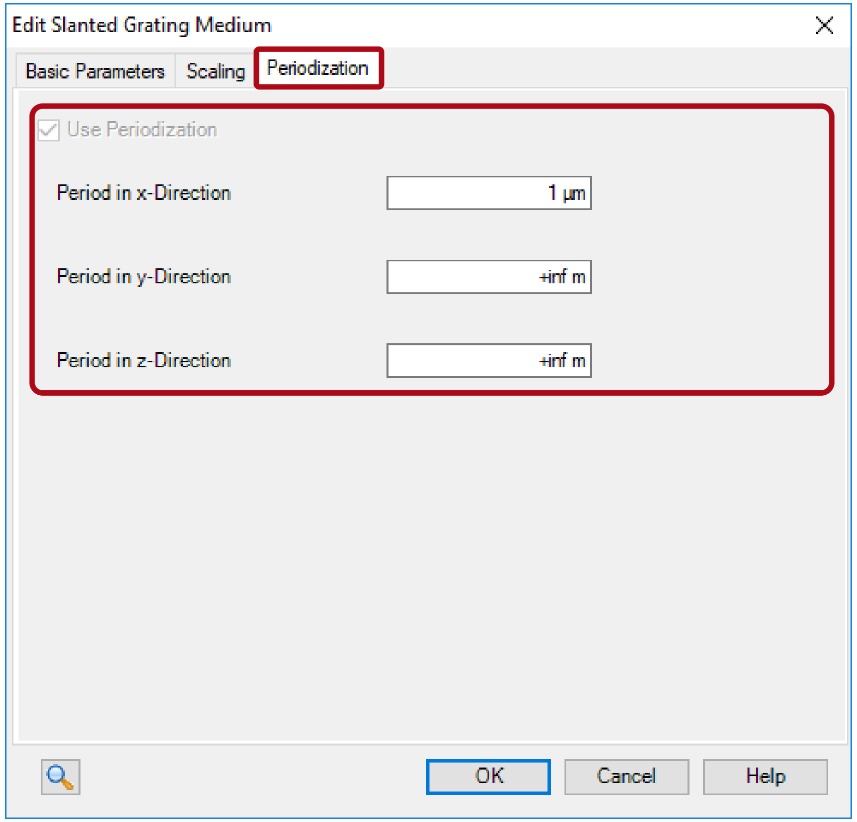
- In order to add a configurable coating, the *Apply Coating* option has to be activated.
- Now, additional options appear along with a sketch of the structure.

Edit Dialog of the Slanted Grating Medium



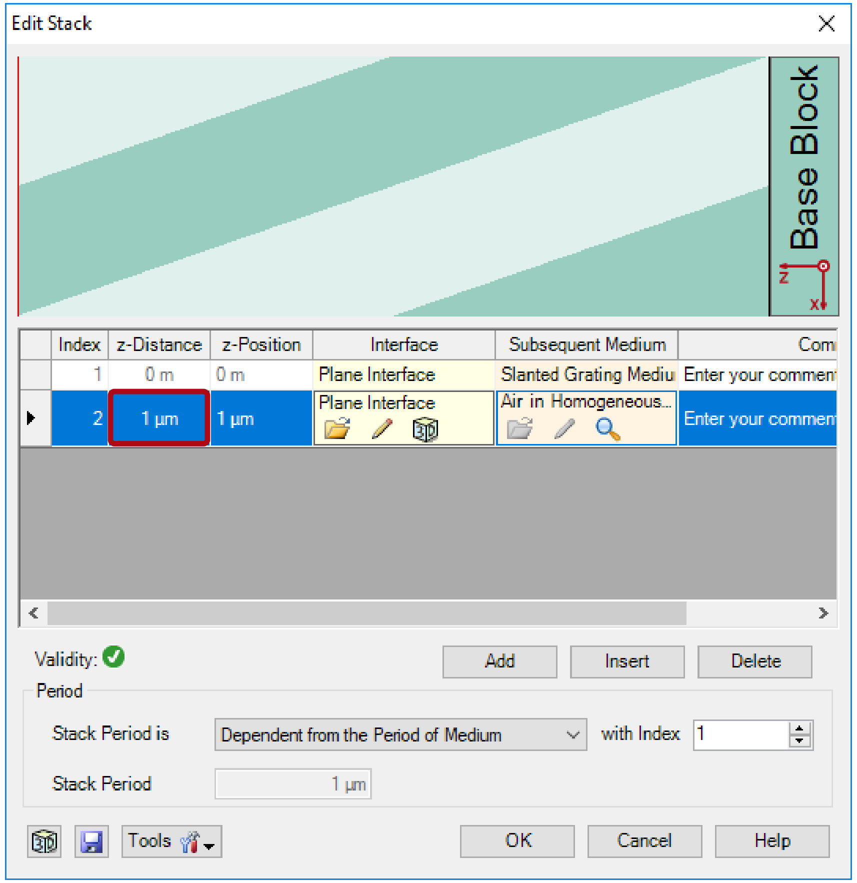
- First, the material of the coating has to be selected.
- Again, the material can either be chosen from the material catalog, or defined by a constant index of refraction.
- Next, the thickness of the coating can be configured for each sidewall, top and bottom individually, as depicted in the sketch.

Edit Dialog of the Slanted Grating



- Due to the slanted grating is defined by a medium, the period has to be set in the periodization tab.
- Because this special medium is designed for gratings, it is always configured to be periodic.

Comment on Usage in Stacks

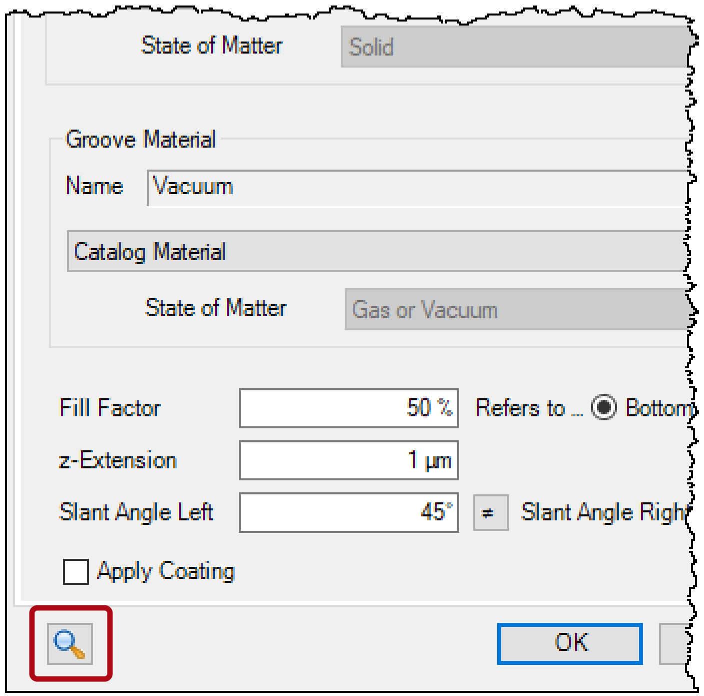


- For the usage of media within an optical stack it is necessary to define two surfaces which act as boundaries of the medium.
- In general, the distance between these interfaces has to be set manually.
- For the slanted grating medium the height (z-extension) of the medium is directly defined inside the medium configuration.
- Thus, the distance between the surfaces is automatically synchronized with the z-extension of the slanted grating medium.

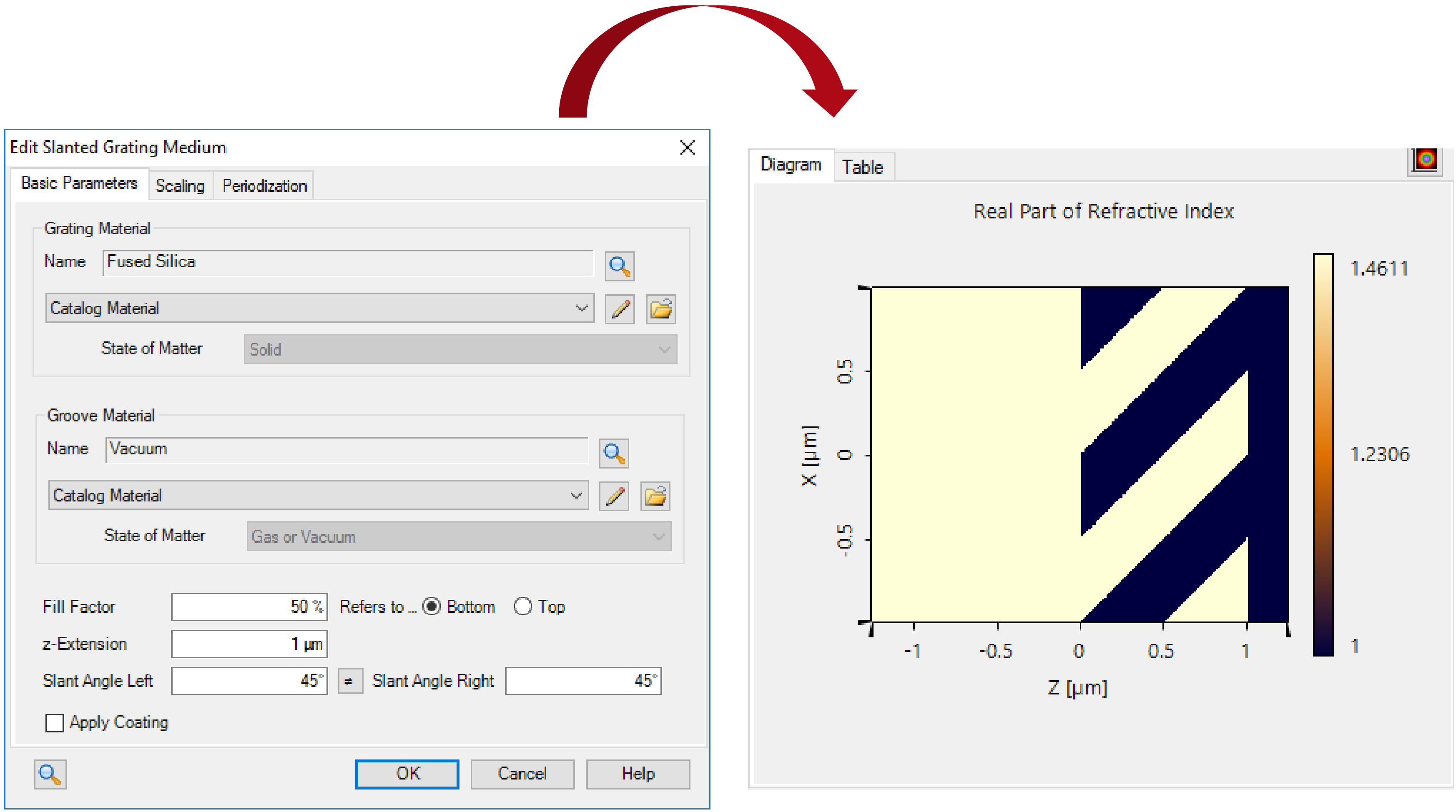
Sample Configurations of the Slanted Grating Medium

Samples of Slanted Grating Medium

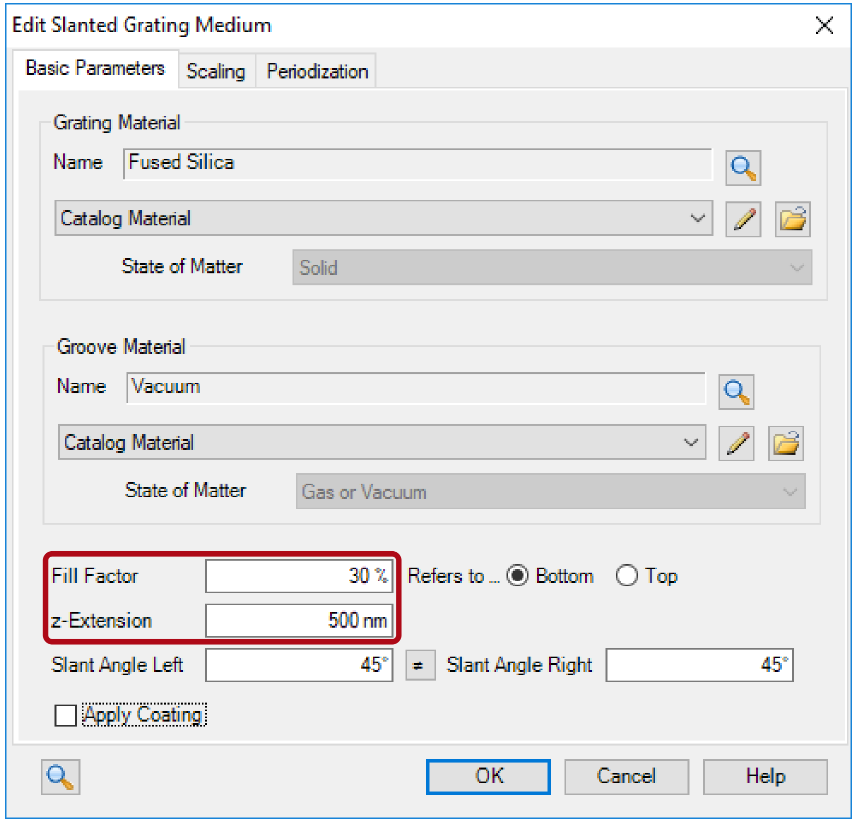
- On the next slides some selected examples of the slanted grating media are shown.
- On the left side of each slide the edit dialog is depicted in order to exhibit the related parameters.
- On the right side, the preview of the medium is displayed.
- The preview of the media can be accessed by the preview button at the bottom part of the dialog.

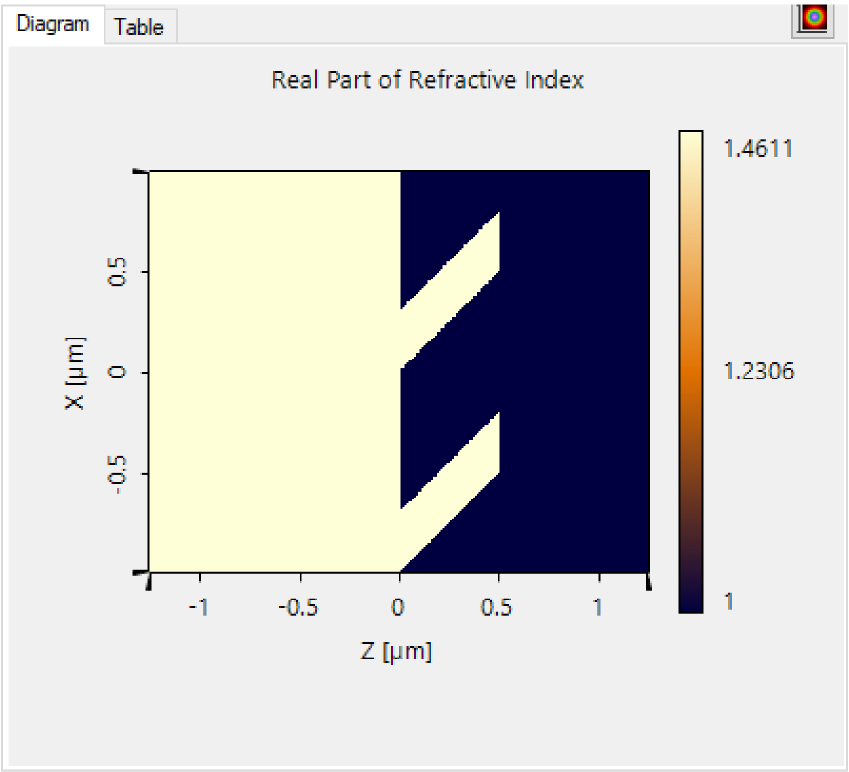


Sample Slanted Grating #1

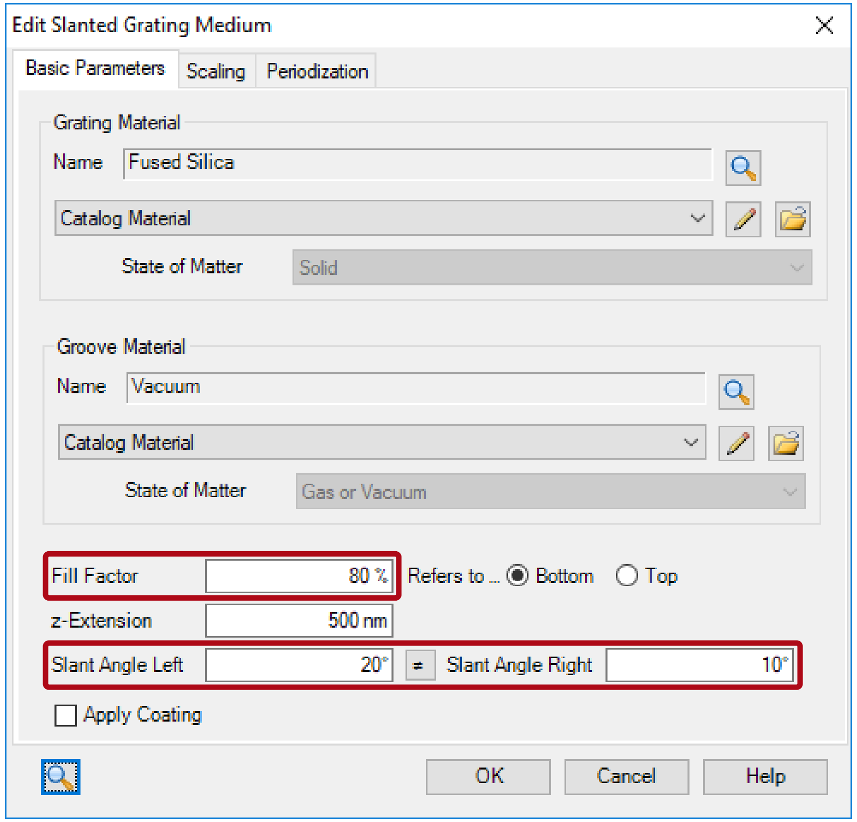


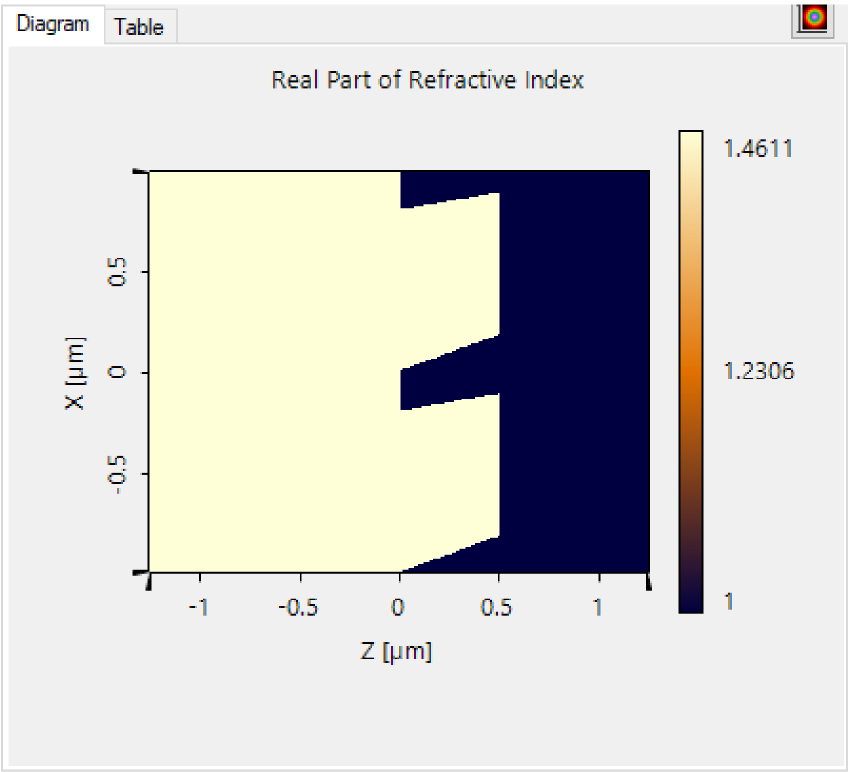
Sample Slanted Grating #2



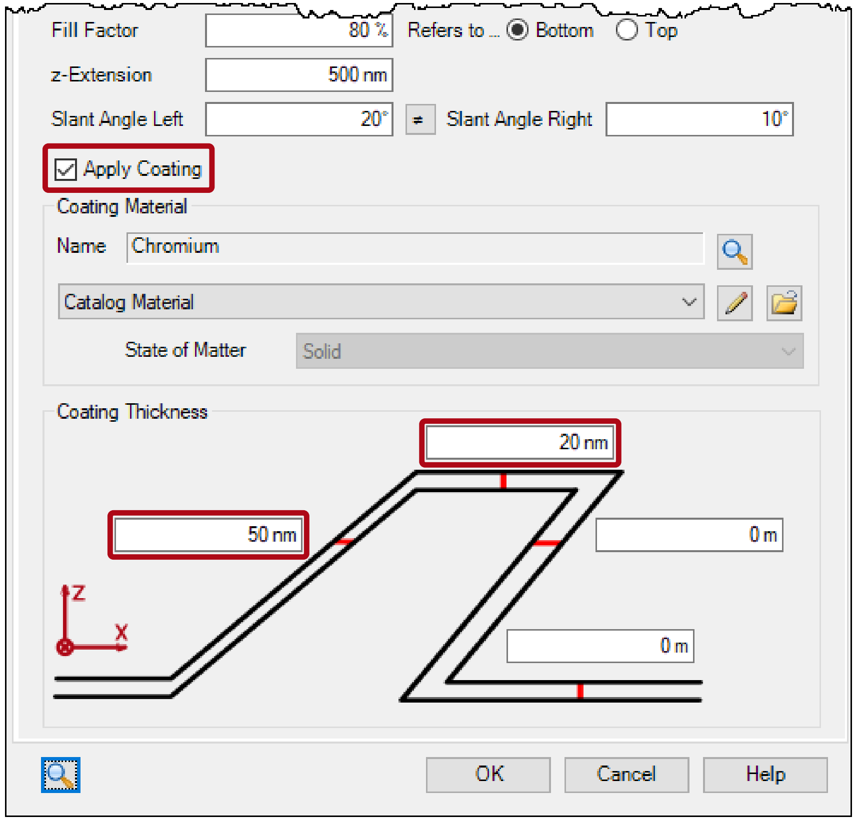


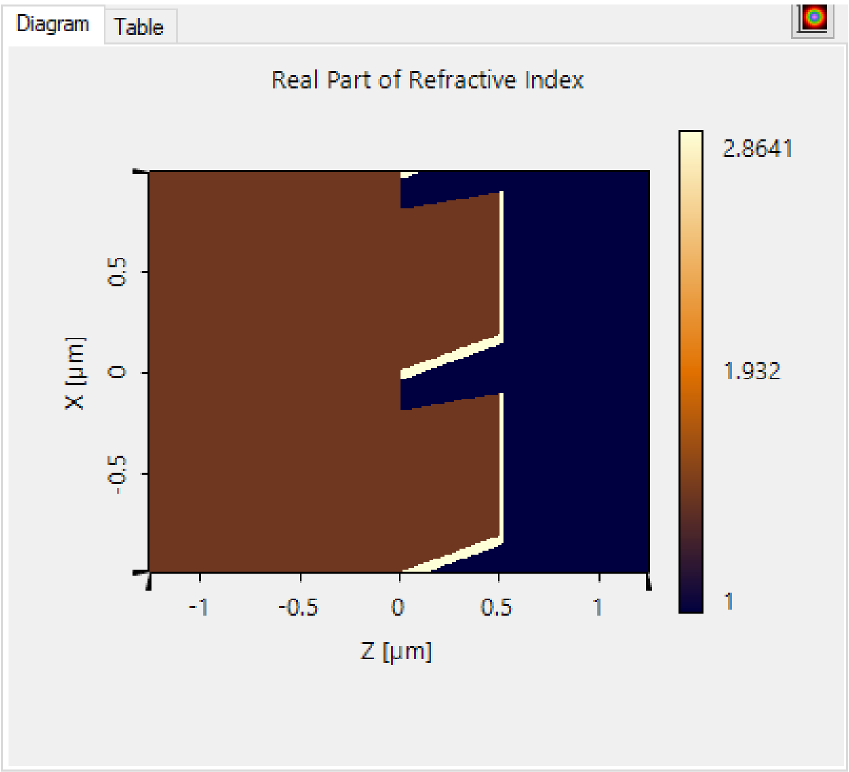
Sample Slanted Grating #3





Sample Slanted Grating #4



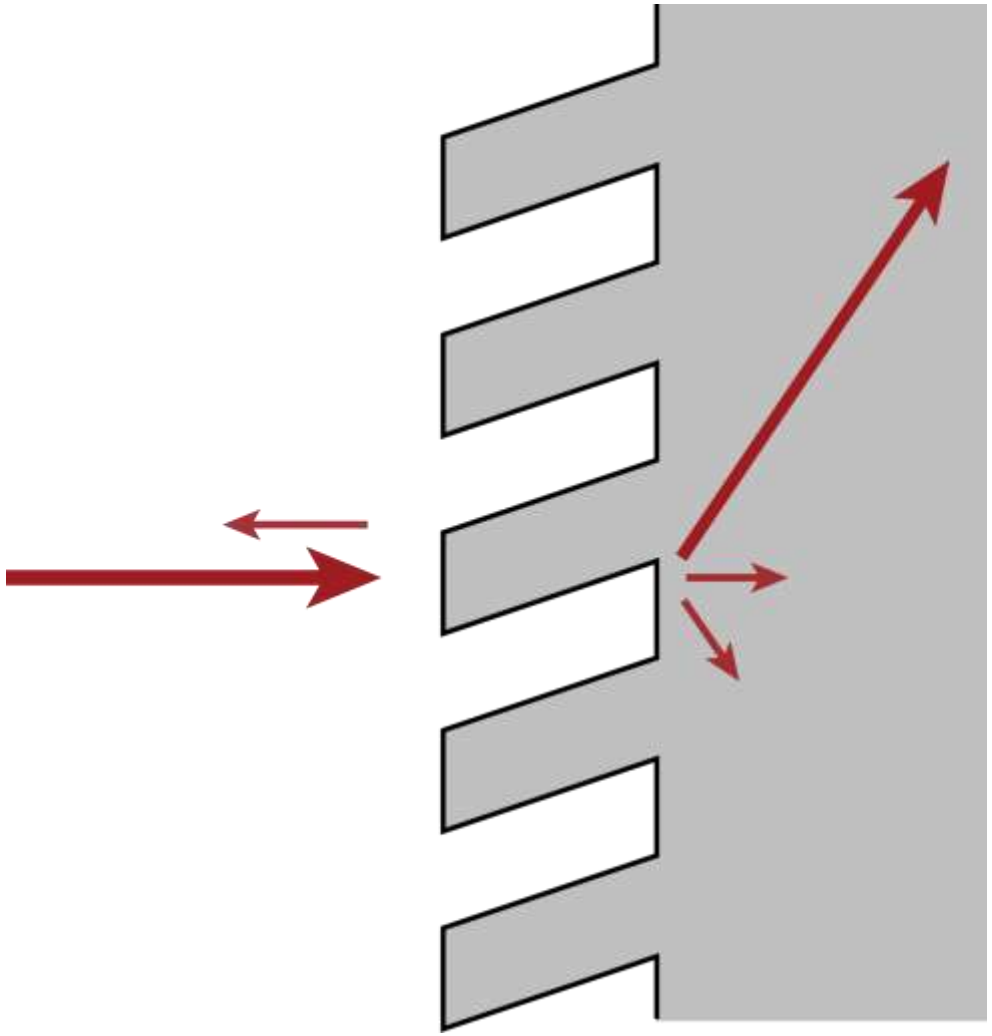


Task5

Parametric Optimization and Tolerance Analysis of Slanted Gratings

Review the workflow of designing a grating by using parametric optimization!

Abstract



Coupling of light into guiding structures with high efficiency is an important issue for many applications, like backlight, optical interconnector, and near-to-eye displays. For such applications, slanted gratings are well known for being capable to couple monochromatic light with high efficiency. In this example, the optimization of a slanted grating with the rigorous Fourier modal method is presented. The optimized grating shows a diffraction efficiency of over 90% for a predefined direction order. In addition, the influence from the slope deviation of the grating is investigated.

Grating Equation

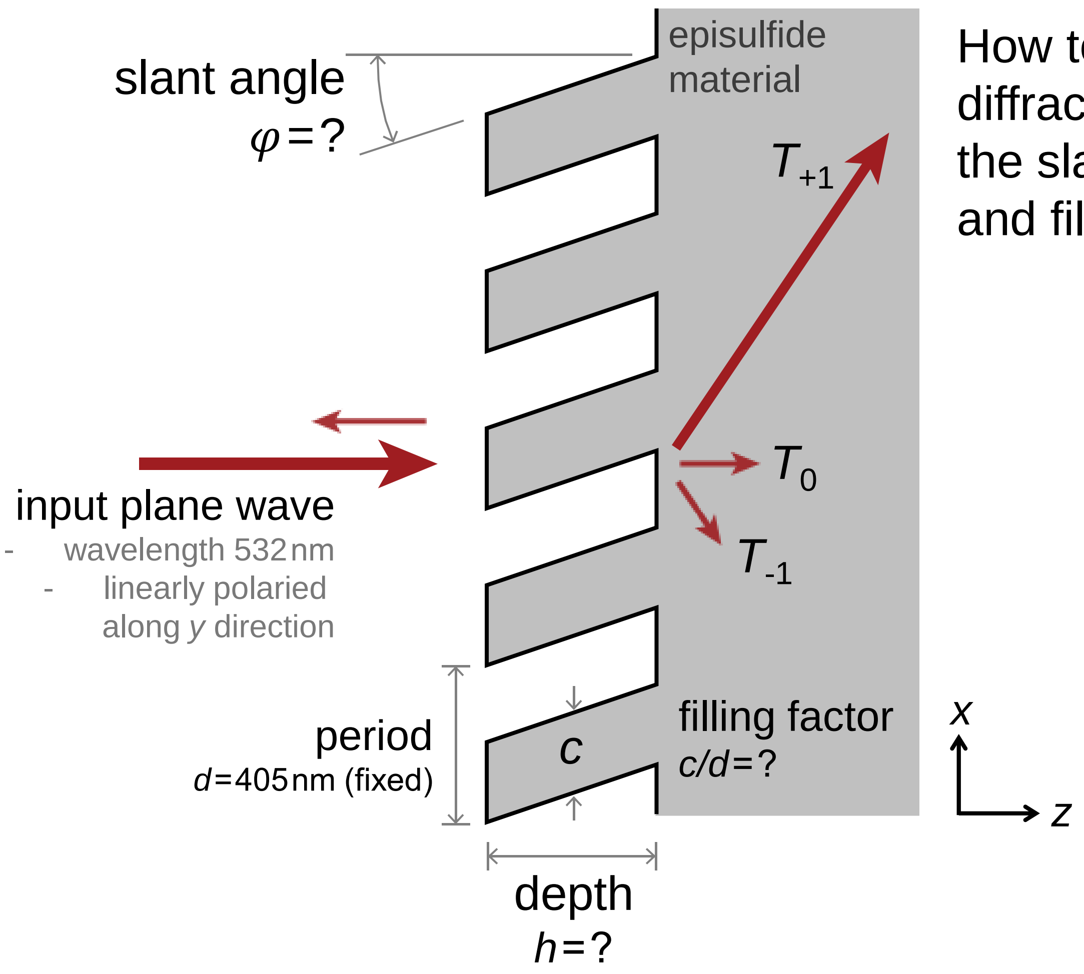
- Incident plane wave has wave vector $\boldsymbol{k}^{\text{in}} = (k_x^{\text{in}}, k_y^{\text{in}}, k_z^{\text{in}})$
- Grating period $\Lambda = (\Lambda_x, \Lambda_y)$
- The output orders are discrete, and wave vector for the order (i, j) is

$$k_x^{\text{out}} = k_x^{\text{in}} + \frac{2\pi}{\Lambda_x} i$$

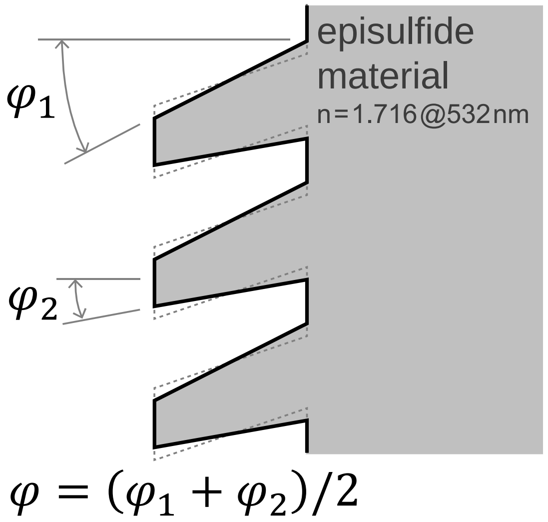
$$k_y^{\text{out}} = k_y^{\text{in}} + \frac{2\pi}{\Lambda_y} j$$

$$k_z^{\text{out}} = \sqrt{\left(\frac{2\pi}{\lambda} n^{\text{out}}\right)^2 - \left({k_x^{\text{out}}}^2 + {k_y^{\text{out}}}^2\right)}$$

Modeling Task



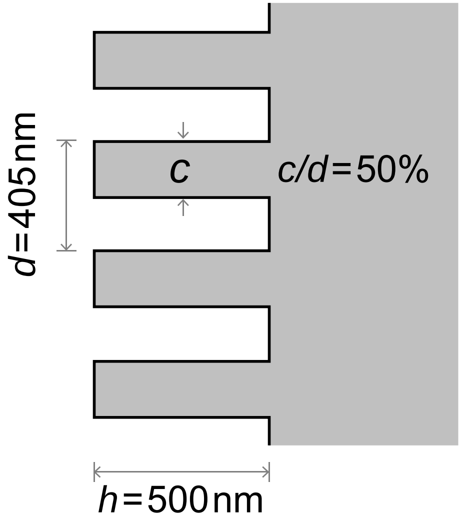
How to optimize the T_{+1} order diffraction efficiency, by adjusting the slant angle φ, grating depth h, and filling factor c/d?



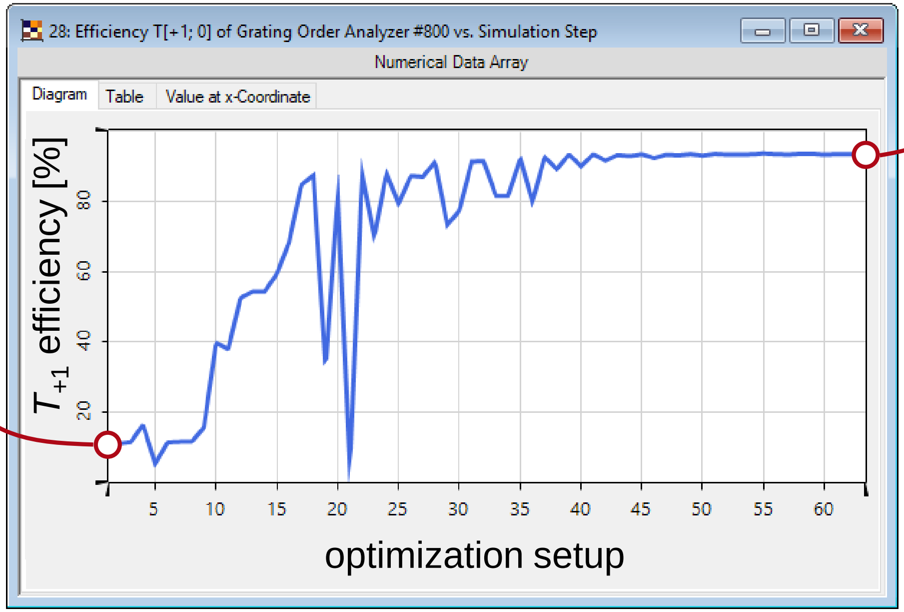
In addition, how to evaluate the grating performance with the slope deviation due to the fabrication technique taken into account?

Results – Parametric Optimization

initial structure

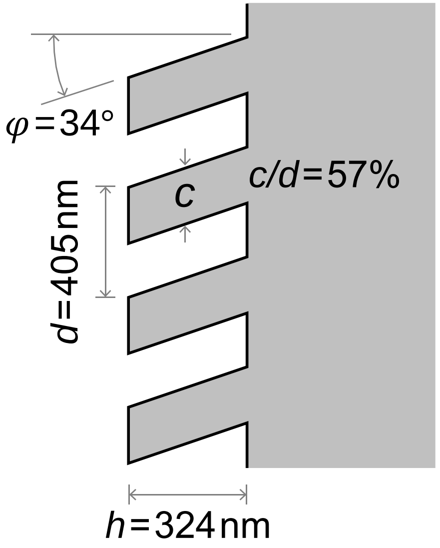


Order	Efficiency
-1	11.551%
0	72.795%
+1	11.551%



parametric optimization with rigorous Fourier modal method for grating efficiency calculation

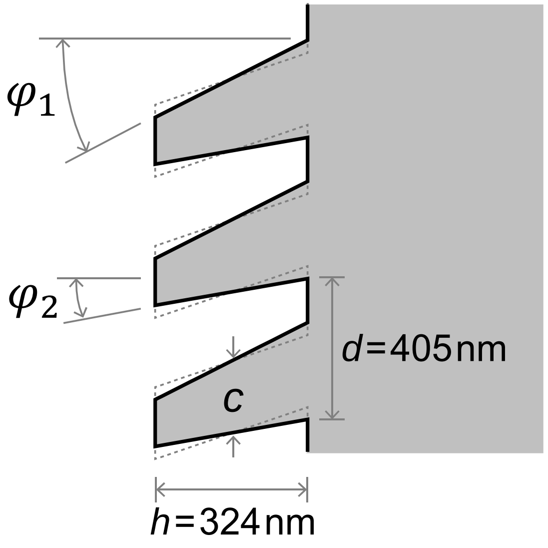
optimized structure



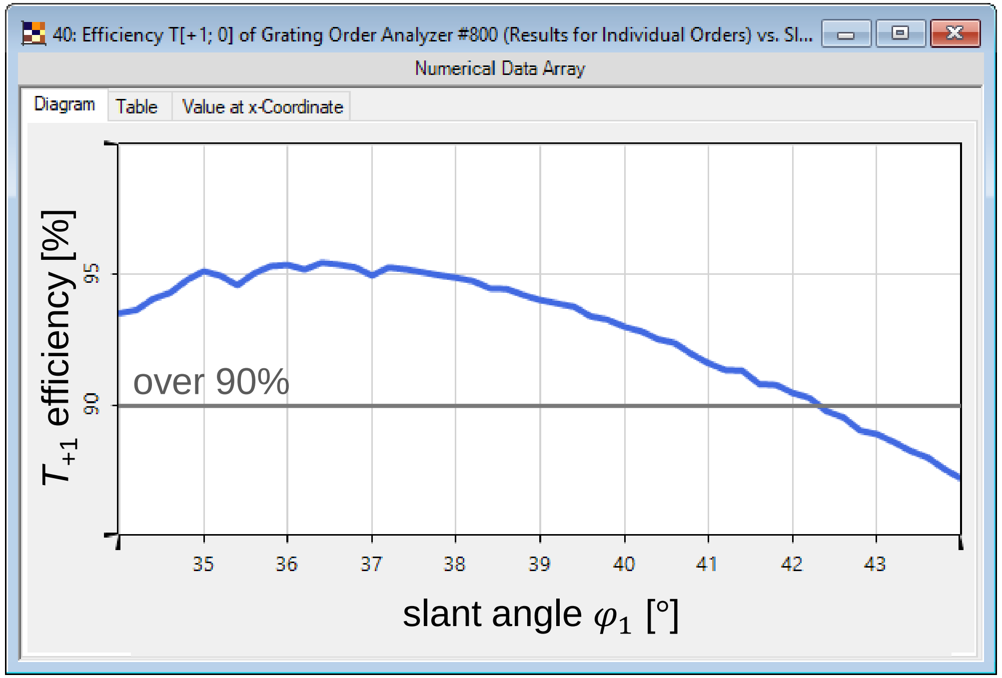
Order	Efficiency
-1	3.257%
0	0.365%
+1	**93.659%**

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 c/d=57%
- varying φ_1 from 34 to 44°



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

Task 5: Video

Klick the following link to watch the video:

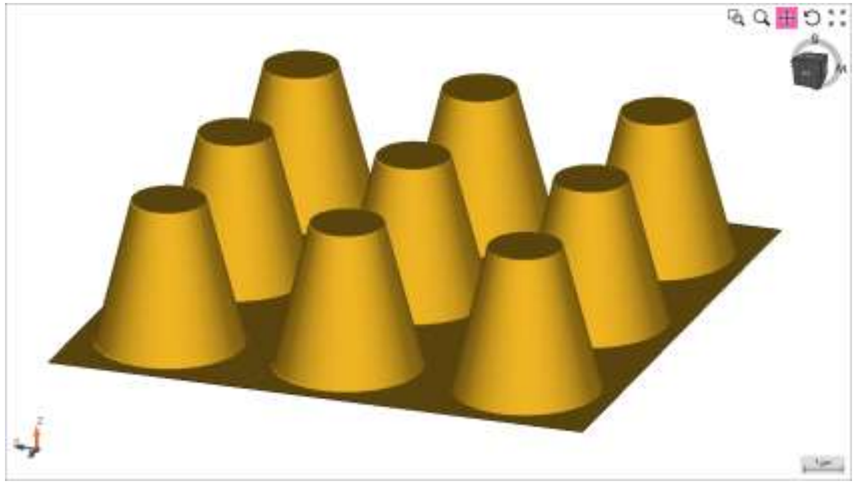
https://youtu.be/EX0IOWmXHKQ

From now on, let's try to configure two-dimentional periodic grating. In VL, we call it 3D grating.

Task 6

Configuration of Grating Structures with Two-Dimensional Periodicity

Abstract



Complex optical grating structures are widely used for several applications such as spectrometers, near-eye display systems, etc. VirtualLab Fusion provides rigorous analysis of arbitrary grating structures in an easy way by applying the Fourier modal method (FMM). In the Grating Software Package, also 3D grating structure can be configured by using various interfaces or/and media within a stack. The user interface to set up the geometry of a stack is user friendly and can be used to generate even more complex grating structures. This use case is focused on the configuration of grating structures which exhibit a two-dimensional periodicity.

This Use Case Shows ...

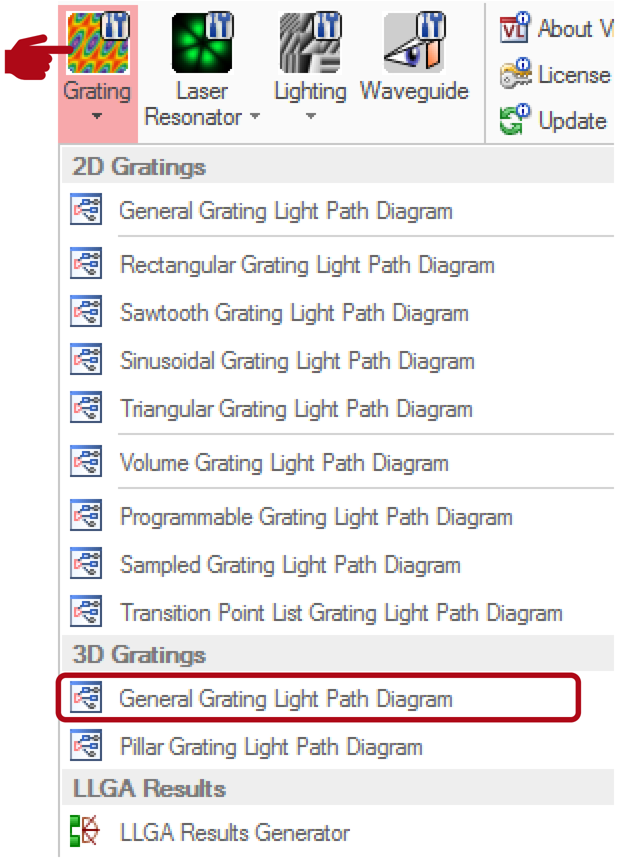
- How to configure two-dimensional grating structures in Grating Toolbox by using
  - medium-based definition type
  - interface-based definition type

- How to change advanced options & inspect defined structure before calculation.

- note: In VirtualLab grating structures, which exhibit a two-dimensional periodicity are called 3D gratings. Consequently, lamellar gratings (1D-periodicity) are called 2D gratings.

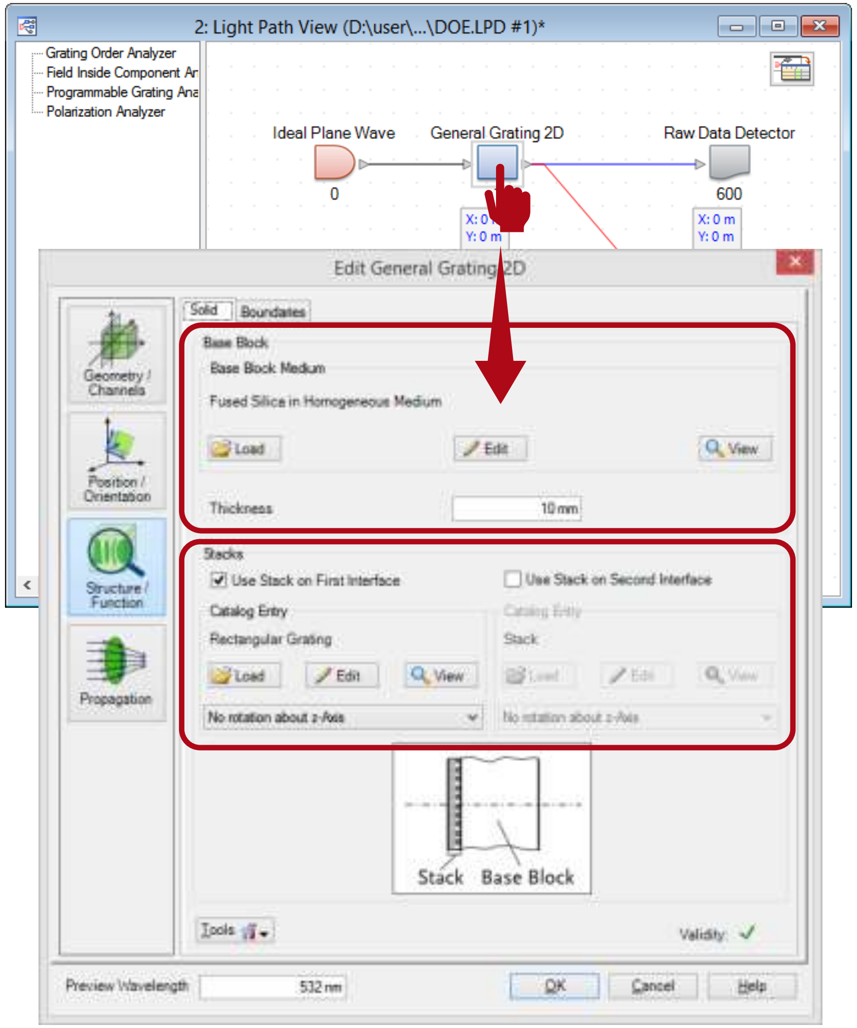
Grating Toolbox Initialization

- Initialization
  - Start ➔ Grating ➔ General Grating Light Path Diagram (3D Gratings)
- note: For usage of special type of grating, e.g. pillar grating, the specific light path diagram can be chosen directly.

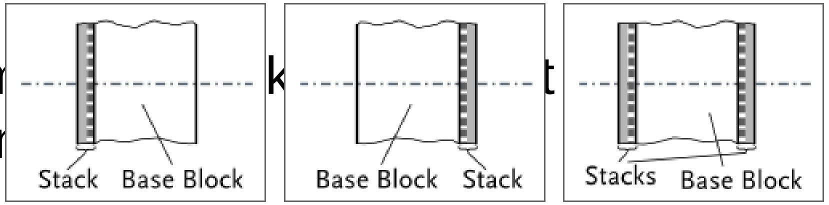


Grating Structure Settings

- First, the thickness and the material of the substrate (*Base Block*) have to be defined.
- In VirtualLab grating structures are defined in a so called stack.
- Stacks can be attached to either one or both sides of the substrate.



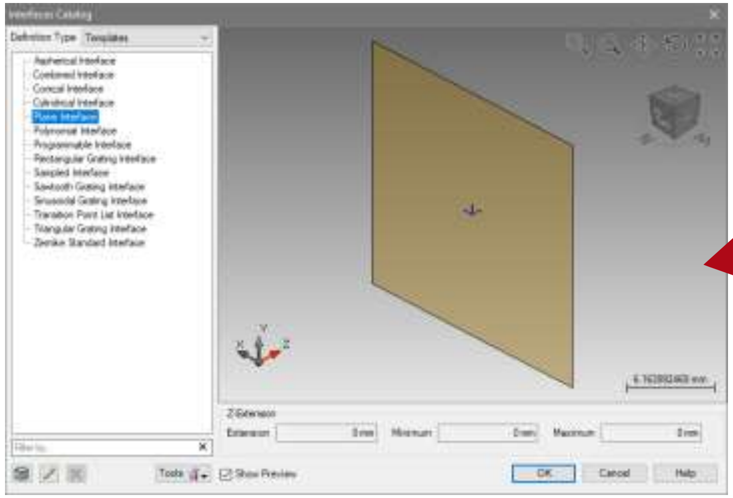
- For exam k t is chose

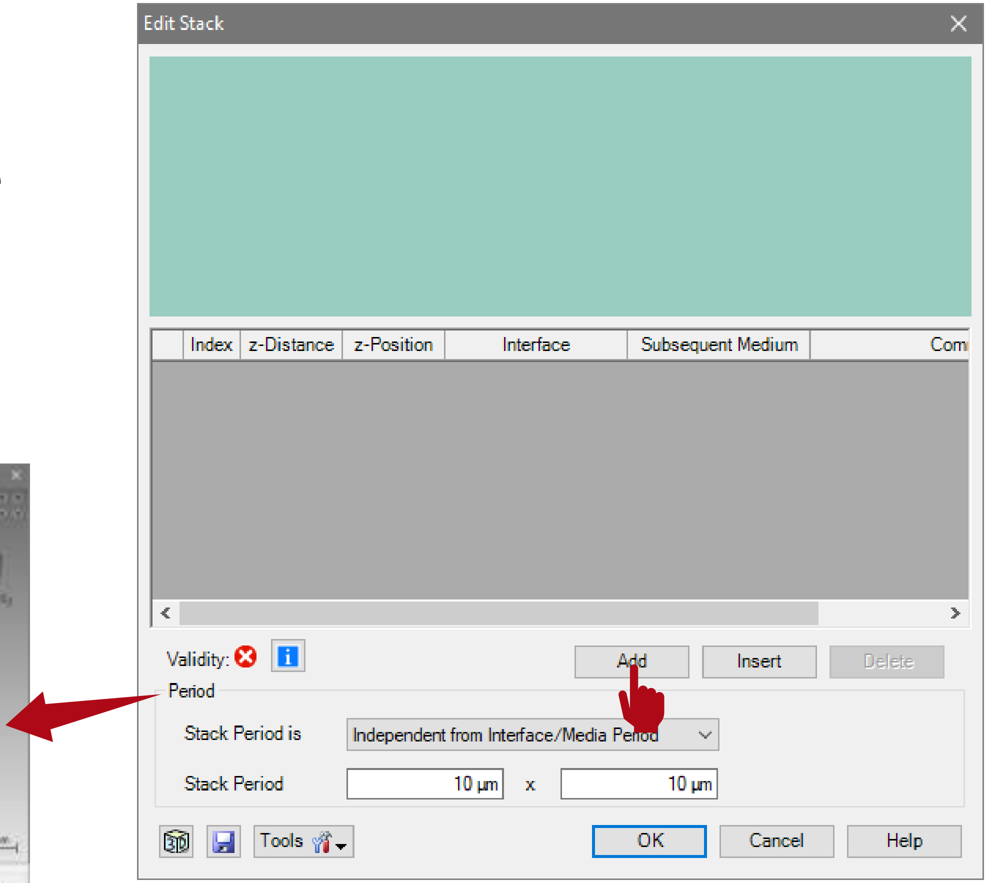


Medium-based Definition Type (Example: Pillar Grating)

Stack Editor

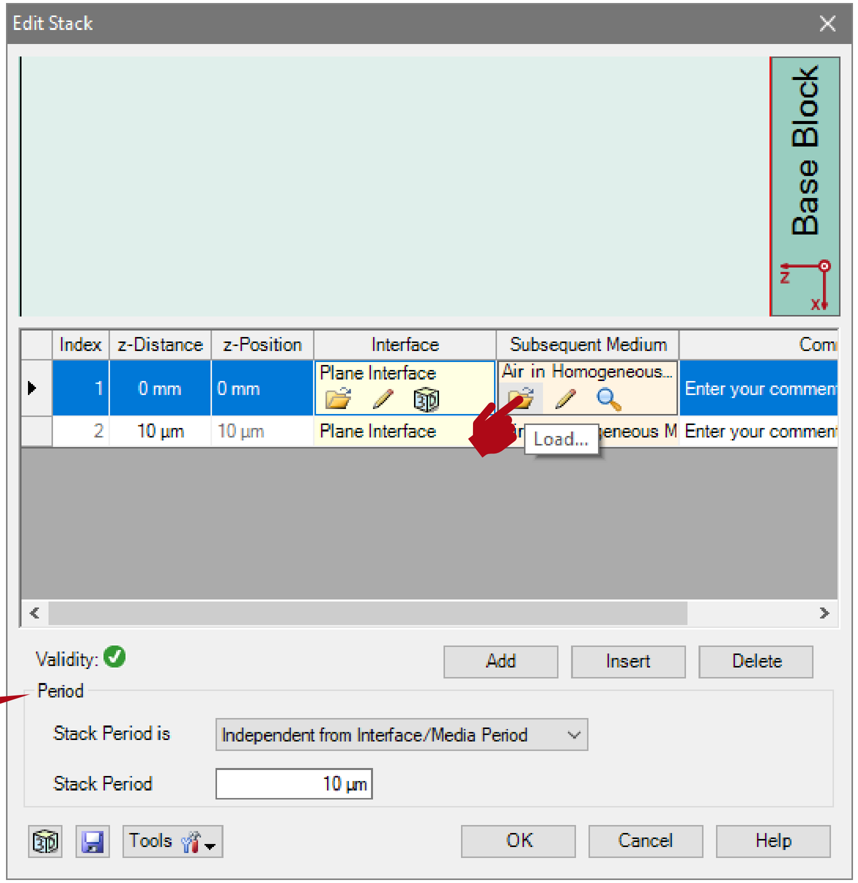
- In the *Stack Editor* interfaces and media can be added or inserted from catalog.
- In order to define a grating by a special medium, two plane interfaces have to be added, which act as boundaries.

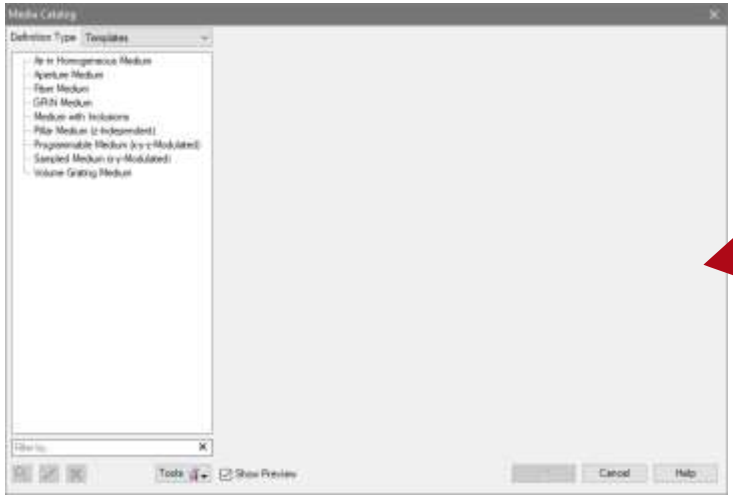




Stack Editor

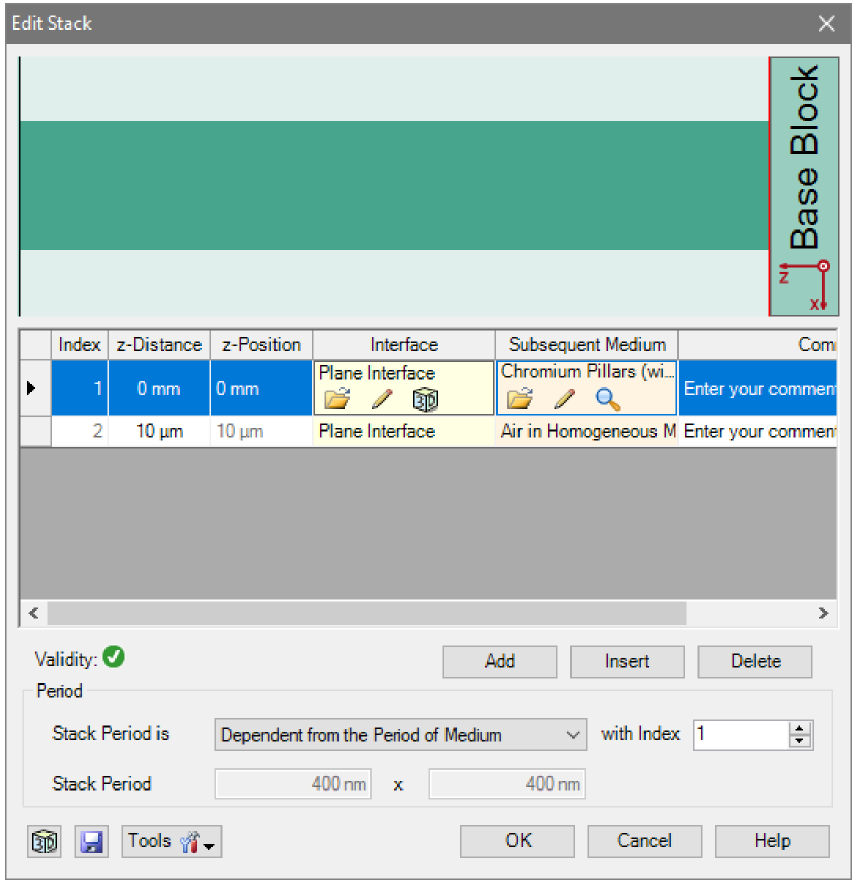
- The medium between the two plane interfaces can be either homogenous or modulated.
- By using a latter one complex grating structures, like pillar gratings, can be described very efficiently.





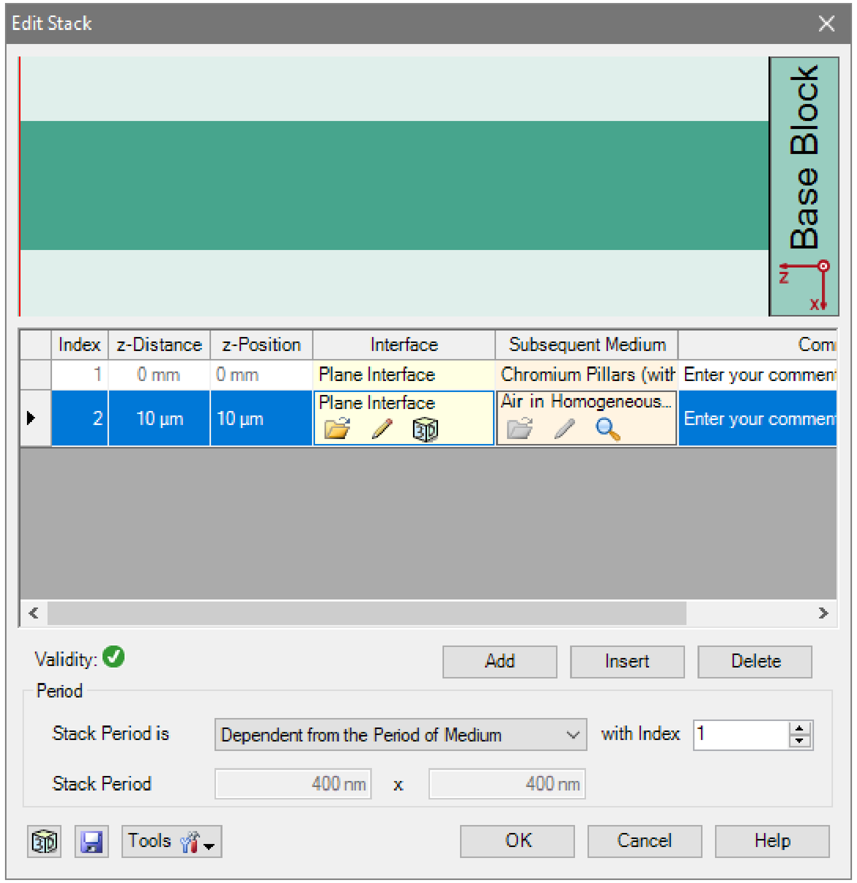
Pillar Grating Medium

- In the catalog category “LightTrans Defined” the *chromium pillars* can be found in the pillar media category.
- This type of medium enables e.g. the simulation of pillar structure as well as pin holes on top of a substrate.
- In this example, rectangular pillars which consist of chromium are located on a fused silica substrate.
- In the view of the stack editor, different materials are indicated by other colors based on their index of refraction (dark means higher).
- note: The stack editor will always provide a cross-sectional view of the x-z plane.



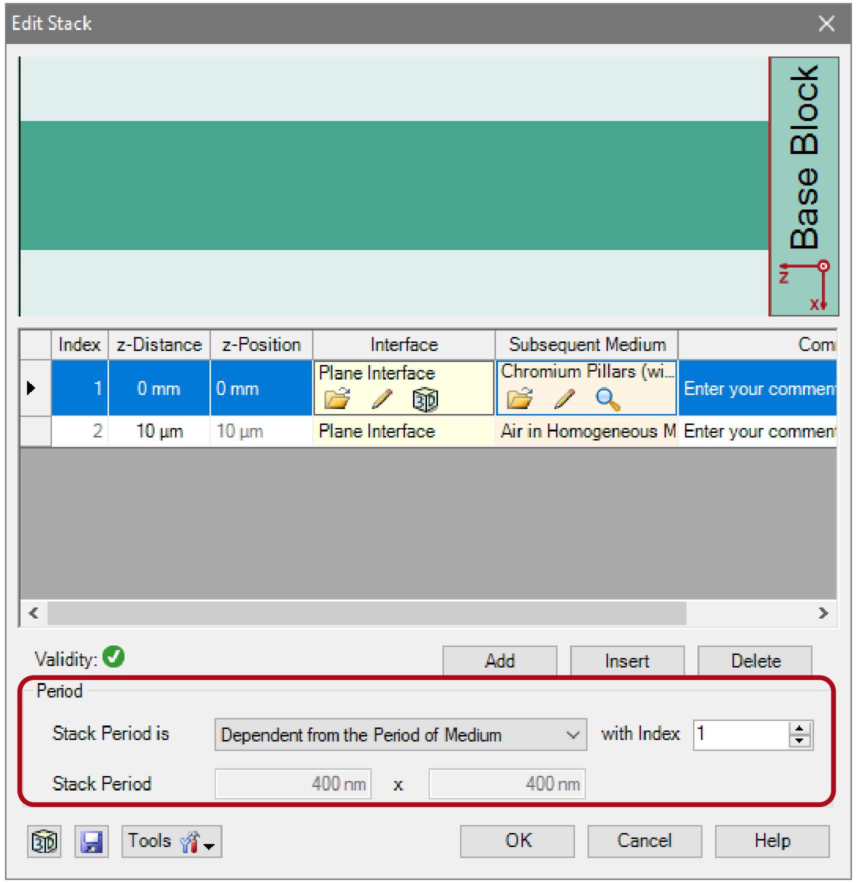
Pillar Grating Medium

- Please note: the order of the interfaces is always counted from the surface of the substrate.
- The selected interface is highlighted red in the view.
- Further, the medium in front of the grating (means behind last interface) can not be defined here. It is automatically taken from the material in front of the grating component.
- This material can be changed in the *Light Path Editor*.



Pillar Grating Medium

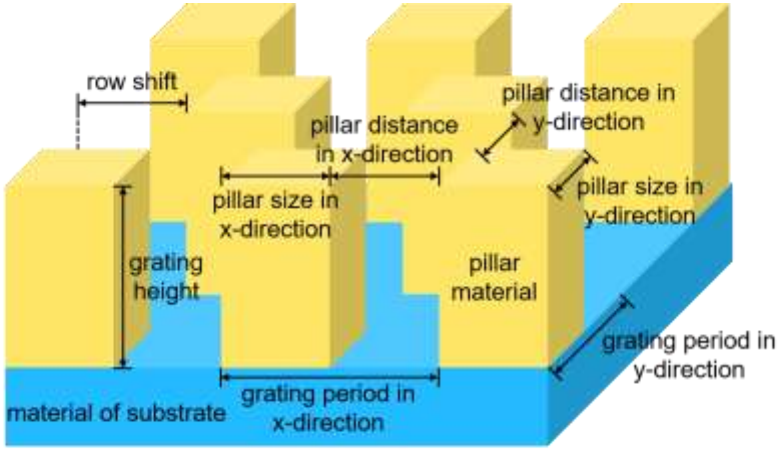
- The *Stack Period* allows to control the period of the whole configuration.
- In case of a grating exhibiting a two-dimensional periodicity the period has to be defined in x- and y-direction.
- This period is also taken for the periodic boundary conditions of the FMM algorithm.
- In case of simple grating structures, it is recommended to choose the option *Dependent from Period of Medium* and select the proper index of the periodic medium.

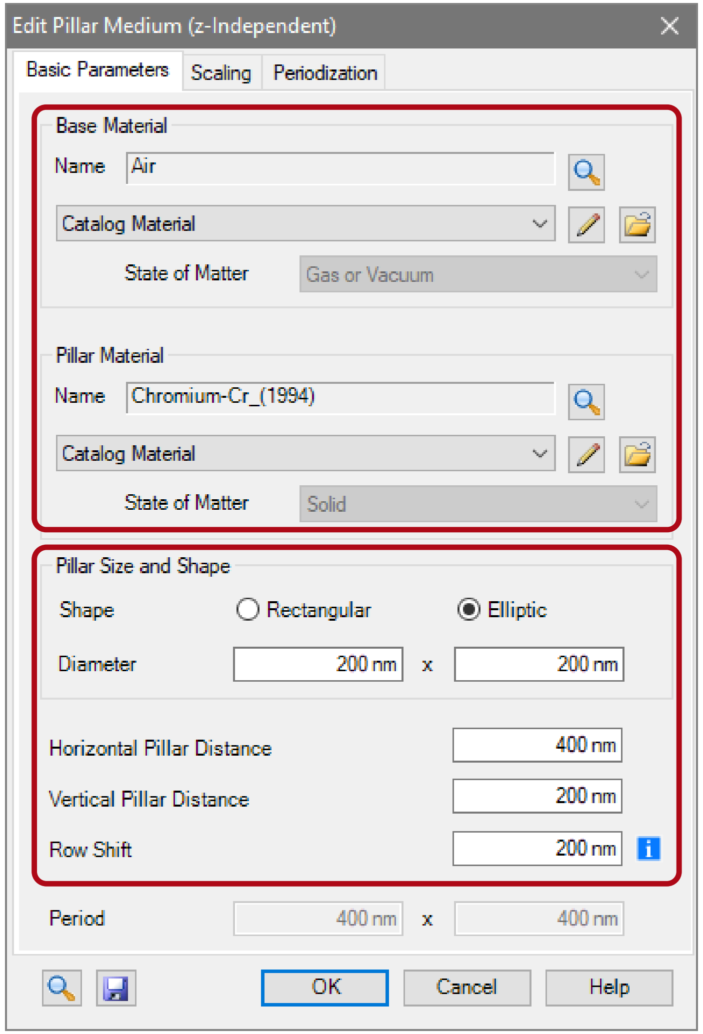


Pillar Grating Medium Parameters

The pillar grating is defined by the following parameters:

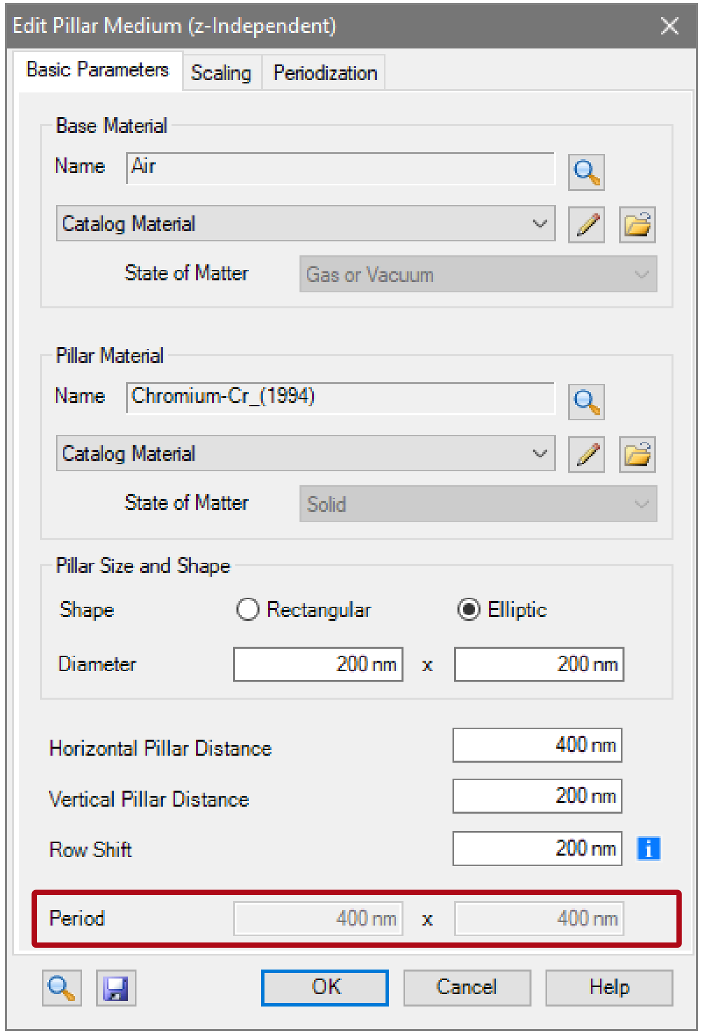
- base material (material of grooves)
- pillar material (material of ridges)
- shape of pillars (either rectangular or elliptic)
- pillar distance in x-direction (horizontal)
- pillar distance in y-direction (vertical)
- row shift (allows a displacement of rows)
- grating period in x- and y-direction





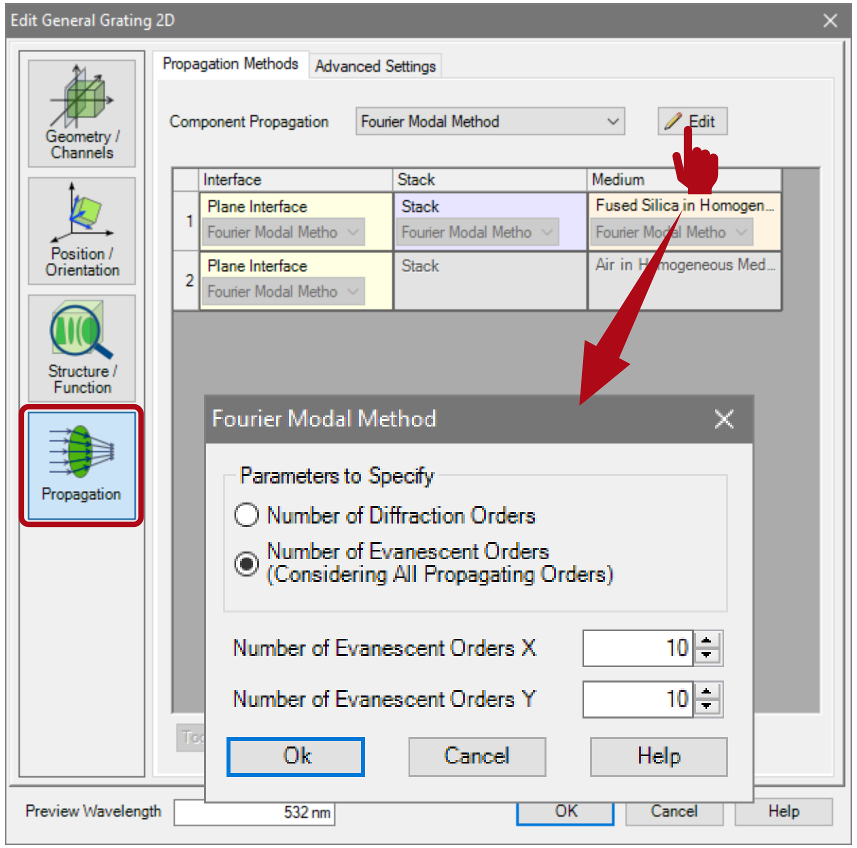
Pillar Grating Medium Parameters

- The period of the pillar grating is calculated based on pillar size and distance automatically.
- Thus, it cannot be set individually and the boxes are shown grayed out.



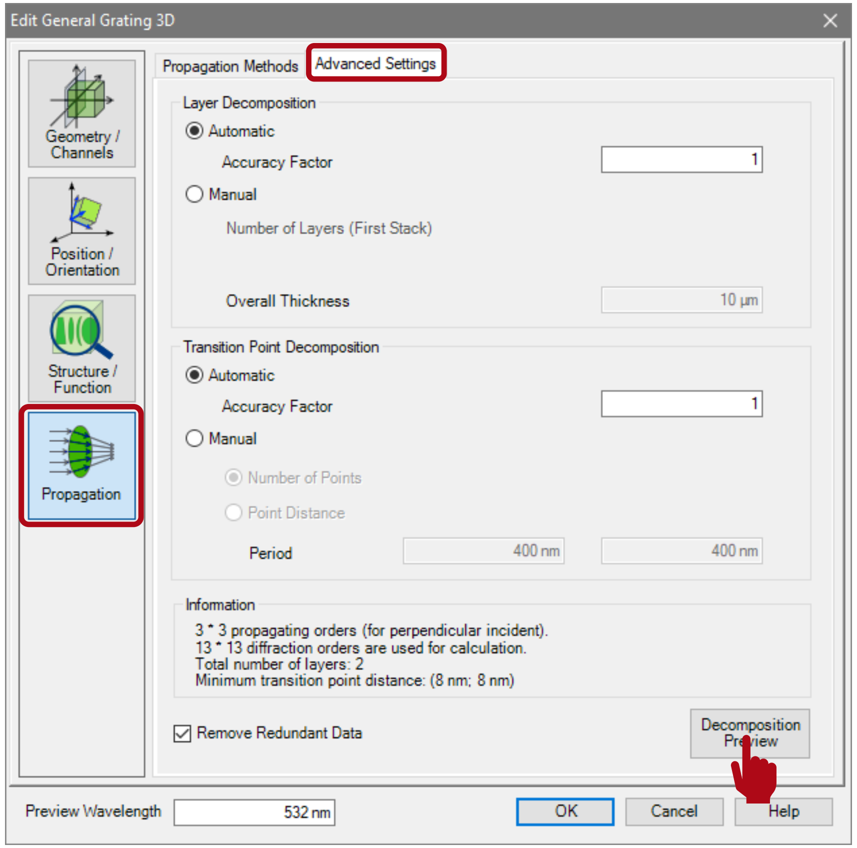
Advanced Options & Information

- In the propagation menu several advanced options are available.
- The propagation method tab allows to edit the accuracy settings of the FMM algorithm.
- Either the numbers of considered total orders or evanescent orders in each direction can be set.
- This might be useful, especially if metallic gratings are considered.
- In contrast, in case of dielectric gratings, the default setting will be sufficient.



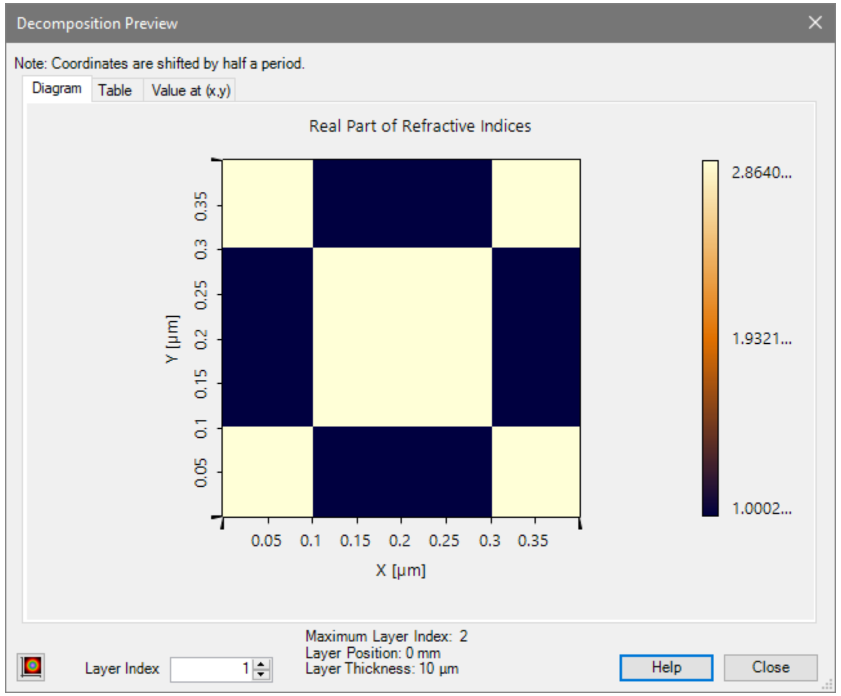
Advanced Options & Information

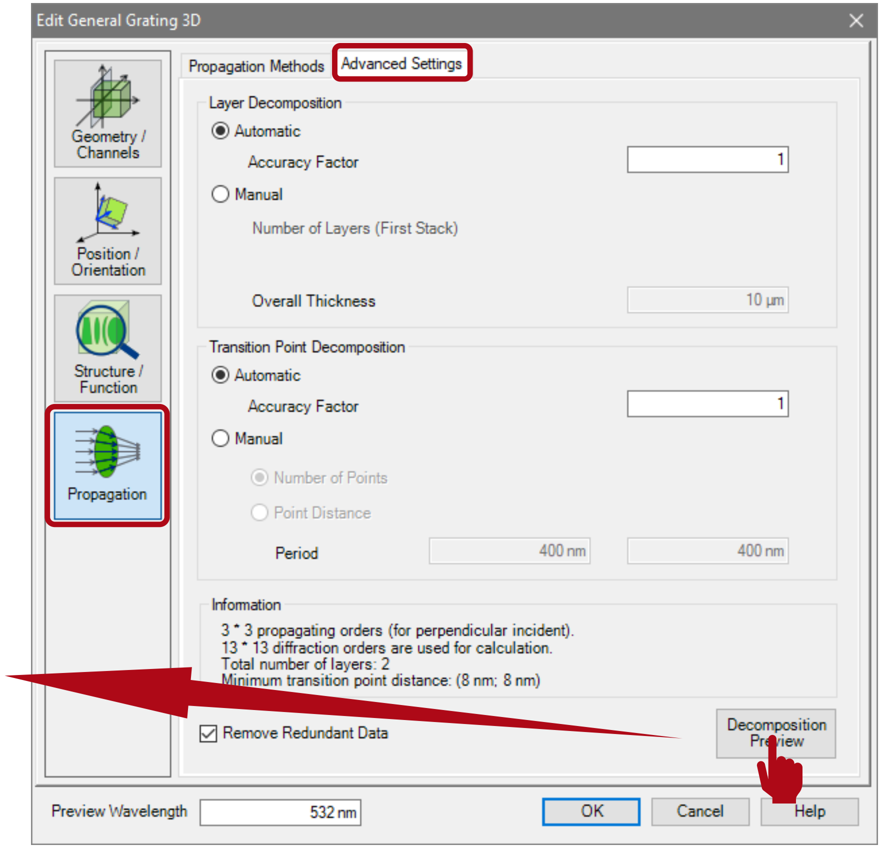
- The *Advanced Settings* tab provides information about the decomposition of the structure.
- The *Layer Decomposition* and *Transition Point Decomposition* settings can be used to adjust the discretization of the structure. The default settings are appropriate for nearly all grating structures.
- Further, information about the number of layers and transition points are provided.
- The *Decomposition Preview* button provides a depiction of the structure data which are used for the FMM calculation. The refractive index is illustrated by a color scale.



Advanced Options & Information

- The decomposition preview of the defined pillar grating (top view).
- VirtualLab suggests a discretization in 2 layers (1 layer is representing the substrate).

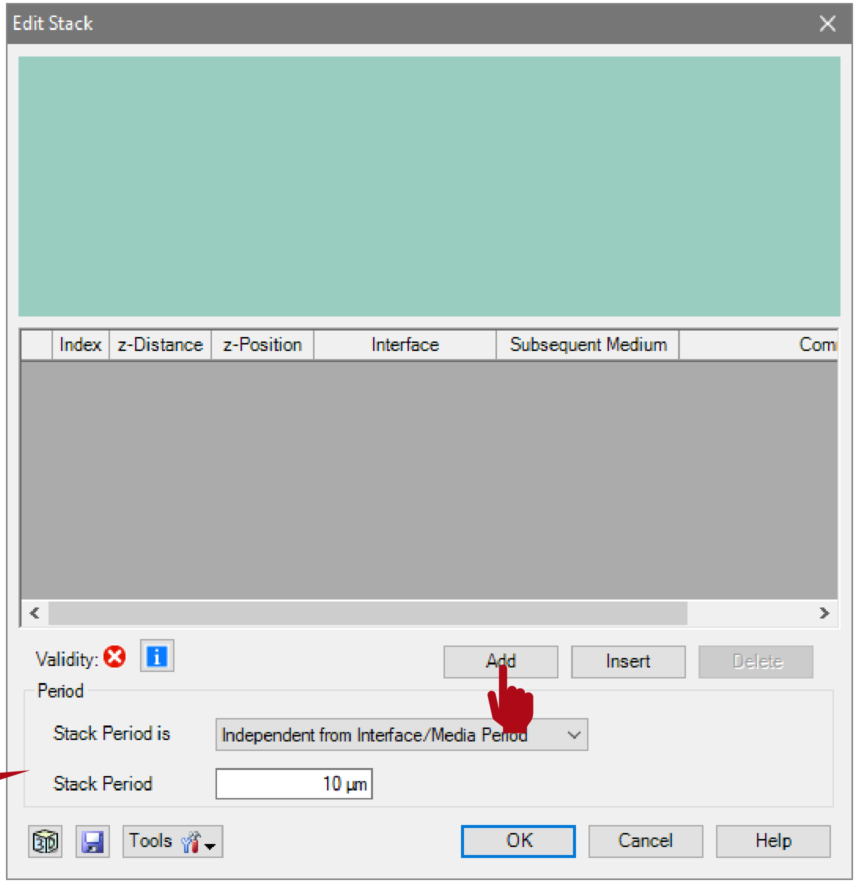


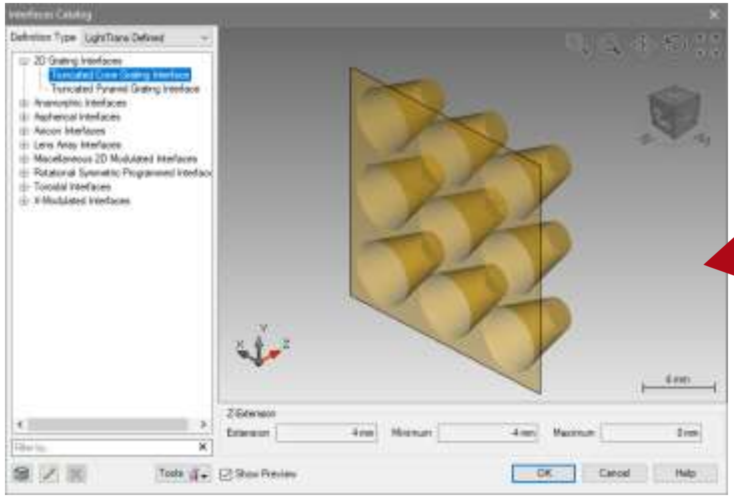


Interface-based Definition Type
(Example: Truncated Cone Grating)

Stack Editor

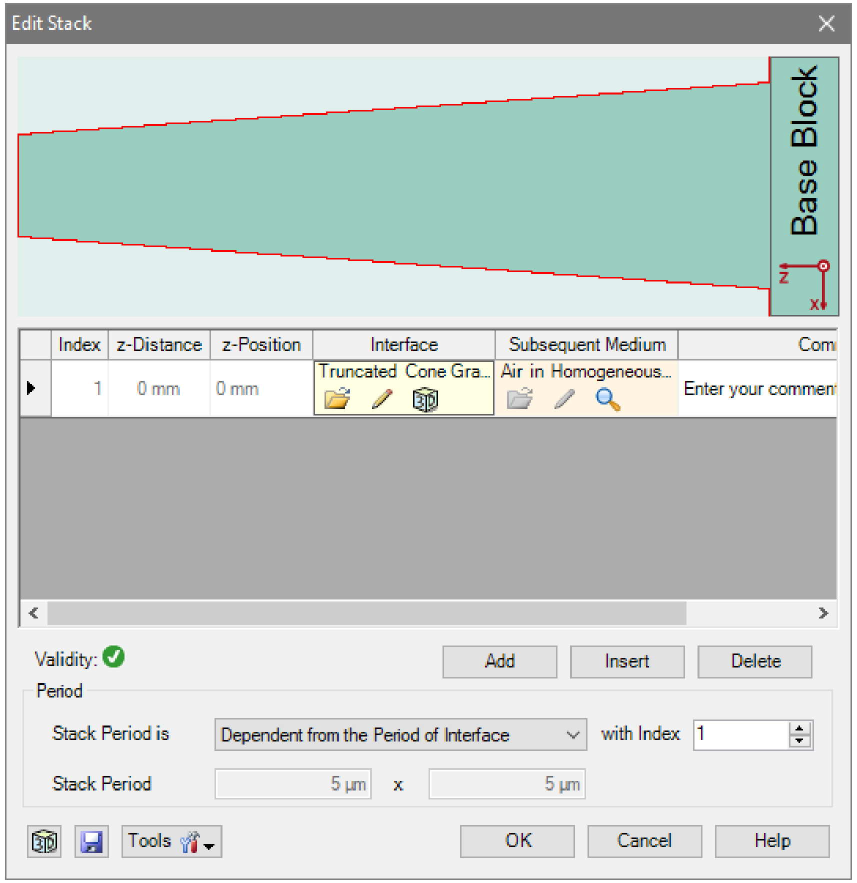
- In the *Stack Editor* interfaces can be added or inserted from catalog.
- In the category “2D Grating Interface” there are two different interfaces for definition of 3D grating structures.





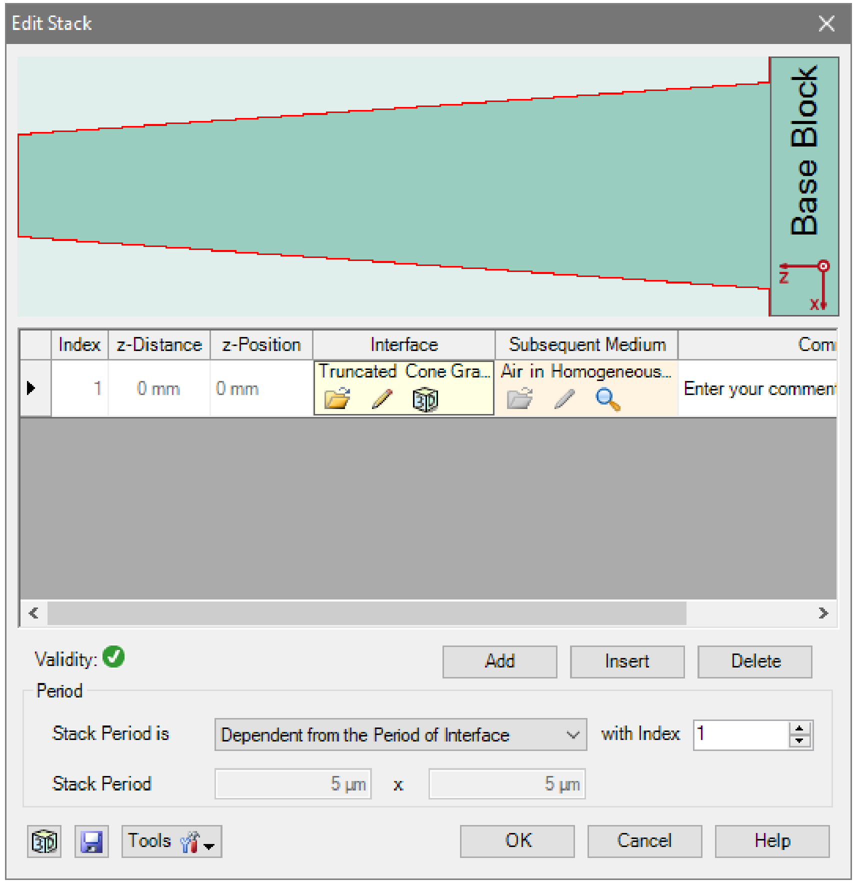
Truncated Cone Grating

- In this example, the “*Truncated Cone Grating Interface*” is used.
- This type of interface enables e.g. the simulation of anti-reflective structures with a circular shape.
- In this example, cones which are made of fused silica located on a substrate of the same material.
- In the view of the stack editor, different materials are indicated by other colors based on their index of refraction (dark means higher).
- note: The Stack Editor will always provide a cross-sectional view of the x-z plane.



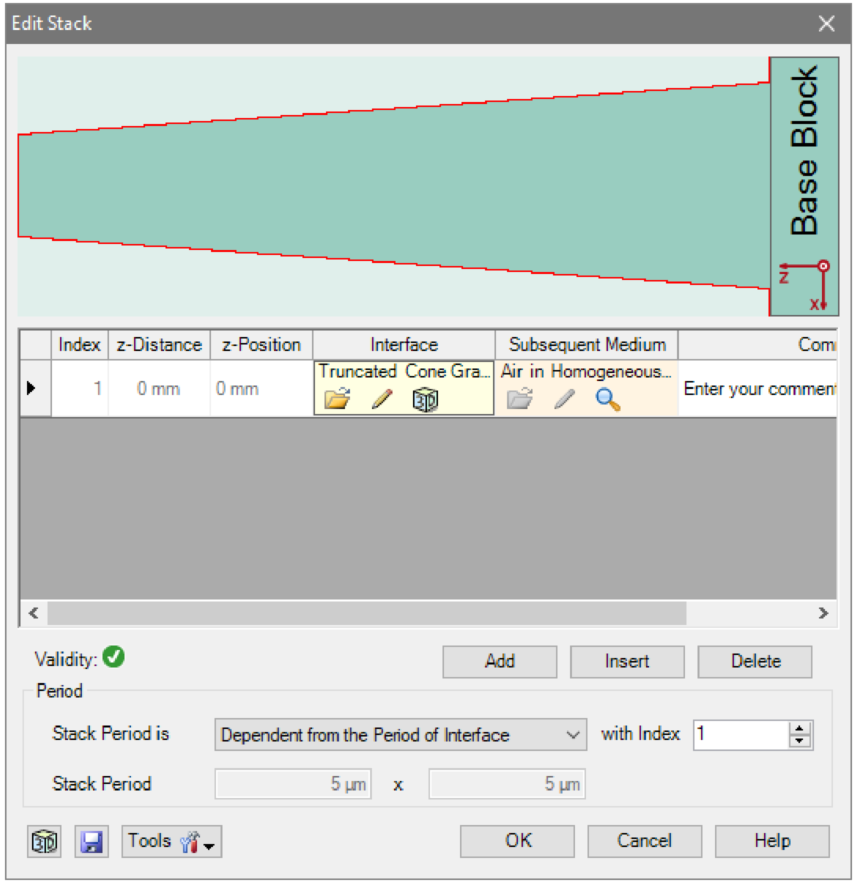
Truncated Cone Grating

- Please note: the order of the interfaces is always counted from the surface of the substrate.
- The selected interface is highlighted red in the view.
- Further, the medium in front of the grating (means behind last interface) can not be defined here. It is automatically taken from the material in front of the grating component.
- This material can be changed in the *Light Path Editor*.



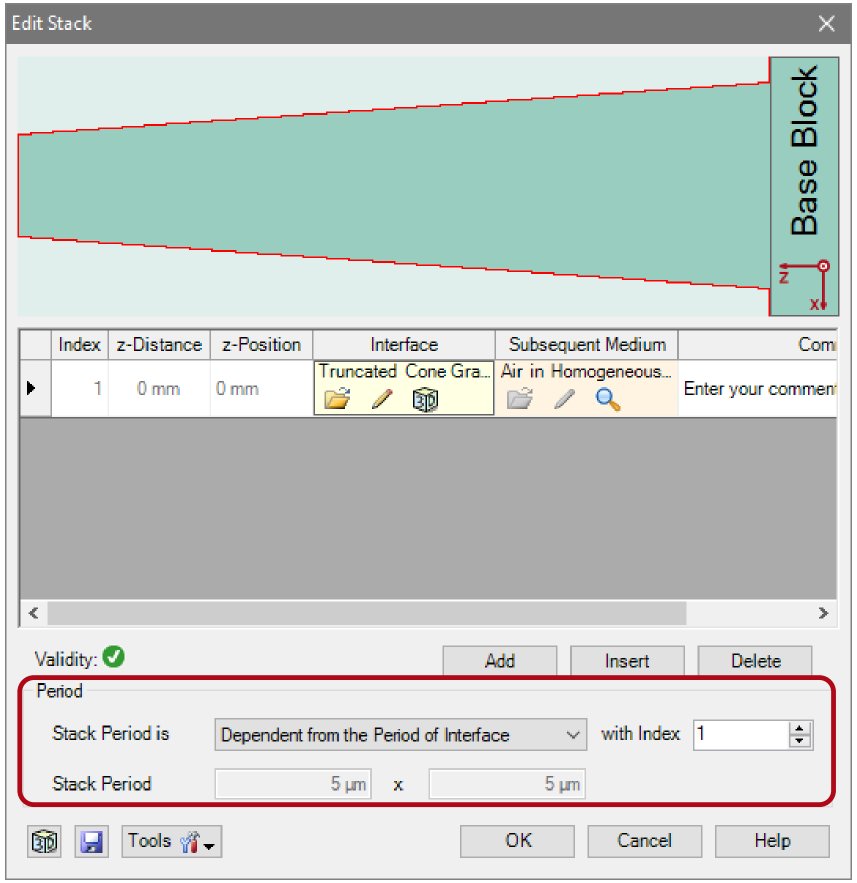
Truncated Cone Grating

- Further, the material of the cones is automatically taken from the material subsequent to the interface.
- In this example, this means, that the material of the substrate (base block) is used.
- If the grating structure is made of a different material, an additional plane interface has to be added in order to separate the grating structure from base block.
- Afterwards, the material between the truncated cone and the plane interface can be chosen as desired.



Truncated Cone Grating

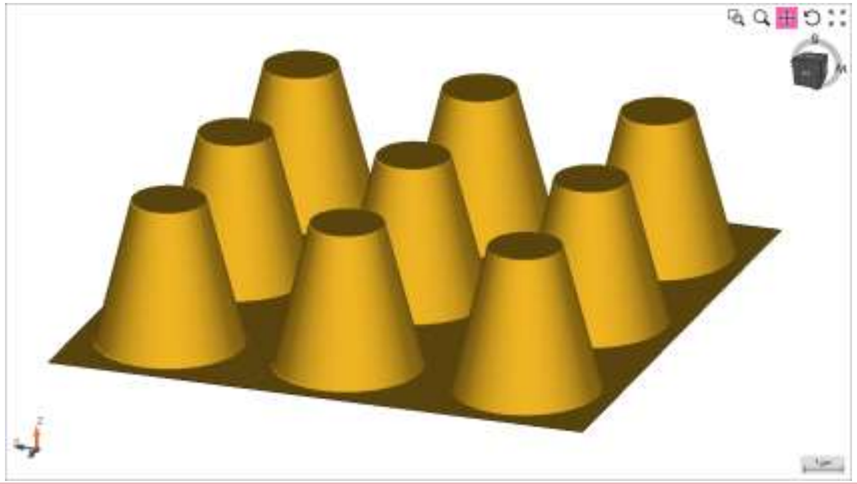
- The *Stack Period* allows to control the period of the whole configuration.
- In case of a grating exhibiting a two-dimensional periodicity the period has to be defined in x- and y-direction.
- This period is also taken for the periodic boundary conditions of the FMM algorithm.
- In case of simple grating structures, it is recommended to choose the option *Dependent from Period of Interface* and select the proper index of the periodic interface.

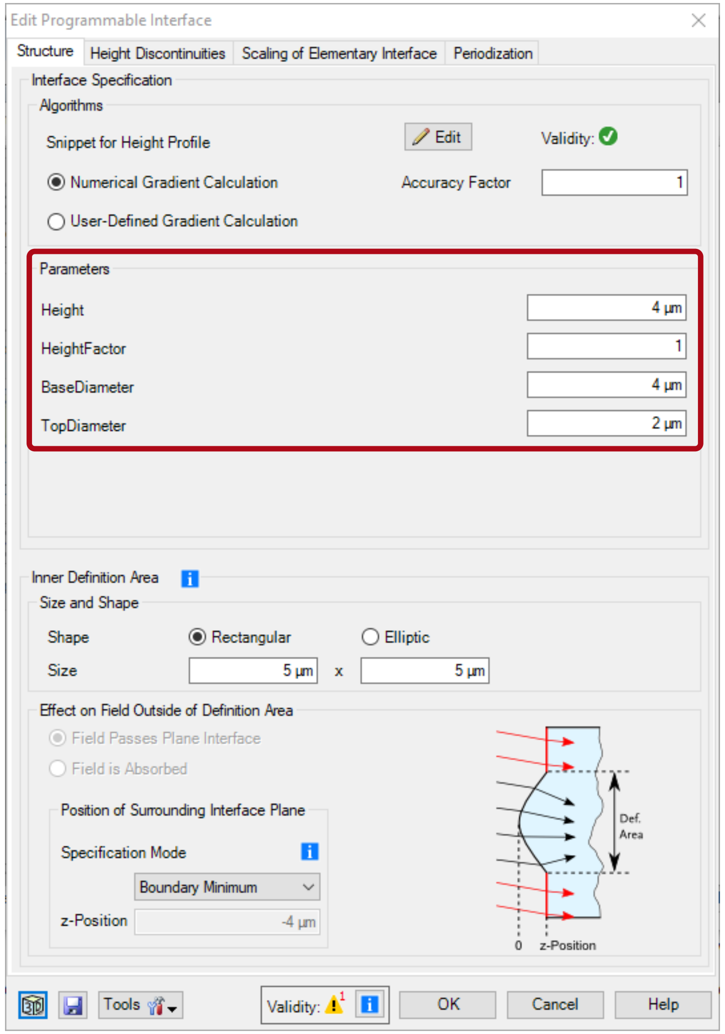


Truncated Cone Grating Parameters

The pillar grating is a programable interface and defined by the following parameters:

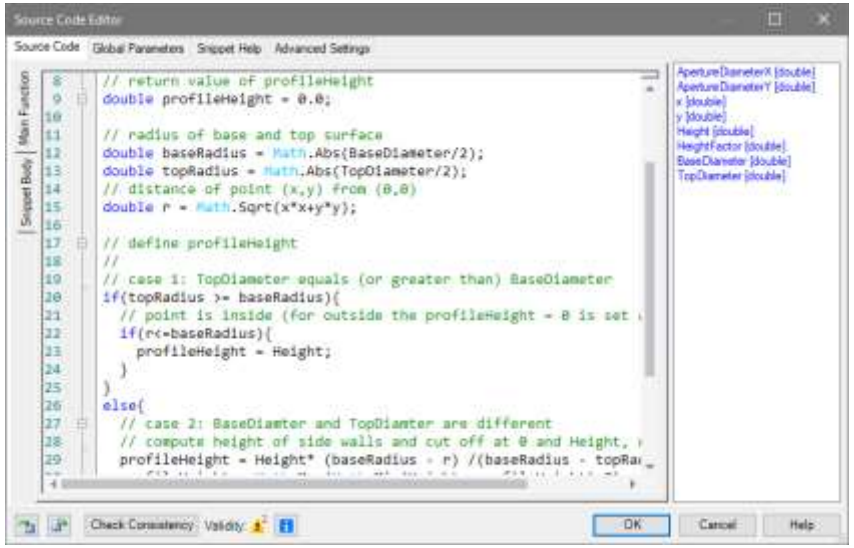
- height of cones
- height factor (e.g. allows to invert the structure
- diameter at the top
- diameter at the bottom (base)
- grating period in x- and y-direction
- the materials are automatically set

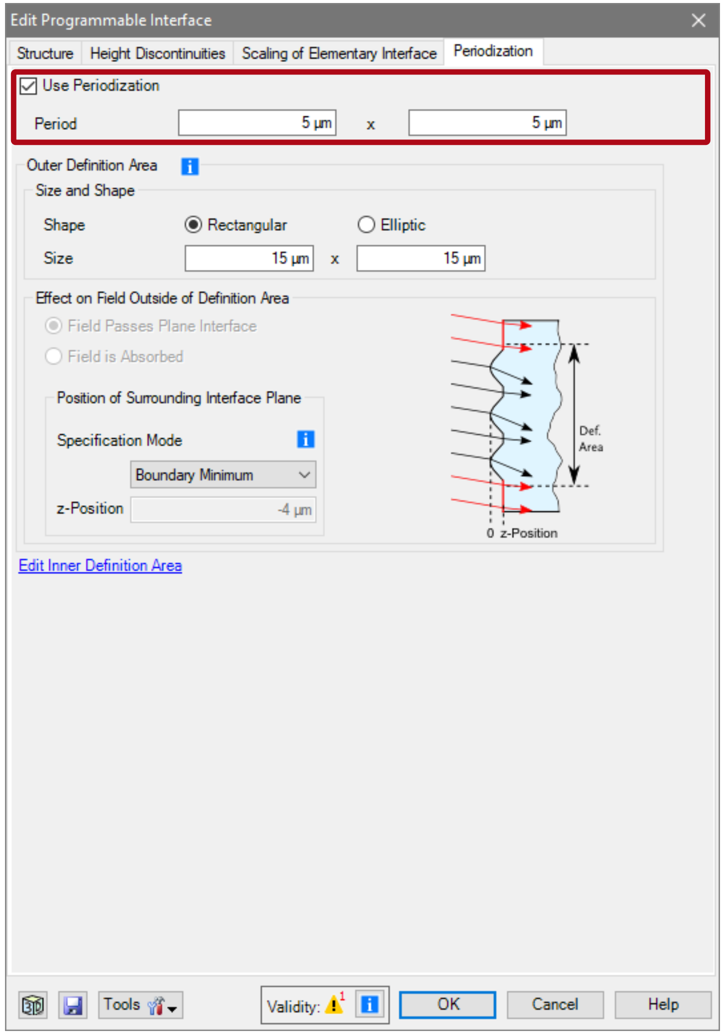




Truncated Cone Grating Parameters

- As this is a general programmable interface, the grating period has to be set in the periodization tab.
- This means also, that the definition of the grating and its parameters can easily adapted by adjusting the code, which defines the structure.





Advanced Options & Information

- Again, in the propagation menu several advanced options are available.
- The propagation method tab allows to edit the accuracy settings of the FMM algorithm.
- Either the numbers of considered total orders or evanescent orders in each direction can be set.
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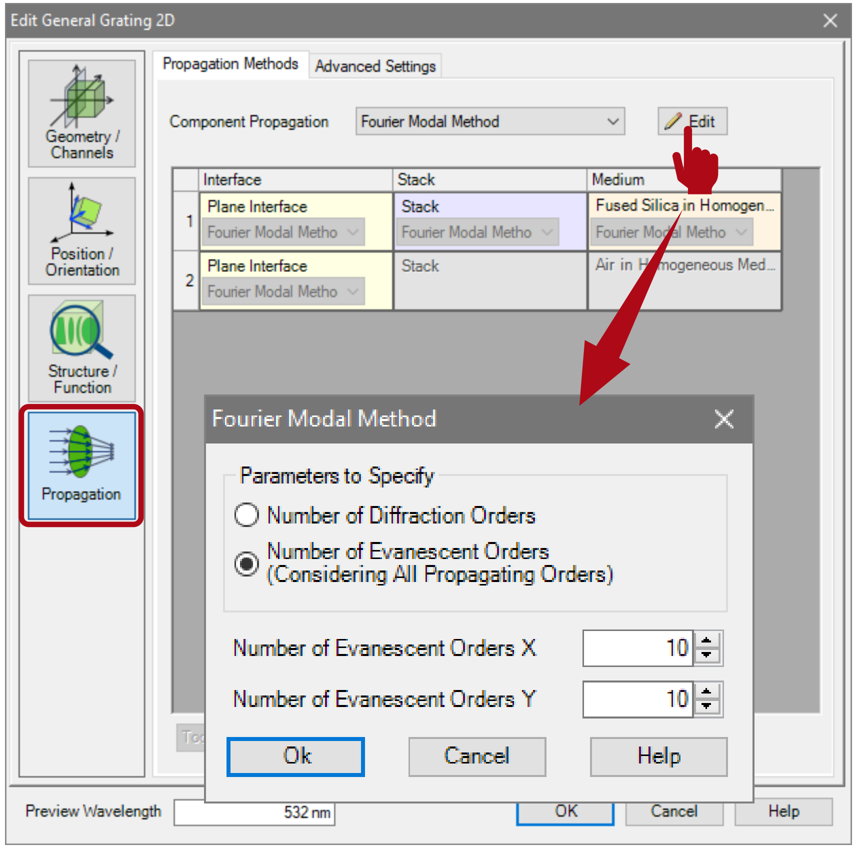
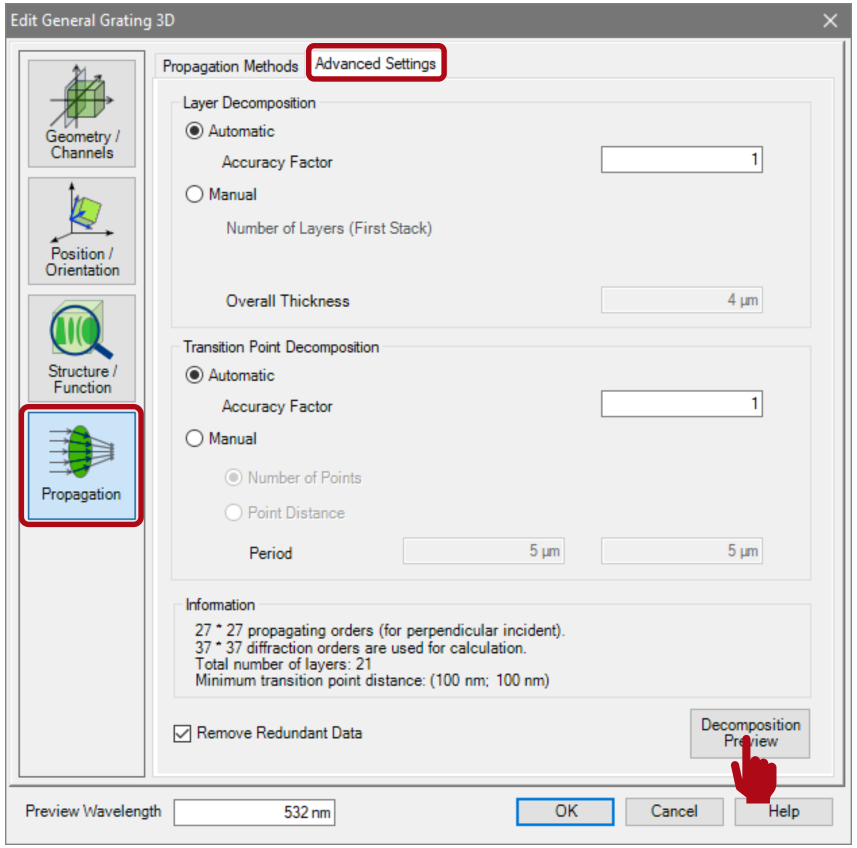
- In contrast, in case of dielectric gratings, the default setting will be sufficient.



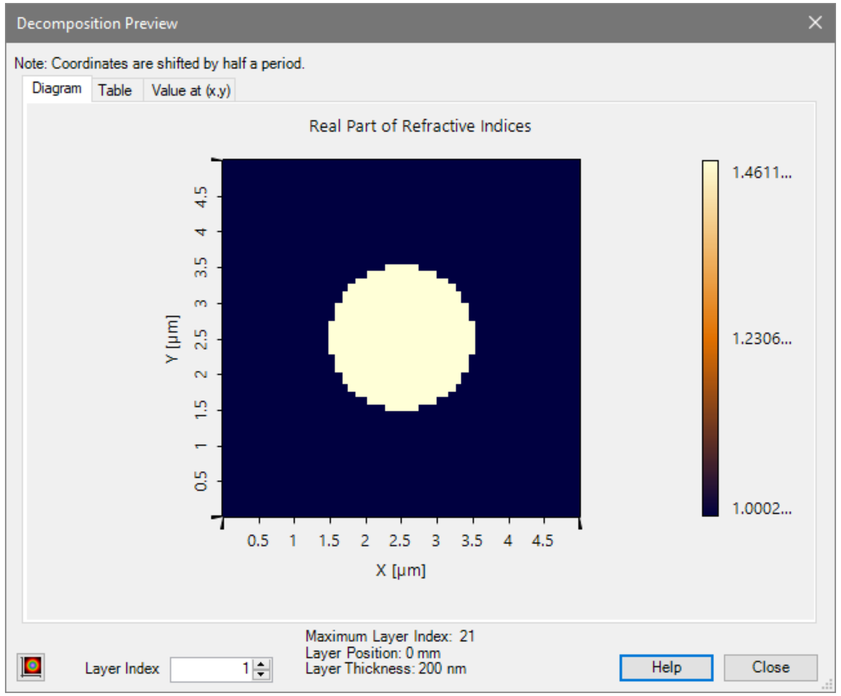
Advanced Options & Information

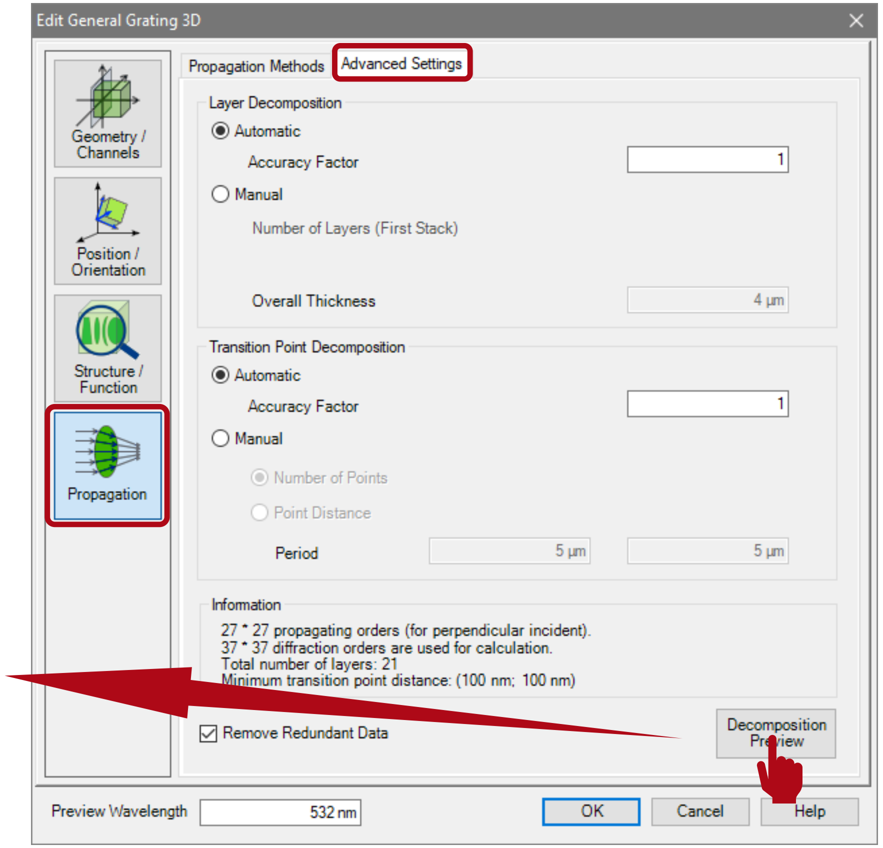
- The *Advanced Settings* tab provides information about the decomposition of the structure.
- The *Layer Decomposition* and *Transition Point Decomposition* settings can be used to adjust the discretization of the structure. The default settings are appropriate for nearly all grating structures.
- Further, information about the number of layers and transition points are provided.
- The *Decomposition Preview* button provides a depiction of the structure data which are used for the FMM calculation. The refractive index is illustrated by a color scale.



Advanced Options & Information

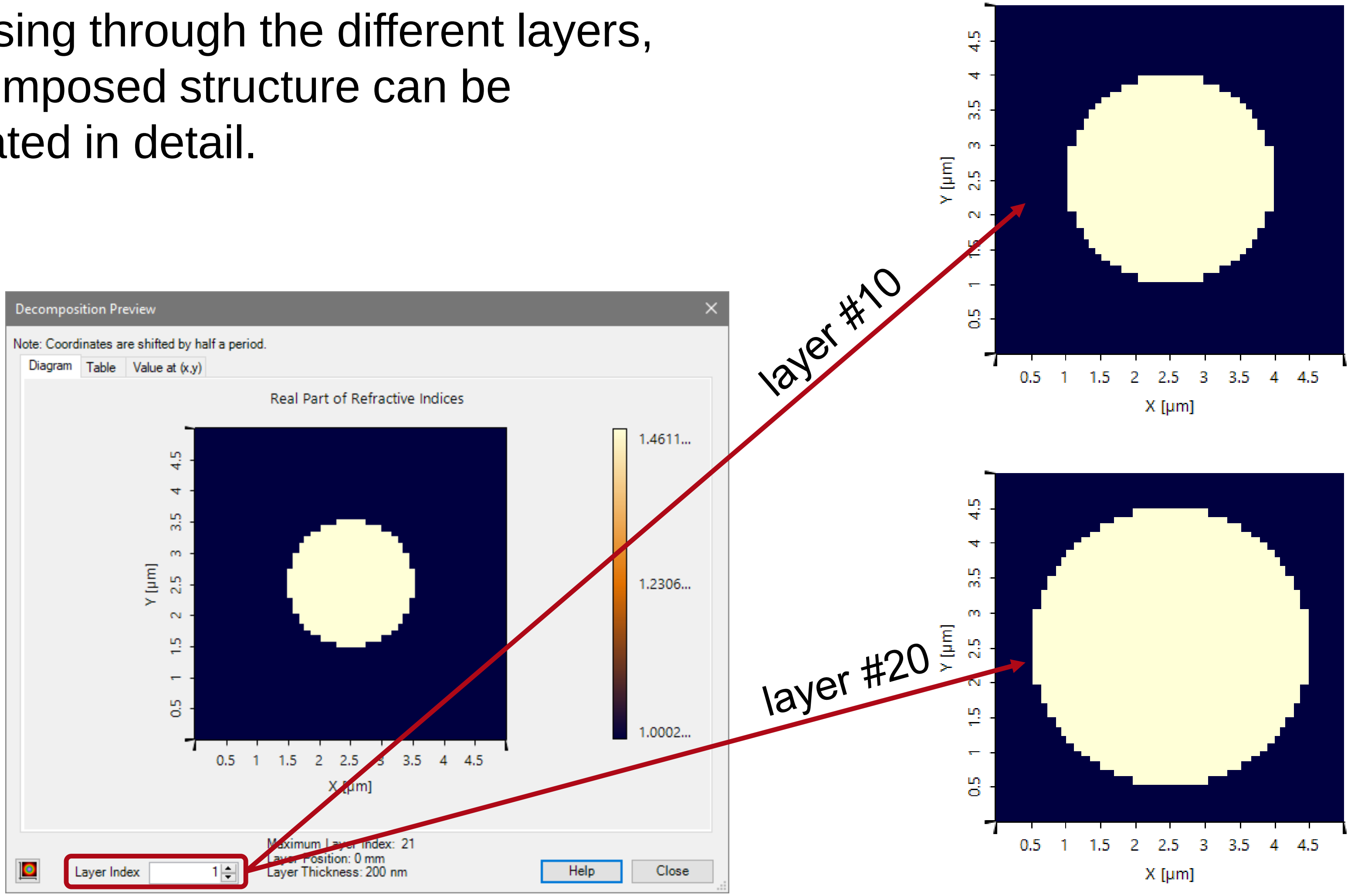
- The decomposition preview of the defined cone grating (top view).
- VirtualLab suggests a discretization in 21 layers (1 layer is representing the substrate).





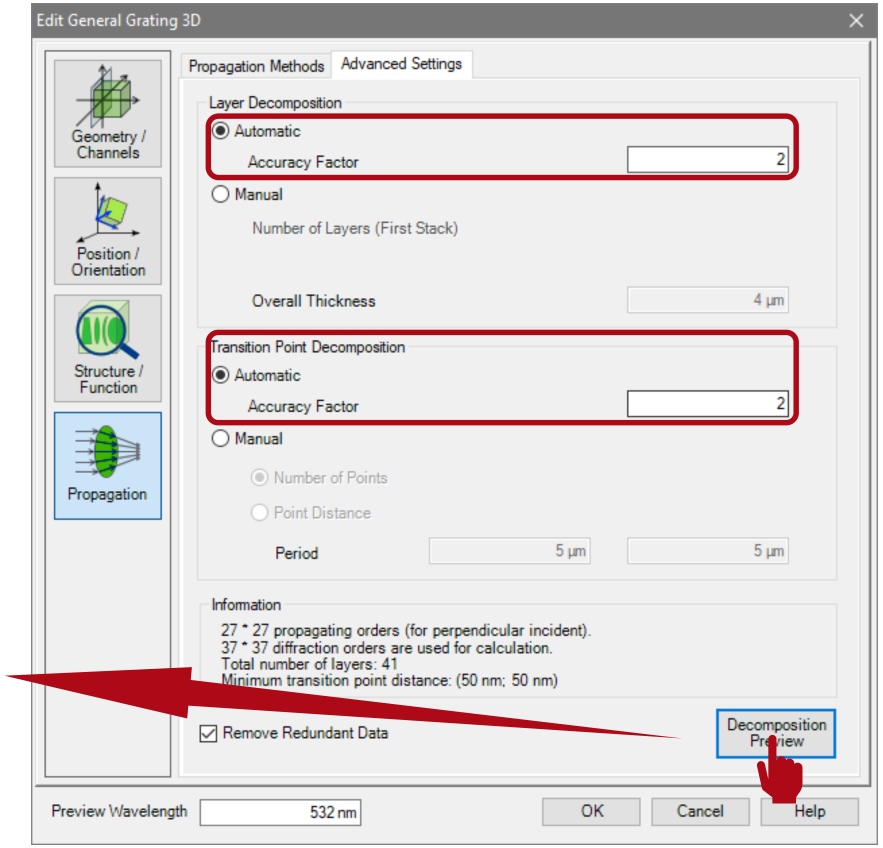
Advanced Options & Information

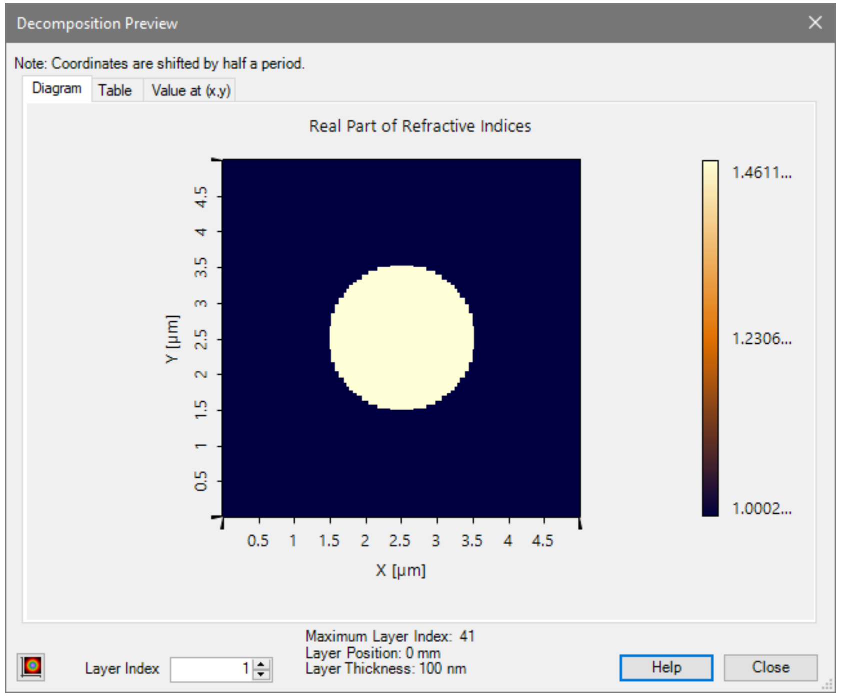
- By browsing through the different layers, the decomposed structure can be investigated in detail.



Advanced Options & Information

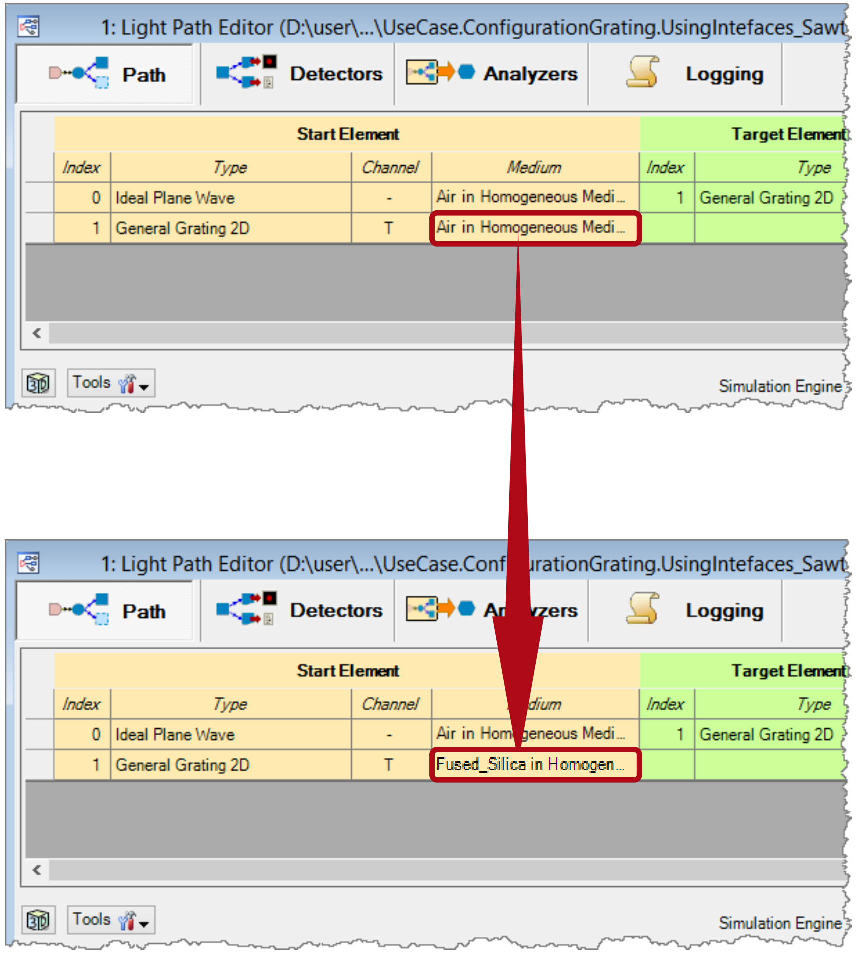
- If the numbers of layers and transition points are increased (e.g. by a factor of 2), the discretization becomes smoother, at the expense of an increased numerical effort.





Remark on the Detector Position

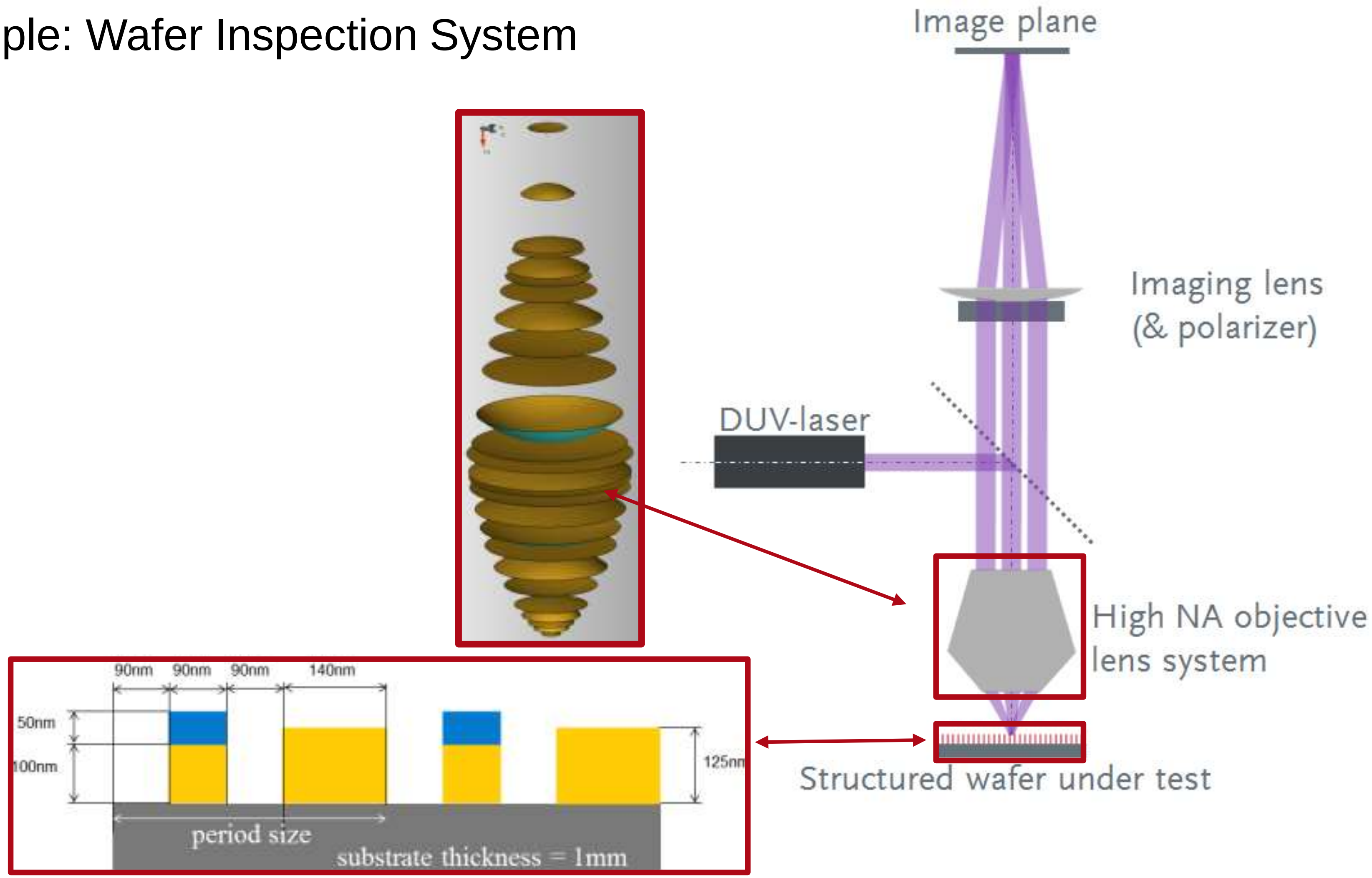
- In VirtualLab the detector is located subsequent to the substrate in air by default.
- This is necessary if the grating is included in a complex optical setup.
- However, the perfect plane and parallel substrate may cause some interference effects, which not occur in reality.
- Thus, for calculation of just grating efficiencies it is appropriate to set the detector inside the substrate material (likewise to most of grating evaluation software).
- This avoids the undesired influence of those interference effects.



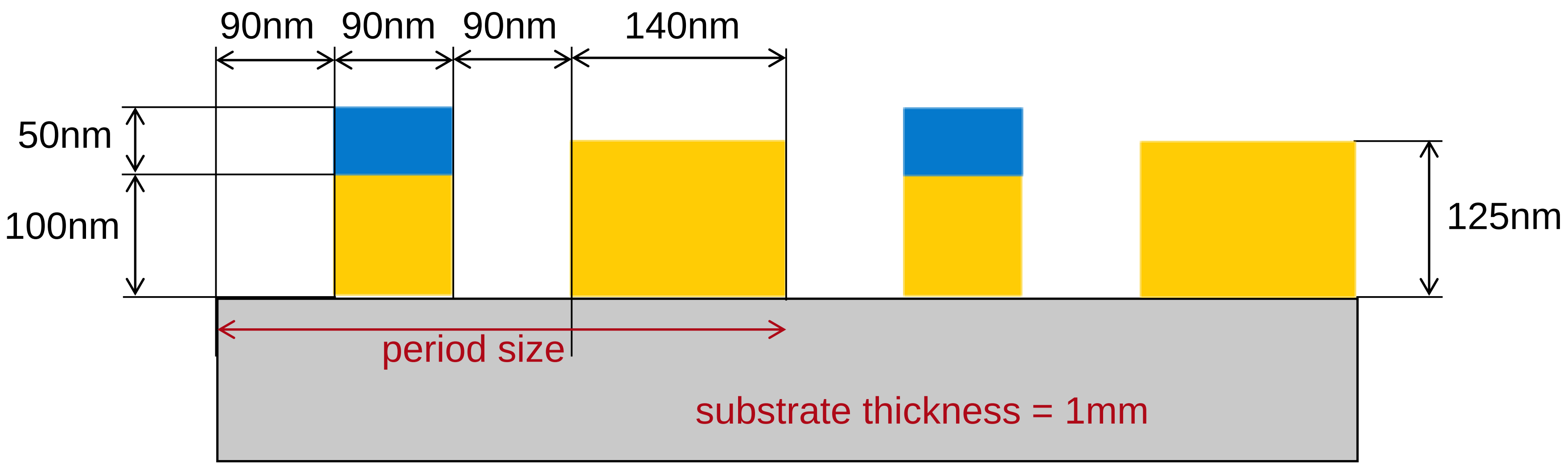
In previous, the grating is modelled and designed in Grating Toolbox. What about configure and simulate a grating in a complex optical system with lenses?

Task 7: Example of Multi-Scale Optical System

Example: Wafer Inspection System

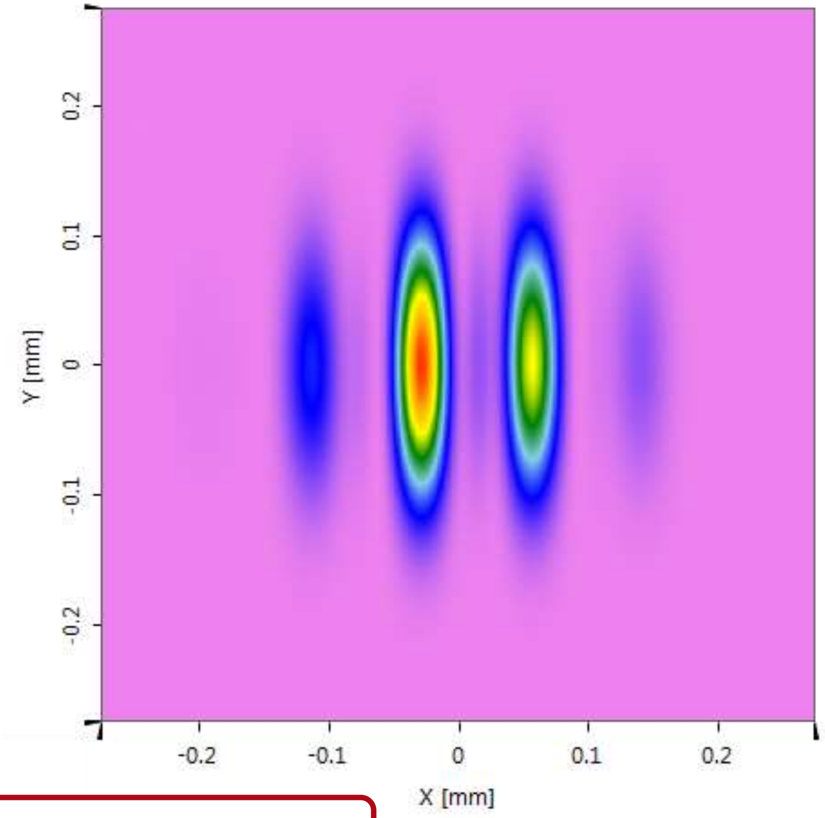


Base Grating Structure

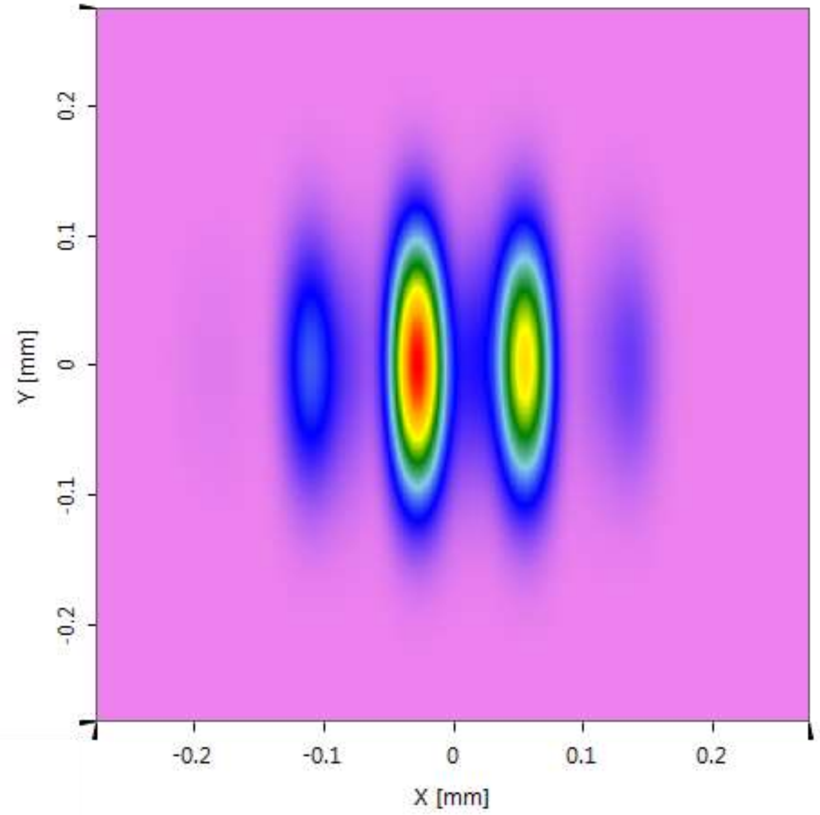


Base Structure Analysis

Intensity Image of Grating after Polarizer in X-Direction

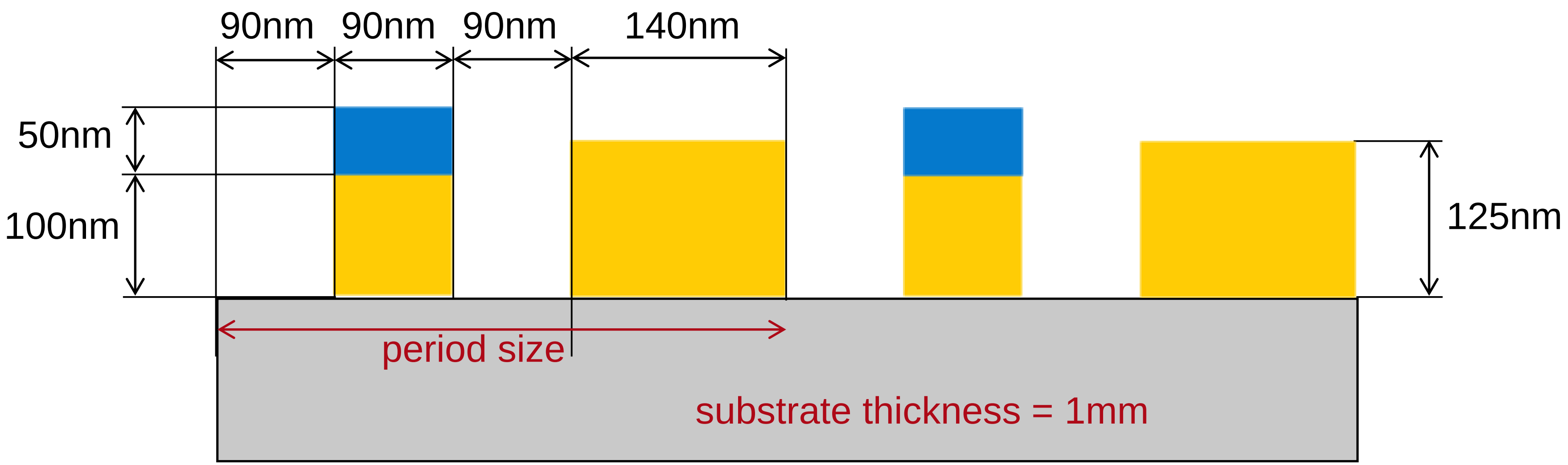


Intensity Image of Grating after Polarizer in Y-Direction

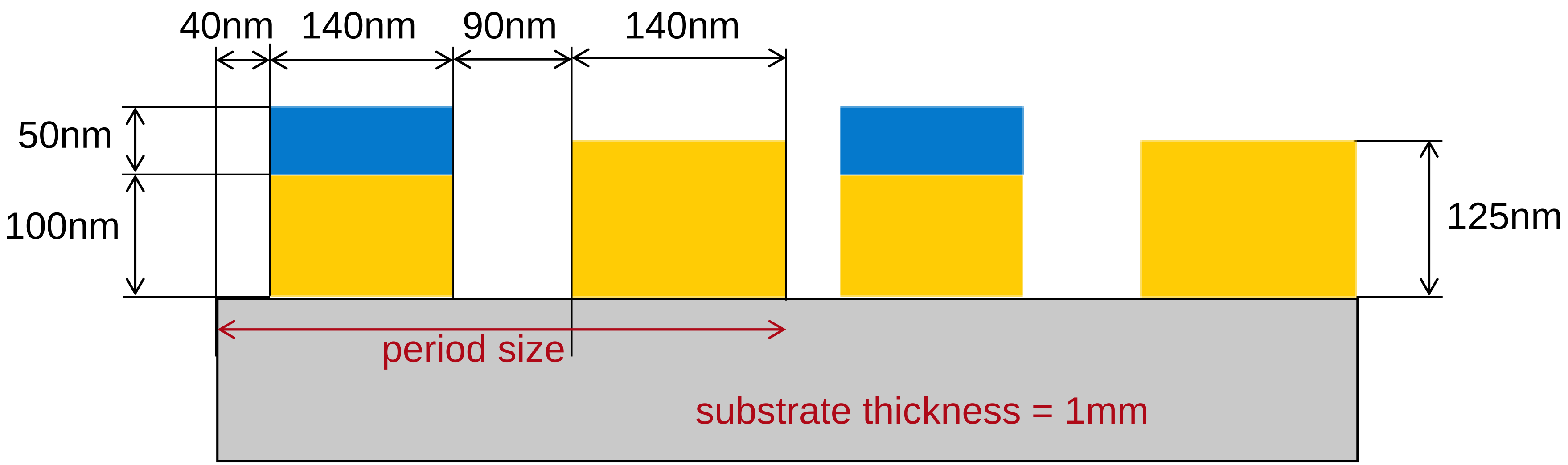


Simulation time few seconds

Base Grating Structure

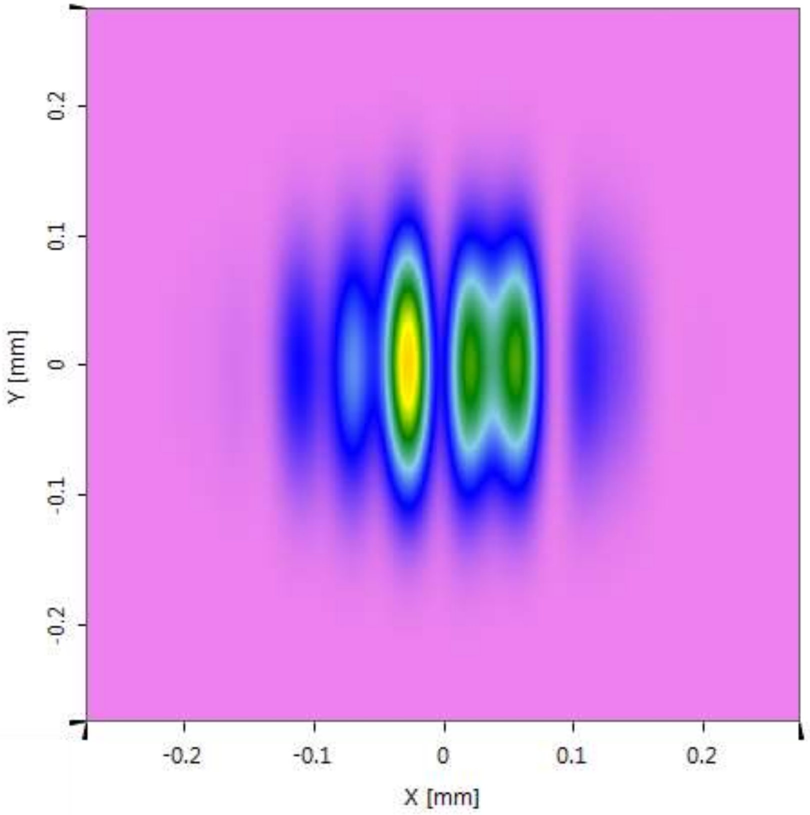


Modified Grating Structure

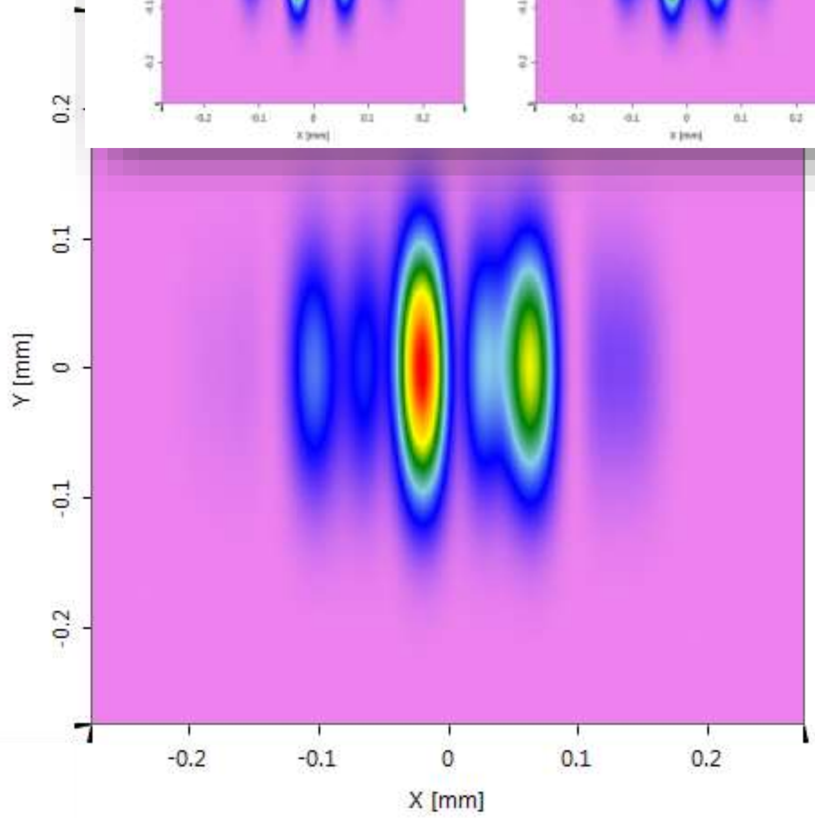


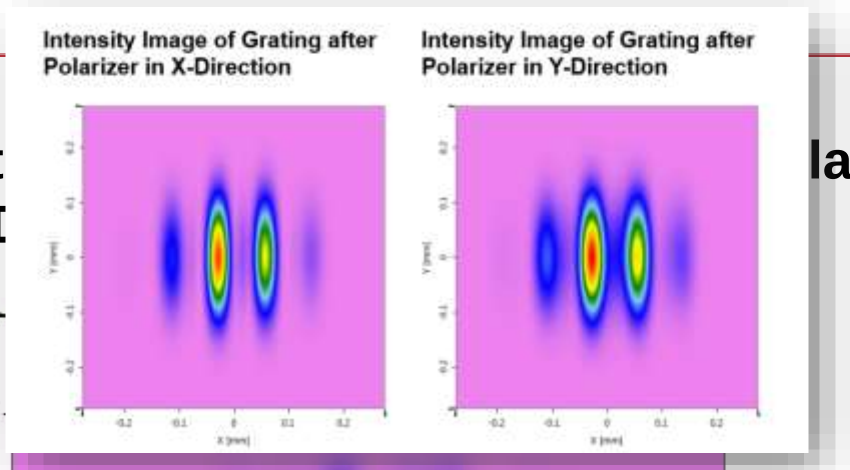
Modified Structure Analysis

Intensity Image of Grating after Polarizer in X-Direction



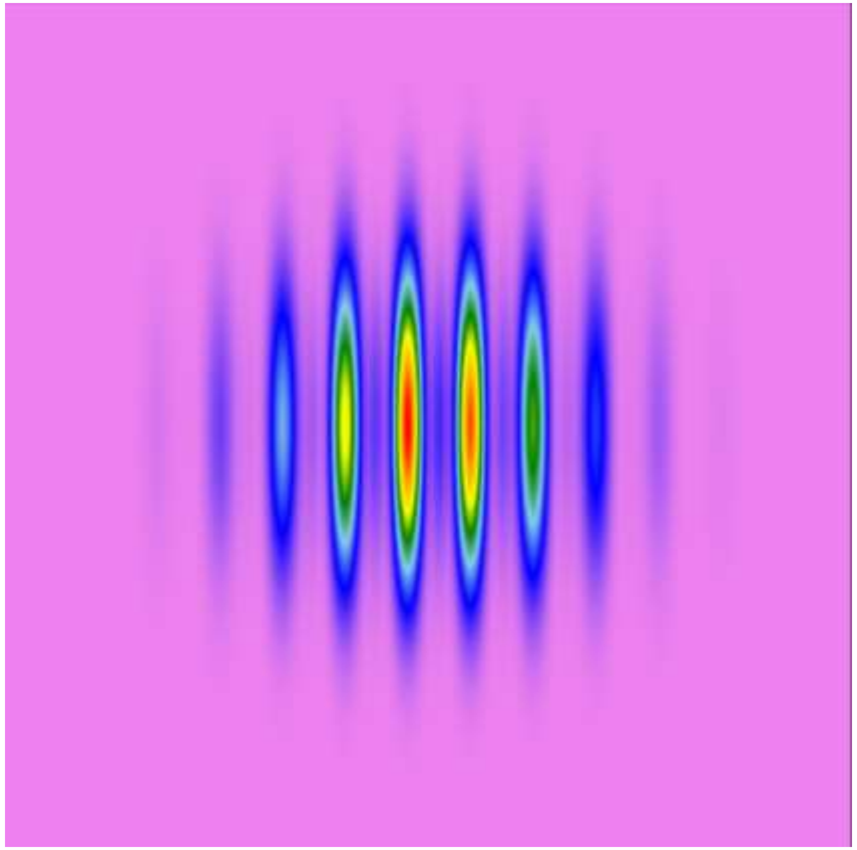
Int larizer in Y-D





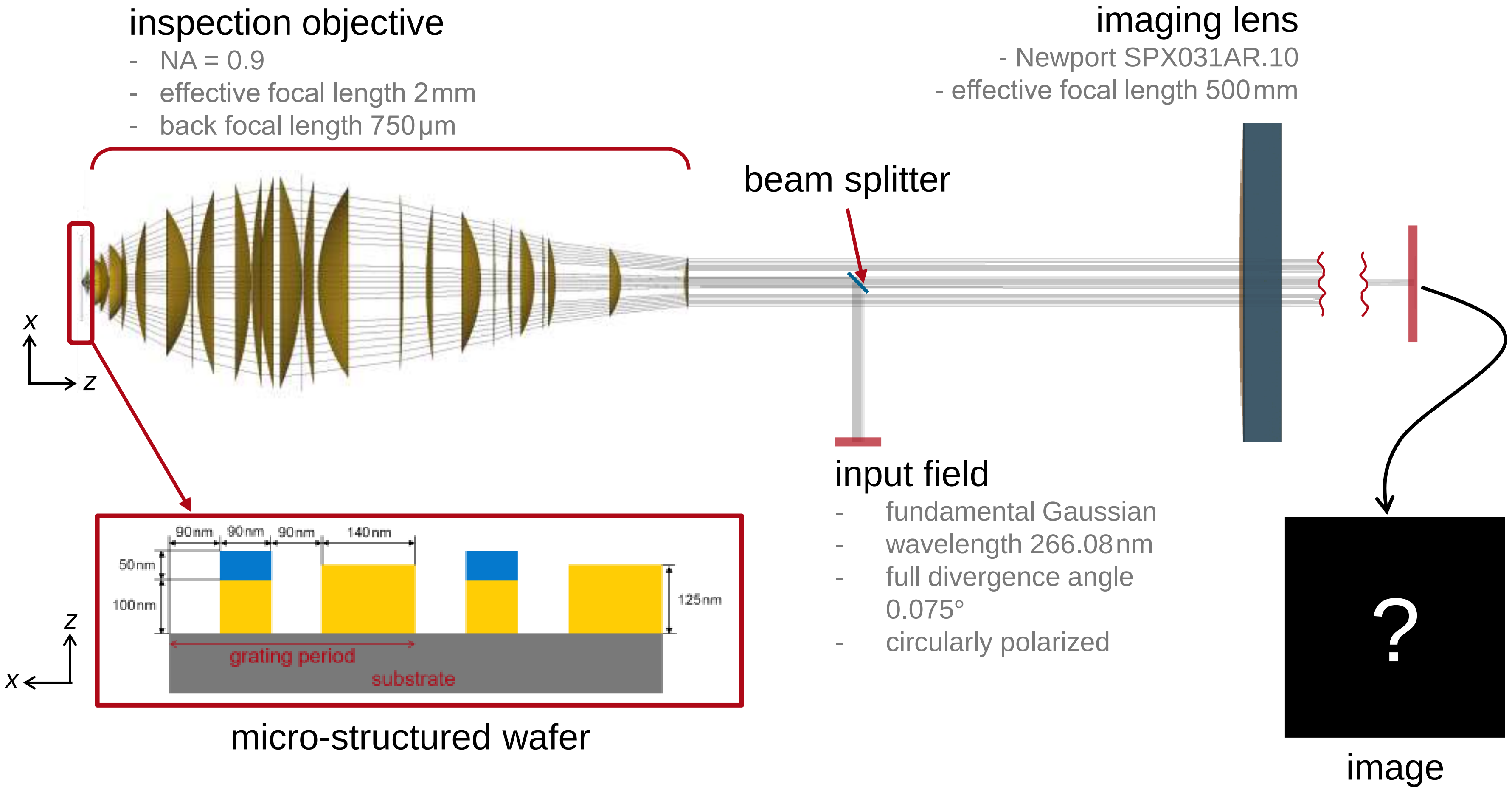
Optical System for Inspection of Micro-Structured Wafer

Abstract

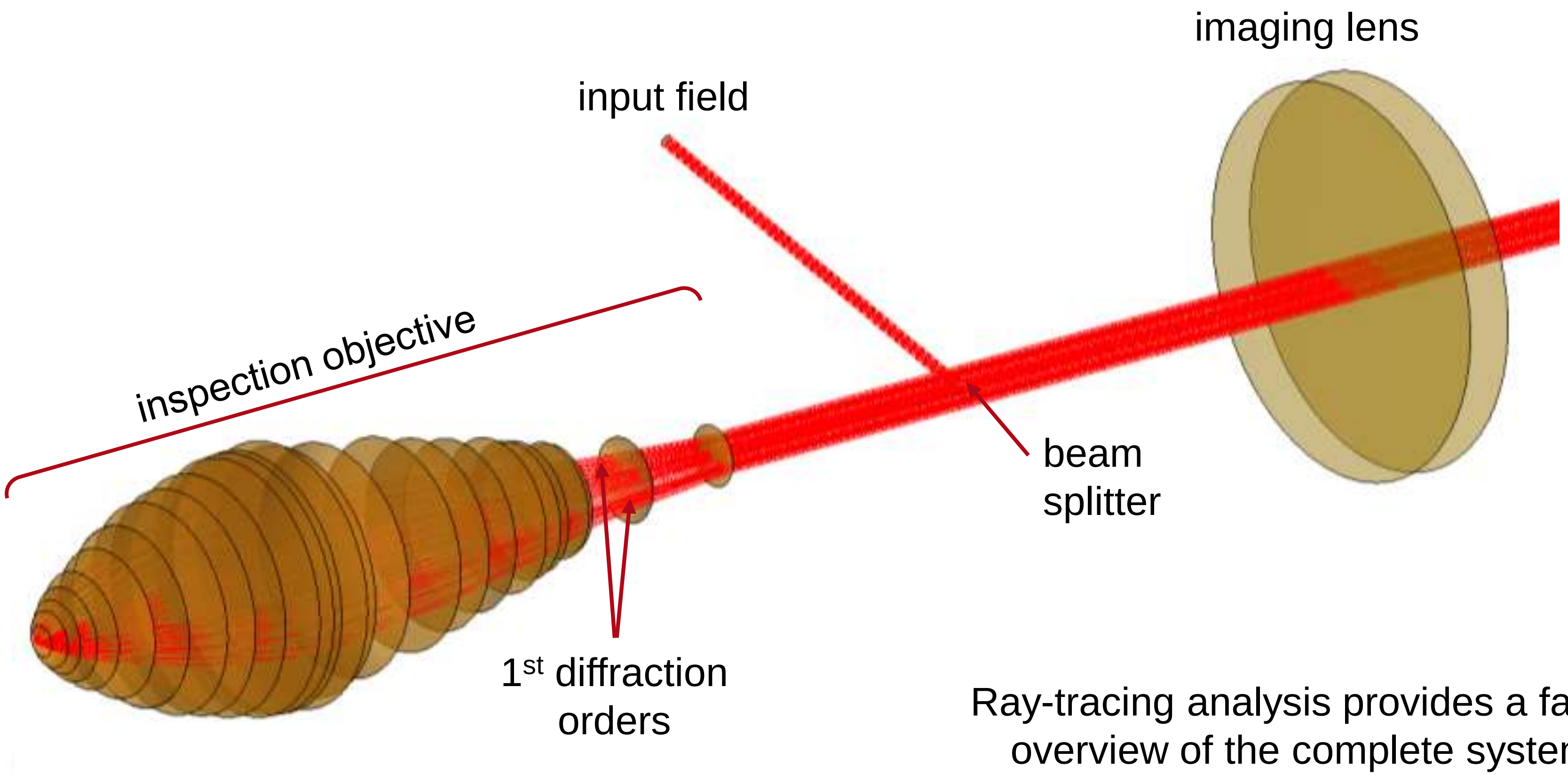


In semiconductor industry, wafer inspection systems are used to detect defects on a wafer and find their positions. To ensure the image resolution for the microstructures, the inspection system often employs a high-NA objective and works in the UV wavelength range. As an example, a complete wafer inspection system including high-NA focusing effect and light interaction with microstructures is modeled, and the formation of image is demonstrated.

