VirtualLab Fusion Technology and Applications

Gratings and Diffractive Optics

Speakers: Site Zhang & Hartwig Crailsheim
LightTrans International, Jena, Germany
25 – 27 September 2019

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Training Schedule

	Introduction to VLF		Gratings & Diffractive Optics		
	Day 1	Day 2	Day 3	Day 4	Day 5
09:00 – 10:30					
10:30 – 11:00	Coffee break		Coffee break		
11:00 – 12:30					
12:30 – 13:30	Lunch		Lunch		
13:30 – 15:00					
15:00 – 15:30	Coffee break		Coffee break		
15:30 – 17:00					

Huiying Zhong &
Olga Baladron-Zorita

**Site Zhang &
Hartwig Crailsheim**

Teams

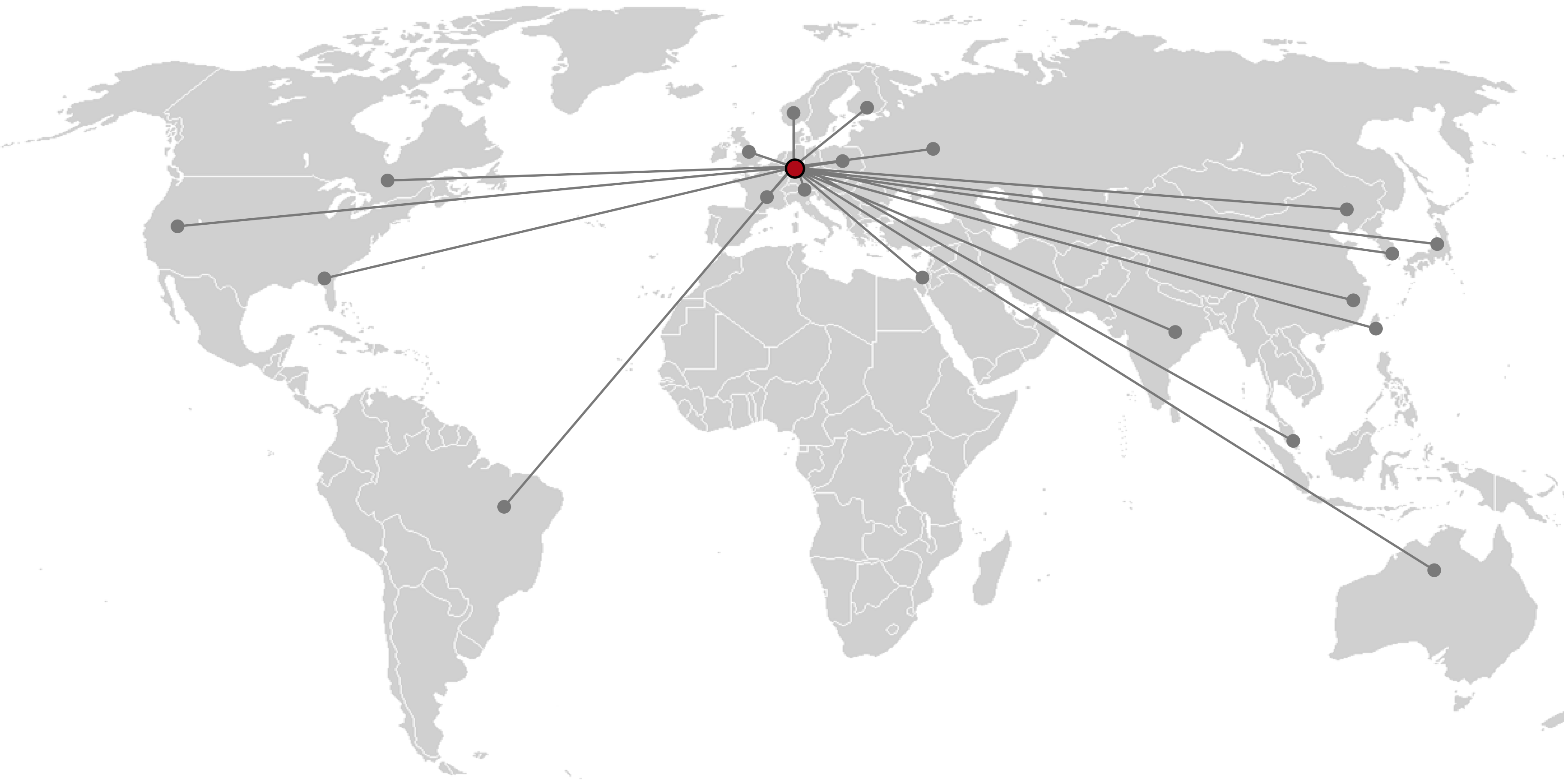
LightTrans (since 1999)

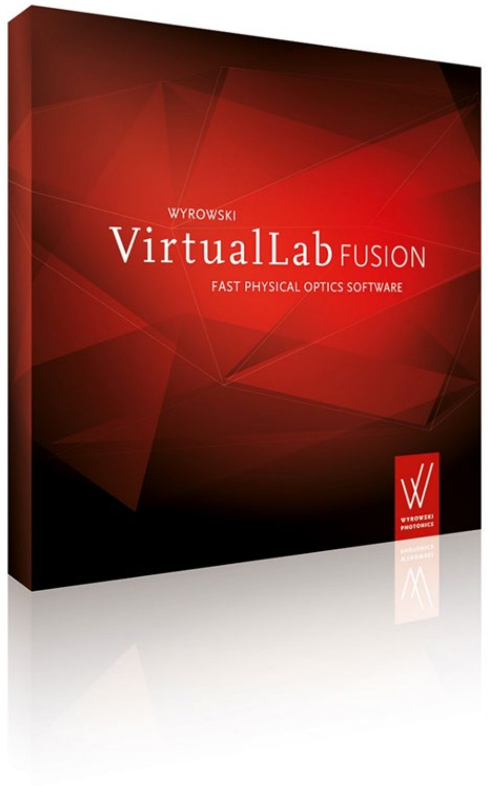
- Optical technologies development
- Technical support, seminars, and trainings
- Engineering projects
- Distribution of VirtualLab Fusion, together with distributors worldwide

(since 2014)

photo from wikitravel

Optical Design Software and Services





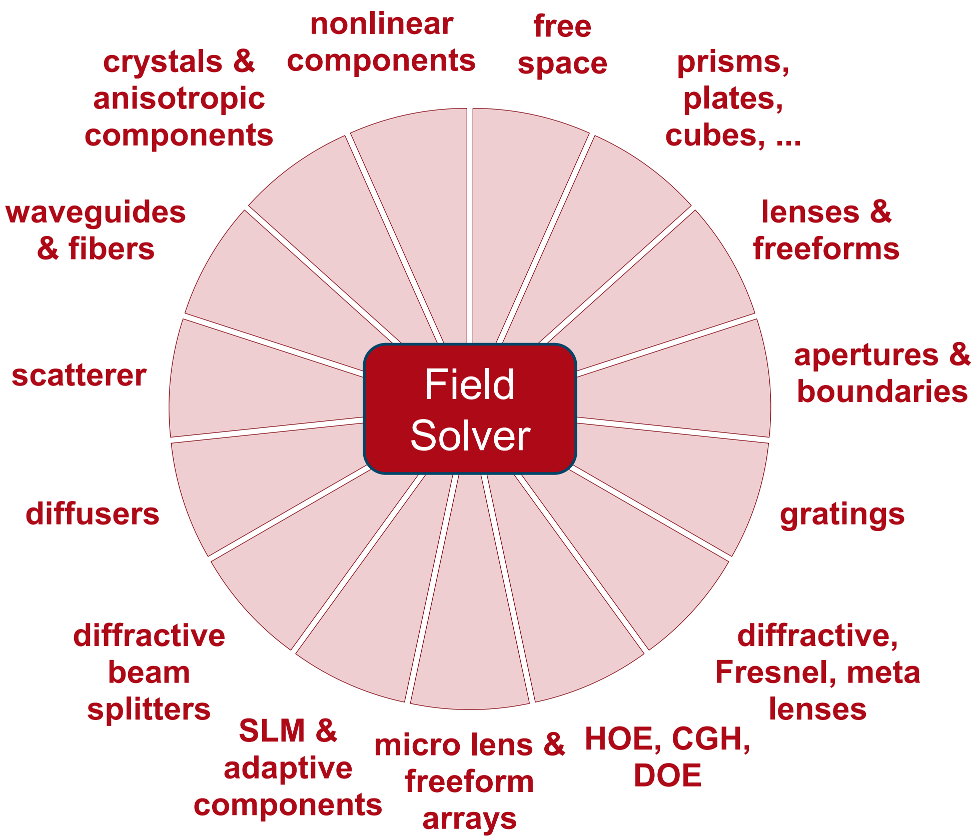
Connecting Optical Technologies / Maxwell Solvers

Problem:

Application of a single field solver, e.g. FEM or FDTD, to the entire system: **Unrealistic numerical effort**

Solution:

- Decomposition of system and application of regional field solvers.
- Interconnection of different solvers and so to solve the complete system.



Introduction to This Course

In modern optical systems gratings can be found in various applications, such as wavelength seperation, lightguide coupling, phase and / or polarization manipulation. The modeling and design of gratings are therefore drawing interests. We demonstrate how grating analysis can be done in VirtualLab Fusion by covering the following topics.

- How to construct grating structures
- Modeling and design of surface-relief gratings
- Analysis of polarization-dependent effects and optimization
- Properties of holographic volume gratings
- Investigation of two-dimensional periodic structures, like nanopillars

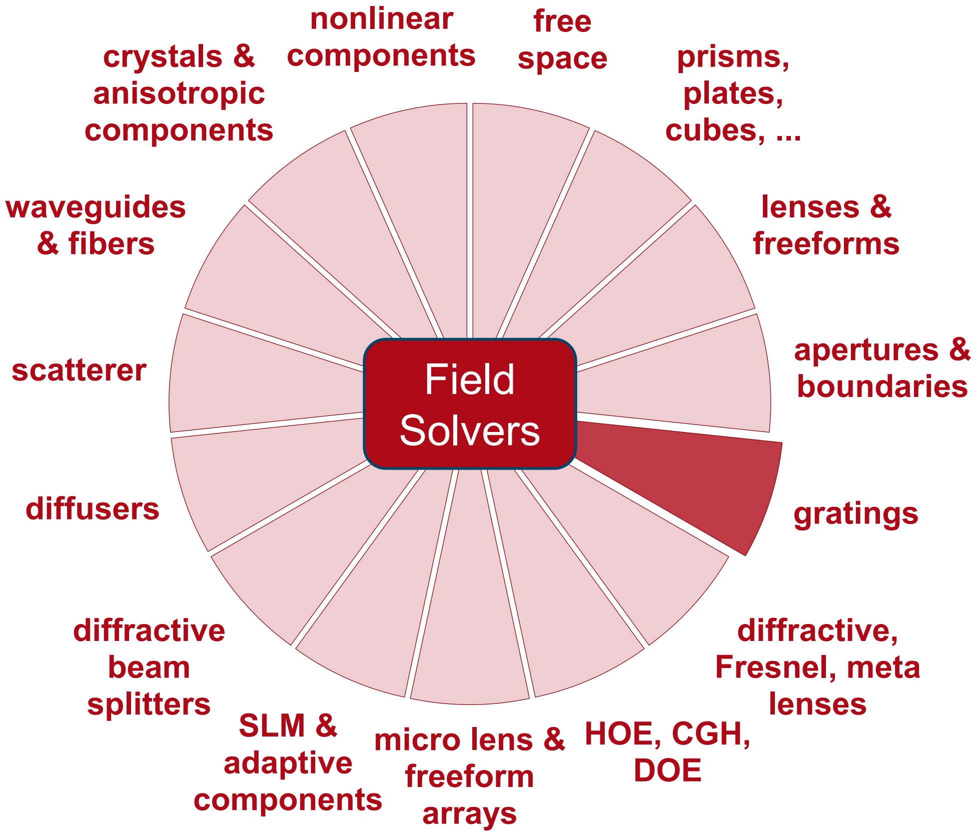
A series of special features and tools for grating analysis will be shown with examples, for example, the Grating Order Analyser and Field Inside Analyzer.

Field Tracing Technologies – Gratings

Aim of this course:

- to be able to construct customized grating structure;
- to know grating modeling technologies;
- to use helpful tools for grating investigation and analysis;
- and, by applying the above to solve practical problems.

learning by examples!



Introduction

- **How to construct grating structures**
- Modeling and design of surface-relief gratings
- Analysis of polarization-dependent effects and optimization
- Properties of holographic volume gratings
- Investigation of two-dimensional periodic structures, like nanopillars

Configuration of Grating Structures by Using Interfaces

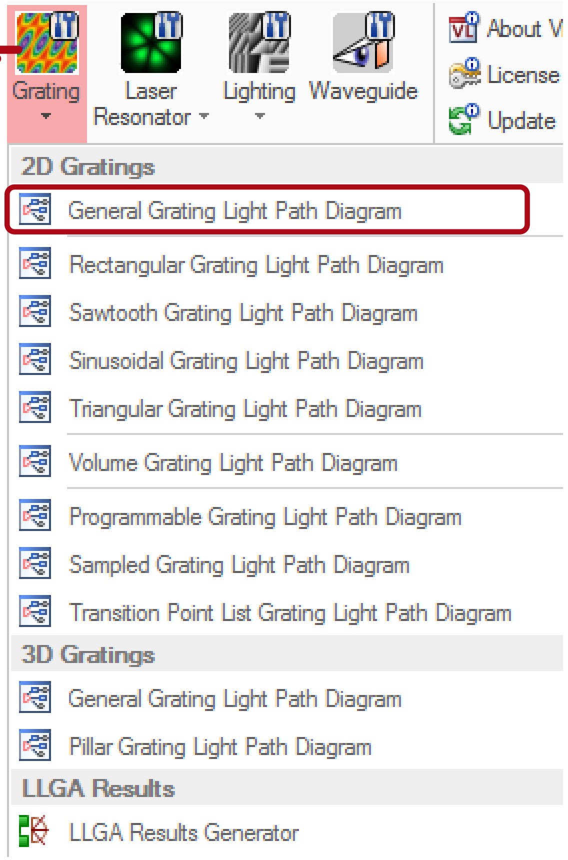
This Use Case Shows ...

- 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.

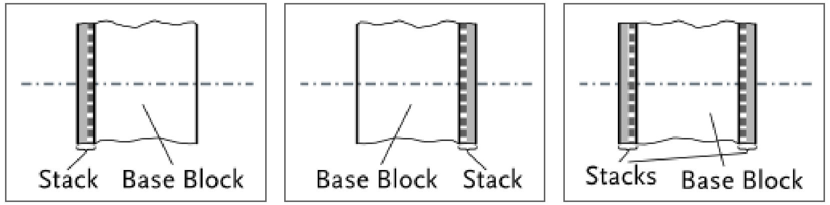
Grating Toolbox Initialization

- 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.

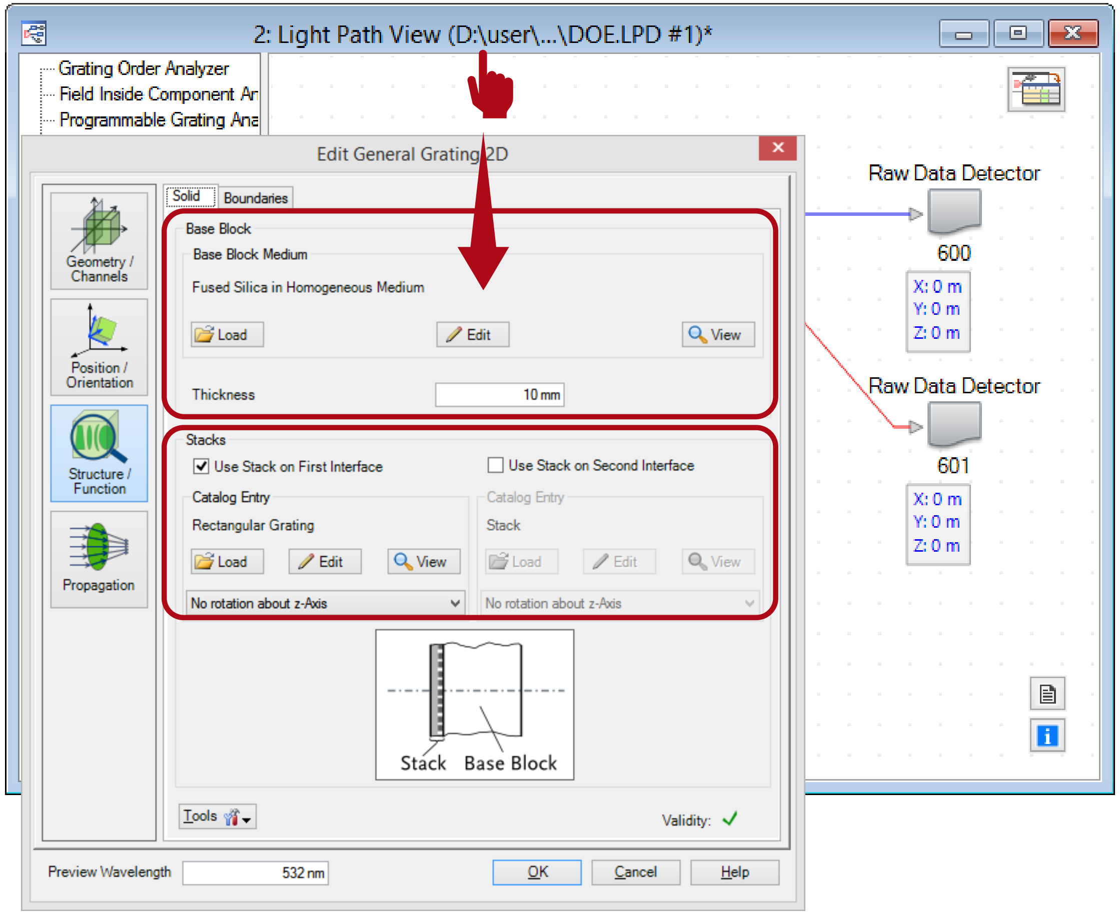


Grating Structure Settings

- 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.

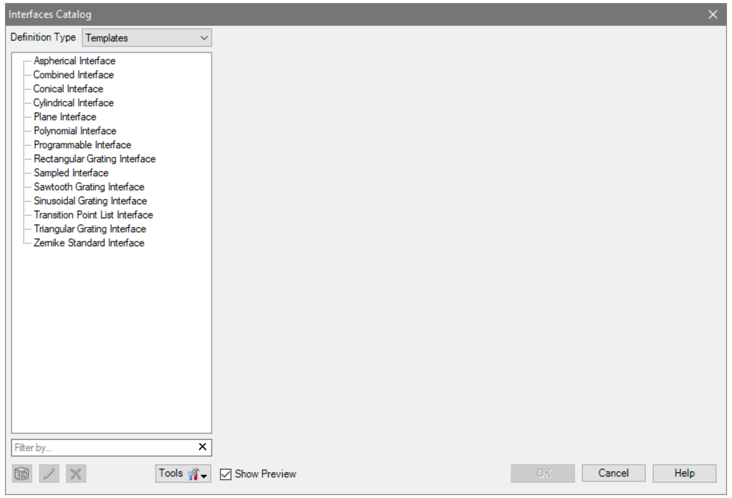


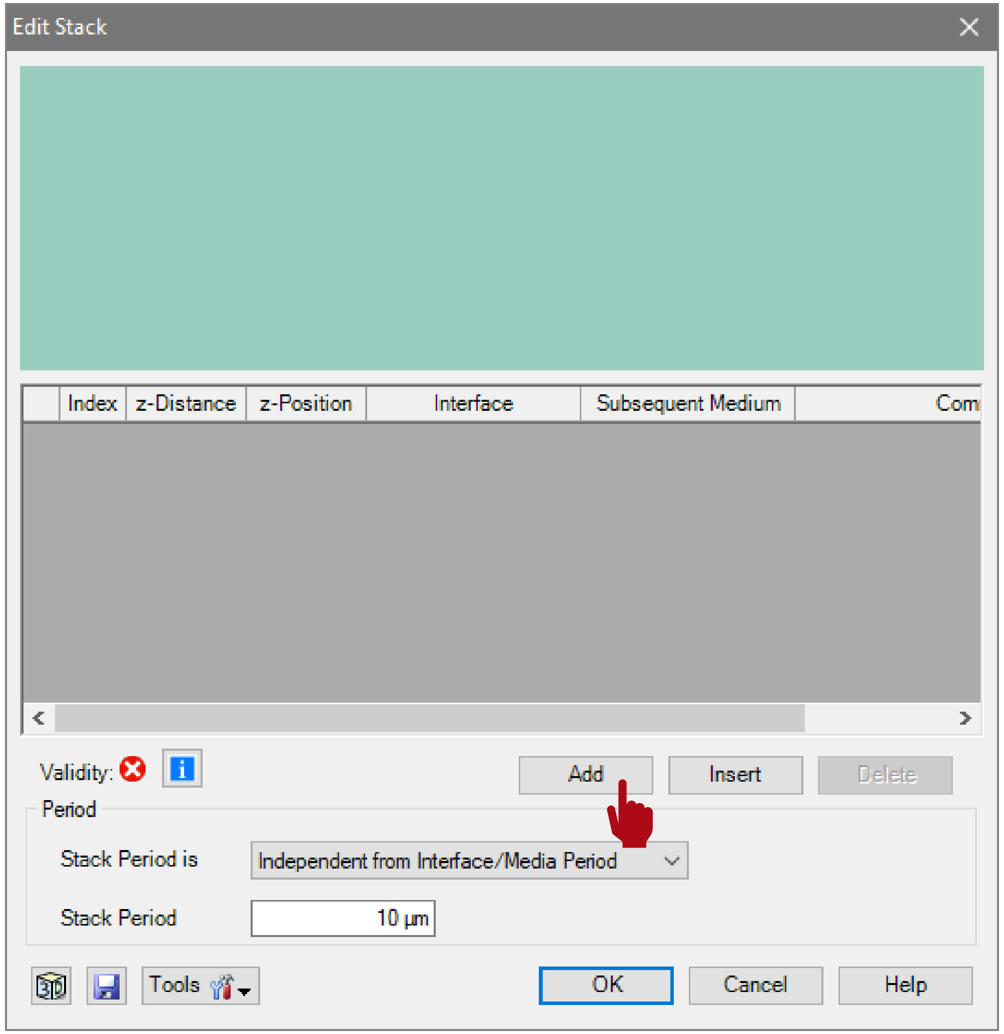
- For example, a stack on the first interface is chosen.



Stack Editor

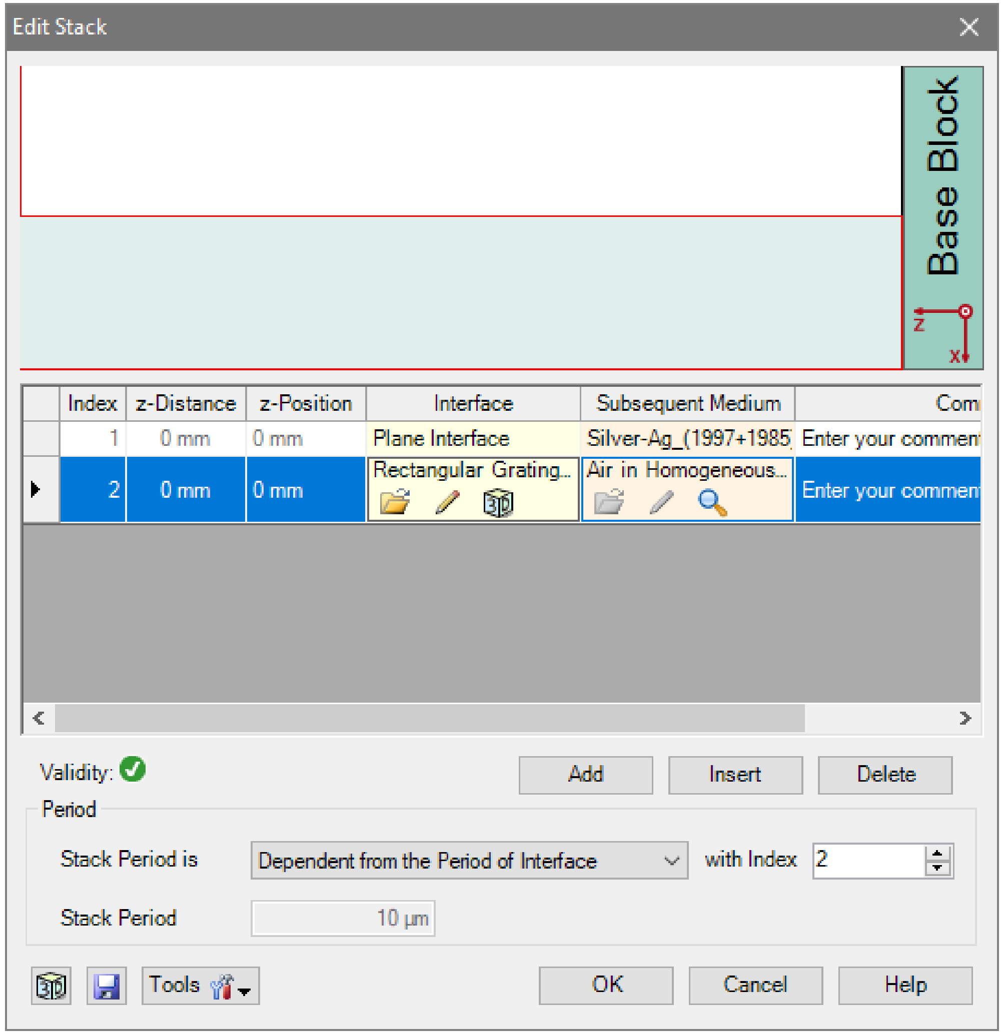
- In the *Stack Editor* interfaces can be added or inserted from catalog.
- The catalog of VirtualLab provides several types of interfaces. All of them can be used to define a grating.





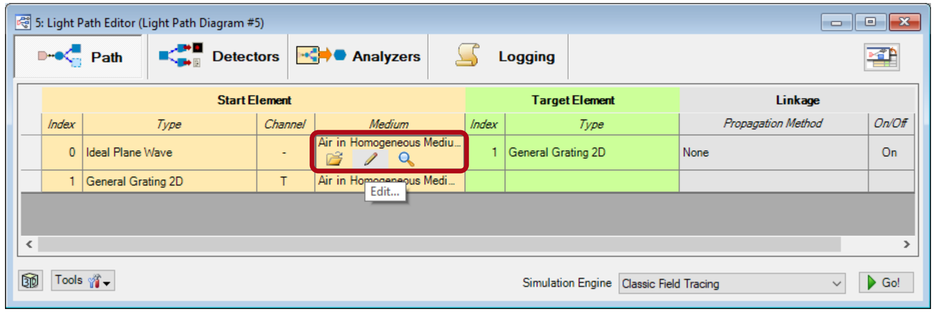
Rectangular Grating Interface

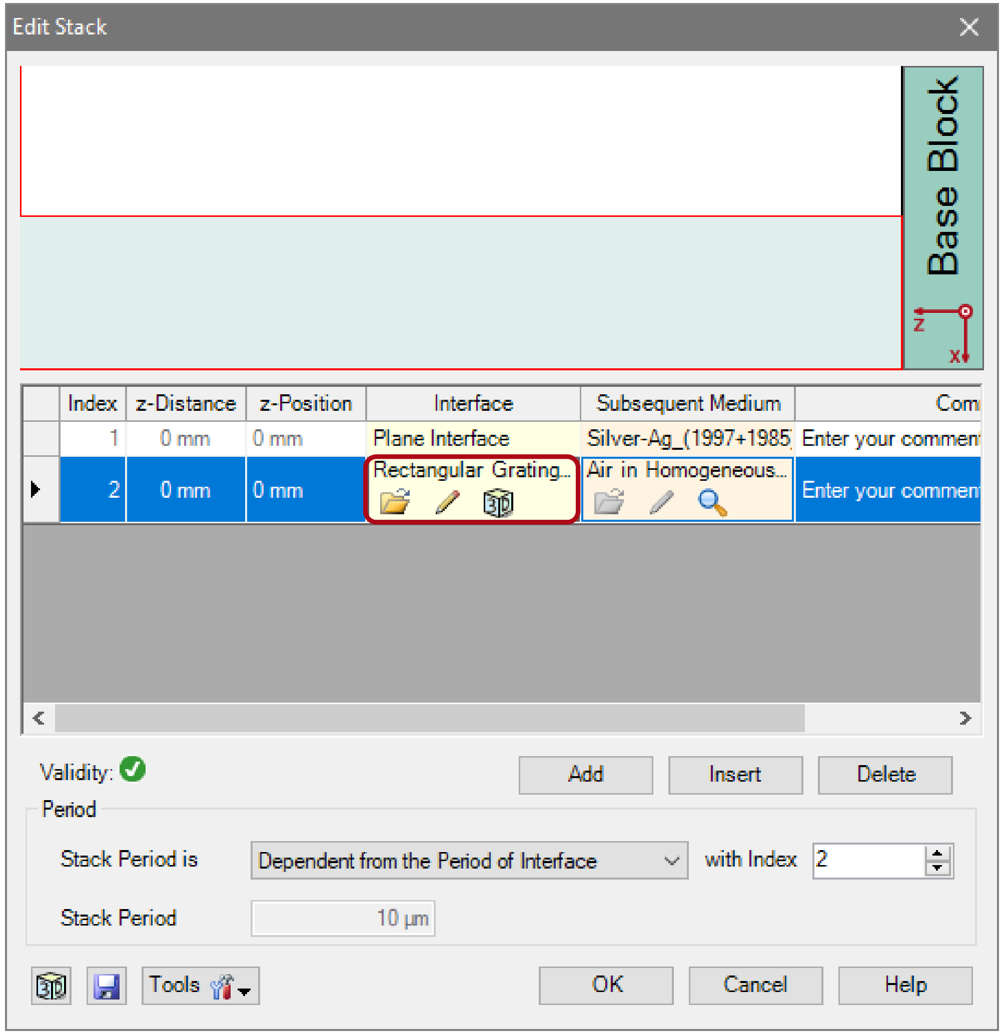
- One possible interface is the rectangular grating interface.
- This type of interface is appropriate for the configuration of simple binary structures.
- In this example, a grating made of silver is on a glass substrate.
- For this purpose, an additional plane interface was added in order to separate 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

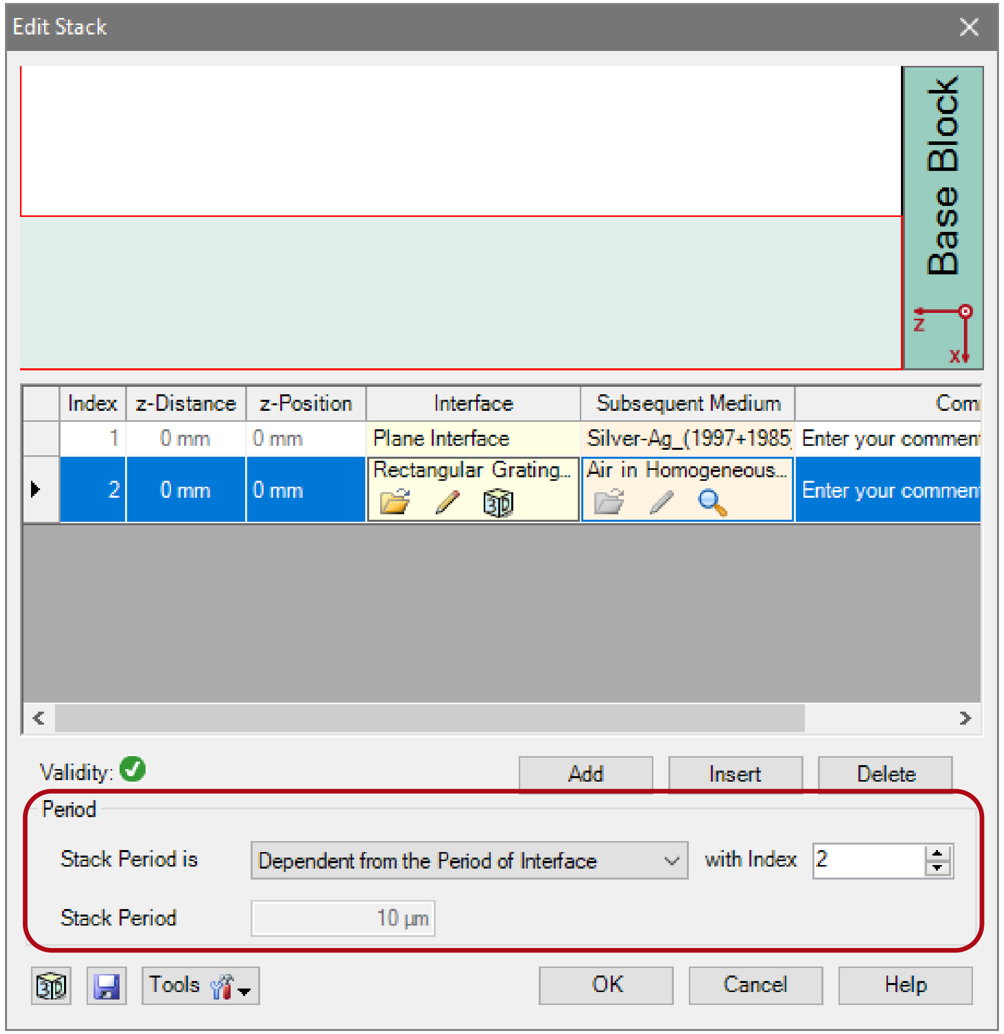
- Please note: the order of the interfaces is always counted from the surface of the substrate.
- The selected interface is highlighted red in the view.
- Further, the medium in front of the grating (means behind last interface) can not be defined here. It is automatically taken from the material in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





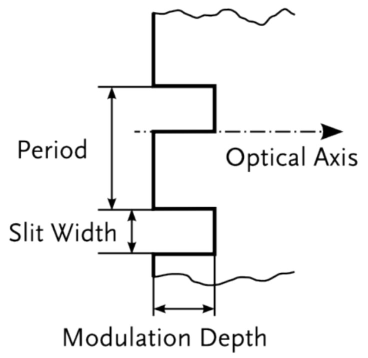
Rectangular Grating Interface

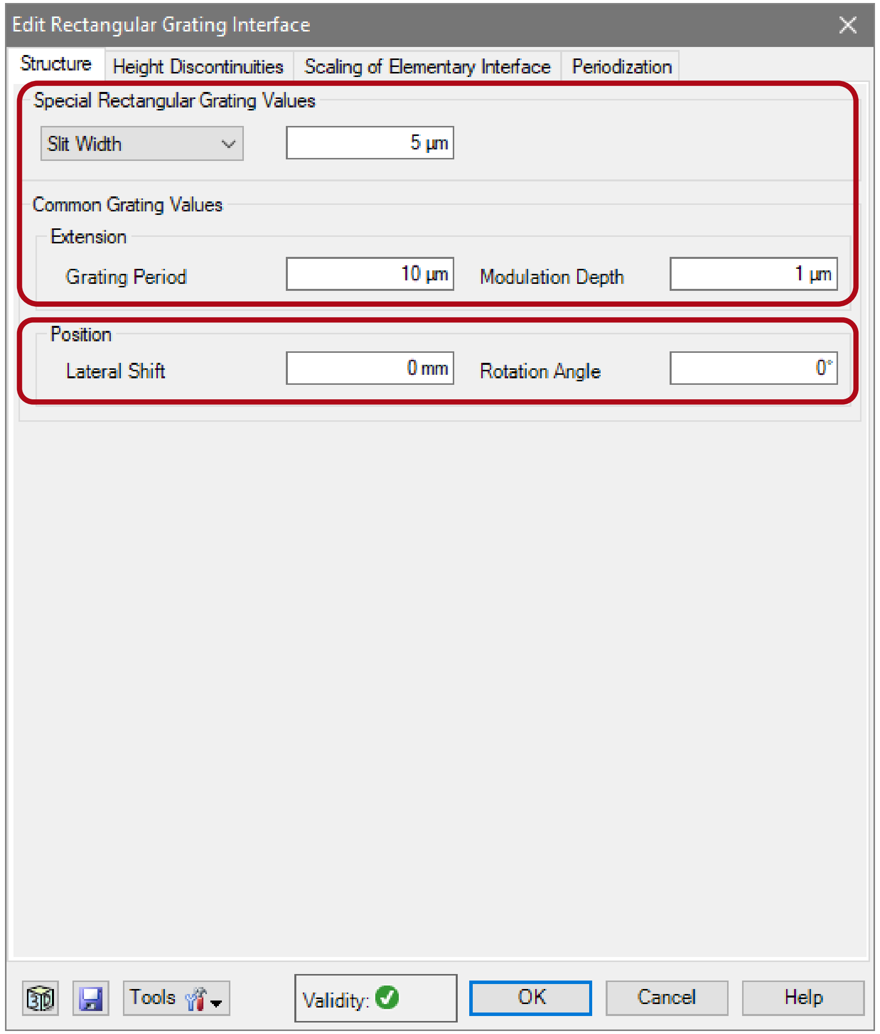
- The *Stack Period* allows to control the period of the whole configuration.
- This period is also taken for the periodic boundary conditions of the FMM algorithm.
- In case of simple grating structures, it is recommended to choose the option *Dependent from Period of Interface* and select the proper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



Rectangular Grating Interface Parameters

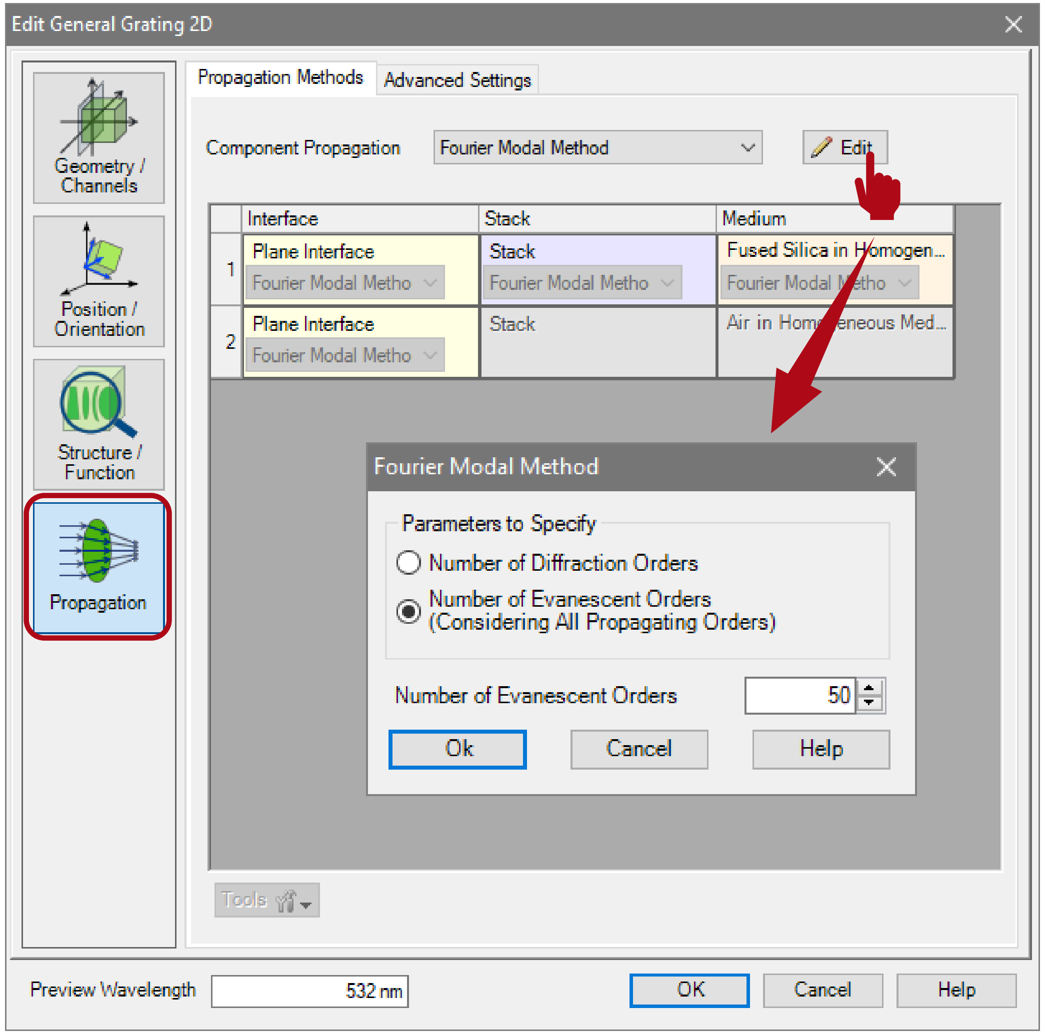
- The rectangular grating interface is defined by the following parameters
  - slit width (absolute or relative)
  - grating period
  - modulation depth
- A lateral shift and rotation can be set optionally.





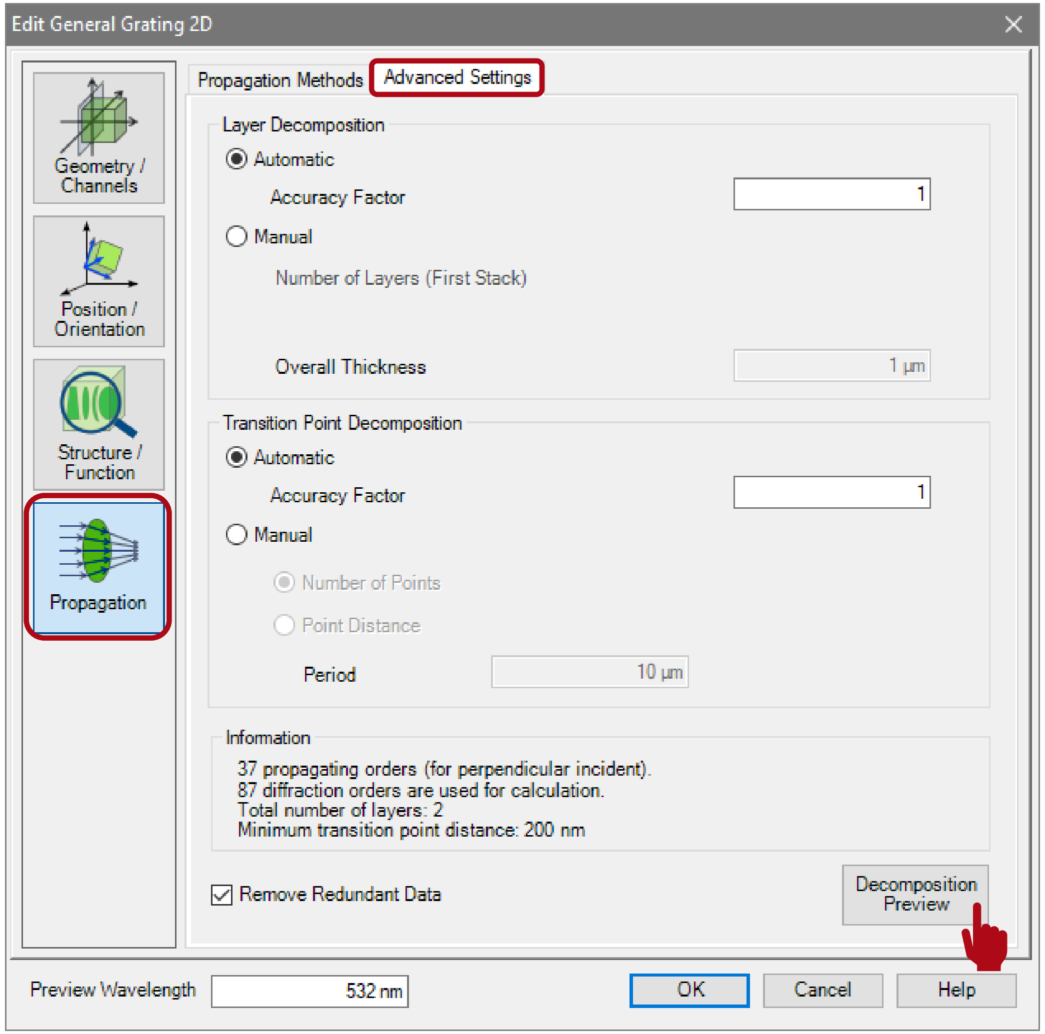
Advanced Options & Information

- 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

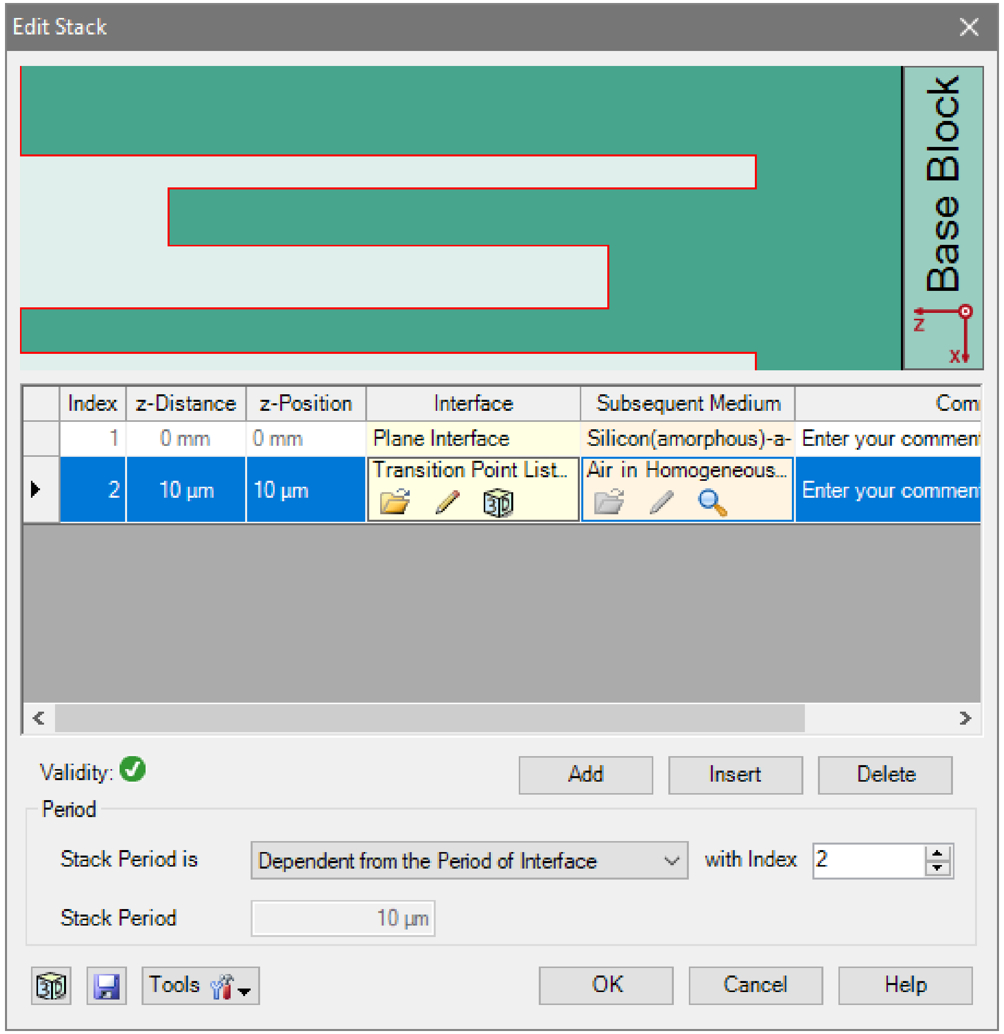
- The *Advanced Settings* tab provides information about the decomposition of the structure.
- The *Layer Decomposition* and *Transition Point Decomposition* settings can be used to adjust the discretization of the structure. The default settings are appropriate for nearly all grating structures.
- Further, 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

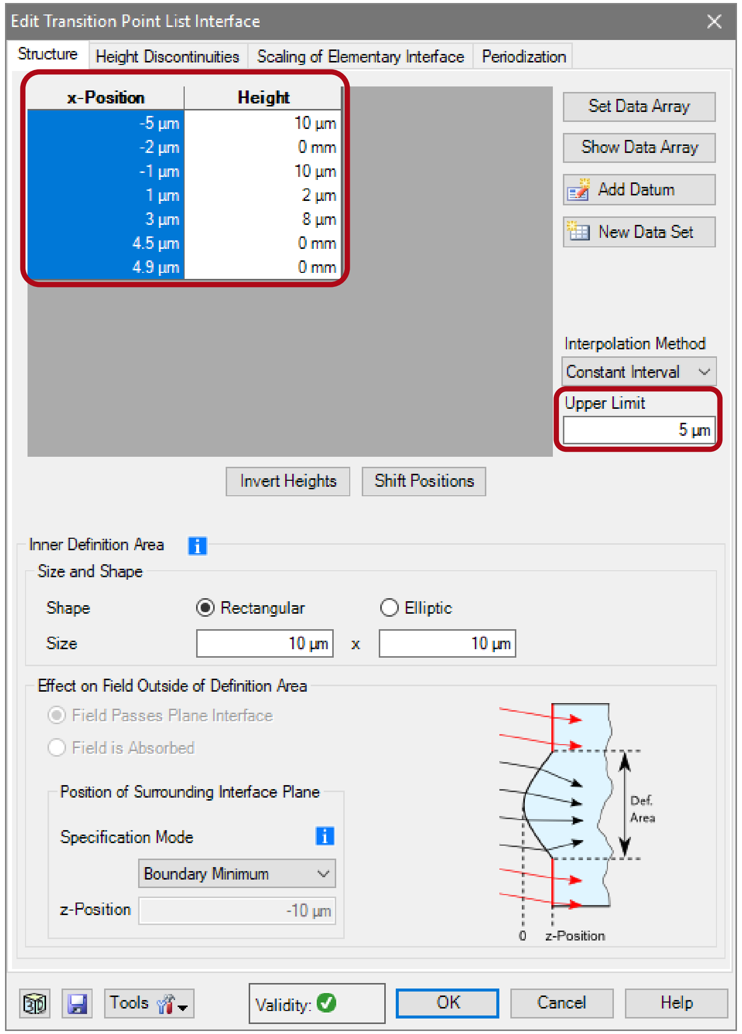
Transition Point List Interface

- 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.



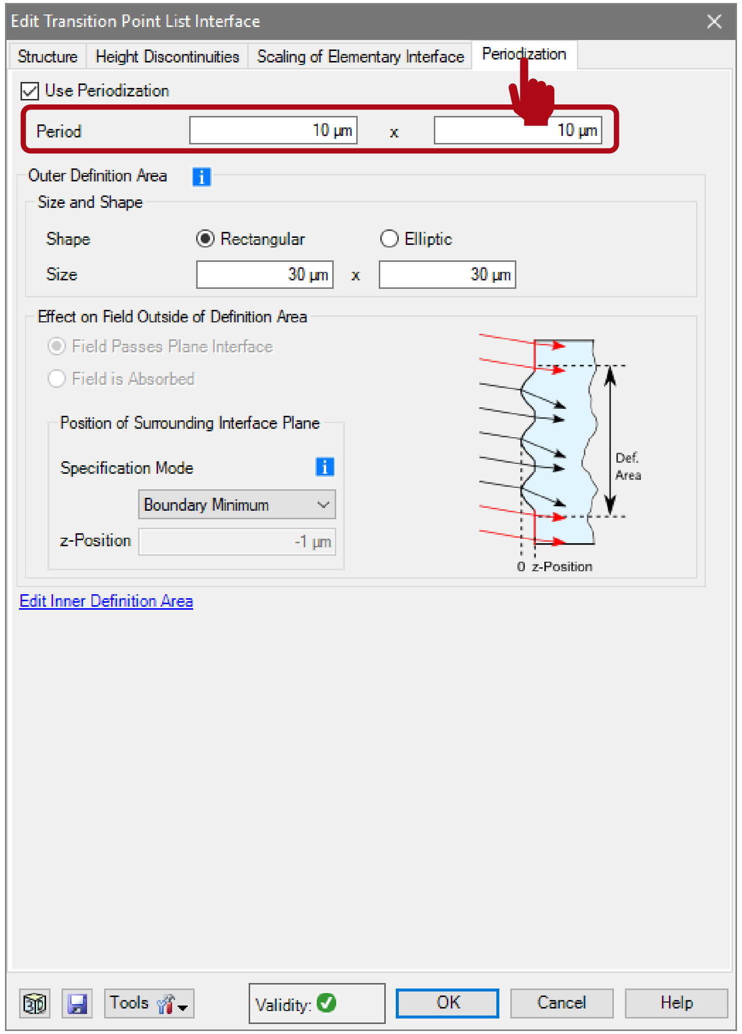
Transition Point List Parameters

- 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.



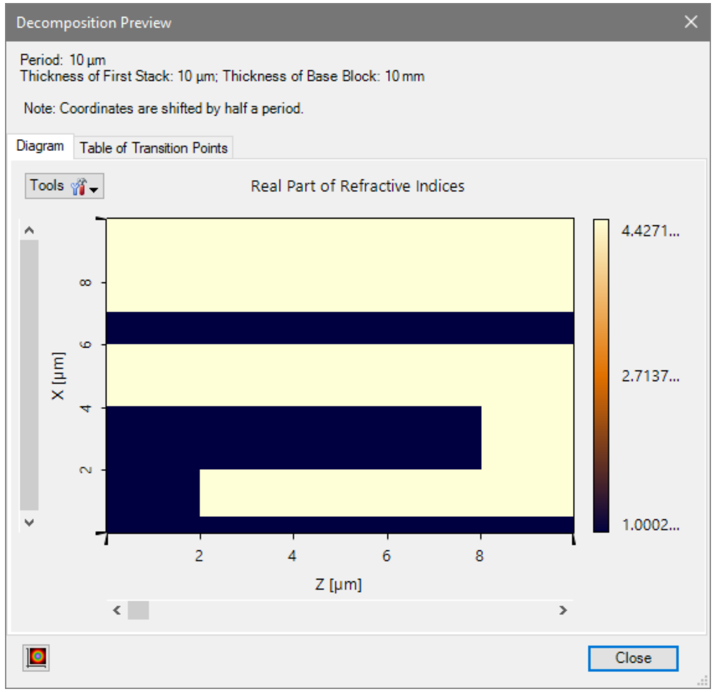
Transition Point List Parameters

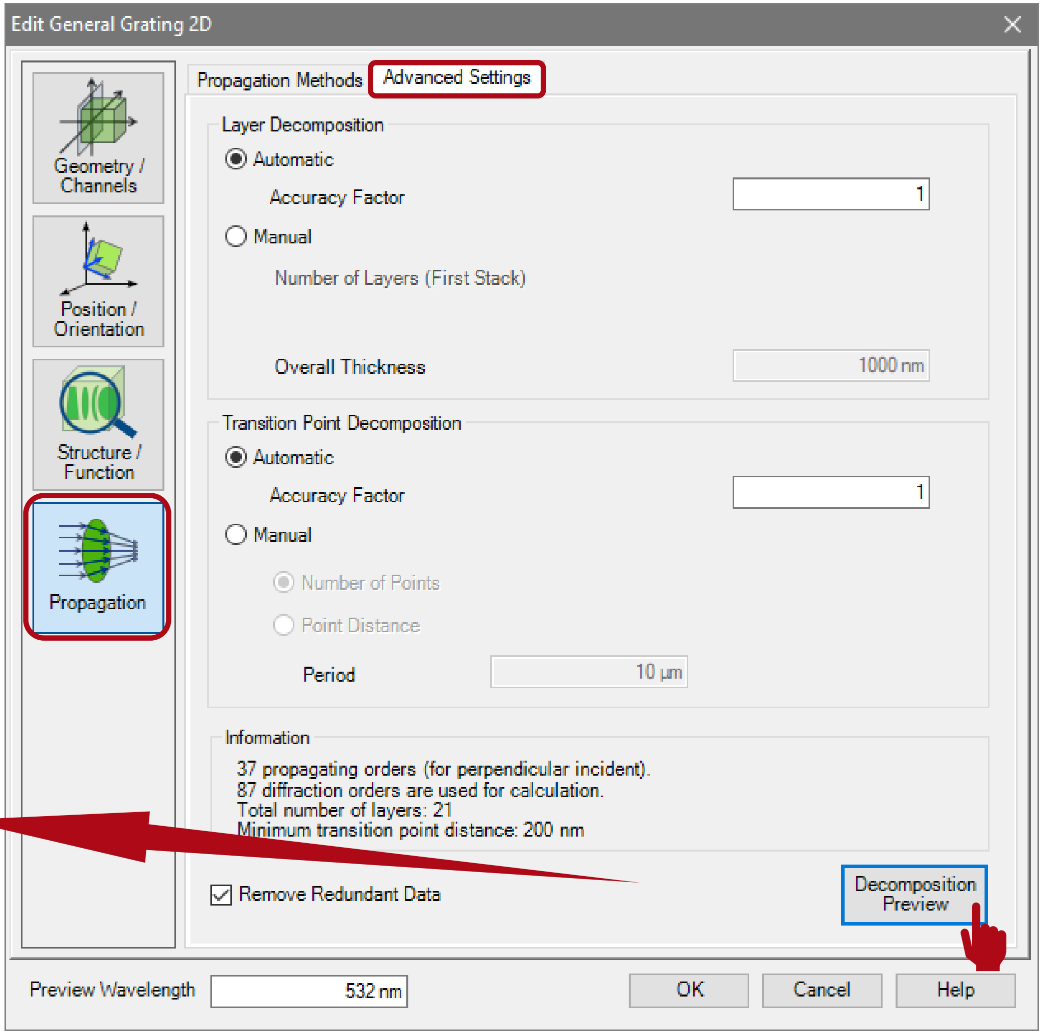
- The period of this interface has to be set in the *Periodization* tab.
- Here, the periods in x- and y-direction can be defined.
- The settings of the inner and outer definition area can be neglected in this case, because the extension of the interface is already truncated by the periodic boundary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



Advanced Options & Information

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

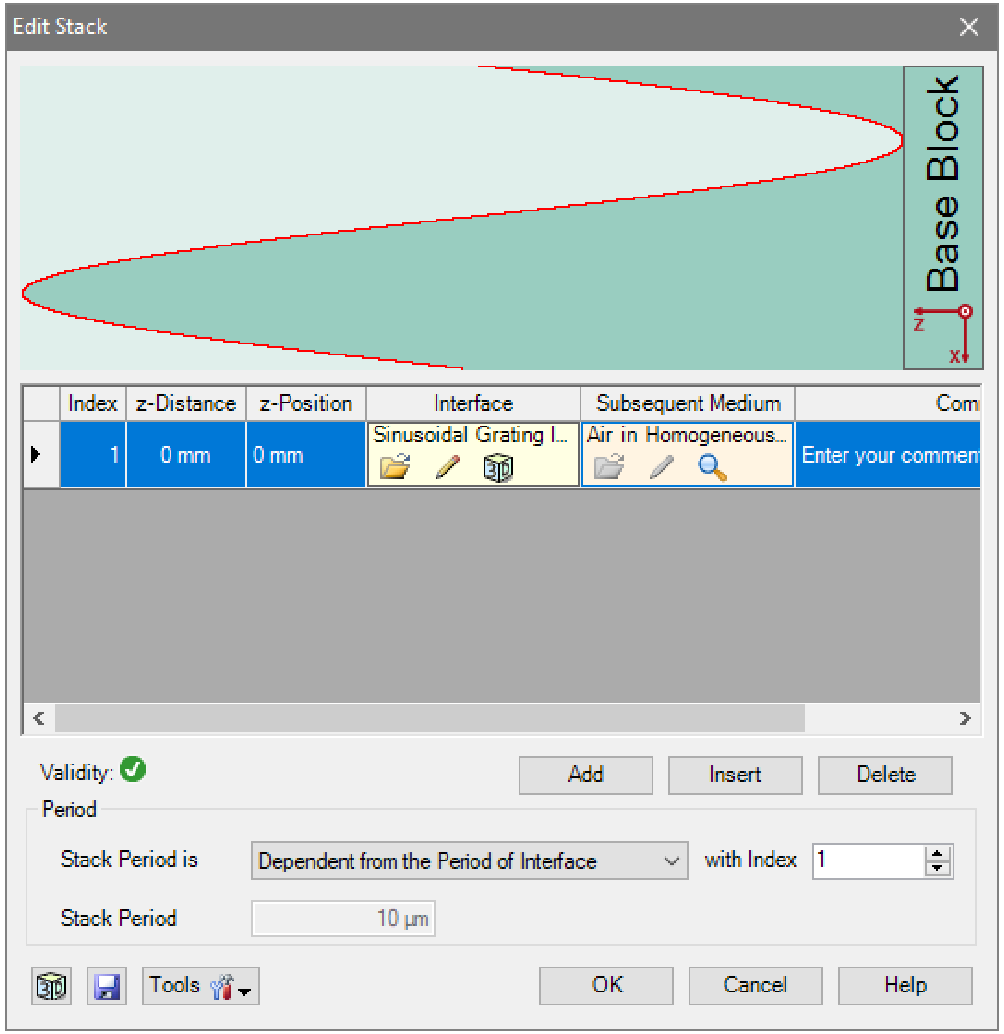




Sinusoidal Grating Interface

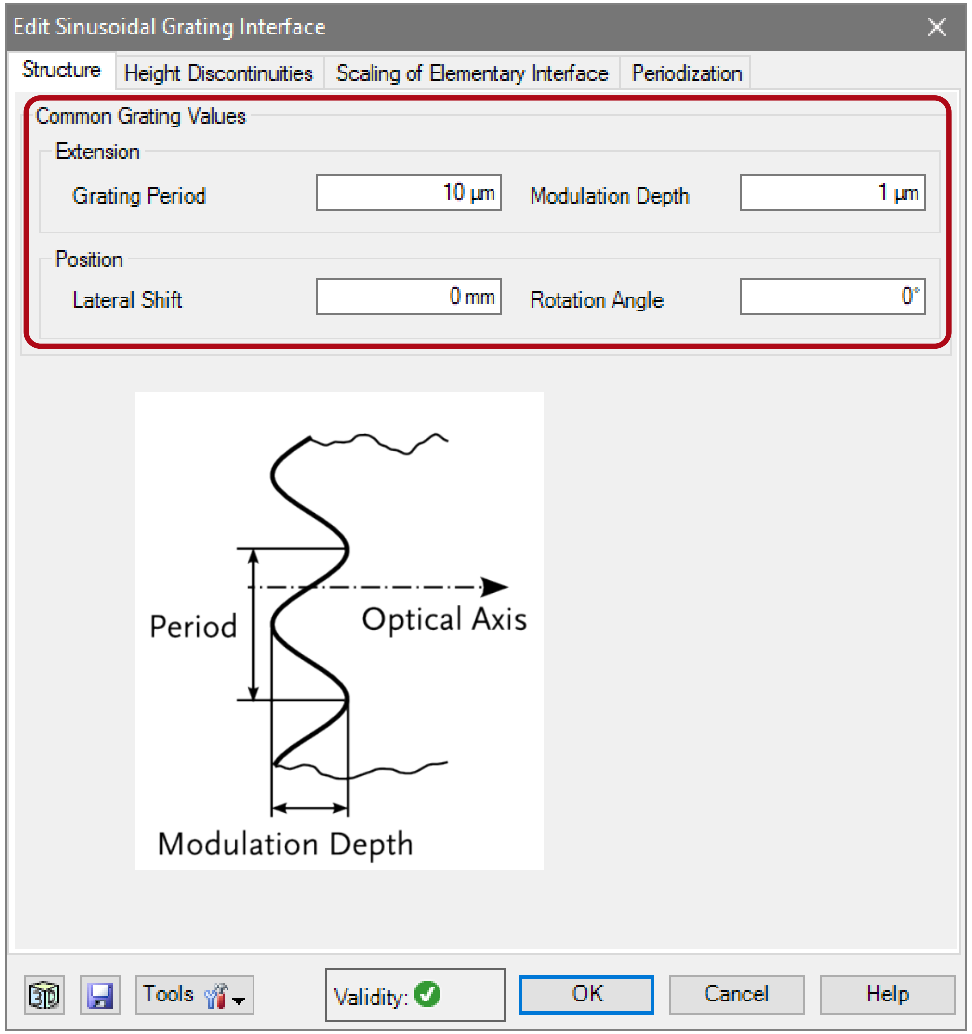
Sinusoidal Grating Interface

- 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



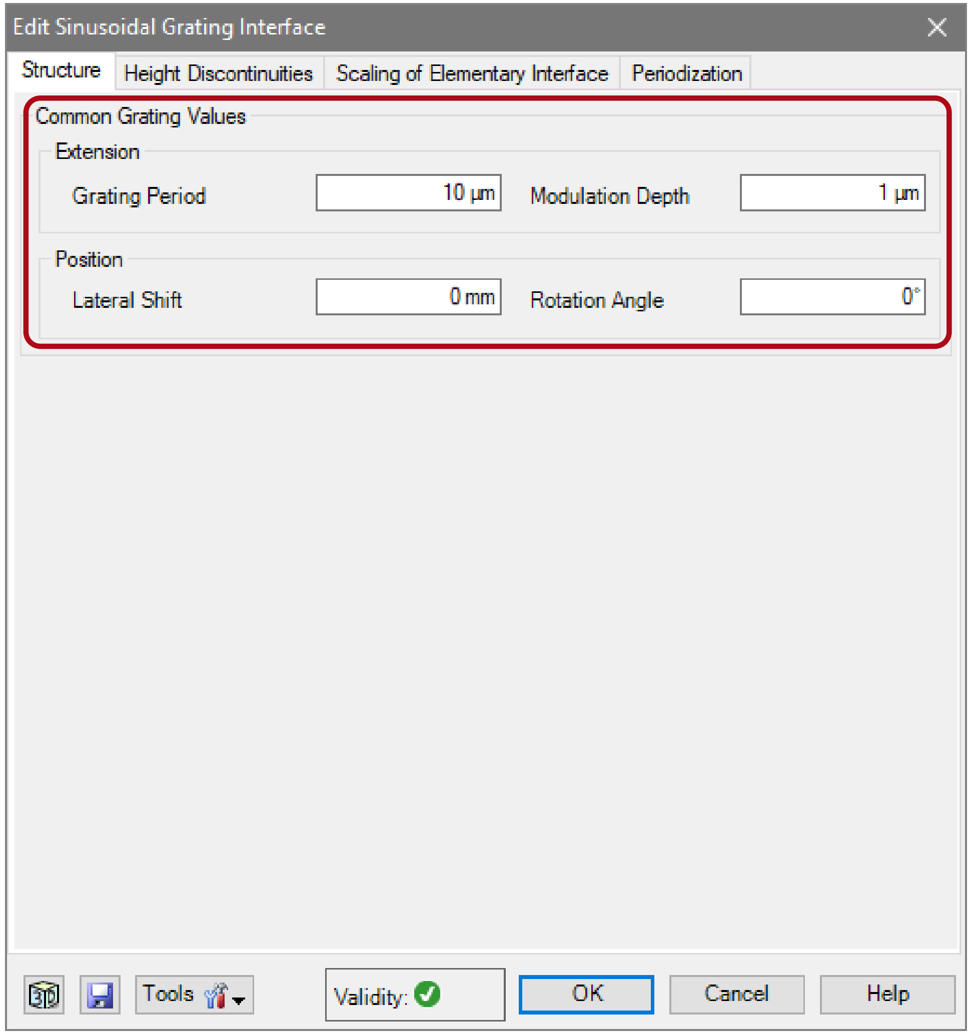
Sinusoidal Grating Interface Parameters

- 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.



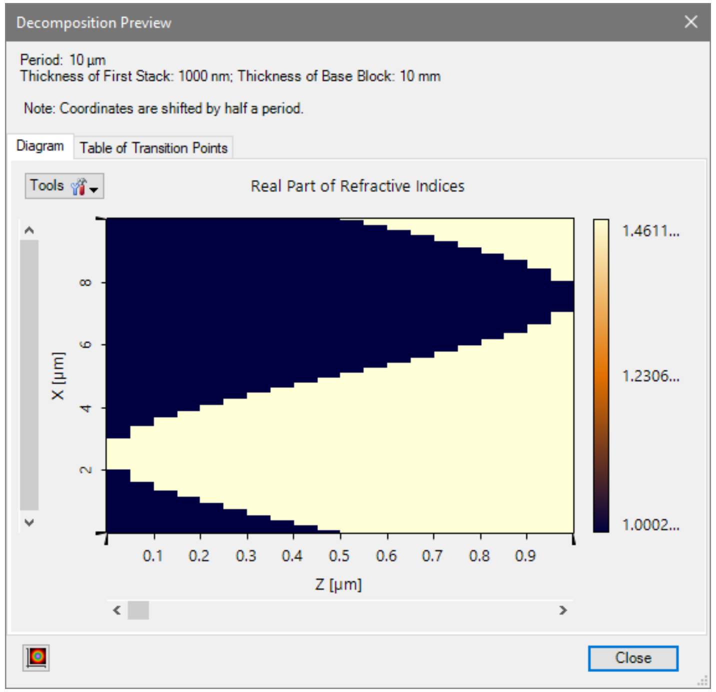
Sinusoidal Grating Interface Parameters

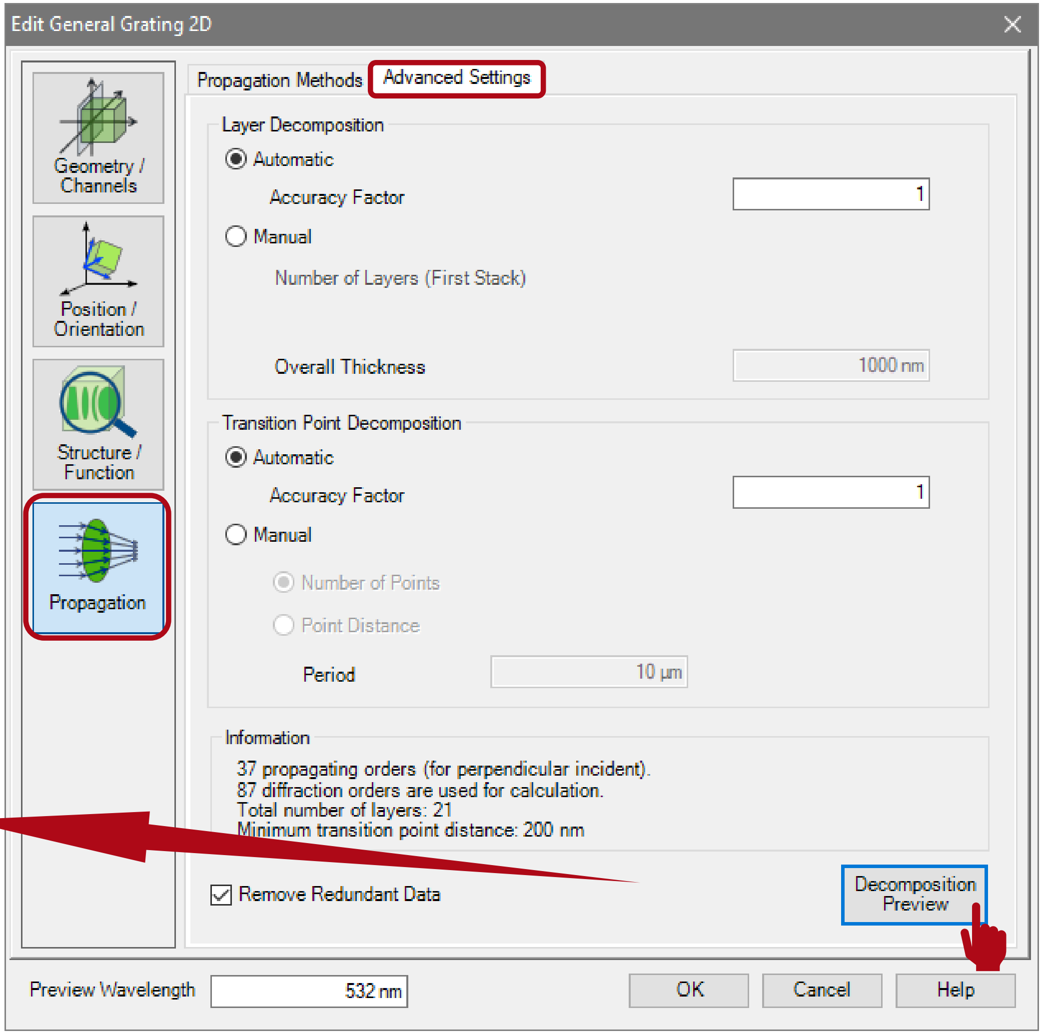
- The sinusoidal grating interface is also defined by the following parameters:
  - grating period
  - modulation depth
- A lateral shift and rotation can be set optionally.
- As this is a grating interface (likewise to the rectangular and sawtooth one) no periodization has to be chosen.



Advanced Options & Information

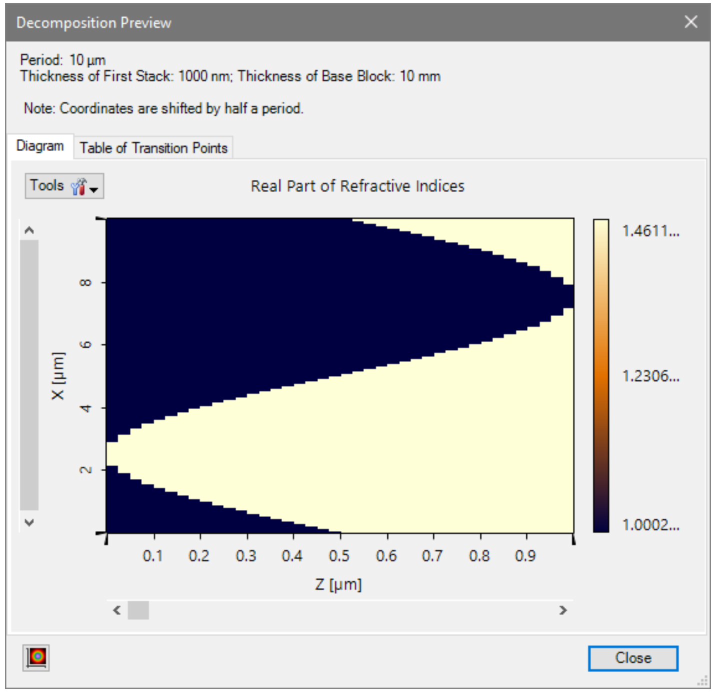
- Again, the data of the decomposed structure can be adjusted and investigated in the advanced settings tab.

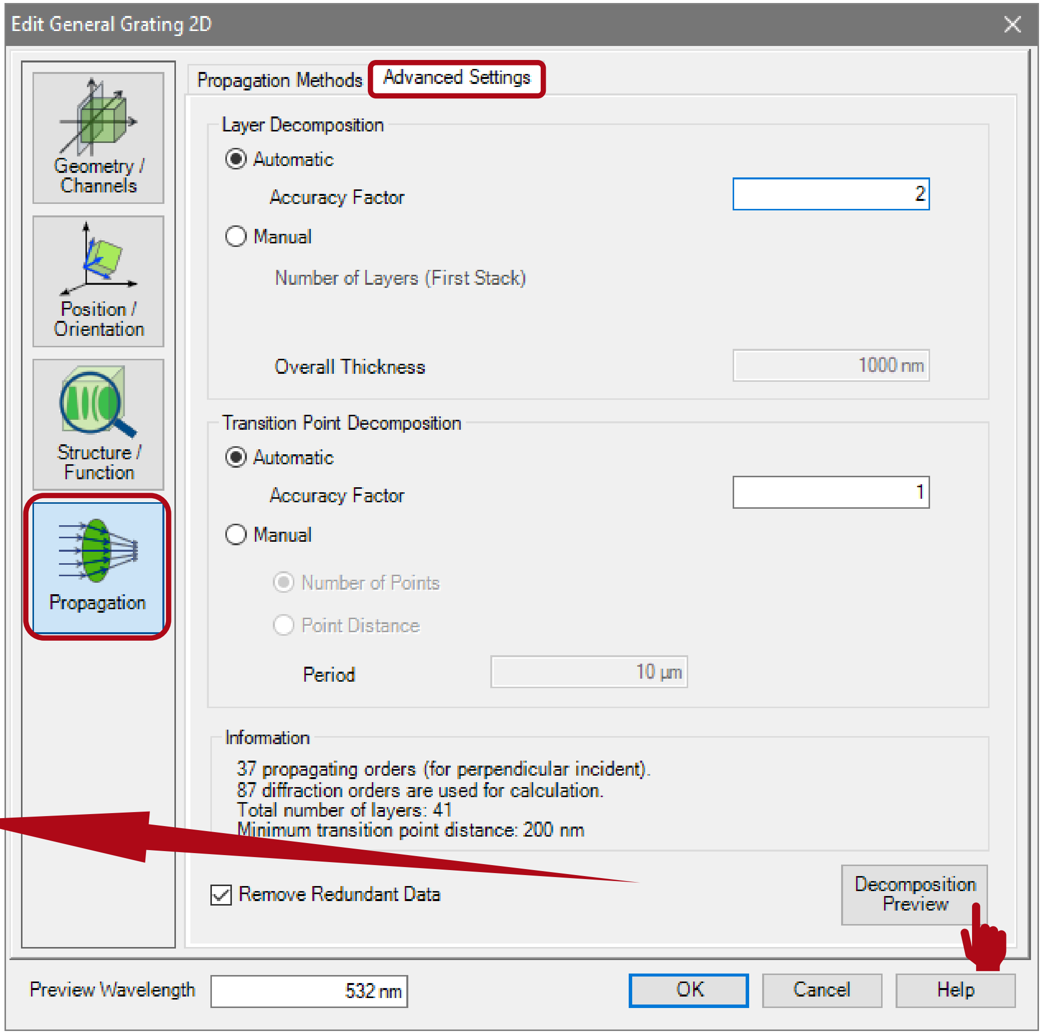




Advanced Options & Information

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

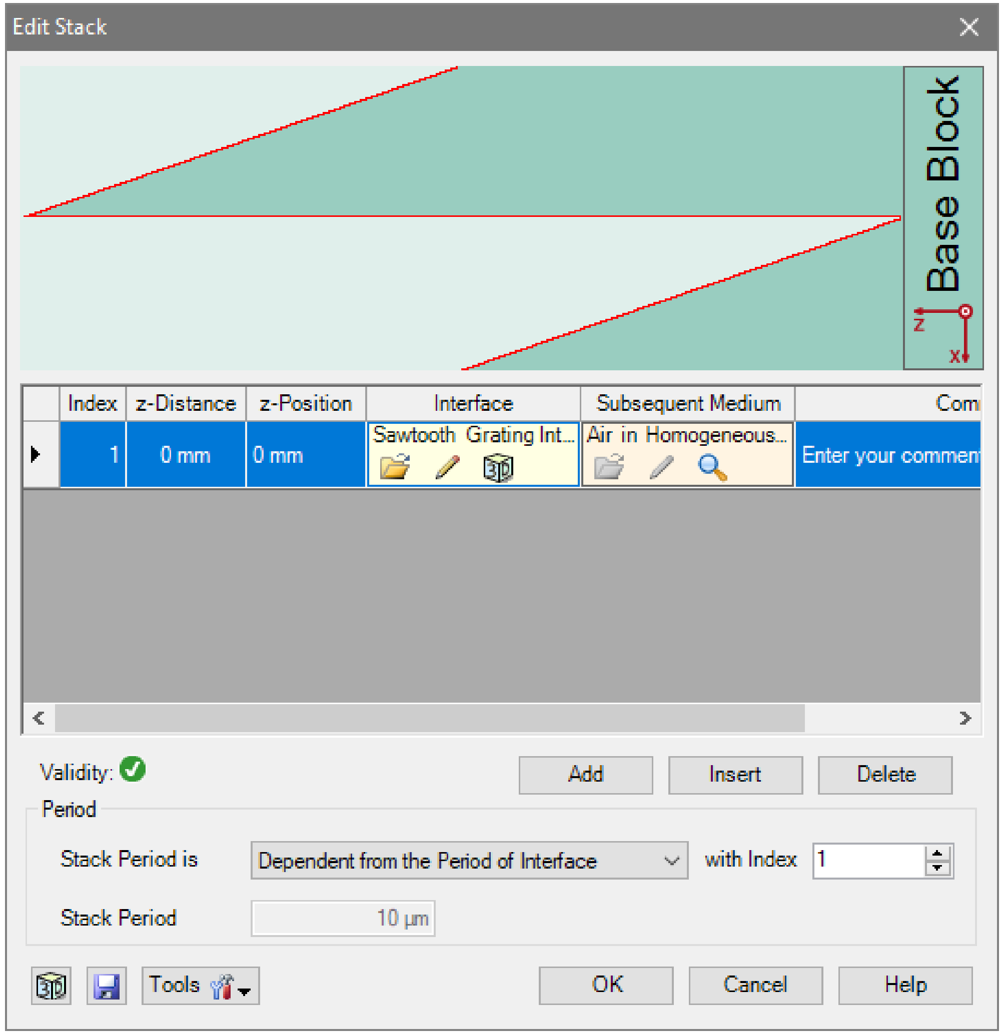




Sawtooth Grating Interface

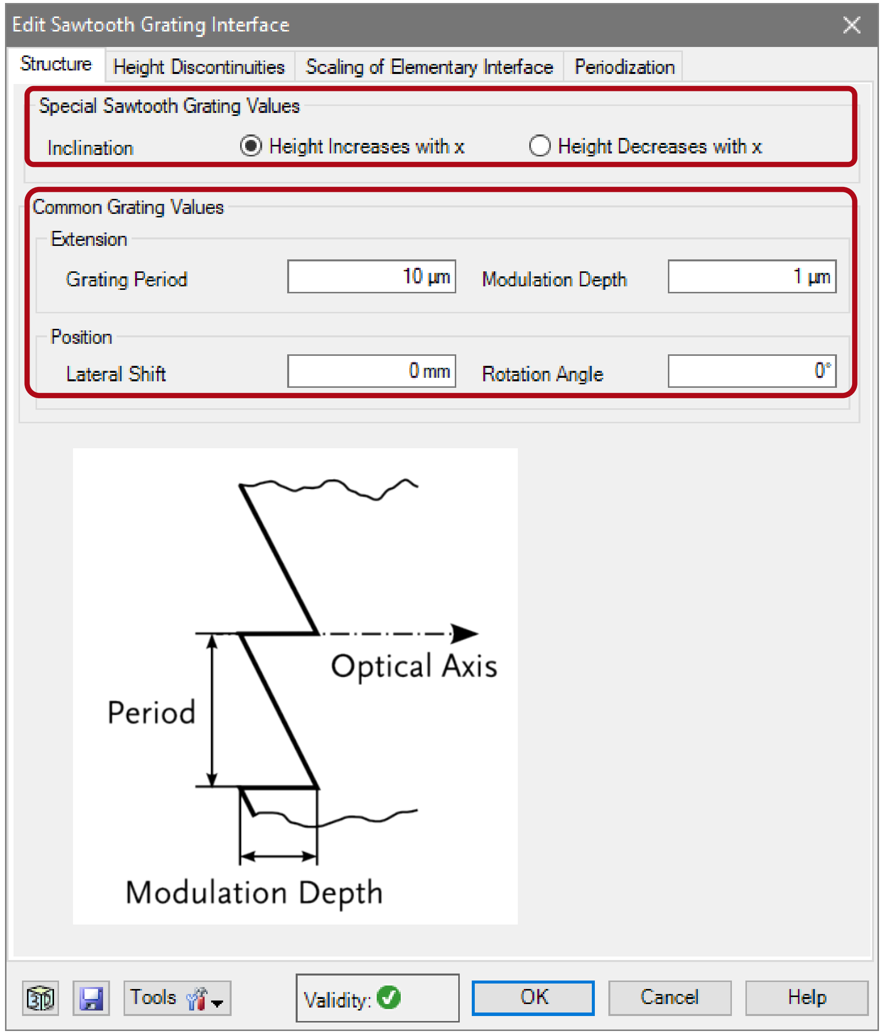
Sawtooth Grating Interface

- 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



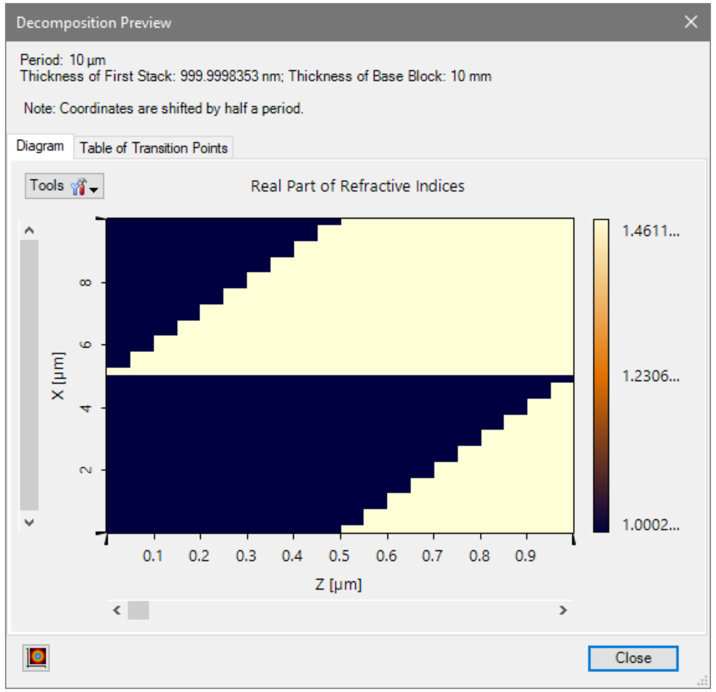
Sawtooth Grating Interface Parameters

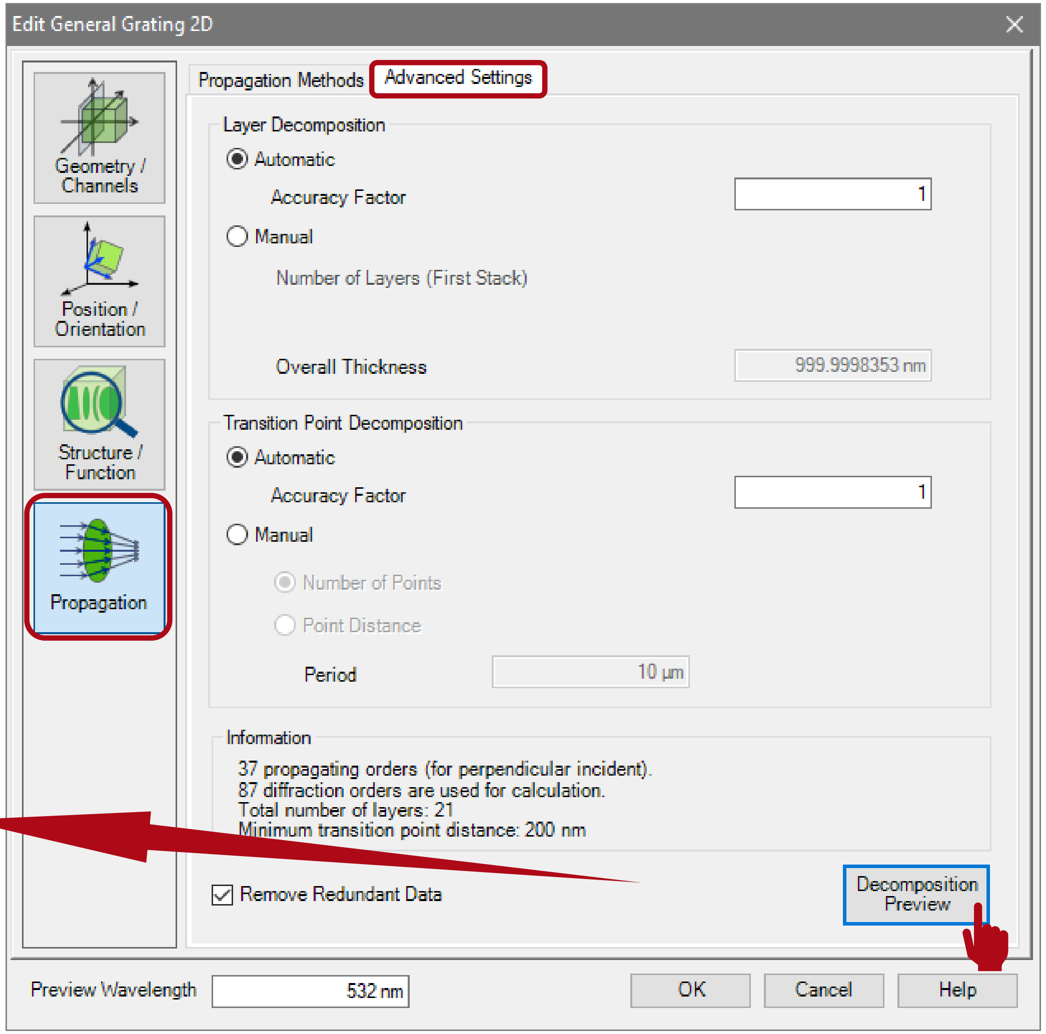
- The sawtooth grating interface is also defined by the following parameters:
  - grating period
  - modulation depth
- Further, the direction of the blaze can be adjusted by setting the inclination.
- A lateral shift and rotation can be set optionally.
- As this is a grating interface (likewise to the 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.

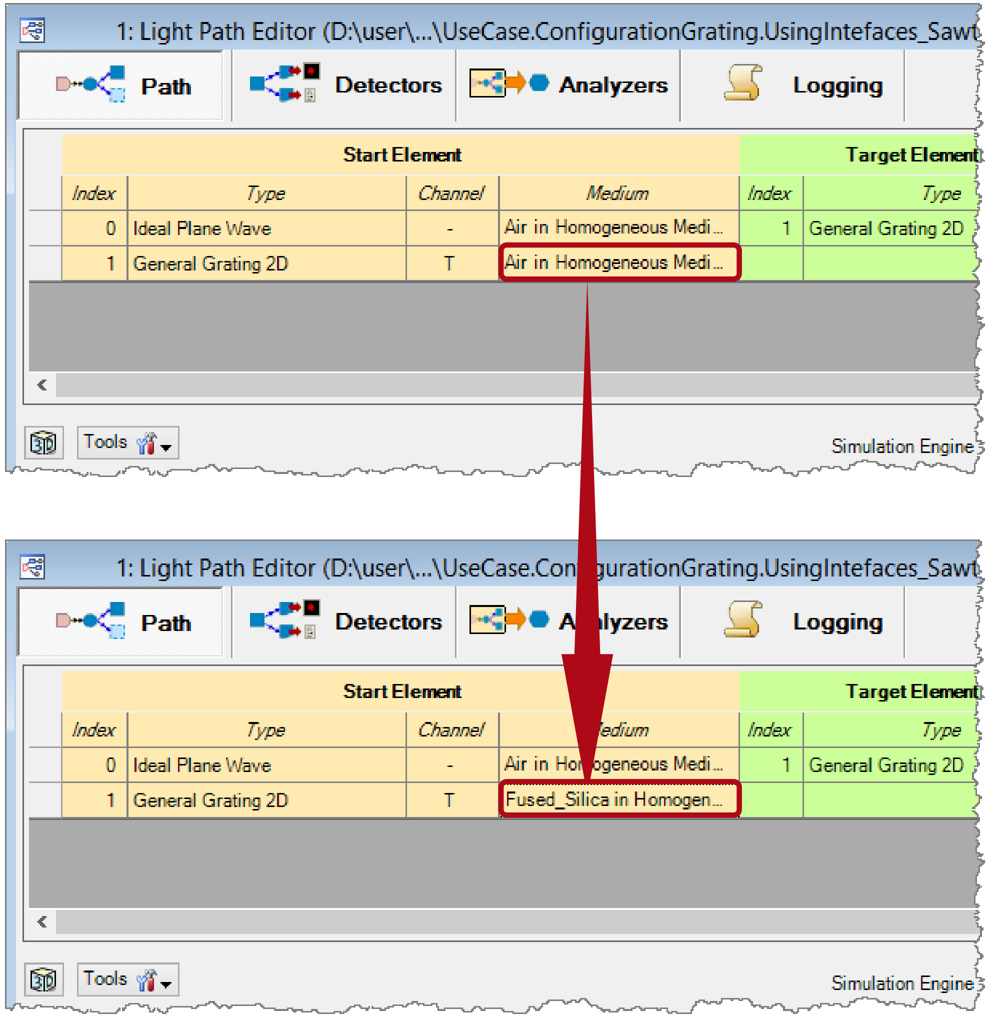




Remark on the Position of the Detector

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.



Document Information

title	Configuration of Grating Structures by Using Interfaces
version	1.1
toolbox(es)	Grating Toolbox
VL version used for simulations	7.4.0.49
category	Feature Use Case
further reading	- Configuration of Grating Structures by Using Special Media - Blazed Grating Analysis by Fourier Modal Method - Ultrasparse Dielectric Nanowire Grid Polarizers

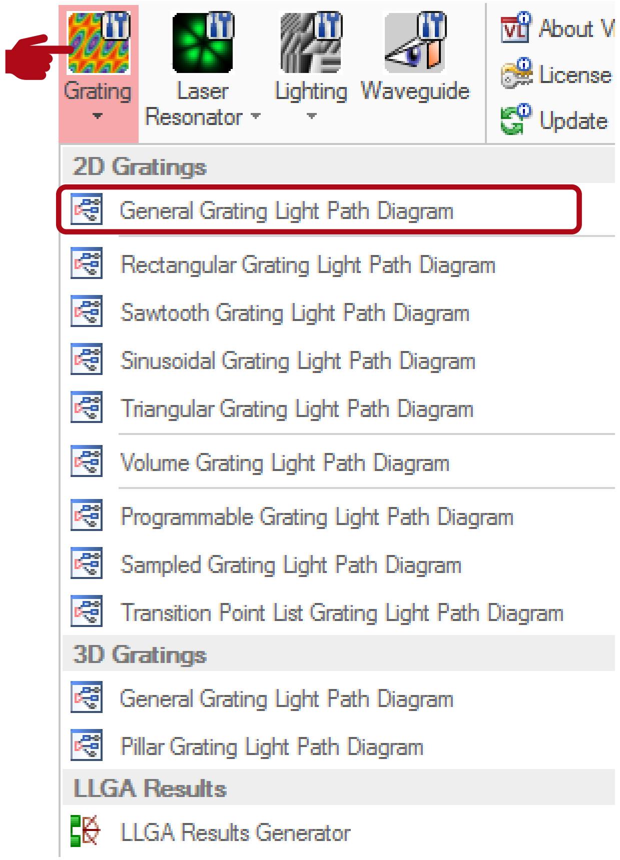
Configuration of Grating Structures by Using Special Media

This Use Case Shows ...

- How to configure grating structures in Grating Toolbox by using special media, e.g.:
  - slanted grating medium
  - volume grating medium
- How to change advanced options & inspect defined structure before calculation.

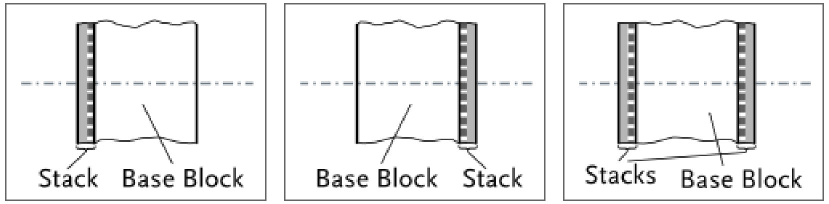
Grating Toolbox Initialization

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

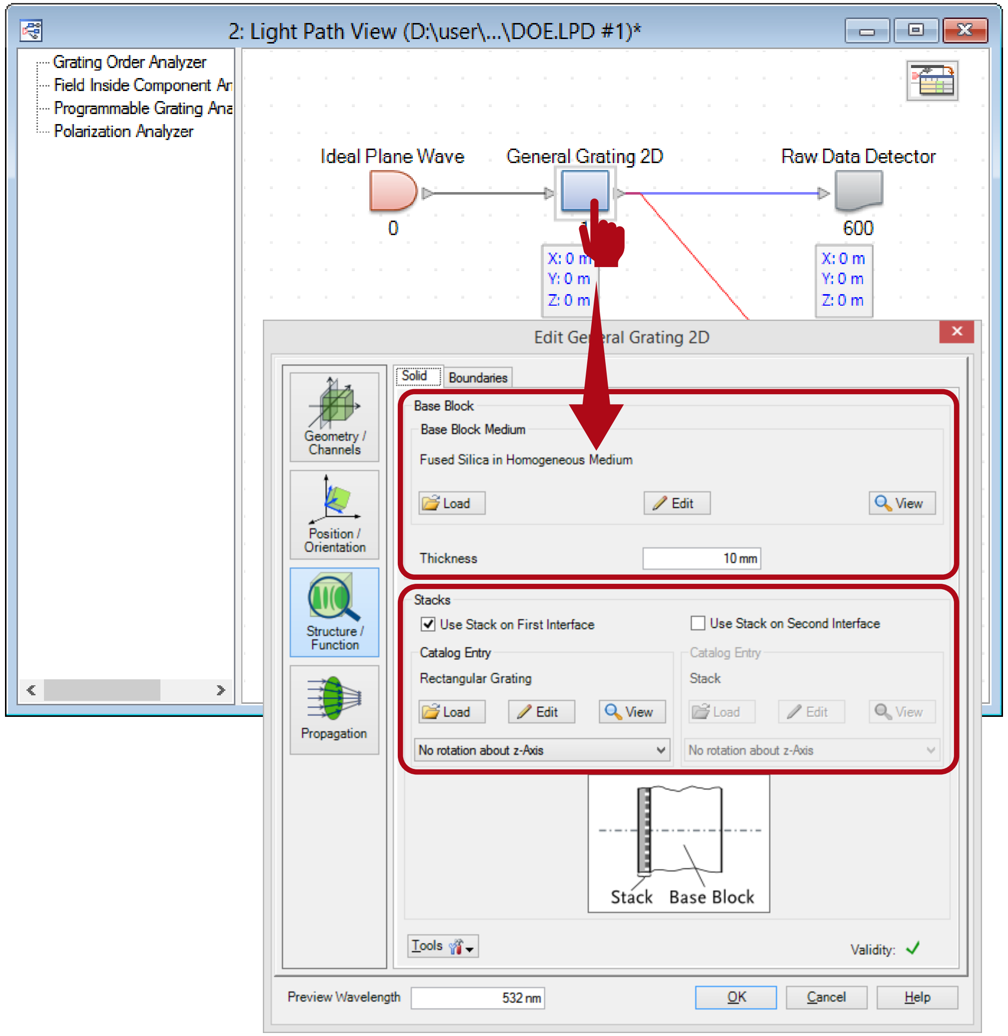


Grating Structure Settings

- 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.

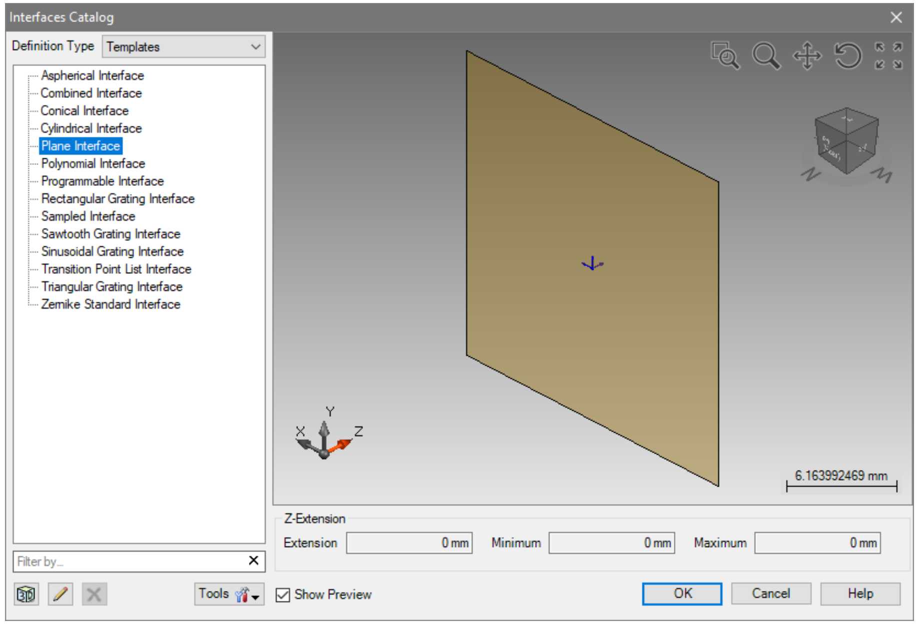


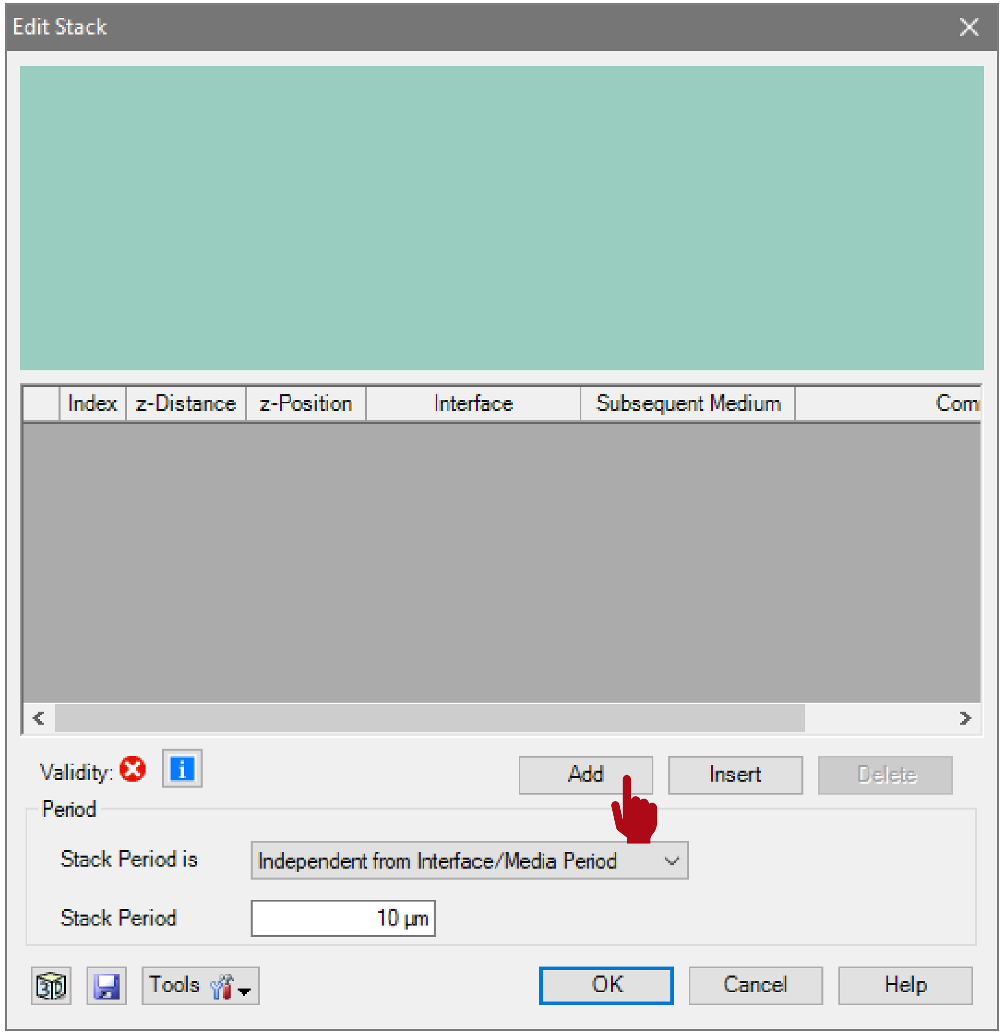
- For example, a stack on the first interface is chosen.



Stack Editor

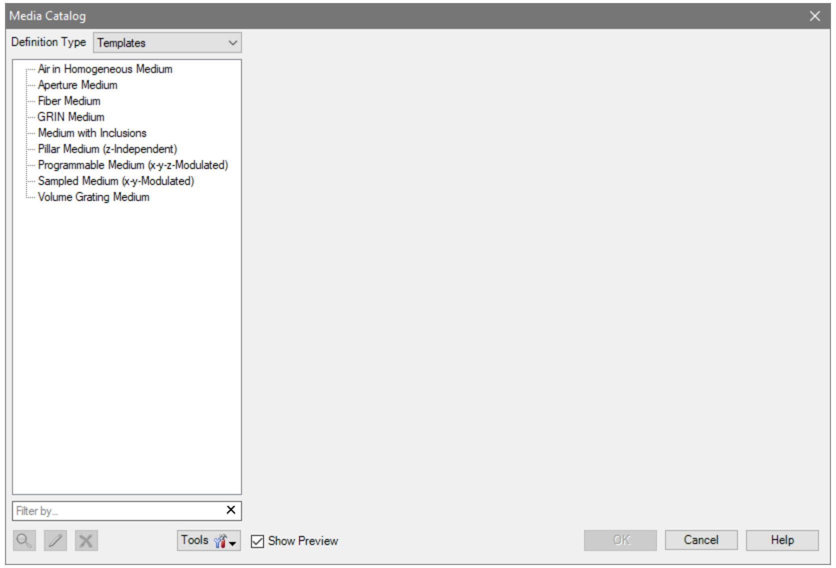
- In the Stack Editor interfaces and media can be added or inserted from catalog.
- In order to define a grating by a special medium, two plane interfaces have to be added, which act as boundaries.

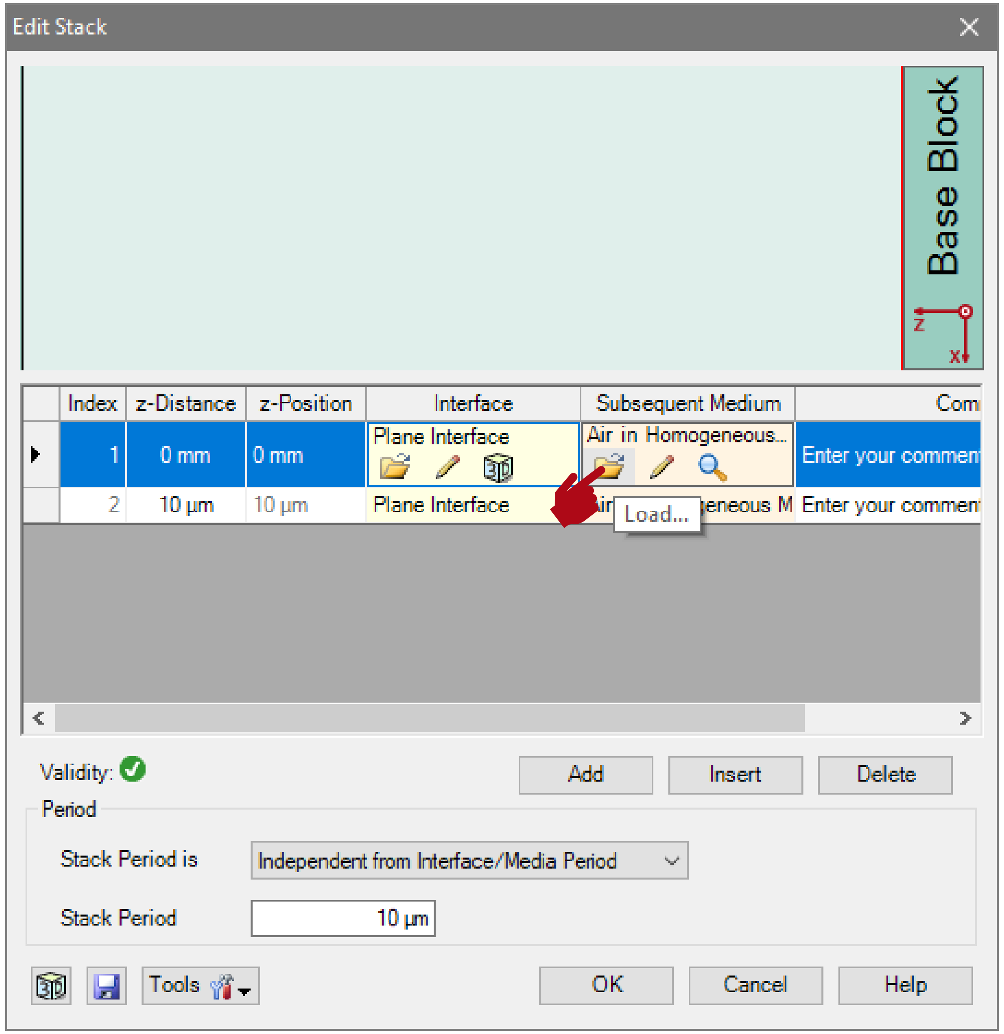




Stack Editor

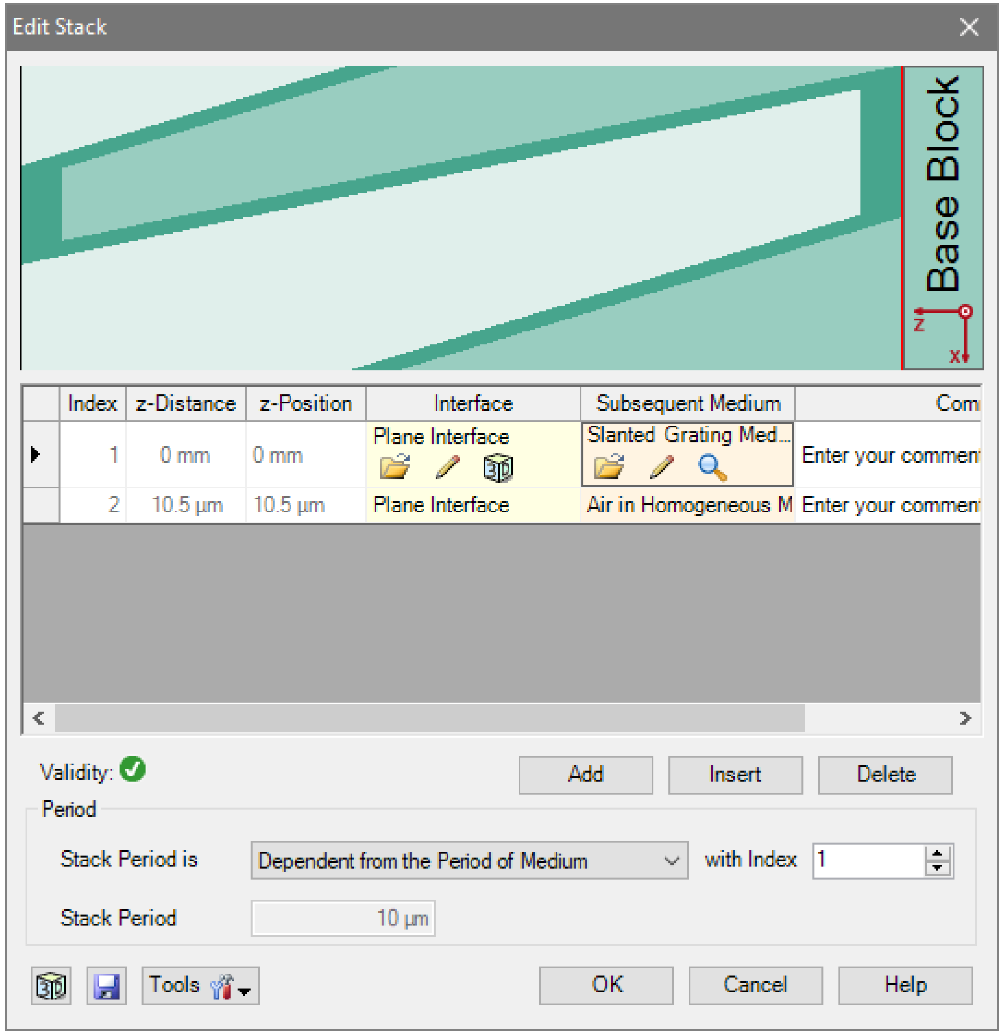
- The medium between the two plane interfaces can be either homogenous or modulated.
- By using a latter one complex grating structures, like slanted gratings, can be described very efficiently.





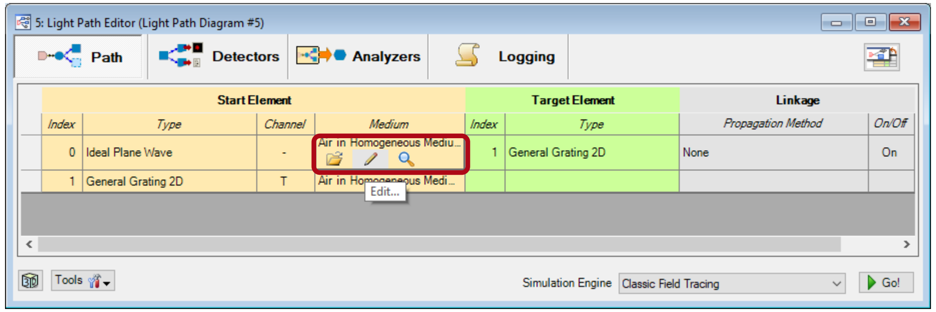
Coated Slanted Grating Medium

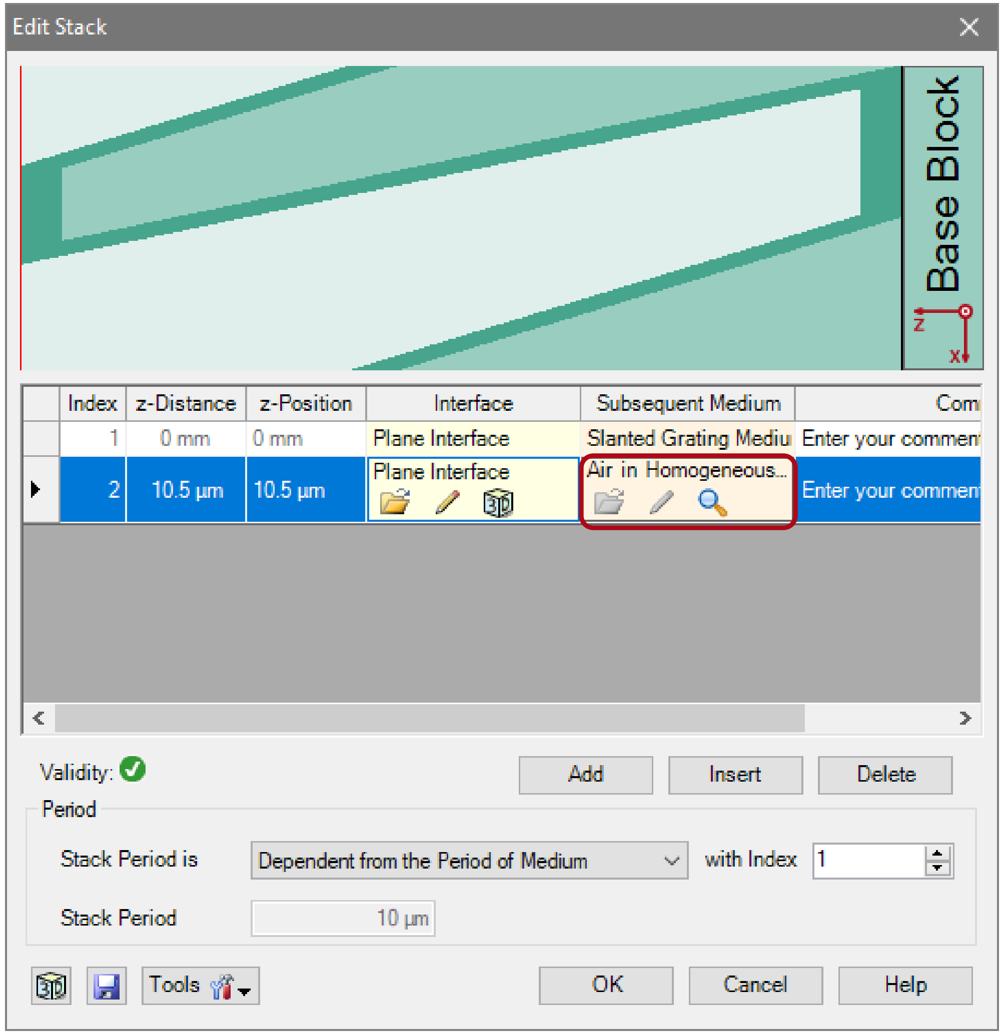
- In the catalog category “Templates” the Slanted Grating Medium can be found.
- This type of medium enables the use of slanted grating structures either with or without an additional coating.
- In this example, a grating made of fused silica with a coating consisting of chromium is located on a glass substrate.
- In the view of the stack editor, different materials are indicated by other colors based on their index of refraction (dark means higher).



Coated Slanted Grating Medium

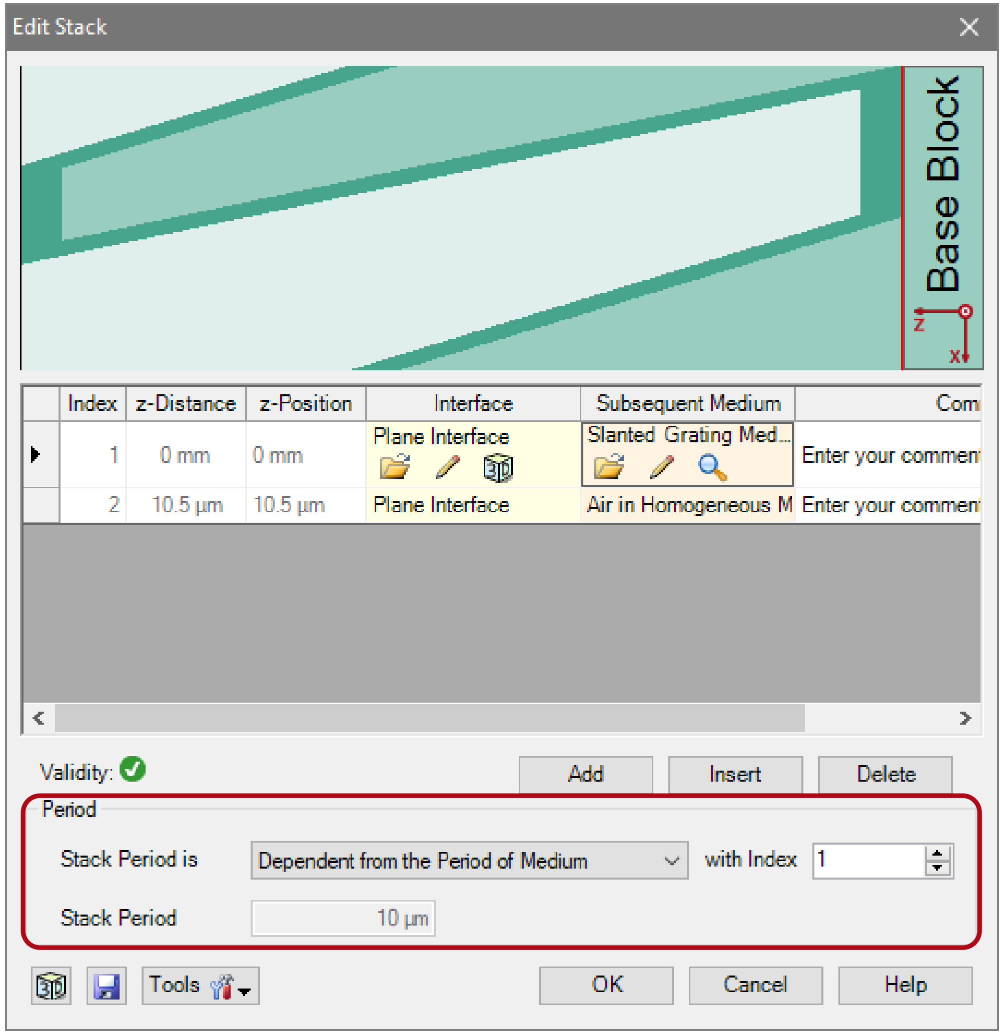
- Please note: the order of the interfaces is always counted from the surface of the substrate.
- The selected interface is highlighted red in the view.
- Further, the medium in front of the grating (means behind last interface) can not be defined here. It is automatically taken from the material in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





Coated Slanted Grating Medium

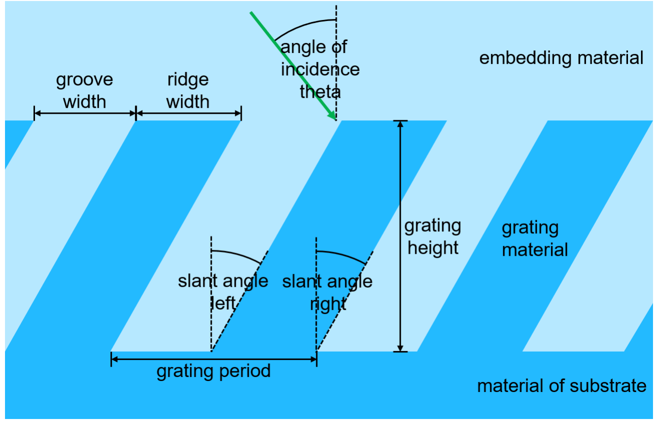
- The Stack Period allows to control the period of the whole configuration.
- This period is also taken for the periodic boundary conditions of the FMM algorithm.
- In case of simple grating structures, it is recommended to choose the option Dependent from Period of Medium and select the proper index of the periodic medium.
- Further, the distance between both interfaces is controlled by the grating height, automatically.