Modeling Task

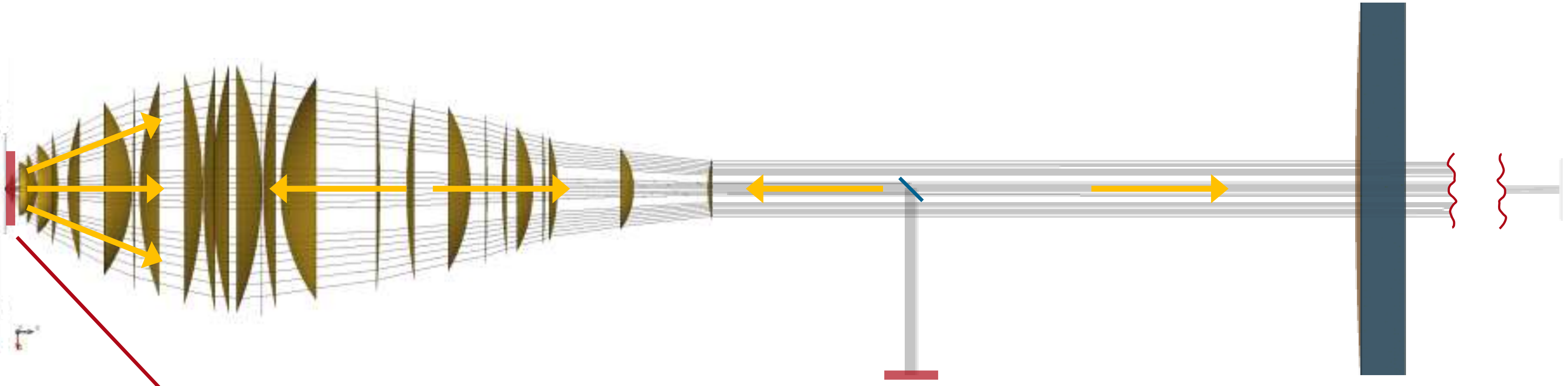


Results

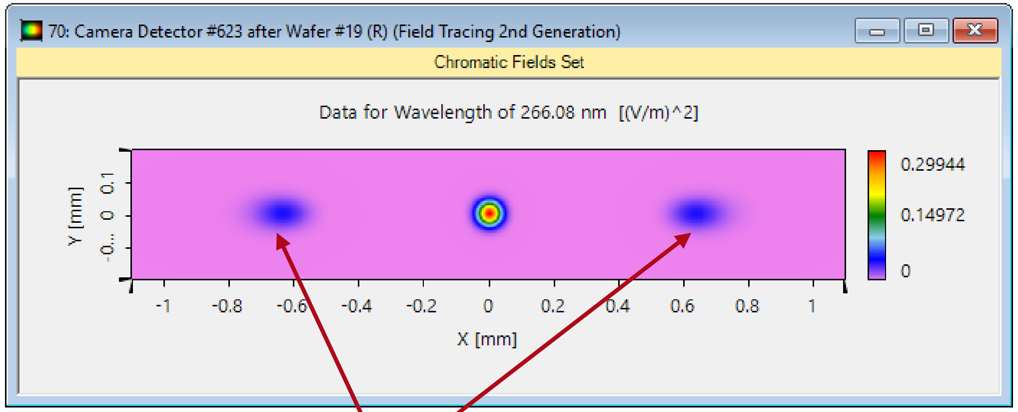


Ray-tracing analysis provides a fast overview of the complete system, including high-NA lens and grating.

Results



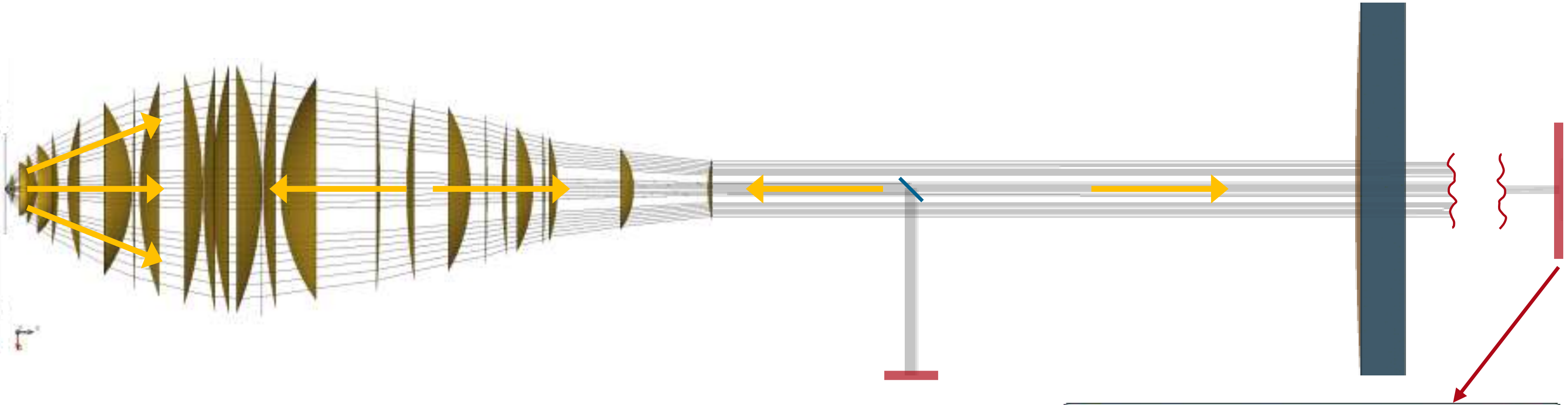
behind micro-structured wafer



1^{st} diffraction orders

Rigorous simulation of grating with Fourier modal method (FMM) is imbedded within the system simulation.

Results



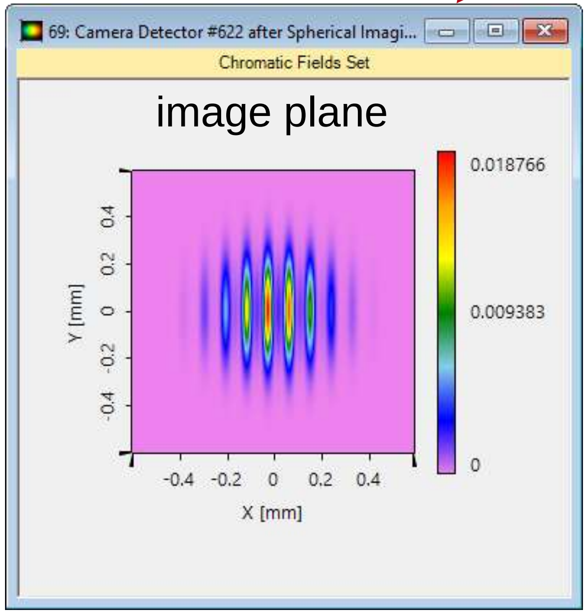


Image is formed by interference of different diffraction orders. Simulation of complete system from input field to image plane takes less than 5 seconds!

Task 7: Tutorial of Wafer Component

Klick the following link to watch the video:

https://youtu.be/JXwmB6Zwgm4

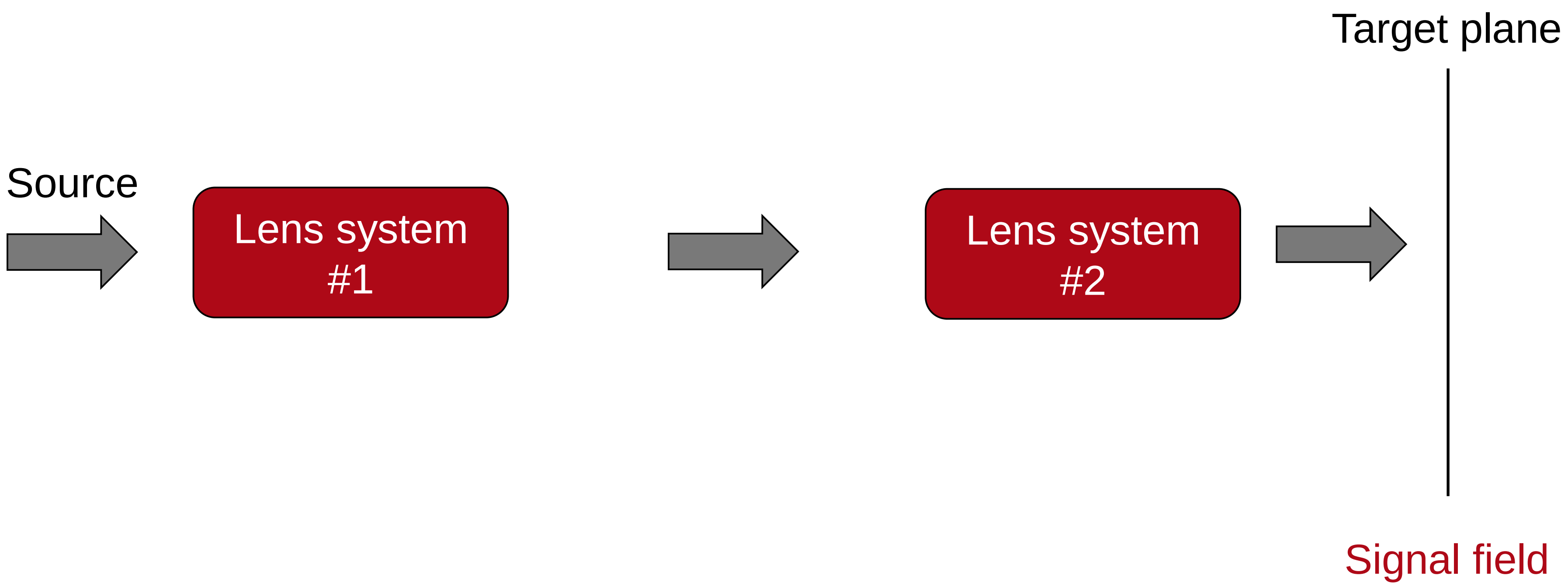
Day 2

Overview of Light Shaping Concept

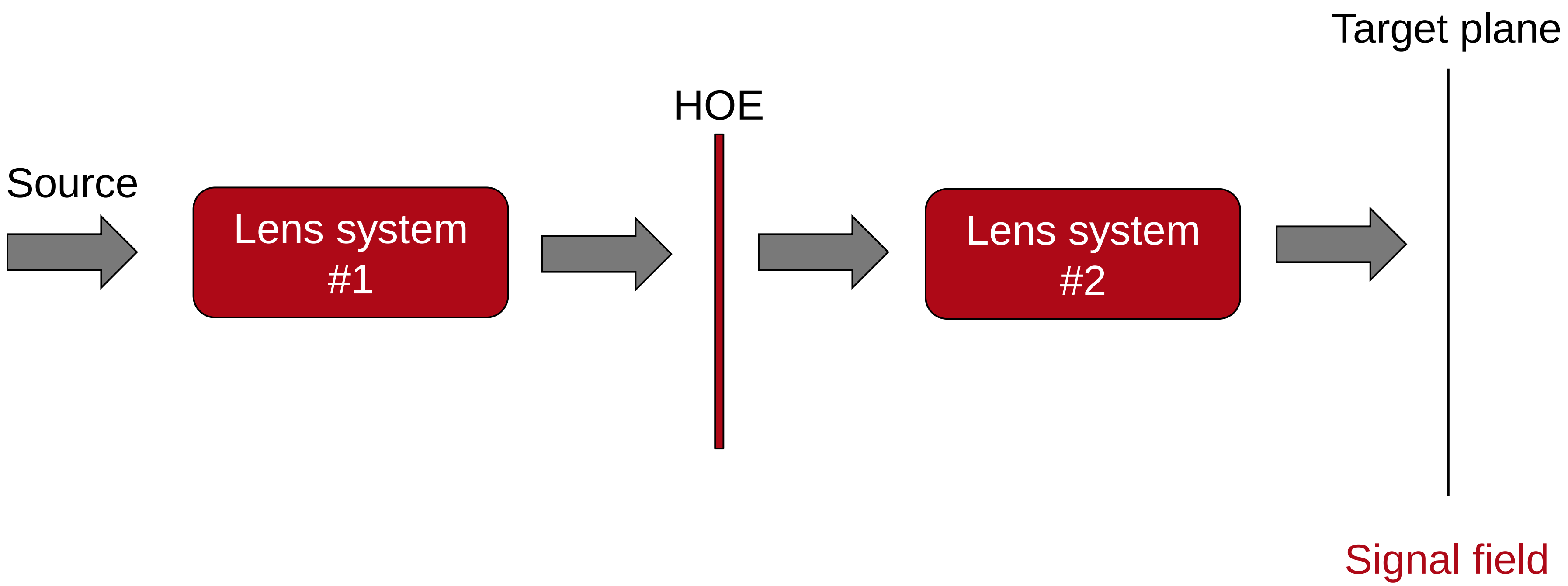
Light shaping by inverse approach

Concept of amplitude matching and consequences

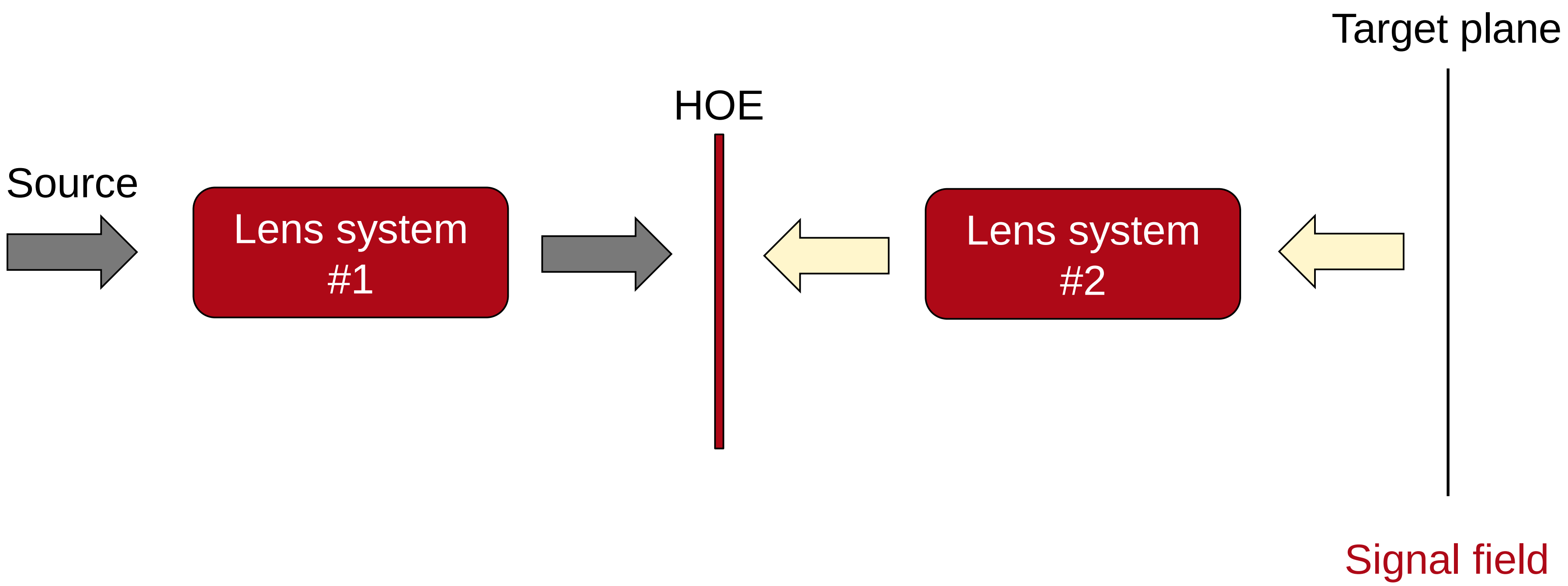
Inverse Design Concept: HOE and Freeform



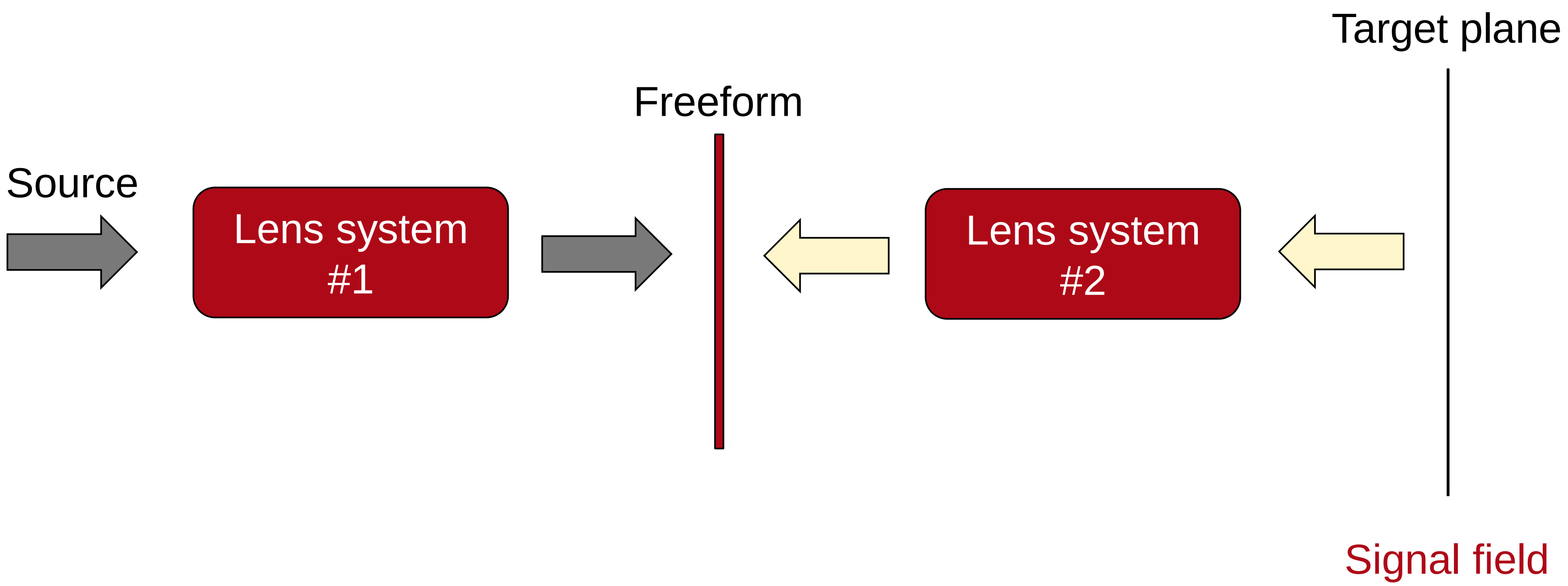
Inverse Design Concept: HOE and Freeform



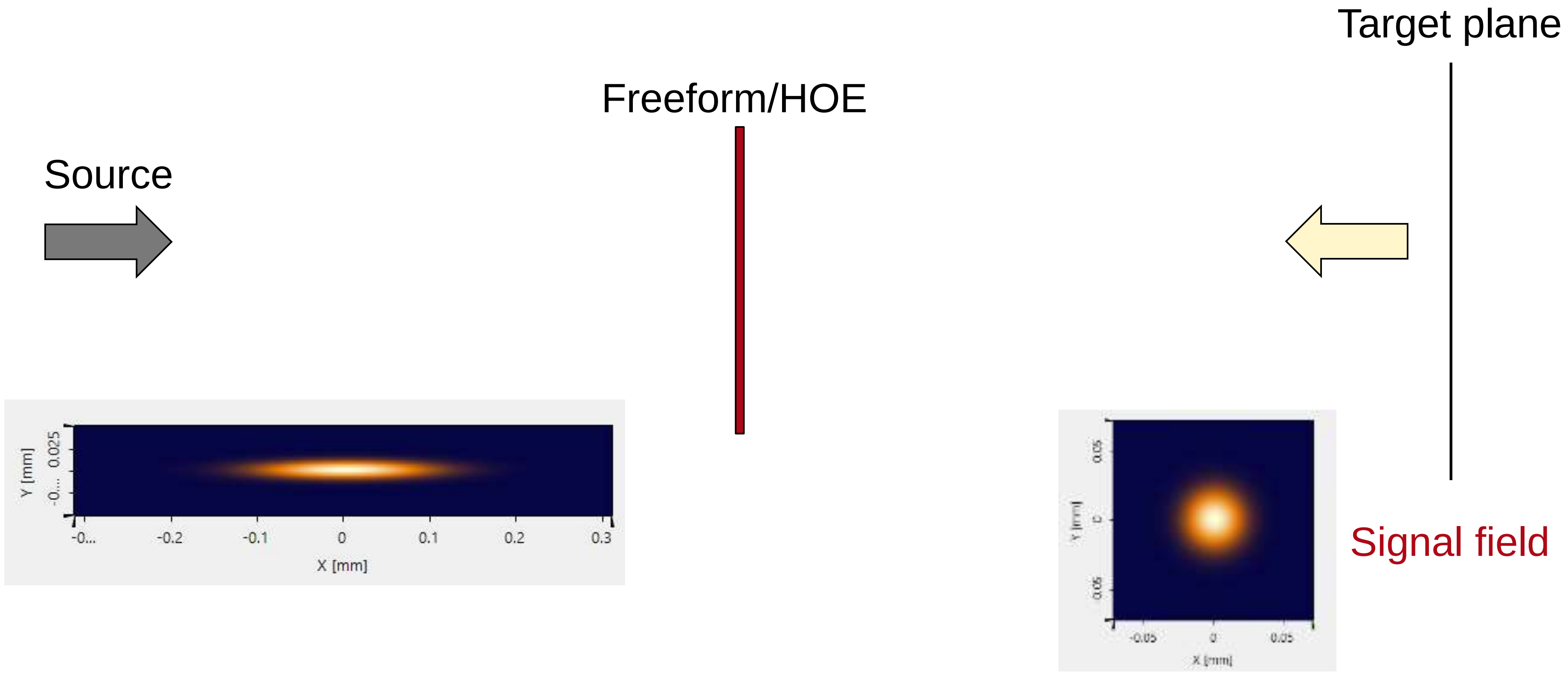
Inverse Design Concept: HOE and Freeform



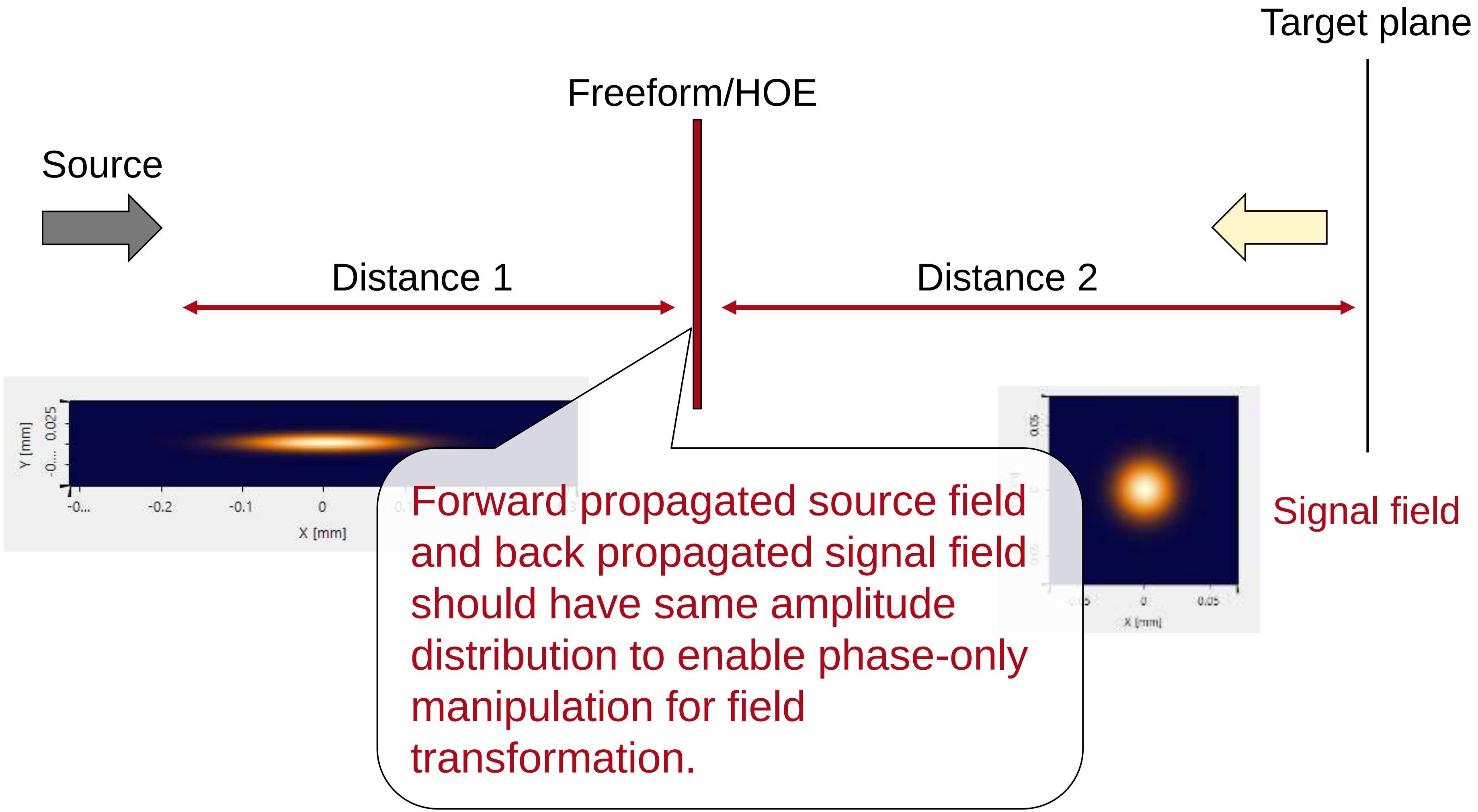
Inverse Design Concept: HOE and Freeform



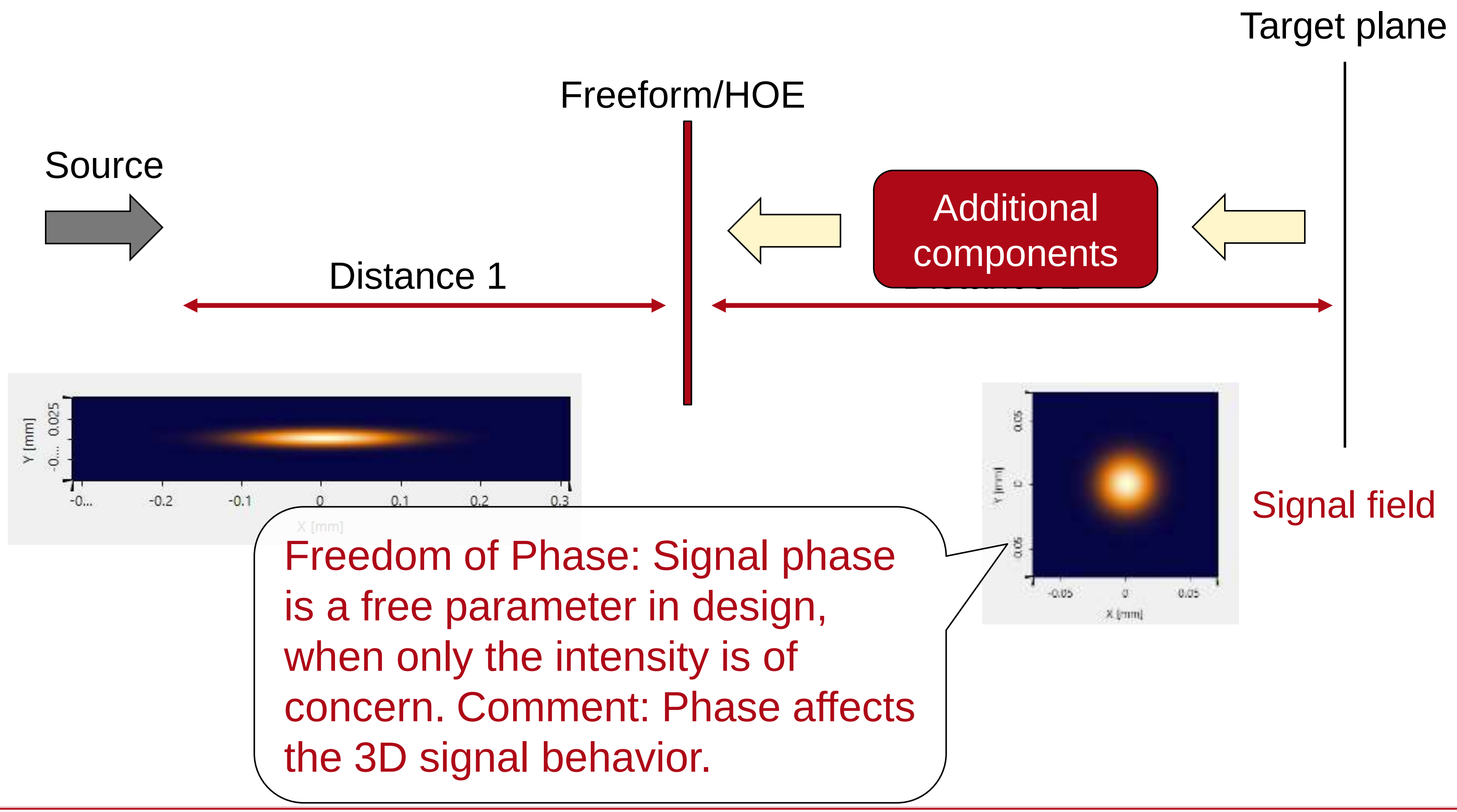
Inverse Design Concept: HOE and Freeform



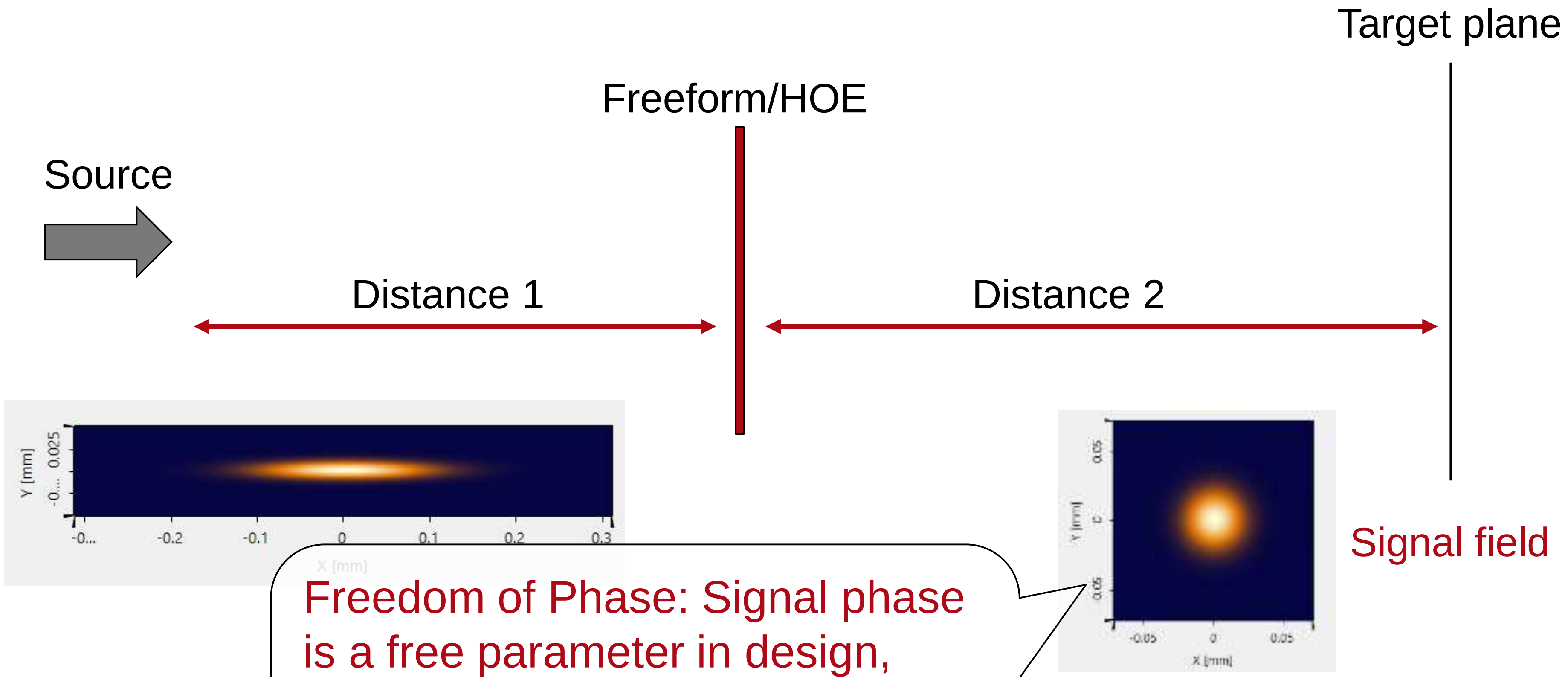
Inverse Design Concept: HOE and Freeform



Inverse Design Concept: HOE and Freeform



Inverse Design Concept: HOE and Freeform



Freedom of Phase: Signal phase is a free parameter in design, when only the intensity is of concern. Comment: Phase affects the 3D signal behavior.

Light Shaping Concepts

- Tailored aberrations
- Stored scanning process
- Multichannel concept: Single Deflection
- Multichannel concept: General

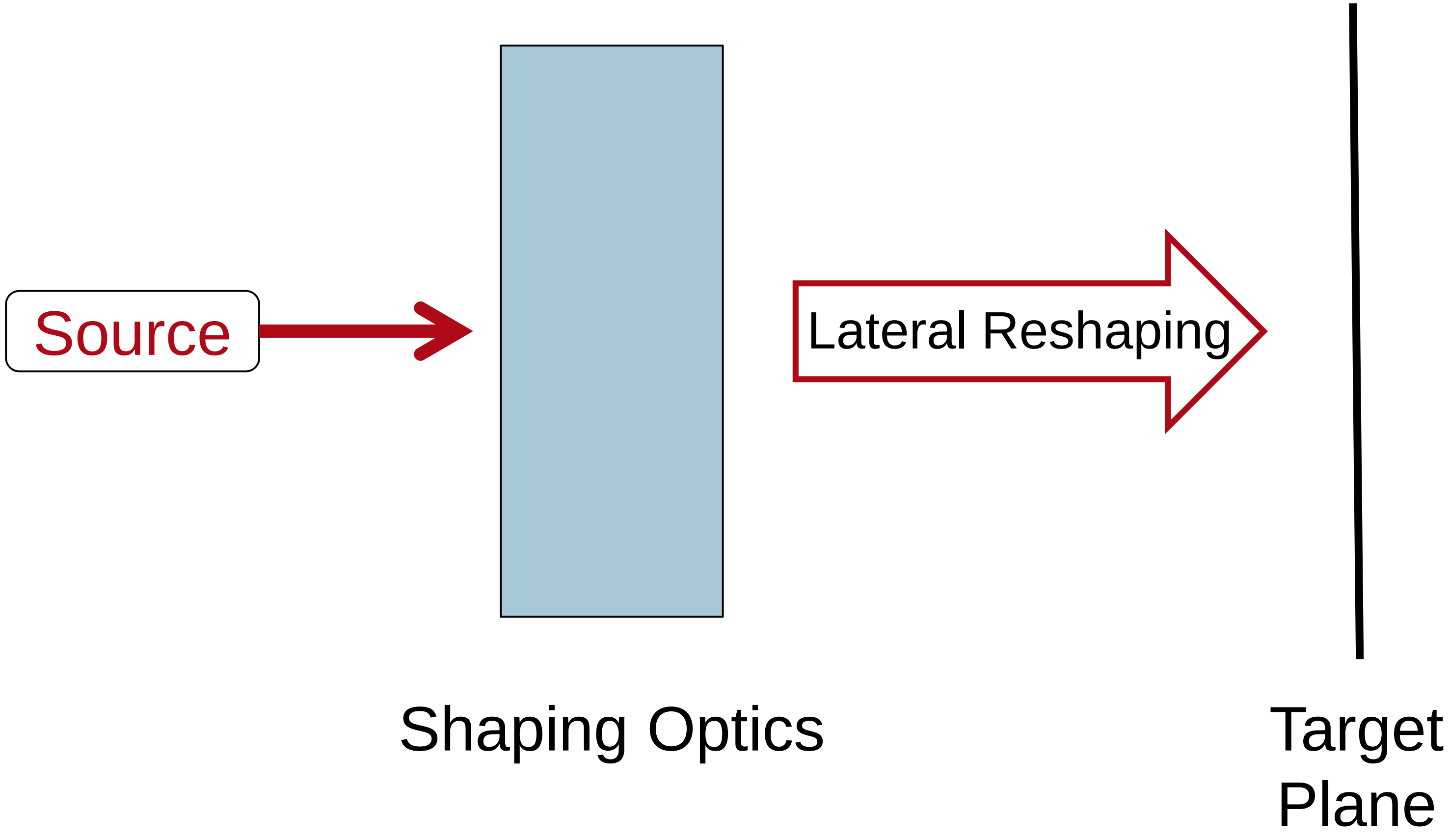
Light Shaping Concepts

- Tailored aberrations
- Stored scanning process
- Multichannel concept: Single Deflection
- Multichannel concept: General

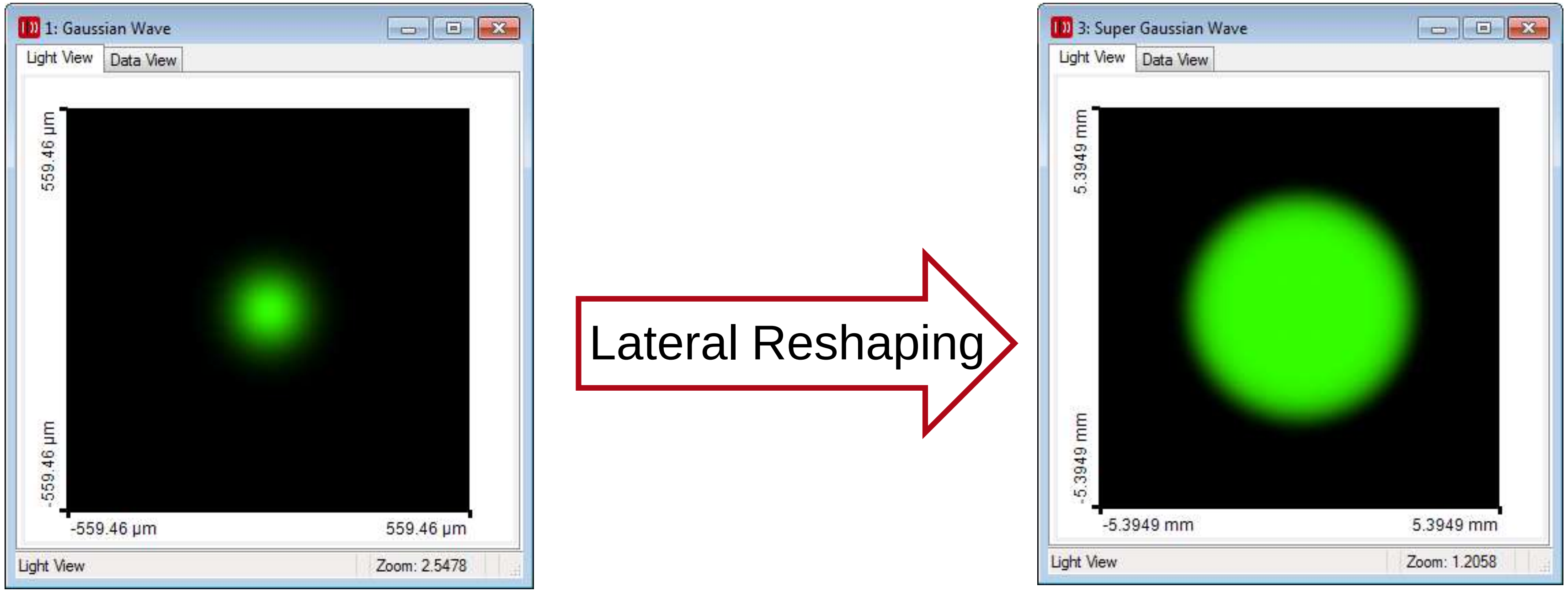
Light shaping by tailored aberrations

Refractive and diffractive optical elements

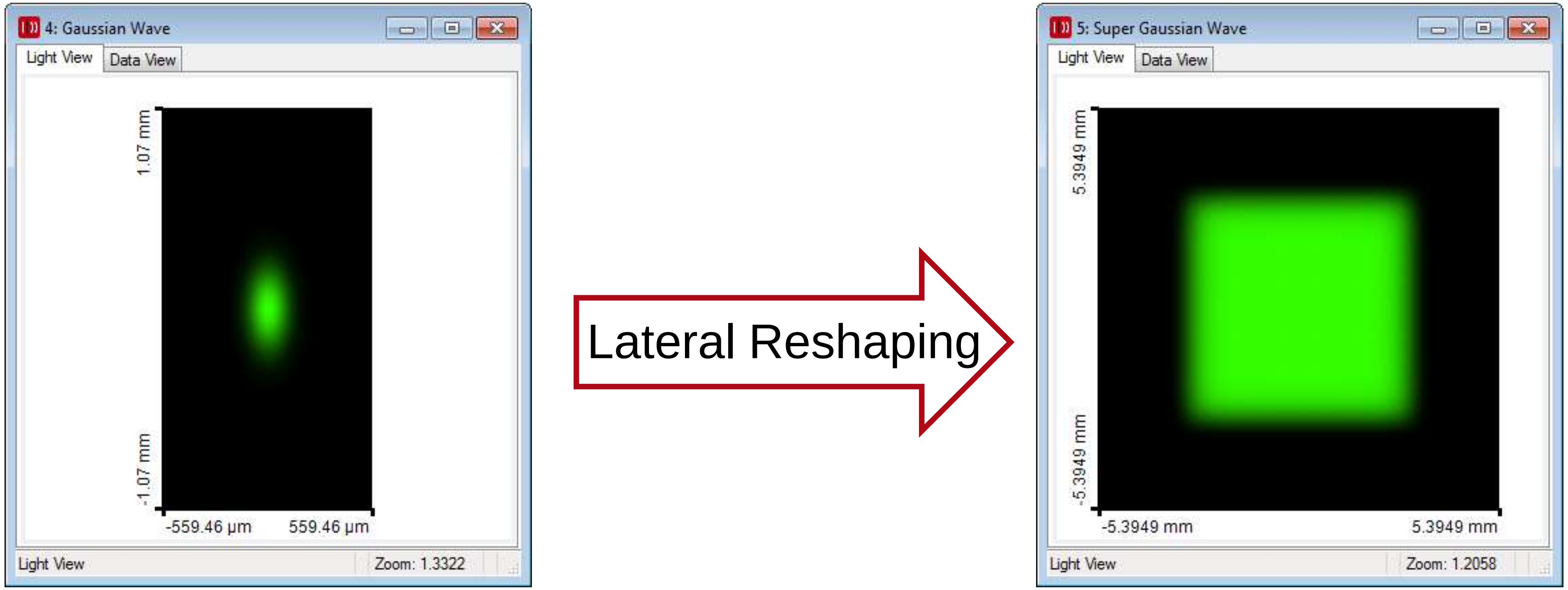
Beam Shaping: The Task



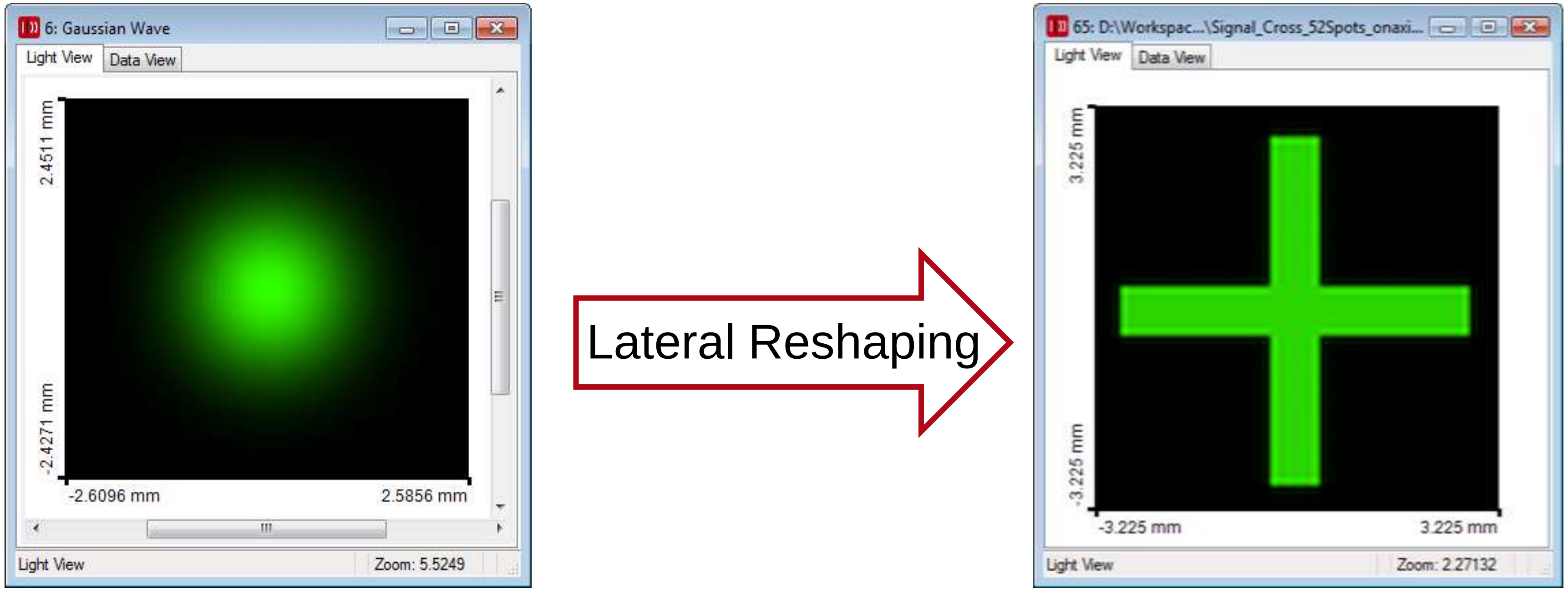
Beam Shaping: The Task



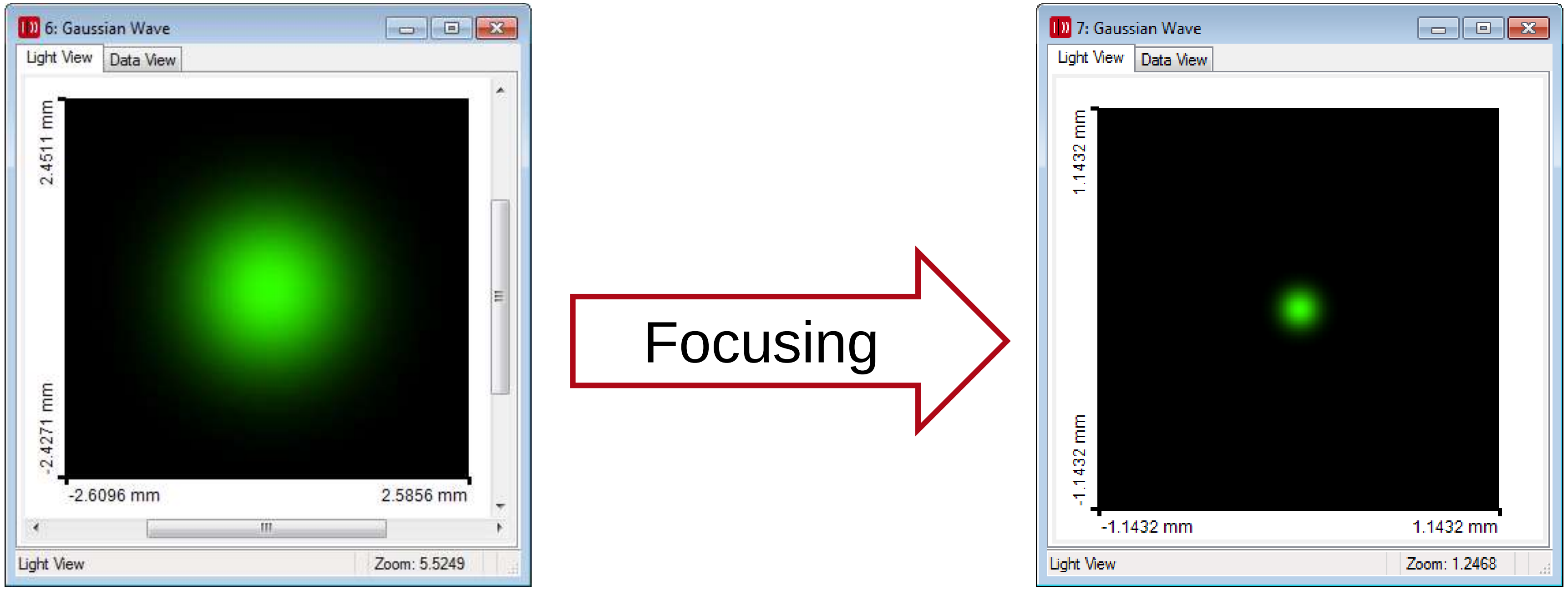
Beam Shaping: The Task



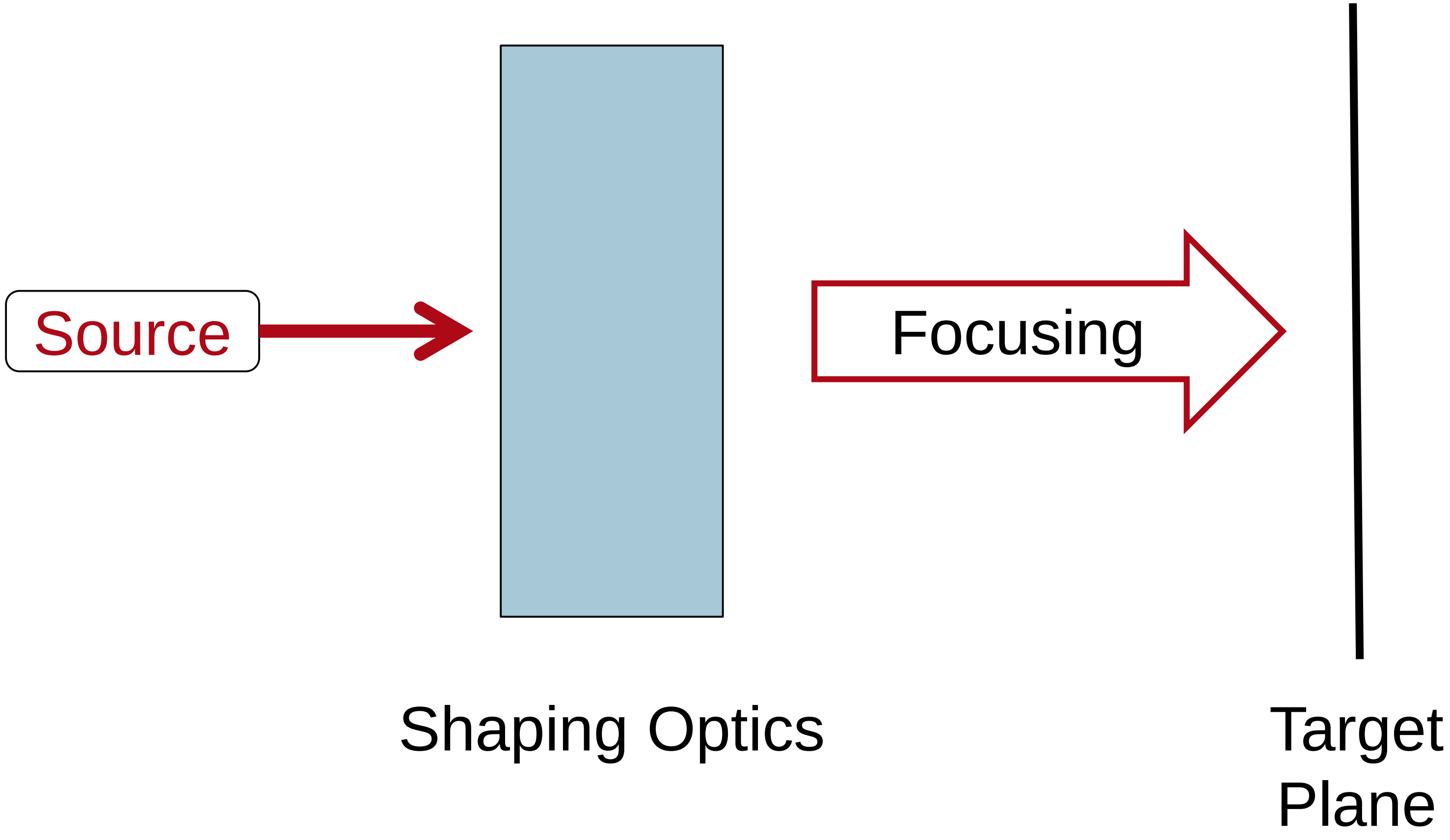
Beam Shaping: The Task



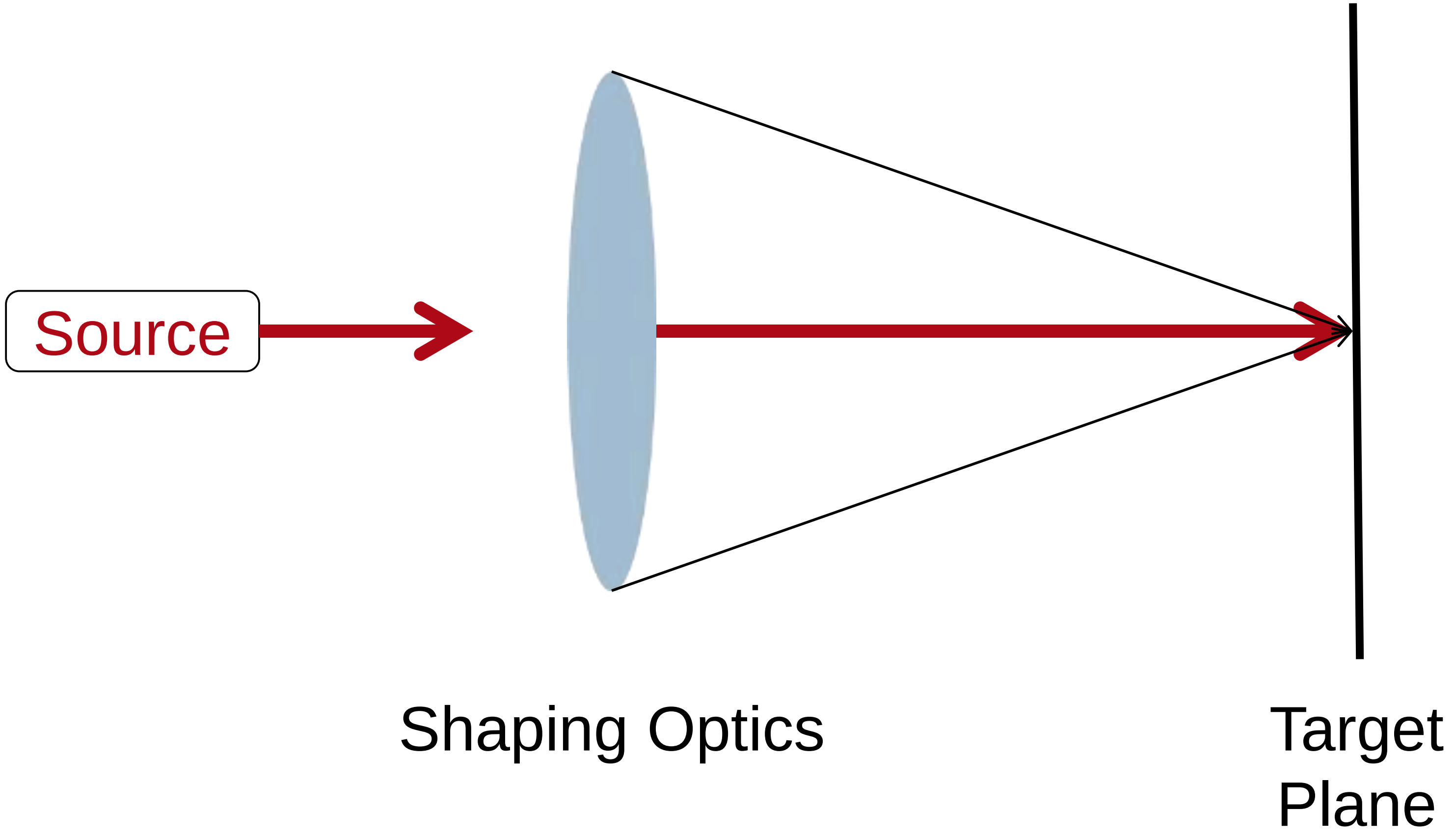
Basic „Beam Shaping“ Task: Focusing



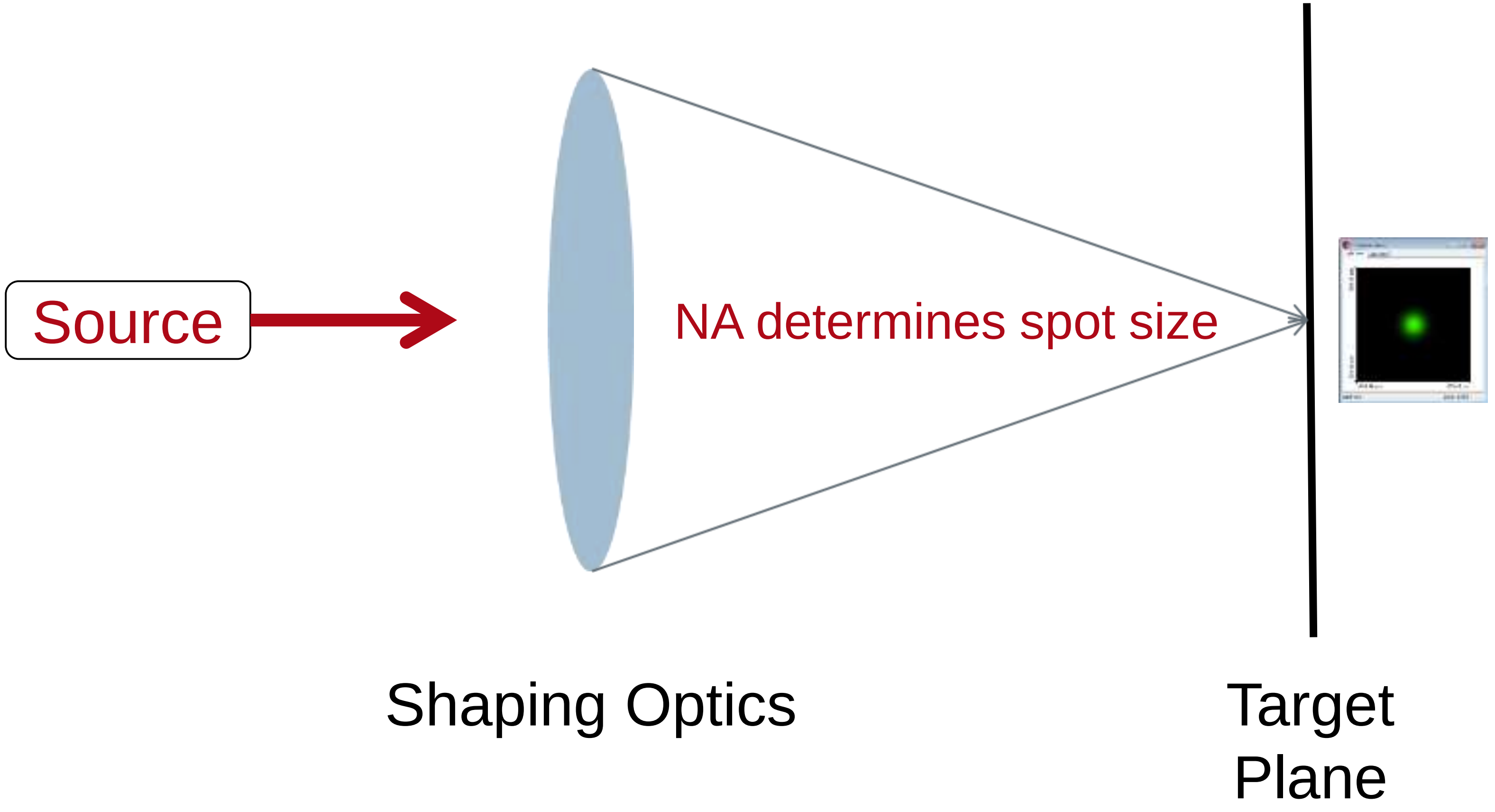
Basic „Beam Shaping“ Task: Focusing



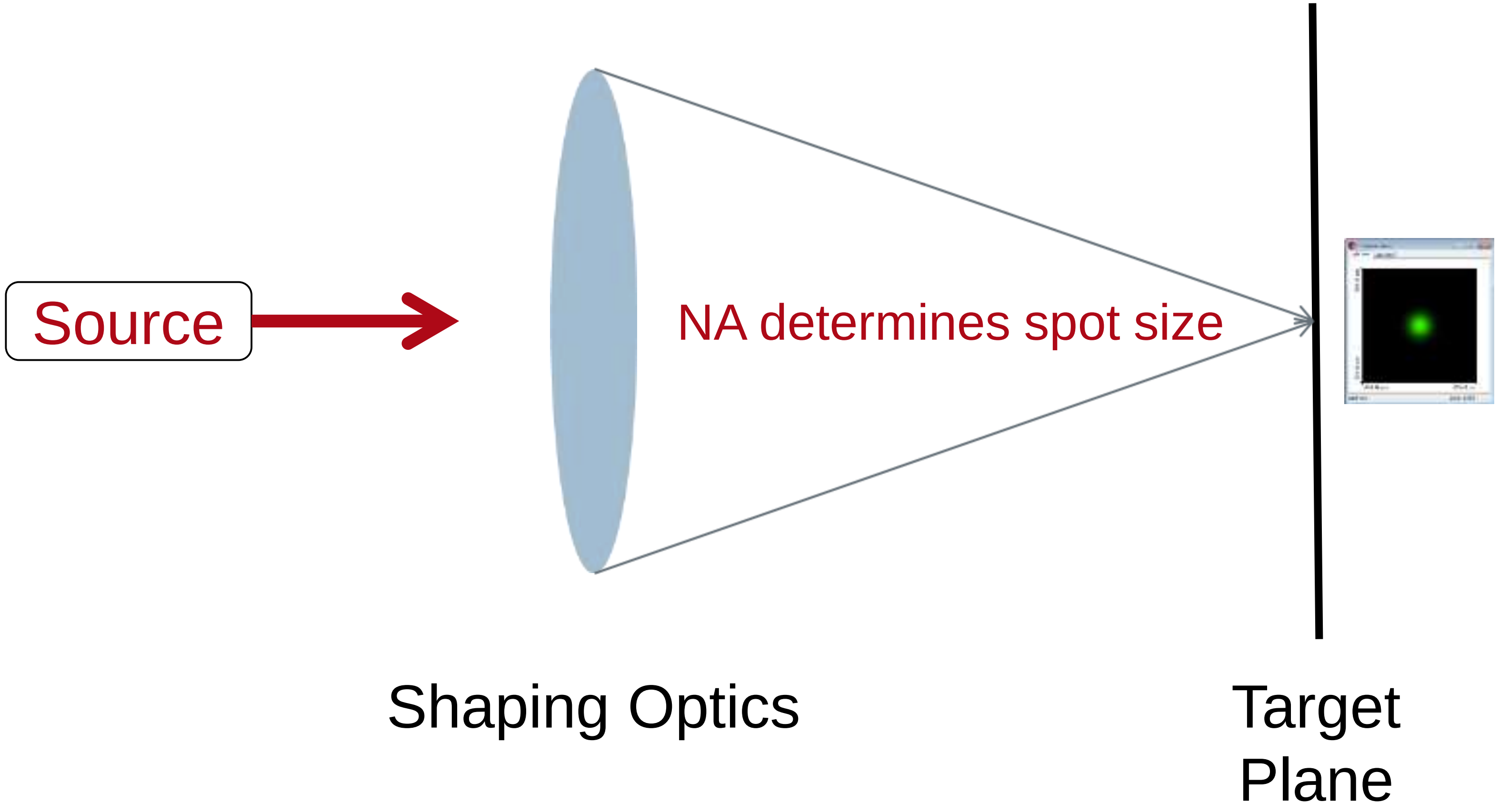
Basic „Beam Shaping“ Task: Focusing



Basic „Beam Shaping“ Task: Focusing

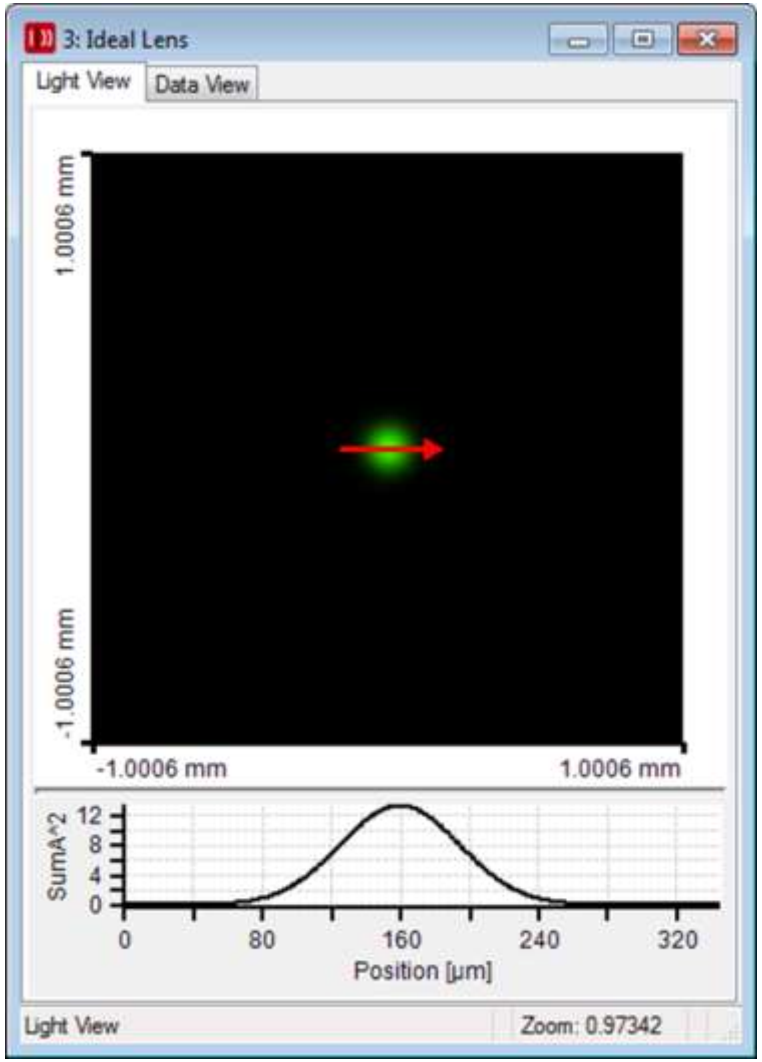


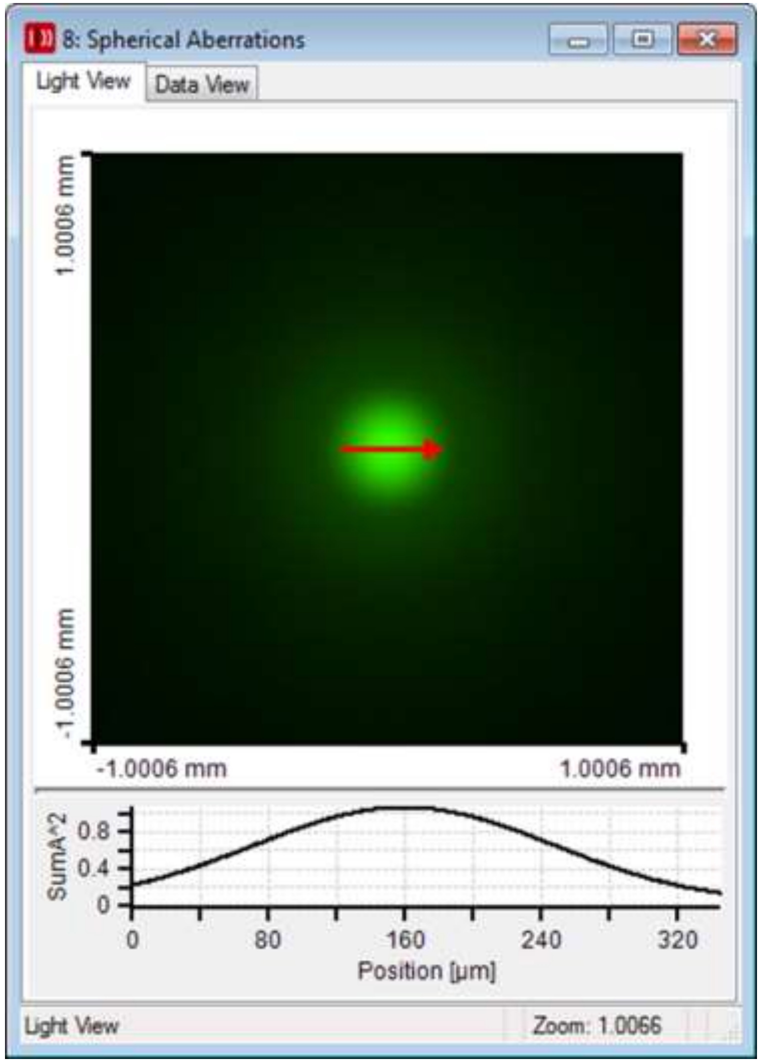
Light Shaping by Aberrations



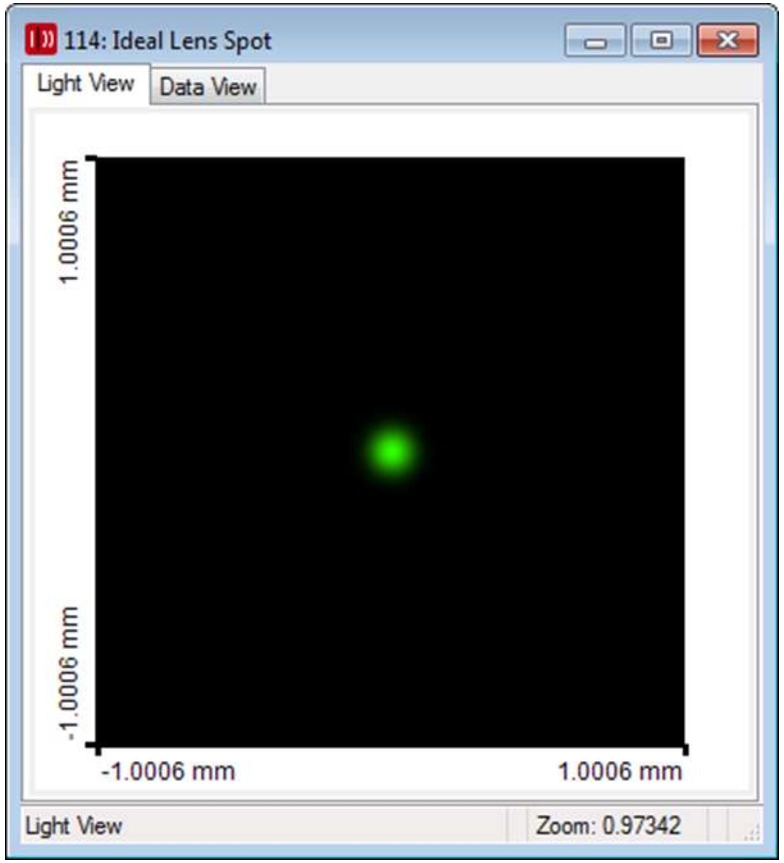
Beam shaping can be understood as the introduction of aberrations to shape the focus!

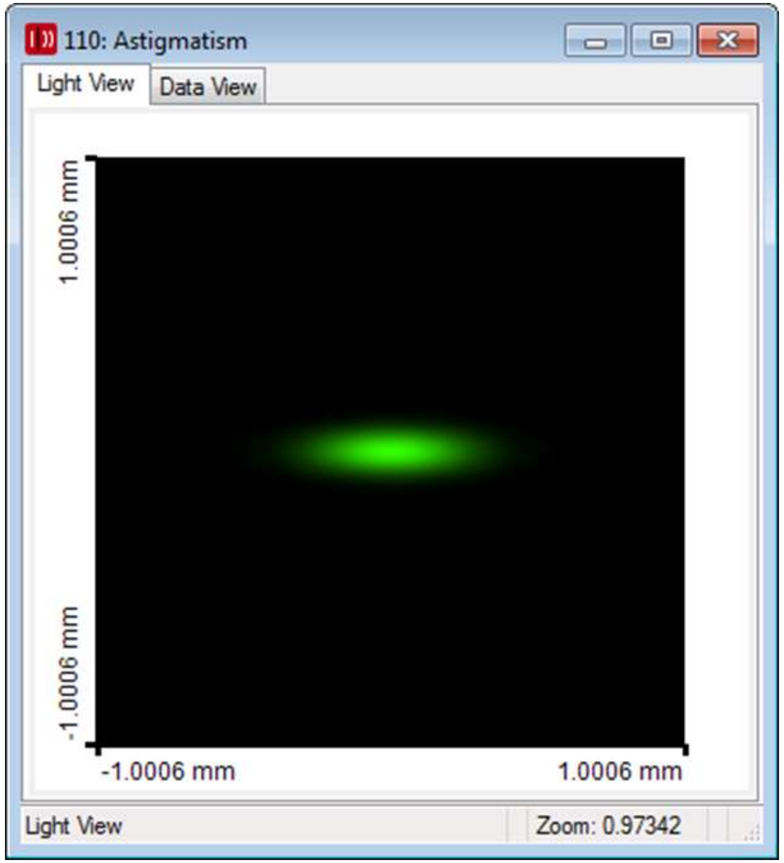
Ideal Lens vs. Spherical Aberrations



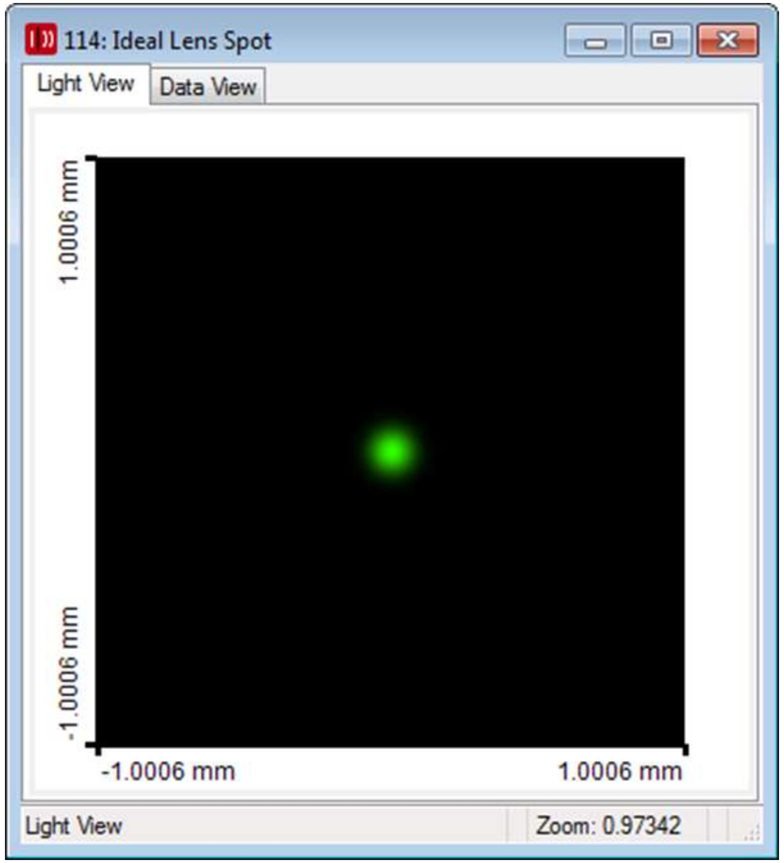


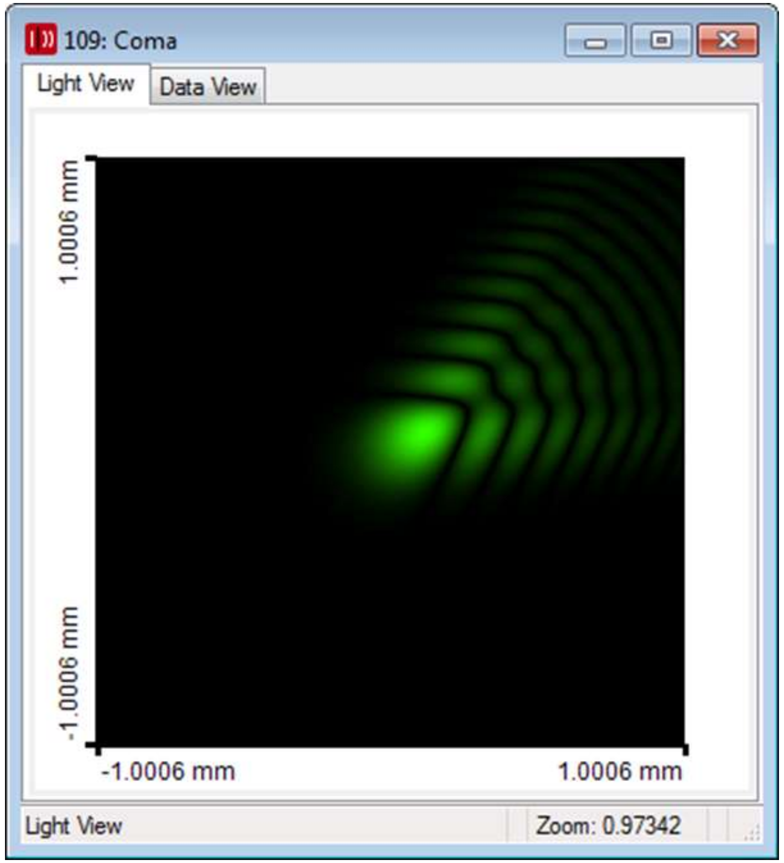
Ideal Lens vs. Astigmatism



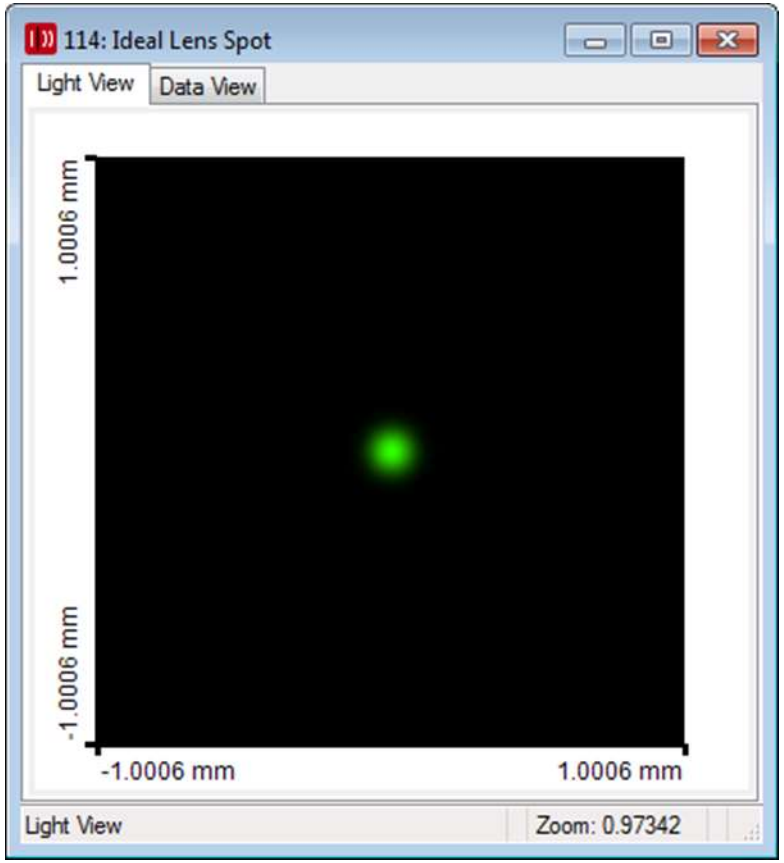


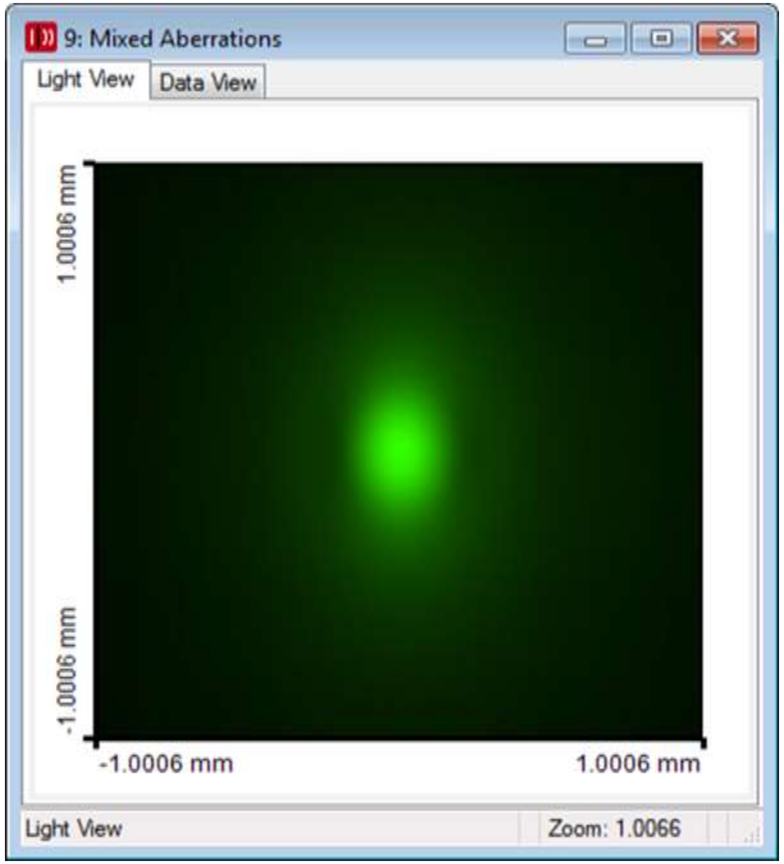
Ideal Lens vs. Coma





Ideal Lens vs. Mixed Aberration





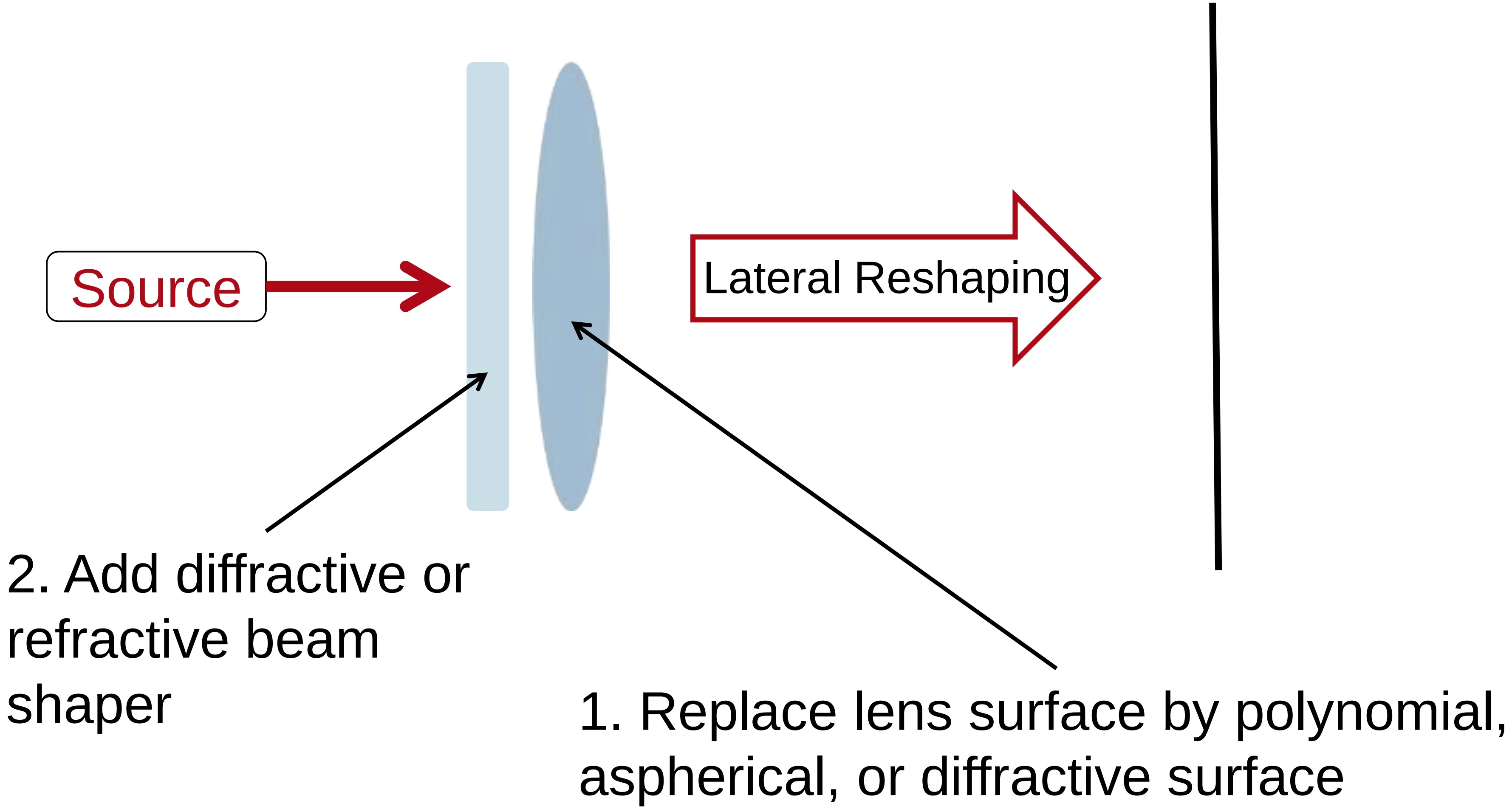
Conclusions for Beam Shaping

- Aberrations enlarge and reshape the focal spot of the ideal lens system

⬇

- The focal spot of the ideal lens system must be
  - Smaller than the demanded shaped spot
  - Not bigger than the smallest feature in the shaped spot
- Designing a beam shaping system must always be started with selecting a lens system the NA of which enables the required focal spot size
- Remark: Aberrations of lens systems are allowed, because beam shaper can compensate that

Introduction of Aberrations



What Kind of Aberrations Are Needed?

- Dependent on the input beam and the required beam profile in the target plane aberrations must be introduced
- A basic approach to estimate the required aberrations for a given beam shaping problem is based on
  - Determination of geometrical distortion to redistribute energy
  - Calculation of phase function, which realizes the geometrical distortion

Light Shaping Concepts

- Tailored aberrations
- Stored scanning process
- Multichannel concept: Single Deflection
- Multichannel concept: General

Geometrical Distortion Concept

Analytical beam shaping with application to laser-diode arrays

Harald Aagedal, Michael Schmid, Sebastian Egner, Jörn Müller-Quade, and Thomas Beth

Institut für Algorithmen und Kognitive Systeme, Universität Karlsruhe, Am Fasanengarten 5, D-76128 Karlsruhe, Germany

Frank Wyrowski

Institut für Angewandte Physik, Friedrich-Schiller-Universität, Max-Wien-Platz 1, D-07743 Jena, Germany

Vol. 14, No. 7/July 1997/J. Opt. Soc. Am. A 1549

Geometrical Distortion Concept

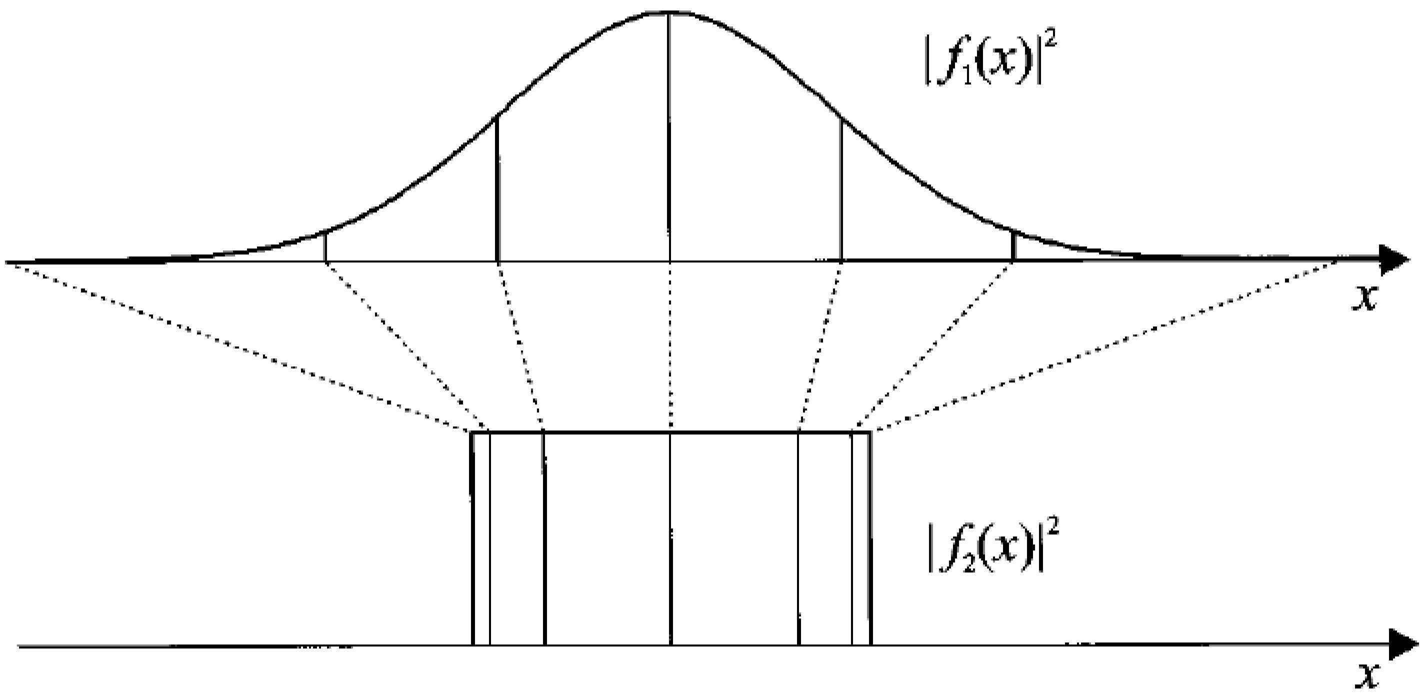


Fig. 1. Distortion transforming a Gaussian beam to a uniform distribution.

Vol. 14, No. 7/July 1997/J. Opt. Soc. Am. A 1549

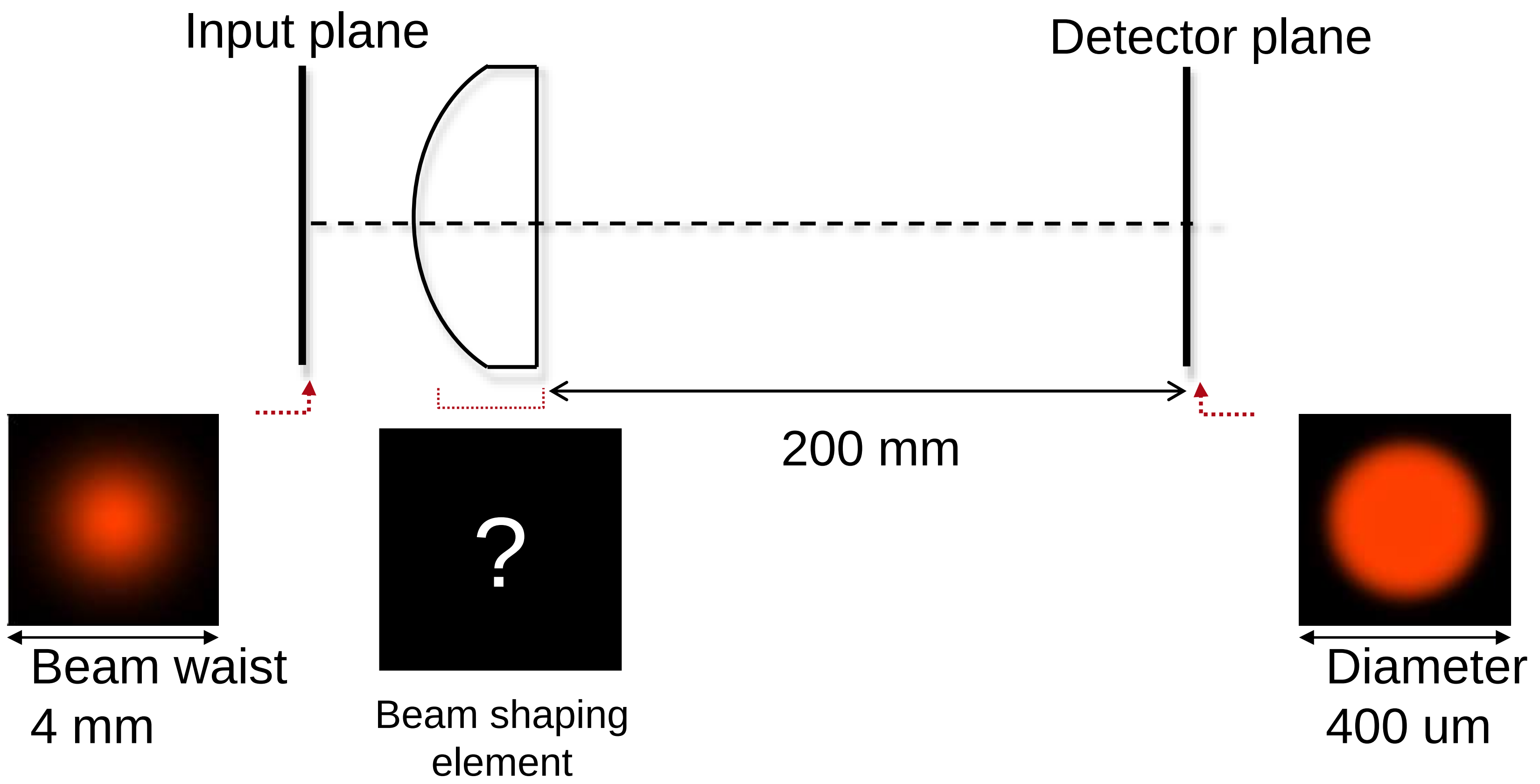
Light Shaping > Refractive Optics

Design of a Refractive Beam Shaper to Generate a Circular Top-Hat

LightTrans International UG

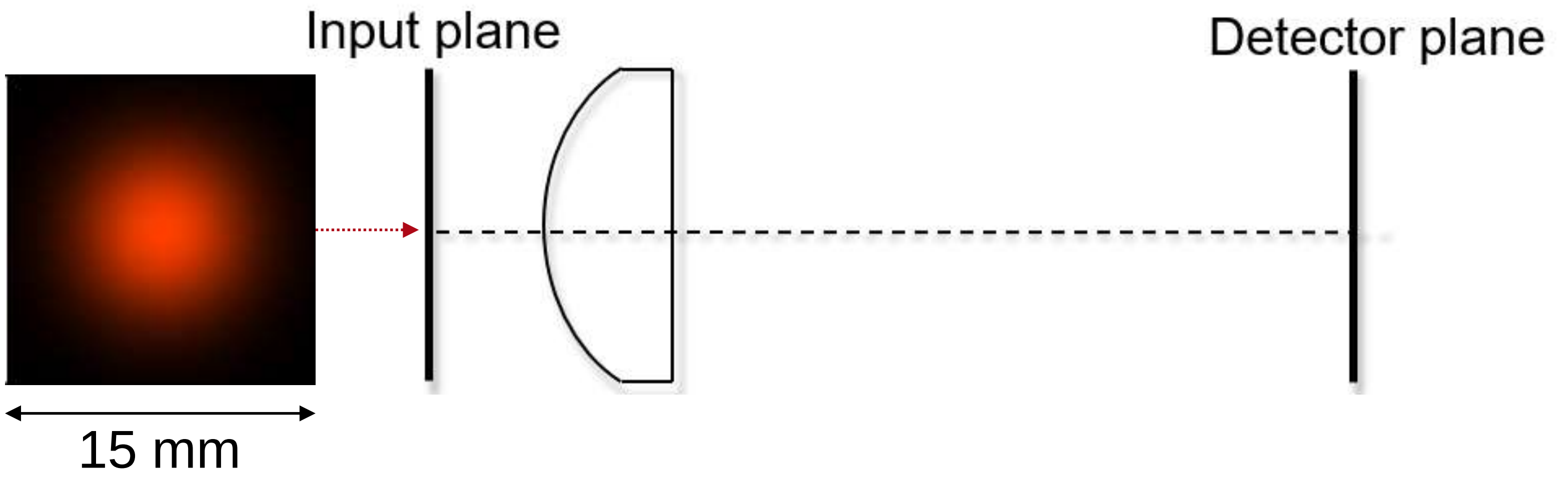
Task 14
in day 3

Task 7 Beam Shaper



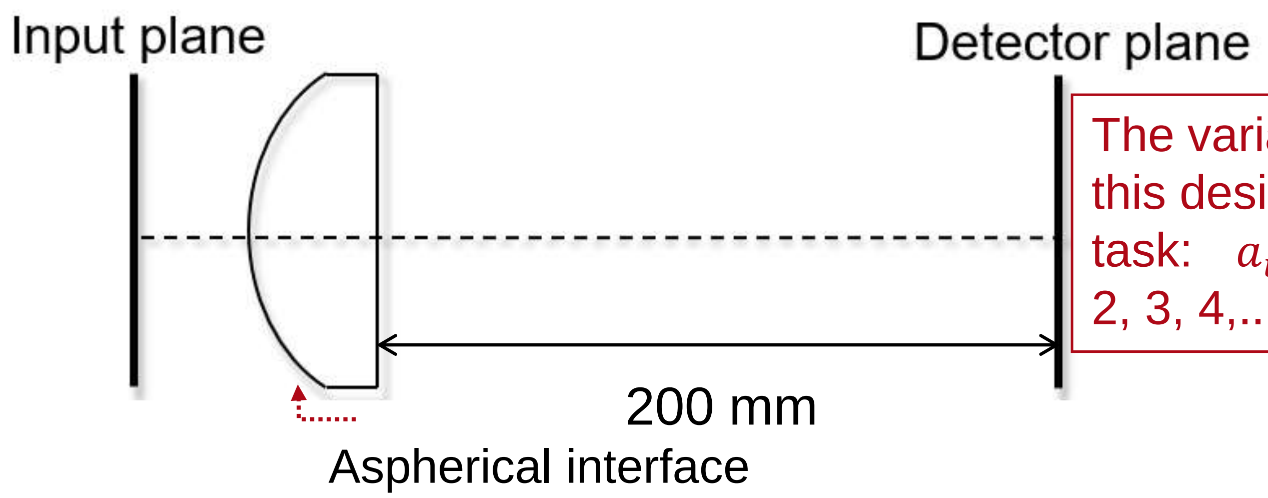
- Design a beam shaping element to shape a laser beam (fundamental mode) to a circular Top-Hat.

Specification: Light Source



Parameter	Description / Value & Unit
type/number	Gaussian beam
coherence/mode	single Hermite Gaussian (0,0) mode
wavelength	632.8 nm
beam diameter ($1/e^2$)	8 mm x 8 mm

Specification: Beam Shaper Element



The variables for this design task: a_i, with i = 2, 3, 4,...,16

- Aspherical interface:

$$h(x,y) = \sum_i a_i r^i$$

with $r = \sqrt{x^2 + y^2}$ and i is polynormial order index

Parameter	Value & Unit
name/type	Aspherical lens
material	N-BK7
thickness	5 mm
size (diameter)	23 mm
Distance to detector	200 mm

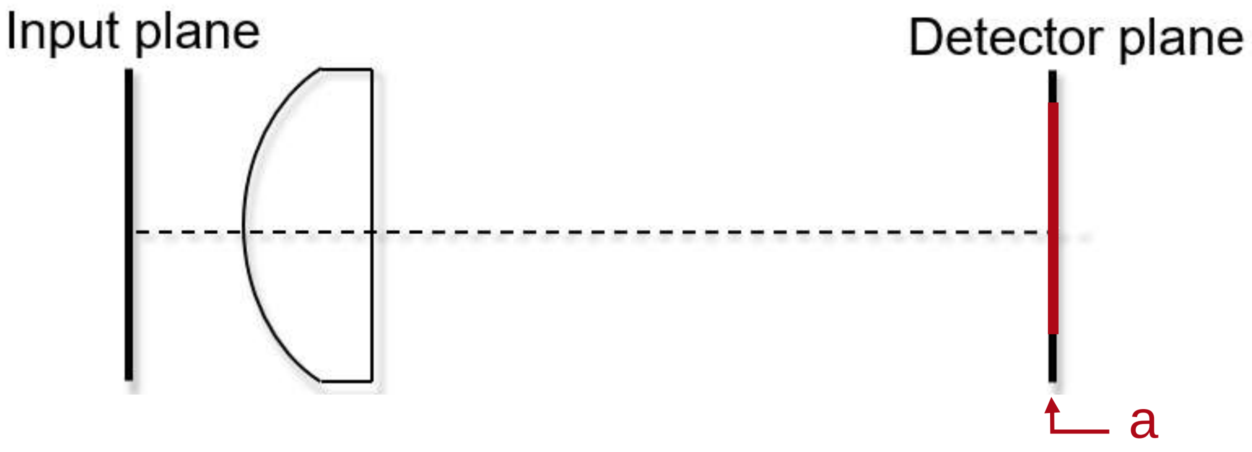
Specification: Desired Pattern

Parameter	Description / Value & Unit
type/number	Top-Hat (Super-Gaussian Wave)
wavelength	632.8 nm
beam diameter ($1/e^2$)	400 µm x 400 µm
edge width	40 µm

Specifications: Merit Functions for Design

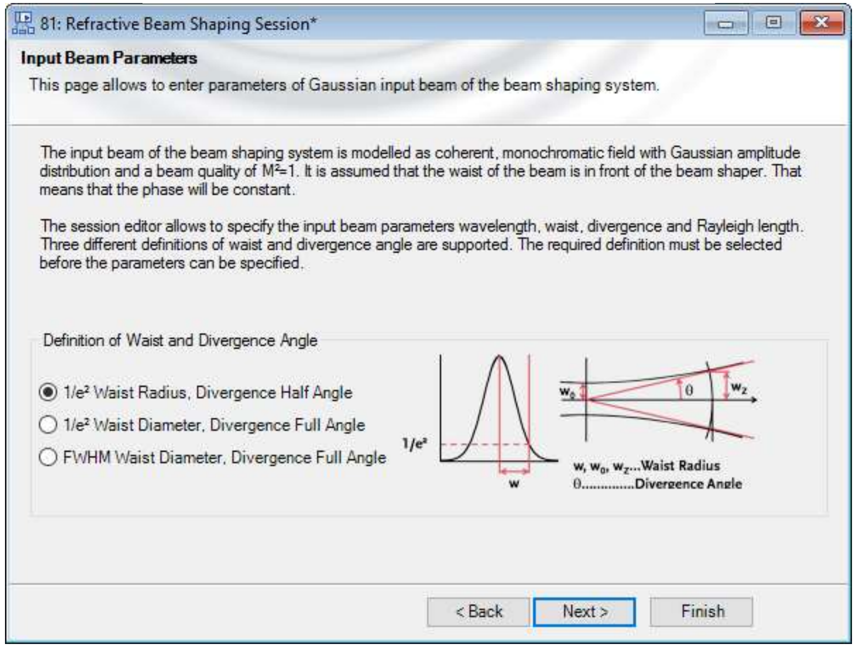
Parameter	Description / Value & Unit
conversion efficiency	> 90%
signal to Noise Radio (SNR)	> 22 dB
maximum relative intensity of stray light	< 10%

Specifications: Detector



Position	Modeling Technique	Detector/Analyzer
a	field tracing	Intensity
b	field tracing	Value of merit functions

Optimization Process

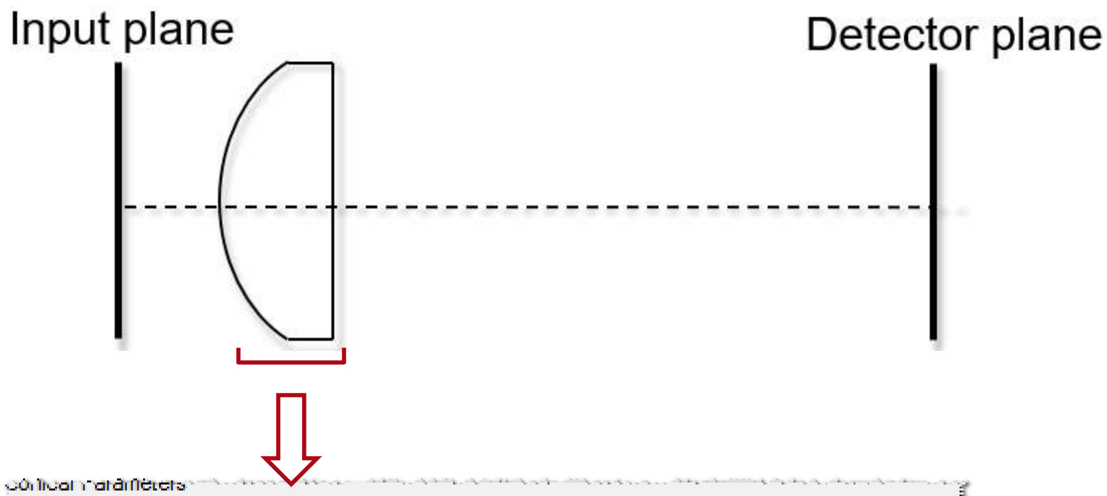


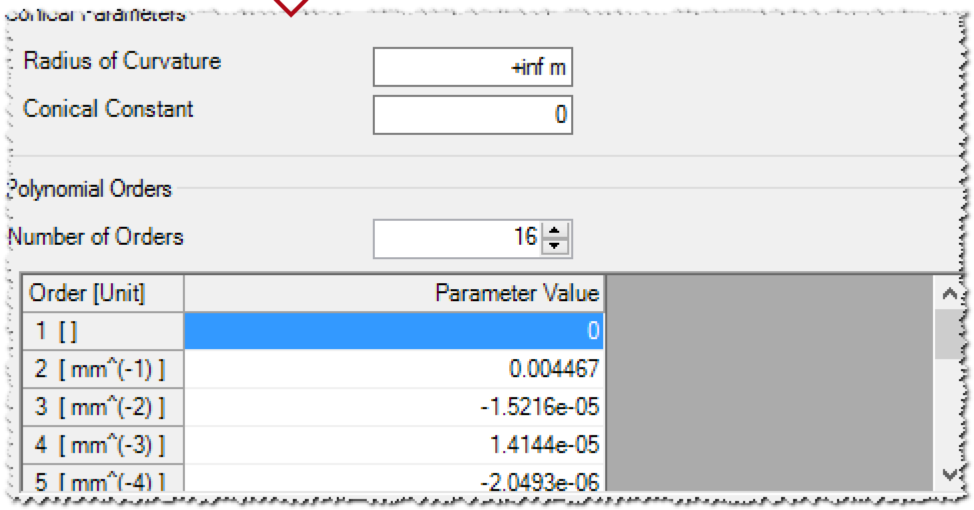
- Design Process is easily done by using the *Refractive Beam Shaping Session*.
  - Fill the parameters in illustration
  - Next!
- Click *Finish*, the beam shaper design is done immediately.

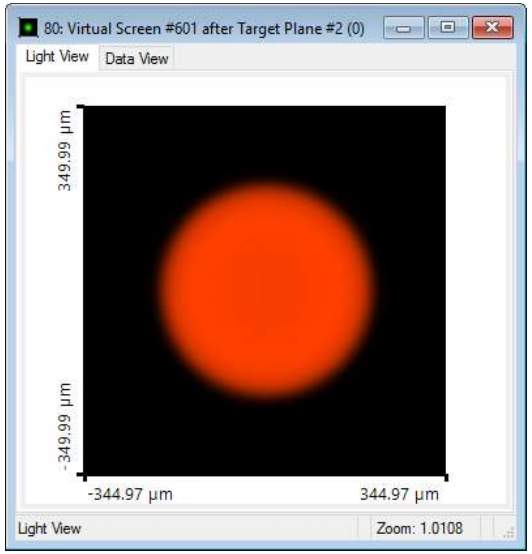
Design time → ~0.016 s !!!

* RO.0001_Refractive_Top_Hat_Beam_Shaper_Session_Editor.seditor

Results: Refractive Beam Shaper







Parameter	Value & Unit
conversion efficiency	90.24%
SNR	22.353 dB
stray light	10.872%

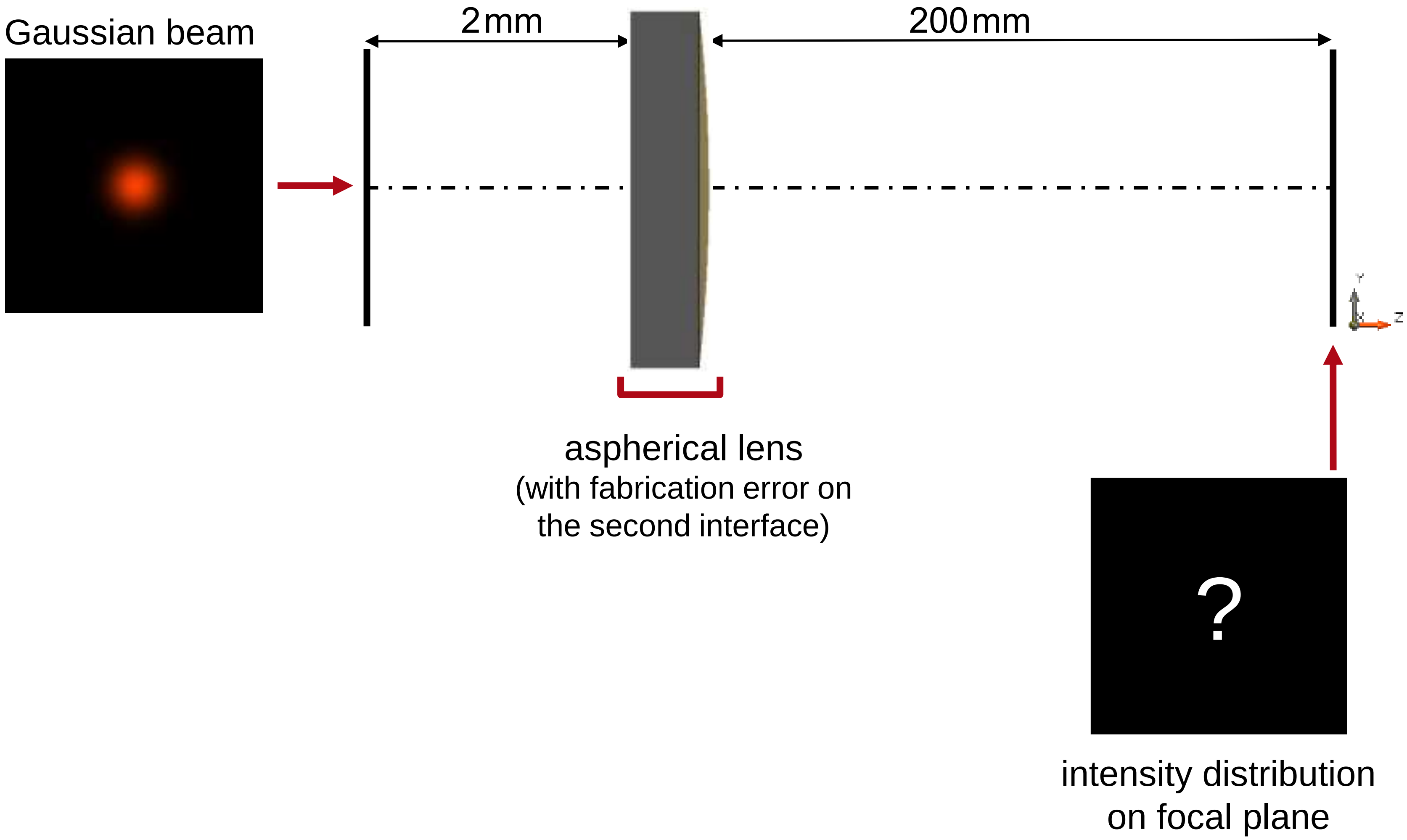
Light Shaping > Refractive Optics

Modeling of a Refractive Beam Shaper with Measured Height Profile

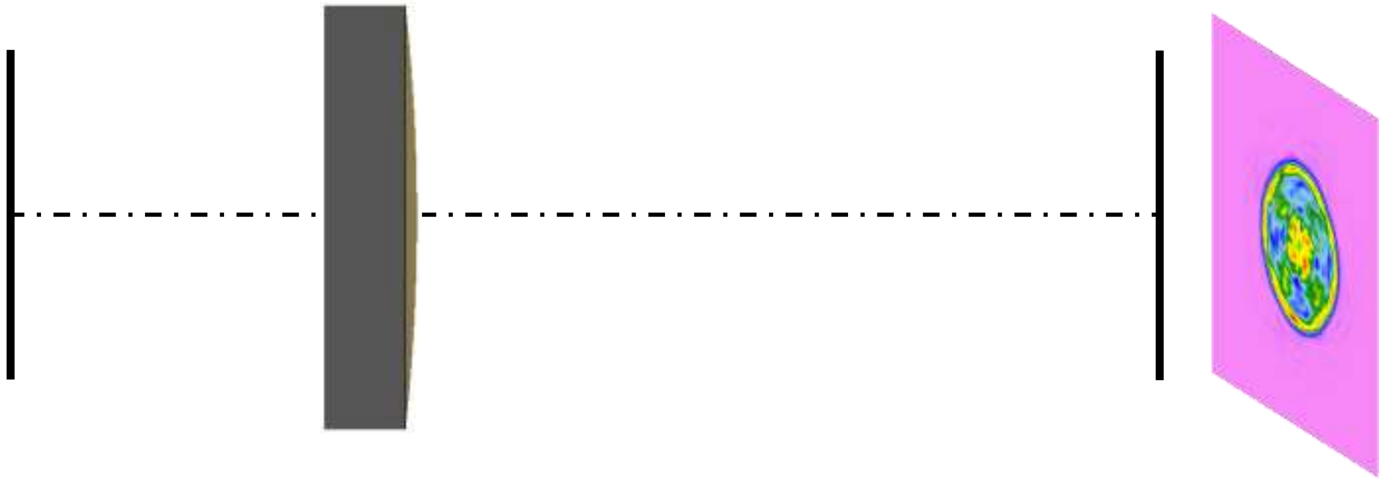
LightTrans International UG

Task 15
in day 3

Task/System Illustration

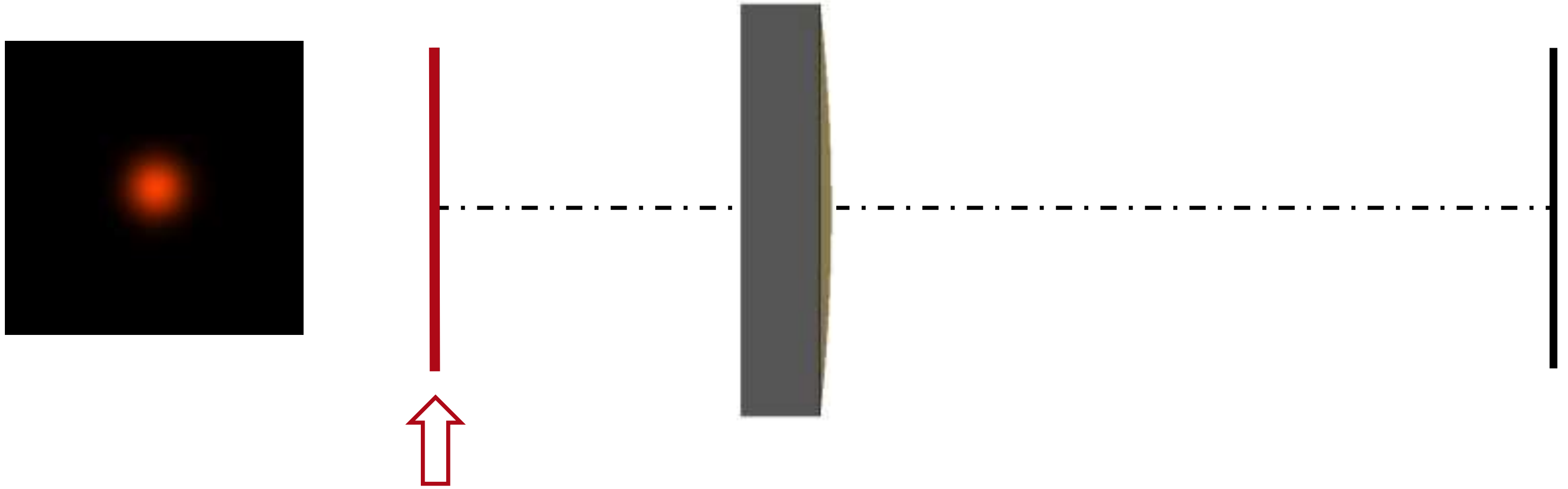


Highlights



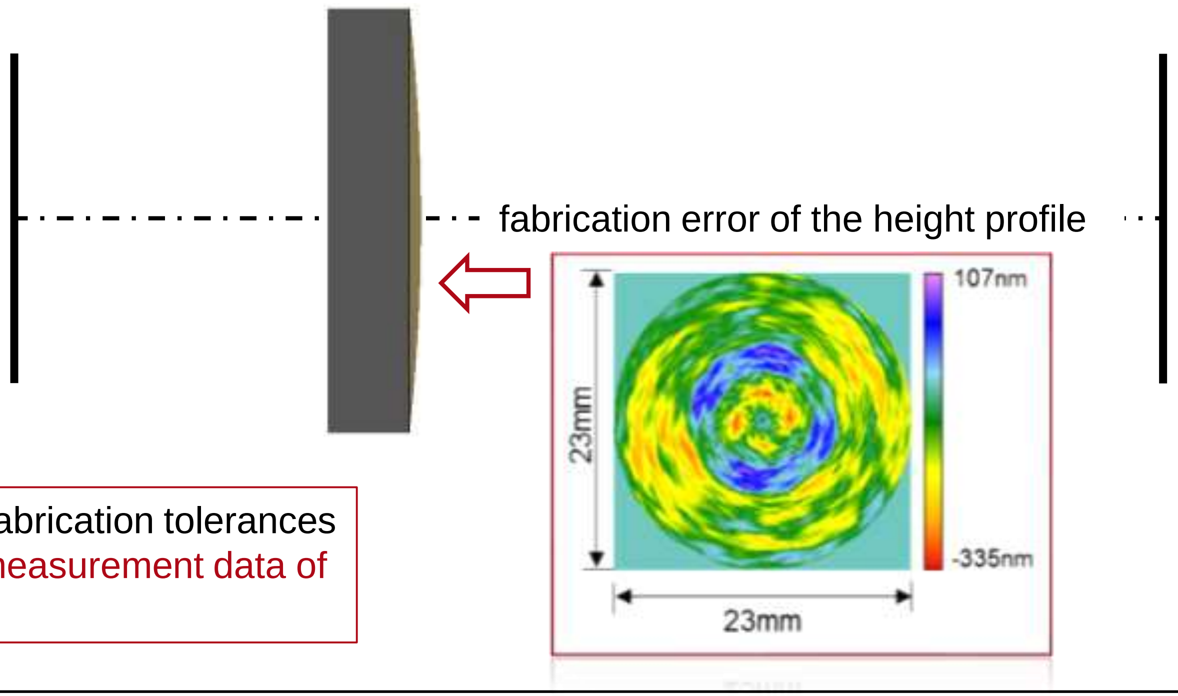
- simulation of fabrication tolerances by importing measurement data of height profiles

Specification: Light Source



Parameter	Description / Value & Unit
type/number	Gaussian beam
coherence/mode	single Hermite Gaussian (0,0) mode
wavelength	632.8 nm
polarization	linear in x-direction (0°)
waist radius ($1/e^2$)	4 mm × 4 mm

Specification: Focusing Asphere

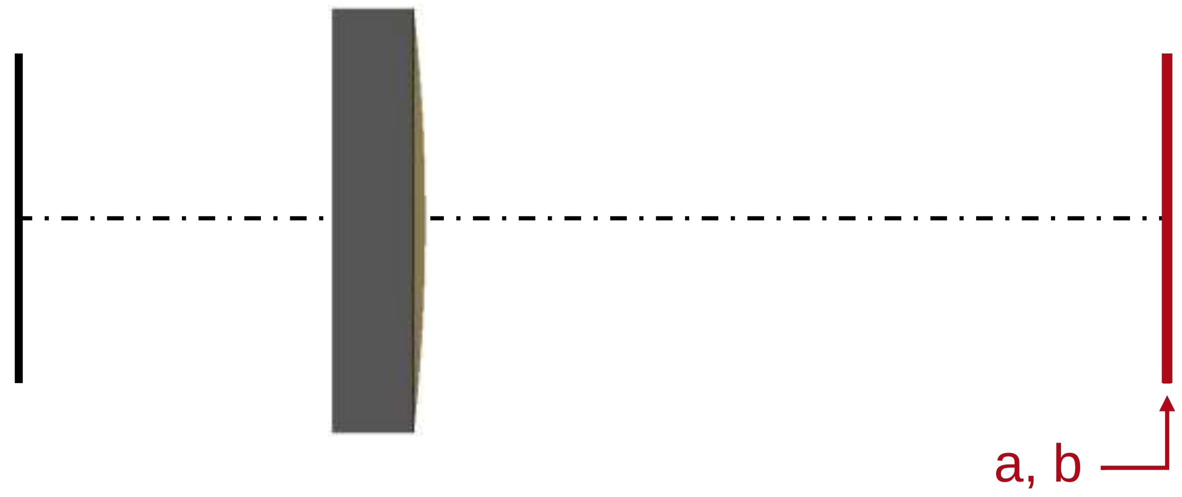


Highlights

- simulation of fabrication tolerances by importing measurement data of height profiles

Parameter	Value & Unit
name/type	convex-plano aspherical lens
first interface	plane interface
second interface	aspherical interface with measured height profile error
material (M)	N-BK7

Specification: Detectors

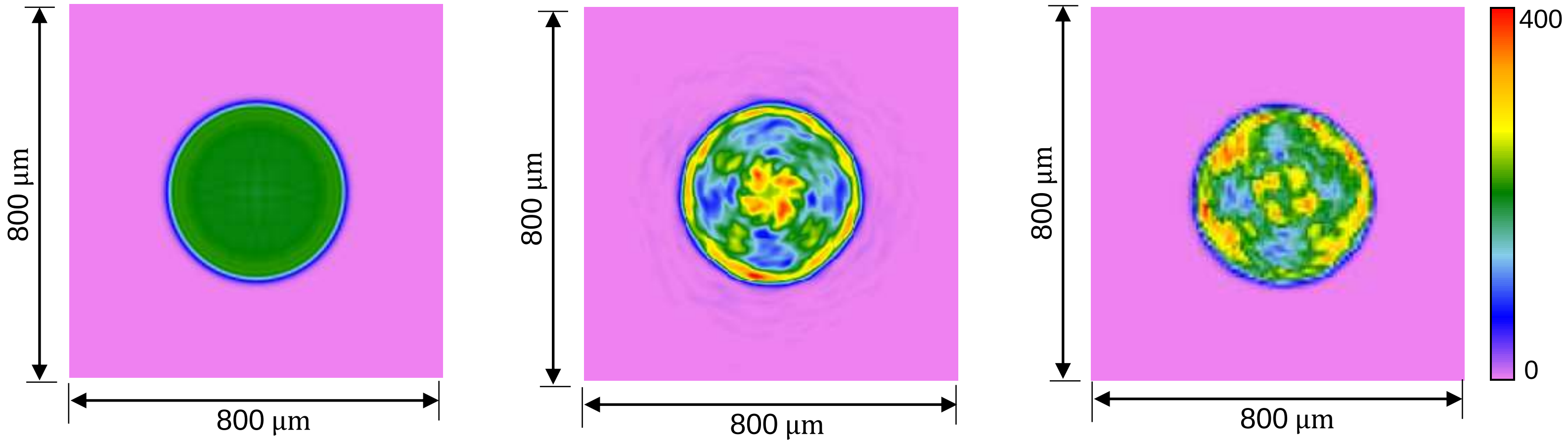


Position	**Modeling Technique**	**Detector/Analyzer**
a	field tracing	intensity distribution
b	field tracing	merit function detector

Results: Intensity Distribution

Highlights

- simulation of fabrication tolerances by importing measurement data of height profiles



intensity of field at focal plane (without fabrication tolerances)

intensity of field at focal plane (with fabrication tolerances)

measured intensity at focal plane (with fabrication tolerances)

Results: Merit Function Detector

Highlights

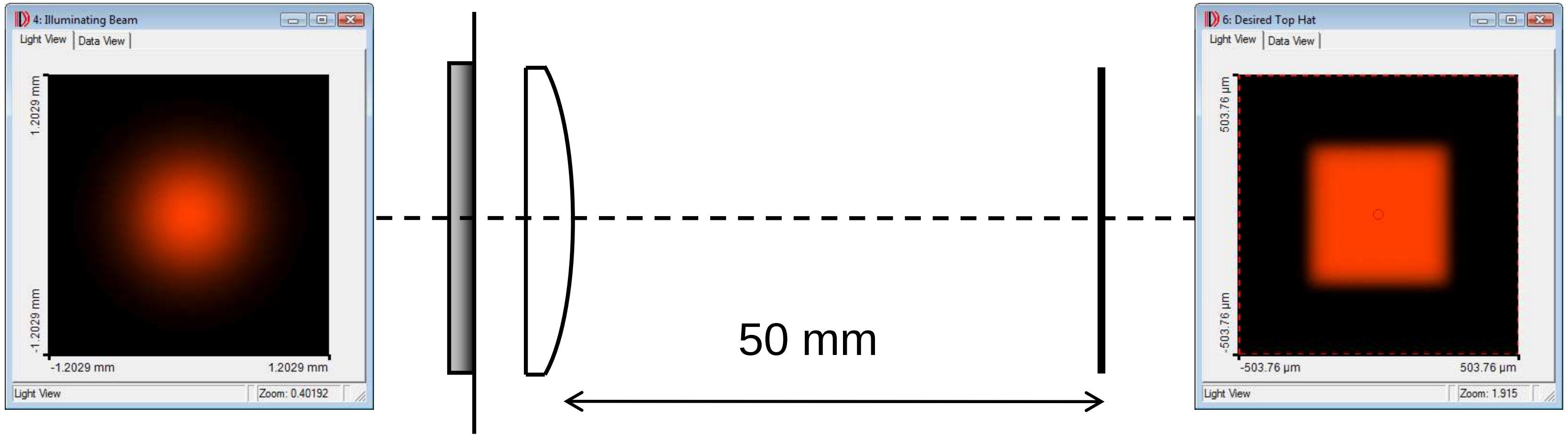
- simulation of fabrication tolerances by importing measurement data of height profiles

Detector/Analyzer	Result (without fabrication error)	Result (with fabrication error)
signal-to-noise ratio (SNR)	26.49dB	14.66dB
conversion efficiency	91.21%	87.15%
uniformity error	93.65%	99.73%

Modeling Task

Diffractive Beam shaper
Diameter: 2 × 2 mm
Phase Levels: 16

Target
Plane



Illuminating Beam
Intensity

1f-Setup
Focal Length f=50 mm

Top Hat Intensity
(free of speckles)

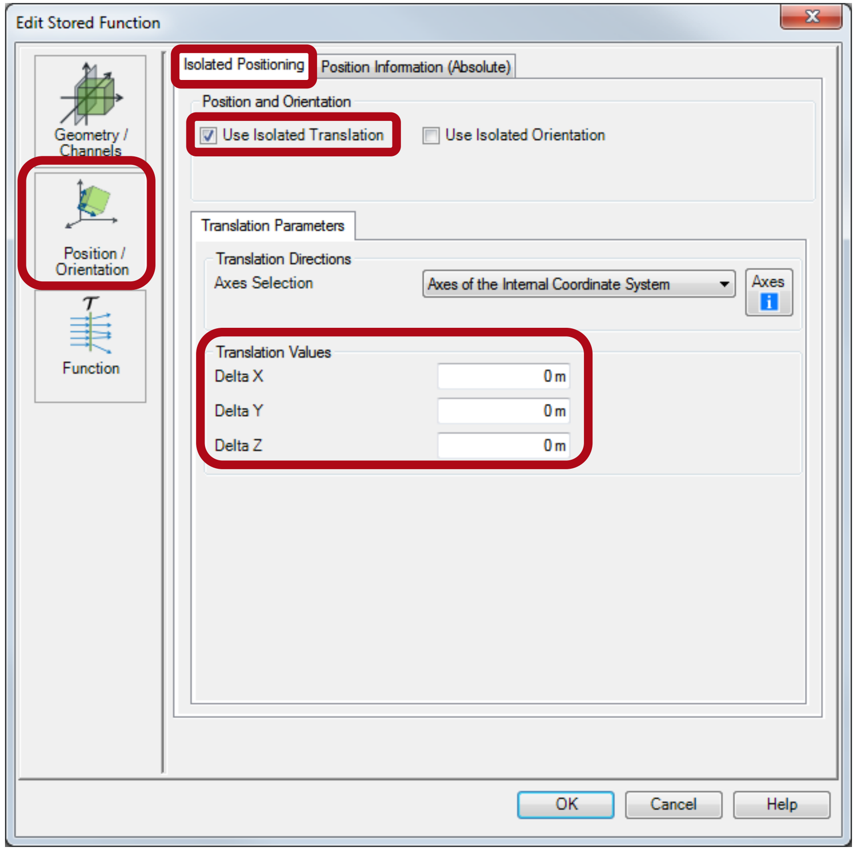
Tolerance Analysis

Modeling Task

- The following tolerances of the system are to be analyzed.
- The ± tolerance values are regarded as 3-times ± the standard deviation σ.

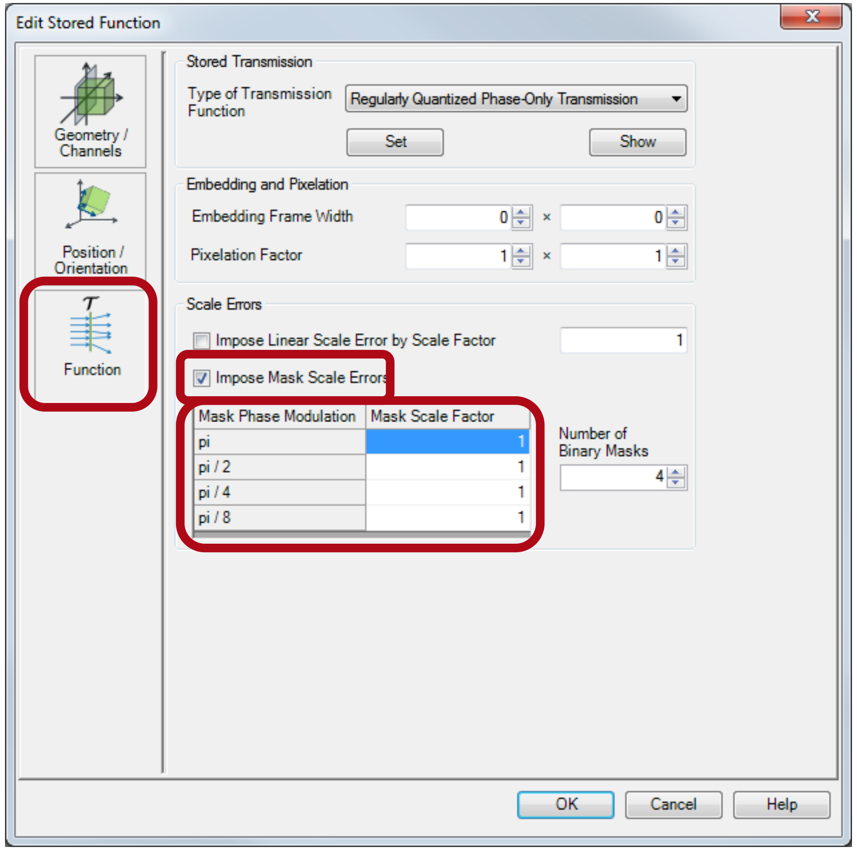
Varied Parameters	Value and Tolerances
Waist Radius of Input Beam	(500 ± 25) µm
Etching Depths of all 4 Binary Masks	± 2 % of original height
x-Position of Beam Shaper	(0 ± 10) µm
y-Position of Beam Shaper	(0 ± 10) µm
Focal Length of Lens	(50 ± 0.5) mm

Simulation of Alignment Tolerances



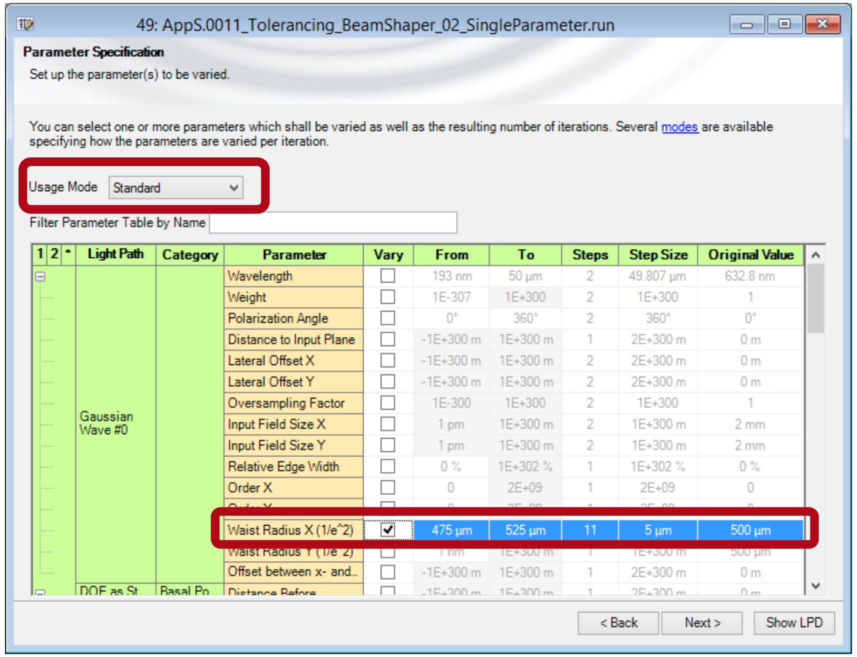
- Simulation of shift tolerances must be activated on *Tolerancing* page of *Stored Function* component and *Target Plane* component.
- Tolerance values are varied by *Parameter Run.* The values set in the component dialog are ignored.

Simulation of Etching Depth Tolerances



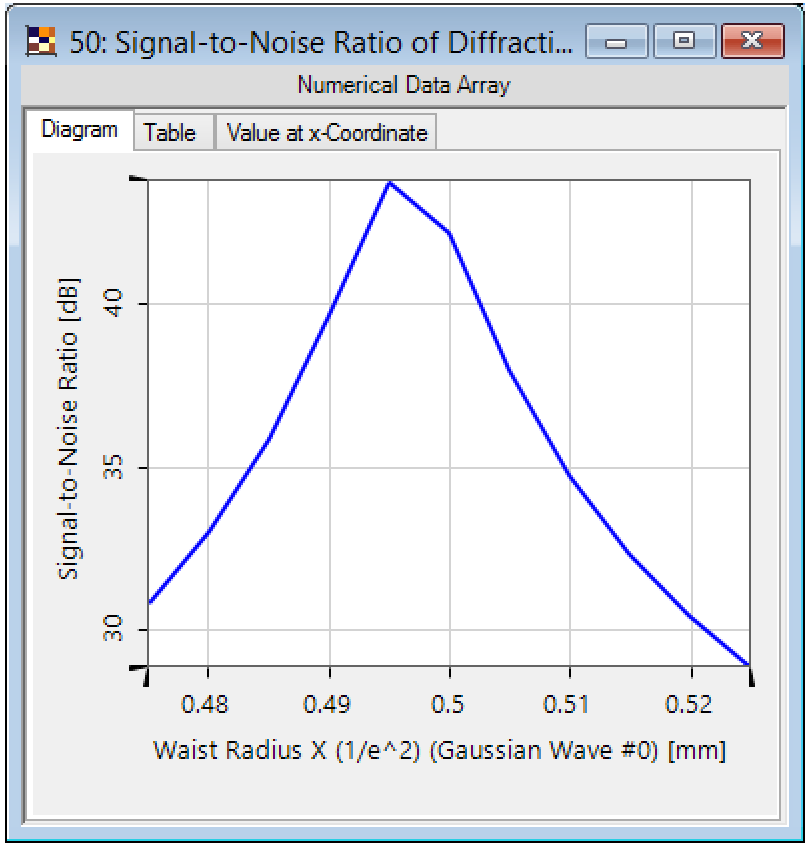
- Simulation of mask etching depth errors must be activated on *Function* page of *Stored Function* component.
- Tolerance values are varied by *Parameter Run*. The respective settings in the component dialog are ignored.
- A tolerance value of 1 represents an optimum etching depth.

Single Parameter Variation



- The laser beam radius has typically a strong influence on the optical performance of a beam shaping system.
- The *Usage Mode: Standard* must be selected for the variation of a single parameter.
- *Waist Radius X* parameter must be selected.

Single Parameter Variation

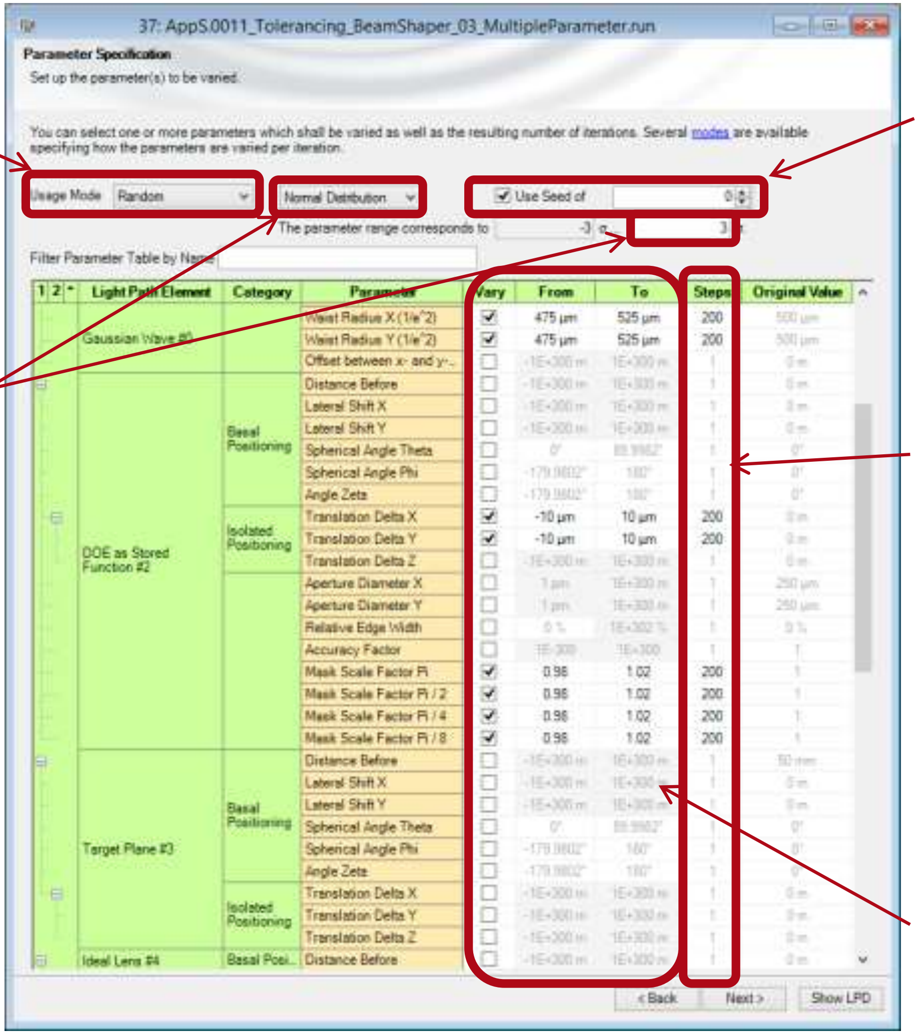


- The beam shaping system shows a strong sensitivity for a variation of the laser beam radius.
- The Signal to Noise Ratio (SNR) will drop to 28.8dB.

Monte-Carlo Simulation

Random mode for Monte Carlo simulation

Parameter Variation has a *Normal Distribution* with a certain standard deviation σ

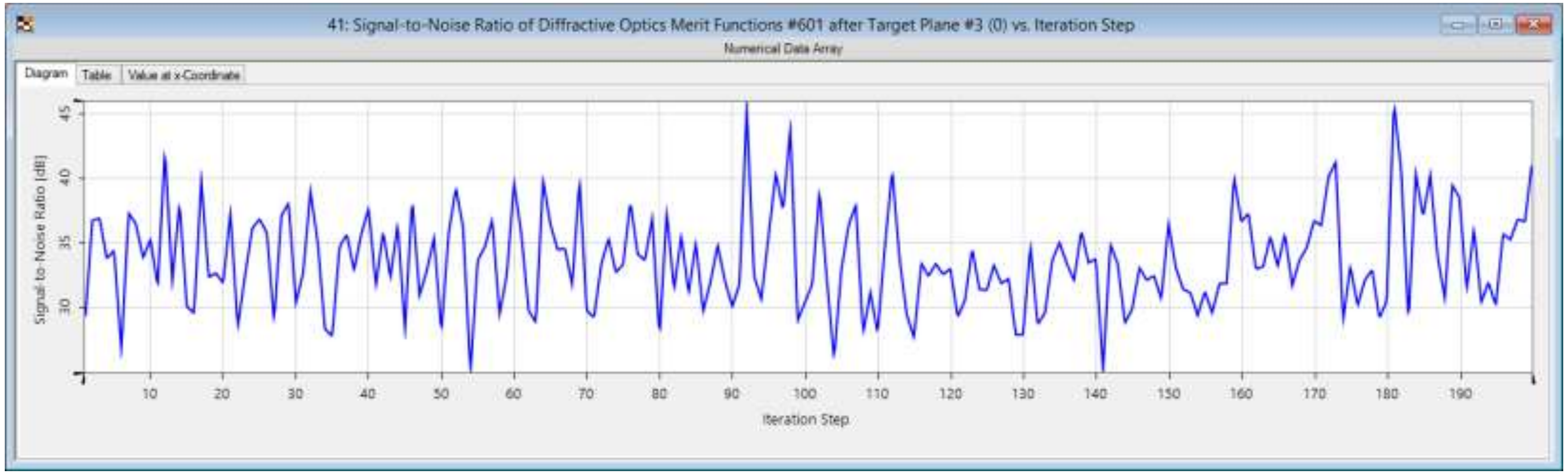


A Seed can be used for reproducible results of the ‘random’ series.

Total number of variations

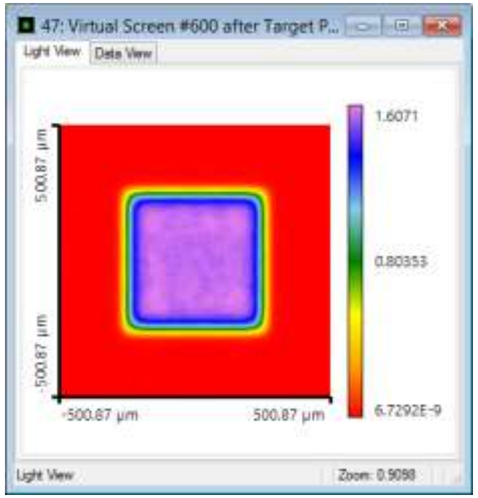
Minimum and maximum value of all tolerances defined by $\pm 3\sigma$

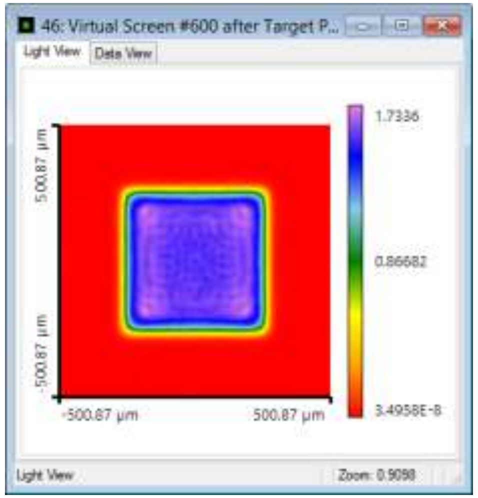
Monte-Carlo Simulation



- Variation of the SNR depending on the random parameter set.
- The minimum SNR can be found from the diagram via the menu entry Detectors > Minimum.
- Minimum SNR: 24.9 dB
- Average SNR: 33.7 dB

Resulting Field Distributions





- Left: Ideal output intensity (SNR = 42.2 dB).
- Right: Light pattern with lowest SNR (SNR = 24.9 dB)
- Export of Monte-Carlo simulation results to external software (for example Microsoft Excel) allows further statistical evaluations.

Geometrical Distortion Concept

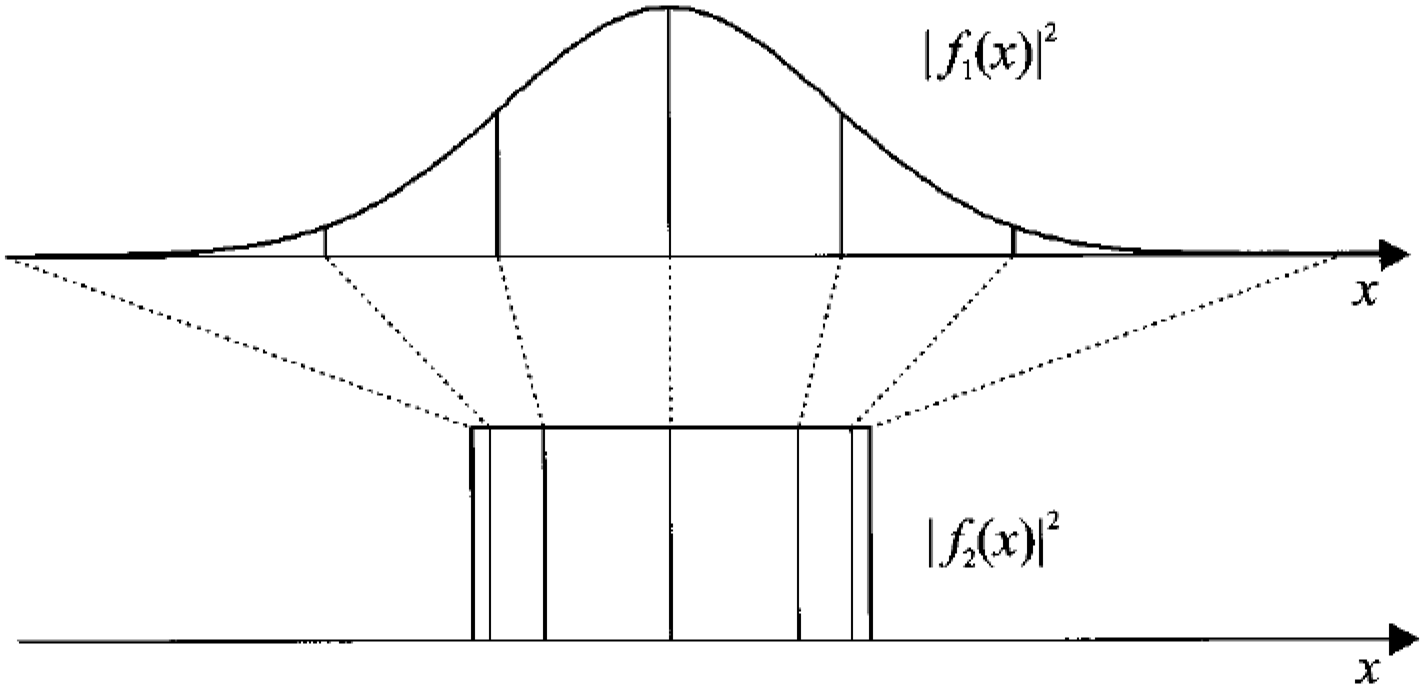
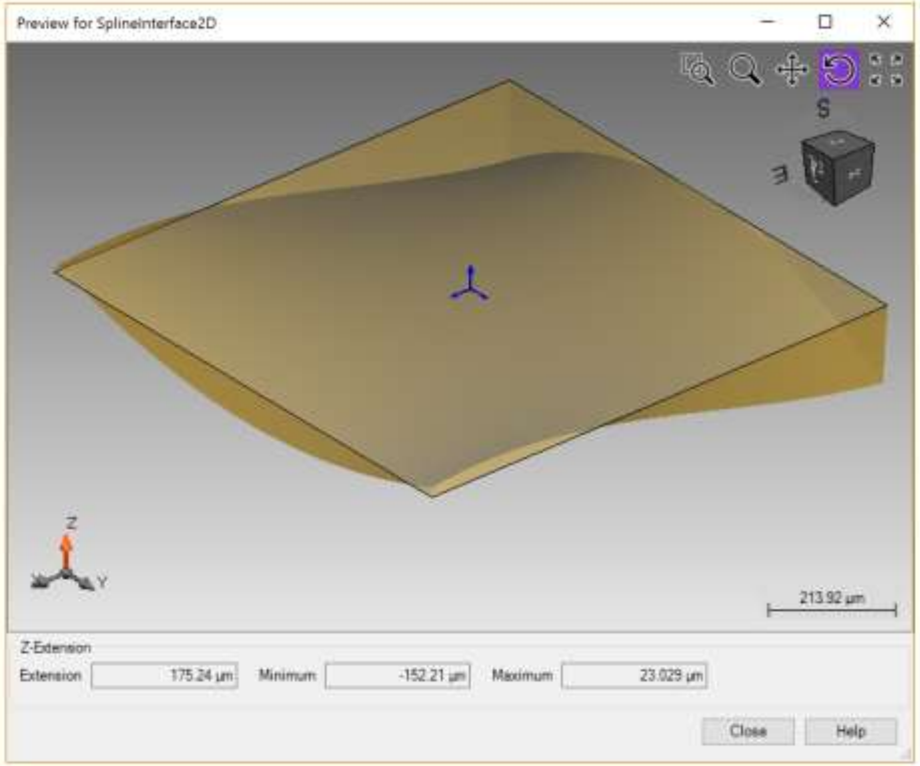
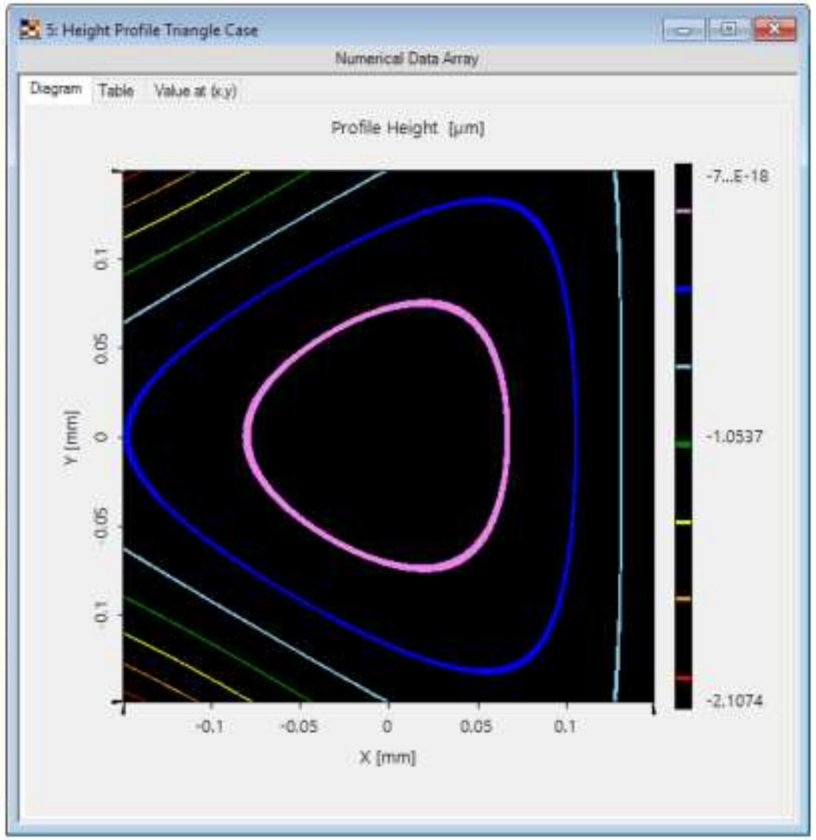


Fig. 1. Distortion transforming a Gaussian beam to a uniform distribution.