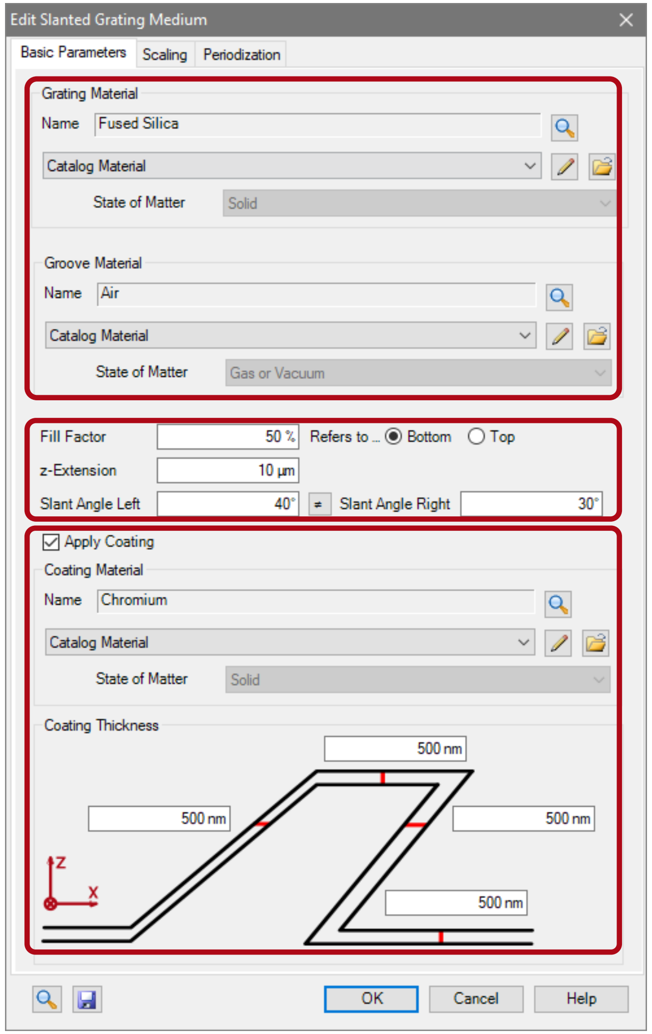


Coated Slanted Grating Medium Parameters

The slanted grating is defined by the following parameters:

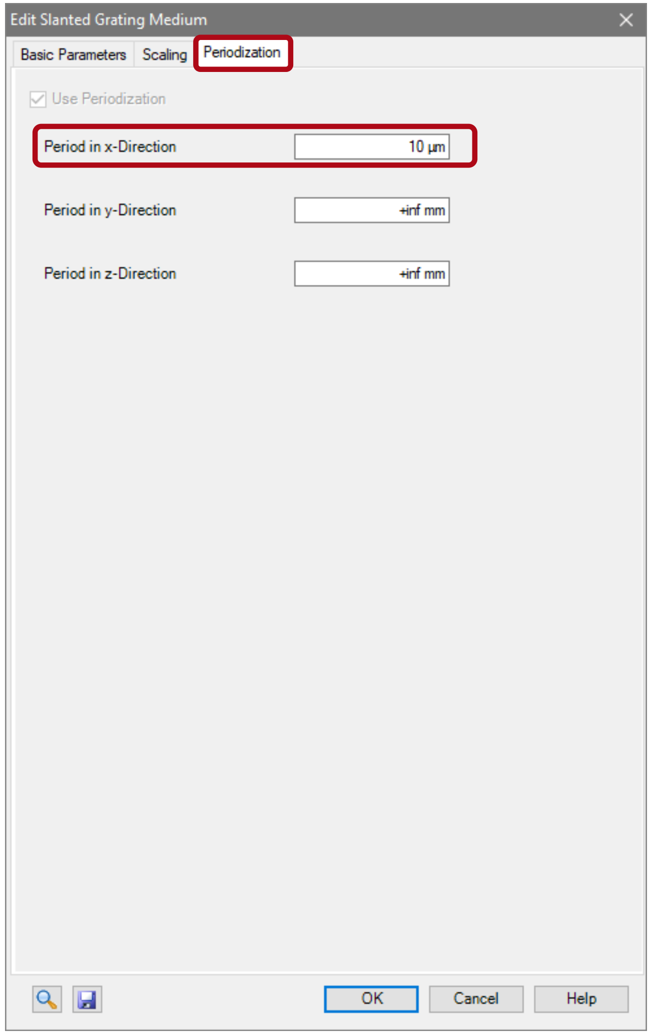
- grating material (material of ridges)
- material of grooves
- fill factor (ether referring to top or bottom)
- z-extension (grating height along z-direction)
- slant angle of side walls (left and right)
- material of coating
- thickness of coating for each side individually
- grating period





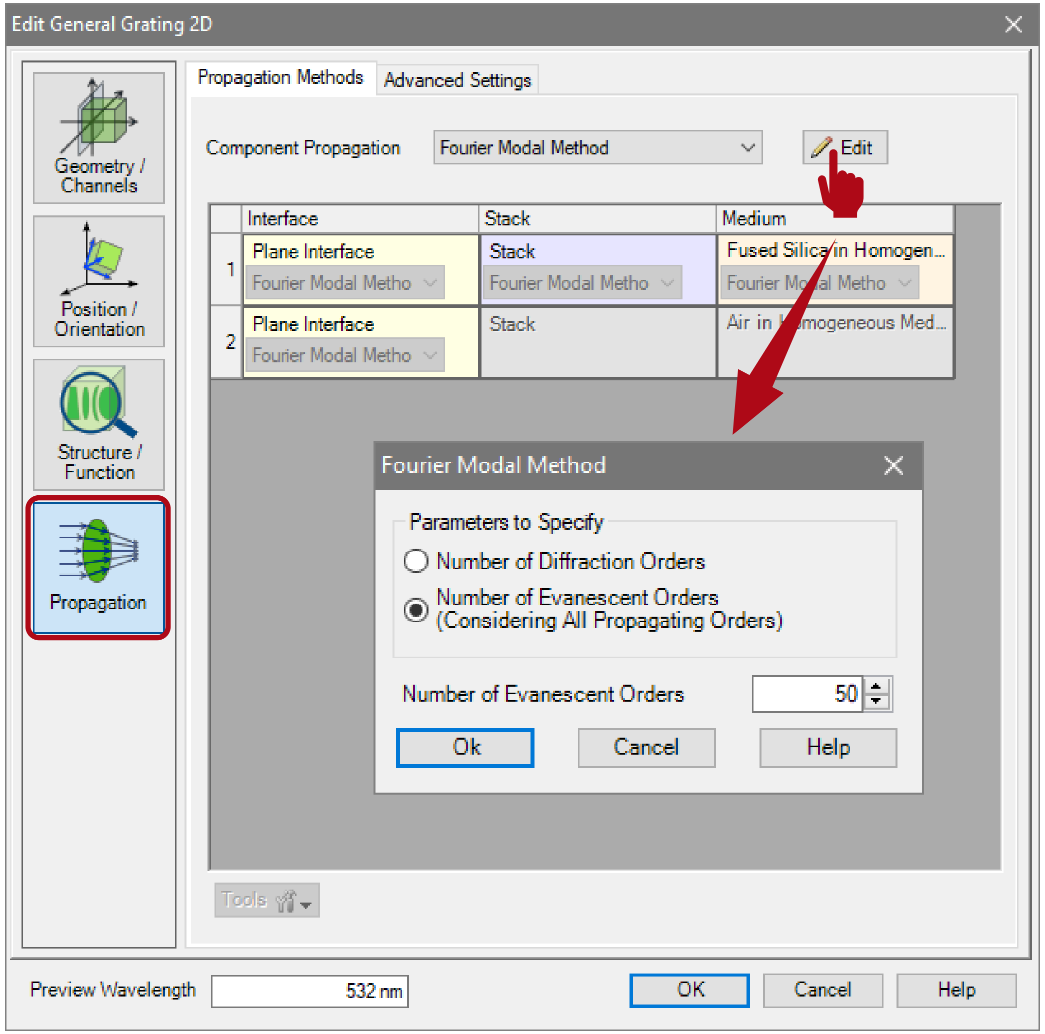
Coated Slanted Grating Medium Parameters

- As this grating is based on a medium definition type, the grating period has to be set in the periodization tab.



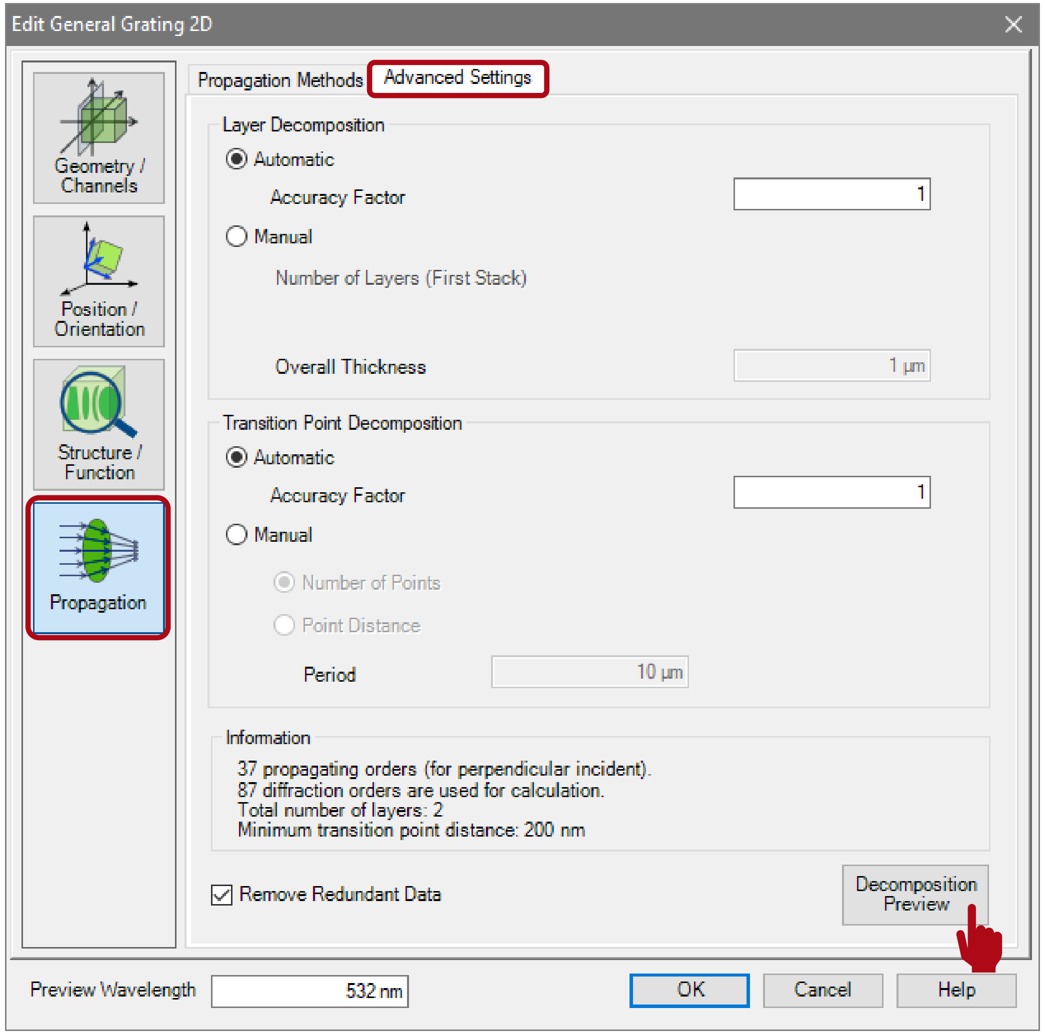
Advanced Options & Information

- 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.



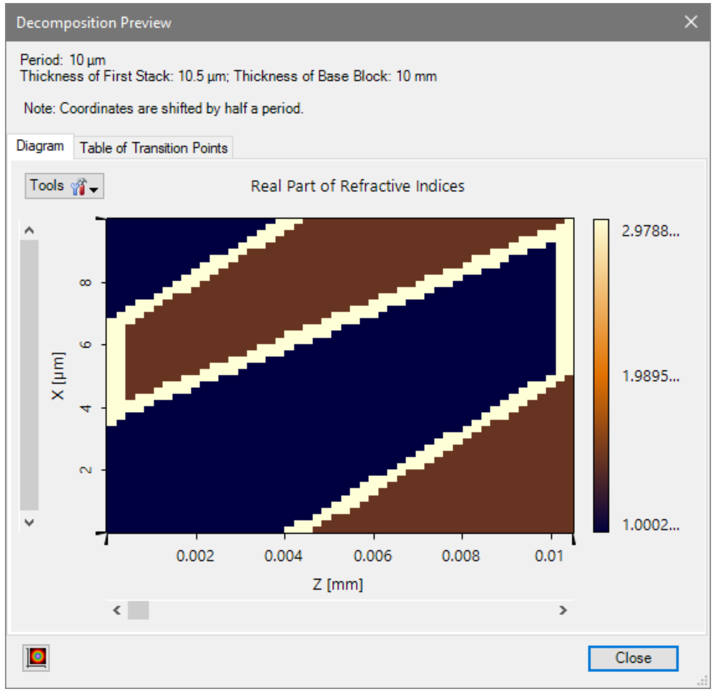
Advanced Options & Information

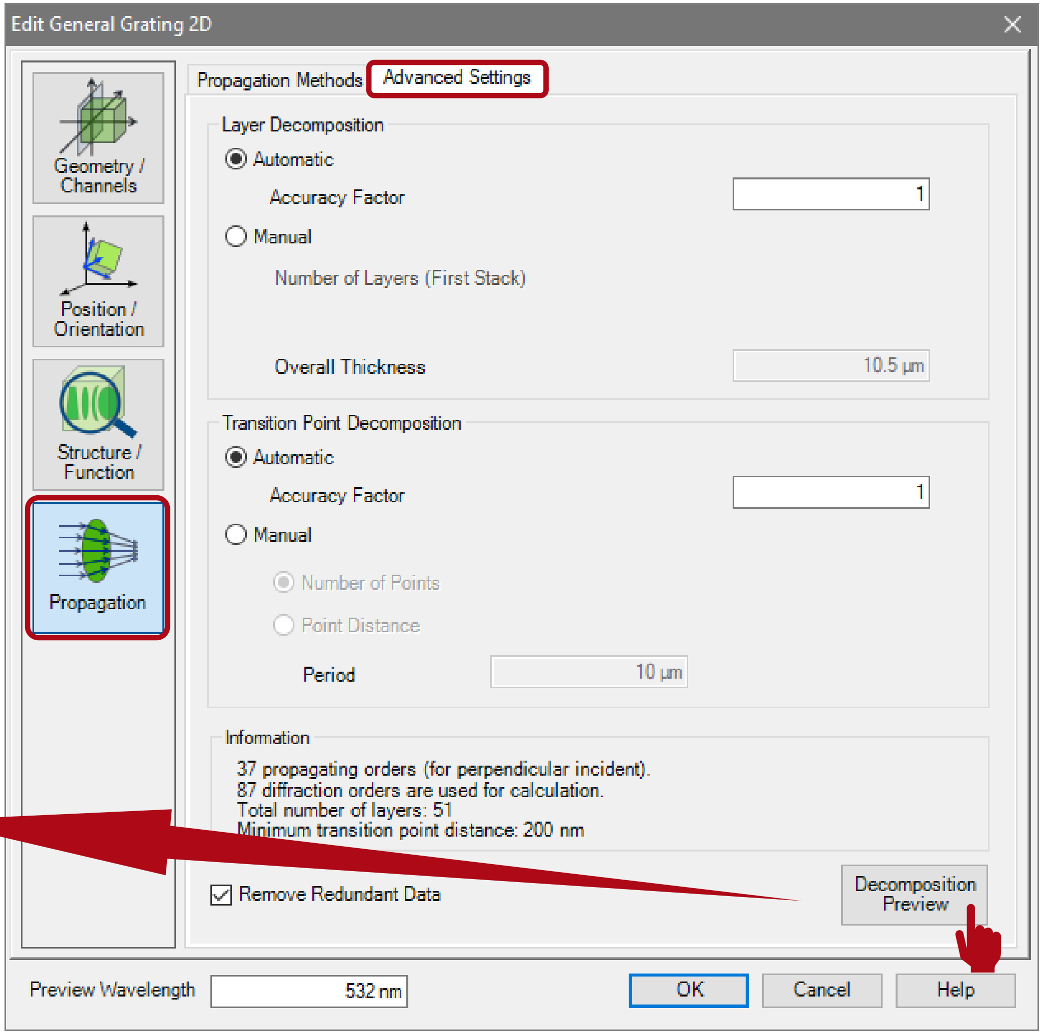
- The Advanced Settings tab provides information about the decomposition of the structure.
- The Layer Decomposition and Transition Point Decomposition settings can be used to adjust the discretization of the structure. The default settings are appropriate for nearly all grating structures.
- Further, 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.



Advanced Options & Information

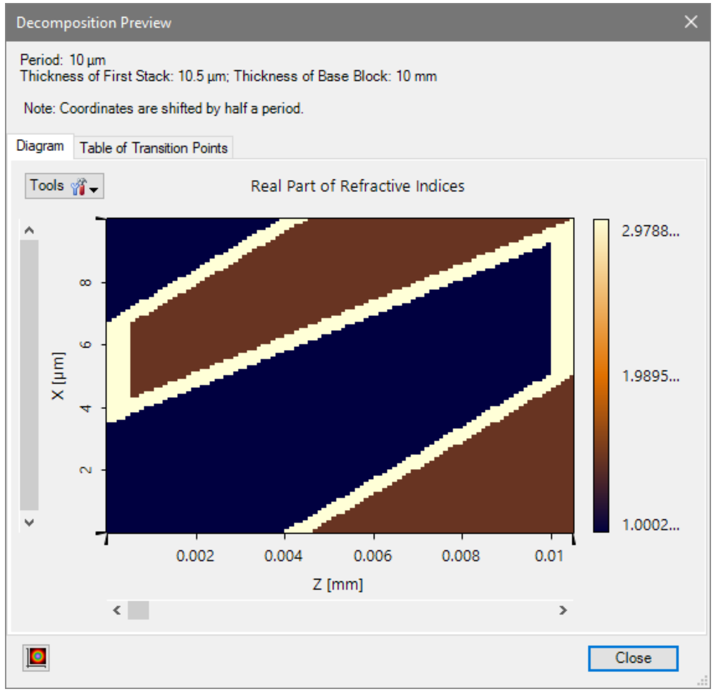
- The decomposition preview of the defined coated slanted grating.
- VirtualLab suggests a discretization in 51 layers (1 layer is representing the substrate)

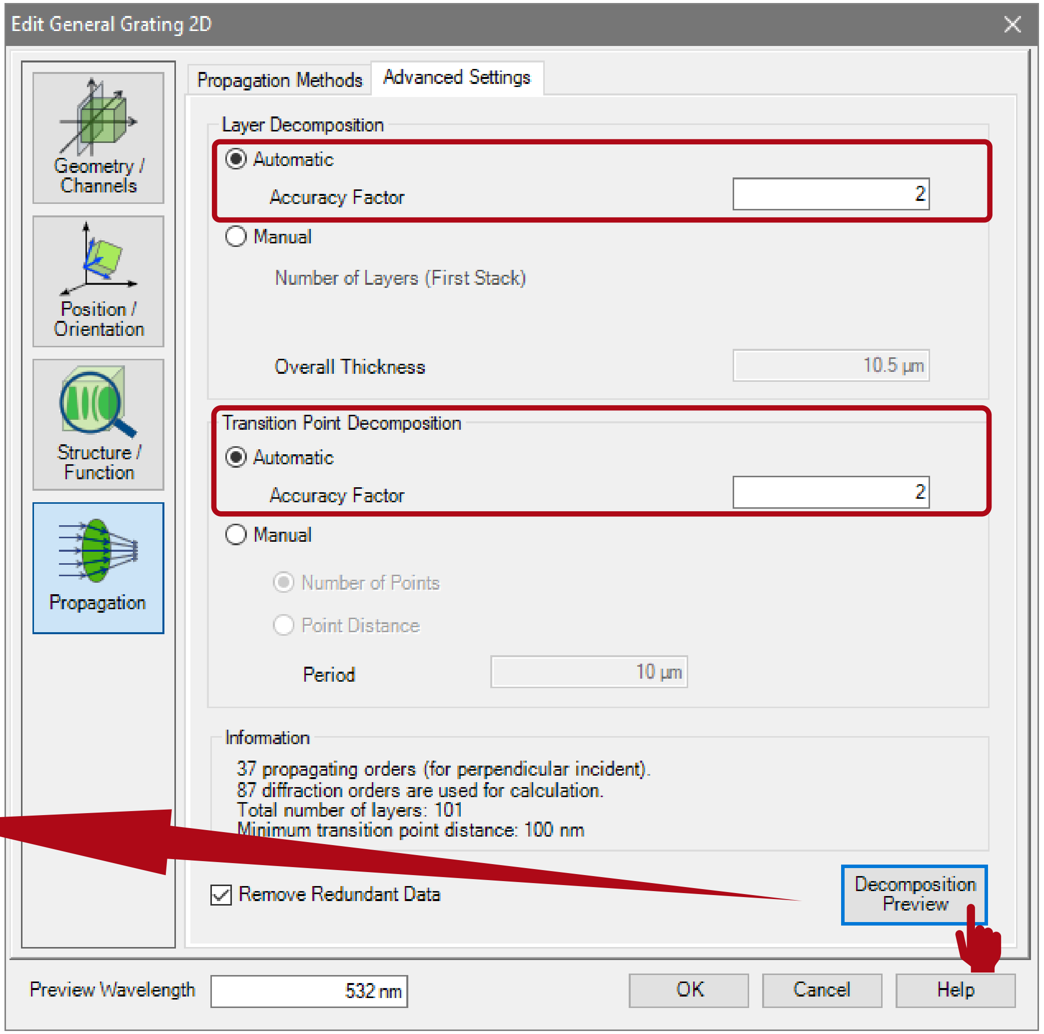




Advanced Options & Information

- If the numbers of layers and transition points are increased (e.g. by a factor of 2), the discretization becomes less rough. (because a medium is sampled both values have to be increased)

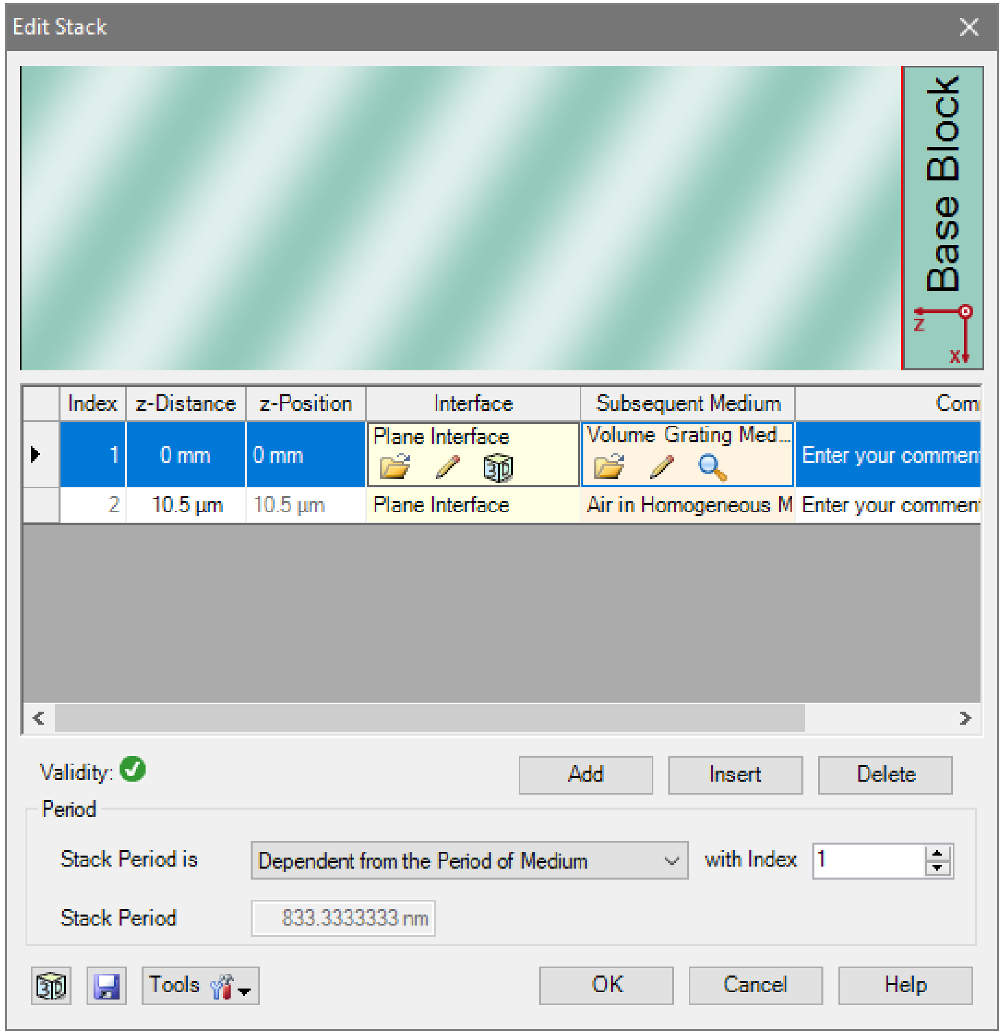




Volume Grating Medium

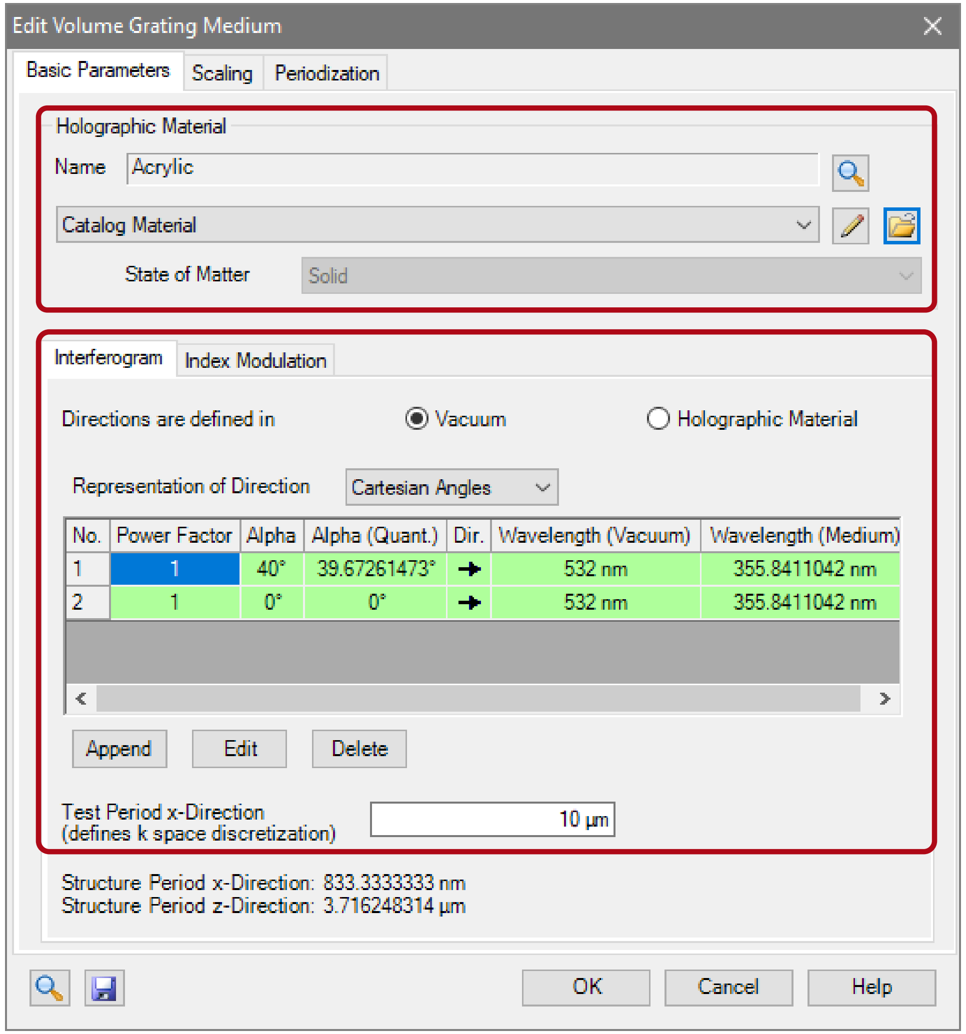
Volume Grating Medium

- Another type of medium which can be used for the configuration of gratings is the volume grating medium.
- This interface allows to configure a modulations of the refractive index, which was e.g. generated by holographic exposure.
- Again, two plane interfaces are used as boundaries of the medium.



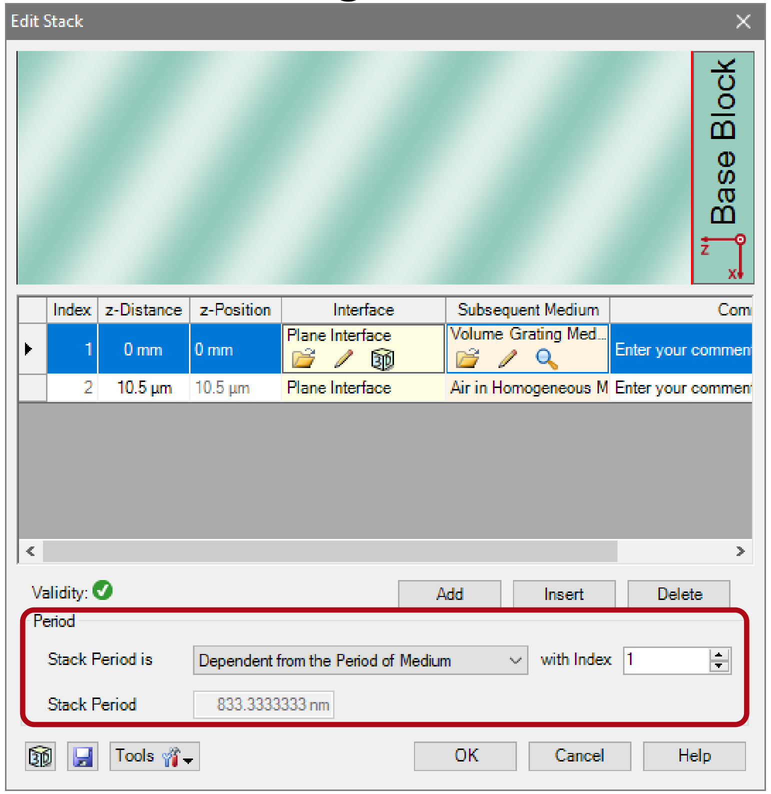
Volume Grating Medium Parameters

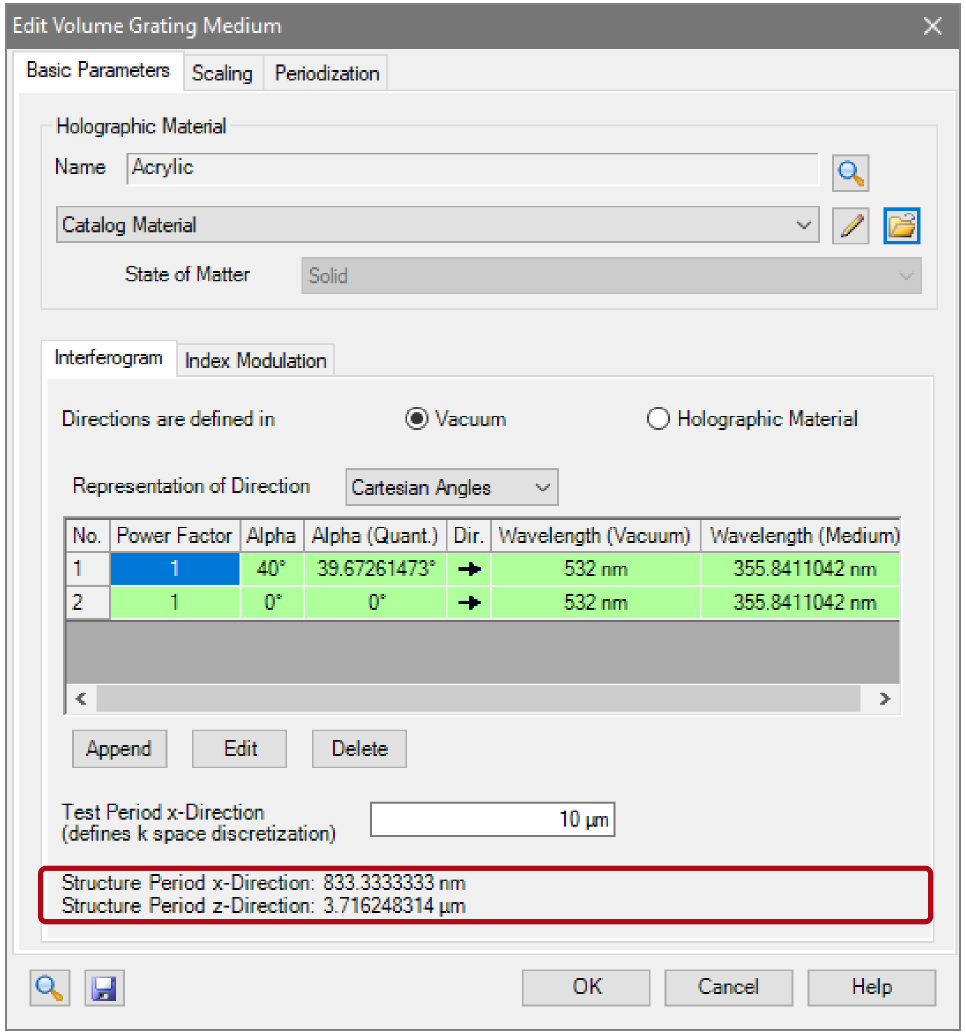
- In order to describe volume grating VirtualLab simulates the interference pattern of a certain number on impinging waves.
- First, a holographic medium has to be chosen, that provides the initial index of refraction.
- Further, the period and orientation of the index modulation are controlled by the angle of incidence (alpha) and wavelength of reference and signal wave.
- Moreover, by introducing a quantized k-space respectively incidence angle, the numerical effort can be reduced significantly.



Volume Grating Medium Parameters

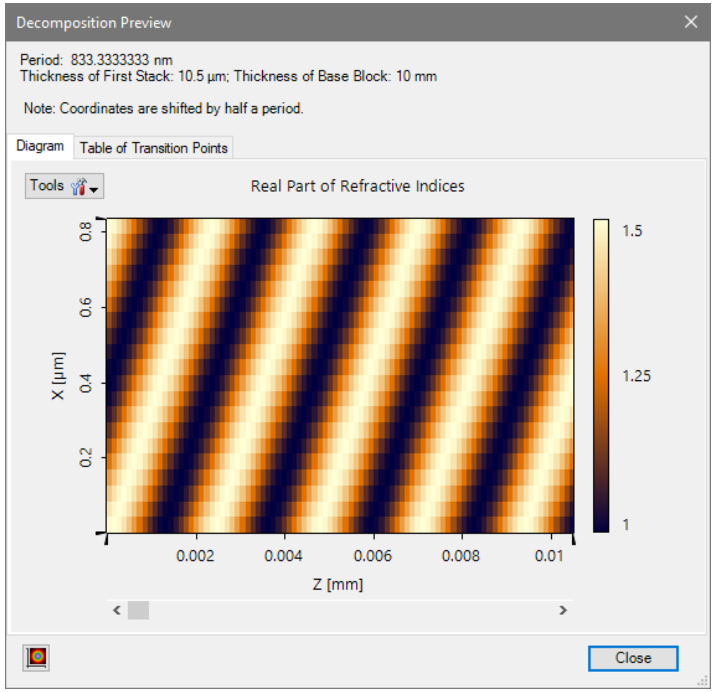
- The resulting period of the volume grating can be found either in the setting or stack dialog.

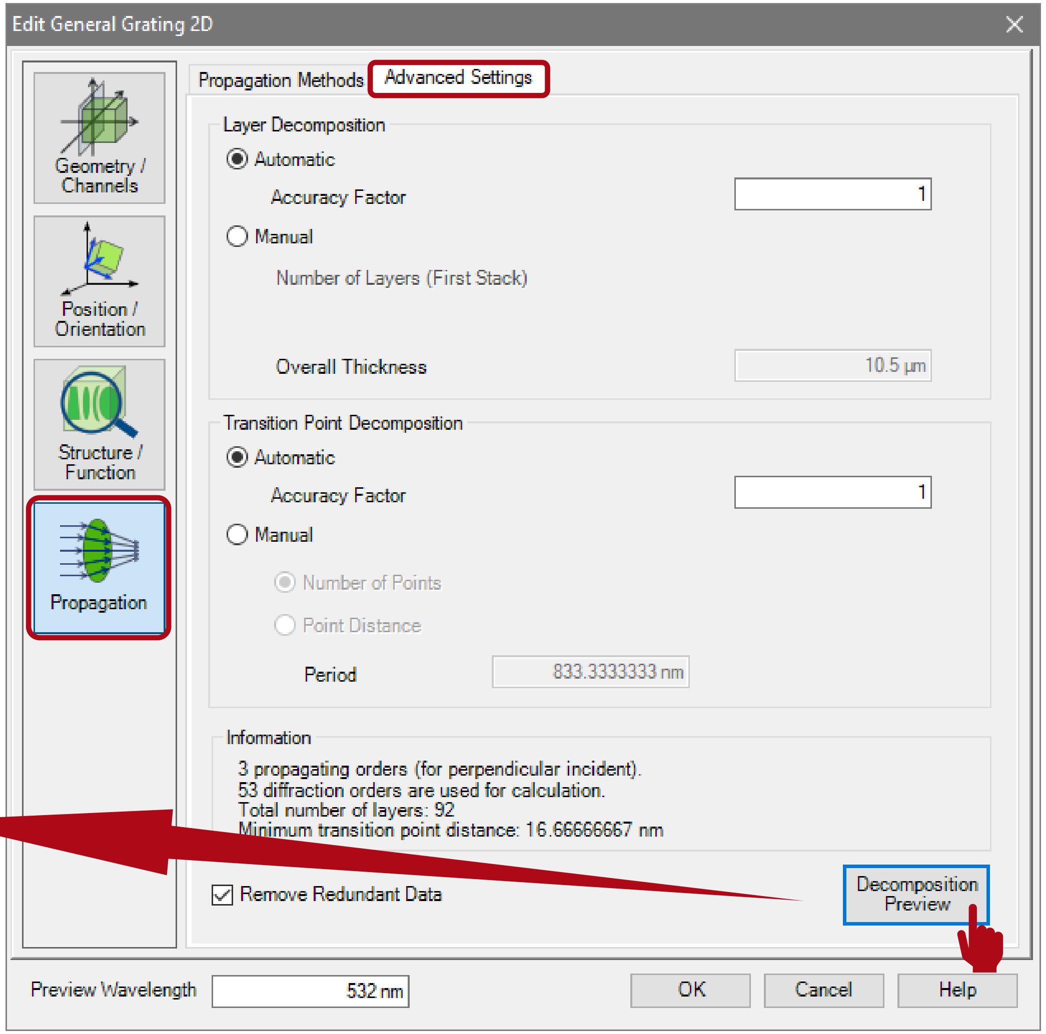




Advanced Options & Information

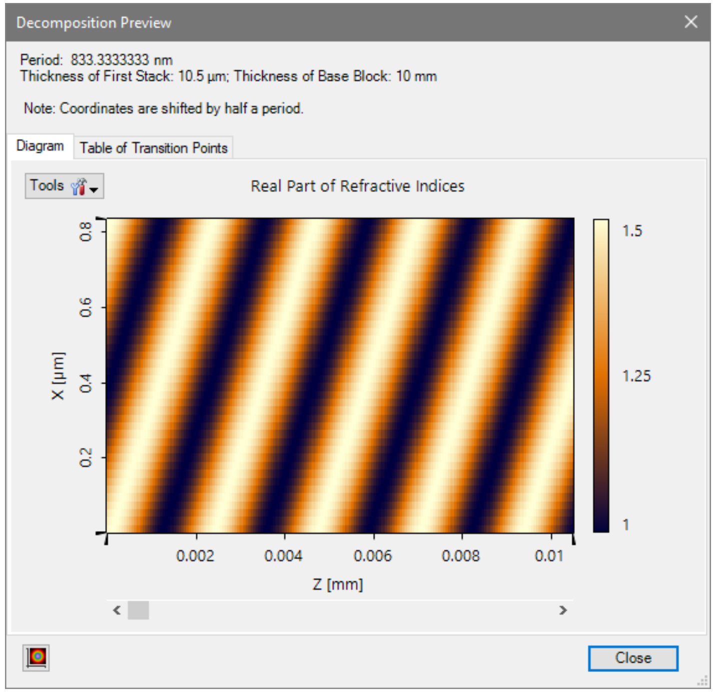
- Again, the data of the decomposed structure can be adjusted and investigated on the advanced settings tab page.

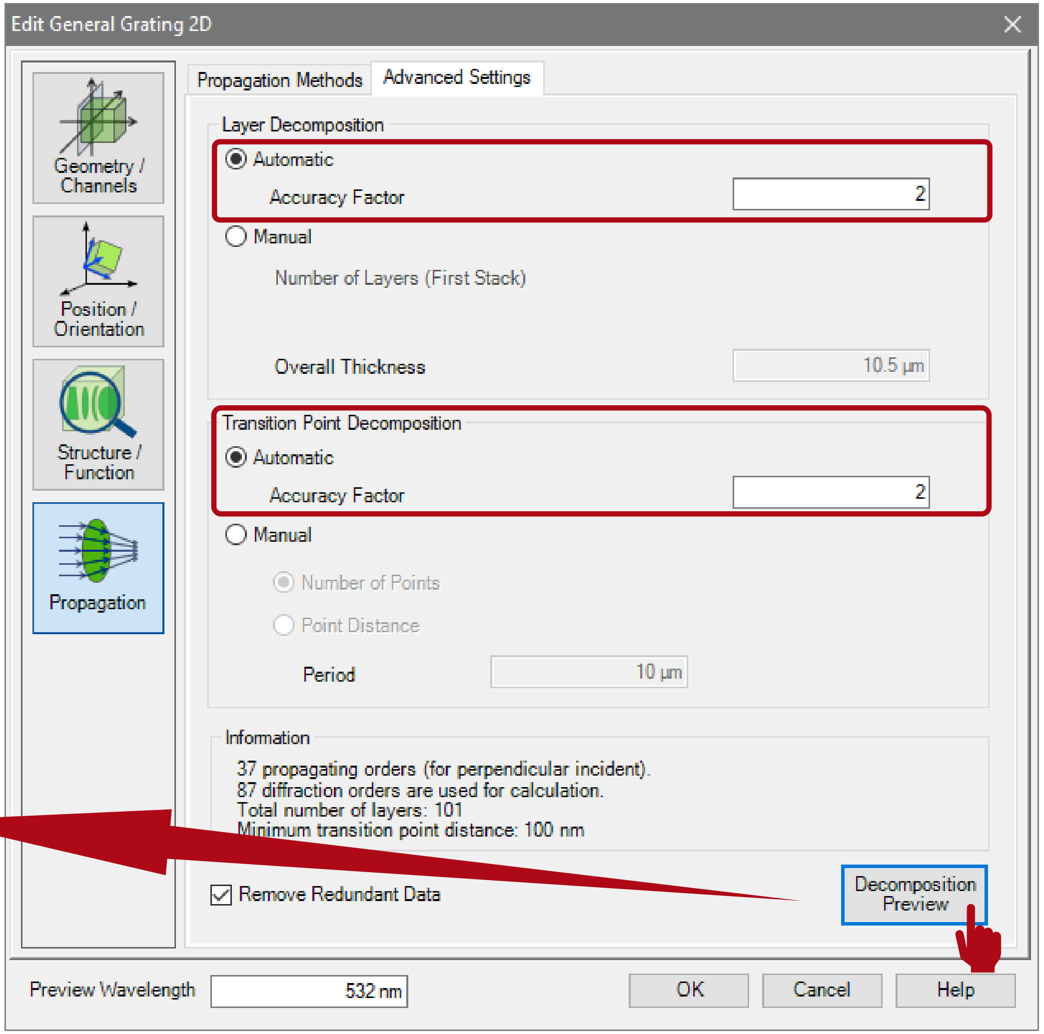




Advanced Options & Information

- 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.

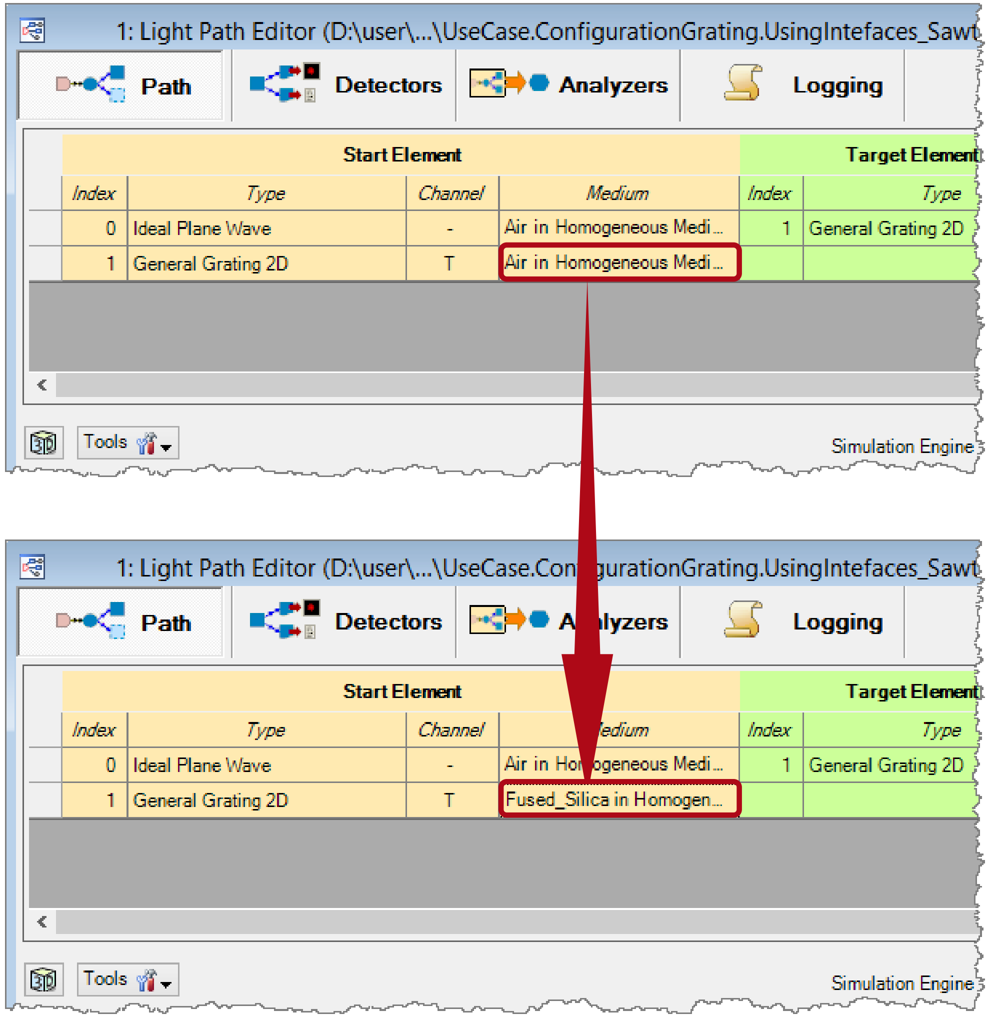




Remark on the Position of the Detector

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.



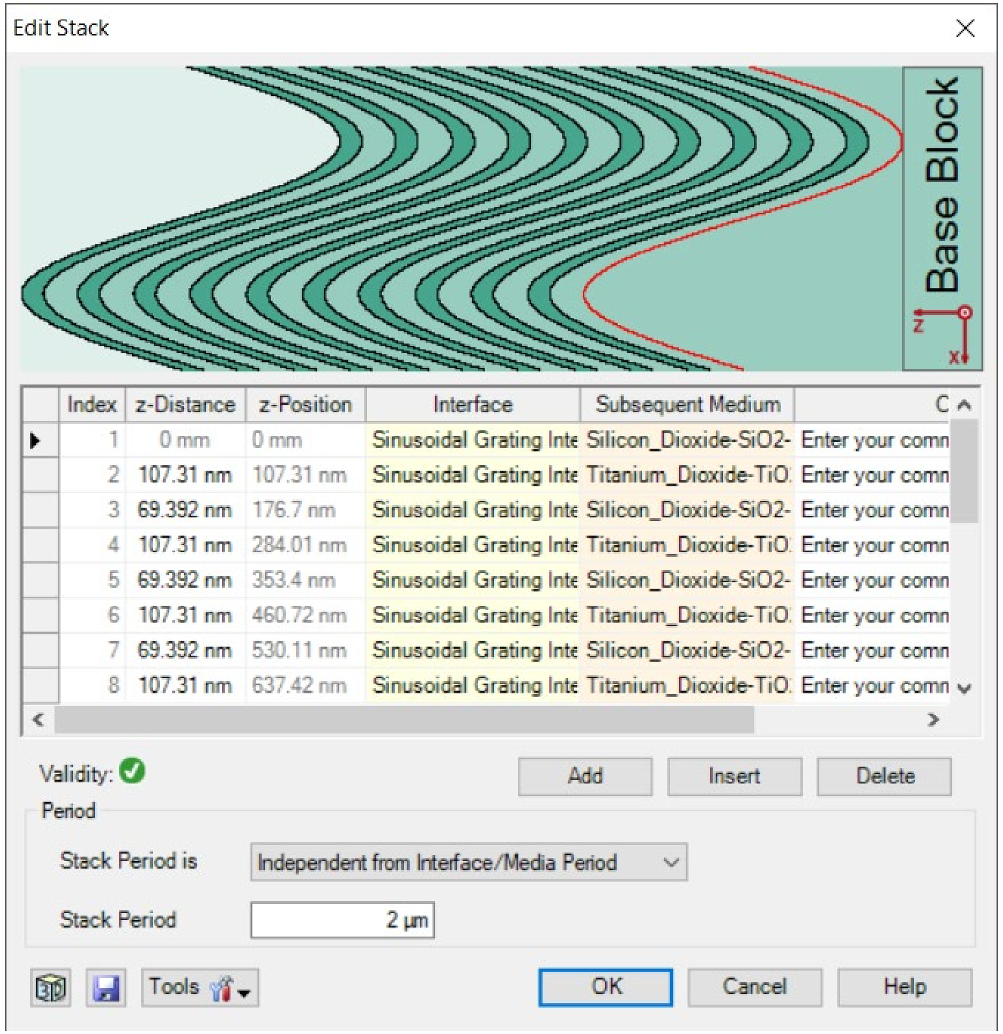
Document Information

title	Configuration of Grating Structures by Using Special Media
document code	GRT.0005
version	1.1
toolbox(es)	Grating Toolbox
VL version used for simulations	7.4.0.49
category	Feature Use Case
further reading	- Configuration of Grating Structures by Using Interfaces - Rigorous Simulation of Holographic Generated Volume Grating

Grating Order Analyzer

Grating Order Analyzer_...

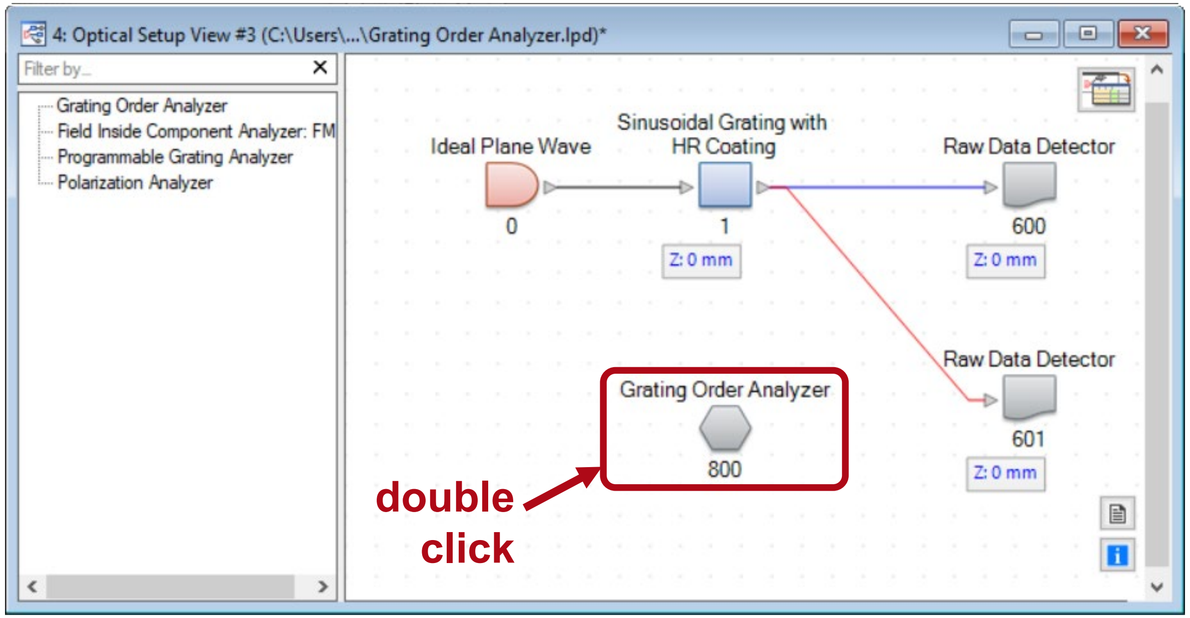
Grating Specification



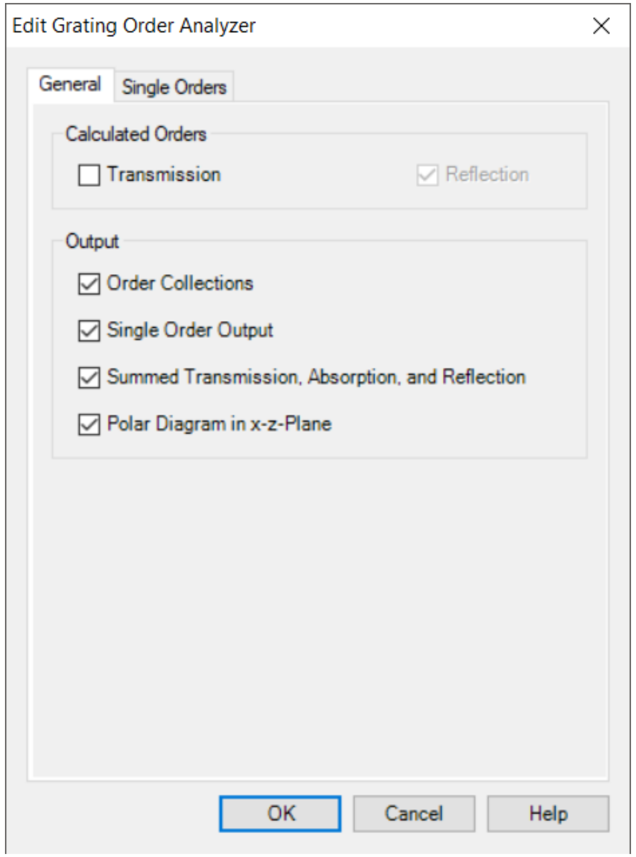
- For the demonstration of the Grating Order Analyzer for 1D gratings we use a sinusoidal grating with HR coating.
- The grating parameters can be specified within the stack that can be accessed in the edit dialog of the grating component.

Grating Order Analyzer Settings

- 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 it element in the optical setup view.