Vol. 14, No. 7/July 1997/J. Opt. Soc. Am. A 1549

Laser Beam Shaping: R&D





Laser Beam Shaping: R&D

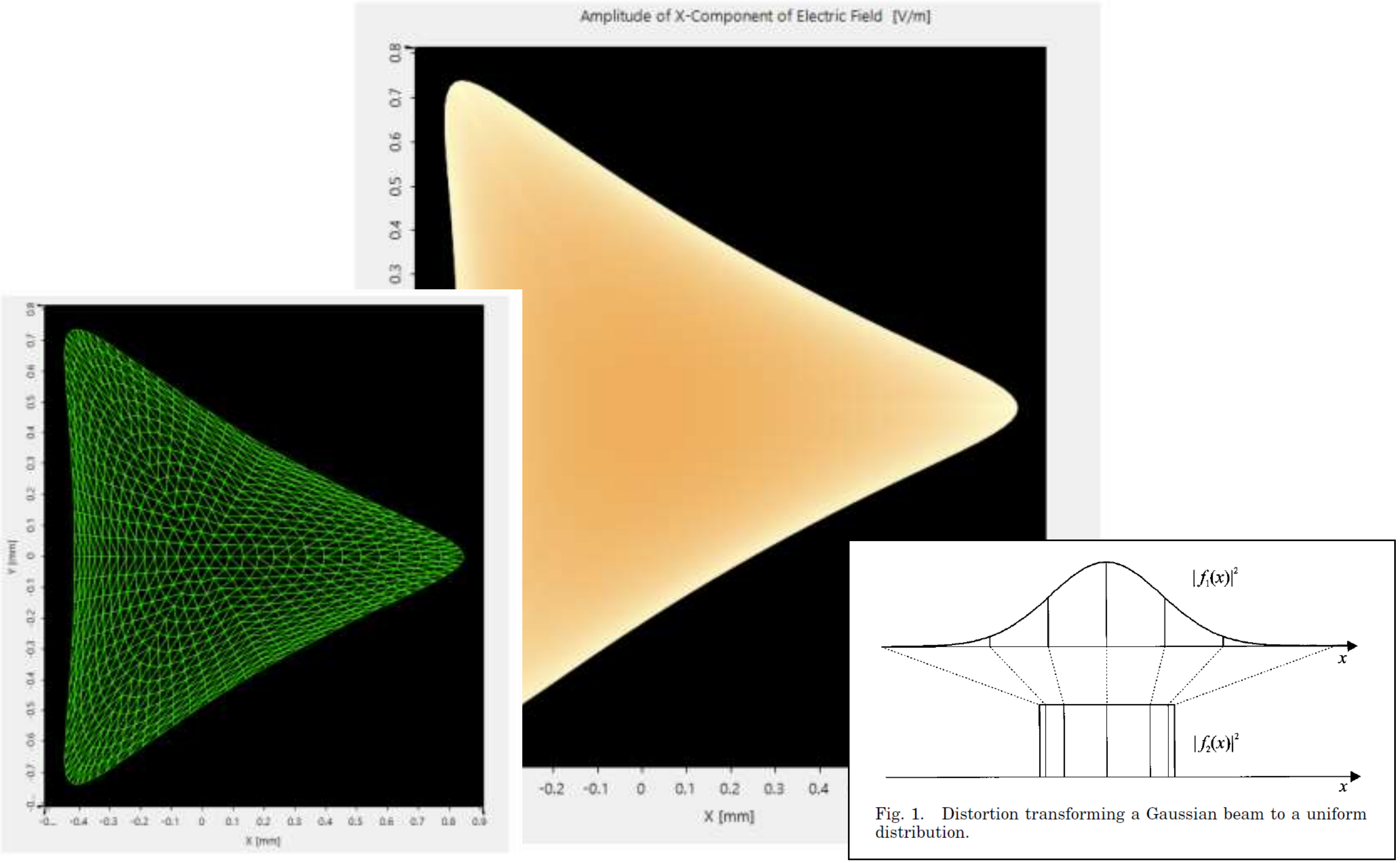
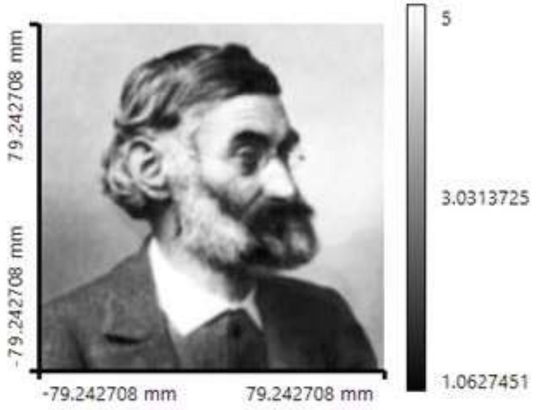
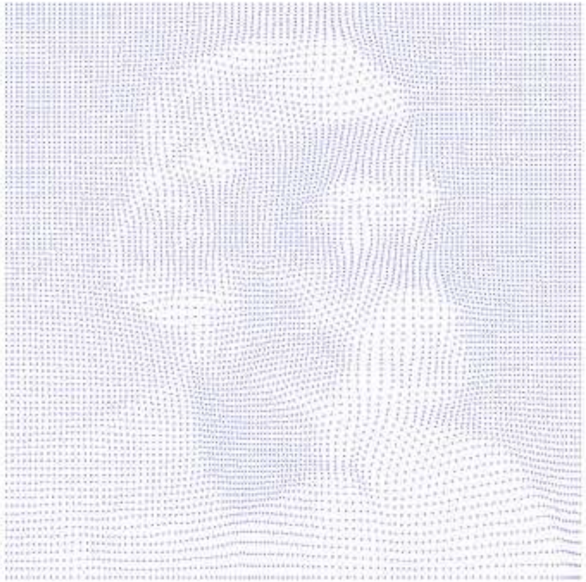
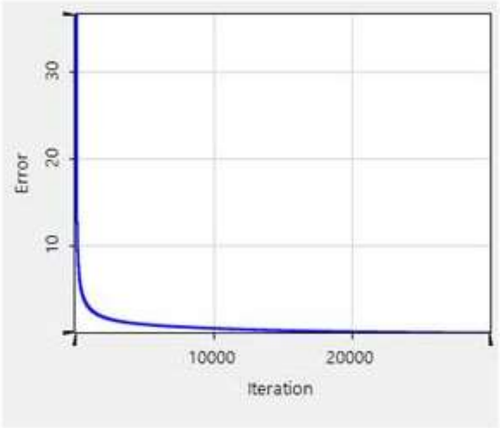


Fig. 1. Distortion transforming a Gaussian beam to a uniform distribution.

Light Shaping: R&D







Light shaping by stored scanning process

Diffractive optical elements

Light Shaping Concepts

- Tailored aberrations
- Stored scanning process
- Multichannel concept: Single Deflection
- Multichannel concept: General

Light Shaping Concepts

- Tailored aberrations
- Stored scanning process
- Multichannel concept: Single Deflection
- Multichannel concept: General

Function Principle of DOE

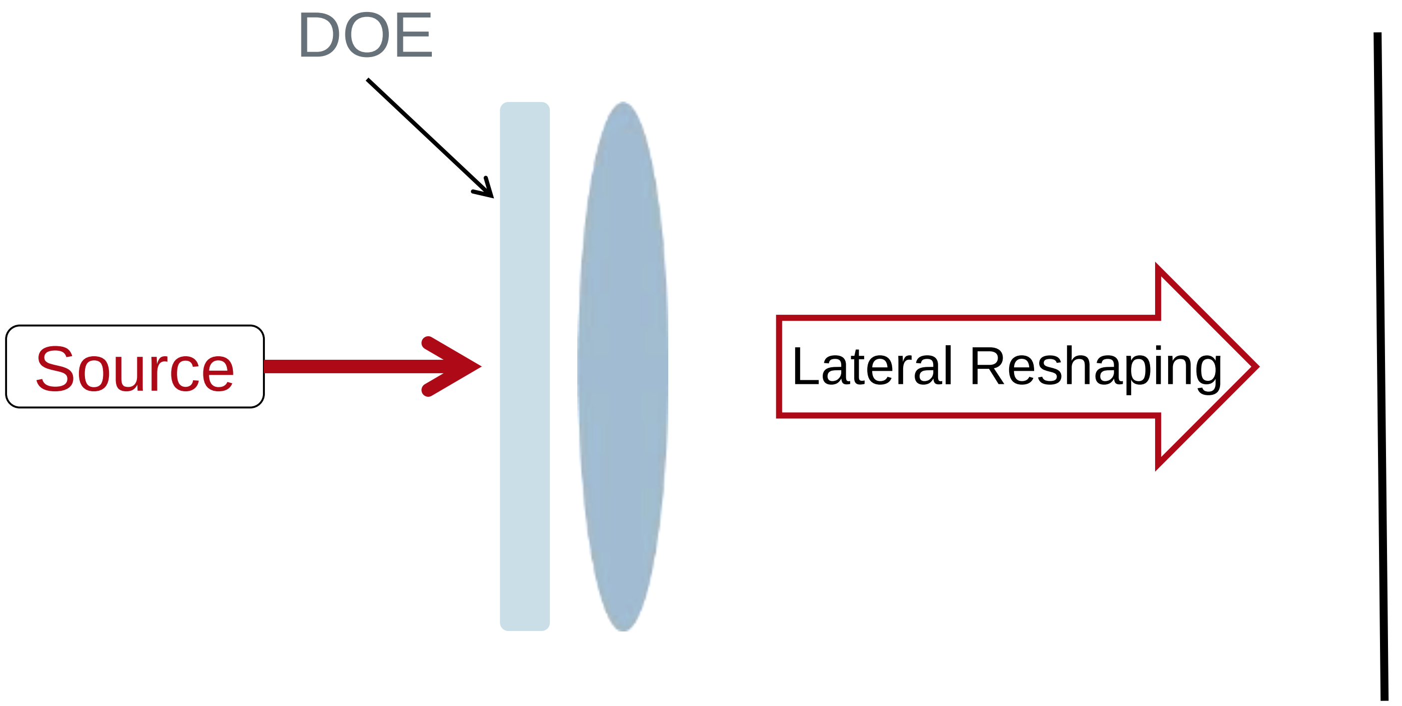
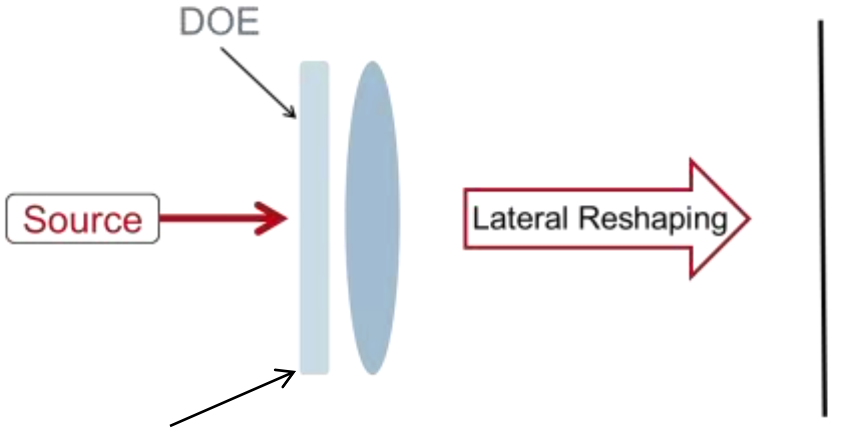
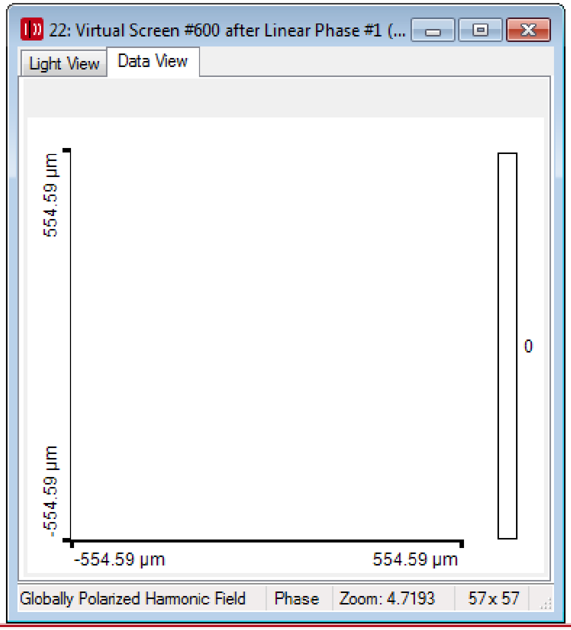


Illustration of Deflection



Phase of transmission



Intensity in target

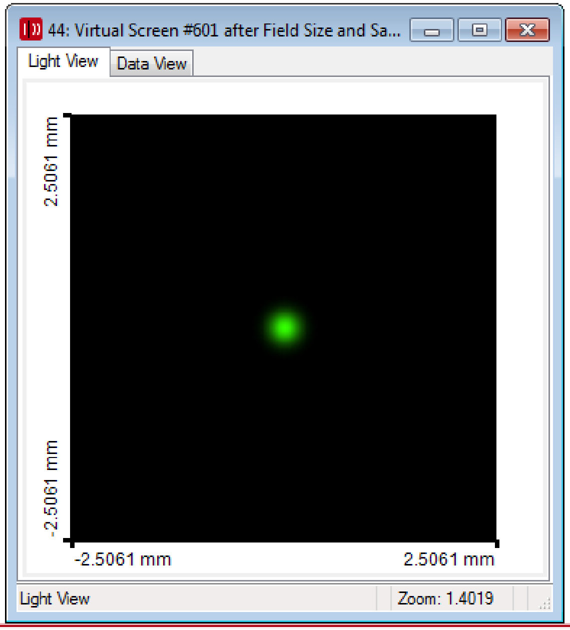
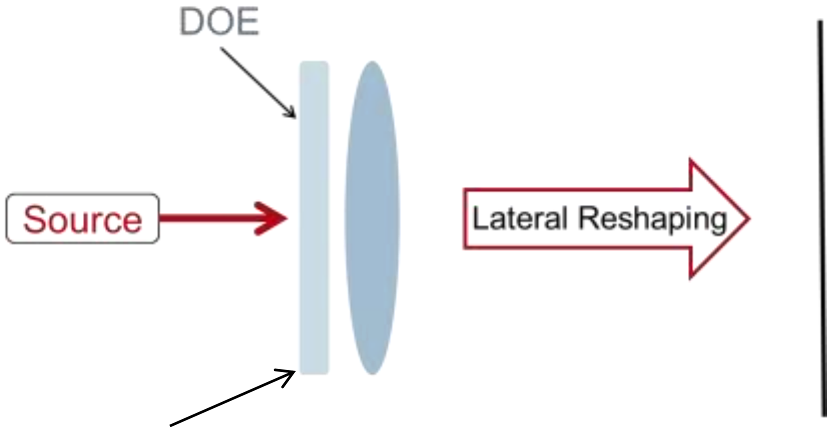
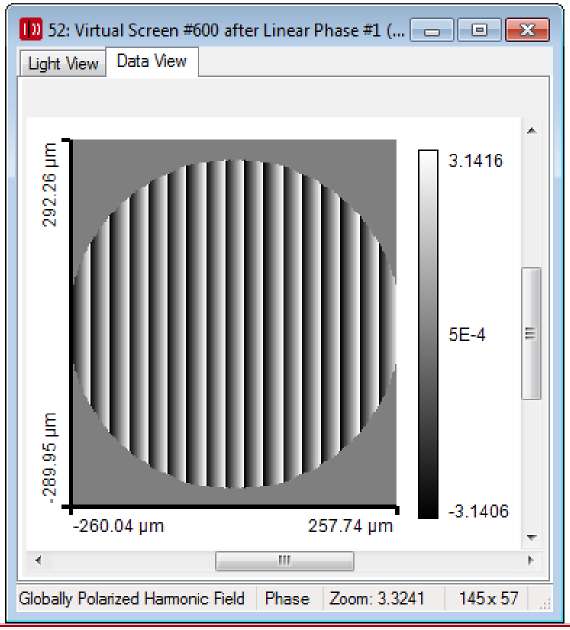


Illustration of Deflection



Phase of transmission



Intensity in target

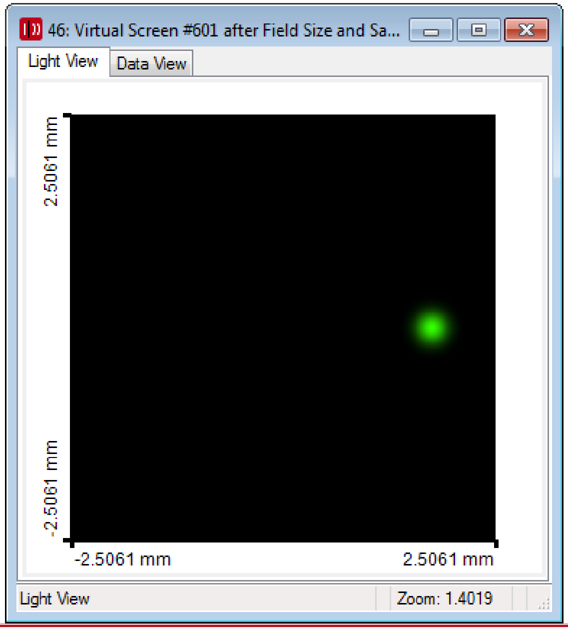
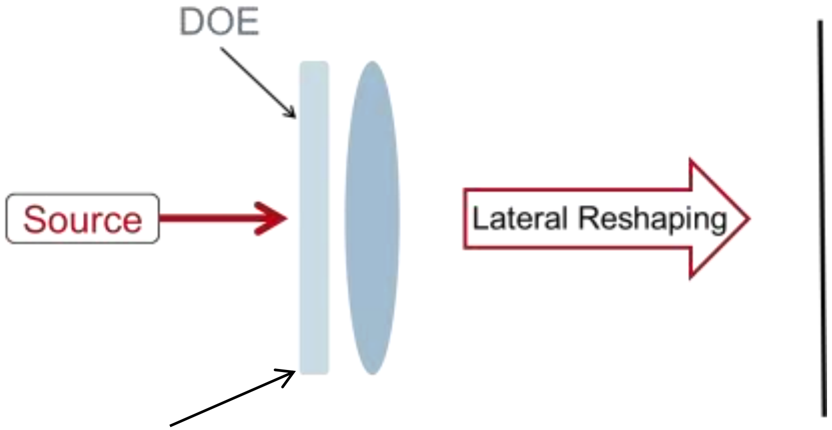
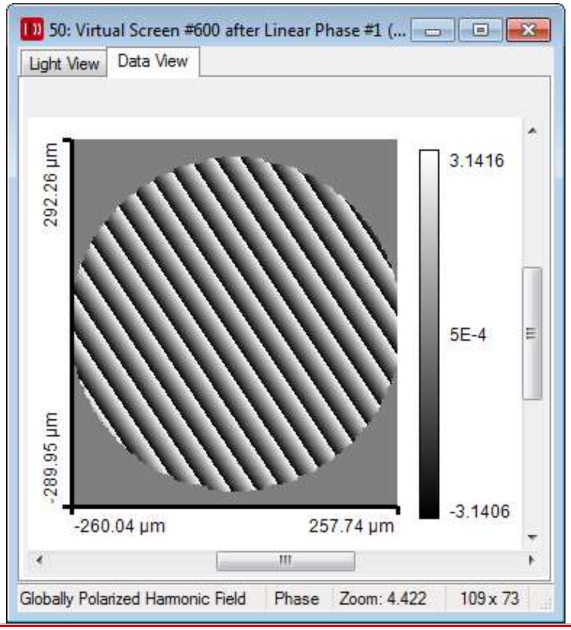


Illustration of Deflection



Phase of transmission



Intensity in target

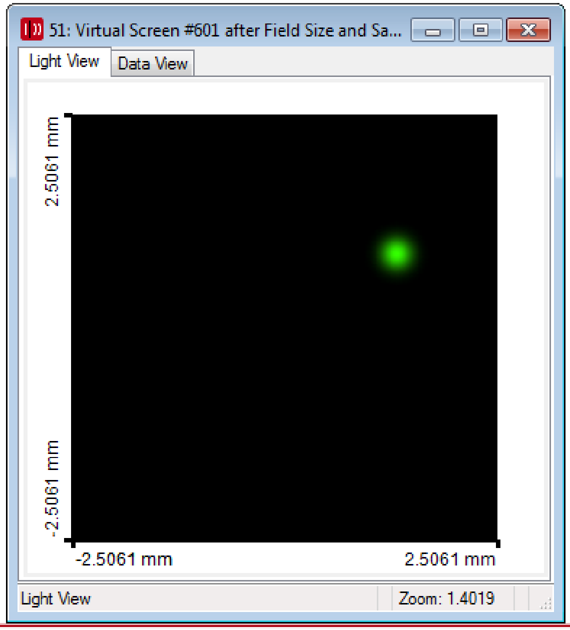
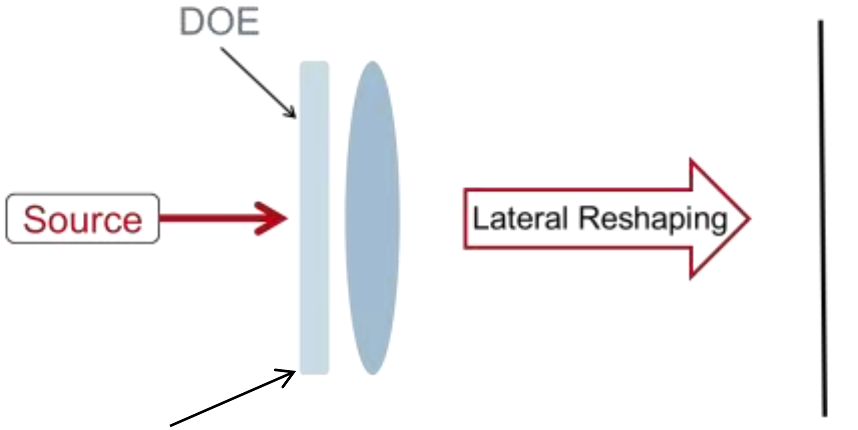
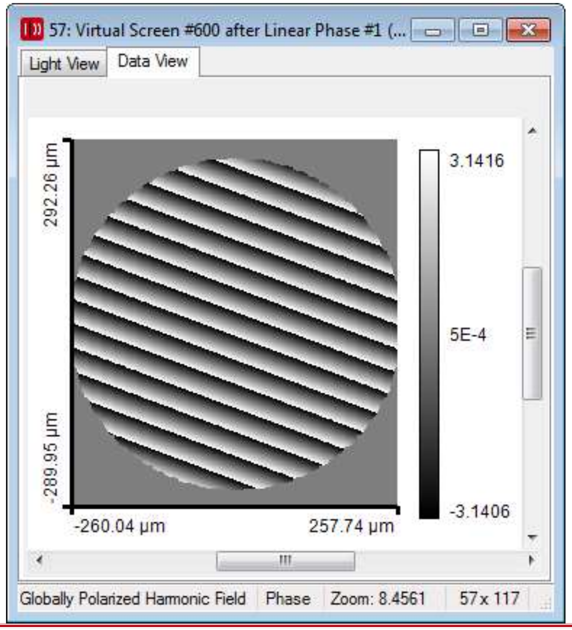


Illustration of Deflection



Phase of transmission



Intensity in target

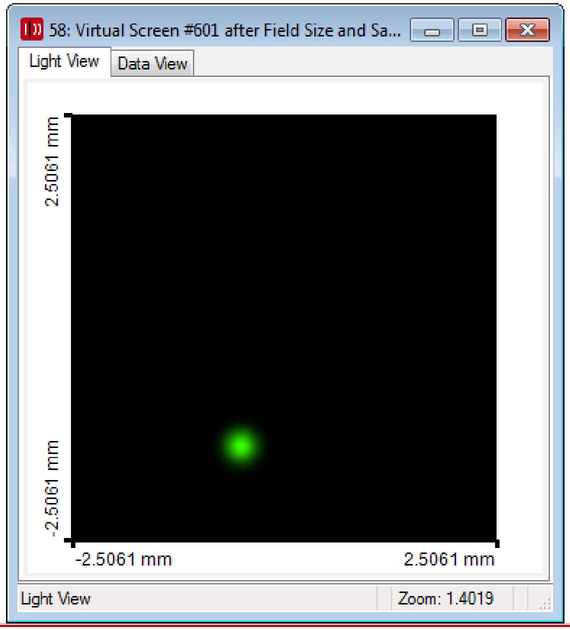
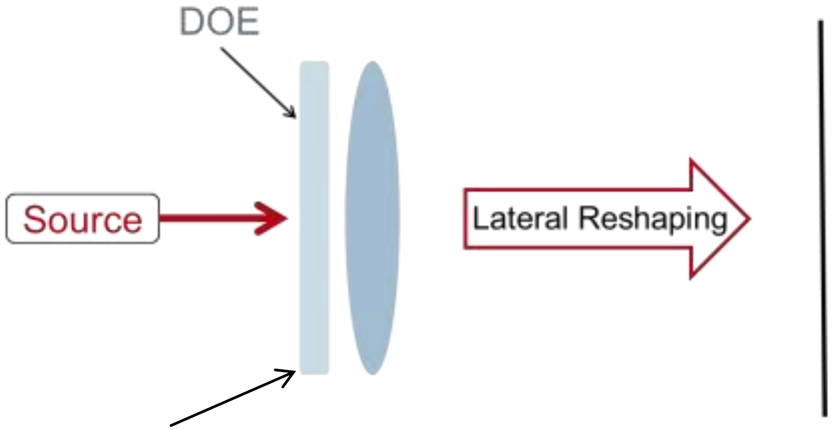
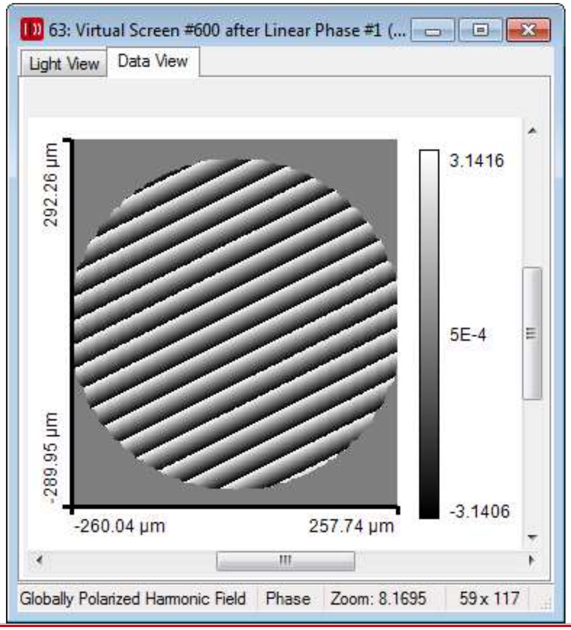


Illustration of Deflection



Phase of transmission



Intensity in target

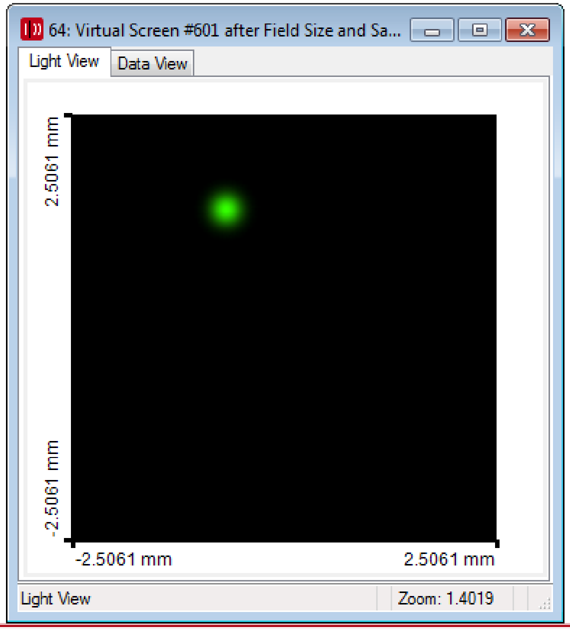
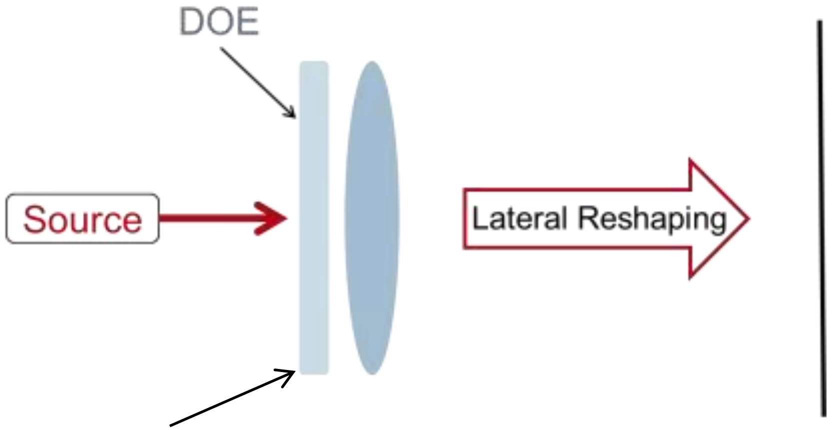
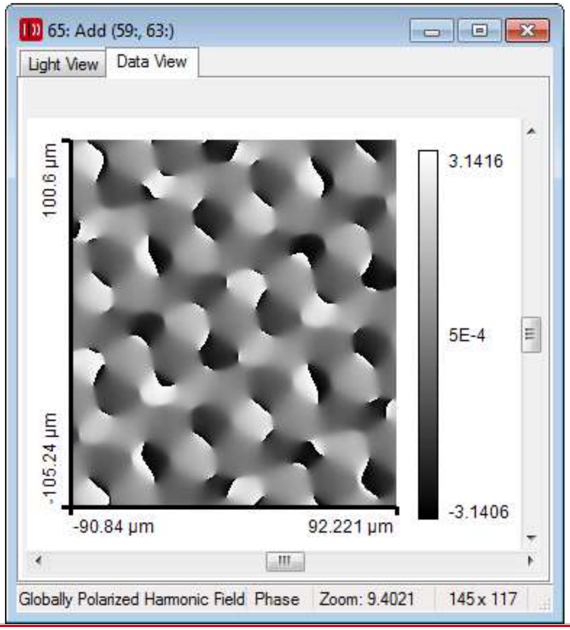


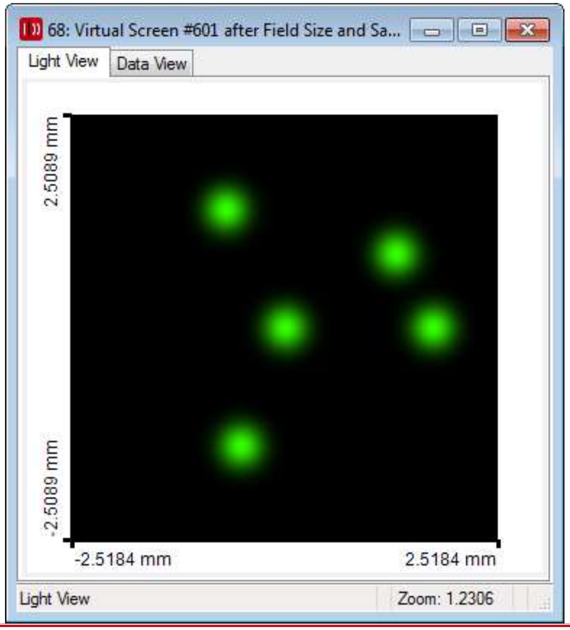
Illustration of Deflection: Sum



Phase of transmission

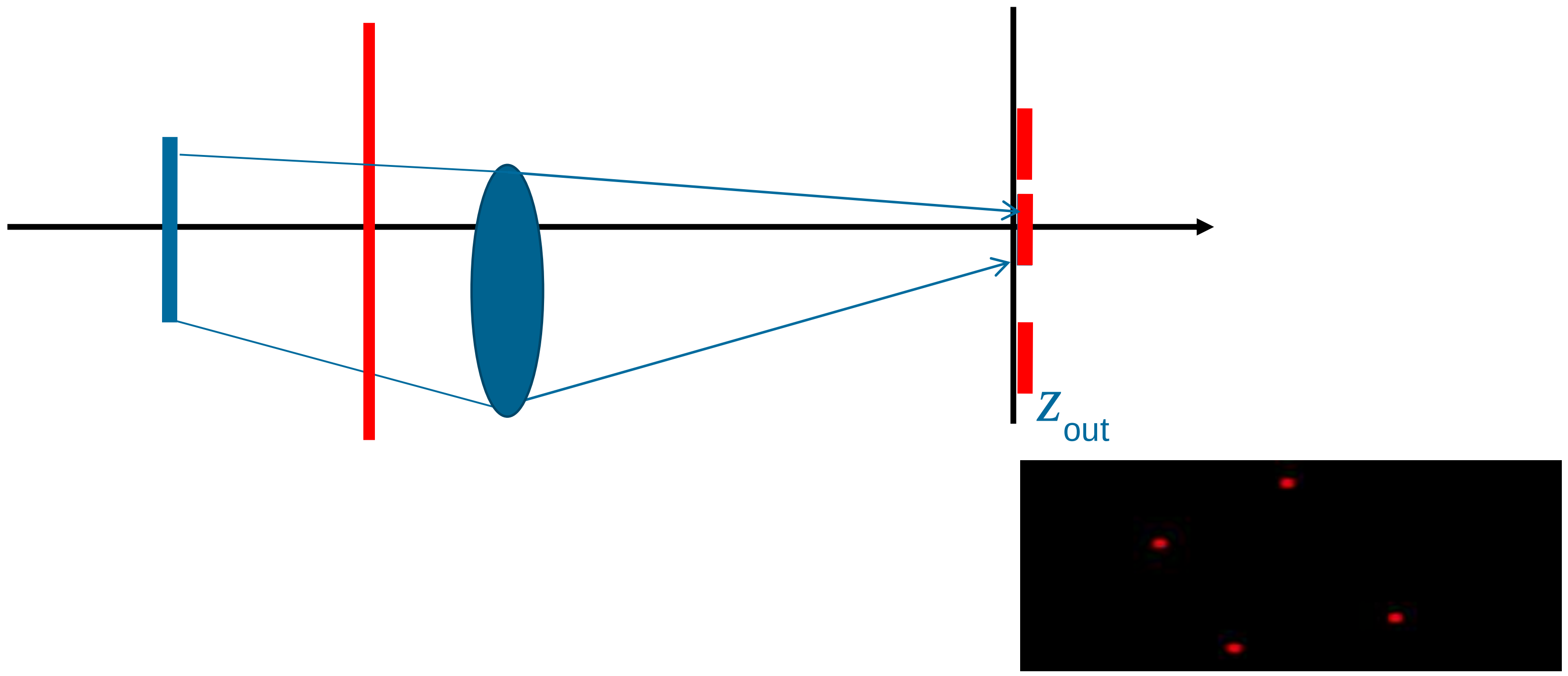


Intensity in target



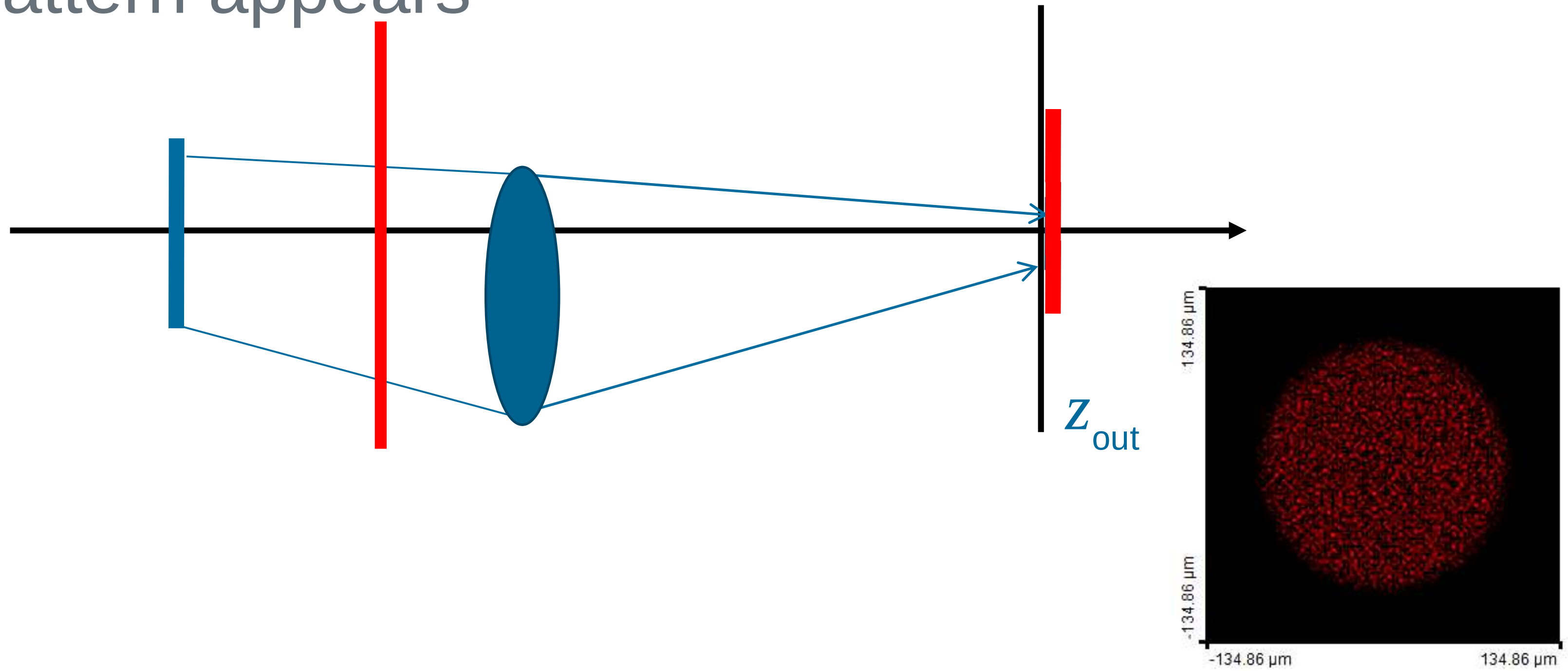
Basic Design Situations: Splitting

Diffractive Beam Splitting: Deflected output fields (beams) do not overlap



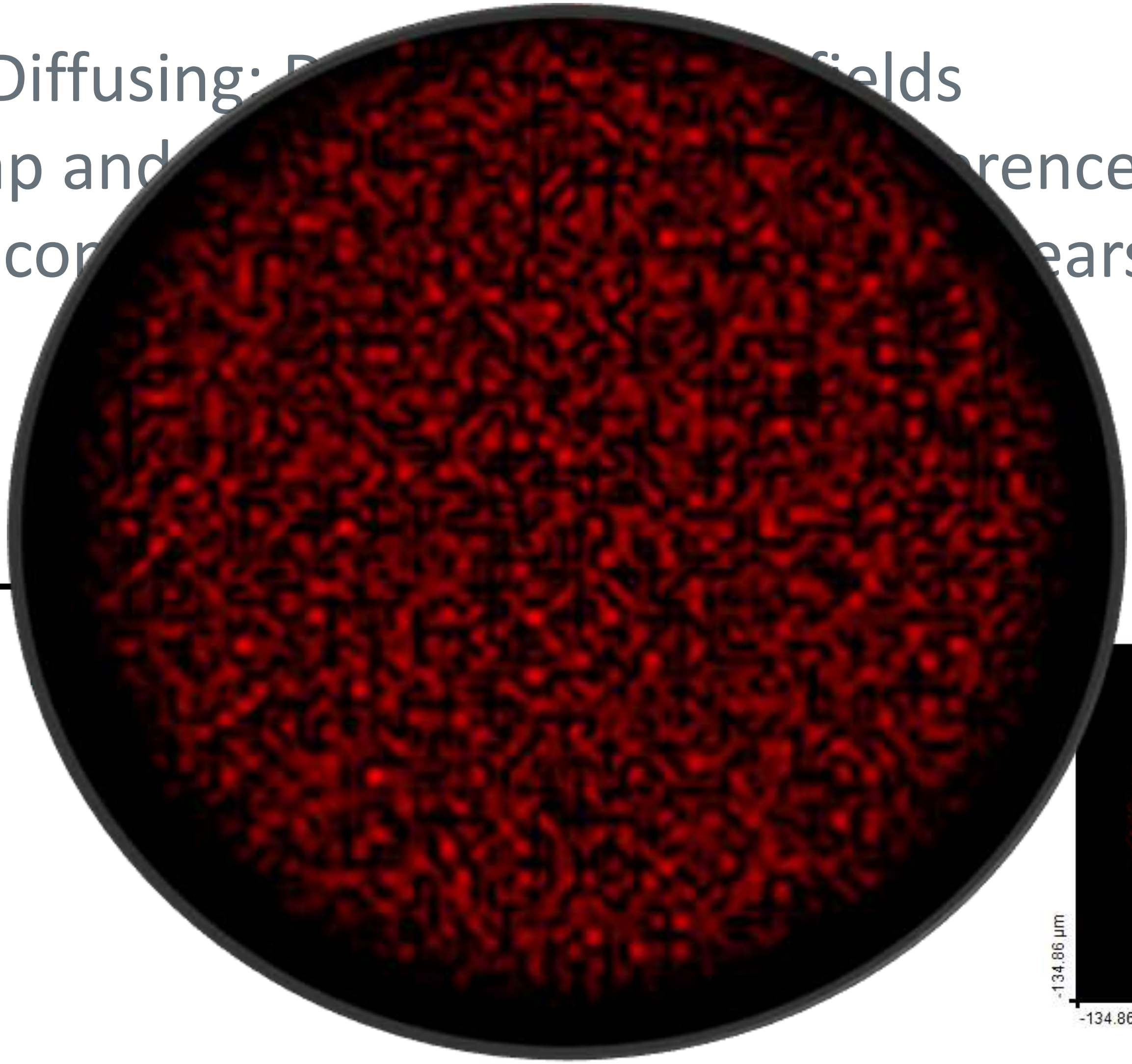
Basic Design Situations: Diffusing

Light Diffusing: Deflected output fields overlap and (partially) coherent interference is not controlled but speckle pattern appears



Basic Design Situations: Diffusing

Light Diffusing: D… fields
overlap and … erence
is not co… ears.



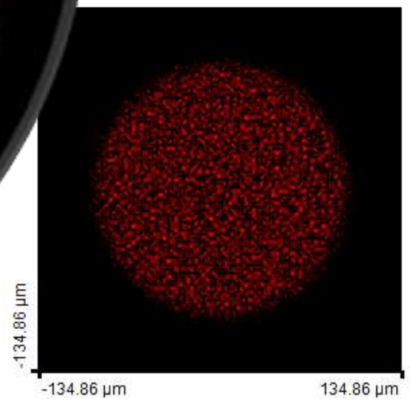


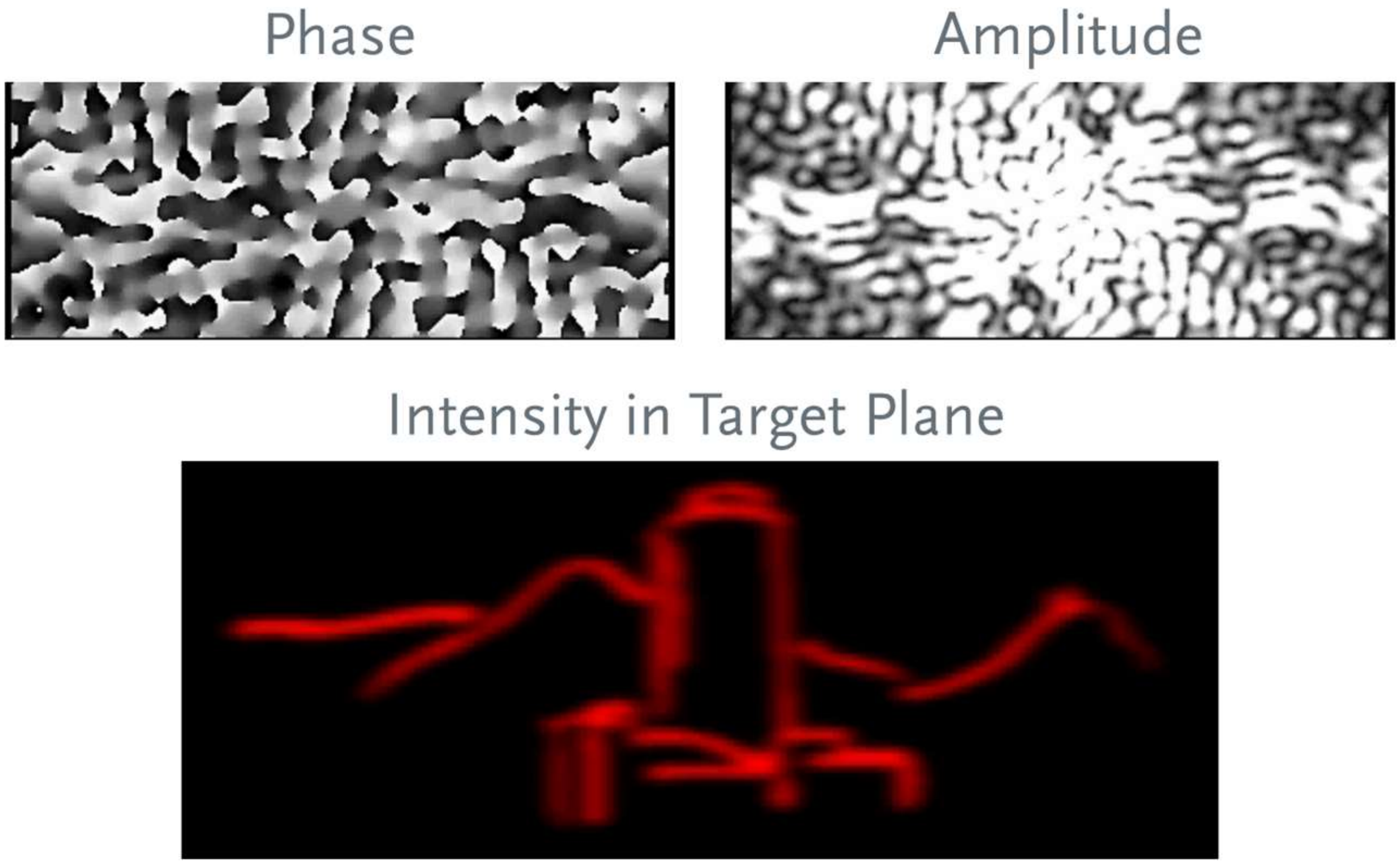
Illustration of Diffuser Concept

Phase

Amplitude

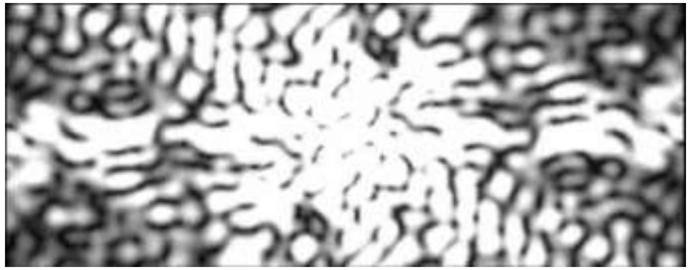
Intensity in Target Plane

Illustration of Diffuser Concept

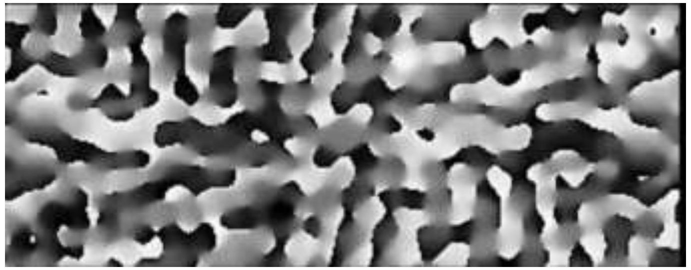


Light Diffusing

Amplitude

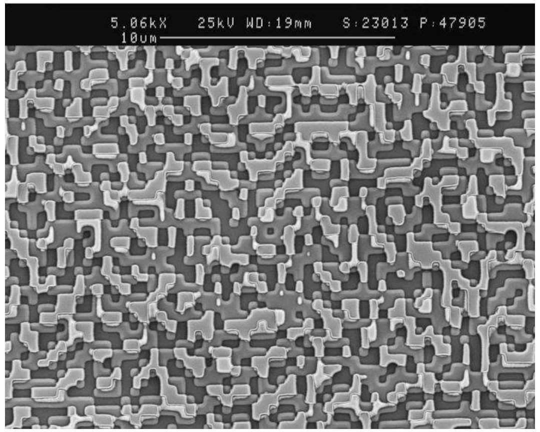


Phase



Advanced diffractive optics design techniques

Design technique (IFTA) implemented in VirtualLab™



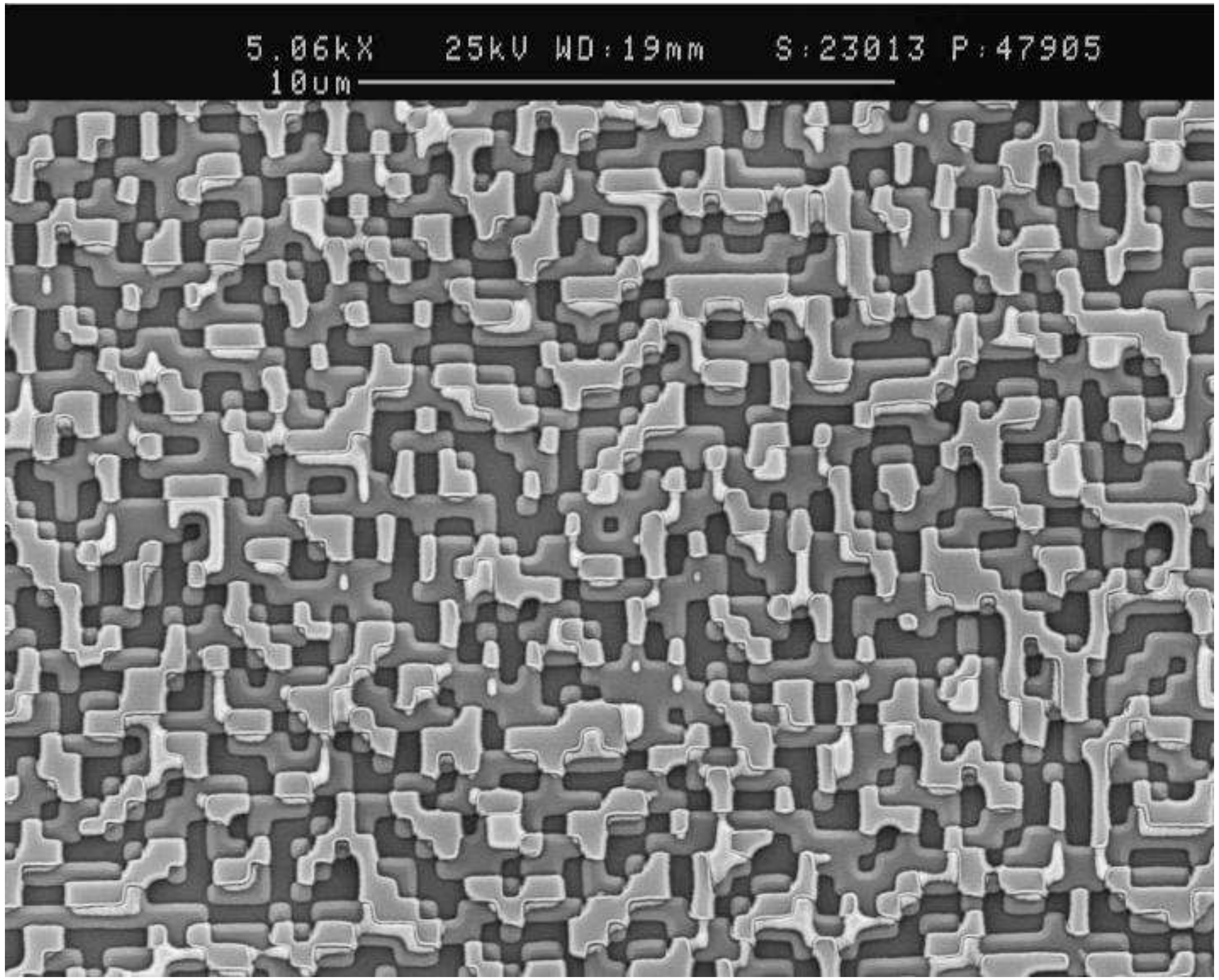
Micro-structured surface profile

Fabricated at IAP, University of Jena

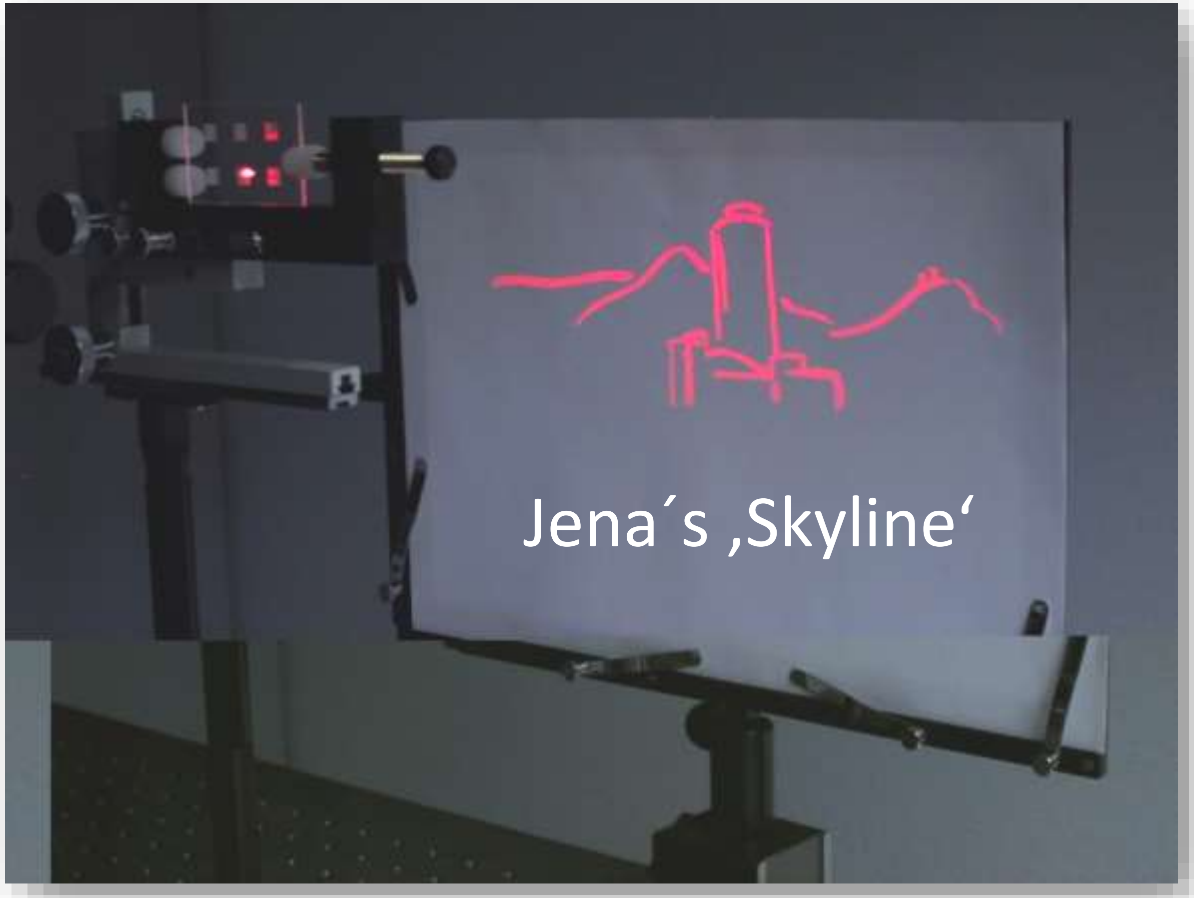
Feature Sizes of Element

Feature size
about 400 nm

4 height levels

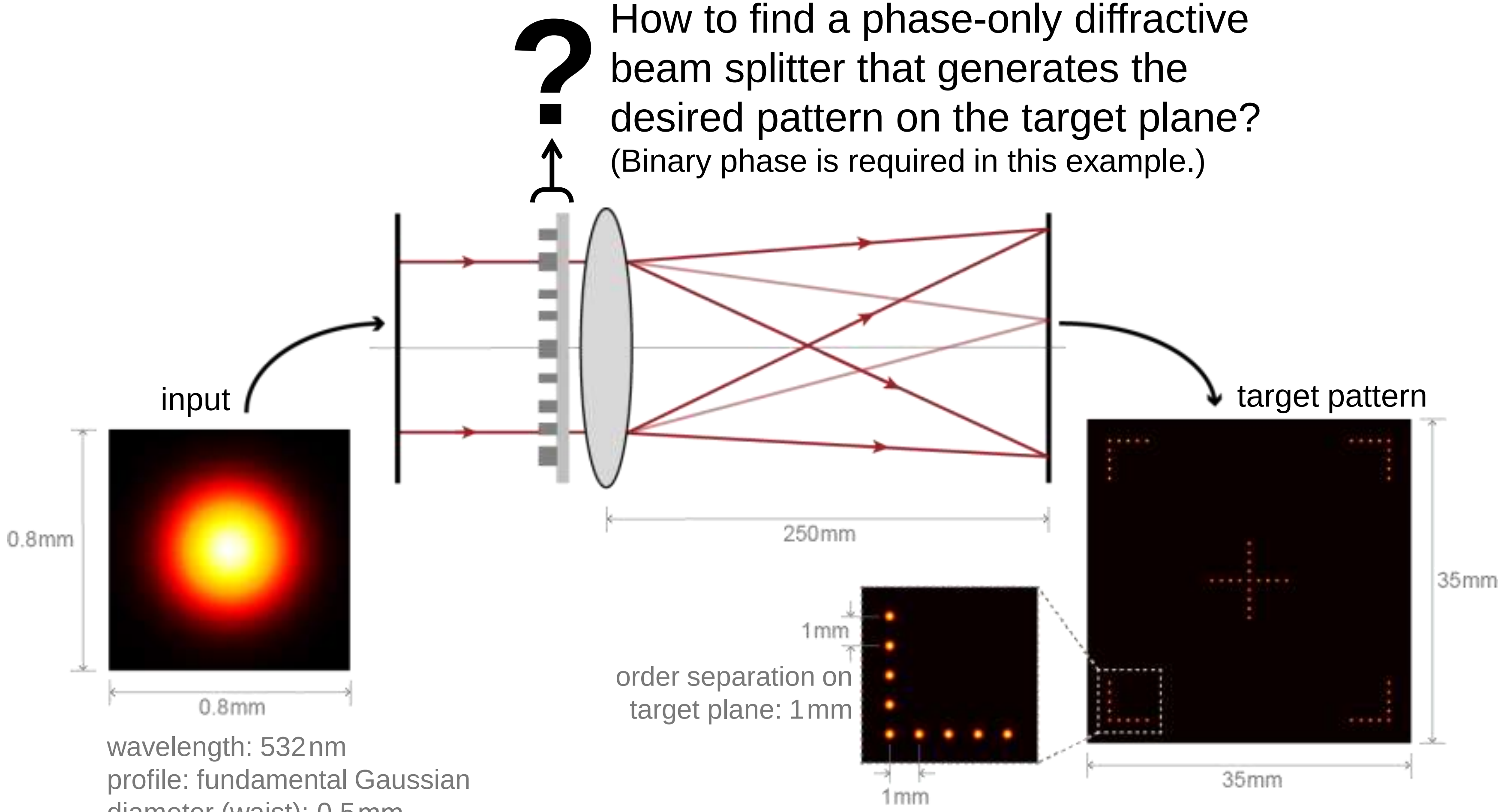


Optical Experiment



Task8_BeamSplitter

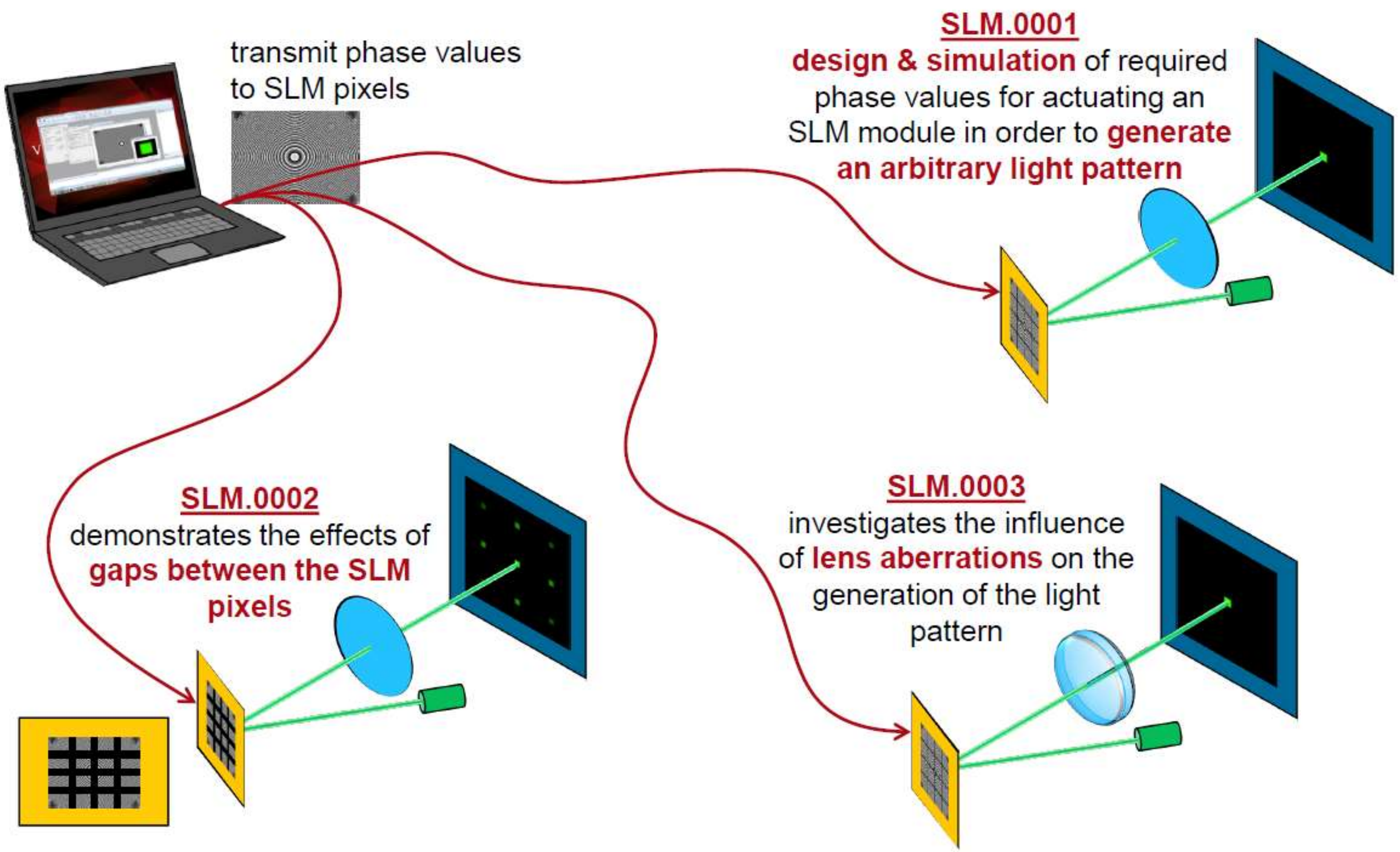
How to find a phase-only diffractive beam splitter that generates the desired pattern on the target plane?
(Binary phase is required in this example.)



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

Laser Show China

Spatial Light Modulator

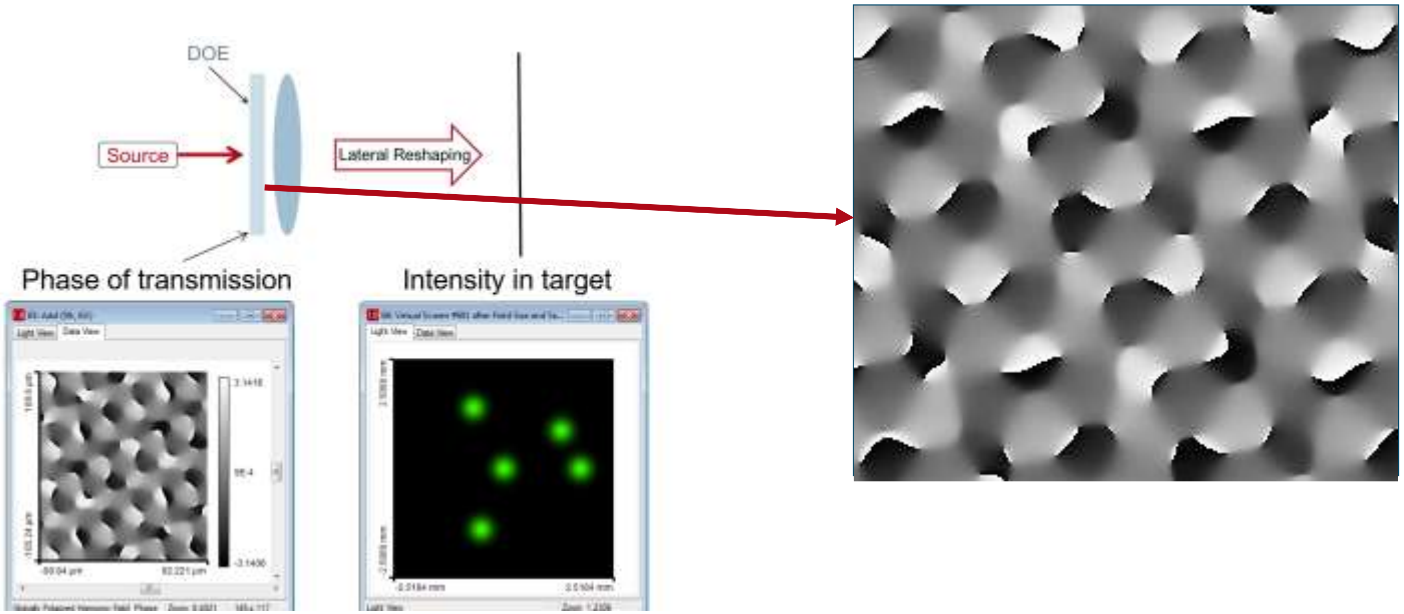


Spatial Light Modulator

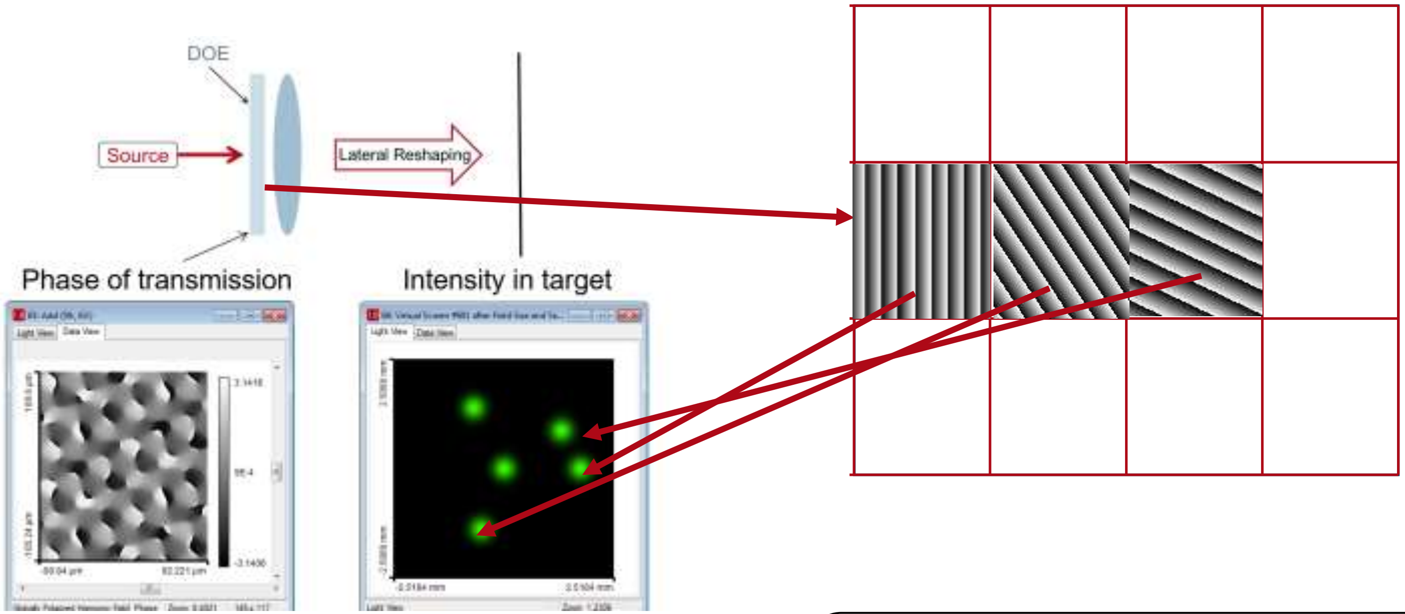
Light shaping by multichannel concept

Diffractive and refractive optical elements

Array of Deflectors

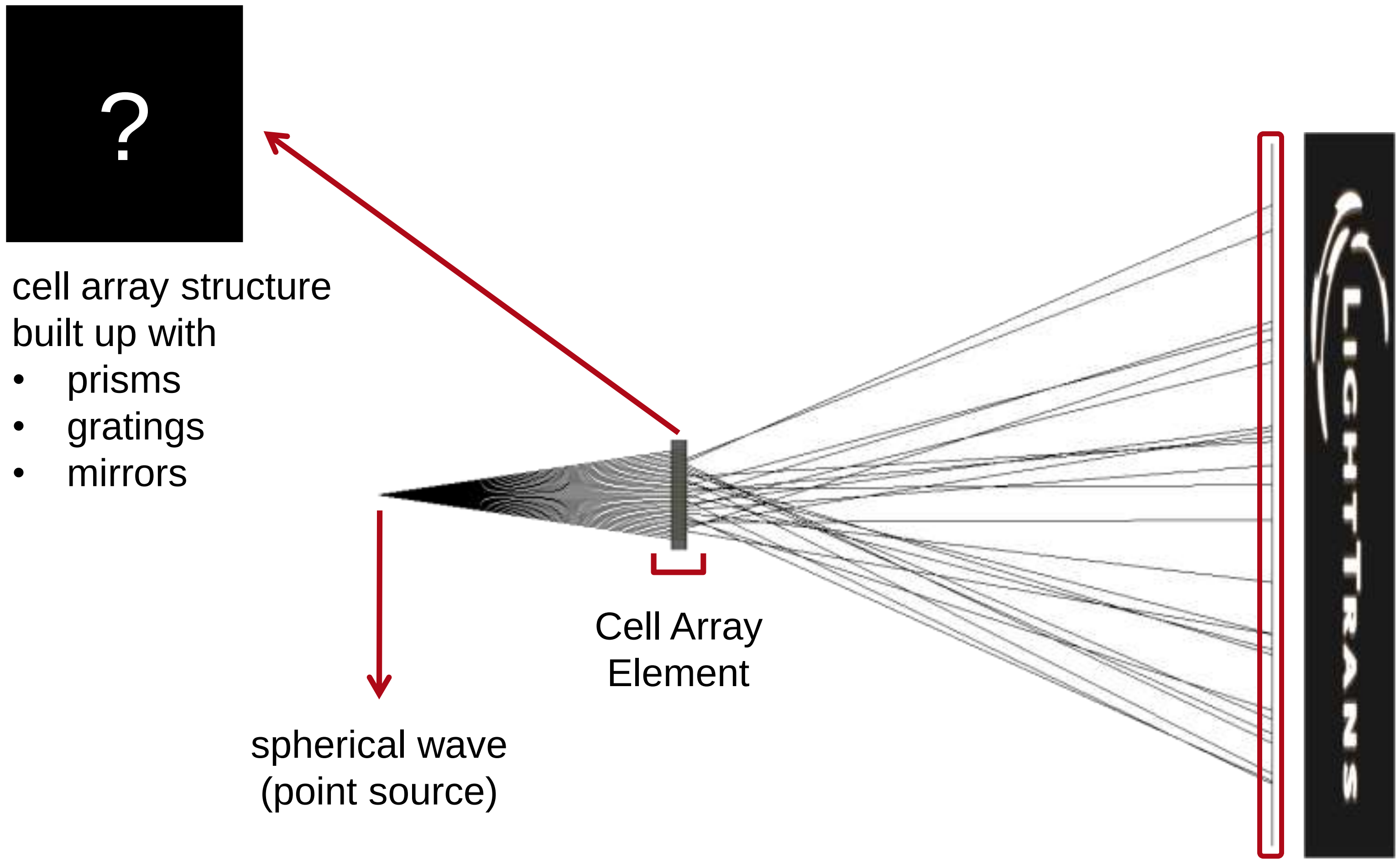


Array of Deflectors

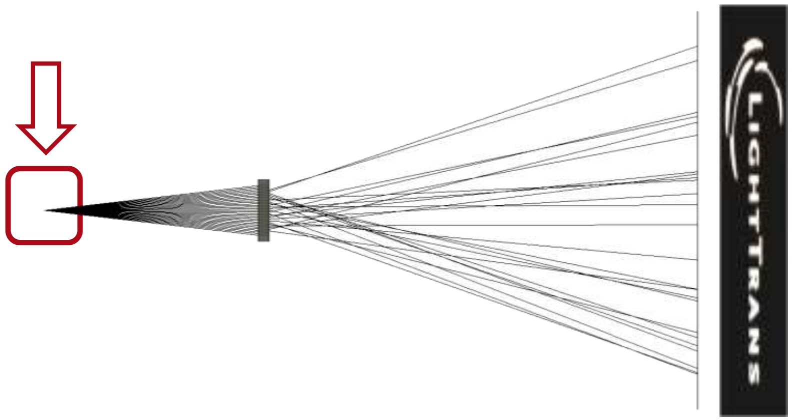


Deflection can be done by gratings, prisms, mirrors.

Task/System Illustration

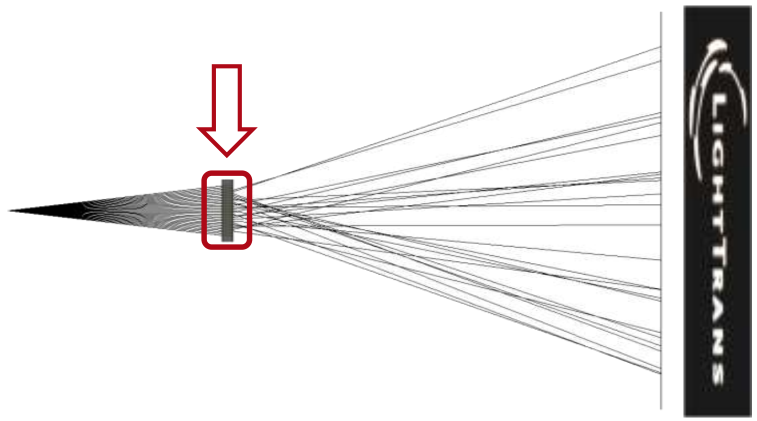


Specification: Light Source



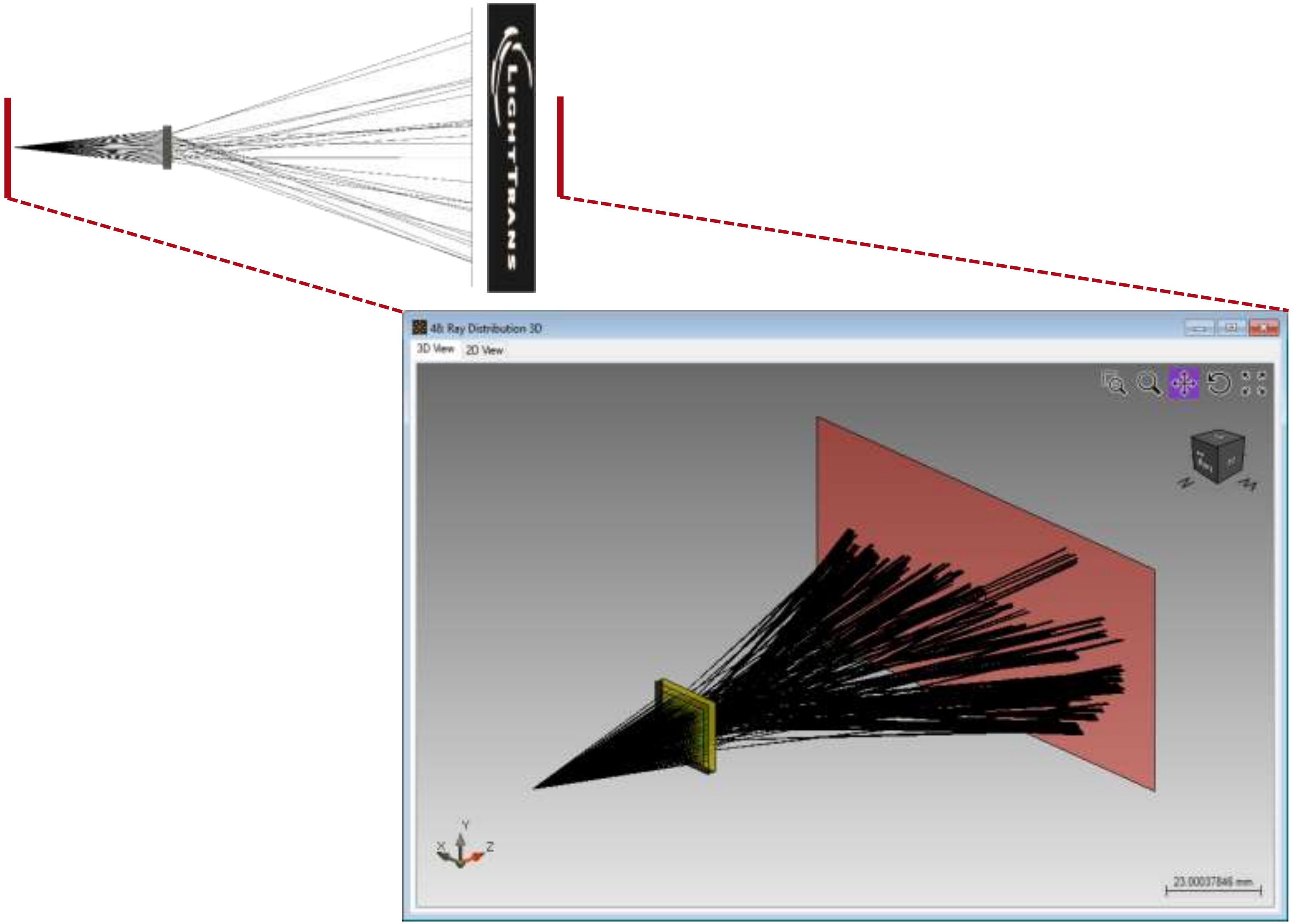
Parameter	Description / Value & Unit
type	RGB LED
emitter size	100x100µm
wavelength	(473, 532, 635)nm
polarization	right circularly polarized light
number of lateral modes	3x3
Total number of lateral and spectral modes	27

Specification: Cell Array

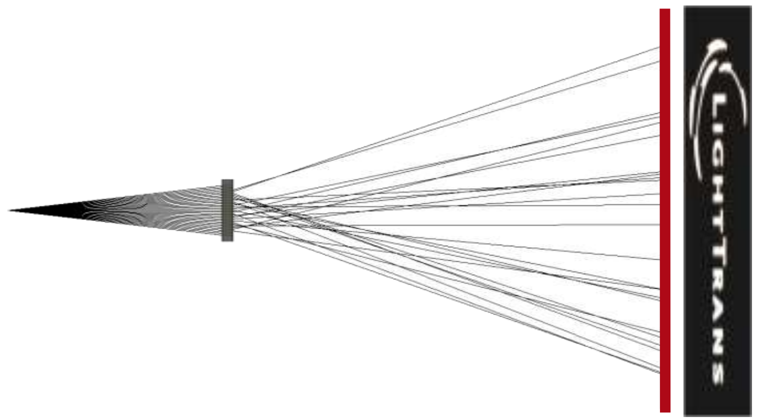


Parameter	Value & Unit
number of cells	100x100
cell size	125x125µm
array aperture	12.5x12.5mm

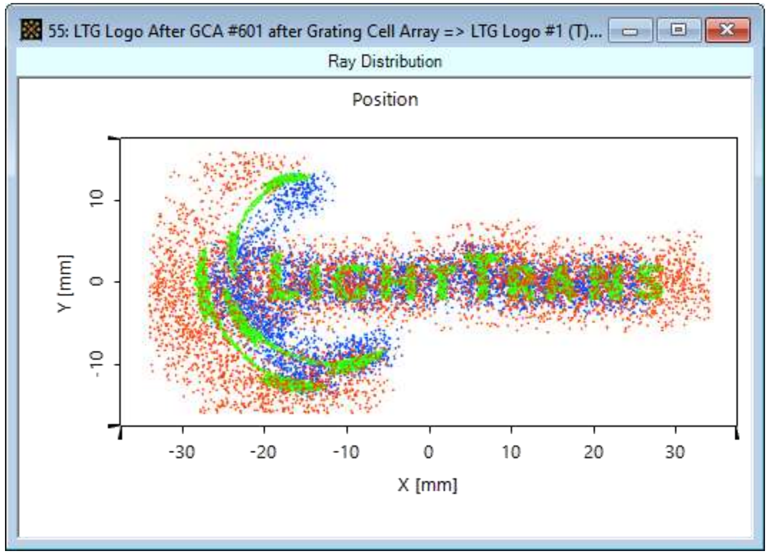
Results: 3D System Ray Tracing

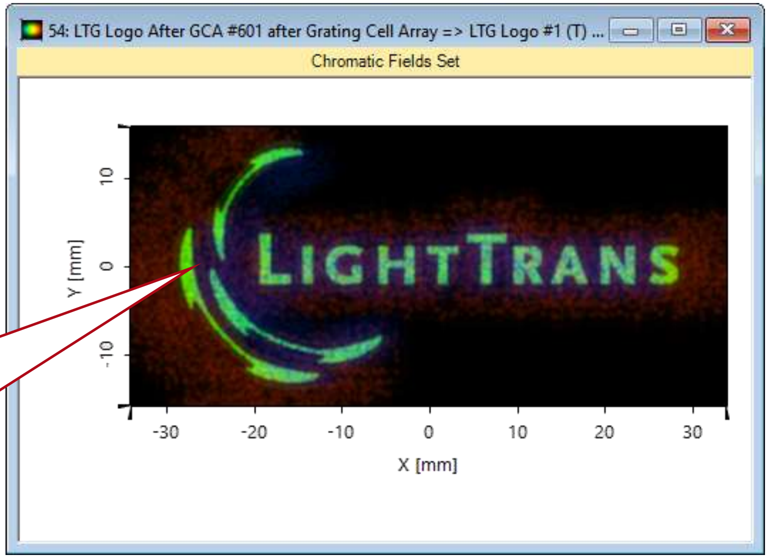


Results: Grating Cells Array



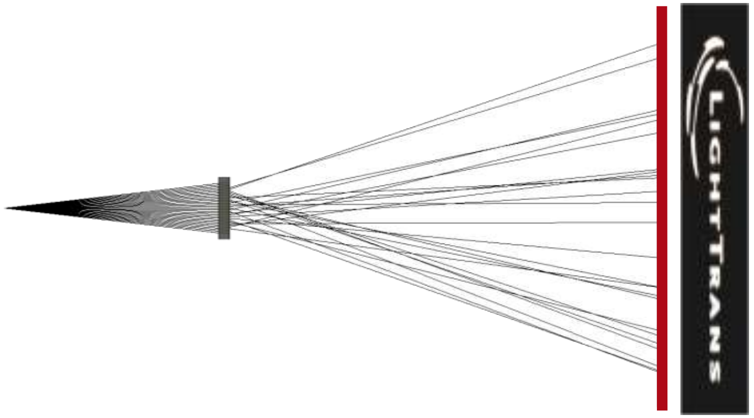
spot diagram



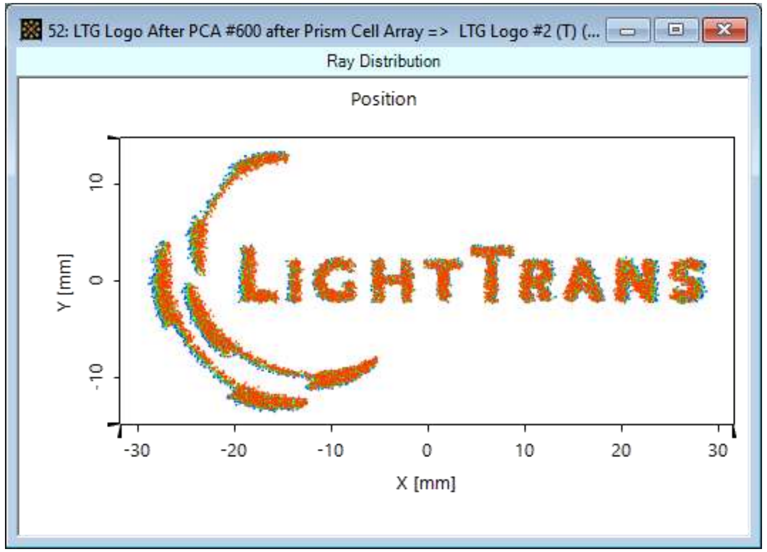


for grating cells array strong dispersion effects occur

Results: Prism Cells Array

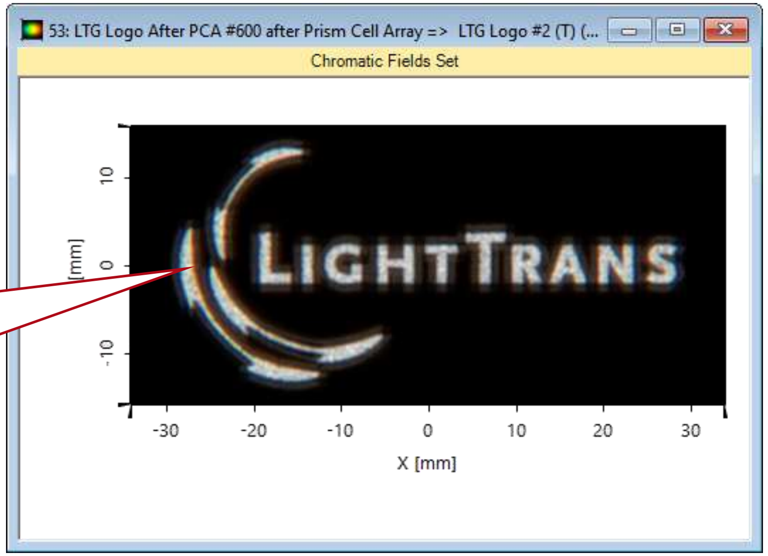


spot diagram



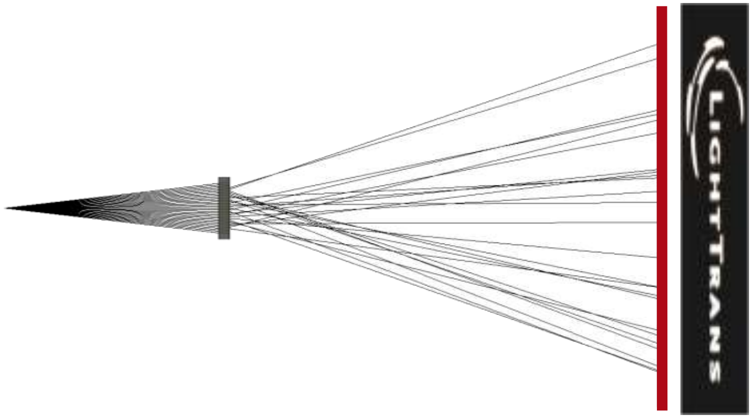
pattern

(real lor view)

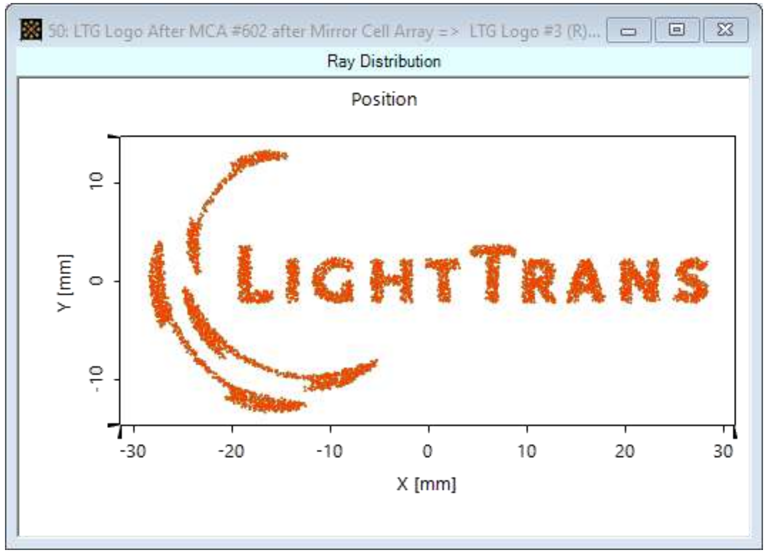


the dispersion is significantly reduced by using prisms

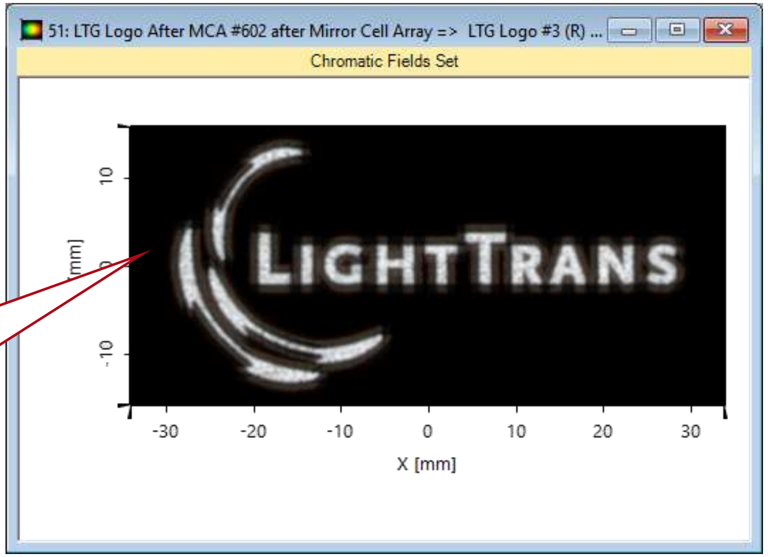
Results: Mirror Cells Array



spot diagram



y pattern
(rea
olor view)

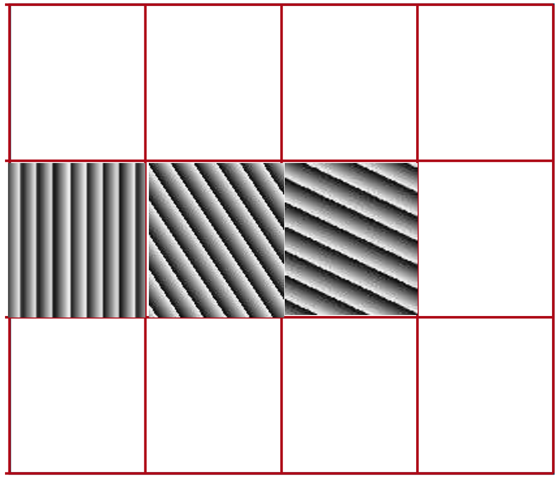


due to reflective approach no dispersion effects occur

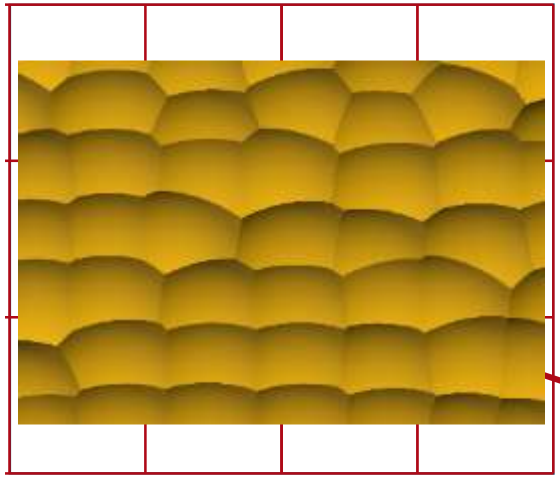
Light shaping by arrays of microoptical components

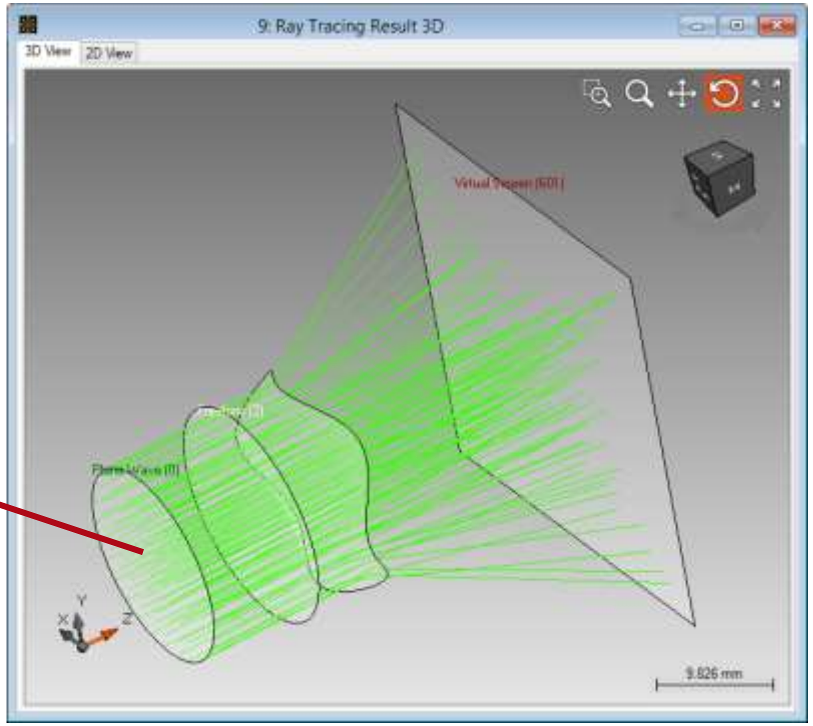
Diffractive and refractive optical elements

Array of Microoptical Components



Array of Microoptical Components

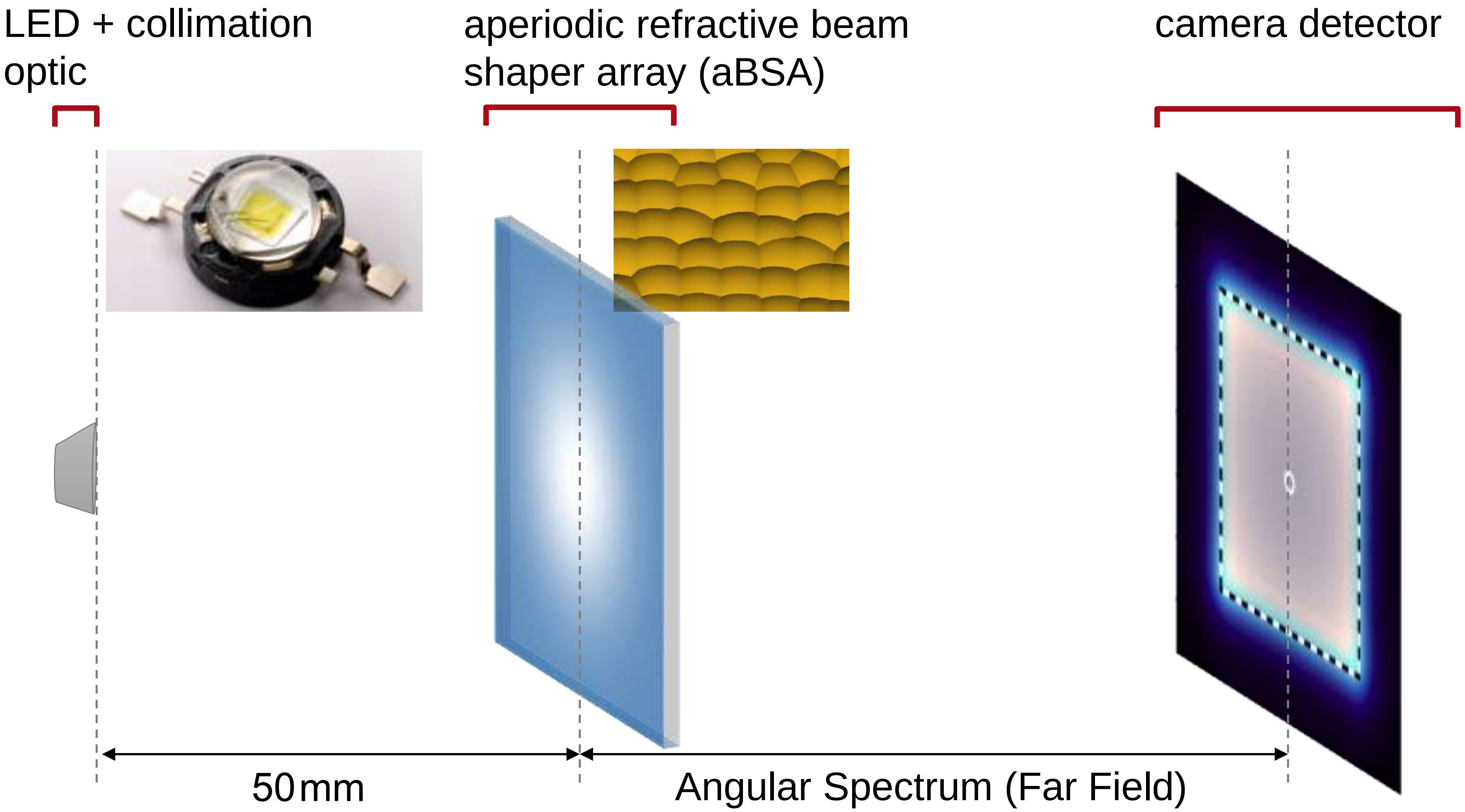




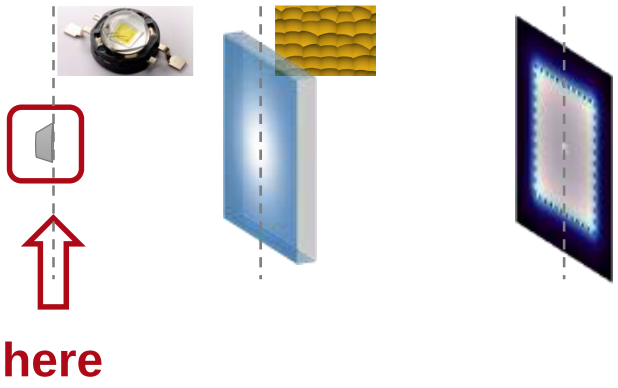
Light Shaping > Aperiodic Microlens Array

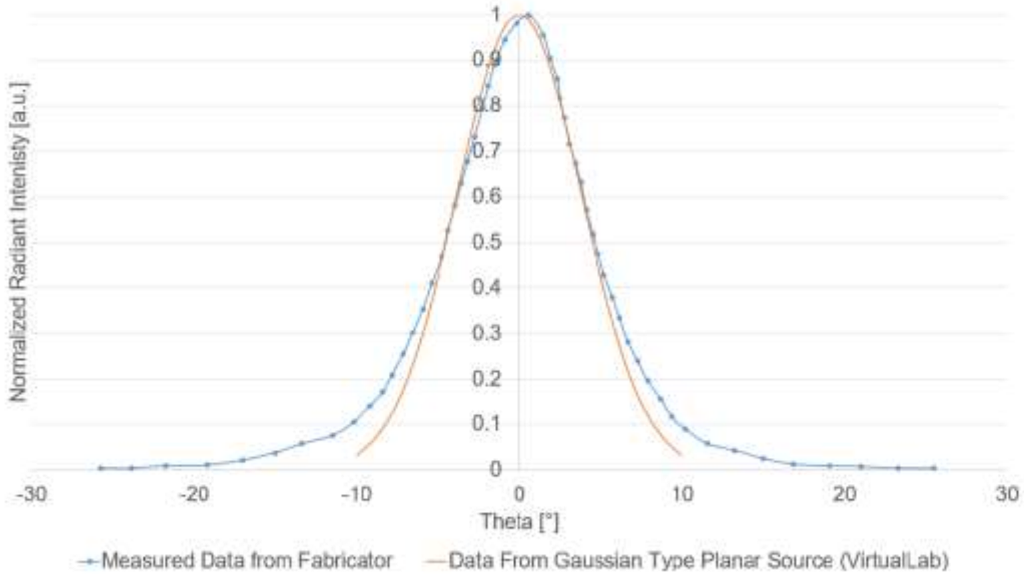
LED Top Hat Generation using Aperiodic Refractive Beam Shaper Array

Task/System Illustration



Specs: Light Source

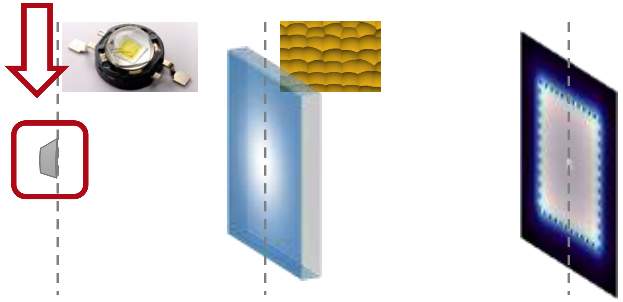




Parameter	Description / Value & Unit
name/type	Seoul Z-LED P4 from Seoul Semiconductors
partially coherent source type	Gaussian type planar source
collimation	TIR lens from Carclo Optics (part no. 10003)
spectrum	pure white light spectrum
FWHM radiant intensity	9°

Specs: Light Source

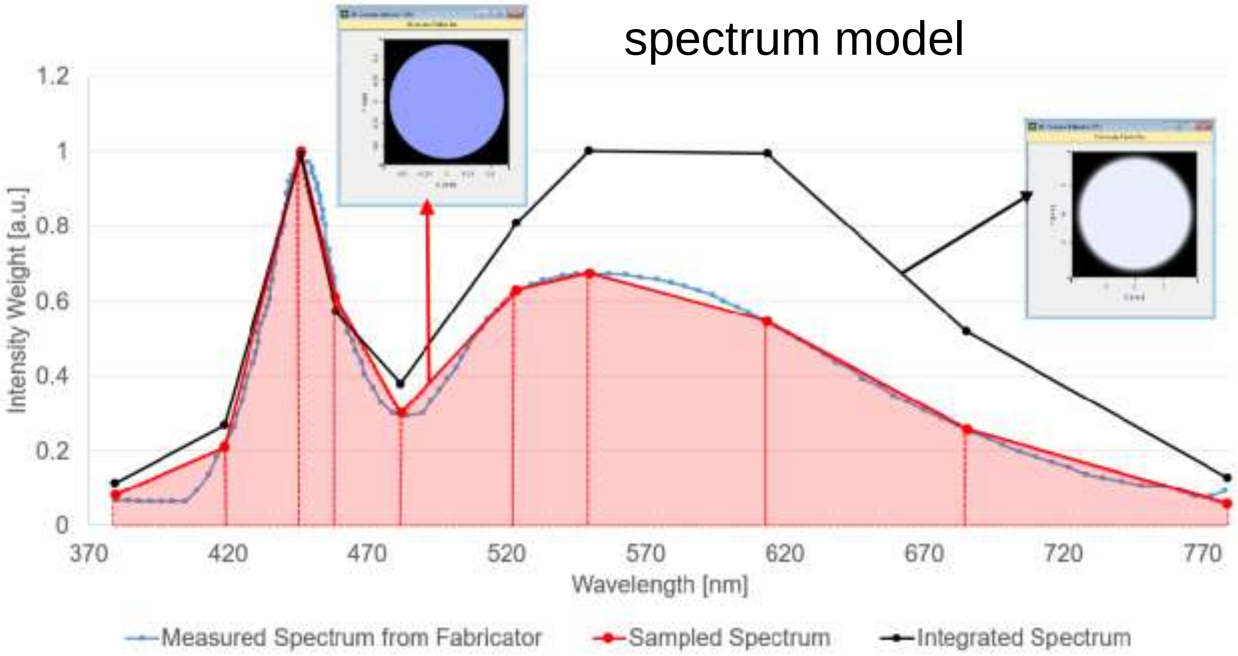
here



Highlights

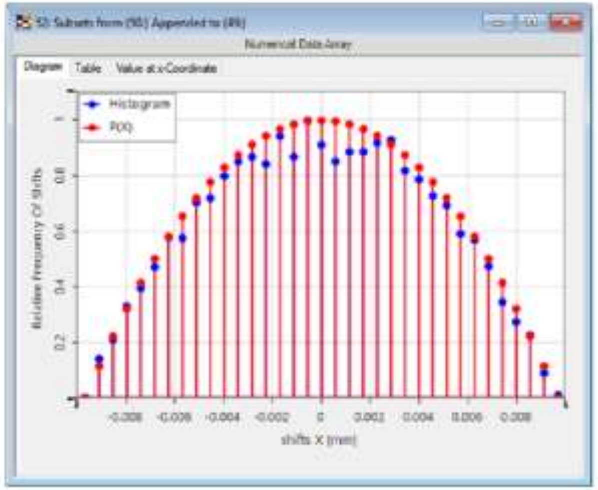
- fast and accurate modeling of a white light LED
- design and analysis an aperiodic refractive beam shaper array to optimize a top hat intensity pattern

spectrum model

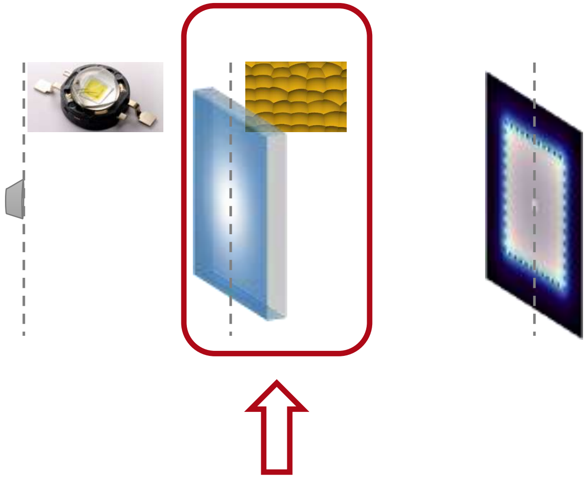


significant performance improvement
non-equidistant sampling of the spectrum

Specs: Aperiodic Refractive Beam Shaper Array



Histogram of Cell Distribution Function



here

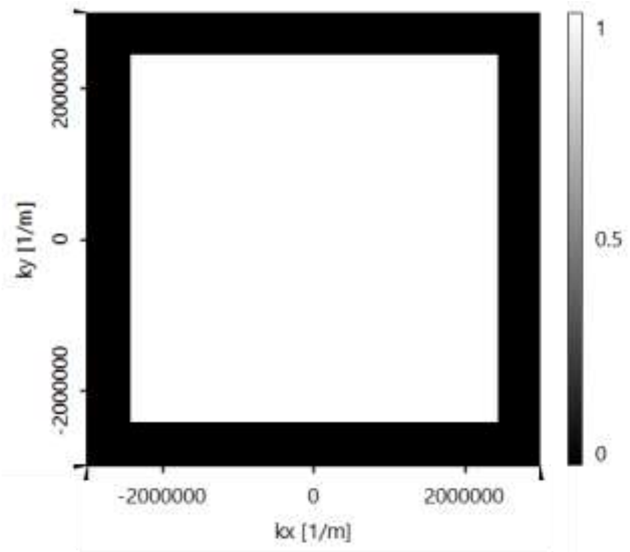
Parameter	Description / Value & Unit
cell array aperture	20x20 mm
number of cells	124x124
cell distribution function	quadratic polynomial
substrate thickness	1 mm
substrate material	fused silica

Highlights

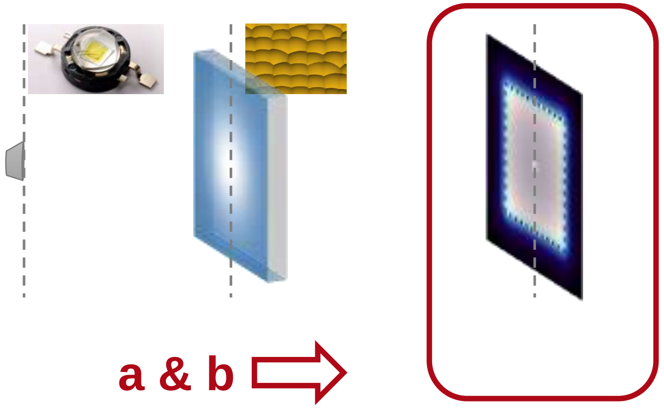
- fast and accurate modeling of a white light LED
- design and analysis an aperiodic refractive beam shaper array to optimize a top hat intensity pattern

parametrization of the distribution function allows optimization regarding a desired target pattern

Specs: Evaluation

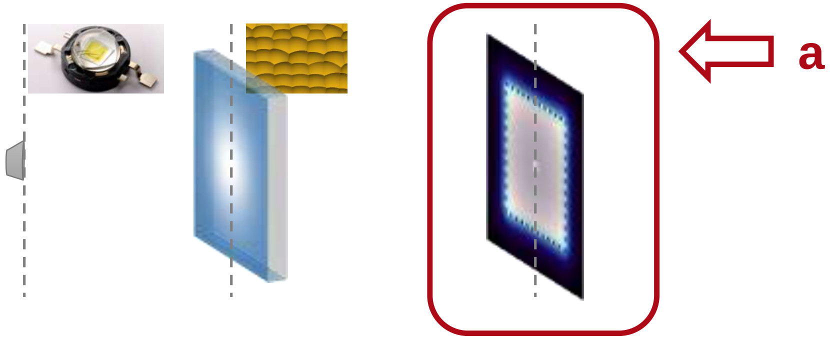


Desired Target Pattern



Position	Type of Evaluation	Description / Value & Unit
a	camera detector	evaluates intensity pattern
b	performance criteria evaluation	evaluates conversion & window efficiency and uniformity error regarding the desired target pattern

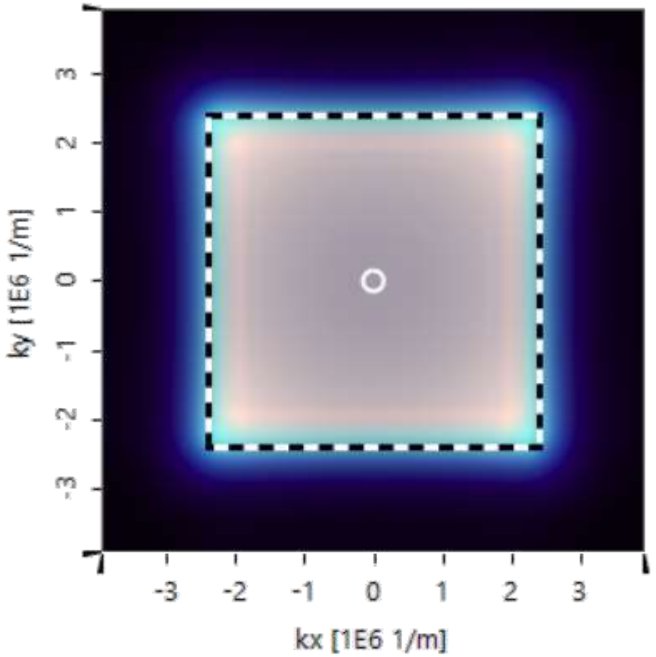
Results: Intensity Pattern (real color view)



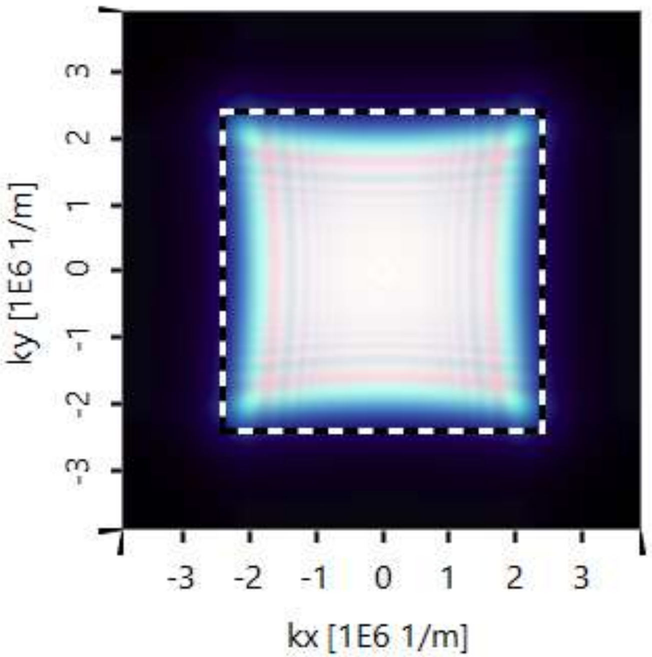
Highlights

- fast and accurate modeling of a white light LED
- design and analysis an aperiodic refractive beam shaper array to optimize a top hat intensity pattern

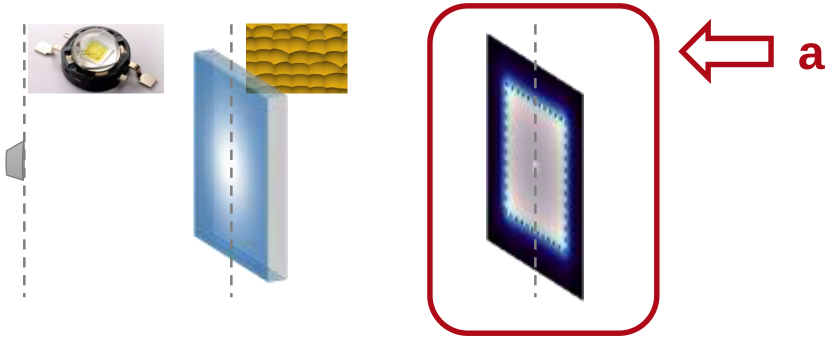
aperiodic beam shaper array



periodic microlens array



Results: Performance Criteria Evaluation



Highlights

- fast and accurate modeling of a white light LED
- design and analysis an aperiodic refractive beam shaper array to optimize a top hat intensity pattern

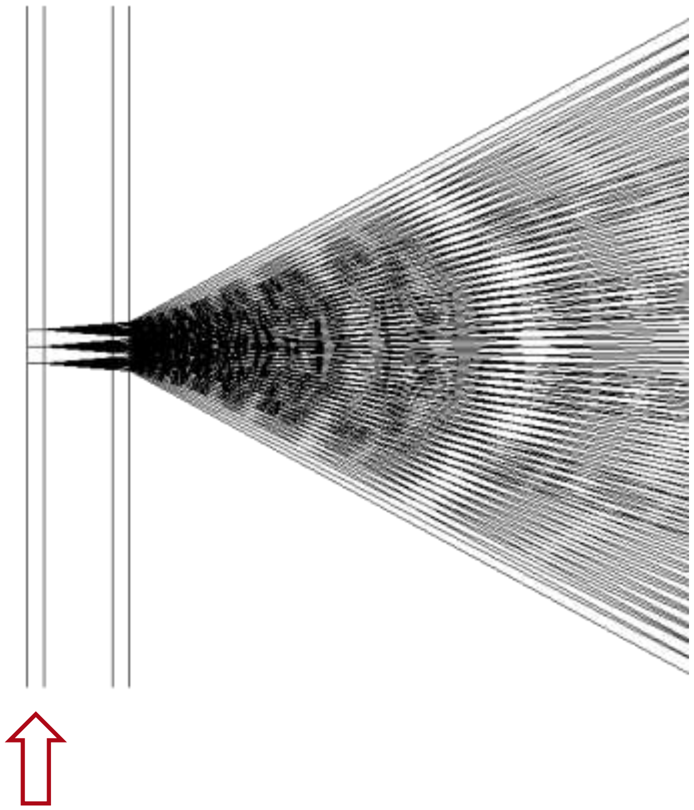
Parameter	Value & Unit Aperiodic Beam Shaper Array	Value & Unit Microlens Array
window efficiency	92.23 %	99.93 %
conversion efficiency	89.34 %	80.18 %
uniformity error	17.92 %	49.08 %

Virtual And Mixed Reality > Pattern Generation

High-NA Pattern Generation Using Two Beam Splitter Elements

LightTrans International UG

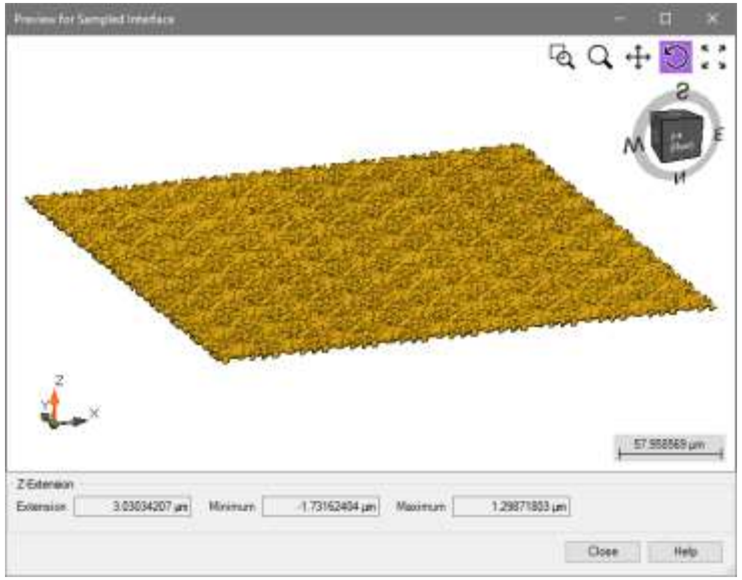
Specification: First Beam Splitter



paraxial beam splitter

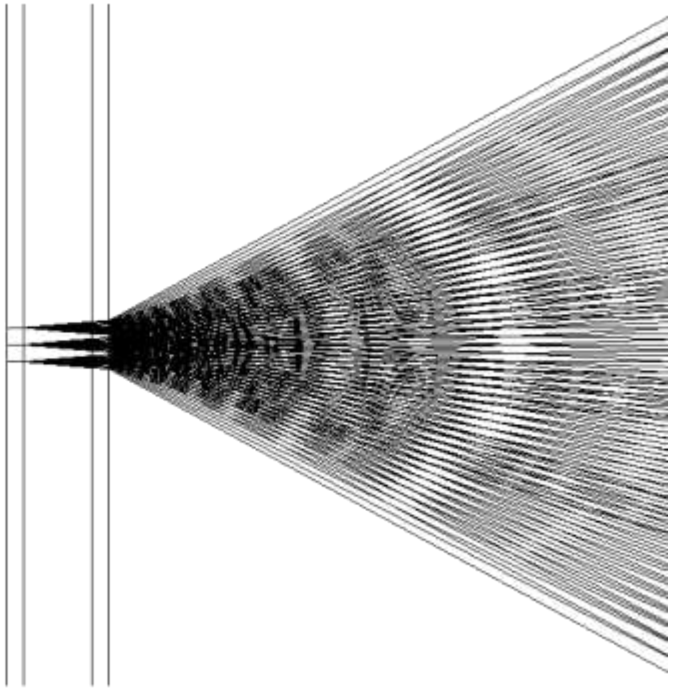
Parameter	Value & Unit
number of orders	11x11
order separation	1x1°
period	30.35x30.35µm
pixel size	690x690nm
discrete height levels	8
material	fused silica

surface profile

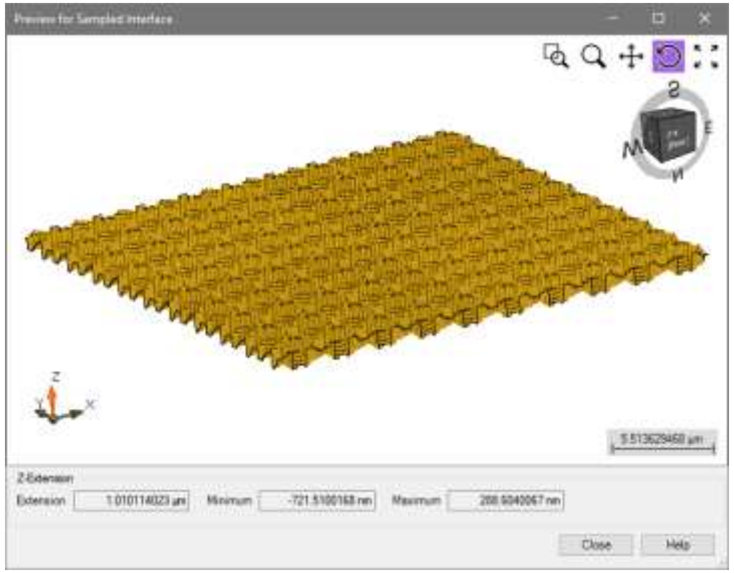


Specification: Second Beam Splitter

Parameter	Value & Unit
number of orders	5x5
order separation	11x11°
period	2.73x2.73µm
pixel size	130x130nm
discrete height levels	8
material	fused silica

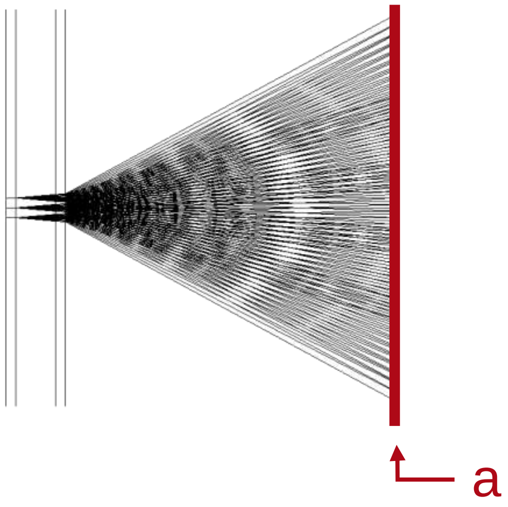


high-NA beam splitter

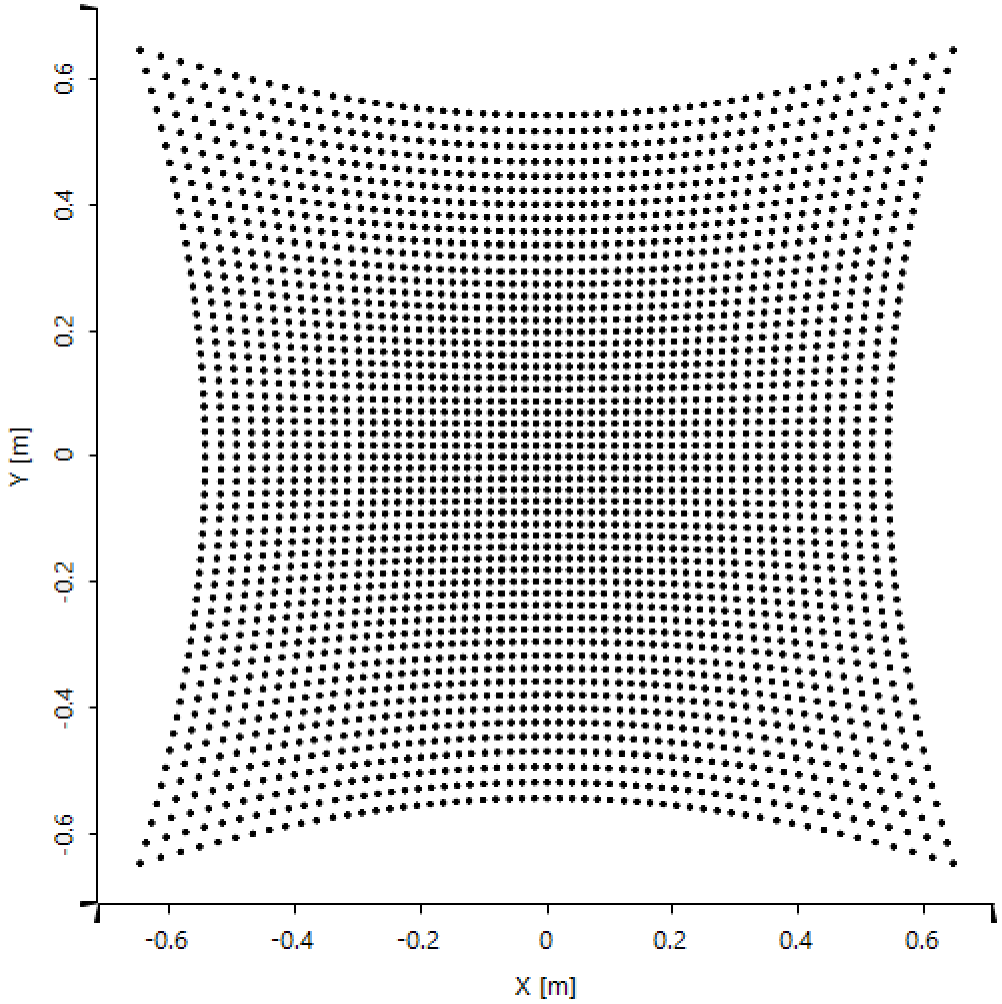


surface profile

Results: Spot Diagram

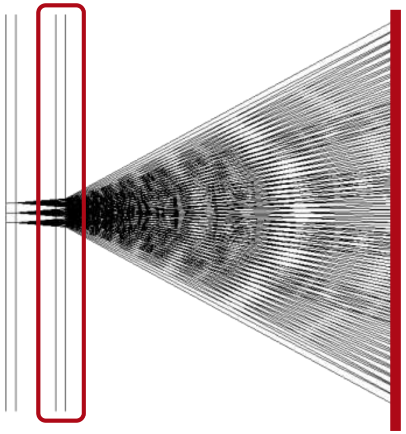


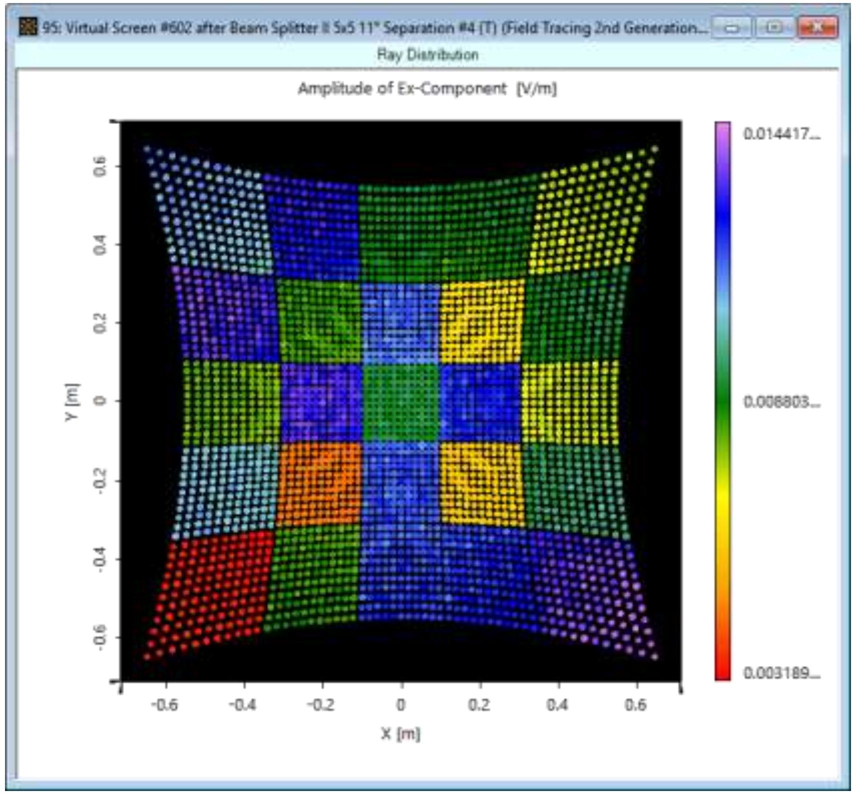
combination of both beam splitter generate **55x55 order** with **55x55° full opening spread**



spot diagram

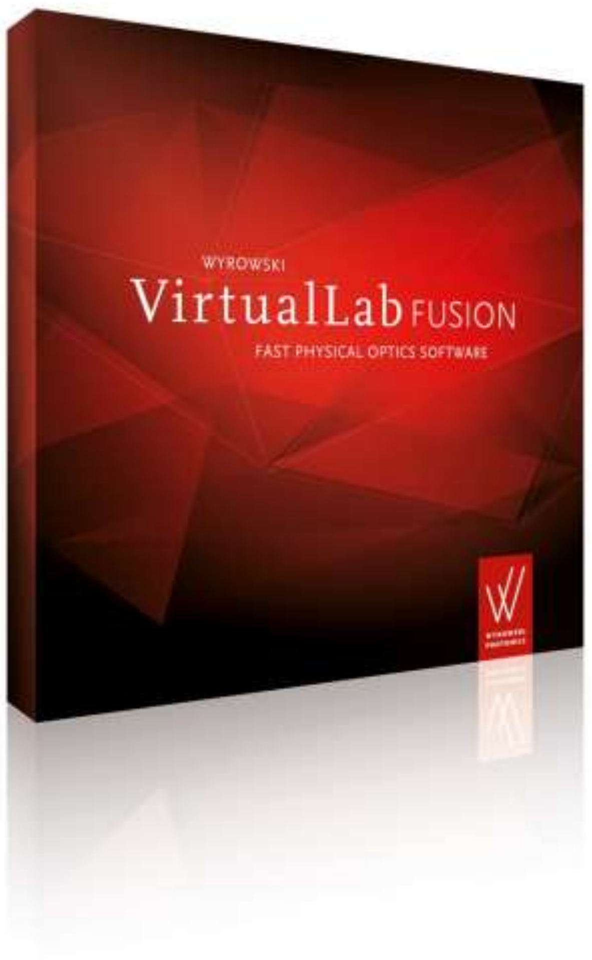
Results: Output Evaluation





Light Shaping Concepts

- Tailored aberrations
- Stored scanning process
- Multichannel concept: Single Deflection
- Multichannel concept: General



Now, let‘s start from design of beam splitter by using IFTA

IFTA Concept

Iterative Fourier Transformation Algorithm

IFTA Approach

- The Iterative Fourier Transform Algorithm (IFTA) represents a very efficient optimization method for the design and optimization of diffractive optical elements (DOEs).
- Compared to a parametric optimization approach the IFTA has the advantage that a much larger number of degrees of freedom can be used. Pratically each sampling point of the DOE is considered as such and is optimized.

Optimization of Diffractive Optical Elements

Introduction to Iterative Fourier Transform Algorithm

Design Option

VirtualLab provides different methods for designs and optimizations.

E.g. via

- Parametric Optimization
- Iterative Fourier Transformation Algorithm (IFTA)
- Cells Array Approaches
- Inverse Design

Iterative Fourier Transform Algorithm

For the design and optimization of the following diffractive optical element (DOE) types

- beam splitters
- light diffusers
- beam shapers

a well established method poses the Iterative Fourier Transformation Algorithm (IFTA).

VirtualLab provides a strong IFTA optimization document with many tuning options.

IFTA: Fundamental Design Steps

1. Transmission design → optimization of optical function of optical elements with consideration of special structural constraints of later structure design.

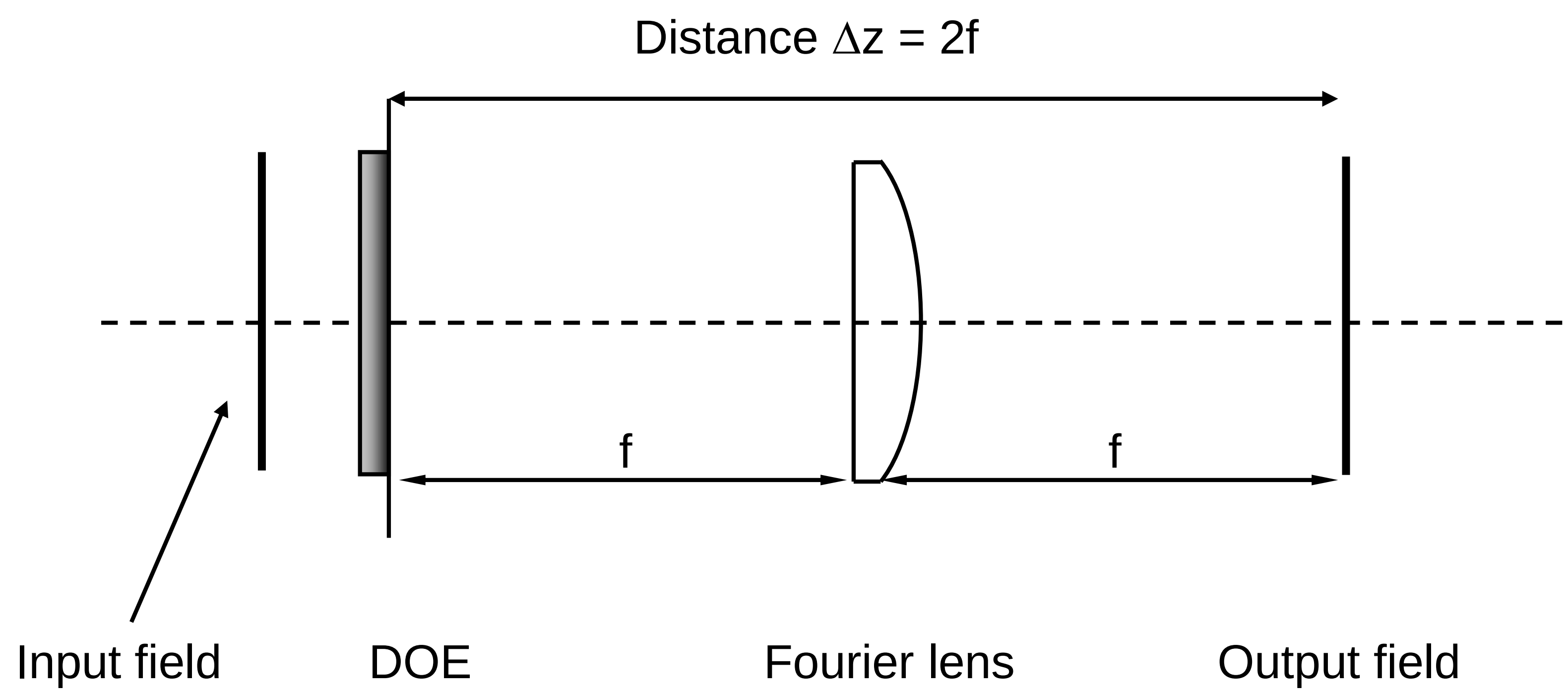
2. Structure design → calculation of structure (surface profile, refractive index distribution) that creates the desired transmission.

The second (structure) step is based on the so-called Thin Element Approximation (TEA) theory. The range of validity for TEA is typically till smallest feature sizes of few times the wavelength.

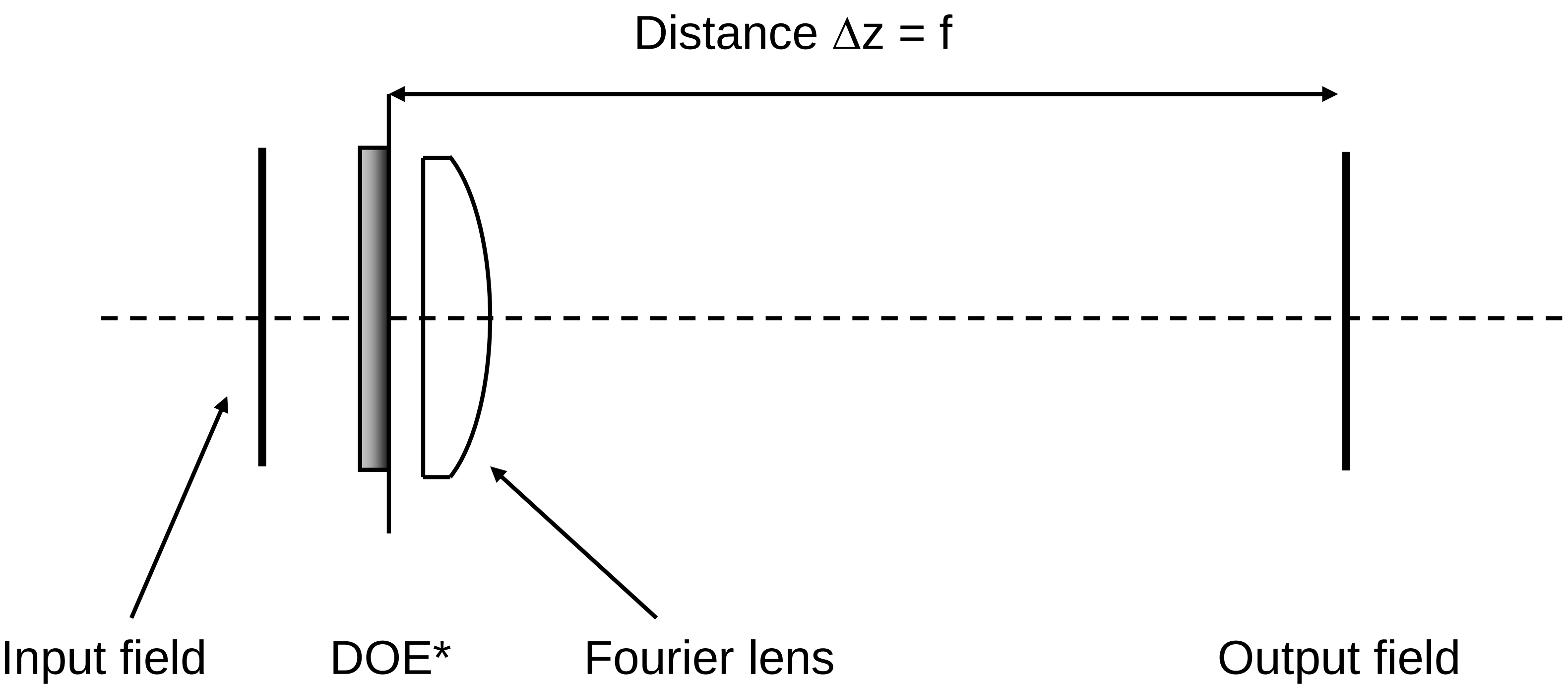
Optimization of Diffractive Optical Elements

Optical Setups

2f-Setup

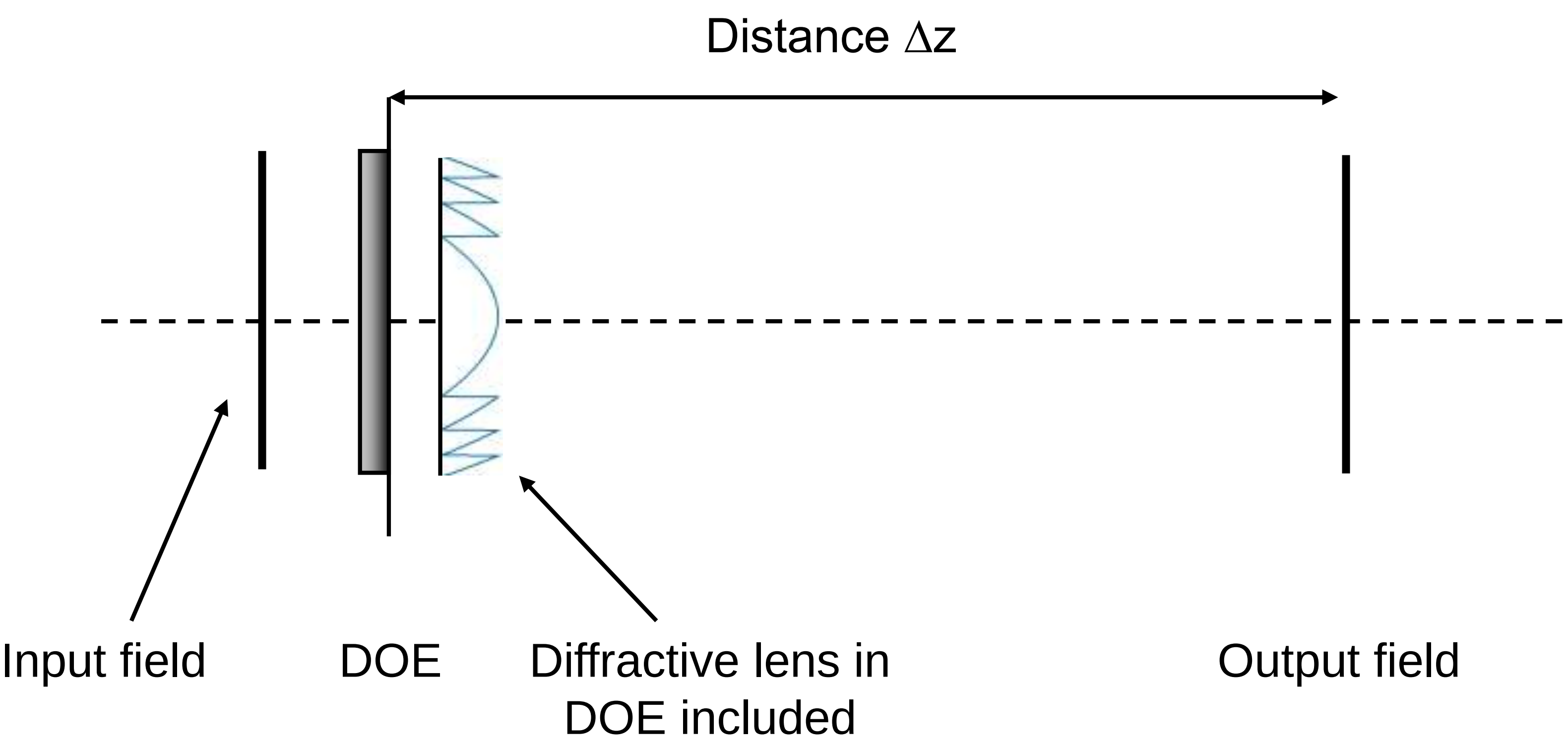


1f-Setup

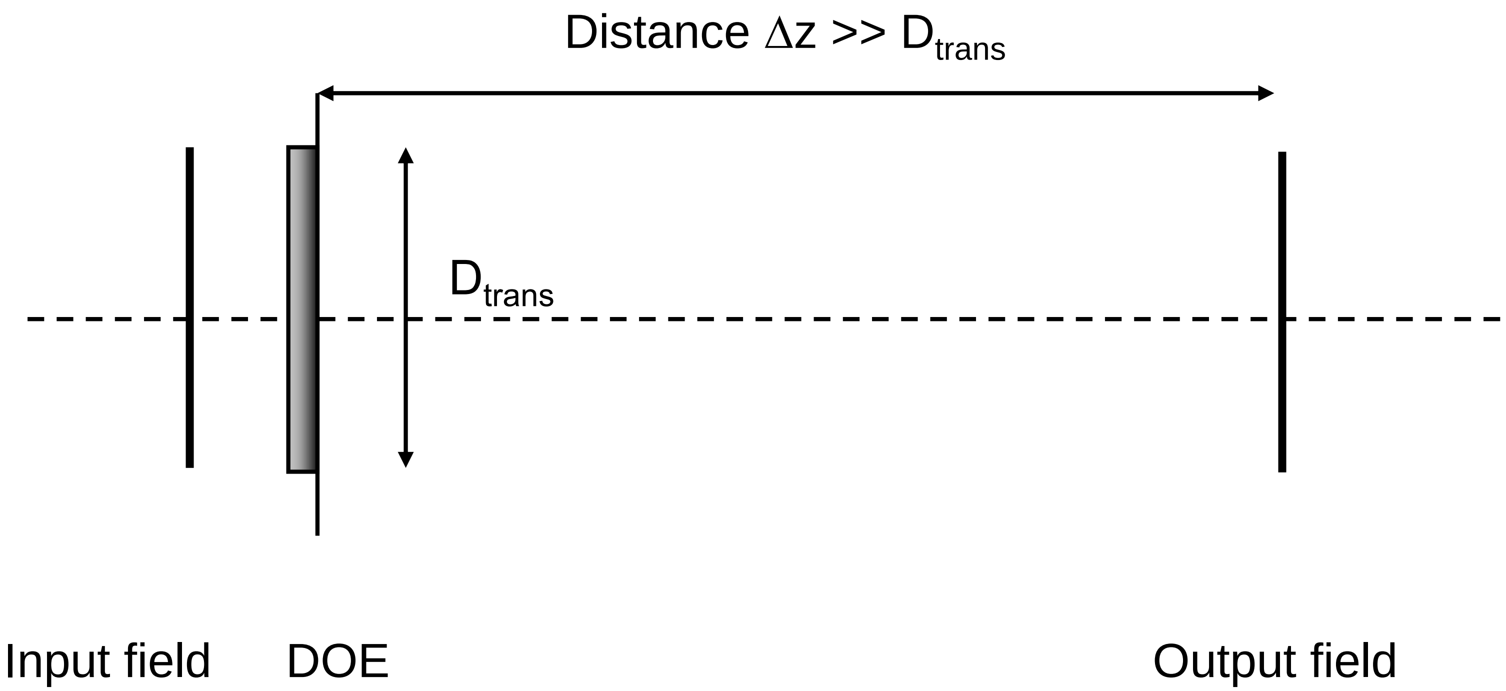


*Swap of DOE and Fourier lens possible

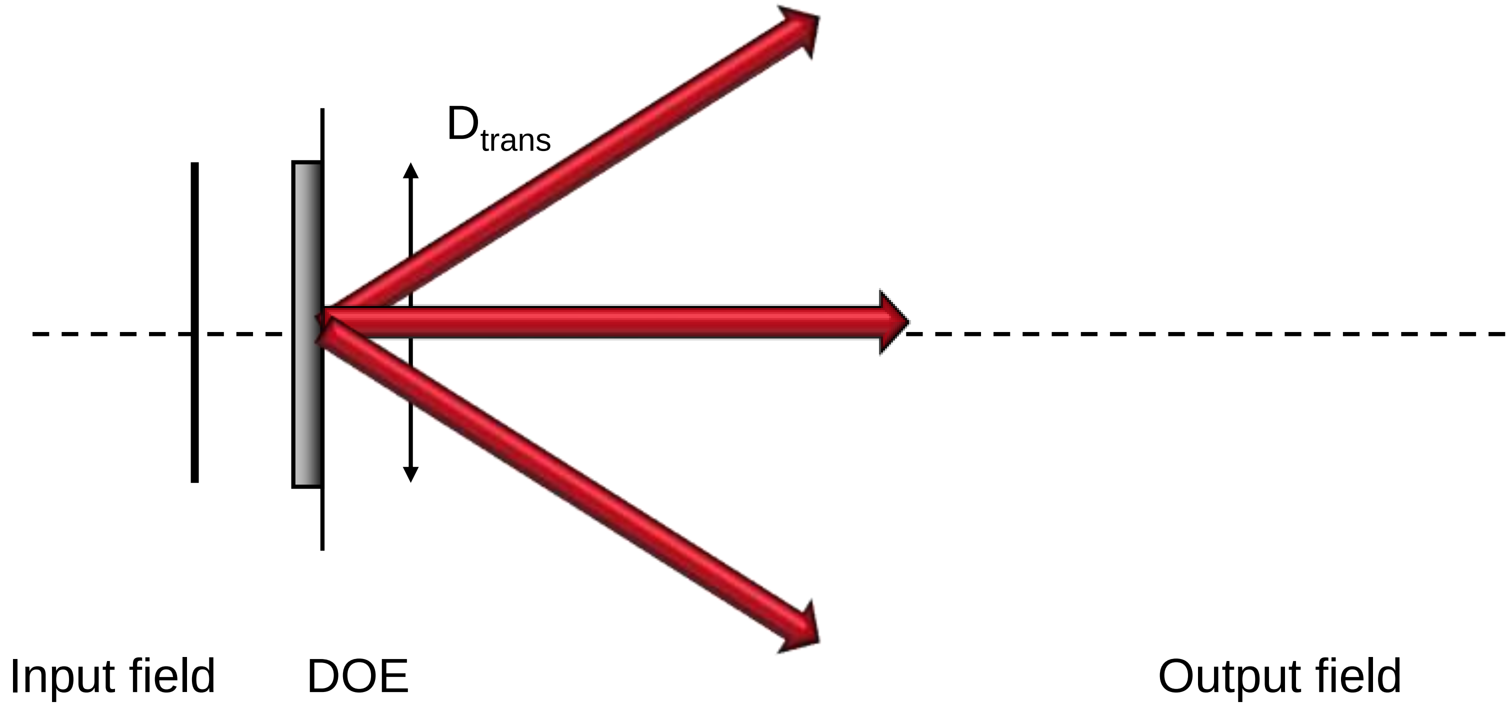
Fresnel Setup



Far Field



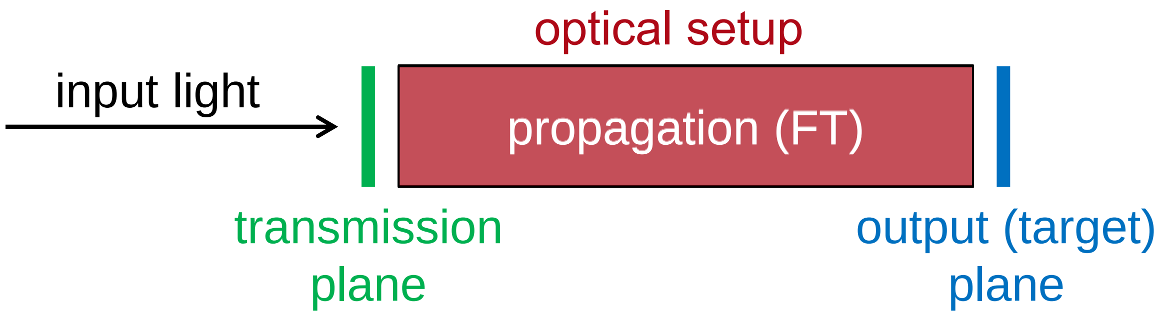
Angular Spectrum

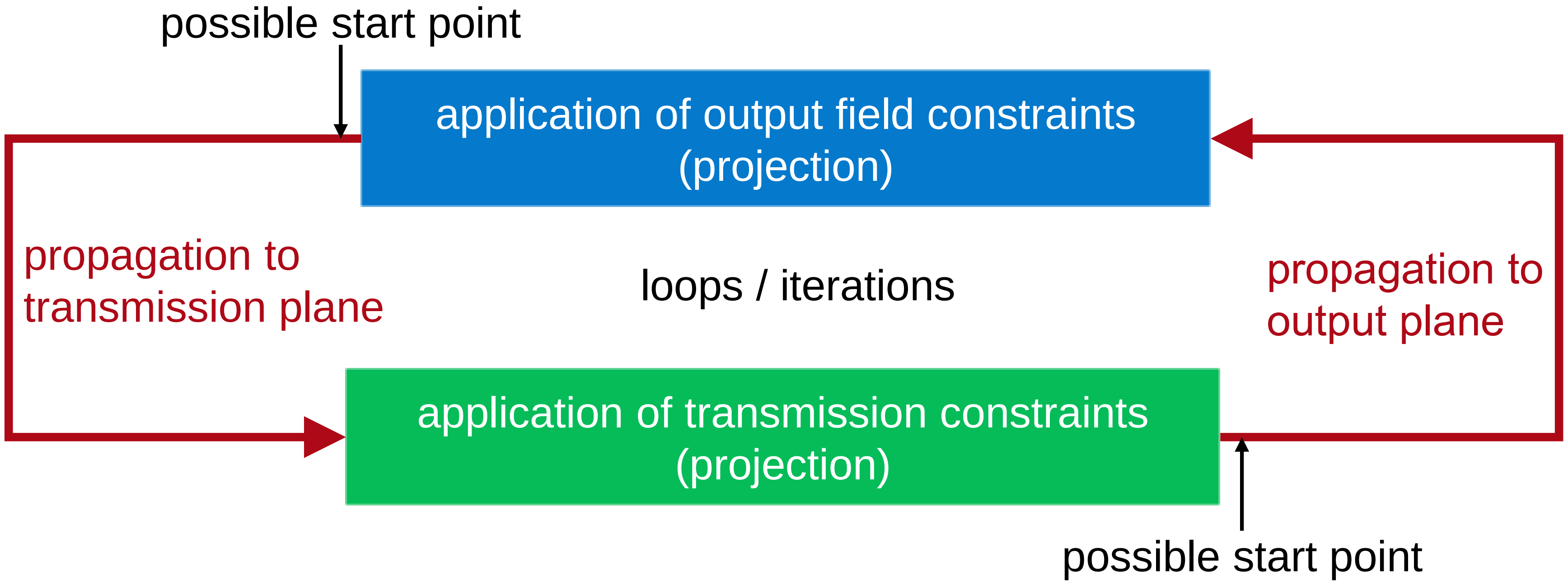


Design Know How (v0.9.1)

VirtualLab's IFTA Concept

IFTA: Fundamental Working Principal





IFTA: Design & Optimization in Steps

- In general the IFTA is a concept based on the Gerchberg Saxton algorithm. But since its introduction many other extensions were developed.
- The IFTA document used in VirtualLab consists of five different design steps.
- In each iteration different constraints are introduced applied to either the output field and/or the transmission function.
- Next the different design steps are discussed.

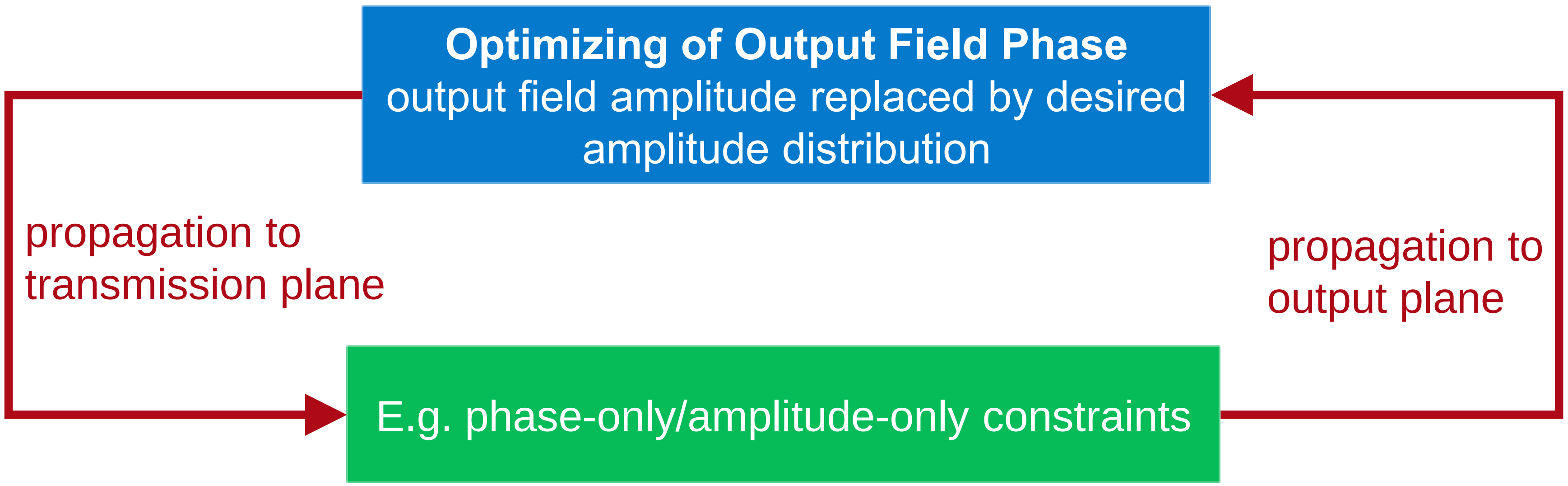
IFTA Step 1: Initial Conditions

Specification of start transmission or output phase values

- Depending on the IFTA starting point an initial signal phase or transmission should be generated.
- The initial values determine the optical properties of the solution.
- The design results (quality) often strongly depends on the initial values.

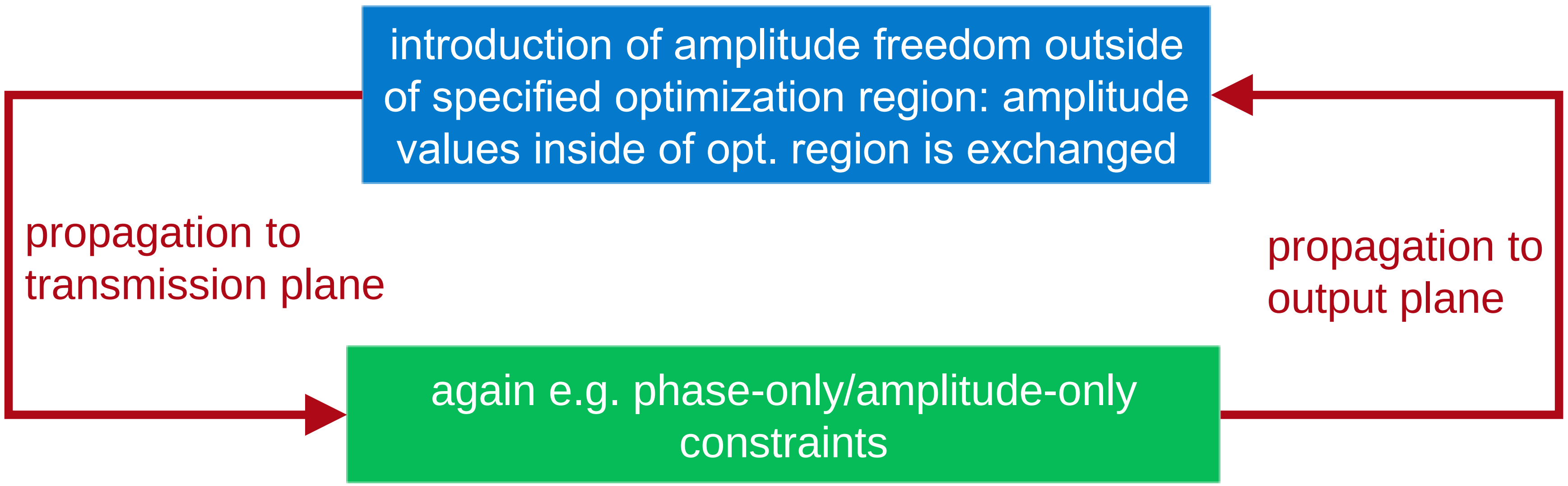
IFTA Step 2: Phase Synthesis

Assumed starting point:
in output field plane



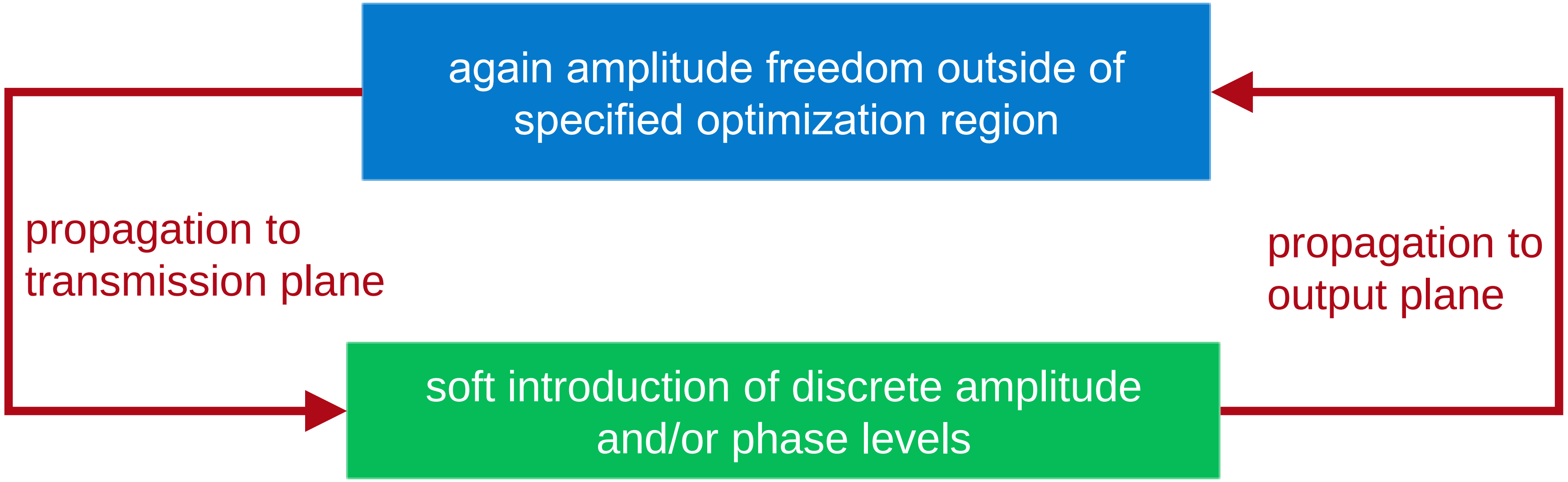
IFTA Step 3: SNR Optimization

Assumed starting point:
in output field plane



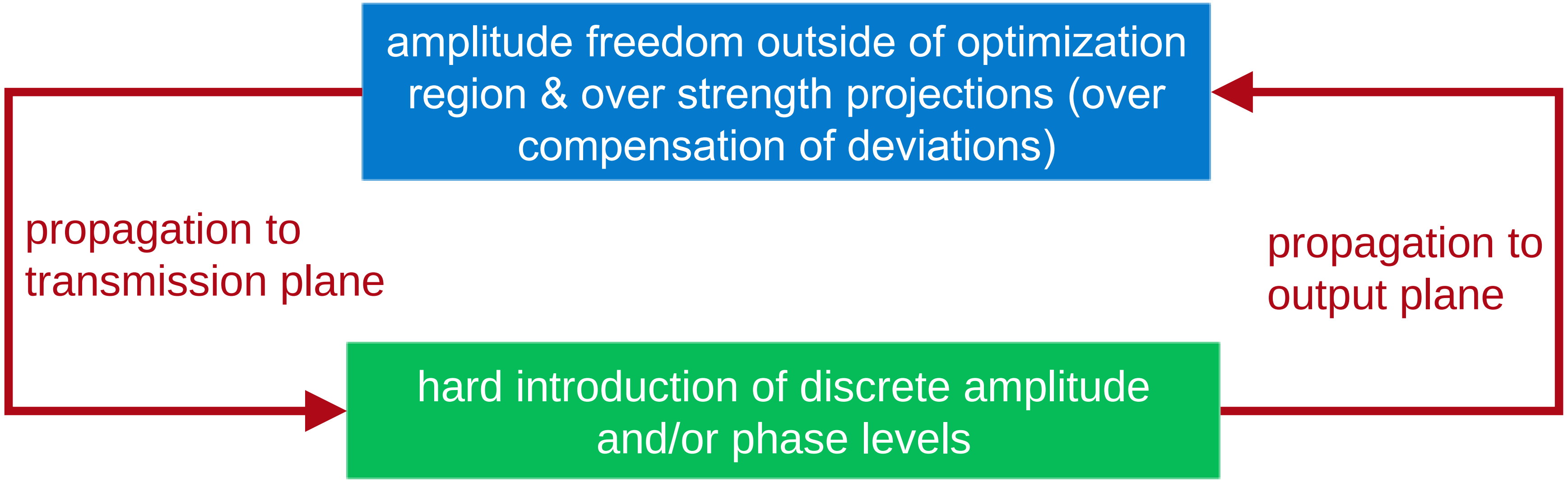
IFTA Step 4: Soft Quantization

Assumed starting point:
in output field plane



IFTA Step 5: SNR Opt. of Quantized Transmissions

Assumed starting point:
in output field plane



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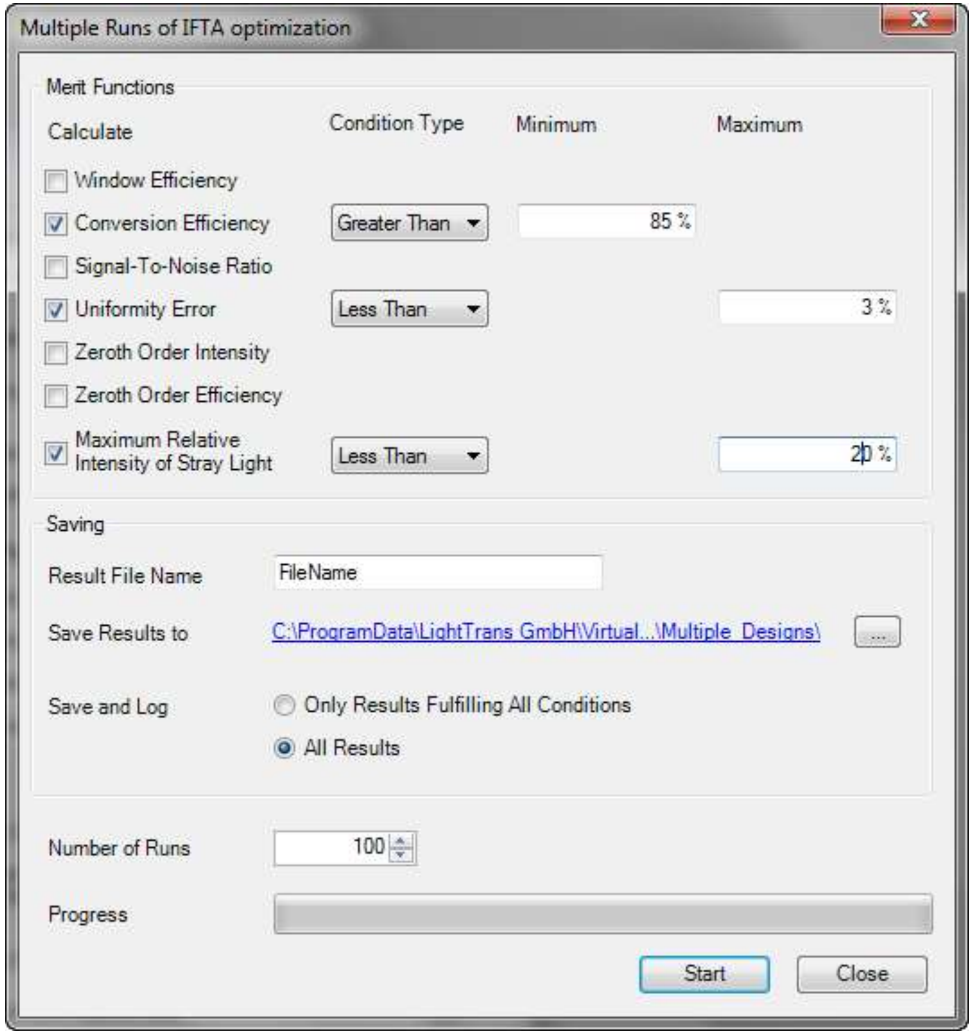
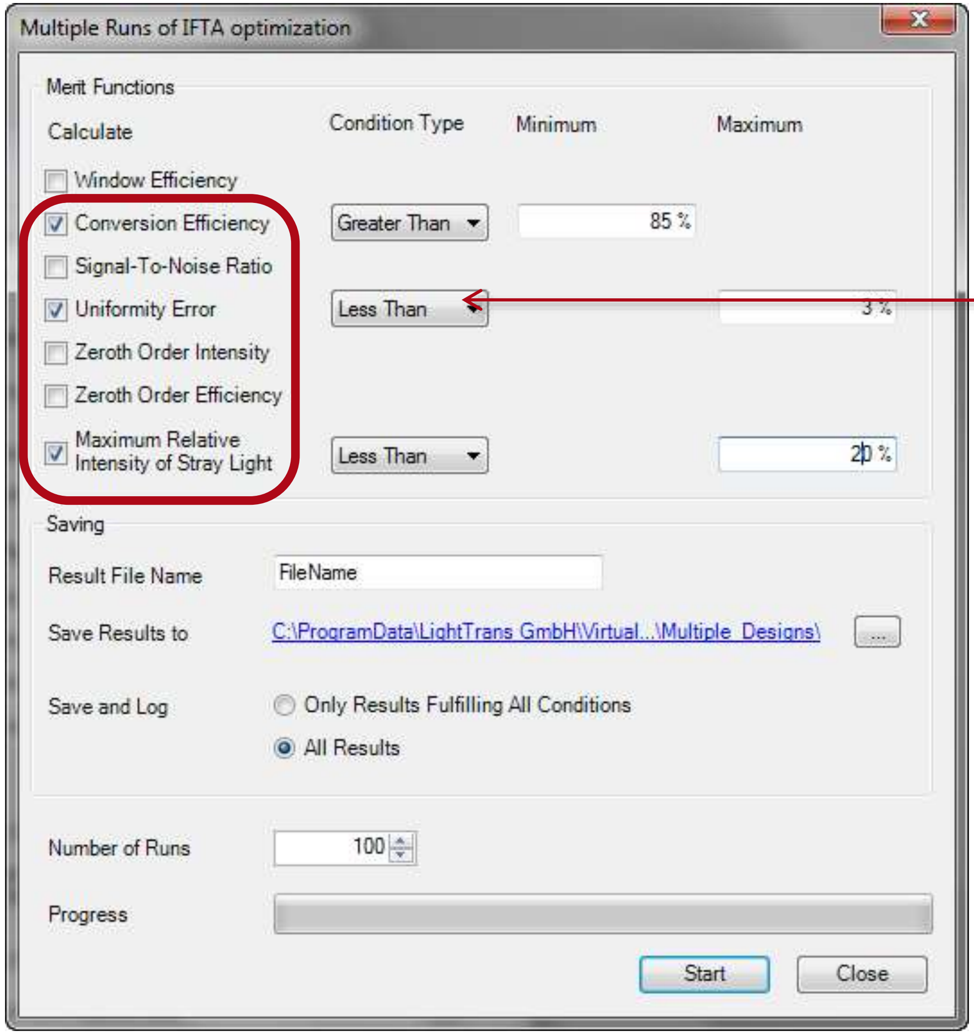
IFTA Optimization - Multiple Runs

IFTA Optimization - Multiple Runs



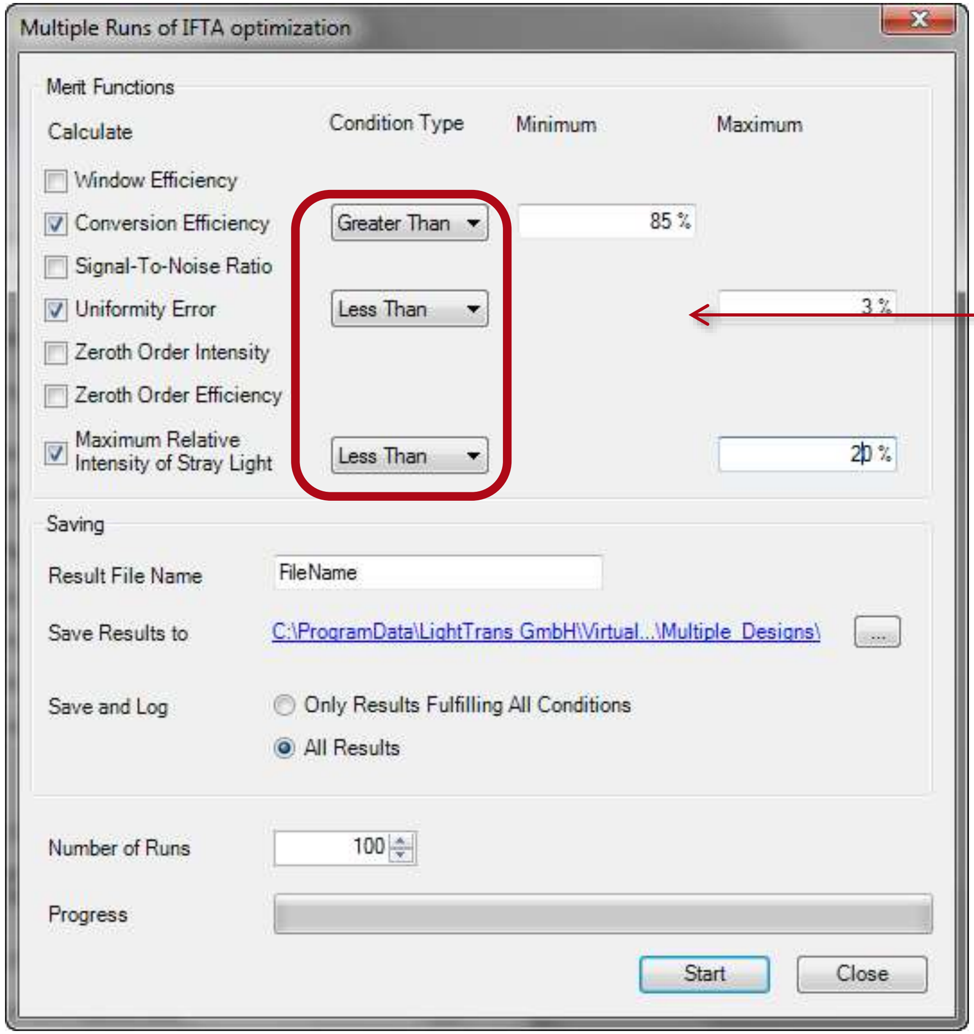
- The dialog can run a prepared IFTA Optimization document multiple times with random start conditions.
- Dialog will keep the best results.
- Menu item is just available if a IFTA Optimization document is selected.

IFTA Optimization - Multiple Runs



Select a merit function that should be calculated and logged for every design.

IFTA Optimization - Multiple Runs

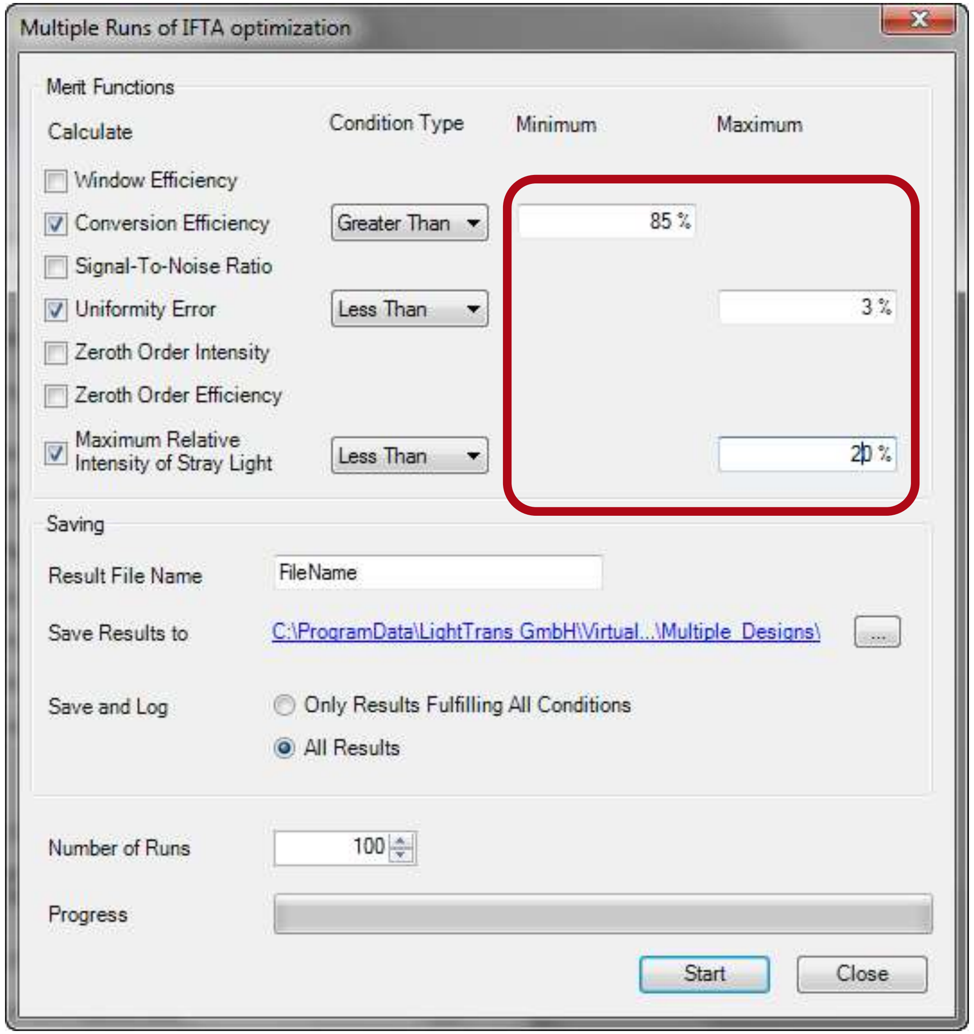


For every merit function a constraint can be selected.

Constraint types:

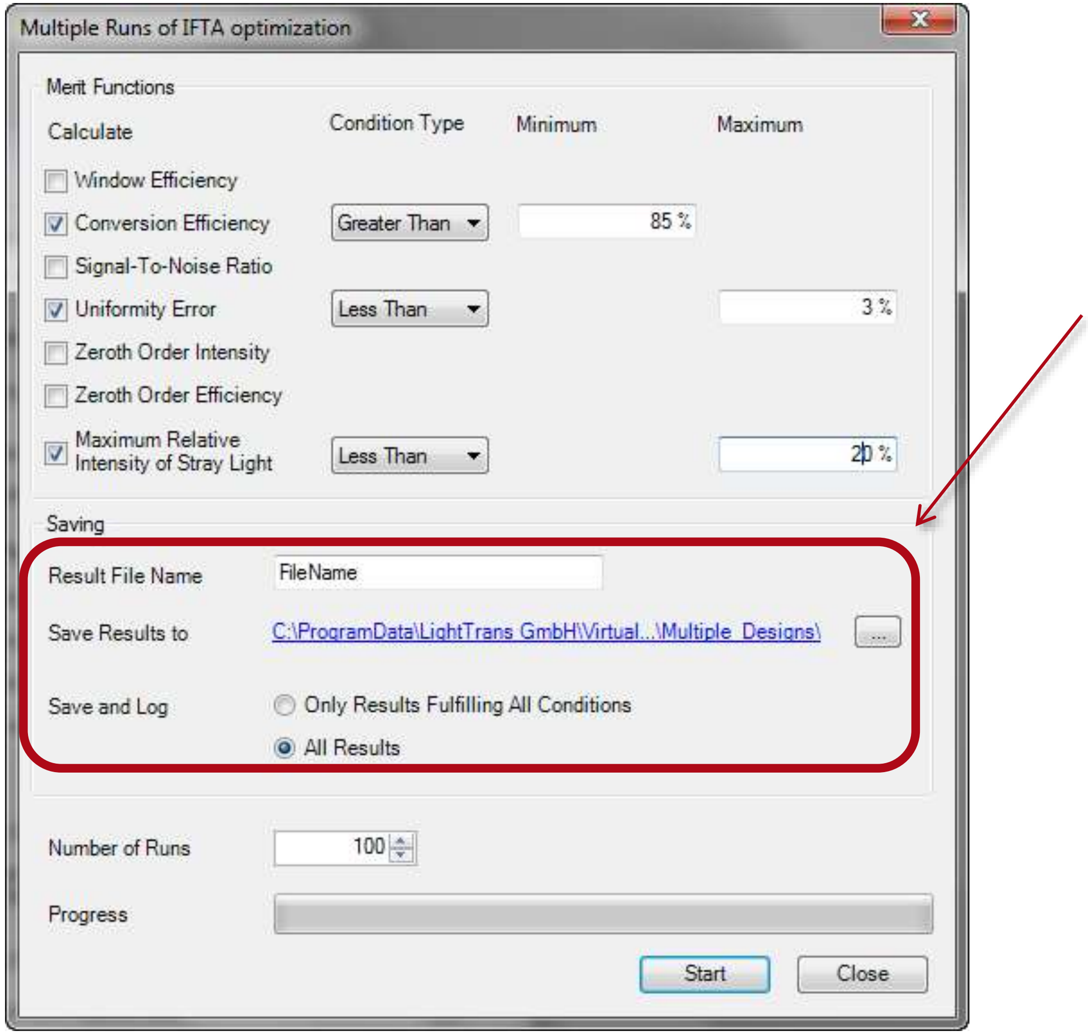
- Upper limit
- Lower limit
- Between upper and lower limit
- No constraint

IFTA Optimization - Multiple Runs



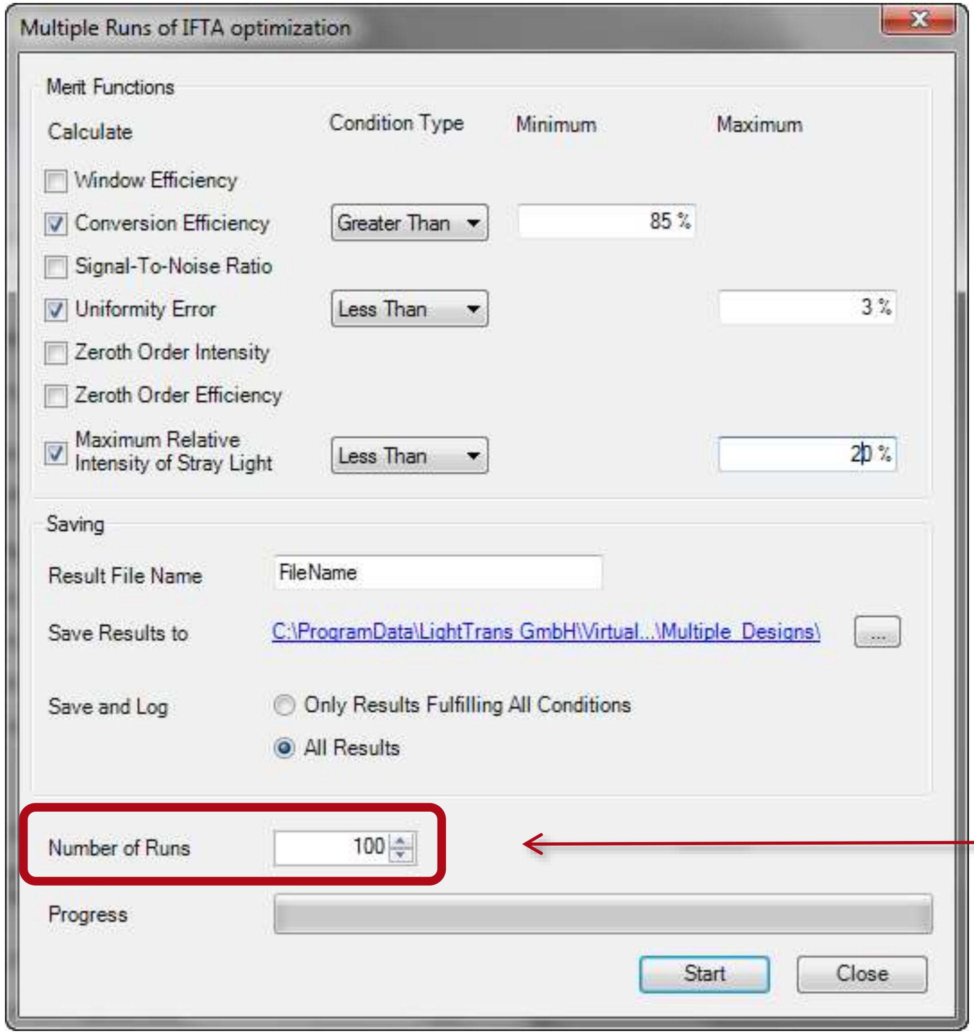
← Upper and lower limit values.

IFTA Optimization - Multiple Runs



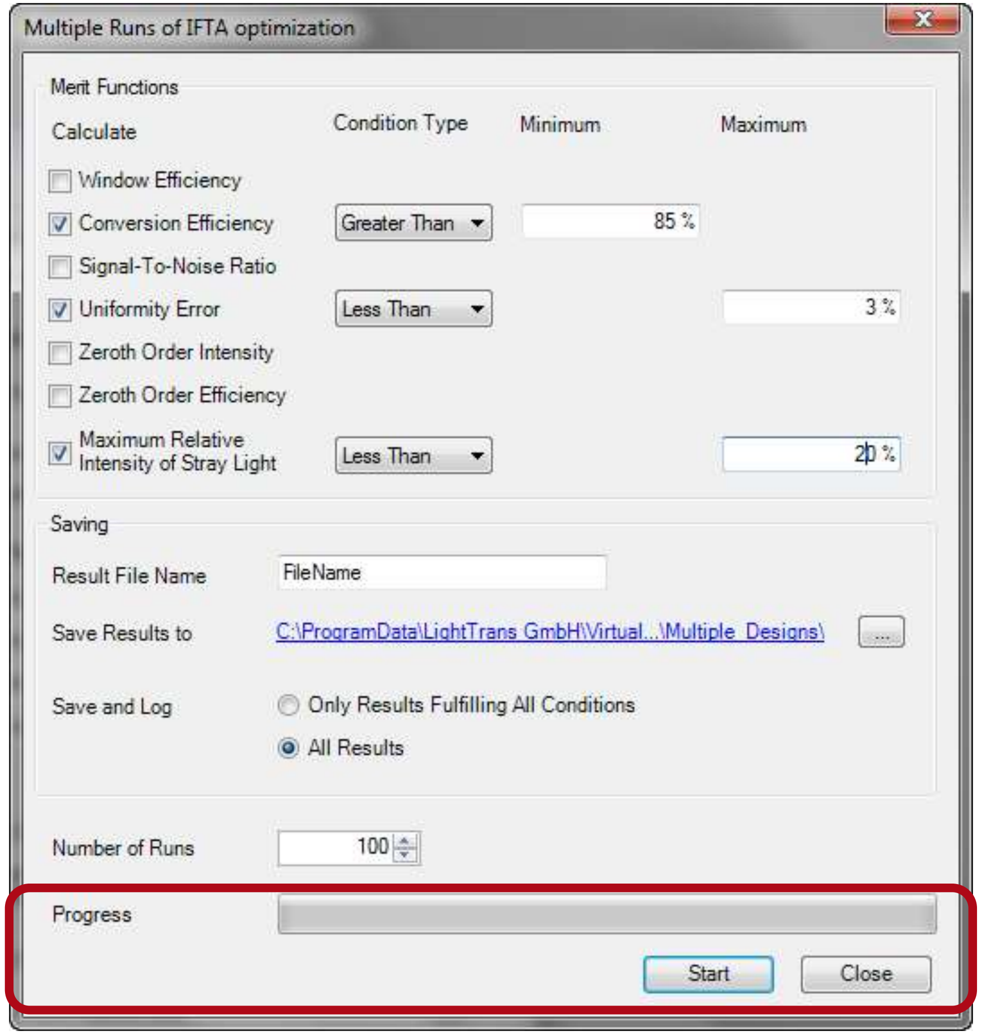
- Optimized transmissions can be stored in customized path.
- Customized file name of transmission.
- Every transmission can be stored or just transmissions fulfilling the conditions.

IFTA Optimization - Multiple Runs



Number of optimizations with random start conditions

IFTA Optimization - Multiple Runs



← Progress and Start/Stop button

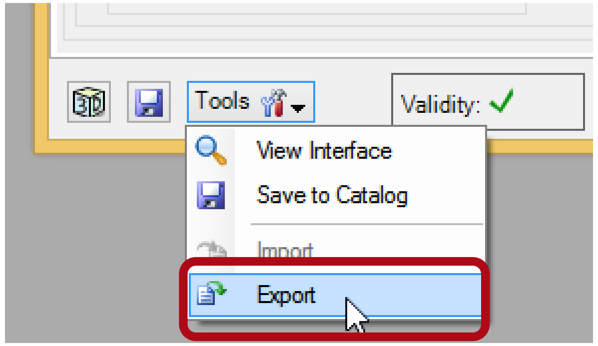
IFTA Optimization - Multiple Runs

- The optimization results are stored in a .CSV file.
- This file can be opened in Excel. It shows the optical performance of all stored results.
- The .CSV file is stored in the same folder like the transmission functions.

(v0.9.1)

Export of Fabrication Data of Interfaces in the Starter Toolbox

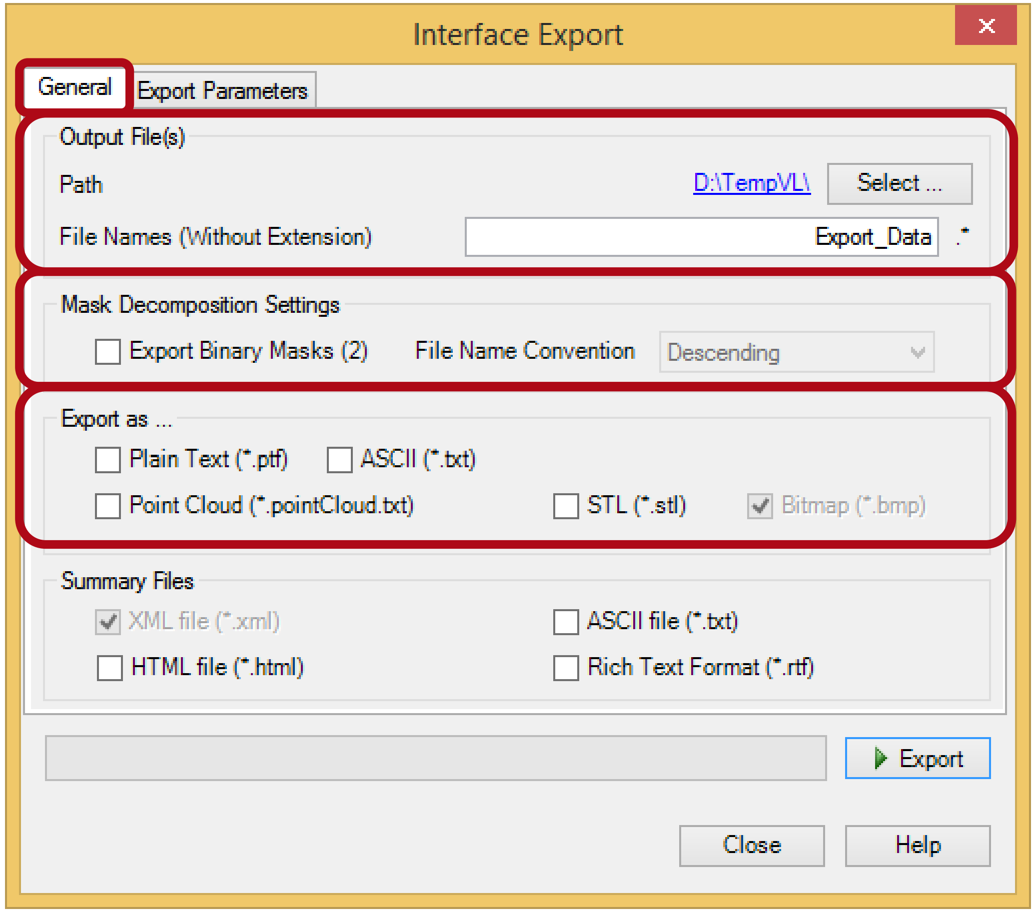
Fabrication Data Export



Edit dialog of optical interface

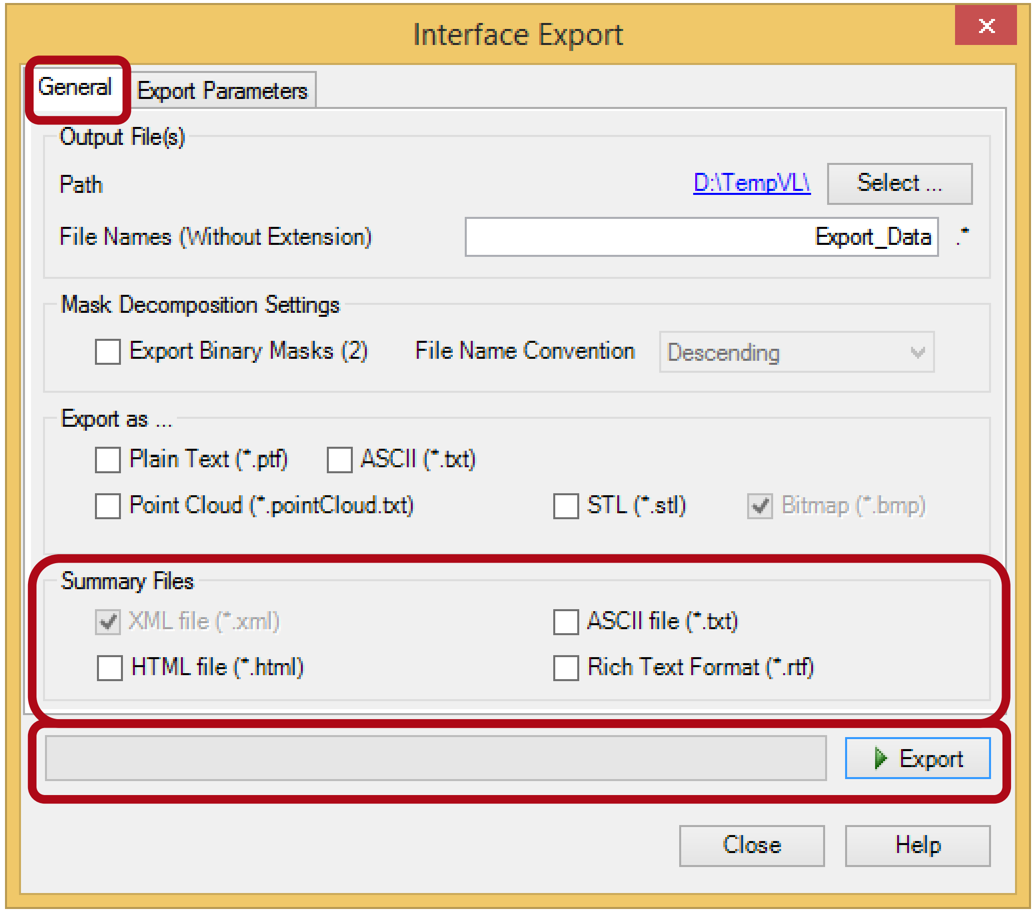
- Any surface profile can be exported into:
  - ASCII-format
  - Bitmap format
  - GDSII-format
  - CIF-format
- Surface profiles with discrete height levels and rectangular pixels can be decomposed in etching masks.
- Export does not only work for predefined surfaces but also for:
  - Sampled interface
  - Programmable interface
  - Combined interface

Fabrication Data Export



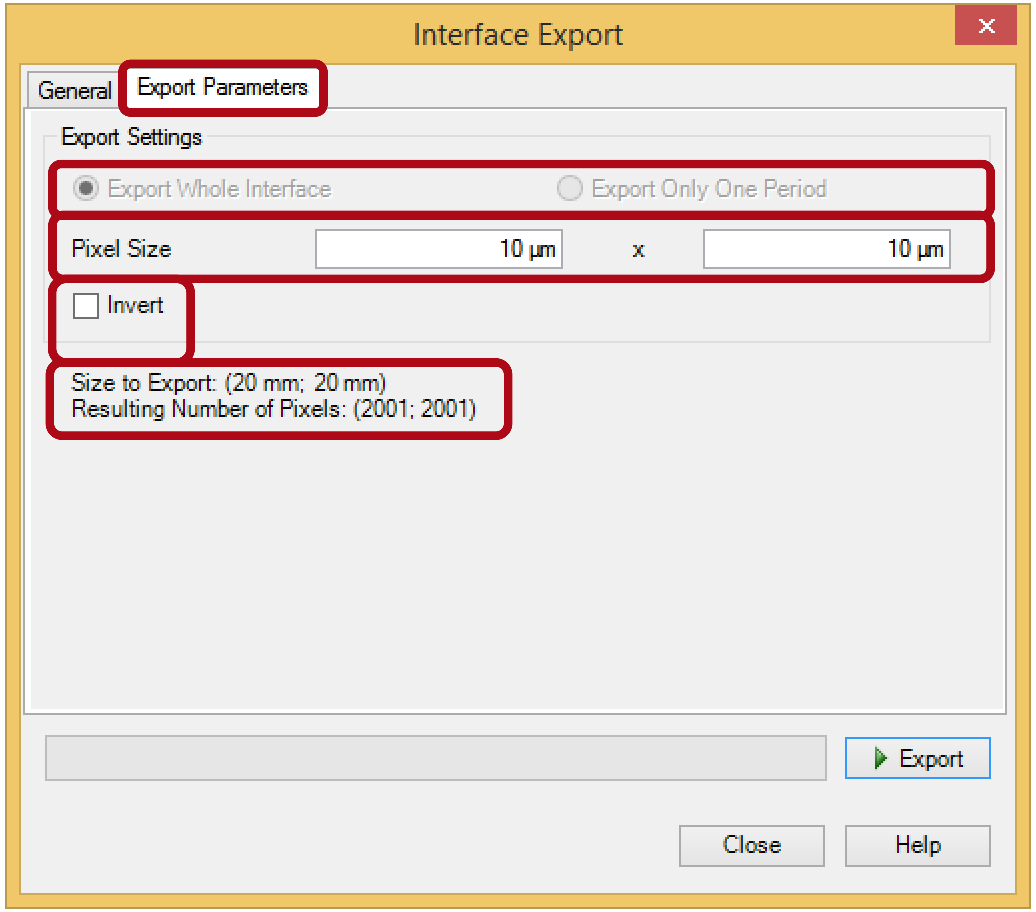
- Path and filename
- Decomposition in etching masks (DOE's with discrete height levels only). The *File Name Convention* determines the enumeration of the mask files.
- Formats of height data files.
  - Plain Text/ ASCII/ Point Cloud
  - STL
  - GDSII/CIF
  - Bitmap
- GDSII and CIF format only available in case of binary masks data (*Export Binary Masks*)

Fabrication Data Export



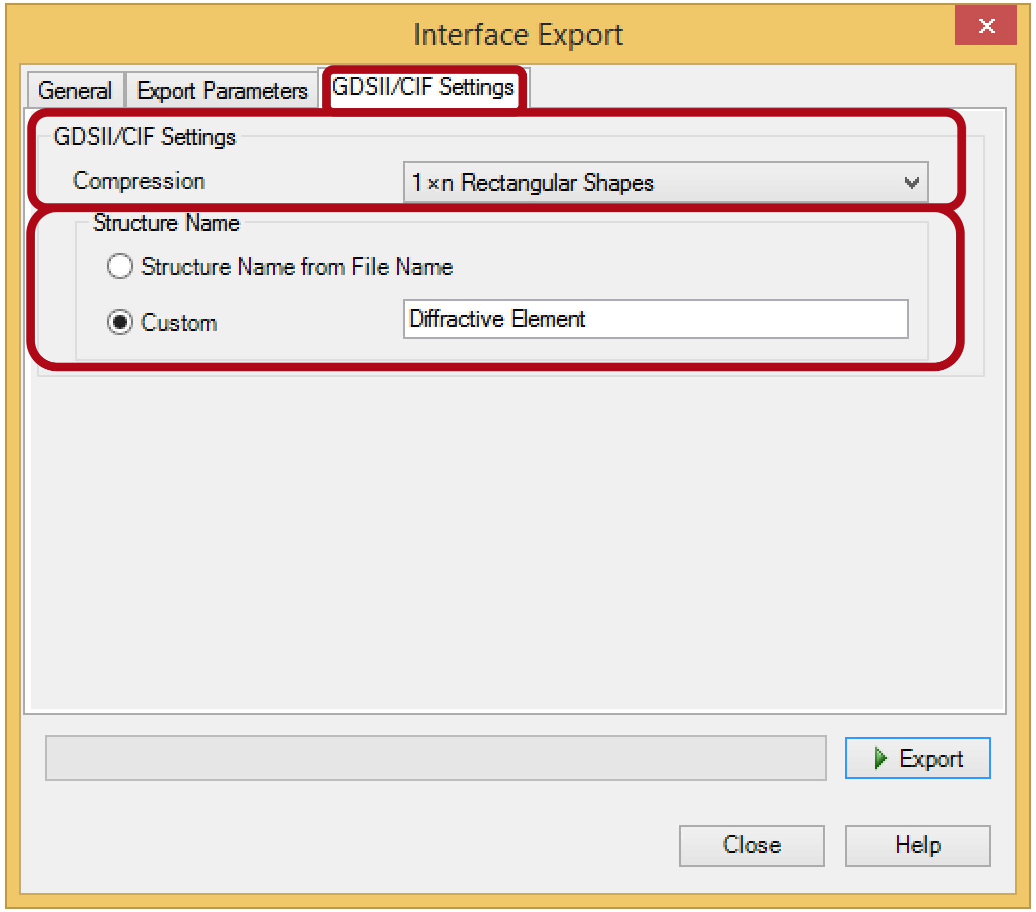
- Format of description file with additional information.
- Export button and progress bar.
- Export may take a longer time and can require a huge number of RAM and hard disc memory depending on the DOE diameter and number of data points.

Fabrication Data Export



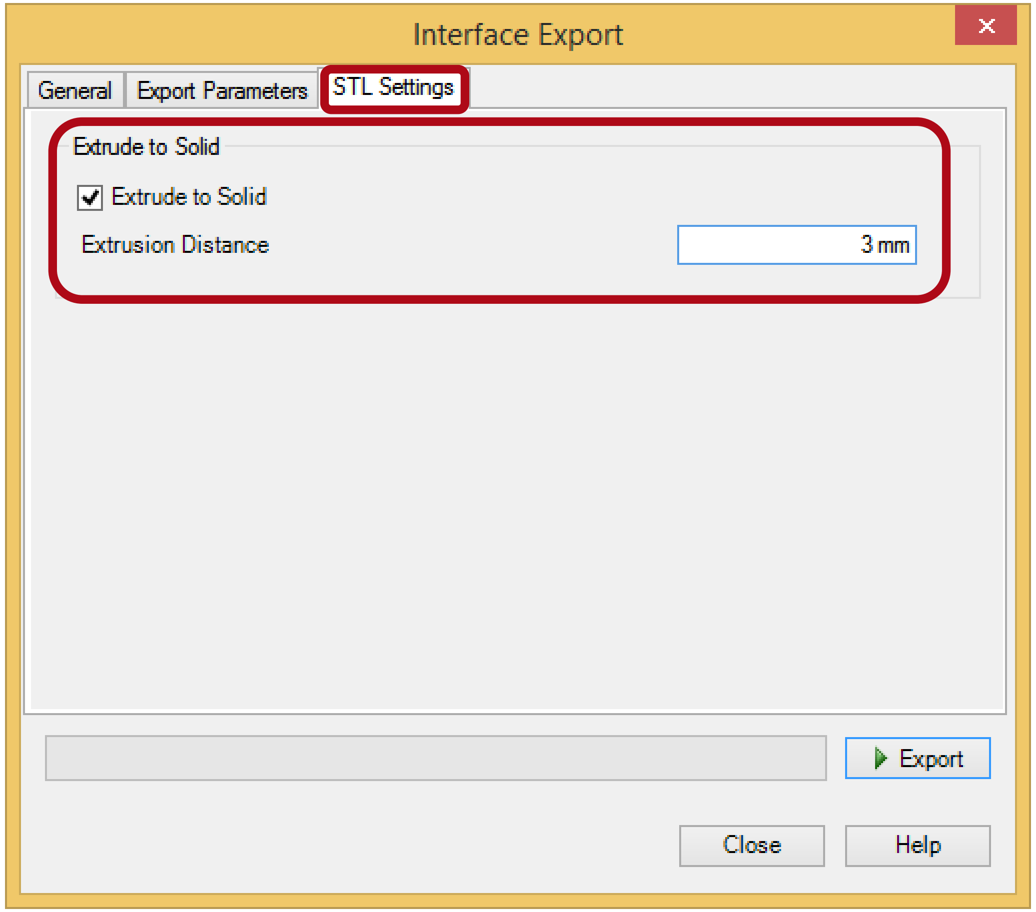
- Export of the whole surface or of just one period.
- Allows to increase the number of data points to be exported (should not be modified for pixelated surfaces).
- Inverts surface profile.
  By checking this option the structure is inverted before the export.
- Diameter and number of data points of exported surface area.

Fabrication Data Export



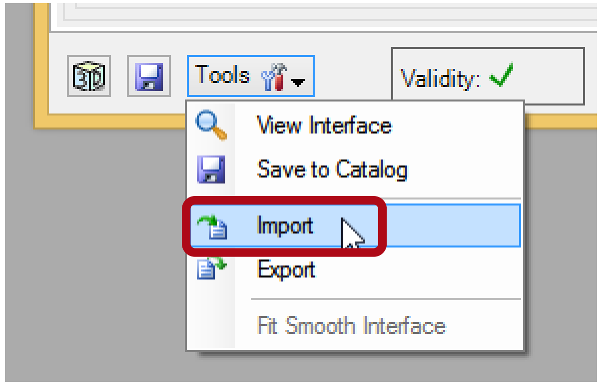
- In case of checked “Export Binary Masks”, GDSII format can be selected.
- Compression:
  - Every surface pixel can be exported as a single shape
  - Pixels of one line with same height can be merged into rectangular shapes (smaller files).
- GDSII/CIF files contain a DOE structure with a specific name. This name can be customized or equal to the file name.

Fabrication Data Export



- For checked STL export a further tab „STL Settings“ appears.
- *Extrude to Solid* option creates a 3D substrate with a micro structured surface.
- If this feature is disabled only a 3D surface will be generated.

Fabrication Data Import



Edit dialog of optical interface

The sampled interface enables the import of fabrication data that was exported by VirtualLab.

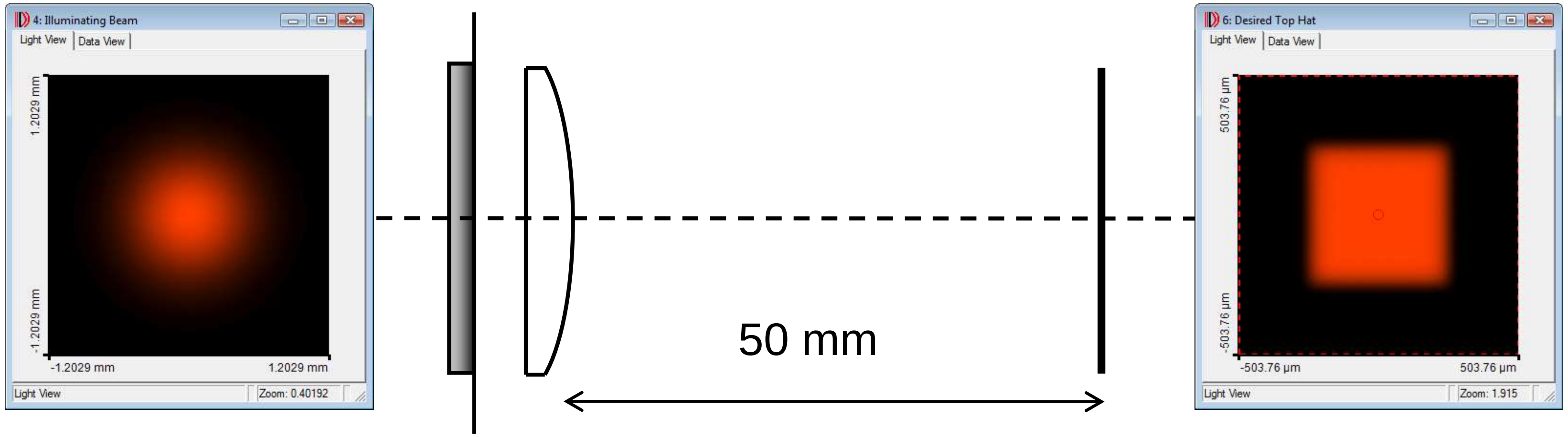
Tolerance Simulation in VirtualLab

- All three approaches described on the previous slide can be handled with the Parameter Run of VirtualLab.
- This application scenario will show a single parameter variation as well as a Monte Carlo Simulation using the slightly modified beam shaper system from the application scenario LBS.001 as example.

Modeling Task

Diffractive Beam shaper
Diameter: 2 × 2 mm
Phase Levels: 16

Target
Plane



Illuminating Beam
Intensity

1f-Setup
Focal Length f=50 mm

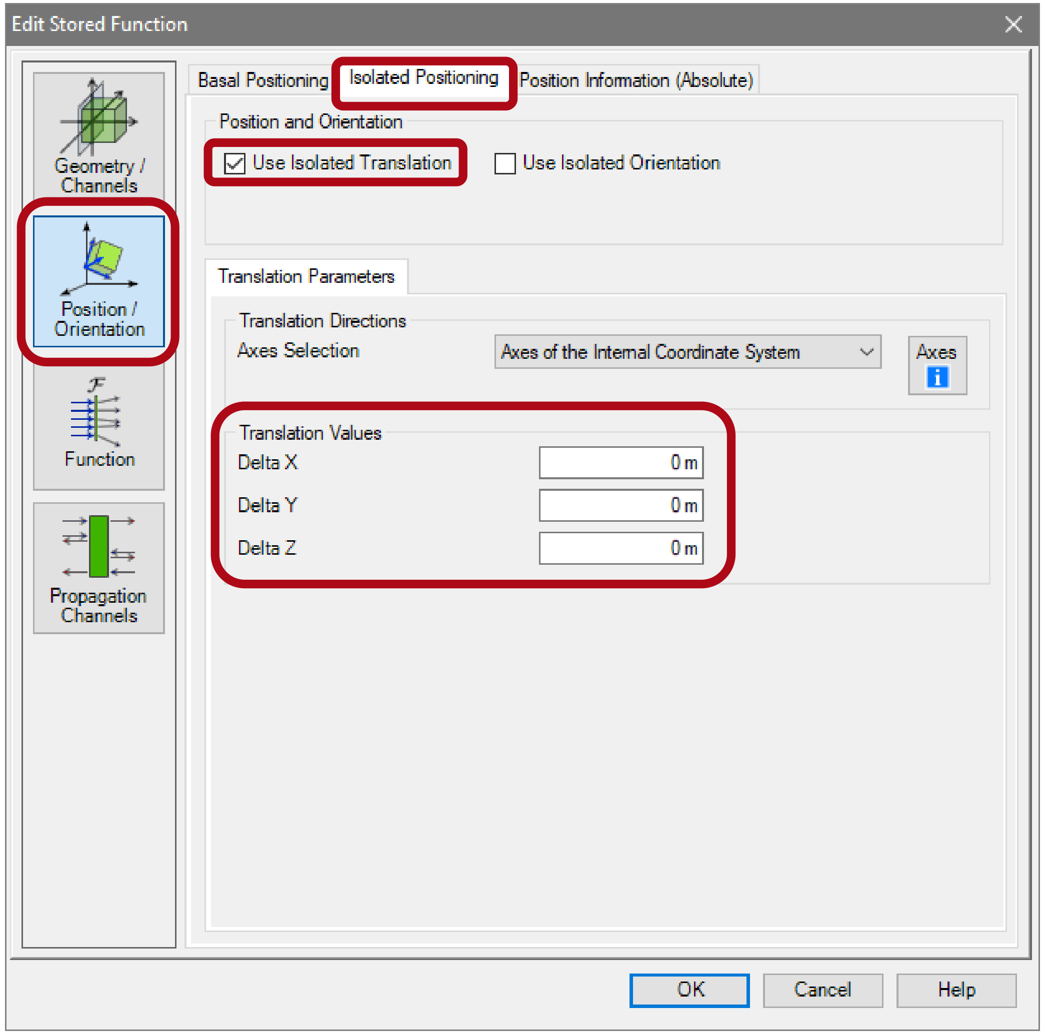
Top Hat Intensity
(free of speckles)

Modeling Task

- The following tolerances of the system are to be analyzed.
- The ± tolerance values are regarded as 3-times ± the standard deviation σ.

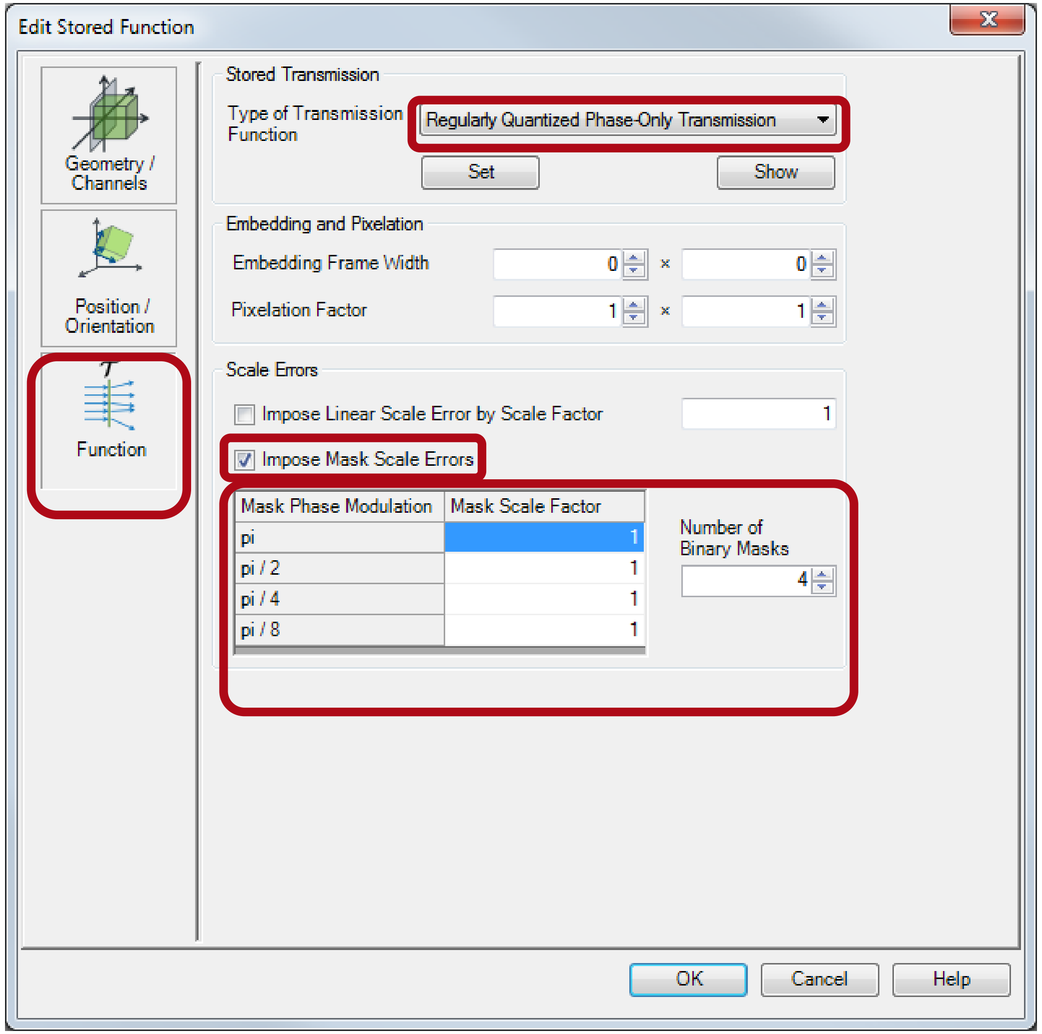
Varied Parameters	**Value and Tolerances**
Waist Radius of Input Beam	(500 ± 25) µm
Etching Depths of all 4 Binary Masks	± 2 % of original height
x-Position of Beam Shaper	(0 ± 10) µm
y-Position of Beam Shaper	(0 ± 10) µm
Focal Length of Lens	(50 ± 0.5) mm

Simulation of Alignment Tolerances



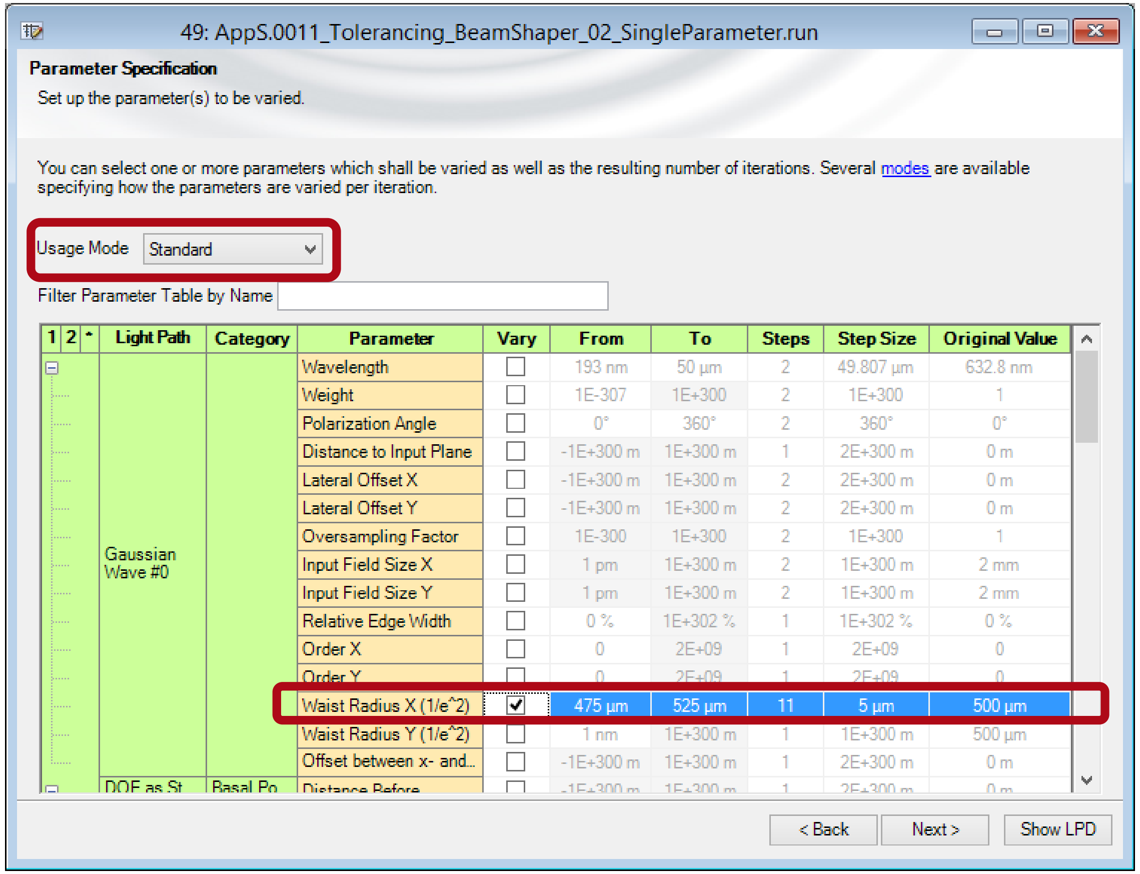
- For simulation of shift tolerances the isolated translation usage must be activated for the *Stored Function* and *Target Plane* component.
- Tolerance values are varied by *Parameter Run.* The values set in the component dialog are ignored.

Simulation of Etching Depth Tolerances



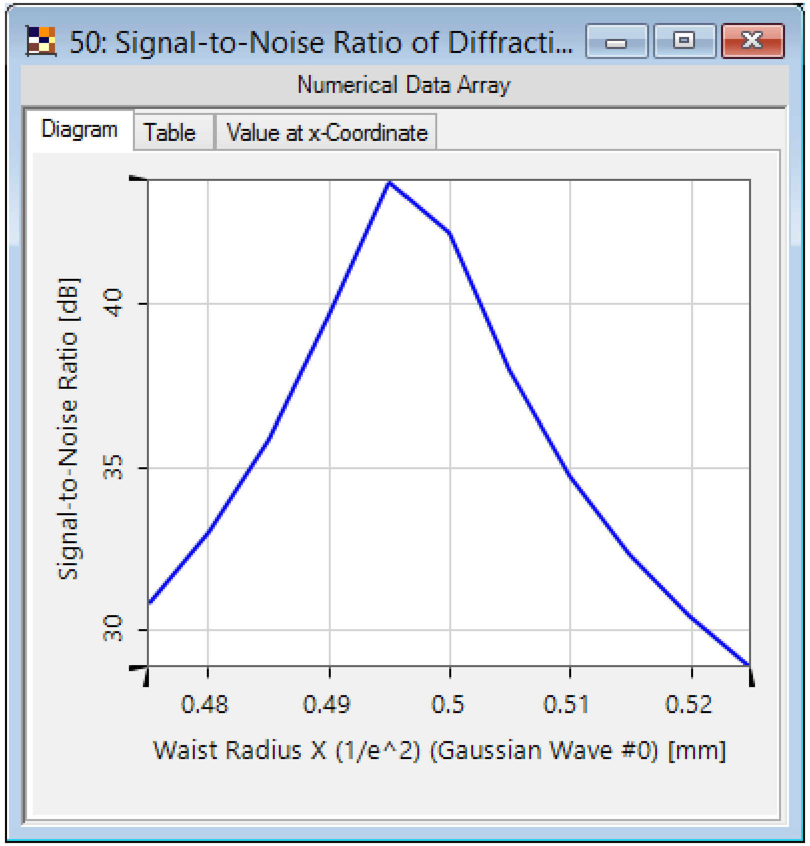
- Simulation of mask etching depth errors must be activated on *Function* page of *Stored Function* component.
- Tolerance values are varied by *Parameter Run*. The respective settings in the component dialog are ignored.
- A tolerance value of 1 represents an optimum etching depth.

Single Parameter Variation



- The laser beam radius has typically a strong influence on the optical performance of a beam shaping system.
- The *Usage Mode: Standard* must be selected for the variation of a single parameter.
- *Waist Radius X* parameter must be selected.

Single Parameter Variation

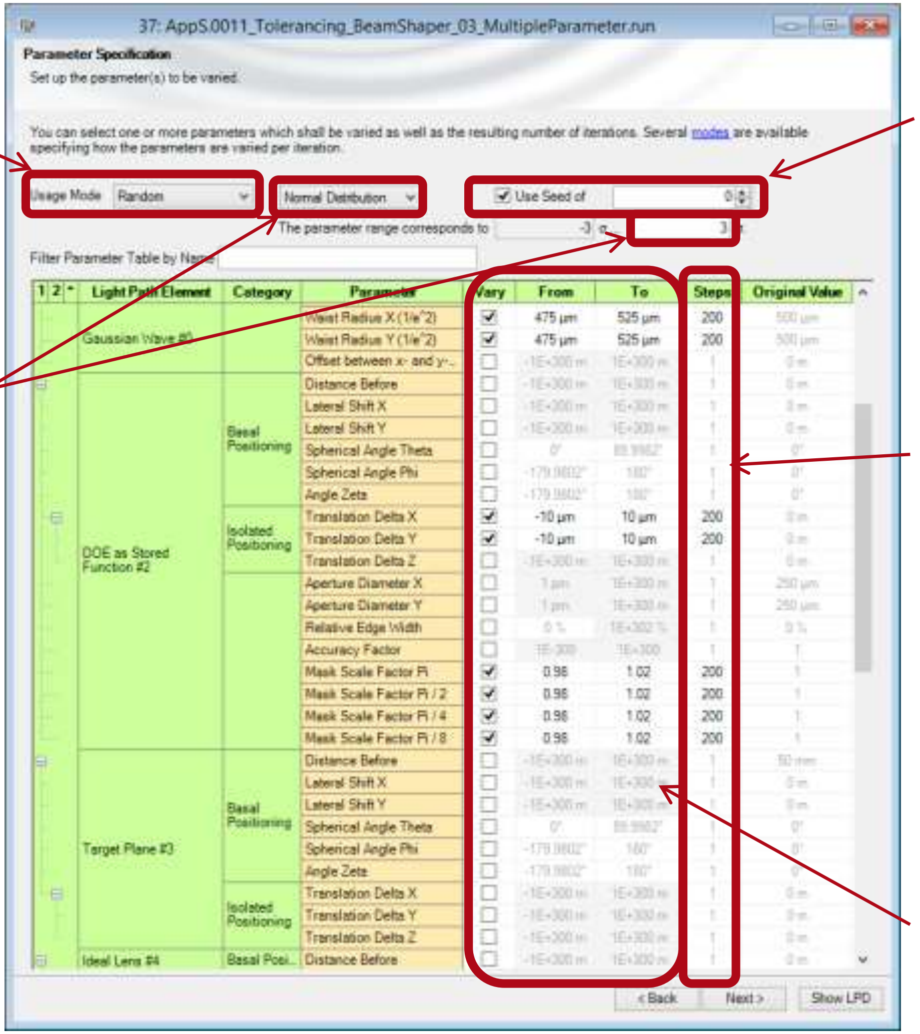


- The beam shaping system shows a strong sensitivity for a variation of the laser beam radius.
- The Signal to Noise Ratio (SNR) will drop to 28.8dB.

Monte-Carlo Simulation

Random mode for Monte Carlo simulation

Parameter Variation has a *Normal Distribution* with a certain standard deviation σ

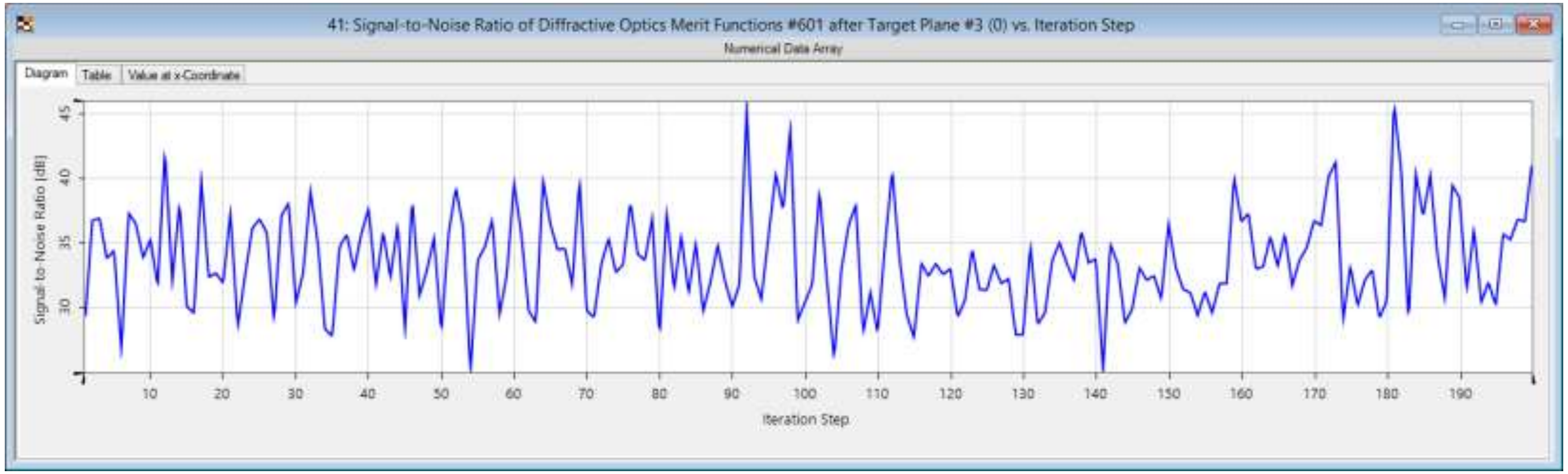


A Seed can be used for reproducible results of the 'random' series.

Total number of variations

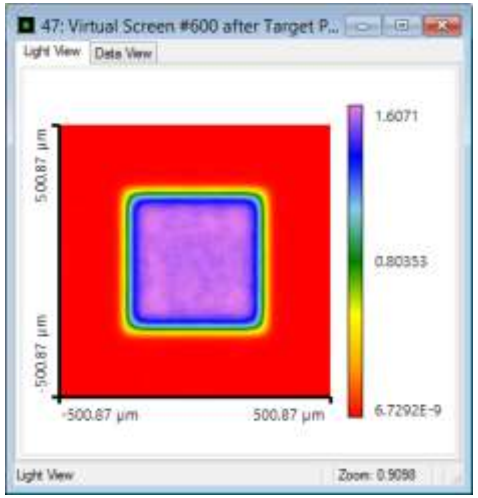
Minimum and maximum value of all tolerances defined by $\pm 3\sigma$

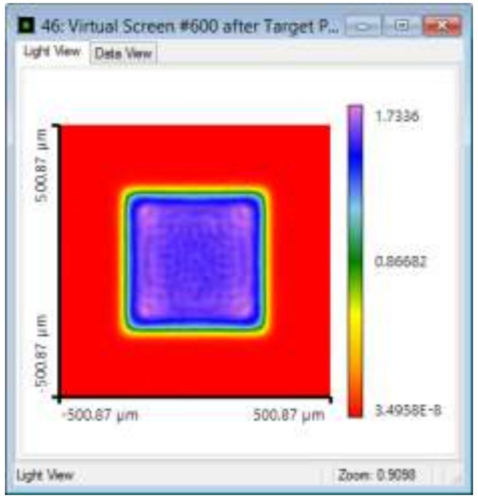
Monte-Carlo Simulation



- Variation of the SNR depending on the random parameter set.
- The minimum SNR can be found from the diagram via the menu entry Detectors > Minimum.
- Minimum SNR: 24.9 dB
- Average SNR: 33.7 dB

Resulting Field Distributions





- Left: Ideal output intensity (SNR = 42.2 dB).
- Right: Light pattern with lowest SNR (SNR = 24.9 dB)
- Export of Monte-Carlo simulation results to external software (for example Microsoft Excel) allows further statistical evaluations.

Conclusion

- VirtualLab supports analysis of alignment and fabrication tolerances.
- Parameter Run can perform single parameter variations as well as Monte-Carlo simulations.
- Monte-Carlo simulation gives an overview of worst and average optical performance.

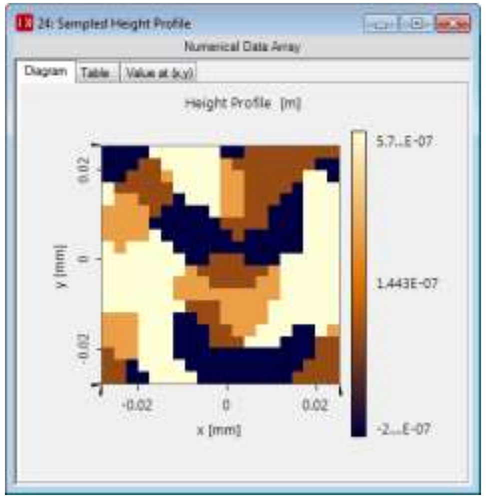
Micro Optical Component

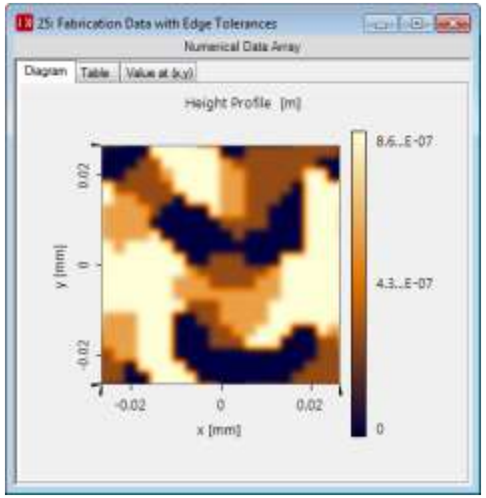
Modeling of Rounding of Pixels

Modeling of Rounding of Pixels

- Several micro structured surfaces consists of rectangular pixels.
- It is typically assumed that pixels have rectangular side walls and sharp edges.
- Exposure and etching processes during the fabrication of micro structured surfaces can lead to a rounding of pixel edges.
- The edge rounding can be modeled in a good approximation by convolution with a Gaussian beam.

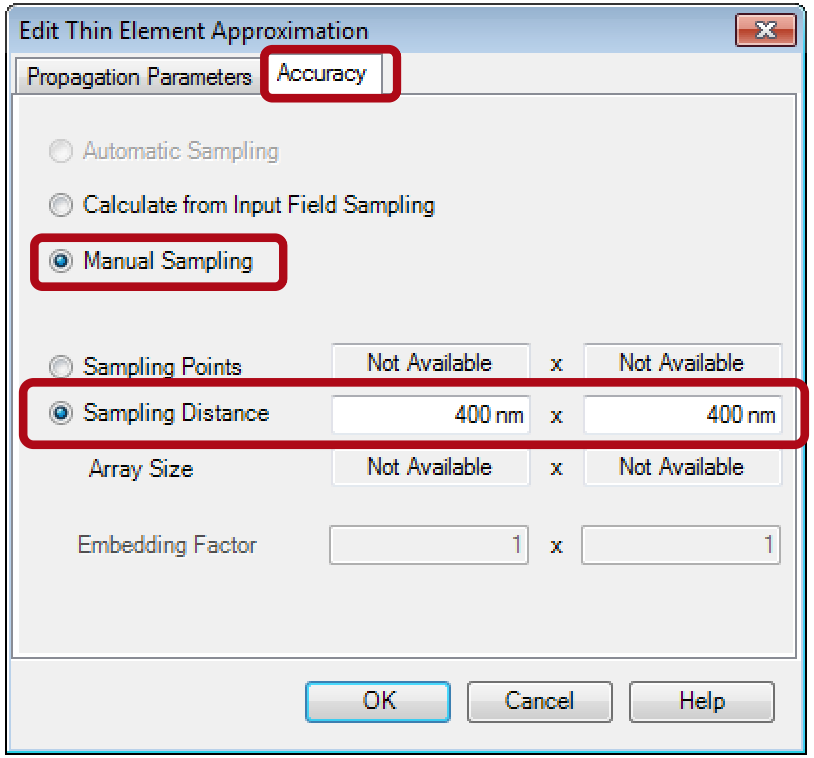
Example with Data from Scenario 23.01





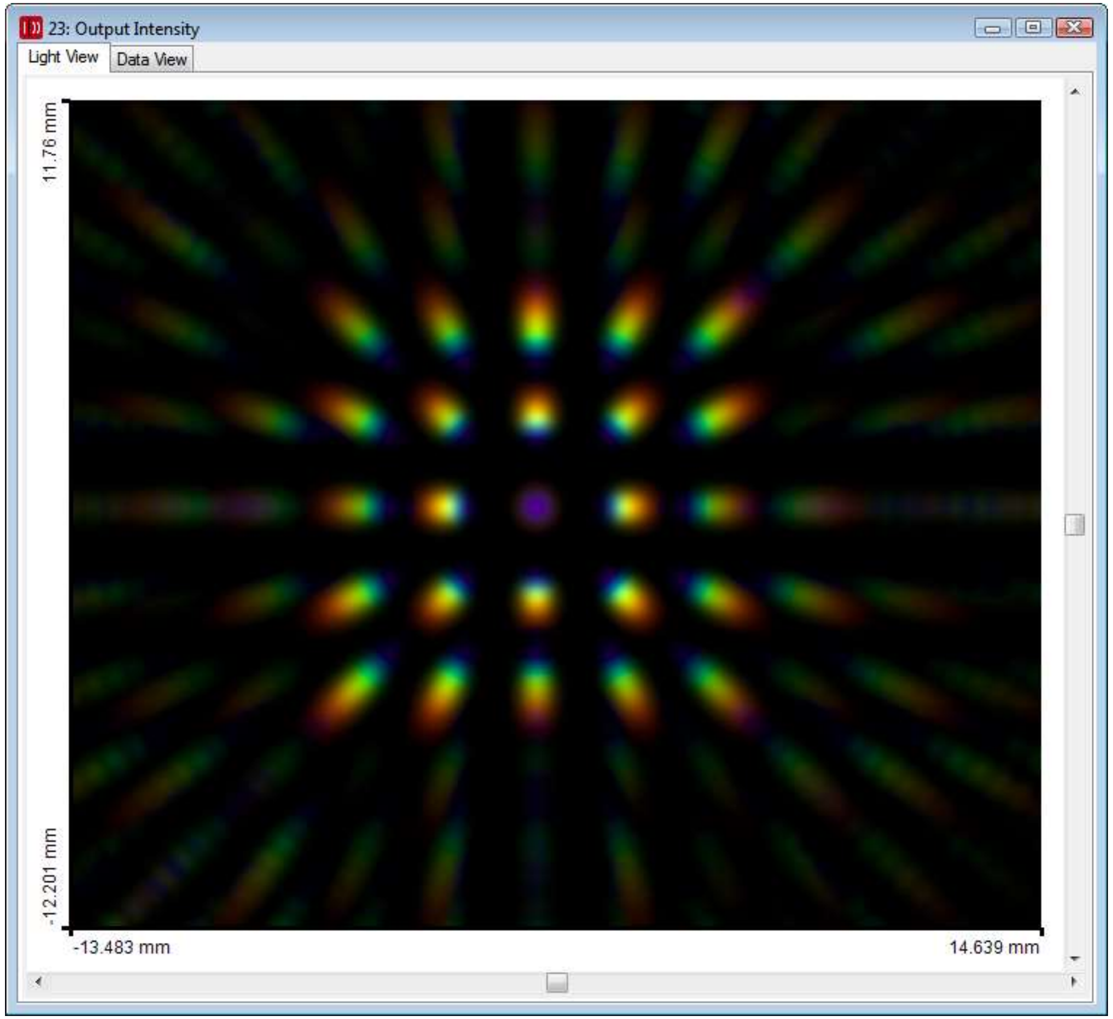
- VirtualLab Module **`Module_RoundedEdge_Tolerances.cs`** can be used to calculate from a perfect profile a profile with rounded edges.
- Calculation steps:
  - Get a *Data Array* with the perfect profile from the sampled interface.
  - Apply the module.
  - Set the *Data Array* with the modified profile into the sampled interface.
- Left side: edge rounding 2 µm, sampling distance 400 nm.

Propagation Sampling Distance



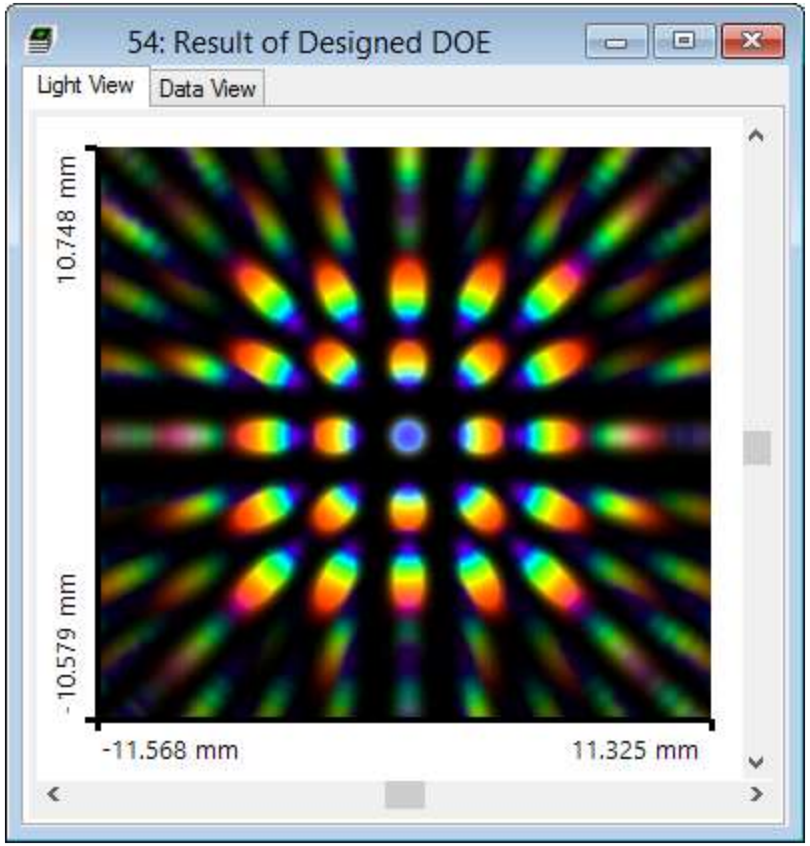
- Field sampling distance of interface propagation must be reduced in order to take into account field phase modulation at pixel edges.
- Field sampling distance should be equal to profile sampling distance.

Simulation Result

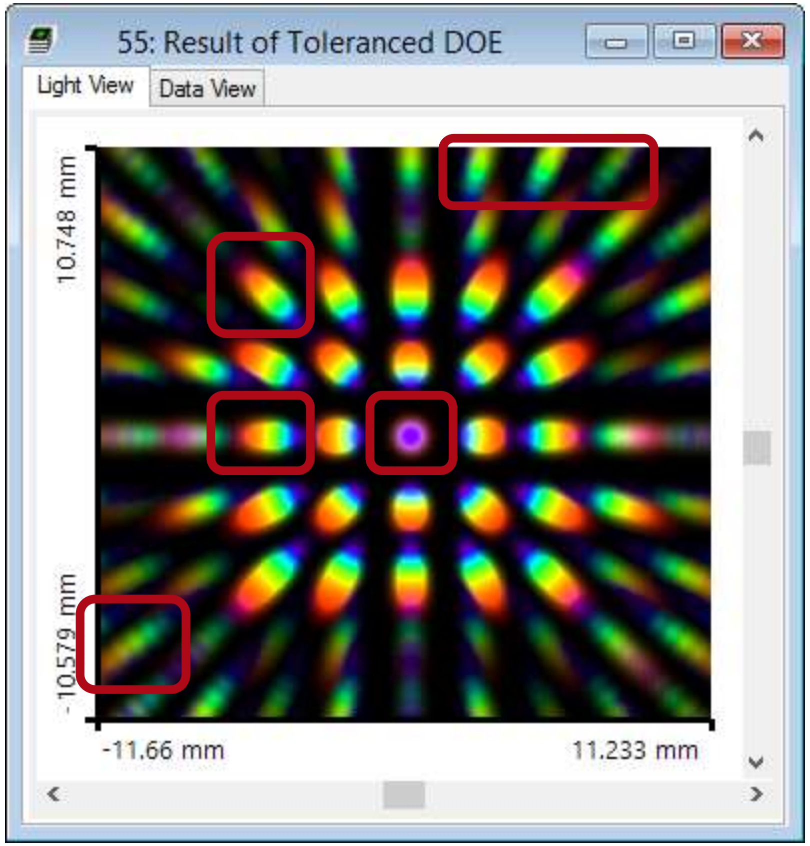


Results with 4x Increased Brightness

Simulation Result of Designed DOE



Simulation Result of DOE with Rounded Edges



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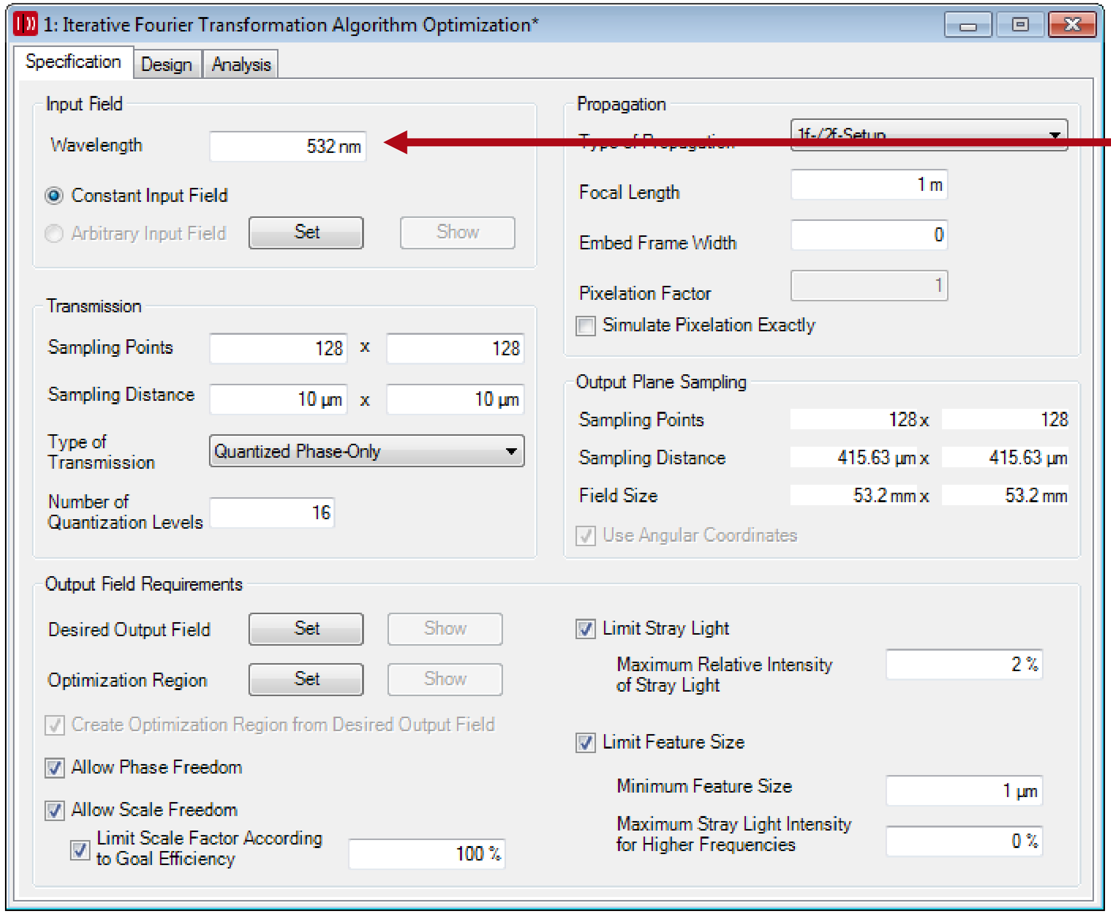
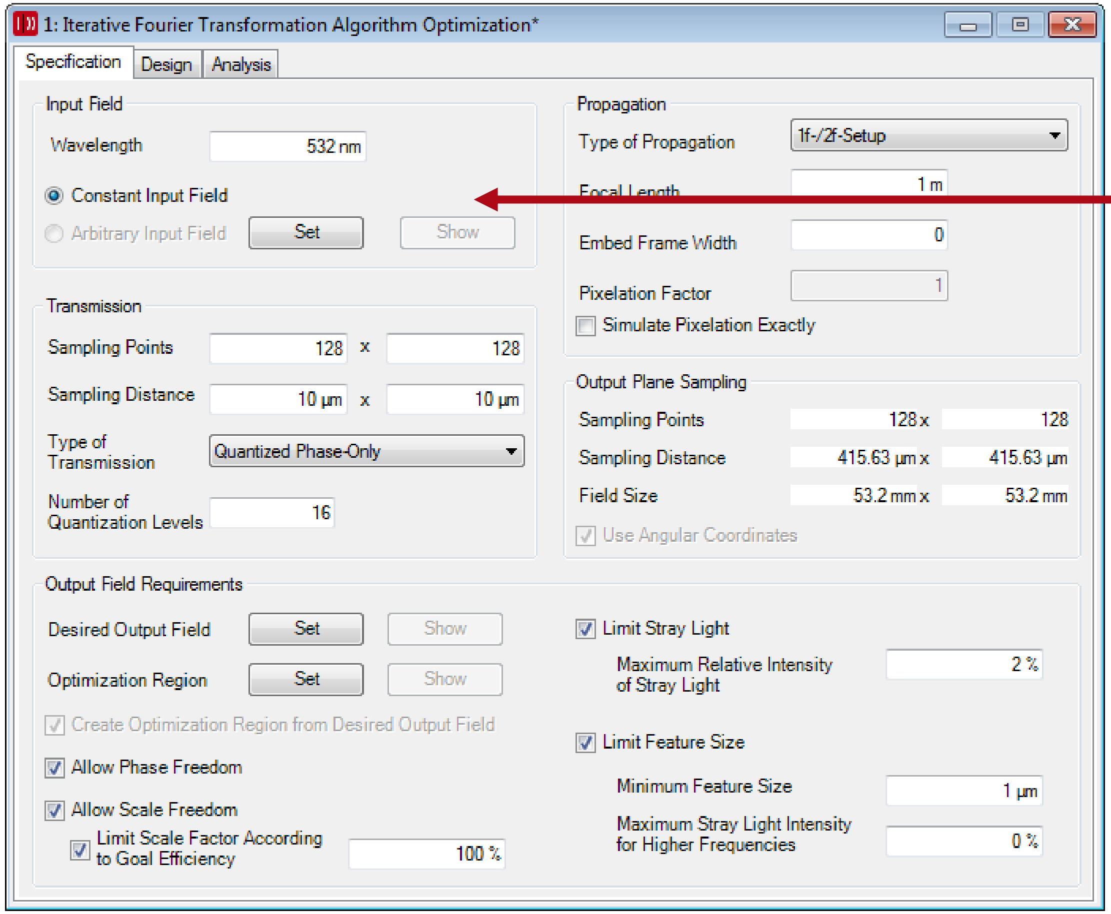
Manual Configuration of IFTA Optimization Document

Design Specification



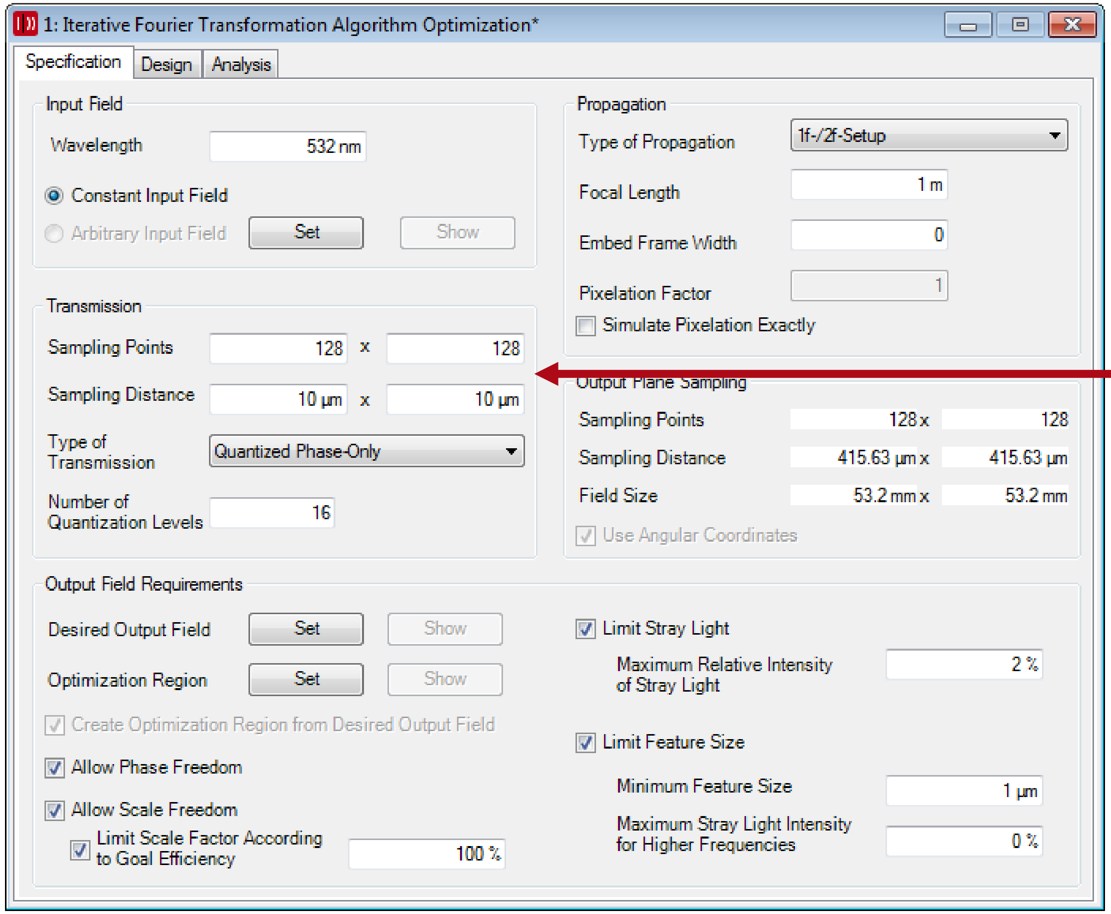
Wavelength
(This IFTA document considers vacuum as embedding medium.
In case of other media, the wavelength is accordingly adjusted.)

Design Specification



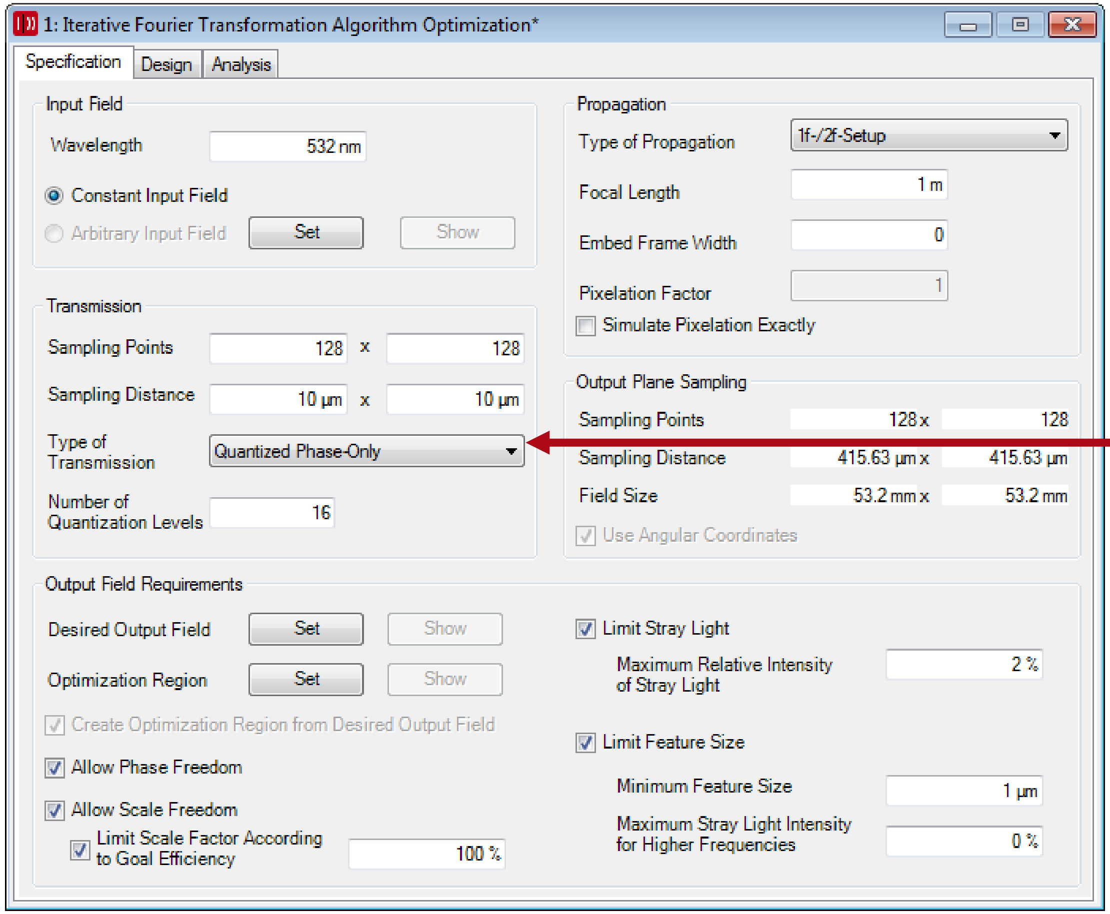
Input field should be constant for beam splitters and diffusers.

Design Specification



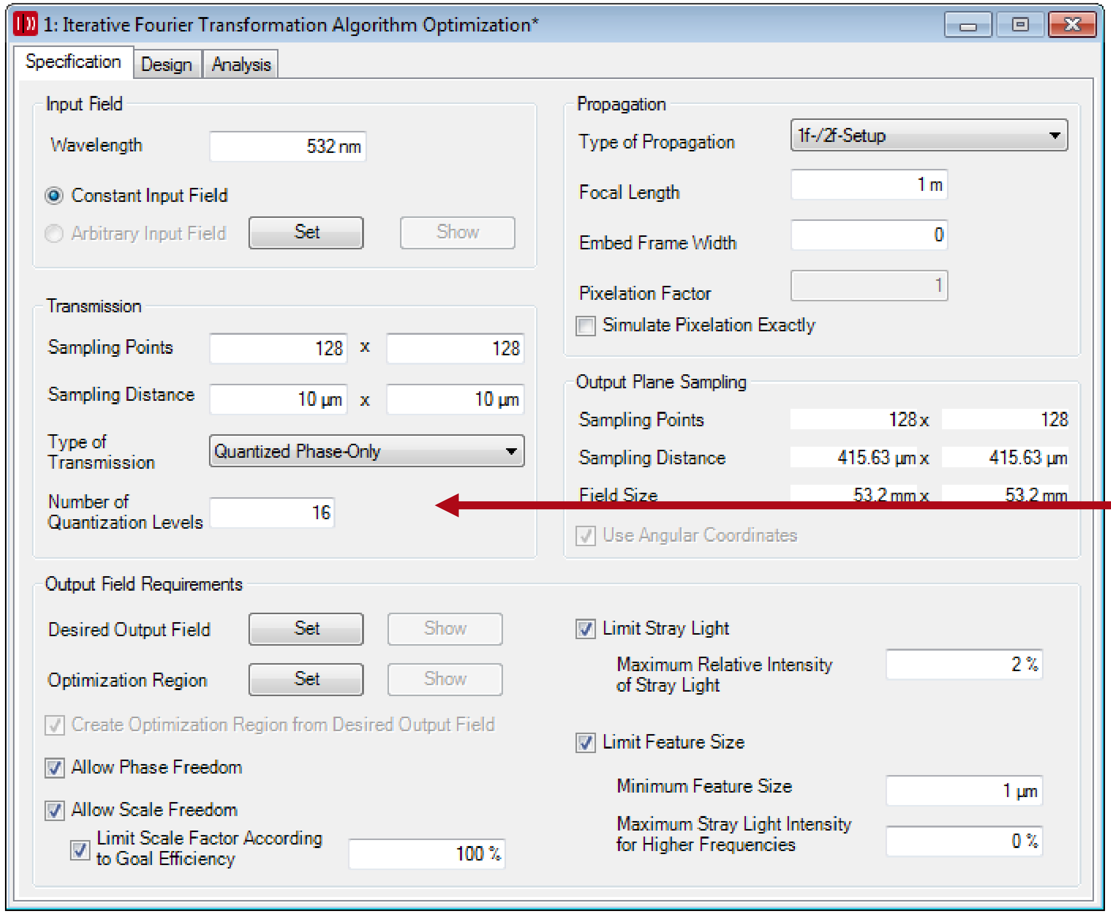
Transmission sampling parameters

Design Specification



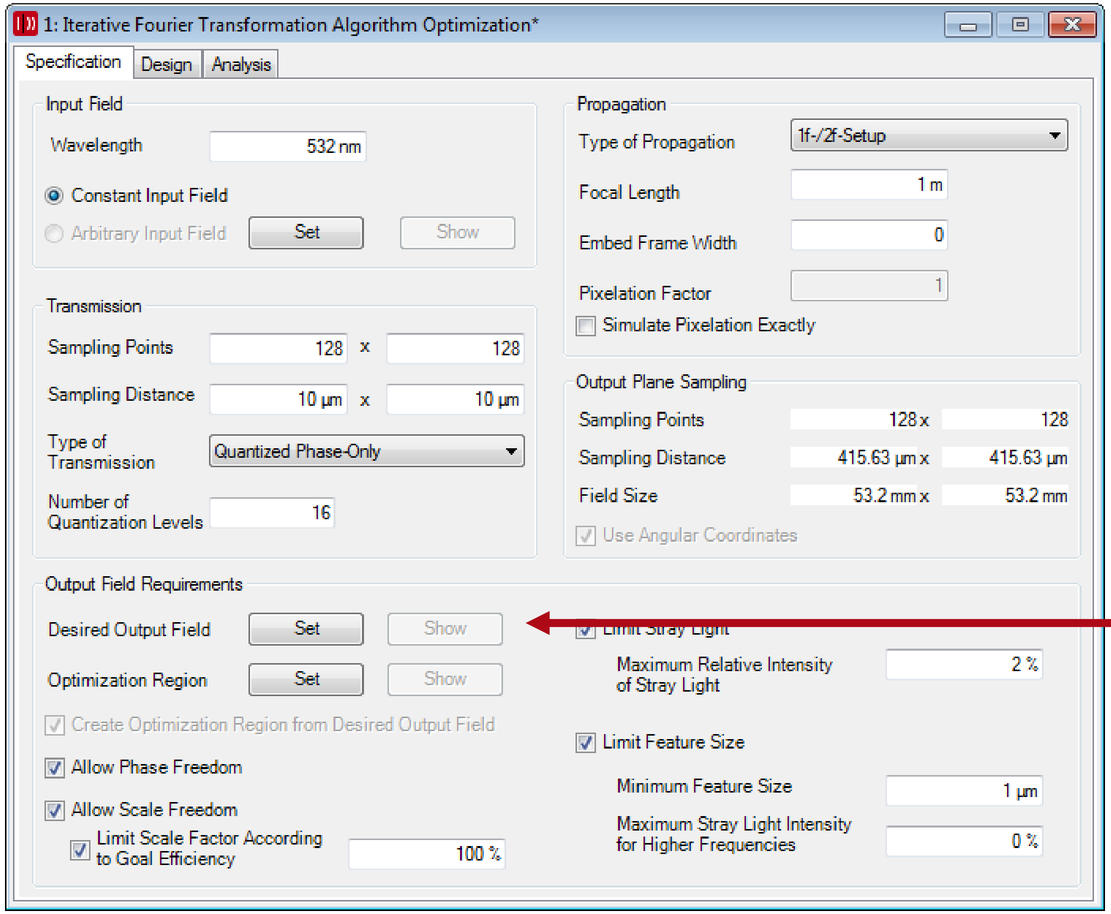
Transmission type:
- Phase-only
- Amplitude-only
- Complex
- Quantized
- Continuous

Design Specification



Number of quantization steps

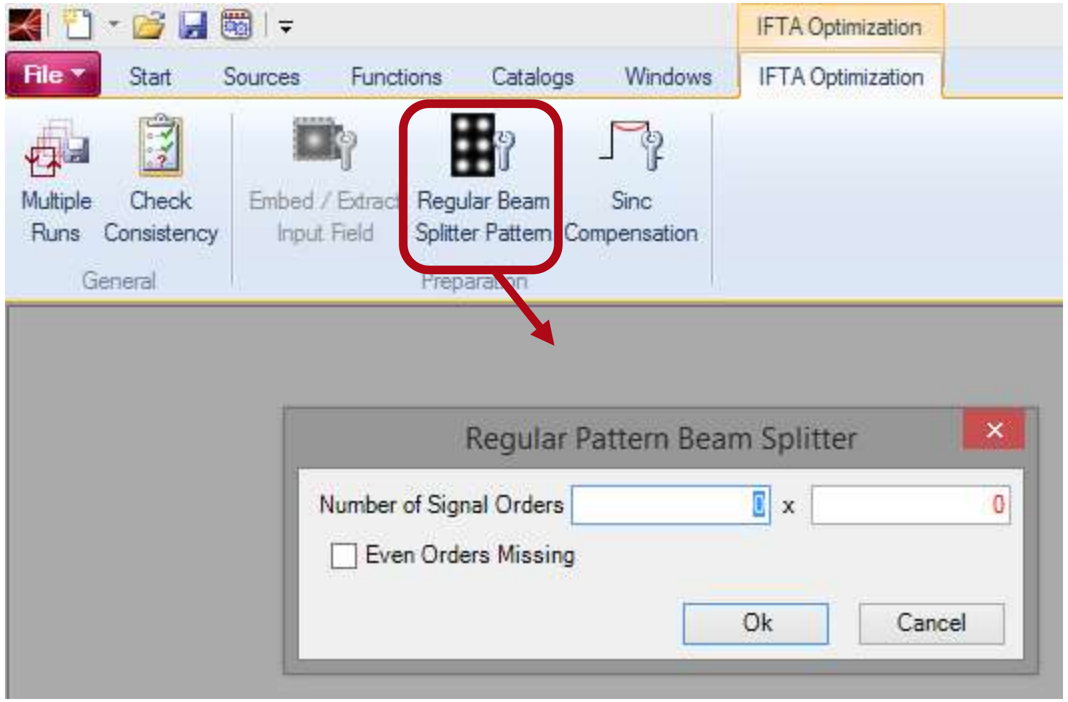
Design Specification



Desired Output Field
(Signal Field)

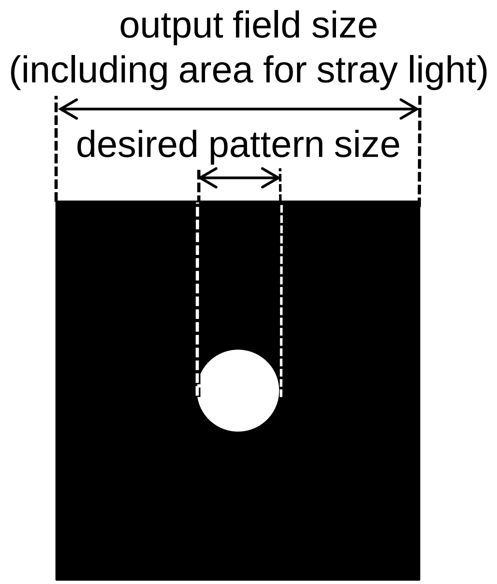
Beam-Splitting Design Specification

Function for Creation of Signal Fields of Regular Beam Splitters

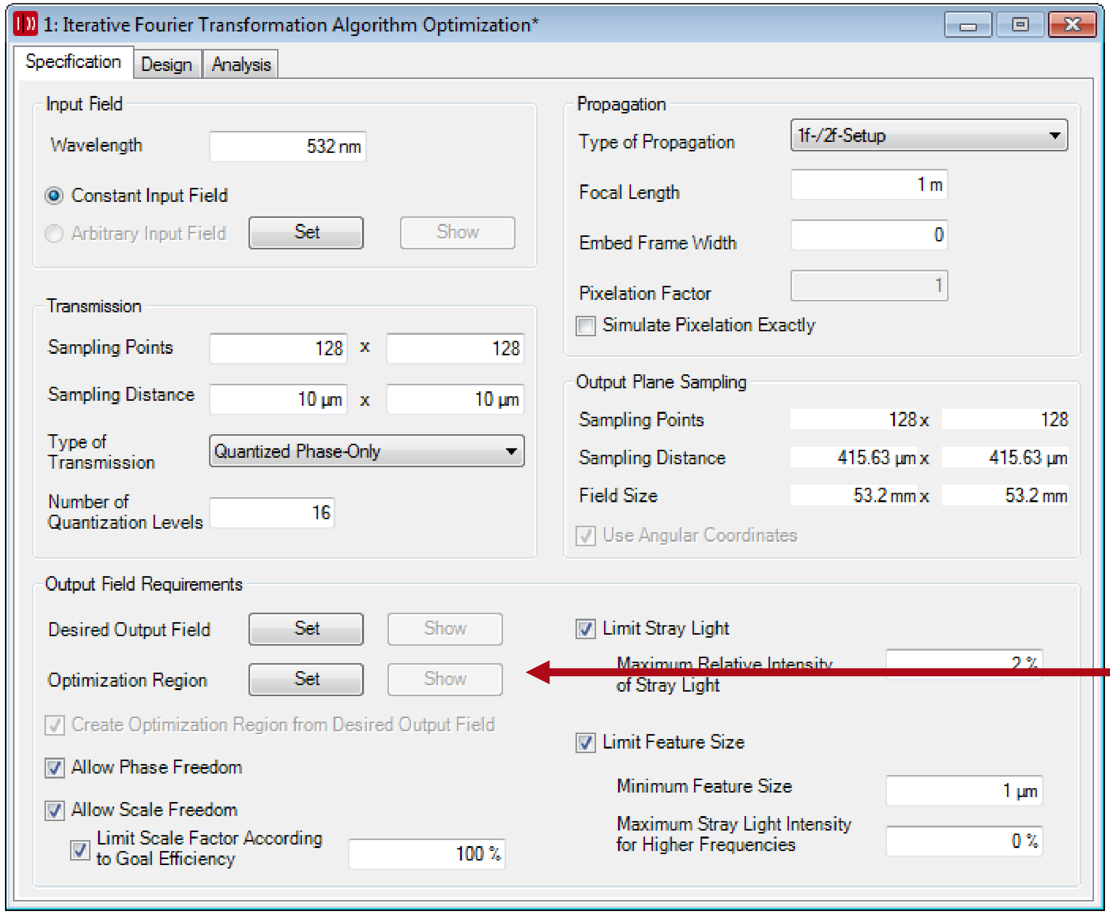


Desired Output Field Size

There is no perfect DOE that deflects all light to 100% as desired, i.e. 100% conversion efficiency. There is always some stray light. Thus it is important to allow the IFTA to place such stray light in certain areas. This is called “amplitude freedom”. The larger the area for this amplitude freedom, the larger the scope of the algorithm to finde solutions with low stray light that can be distributed over a larger area. As rule of thumb for beam splitters and light diffusers we recommend an ouput field size ~4x the desired pattern size.



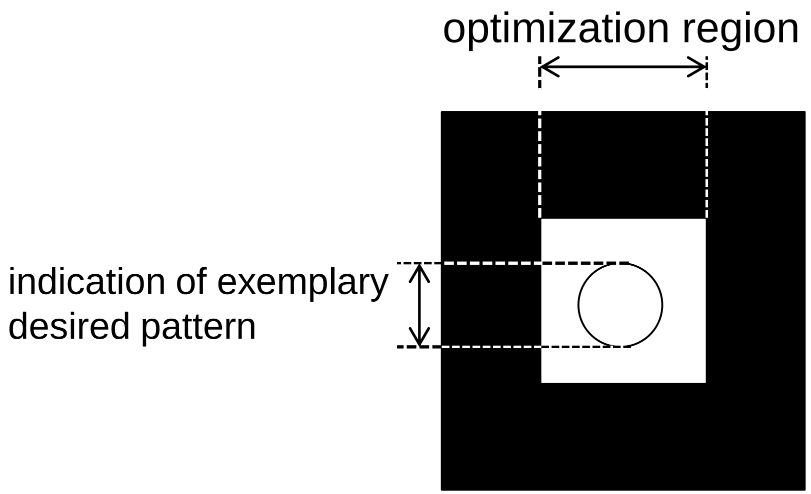
Design Specification



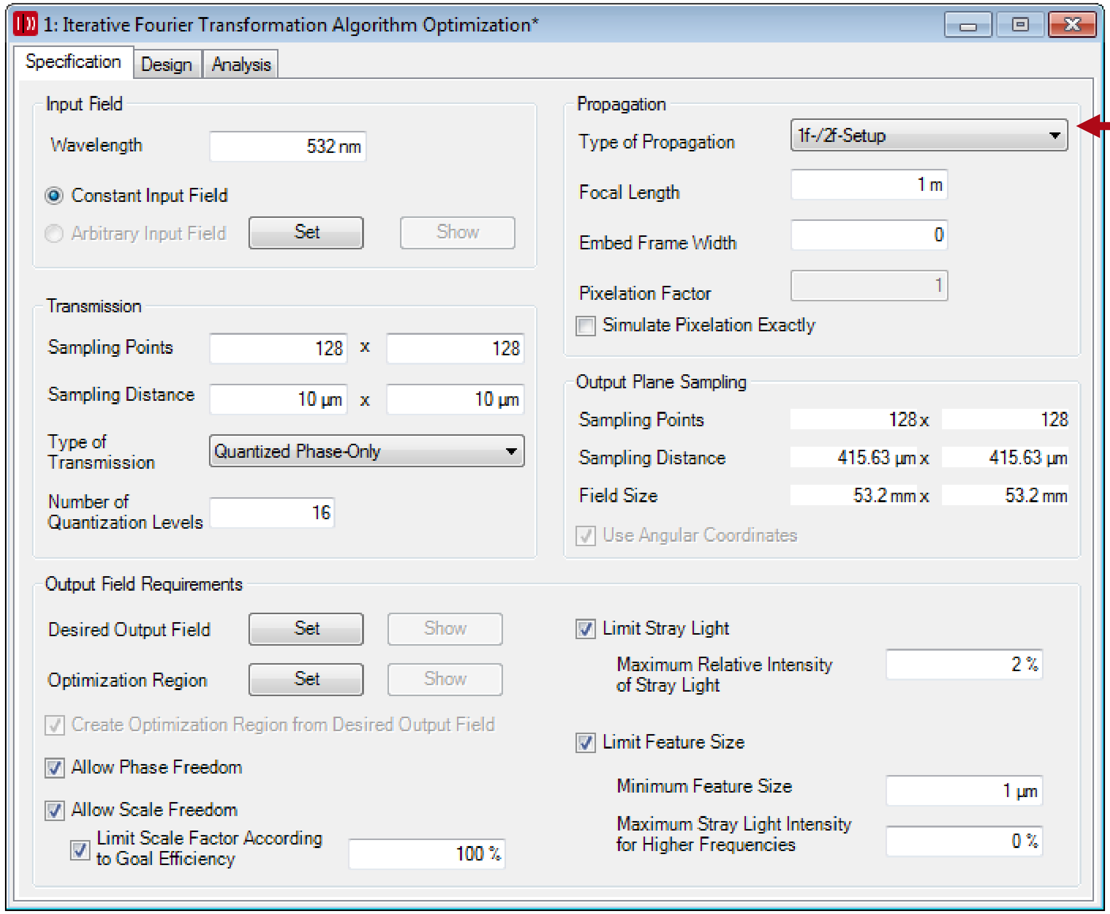
Optimization Region (Signal Region) can be equal to signal field

Optimization Region

The optimization (signal) region specifies by values >0 the area where the IFTA optimizes the target values according the desired output field. Outside of this region the IFTA is allows to place the straylight more freely.
Thus typically in case the optimization region is larger as the desired pattern, the contrast will be improved, i.e. there will be distinctly less stray light in the area of the optimization region, but outside of it, the noise will be more visible.

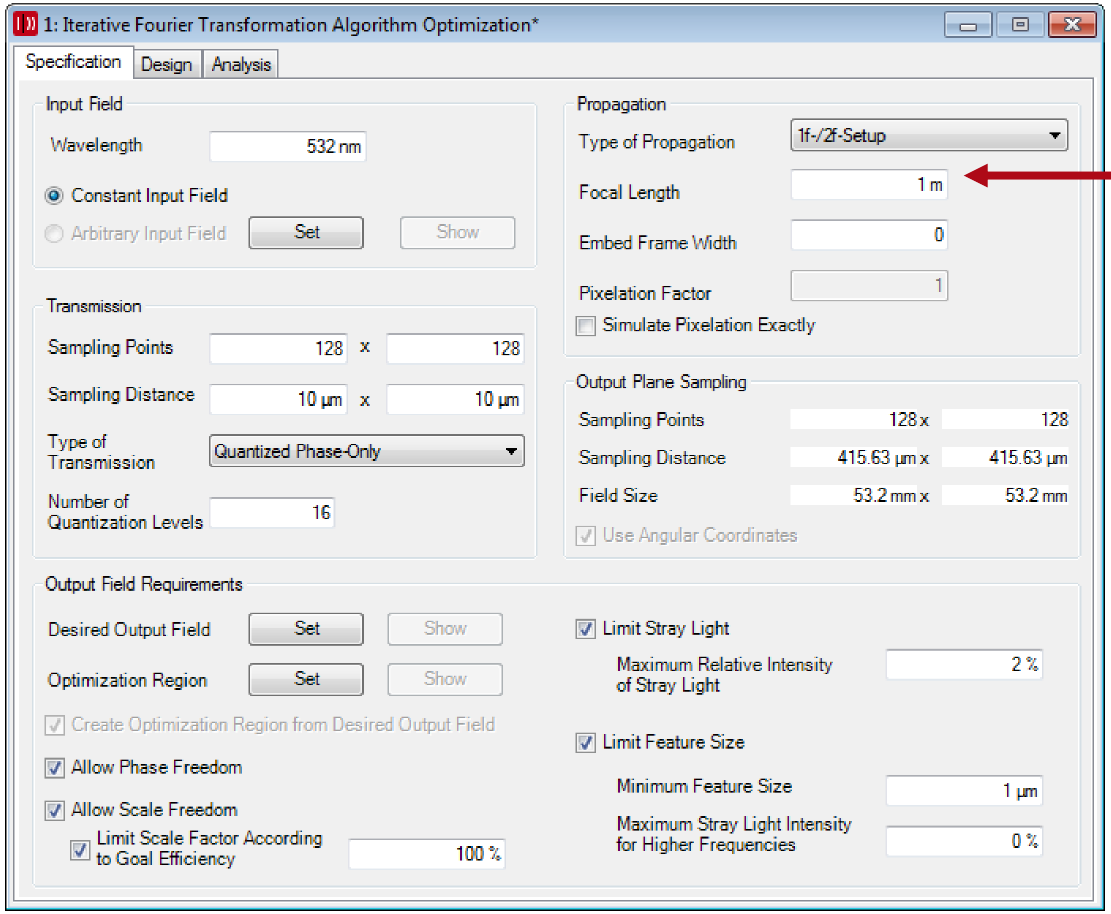


Design Specification



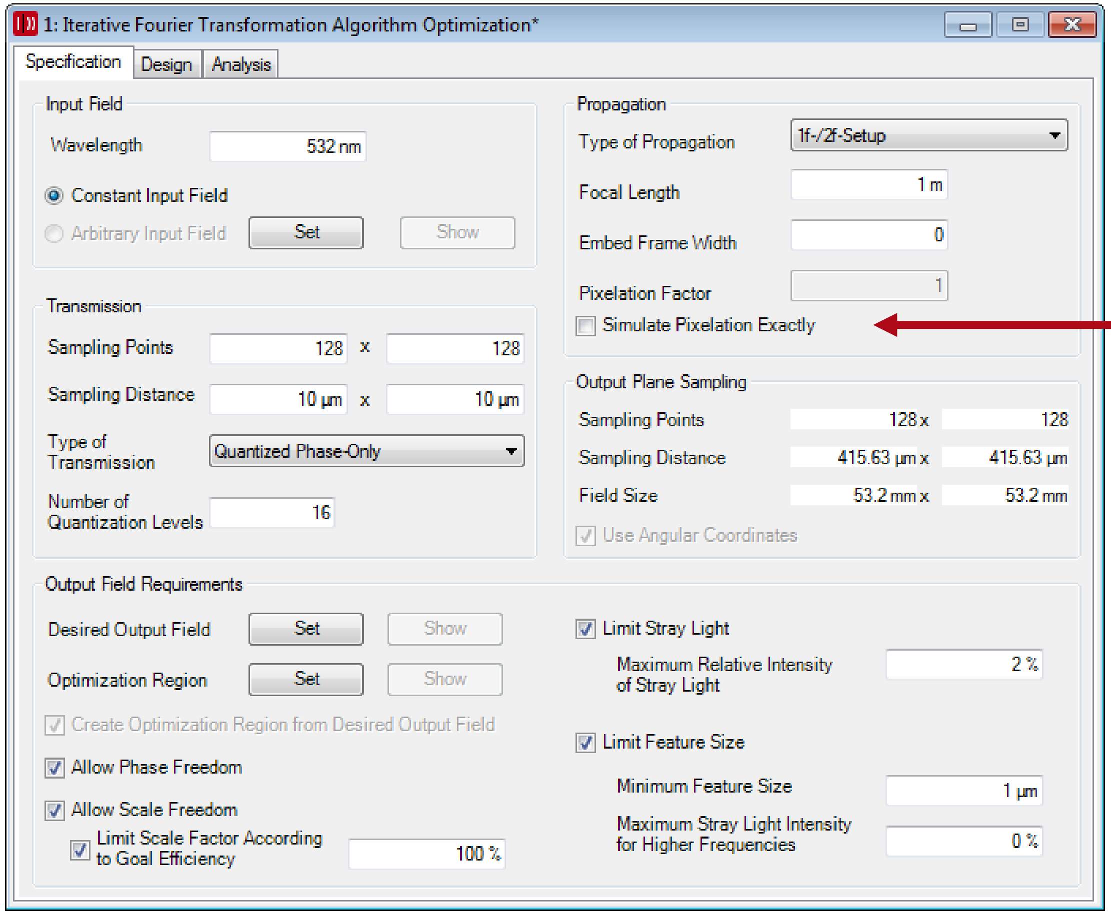
Propagation method: Far Field (1f or 2f Setup)

Design Specification



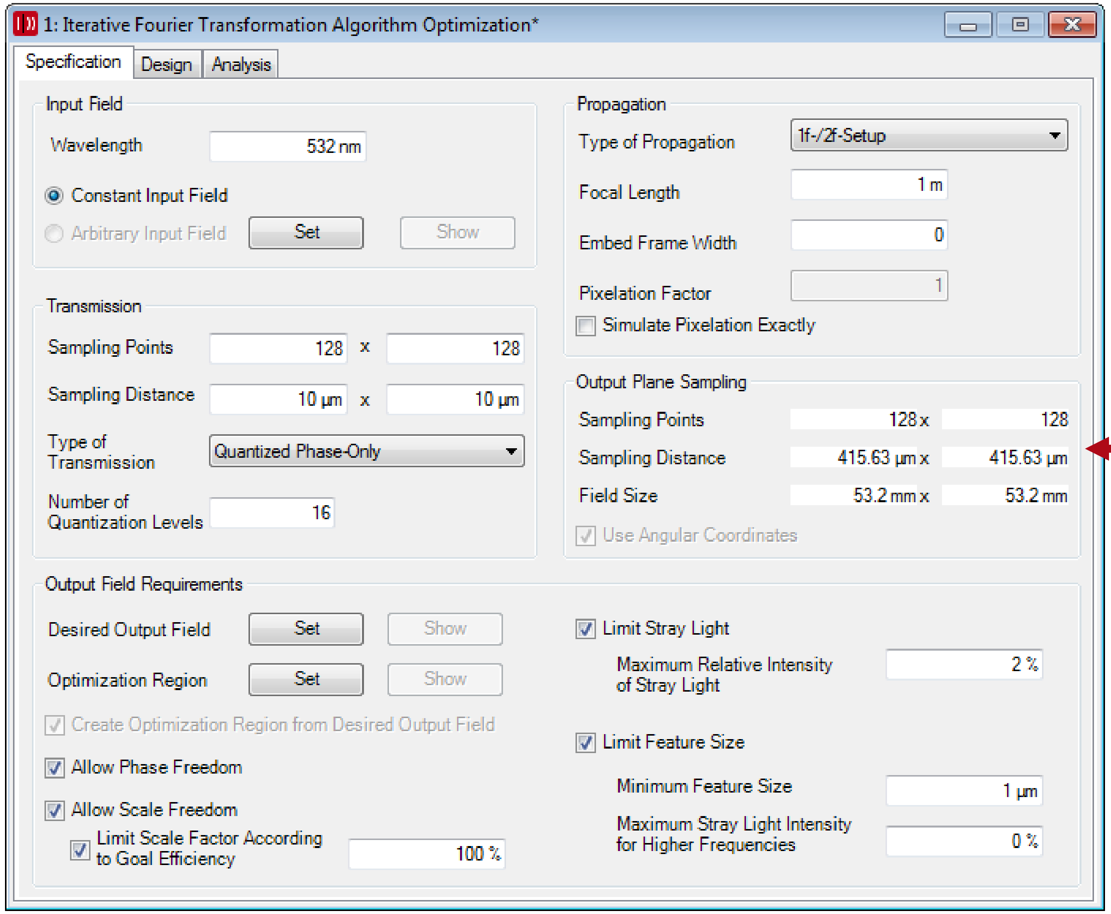
Focal length in case of 2f-setup

Design Specification



Simulate pixelation during design

Design Specification

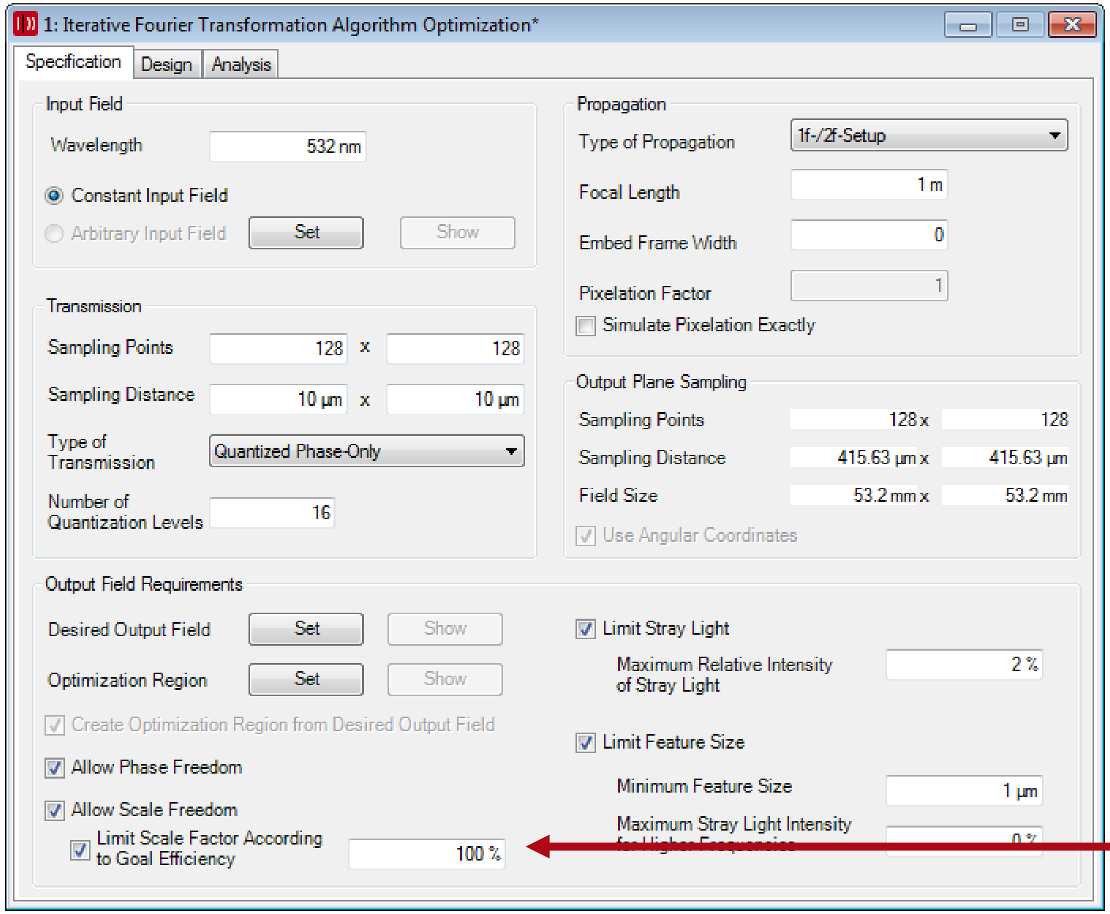


Signal field sampling parameters (are set automatically due to transmission parameters)

Advanced Optimization

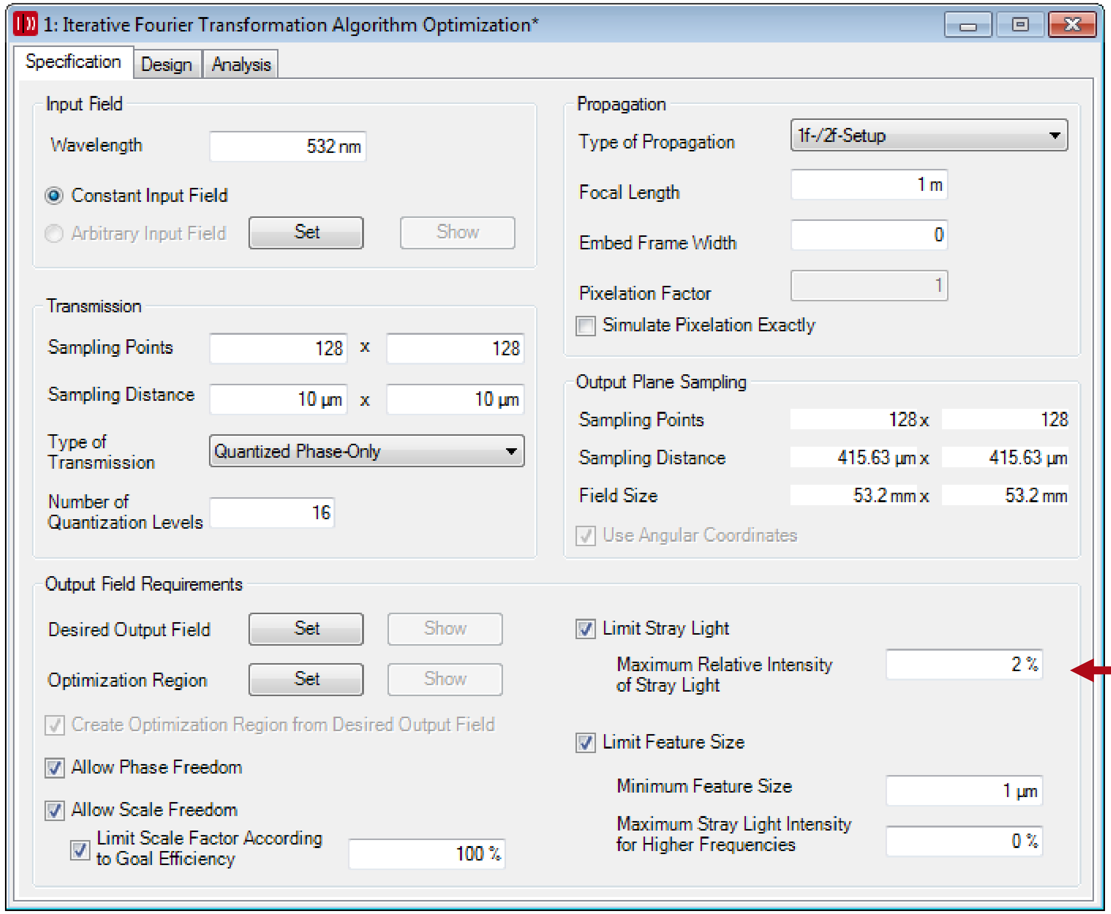
- Normally the IFTA maximizes the SNR.
- The conversion efficiency is reduced as necessary.
- The goal efficiency allows to find the best solution for a given conversion efficiency.
- It helps to find compromises between SNR and conversion efficiency.

Additional Design Specifications



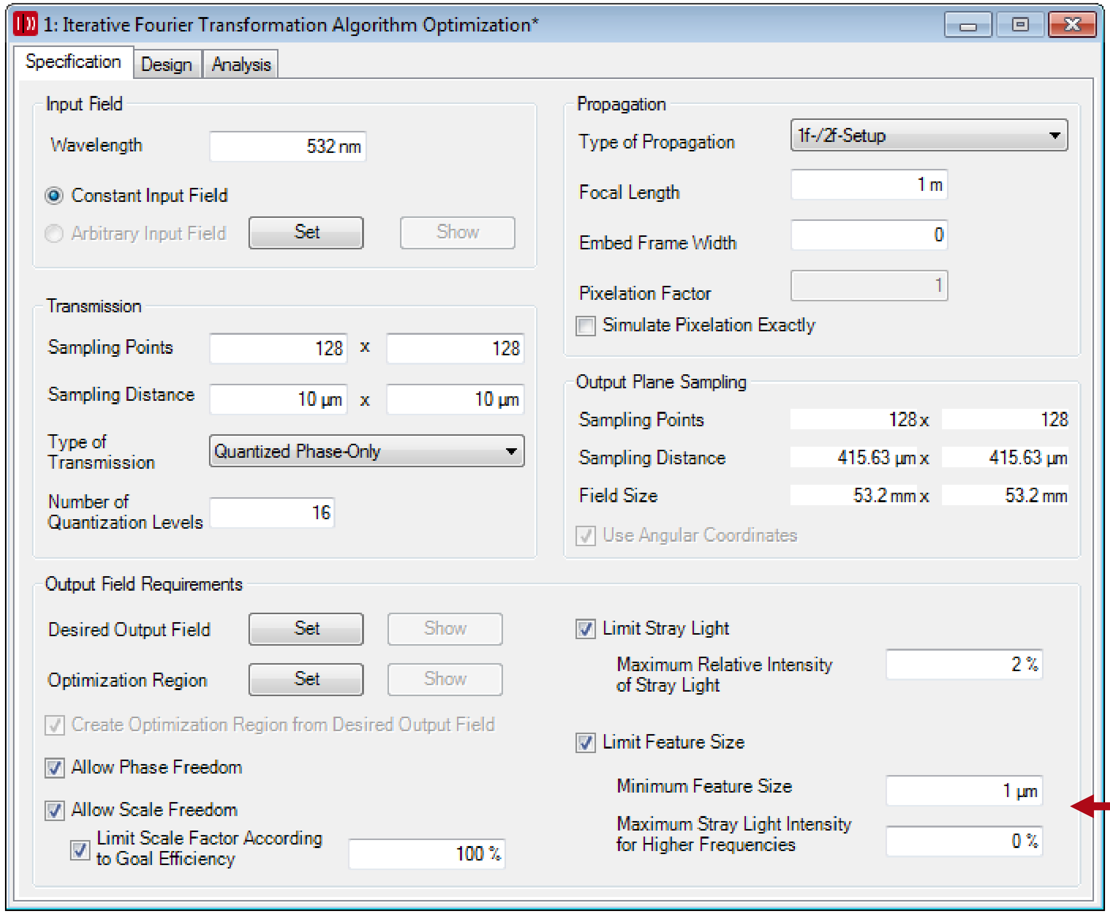
Goal efficiency

Additional Design Specifications



Limits the noise intensity relative to the signal orders

Additional Design Specifications



Limits the feature size of the structures

Overview of Parameters and Effect

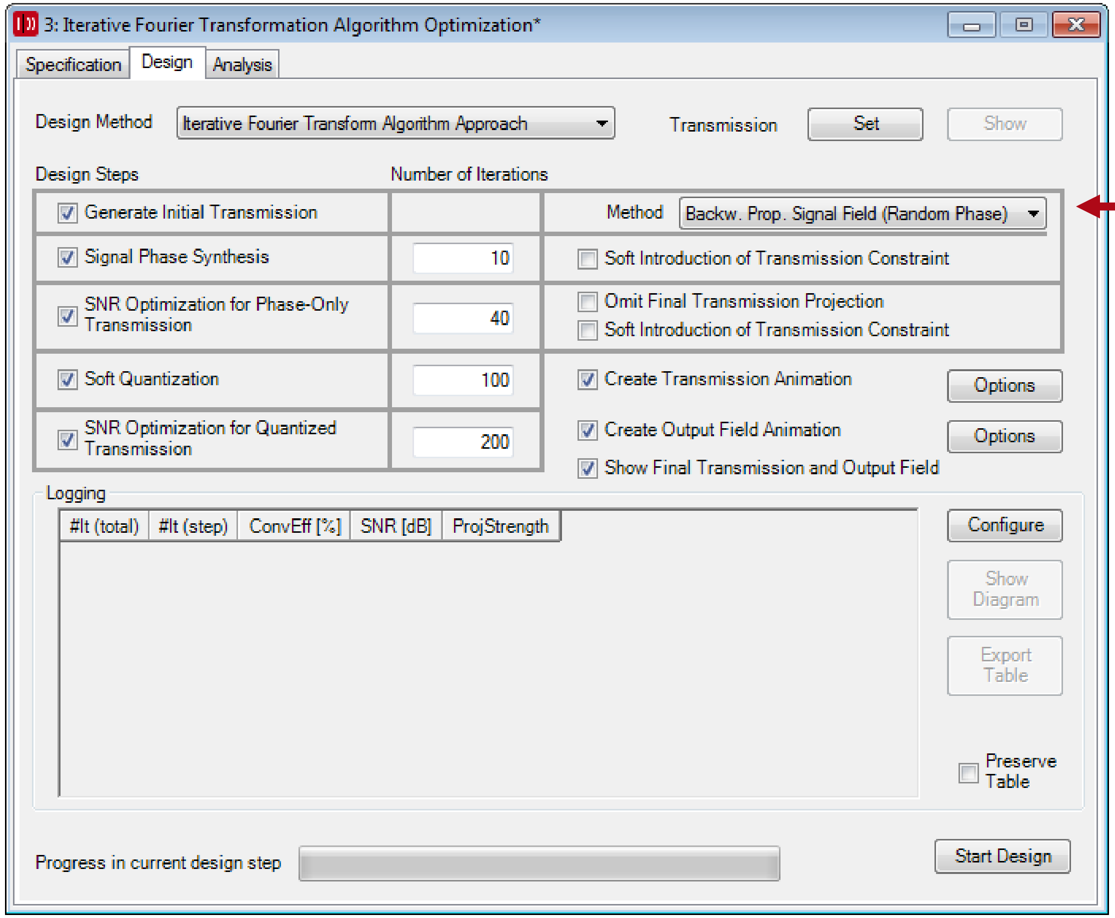
Parameter		Effects on Merit Functions and Structures			
Name	Parameter Change	Uniformity Error	Efficiency	Maximum Noise	Feature Size
Output Field Diameter	increased	decreased and converges to limit	increased and converges to limit	decreased and converges to limit	decreased
Goal Efficiency	increased	increased	increased, theoretical maximum efficiency exists	decreased	number of small features is reduced
Limit Maximum Relative Noise Intensity	decreased	typically increased	typically decreased	decreased	decreased
Feature Size Limit	introducted	increased	decreased	increased	can be controlled

Red Cells indicate main purpose of the parameter change.

IFTA: Design Procedure Settings

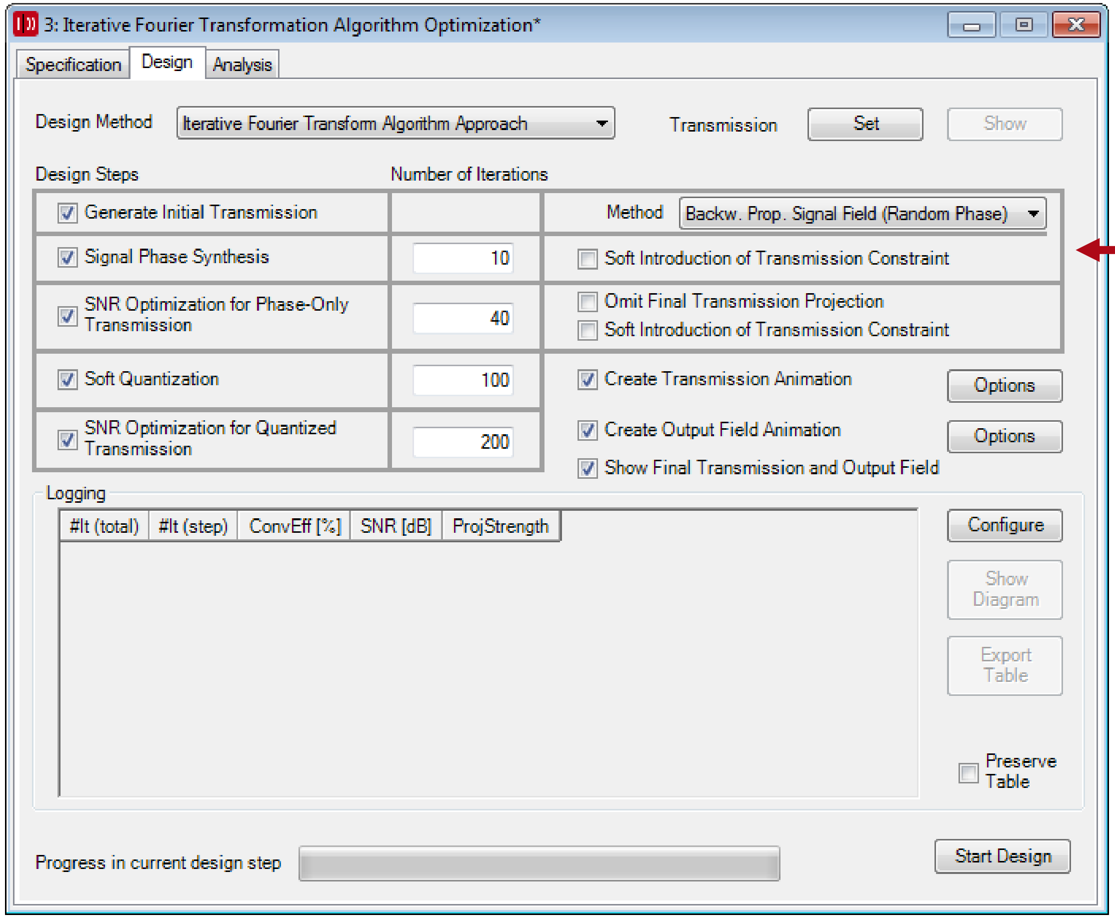
- The design process consist of up to 5 different steps that will be explained in the next transparencies.
- Further, the user can decide and specify which and how certain steps are to be executed.
- Depending on the design specification settings not all steps are allowed.