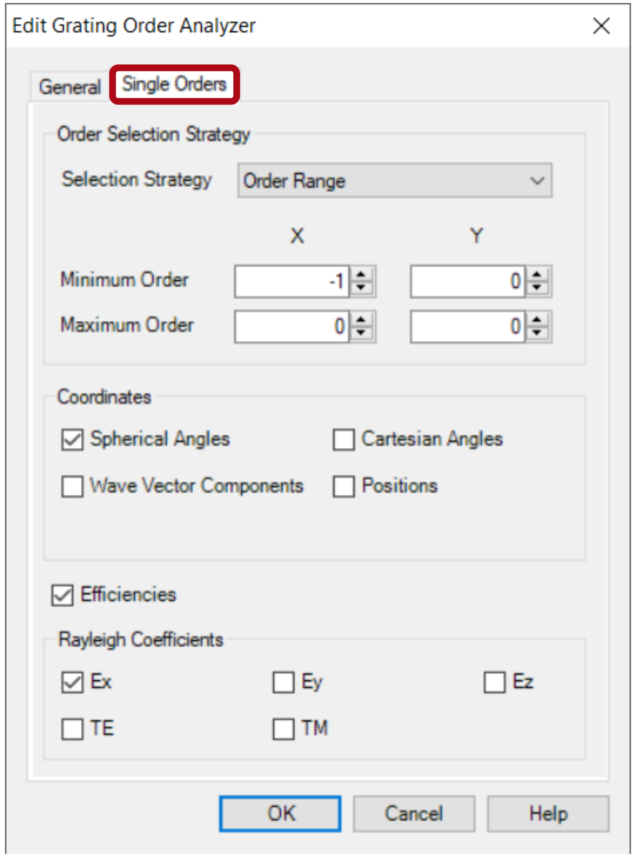


General Settings



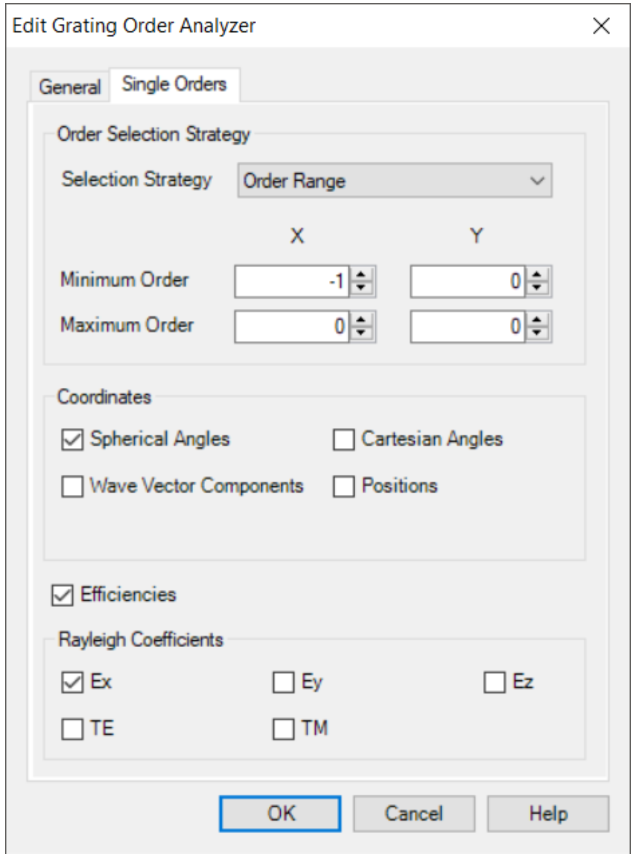
- In the General tab, you can select whether transmission and/or reflection shall be analyzed.
- In addition you can specify whether you would like to evaluate the summed transmission, absorption and reflection values, and whether you would like to show a polar diagram.

Single Orders Settings



- 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 Fusion to analyze and optimize the grating for specific orders.

Single Orders Settings



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 coefficient $\mathbf{E_x}$, $\mathbf{E_y}$, $\mathbf{E_z}$, **TE** or **TM**.

Outputs in Detector Tab

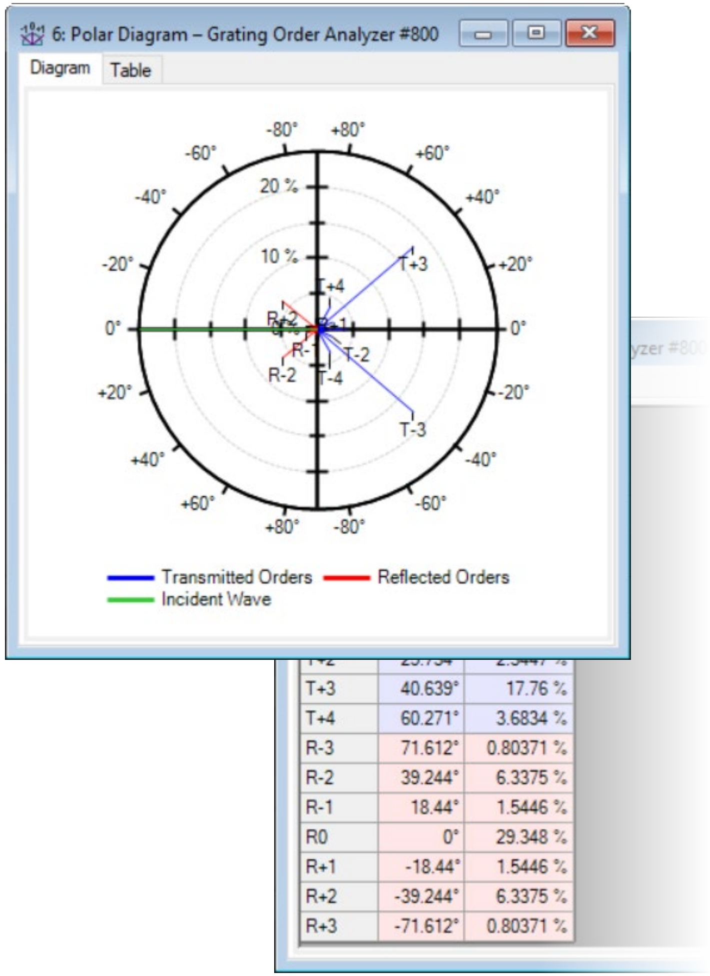
Detector Results

	Date/Time	Detector	Sub - Detector	Result
12	03/24/2019 09:11:50	Grating Order Analyzer #800	Overall Reflection Efficiency	46.719 %
11			Overall Transmission Efficiency	53.281 %
10			Overall Reflection and Transmission Efficiency	100 %
9			Absorption	0 %
8	03/24/2019 09:11:50	Grating Order Analyzer #800 (Results for Individual Orders)	Spherical Angle Theta R[-1; 0]	18.44°
7			Spherical Angle Phi R[-1; 0]	0°
6			Efficiency R[-1; 0]	1.5446 %
5			Rayleigh coefficient Ex R[-1; 0]	121.05 · exp(-1.695 · i) mV/m
4			Spherical Angle Theta R[0; 0]	0°
3			Spherical Angle Phi R[0; 0]	0°
2			Efficiency R[0; 0]	29.348 %
1			Rayleigh coefficient Ex R[0; 0]	541.74 · exp(-0.11644 · i) mV/m

Messages Detector Results

- If the Grating Order Analyzer is processed within the Optical Setup, 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.

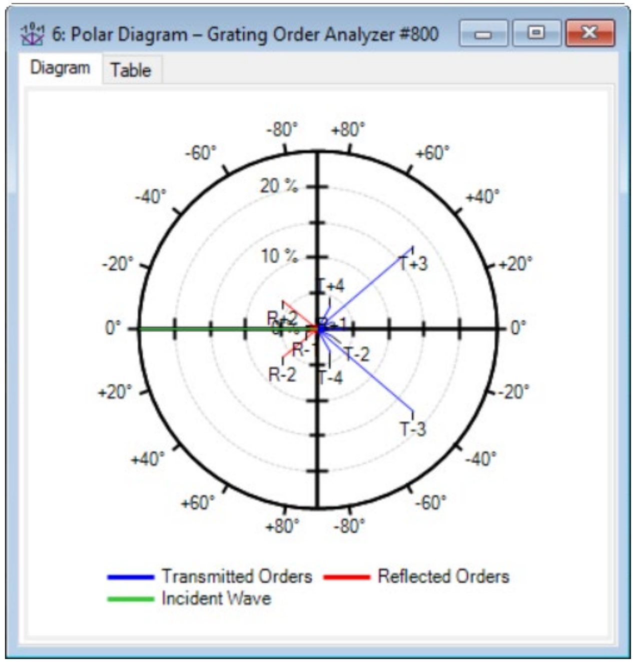
Outputs in Polar Diagram



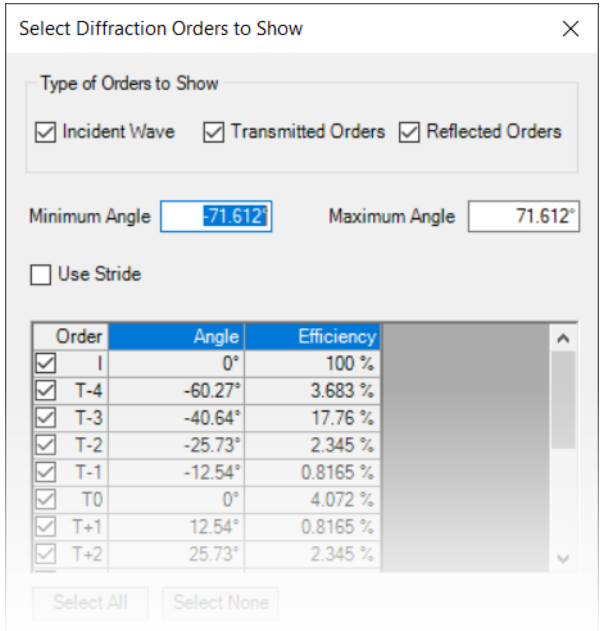
T+3	40.639°	17.76 %
T+4	60.271°	3.6834 %
R-3	71.612°	0.80371 %
R-2	39.244°	6.3375 %
R-1	18.44°	1.5446 %
R0	0°	29.348 %
R+1	-18.44°	1.5446 %
R+2	-39.244°	6.3375 %
R+3	-71.612°	0.80371 %

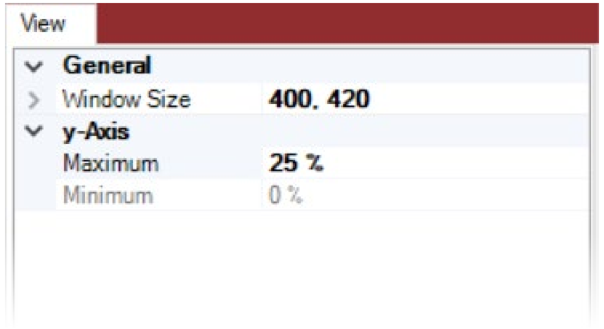
- The polar diagram output of the Grating Order Analyzer plots the efficiencies of both the reflected and the transmitted orders versus the angles in the x-z-plane.
- It also provides a table of all angles and efficiencies of the displayed orders.

Polar Diagram Settings

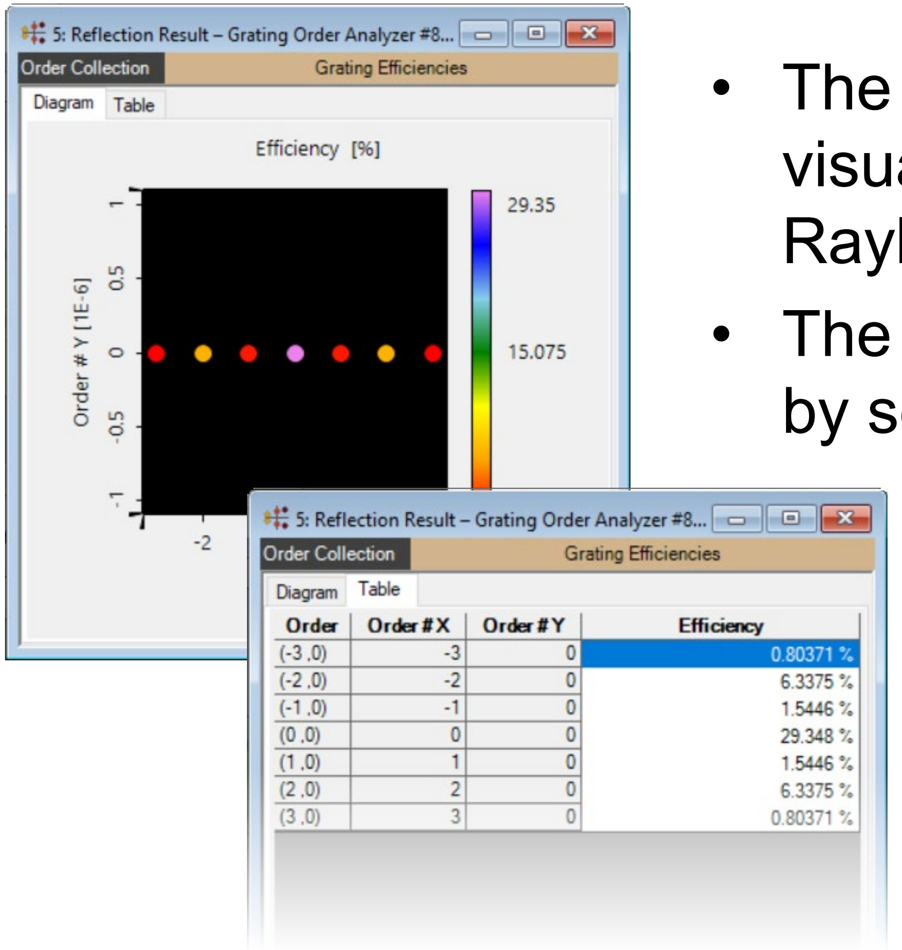


- You can zoom into the polar diagram with the mouse wheel, the Property Browser and the ribbon.
- You can configure which orders are shown by right-clicking on the diagram.





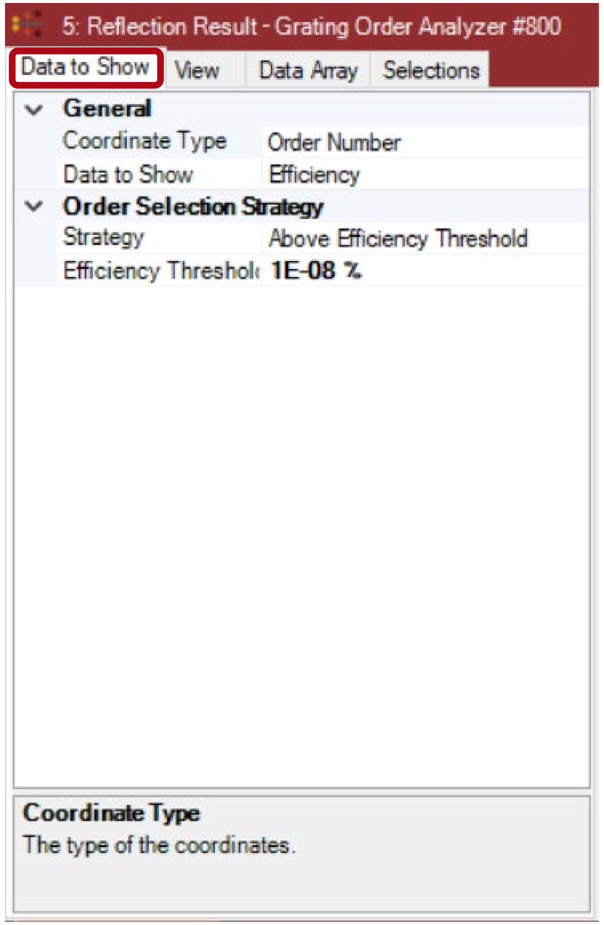
Outputs in Order Collection



Order	Order # X	Order # Y	Efficiency
(-3 ,0)	-3	0	0.80371 %
(-2 ,0)	-2	0	6.3375 %
(-1 ,0)	-1	0	1.5446 %
(0 ,0)	0	0	29.348 %
(1 ,0)	1	0	1.5446 %
(2 ,0)	2	0	6.3375 %
(3 ,0)	3	0	0.80371 %

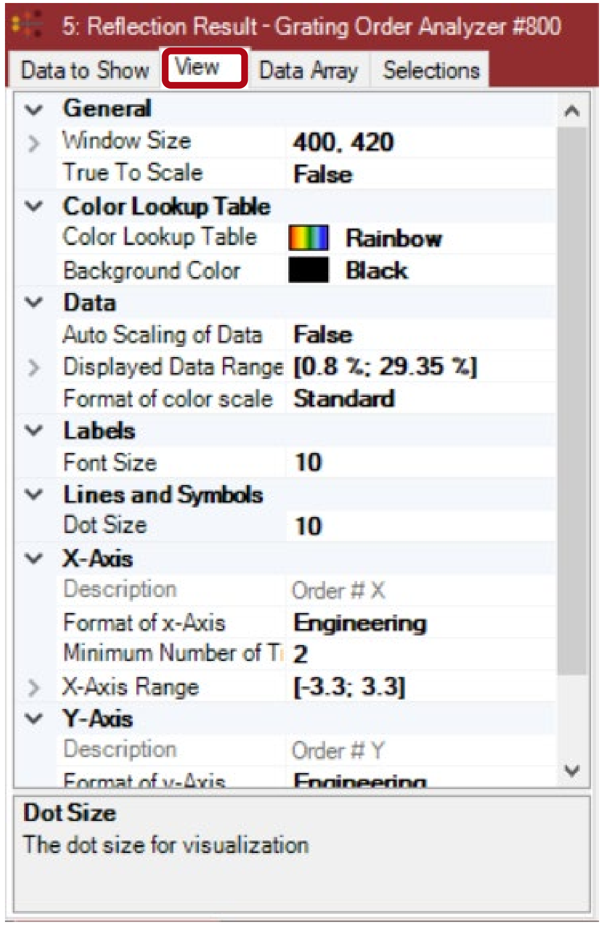
- The Grating Order Collection object is used to visualize the calculated grating efficiencies or the Rayleigh coefficients over different coordinates.
- The user can configure the data that shall be shown by setting diverse options via the property browser.

Order Collection Settings



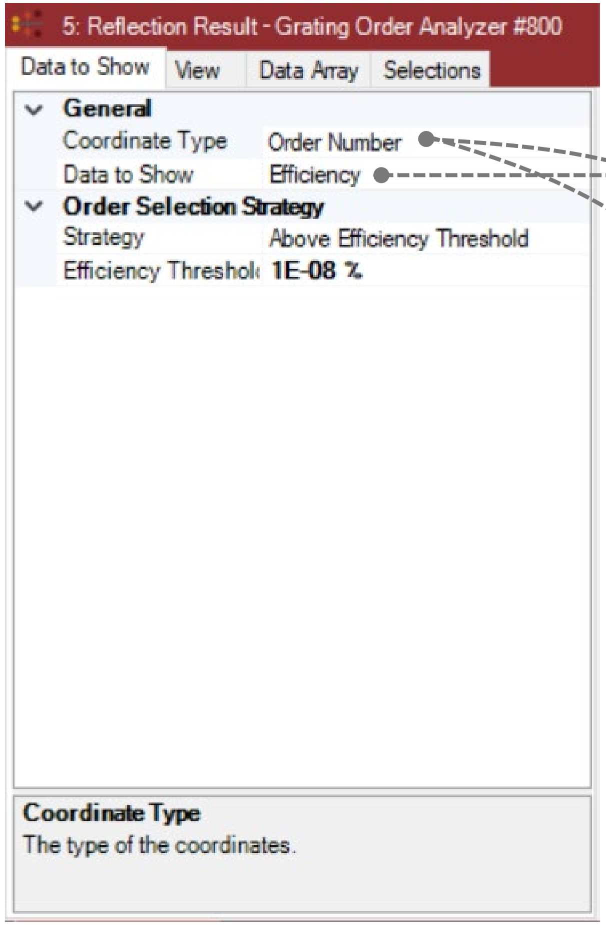
Option	Description
Coordinate Type	This property can be used to define the coordinates over which the data shall be visualized. Currently the order collection supports the visualization over **Cartesian Angles**, **Spherical Angles**, **Wave Number Vectors** and **Positions**.
Data to Show	It is possible 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 coordinate type. For Rayleigh coefficients $\mathbf{E_x}$, $\mathbf{E_y}$, $\mathbf{E_z}$, **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.

Order Collection Settings

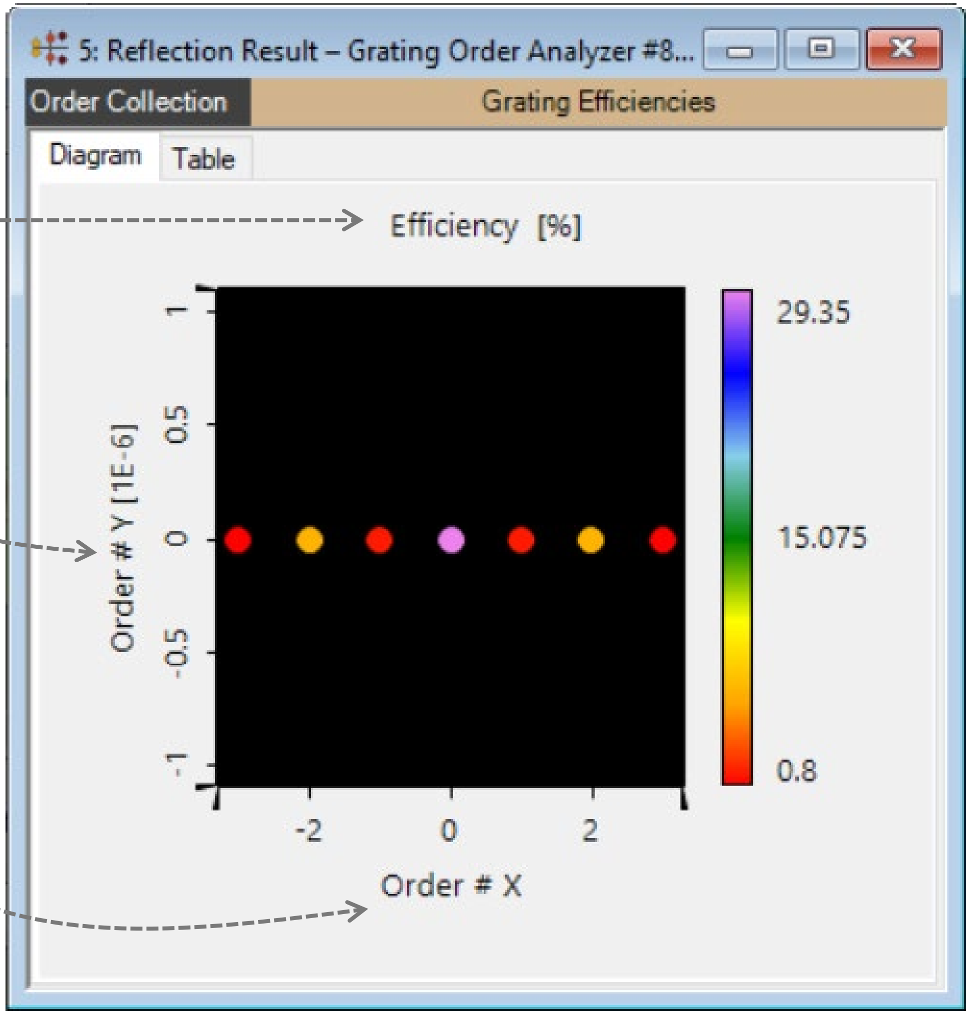


- In the View tab of the property browser, the user can set up additional view parameters.
- Most important for the customization of the view are the color settings.
- The user can select the background color for the view as well as the color lookup table that shall be used to define the colors for the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

Example of Customized Order Collection Settings

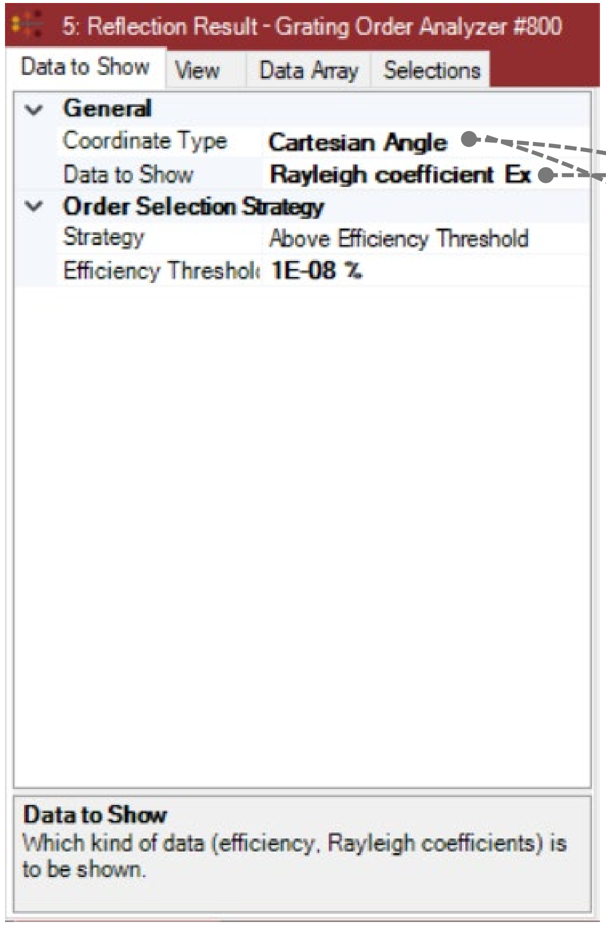


settings

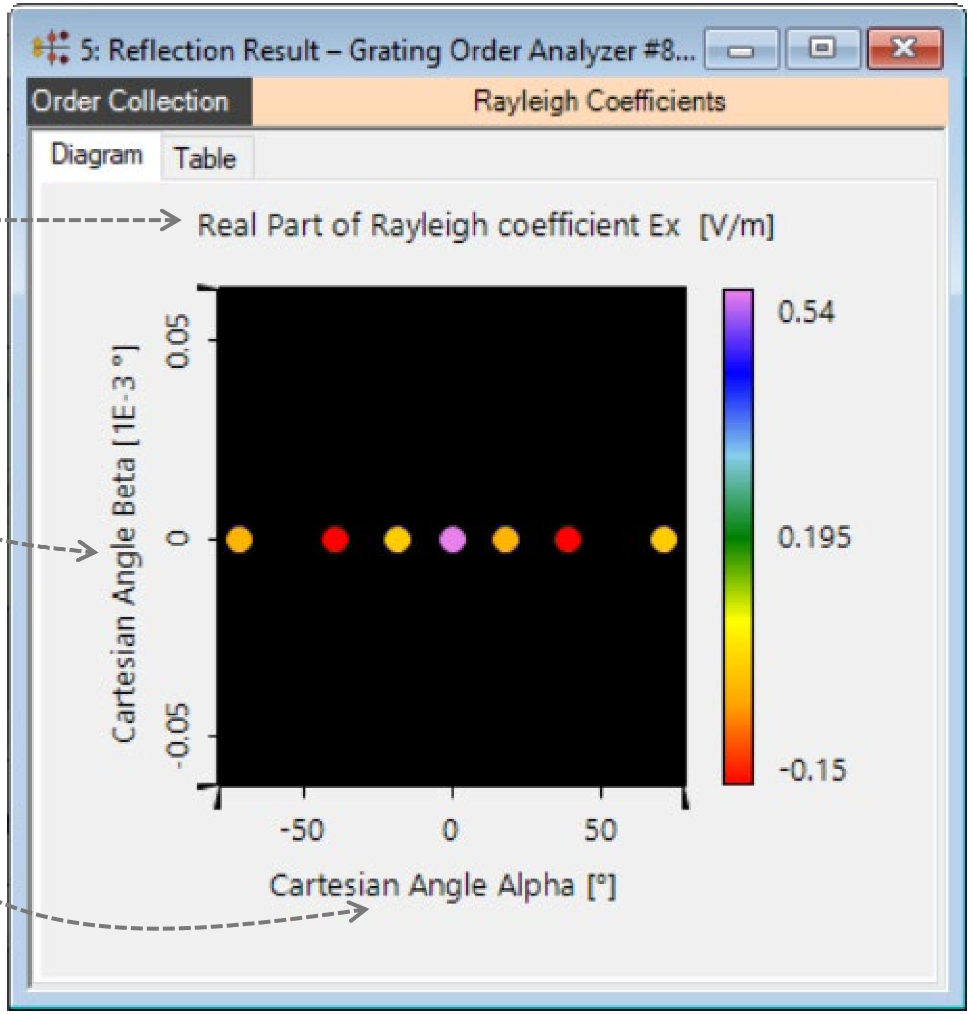


result

Example of Customized Order Collection Settings

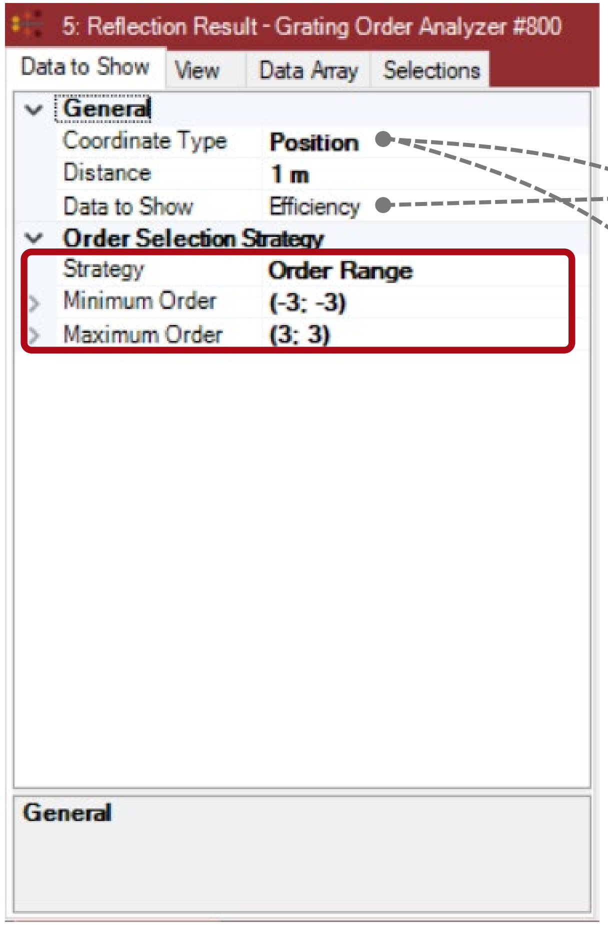


settings

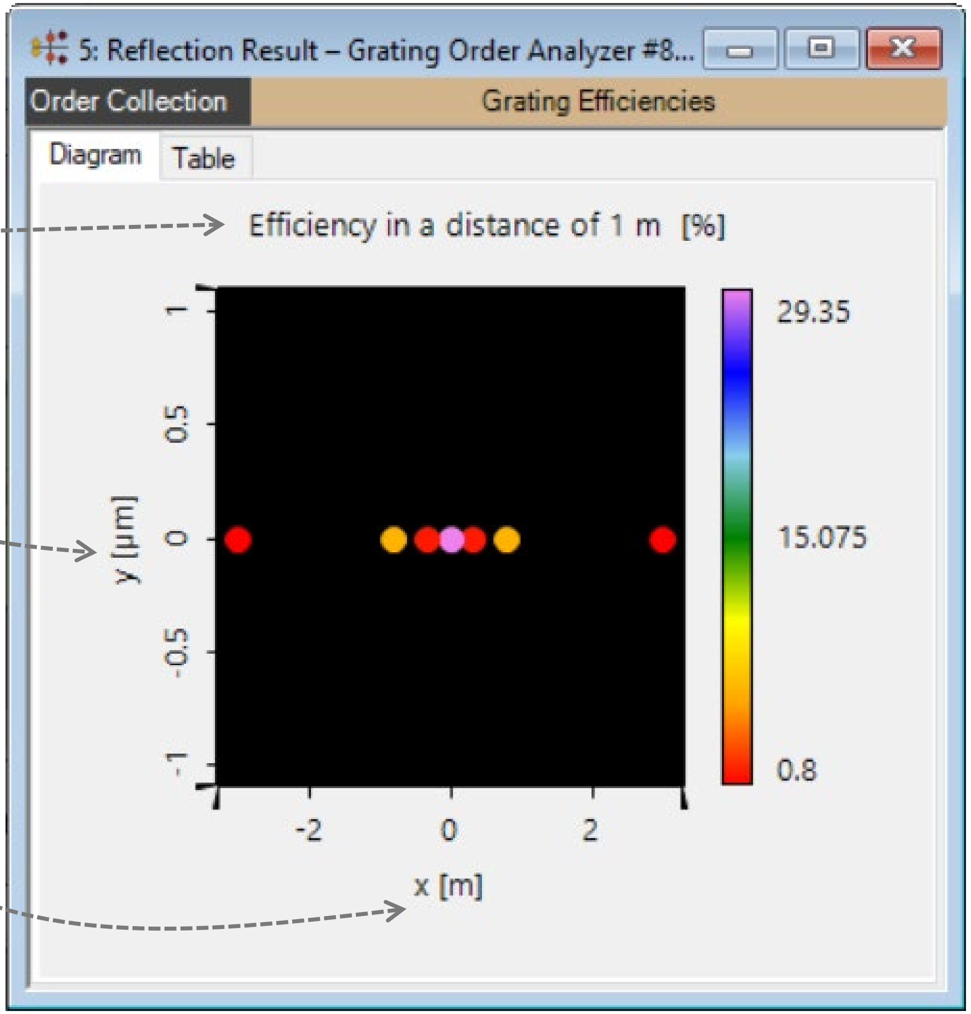


result

Example of Customized Order Collection Settings

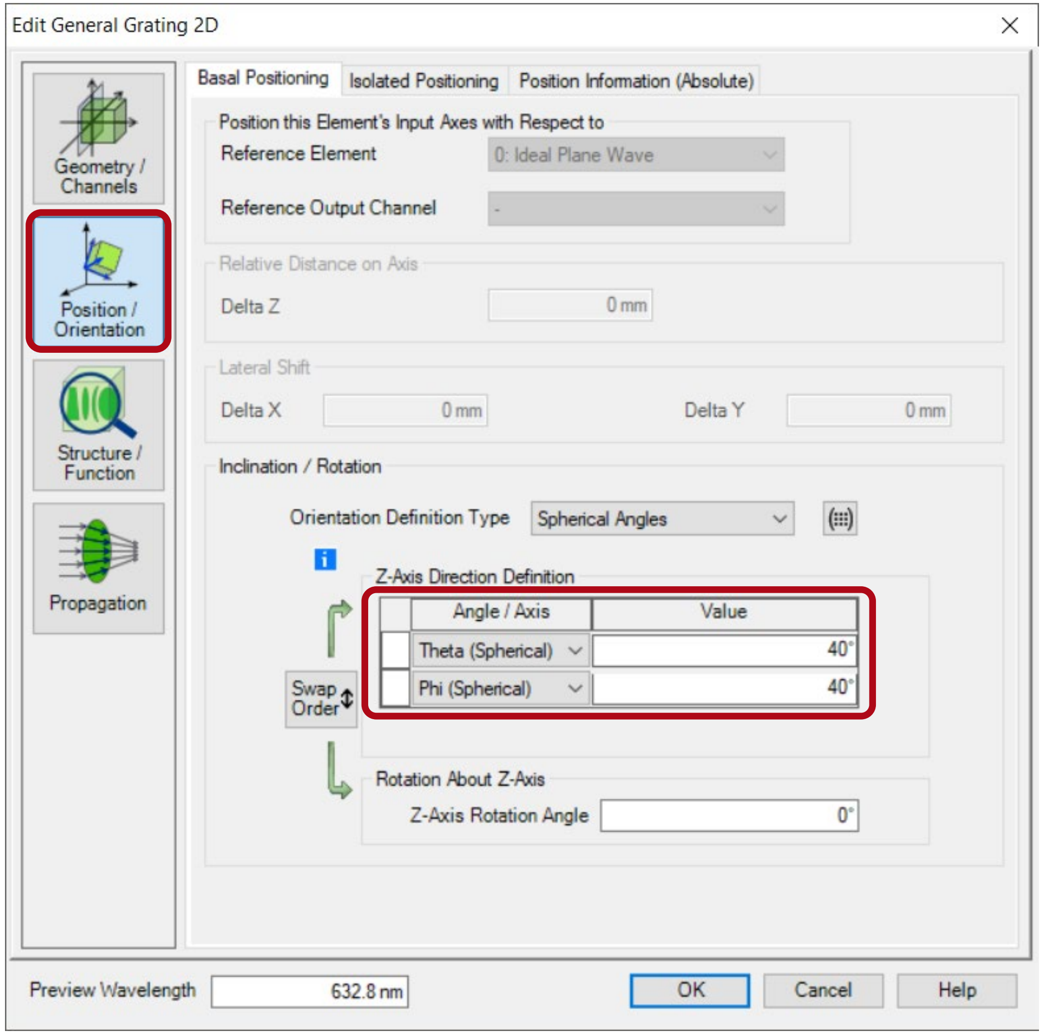


settings



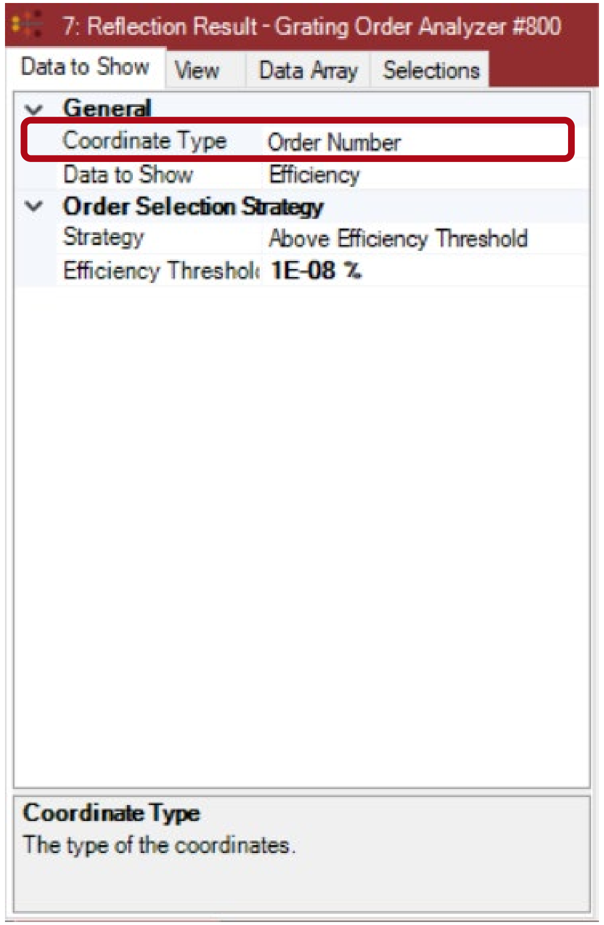
result

Visualization of Conical Diffraction

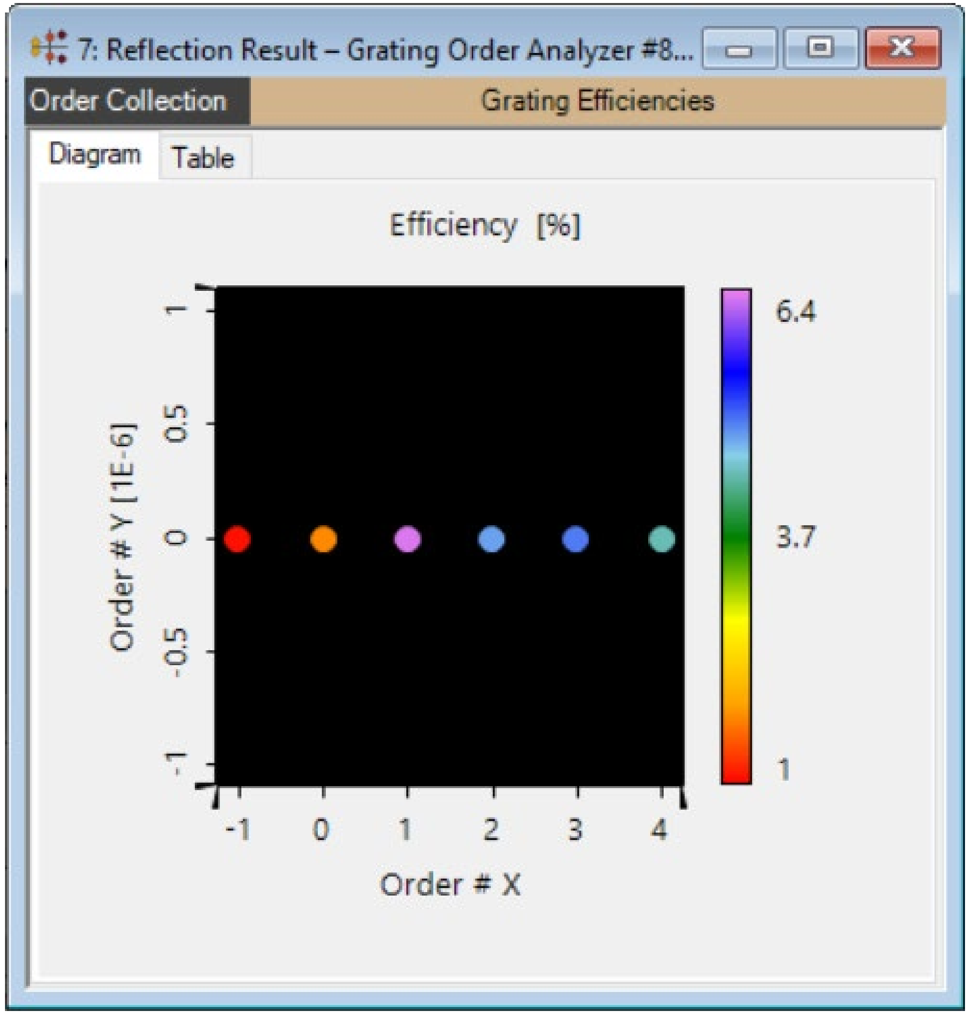


- Within the positions and orientation definition of the grating the user can define an arbitrary orientation.
- This is done in the Position / Orientation tab within the edit dialog of the grating.
- For this use case we use Theta = 40° and Phi = 40°.

Efficiencies vs. Diffraction Order Number

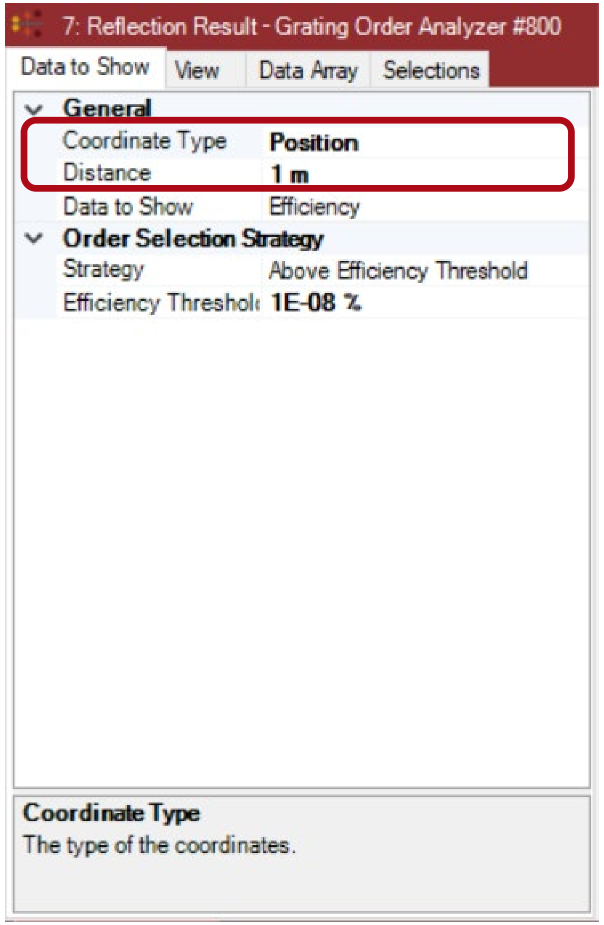


settings

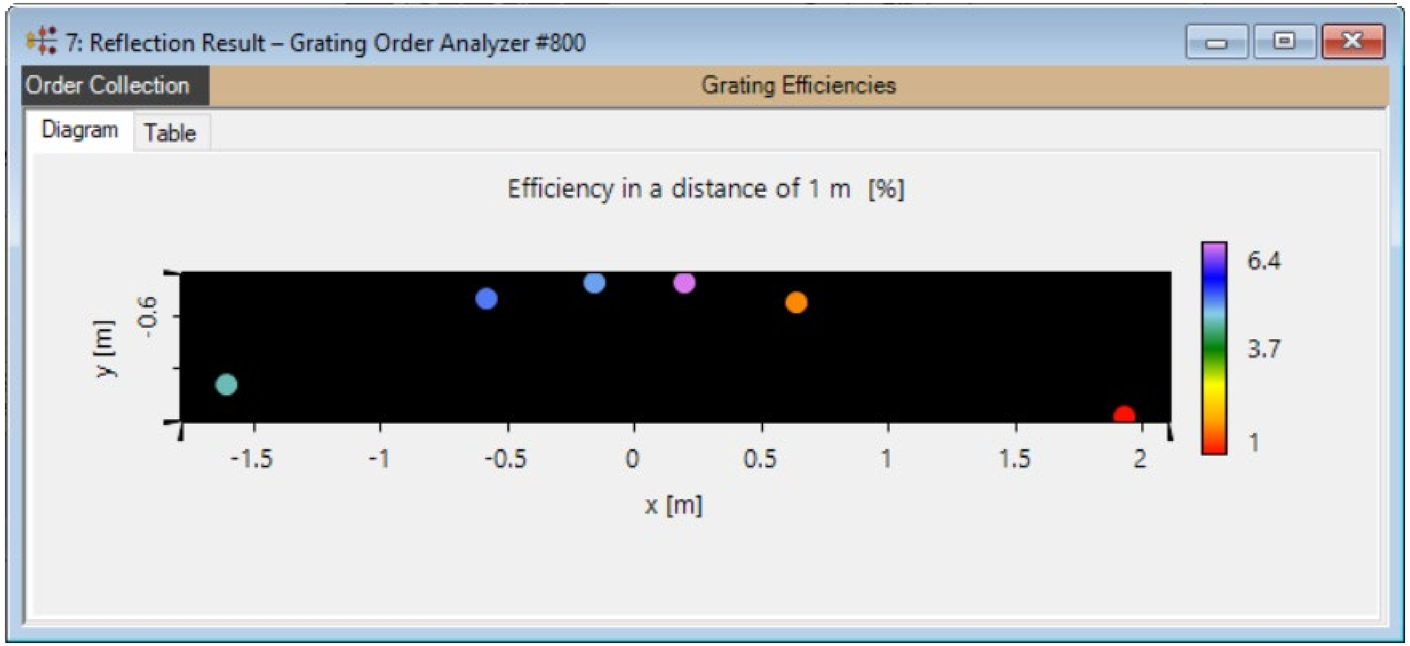


result

Efficiencies vs. Diffraction Order Position

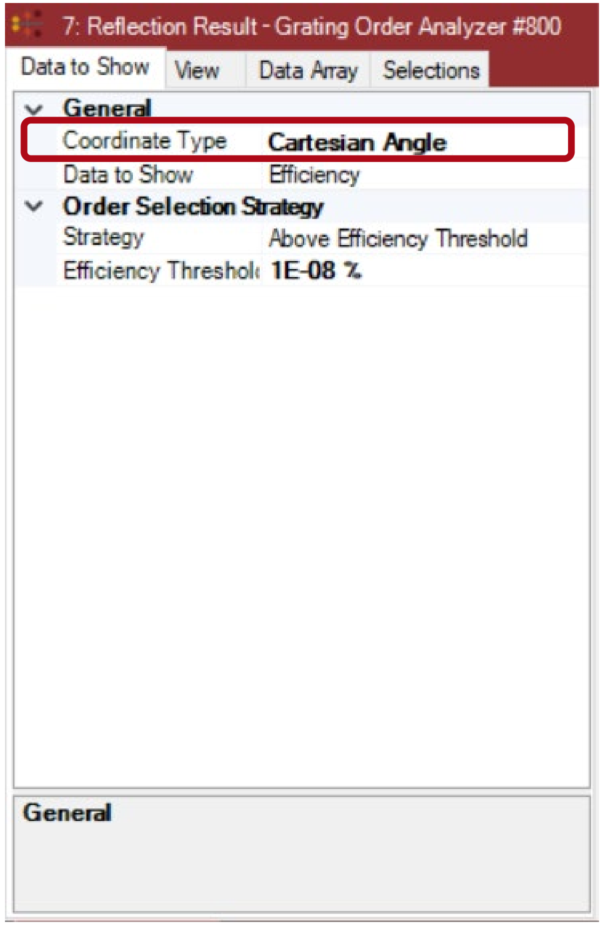


settings

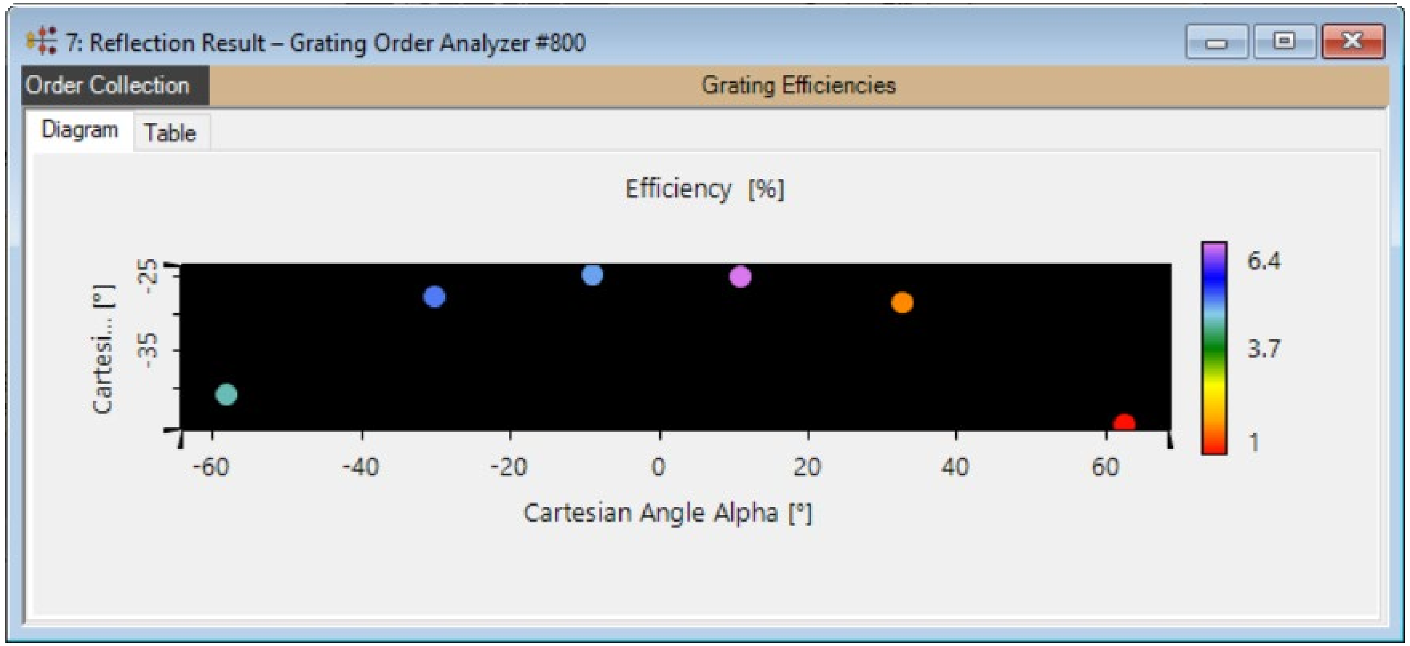


result

Efficiencies vs. Diffraction Order Cartesian Angle



settings



result

Document Information

title	Grating Order Analyzer
document code	GRT.0002
version	1.1
toolbox(es)	Grating Toolbox
VL version used for simulations	7.4.0.49
category	Feature Use Case
further reading	- Analysis of Blazed Grating by Fourier Modal Method - Optimization of Lightguide Coupling Grating for Single Incidence Direction

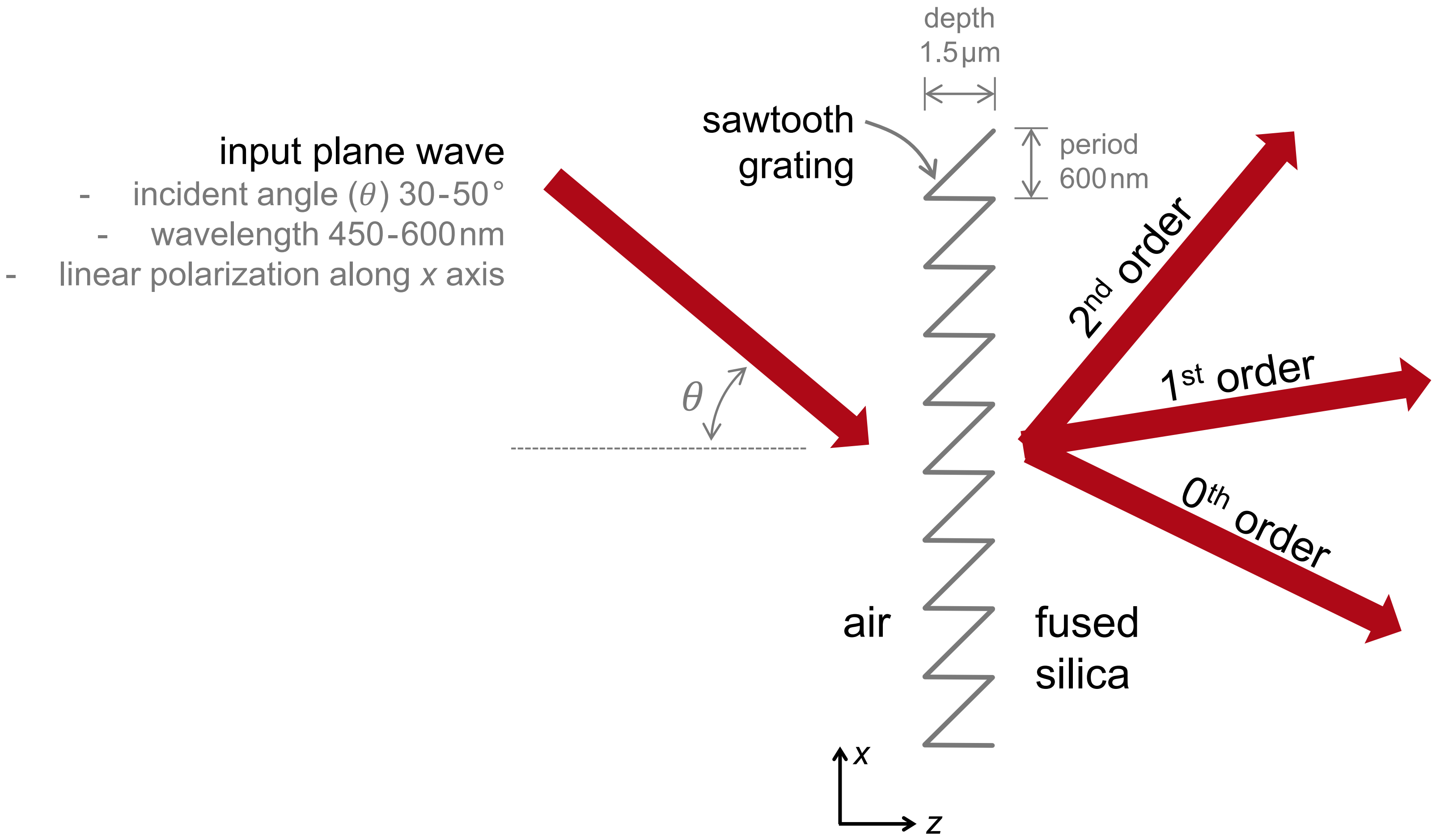
Introduction

- How to construct grating structures
- **Modeling and design of surface-relief gratings**
- Analysis of polarization-dependent effects and optimization
- Properties of holographic volume gratings
- Investigation of two-dimensional periodic structures, like nanopillars

Analysis of Blazed Grating by Fourier Modal Method

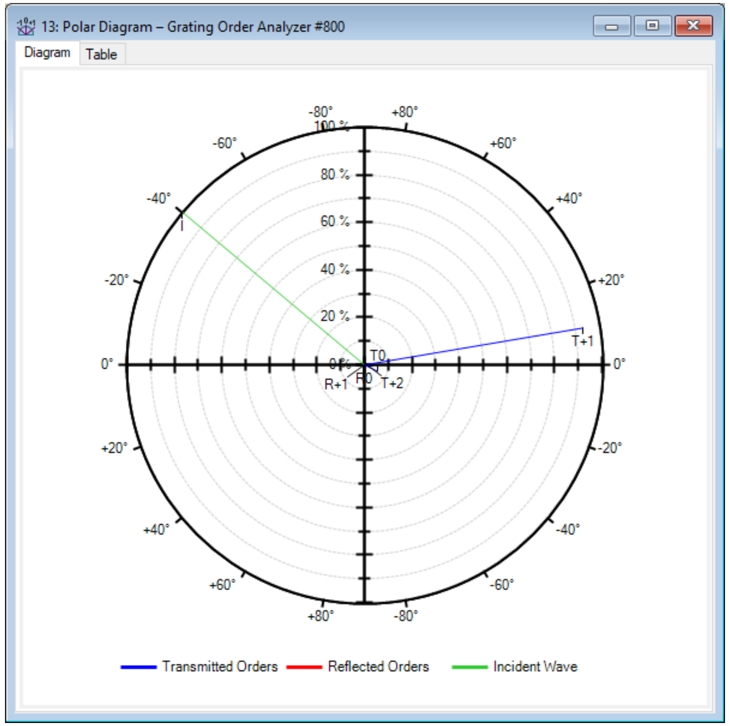
Blazed Grating Analysis by FMM_...

Modeling Task



How to evaluate the efficiency of a specific diffraction order?