Generation of Start Transmission



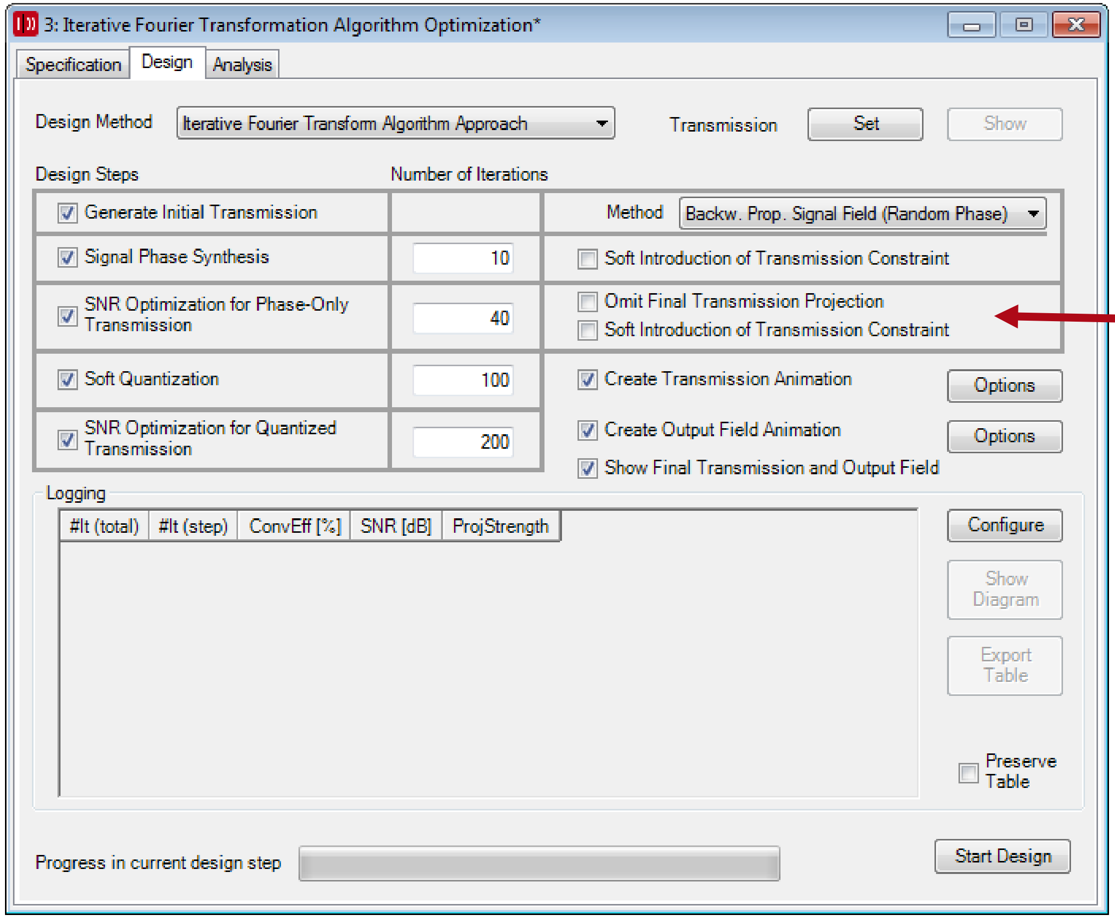
Generation of start transmission

Phase Synthesis



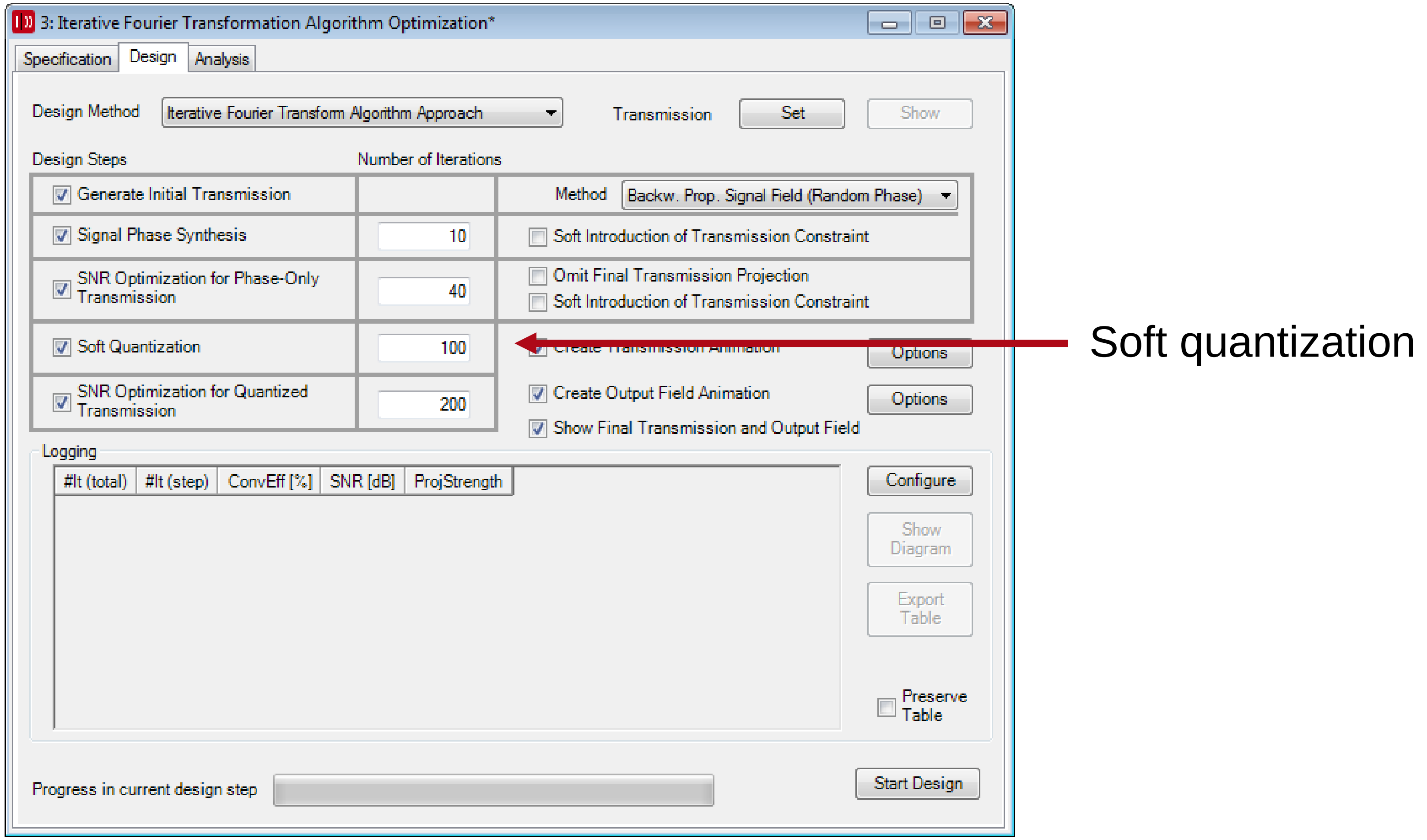
Phase synthesis

Phase Synthesis

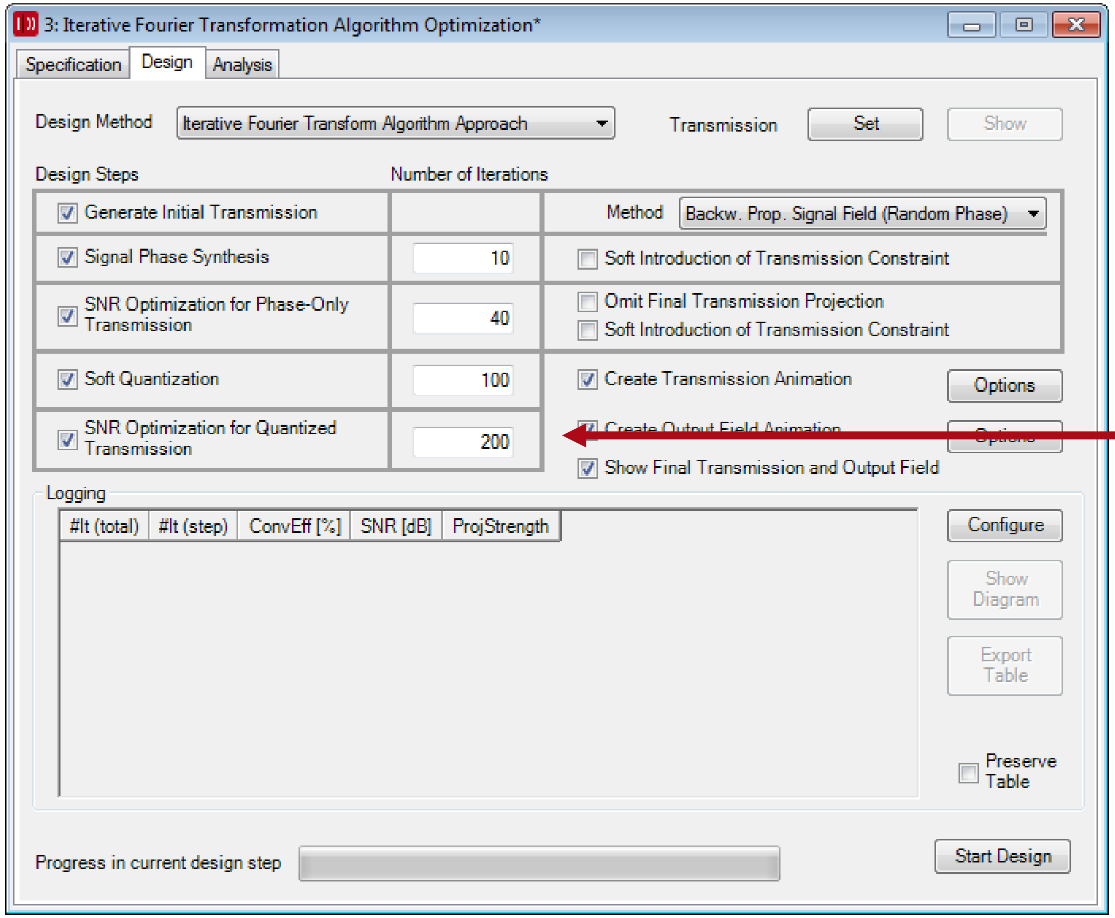


SNR Optimization of Transmission without Discrete Levels.

Soft Quantization

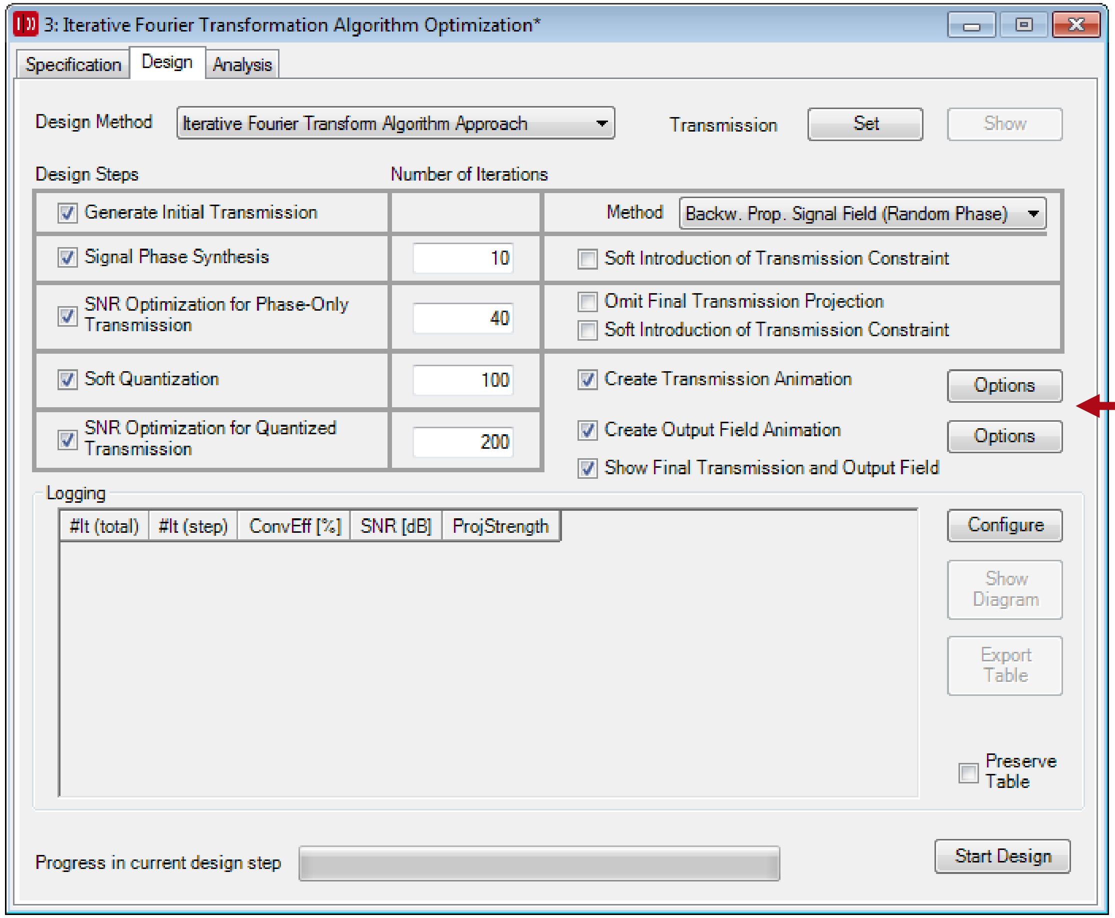


SNR Optimization Quantized Transmissions



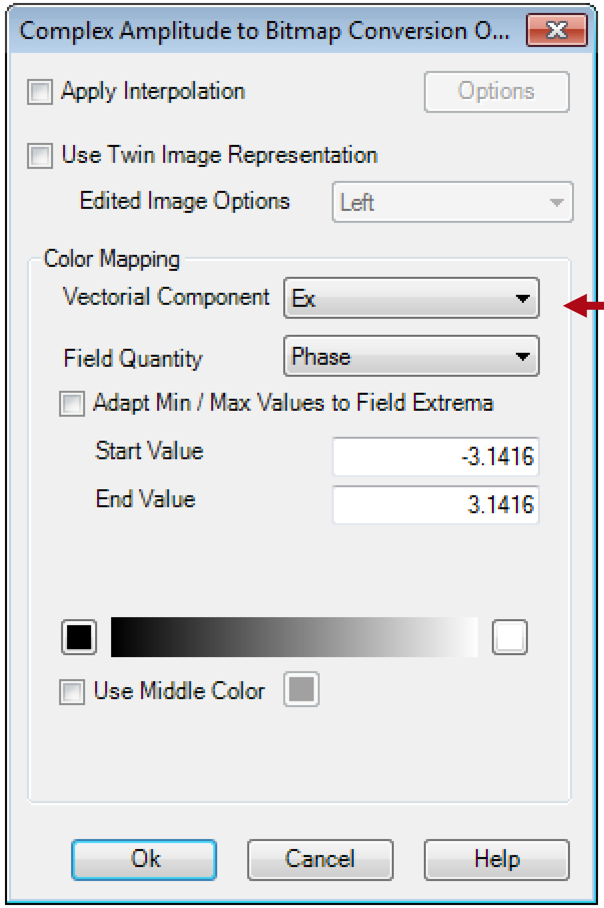
SNR optimization for quantized transmissions

Animation



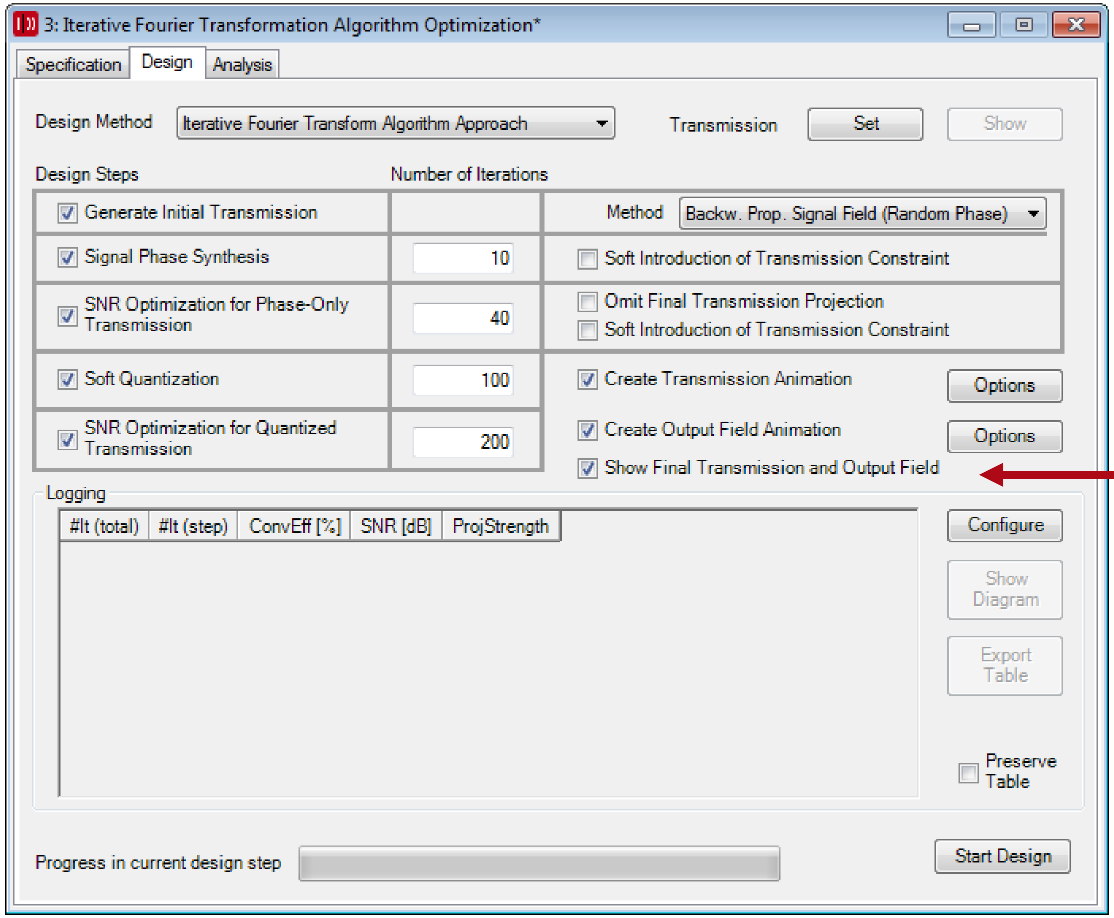
Activates animations during the optimization

Animation



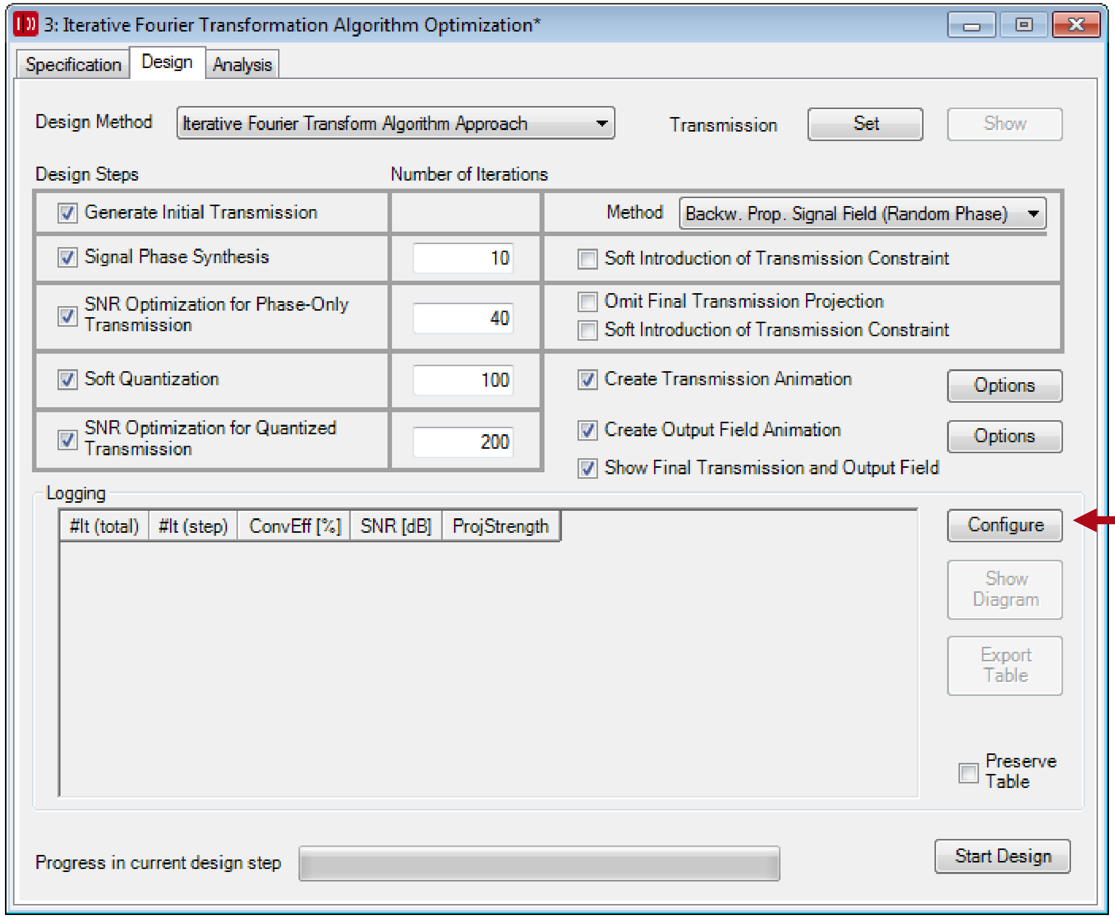
Field quantity to display

Animation



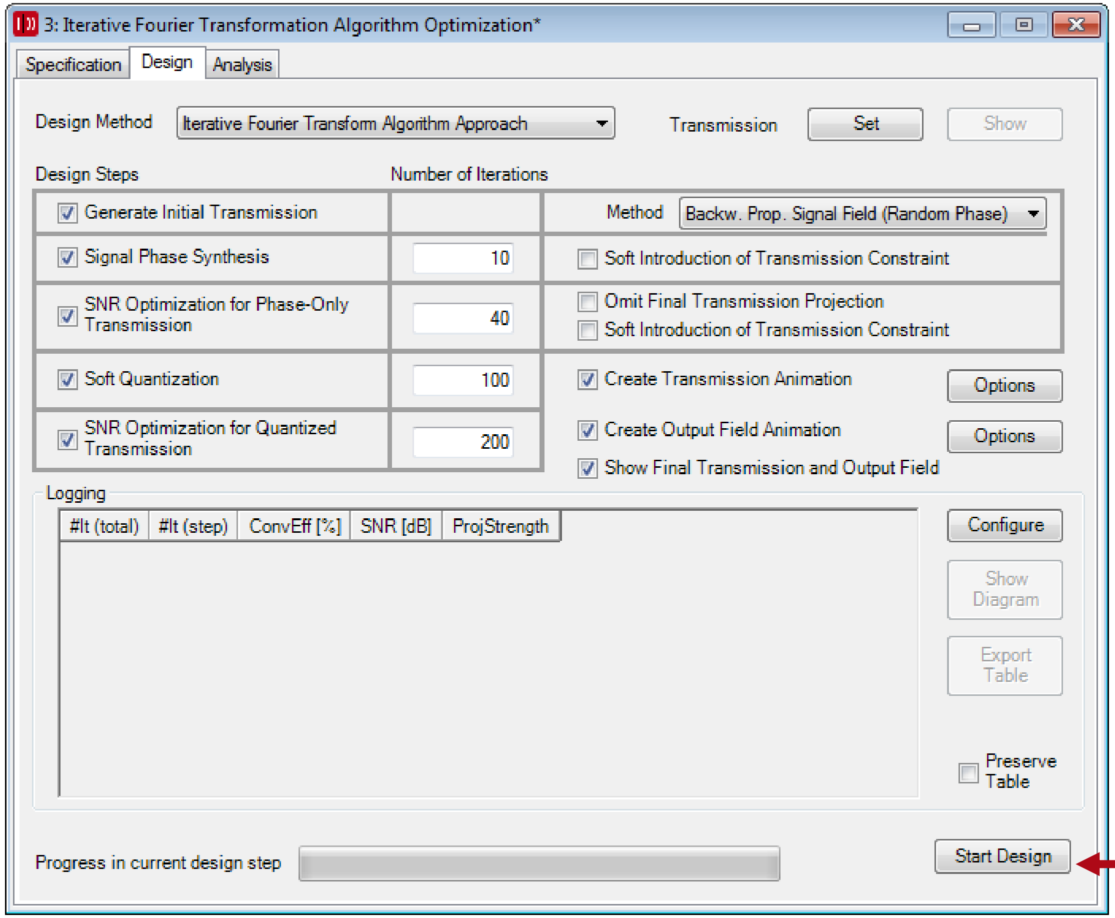
Displays Transmission and Output Field after End of the Optimization

Animation



Selection of merit functions to be logged during the optimization. Logging of merit function is not required for success-full optimization and costs additional time.

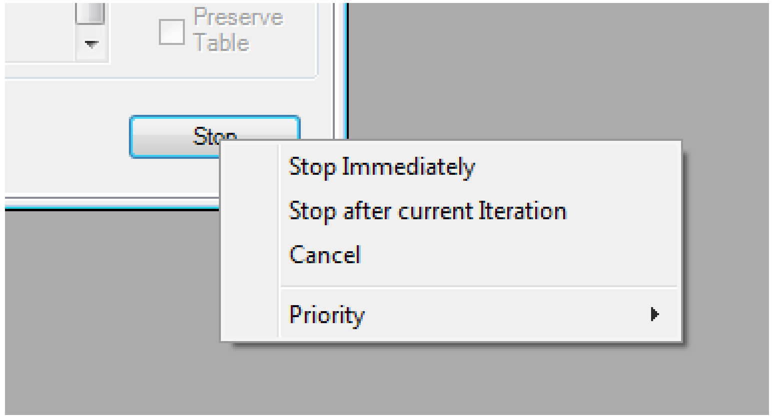
Start/Stop of Optimization



Start/Stop button

Start/Stop of Optimization

Start/Stop of Propagation



Allows to

- stop optimization immediately
- stop optimization after finishing of iteration
- change simulation priority

IFTA Result Evaluation

IFTA Evaluation for Splitters & Diffusers

Plane Wave Input

- By default the IFTA performs the design and optimization based on a plane wave as input light.

Diffraction Orders

- This plane wave is then deflected into diverse directions defined by the designed DOE. These directions generated by such a DOE are called diffraction orders.

1 Plane Wave – 1 k-Value

- A Fourier transform of a single ideal plane wave gives exactly one value in the Fourier domain representing its direction.

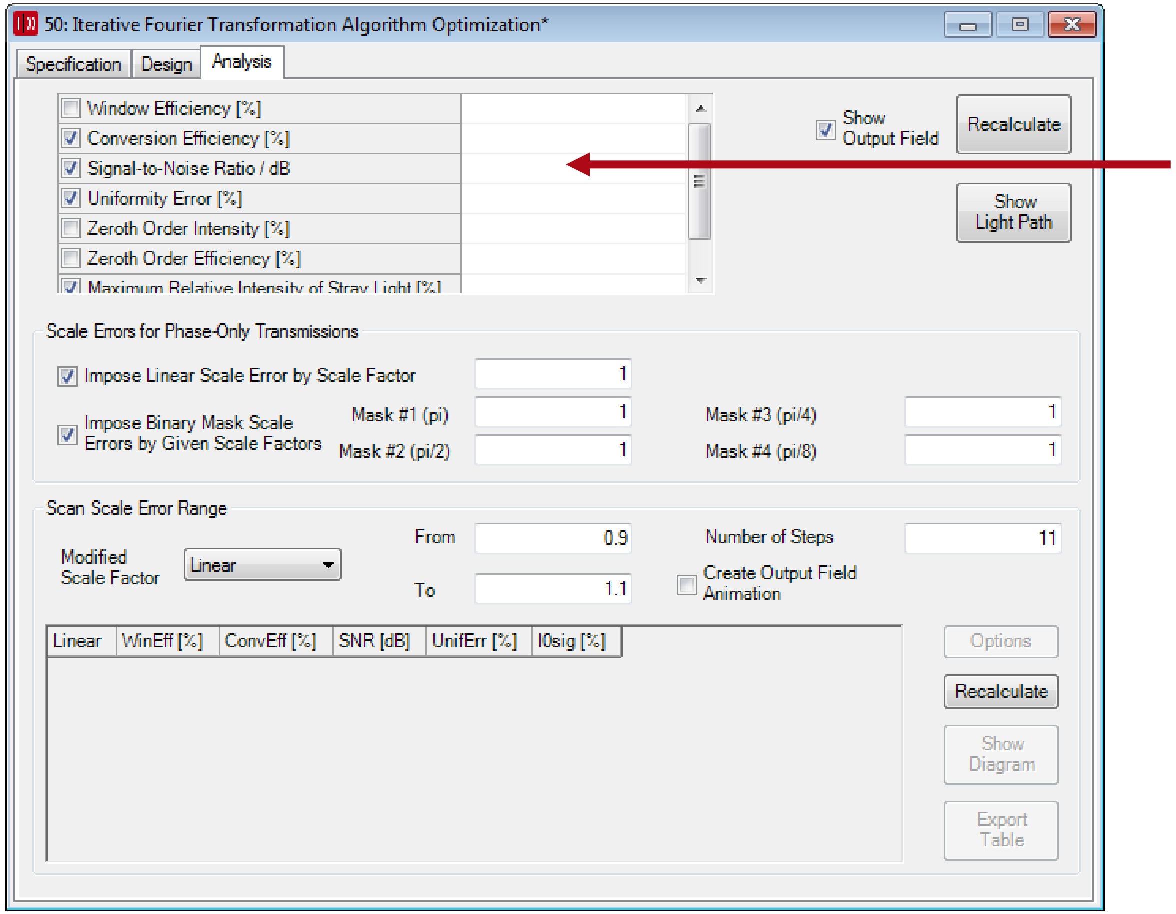
FT → 1 Pixel per Diffraction Order

- Thus by Fourier transform of the regarded field directly behind the DOE (consisting of these different plane waves with different directions) each of these deflected plane waves create one (pixel) value in the calculated output plane. I.e. each pixel represents the efficiency of the particular diffraction order.

Final Evaluation → Real Source

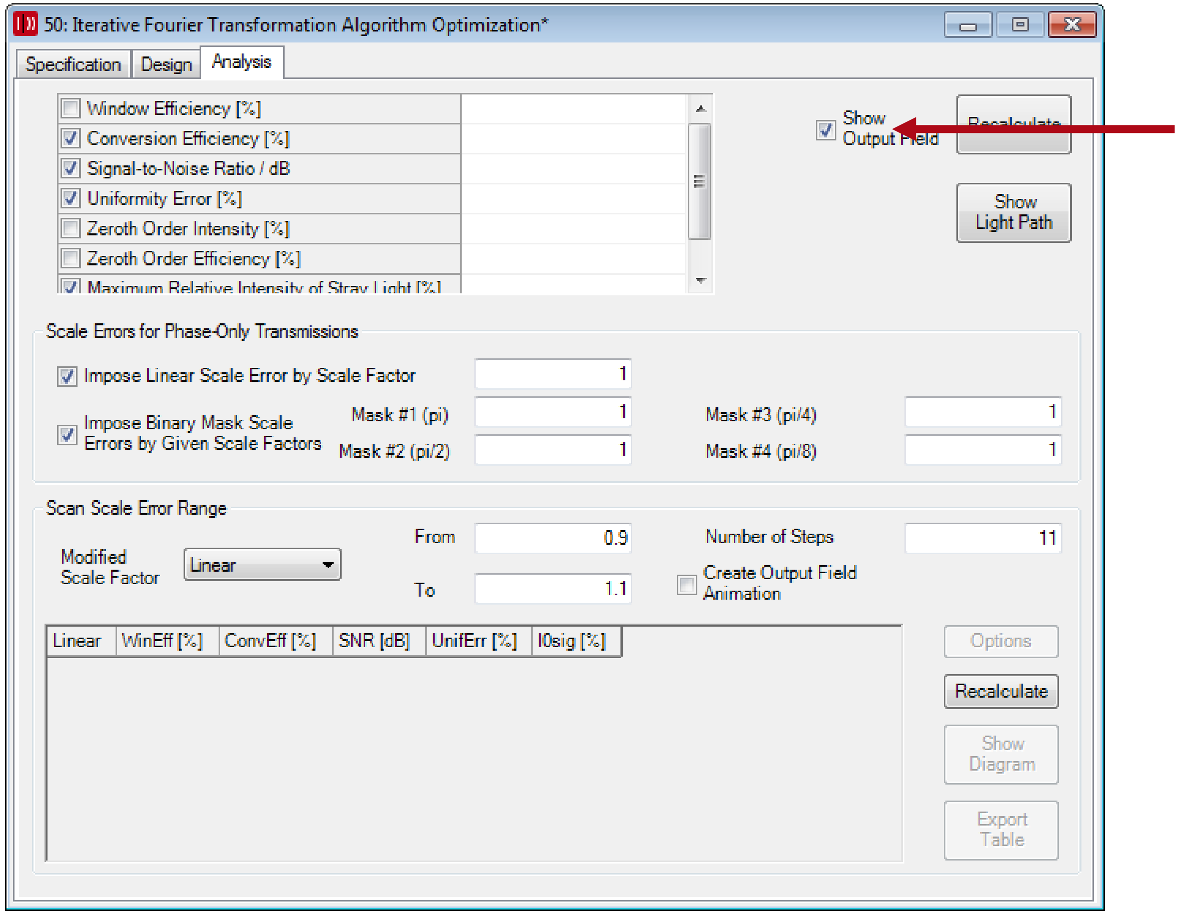
- Later a real input light (e.g. a Gaussian beam) is used. This does not change the effect.
  Now, instead of a plane wave, this Gaussian is deflected accordingly. And to each deflected Gauss beam there is a corresponding diffraction order, whose calculated efficiency defines the energy carried by this particular Gaussian.

Analysis of Transmission Design Result



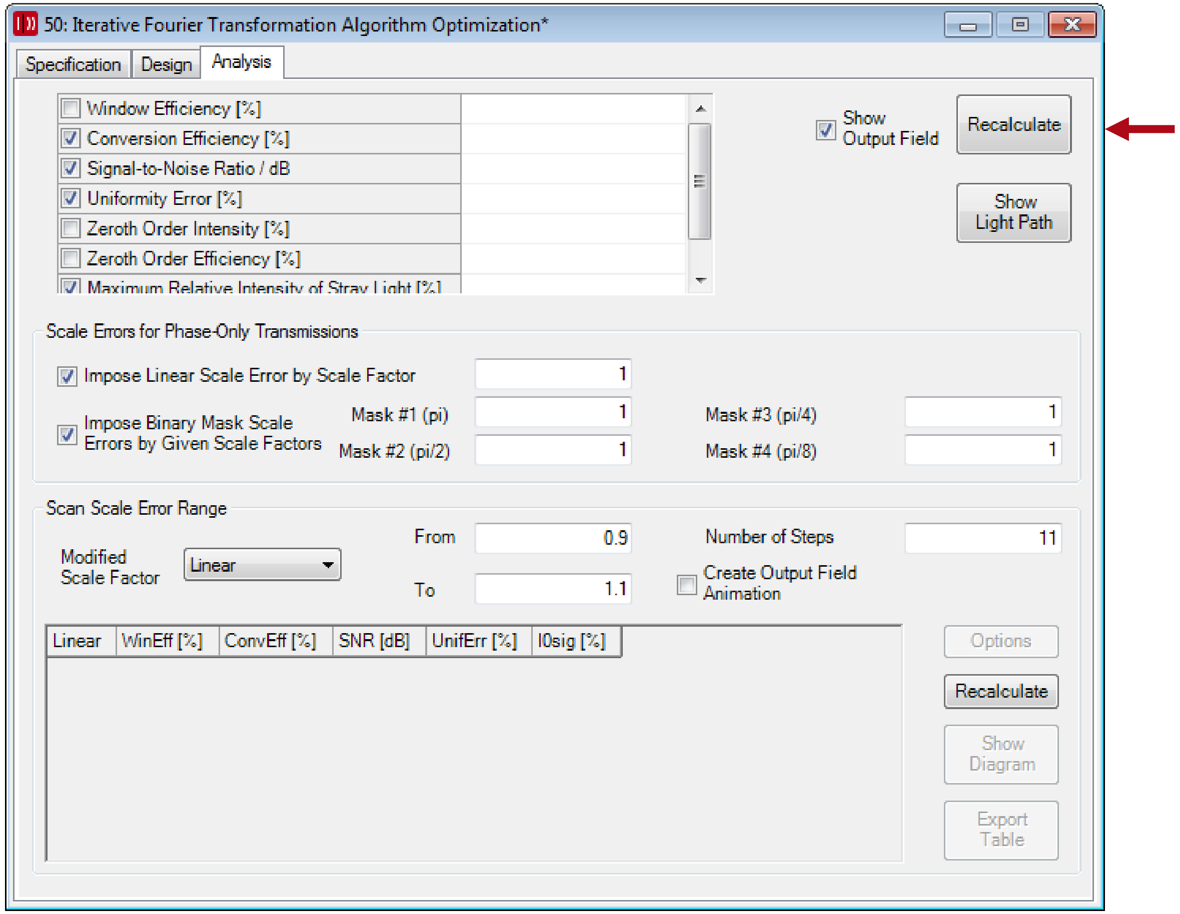
Selection of merit functions and merit functions results.

Analysis of Transmission Design Result



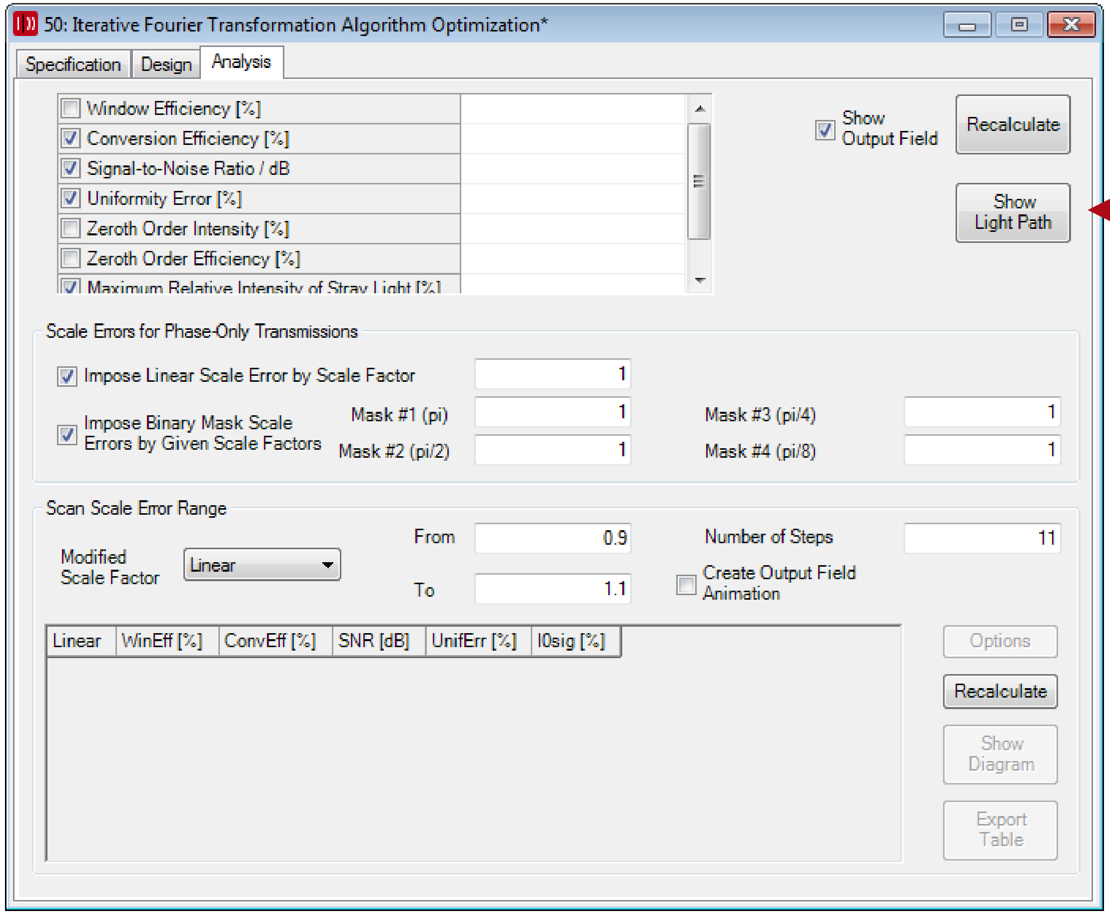
Displays field in target plane.

Analysis of Transmission Design Result



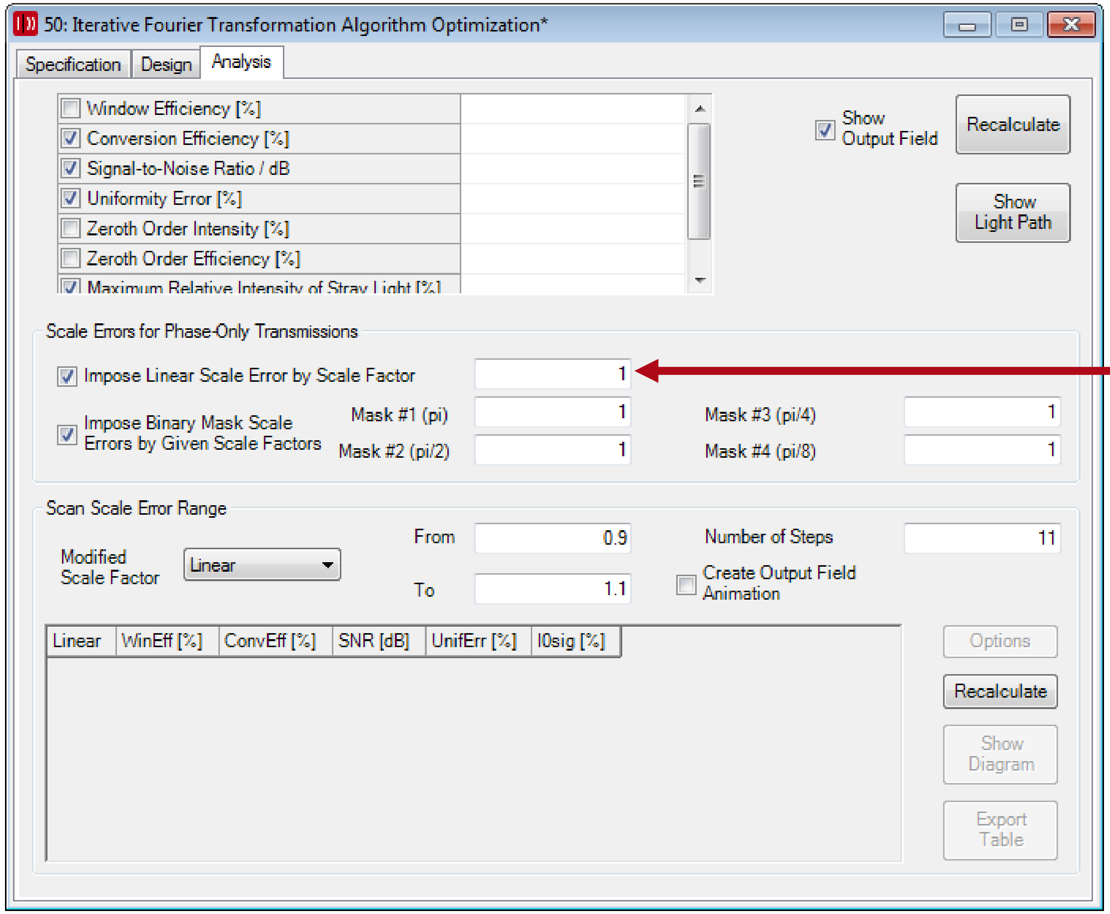
Recalculates field in target plane and merit functions results.

Analysis of Transmission Design Result



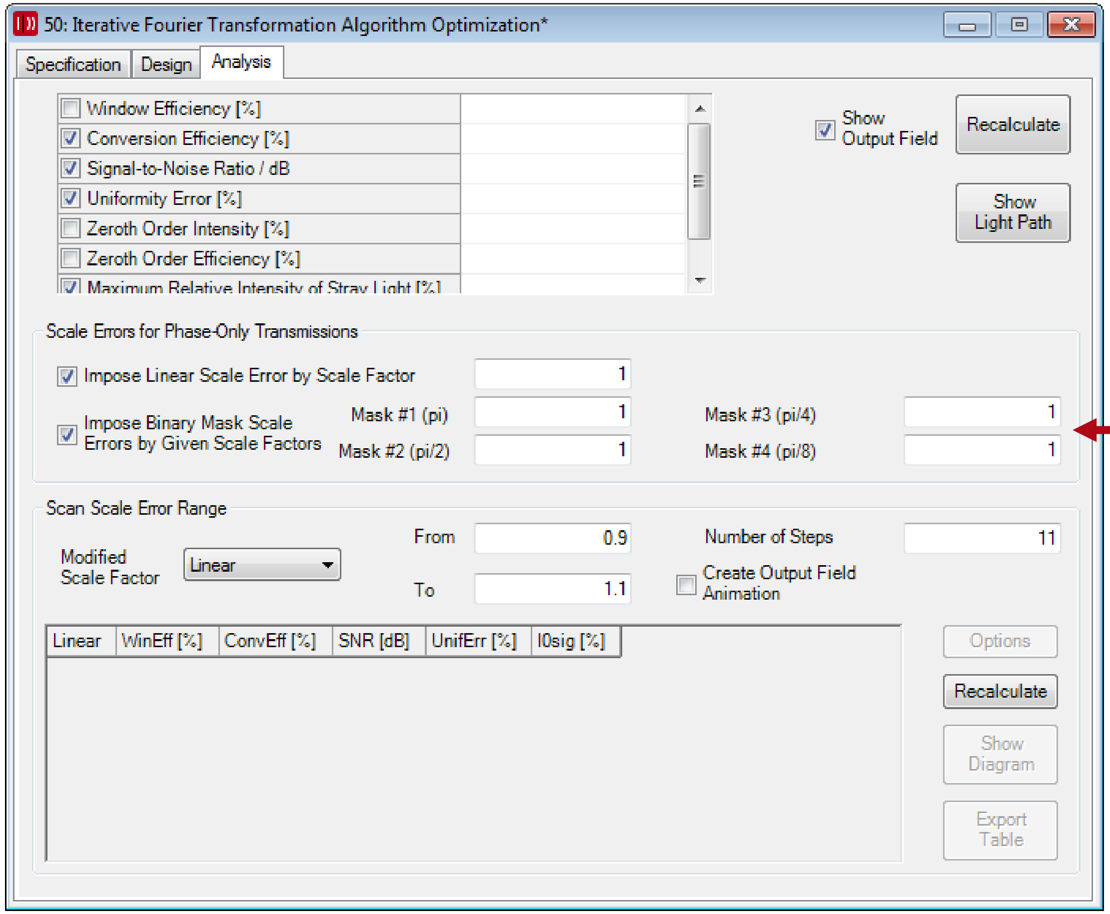
Creation of light path diagram

Analysis of Transmission Design Result



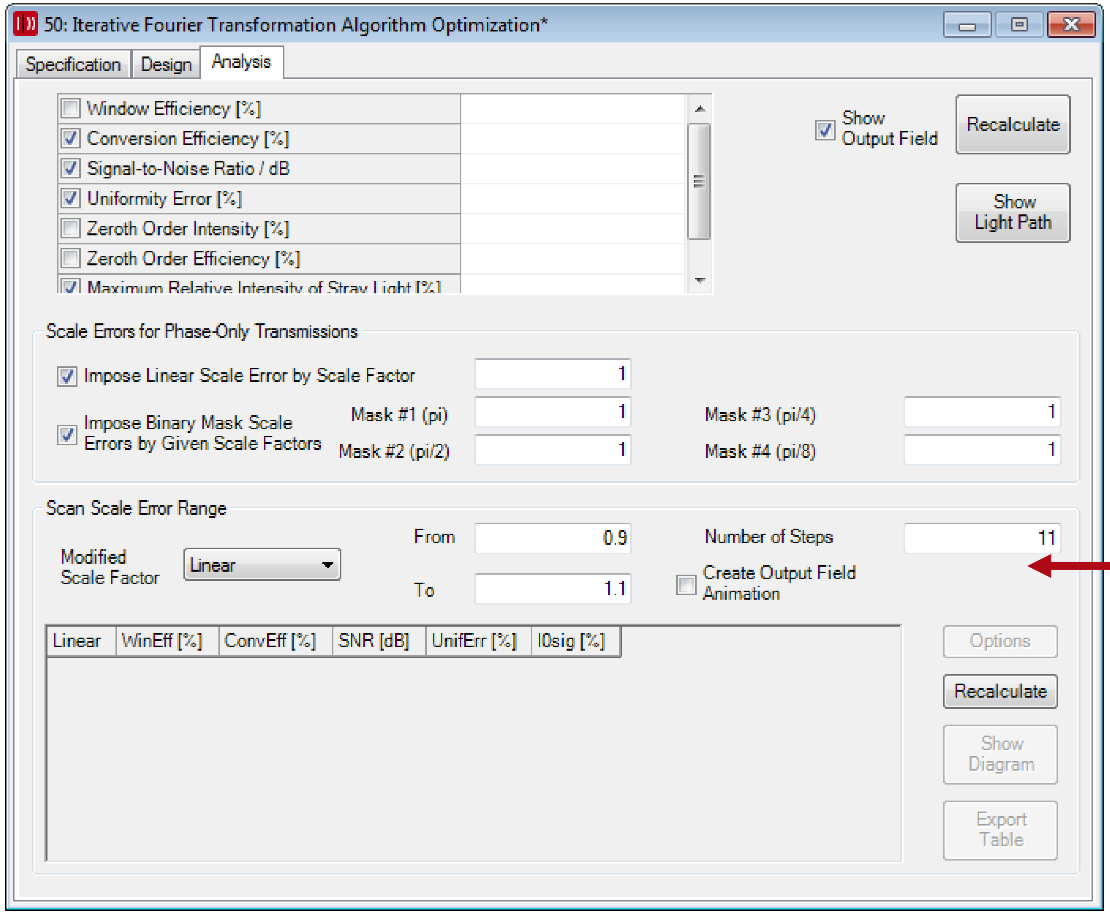
Simulation of linear scale errors

Analysis of Transmission Design Result



Simulation of scale errors of different masks

Analysis of Transmission Design Result



Scale errors can be varied within a defined range

Workflow of DOE design

- Parameters of DOE and related pattern calculation
  - DOE:
    - pixel size δx
    - Period p <beam size d
  - Pattern
    - Size D_{pattern} (with scaling factor a, one may know the design pattern size $D_{\mathrm{design}} = D_{\mathrm{pattern}} * a$
    - Resolution Δx
  - From manufacture, one may get the data δx and d, then calculate the size and resolution of pattern
    - $D_{\mathrm{pattern}} = \frac{\lambda z}{a * \delta x}$ (far field) or $D_{\mathrm{pattern}} = \frac{\lambda f}{a * \delta x}$ (1f/2f setup)
    - $\Delta x = \lambda z / p$(far field) or$\Delta x = \lambda f / p$(1f/2f setup)
- Input the parameters into session editor
- IFTA to design the transfer function

Workflow of DOE design

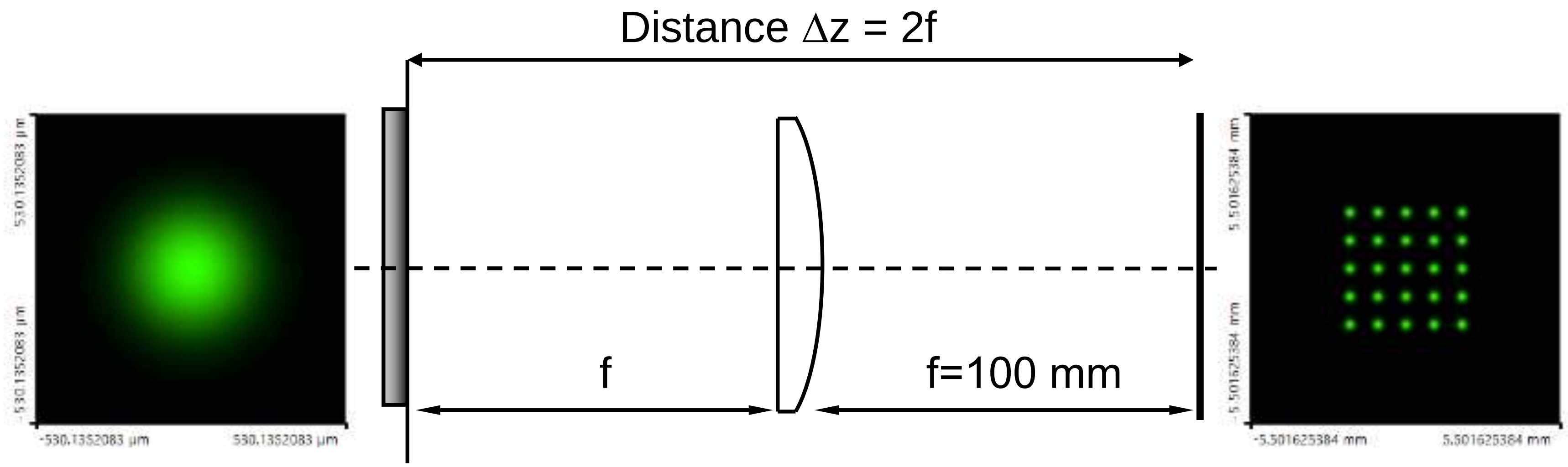
- Parameters of DOE and related pattern calculation
- Input the parameters into session editor
- IFTA to design the transfer function
  - Check the step numbers of each processure
  - Multi-run is sometimes necessary
- Design the structure from transfer function
- Check the simulation result
  - High NA need the further optimization of the real structure
- Tolerance analysis
- Export the real structure

Illustration

Optimization of Diffractive Optical Elements

Design of Regular Array Beam Splitters

Illustration Beam Splitter



Wavelength: 532nm
Laser Beam Diameter (1/e²): 200µm

Diffractive Beam Splitter Element
4 Phase Levels
rect. 1x1 mm Diameter

Fourier Lens

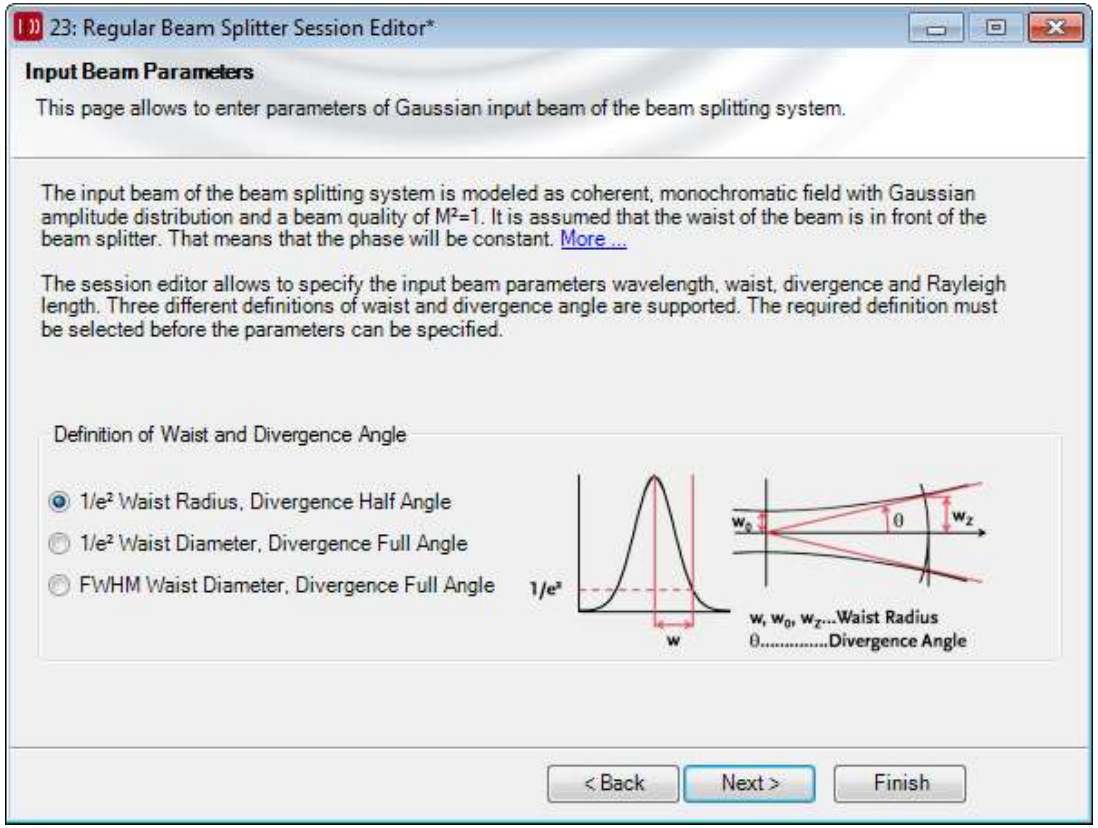
Target Plane

Spot Array of 5 x 5 discrete Beam Spots

Regular Array Beam Splitters

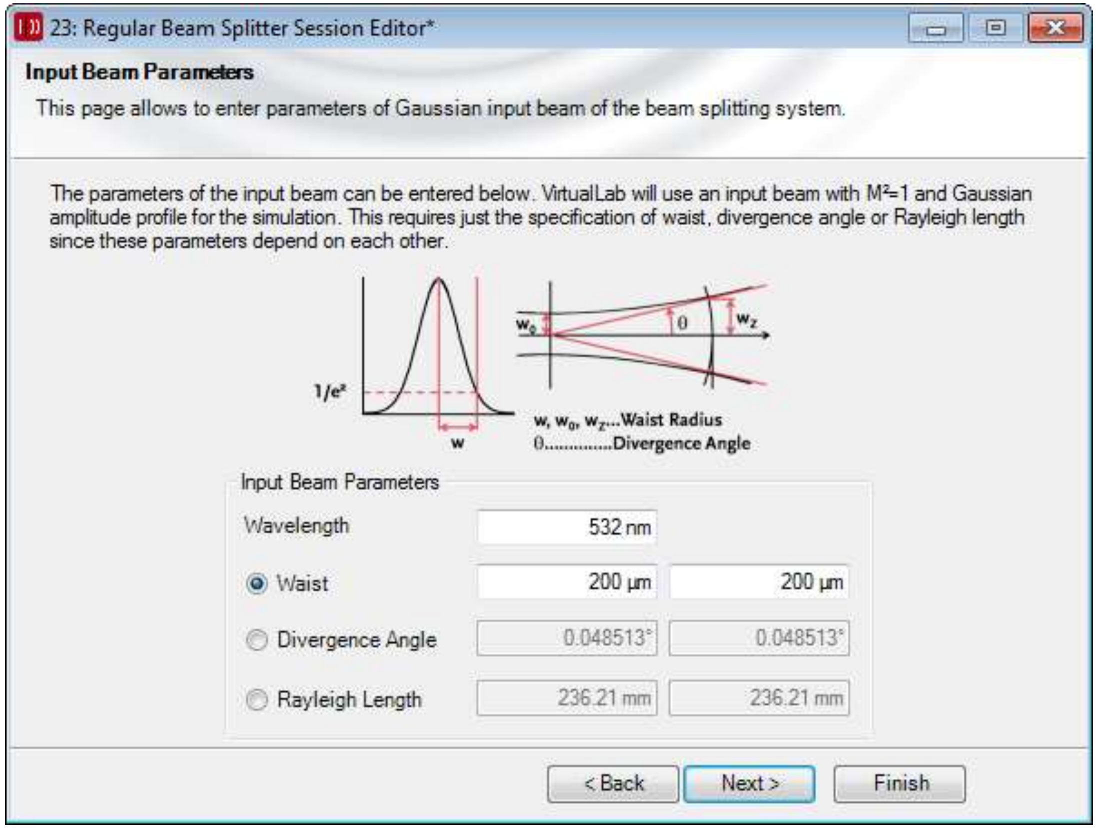
- Design of periodic diffractive beam splitters.
- Design of beam splitters for splitting of one laser beam in rectangular array of beams with equal power.
- All beams are on equidistant grid.
- Session editor assists users during generation of *Optimization Document* and *Light Path Diagram*.

Regular Array Beam Splitters



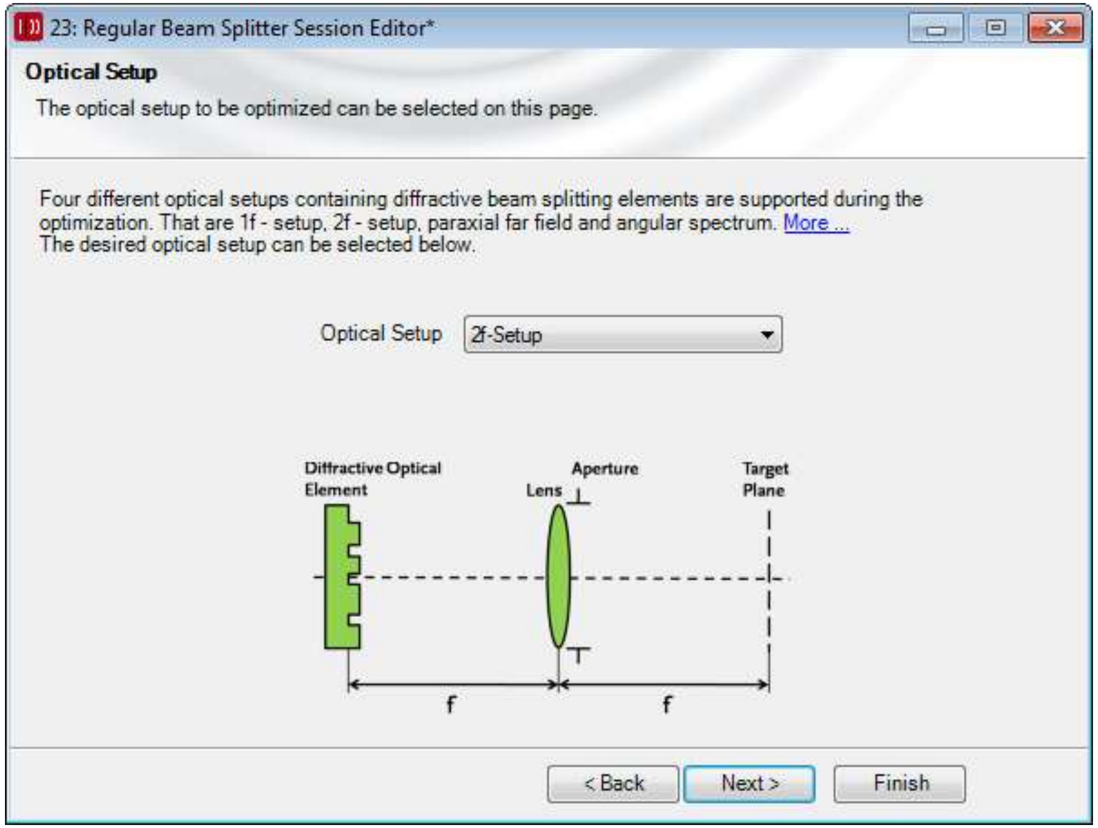
- Specification of Gaussian illuminating beam.
- The beam is just used to check if the spot diameter in the target plane is smaller than the order distance.
- The illuminating beam is not used for optimization. → User can use session editor also for non Gaussian beams.

Regular Array Beam Splitters



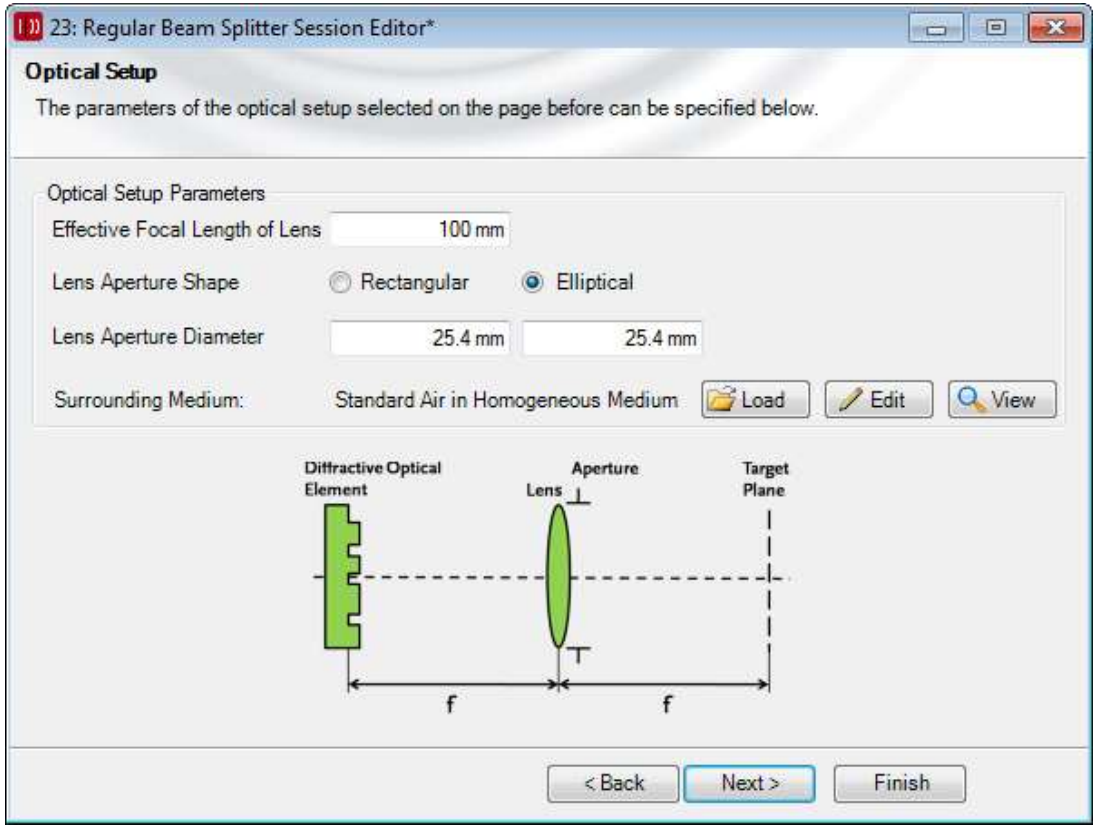
- The definition of Gaussian beam parameters must be specified.
- Supported definitions:
  - Diameter $1/e^2$
  - Radius $1/e^2$
  - Diameter FWHM
- Beam parameters must be entered.
- It is assumed that the beam waist is in front of the beam splitter.

Regular Array Beam Splitters



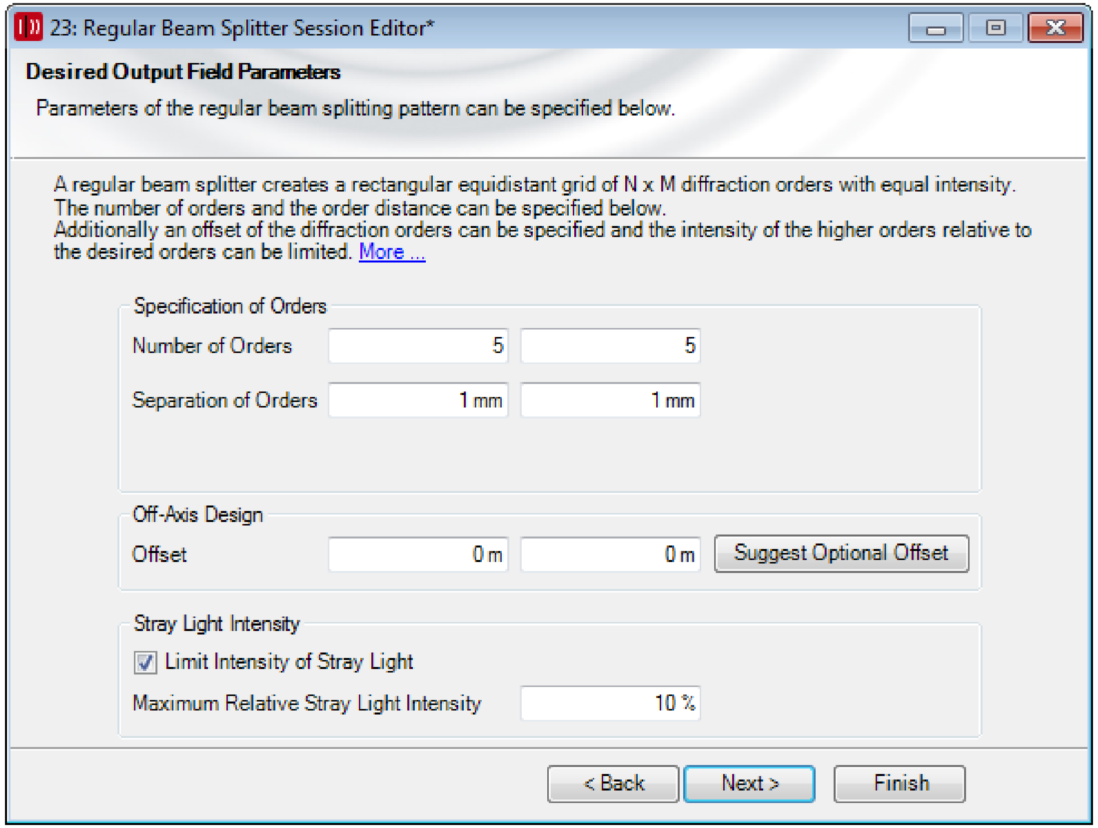
- Selection of optical setups.
- The following setups are supported:
  - 1f-setup
  - 2f-Setup
  - Paraxial far field
  - Angular spectrum

Regular Array Beam Splitters



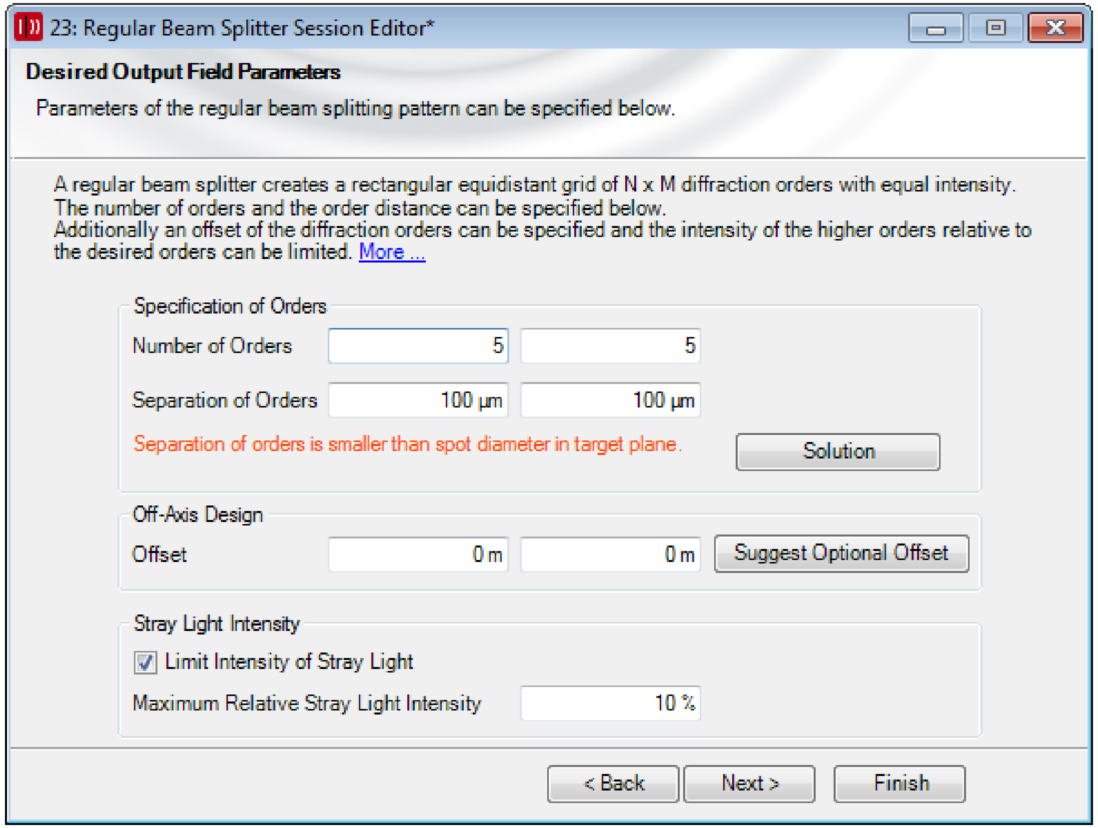
- The setup parameter must be entered.
- Setups are simulated during optimization by Fourier transform. The apertures of lenses are not included.

Regular Array Beam Splitters



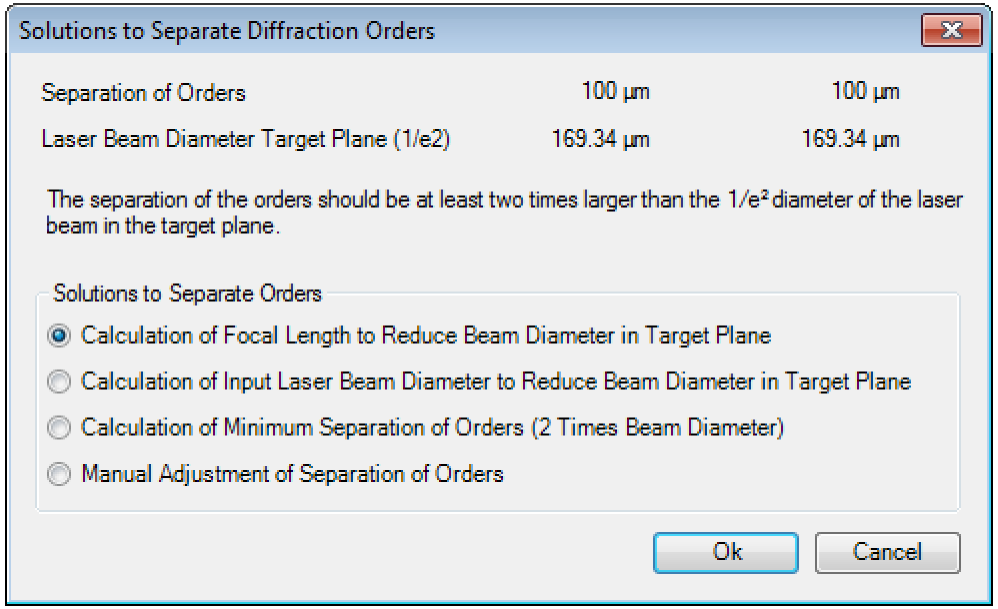
- The number of orders and the order distance must be entered.
- An offset can be added to the orders to separate the zeroth order.
- The *Maximum Relative Stray Light Intensity* helps to control the intensity of the higher diffraction orders.

Regular Array Beam Splitters



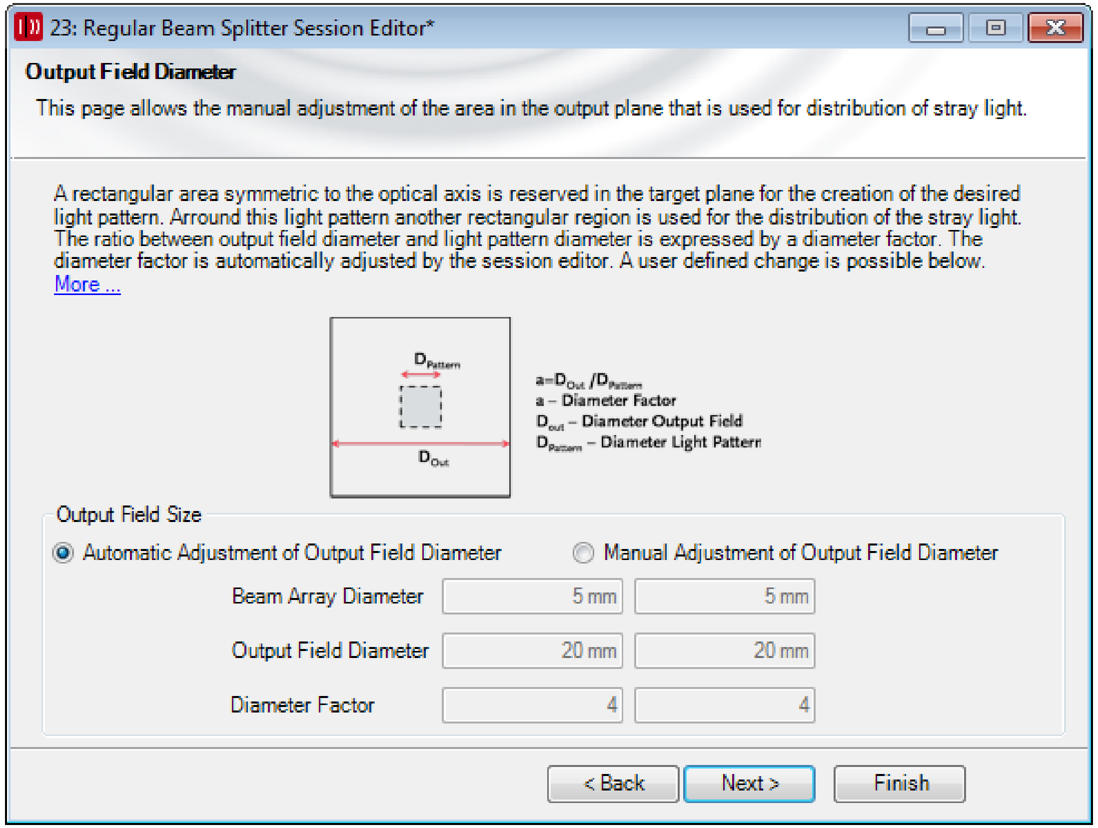
- If the order distance is not larger than the spot diameter are warning is displayed.
- A *Solution* button shows options to solve the problem

Regular Array Beam Splitters



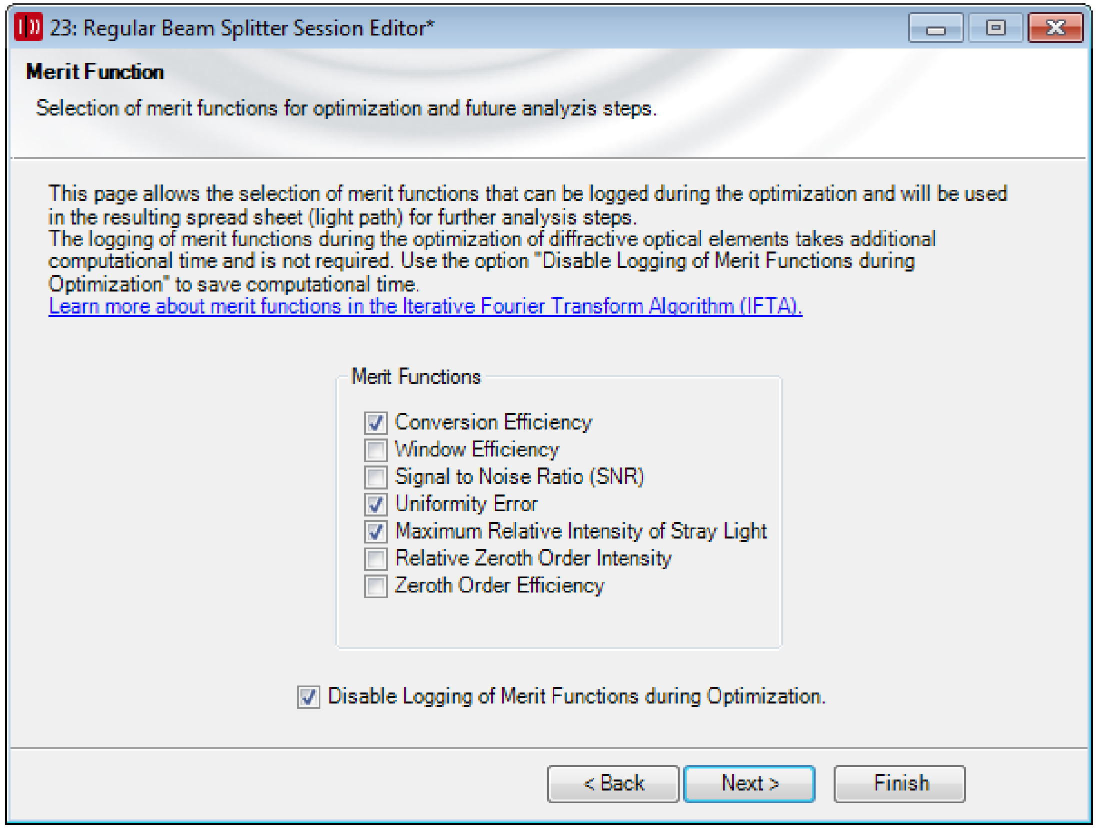
- The orders can be separated by
  - Changing the input beam diameter
  - Changing the focal length or distance of the setup.
  - Modifying the order distance
- The dialog will mention the spot diameter compare it with the current order separation.

Regular Array Beam Splitters



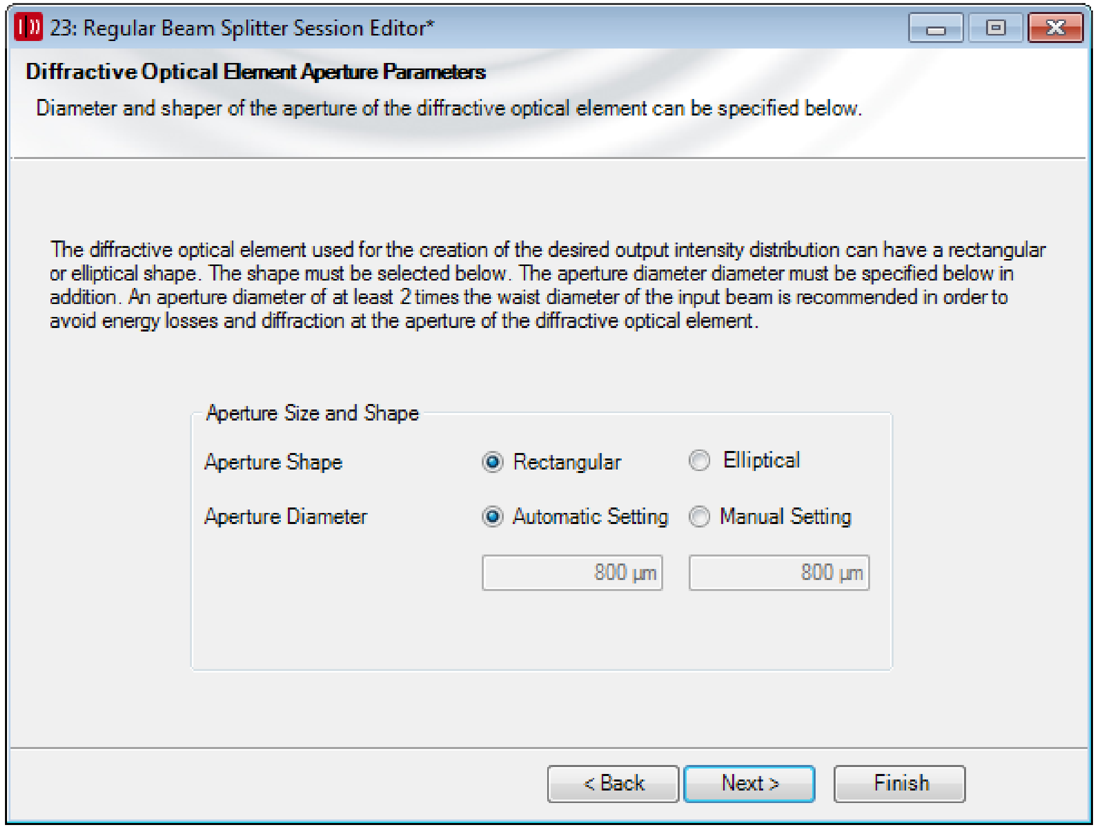
- The size of the output field must be larger than the desired light pattern diameter.
- The space is required for stray light and to reduce the amount of energy diffracted to sinc-orders.
- Sinc-orders are generated by diffraction at rectangular pixels of beam splitter.

Regular Array Beam Splitters



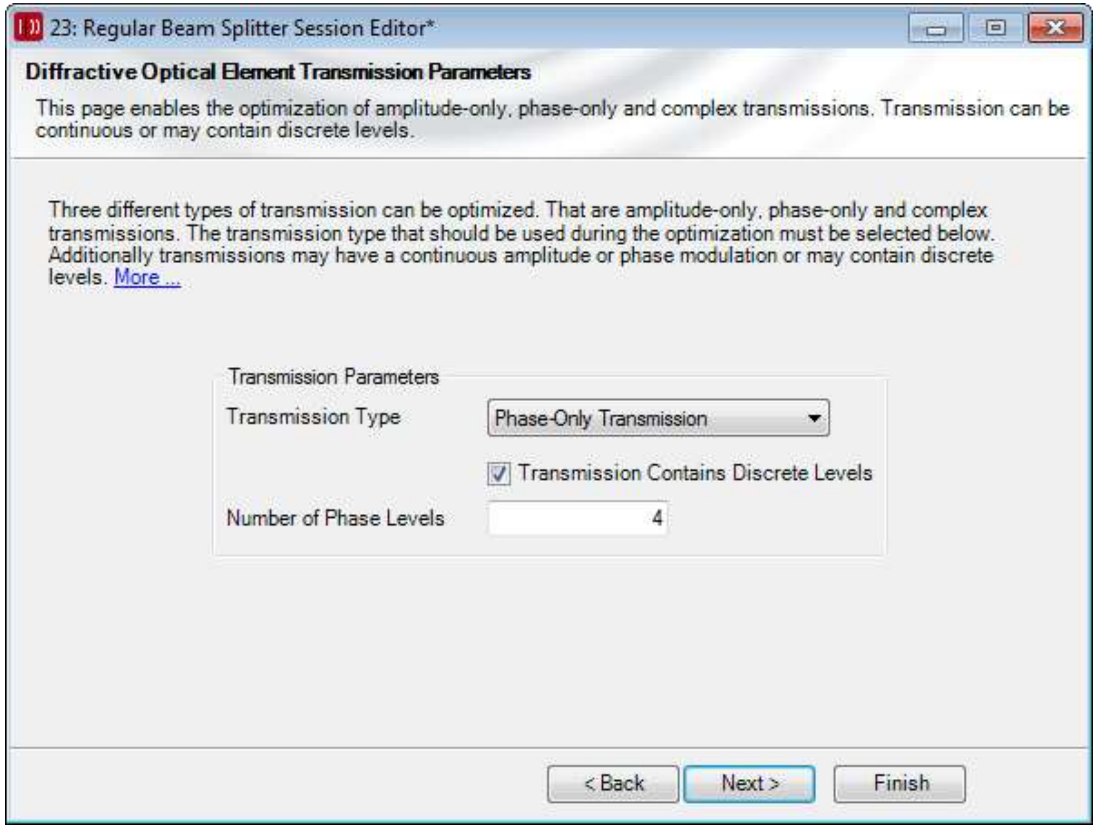
- Selection of merit functions.
- For the optimization a logging of merit function is not required and will cost time.

Regular Array Beam Splitters



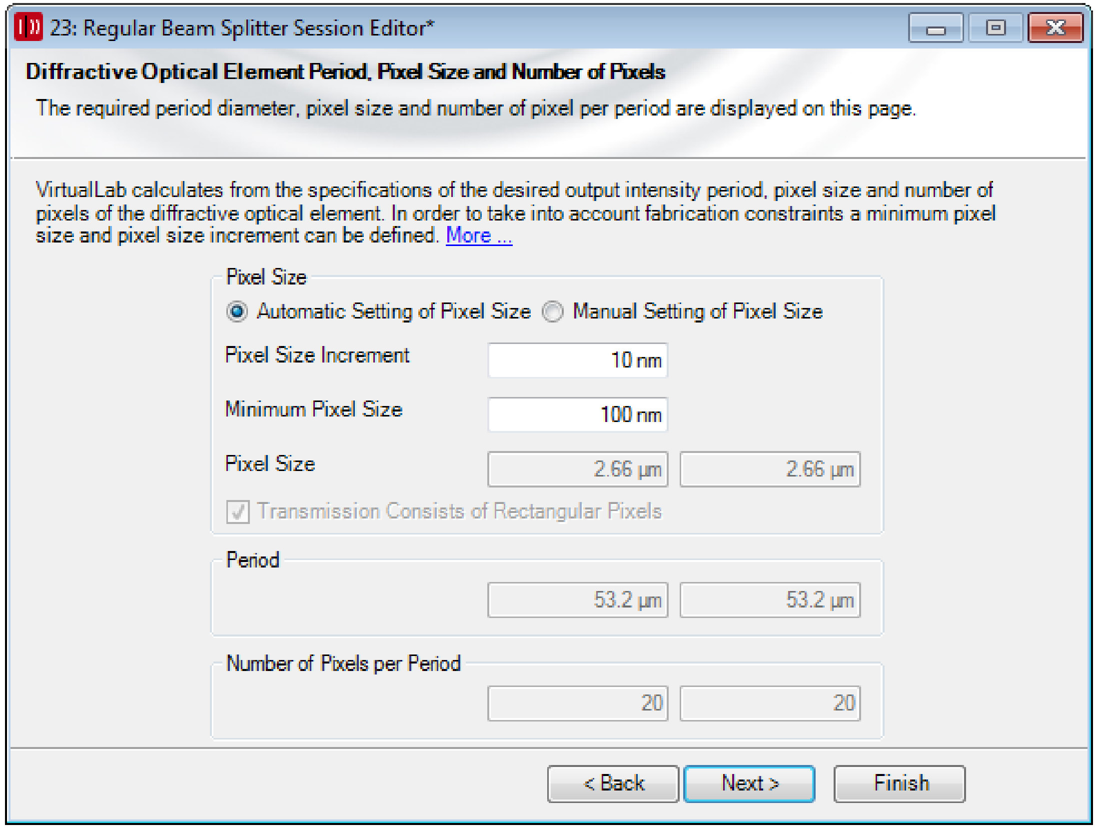
- Aperture shape and diameter of beam splitter.
- Only one period of the beam splitter will be optimized.
- The beam splitter aperture is just used for analysis of optimized system.

Regular Array Beam Splitters



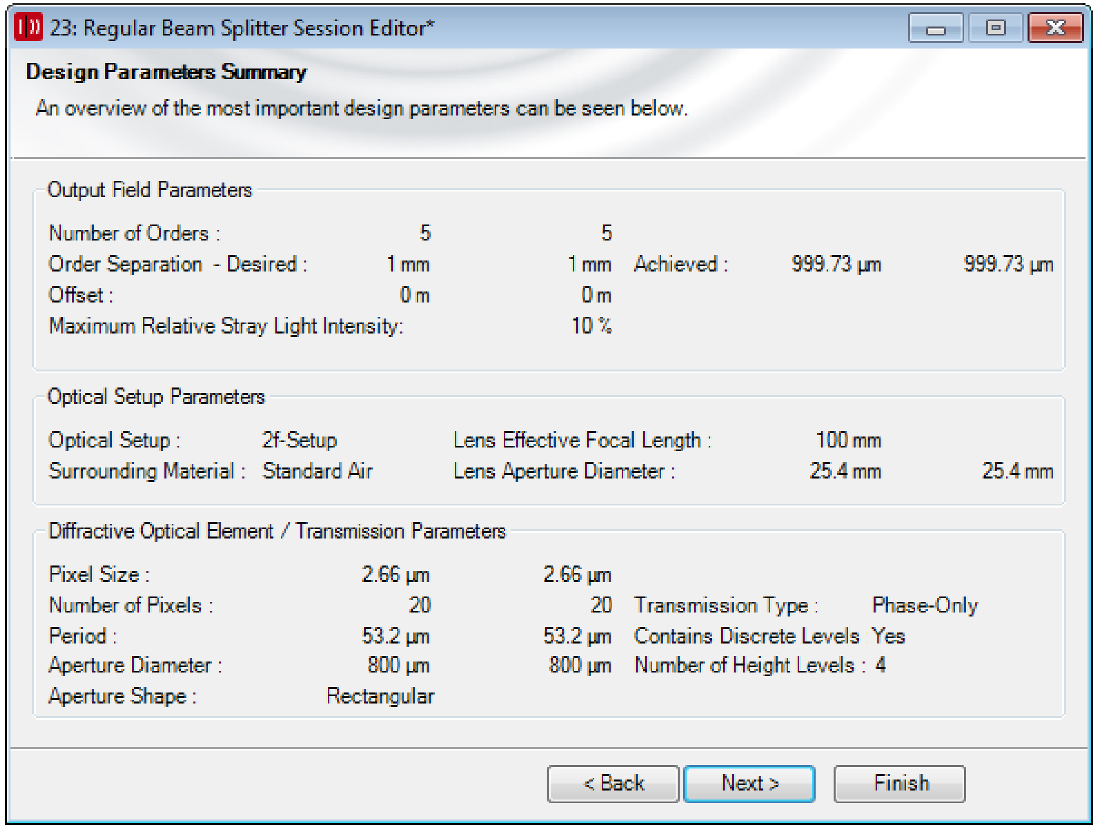
- Selection beam splitter transmission type:
  - Amplitude-Only
  - Phase-Only
  - Complex
- Transmissions with discrete or continuous phase or amplitude distributions can be optimized.

Regular Array Beam Splitters



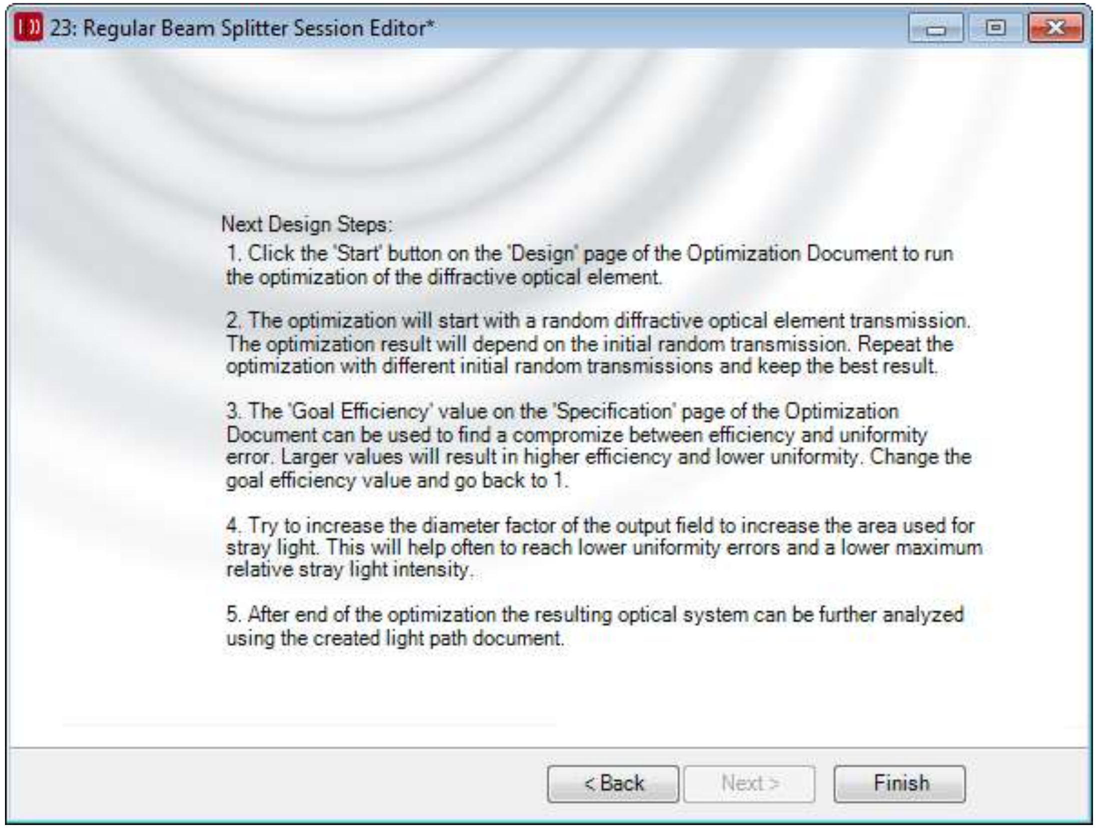
- Pixel size, period and pixels per period are calculated.
- Calculation takes into account minimum pixel size and pixel size increment.

Regular Array Beam Splitters



- Summary of all design data.
- Because of pixel size increment rounding effects will appear that can lead to significant deviations of the order distance from the desired value.

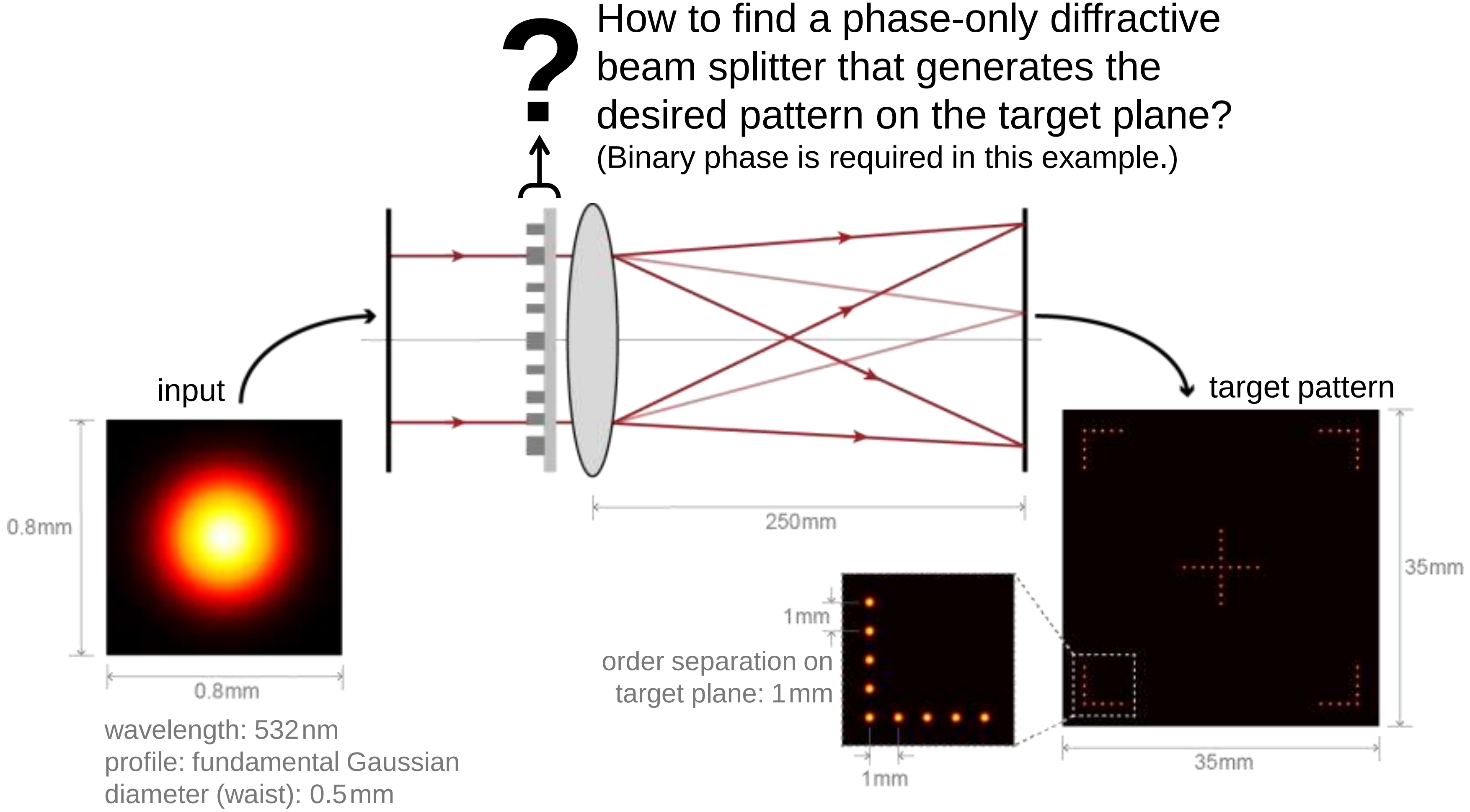
Regular Array Beam Splitters



- Over of next design steps.
- Click *Finish* to create *Optimization Document* and *Light Path Diagram*.

Task8_BeamSplitter

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.)



Task 8: Video

Klick the following link to watch the video:

https://youtu.be/ZV69k3LzbHM

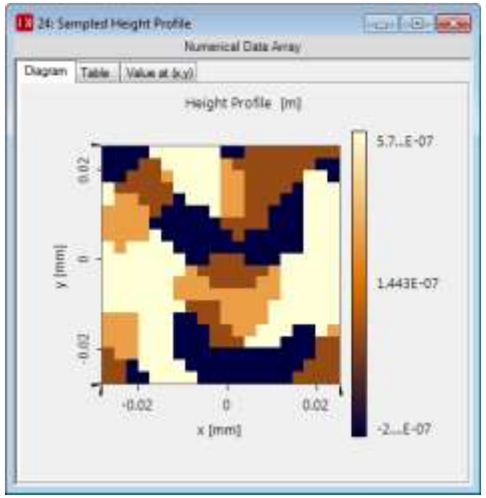
Task 9: Tolerance Round Pixels

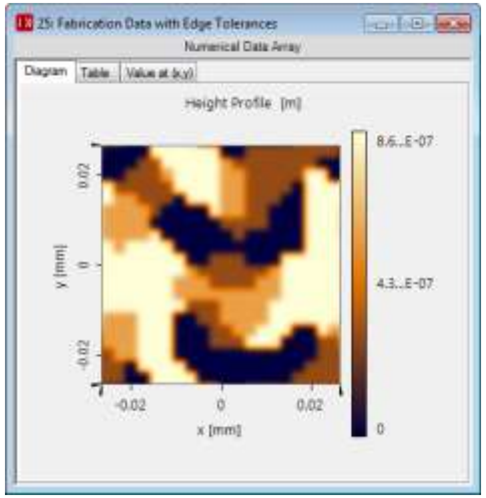
Modeling of Rounding of Pixels

Modeling of Rounding of Pixels

- Several micro structured surfaces consists of rectangular pixels.
- It is typically assumed that pixels have rectangular side walls and sharp edges.
- Exposure and etching processes during the fabrication of micro structured surfaces can lead to a rounding of pixel edges.
- The edge rounding can be modeled in a good approximation by convolution with a Gaussian beam.

Example with Data from Scenario 23.01

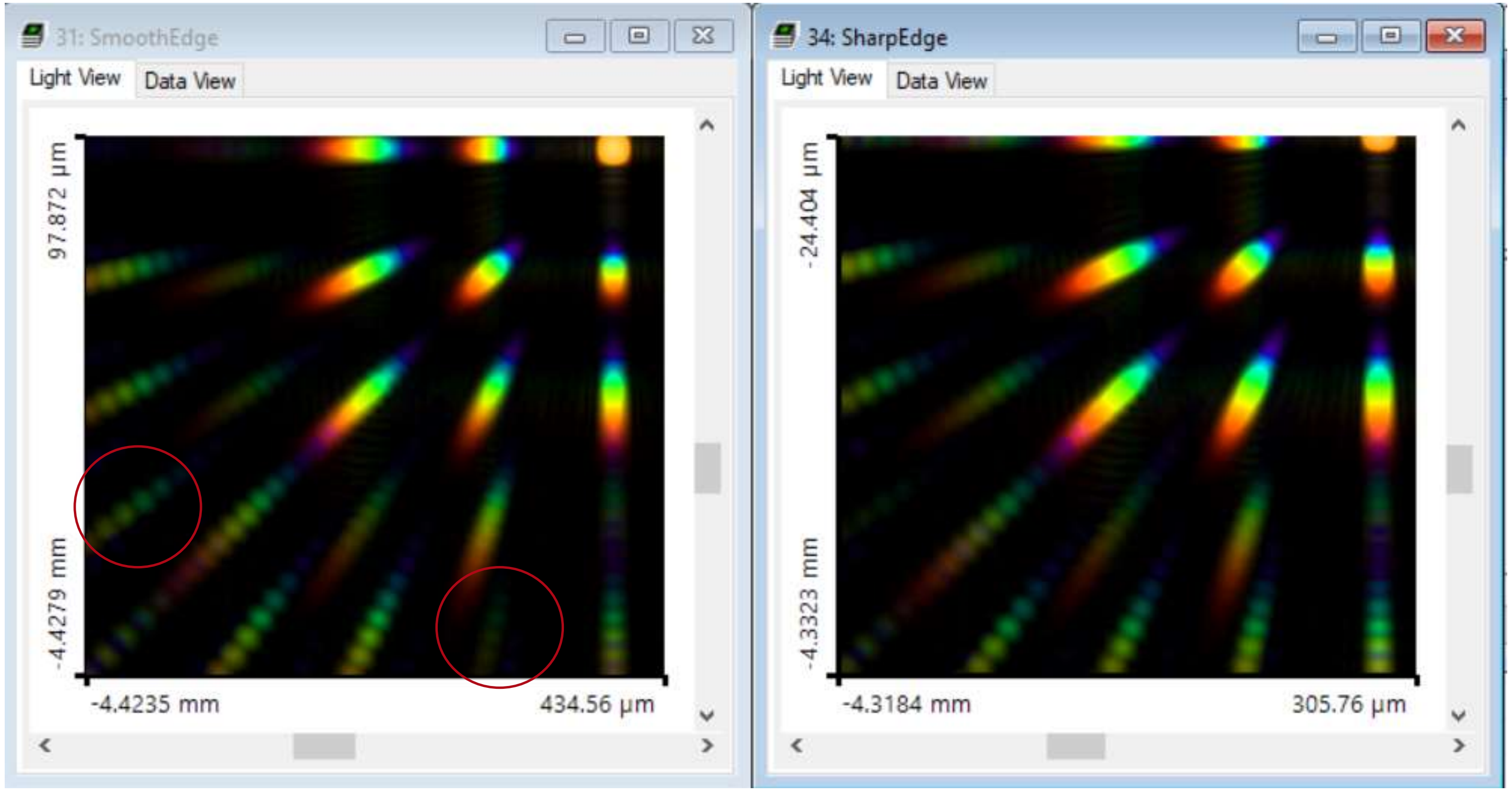




- VirtualLab Module **`Module_RoundedEdge_Tolerances.cs`** can be used to calculate from a perfect profile a profile with rounded edges.
- Calculation steps:
  - Get a *Data Array* with the perfect profile from the sampled interface.
  - Apply the module.
  - Set the *Data Array* with the modified profile into the sampled interface.
- Left side: edge rounding 2 µm, sampling distance 400 nm.

Results with 4x Increased Brightness

- Simulation Result of DOE with Rounded Edges
- Simulation Result of Designed DOE



Task 9: Video

Klick the following link to watch the video:

https://youtu.be/00igeoy68H4

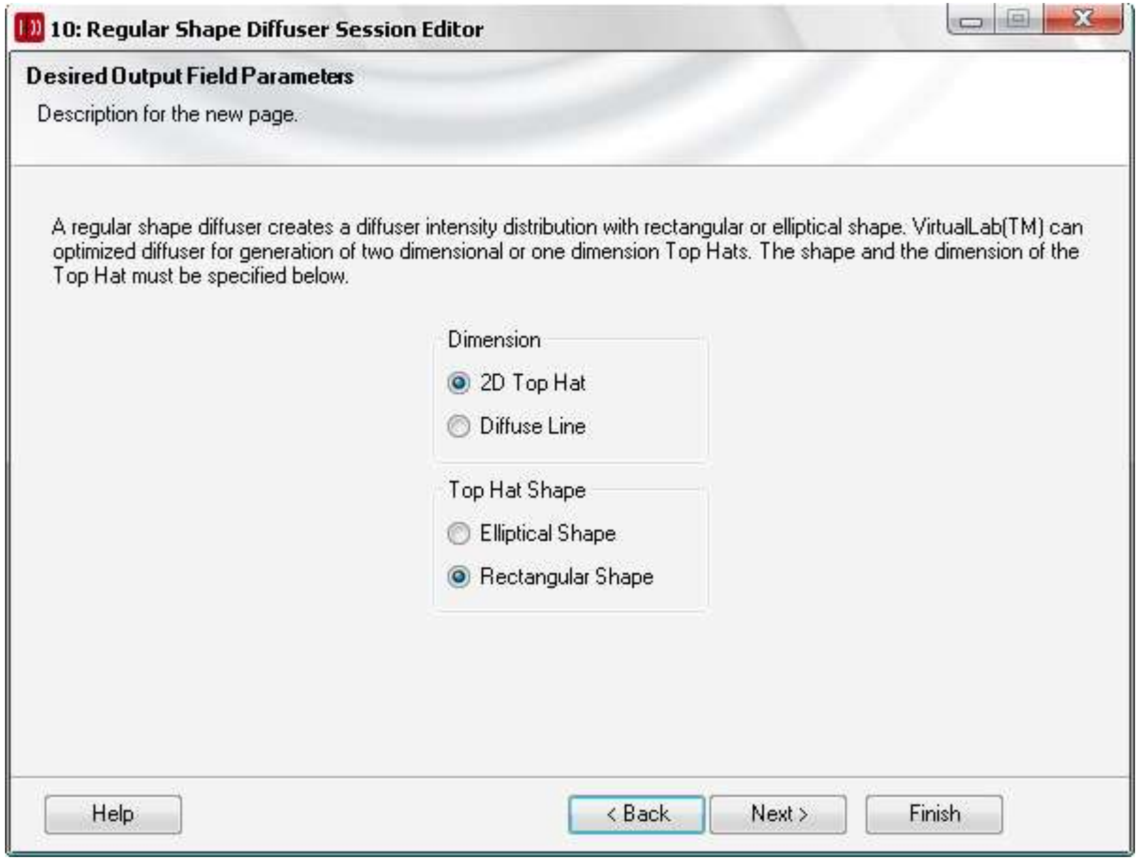
(v0.9)

Regular Shape Diffuser Session Editor

Regular Shape Diffuser Session Editor

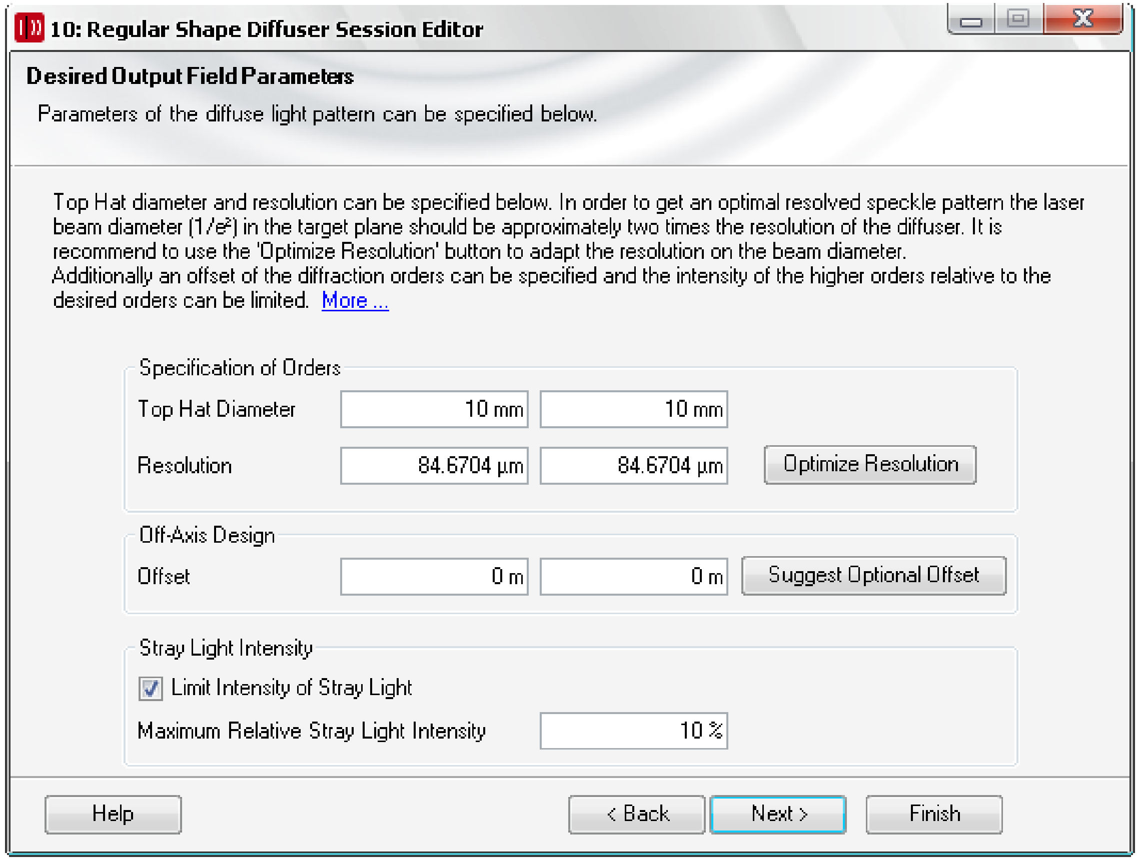
- Design of periodic diffractive diffusers.
- Design of diffuser for generation of rectangular, circular or line shape diffuse intensity distributions.
- Session editor assists users during generation of *Optimization Document* and *Light Path Diagram*.

Regular Shape Diffuser Session Editor



- Diffuser session editors differ only in specification of output field from beam splitter session editors.
- Selection between generation of diffuse 2D Top Hat and diffuser line.
- 2d Top Hats with elliptical or rectangular shape can be generated.

Regular Shape Diffuser Session Editor



- Top hat diameter and resolution (diffraction order distance) can be specified here.
- If spots do not overlap an warning message will be displayed.
- *Optimize Resolution* button helps to adjust all system parameters so that the spot diameter is two times the diffraction order distance.

DO.002 (3.0)

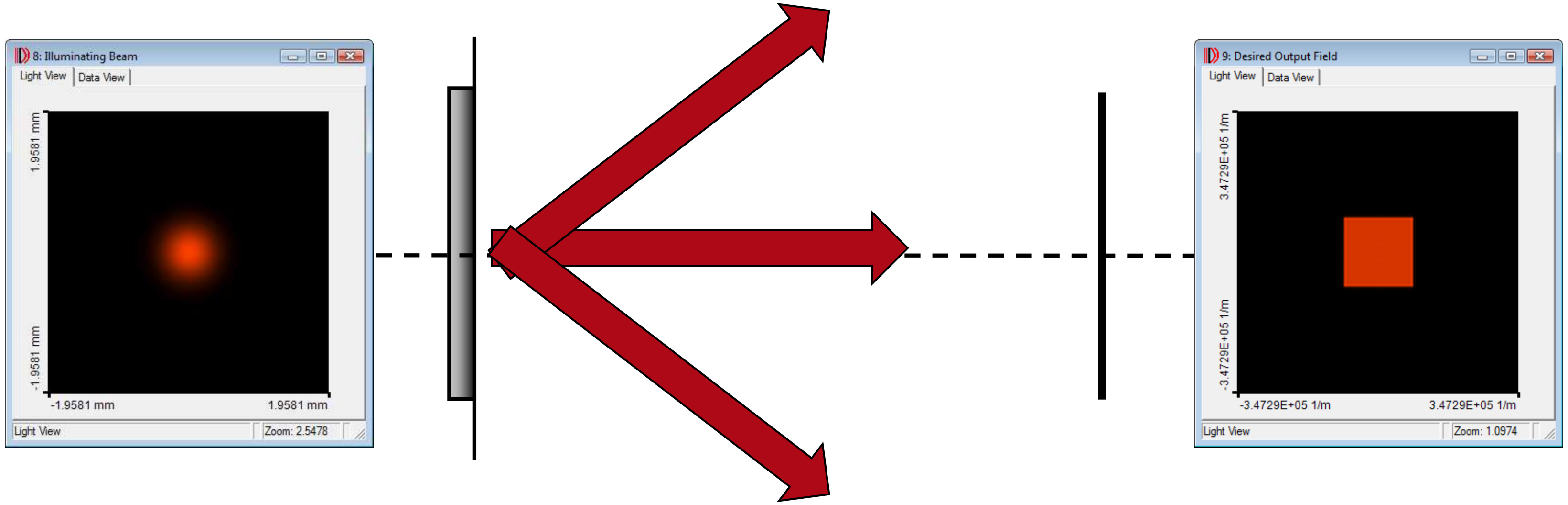
Design & Optimization of Diffractive Light Diffuser for Top Hat Generation

This application scenario demonstrates the design and optimization of a diffractive optical element (DOE) as light diffuser for the geneation of a rectangular top hat pattern.

Modeling Task

DOE: Diffuser
Diameter: 1.4mm x 1.4mm
Phase Levels: 2
Pixel Size: >1µm

Target
Plane

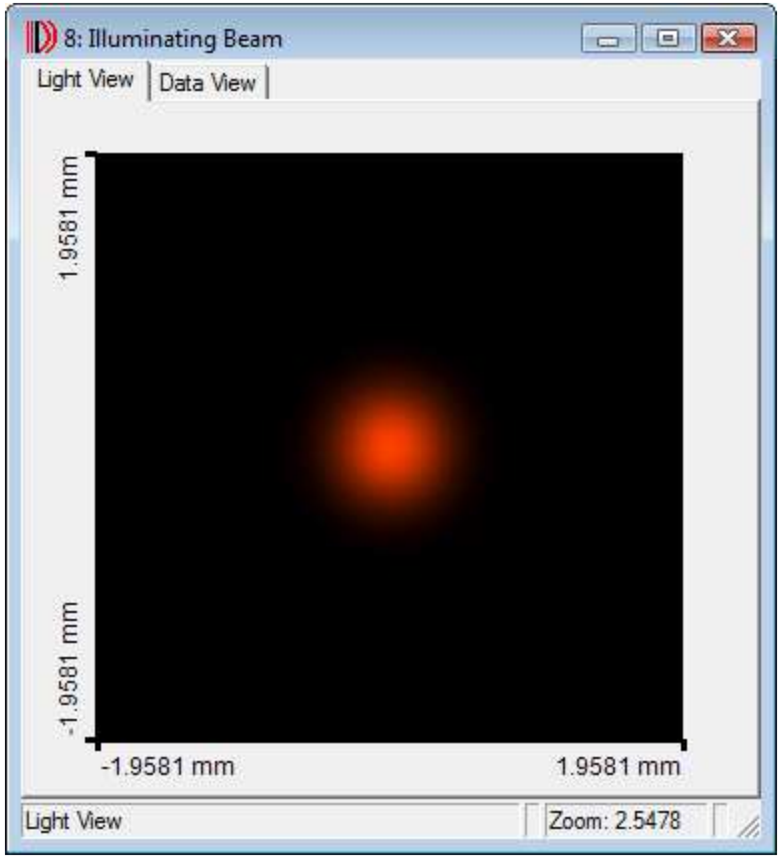


Illuminating Beam
Intensity

Angular Spectrum Setup

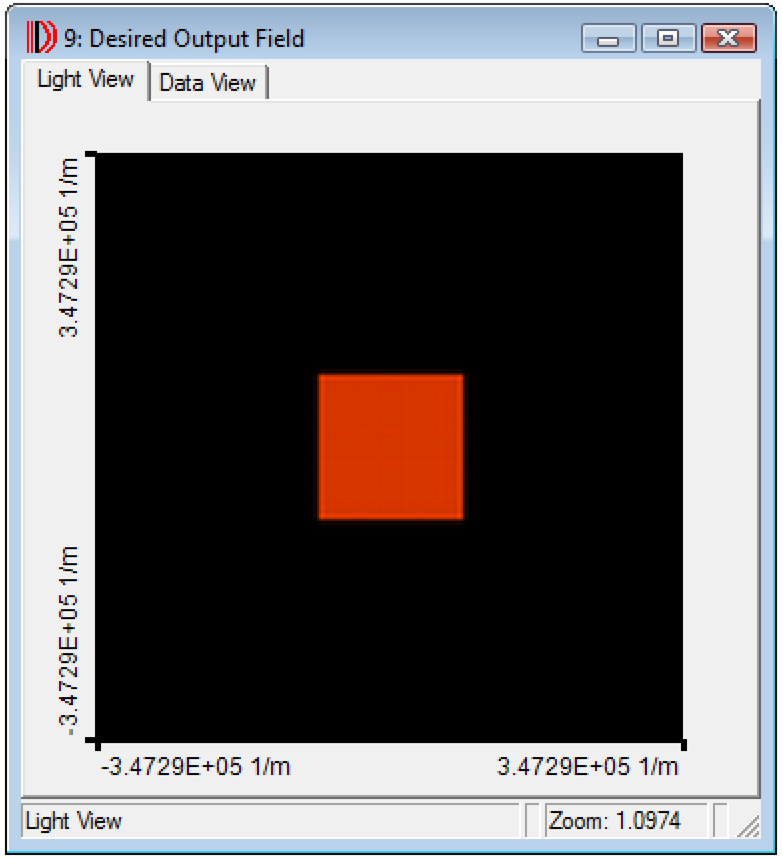
Top Hat Intensity

Illuminating Beam Parameters



- Wavelength: 632.8nm
- Laser Beam Diameter ($1/e^2$): 700µm

Desired Output Field Parameters

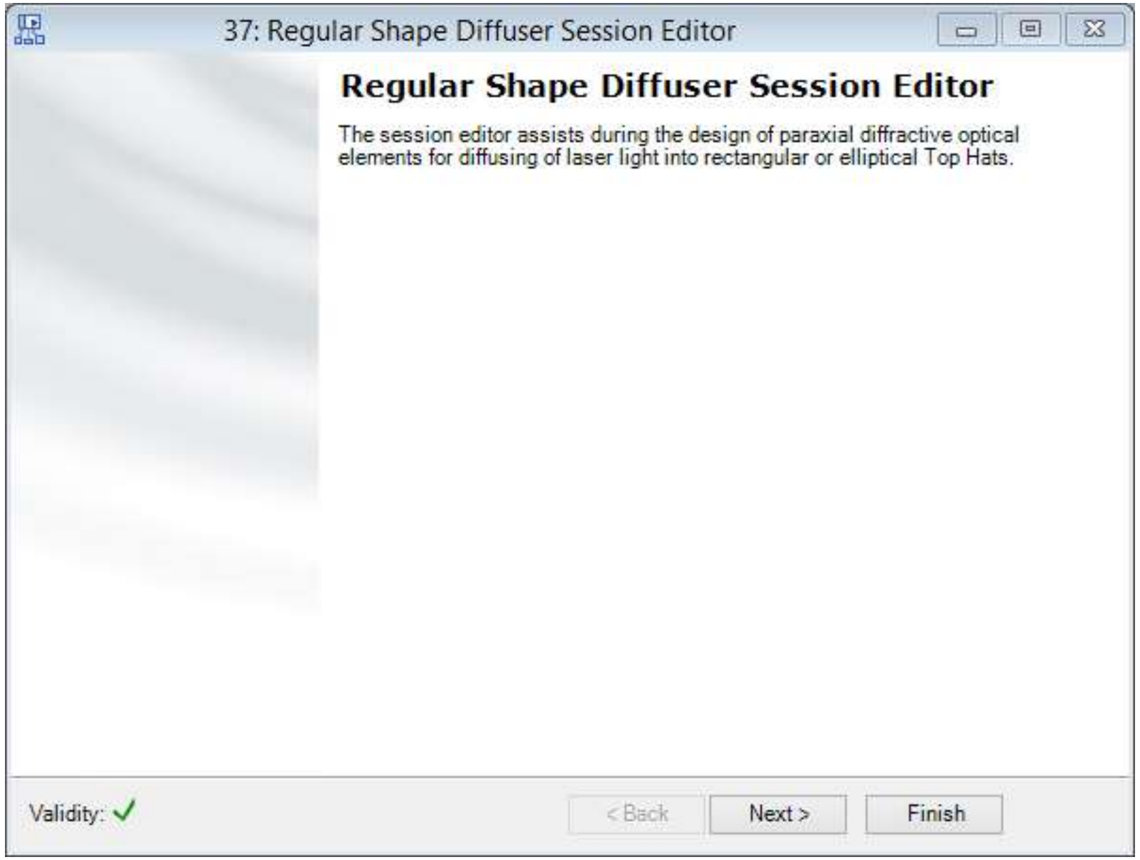


- Diameter: 1°
- Resolution: ≤0.03°
- Efficiency: >70%
- Stray light: <20%

Design & Optimization Approach

- VirtualLab allows different design and optimization approaches.
- For this presented scenario the Iterative Fourier Transformation Algorithm (IFTA) is used for the design and optimization of the desired diffractive optical element (DOE).

Configuration Approach

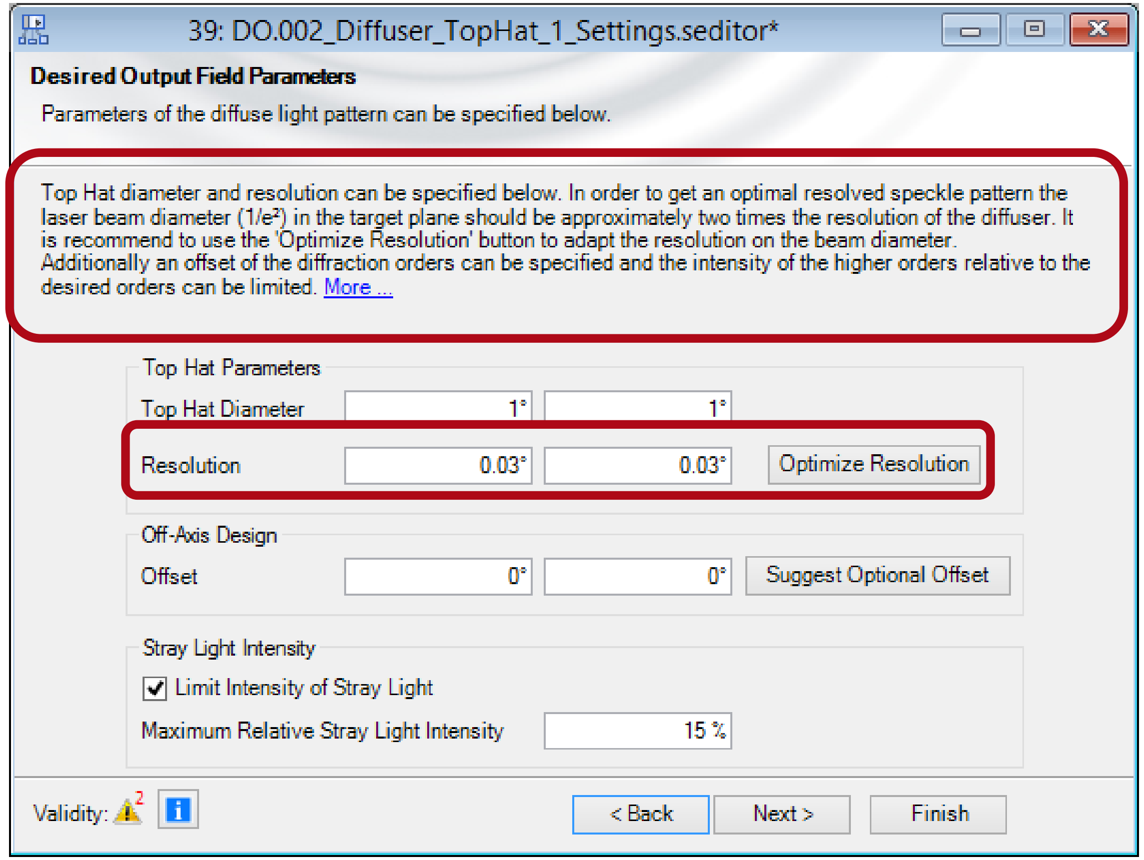


You can either

- use assisting session editors for the setup of the optical system and the configuration of the optimization and design documents
- or configure everything manually (more advanced).

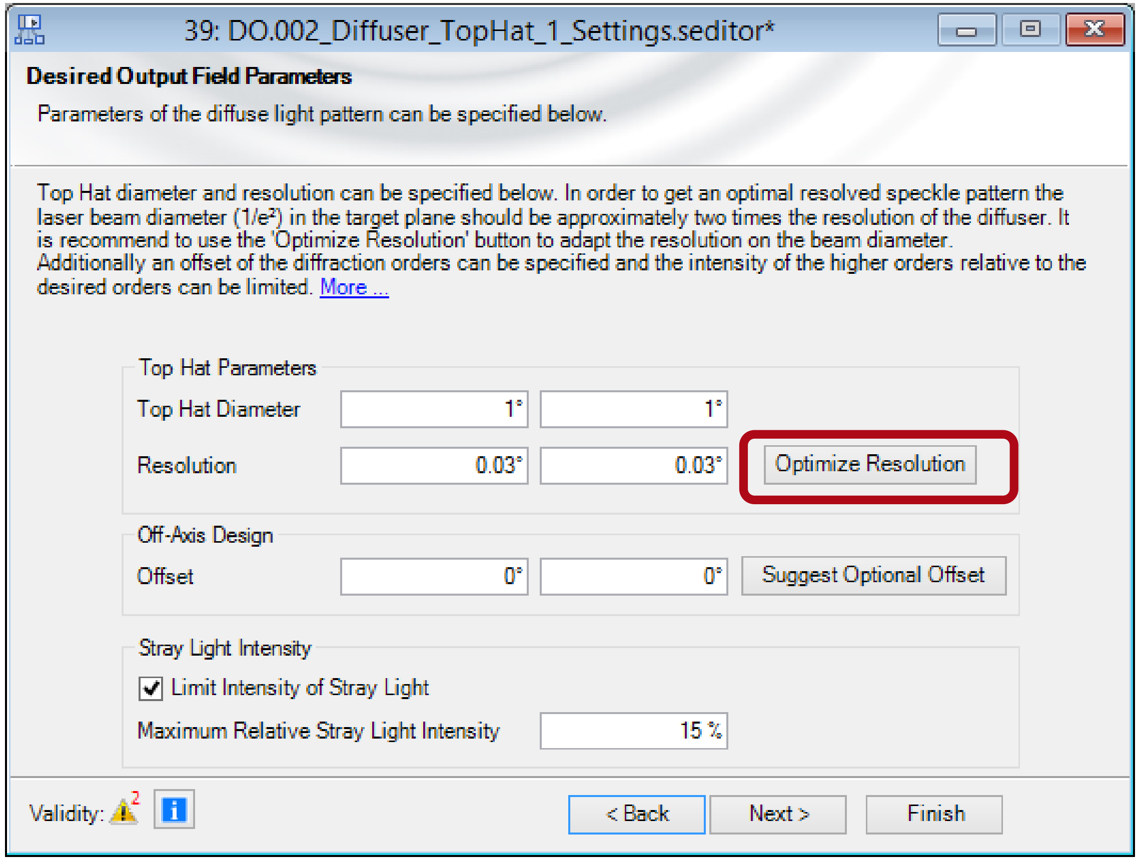
Adjacent you see the session editor‘s start page. This dialog is accessed via *Start* ribbon > *Diffractive Optics* > *Regular Shape Diffuser*.

Hints during the Specification Procedure



- Specify the desired optical resolution of the light pattern to be created.
- VirtualLab gives some helpful advices.
- Take into account that the light pattern consists of speckles in case of coherent illumination. In order to clearly resolve the desired pattern the speckles should be smaller than the smallest details of the light pattern.
- The speckle sizes are influenced by the set resolution, but cannot be arbitrarily controlled.

Warnings

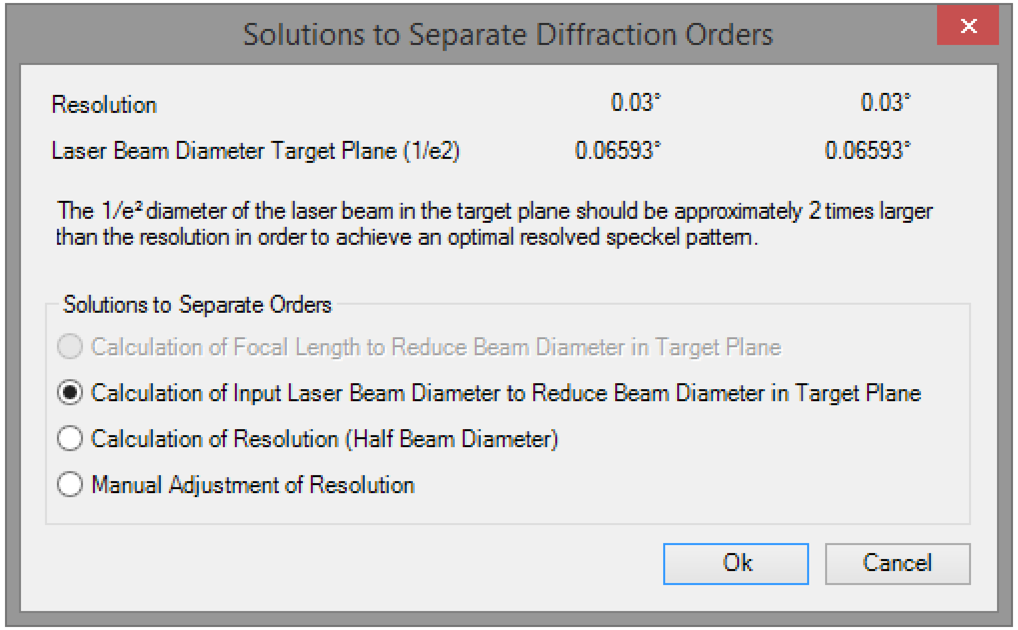


Red warning messages will appear if:

- Desired resolution can’t be reached by the specified optical system.
- The optical system will create discrete spots instead of a speckle pattern.
- Not all details of the desired light pattern can be resolved by optical system or the specified resolution.

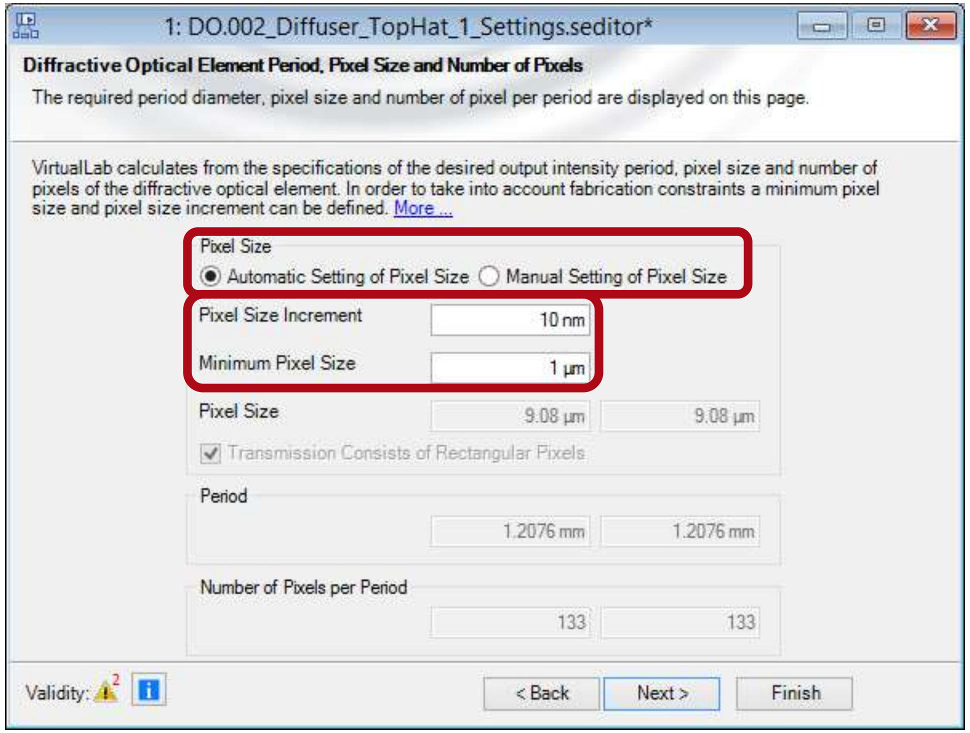
Click the Optimize Resolution button to get help to adjust system parameters.

Help for Parameter Changes



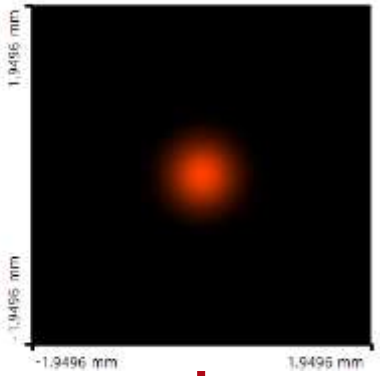
- This dialog shows if the resolution is suitable for typical diffuser designs.
- Here everything is fine.
- Additionally via this tool VirtualLab offers certain options for parameter adjustments to achieve an optimal ratio of laser beam diameter and resolution.

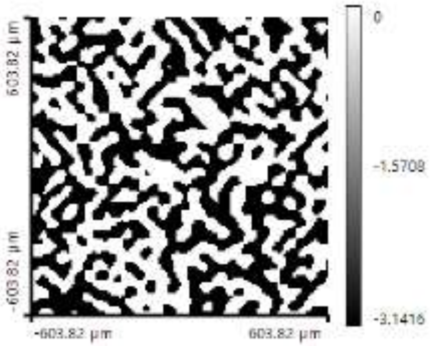
DOE Transmission Parameters

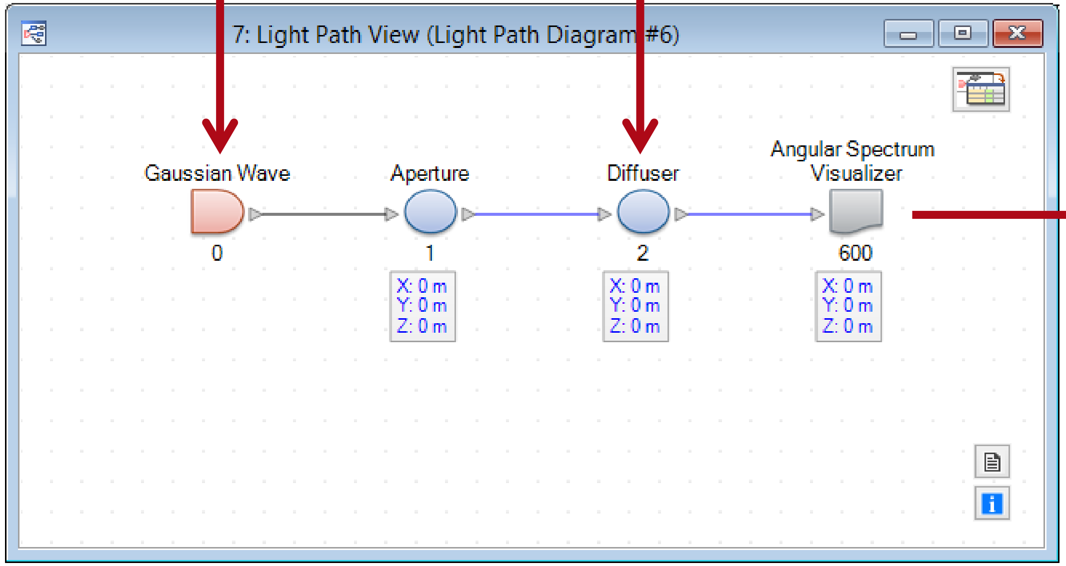


- Pixel size and period of the diffuser transmission are calculated automatically.
- The Pixel Size Increment indicates the step size in that the pixel size can be changed by the machine used for fabrication of the diffuser and the positioning accuracy, respectively.
- Expert user may set a user defined pixel size.

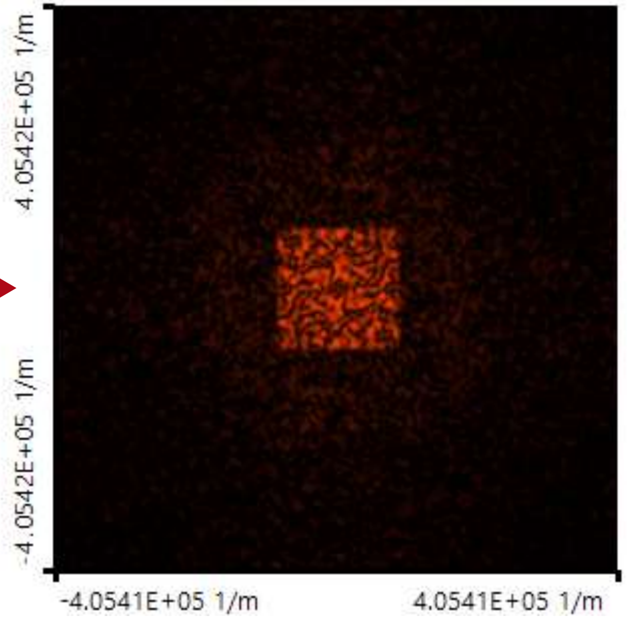
System Analysis with Light Path Diagram (LPD)







Simulation Result:
Rectangular Top Hat
Efficiency ~73.8%
Max. Stray Light ~19.6%



Summary

- VirtualLab provides easy to use tools for the design and optimization of diffractive light diffuser elements for generation of regular (diffuse lines or top hats) and arbitrary light patterns.

- Assisted design steps enable also optical engineers inexperienced in diffractive optics to benefit from current developments.

Task10: Modeling Task

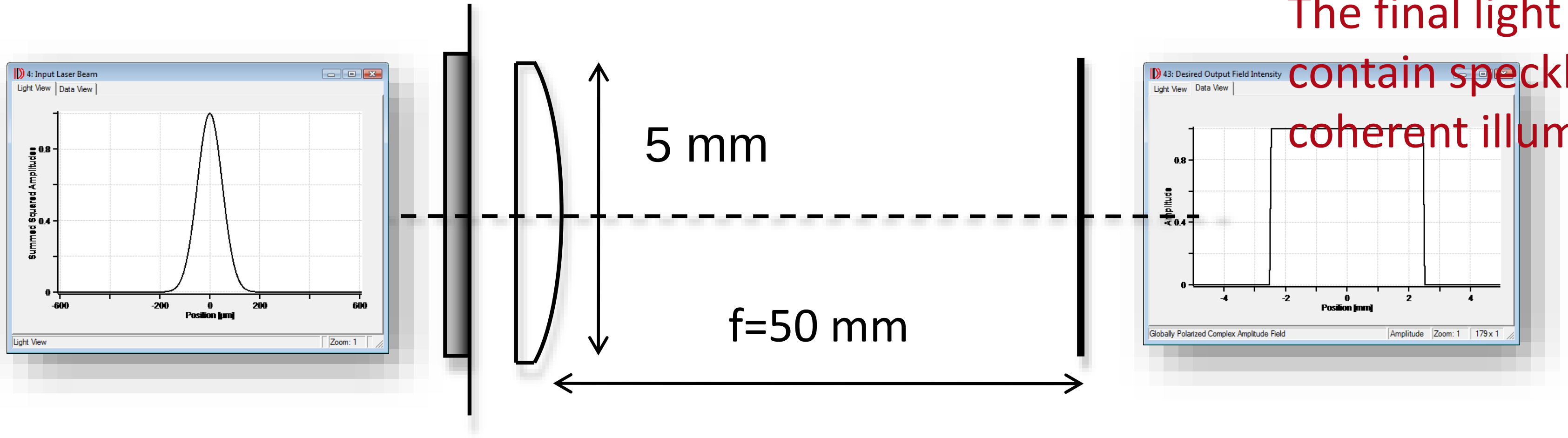
Wavelength: 632.8 nm
Laser Beam
Diameter (1/e²): 700 µm

Fourier Lens

Target
Plane

Diameter: 5 mm
Efficiency: >80 %
Noise limit: 5 %

The final light distribution will contain speckles because of coherent illumination!!!



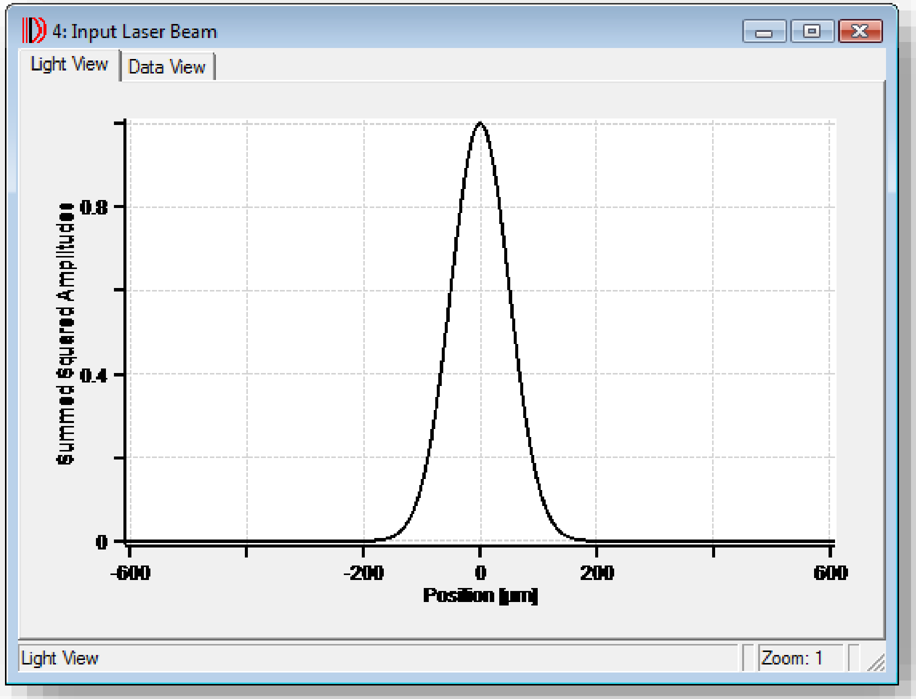
Illuminating
Beam Intensity

Diffractive Diffuser
Phase Levels: 4
Pixel Size: >0.1µm
Diameter: 1.4 mm

Line Focus Intensity

Modeling Task

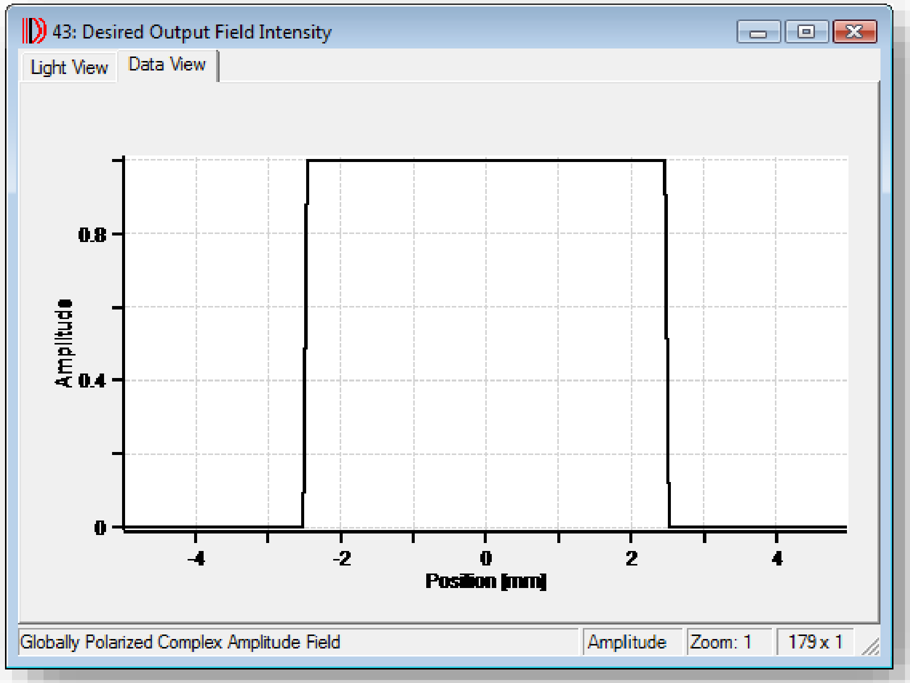
Illuminating Beam Parameters



Wavelength: 632.8 nm
Laser Beam
Diameter ($1/e^2$): 700 µm

Modeling Task

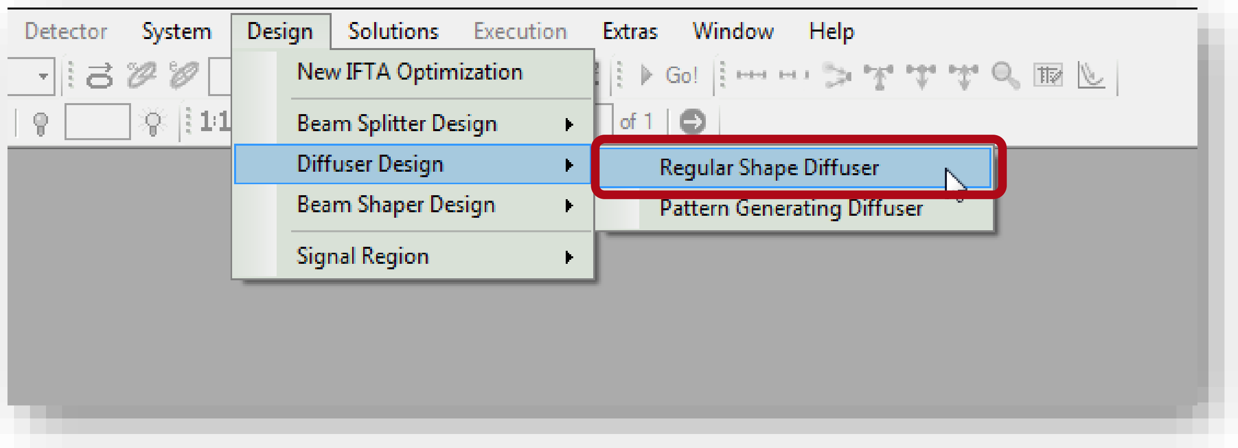
Desired Output Field Parameters



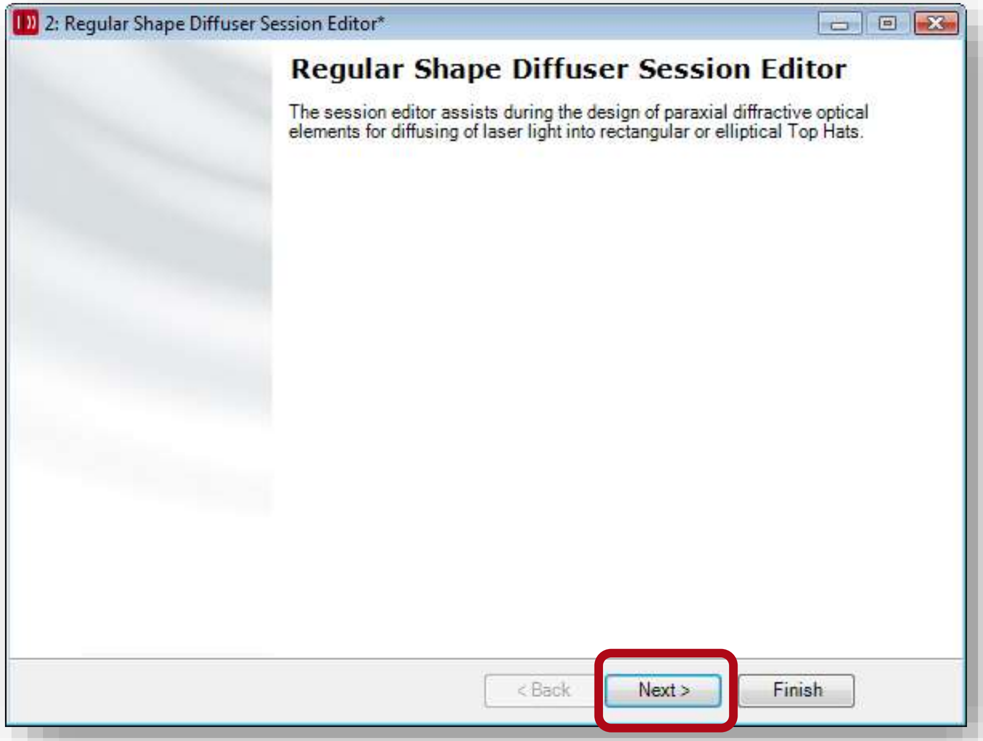
Diameter: 5 mm
Efficiency: >80 %
Noise limit: 5 %

The final light distribution will contain speckles because of coherent illumination!!!

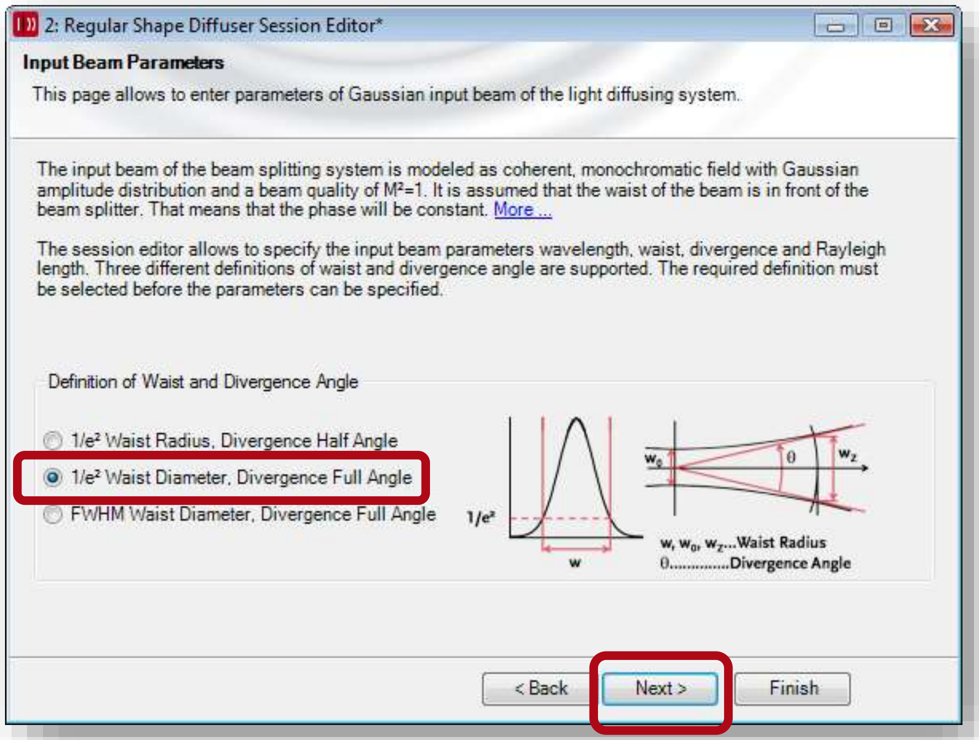
Setup of Design Parameters



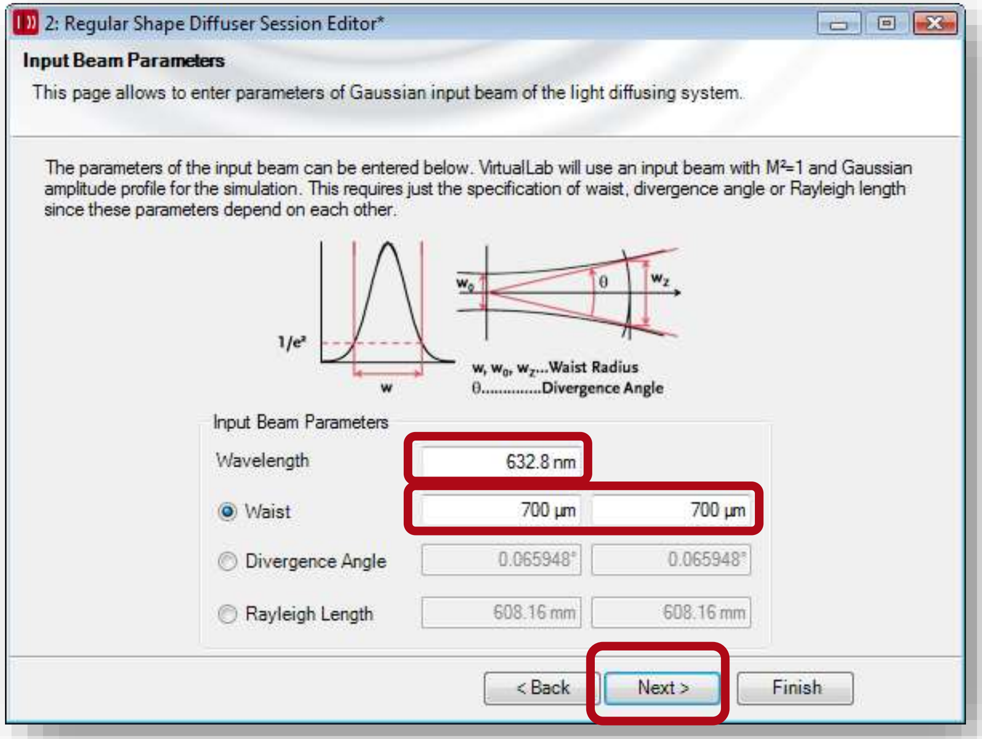
1. Illuminating Beam Specification



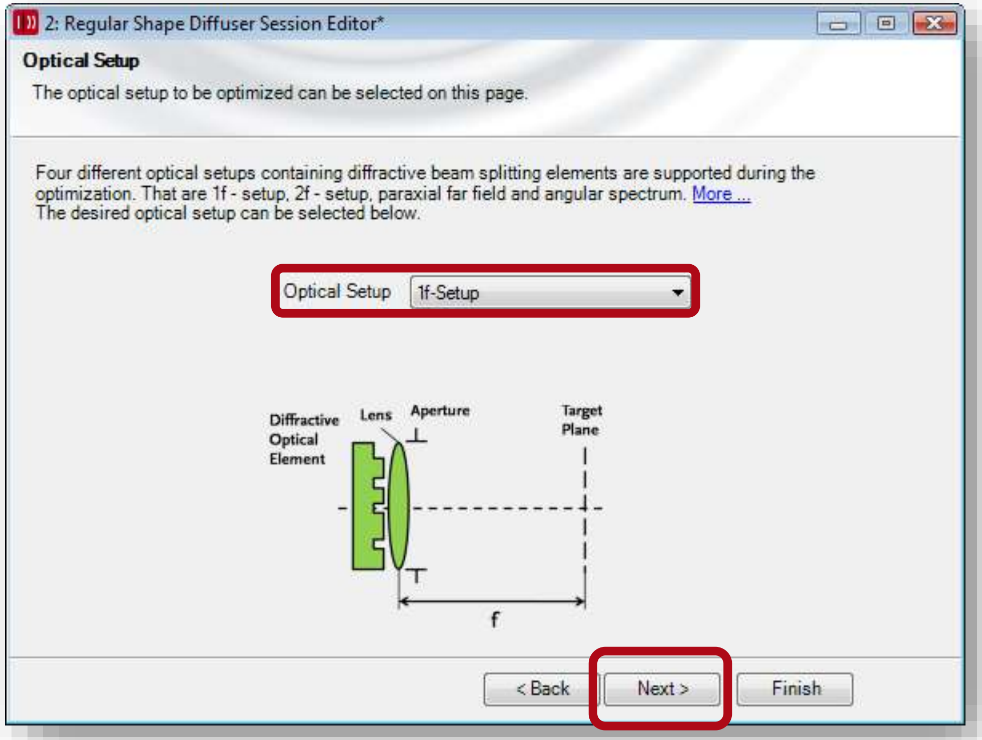
1. Illuminating Beam Specification



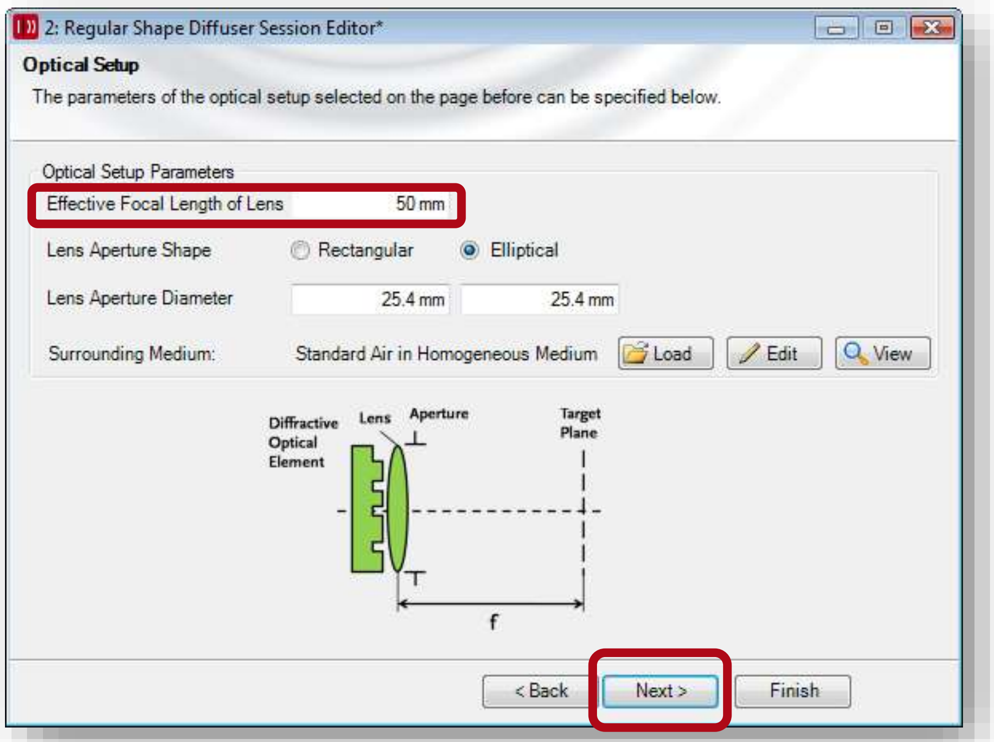
1. Illuminating Beam Specification



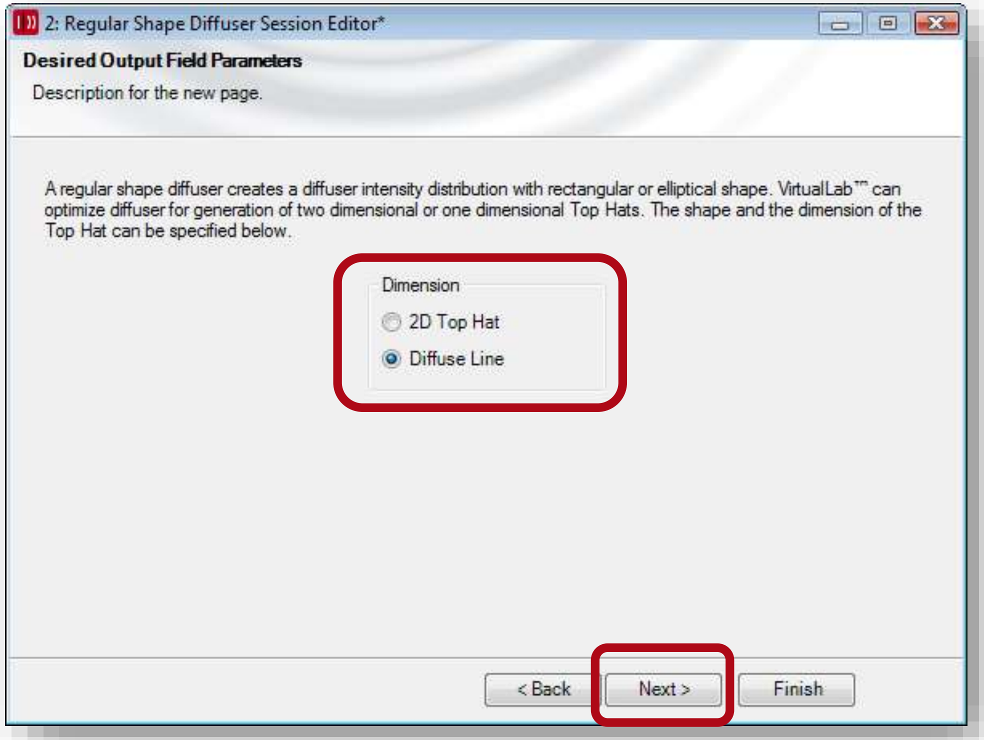
2. Optical Setup



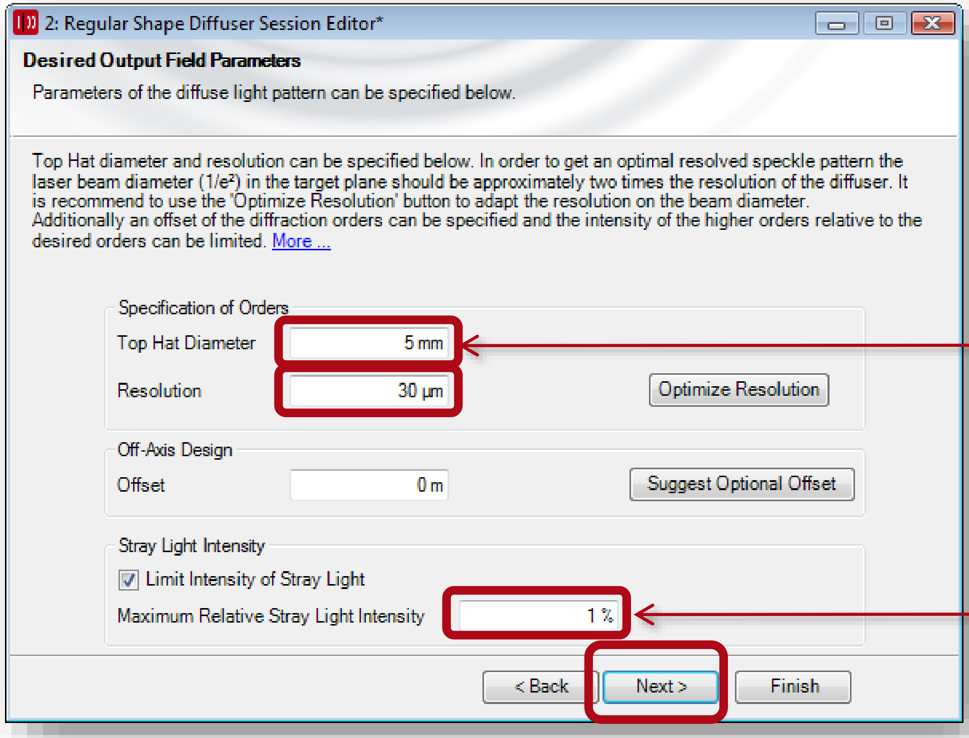
2. Optical Setup



3. Desired Output Field Specification



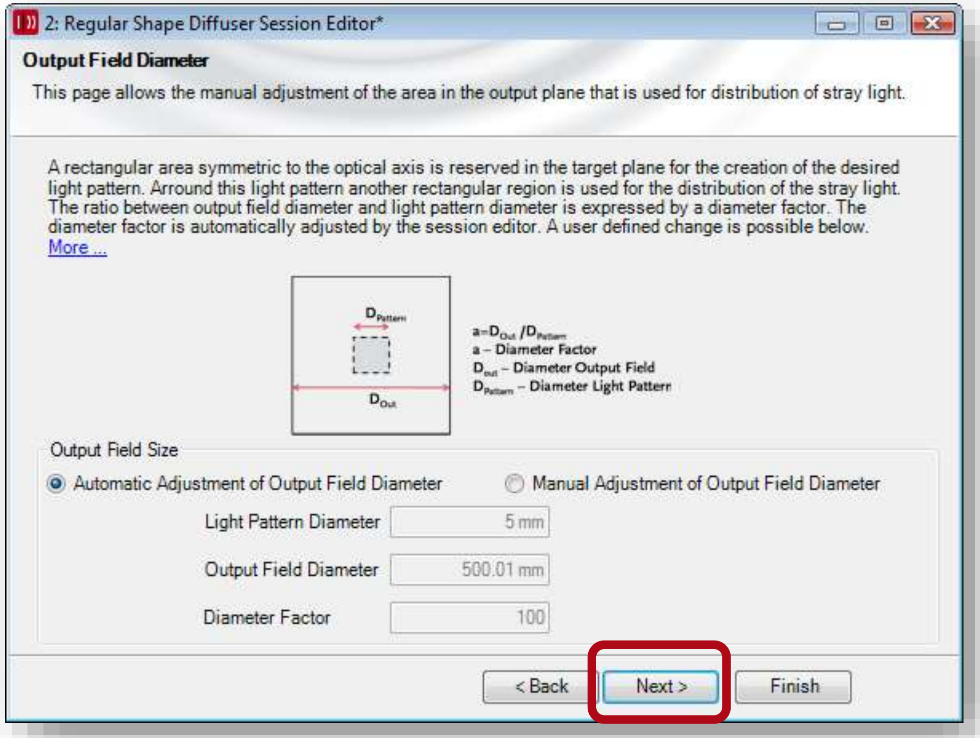
3. Desired Output Field Specification



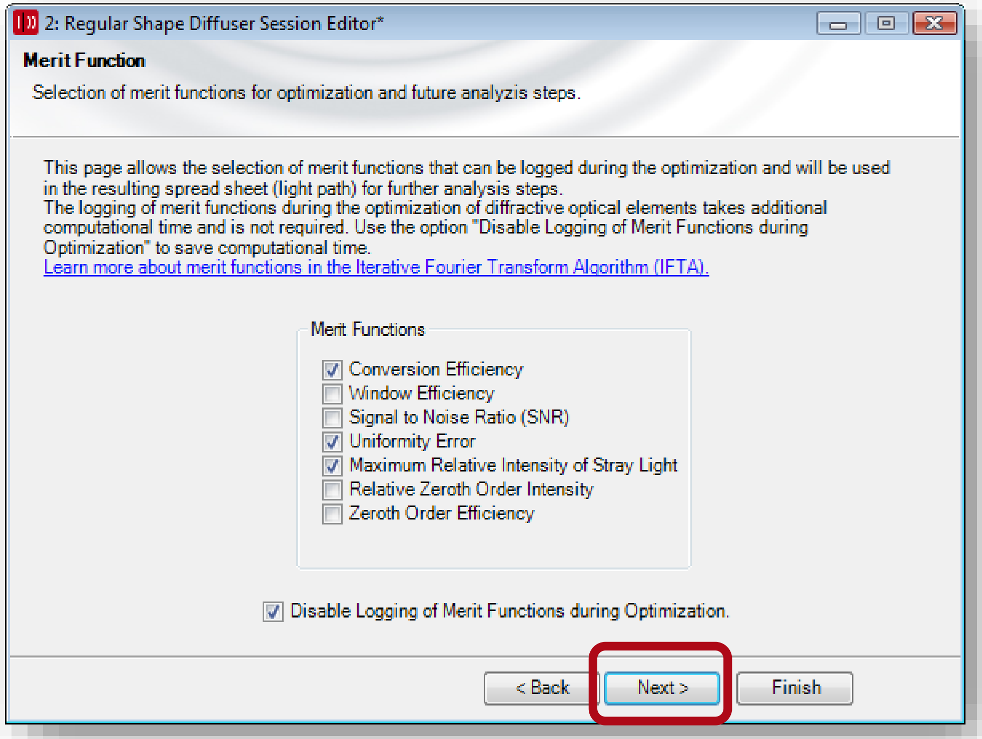
Automatically calculated but can be modified by user.

The stray light limit can be smaller.

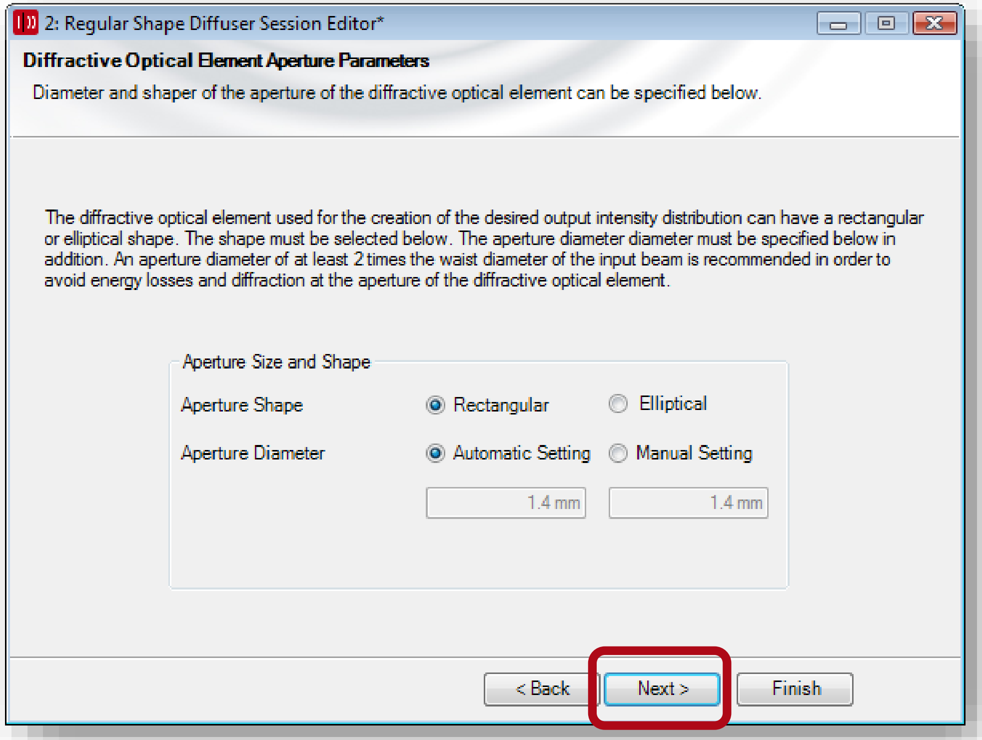
3. Desired Output Field Specification



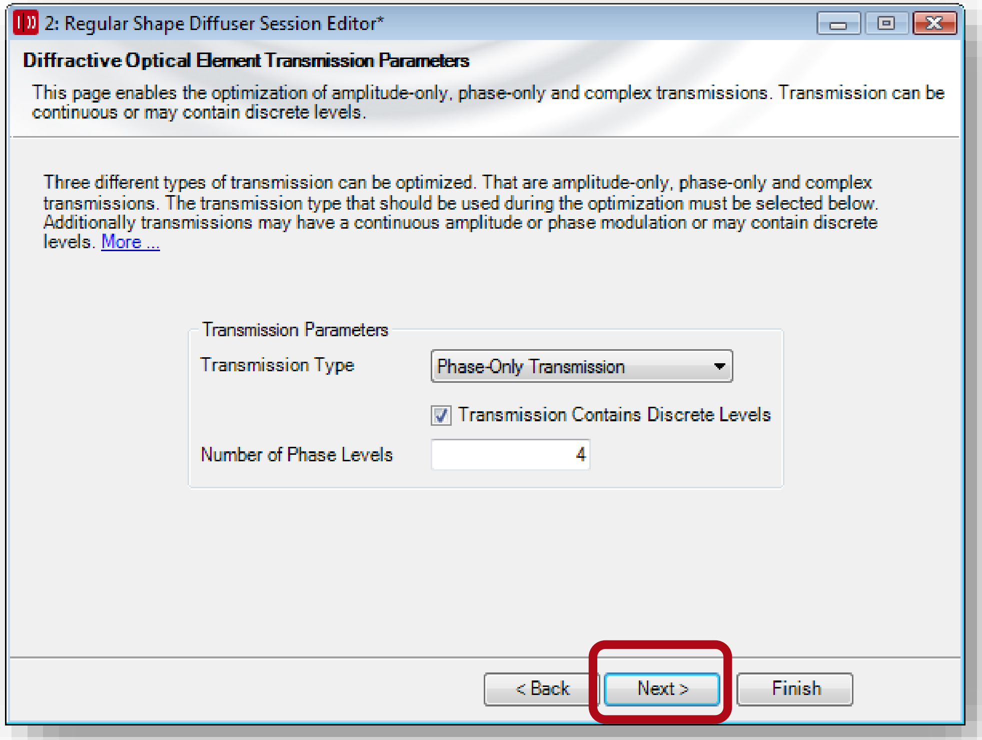
4. Merit Functions Selection



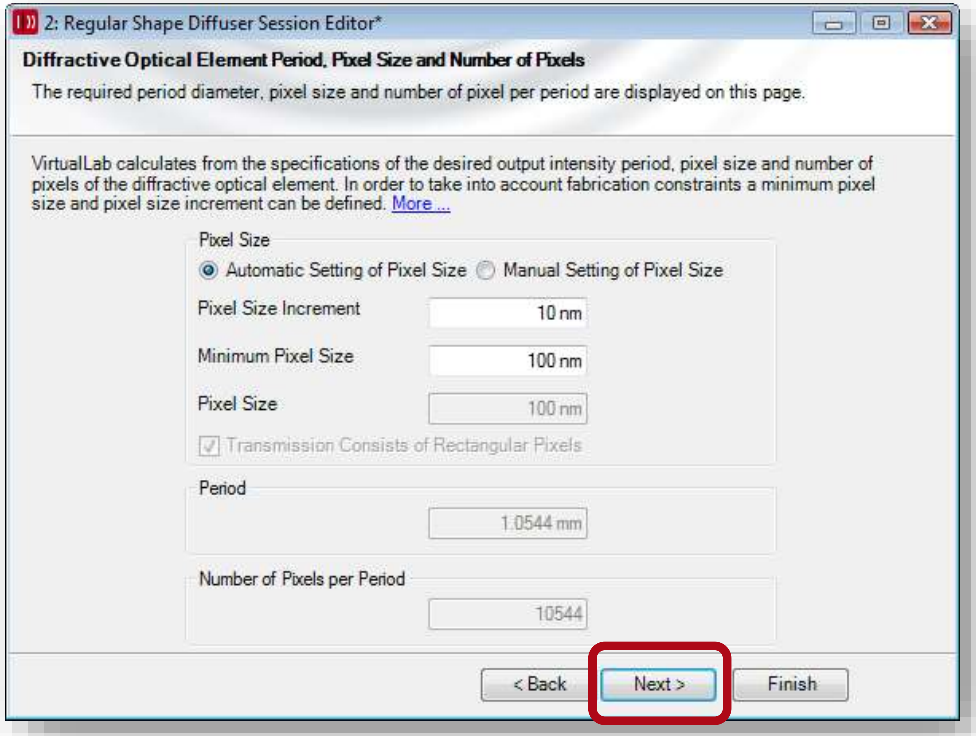
5. Diffuser Parameter



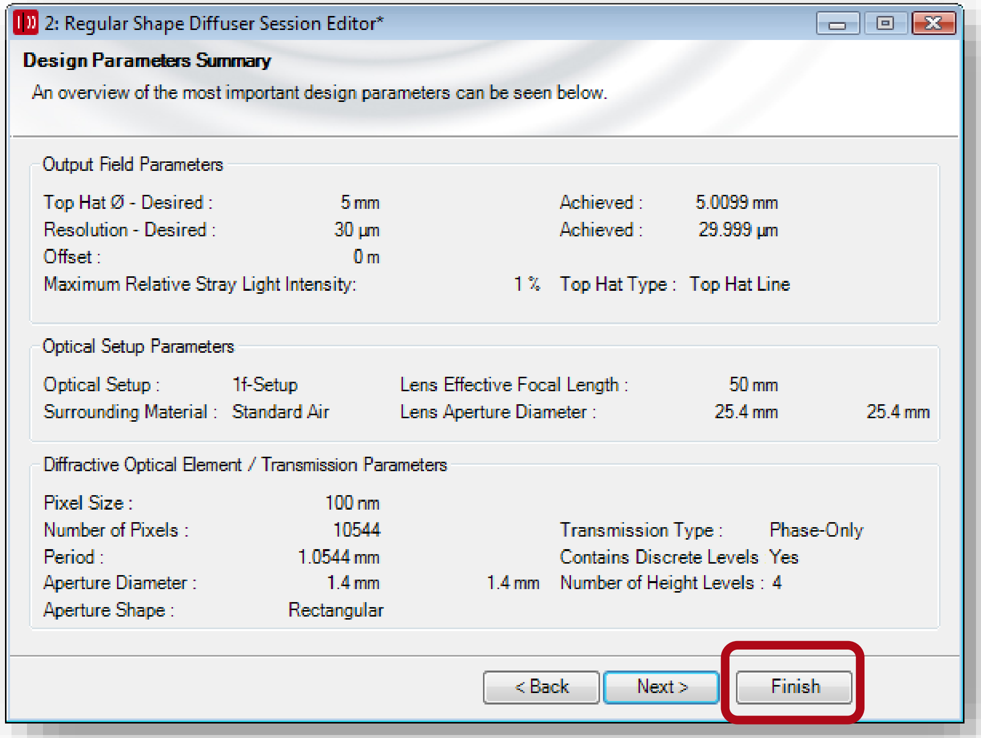
5. Diffuser Parameter



5. Diffuser Parameter

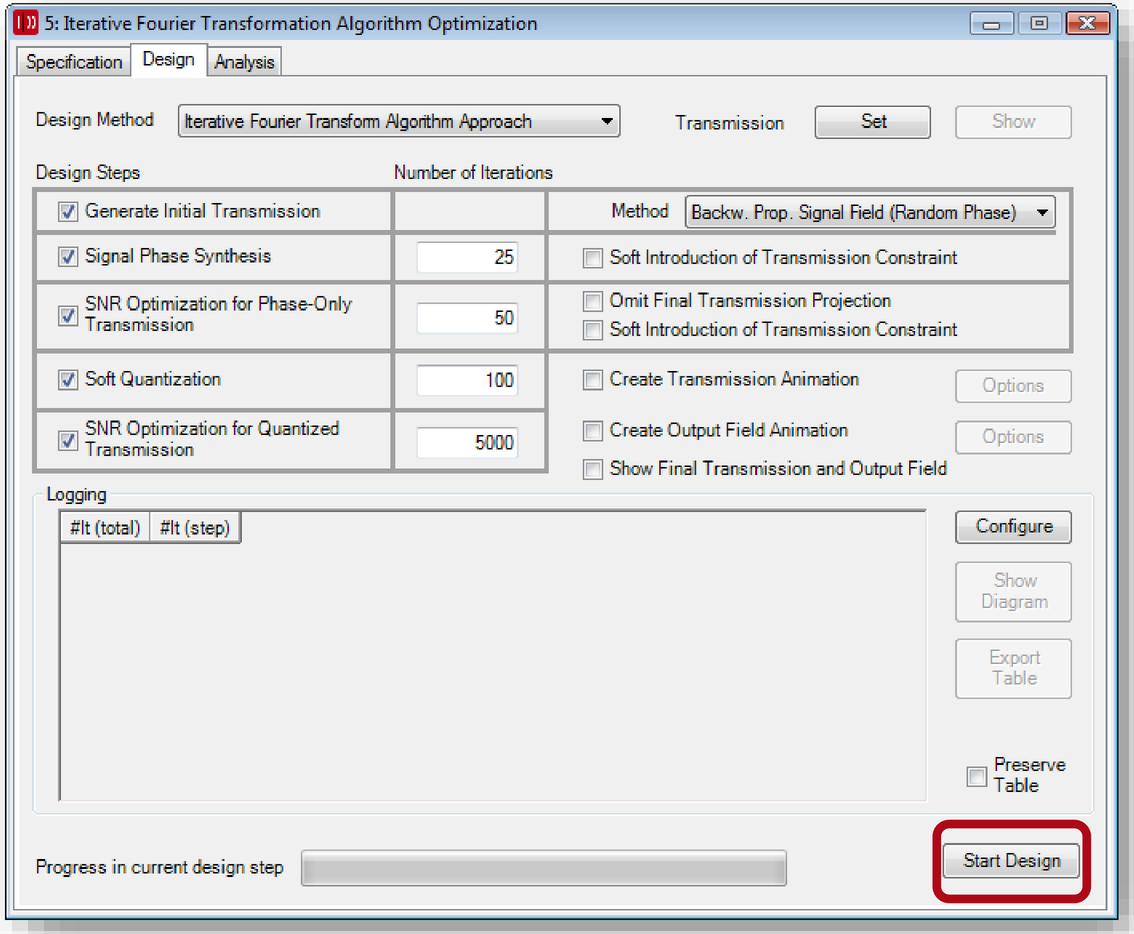


6. Summary

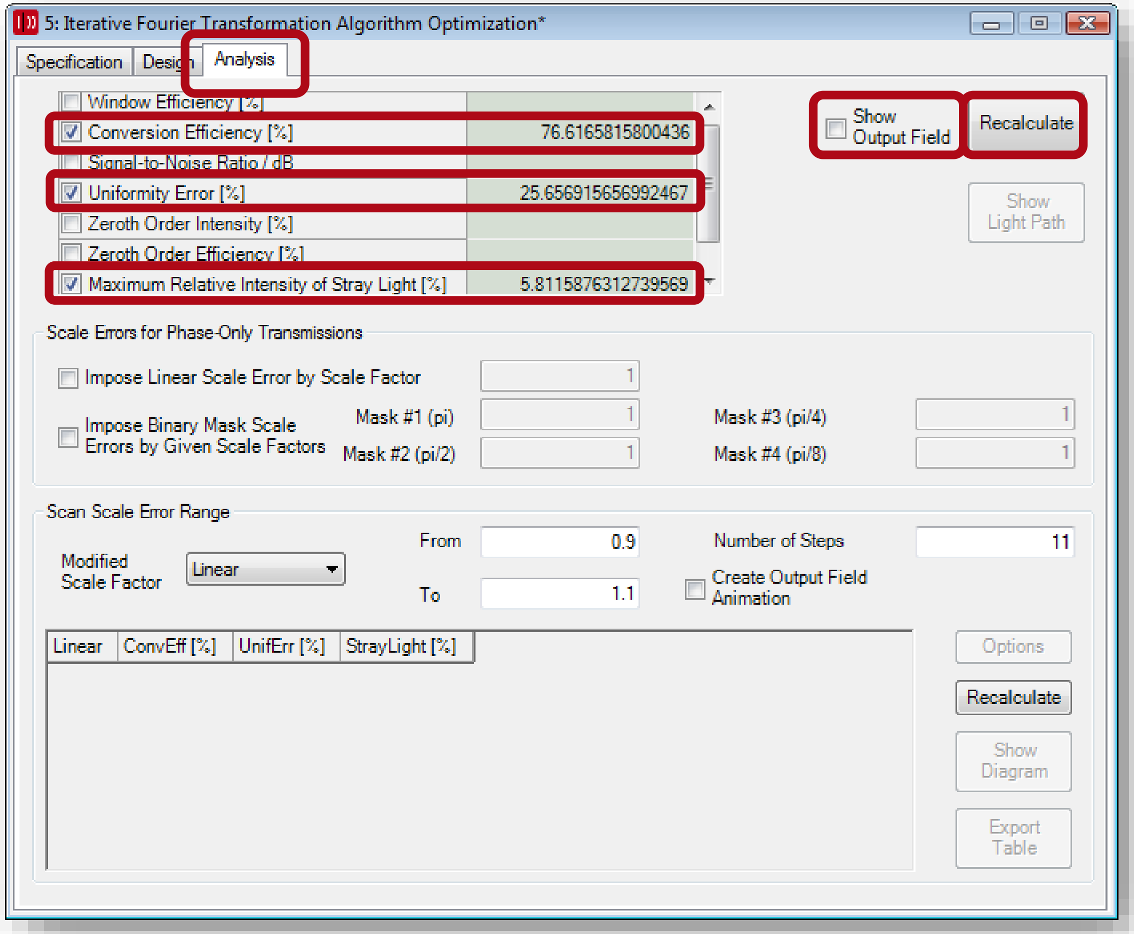


Results in

7. Diffuser Optimization

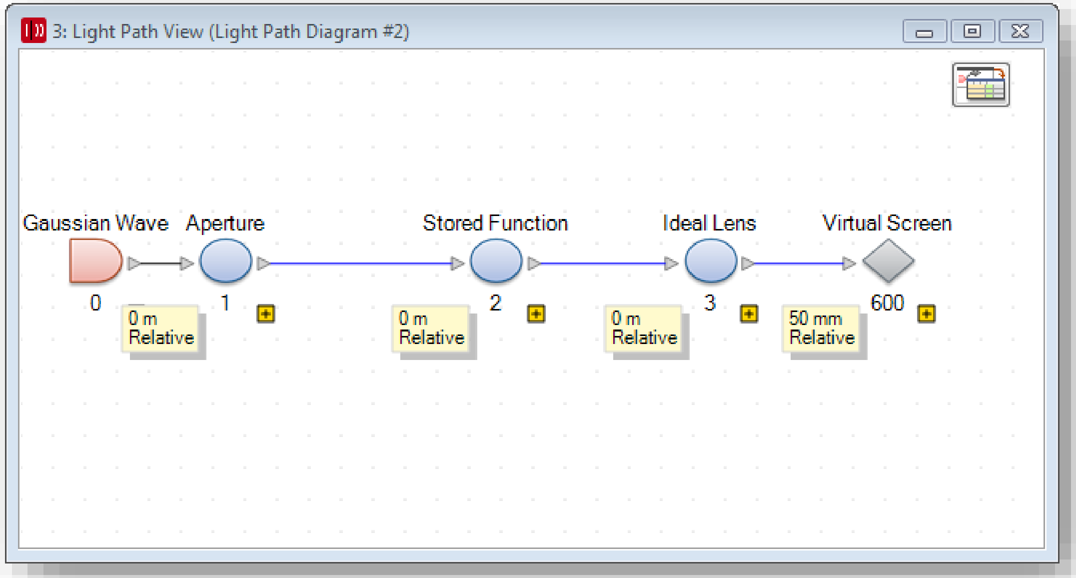


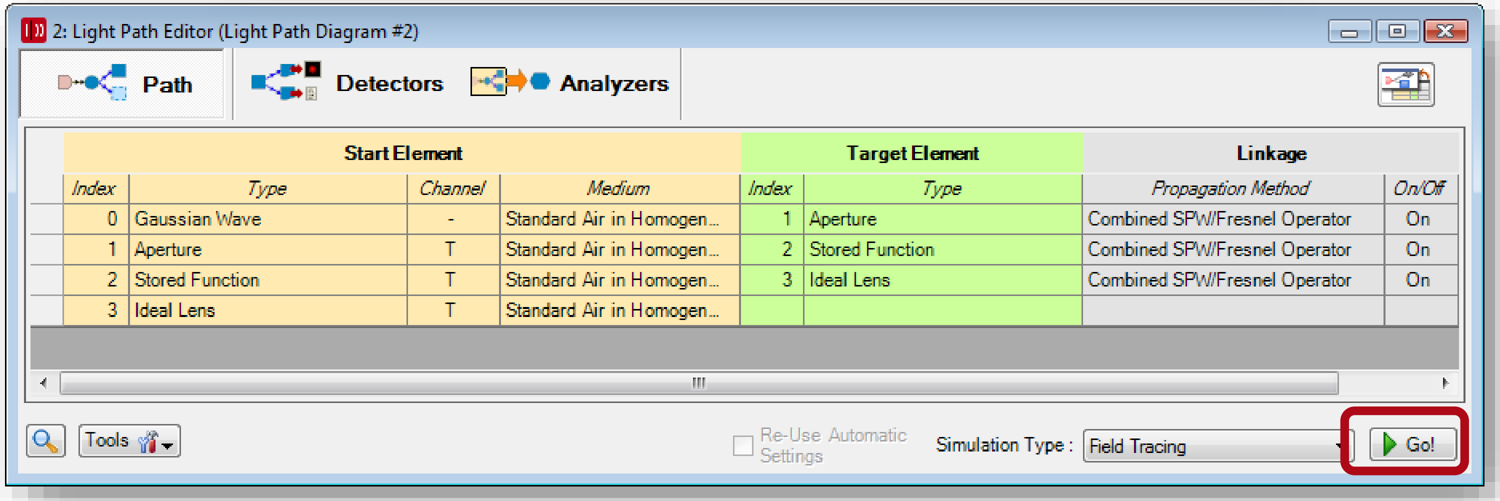
7. Diffuser Optimization



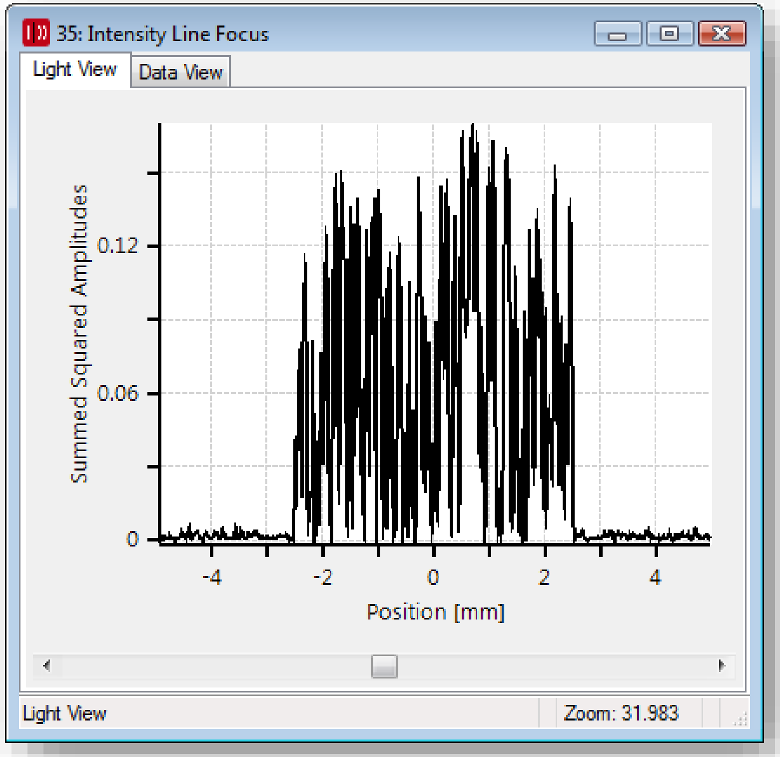
The Analysis tab allows to calculate the merit functions results of the output field generated by the diffuser.
Repeat optimization and keep best diffuser transmission.

8. Light Path

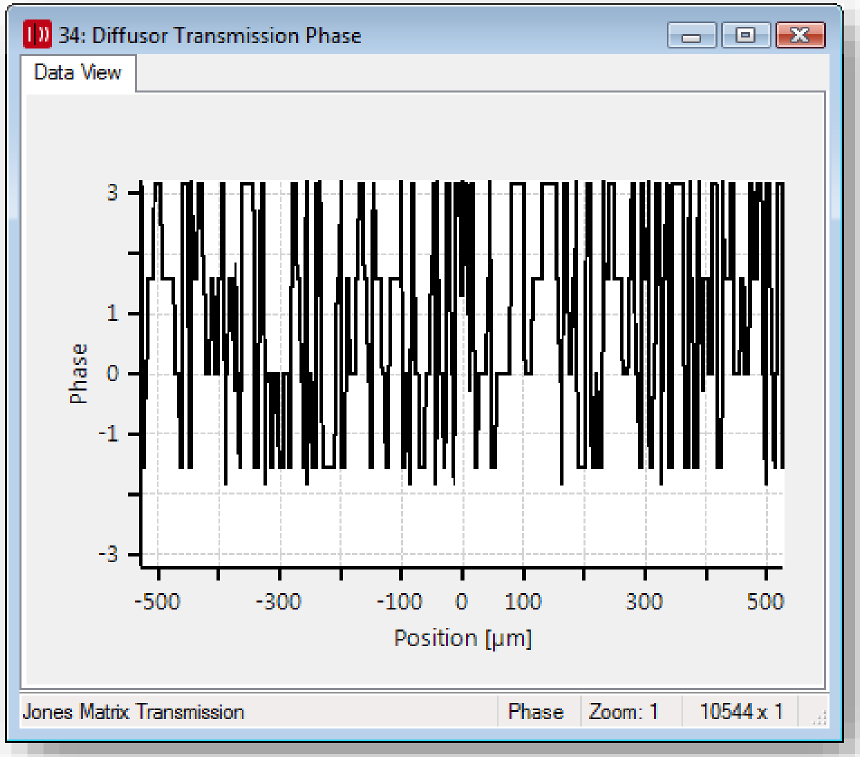

3: Light Path View (Light Path Diagram #2)
Gaussian Wave
Aperture
Stored Function
Ideal Lens
Virtual Screen
0
1
2
3
600
0 m Relative
0 m Relative
0 m Relative
50 mm Relative


2: Light Path Editor (Light Path Diagram #2)
Path
Detectors
Analyzers
Start Element
Target Element
Linkage
Index | Type | Channel | Medium | Index | Type | Propagation Method | On/Off
0 | Gaussian Wave | - | Standard Air in Homogen... | 1 | Aperture | Combined SPW/Fresnel Operator | On
1 | Aperture | T | Standard Air in Homogen... | 2 | Stored Function | Combined SPW/Fresnel Operator | On
2 | Stored Function | T | Standard Air in Homogen... | 3 | Ideal Lens | Combined SPW/Fresnel Operator | On
3 | Ideal Lens | T | Standard Air in Homogen...
Tools
Re-Use Automatic Settings
Simulation Type :
Field Tracing
Go!

8. Simulation Results

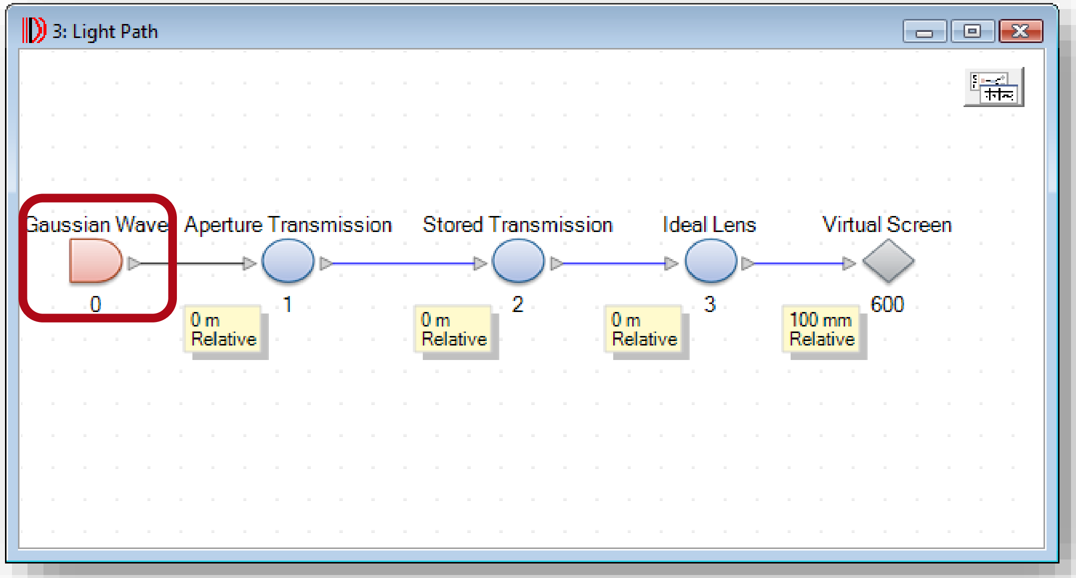


Intensity Line Focus

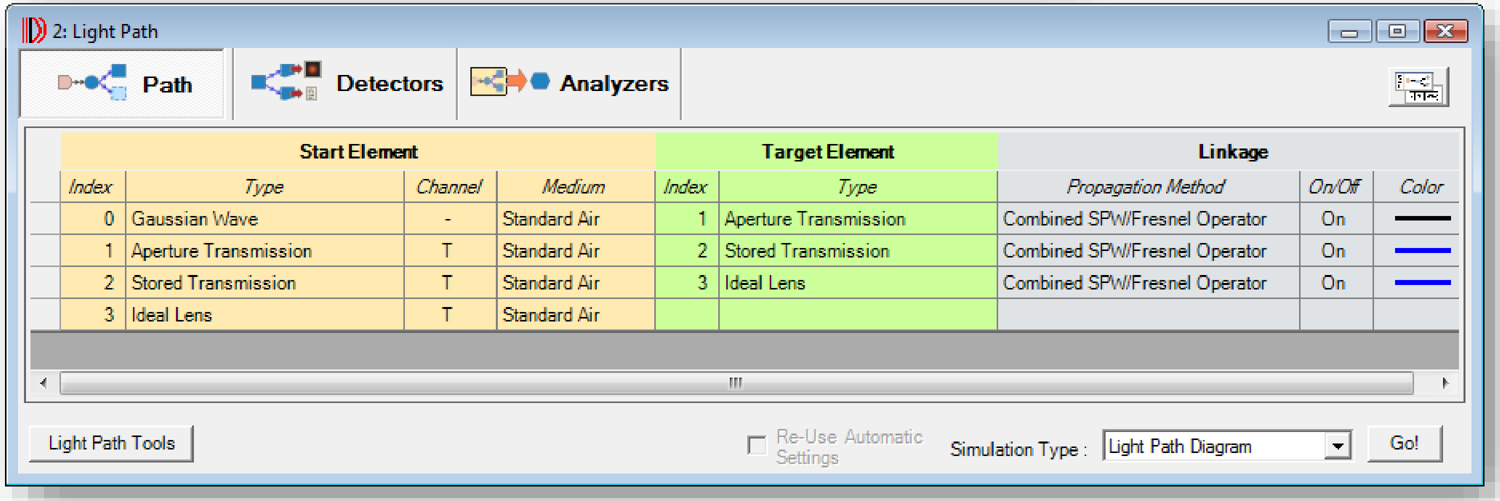


Diffuser Transmission Phase
(Click φ on toolbar)

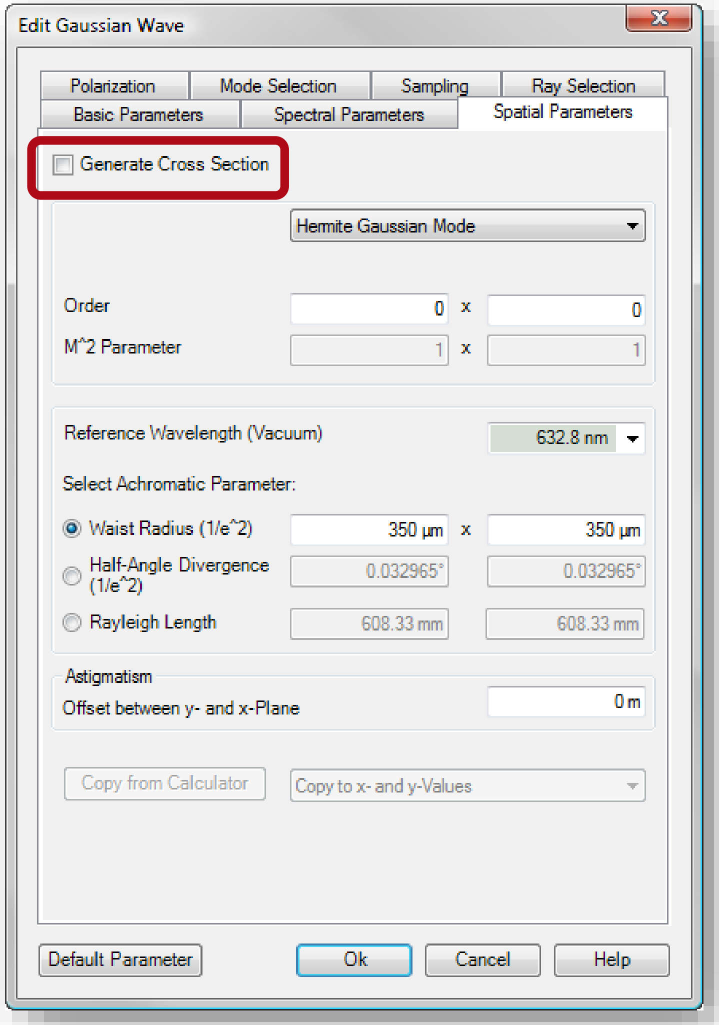
9. Light Path



Double click Gaussian Wave light source.

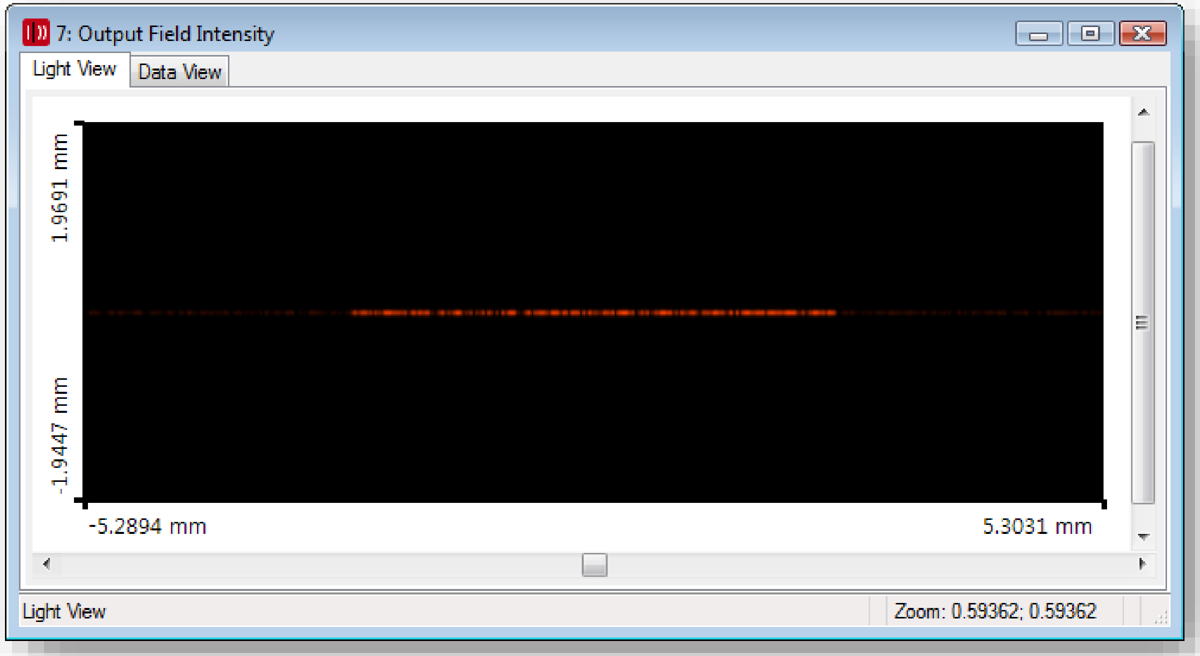


9. Gaussian Wave Light Source



- Switch off Generate Cross Section.
- Click Ok button.
- Press Go! on the Light Path Table

10. Simulation Results



2D Intensity distribution in target plane

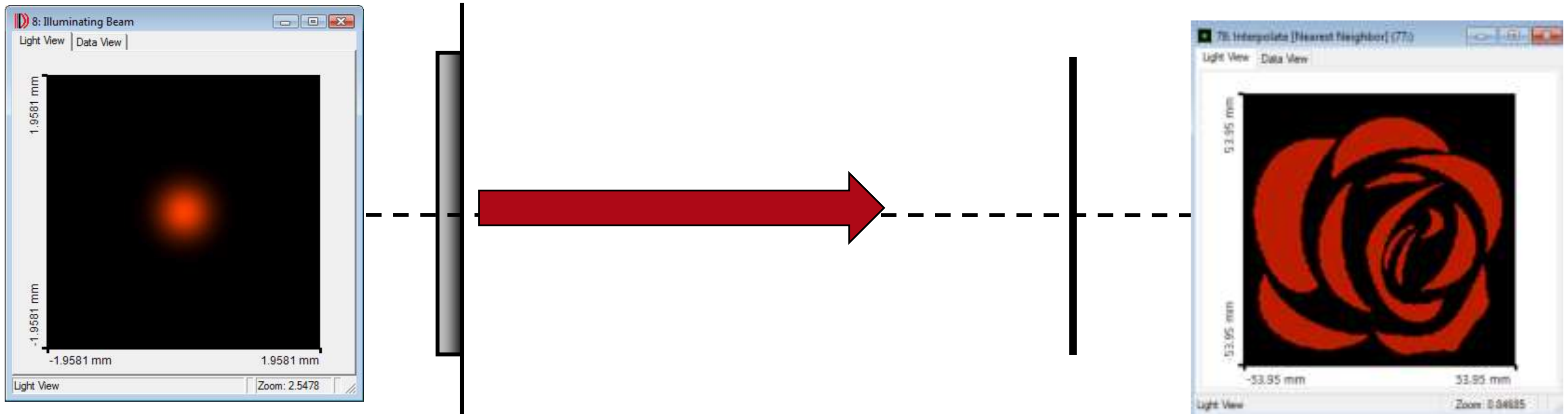
Conclusion

- VirtualLab™ assists customer during design of diffractive optical elements for generation of diffuse lines or Top Hats.
- Assisted design steps enable also optical engineers inexperienced in diffractive optics to benefit from current developments.

Task 11 Modeling Task

DOE: Diffuser
Diameter: 1mm x 1mm
Phase Levels: 4
Pixel Size: >2µm

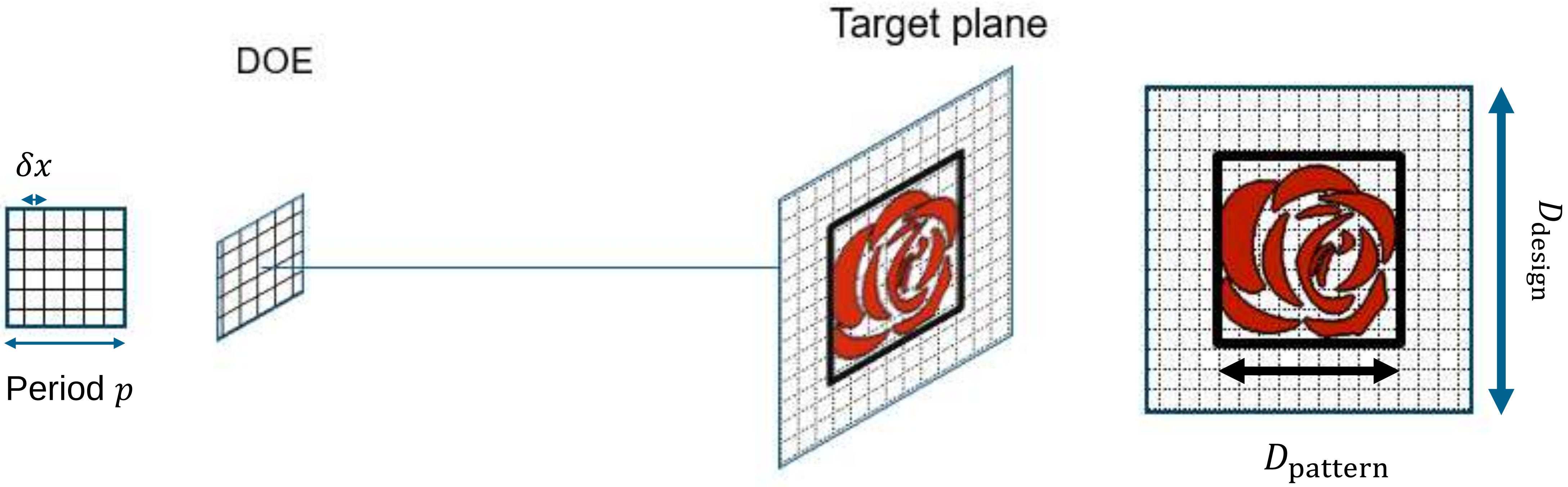
Target
Plane



Illuminating Beam
Intensity
Wavelength 650nm
Diameter: 1mm

Far field z=1 m

Workflow



DOE
Target plane
δx
Period p
D_{design}
D_{pattern}

Workflow of DOE design

- Parameters of DOE and related pattern calculation
  - DOE:
    - pixel size δx $\delta x = 2\mu\mathrm{m}$
    - Period p <beam size d $p < 1\mathrm{mm}$
  - Pattern $a = 3$
    - Size D_{pattern} (with scaling factor a, one may know the design pattern size $D_{\mathrm{design}} = D_{\mathrm{pattern}} * a$
    - Resolution Δx
  - From manufacture, one may get the data δx and d, then calculate the size and resolution of pattern D_{pattern}=108mm
    - $D_{\mathrm{pattern}} = \frac{\lambda z}{a*\delta x}$ (far field) or $D_{\mathrm{pattern}} = \frac{\lambda f}{a*\delta x}$ (1f/2f setup)
    - $\Delta x = \lambda z/p$(far field) or$\Delta x = \lambda f/p$(1f/2f setup) $\Delta x = 0.65\mathrm{mm}$
- Input the parameters into session editor
- IFTA to design the transfer function

Workflow of DOE design

- Parameters of DOE and related pattern calculation
- Input the parameters into session editor
- IFTA to design the transfer function
  - Check the step numbers of each processure
  - Multi-run is sometimes necessary
- Design the structure from transfer function
- Check the simulation result
  - High NA need the further optimization of the real structure
- Tolerance analysis
- Export the real structure

Task 11:Video

Klick the following link to watch the video:

https://youtu.be/89-kkd4XwYk

Task 12

Rigorous Parametric Optimization of Diffractive Beam Splitters

Keywords: Fourier modal method, FMM, iterative Fourier transformation algorithm, IFTA, 1D, grating, binary, improvement, high NA, efficiency, uniformity

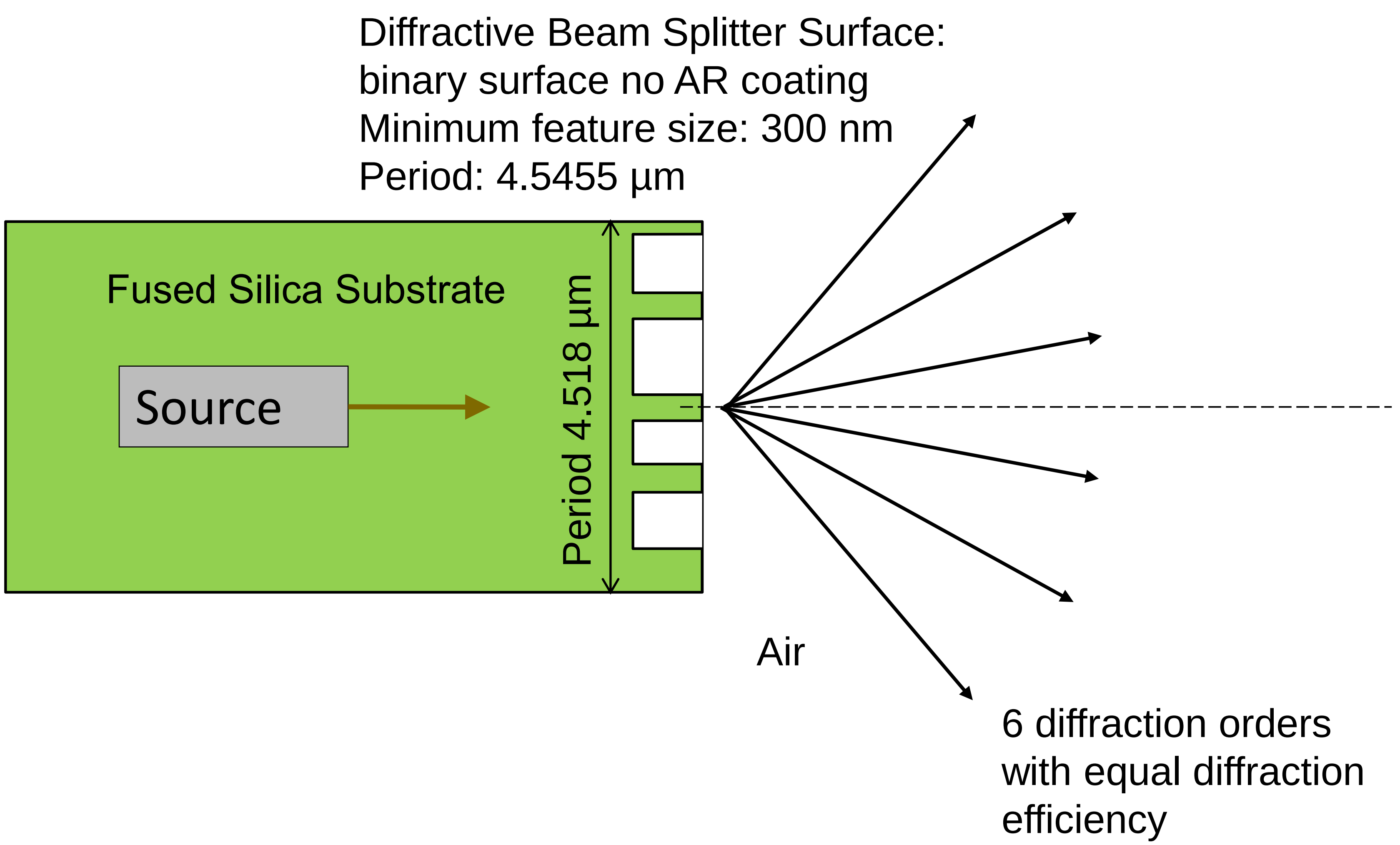
Description

- This scenario demonstrates the rigorous parametric optimization of a diffractive binary 1:6 beam splitter element.

Abstract

- Diffractive beam splitting elements are typically computer optimized gratings splitting a single laser beam into several beams with well defined power ratios of the desired diffraction orders.
- The optimization of diffractive beam splitters is typically done by the Iterative Fourier Transform Algorithm (IFTA).
- However the required design steps are based on approximations which are not valid for large diffraction angles and small surface features in the range of the wavelengths of light.
- This application scenario shows
  - The optimization of a high NA diffractive 1:6 beam splitter by the IFTA.
  - The rigorous electromagnetic analysis of the beam splitter by Fourier Modal Method (FMM).
  - The definition of customized merit functions for the evaluation/optimization of diffraction orders efficiencies.
  - The improvement of the beam splitter surface by parametric optimization and analysis by FMM.

Modeling Task



Modeling Task

Illumination Wave

- Plane Wave
- Vacuum wavelength: 632.63nm
- Polarization: Linearly polarized in x-direction
- Incident angle: 0°
- Source field diameter: infinite
- Source field defined in fused silica

Distribution of Desired Diffraction Orders

- Beam splitter is a so-called even order missing grating. Only odd orders are used and inner 6 odd orders should have equal intensities.
- Diffraction order positions in 100 mm distance and the associated diffraction angles that correspond to the given period of 4.5455 µm are listed below:

Order #	**Position / mm**	**Angle / °**
-5	-96.848	-44.073
-3	-45.935	-24.672
-1	-14.051	-8
1	14.051	8
3	45.935	24.673
5	96.848	44.073

Merit Functions for Desired Diffraction Orders

Merit Function	Optimization Goal	Desired Condition
Uniformity Error U	Smaller than limit	< 0.5%
Total Diffraction Efficiency η	to be maximized	

Mathematically these conditions mean:

$$U = \frac{\eta_{max} - \eta_{min}}{\eta_{max} + \eta_{min}} < 0.5\% \quad \text{and} \quad \eta = \eta_1 + \eta_{-1} + \eta_3 + \eta_{-3} + \eta_5 + \eta_{-5} > 80\%$$

with η_i … the efficiency of particular diffraction order i with

$$i \in \{-5; -3; -1; +1; +3; +5\}$$

Fabrication Condition

- Often the manufacturer also have limitation regarding smallest occurring structure sizes.
- For this scenario we assume that the smallest distance between two transition points should not be smaller than 300nm.

Design Steps

1. Optimization of initial guess of a high NA diffractive 1:6 beam splitter by the IFTA.
2. Generation of transition point list: Binary gratings are often described by a list of transition points.
3. Definition of customized merit functions for the rigorous evaluation/optimization of diffraction orders efficiencies.
4. Rigorous electromagnetic analysis of the beam splitter by Fourier Modal Method (FMM).
5. Improvement of the binary beam splitter surface by parametric optimization and analysis by FMM.

IFTA Optimization of Beam Splitter

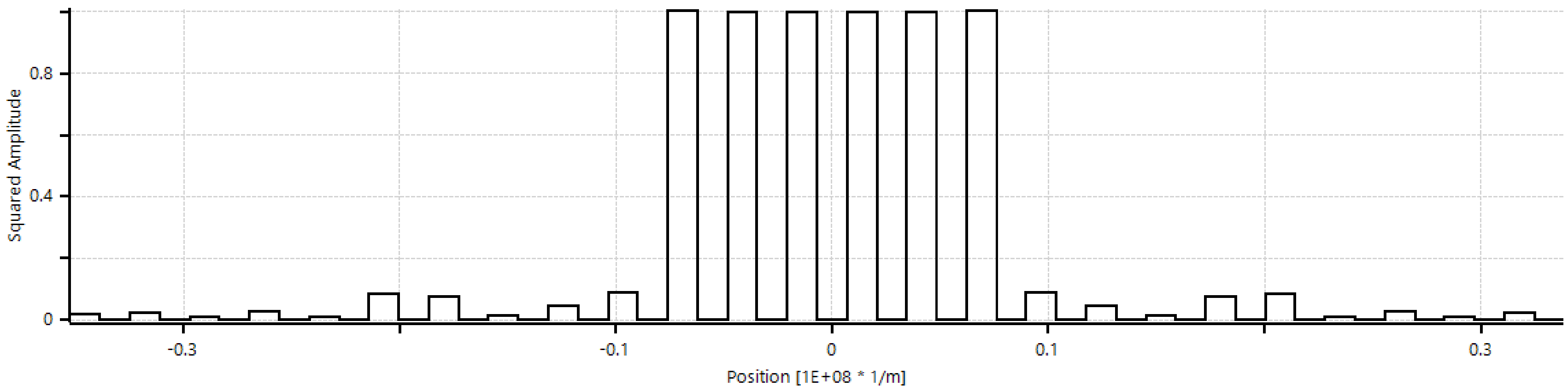
For the optimization of the phase only beam splitter transmission the IFTA optimization document is used.

The evaluated resulting merit functions are

- Efficiency (excluding Fresnel losses): 84.5%
- Uniformity error: 0.13%

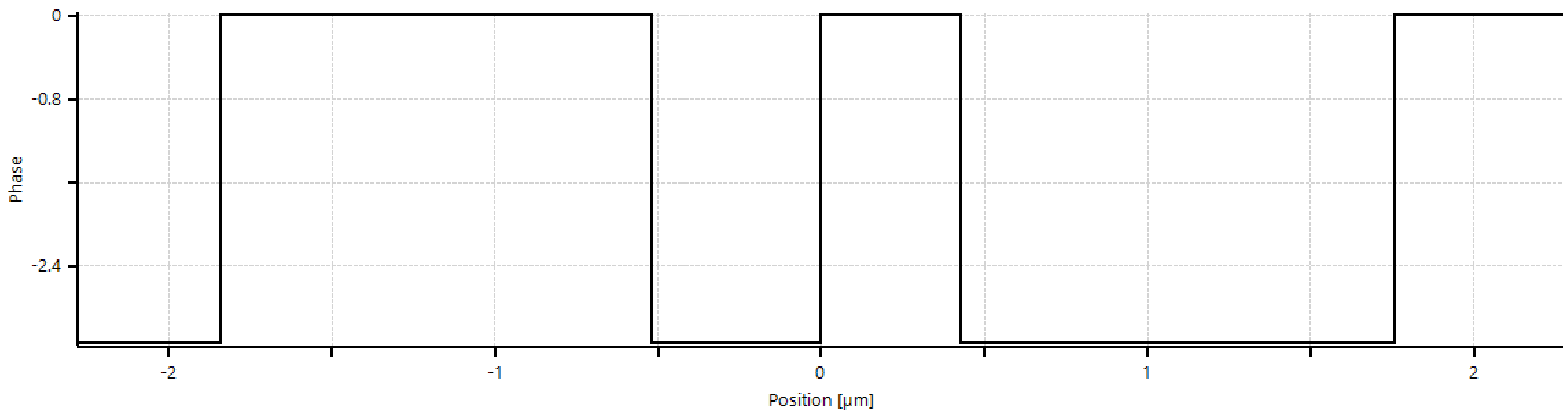
File: Sc570_Rigorous_Beam_Splitter_Optimization_1_IFTA.dp

IFTA Optimization Result



- Relative power of diffraction orders of diffractive beam splitter.
- The analysis is done based on the optimized transmission function.

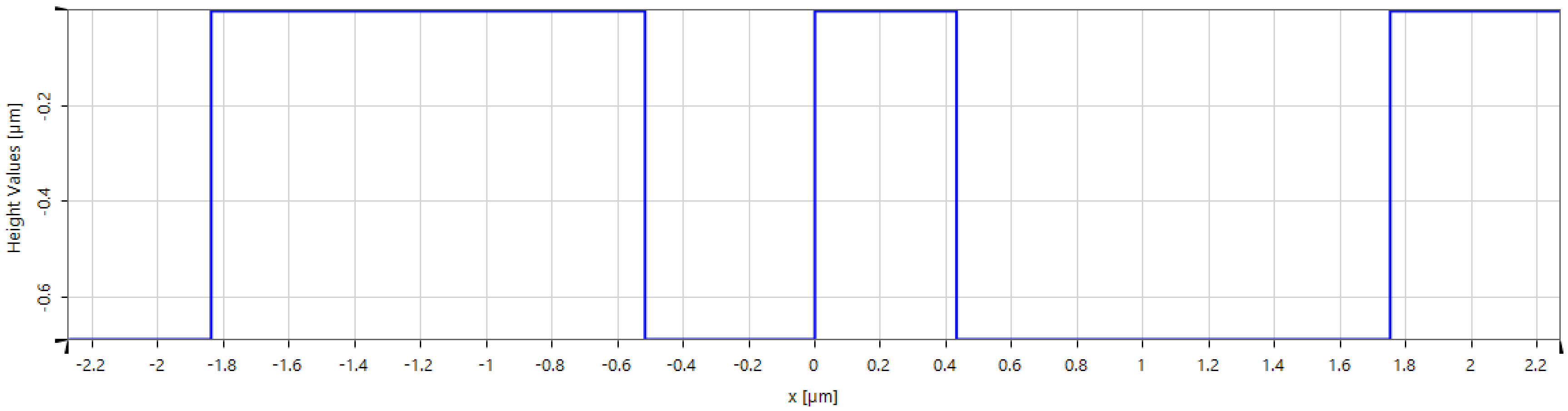
IFTA Optimization Result



Binary phase of optimized transmission function of diffractive beam splitter

Calculation of Surface Profile

- Surface profile must be calculated from the transmission function.
- Surface can be calculate by thin element approximation (TEA).
- TEA assumes that height profile is proportional to the transmission phase.
- Display of transmission: Design page of IFTA optimization document, Transmission→ Show button.
- Calculation of surface profile: Design→Structure Design function. (see also Tutorial 144.01).
- For the display of the calculated height profile: Double click the resulting component, edit the sampled surface and click the show button.



Calculation of Transition Points

- Smallest feature of surface has around 500nm size.
  → a rigorous electromagnetic analysis is required to evaluate optical performance since the thin element approximation used for surface calculation is not sufficiently accurate for this feature size.
- Parametric optimization is a possible way to improve the optical performance. This requires description of surface by transition points.
- Via VirtualLab module the the transition points list is converted to a sampled surface profile.
- Modules cannot be used with the Trial version.

File: Sc570_Rigorous_Beam_Splitter_Optimization_2_Module.cs

Calculation of Transition Points

Diagram | Table | Value at x-Coordinate

x	Height Values
-2.27275 µm	-691.9250942 nm
-1.84175 µm	0 m
-518.75 nm	-691.9250942 nm
-250 pm	0 m
431.25 nm	-691.9250942 nm
1.75425 µm	0 m

- Run VirtualLab module and select sampled surface.
- The module returns a data array with a transition point list.

File: Sc570_Rigorous_Beam_Splitter_Optimization_3_TransitionPoints.da

Setup of LPD for Rigorous Analysis

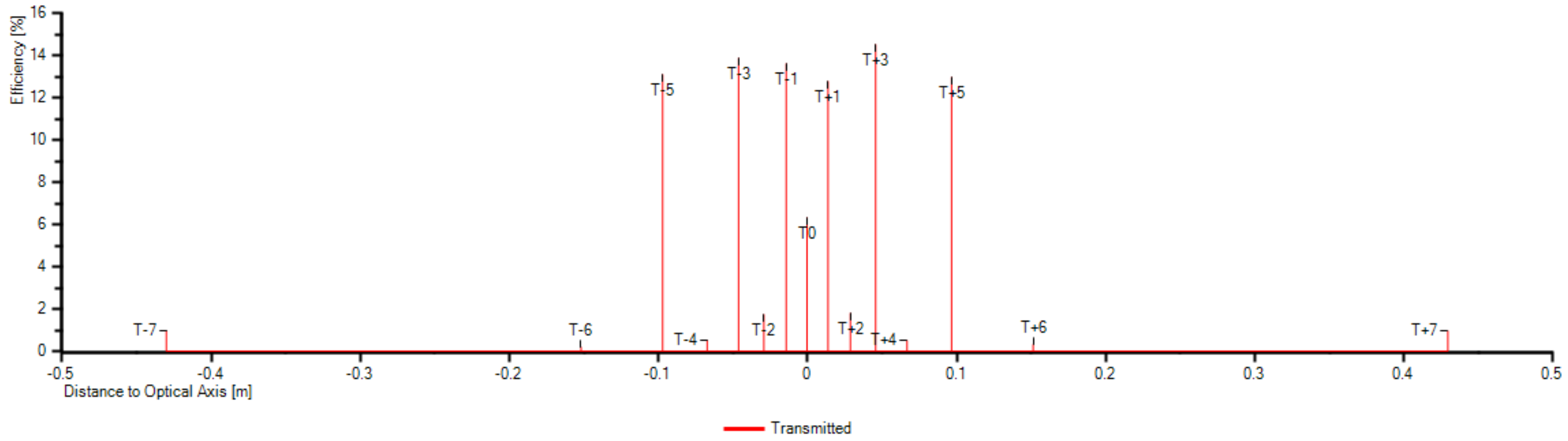
- Setup of Grating Toolbox light path diagram (LPD) for rigorous linear (2D) grating analysis.
- Modeling of beam splitter surface by created transition point list interface.
- Very close transition points with distances smaller than the fabrication resolution limit should be removed. Resulting reduction of the optical performance can be compensated during later parametric optimization.

File: Sc570_Rigorous_Beam_Splitter_Optimization_4_LPD.lpd

Programmable Grating Analyzer

- Programmable grating analyzer allows the definition of customized merit functions for evaluation of efficiencies and Rayleigh coefficients of diffraction orders.
- Programmable grating analyzer included in sample file contains code snippet for the calculation of uniformity error and diffraction efficiency of 6 required orders.
- Source code editor is disabled in Trial version of VirtualLab.

Rigorous Analysis of Beam Splitter



- Efficiencies of orders calculated by rigorous analysis by Fourier Modal Method (FMM). The analyzed surface profile was optimized by IFTA and thin element approximation.
- Efficiency (including Fresnel losses): 80.9%
- Uniformity error: 6.4%
- Significant increase of uniformity error.

Parametric Optimization

- The parametric optimization document is used to improve the result based on rigorous analyses.
- Free parameters:
  - All transition point positions
  - Scaling of profile height by scaling factor.

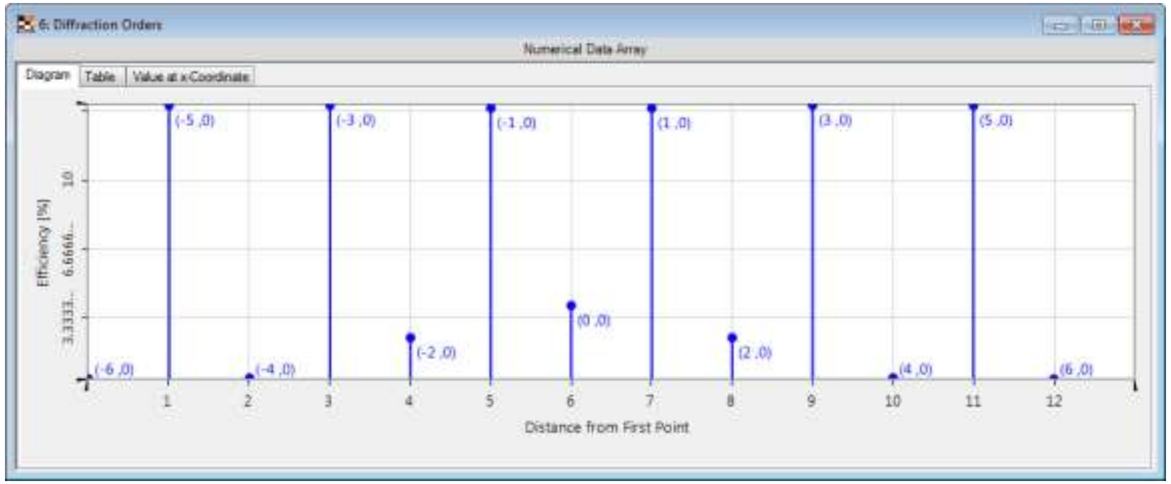
File:

Sc570_Rigorous_Beam_Splitter_Optimization_5_ParamOpt.opt

Parametric Optimization

- Merit functions regarded for optimization:
  - Uniformity error (named value#1)
  - Diffraction efficiency (named value #2)
  - Minimum feature size
- Optimization priority of merit functions:
  - Feature size limit
  - Uniformity error
  - Diffraction efficiency
- Priority is controlled by merit function weights

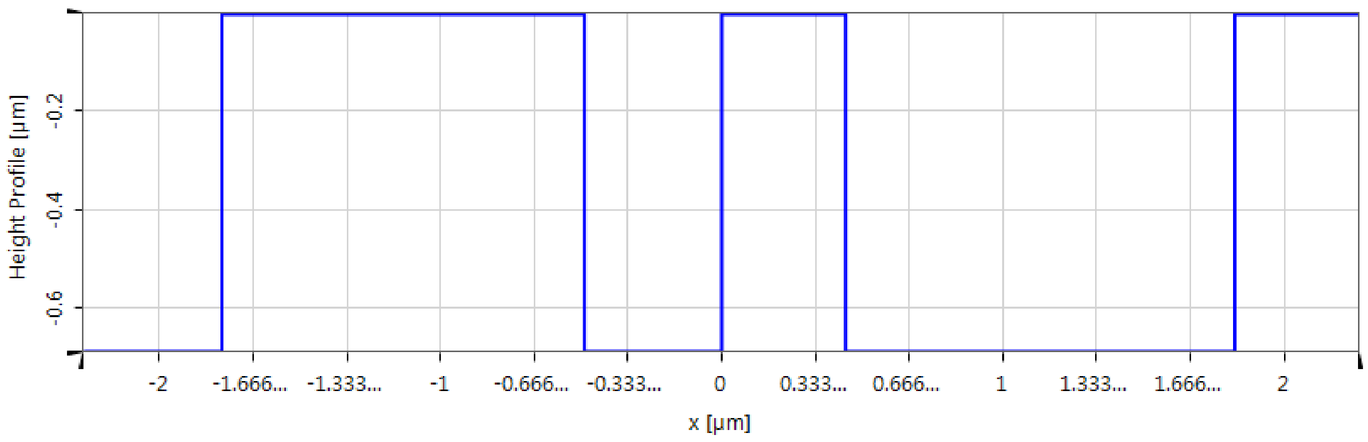
Optimization Result



- Figure: Efficiency of diffraction orders of beam splitter.
- Efficiency (including Fresnel losses): 81.85%
- Uniformity error: 0.5%

File: Sc570_Rigorous_Beam_Splitter_Optimization_6_OptLPD.lpd

Optimization Result



- Optimized surface profile
- Minimum feature size: 442 nm

Summary

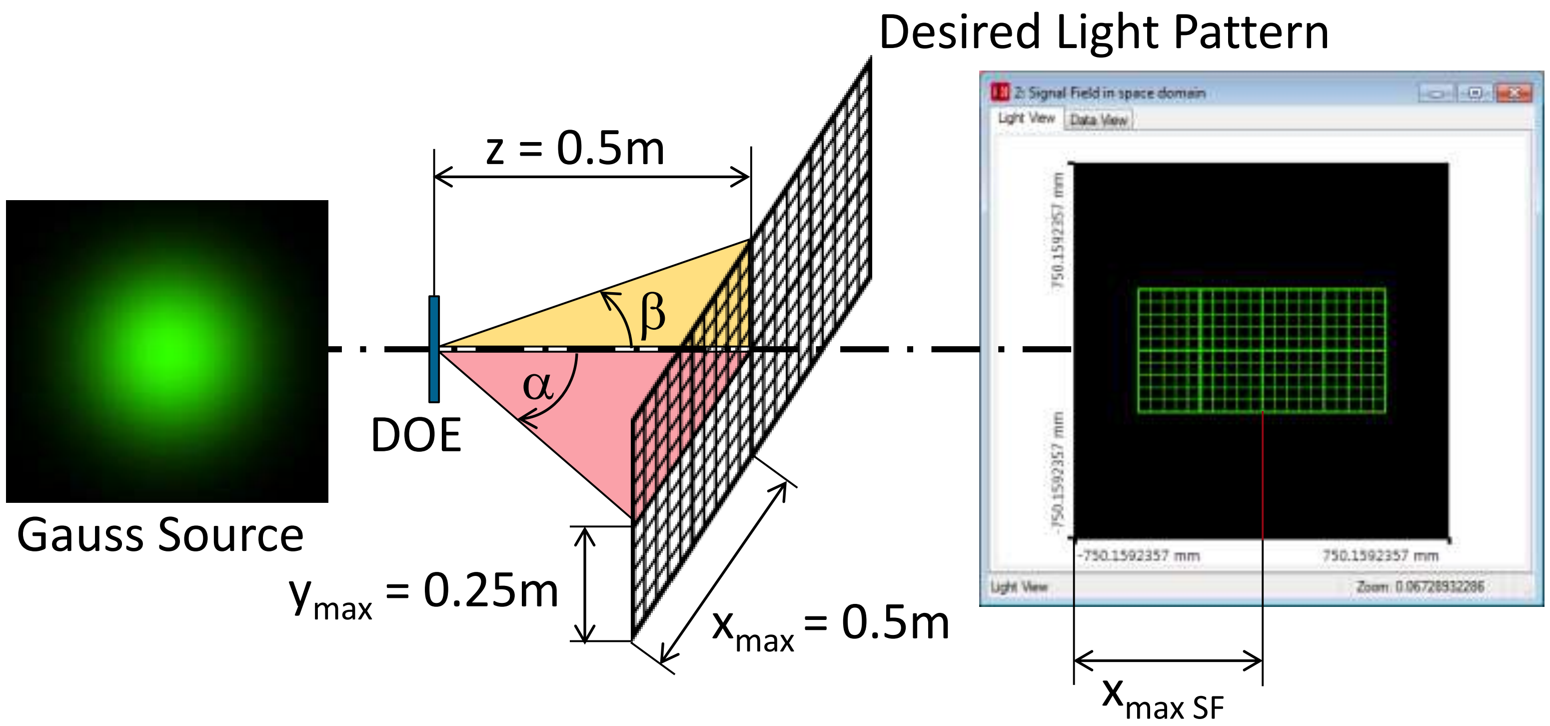
- VirtualLab allows parametric optimization of diffractive beam splitters.
- Simulation of diffraction efficiency of beam splitter during optimization by Fourier Modal Method (FMM).
- Initial guess for parametric optimization can be optimized by Iterative Fourier Transform Algorithm (IFTA).
- Diffractive beam splitter surface should be modeled for parametric optimization by transition points.

Task 13

Design & Optimization of High NA Pattern Diffusers

Keywords: high angle design, compensation, pincushion, barrel, distortion, intensity attenuation, preparation of signal field, DOE, loss, desired light target pattern, IFTA

Task Description



Diffuser design for generation of high NA light pattern in far field of DOE

Task Description

- Source parameters:
  - Wavelength of Gaussian source: 532nm
  - Diameter is to be chosen suitably according to final DOE
- System parameters:
  - Distance from DOE to screen: $z = 0.5m$
- Desired output field:
  - Desired light pattern: $1.0m \times 0.5m$ grid
  - Desired resolution of light pattern: $\pm$ 0.5mm
    (i.e. smallest distance between diffraction orders in the target plane: $\Delta x_{TP} = 1mm$ (off-axis))
  - Target pattern according to sample file „Sc385_HighNA_DiffuserDesign_01_DesiredLightPattern.bmp“
- DOE parameters:
  - Number of DOE‘s phase levels: 4

Design Type and Steps

Far field application

Optimization of a DOE for generation of an high NA angular distribution.

Info

DOE generates an angular distribution in the wavenumber domain (k_x, k_y).

Design steps

A. Calculation of pixel size, period and number of pixels of DOE.
B. Presetting of Iterative Fourier Transformation Algorithm (IFTA) optimization document according calculated parameters.
C. Generation of a precompensated angular light distribution (signal field) in wave number domain from desired intensity distribution in target plane as design target pattern (DTP). Analogous an specific optimization region could be defined.
D. Final settings (defining the actual DTP) of IFTA optimization document.

A. Calculations

1. Calculation of smallest pixel (feature) size of the DOE from a reasonable start value of the x extension of the signal field (here $x_{max\ SF}$ is only 0.75 m):

$$\Delta x_{\text{DOE}} = \frac{\lambda_{\text{vac}} \sqrt{x^2_{\text{max SF}} + z^2}}{2 n_{\text{air}}(\lambda_{\text{vac}}) x_{\text{max SF}}}$$

   Round this value to a fabricable size ($\Delta x'_{DOE}$) taking into account the manufacturer's capabilities regarding positioning increment and minimum feature size. Here the value was rounded to $\Delta x'_{DOE}$ = 320 nm. From this recalculate the accordant value for $x'_{max\ SF}$.

2. Calculation of the DOE's maximum period p_{max}:

$$\text{with} \quad \Delta u = \frac{(x_{\text{max}} + \Delta x_{\text{TP}}) n_{\text{air}}(\lambda_{\text{vac}})}{\lambda_{\text{vac}} \sqrt{(x_{\text{max}} + \Delta x_{\text{TP}})^2 + z^2}} - \frac{x_{\text{max}} n_{\text{air}}(\lambda_{\text{vac}})}{\lambda_{\text{vac}} \sqrt{x^2_{\text{max}} + z^2}} \quad \Rightarrow \quad p_{\text{max}} = \frac{1}{\Delta u}$$

3. Calculation of pixels per DOE period #s and rounding gives the number of sampling points #s'. For this example #s' = 2355

$$\#s' := \left. \frac{p_{\text{max}}}{\Delta x'_{\text{DOE}}} \right|_{\text{rounded to next odd integer}} \quad \Rightarrow \quad p'_{\text{max}} = \#s' \cdot \Delta x'_{\text{DOE}}$$

A. Calculations

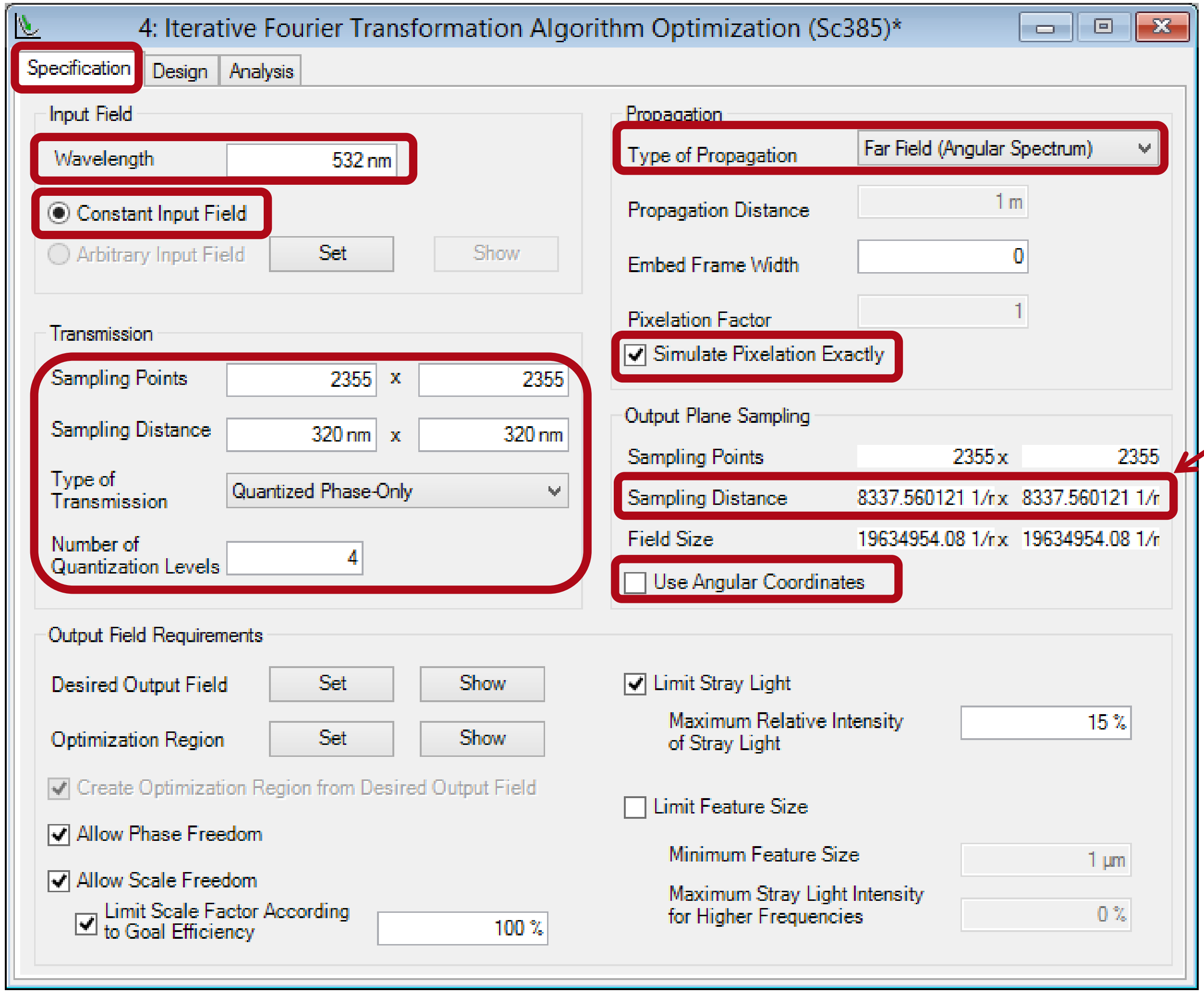
4. Calculation of achievable (marked with prime ‘) maximum diffraction angle

$$x'_{\mathrm{max}} = \frac{\lambda_{\mathrm{vac}} z}{\sqrt{n_{\mathrm{air}}^2(\lambda_{\mathrm{vac}}) 4 \Delta x'^2_{\mathrm{DOE}} - \lambda_{\mathrm{vac}}^2}} \quad \Rightarrow \quad \alpha'_{\mathrm{max}} = \arctan\left(\frac{x'_{\mathrm{max}}}{z}\right)$$

5. Calculation of achieved on-axis resolution of output intensity

$$\text{with} \quad u'_{\mathrm{min}} := \Delta u' = \frac{1}{p'_{\mathrm{max}}} \quad \Rightarrow \Delta x'_{\mathrm{TP}} = \frac{u'_{\mathrm{min}} \lambda_{\mathrm{vac}} z}{\sqrt{n_{\mathrm{air}}^2(\lambda_{\mathrm{vac}}) - u'^2_{\mathrm{min}} \lambda_{\mathrm{vac}}^2}}$$

B. Presetting of IFTA Optimization Document



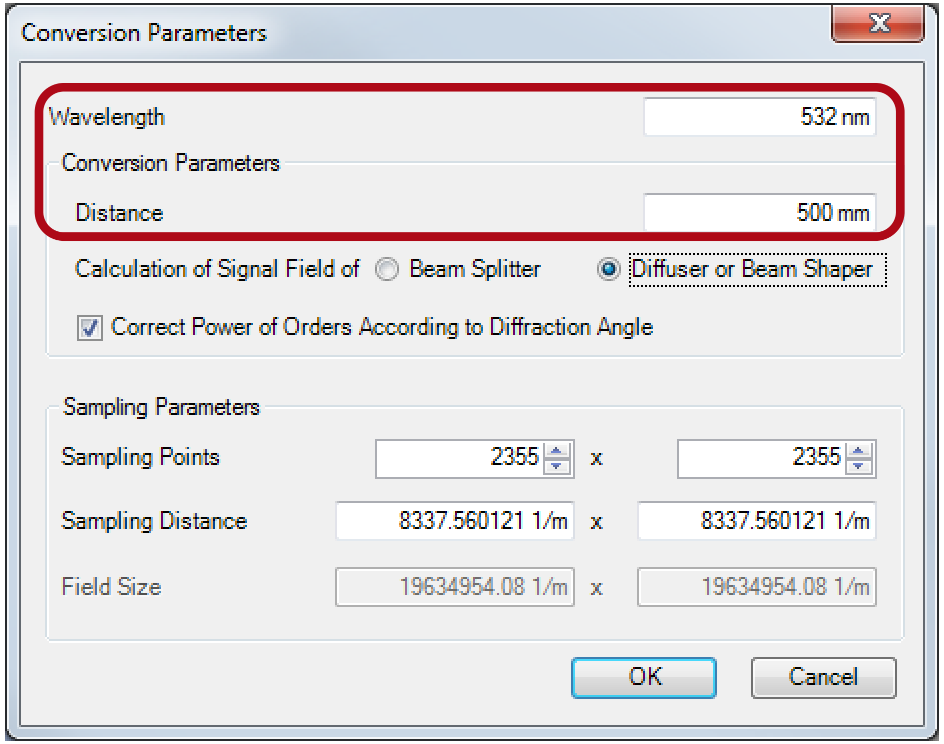
to be used in Mod014

C.1 Generate Precompensated Signal Field

- The module Mod014 calculates an angular light intensity distribution in wave number domain from a given spatial light intensity distribution in the target plane.

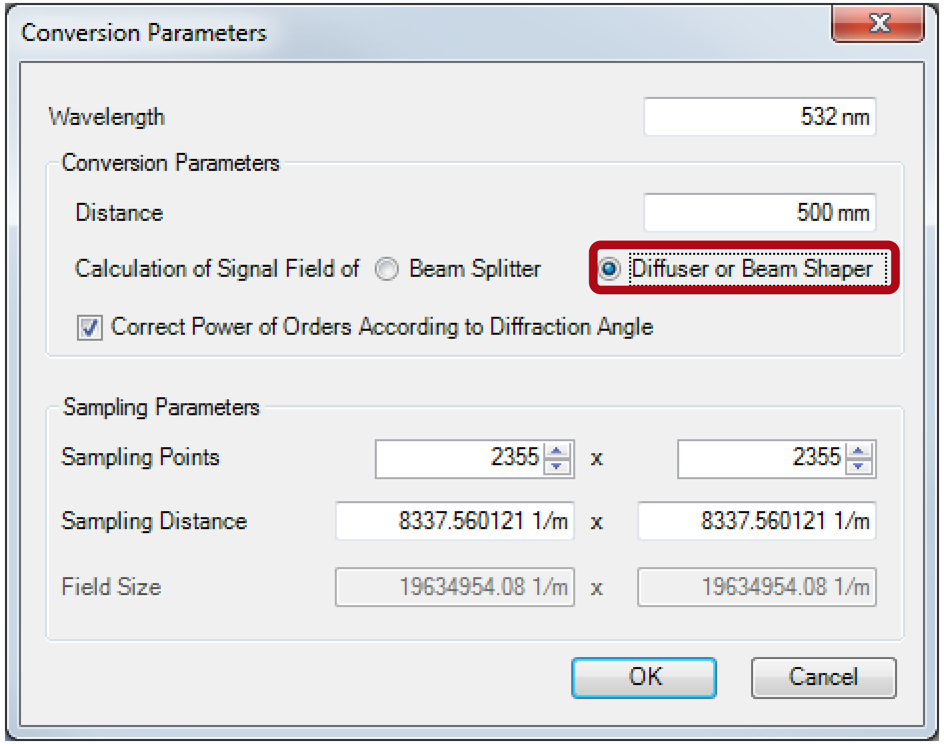
- Sampling distance calculated by the IFTA optimization document represented in wave number values must be entered in the module dialog (option “Use Angular Coordinates” has to be unchecked in IFTA document).

C.2 Module Settings



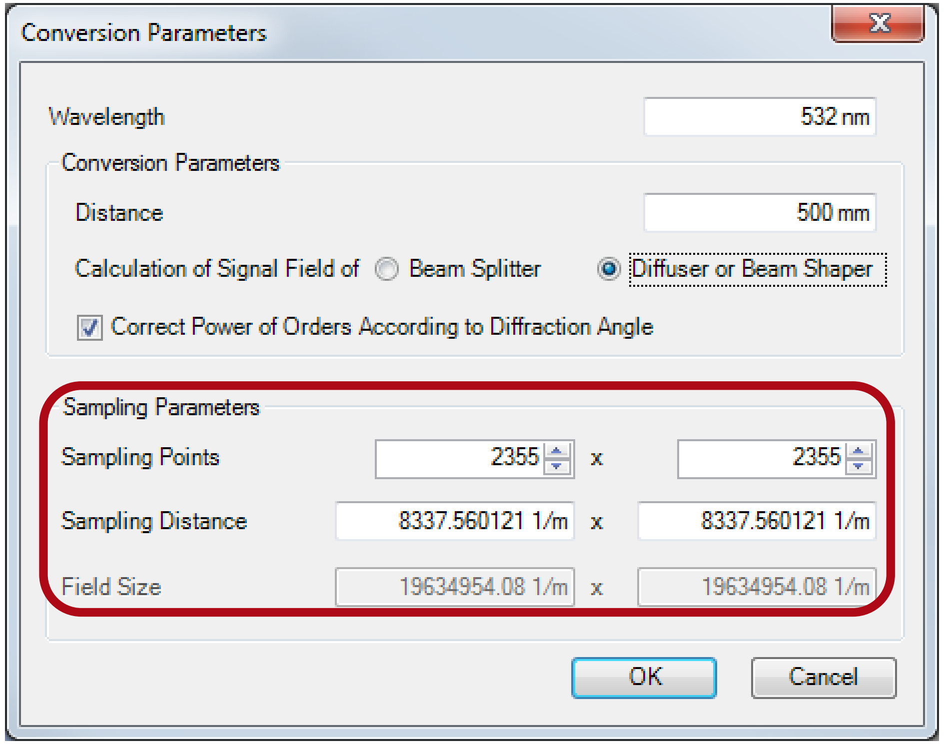
- Design wavelength
- Distance between DOE and target plane (needed for considering the required angles)

C.3 Module Settings



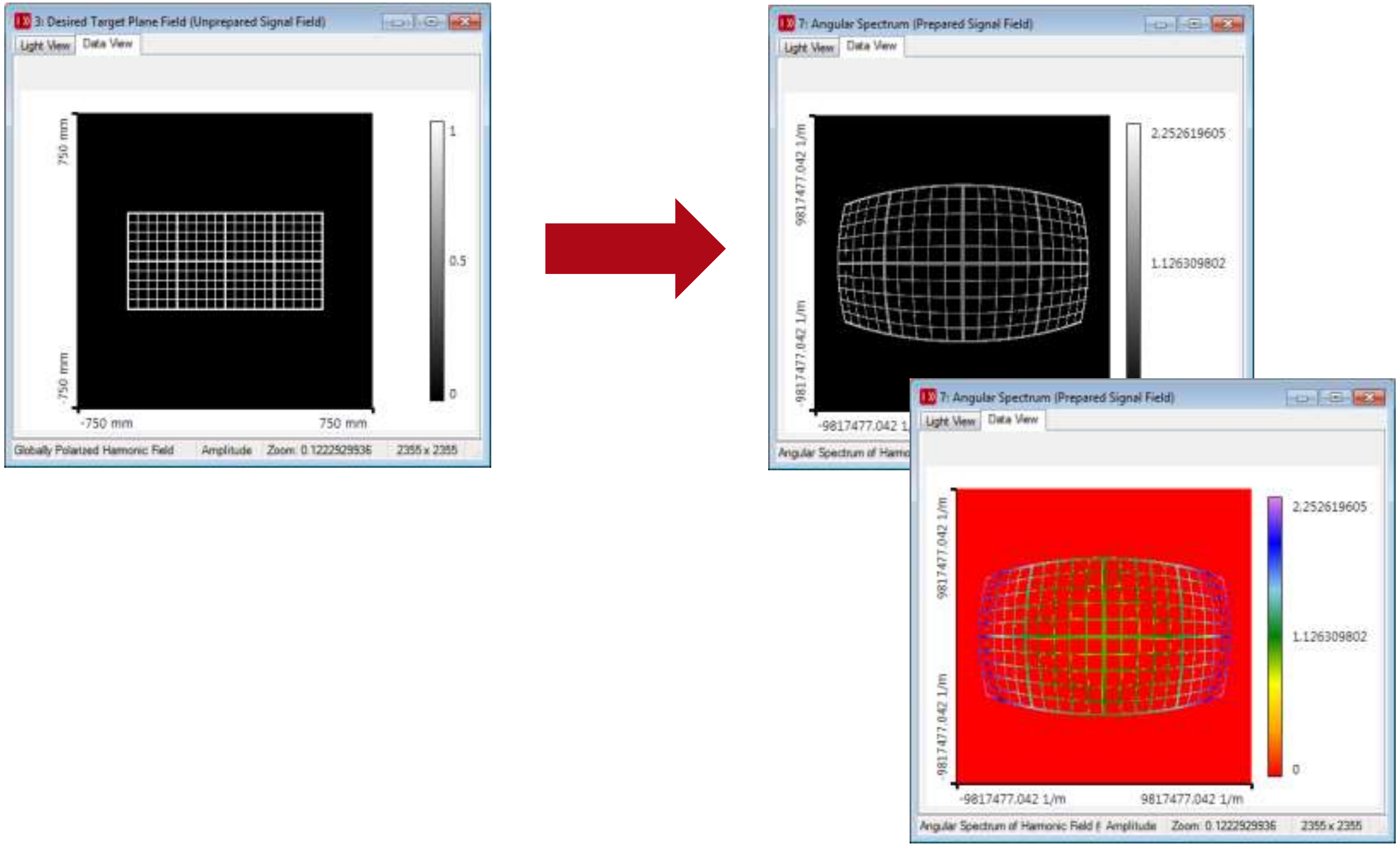
- Selection of diffuser mode

C.4 Module Settings



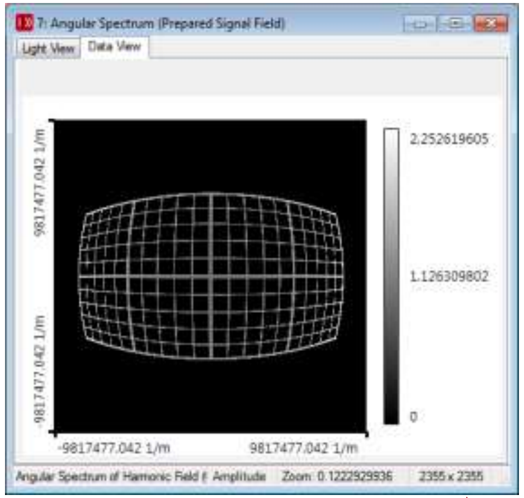
- Sampling points are automatically adapted
- Sampling distance has to be taken from the IFTA optimization document
- The angular field must be in wave number coordinates k_x, k_y

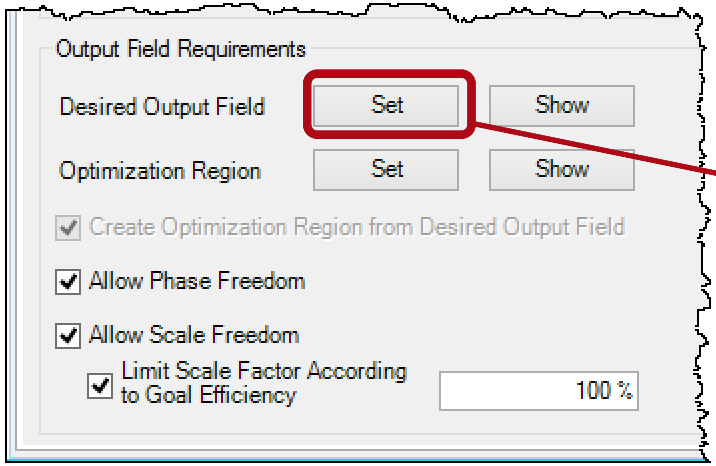
C.5 Compensation by Module

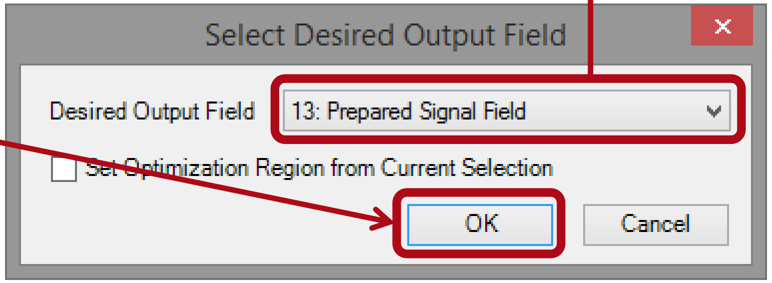


D. Defining DTP in IFTA Optimization Docment

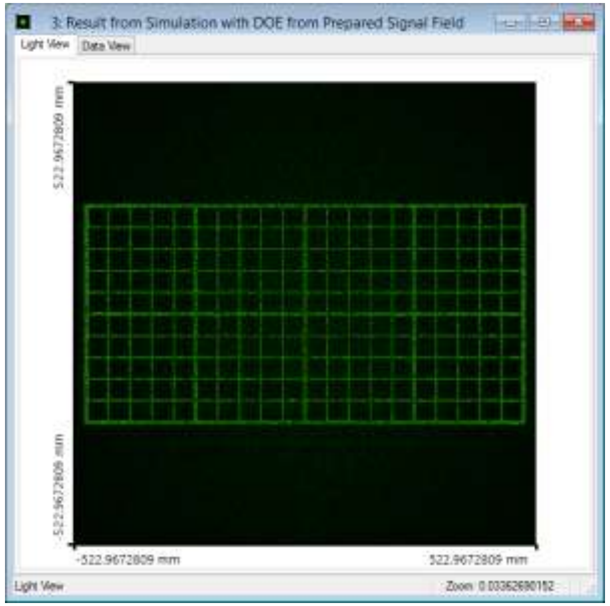
- The generated precompensated DTP is then to be set as desired output field in the IFTA optimization document.

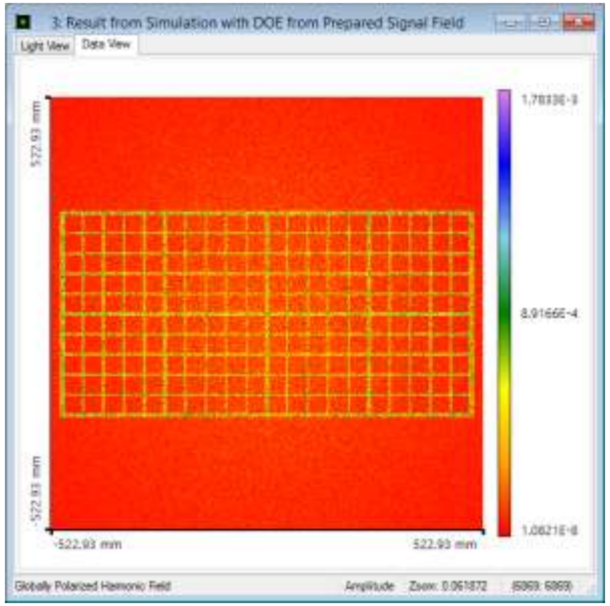






Final Simulation Result with Desiged DOE





Summary

- VirtualLab provides an easy to use tool for designing high NA DOEs for the creation of large light patterns.

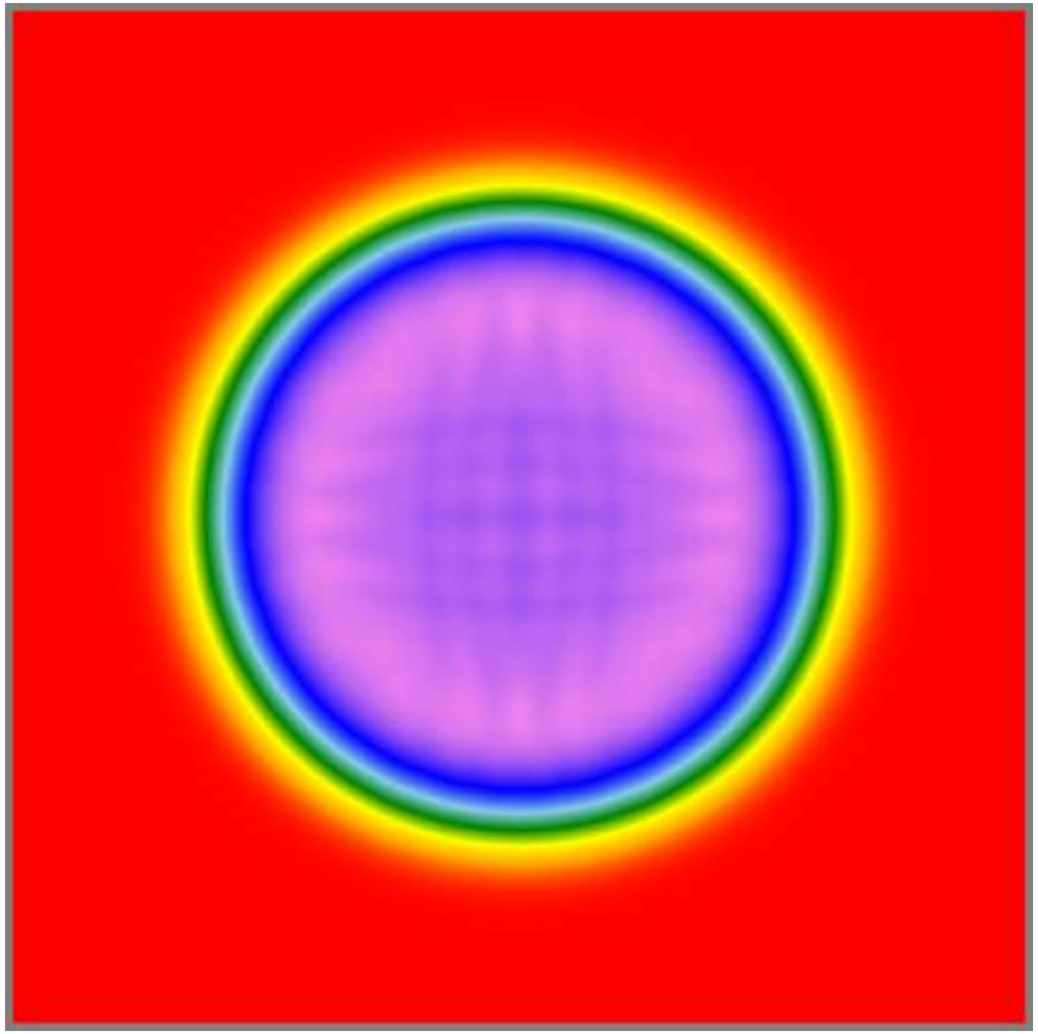
- The typical unwanted effects
  – geometrical distortion and
  – intensity attenuations
  are being fully compensated.

Day 3

Task 14

Design of a Refractive Beam Shaper to Generate a Circular Top-Hat

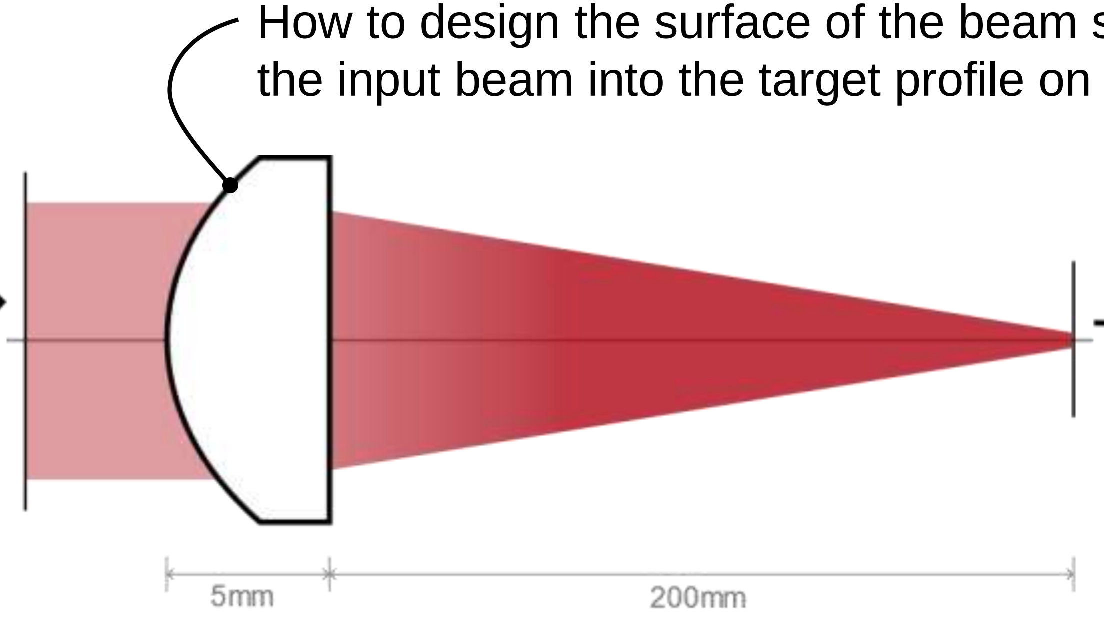
Abstract

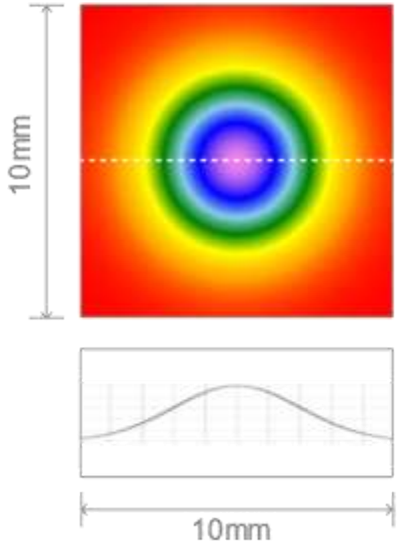


For applications like laser material processing, the laser beam must be shaped into certain distributions on the target plane. Typically, it is desired to obtain homogeneous distributions within an area, for example, a top-hat beam profile. With the user-friendly design tools in VirtualLab, a refractive beam shaper with an aspherical surface is designed for shaping a fundamental Gaussian beam into top-hat profile on the target plane. The performance of the beam shaping element is analyzed in terms of conversion efficiency, SNR, etc.

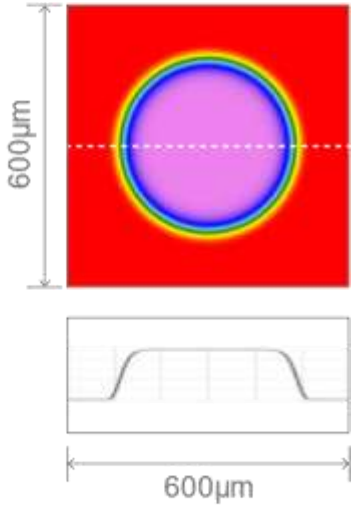
Design Task

How to design the surface of the beam shaper, so to convert the input beam into the target profile on the target plane?





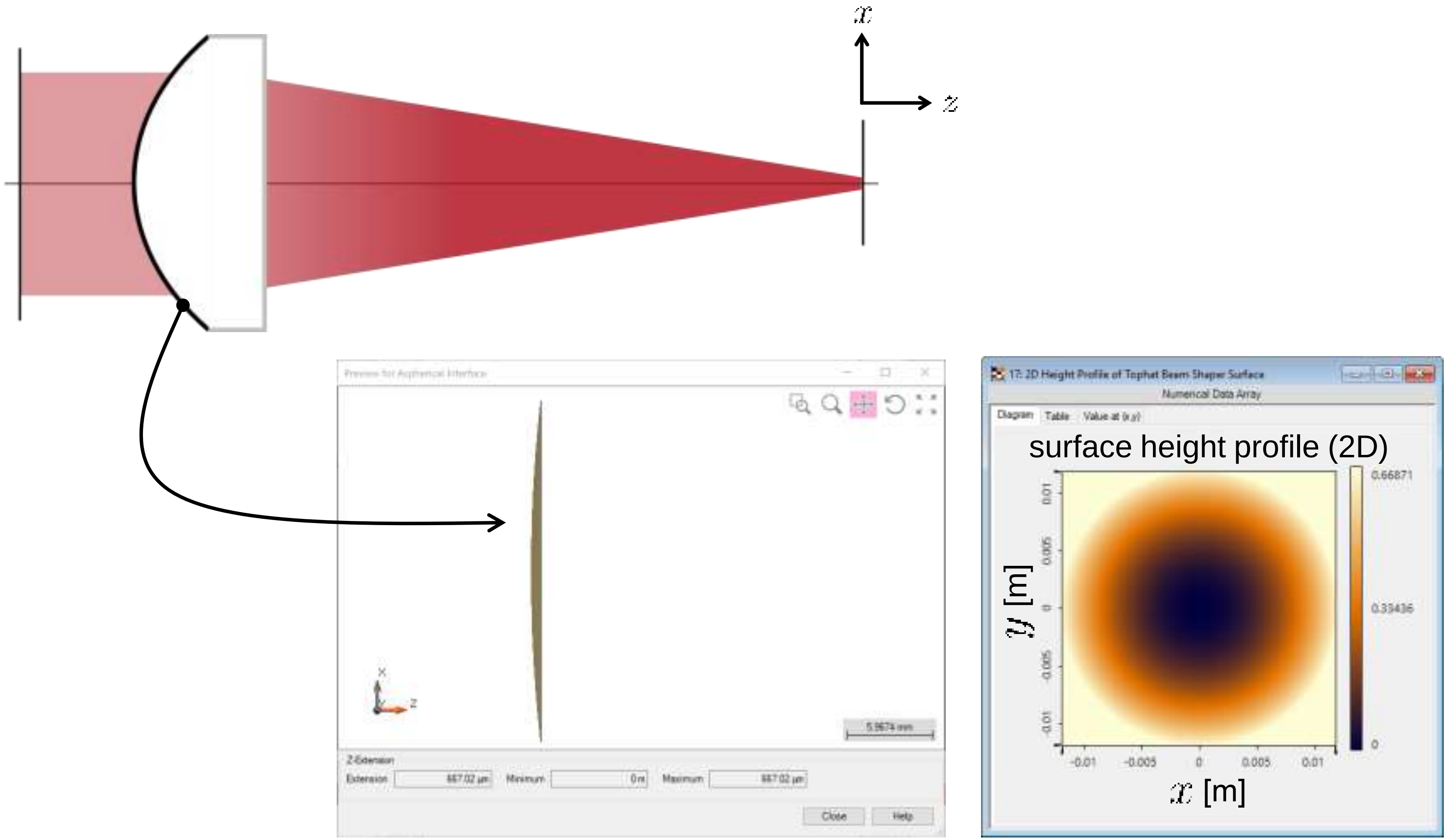
input field
- wavelength: 632.8 nm
- profile: fundamental Gaussian
- diameter (waist): 8 mm



target field
- profile: top-hat
- diamter: 400 µm
- edge width: 40 µm

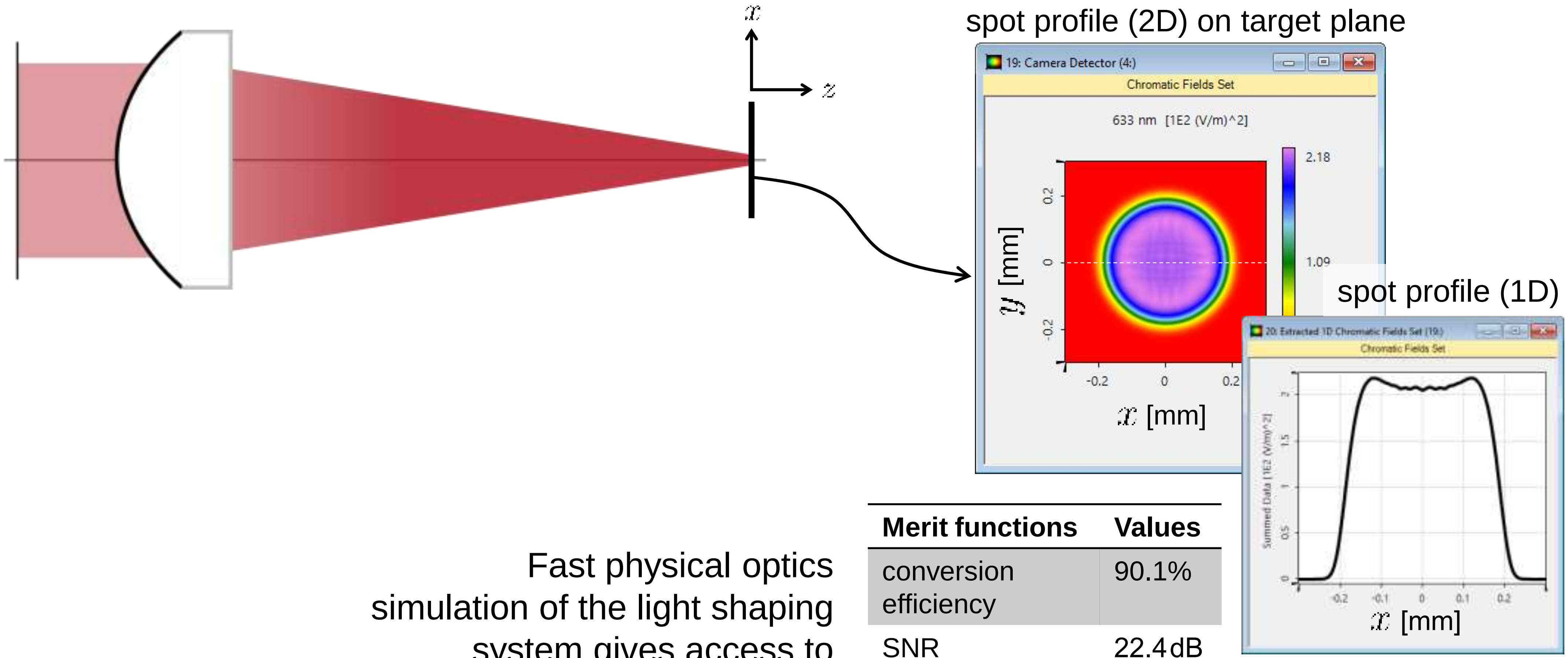
(14-order super Gaussian)

Design Result



The step-by-step guided design session in VirtualLab delivers the result within 25 milliseconds!

Performance Evaluation



Fast physical optics simulation of the light shaping system gives access to multiple merit functions.

Merit functions	Values
conversion efficiency	90.1%
SNR	22.4 dB
stray light	10.9%

Task 15: Video

Klick the following link to watch the video:

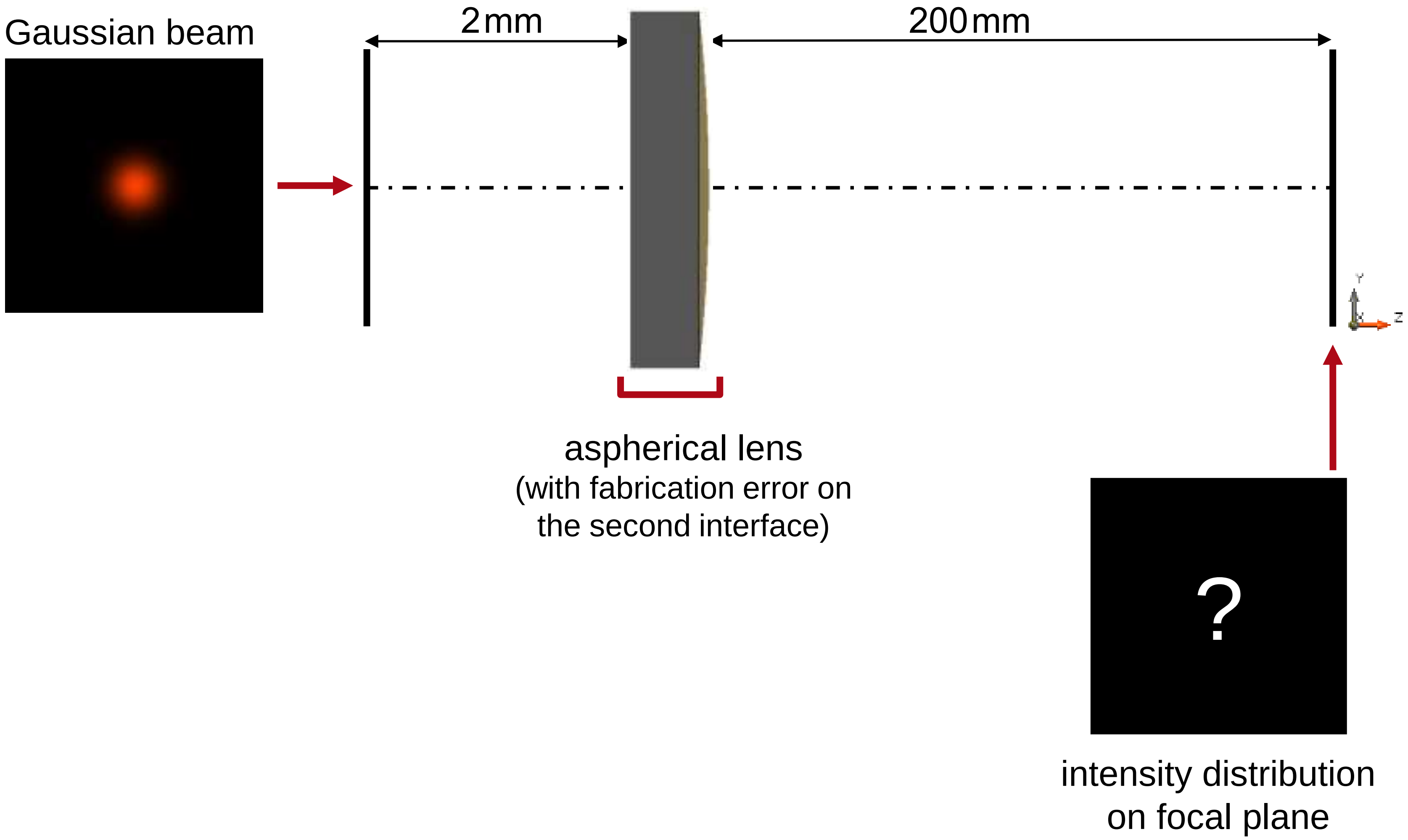
https://youtu.be/oVALvUaX1uI

Task 15

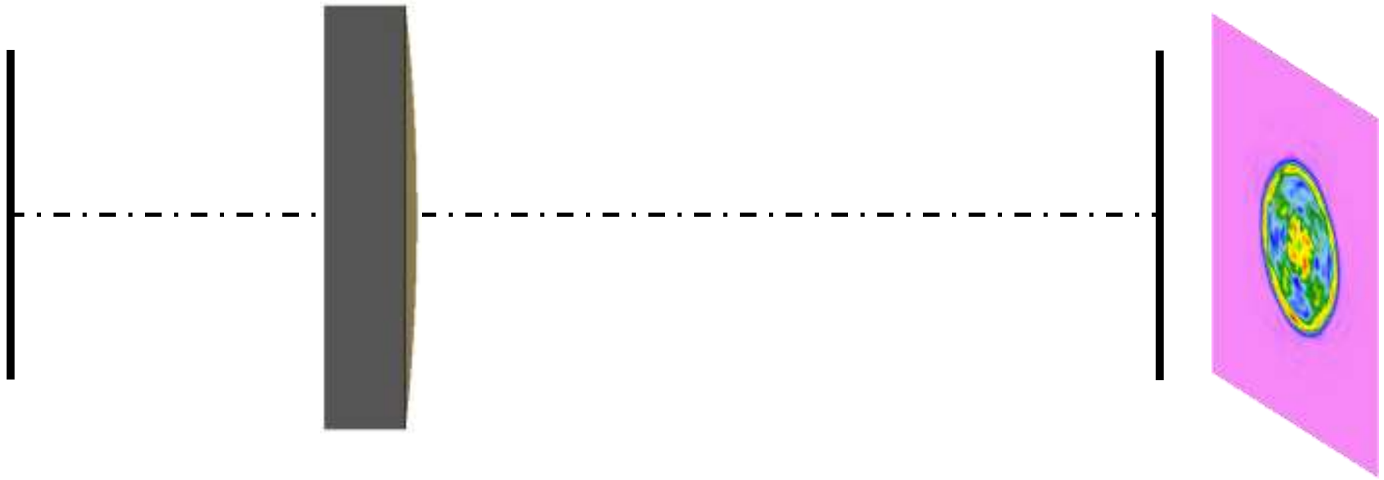
Modeling of a Refractive Beam Shaper with Measured Height Profile

LightTrans International UG

Task/System Illustration

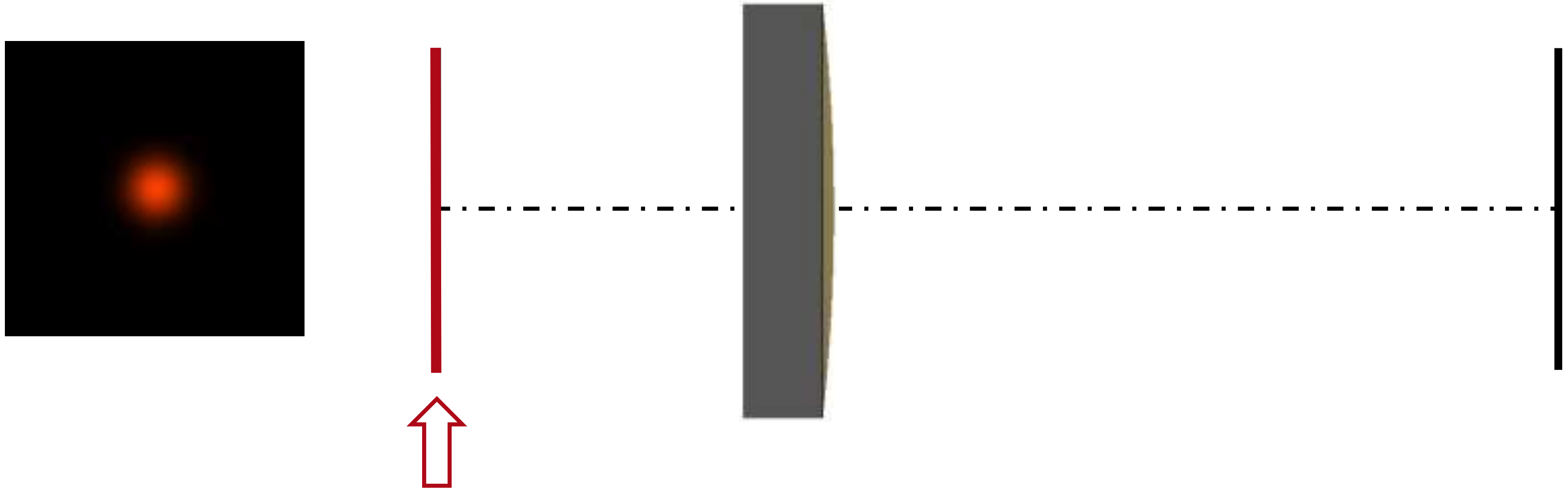


Highlights



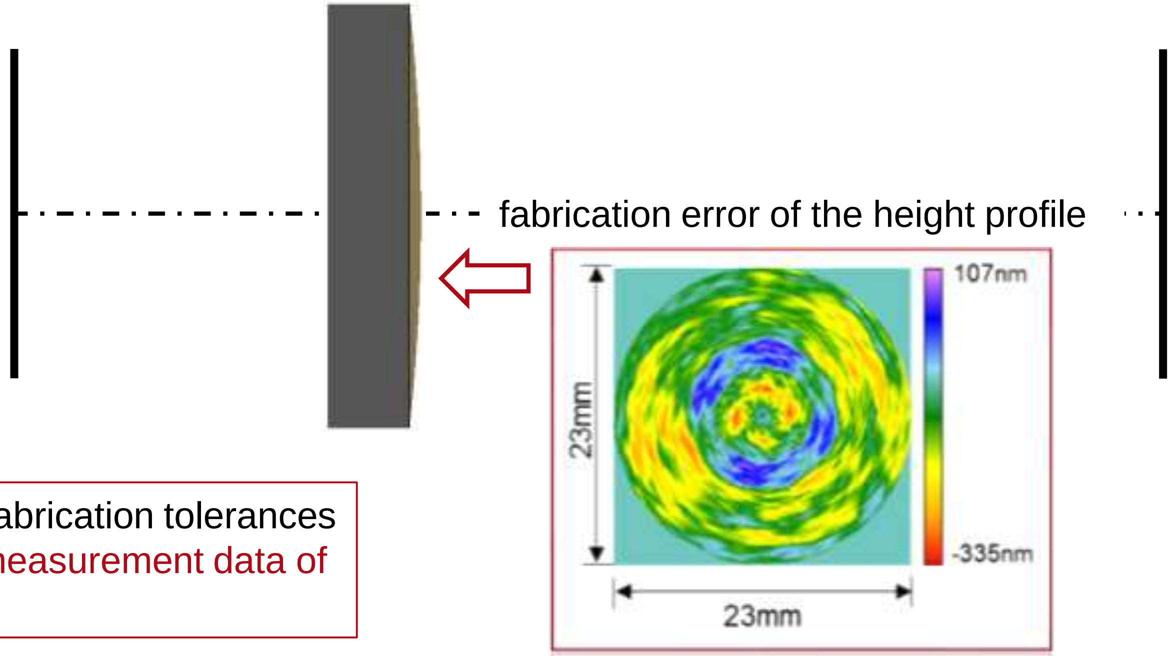
- simulation of fabrication tolerances by importing measurement data of height profiles

Specification: Light Source



Parameter	Description / Value & Unit
type/number	Gaussian beam
coherence/mode	single Hermite Gaussian (0,0) mode
wavelength	632.8 nm
polarization	linear in x-direction (0°)
waist radius ($1/e^2$)	4 mm × 4 mm

Specification: Focusing Asphere

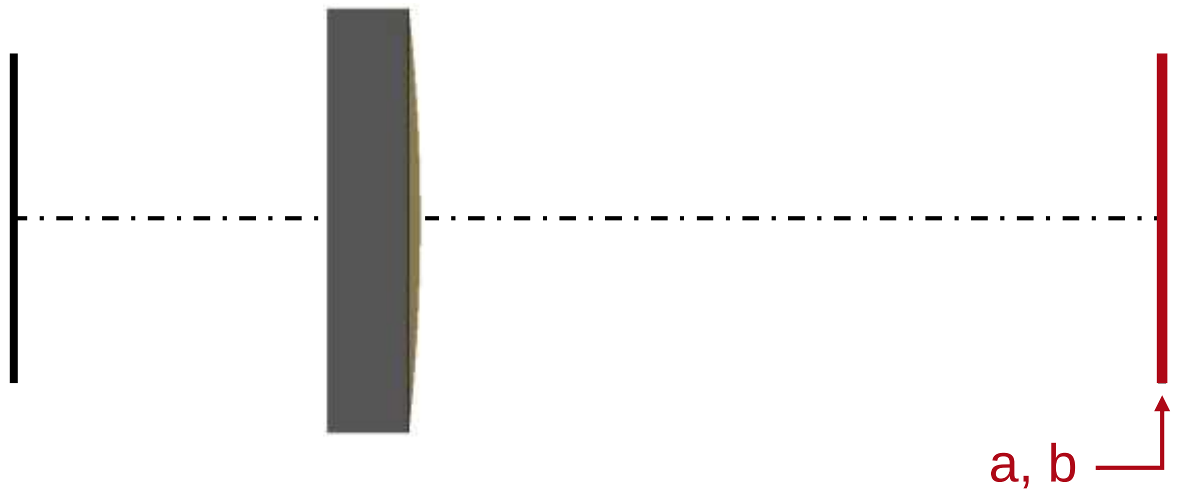


Highlights

- simulation of fabrication tolerances by importing measurement data of height profiles

Parameter	Value & Unit
name/type	convex-plano aspherical lens
first interface	plane interface
second interface	aspherical interface with measured height profile error
material (M)	N-BK7

Specification: Detectors

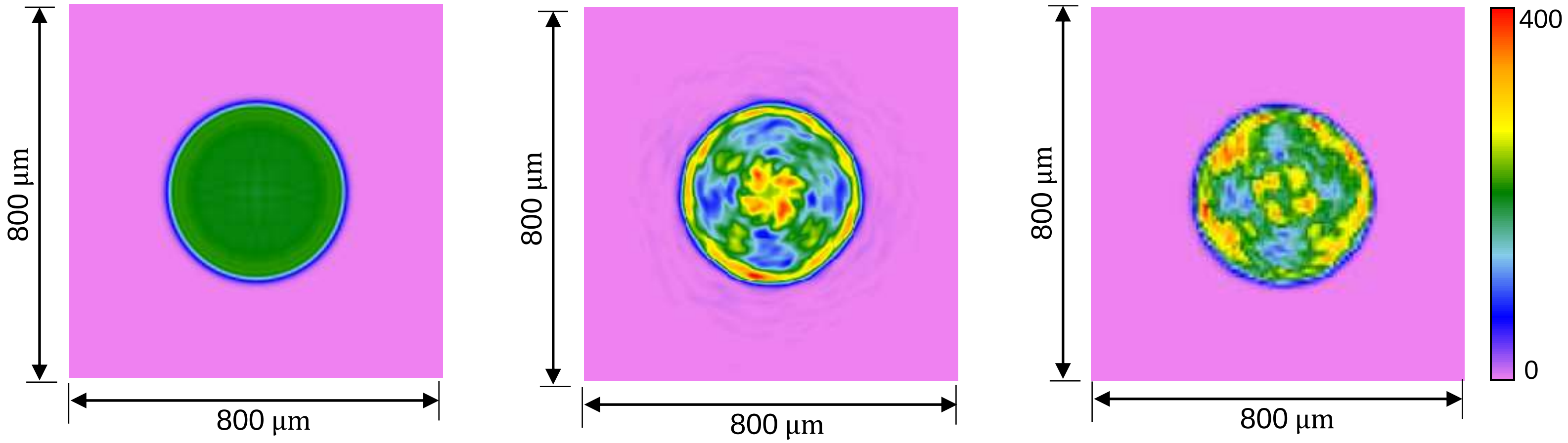


Position	Modeling Technique	Detector/Analyzer
a	field tracing	intensity distribution
b	field tracing	merit function detector

Results: Intensity Distribution

Highlights

- simulation of fabrication tolerances by importing measurement data of height profiles



intensity of field at focal plane (without fabrication tolerances)

intensity of field at focal plane (with fabrication tolerances)

measured intensity at focal plane (with fabrication tolerances)

Task 16

Generation of a Rectangular Top Hat by Diffractive Beam Shaper

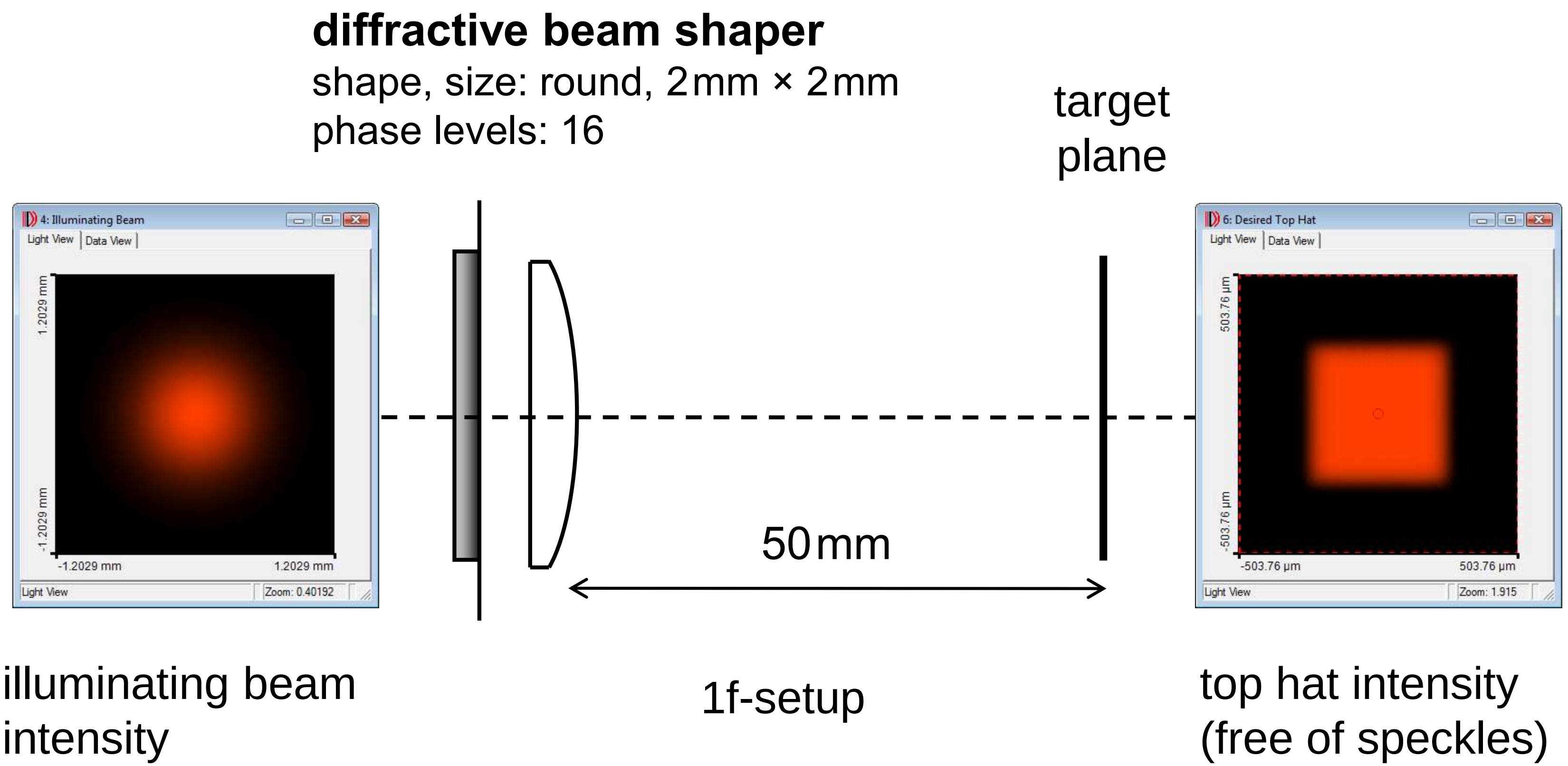
Author: Hartwig Crailsheim (LightTrans)

Related Application Scenarios: Scenario 307.01, LBS.003

Related Tutorials: Tutorial_144.01

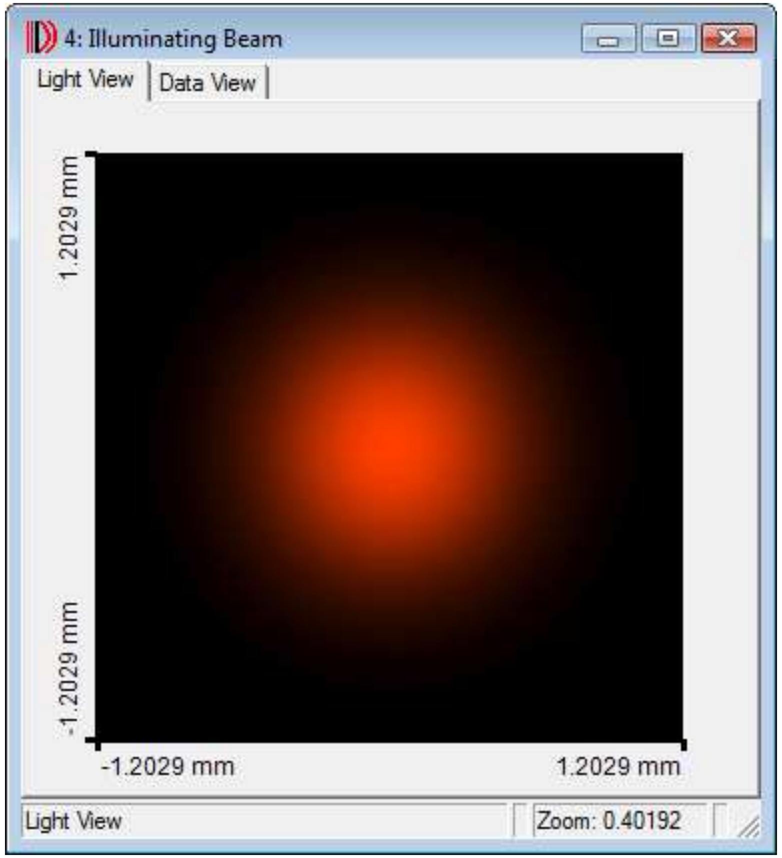
Requirements: Starter Toolbox, Diffractive Optics Toolbox

Modeling Task



surrounding medium: vacuum

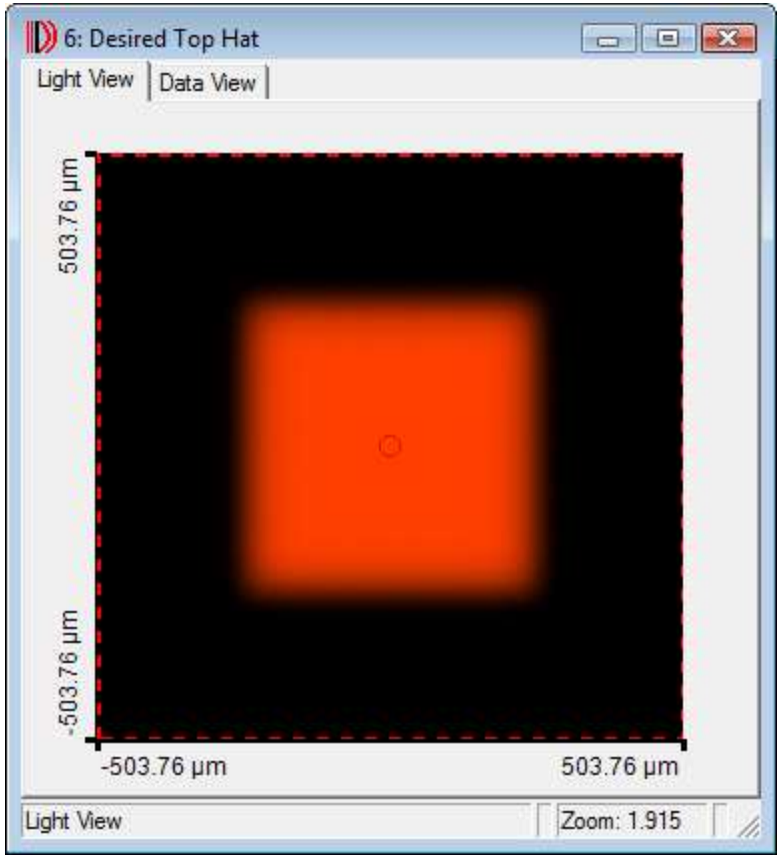
Modeling Task: Input Light Field



Illuminating beam parameters of a Gaussian collimated laser beam

- wavelength: 632.8 nm
- laser beam diameter ($1/e^2$): 1 mm

Modeling Task: Desired Output Light Field



Desired Output Field Parameters

- FWHM-Diameter: 0.5 mm
- Edge Width: 67 µm
- Efficiency: >95%
- SNR: >30 dB
- Stray light: <5%

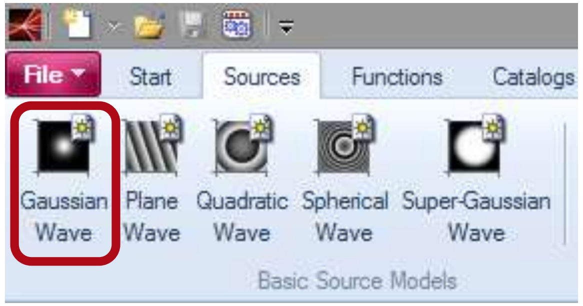
Demonstrated Steps

1. Configuration of input and desired output light field distribution.
2. Design Preparation: Defining of the complete optical setup.
3. Design: Calculation and optimization of a diffractive optical element (DOE).
4. Data Export for manufacturing of the DOE
   (just mentioned, details not part of this tutorial).

STEP 1

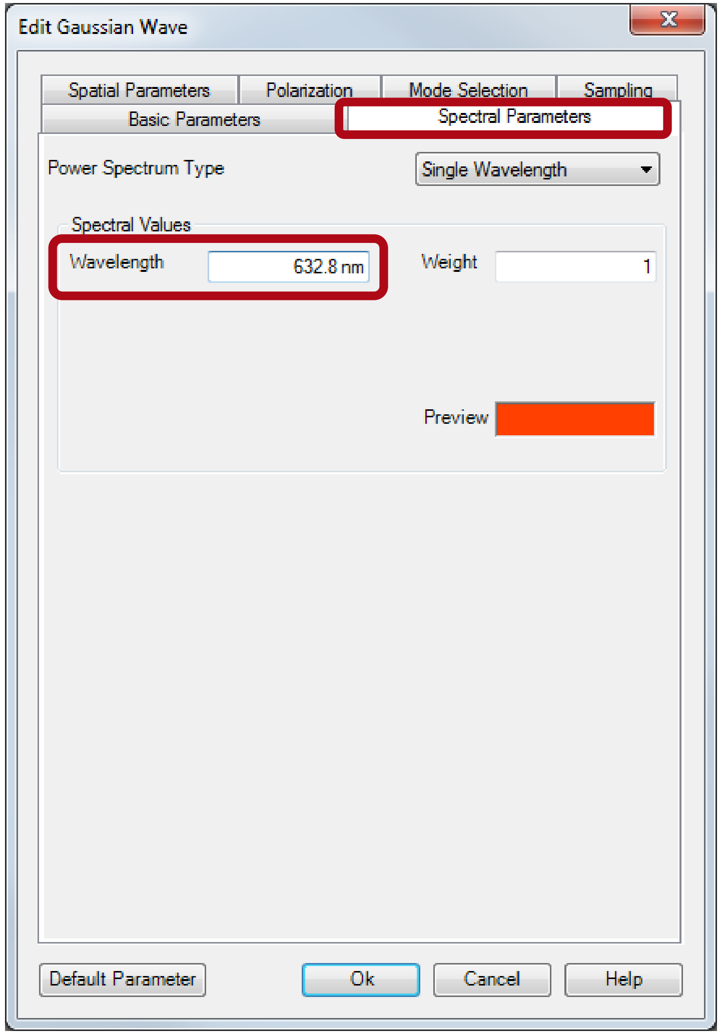
Configuration of Input and Desired Output Light Field Distribution

Generating of an Input Light Field



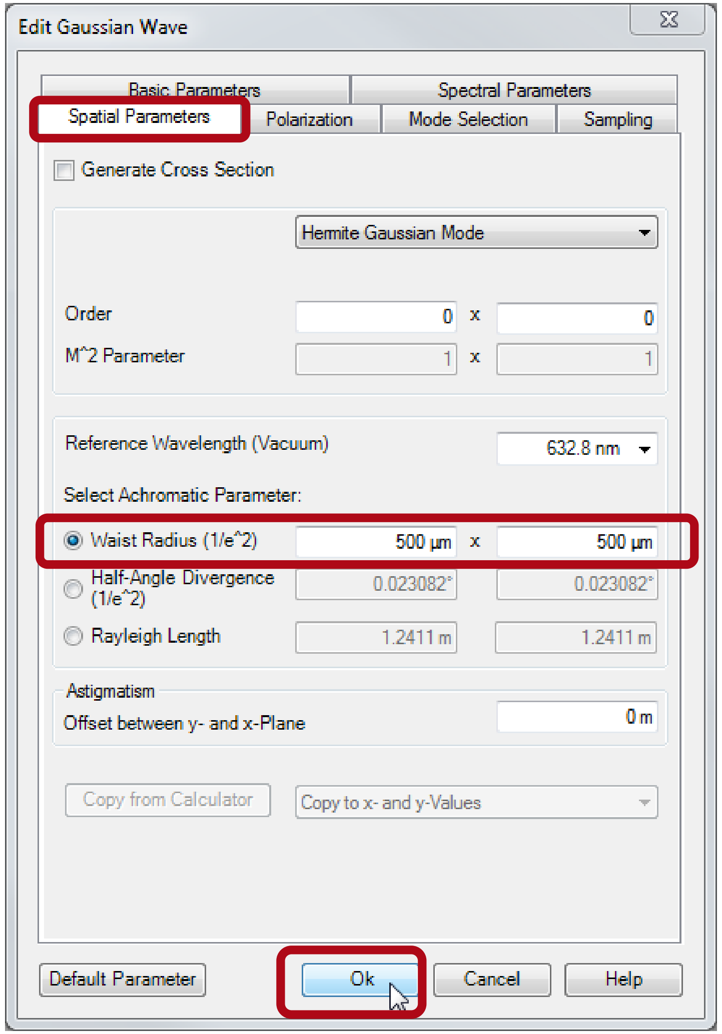
- First the complex amplitude of the illuminating input beam has to be generated.
- Therefore select “Gaussian Wave” from the menu: Source > Basic Source Models

Configuration of Desired Input Field 1



- Set the wavelength in the Spectral Parameters tab to 632.8 nm.