Results from Single FMM Simulation

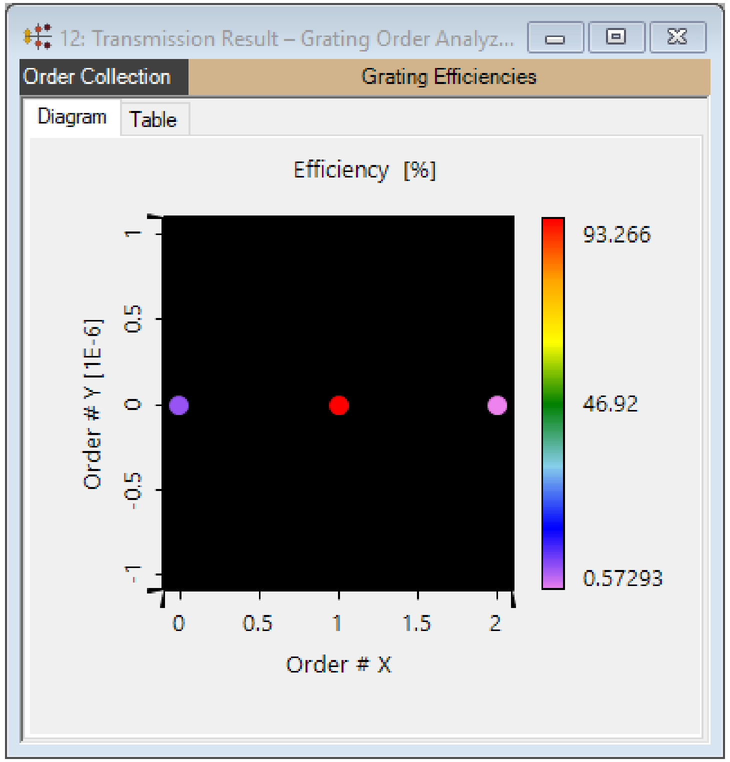


polar diagram
used for projected visualization of grating efficiencies for transmission and reflection

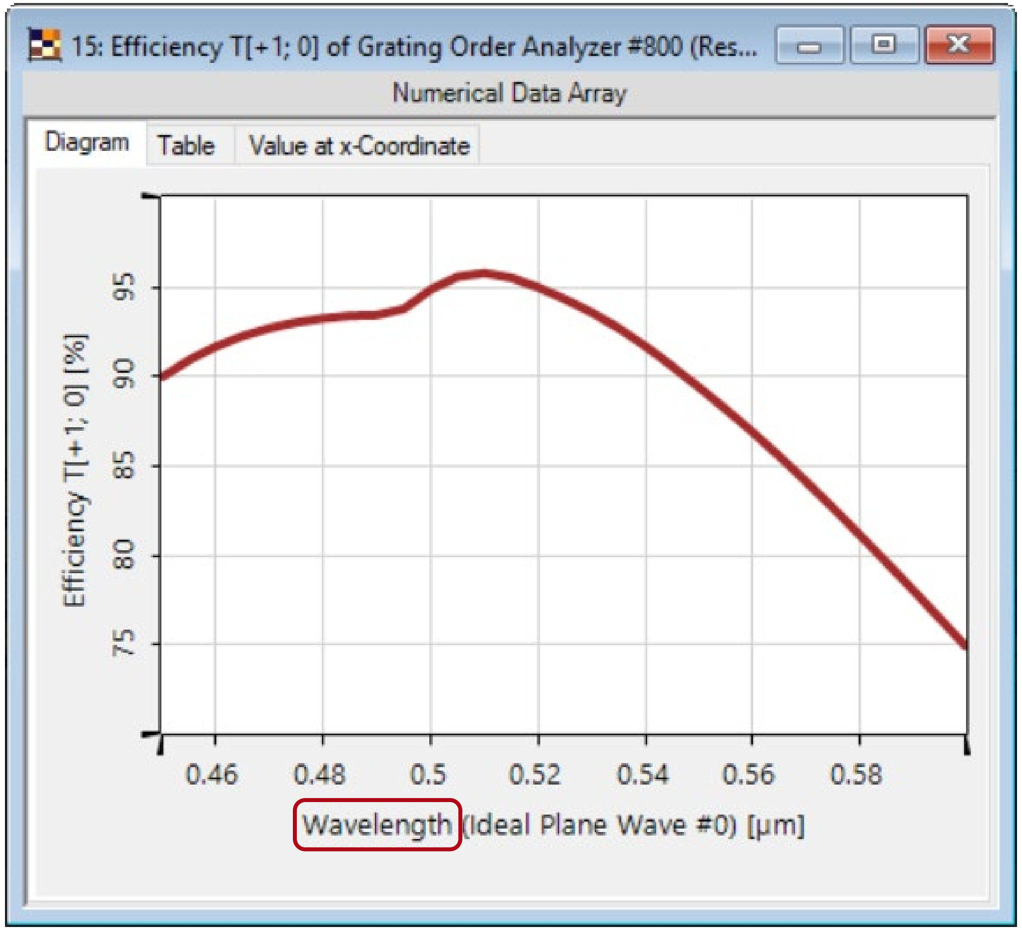
result table (transmission)

	angle	efficiency
0^{th} order	-26.107°	6.1579%
1^{st} order	9.6014°	93.266%
2^{nd} order	50.682°	0.57293%

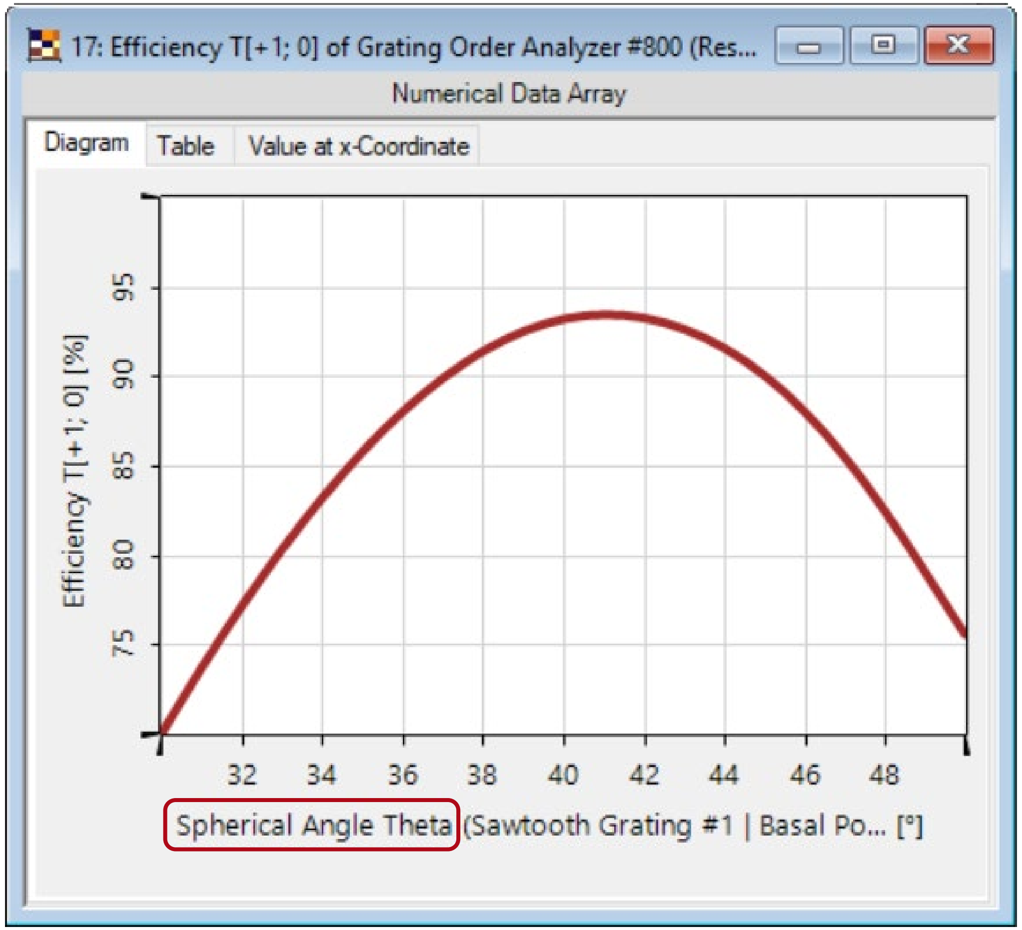
order collection
display of efficiency or other quantity with respect to e.g. diffraction order, angle, etc.



Parameter Scanning (1D)

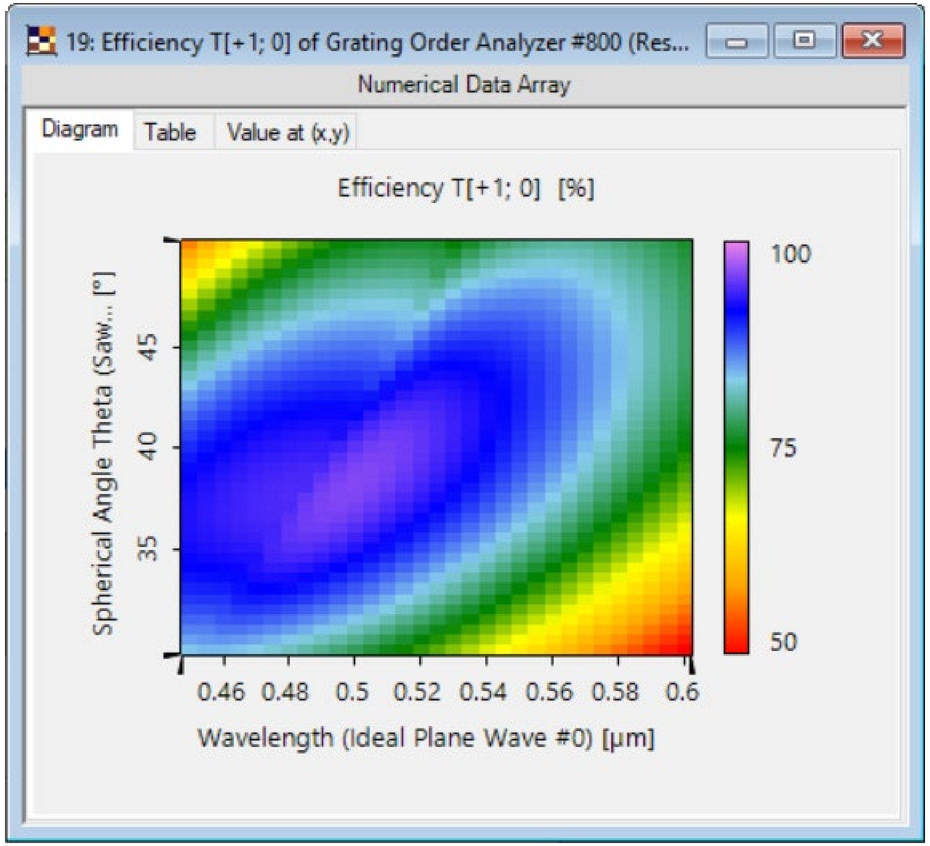


parameter variation (@ θ=40°)
- wavelength from 450nm to 600nm



parameter variation (@ λ=532nm)
- incidence angle theta from 30° to 50°

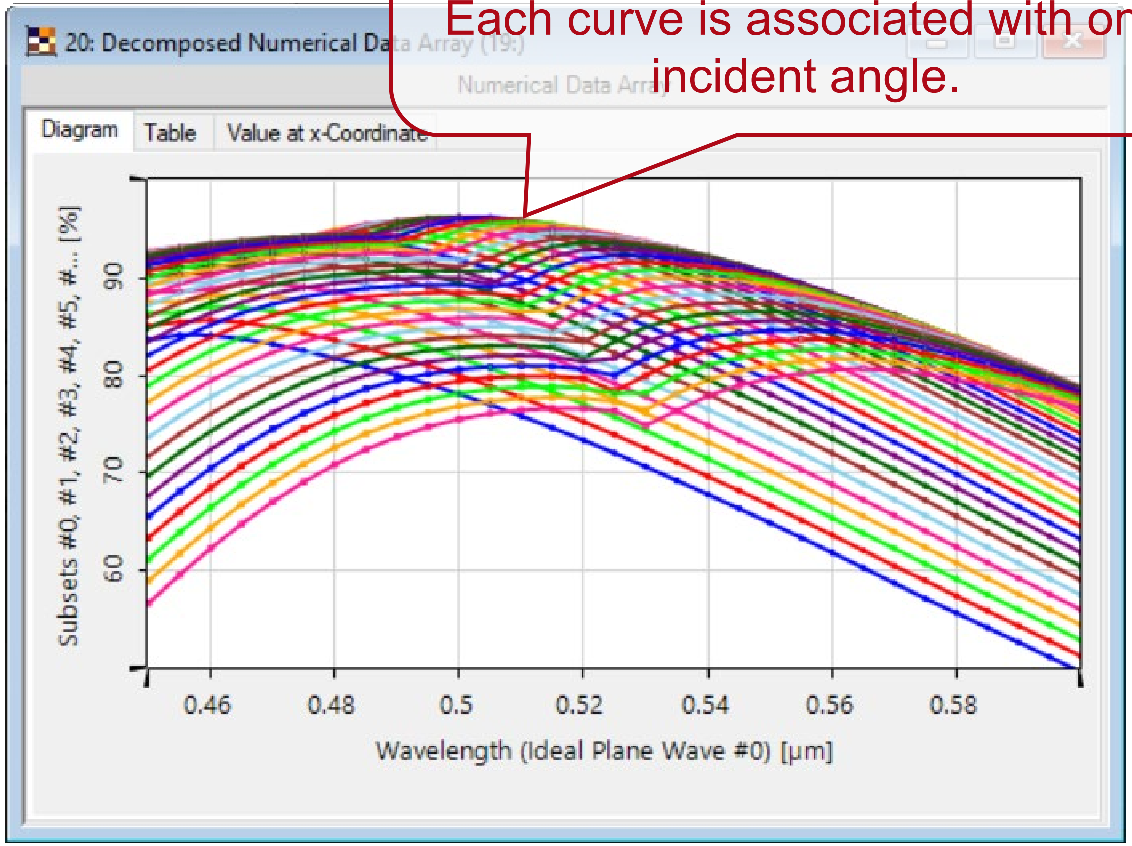
Parameter Scanning (2D)



parameter variation

- wavelength from 450nm to 600nm
- incidence angle theta from 30° to 50°

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



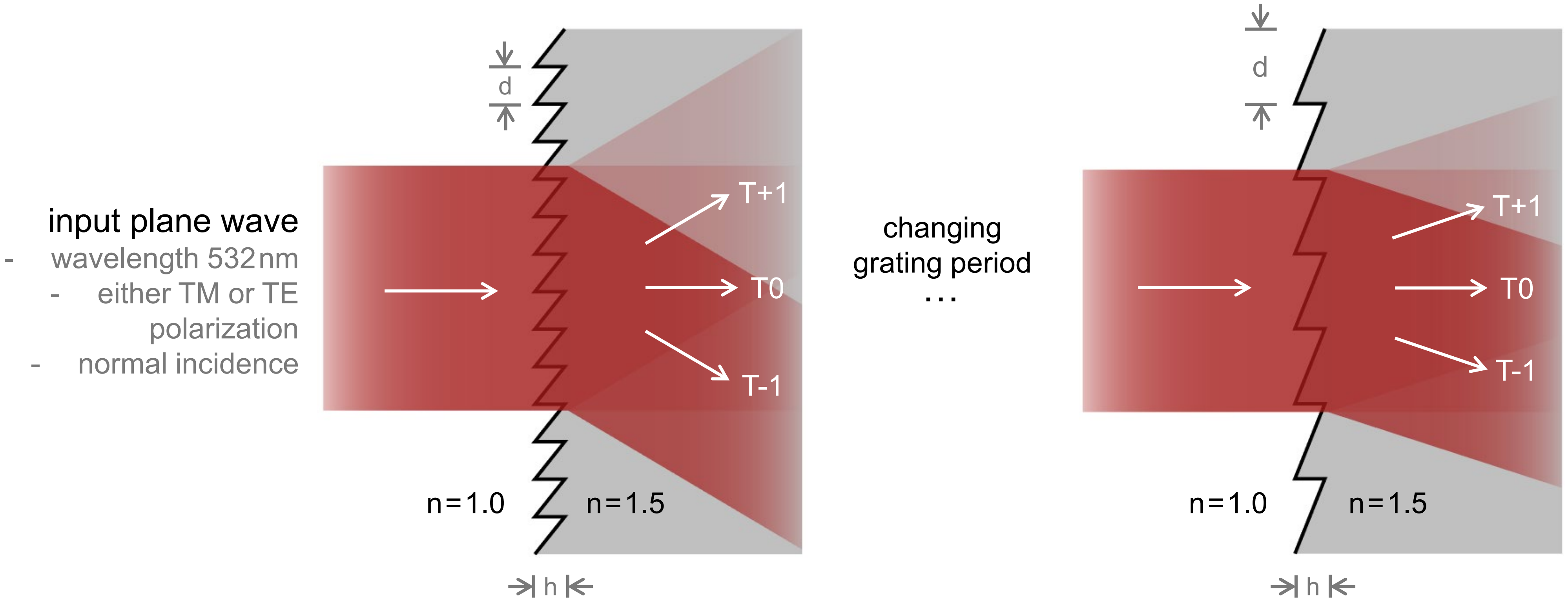
Document Information

title	Analysis of Blazed Grating by Fourier Modal Method
document code	GRT.0001
version	1.1
toolbox(es)	Grating Toolbox
VL version used for simulations	7.4.0.49
category	Feature Use Case
further reading	- Grating Order Analyzer - Optimization of Lightguide Coupling Grating for Single Incidence Direction

Thin-Element Approximation vs. Fourier Modal Method for Grating Modeling

FMM vs TEA_...

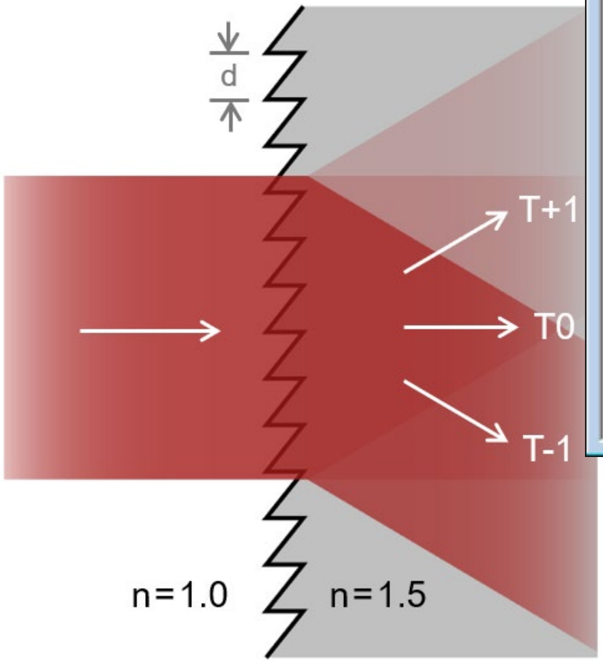
Modeling Task

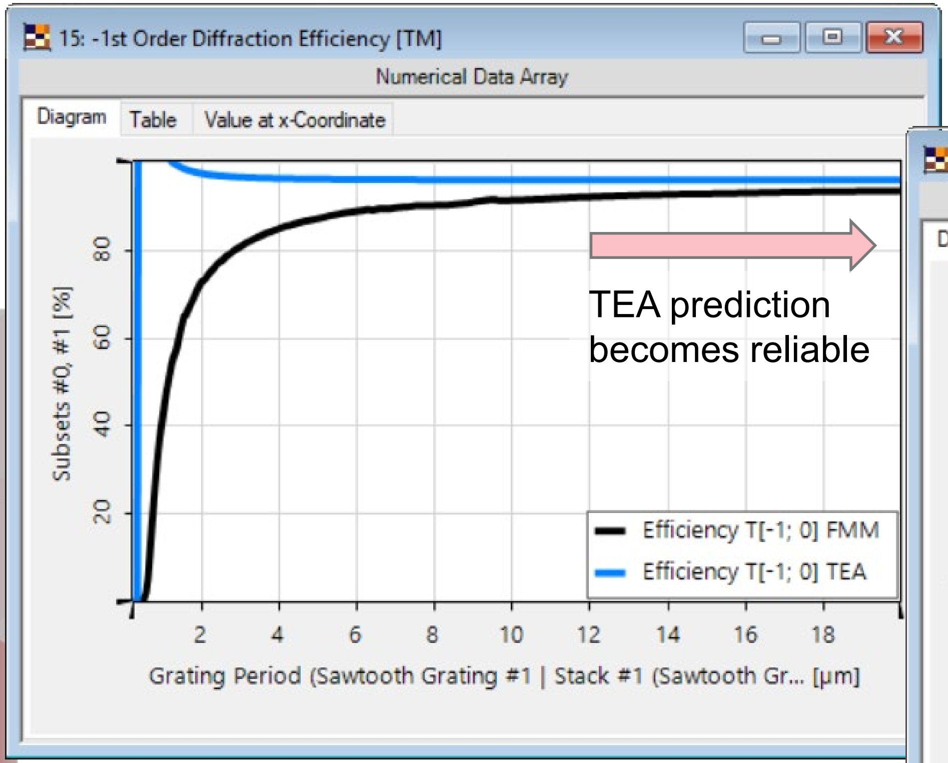


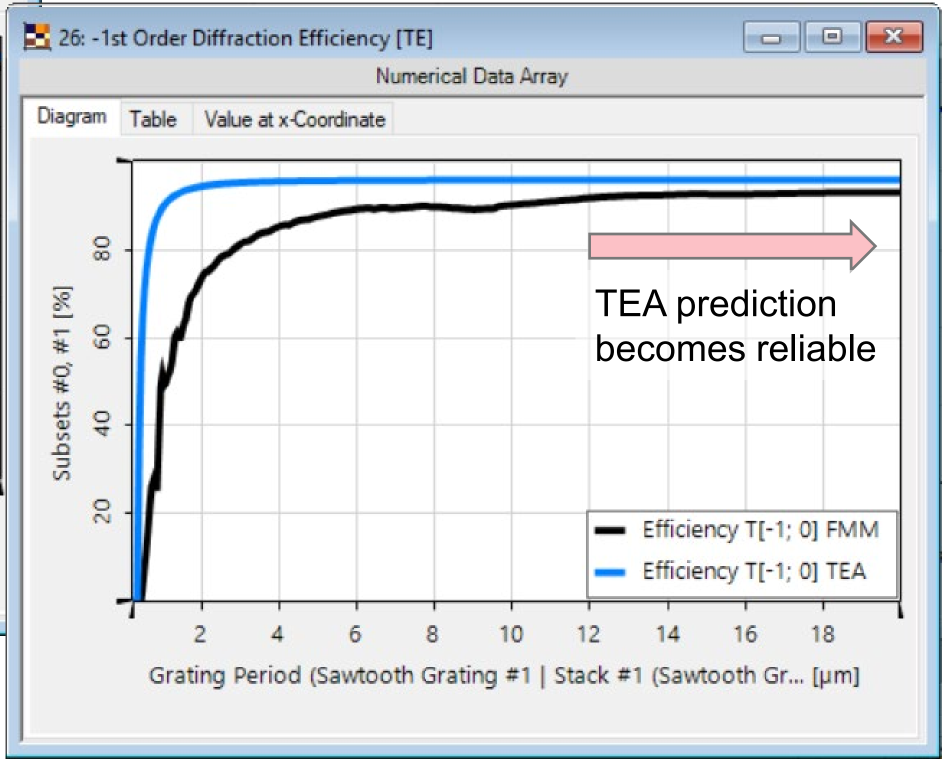
By varying the period of the blazed grating (with fixed grating depth), we compare the simulation results from the rigorous FMM calculation and the approximated TEA calculation.

-1st Diffraction Order Analysis – FMM vs TEA

d varies from
250 nm to 20 µm

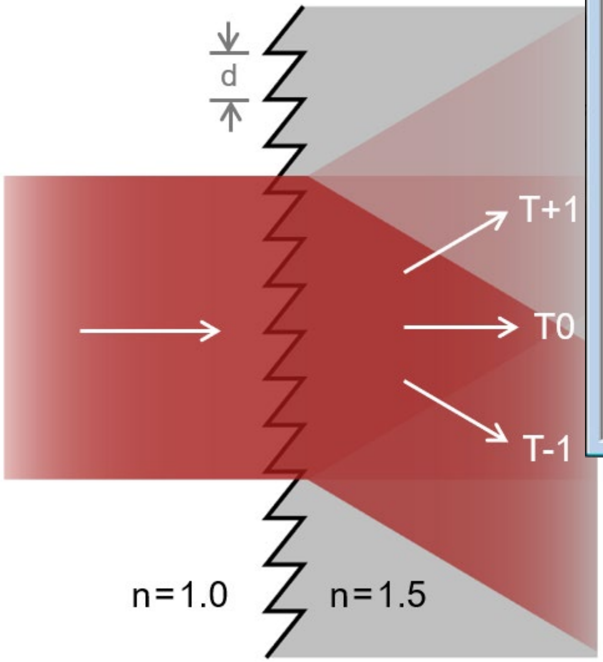


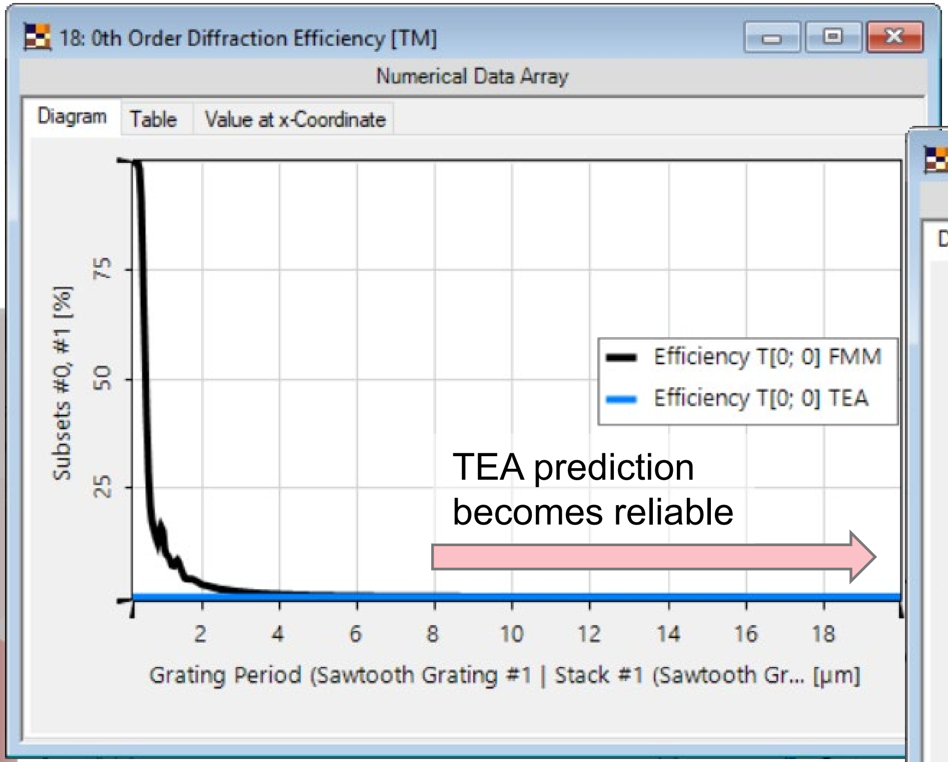


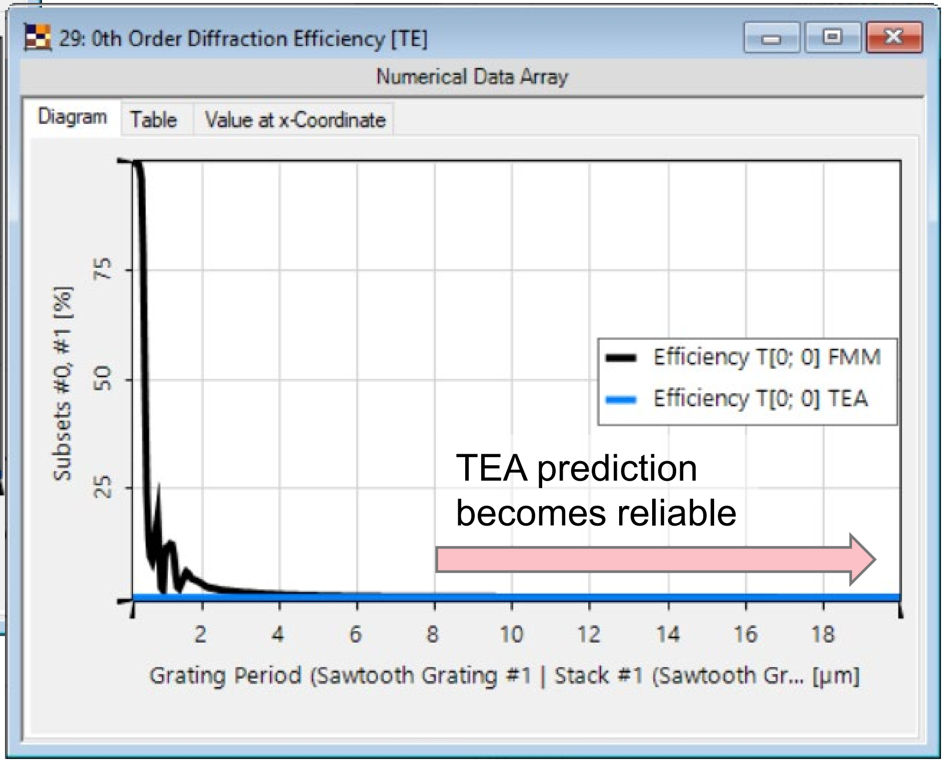


0^{th} Diffraction Order Analysis – FMM vs TEA

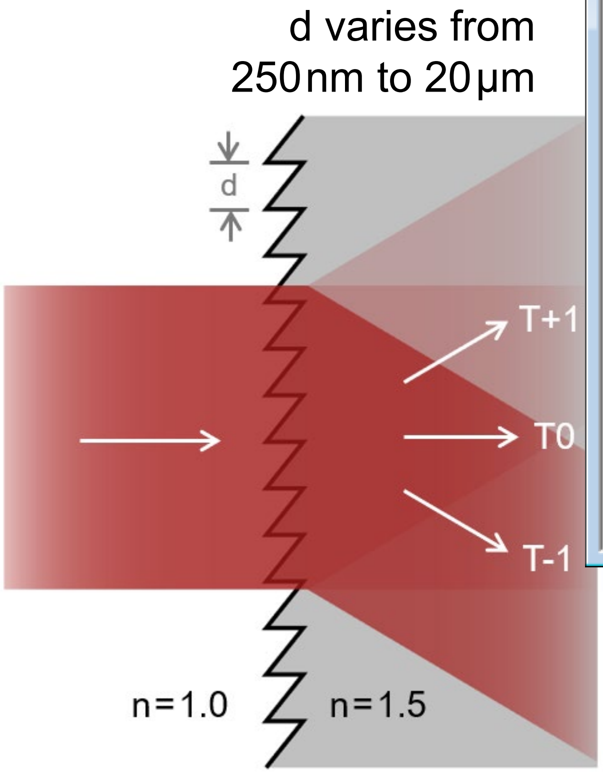
d varies from
250 nm to 20 µm

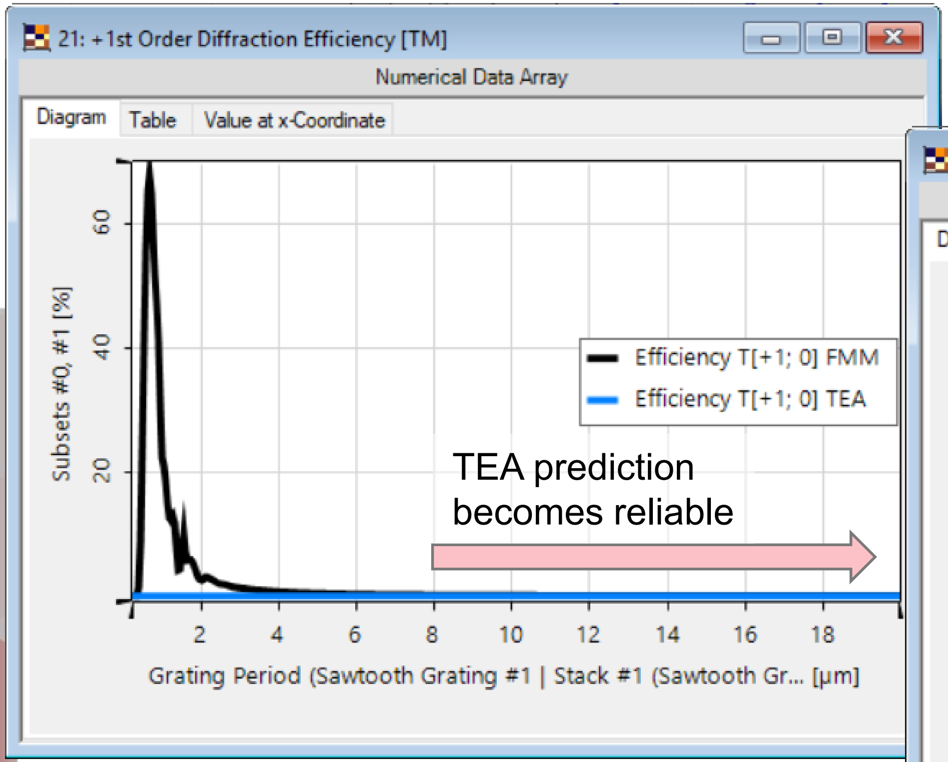


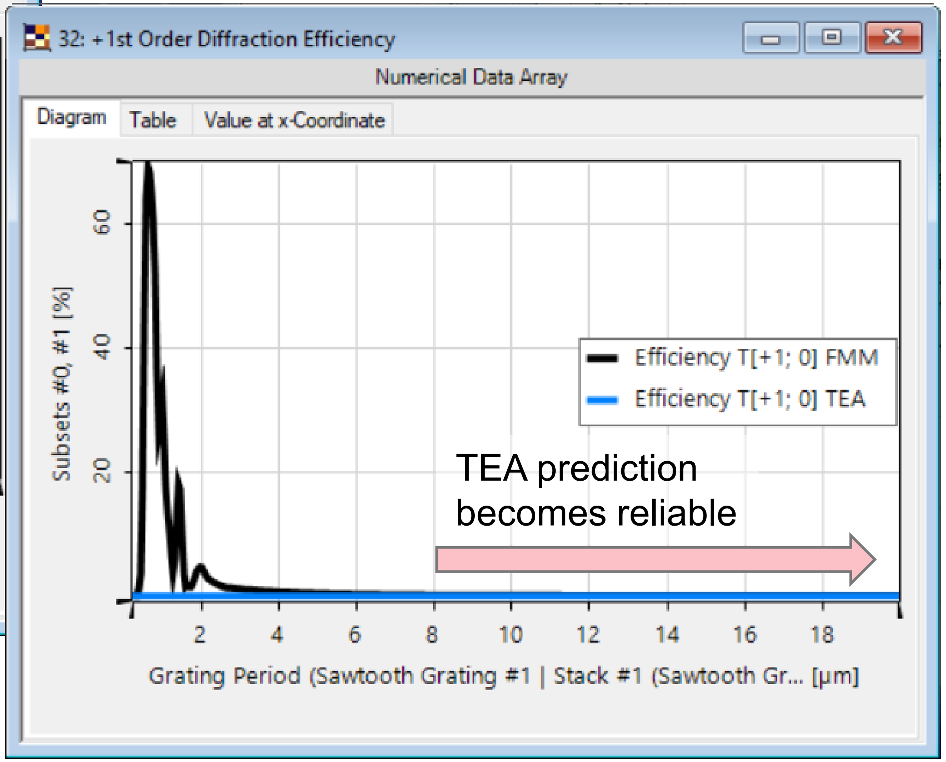




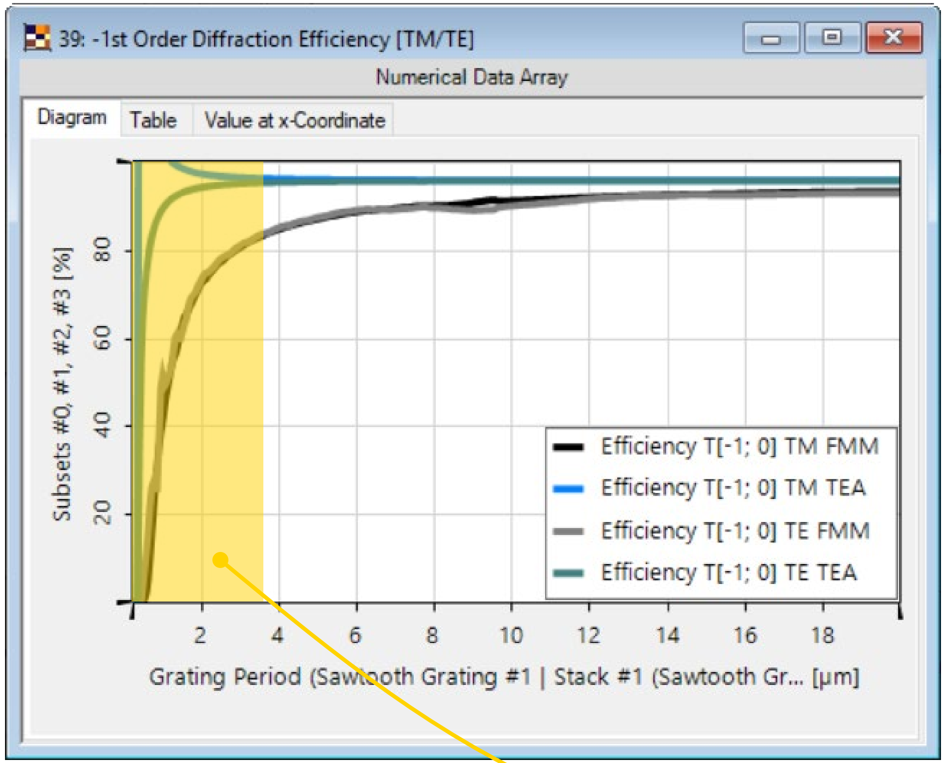
+1st Diffraction Order Analysis – FMM vs TEA



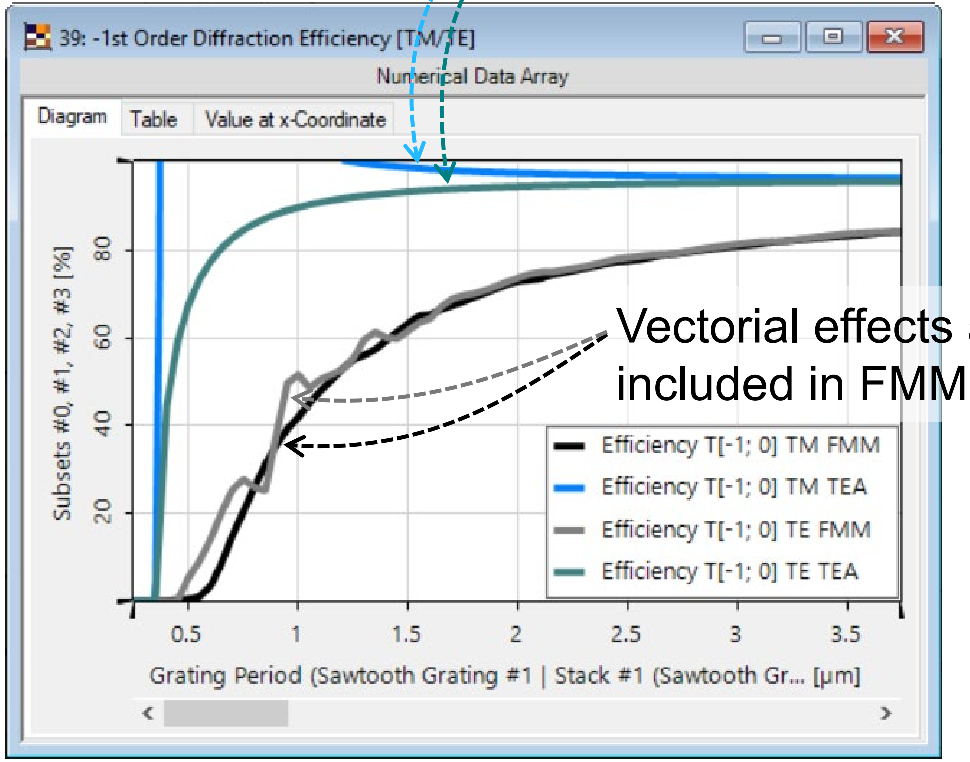




-1st Diffraction Order Analysis – Polarization Effect



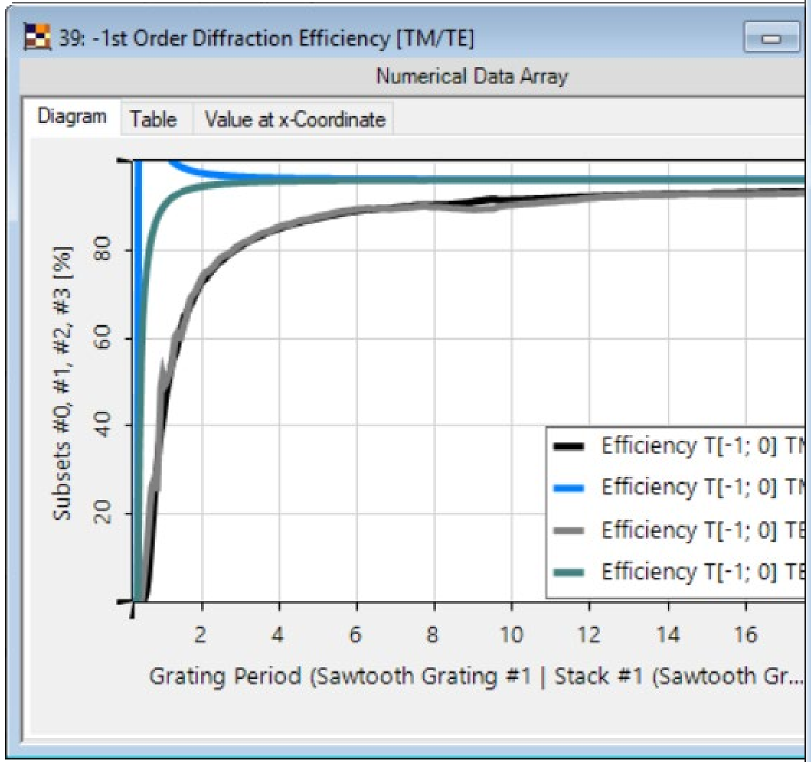
zoomed region

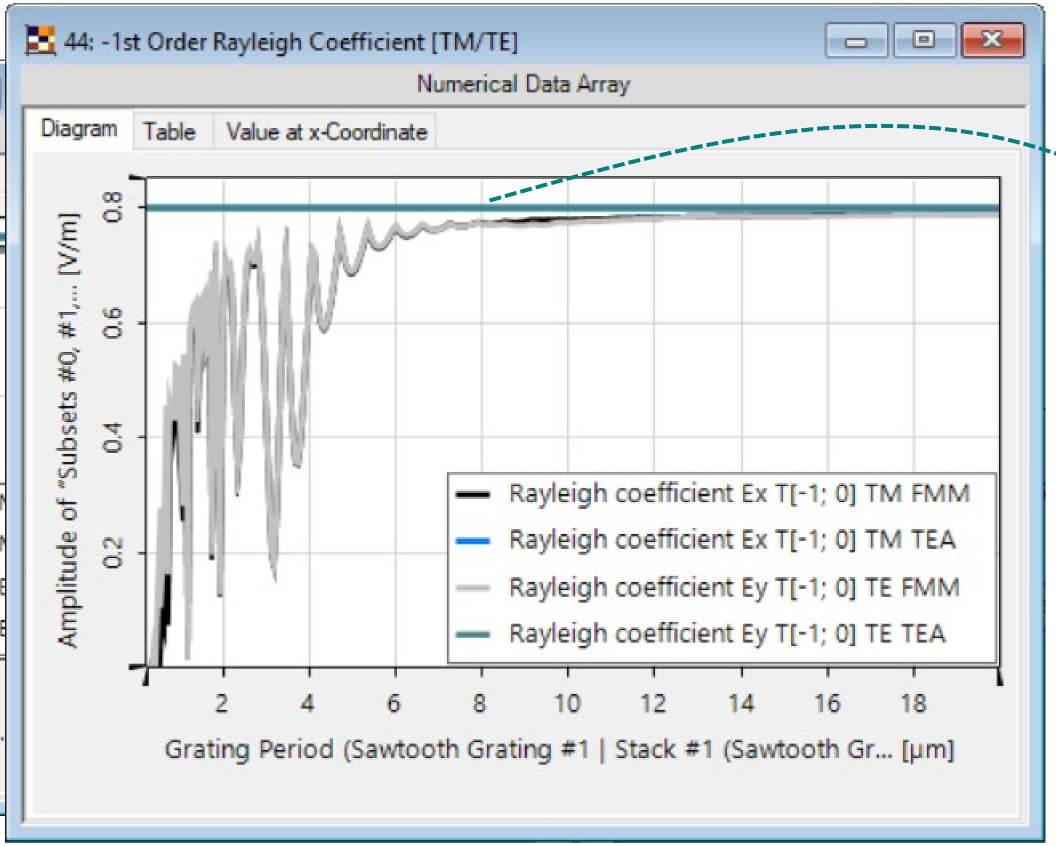


Vectorial effects also in TEA calculation?

Vectorial effects are included in FMM simulation.

-1st Diffraction Order Analysis – Polarization Effect





No vectorial effects considered in TEA calculation!

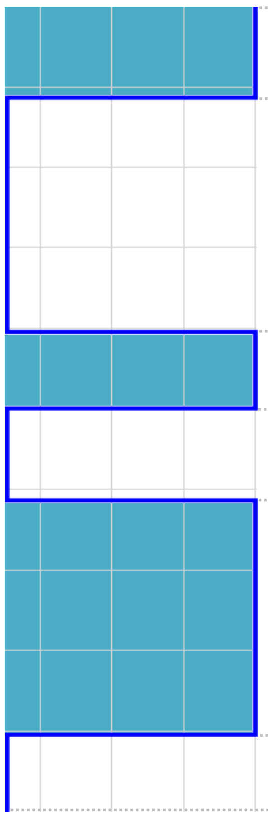
Note the relation between Rayleigh coefficients and diffraction efficiency.

Using Split-Step Beam Propagation Method for Grating Simulation

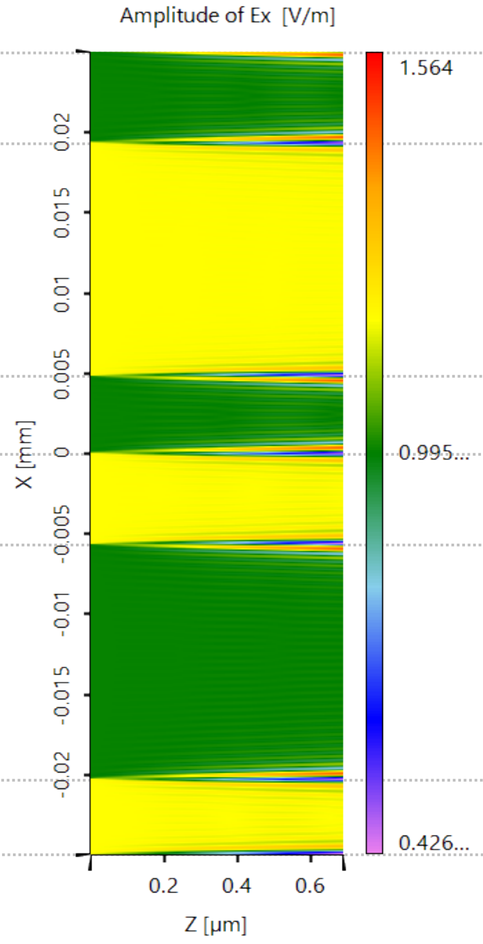
Coming feature for grating simulation

Period = 50µm; Smallest Feature = 4.7410µm

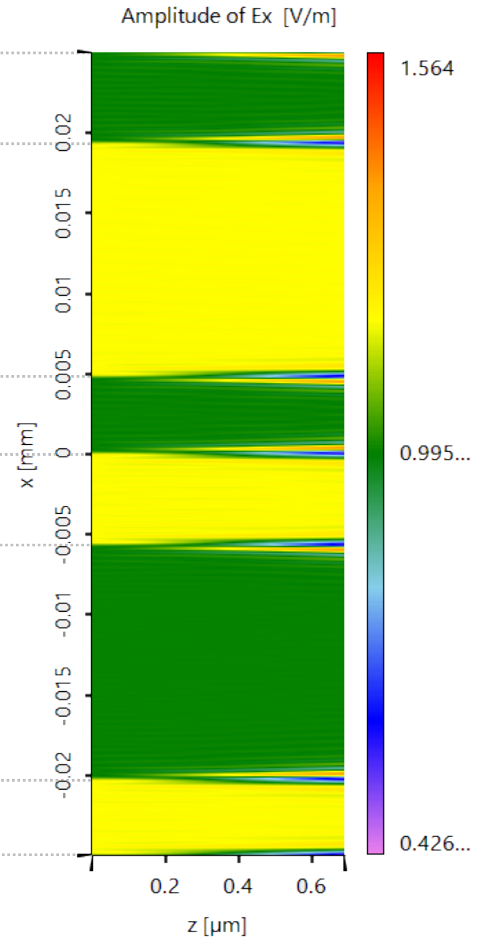
Structure Height Profile



Split Step

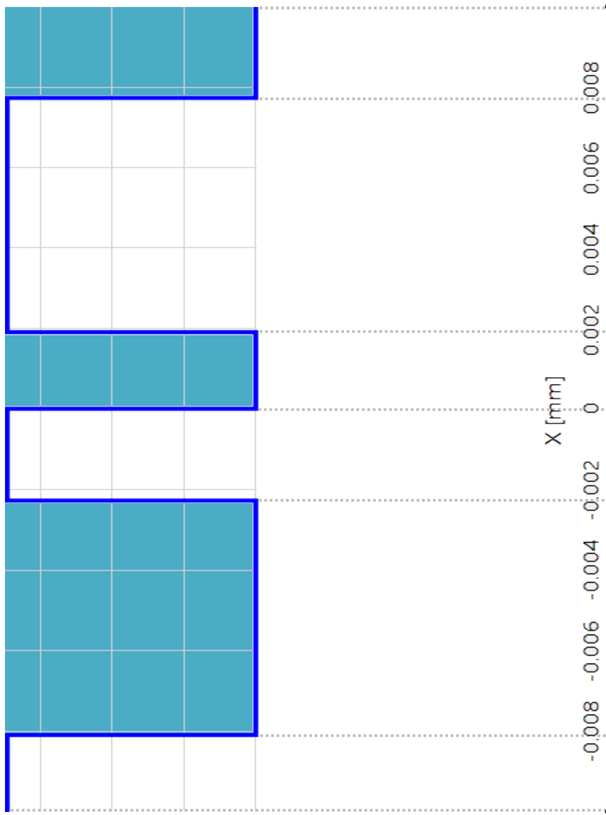


FMM

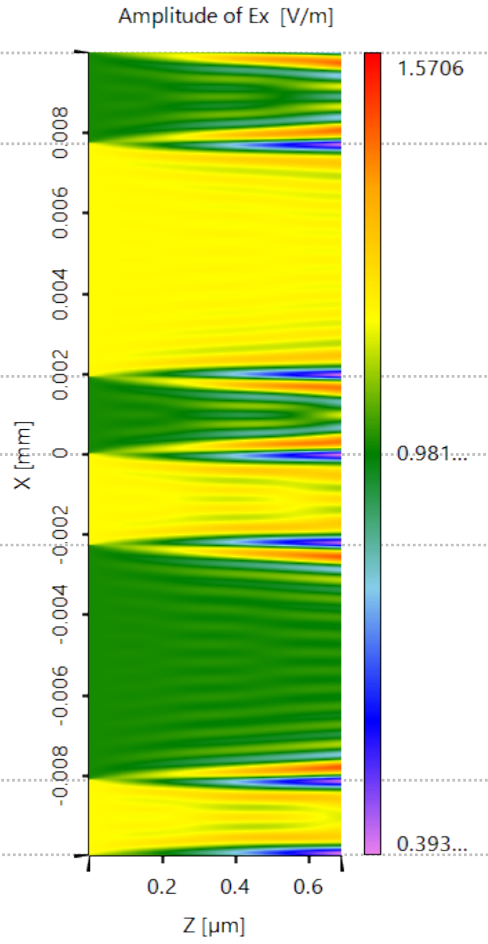


Period = 20µm; Smallest Feature = 1.8964µm

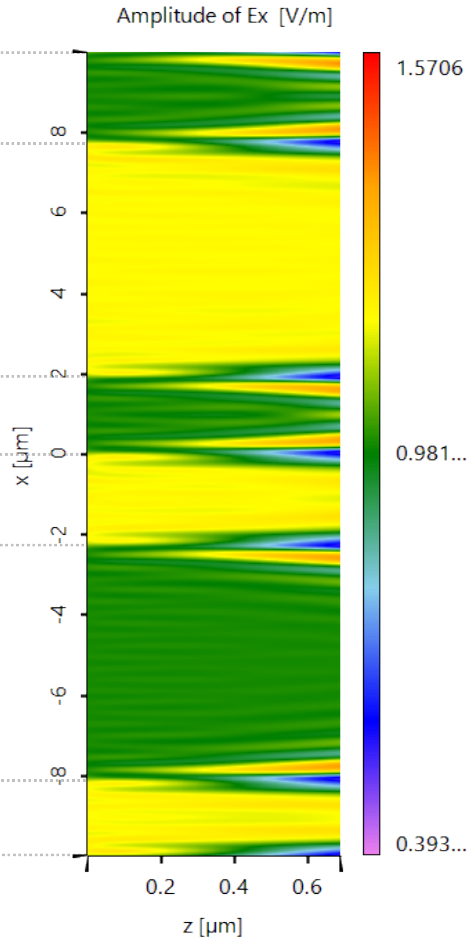
Structure Height Profile



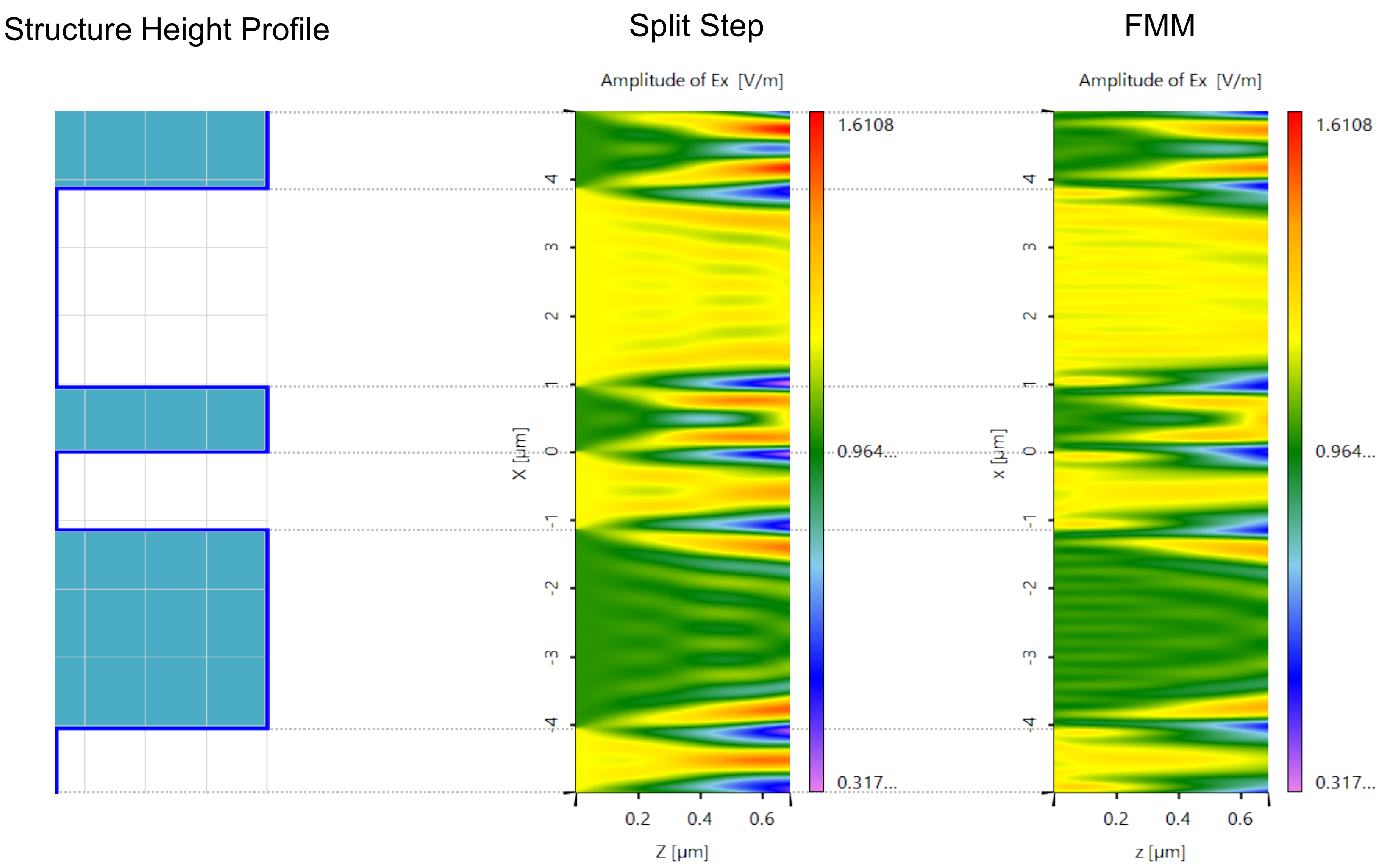
Split Step



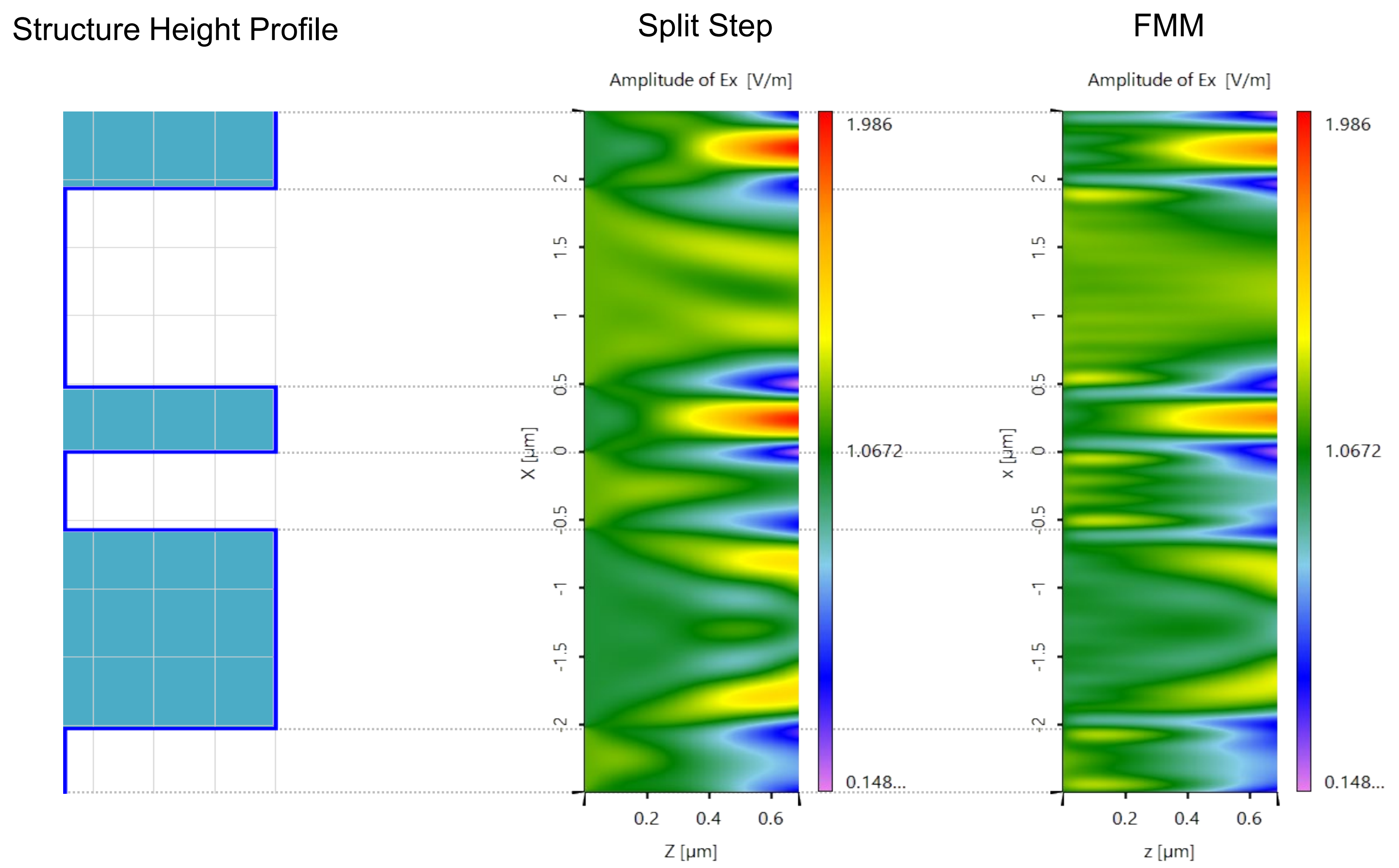
FMM



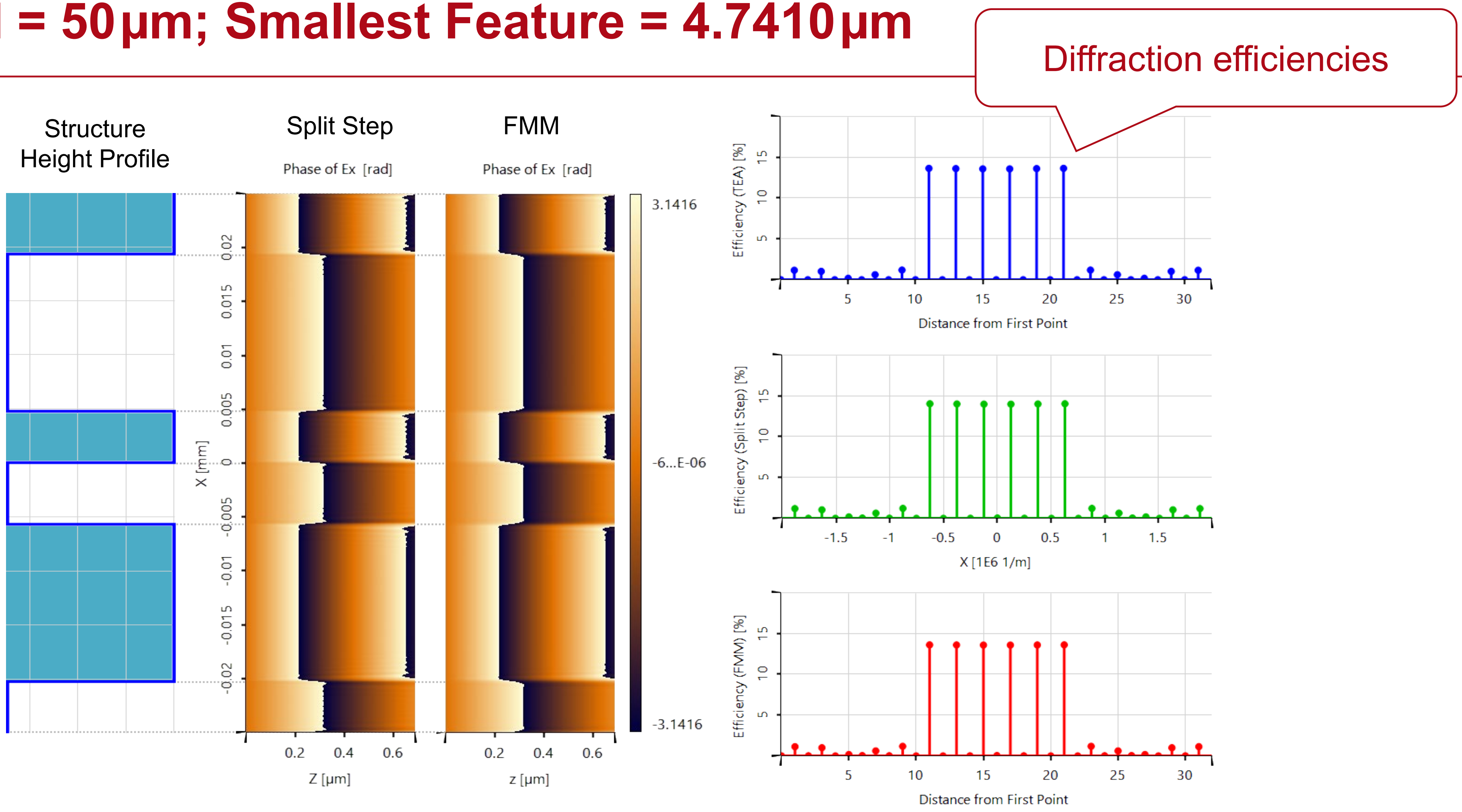
Period = 10µm; Smallest Feature = 0.9482µm