Configuration of Desired Input Field 2



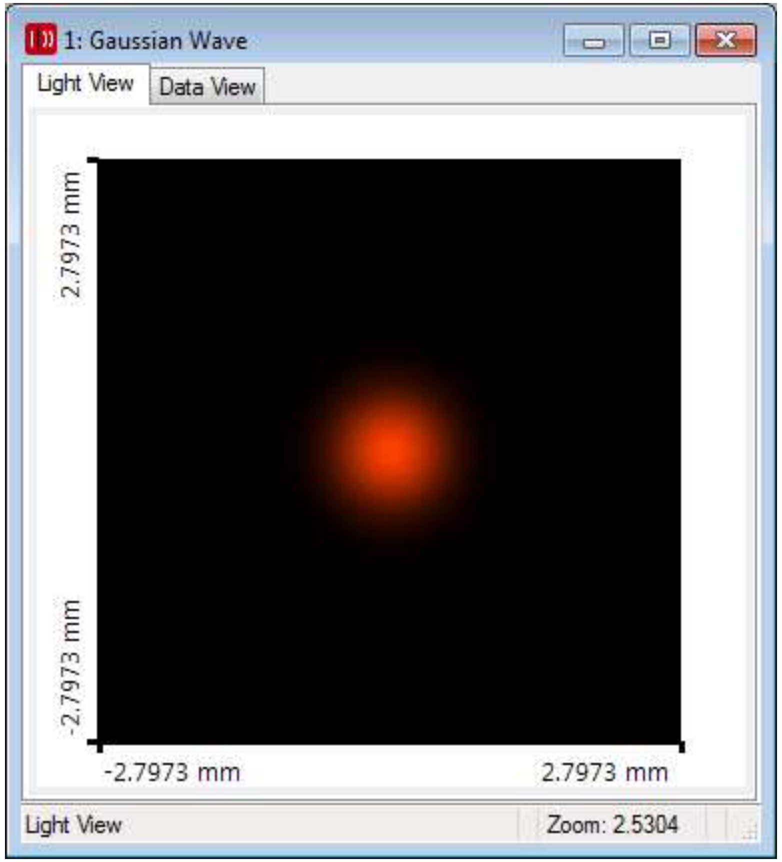
Adjust the spatial parameters in the according tab:

- Waist radius = 500 × 500 µm

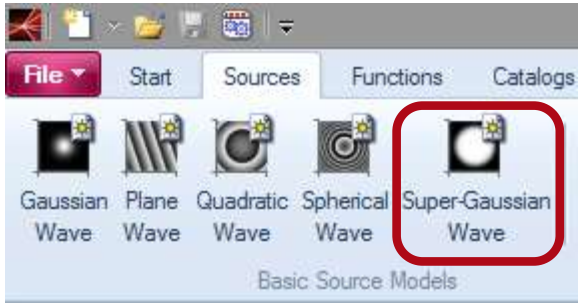
Then confirm with "Ok".

Results in

Light Distribution of the Illuminating Beam

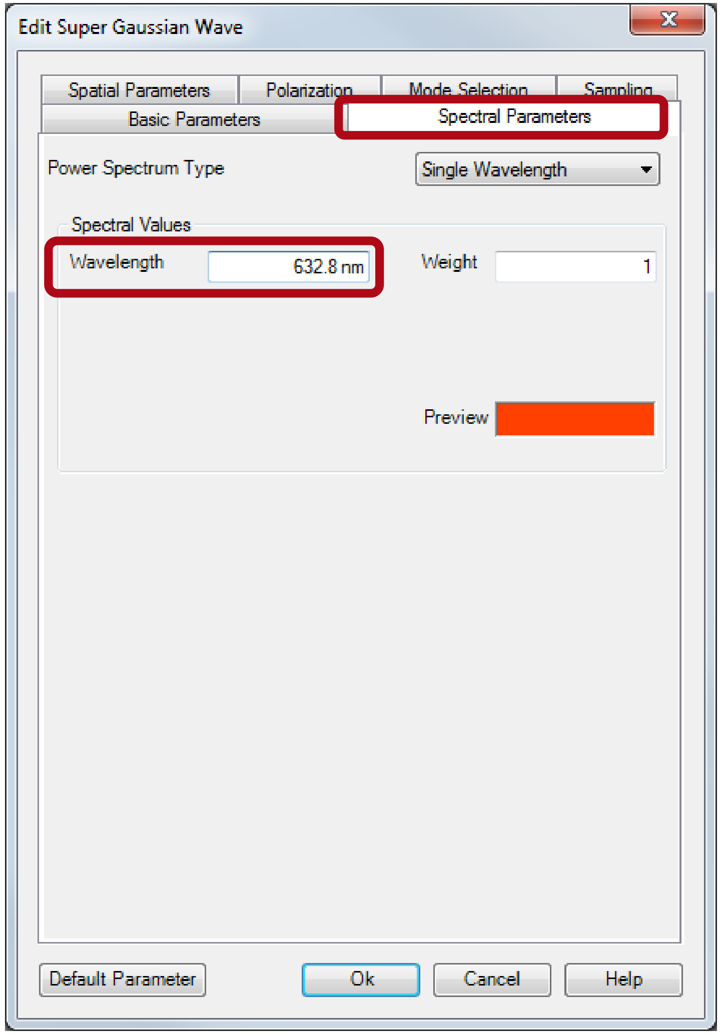


Generating of an Output Light Field



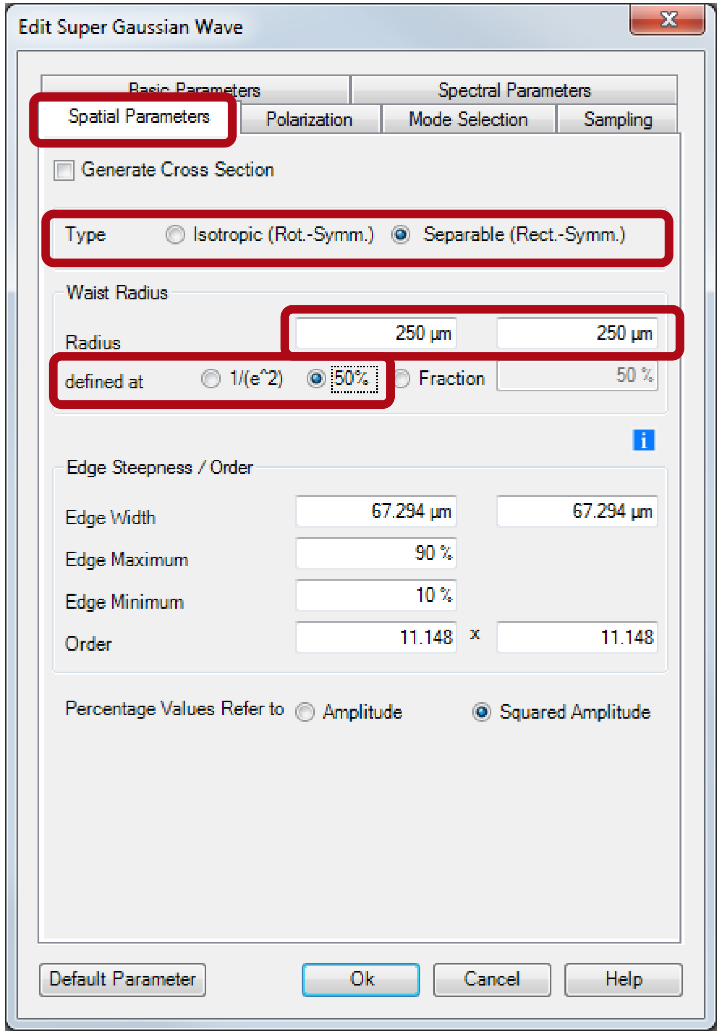
- Now the complex amplitude of the desired output light field distribution has to be generated.
- This signal field will serve as the target field for VirtualLab.
- This is also done by generating a new light source (so don't be confused if you come across terms like "input(!) field").
- Thus select "Super Gaussian Wave" from the menu
  Source > Basic Source Models

Configuration of Desired Output Field 1



- Change the wavelength in the Spectral Parameters tab to 632.8 nm.

Configuration of Desired Output Field 2

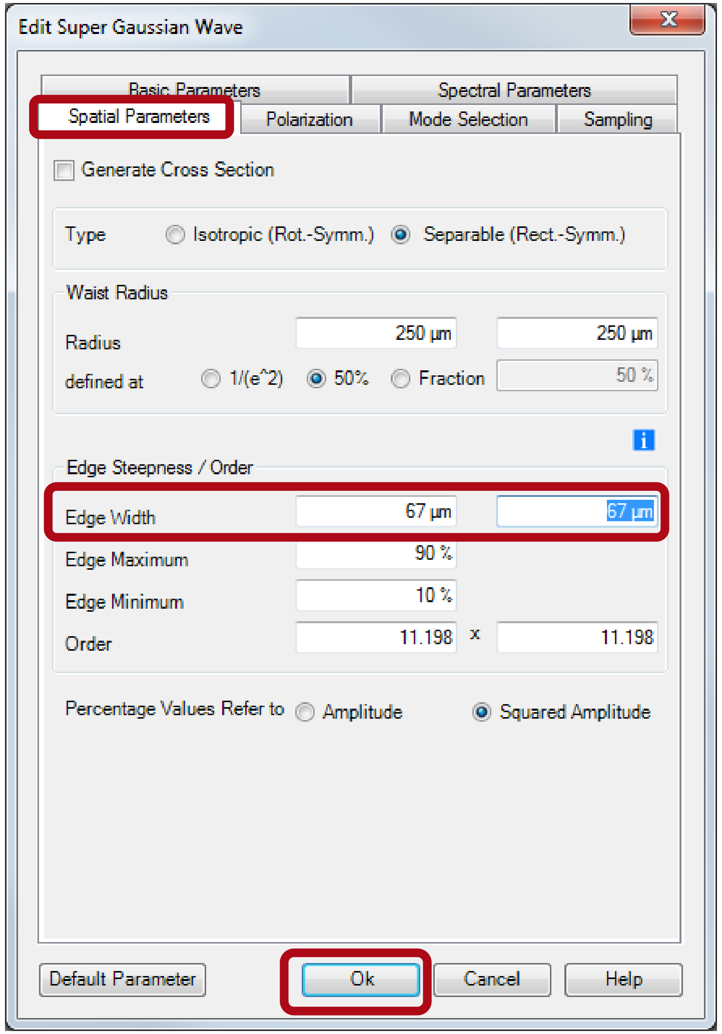


Adjust the spatial parameters in the according tab:

- A rectangular top hat should be generated so select the type "Separable (Rect.-Symm.)"
- Set the radius of the top hat to 250 × 250 µm
- Use the 50 % definition which corresponds to the Full-Width-at-Half-Maximum value.

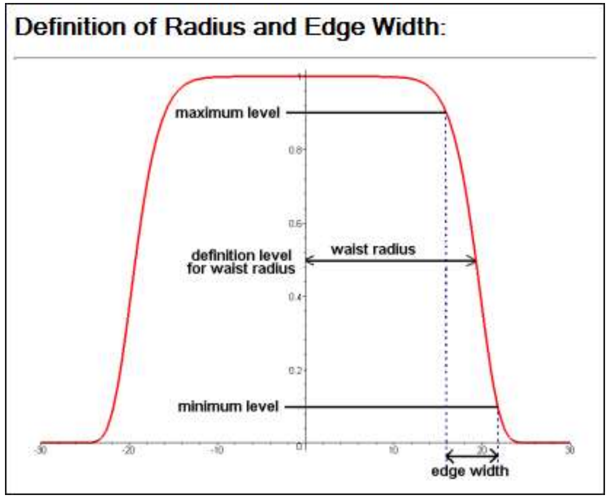
continued…

Configuration of Desired Output Field 3

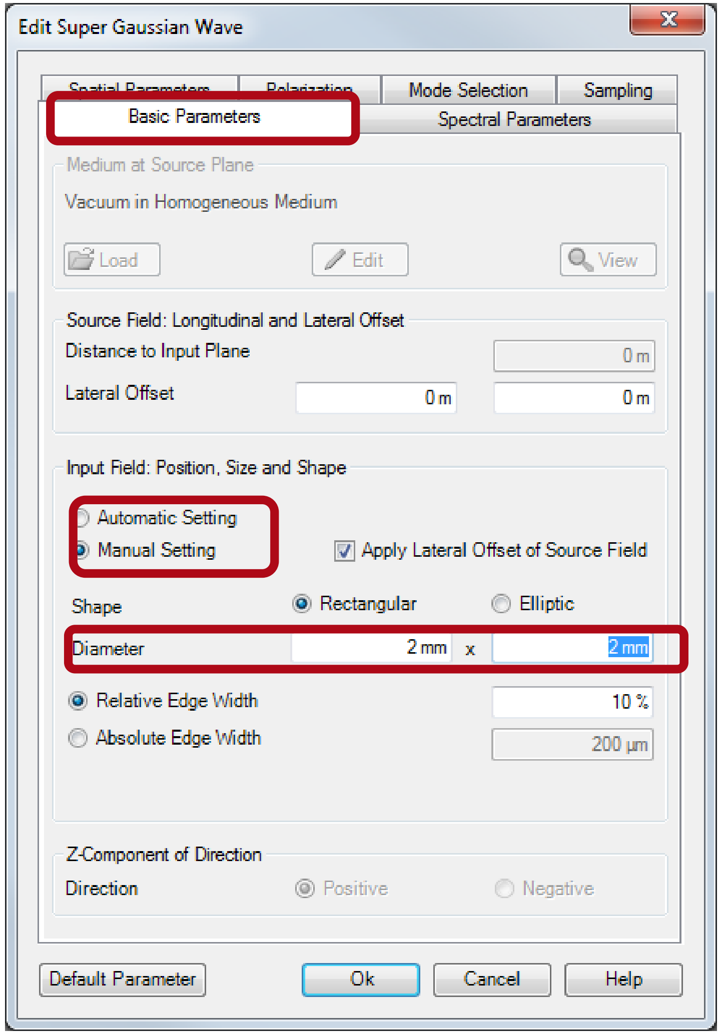


For there are no exact discontinuities in nature it is suggested to specify smooth edges for realistic diffraction effects:

- Change the edge width according the required specifications to 67 × 67 µm.
- Then confirm with “Ok”.



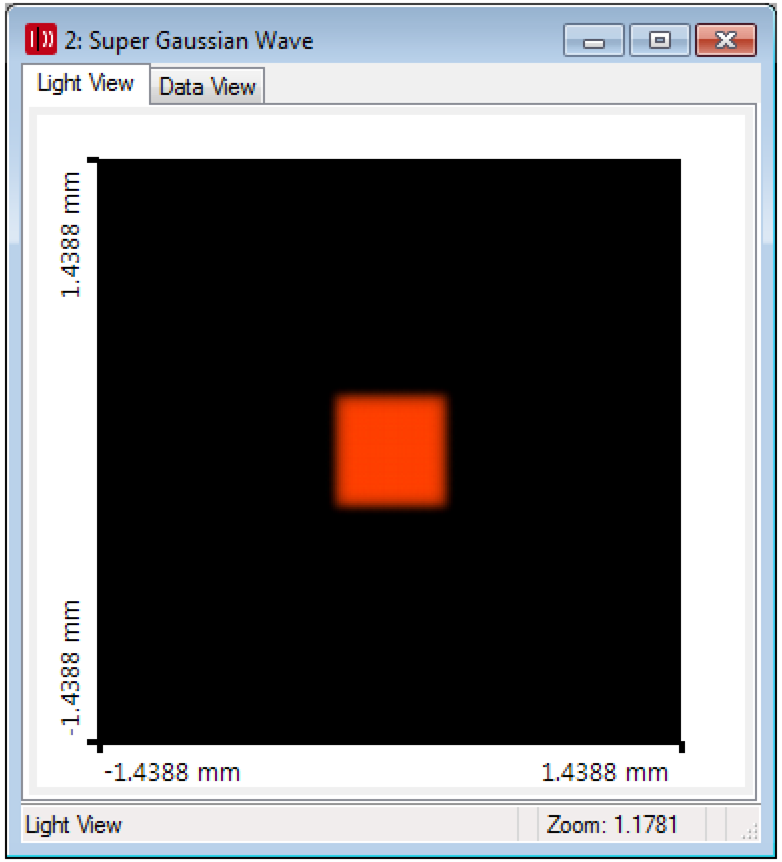
Configuration of Desired Output Field 4



- The DOE cannot diffract all light into the area of interest, i.e. the Top Hat region. There will always be remaining light which is distributed around the desired light distribution.
- So that VL is able to consider this remaining light to a fair and meaningful extent the output field to be simulated should be set to around 4 times larger than the Top Hat's diameter, i.e. in our case 2mm.
- Thus on the tab "Basic Parameters" switch to "Manual Setting" and change the shape to 2 × 2 mm.

Results in

Target Light Distribution



- The reason for the resulting dimension (larger as the set 2 × 2 mm) is due to the Relative Edge Width for which the standard value of 10% was kept.
- Additionally on the tab “Sampling” there is the setting for the “Size of Embedding Frame (Sampling Points)” whose standard value is 10. These frame points always have the value zero.

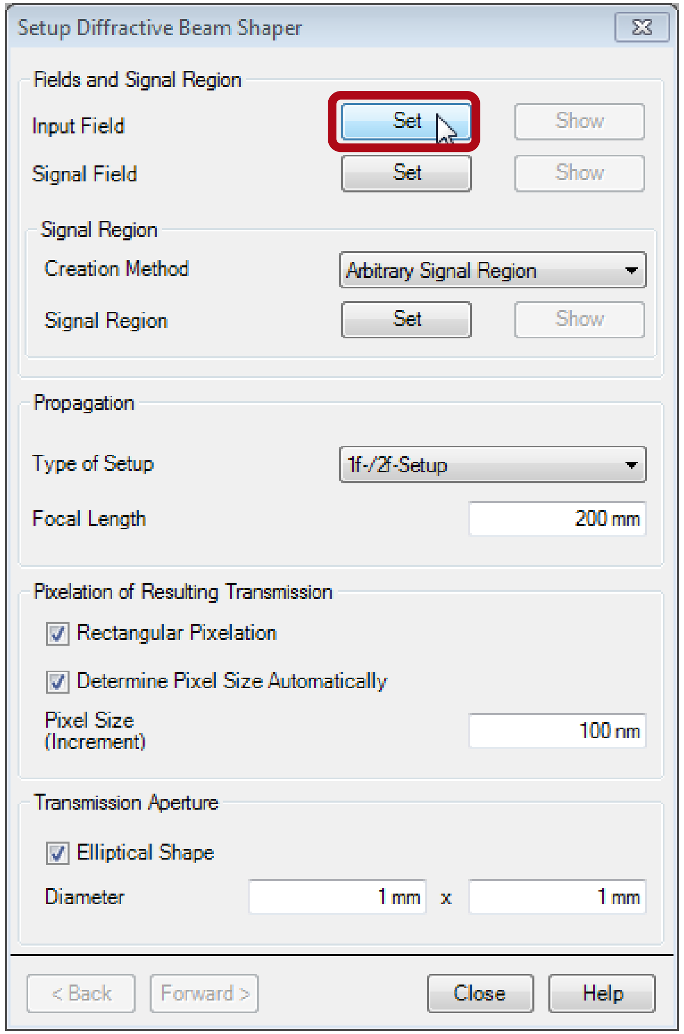
STEP 2

Design Preparation: Defining of the Complete Optical Setup

Preparation for Design 1

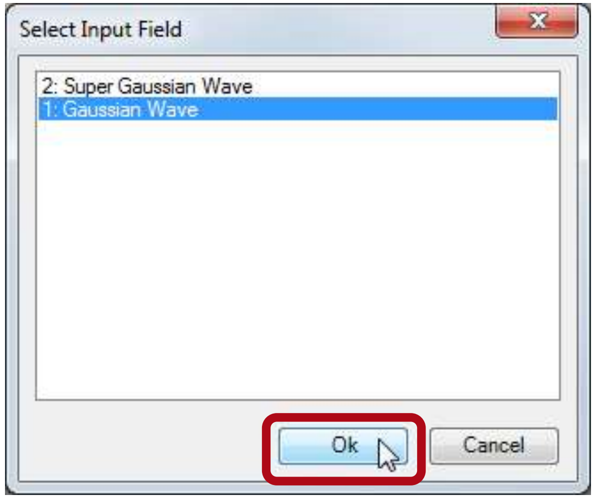
- In order to design the desired DOE the complete setup conditions have to be defined.
- Over the menu go to Design > Beam Shaper Design > Diffractive Beam Shaper… and a dialog will open that assists you with the design steps.

Preparation for Design 2

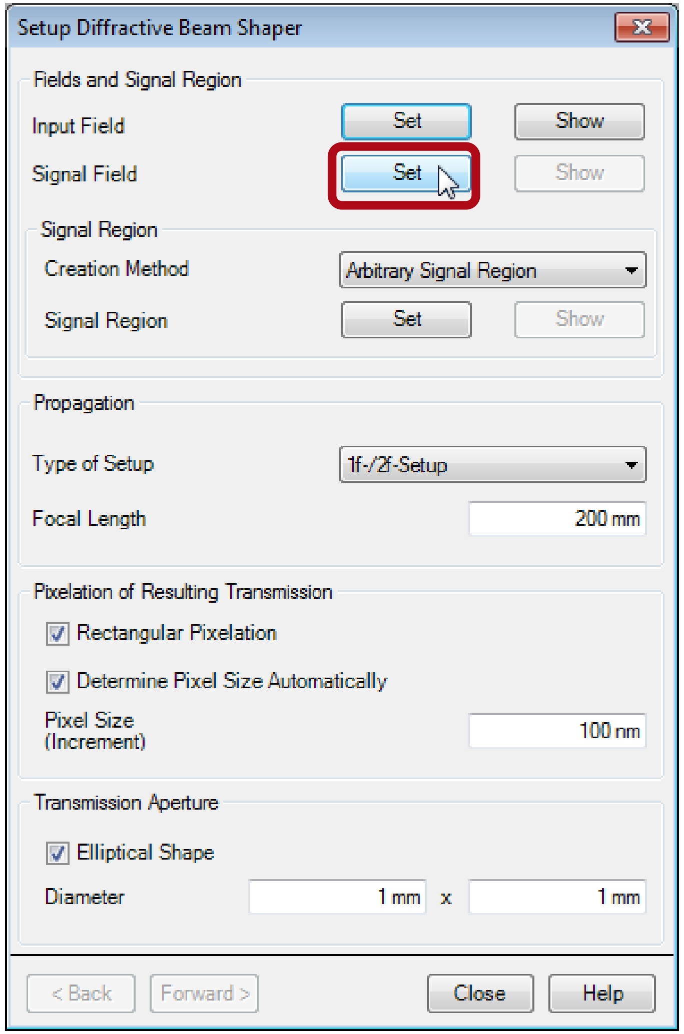


- First for the illuminating beam (Input Field) click “Set”.
- In the so opened dialog select the prepared Gaussian wave and click “Ok”.

Results in

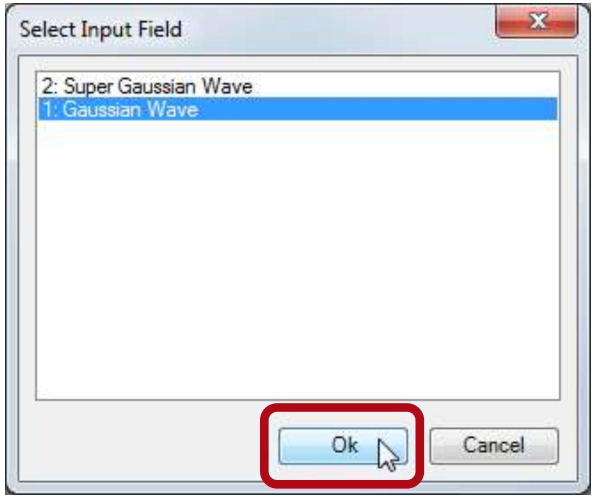


Preparation for Design 3

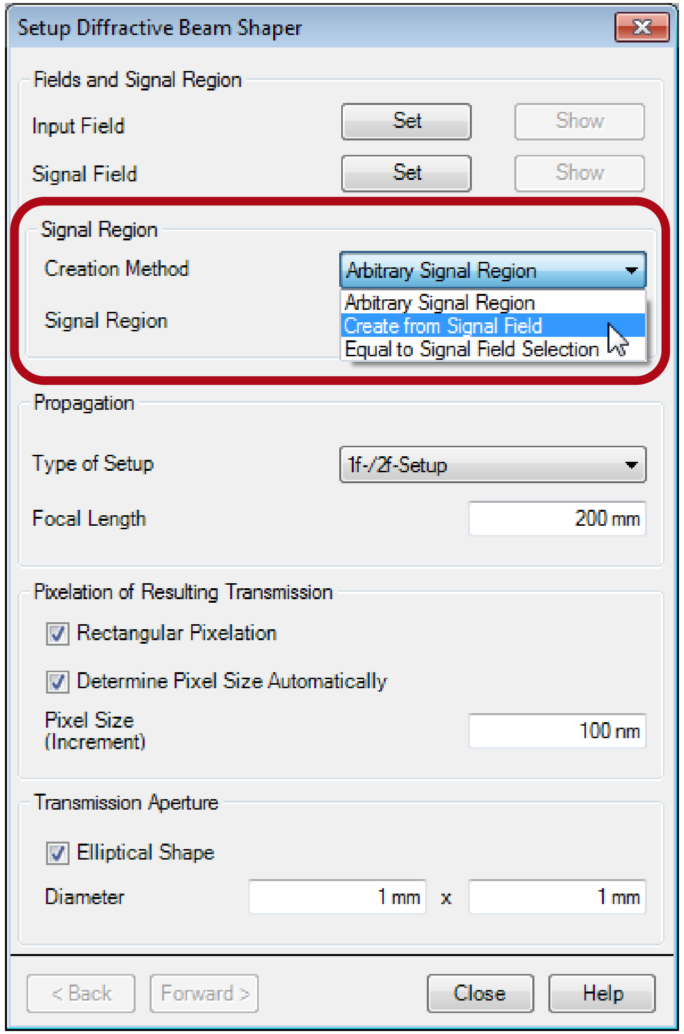


- Then for the desired target field (Signal Field) click “Set”.
- In the so opened dialog select the prepared super-Gaussian wave and click “Ok”.

Results in

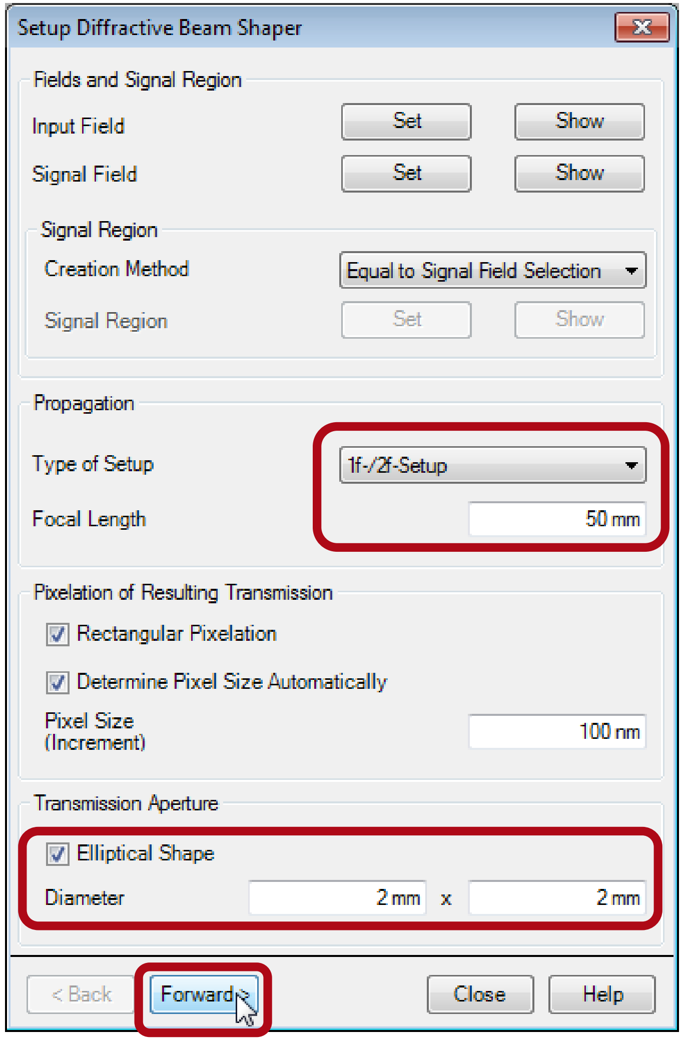


Preparation for Design 4



- For this tutorial the Creation Method “Create from Signal Field” is to be selected.
- This means that a signal region will be created containing all parts of the signal field with amplitude values larger than 10% of the maximum amplitude.

Preparation for Design 5



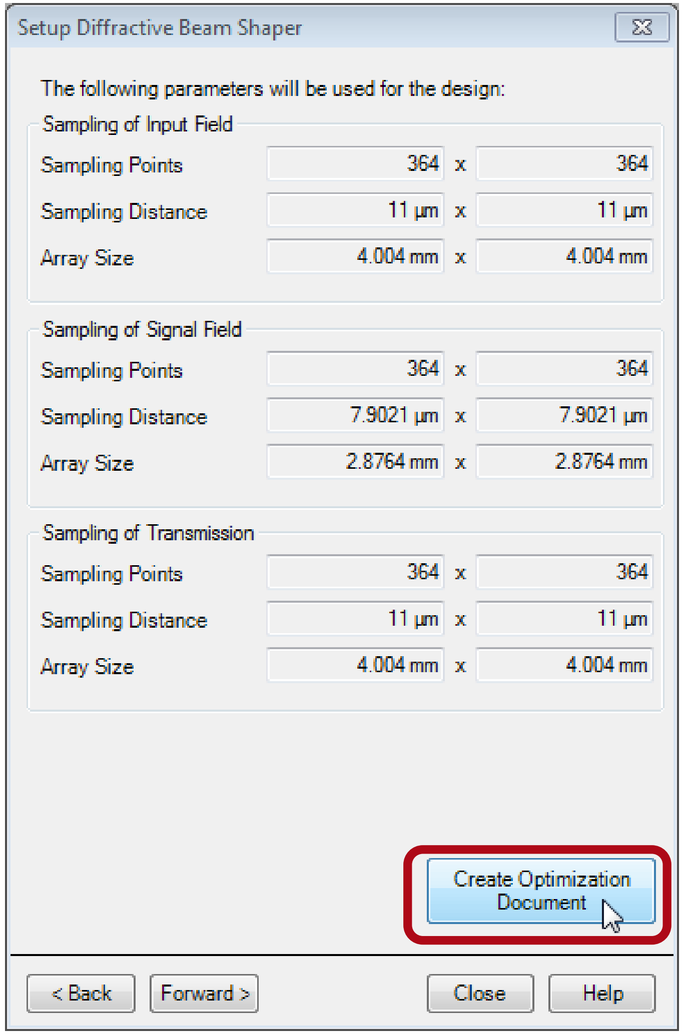
- The task at hand demands a “1f-/2f-Setup” with a focal length of 50 mm.
- For the aperture enter 2 × 2 mm.
- Then click “Forward >”

3. STEP

Design: Calculation and optimization of a diffractive optical element (DOE)

Explanation: The DOE to be calculated and optimized will be represented by a transmission function.

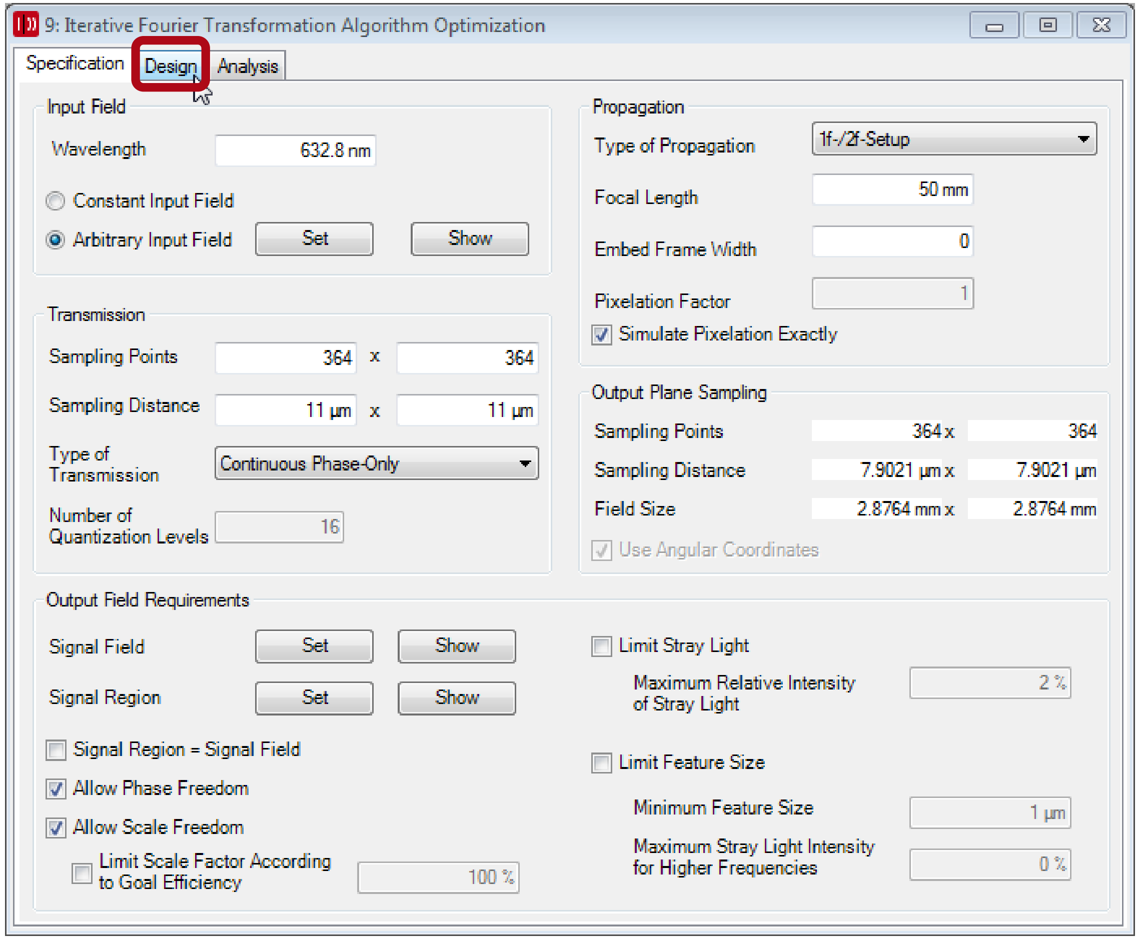
Starting Point for Optimization



- This page contains an overview of parameters that are automatically calculated by VirtualLab.
- VirtualLab adapts all parameters for the optimization of the beam shaping element.
- For example VirtualLab takes care that the number of sampling points is sufficient and the same everywhere (for the input field, the signal field and the transmission). This is necessary for the optimization algorithm.
- Then click “Create Optimization Document”.

Results in

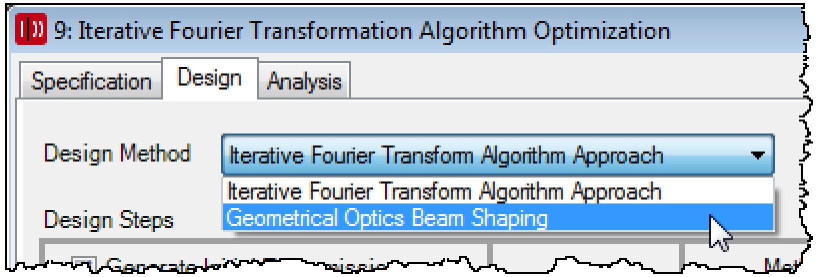
Geometrical Optimization 1



- You get this preset transmission design document named after its main designing method "Iterative Fourier Transformation Algorithm Optimization" (IFTA).
- Switch to the "Design" tab of this document.

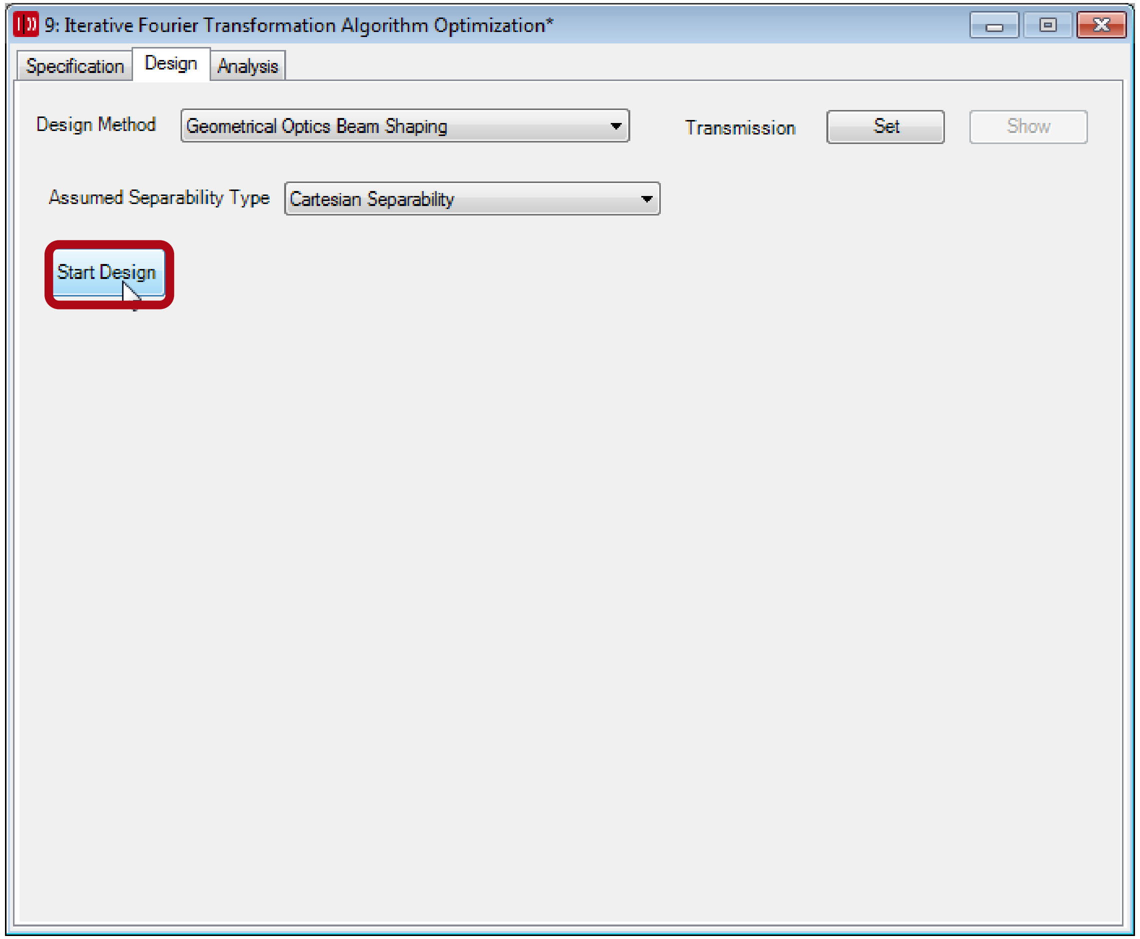
Geometrical Optimization 2

- For a high efficient and speckle-free result some optimization steps have to be performed.
- Typically one starts with a geometrical approach.
- Therefore change the “Design Method” to “Geometrical Optics Beam Shaping”.



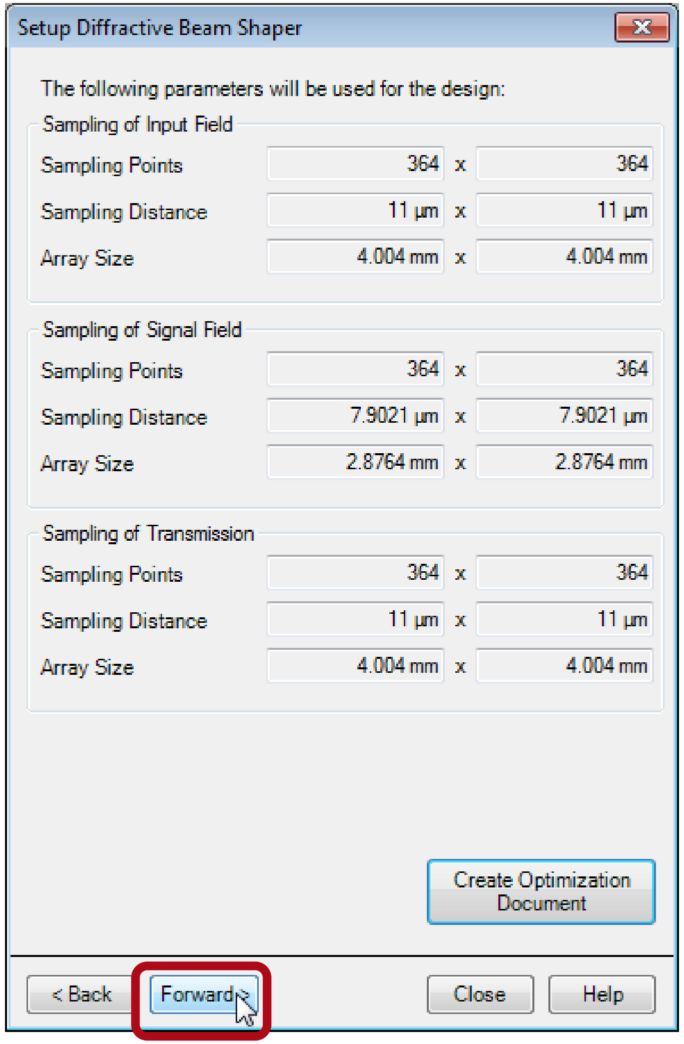
- This method will only produce an approximated solution to begin with. It is not possible to include discrete phase levels of the transmission function.

Geometrical Optimization 3



- Click “Start Design”.
- VL will now calculate and optimize the transmission function of the DOE.
- When VL has finished its geometrical optics beam shaping design it will be indicated in the messages panel at the bottom of the main window.

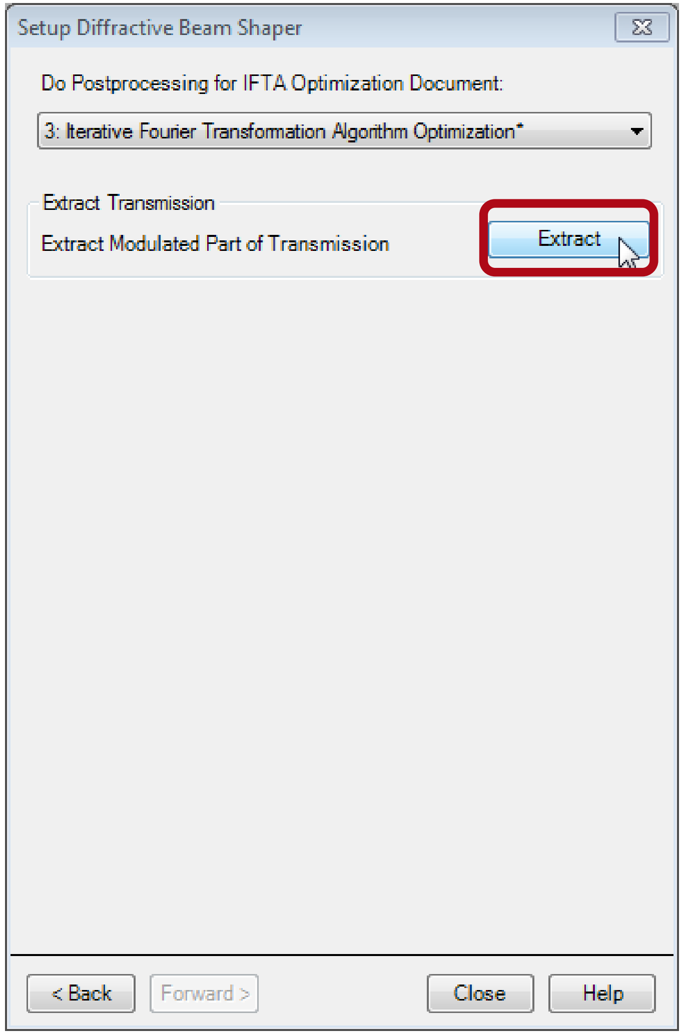
Geometrical Optimization 4



- After this geometrical design switch back to the dialog “Setup Diffractive Beam Shaper” where the relevant data of the just generated transmission function will be extracted.
- Thus click “Forward >”.

Results in

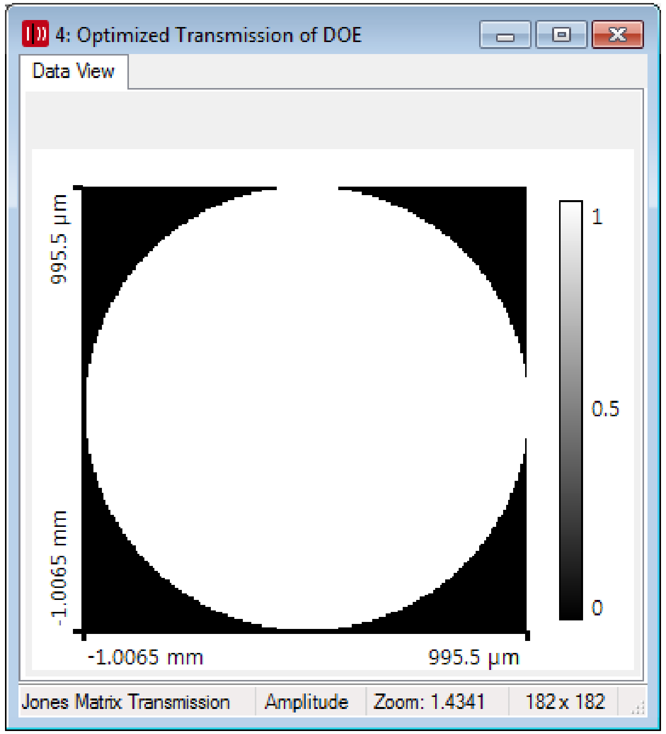
Geometrical Optimization 5



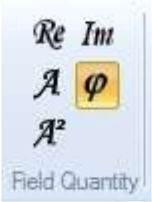
- Click “Extract”.

Results in

Geometrically Optimized Transmission 1

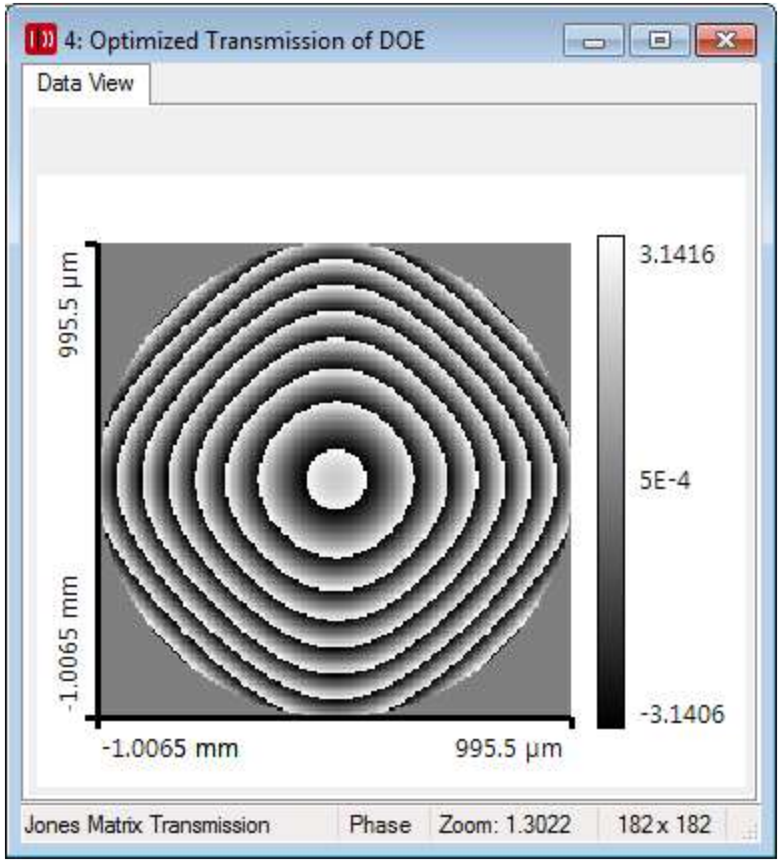


- The amplitude and the aperture respectively of the DOE, i.e. the distribution of the DOE's amplitude modulating property.
- For the information regarding the phase click the accordant icon.



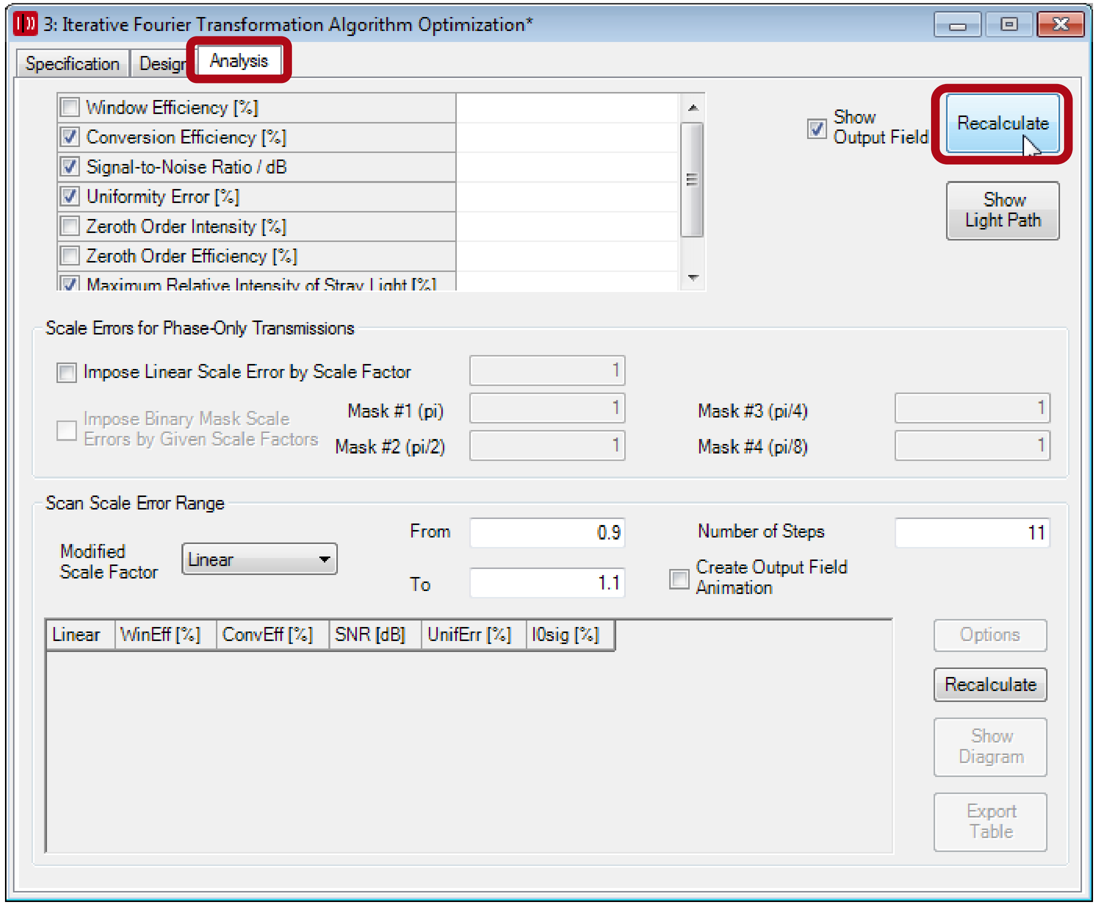
Results in

Geometrically Optimized Transmission 2



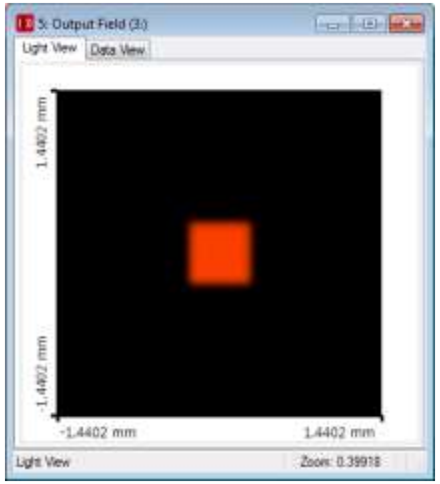
- The phase distribution of the DOE, i.e. the distribution of the DOE’s phase modulating property.
- In order to analyze the light propagation through the optical setup switch back to the design document “Iterative Fourier Transformation Algorithm Optimization”.

Geometrical Results 1



- Go to the tab “Analysis” and click “Recalculate.

Geometrical Results 2



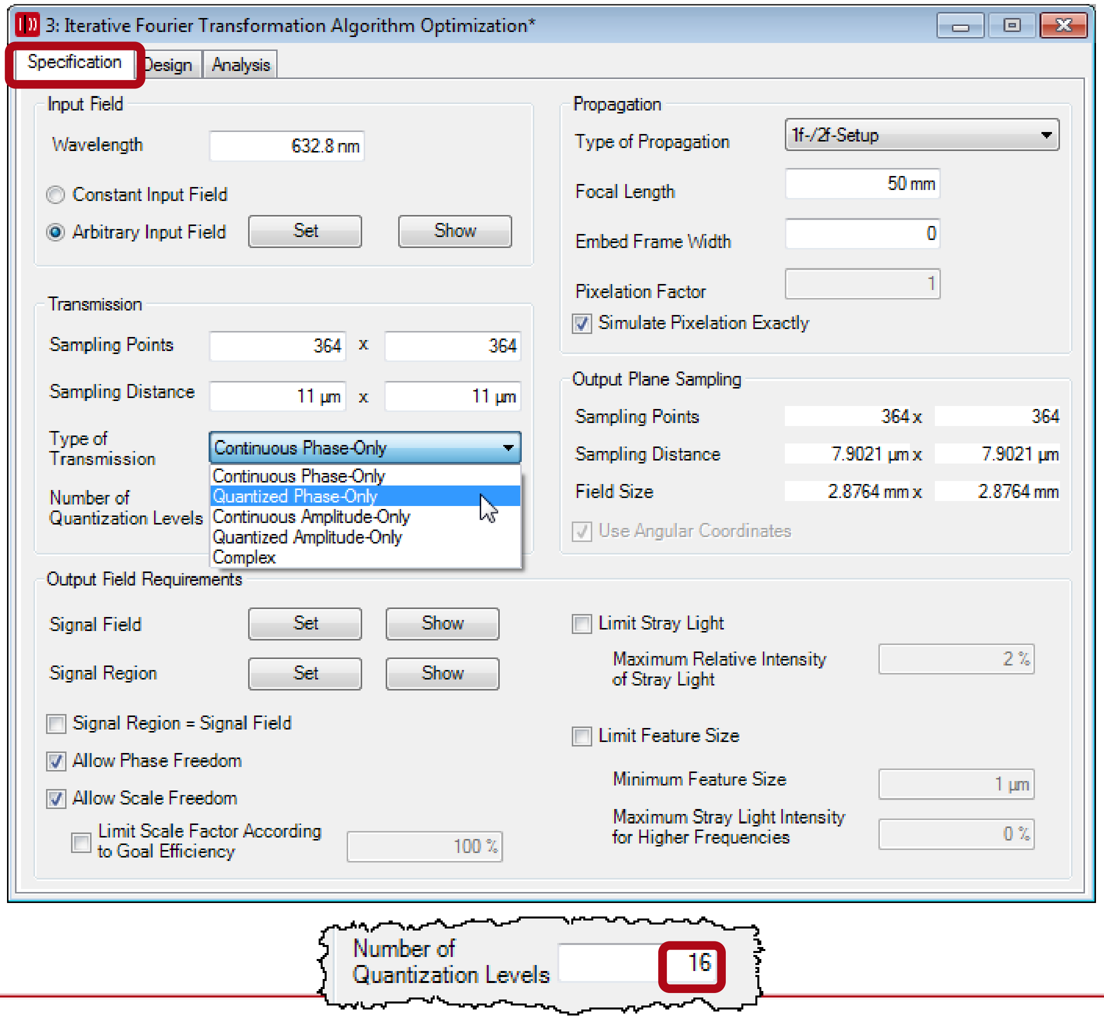
☐	Window Efficiency [%]	
☑	Conversion Efficiency [%]	97.882086297596175
☑	Signal-to-Noise Ratio / dB	29.011091733676729
☑	Uniformity Error [%]	50.379165741753177
☐	Zeroth Order Intensity [%]	
☐	Zeroth Order Efficiency [%]	
☑	Maximum Relative Intensity of Stray Light [%]	2.5263635947899732

- Here you see the result of the geometrical approach.
- The efficiency is almost 98%.
- The Signal-to-Noise Ratio (SNR) is almost 30 dB.
- The requirements are already almost met.

- The SNR is not bad but needs improvement.
- The discrete phase levels (needed due to fabrication constraints) must be introduced.
- Thus for a new optimization go to the tab “Specification”.

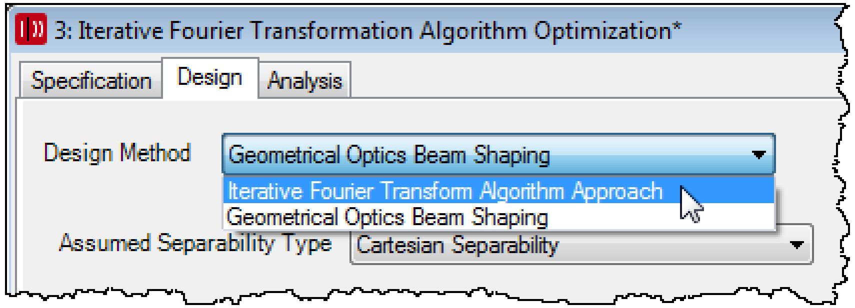
Results in

Geometrically Optimized Transmission 7



- Change the transmission type to “Quantized Phase-Only”
- This means the new optimization of the transmission function will be done for discrete phase levels.
- Leave the number of quantization levels at 16.
- Then go to the tab “Design”.

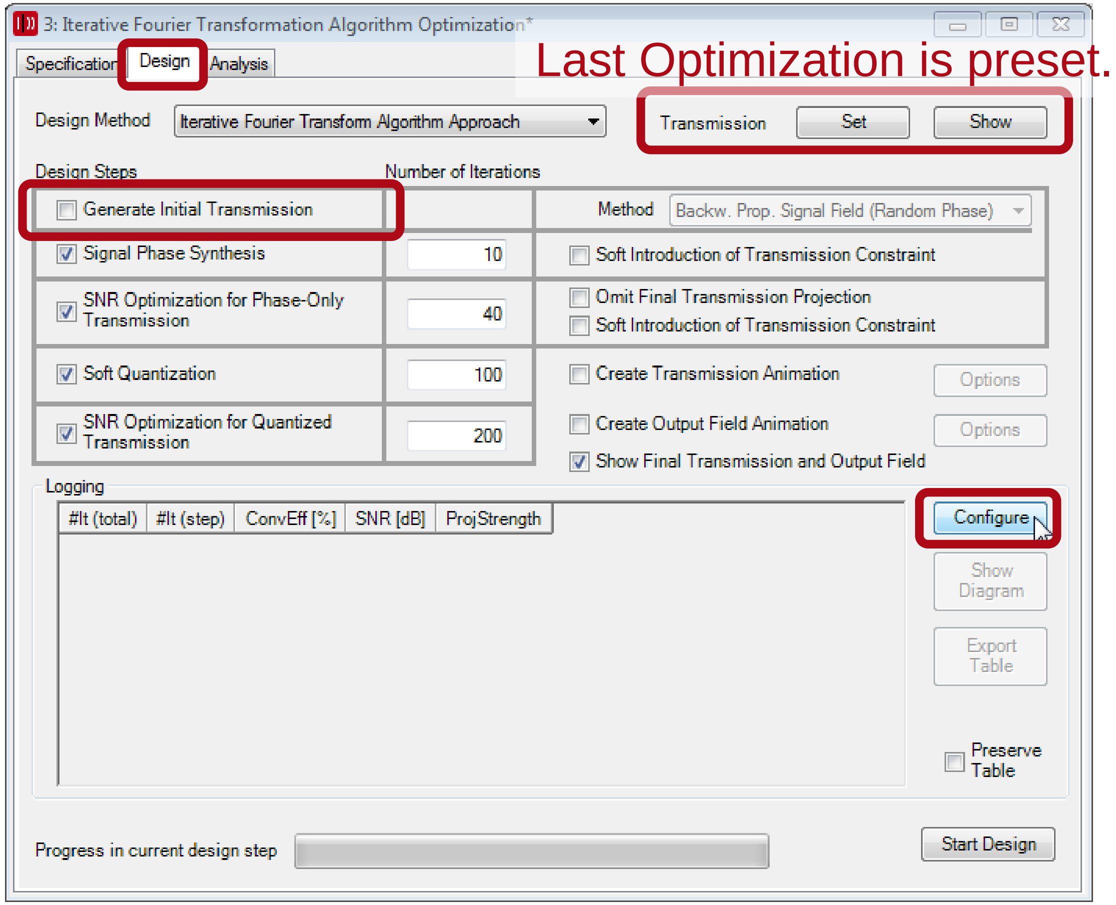
Geometrically Optimized Transmission 8



- Change the design method to “Iterative Fourier Transform Algorithm Approach.

Results in

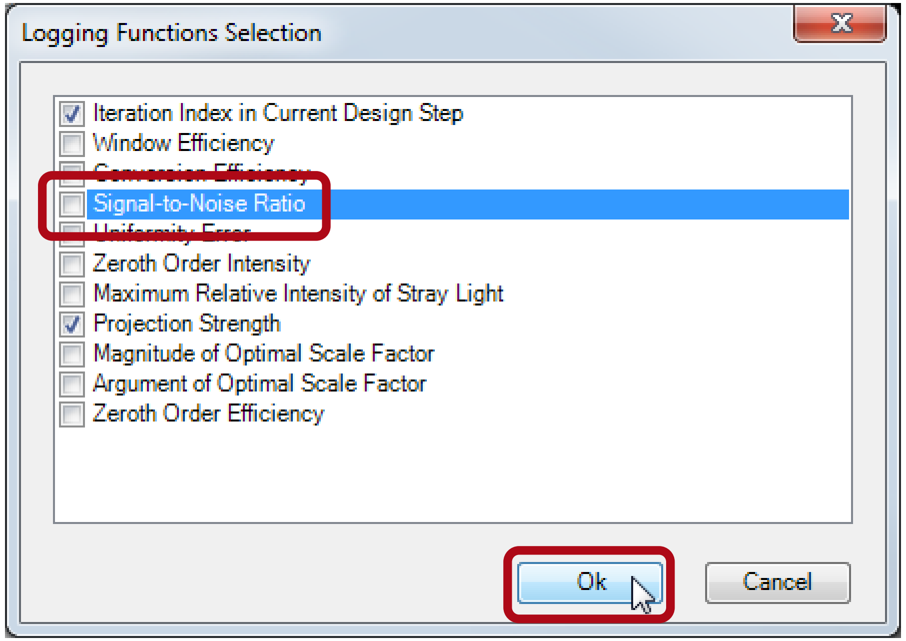
IFTA Optimization 1



- It is important to uncheck the option “Generate Initial Transmission”. For the geometrical approach has already provided a good initial transmission which is preset.
- For speeding up the calculation change the standard settings for logging by clicking “Configure”.

Results in

IFTA Optimization 2



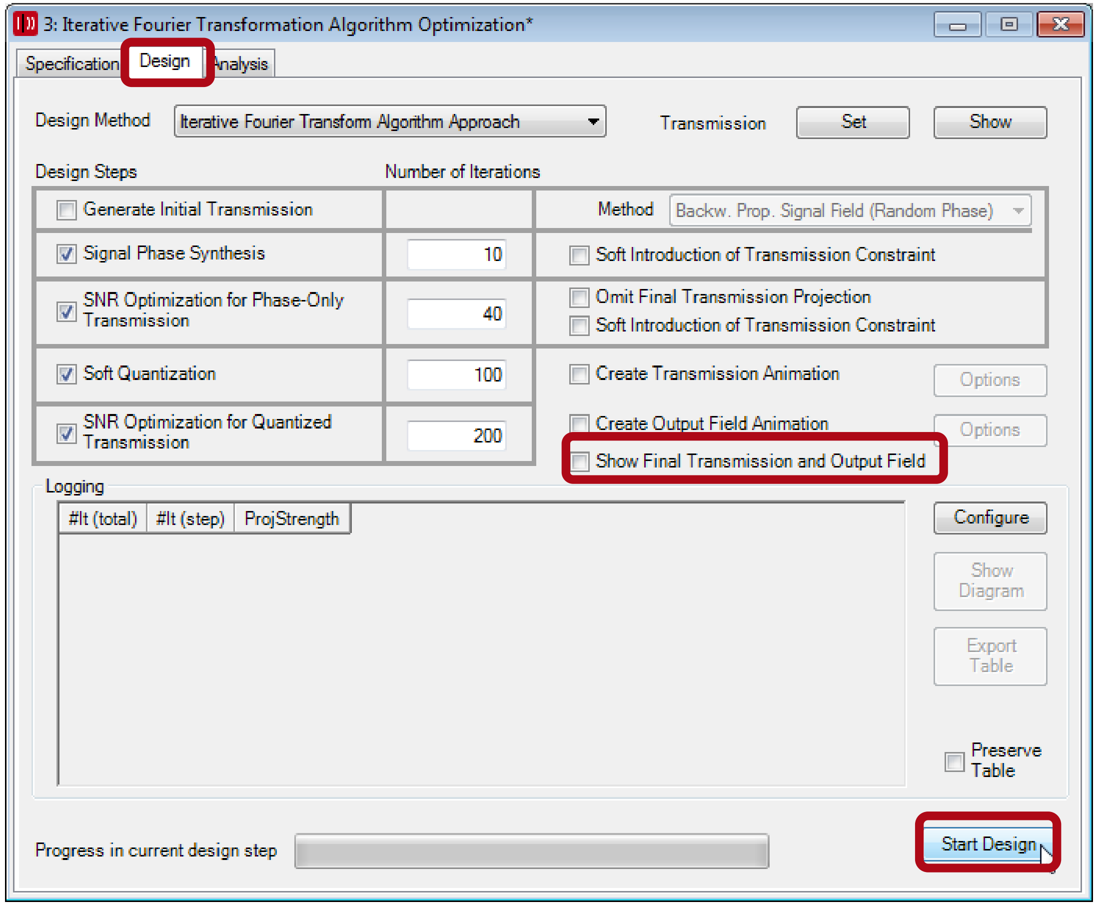
Disable the logging of the following two merit function values:

- Conversion Efficiency
- Signal-to-Noise Ratio

This disabling of some loggings does not affect the optimization.

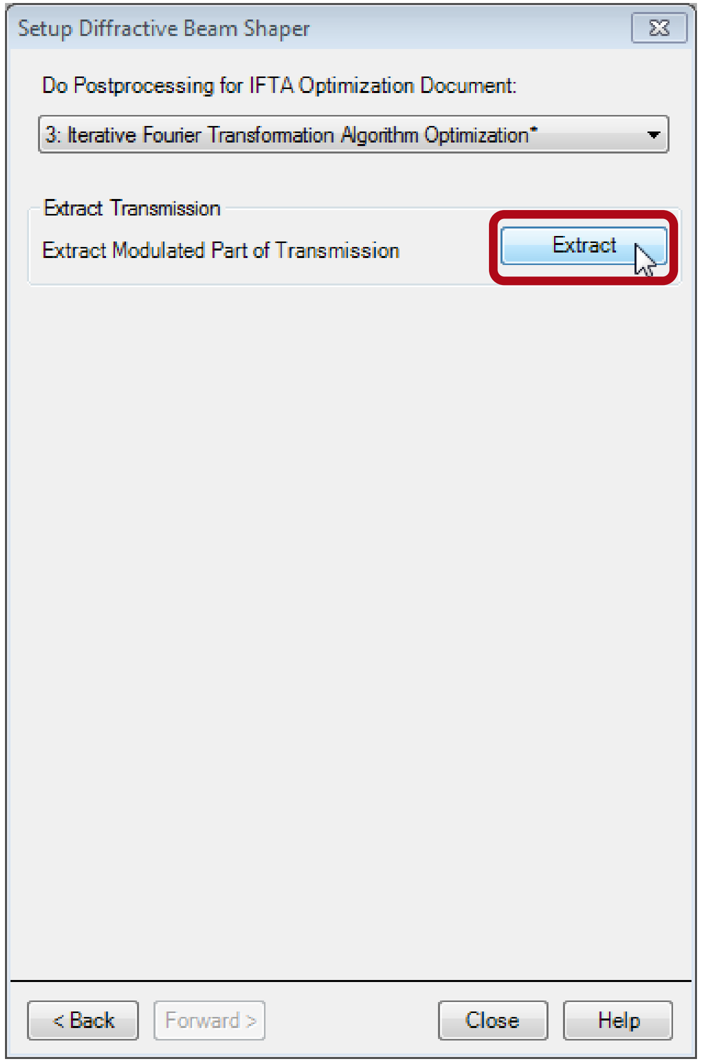
- Confirm with “Ok”.

IFTA Optimization 3

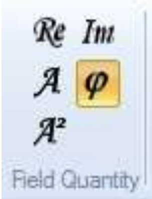


- Uncheck “Show Final Transmission and Output Field” for the relevant data will be extracted using the dialog “Setup Diffractive Beam Shaper”.
- Then click “Start Design.

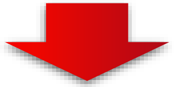
IFTA Optimization 4



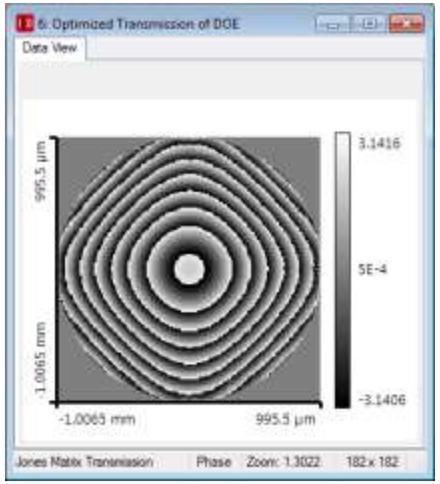
- When the design completed successfully – indicated in the messages panel – switch back to the dialog “Setup Diffractive Beam Shaper” and extract again the data of interest by clicking “Extract”.
- Further activate the phase view.

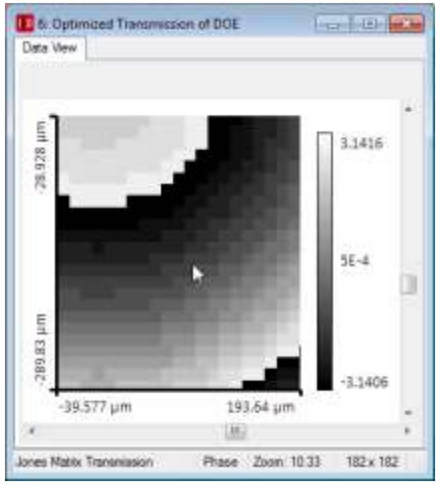


Results in



IFTA Optimized Transmission

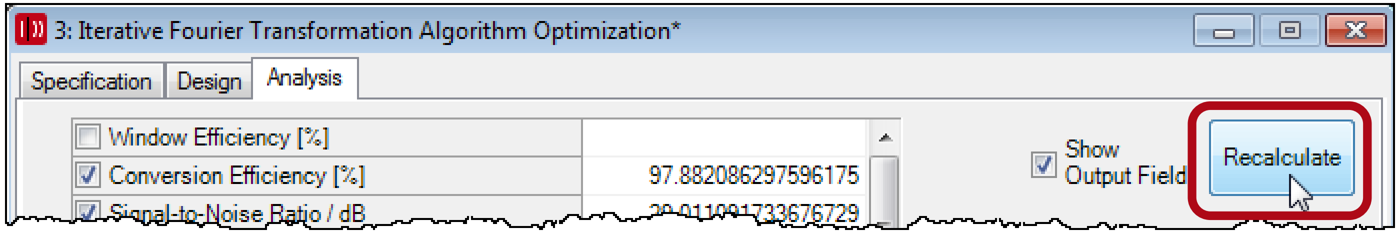




- The result is comparable to the previous one.
- After zooming in (with the mouse wheel) the introduced phase discretization becomes visible.

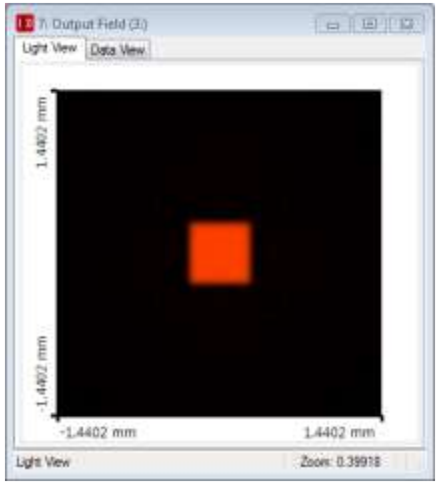
IFTA Results 1

- Again switch back to the Analysis tab of the design document and click “Recalculate”.



Results in

IFTA Results 2



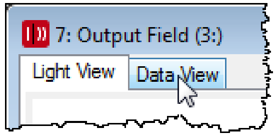
☐ Window Efficiency [%]	
☑ Conversion Efficiency [%]	96.897799114995138
☑ Signal-to-Noise Ratio / dB	48.467698617696094
☑ Uniformity Error [%]	15.433530790091091
☐ Zeroth Order Intensity [%]	
☐ Zeroth Order Efficiency [%]	
☑ Maximum Relative Intensity of Stray Light [%]	1.5324463437275169

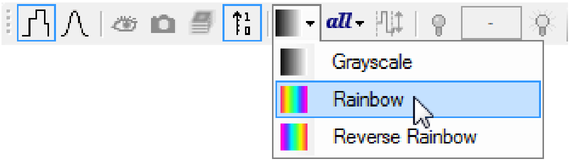
Results from the iterative Fourier transform algorithm approach:

- Efficiency almost 97%
- SNR almost 50%
- Amount of stray light below 2%

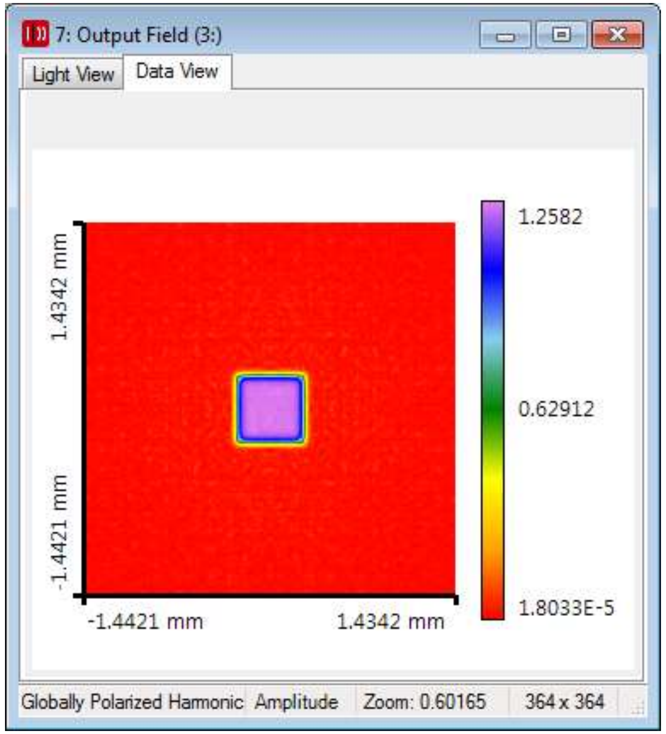
So the specifications are fulfilled.

IFTA Results 3





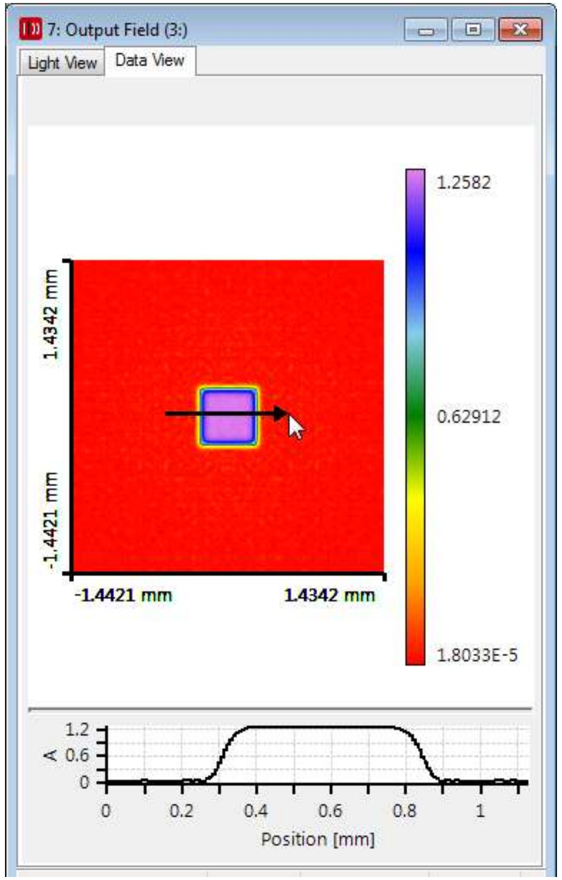
Results in



- To examine the distribution of the light's amplitude in more detail switch to a false color representation.
- Therefore switch first to "Data View" and then click "Rainbow" on the accordant tool bar.

IFTA Results 4

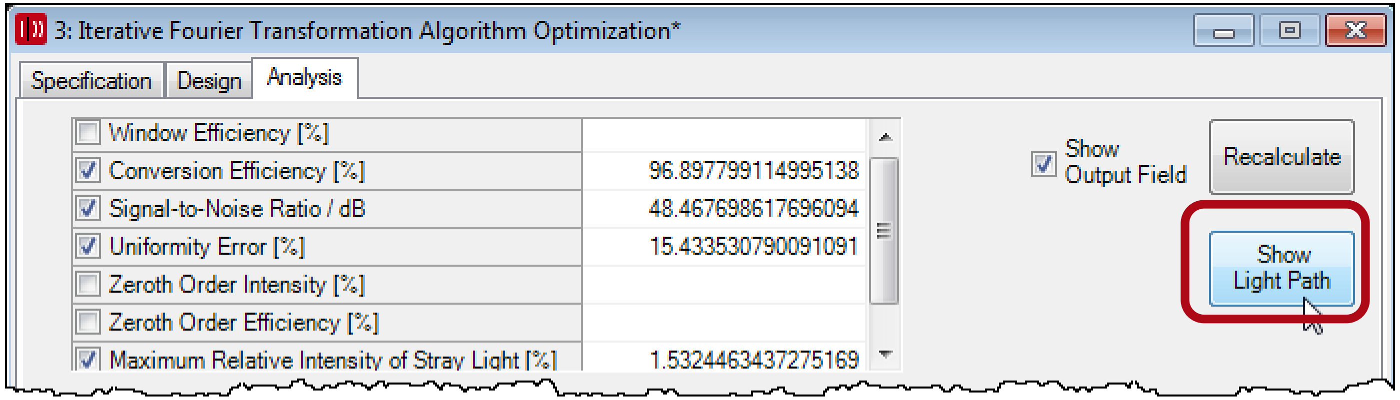
Results in



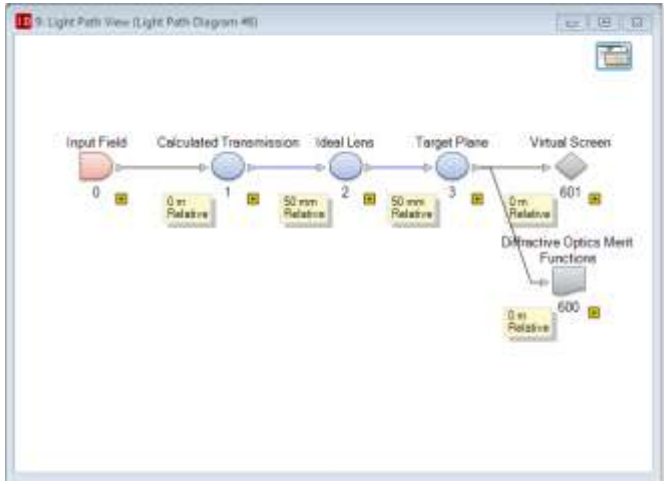
- In order to get the profile of the amplitude distribution select the tool “Profile Line” and draw a line over the area of interest.
- The distribution turns out to be very smooth.

Building of the Light Path Diagram 1

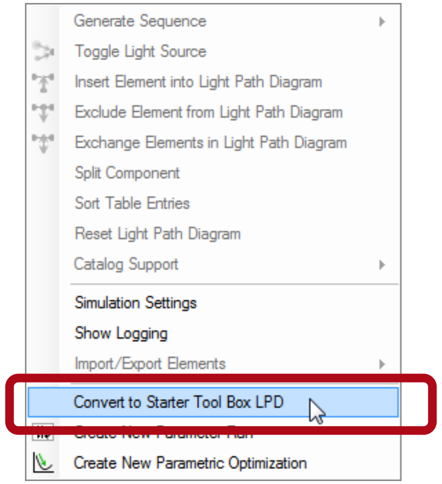
In order to do further analyzes with this optical setup, such as varying of several parameters with the parameter run, one can build a light path diagram that contains the calculated transmission function of the DOE within a so-called stored transmission component by clicking “Show Light Path” on the Analysis tab of the design document.



Building of the Light Path Diagram 2

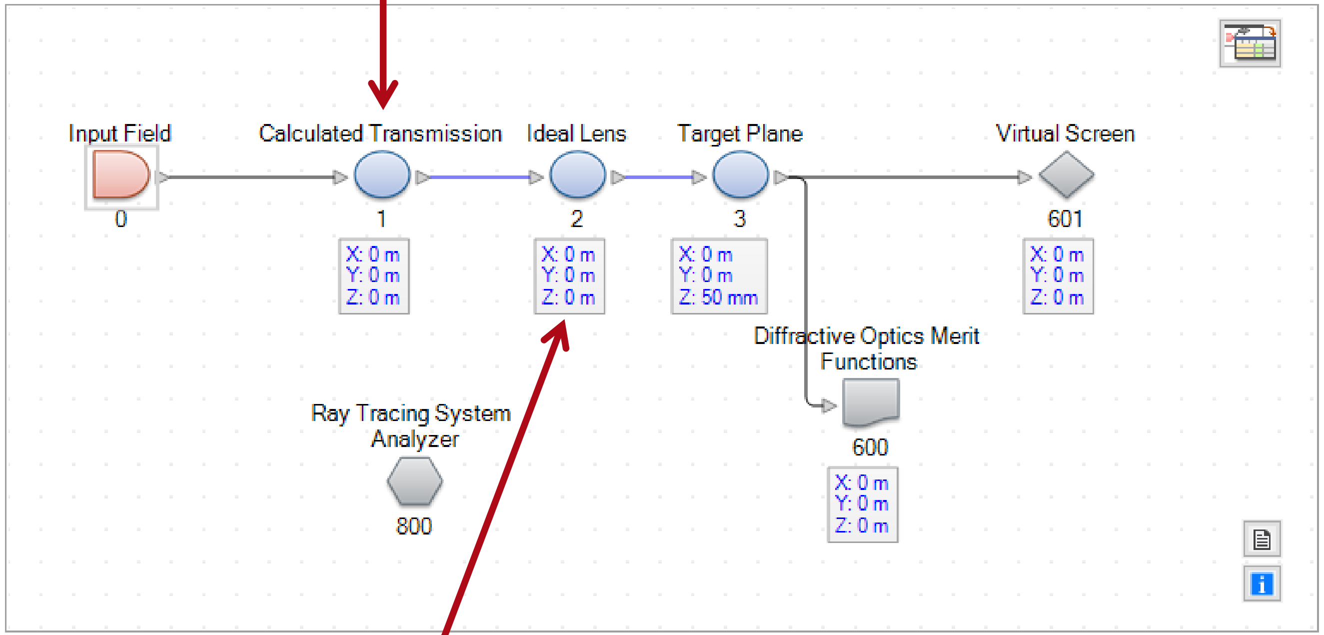


- This preset Light Path Diagram (LPD) has to be adapted a little.
- Note: Only Starter Toolbox LPDs can be changed.
- Thus click "Tools" in the Light Path Editor (LPE) and select "Convert to Starter Tool Box LPD".



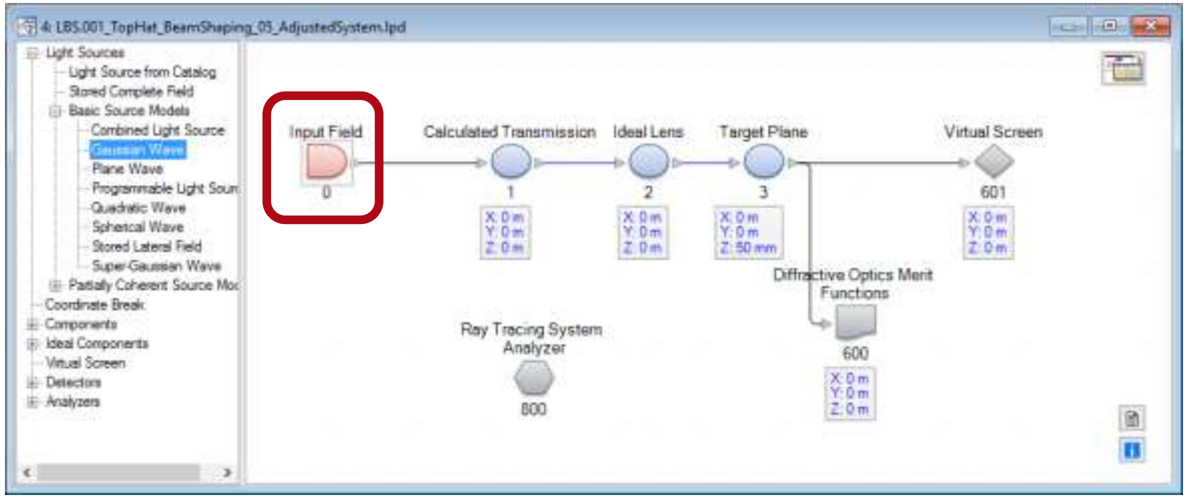
Building of the Light Path Diagram 3

Insert the extracted transmission function with added aperture into the “Calculated Transmission” element and pixelation factor of 5 × 5.



Further change the 2f-setup of the Ideal Lens to a 1f-setup by setting the first distance to 0.

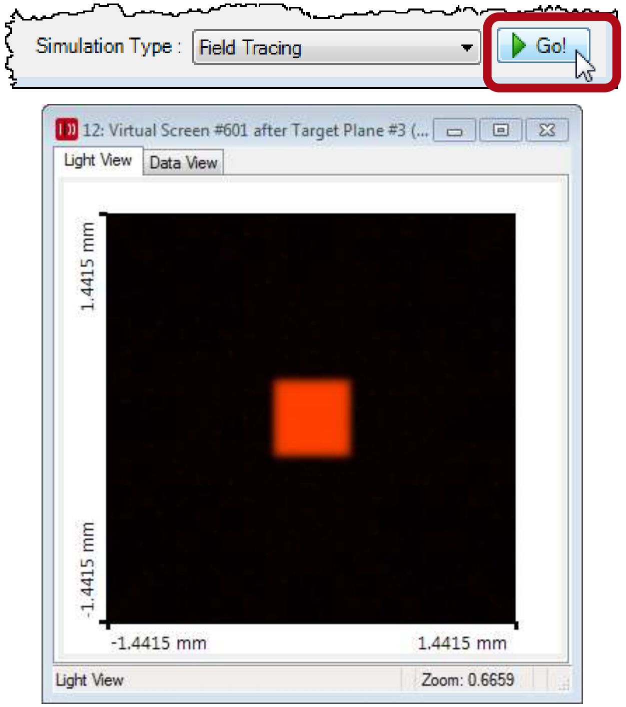
Building of the Light Path Diagram 4



- The first element could be replaced with a Gaussian Wave as by default it is no adjustable light source but a “Stored Field” source that has the generated input field stored inside.

- But for this demonstration the stored complex field is kept as the input field.

Simulation and Results



- Starting the simulation with "Go!" and the light field distribution as well as the results of the diffractive optics merit functions are displayed.
- Results of the output field:
  Efficiency: 98.5%
  SNR: 43.4 dB
  Stray Light: 1.7%

Sub - Detector	Result
Conversion Efficiency (Classic Field Tracing)	98.518 %
Signal-to-Noise Ratio (Classic Field Tracing)	43.299 dB
Uniformity Error (Classic Field Tracing)	12.694 %
Maximum Relative Intensity of Stray Light (Classic Field Tracing)	1.6895 %

STEP 4

Data Export for manufacturing of the DOE

(just mentioned, details not part of this tutorial)

Data Export for Fabrication

- For fabrication purpose export the data of the transmission function of the DOE.
- How to do this is shown in the "Tutorial_144.01_Structure_Design_and_Fabrication_Export".

Starter Toolbox

How to configure the microstructure?

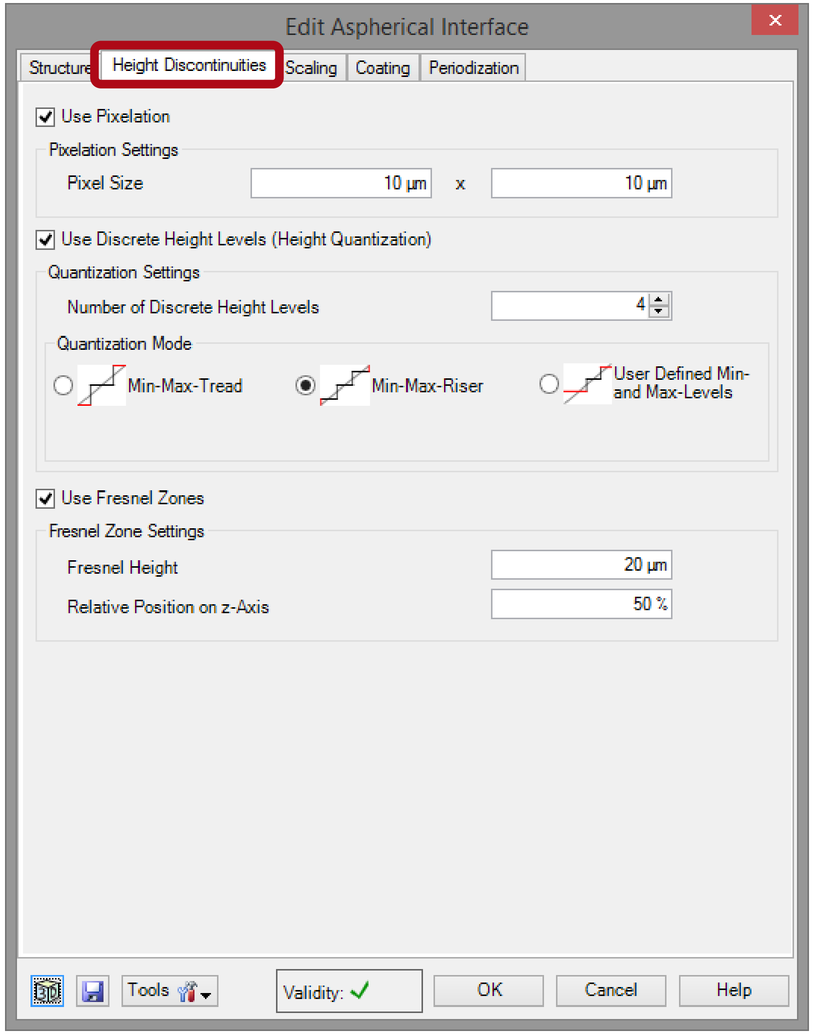
How to simulate it?

(v1.1)

Modeling of Discrete Height Levels, Rectangular Pixels and Fresnel Zones

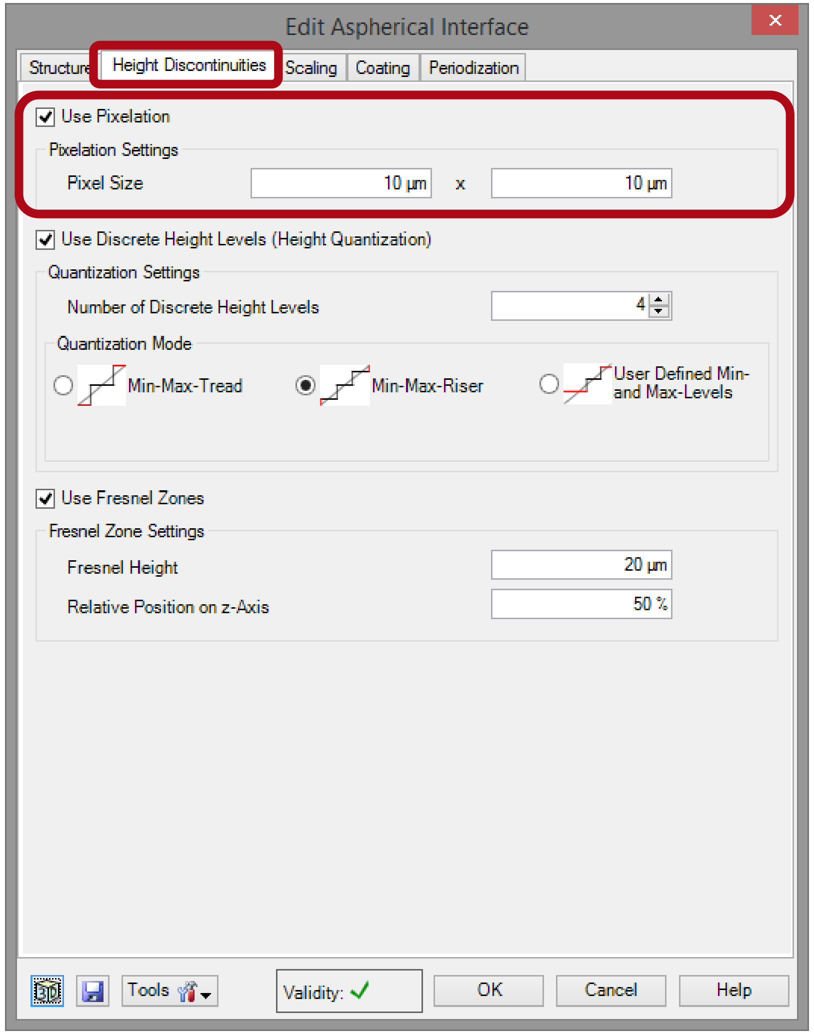
Handling of Height Discontinuities

Height Discontinuities Page



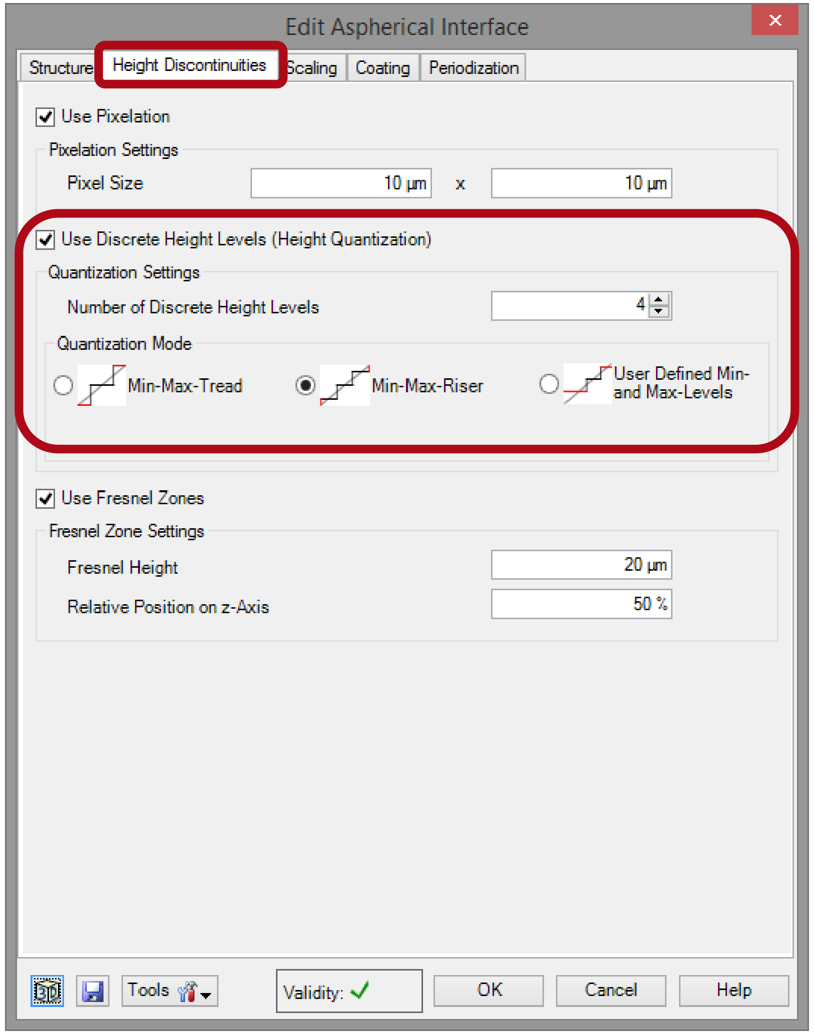
- Every optical interface contains a ‘Height Discontinuities’ page.
- This page enables the modeling of
  - Rectangular pixels
  - Discrete height levels
  - Fresnel zones

Modeling of Rectangular Pixels



- *Use Pixelation* enables modeling of rectangular pixels with given size.
- Rectangular pixel may appear during the fabrication of a DOE and must be included in the optics simulation.

Modeling of Discrete Height Levels

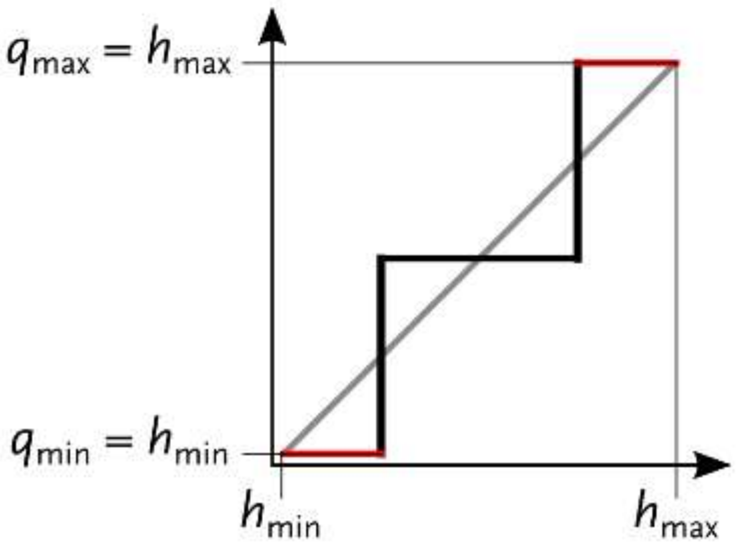


- *Use Discrete Height Levels (Height Quantization)* enables the modeling of discrete height levels

Modeling of Discrete Height Levels

- Discrete height levels can be introduced by three modes of operation:
  - Min-Max-Tread
  - Min-Max-Riser
  - User Defined Min-Max-Levels
- The modes of operation control the height values of the lowest and higher quantization level.

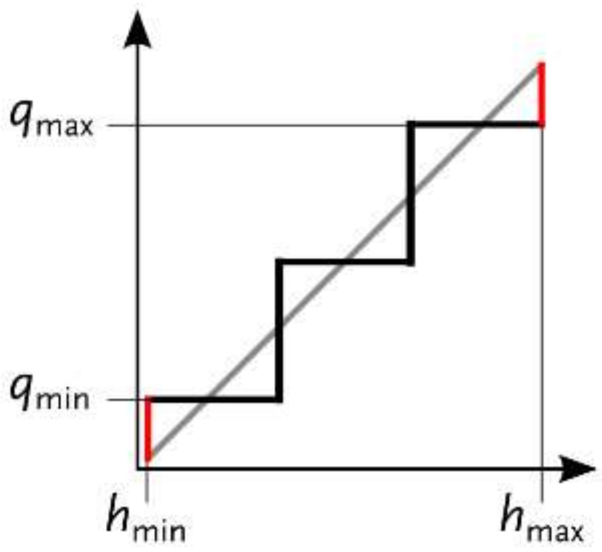
Modeling of Discrete Height Levels



Min-Max-Tread

- *Min-Max-Tread* mode
- The height of the lowest level is equal to the minimum height of the continuous surface.
- The height of the highest level is equal to the maximum height of the continuous surface.

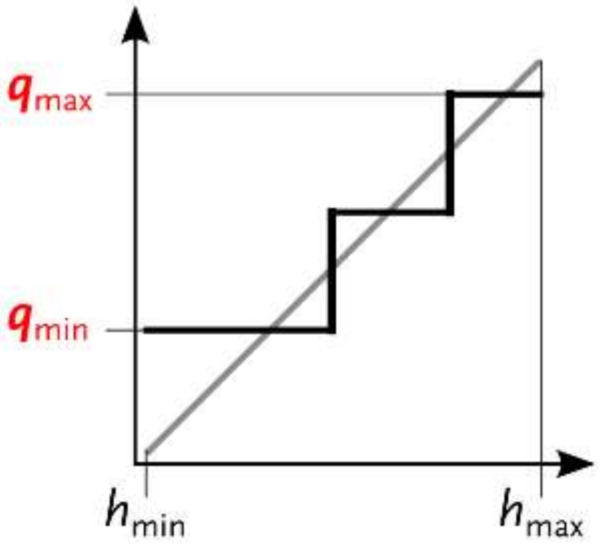
Modeling of Discrete Height Levels



Min-Max-Riser

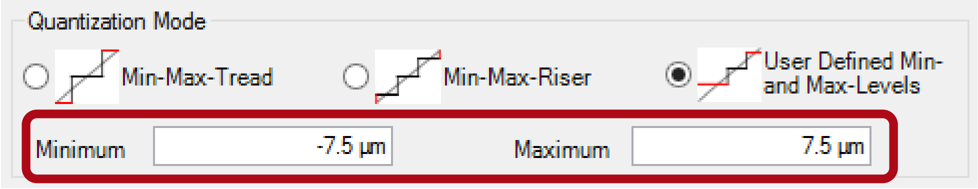
- *Min-Max-Rise* mode
- The height of the lowest level is defined by the minimum height of the continuous surface plus the half of the height level step size.
- The height of the highest level is defined by the maximum height of the continuous surface minus the half of the height level step size.

Modeling of Discrete Height Levels

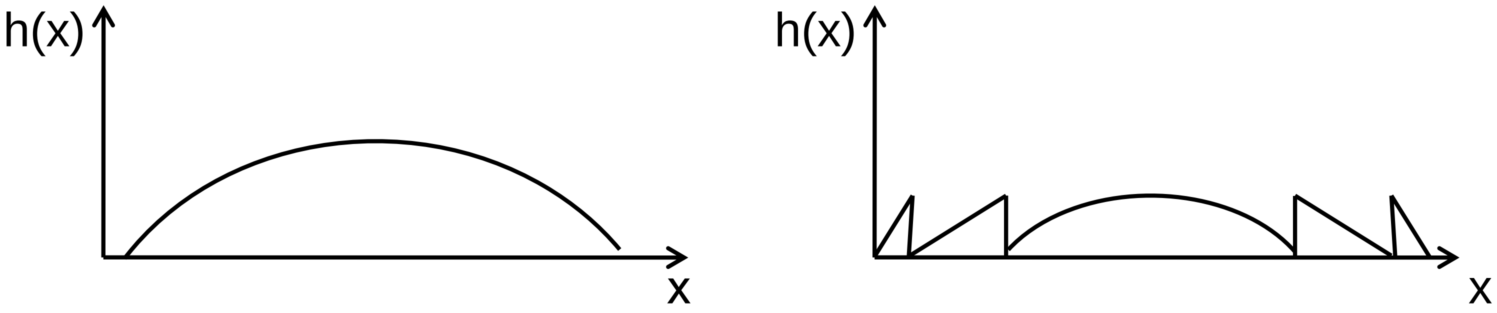


User Defined

- *User Defined Min-Max-Levels* mode
- The heights of the lowest level and of the highest level are defined by the user.

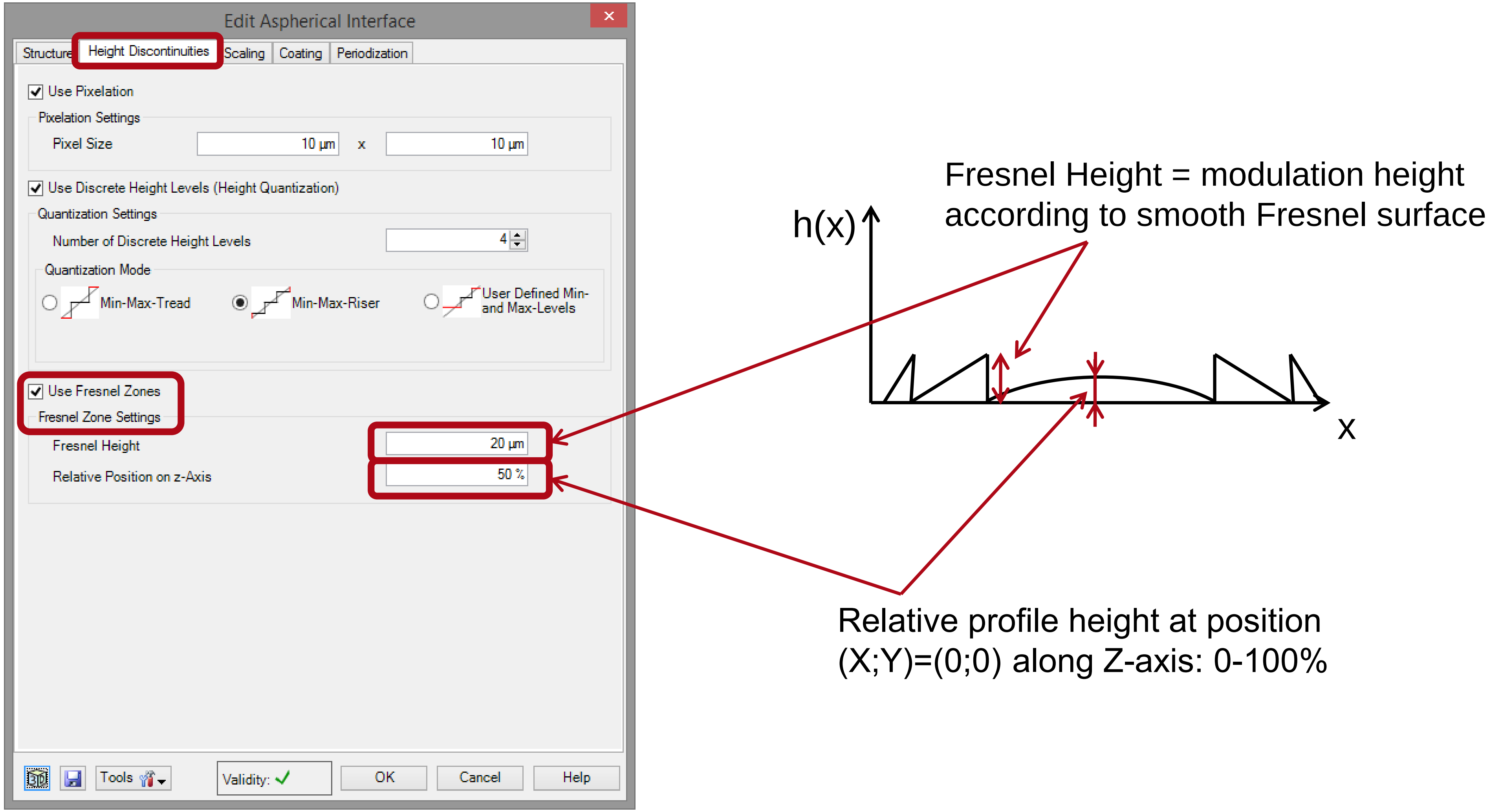


Modeling of Fresnel Zones



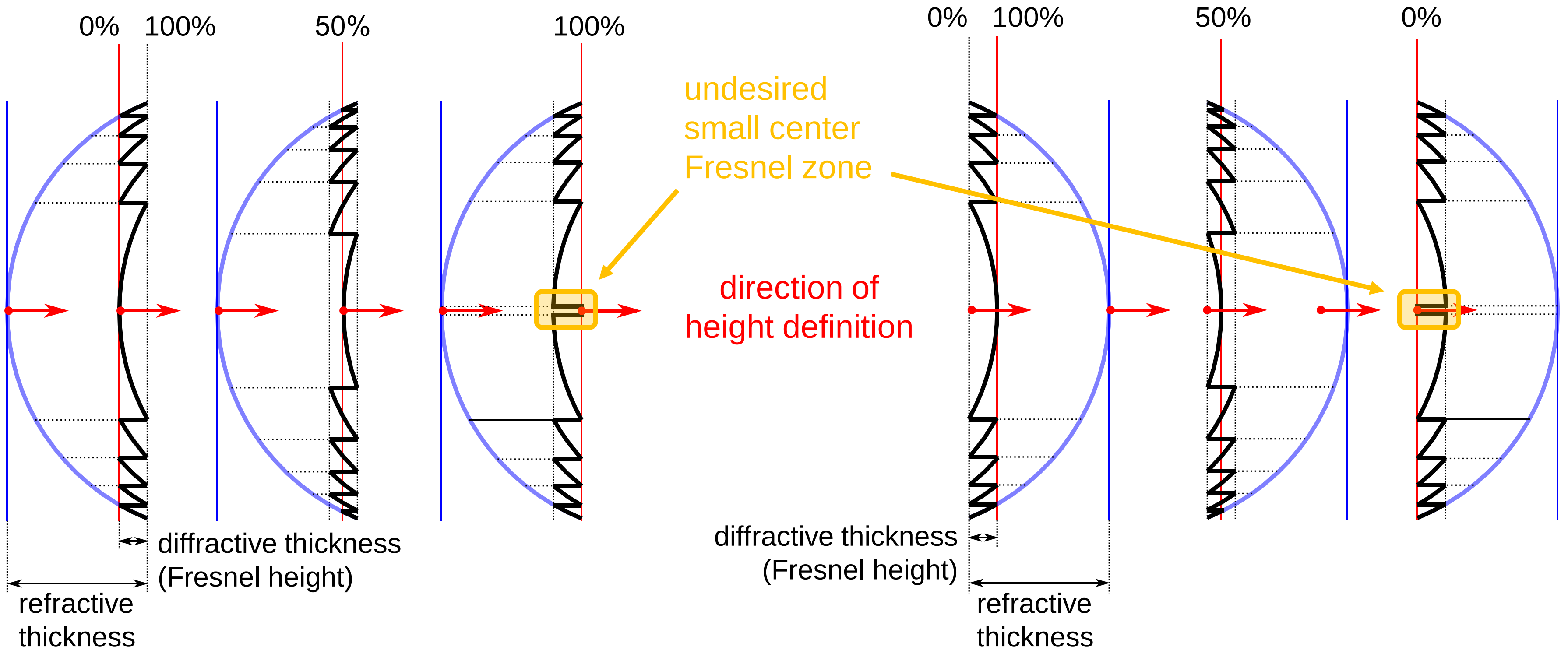
- The Fresnel zones option allows the introduction of Fresnel lens type jumps for arbitrary height profiles.
- The heights/depths of these Fresnel zones can be specified.

Modeling of Fresnel Zones

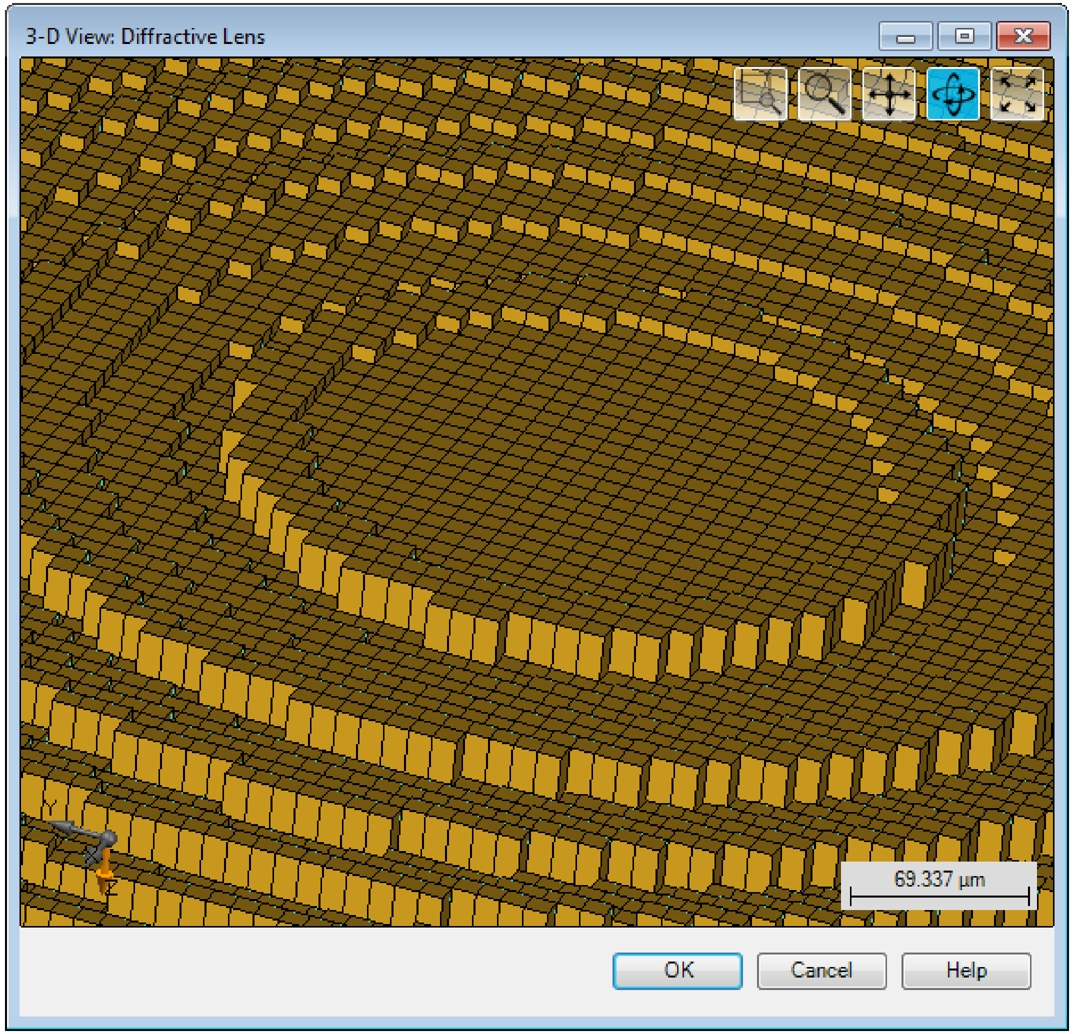


Center Height Level of Fresnel Structure

Depending on the orientation of the curvature a different height level enables the largest possible center Fresnel zone.
Default height level is 50% which ensures in most cases a suitable solution.



Diffractive Lens



Diffractive lens modeled by Fresnel zones, rectangular pixels and discrete height levels.

Micro Optical Components

Import of Surface Data from Data Array

Sampled Interface – Demonstrative Sample File

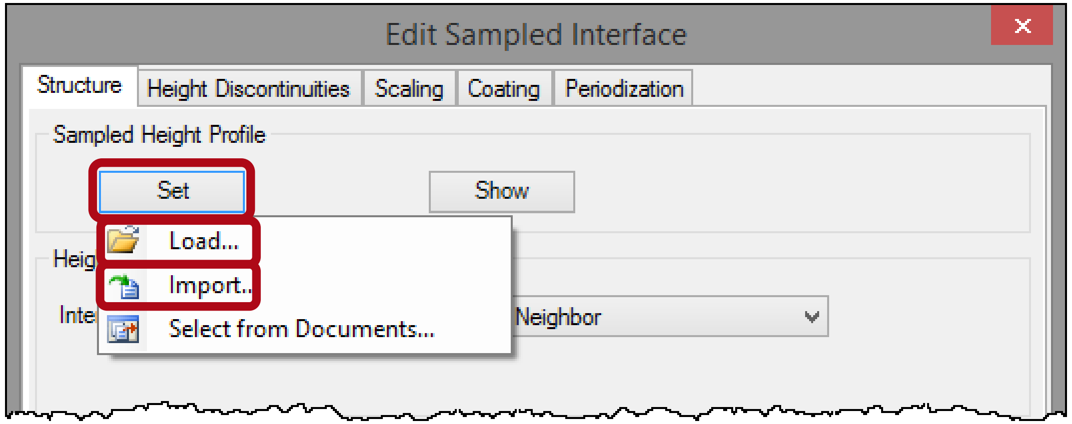
As demonstration the data of a Gaussian height profile is to be used via sampled interface.

Files:

- SurfaceDataToSampledInterface.lpd
- SurfaceDataToSampledInterface_HeightProfile.da

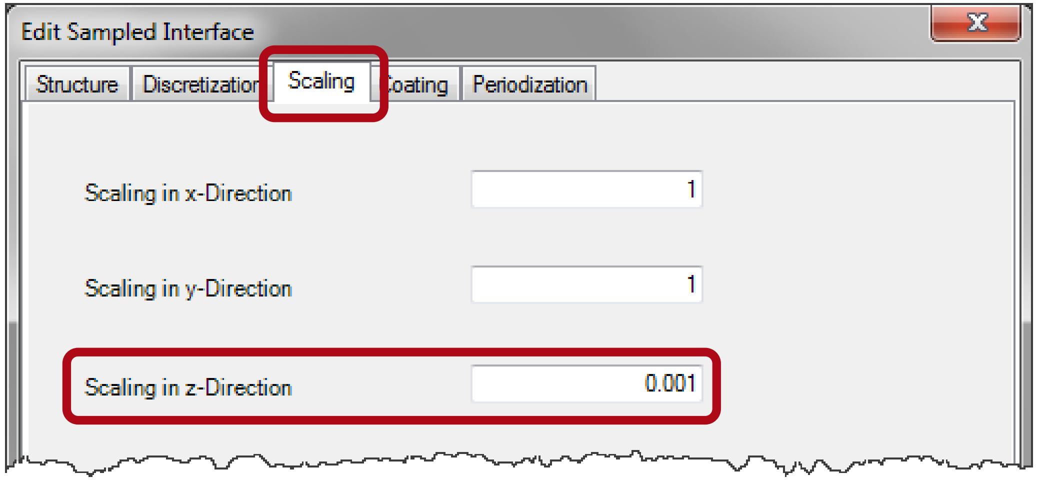
Surface Data Import Constraints

- The imported data array must fulfill the following constraints:
  - Only one real-valued, equidistantly sampled subset
  - The coordinates must have the unit length.
  - The data must have the unit length.
- In case of a descrepancy, the loaded/imported data is shown as separate document so that you can change it accordingly.
- The changed data array can then be set via …



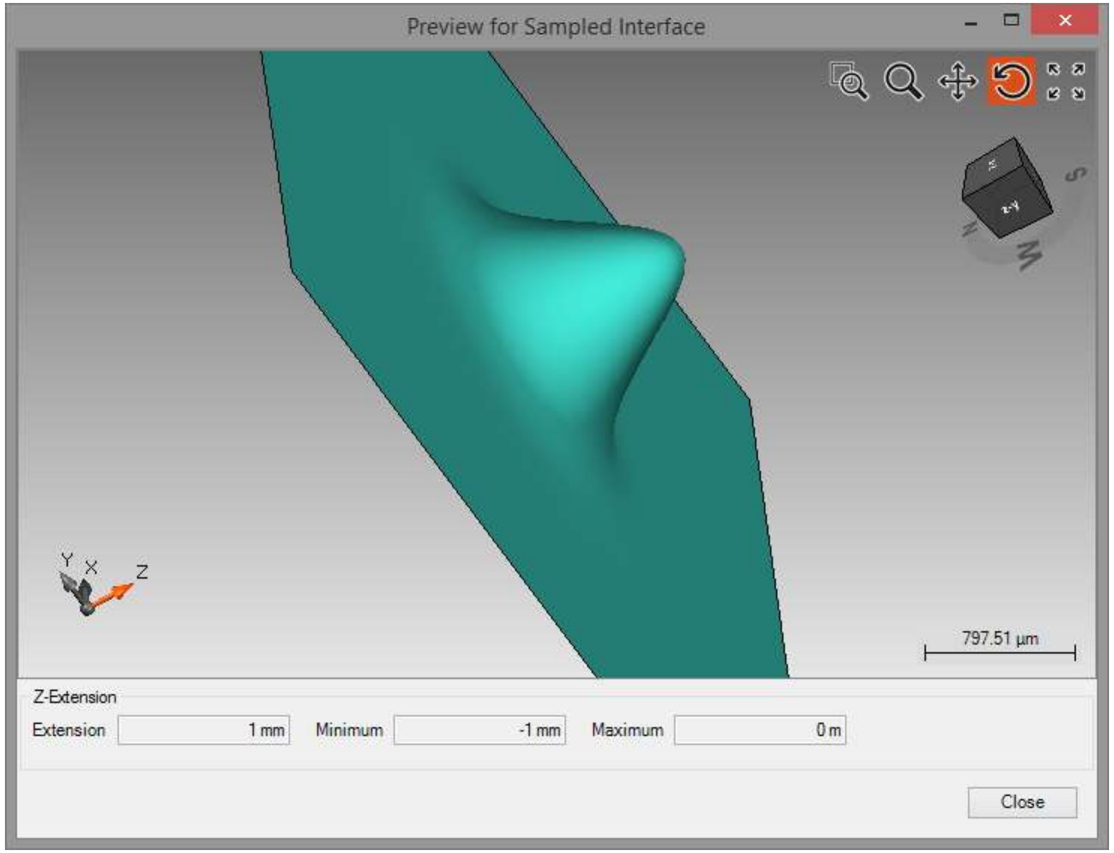
Scale the Height Data

VirtualLab assumes that the given height values have the unit which are set in the global options (default = „meters“). If this is not the case, you can scale the interface accordingly. In the sample file the heights are given in millimeters instead.

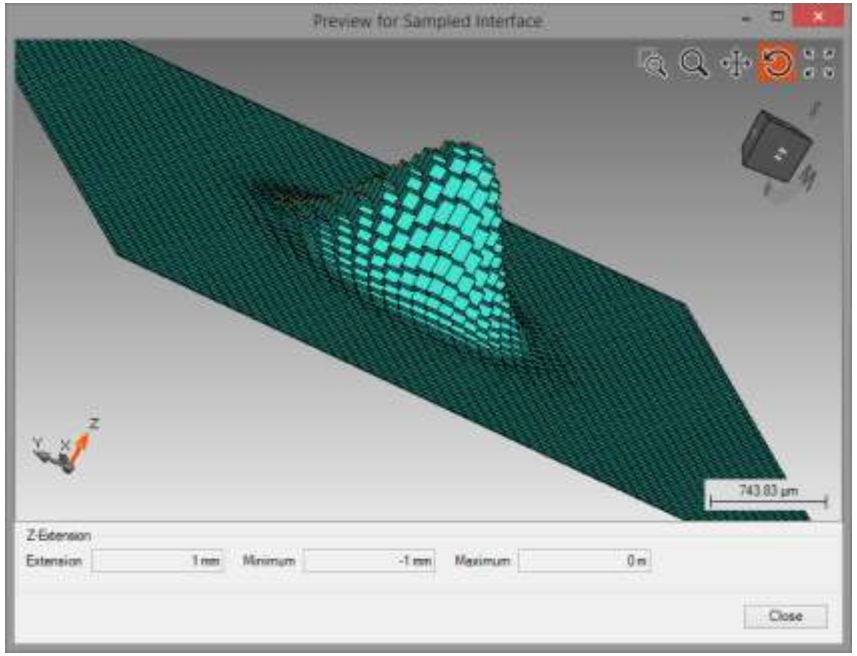


3D View of Sampled Interface

Cubic 8 Point Interpolation



Nearest Neighbor Interpolation



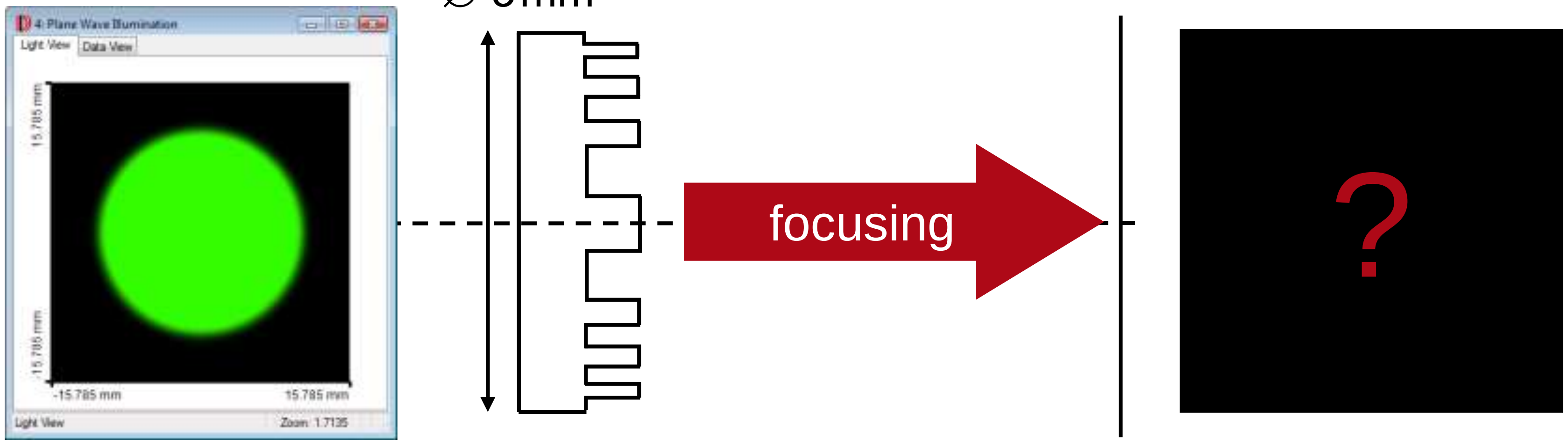
Task17

Analysis of System with Binary Lens

Modeling Task

round
∅ 3mm

PSF & MTF calculation



plane wave
wavelength: 532 nm
∅ 2.5 mm
with 5 % edge width

- diffractive lens (based on conical surface)
- 2 levels

focal plane

effective focal length f=200 mm

Specs: Lens Data & Simulation Hint

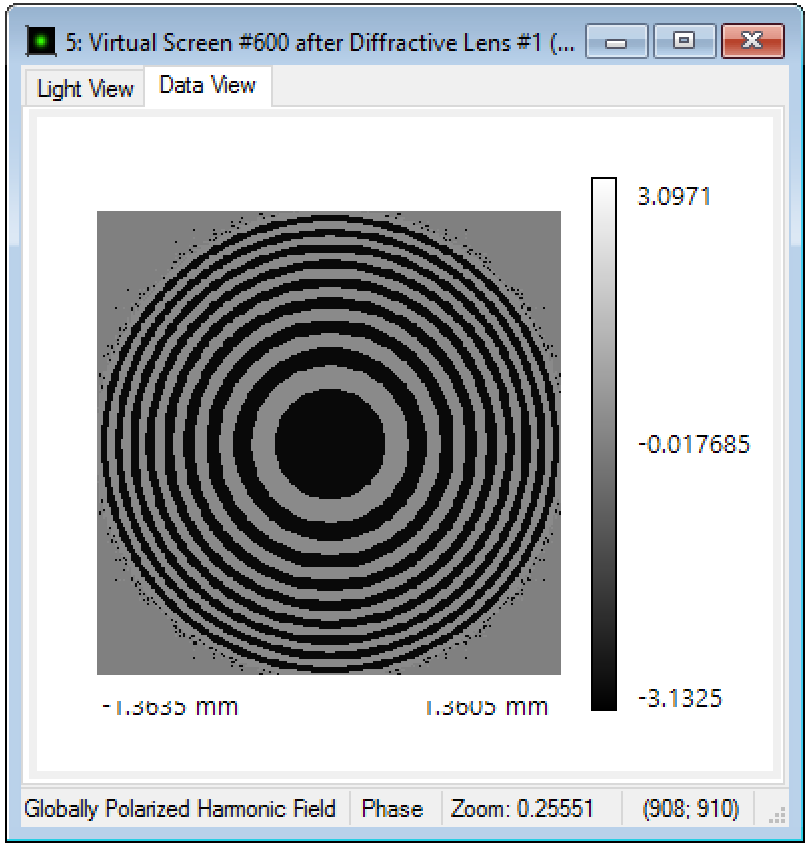
Lens Data

- substrate & its center thickness: Fused Silica, 1 mm
- starting point: conical surface with Conical Constant = 0 in DIC
- effective focal length: 200 mm → radius of curvature: -92.143 mm (see *Spherical Lens Calculator*)
- diameter of round lens: 3 mm
- modulation depth: 0.5 * 1.1544 µm (see *Modulation Depth Calculator*)
- height levels: 2
- fabricable pixel size: 10 µm

Simulation Settings

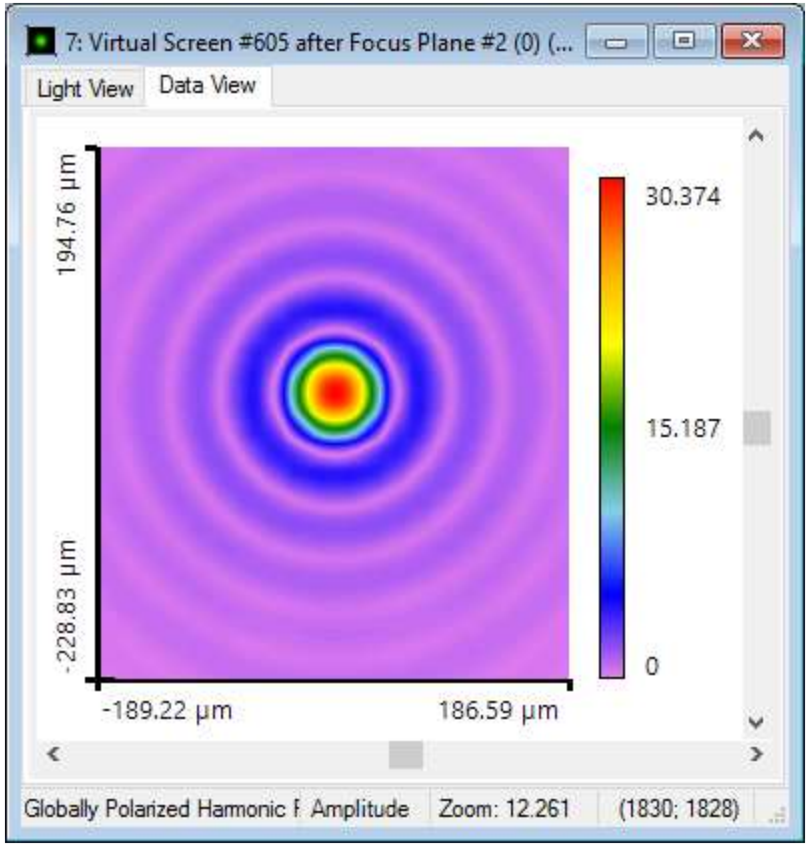
- Use the propagation method *Combinded SPW/Fresnel Operator* for the free space between the diffractive lens and the focal plane.

Expected Result: Phase Directly after Lens

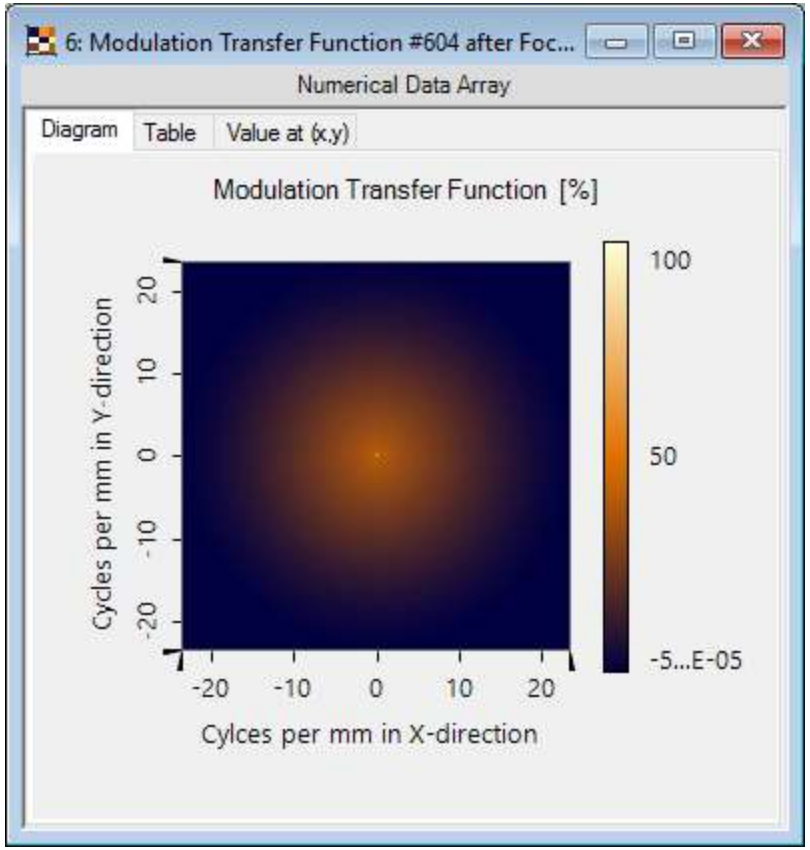


phase of field after lens

Expected Result: PSF & MTF

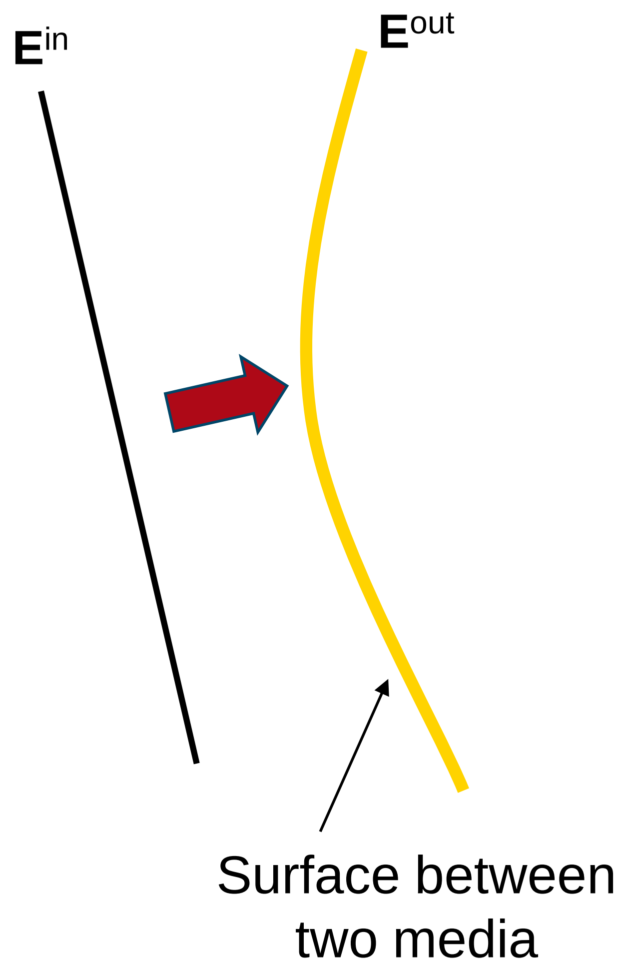


PSF



2D MTF

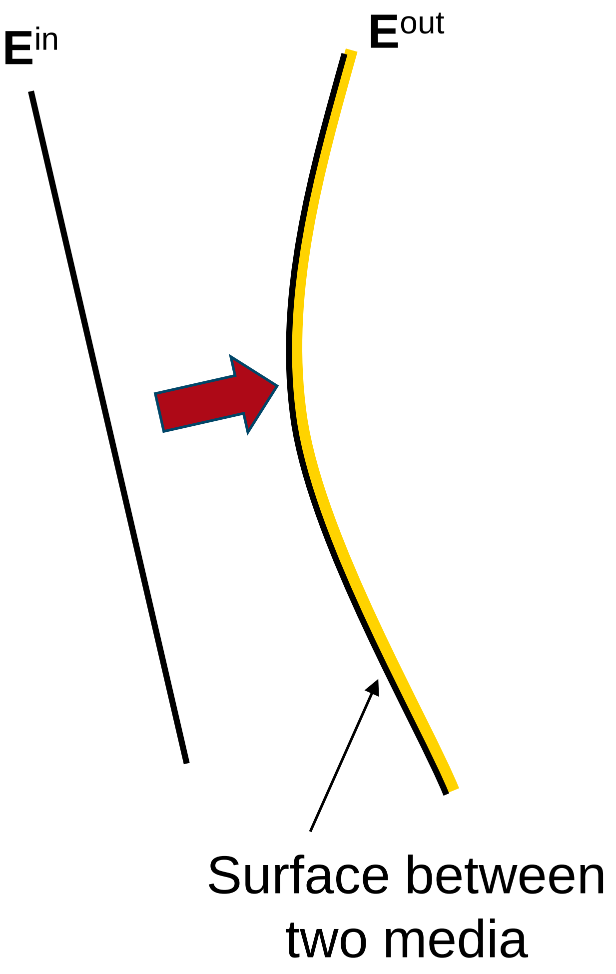
Local Plane Interface Approximation (LPIA)



- Field is propagated onto the surface.

$$\tilde{V}^{\text{out}}(k_x, k_y) = \int_{K^2} \tilde{B}(k_x, k_y, k'_x, k'_y) \tilde{V}^{\text{in}}(k'_x, k'_y)\, \mathrm{d}k'_x\, \mathrm{d}k'_y$$

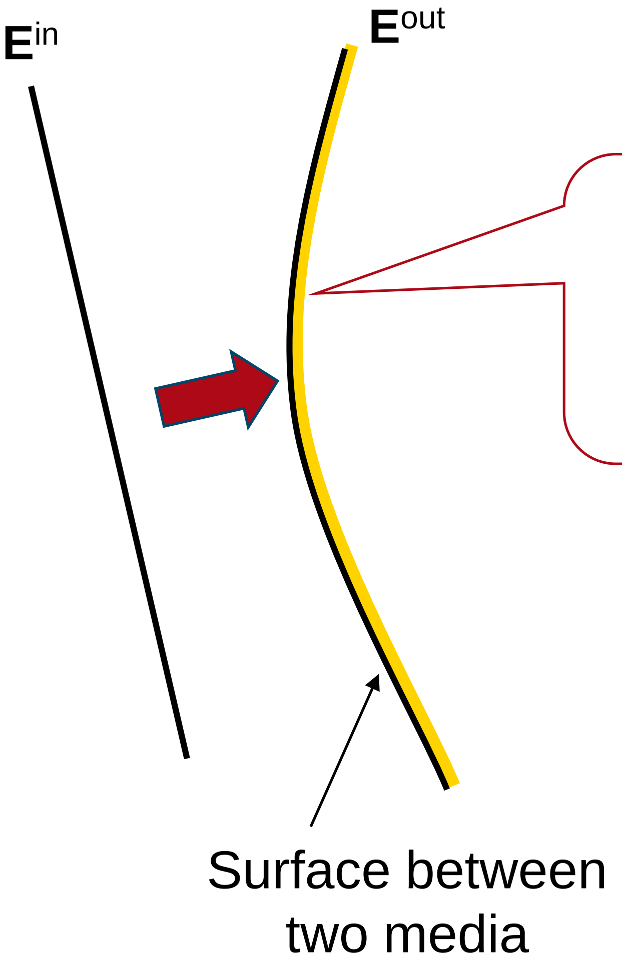
Local Plane Interface Approximation (LPIA)



- Field is propagated onto the surface.
- Response is obtained by local satisfaction of boundary condition.

$$\tilde{V}^{\text{out}}(k_x, k_y) = \int_{K^2} \tilde{B}(k_x, k_y, k'_x, k'_y)\tilde{V}^{\text{in}}(k'_x, k'_y)\,\mathrm{d}k'_x\,\mathrm{d}k'_y$$

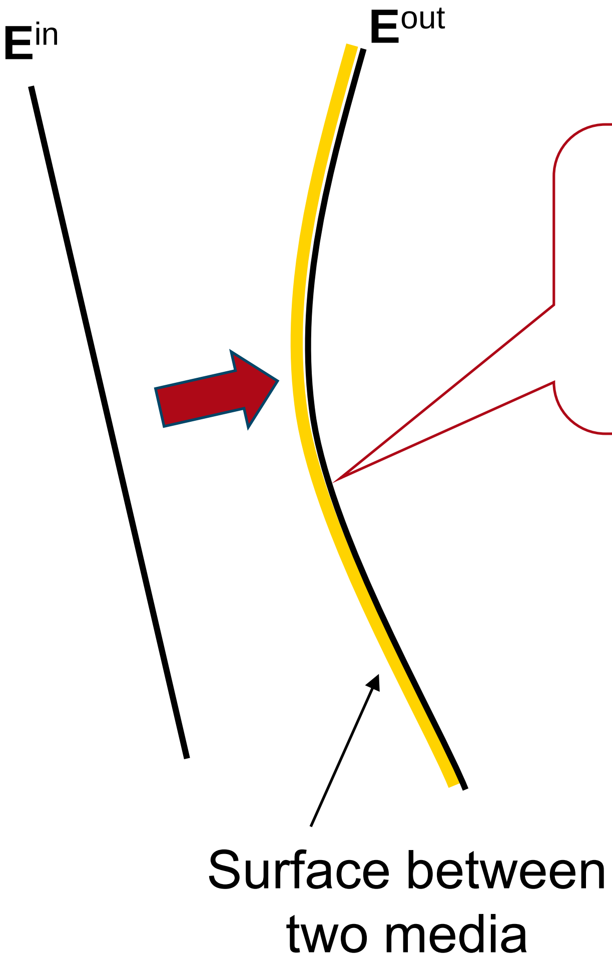
Local Plane Interface Approximation (LPIA)



LPIA: Local satisfaction of boundary condition under the assumption of local plane waves and **local plane interface.**

$$\tilde{V}^{\text{out}}(k_x, k_y) = \int_{K^2} \tilde{B}(k_x, k_y, k_x', k_y')\, \tilde{V}^{\text{in}}(k_x', k_y')\, \mathrm{d}k_x'\, \mathrm{d}k_y'$$

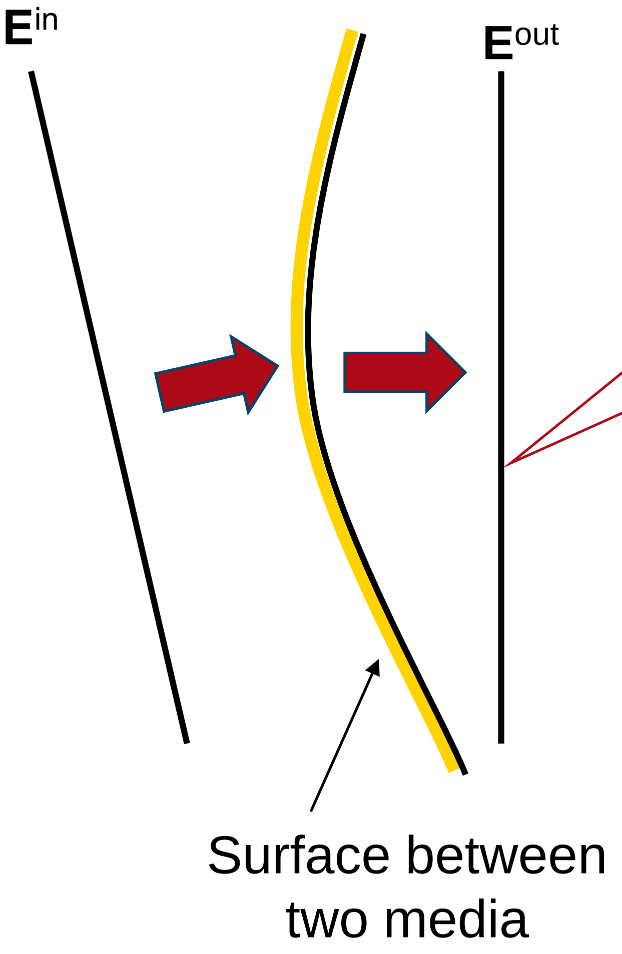
Local Plane Interface Approximation (LPIA)



Further propagation into suitable reference plane by free-space propagation.

$$\tilde{V}^{\text{out}}(k_x, k_y) = \int_{K^2} \tilde{B}(k_x, k_y, k'_x, k'_y)\, \tilde{V}^{\text{in}}(k'_x, k'_y)\, \mathrm{d}k'_x\, \mathrm{d}k'_y$$

Local Plane Interface Approximation + Propagation

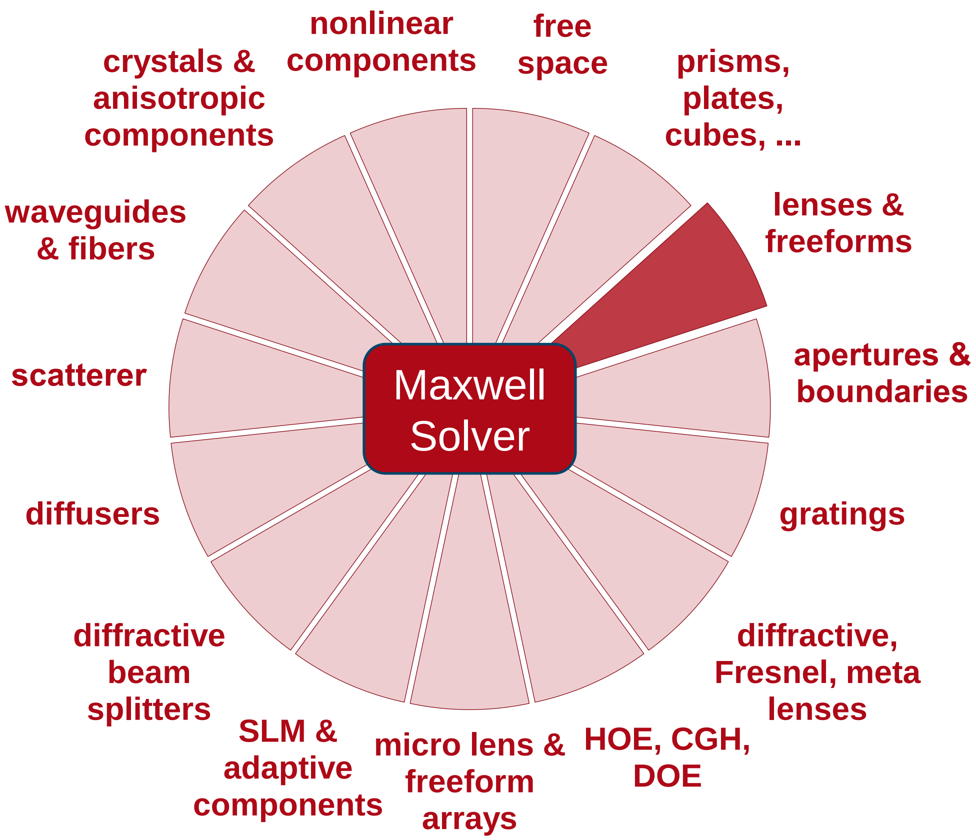


Further propagation into suitable reference plane by free-space propagation.

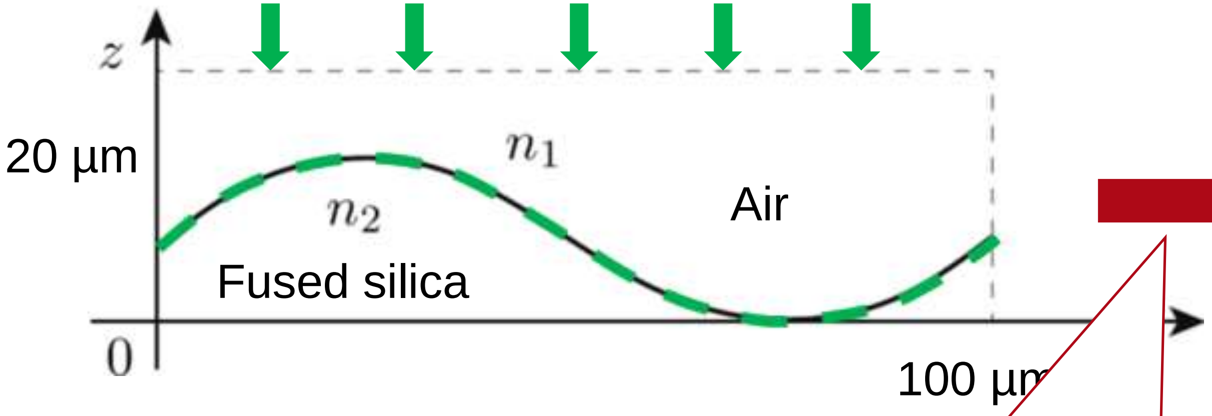
$$\tilde{V}^{\text{out}}(k_x,k_y) = \int_{K^2} \tilde{B}(k_x,k_y,k'_x,k'_y)\,\tilde{V}^{\text{in}}(k'_x,k'_y)\,\mathrm{d}k'_x\,\mathrm{d}k'_y$$

Lenses, Freeforms and Any Components with Curved Surfaces

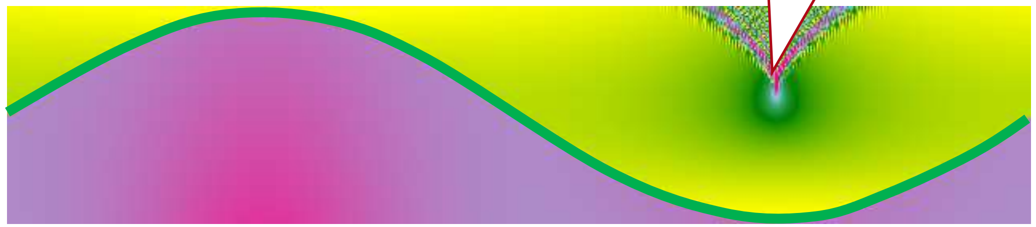
- Rigorous operator for spherical surfaces (Mie theorie).
- Local Plane Interface Approximation: Propagation through curved surfaces by local satisfaction of boundary condition between different media.
- **Very reliable and fast technique for smooth surfaces.**



Simulations: Transmitted Field On Surface (TE polarized)



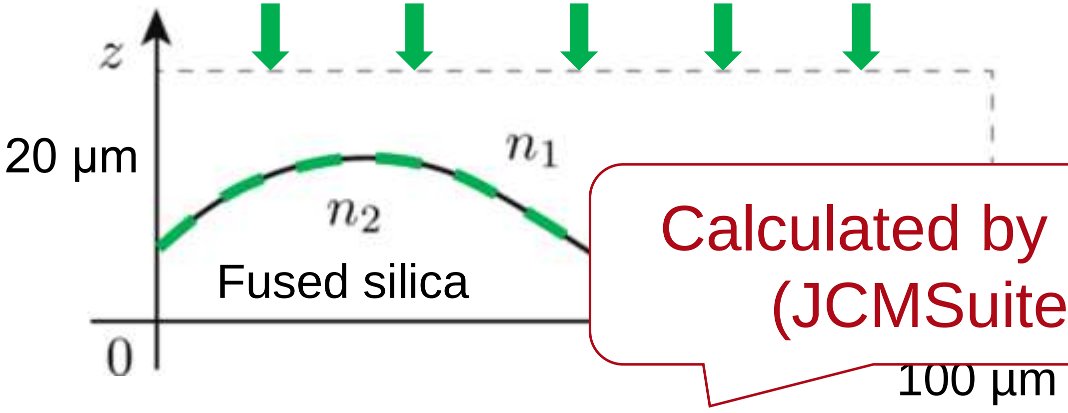
Field inside



High NA focus!

Calculated by FEM (JCMSuite)

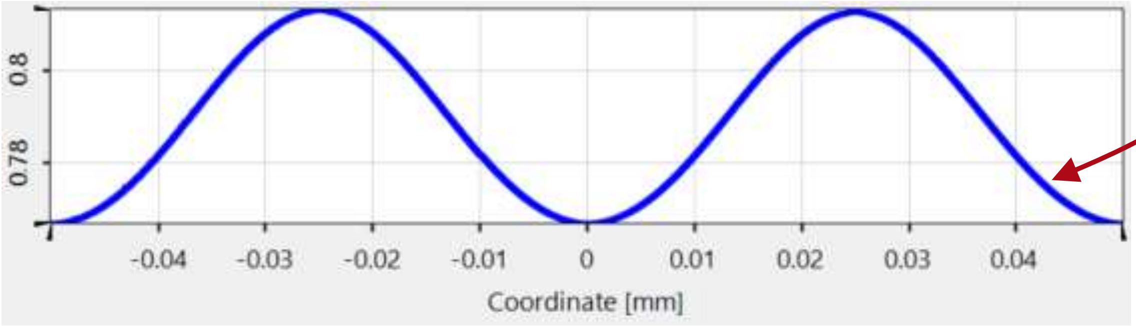
Simulations: Transmitted Field On Surface (TE polarized)



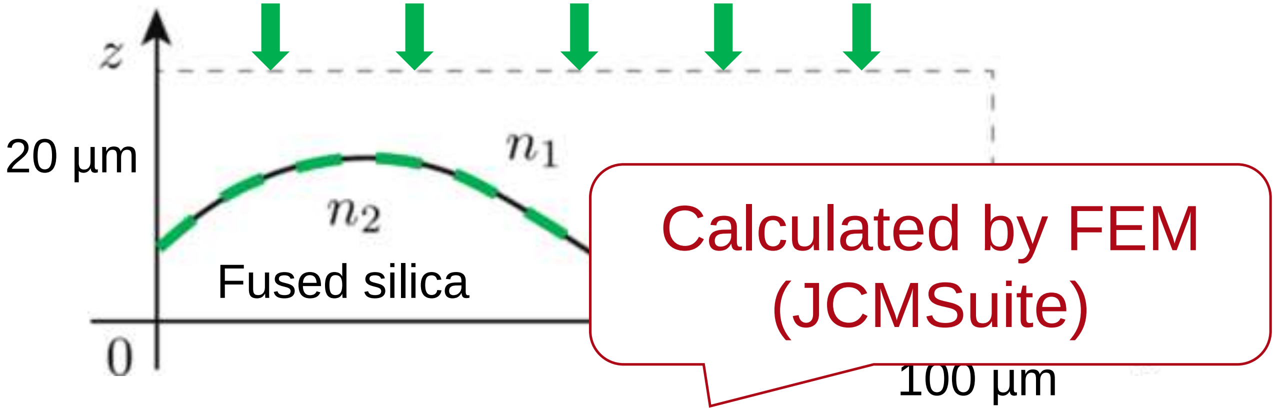
Calculated by FEM (JCMSuite)

Field inside

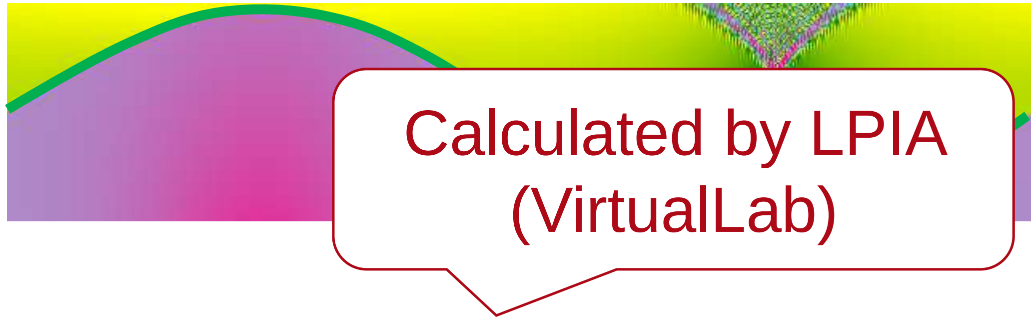
Field on interface: Rigoros



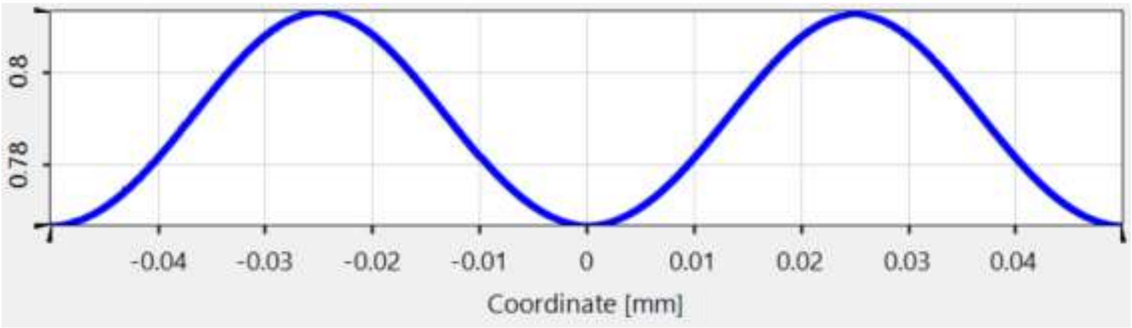
Simulations: Transmitted Field On Surface (TE polarized)



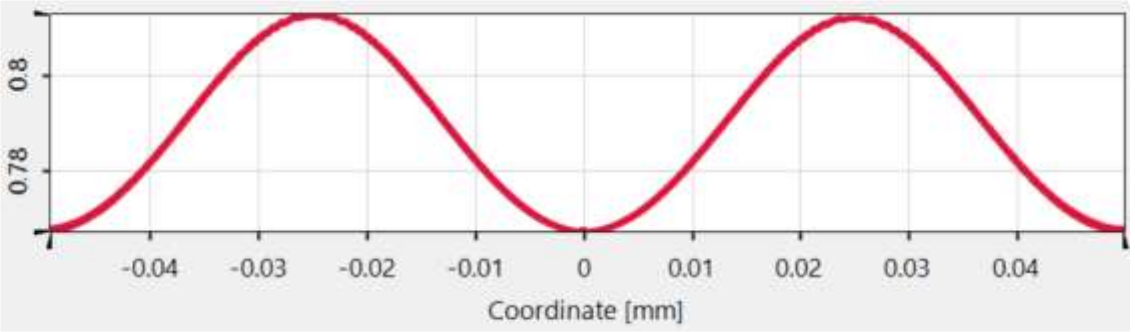
Field inside



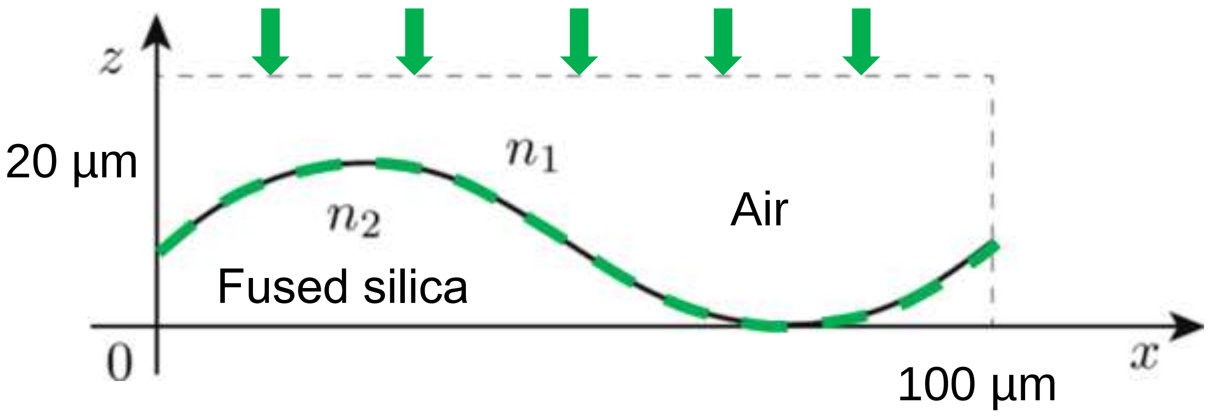
Field on interface: Rigoros



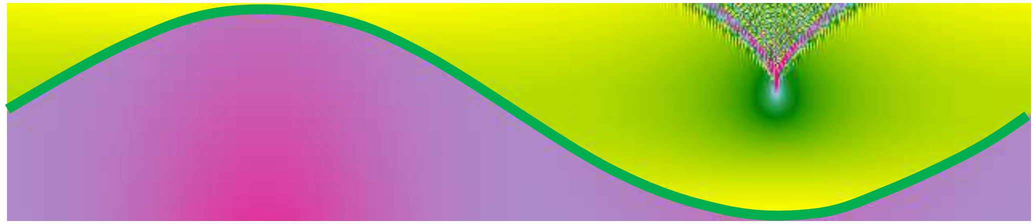
Field on interface: LPIA



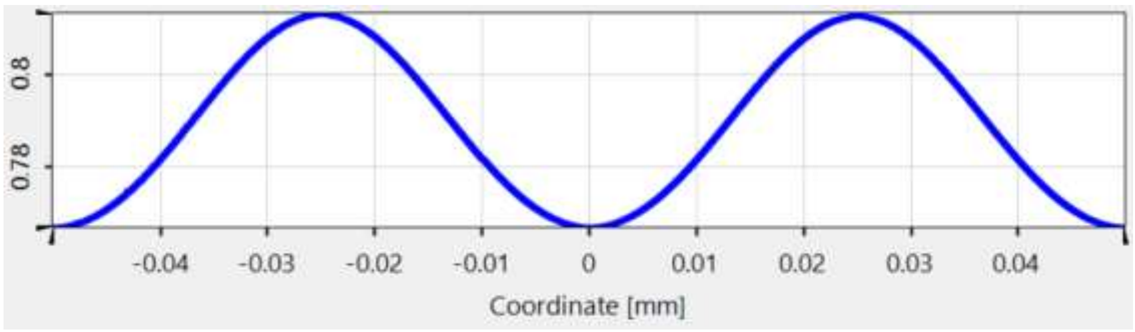
Simulations: Transmitted Field On Surface (TE polarized)



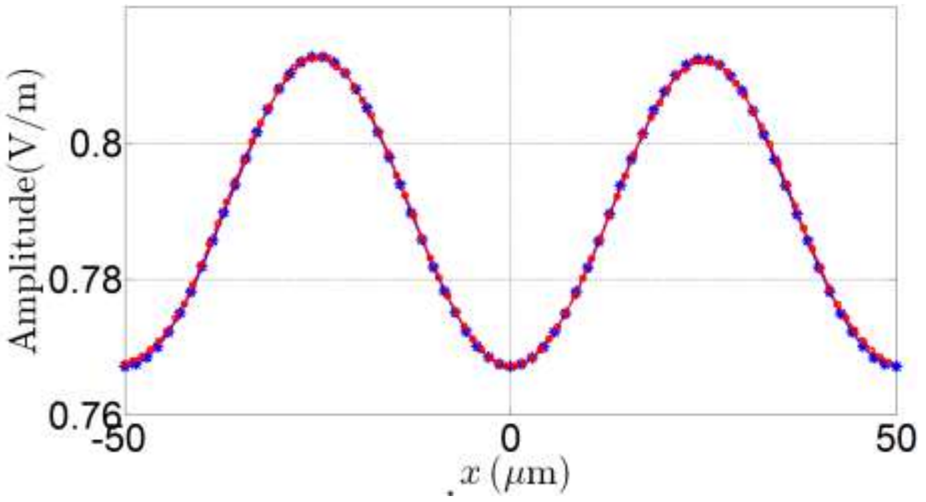
Field inside



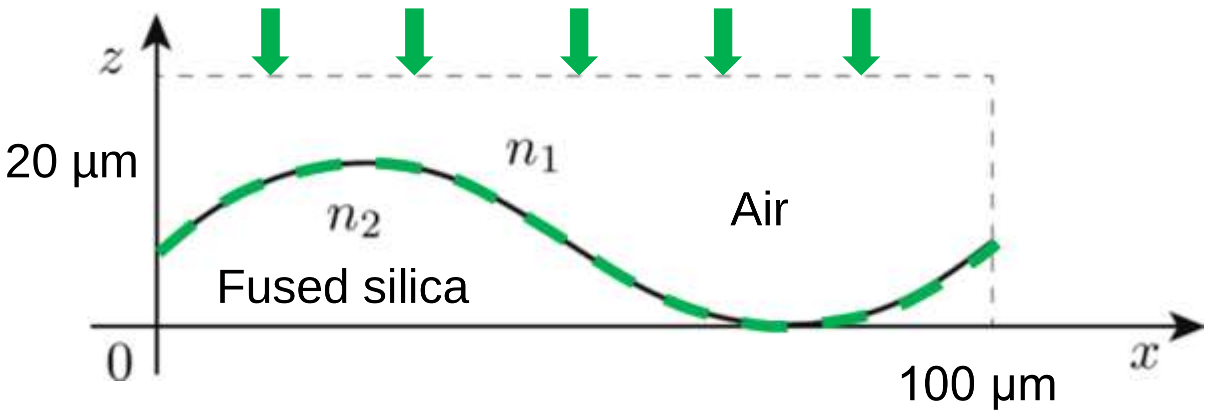
Field on interface: Rigoros



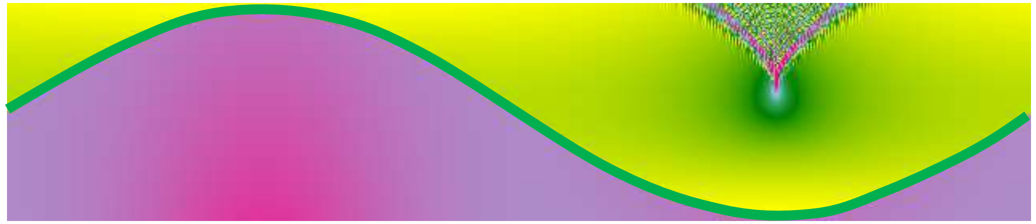
Field on interface: Comparison



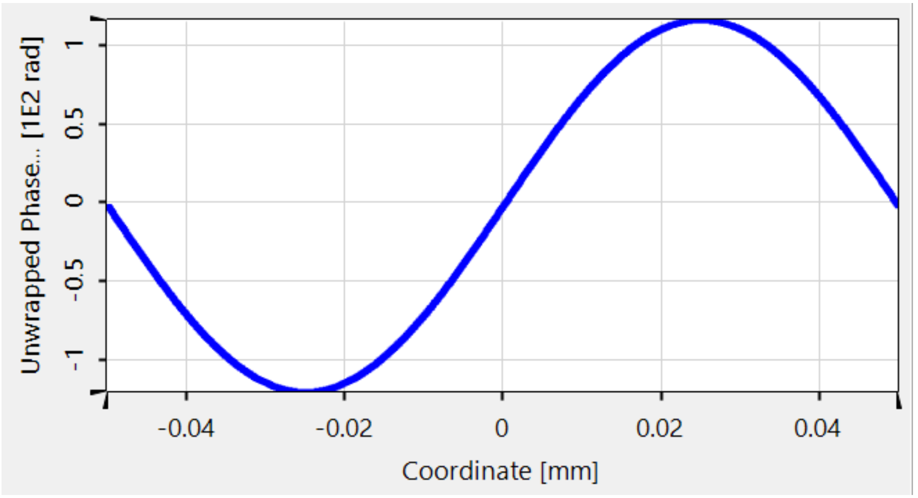
Simulations: Transmitted Phase On Surface (TE polarized)



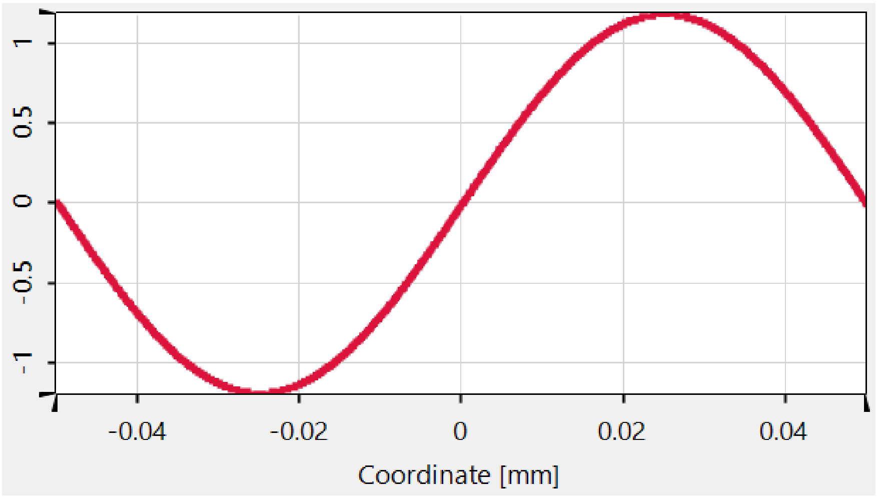
Field inside



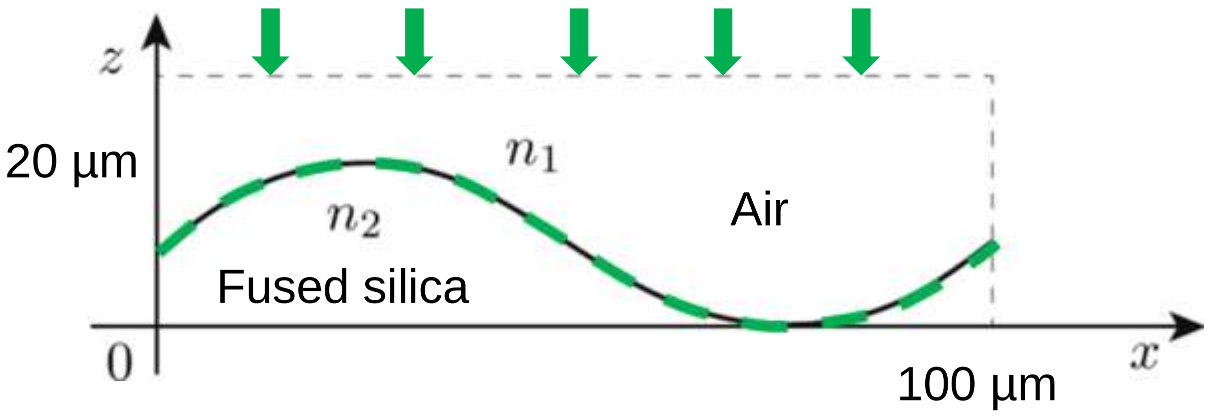
Phase on interface: Rigoros



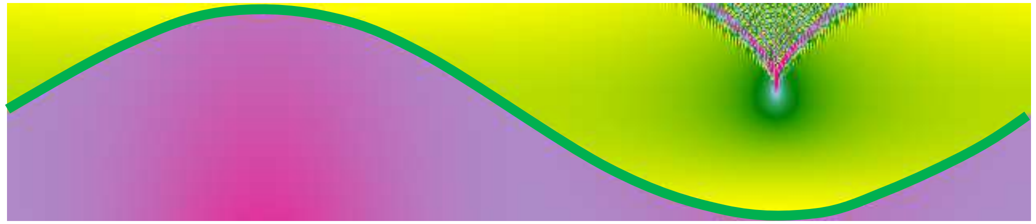
Phase on interface: LPIA



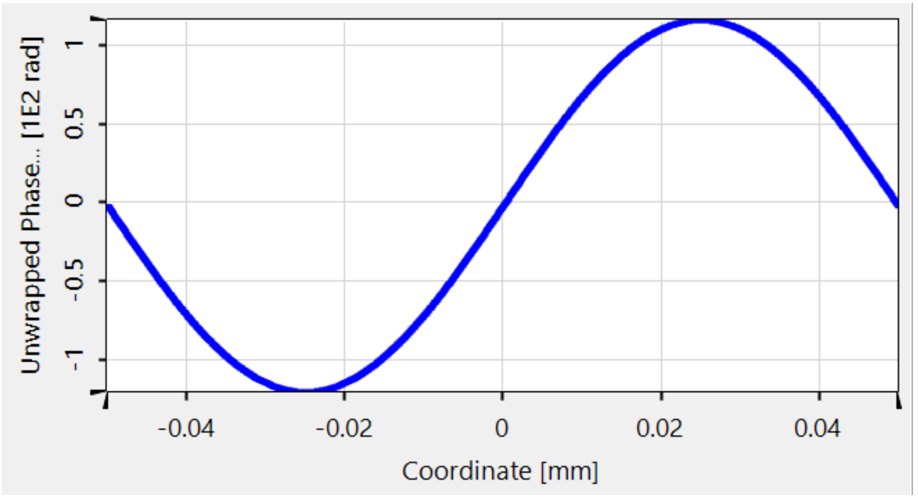
Simulations: Transmitted Phase On Surface (TE polarized)



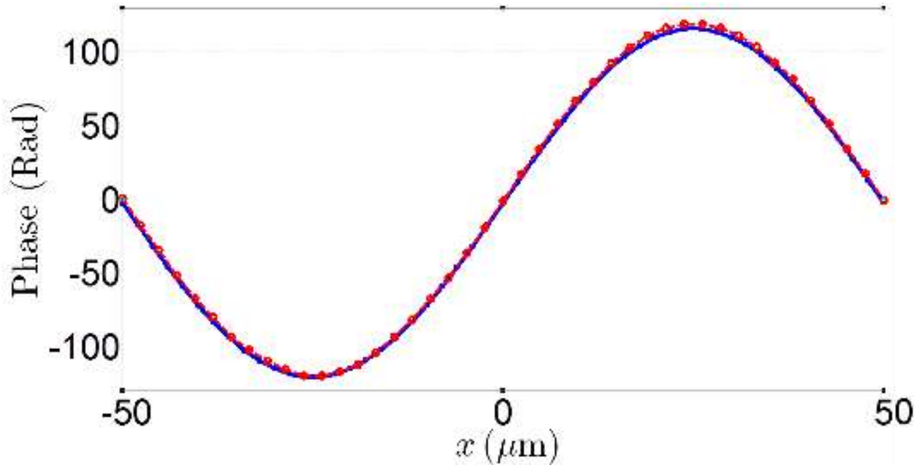
Field inside



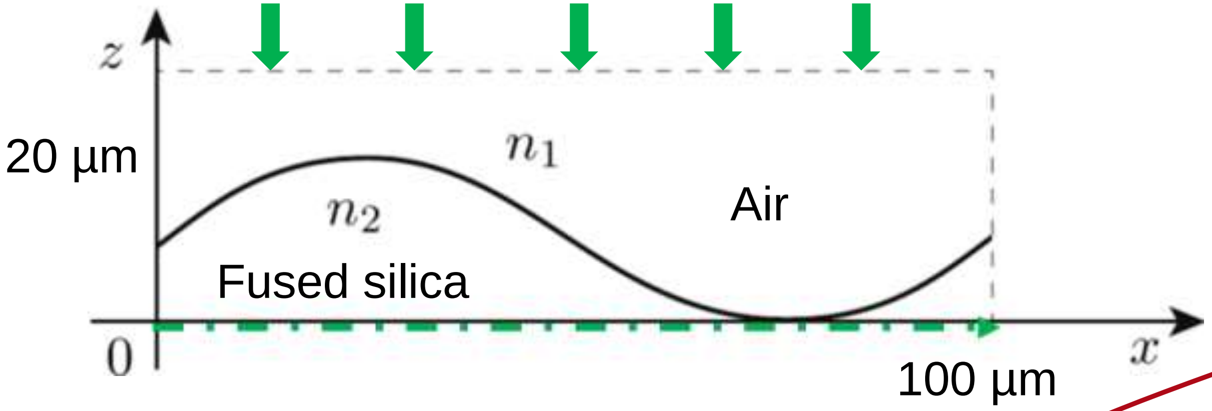
Phase on interface: Rigoros



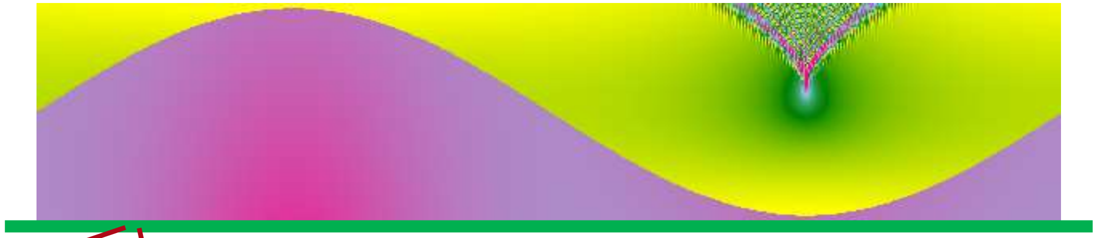
Phase on interface: Comparison



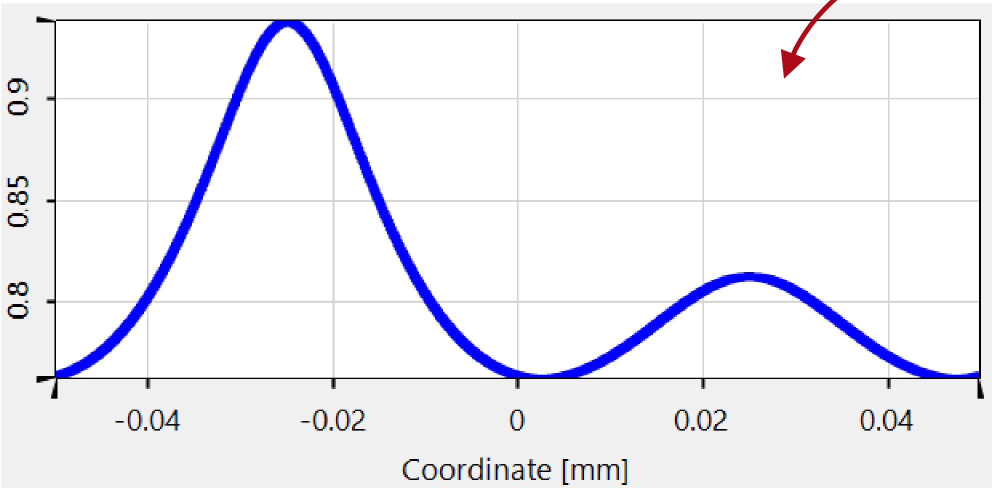
Simulations: Transmitted Field Propagated (TE polarized)



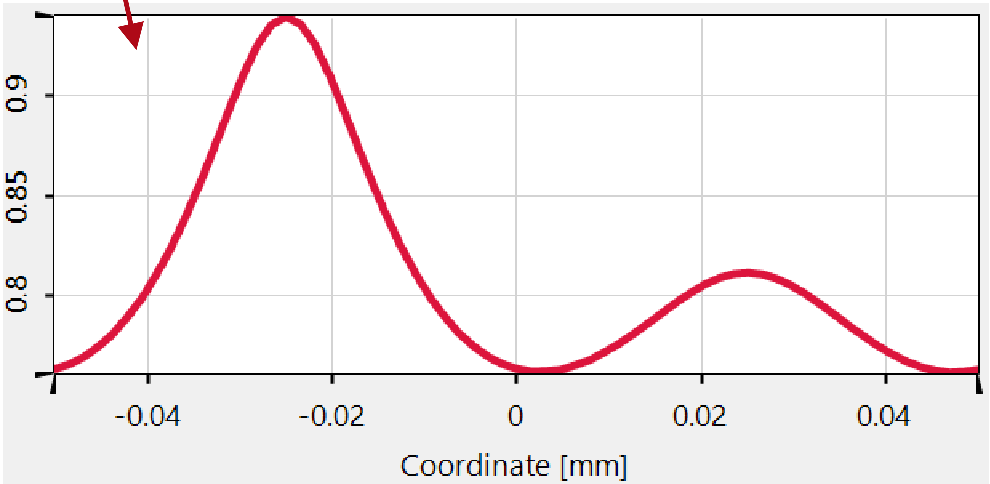
Field inside



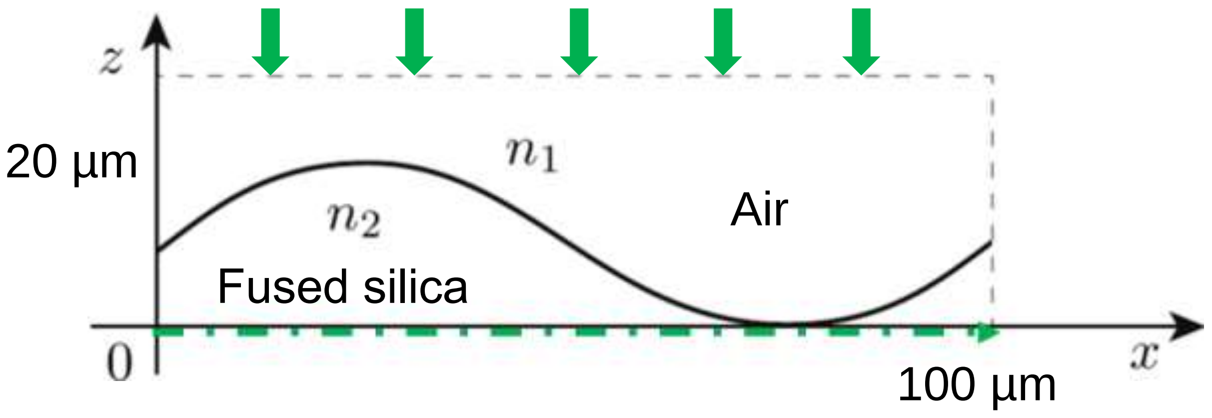
Field propagated: Rigoros



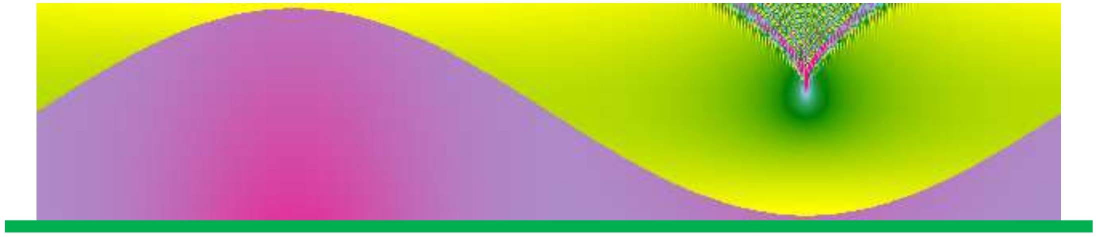
Field propagated: LPIA + Propagation



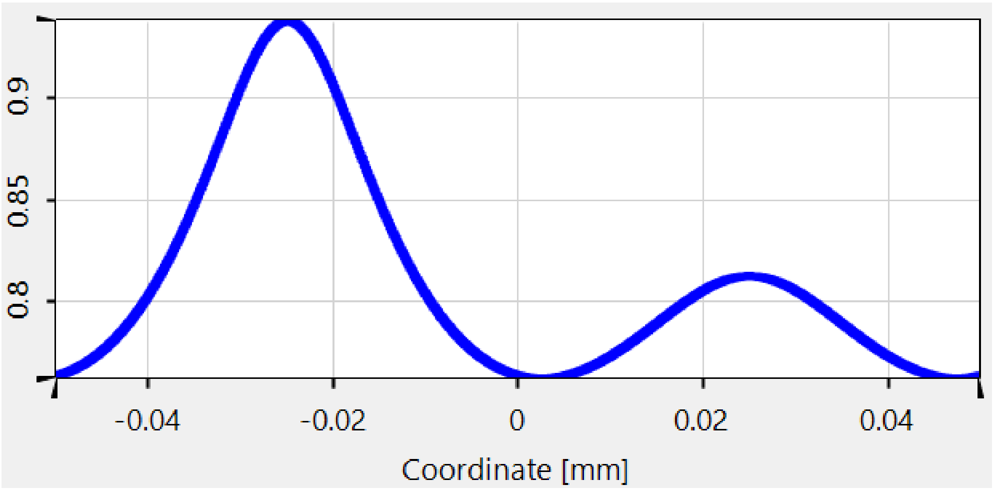
Simulations: Transmitted Field Propagated (TE polarized)



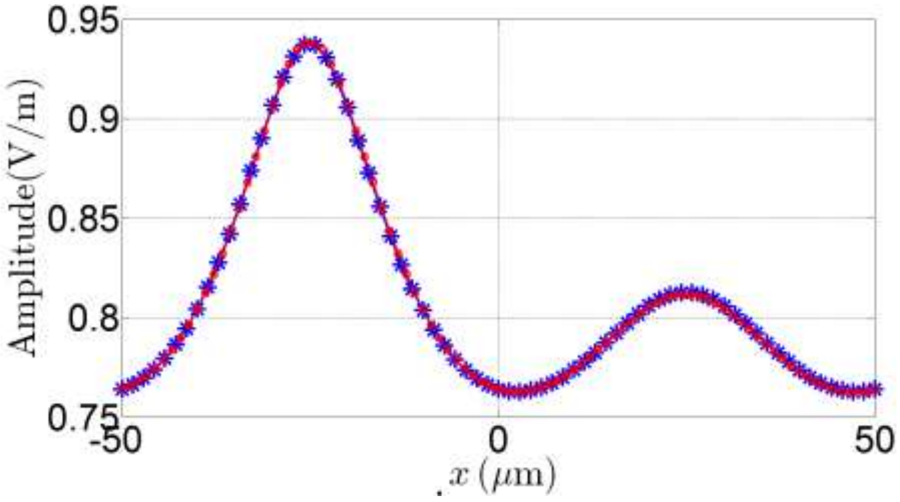
Field inside



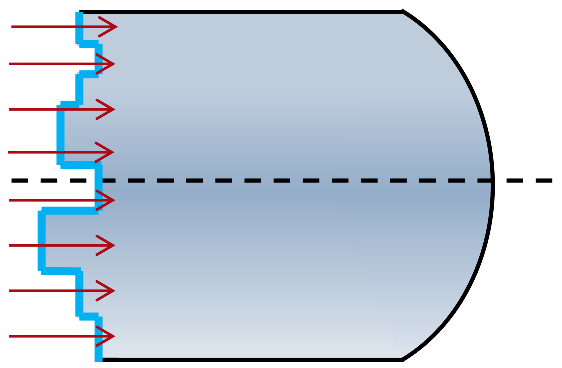
Field propagated: Rigoros



Field propagated: Comparison

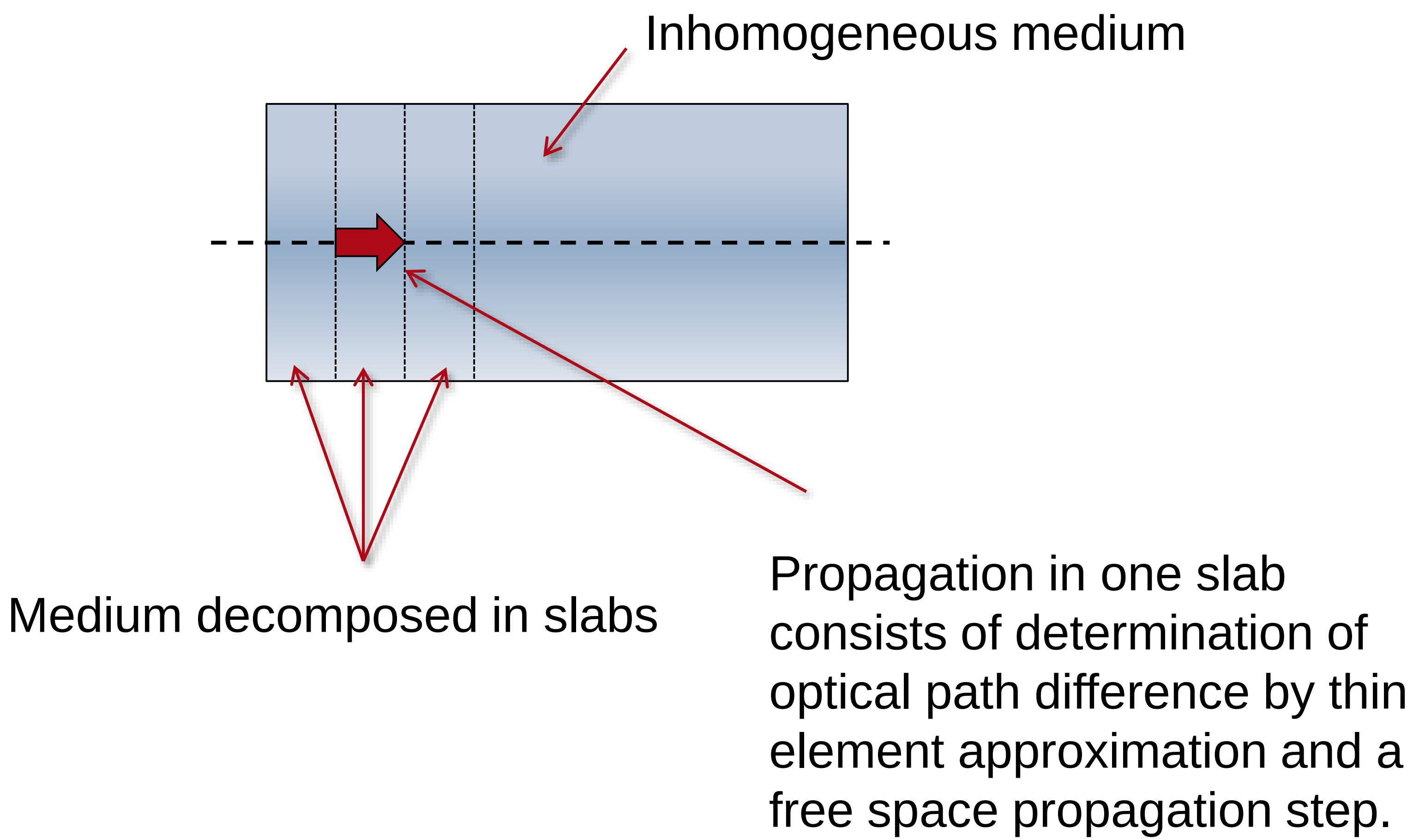


Thin Element Approximation (TEA)

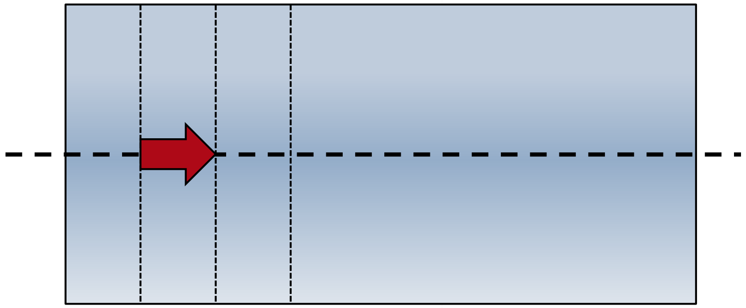


- Thin Element Approximation is a geometrical optics propagation model.
- Takes into account optical path parallel to the optical axis.
- Neglects:
  - Refraction effects
  - Polarization effects (scalar propagation method)
  - Diffraction and interferences
  - Multiple reflections inside of structure
- Typically valid for
  - propagation through surfaces with features larger than 5 wavelengths
  - paraxial input and output fields

Split Step Beam Propagation Method



Split Step Beam Propagation Method



- Takes into account optical path parallel to the optical axis, diffraction and interferences.
- Neglects:
  - Refraction effects
  - Polarization effects (scalar propagation method)
  - Multiple reflections inside of structure
- Typically valid for paraxial fields and paraxial components.

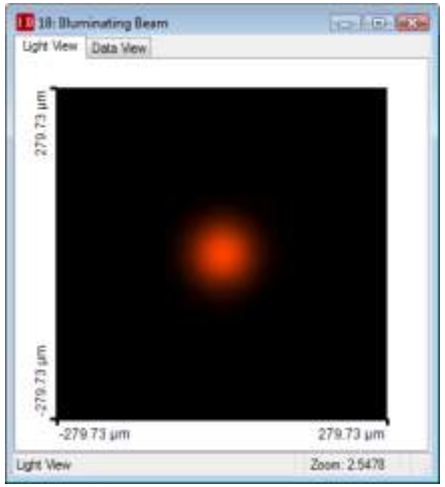
Scenario 90 (3.0)

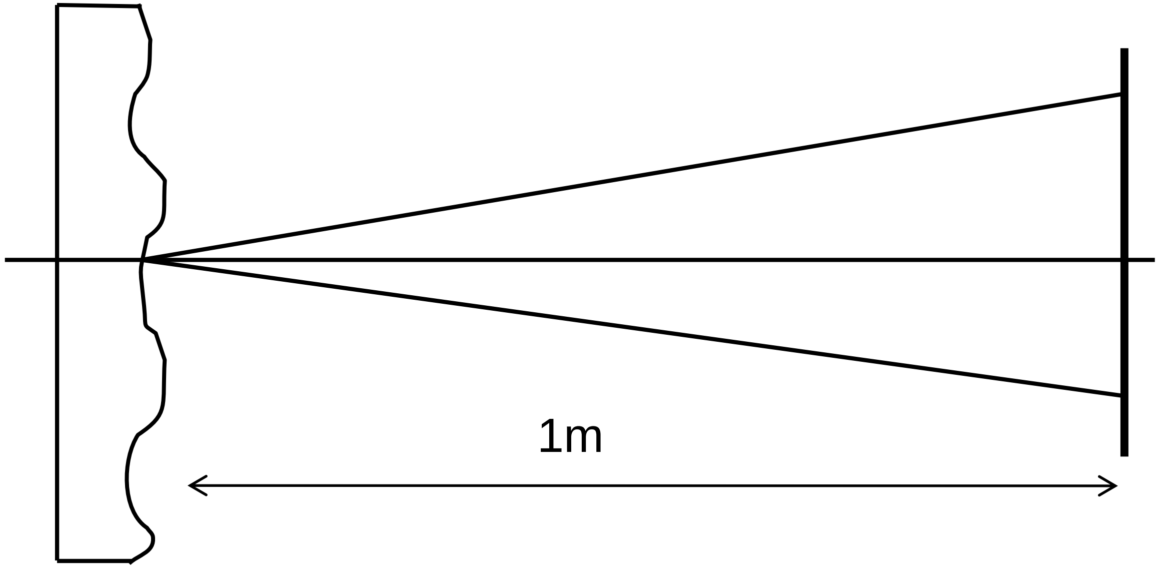
Simulation of Scattering at Rough Surface

Surfaces in VirtualLab are usually smooth. In contrast, real surfaces are always rough to a certain degree.

This application scenario demonstrates the simulation of a Gauss beam that passes a glass plate with a rough surface according to measured height profile data. In 1m distance the scattered light is analyzed.

Modeling Task



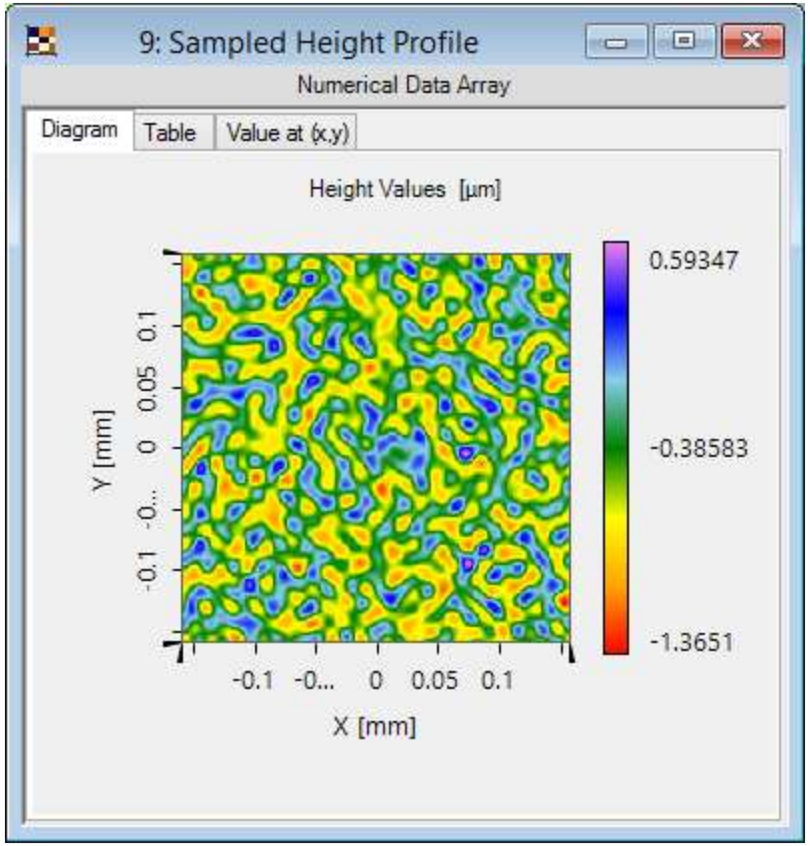


Gaussian laser beam
λ: 632nm
($1/e^2$) diameter: 100µm

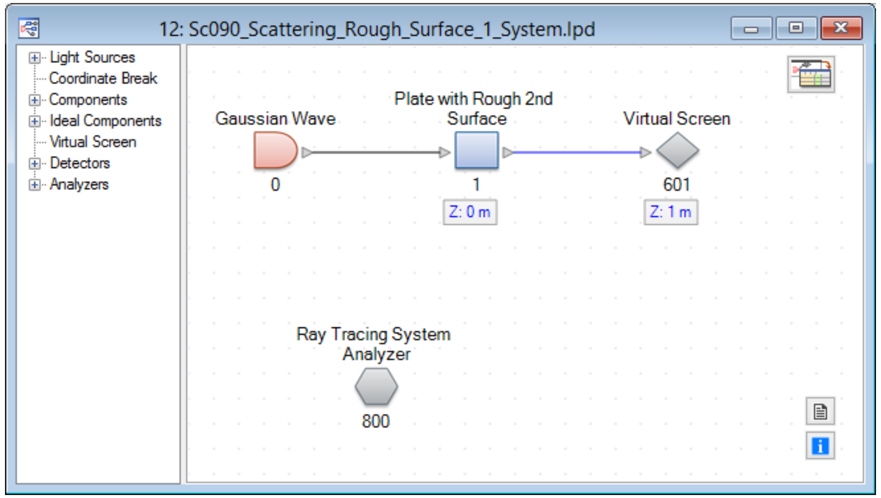
Glass Plate
(Fused Silica)
with rough
2nd surface

Scatterd Light Field
on Screen=?

Measured Surface Profile Data



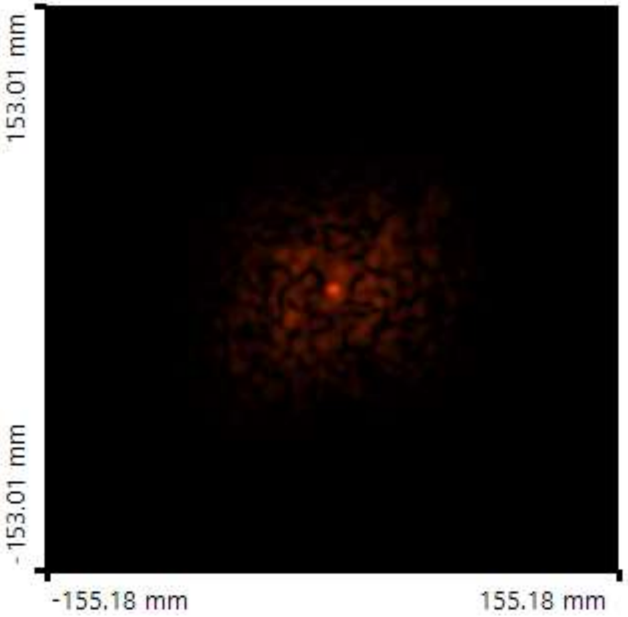
Light Path Diagram



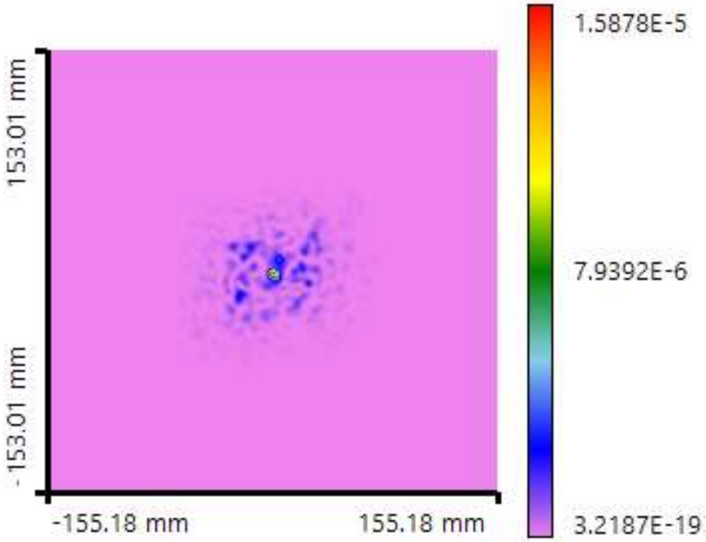
- For diffractive scenarios with paraxial regarded angles the thin element approximation (TEA) provides suitable simulation results.
- The presented example shows a typical rough sourface simulation with perpendicular incident light and scattered light that has deflection angles less than 5°. So it is justified to use TEA.

Result: Diffraction Pattern

in real colors



in false (reverse rainbow) colors



Summary

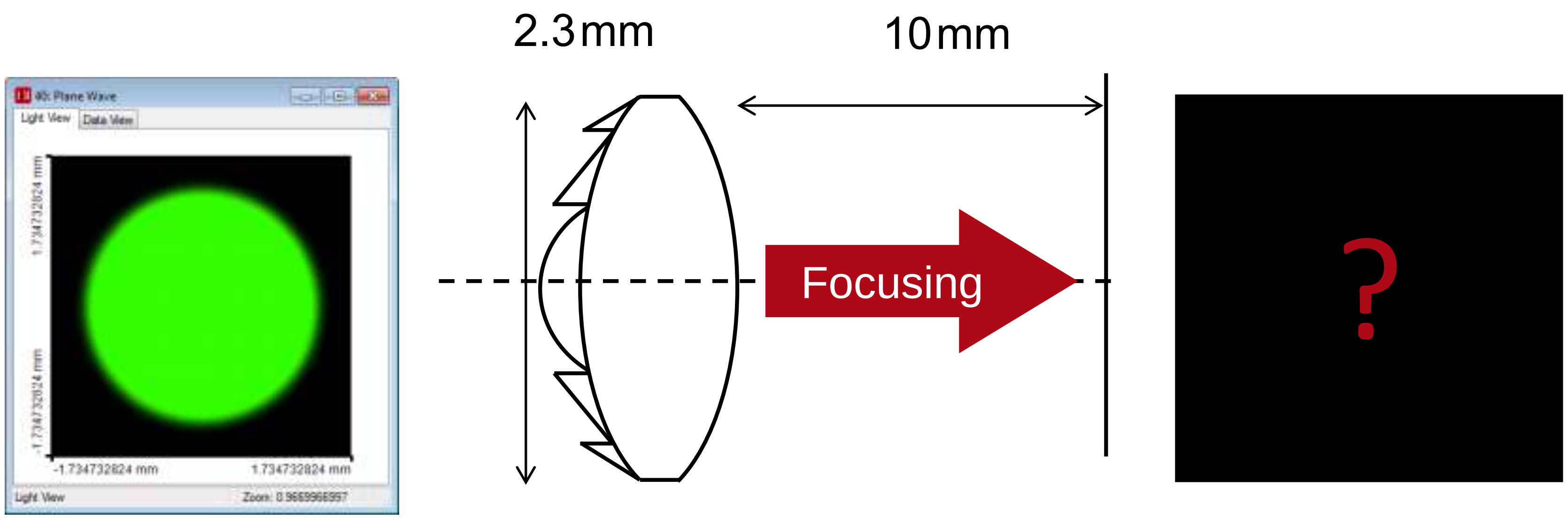
- VirtualLab enables the simulation of scattering at rough surfaces.
- Measurement data can be imported from ASCII files.
- Allows the simulation of fabrication tolerances of surfaces.

AppS.0009 (1.2)

Simulation of a Bifocal Hybrid Lens

Keywords: bifocal Lens, combined Interface, hybrid lens, multifocal lens, multifocal, bifocal

Task Description

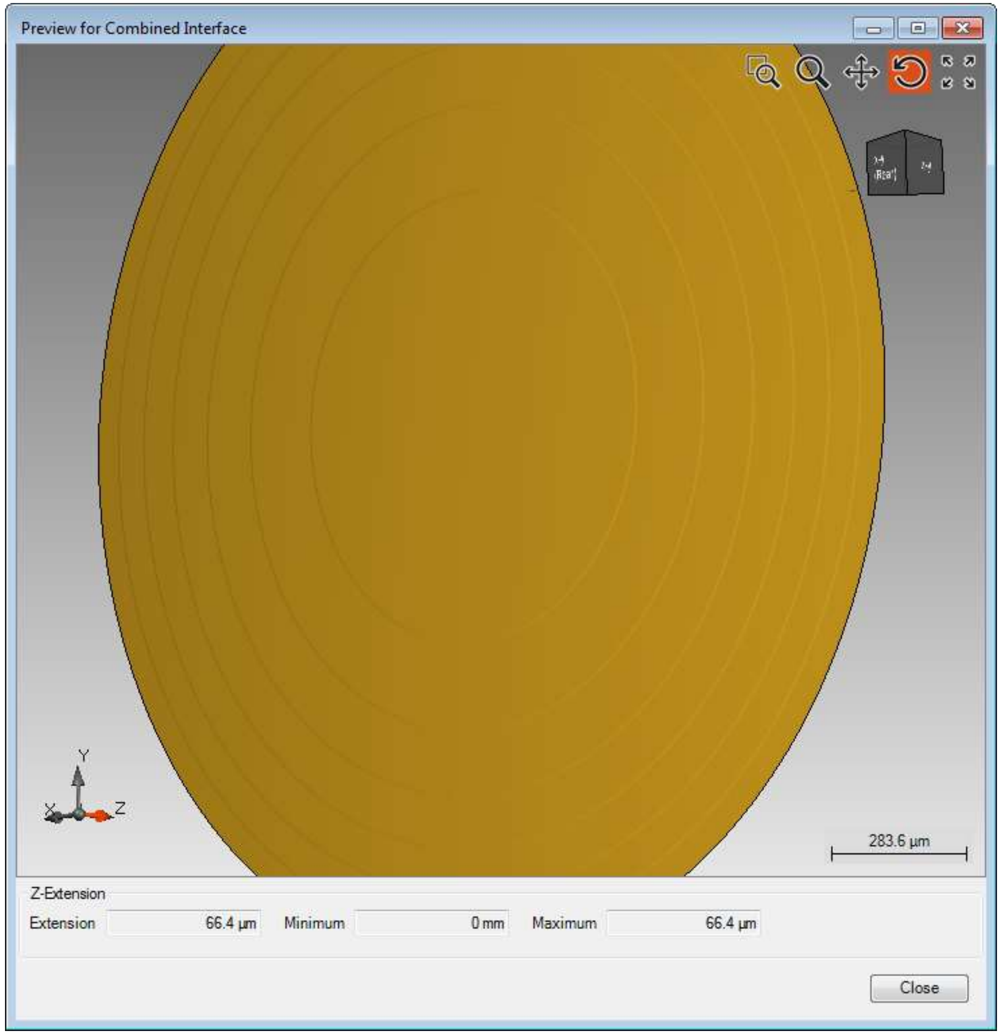


plane wave

bifocal lens with hybrid surface

target plane

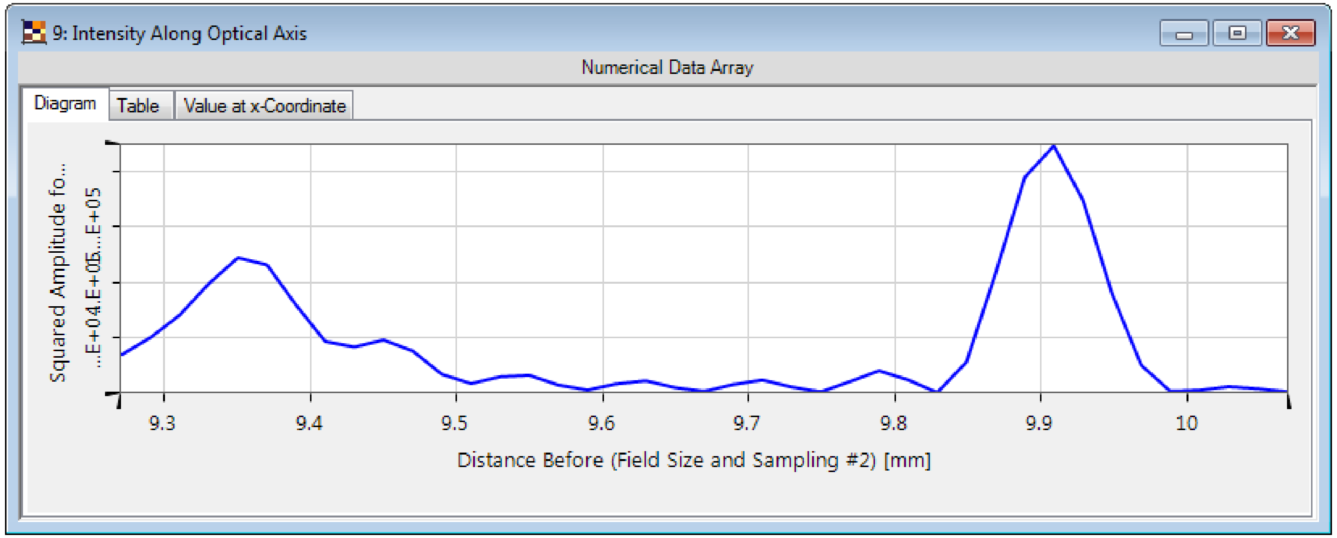
Task Description



- Center thickness of lens: 1 mm.
- Diameter: 2.3 mm
- Radius of curvature of the spherical surface: 10 mm
- Hybrid surface modeled as a superposition of a spherical and a diffractive lens surface.
- Superposition of surface profiles by combined interface of VirtualLab.
- Diffractive lens parameters:
  - Radius: Infinity
  - A2: 0.0022608
  - A4: 0.00038131
  - A6: 2.74E-06

On-Axis Intensity

The **intensity along the optical axis** can be taken as indicator for the focal positions. Via **parameter run** the position behind the lens is varied. **To speed up** the simulation, a **separate LPD** with the light distribution 9.37 mm behind the lens as input field is used. Hence, the **muliple propagation through this hybrid lens is avoided**.



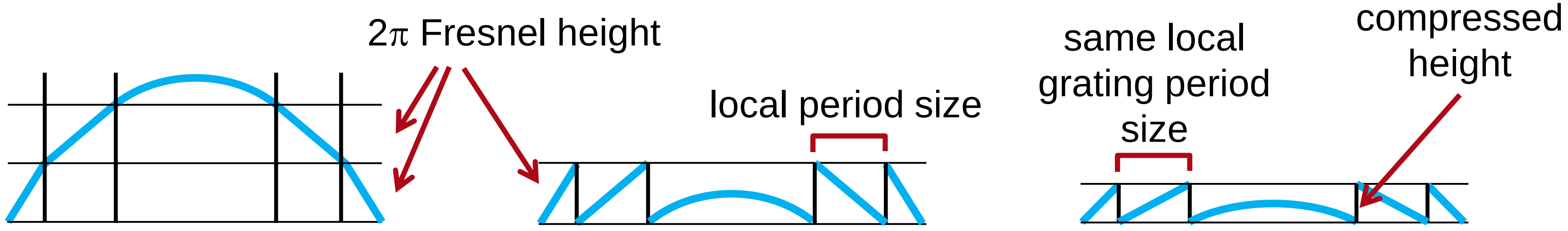
On-axis intensity depending on distance from lens. The two focal points in a distance of 550 µm (at 9.37 mm and 9.91 mm) are visible.

files: AppS.0009_Bifocal_Hybrid_Lens_2.run & …_3.da

Explanation for Different Focal Distance

The light deflecting effect of a classic Fresnel lens structure is based on

- the local period sizes
- and the actual structure within this period.

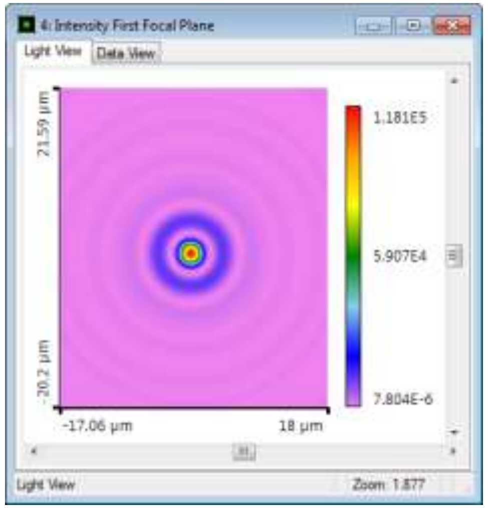


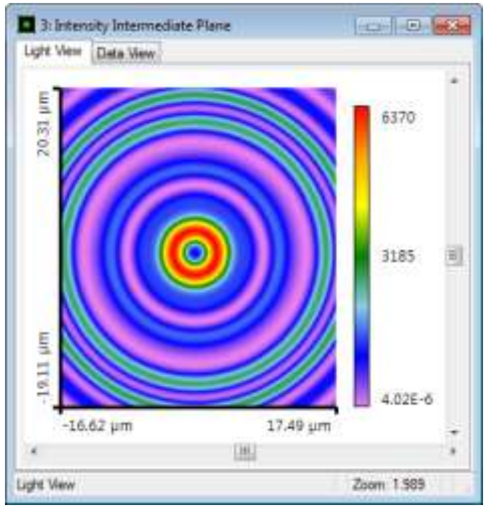
1. refractive lens structure
2. Fresnelized lens structure
3. diffractive lens with uncorrelated refractive structure

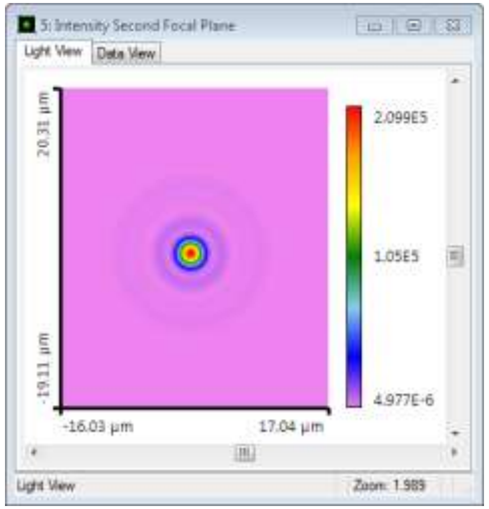
1.&2.: The structure of a classic Fresnelized lens is in accordance with the light deflecting effect due to the local gratings. **Ray & Field Tracing will see a comparable focal length**: The direction of rays hitting the local gratings‘ structures would be deflected in the same direction as the desired 1^{st} outgoing diffraction orders would have.

3. If the structure is changed (e.g. compressed), then the correlation is gone and the **results from Ray vs. Field Tracing will differ**. We have a general diffractive lens to be regarded. The presented lens belongs to this category.

Field Tracing: Point Spread Functions







PSF in 1st focal plane, 9.37 mm after lens

PSF between focal planes, 9.67 mm after lens

PSF in focal plane 2, 9.92 mm after lens

file used: AppS.0009_Bifocal_Hybrid_Lens_1.lpd

Conclusion

- VirtualLab allows the modeling hybrid lens surface by a superposition of a diffractive and a refractive surface.
- Superposition of two surfaces by combined interface.
- System analysis by Classic Field Tracing engine of VirtualLab enables the detection of the two focal planes, points spread functions and the on-axis intensity.

UseCase.0076 (1.1)

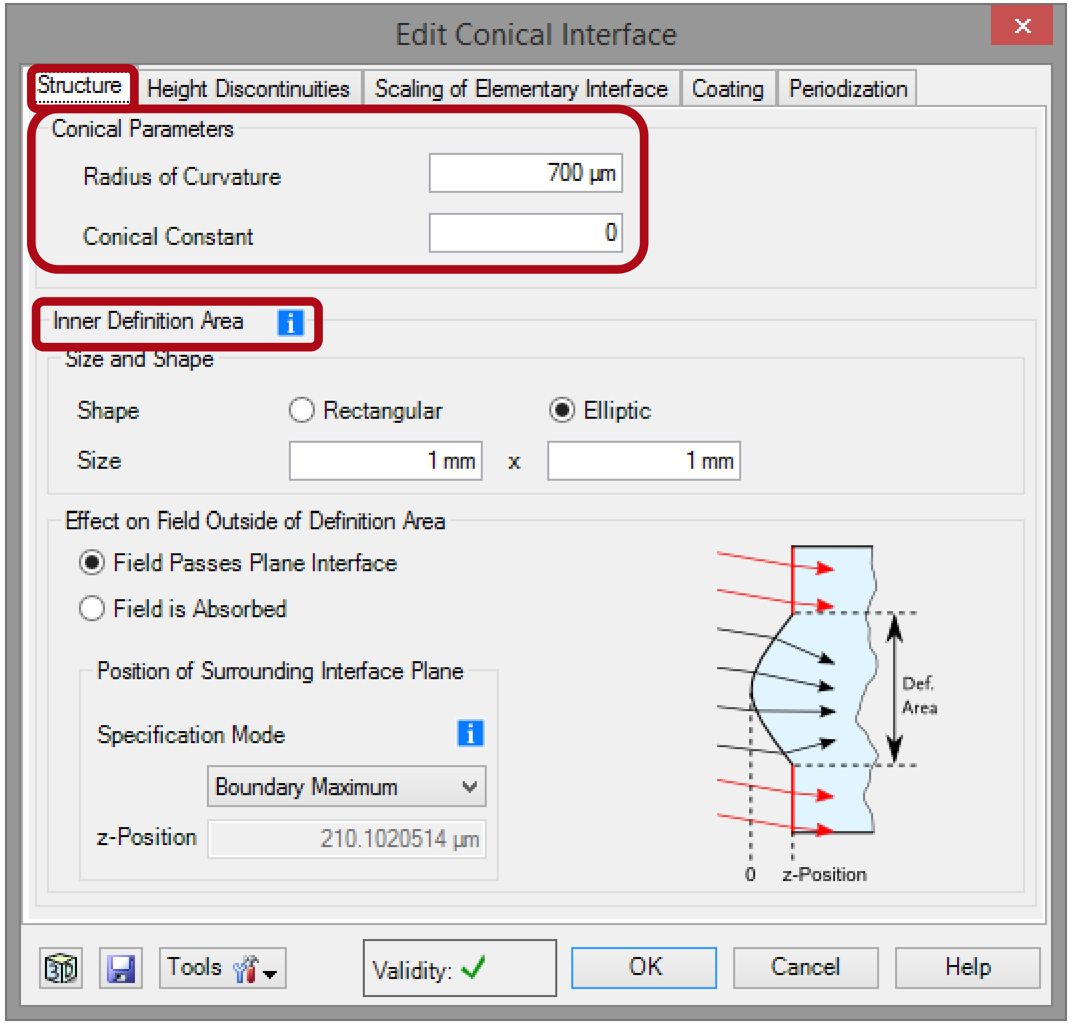
Periodization Options of Optical Interfaces

Keywords: Interface, Periodization, Arrays, Lens, Mirror

Description

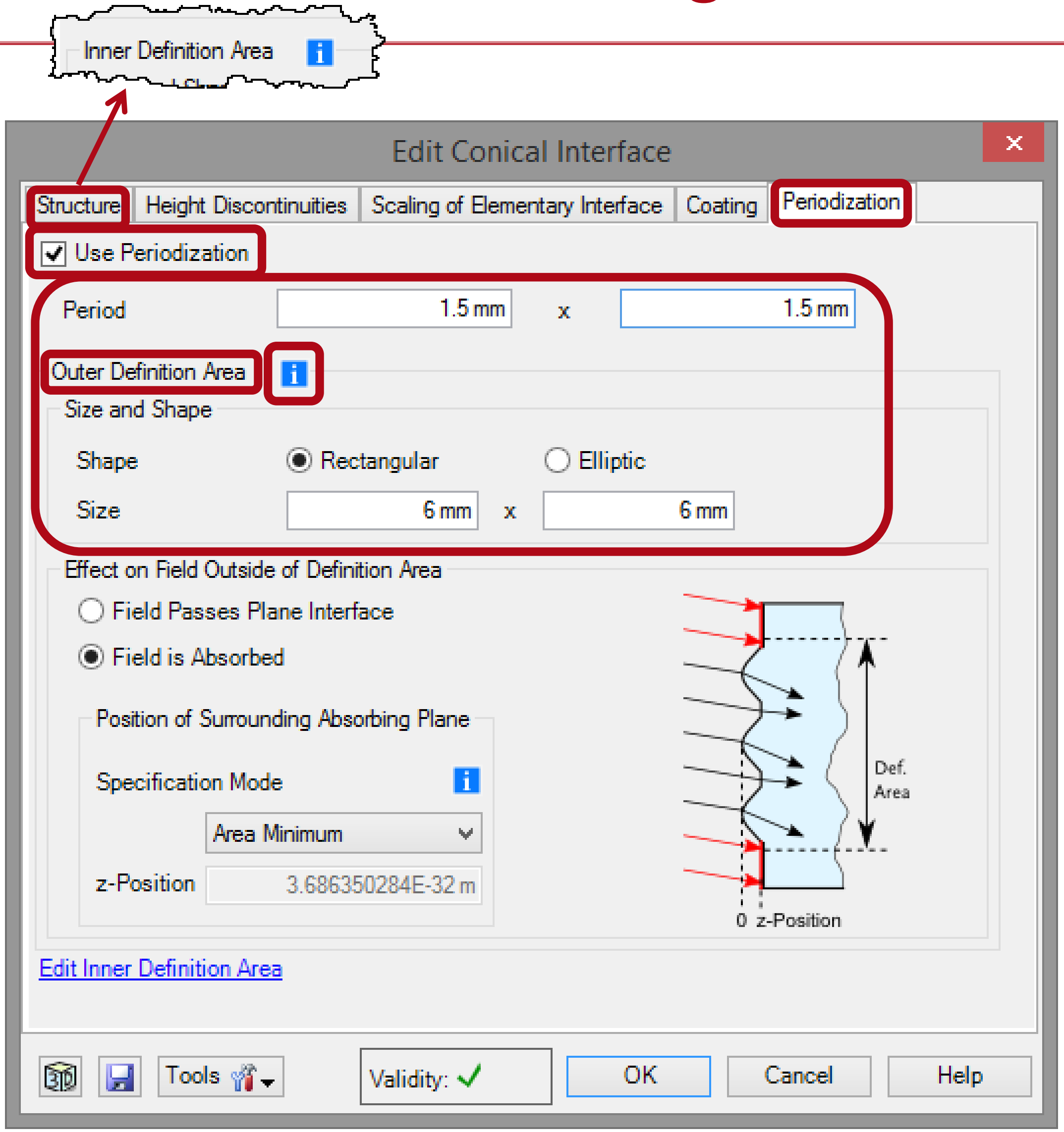
- This use case demonstrates the options of periodization of optical interfaces.
- Any optical interface in VirtualLab can be periodically replicated.
- This option can be used to define e.g. mirror or lens arrays.
- There are several definition areas to define periodic structures.

Typical Edit Dialog of a Surface



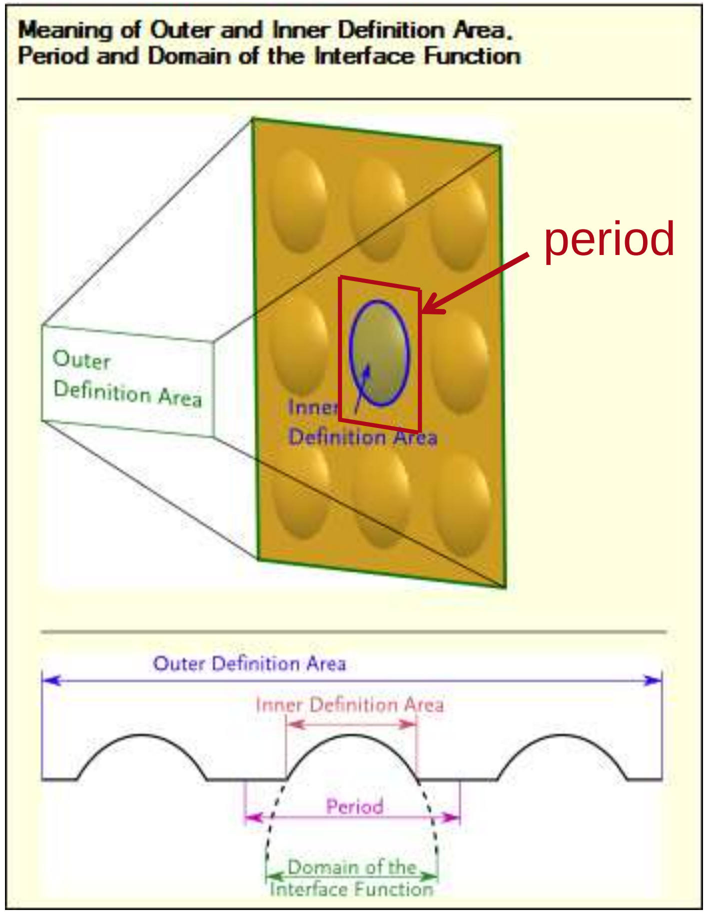
- On the Structure tab the user can configure parameters for the surface type, i.e. the elementary/interface function.
- Also the size and shape is specified for the so-called „Definition Area".
- The following slides explain the different used terms in more detail.

Periodization Settings



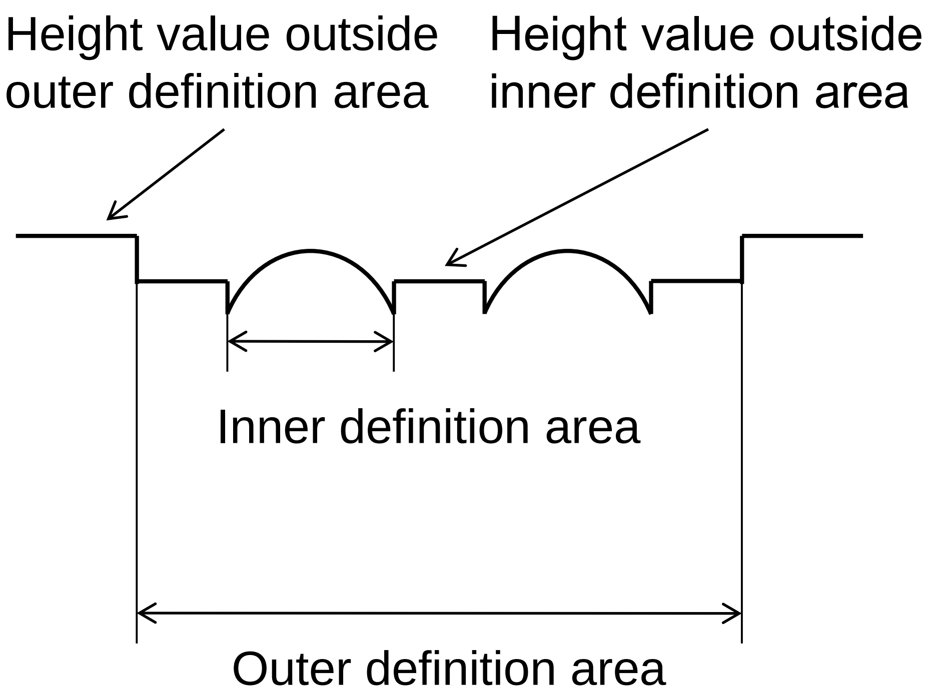
- The moment the periodization is activated via Periodization tab VirtualLab distinguishes between a so-called „Outer Definition Area“ and an „Inner Definition Area“ (before just „Definition Area).
- On the Periodization tab the size of one period and the Outer Definition Area can be defined.
- Via „i“ icons more information is displayed.

Definitions: Areas



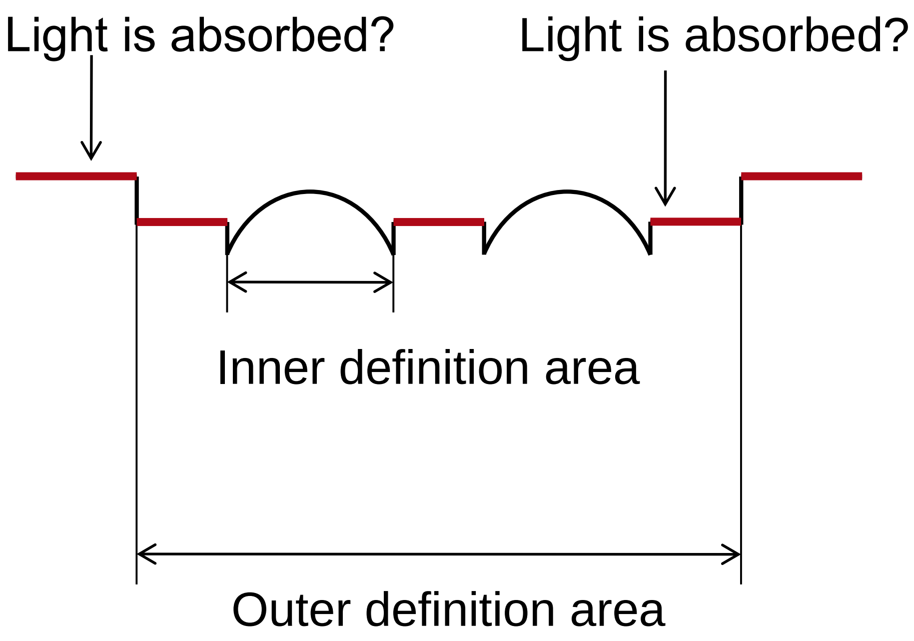
- Inner definition area:
  - Defines the shape and size of one cell of the array.
  - contains height profile defined by structure parameters.
  - The inner definition area can be smaller than the period.
- Outer Definition area: aperture/dimension of the array

Definitions: Heights



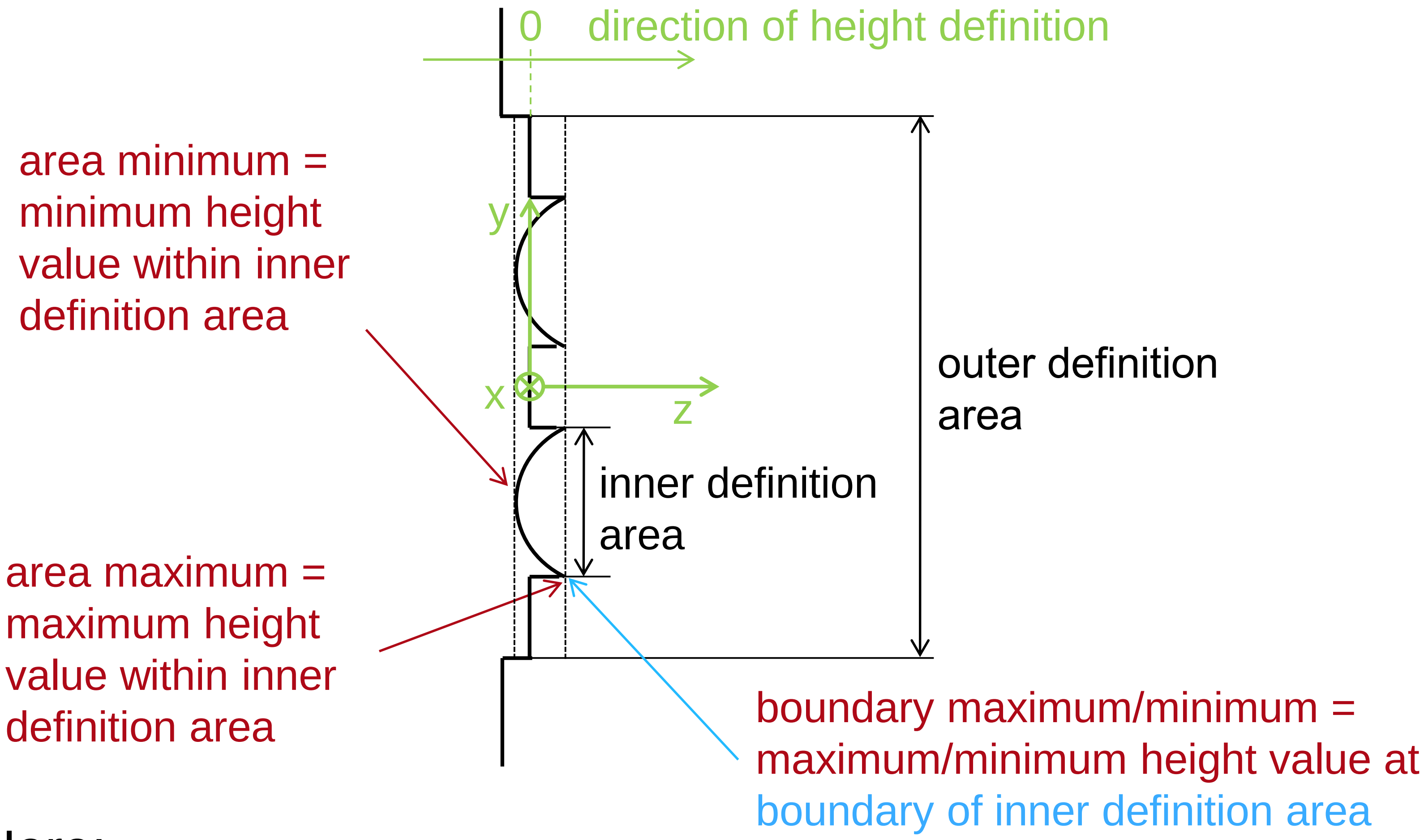
- The height value between the cells (outside of inner definition area) can be controlled by the user.
- Comparable the height value outside of the aperture area (outside of outer definition area) can be controlled.
- The last option is also available for non periodic surfaces.

Definitions: Absorption



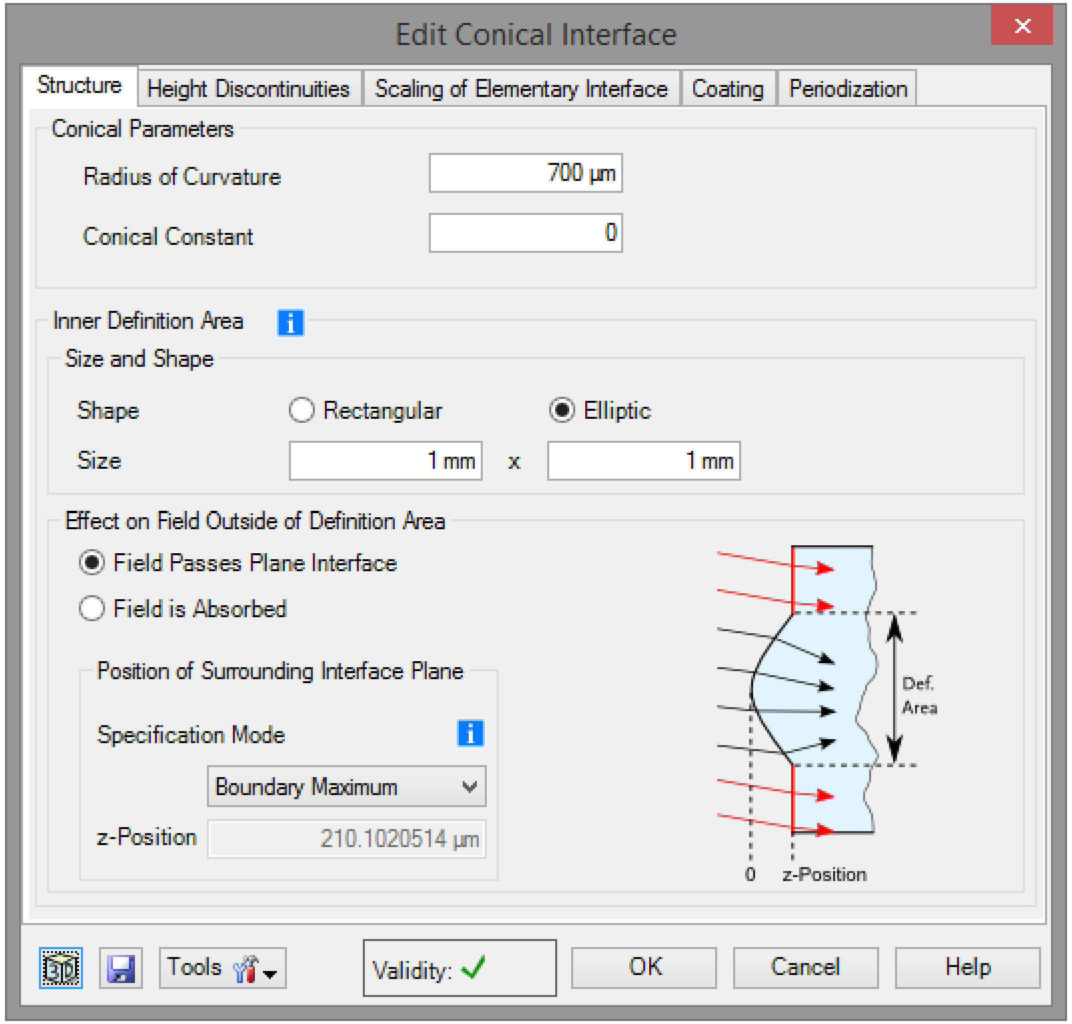
- Light can be absorbed in areas between cells (outside of inner definition area) or can pass the surface and is deflected.
- Light can be absorbed outside of array aperture (outside of outer definition area) or can pass the surface and is deflected.
- The last option is also available for non periodic surfaces.

Definitions: References



Here:
Boundary maximum is the same as the area maximum.

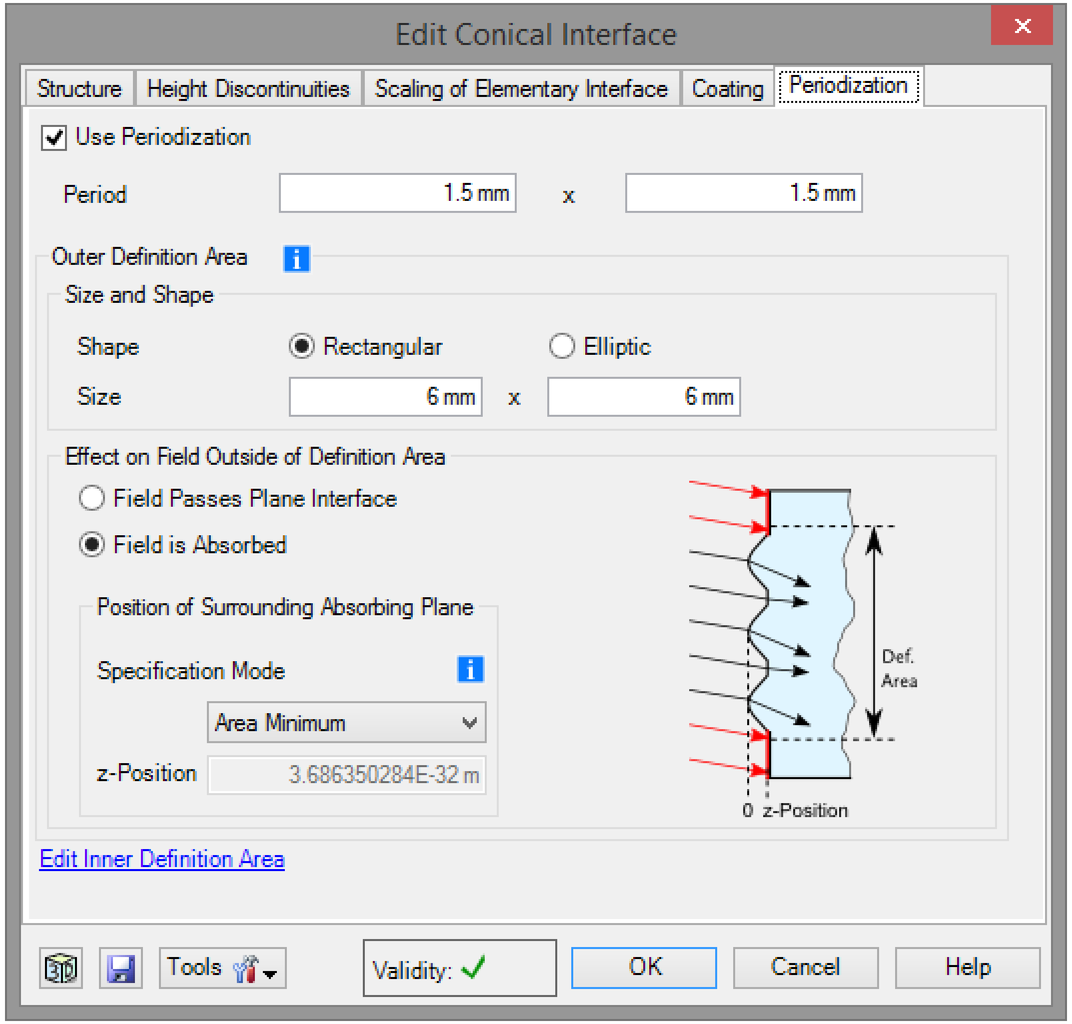
Configurations: Single Structure



- The structure of an optical interface can be configured in the ‘Structure’ page.
- Definition of the Radius of Curvature and Conical Constant
- Size and Shape of the inner definition area
- Selection if light can pass the region outside of the inner definition area.
- Height value outside the inner definition area.

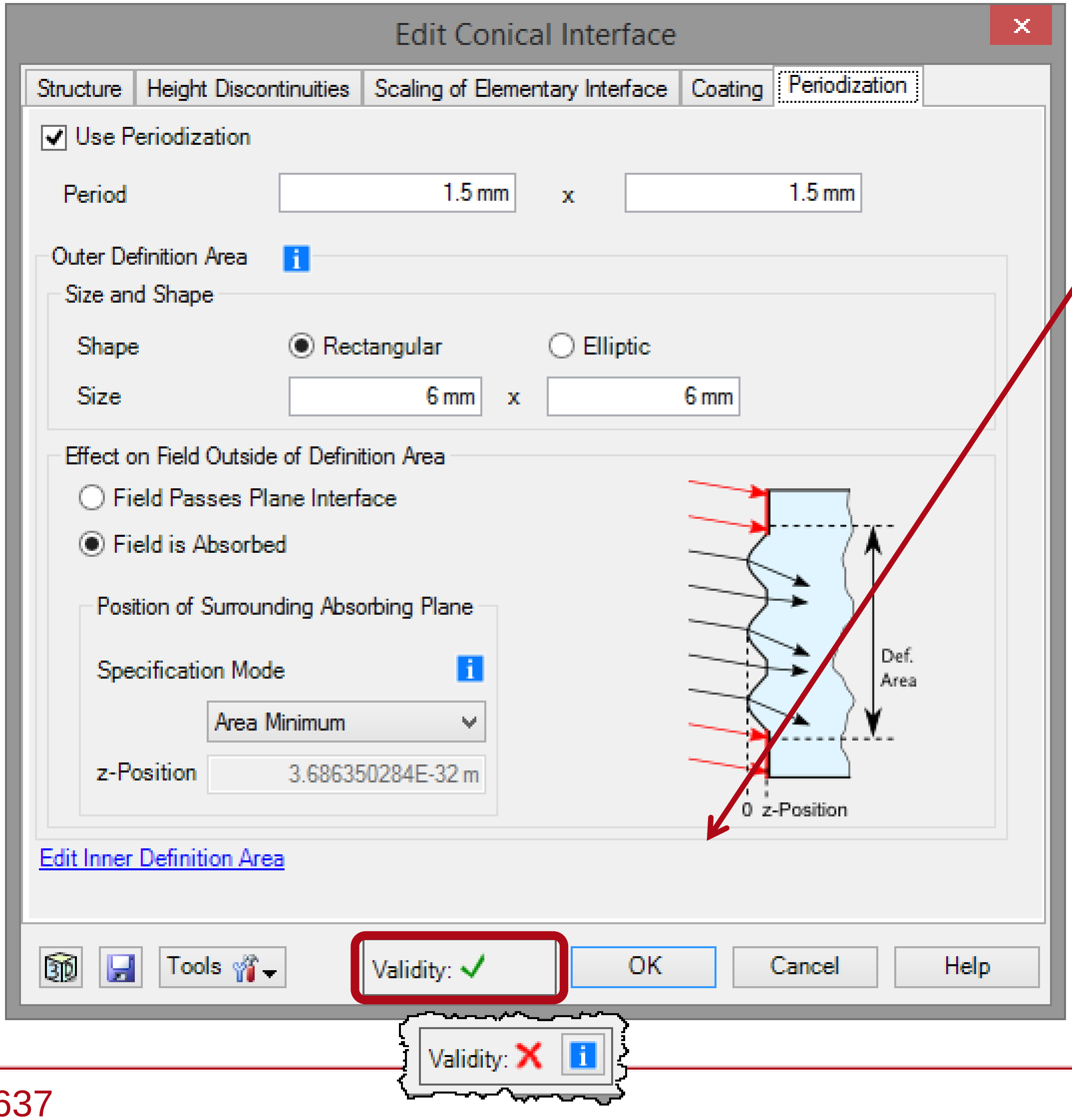
filename: UseCase.0076_PeriodicSurface.lpd

Configurations: Periodization



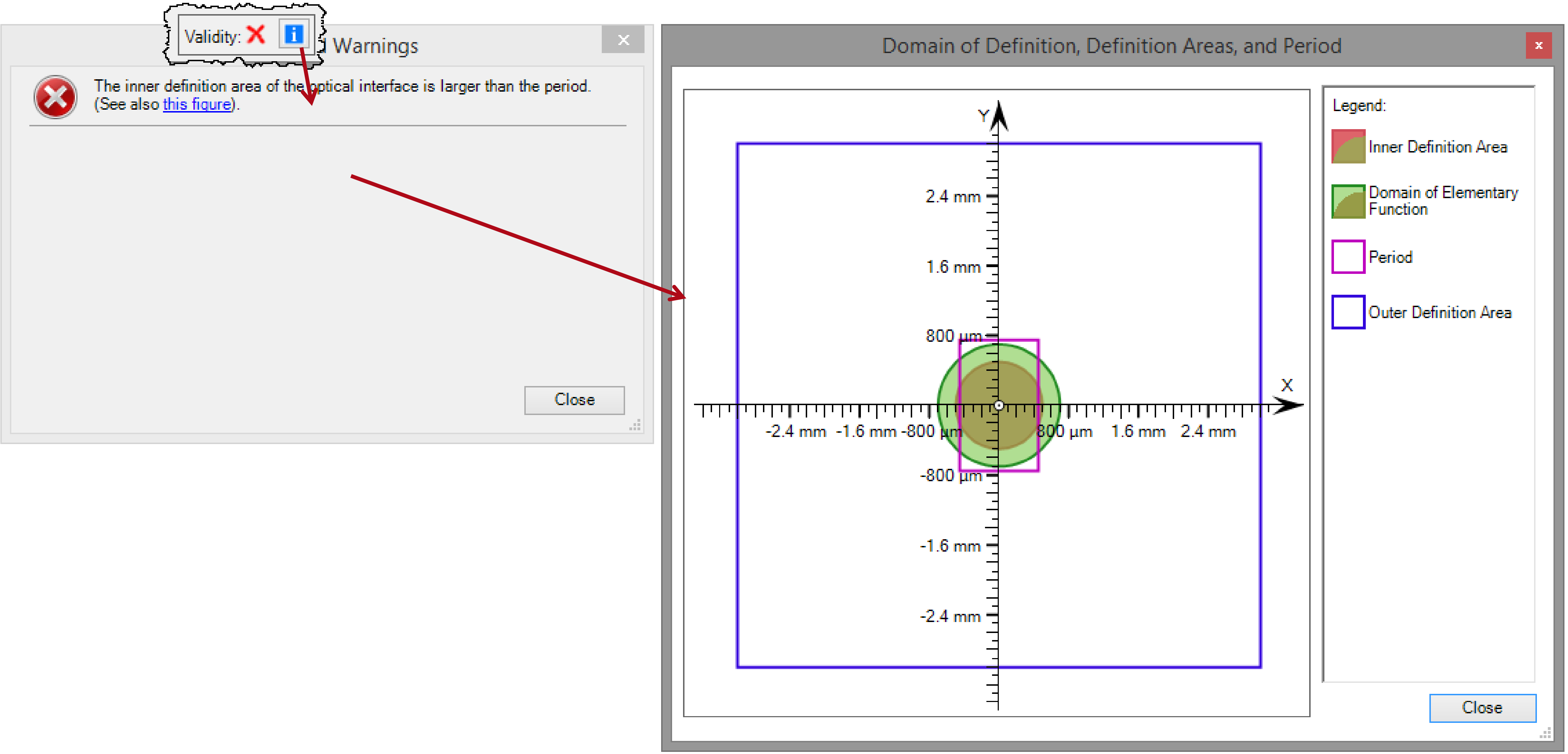
- A periodization of an optical interface can be activated in the ‘Periodization’ page.
- Definition of period.
- Size and shape of the outer definition area.
- Selection if light can pass the region outside of the outer definition area.
- Height value outside the outer definition area.

Validity of Parameters

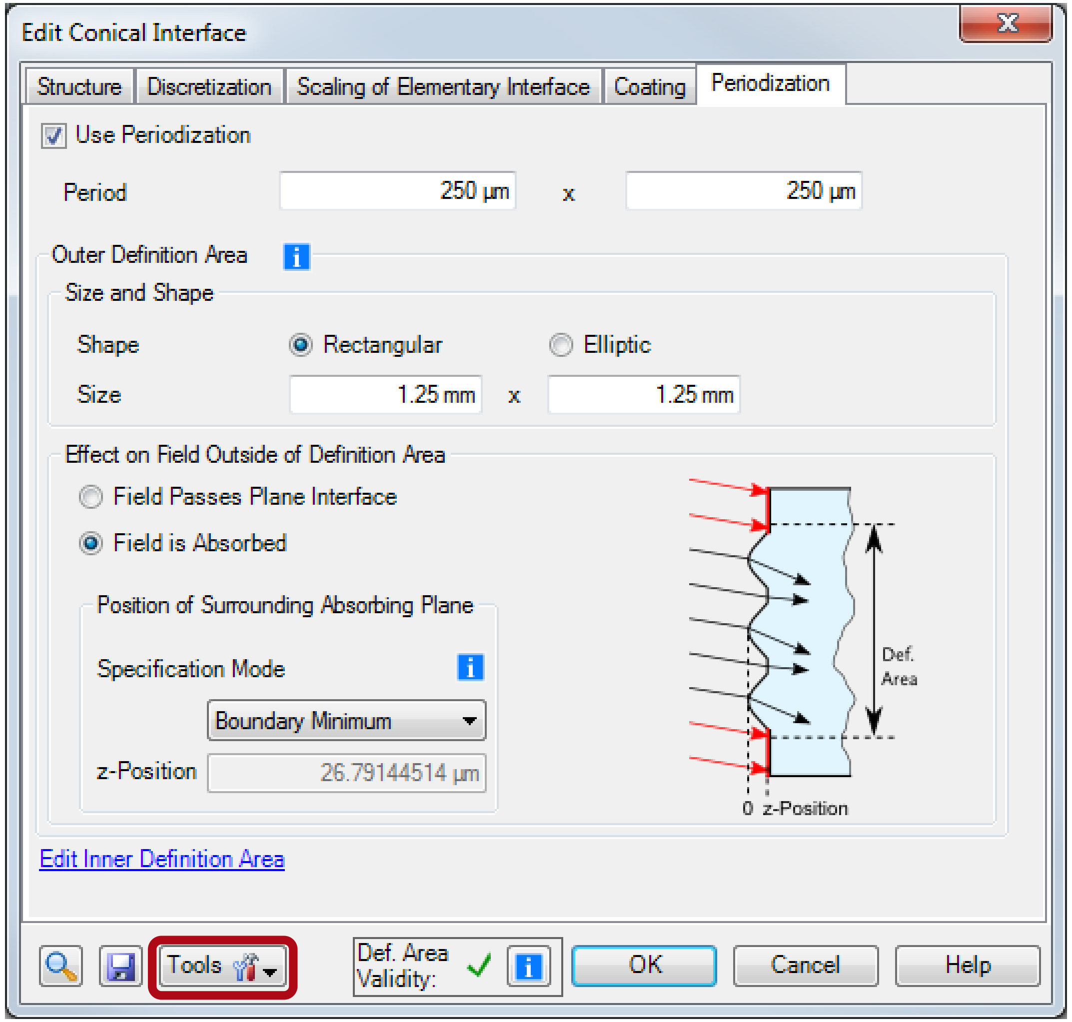


- The dialog shows if all settings are consistent (green checkmark).
- In case of a wrong setting (red cross) clicking the “i” icon gives more information about the misafjustment.

Validity of Parameters: Schematic



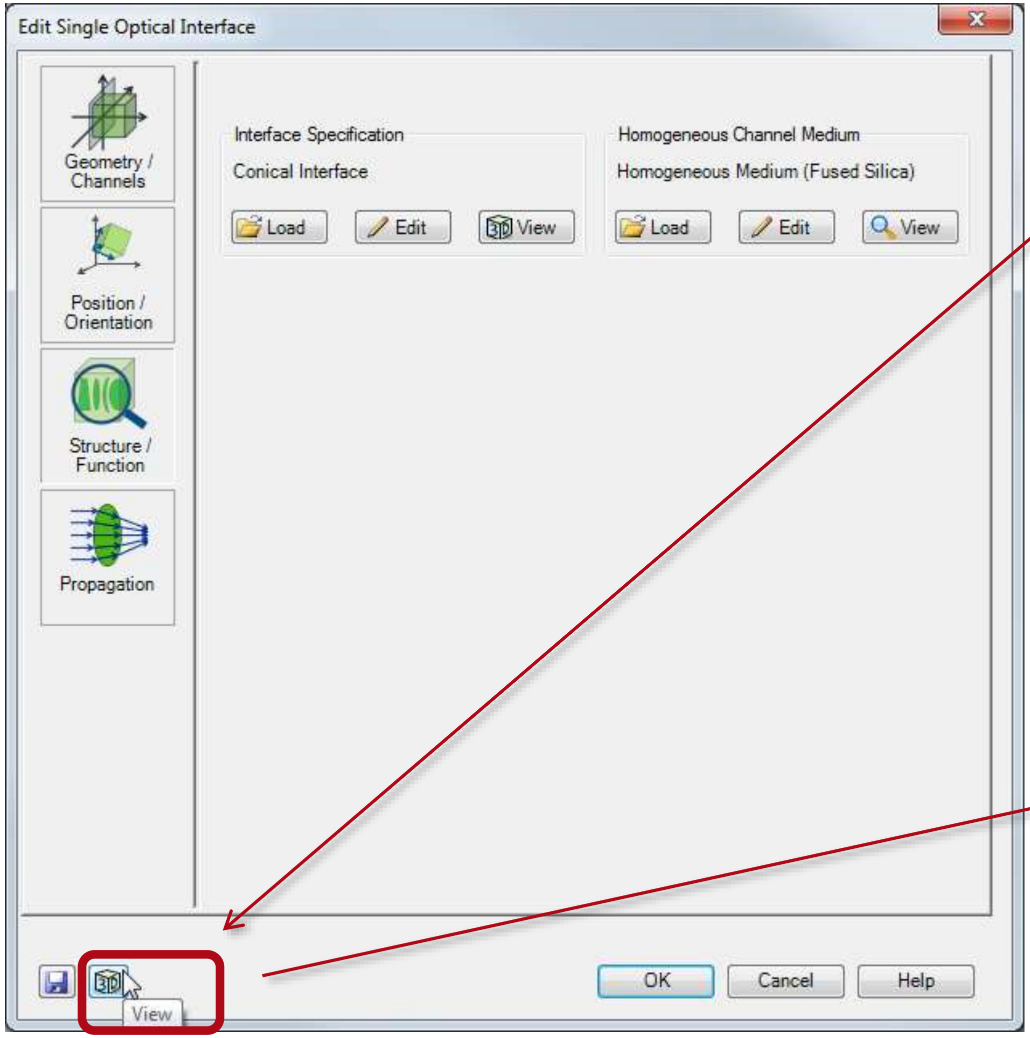
Interface Tools



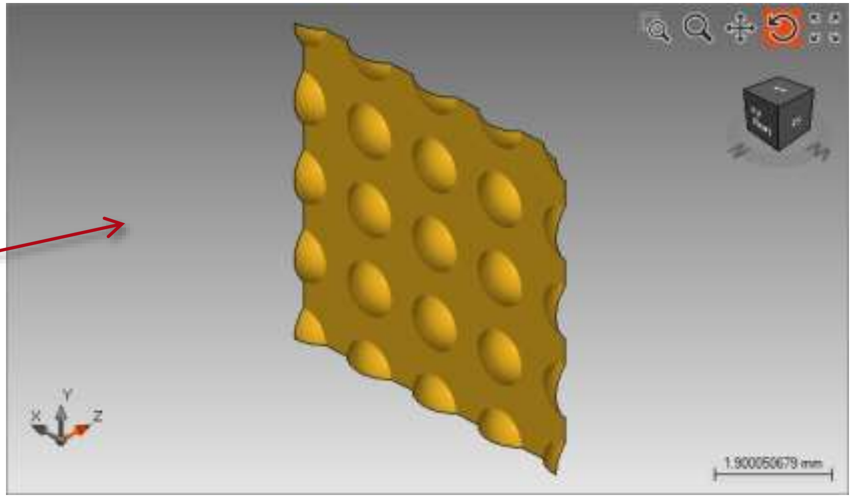
Interface tools allow to:

- Import surface profile
- Export surface profile
- Save to catalog
- View surface

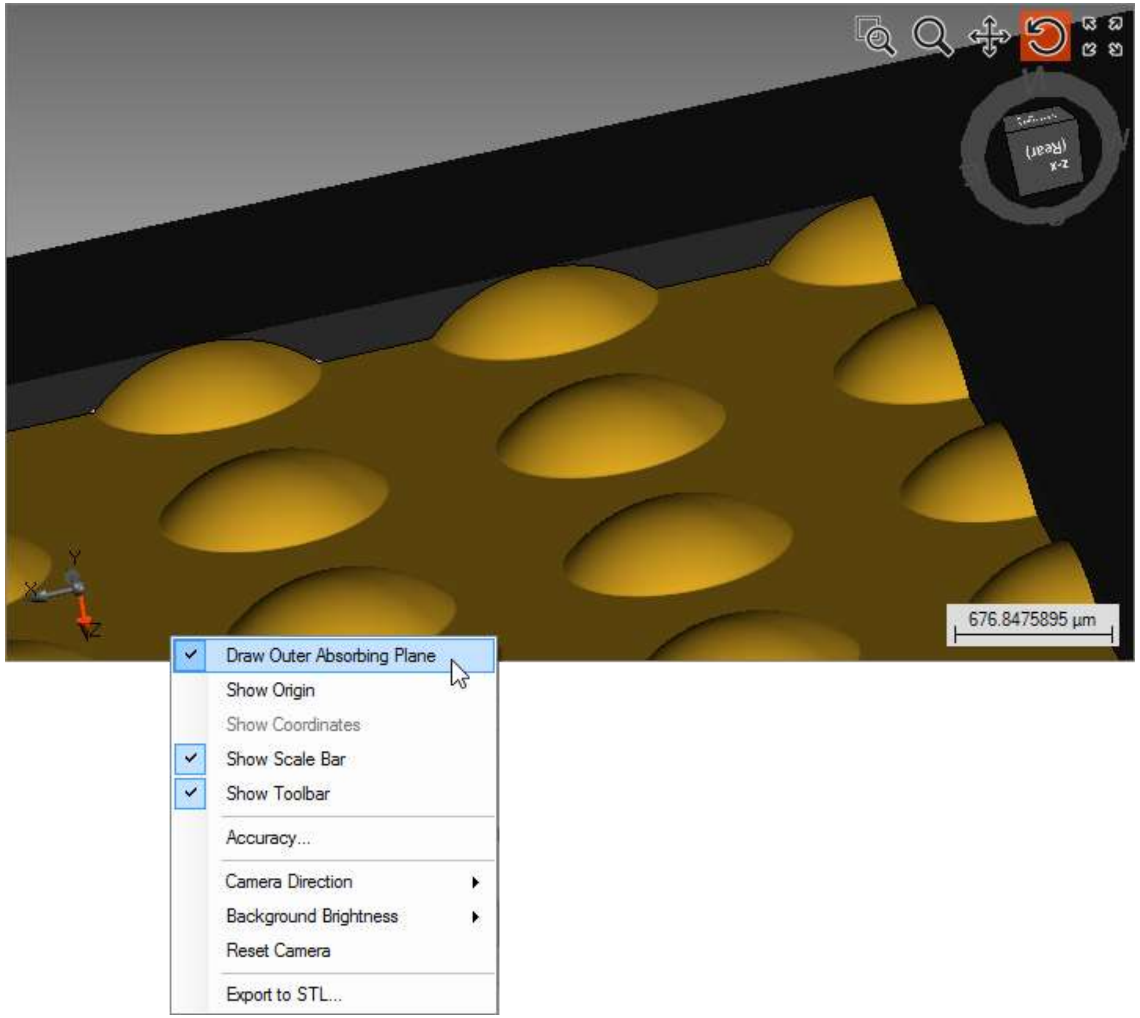
3D View



By clicking on the 3D-View icon an illustration of the set optical component is shown.



3D View: Options



- Outer and inner definition area can be displayed.
- Absorbing areas are marked in black.
- Context menu allows to enable drawing of outer definition area.
- Accuracy factor can increase display resolution.

Summary

- Any optical interface can be periodically replicated to generate arbitrary array structures.
- Inner and outer definition arrays allow definition of complex array structures.
- Example for the simulation of an high NA lens array can be found in Application Scenario AppS.0010.

Task 19

Simulation of high NA Micro Lens Array

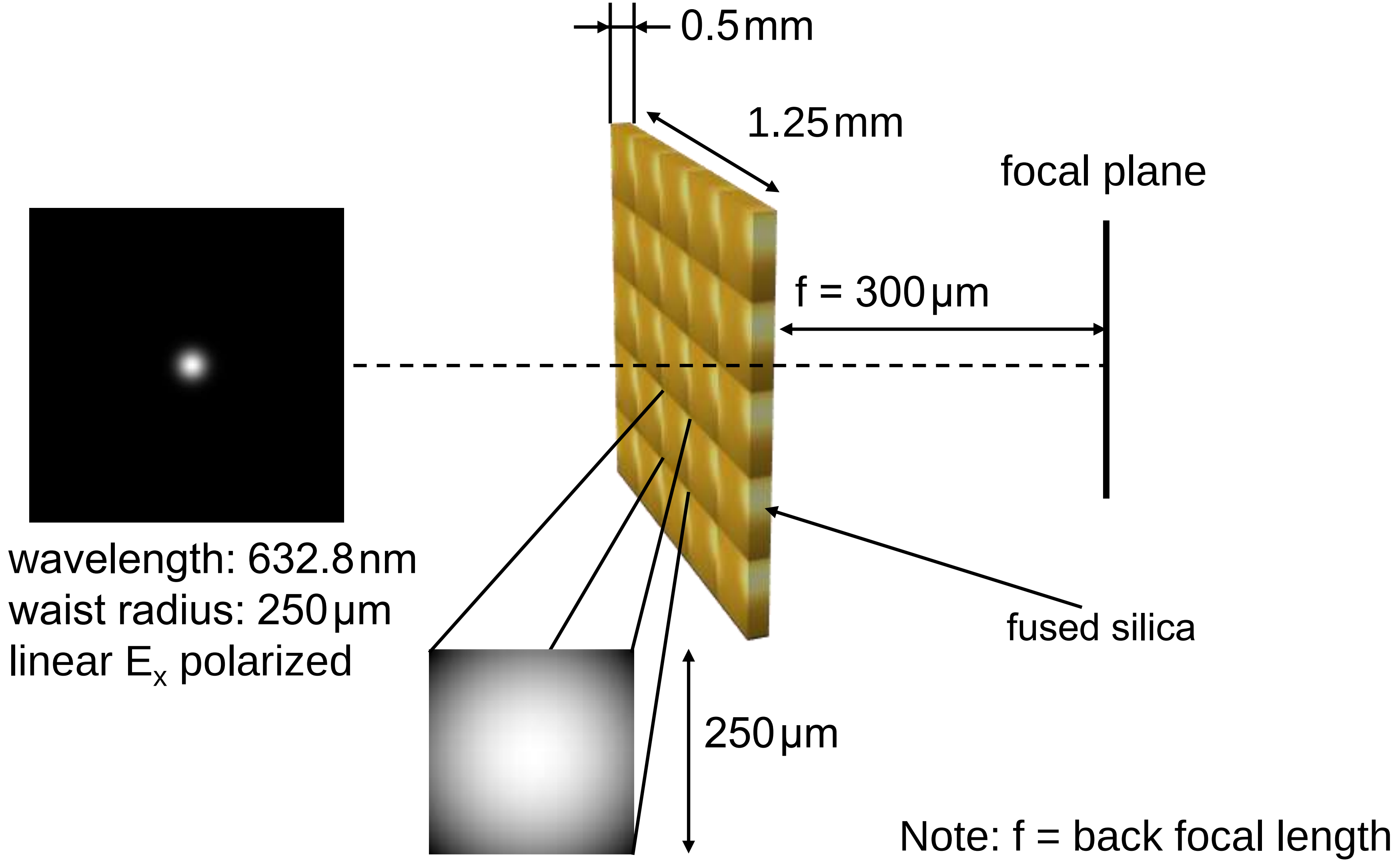
Keywords: microlens, array, homogenization system, periodization, diffraction, high NA, lens

Description

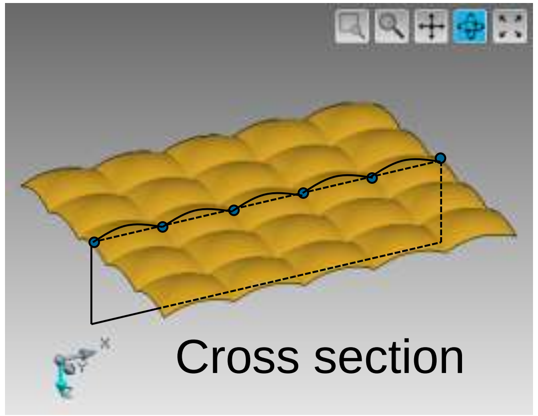
- This application scenario demonstrates the simulation of a high NA refractive micro lens array.

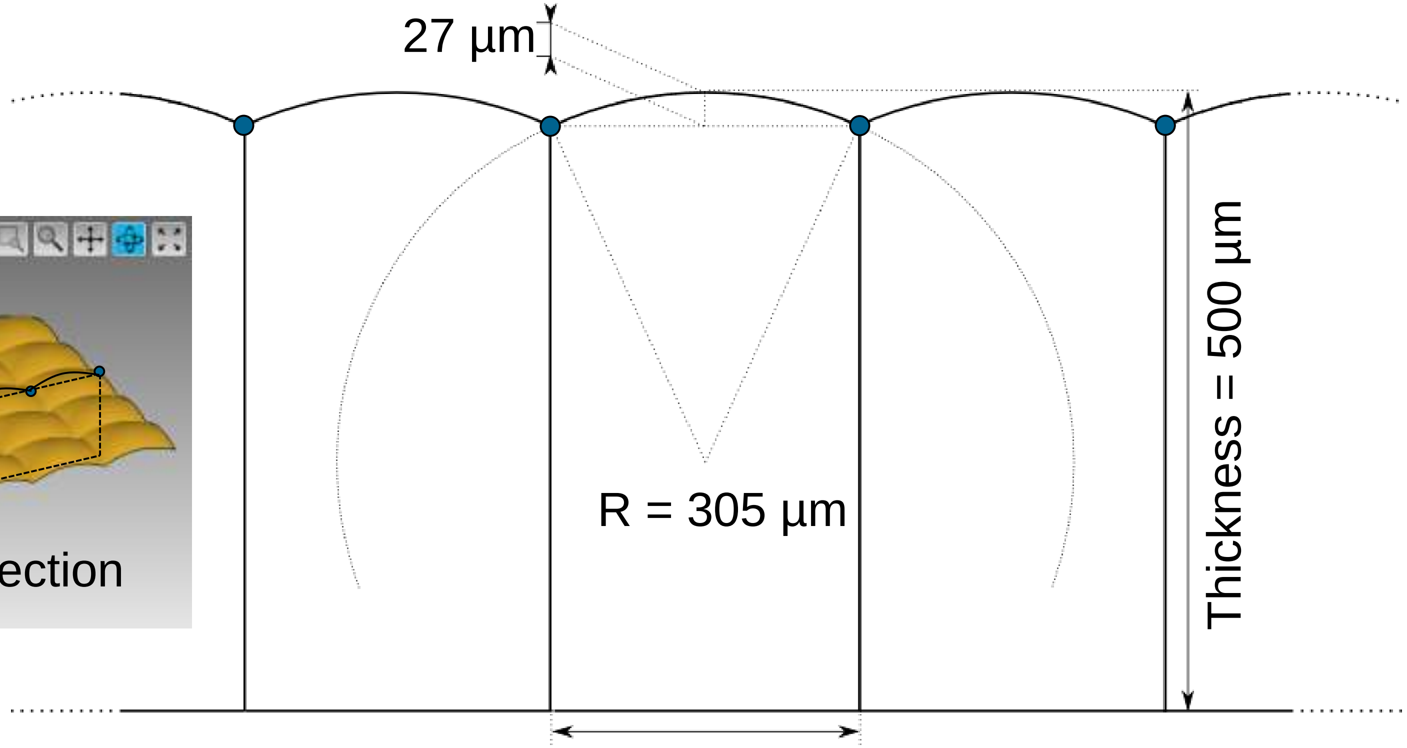
- The micro lens array is generated with the help of the periodization option. Details about the periodization of arbitrary interface profiles can be found in Use Case 0076.

Modeling Task 1



Modeling Task 2



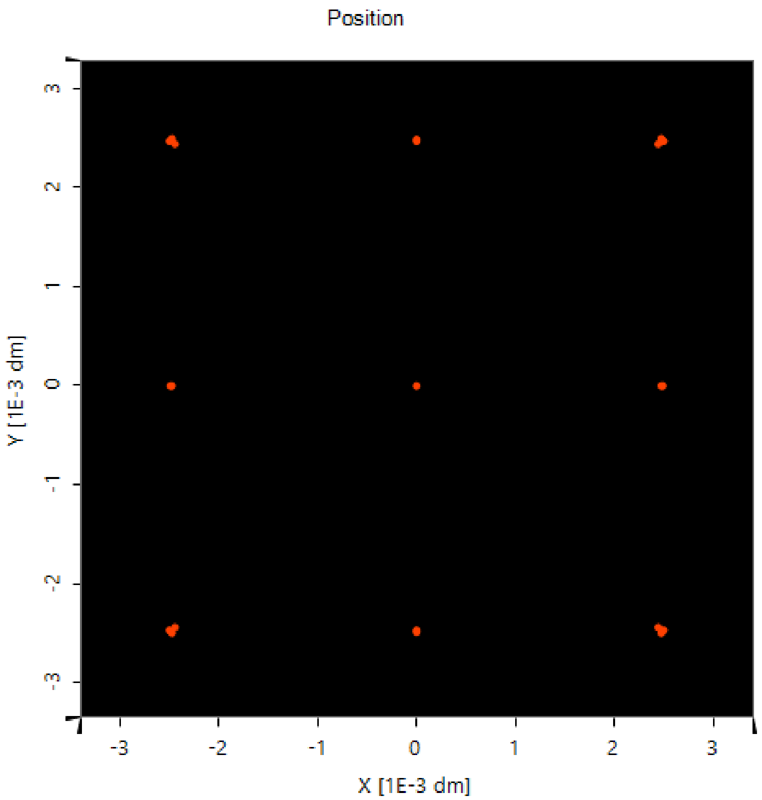


Spherical Lens

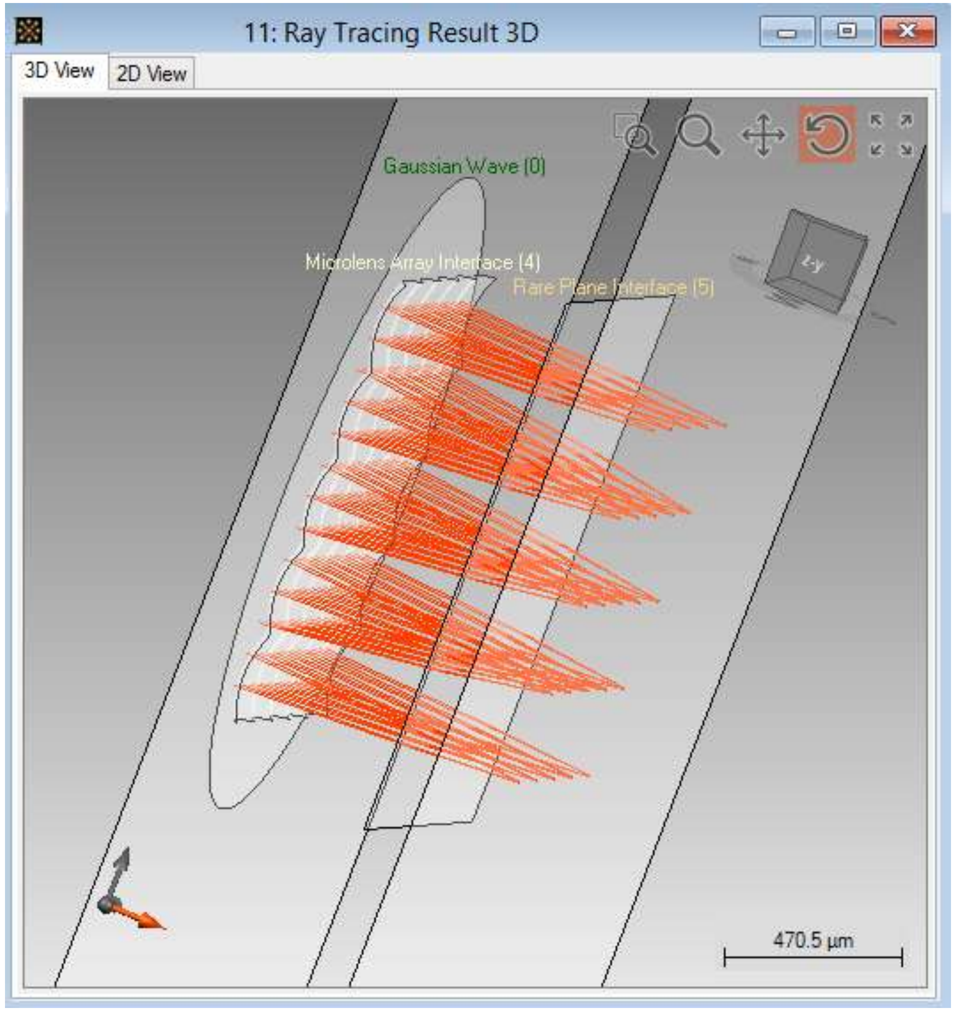
- Radius of Curvature R: 305 µm
- Conical Constant: 0

Simulation by Ray Tracing

Simulation Results 1: 3D-View and Dot Diagram

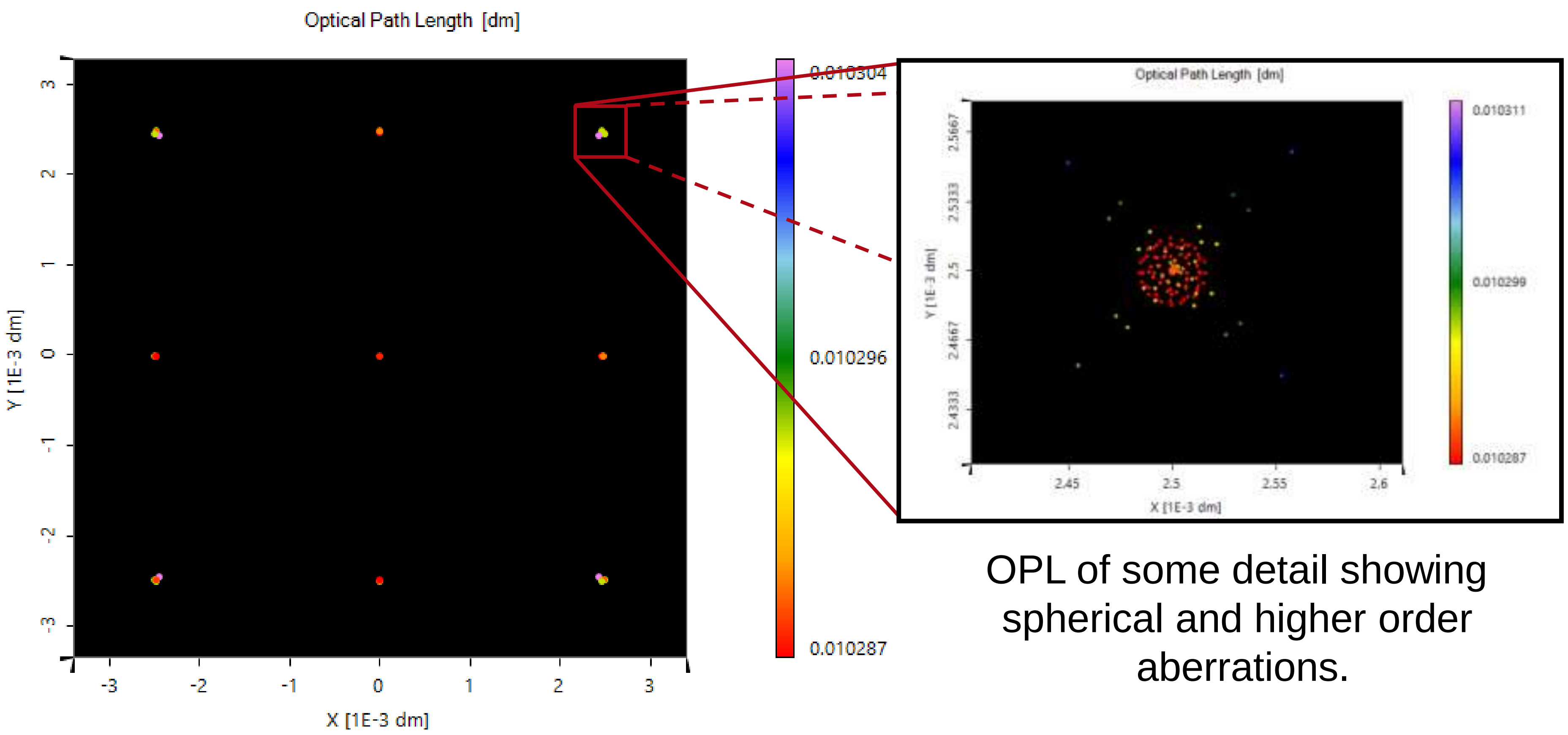


Dot Diagram in Focal Plane



3D Ray Tracing View

Simulation Results 2: OPL Analysis

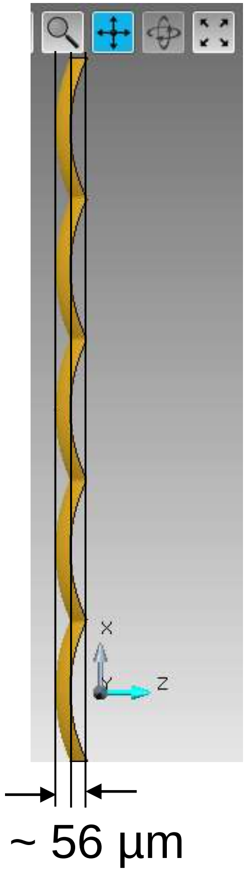


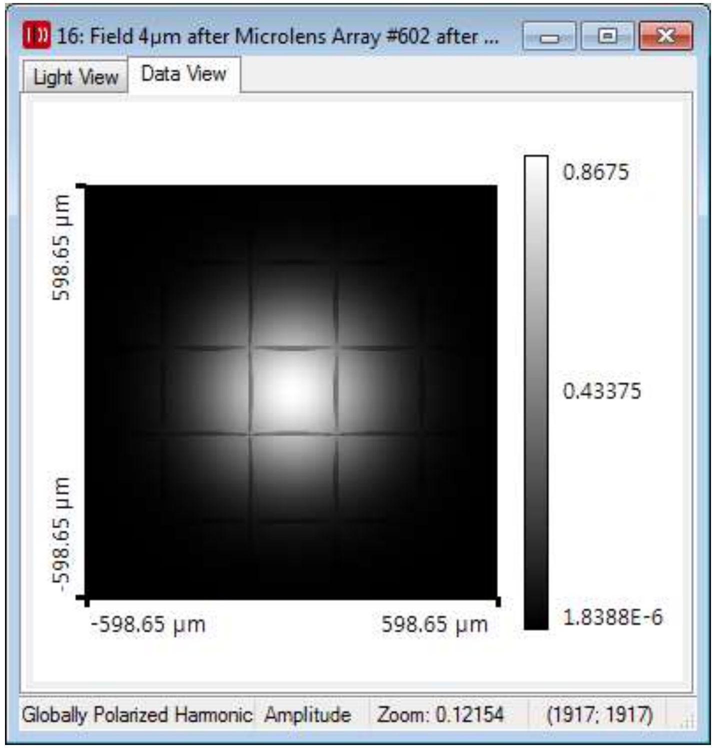
Different rays have different optical path lengths (OPL).

OPL of some detail showing spherical and higher order aberrations.

Simulation by Field Tracing

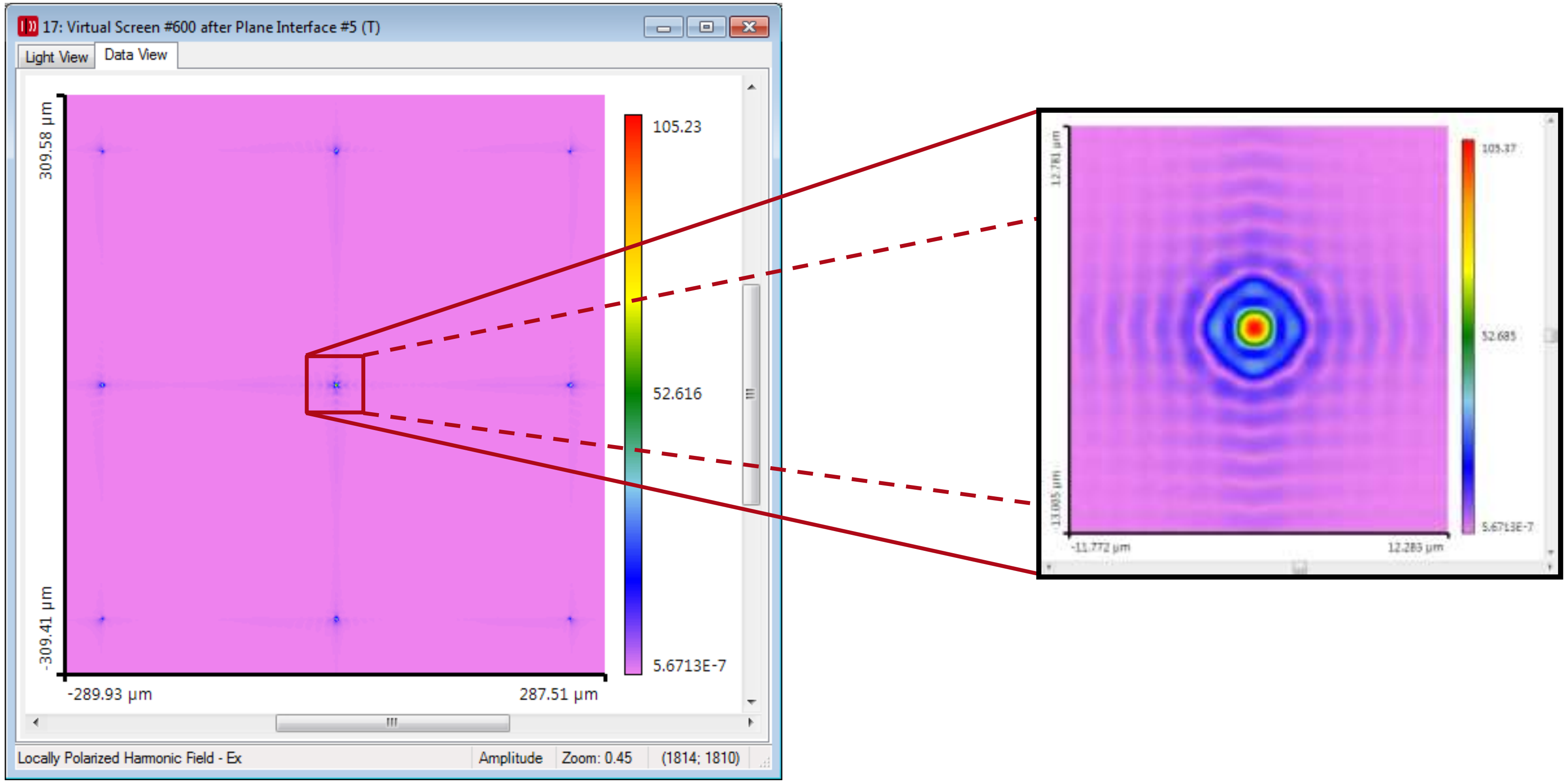
Simulation Results 1: Near-Field





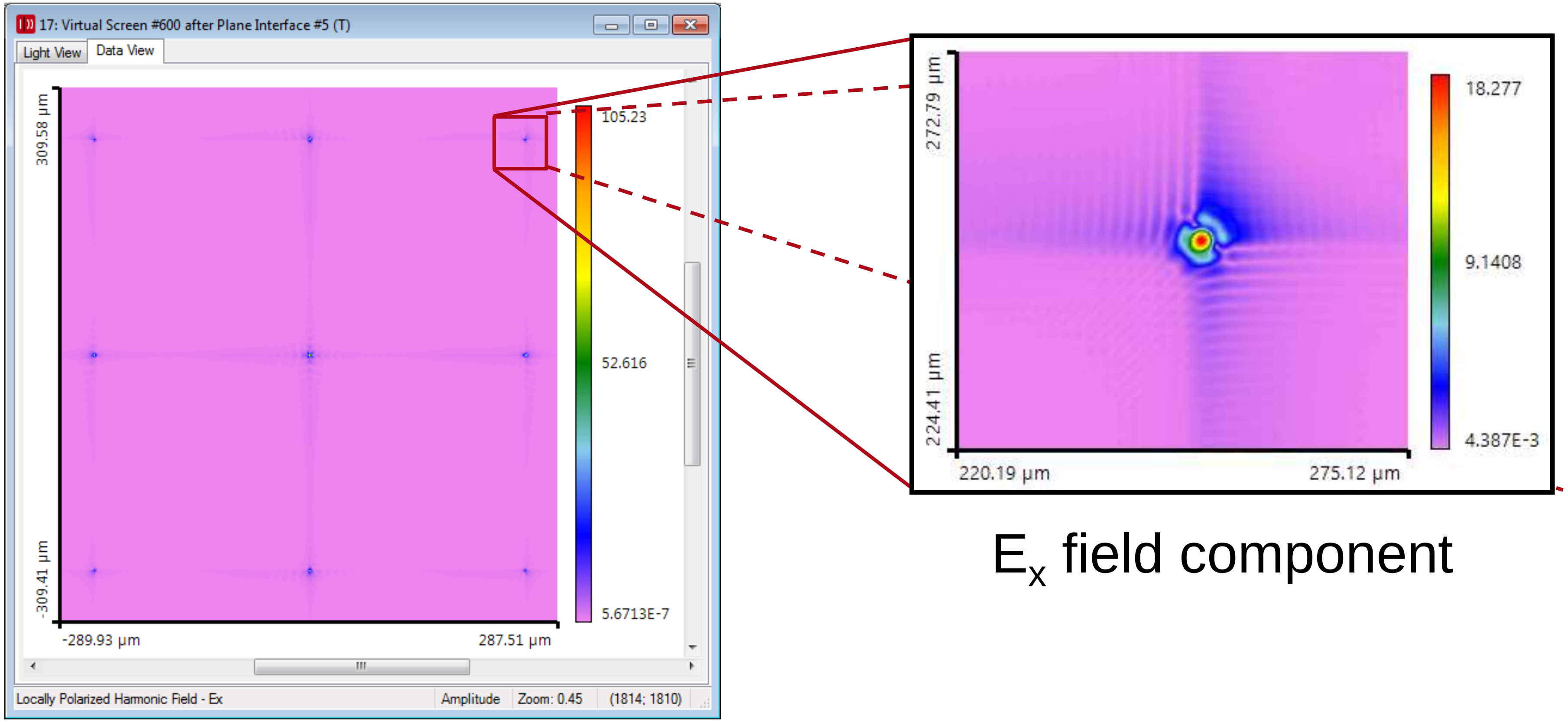
Field 4 µm after the micro lens array (60 µm behind apex = reference point) where refraction already led to shadows.

Simulation Results 2: Field in Focal Plane



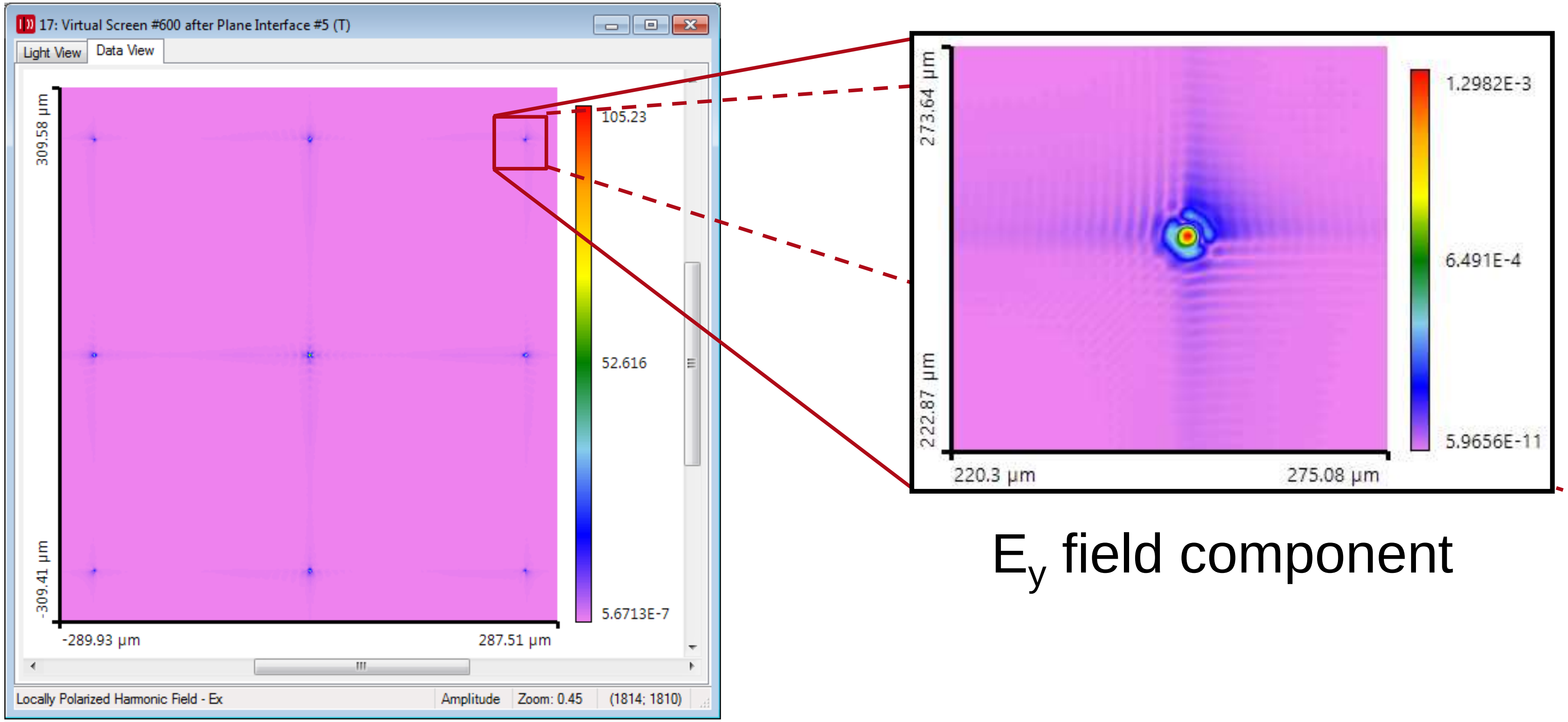
Resulting field in the focal plane with some central detail.

Simulation Results 3: Polarization Effects



E_x field component

Simulation Results 3: Polarization Effects



E_y field component

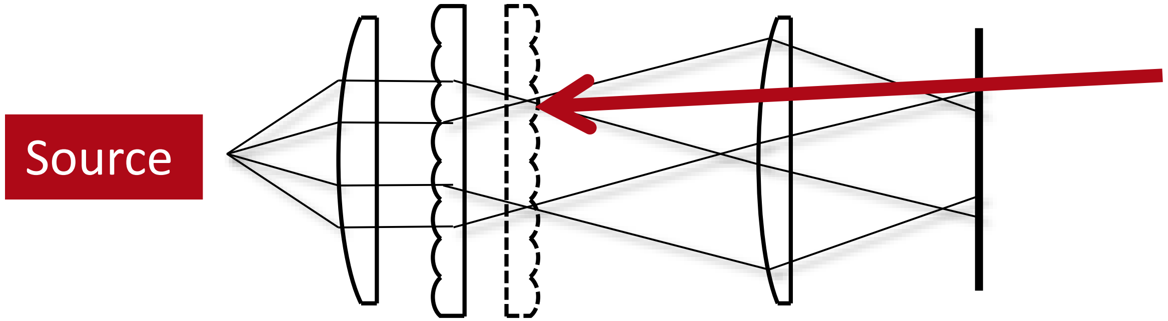
There is a weak polarization cross-talk at the lens interface!

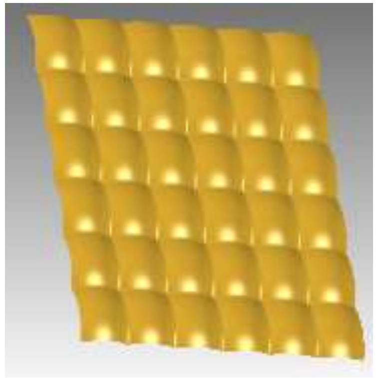
Conclusion

- VirtualLab allows the simulation of various systems of lens and mirror arrays by ray tracing and field tracing.
- Ray tracing can be used for the aberration analysis. Field tracing includes additional physical optics effects like polarization cross-talk and diffraction.
- Paraxial and non-paraxial lens and mirror arrays can be modeled including aberrations, diffraction and vectorial effects.

Global Homogenization Elements

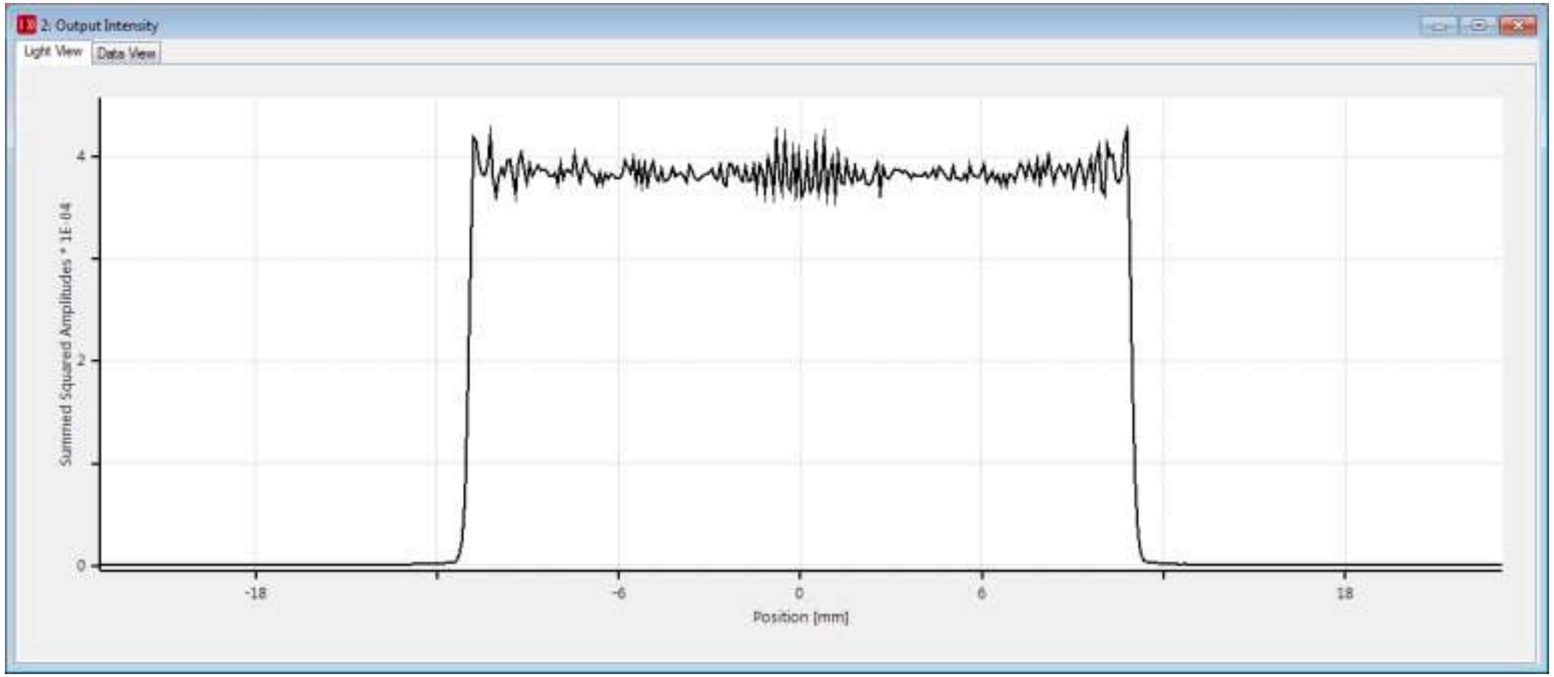
Micro Lens Arrays





- Lens arrays are used for the generation of a homogeneous light distribution.
- Shape of light distribution depends on lens aperture (and lens shape). → lens apertures typically limited to circular, rectangular and hexagonal shape.
- More flexible light shaping by freeform lens surfaces possible → difficult to design and to fabricate.
- Shaping of monochromatic and white LED light.

Micro Lens Arrays



Typical Light Distribution

Task 20

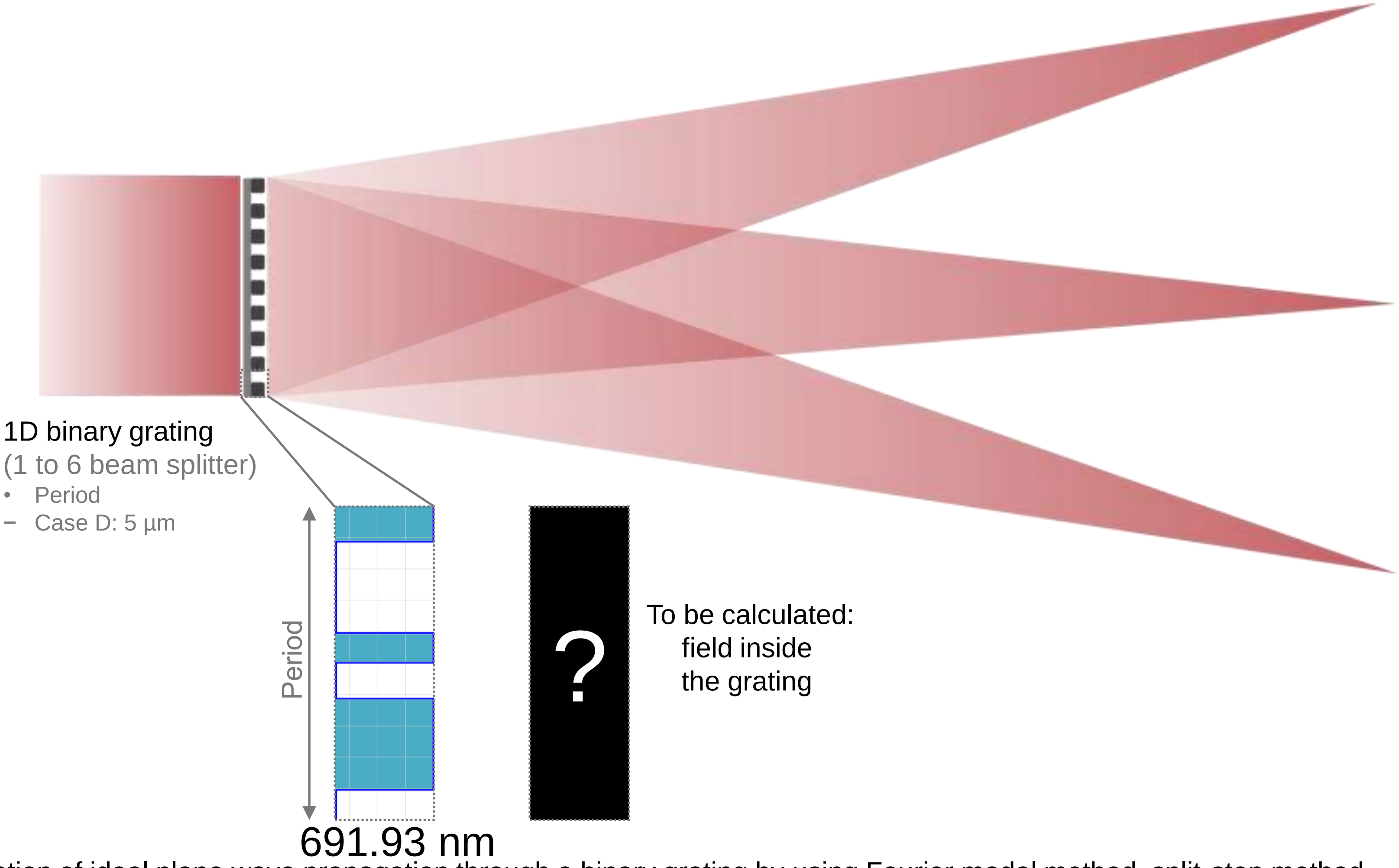
Comparison of Different Method of Modeling Binary Grating

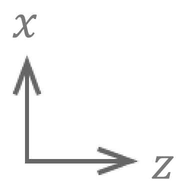
Try to use different method to show field inside microstructure. Show the calculates of field inside grating by FMM and Split-step method.

During the training, this task is not really practiced. But when grating period becomes larger, and diffraction cannot be neglected, Split-step method becomes a good choice. This task shows you how to enable split-step method.

Task Description

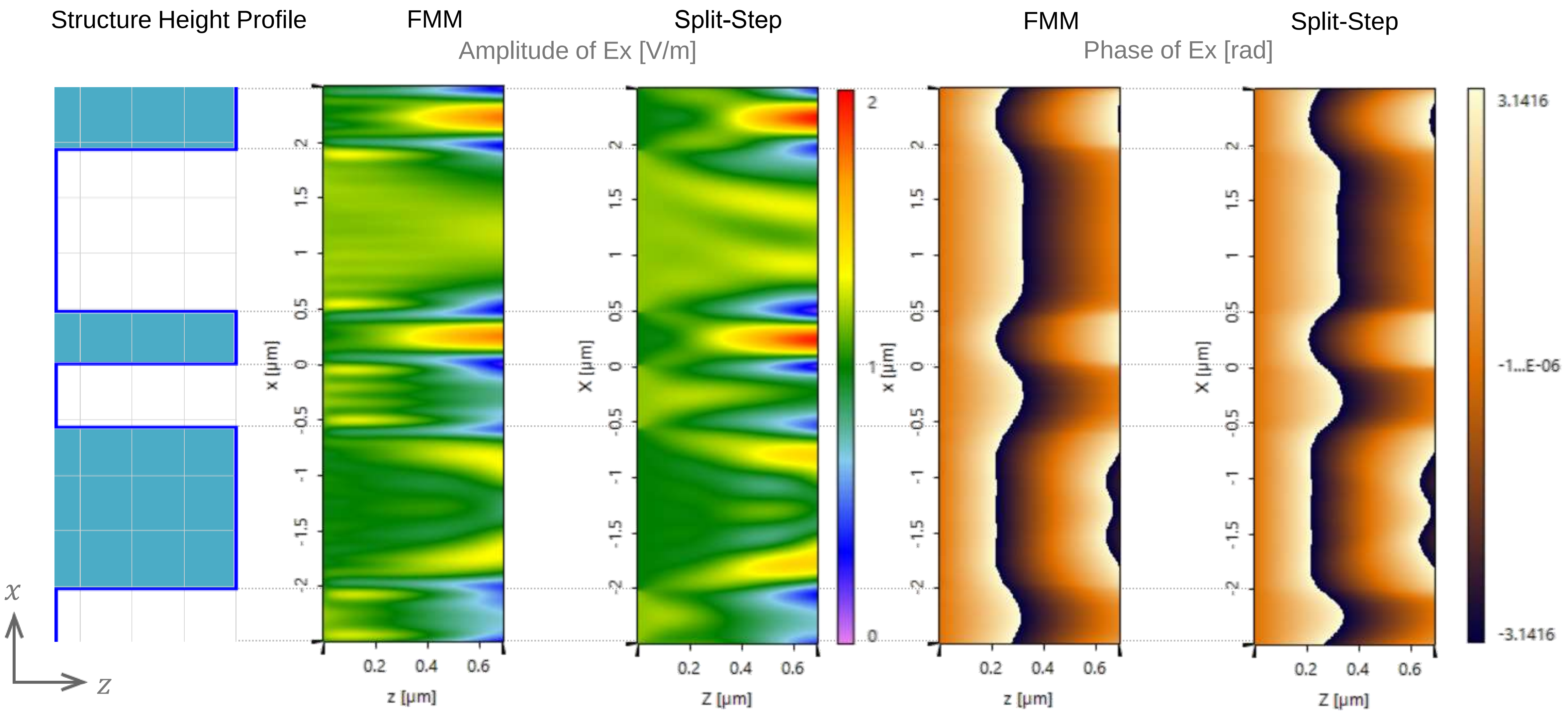
Ideal plane wave
- Wavelength is 632.8 nm
- Polarization state:
  - Case D: E_x −polarized





- Calculation of ideal plane wave propagation through a binary grating by using Fourier modal method, split-step method

Case D Amplitude: Period=5 μm, Smallest Feature = 0.4741 μm



Task 20: Video

Klick the following link to watch the video:

https://youtu.be/wpab9wxRik8