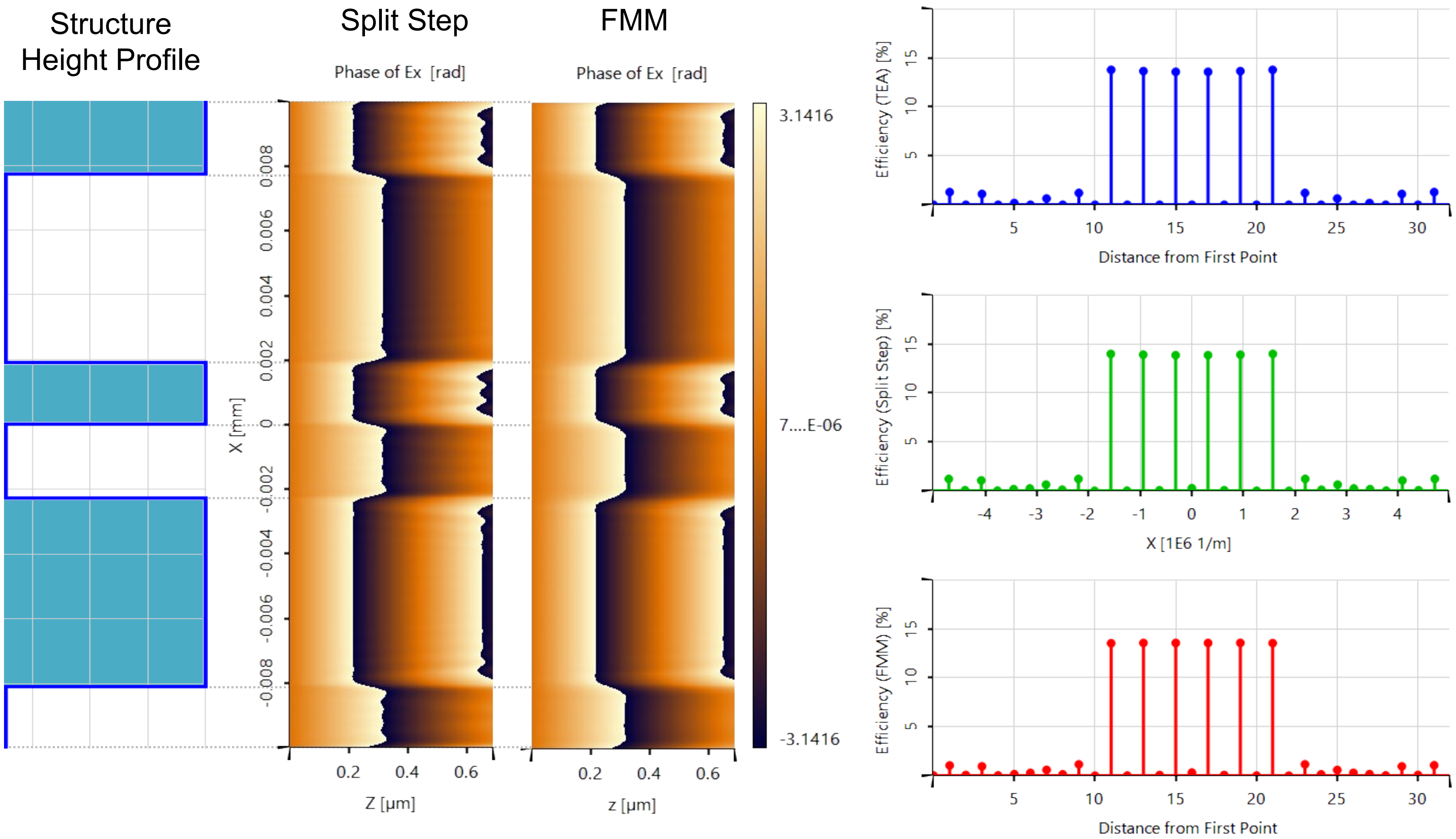
Period = 5µm; Smallest Feature = 0.4741µm



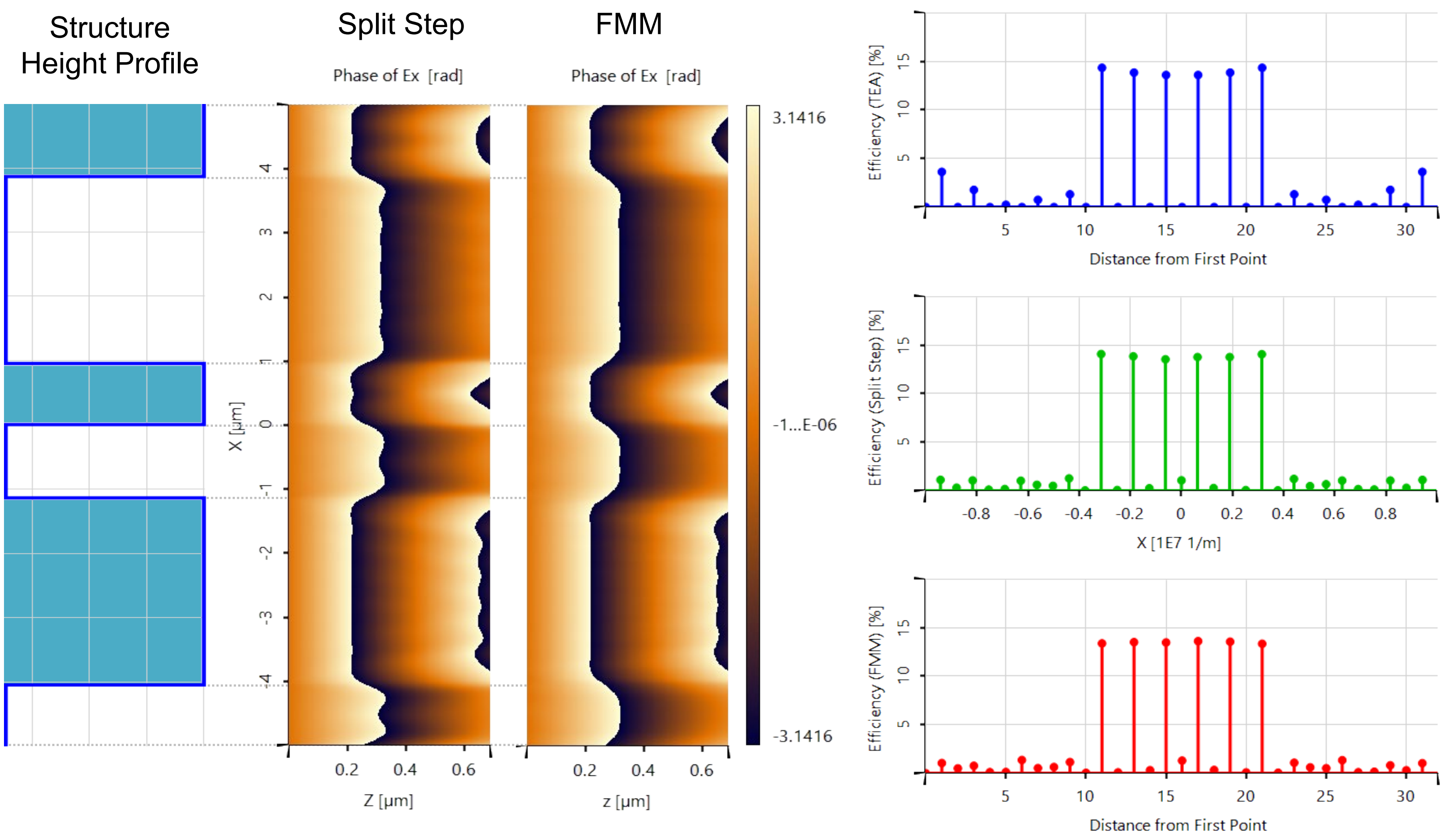
Period = 50µm; Smallest Feature = 4.7410µm



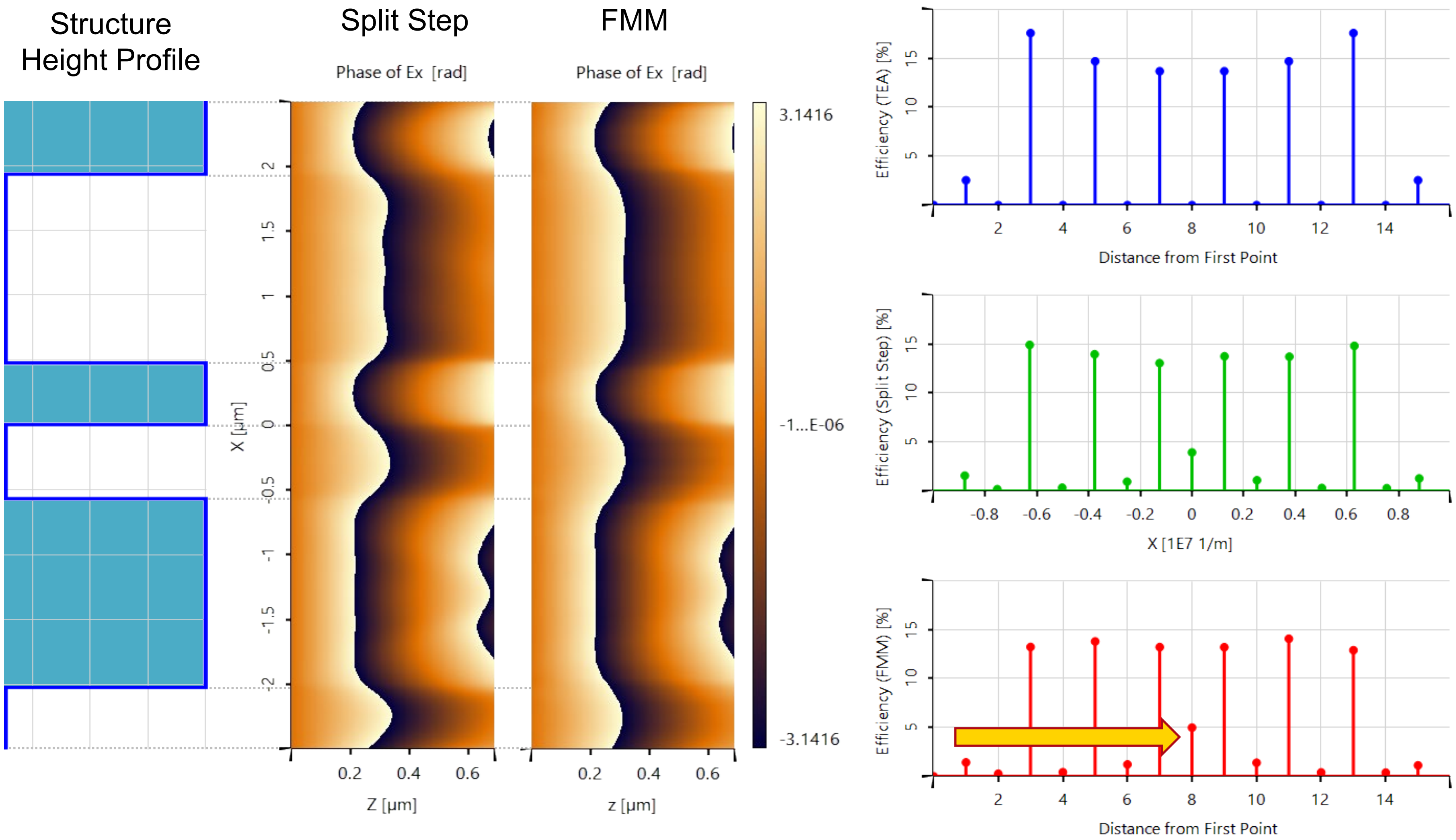
Period = 20µm; Smallest Feature = 1.8964µm



Period = 10µm; Smallest Feature = 0.9482µm



Period = 5µm; Smallest Feature = 0.4741µm



Analysis of Slanted Gratings for Lightguide Coupling

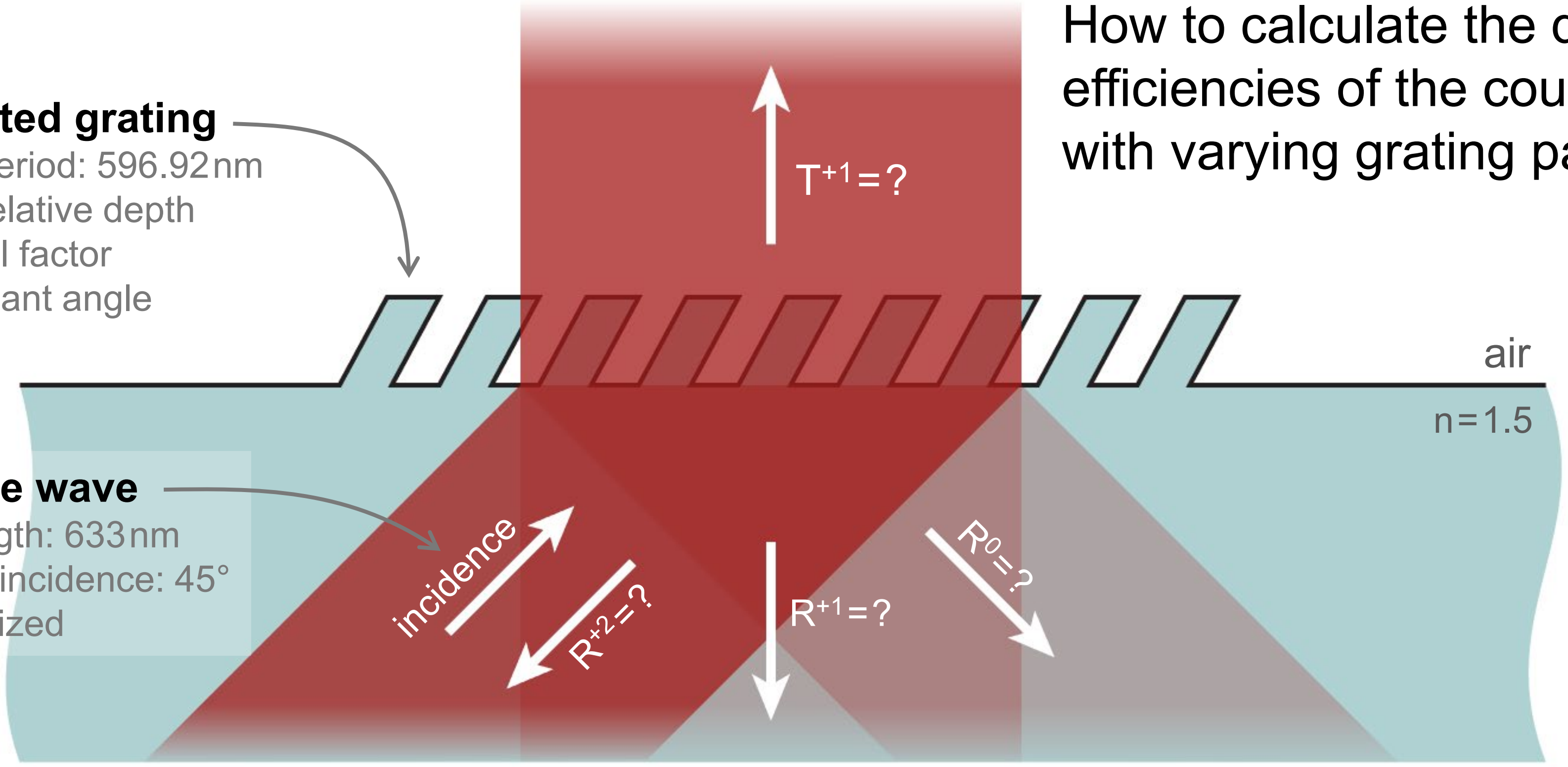
Modeling Slanted Grating_...

Modeling Task

slanted grating
- period: 596.92 nm
- relative depth
- fill factor
- slant angle

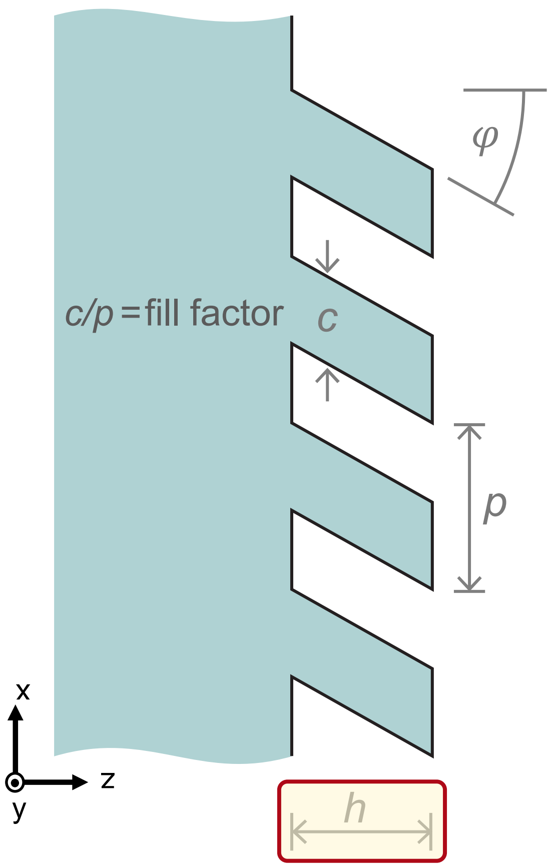
to be varied (relative depth, fill factor, slant angle)

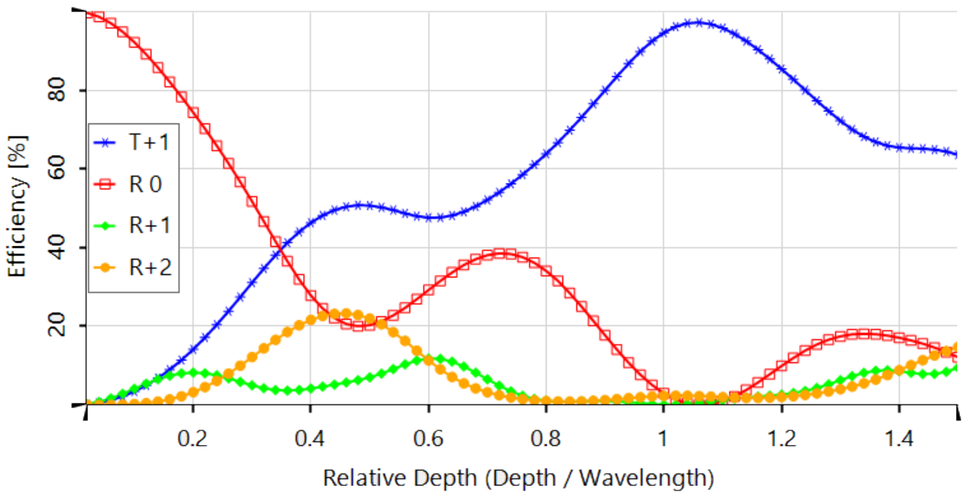
input plane wave
- wavelength: 633 nm
- angle of incidence: 45°
- TE polarized



How to calculate the diffraction efficiencies of the coupling grating, with varying grating parameters?

Diffraction Efficiency vs. Relative Depth





simulation by Fourier modal method (FMM), also known as RCWA, in VirtualLab Fusion

Grating Parameter	Value & Unit
relative depth	**to be varied**
slant angle φ	-30°
fill factor c/p	50%

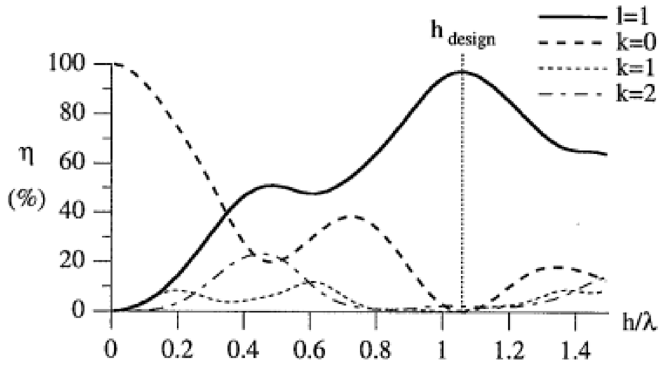
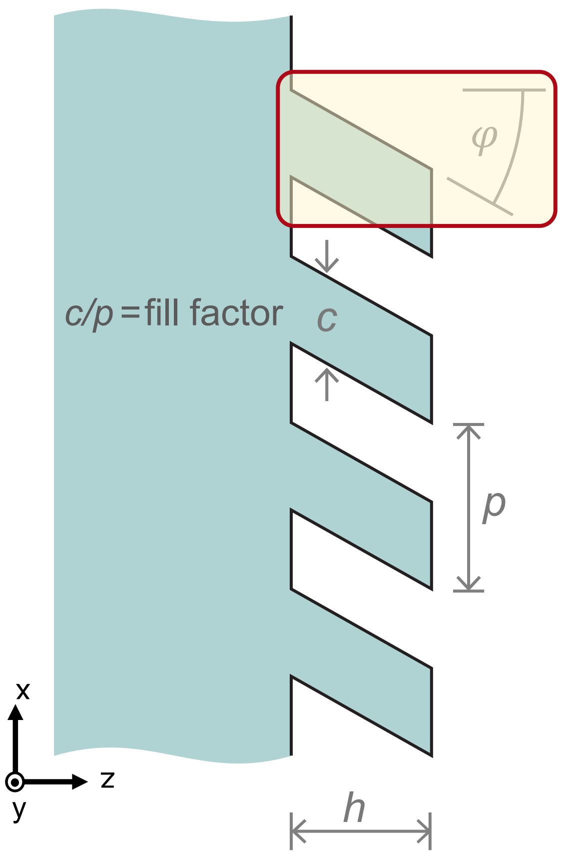
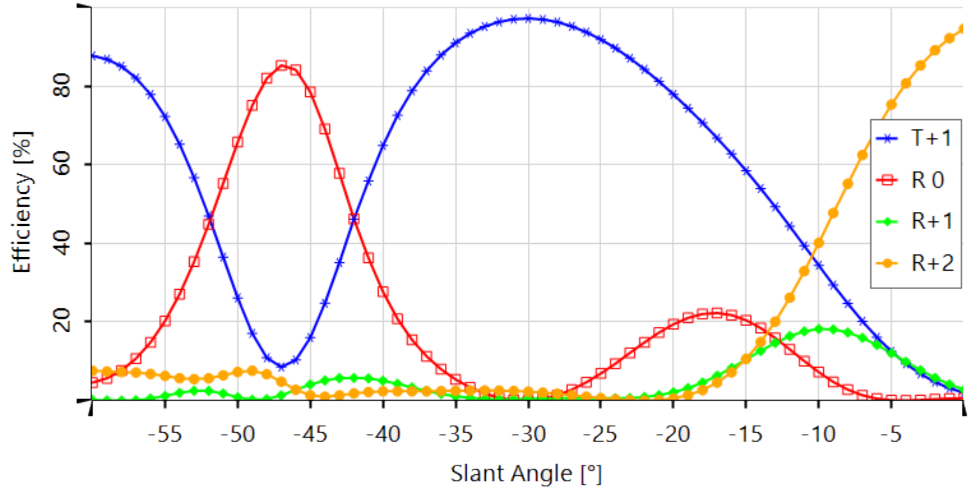


Figure from J. Michael Miller, *et al.*, Appl. Opt. 36, 5717-5727 (1997)

Diffraction Efficiency vs. Slant Angle





simulation by Fourier modal method (FMM), also known as RCWA, in VirtualLab Fusion

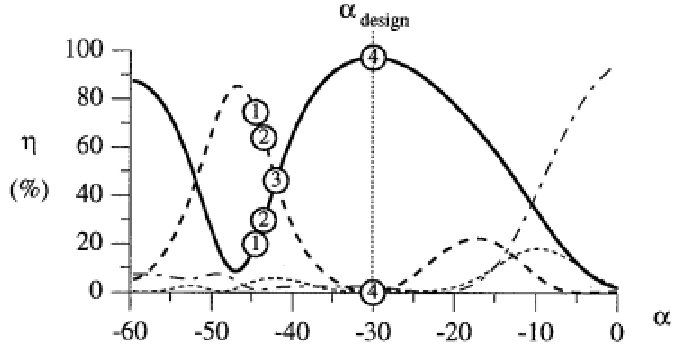
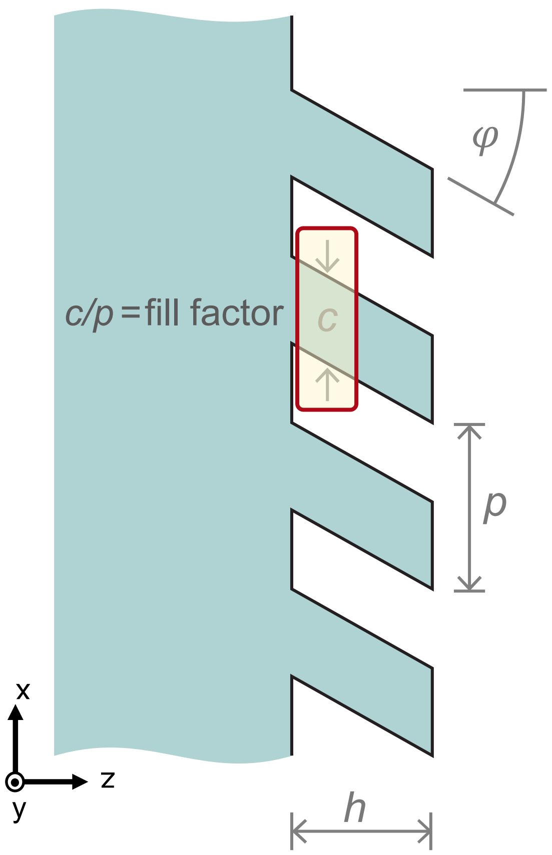
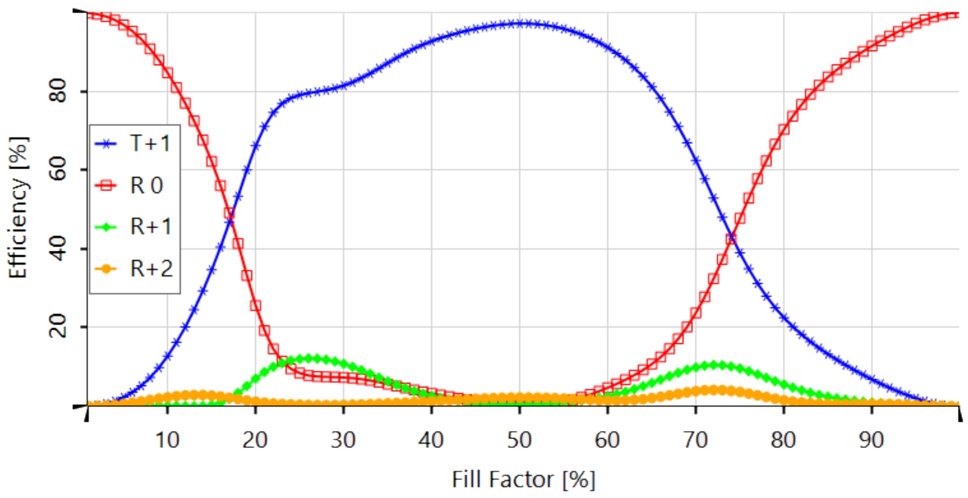


Figure from J. Michael Miller, *et al.*, Appl. Opt. 36, 5717-5727 (1997)

Grating Parameter	Value & Unit
relative depth	1.058λ
slant angle φ	**to be varied**
fill factor c/p	50%

Diffraction Efficiency vs. Fill Factor





simulation by Fourier modal method (FMM), also known as RCWA, in VirtualLab Fusion

Grating Parameter	Value & Unit
relative depth	1.058 λ
slant angle φ	-30°
fill factor c/p	**to be varied**

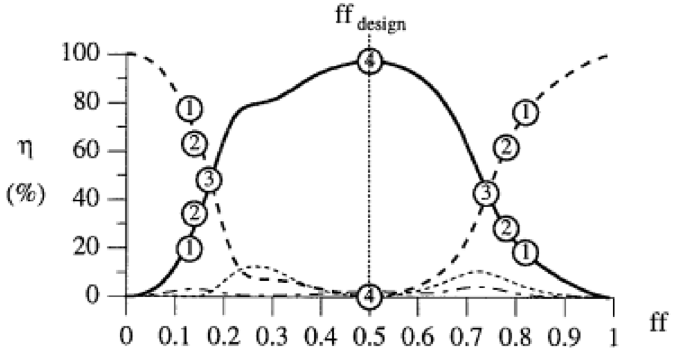
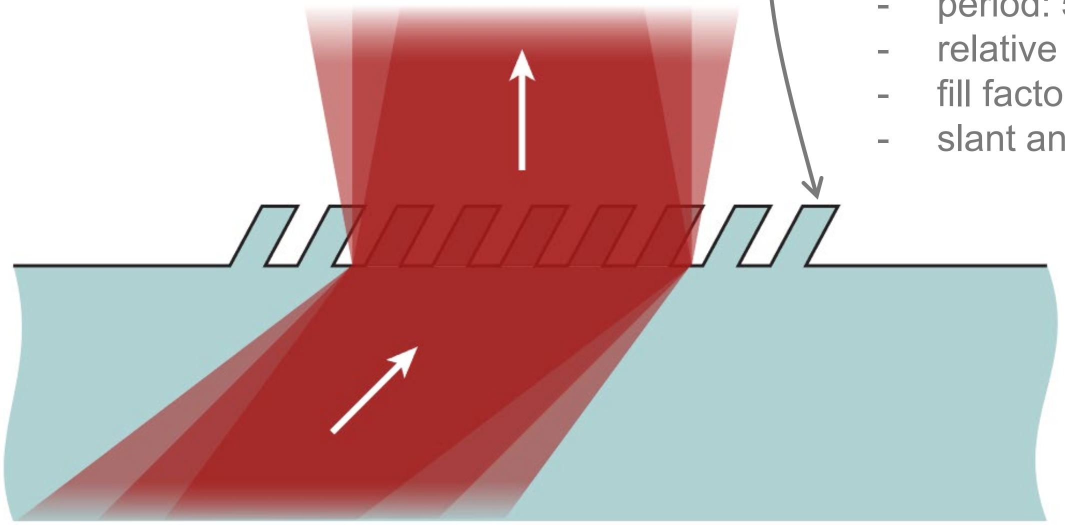


Figure from J. Michael Miller, *et al.*, Appl. Opt. 36, 5717-5727 (1997)

Diffraction Efficiency vs. Varying Incidence Angle

slanted grating
(fixed parameters
taken from reference)

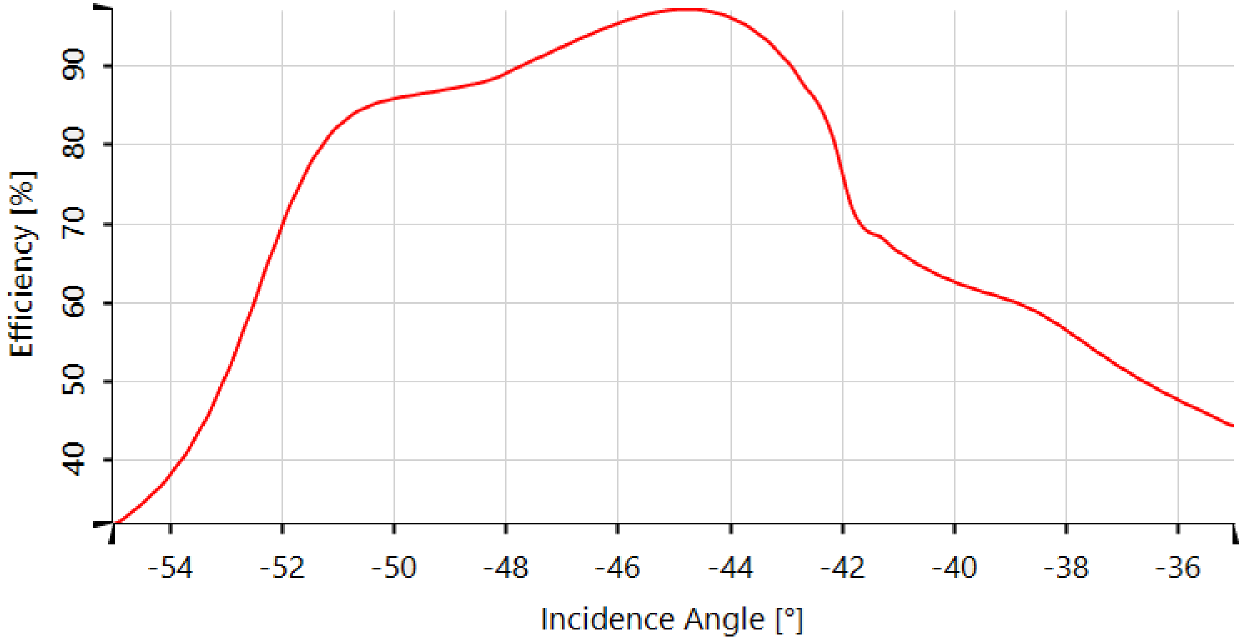
- period: 596.92 nm
- relative depth 1.058 λ
- fill factor 50 %
- slant angle -30°



input plane wave

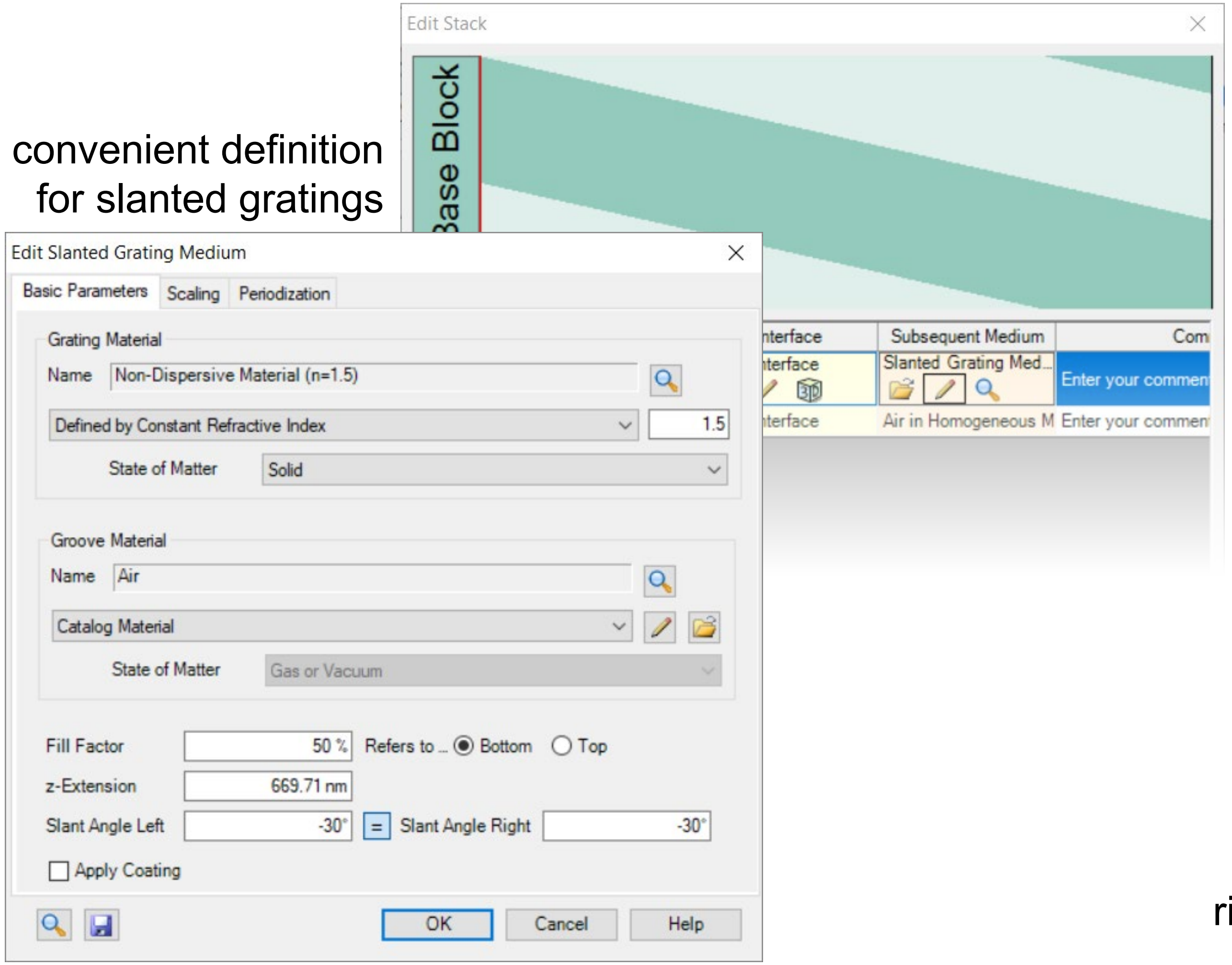
- wavelength: 633 nm
- angle of incidence: **45±10°**
- TE polarized

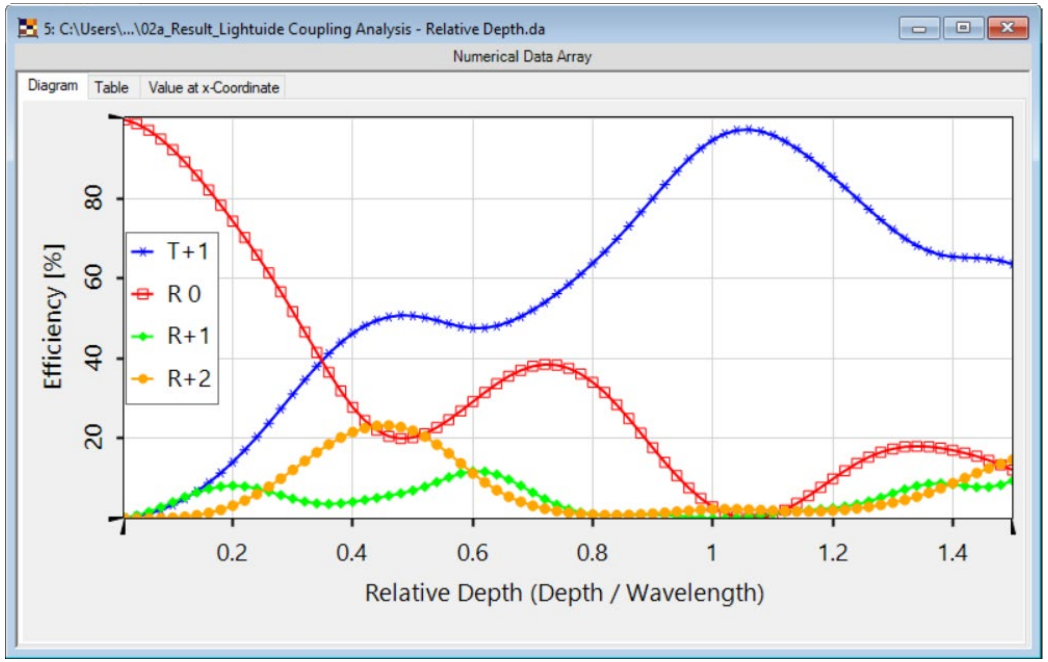
Grating diffraction efficiency is usually sensitive to the angle of incidence.



Peek into VirtualLab Fusion

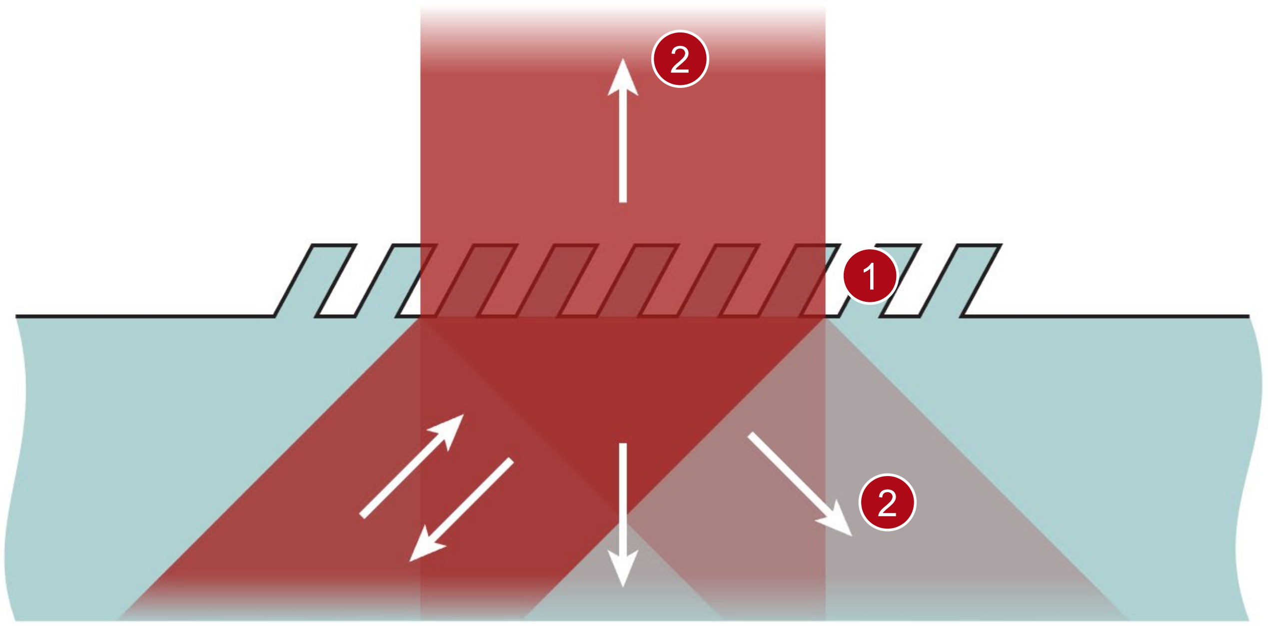
convent definition
for slanted gratings

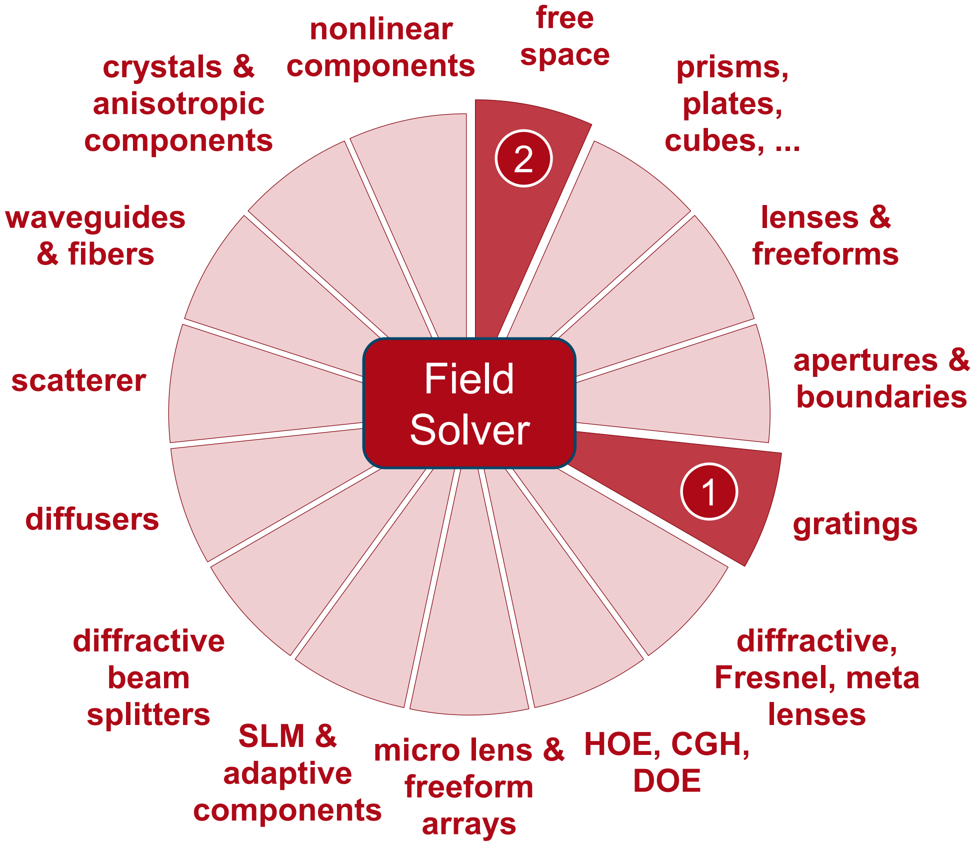




rigorous diffraction efficiency calculation and visualization

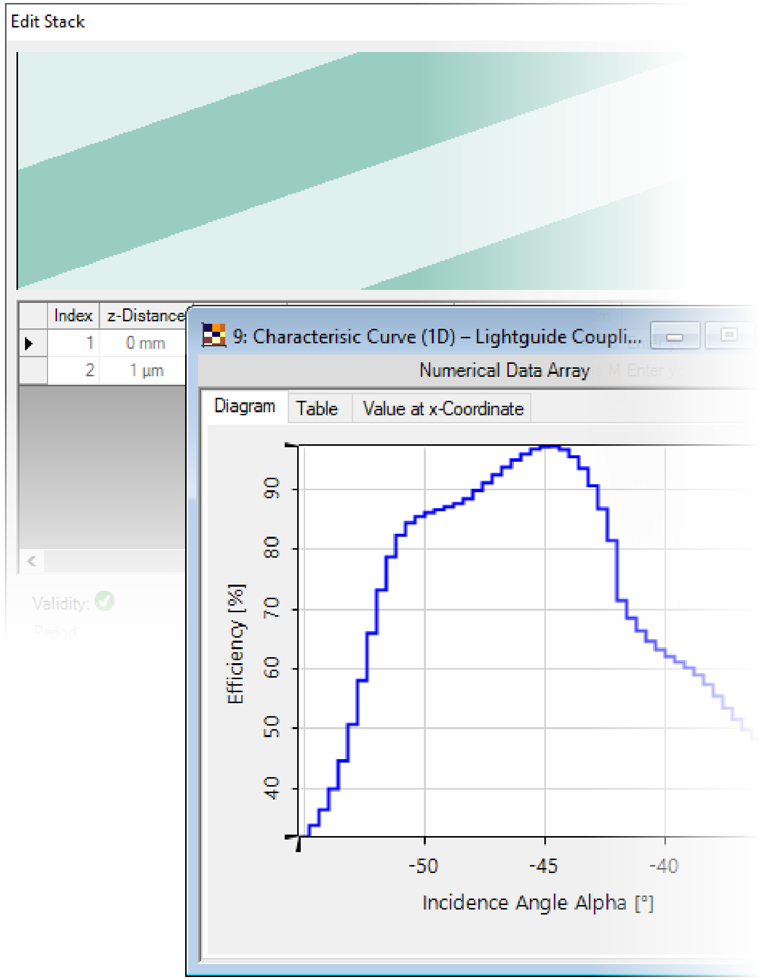
VirtualLab Fusion Technologies





Workflow in VirtualLab Fusion

- Configuration of lightguide coupling grating structure
  - Advanced Configuration of Slanted Grating [Use Case]
  - Configuration of Grating Structures by Using Special Media [Use Case]
  - Configuration of Grating Structures by Using Interfaces [Use Case]
- Analyze coupling grating diffraction efficiency
  - Customized Detector for Lightguide Coupling Grating Evaluation [Use Case]
- Check efficiency by scanning over specific parameter
  - Usage of Parameter Run [Use Case]



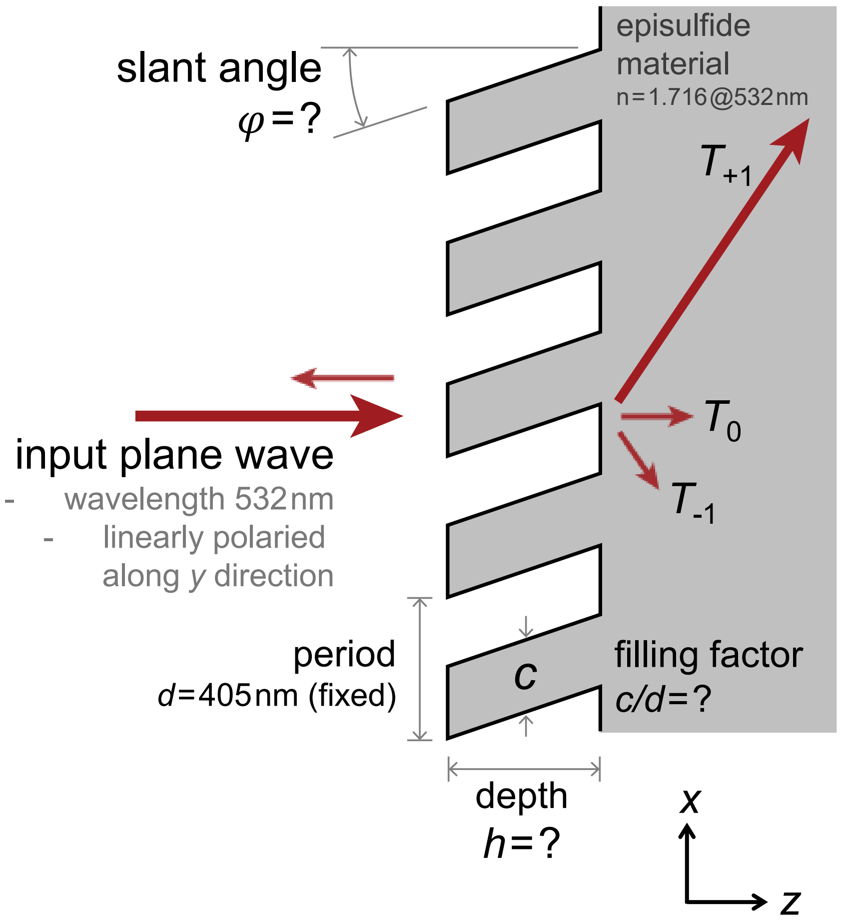
Document Information

title	Analysis of Slanted Gratings for Lightguide Coupling
document code	GRT.0009
version	2.0
toolbox(es)	Grating Toolbox
VL version used for simulations	VirtualLab Fusion Summer Release 2019 (7.6.1.18)
category	Application Use Case
further reading	- Parametric Optimization and Tolerance Analysis of Slanted Gratings - Configuration of Grating Structures by Using Special Media

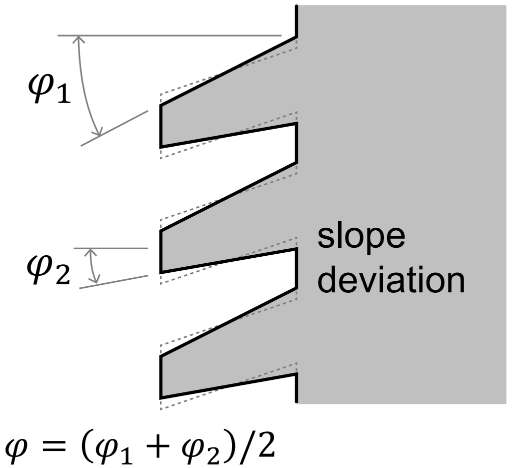
Parametric Optimization and Tolerance Analysis of Slanted Gratings

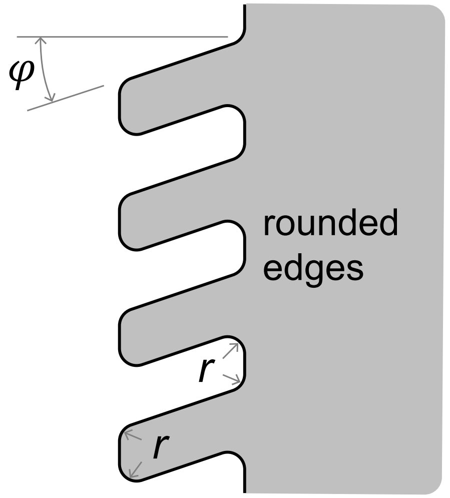
Slanted Grating_...

Modeling Task



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

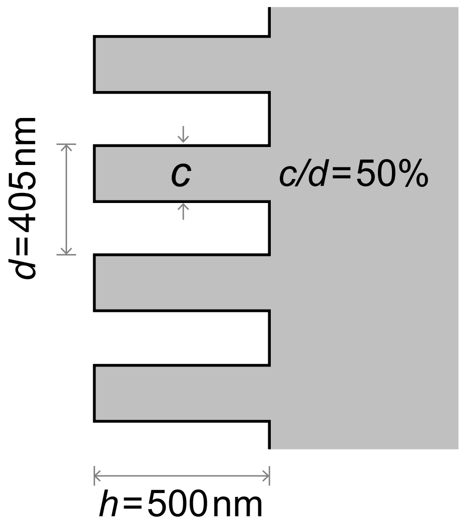




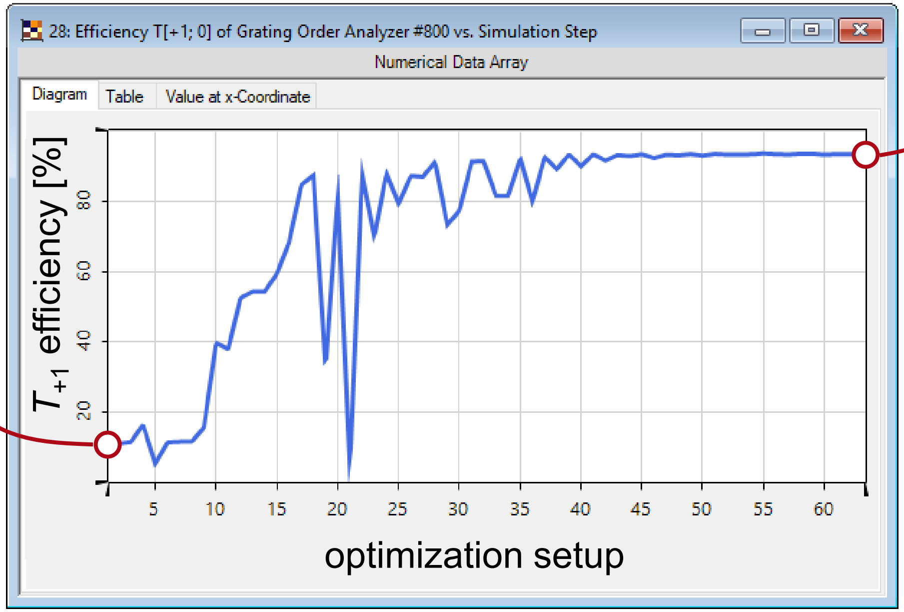
In addition, how to evaluate the grating performance with the slope deviation and the rounded edges due to the fabrication technique taken into account?

Parametric Optimization for 1st Order

initial structure

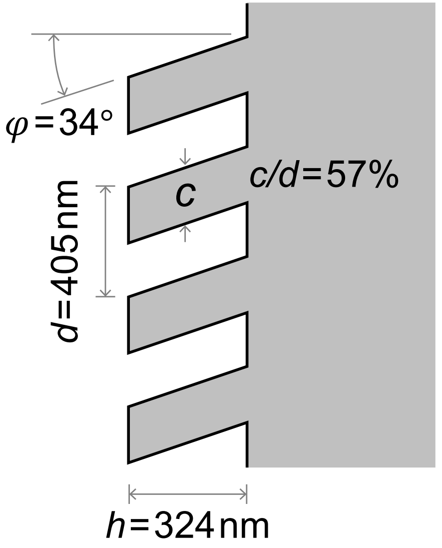


Order	Efficiency
-1	11.551%
0	72.795%
+1	11.551%



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

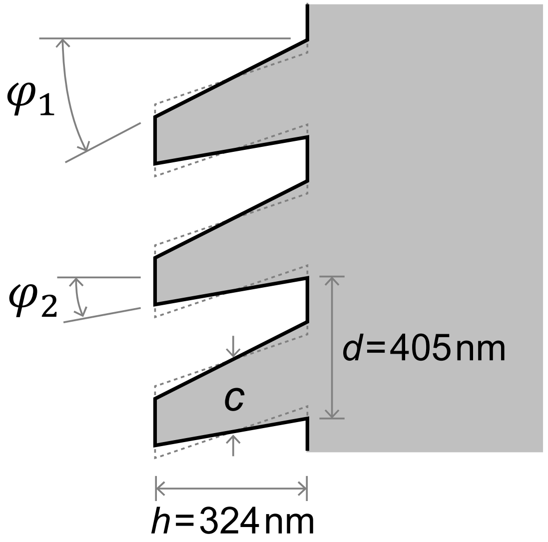
optimized structure



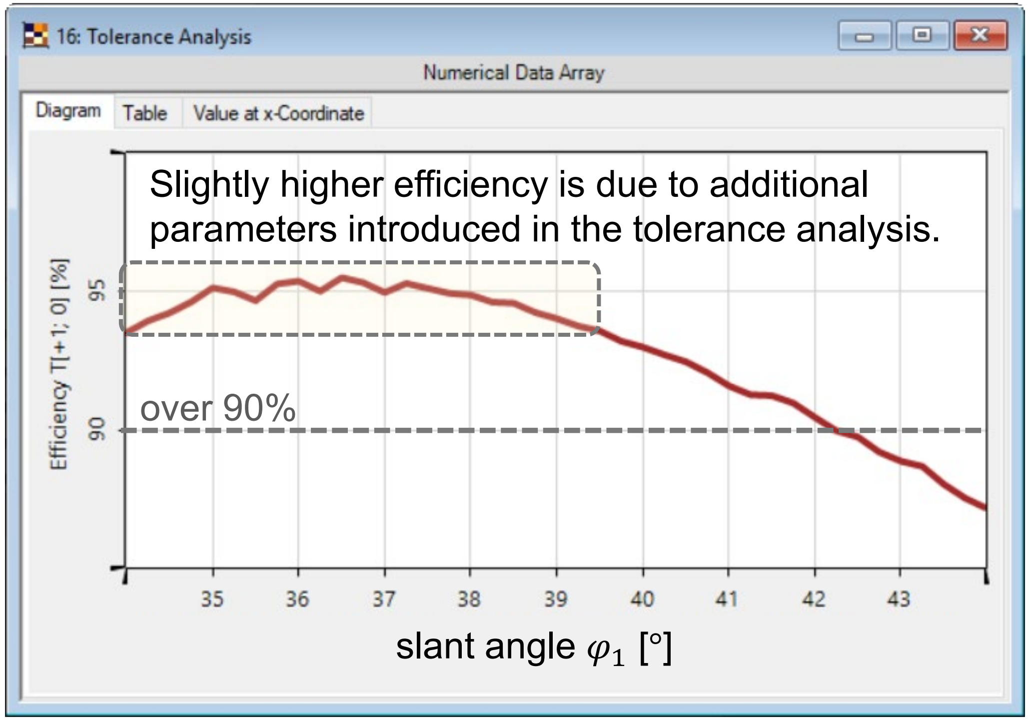
Order	Efficiency
-1	3.257%
0	0.365%
+1	**93.659%**

Results – Tolerance Analysis

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



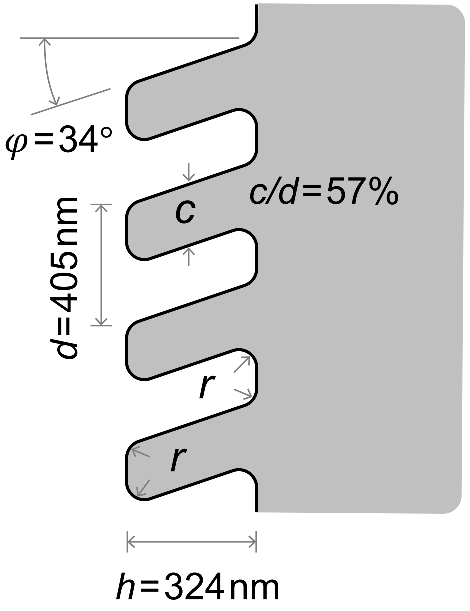
- fixed average slant angle $\varphi = (\varphi_1 + \varphi_2)/2 = 34°$
- fixed filling factor (average) c/d=57%
- varying φ_1 from 34 to 44°



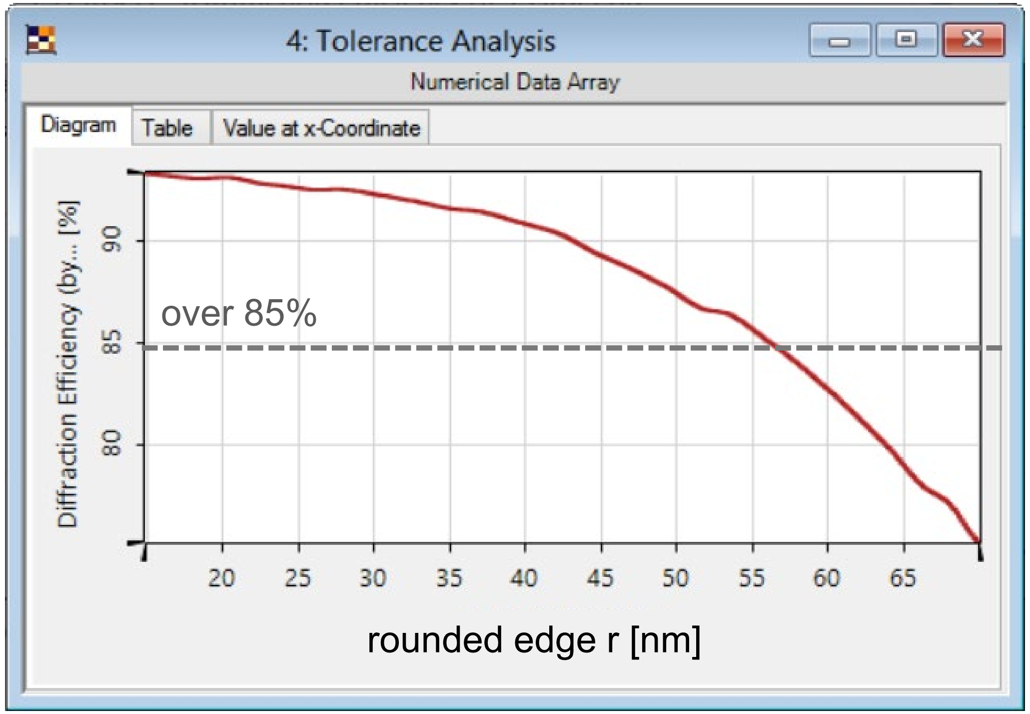
Rigorous simulation with Fourier modal method (FMM), for tolerance analysis over 50 steps, takes 30 seconds.

Results – Tolerance Analysis

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



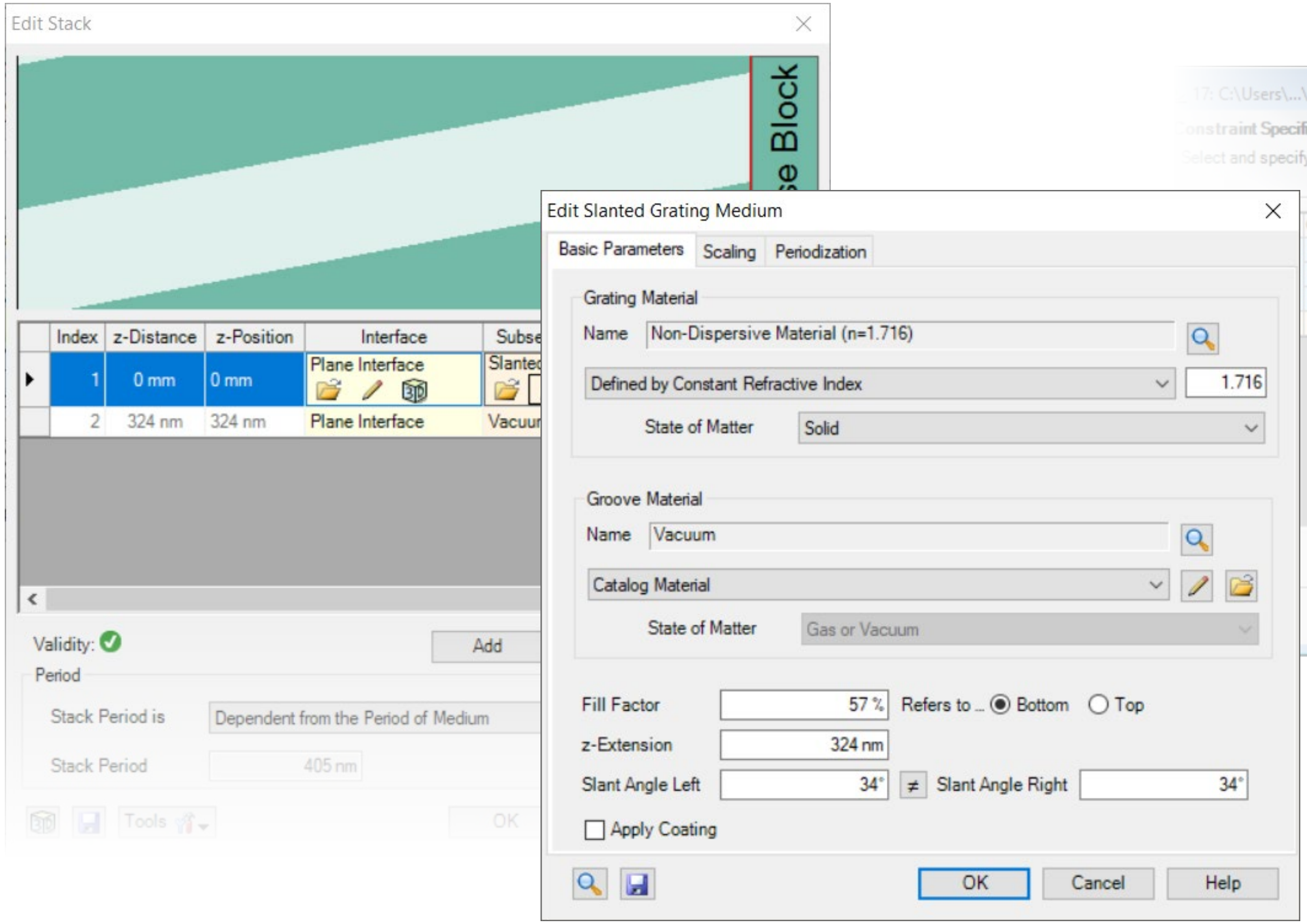
- fixed average slant angle $\varphi = 34°$
- fixed filling factor c/d=57%
- varying *r* from 15nm 70nm



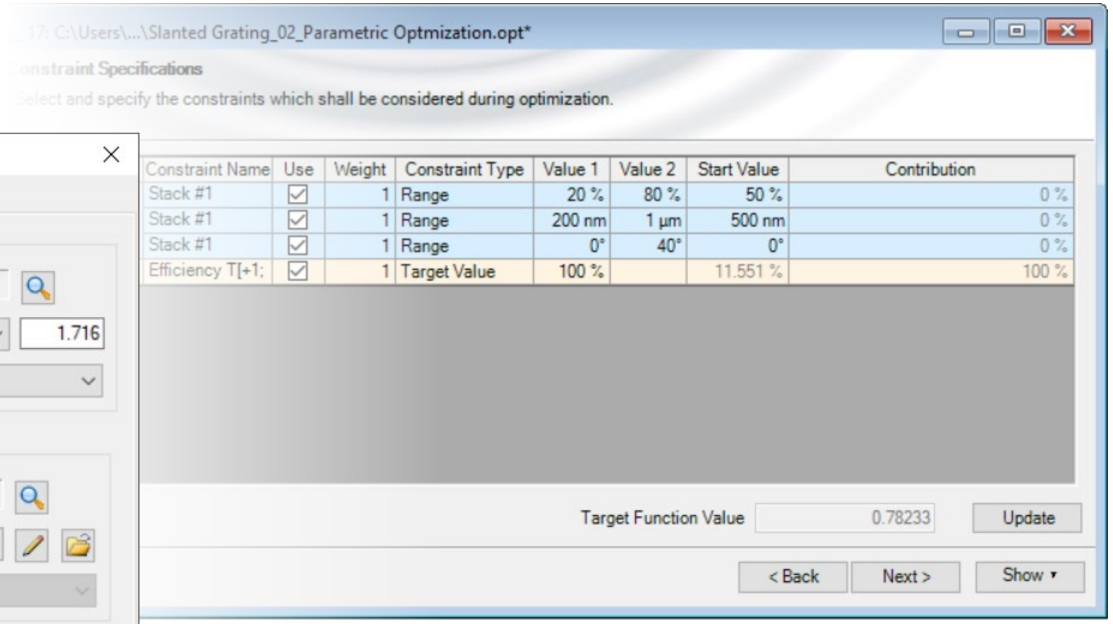
Rigorous simulation with Integral Method (IM), for tolerance analysis over 30 steps, takes 9 seconds.

Peek into VirtualLab Fusion

flexible and easy settings of slanted gratings

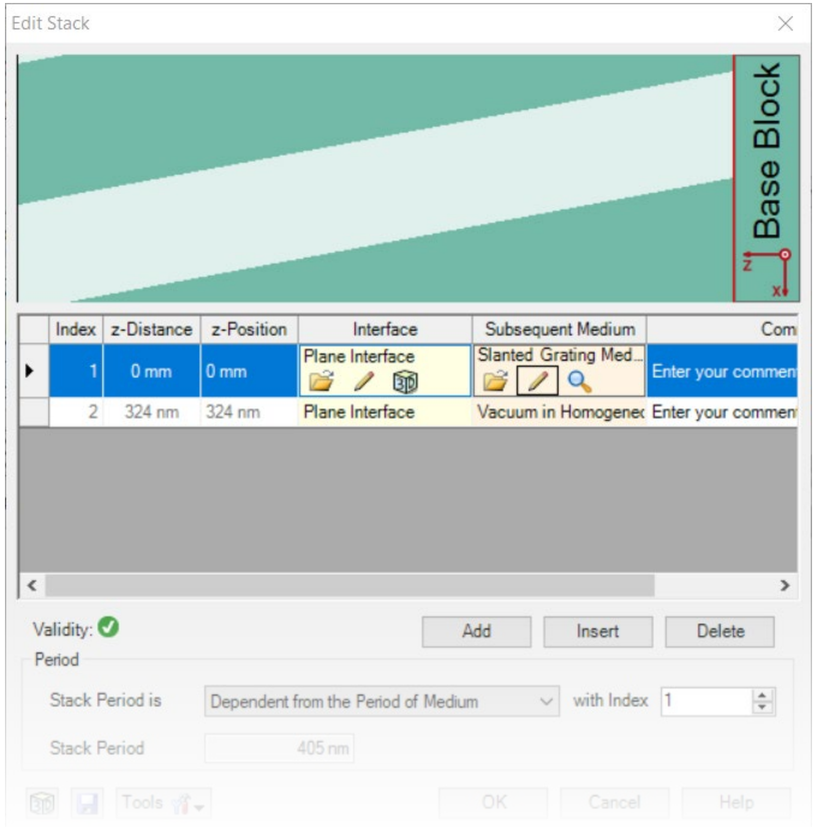


parametric optimization of grating parameters

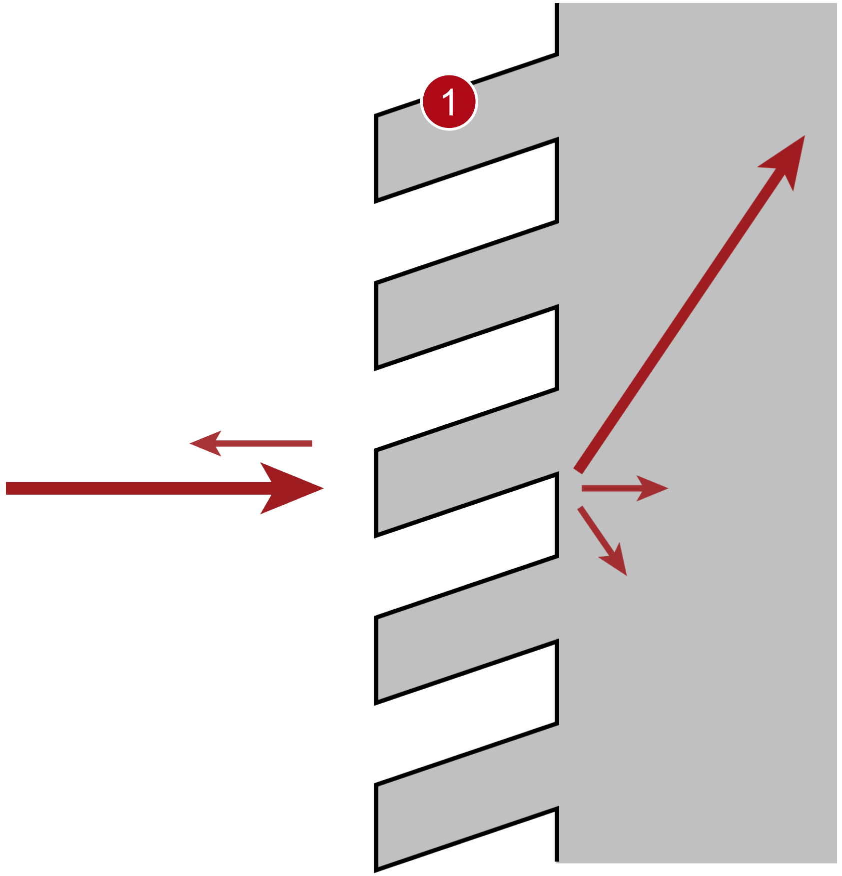


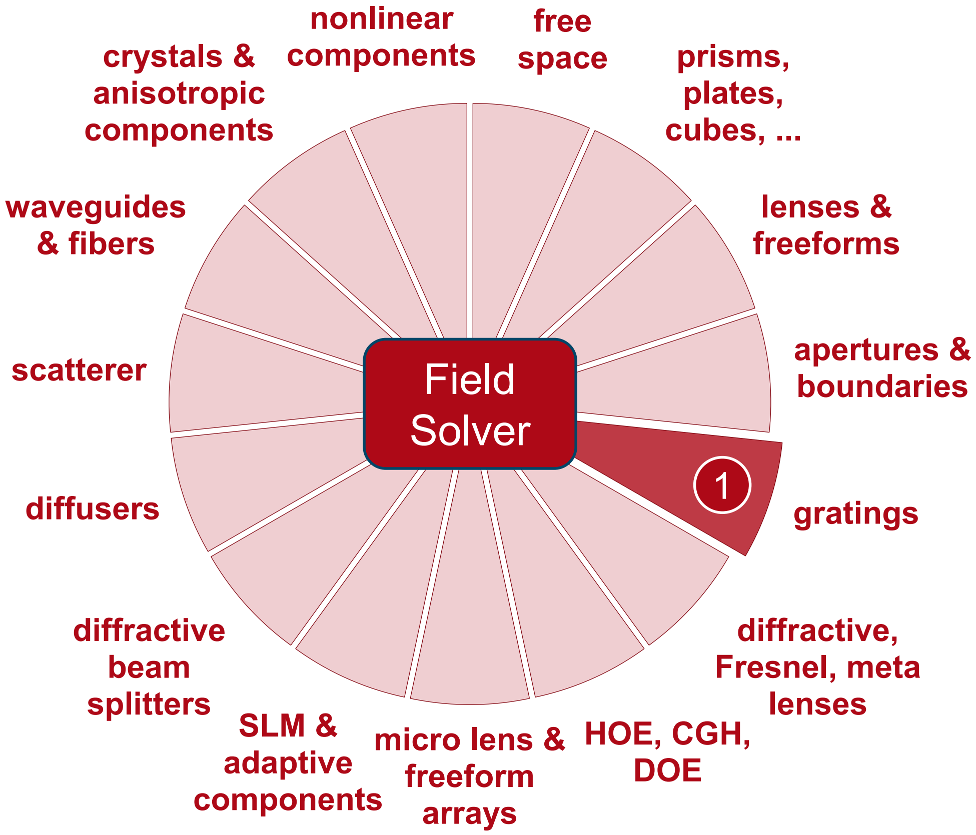
Workflow in VirtualLab Fusion

- Construct grating structure
  - Configuration of Grating Structures by Using Special Media [Use Case]
  - Advanced Configuration of Slanted Gratings [Use Case]
- Analyze grating diffraction efficiency
  - Grating Order Analyzer [Use Case]
- Optimize grating parameters with Parametric Optimization
- Tolerance analysis with Parameter Run
  - Usage of the Parameter Run Document [Use Case]



VirtualLab Fusion Technologies



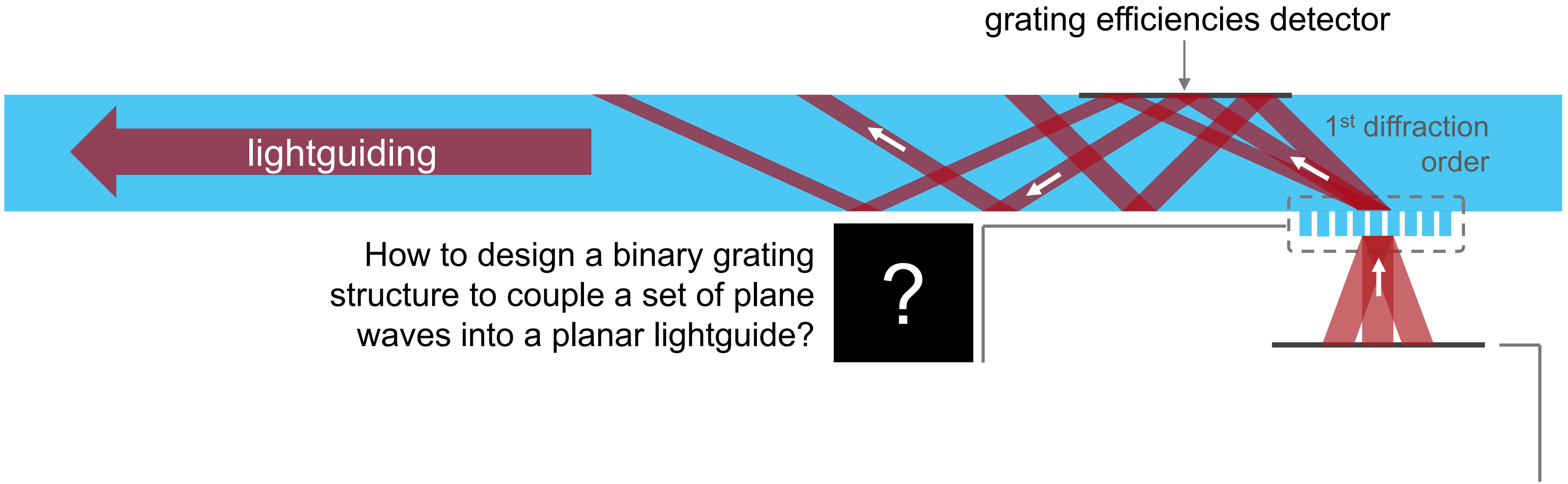


Document Information

title	Parametric Optimization and Tolerance Analysis of Slanted Gratings
document code	GRT.0007
version	1.2
toolbox(es)	Grating Toolbox
VL version used for simulations	7.6.0.78
category	Application Use Case
further reading	- Parametric Optimization and Tolerance Analysis of Slanted Gratings - Optimization of Lightguide Coupling Grating for Single Incidence Direction

Optimization of Binary Grating for Lightguide Coupling over Desired FOV

Optimization Task

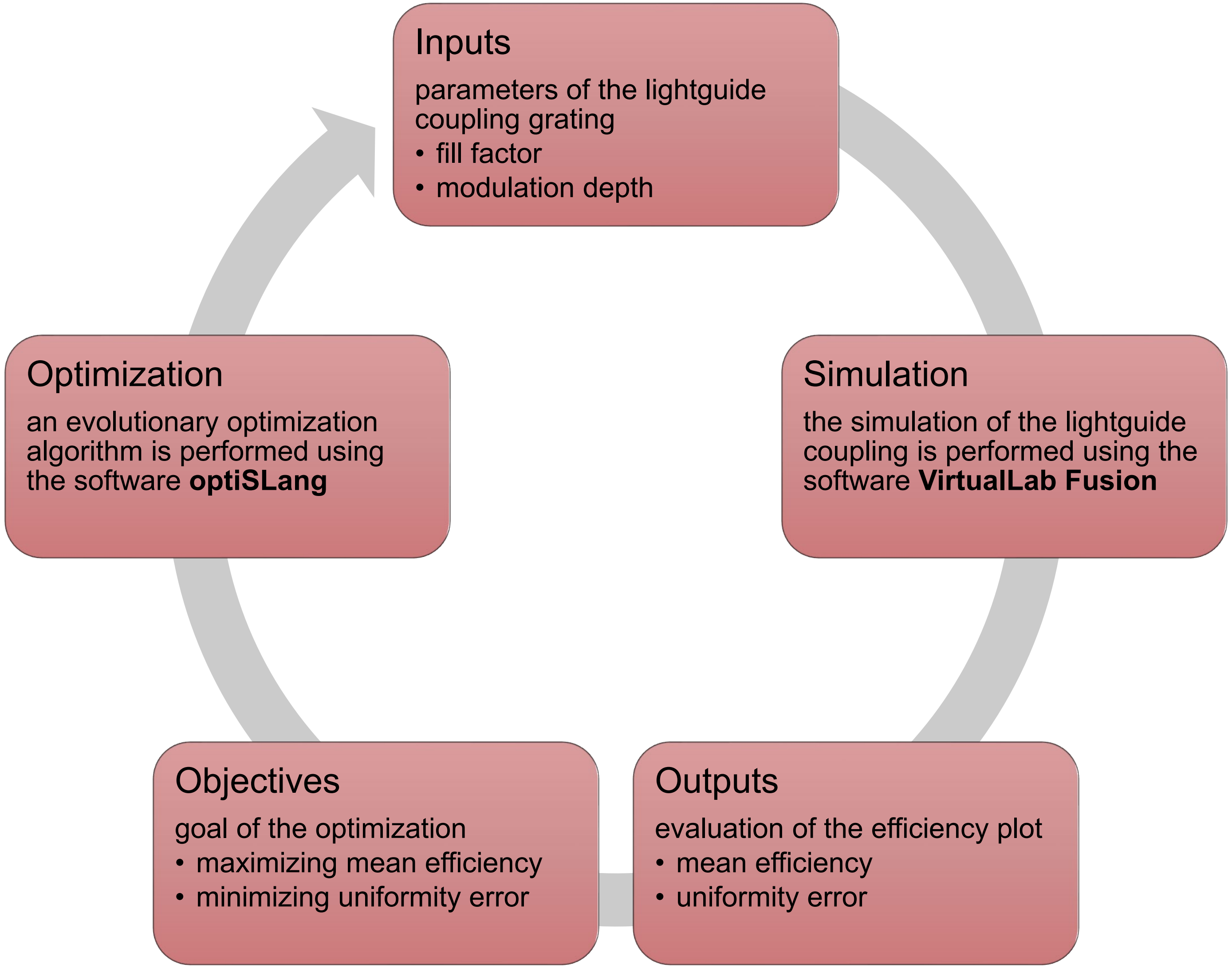


How to design a binary grating structure to couple a set of plane waves into a planar lightguide?

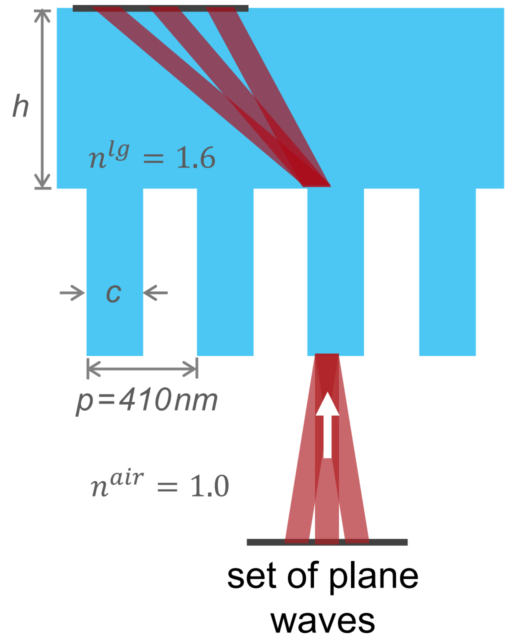
set of plane waves
- field of view (-15..15, -10..10)°
- wavelength 532 nm
- linearly polarized along x-axis

Optimization Workflow

- the following optimization workflow is applied to design a binary grating for efficient lightguide coupling
  1. Define the inputs
  2. Perform the simulation
  3. Calculate the outputs
  4. Check the objectives
  5. Perform the optimization
- depending on the optimization strategy new input parameters are defined by the algorithm
- in principle this is repeated in a loop until the objectives are achieved



Simulation Results and Configuration of the Merit Function



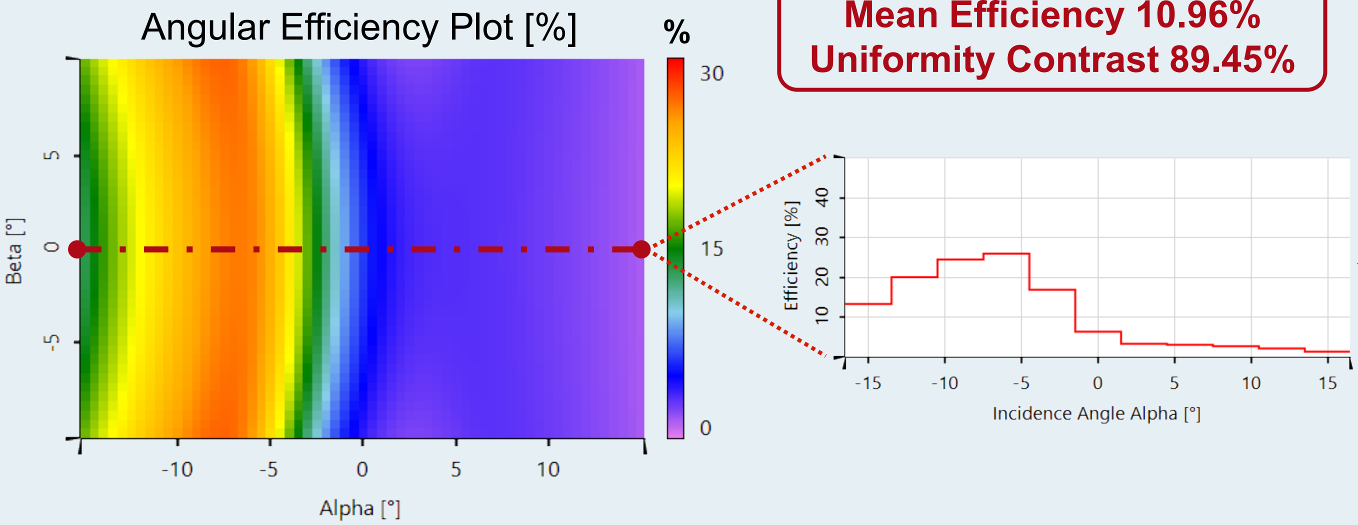
- variation of the **fill factor** *c/p* with the slit width *c* and the period *p*
  - ➢ **0.1% to 99.9%**
- variation of the **modulation depth** *h*
  - ➢ **50 nm to 1500 nm**

Initial Configuration of Grating	
fill factor	50.00%
modulation depth	400.00 nm
period	410 nm
operating order	1st transmitted

to be varied

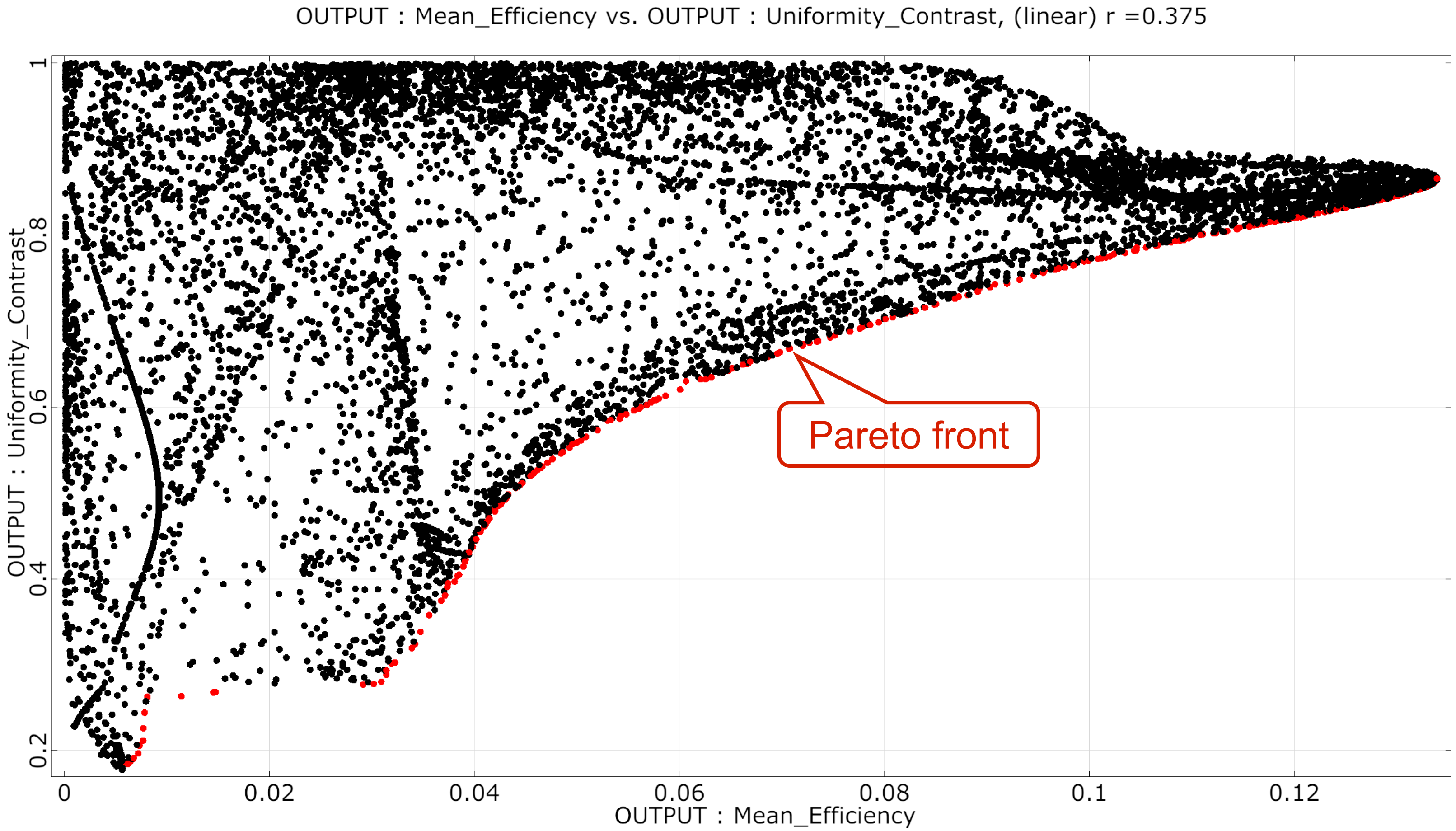
Grating Efficiencies Detector Result

Mean Efficiency 10.96%
Uniformity Contrast 89.45%



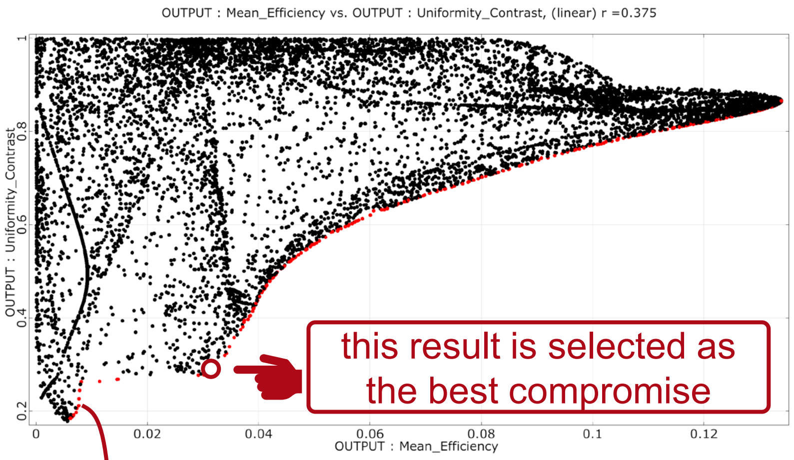
a roughly sampled evaluation of the incidence angles alonge the period is sufficient for the optimization

Optimization Results of optiSLang

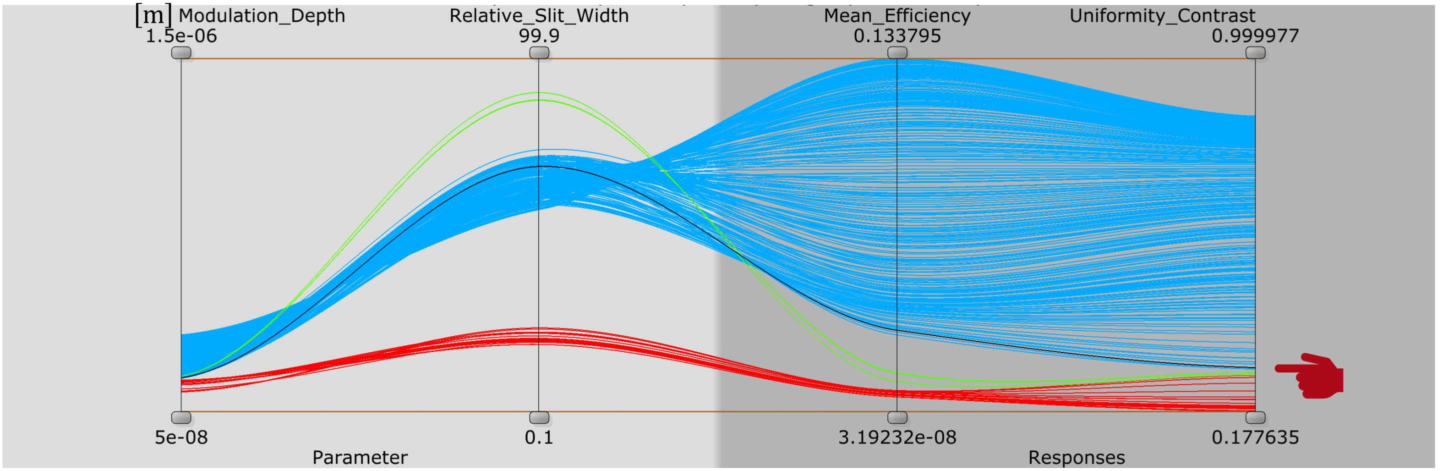


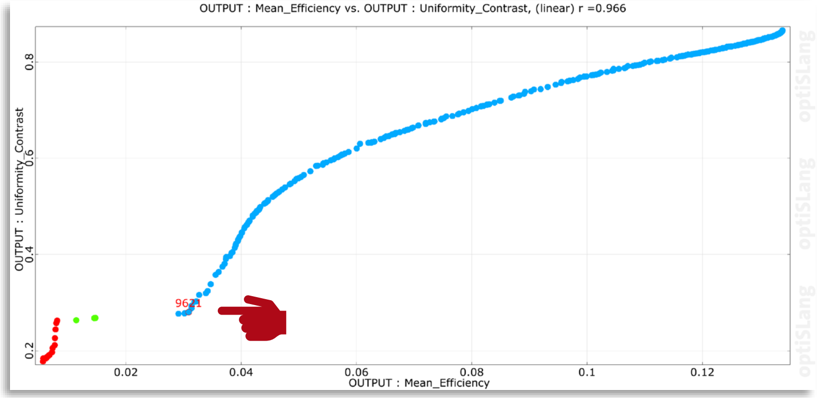
- the optimization results are plotted as a function of the merit functions
  - mean efficiency
  - uniformity contrast
- the Pareto front indicates the optimum compromise between the two merit functions

Advanced Evaluation of the Optimization Results



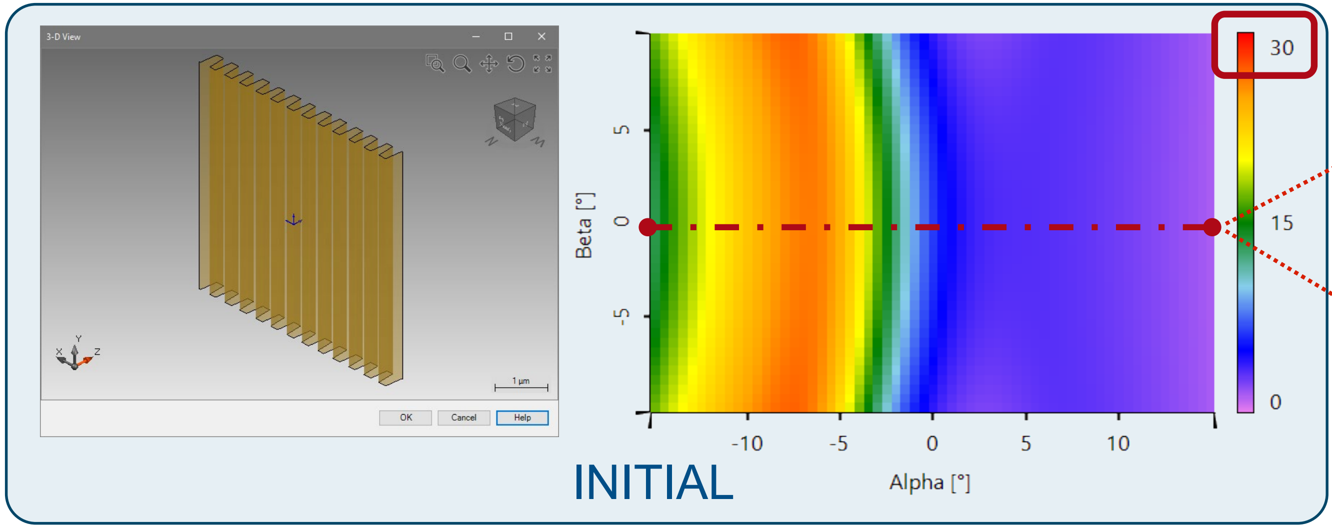
- the optimization results at the Pareto front are visualized in a *Parallel Coordinates Plot* to investigate the effect of the input parameters (responses) to the output parameters in detail
- in addition, a cluster analysis decomposes a specific parameter, e.g. the relative slit width, into a certain number of clusters yielding a better understanding how the input parameters are correlated to the output parameters
- as a result, a design is selected, which is the best compromise for a prioritized low uniformity contrast and an acceptable mean efficiency including manufacturable grating parameters



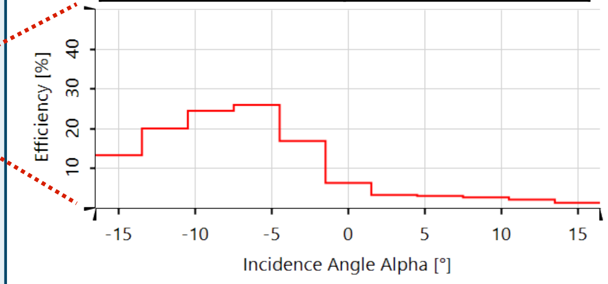


the results at the Pareto front are highlighted and color adapted according to the results of the cluster analysis

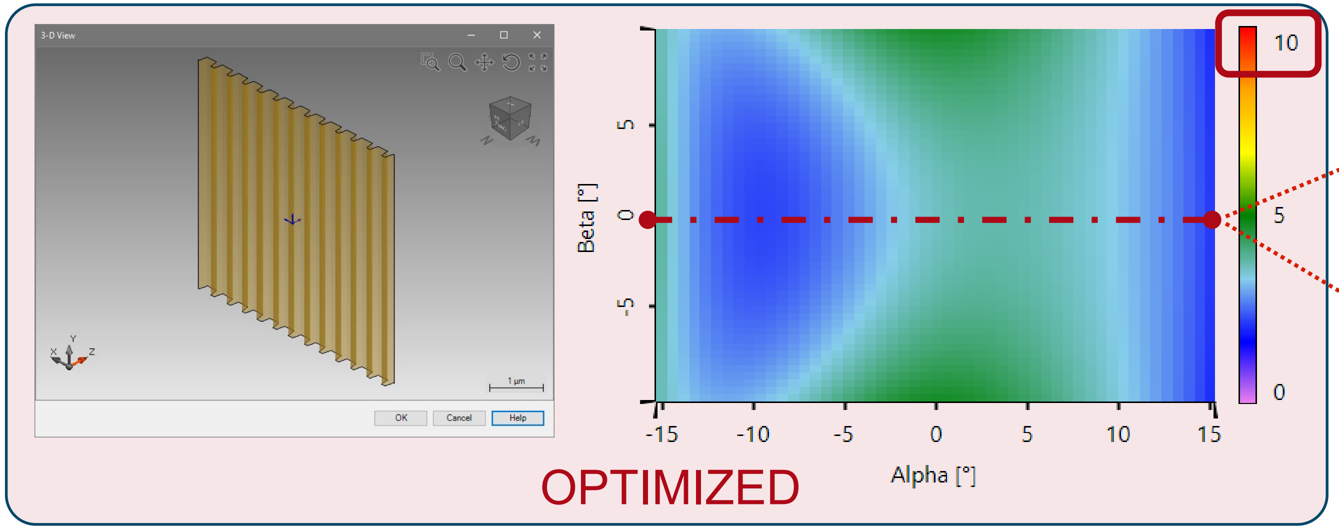
Analysis of Coupling Efficiency for Optimization Result



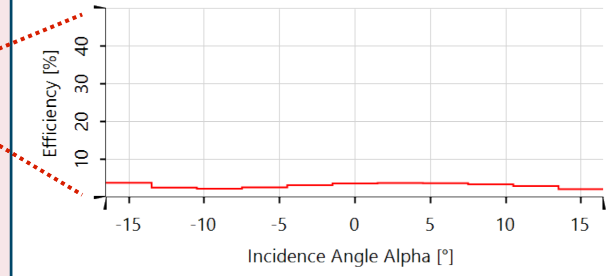
fill factor	50.00%
modulation depth	400.00nm



Mean Efficiency 10.96%
Uniformity Contrast **89.45%**



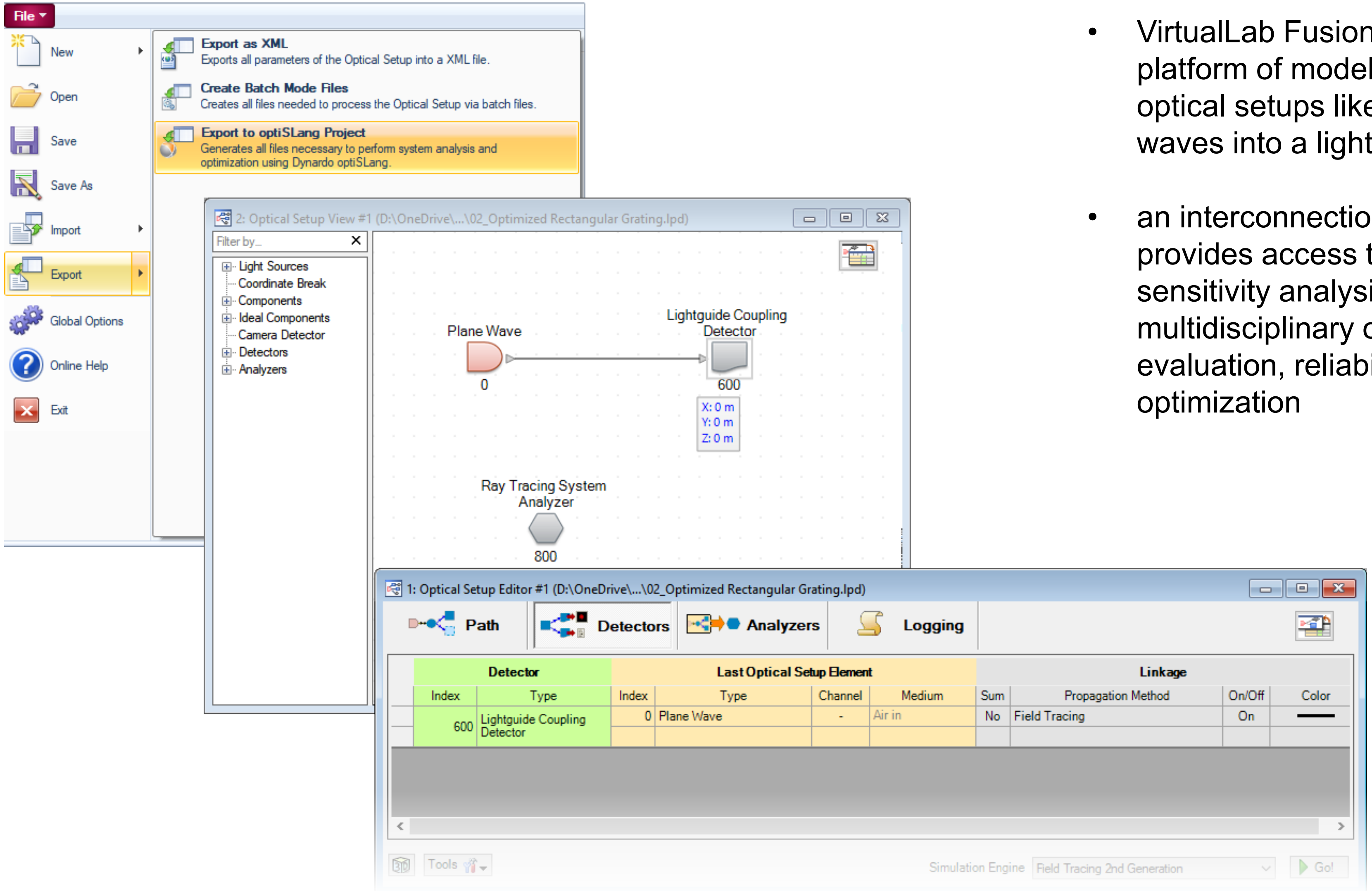
fill factor	68.43%
modulation depth	187.18nm



Mean Efficiency 3.08%
Uniformity Contrast **28.02%**

- finally, the optimization result is analyzed regarding the coupling efficiency using the software VirtualLab Fusion
- as a result, the uniformity contrast was significantly reduced but to the cost of the entire efficiency

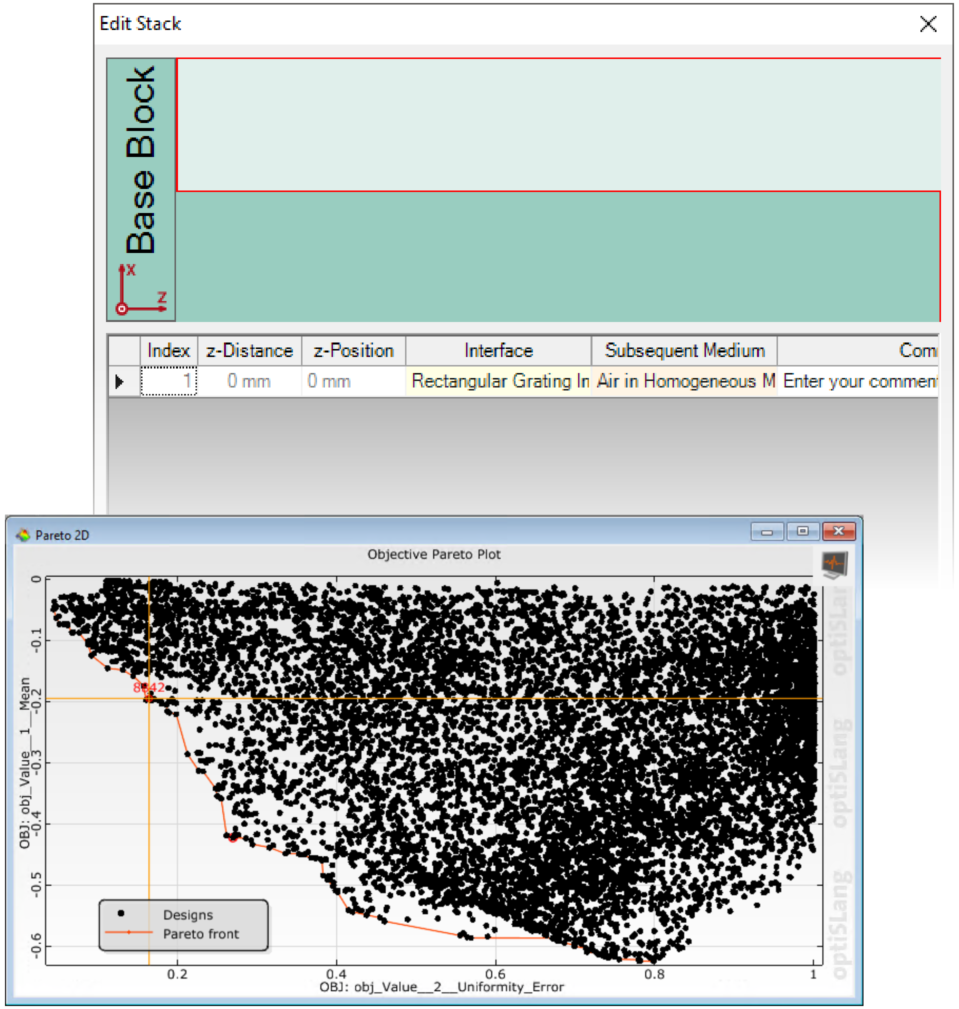
Peek into VirtualLab Fusion



- VirtualLab Fusion is a flexible and customizable platform of modelling tools to simulate complex optical setups like e.g. coupling a set of plane waves into a lightguide
- an interconnection to the software optiSLang provides access to advanced tools for sensitivity analysis, multiobjective and multidisciplinary optimization, robustness evaluation, reliability analysis and robust design optimization

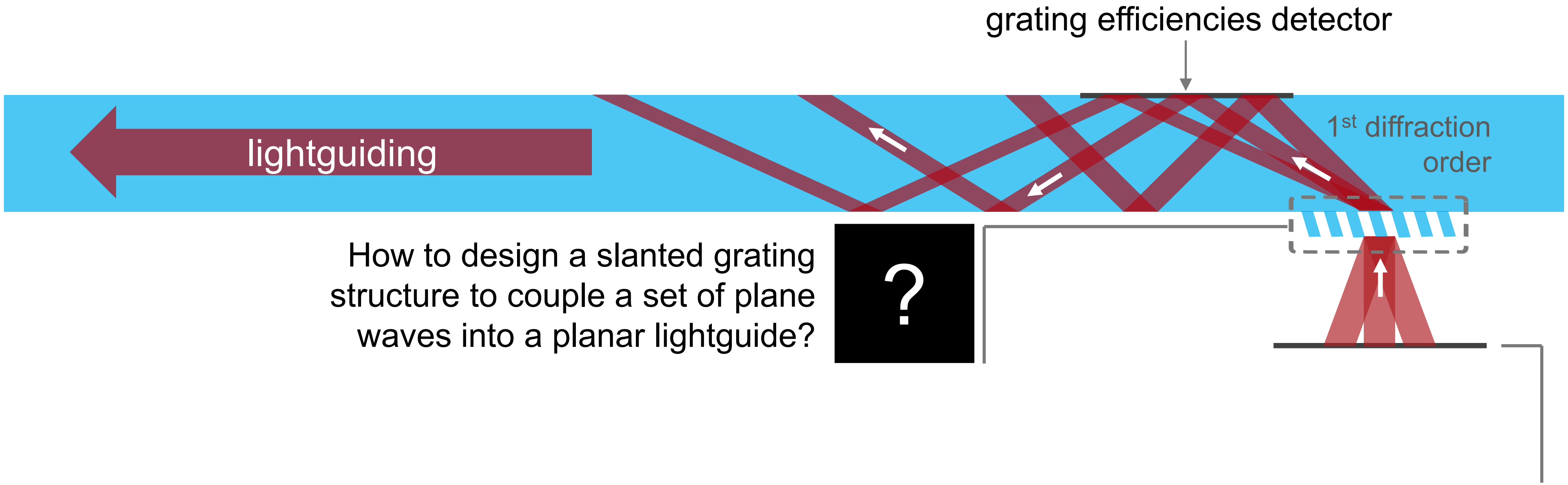
Workflow in VirtualLab Fusion

- Configuration of grating structure
  - Configuration of Grating Structures by Using Interfaces [Use Case]
  - Configuration of Grating Structures by Using Special Media [Use Case]
- Evaluation of coupling efficiency
  - Customized Detector for Lightguide Coupling Grating Evaluation [Use Case]
- Optimization of grating structure
  - Grating Optimization in VirtualLab Fusion Using optiSLang [Use Case]



Optimization of Slanted Grating for Lightguide Coupling over Desired FOV

Optimization Task

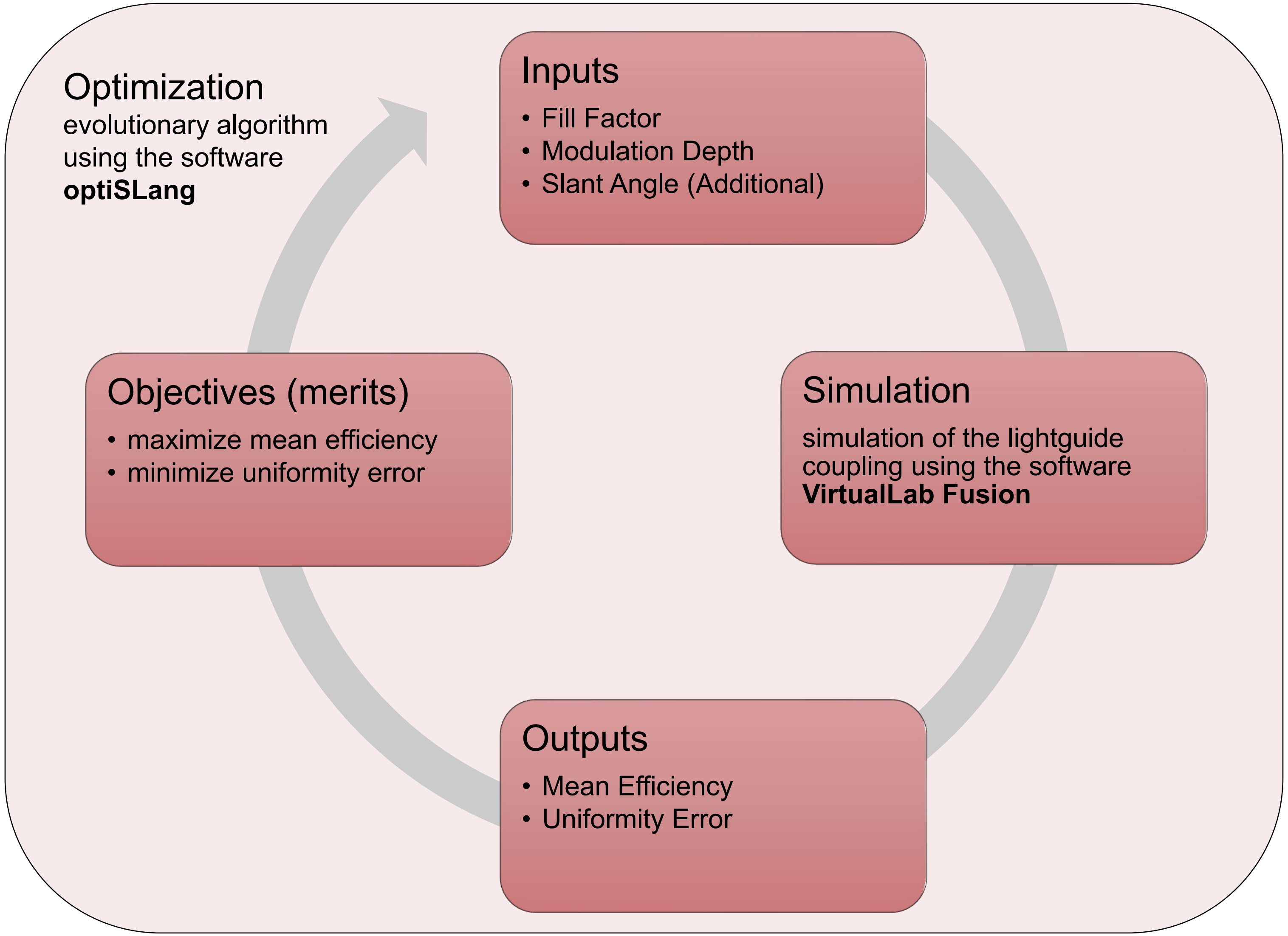


set of plane waves

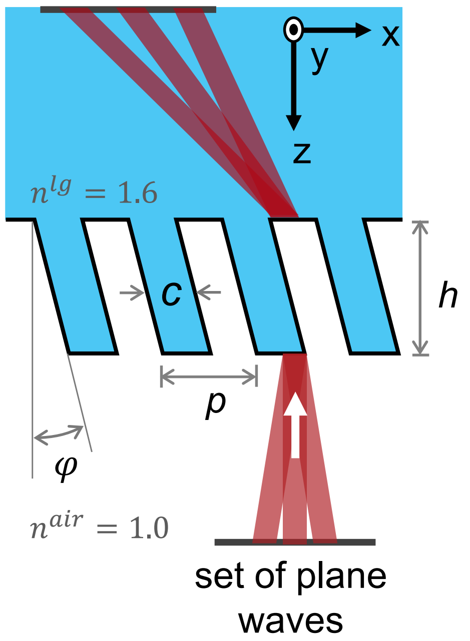
- field of view (-30..30, -15..15)°
- wavelength 532 nm
- linearly polarized along x-axis

Optimization Workflow

- the following optimization workflow is applied to design a slanted grating for efficient lightguide coupling:
    1. Define the inputs and their ranges, start with a reference input combination
    2. Perform the optimization with several simulations
    3. calculate the corresponding outputs
    4. Evaluation of the defined objectives
    5. Next iteration with new inputs
- the optimization algorithm stops after certain iterations and/ or when no more improvement of the objectives can be achieved



Simulation Results and Configuration of the Merit Function

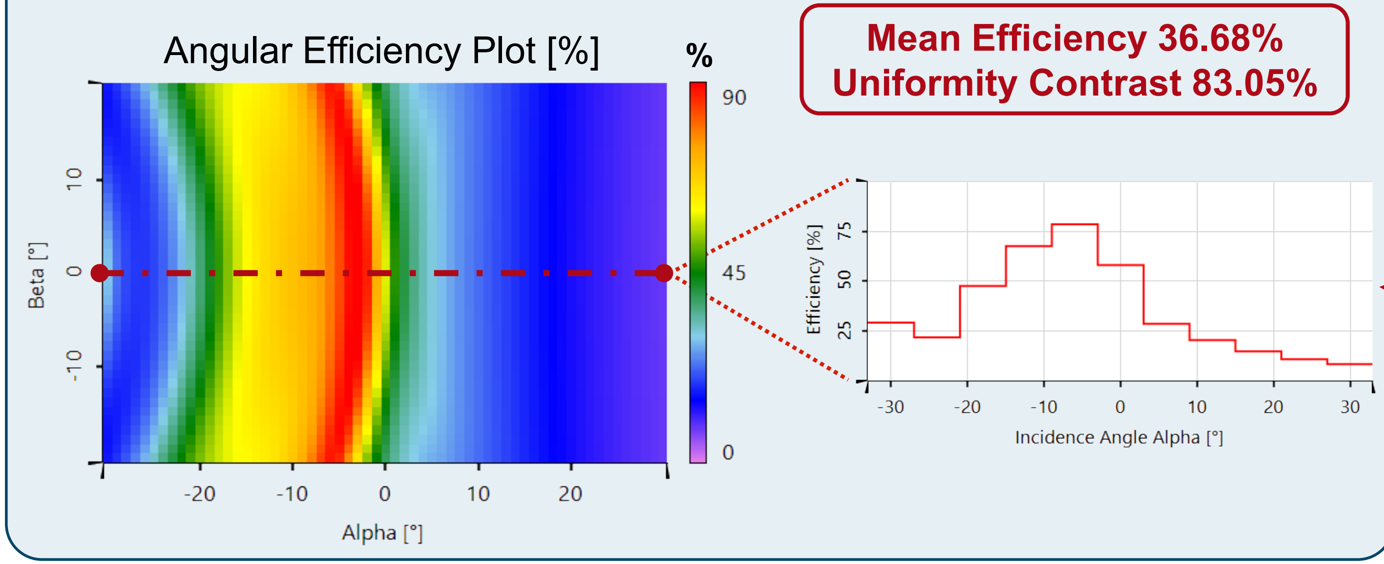


- variation of the **fill factor** *c/p* with the slit width *c* and the period *p*
  - ➢ **0.1% to 99.9%**
- variation of the **modulation depth** *h*
  - ➢ **50 nm to 1500 nm**
- <u>additionally</u>: variation of the **slant angle**
  - ➢ **0° to 50°**

Initial Configuration of Grating	
fill factor	50.00%
modulation depth	400.00 nm
slant Angle	40.00°
period	354 nm
operating order	1st transmitted

to be varied

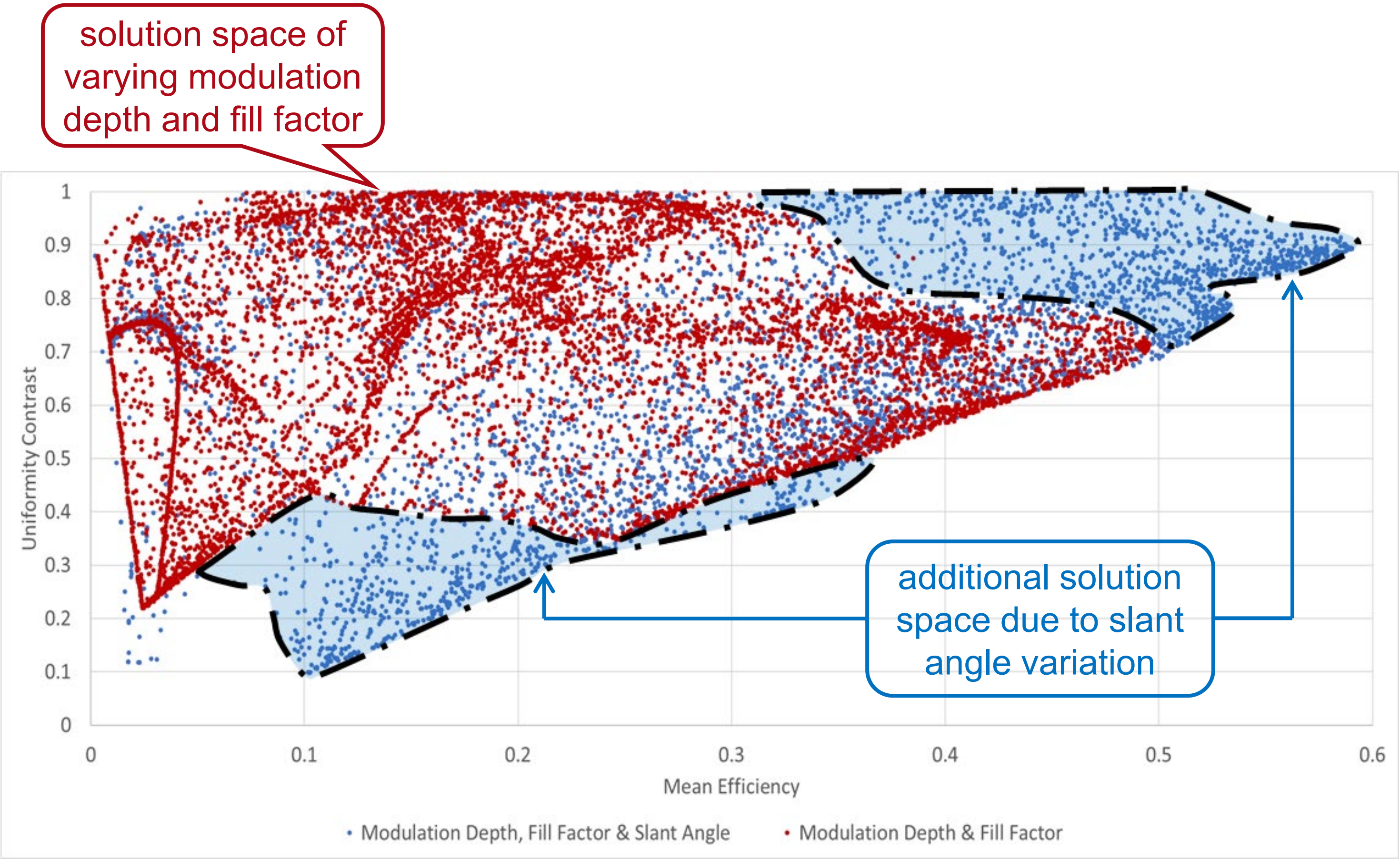
Grating Efficiencies Detector Result



Mean Efficiency 36.68%
Uniformity Contrast 83.05%

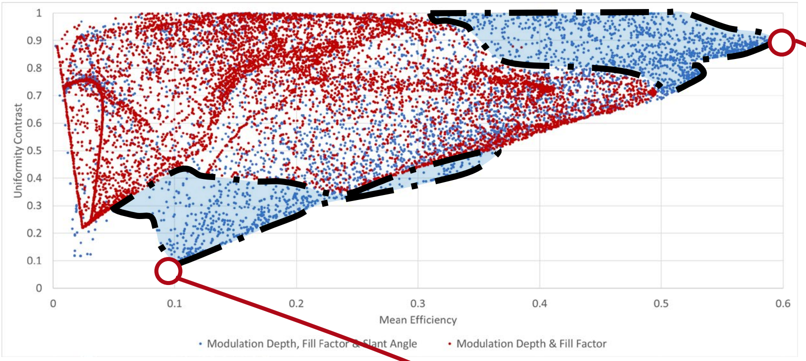
a roughly sampled evaluation of the incidence angles along the period is sufficient for the optimization

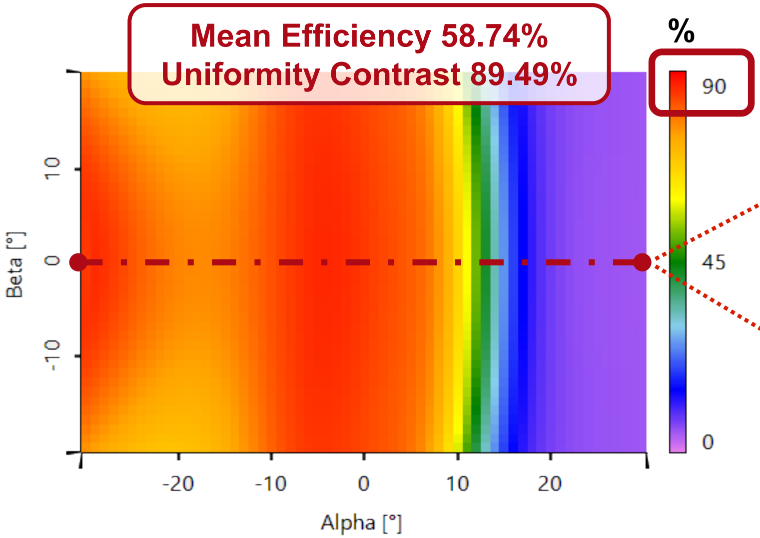
Optimization Result of optiSLang



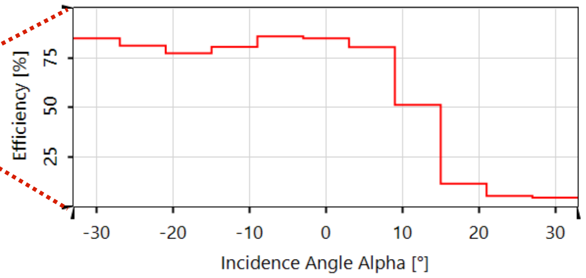
- an evolutionary optimization algorithm is applied using the optimization software optiSLang
- the additional freedom of the slant angle provides additional solutions

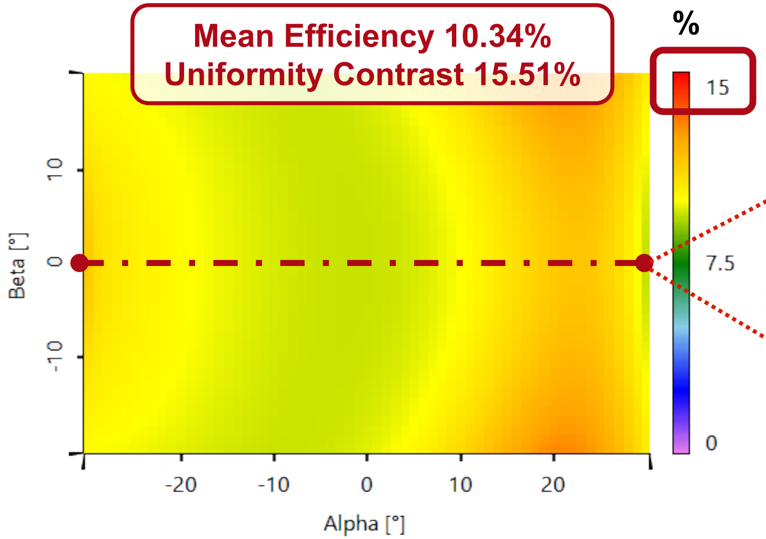
Analysis of Coupling Efficiency for Optimization Results



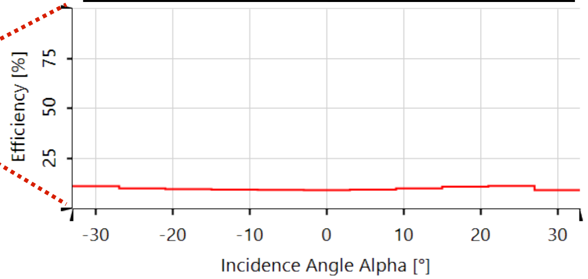


fill factor	70.82%
modulation depth	381.91 nm
slant Angle	24.58°



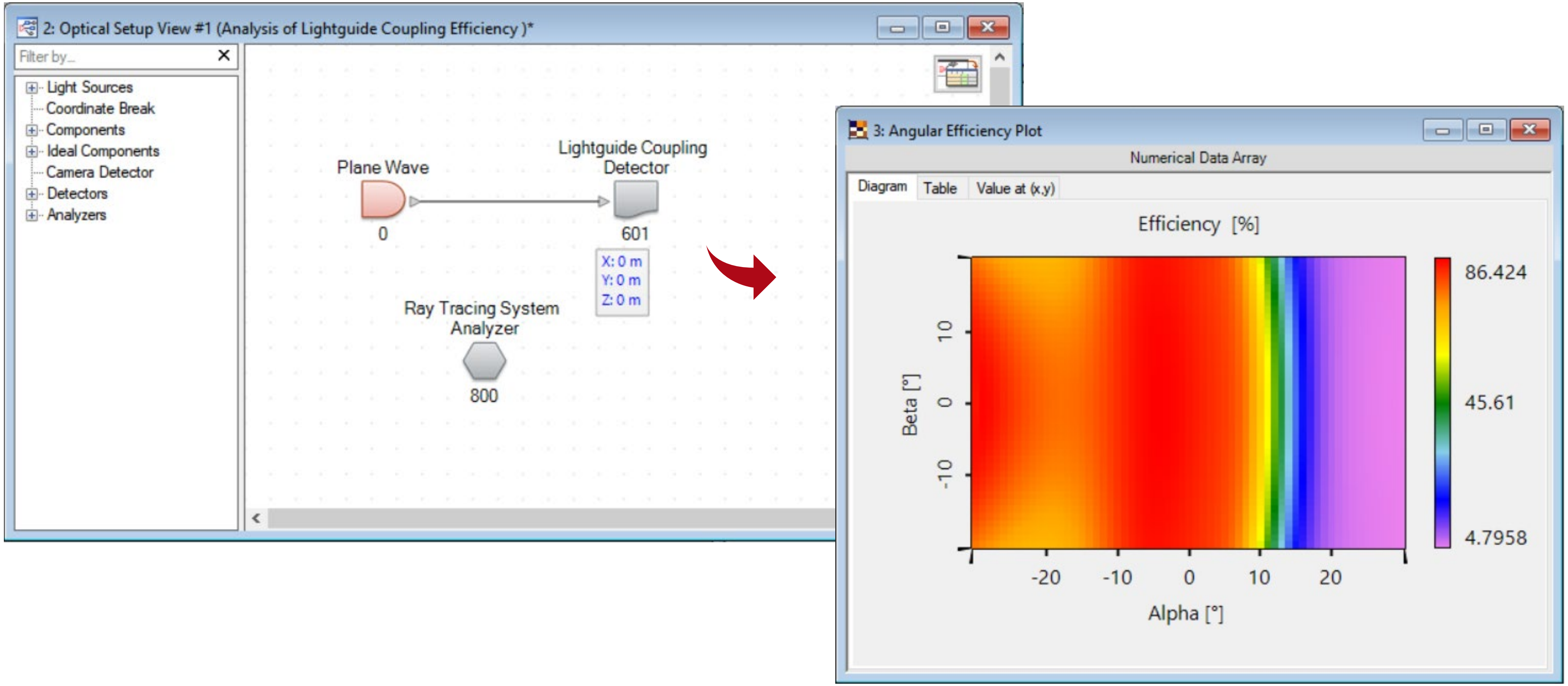


fill factor	90.00%
modulation depth	189.64 nm
slant Angle	14.57°



- an appropriate solution can be selected according specific constraints
- either uniformity contrast or mean efficiency might be prioritized

Peek into VirtualLab Fusion

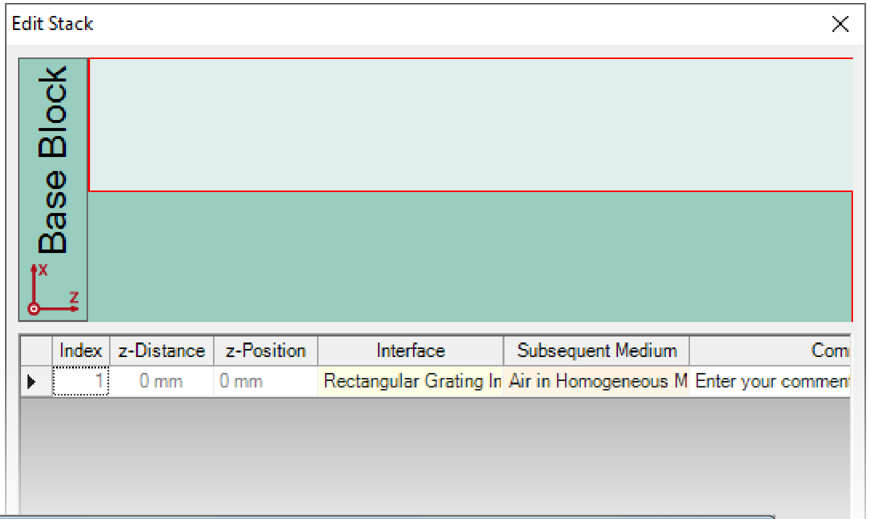


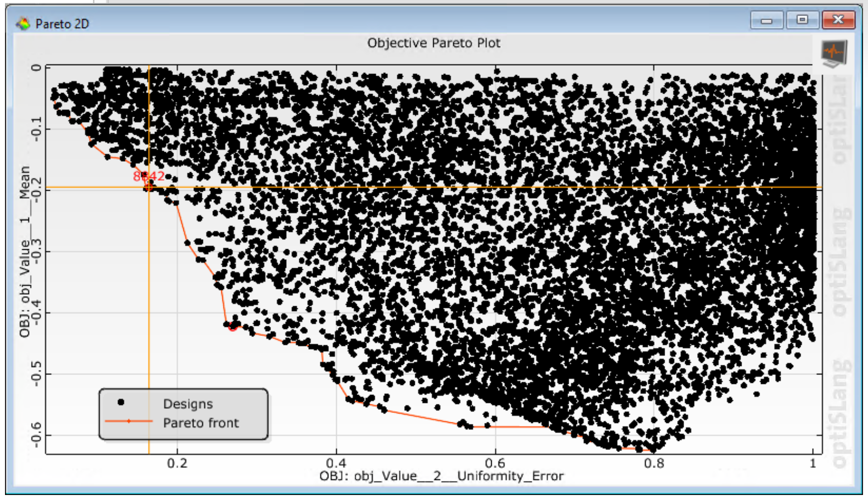
Detector Results

	Date/Time	Detector	Sub - Detector	Result
2	12/07/2018 07:34:24	Lightguide Coupling Detector #601 after Plane Wave #0 (-) (Field Tracing 2nd Generation)	Mean	58.739 %
1			Uniformity Error	89.485 %

Workflow in VirtualLab Fusion

- Configuration of grating structure
  - Configuration of Grating Structures by Using Special Media [Use Case]
  - Advanced Configuration of Slanted Gratings [Use Case]
- Evaluation of coupling efficiency
  - Customized Detector for Lightguide Coupling Grating Evaluation [Use Case]
- Optimization of grating structure
  - Grating Optimization in VirtualLab Fusion Using optiSLang [Use Case]





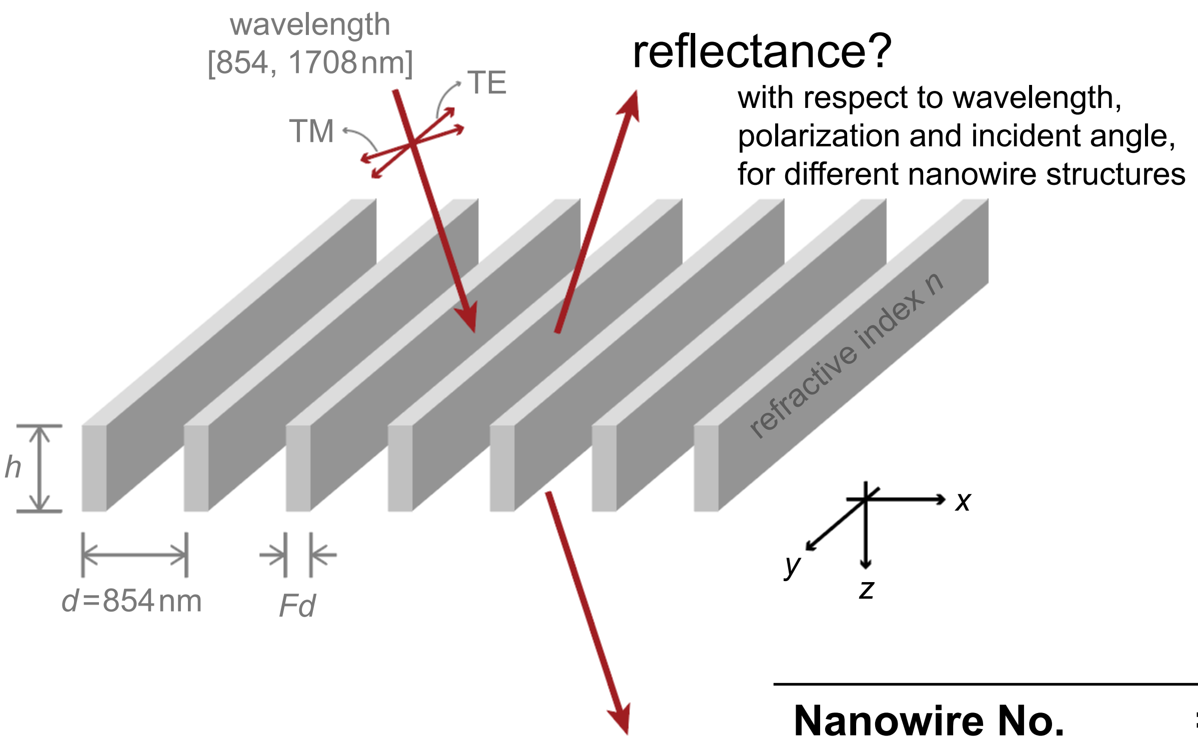
Introduction

- How to construct grating structures
- Modeling and design of surface-relief gratings, like slanted ones
- **Analysis of polarization-dependent effects and optimization**
- Properties of holographic volume gratings
- Investigation of two-dimensional periodic structures, like nanopillars

Ultra-Sparse Dielectric Nano-Wire Grid Polarizers

Ultra-Sparse Nanowire …

Modeling Task

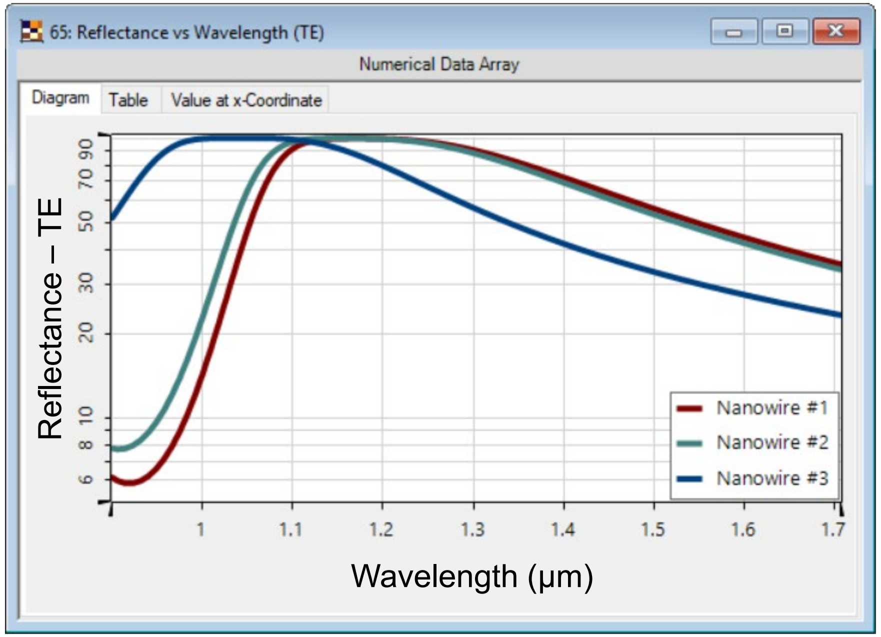


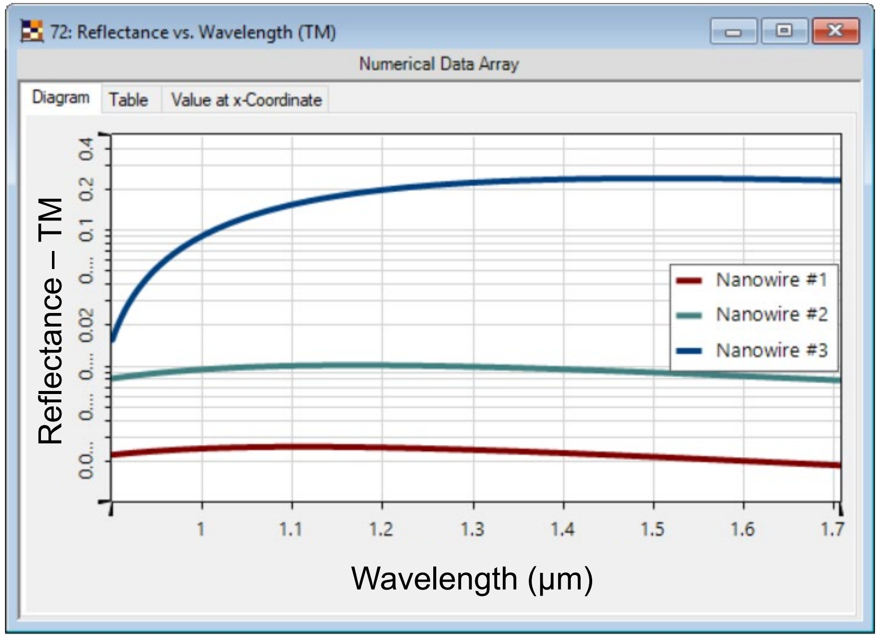
Nanowire No.	#1	#2	#3
refractive index *n*	10	7.07	3.16
height *h*	269 nm	270 nm	292 nm
filling factor *F*	0.01	0.02	0.1

Parameters are taken from reference paper: J. W. Yoon *et al.*, Opt. Express **23**, 28849-28856 (2015).

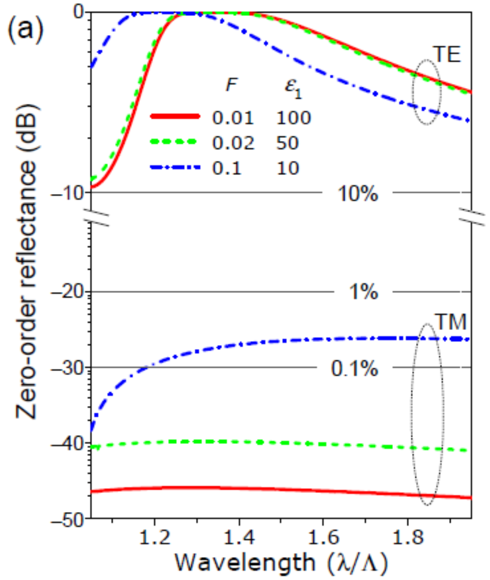
Parameter Scanning (1D)

Fourier modal method (FMM) simulation in VirtualLab Fusion





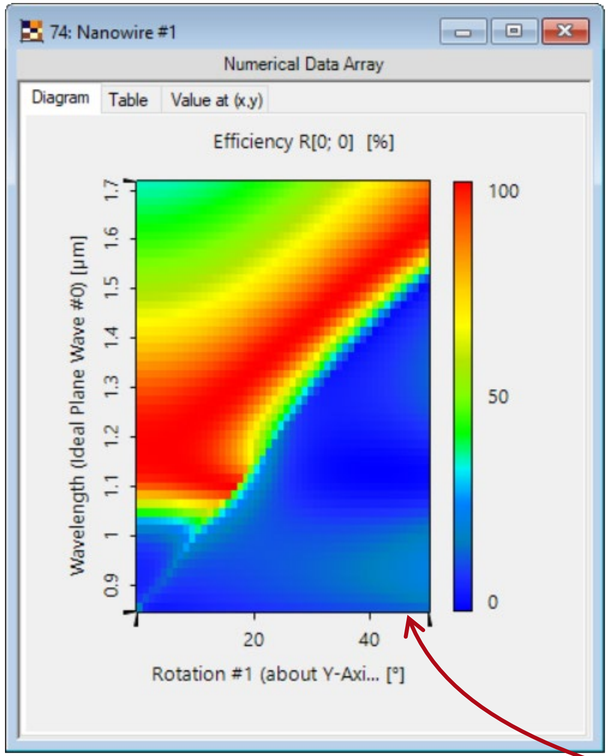
reference results from the literature

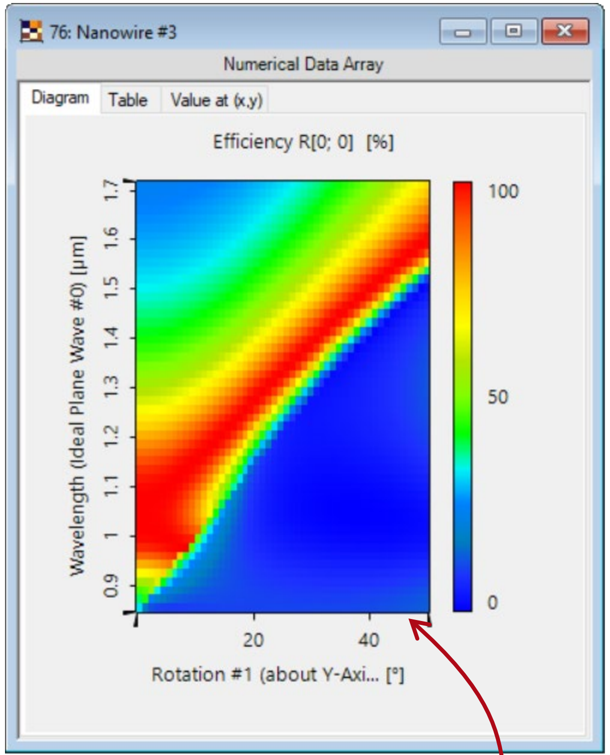


Nanowire No.	#1	#2	#3
refractive index *n*	10	7.07	3.16
height *h*	269 nm	270 nm	292 nm
filling factor *F*	0.01	0.02	0.1

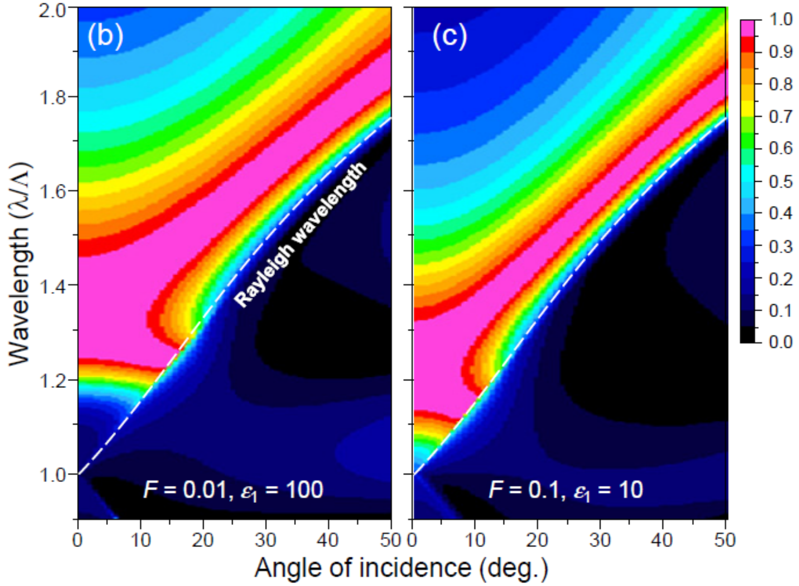
Parameter Scanning (2D)

Fourier modal method (FMM) simulation in VirtualLab Fusion, for TE polarization





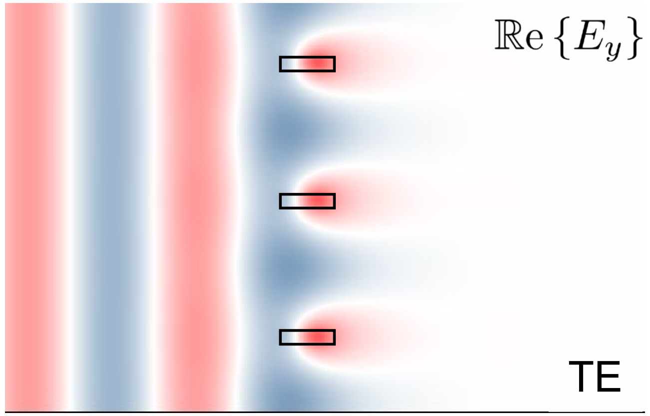
reference results from the literature



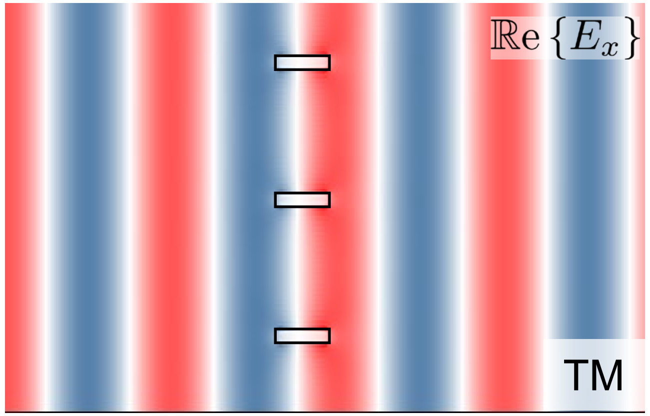
Nanowire No.	#1	#2	#3
refractive index *n*	10	7.07	3.16
height *h*	269 nm	270 nm	292 nm
filling factor *F*	0.01	0.02	0.1

Visualization of Field Inside Grating

Fourier modal method (FMM) simulation in VirtualLab Fusion @1045nm

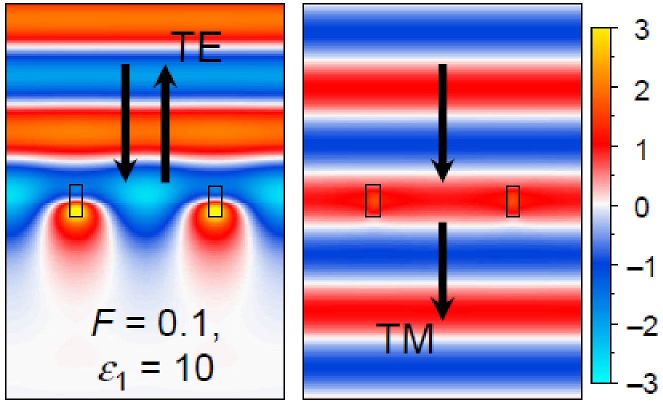


[animation]



[animation]

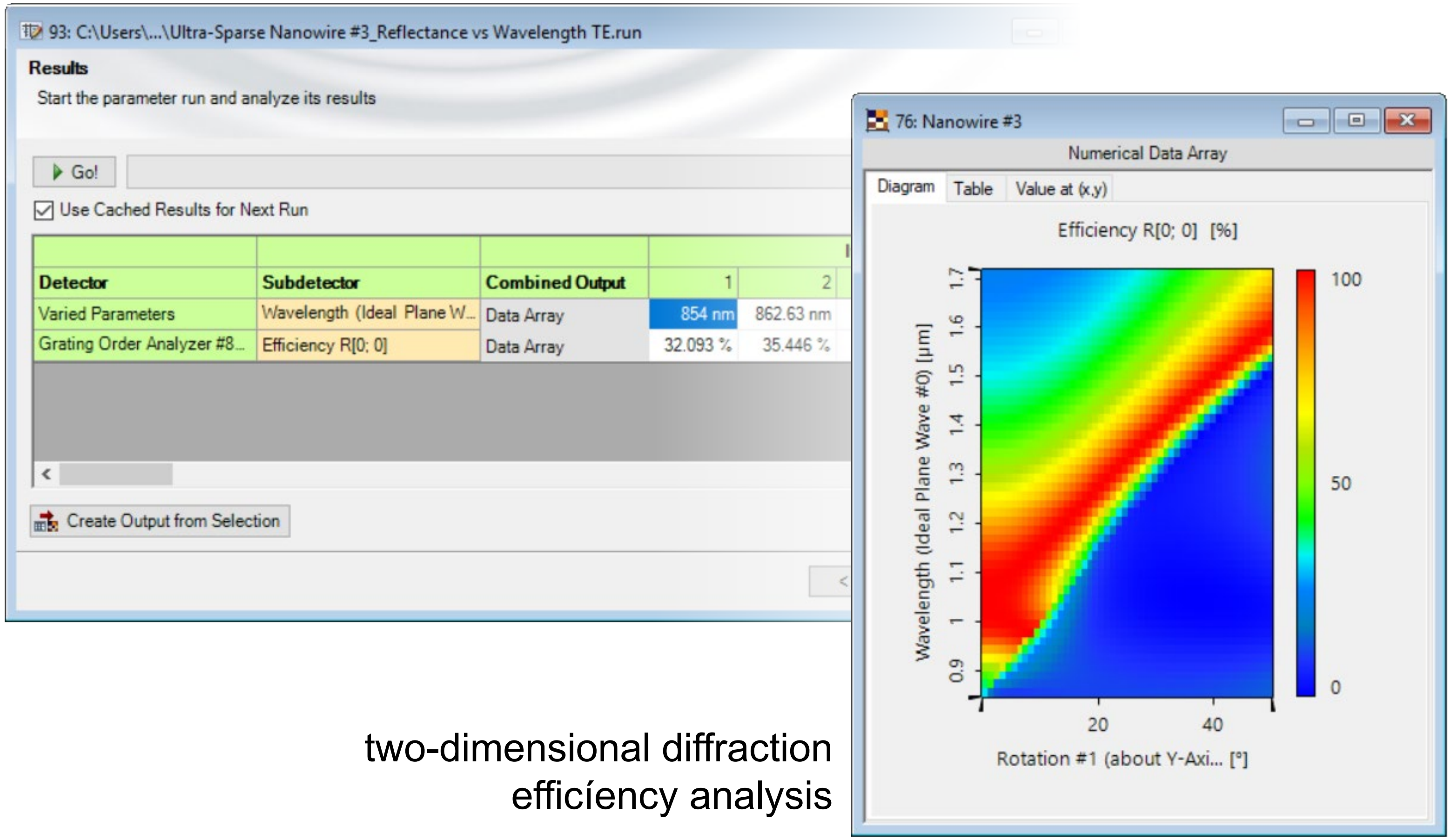
reference results from the literature



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

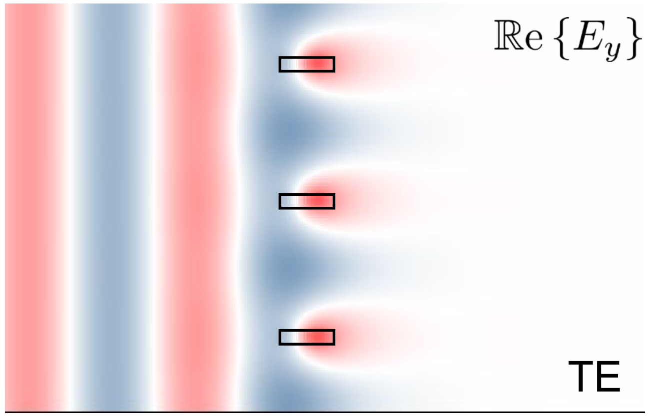
Peek into VirtualLab Fusion

analysis of diffraction efficiency vs. specific parameter(s)



two-dimensional diffraction efficiency analysis

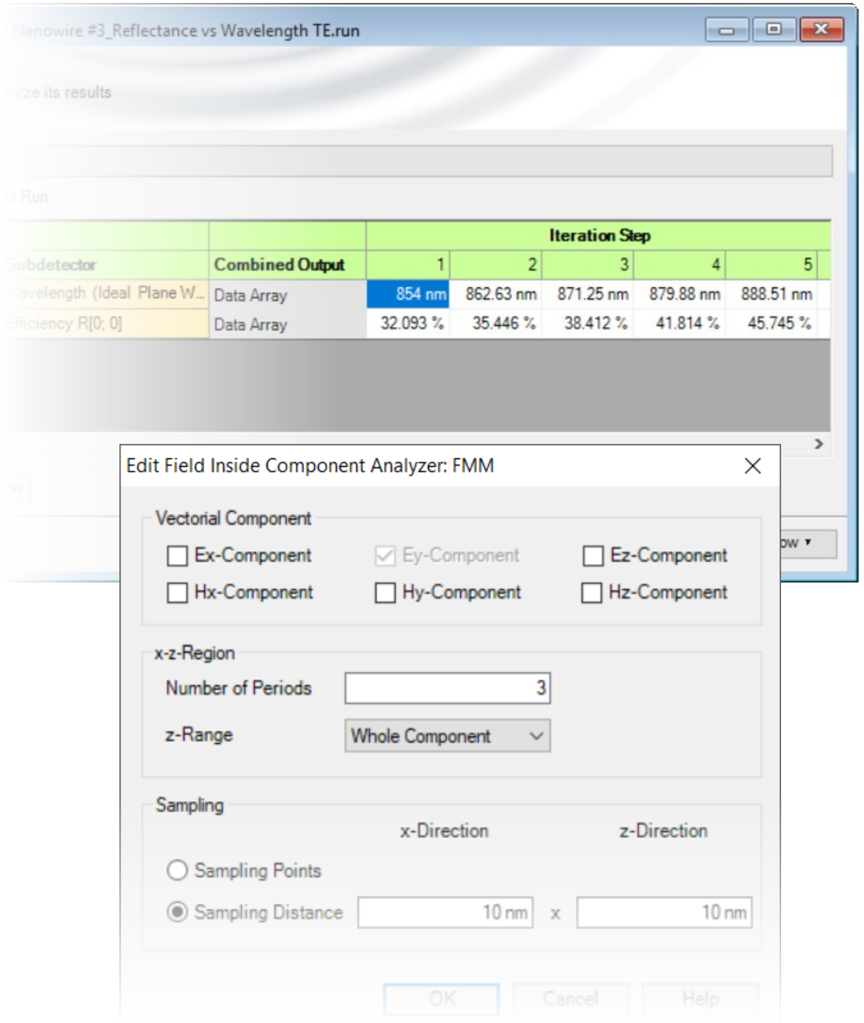
visualization of field inside grating



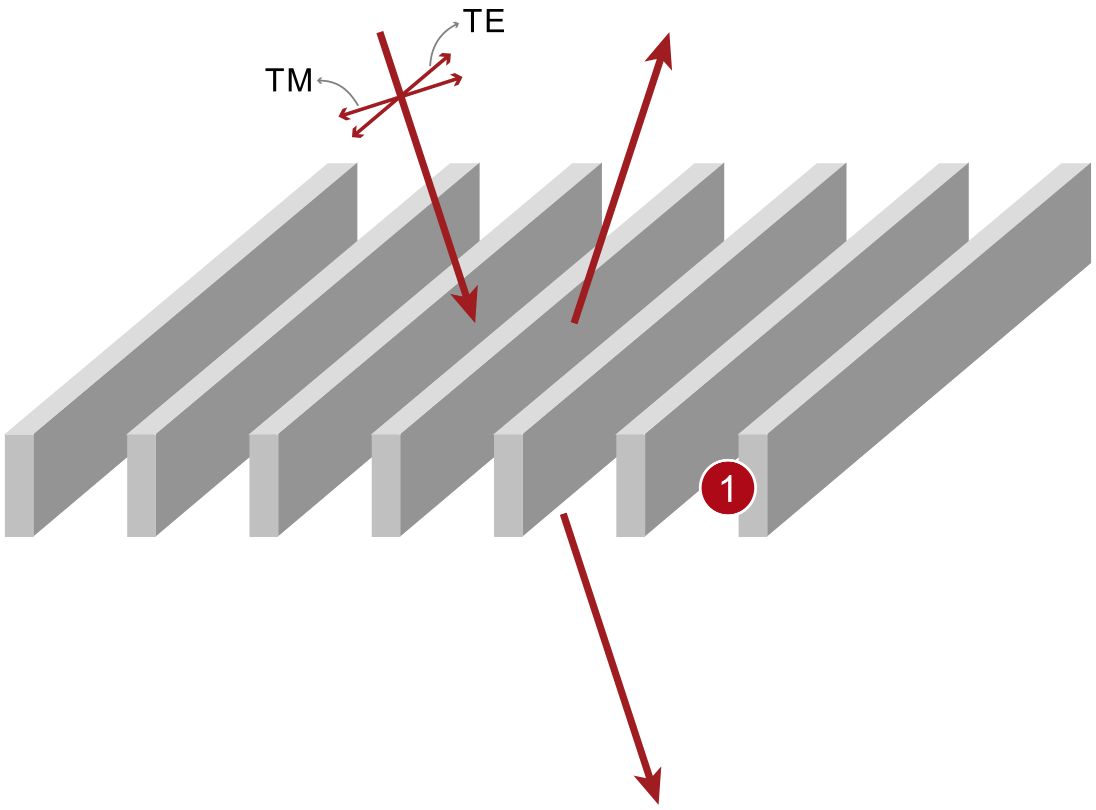
[animation]

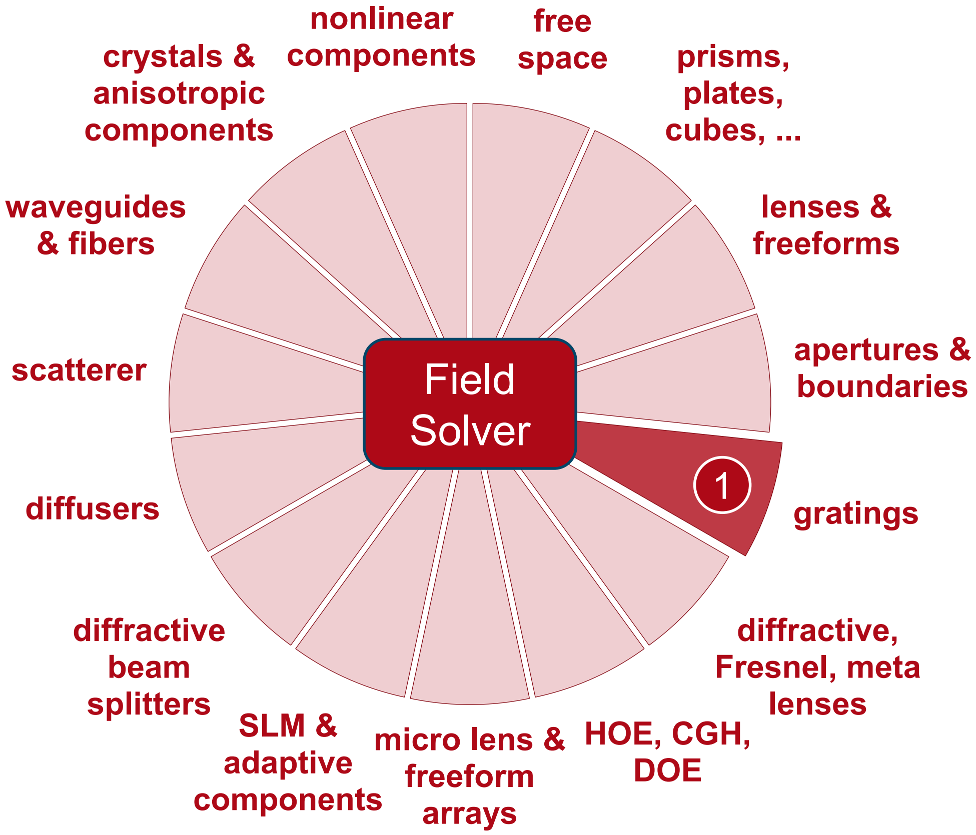
Workflow in VirtualLab Fusion

- Construct grating structure
  - [Configuration of Grating Structures by Using Interfaces] [Use Case]
  - [Configuration of Grating Structures by Using Special Media] [Use Case]
- Analyze grating diffraction efficiency
  - [Grating Order Analyzer] [Use Case]
- Check influence from different parameters with Parameter Run
  - [Usage of the Parameter Run Document] [Use Case]
- Calculate field inside grating structure



VirtualLab Fusion Technologies





Document Information

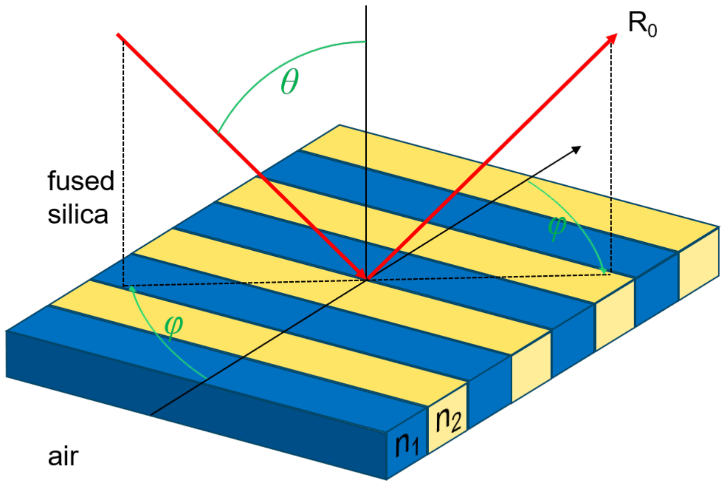
title	Ultra-Sparse Dielectric Nano-Wire Grid Polarizers
document code	GRT.0006
version	1.1
toolbox(es)	Grating Toolbox
VL version used for simulations	7.4.0.49
category	Application Use Case
further reading	- Grating order analyzer - Rigorous Analysis and Design of Anti-Reflective Moth-Eye Structures - Rigorous Analysis of Nanopillar Metasurface Building Block

Investigation of Polarization State of Diffraction Orders

Polarization Conversion Grating_...

Overview

- The topic of this document is the polarization state of light, which was diffracted at a periodic microstructure.
- For this purpose, the reflection of the zeroth order is investigated at an exemplarily binary grating structure and conical incidence, as depicted in the sketch.
- In order to discuss the topic at a particular example, in a second part a grating configuration and the corresponding parameters where chosen according to a work of Passilly *et al*. (2008).



Efficiency & Polarization of Diffraction Orders

- The efficiency of the particular order (n) represents the relation between the power of the incoming light and the amount of light of an outgoing diffraction order. It is calculated from the Rayleigh coefficients.

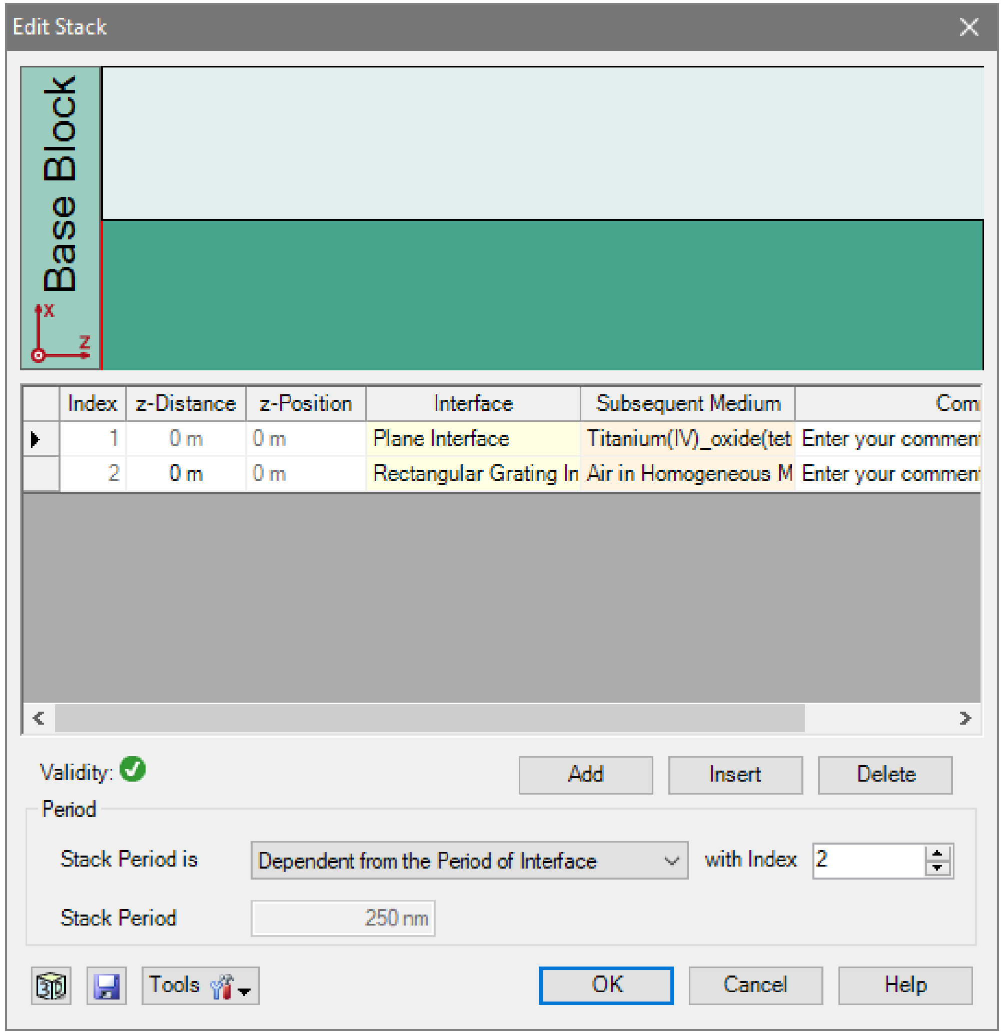
- In case of the Rayleigh coefficients are given in TE/TM, the efficiency can be calculated by $\eta = \left|R_n^{\mathrm{TE}}\right|^2 + \left|R_n^{\mathrm{TM}}\right|^2$ for normalized input.

- If the Rayleigh coefficients are given along x, y and z, the following equation has to be applied: $\eta = \frac{n_{\mathrm{out}}}{A^2 n_{\mathrm{in}} \cos\vartheta_{\mathrm{in}}} \cos\vartheta_{\mathrm{out}} \left[|R_n^x|^2 + \left|R_n^y\right|^2 + |R_n^z|^2\right]$, where $n_{\mathrm{in}}/\ n_{\mathrm{out}}$ are the refractive indices of the superstrate and substrate and $\vartheta_{\mathrm{in}}/\ \vartheta_{\mathrm{out}}$ the incidence and diffraction angles of the particular order. Further A represents the amplitude of the impinging wave.

- This means the coordinate system (CS) of the provided Rayleigh coefficients has to be regarded. Otherwise it has to be rotated to the appropriate CS. By default R_n^x, R_n^y, R_n^z are provided in the CS of the grating.

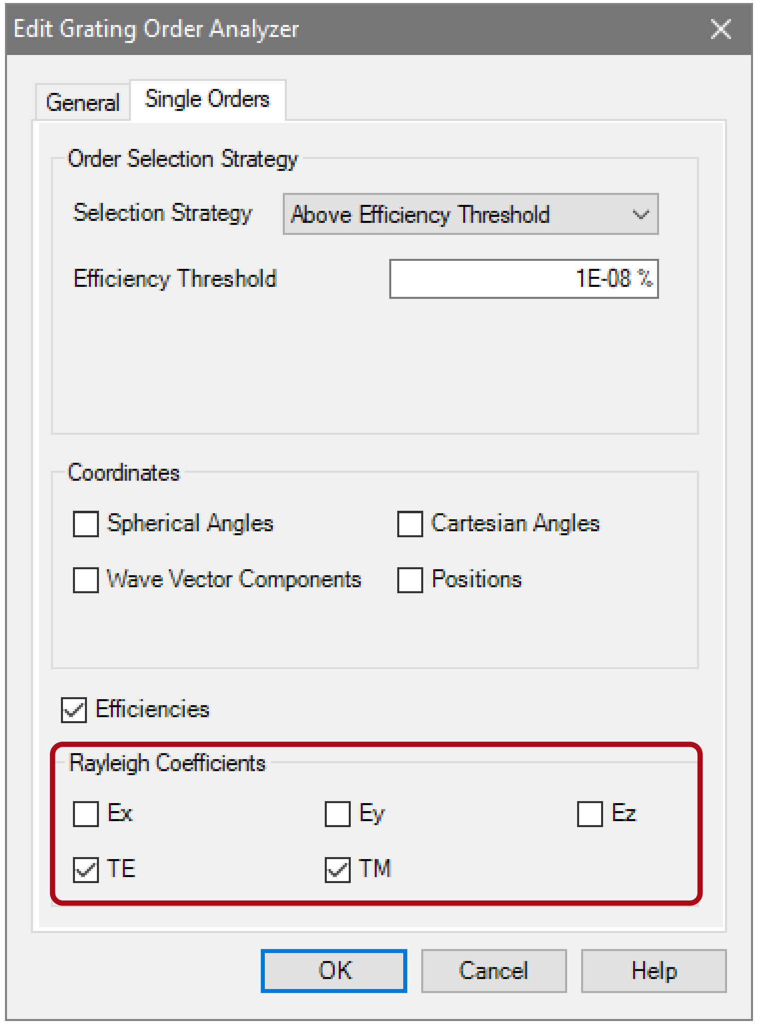
Grating Structure Parameters

- A grating structure with a rectangular shape is investigated.
- For sake of simplicity the configuration of the grating is chosen such, that only the zeroth order in reflection (R_0) is propagating.
- Thus, the following grating parameters are chosen:
  - grating period: 250 nm
  - fill factor: 0.5
  - grating height: 200 nm
  - material n_1: fused silica
  - material n_2: TiO_2 (from catalog)



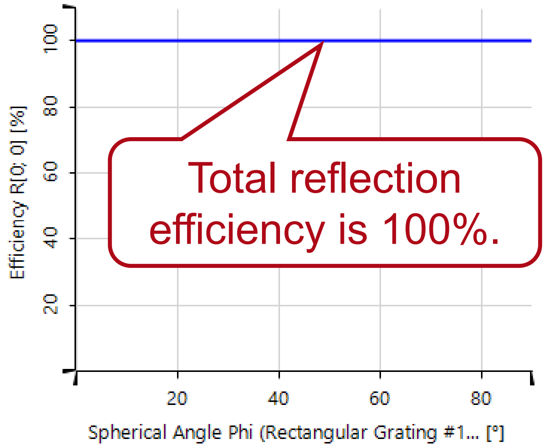
Analysis of Polarization State

- Now, the grating is illuminated with TE-polarized light and a variation of the angle of conical incidence (φ) is applied.
- As mentioned, the squared amplitudes of the Rayleigh coefficients will provide information about the polarization state of the particular order.
- In order to receive the Rayleigh coefficients, please activate the single order output in the grating order analyzer and choose the desired coefficients.

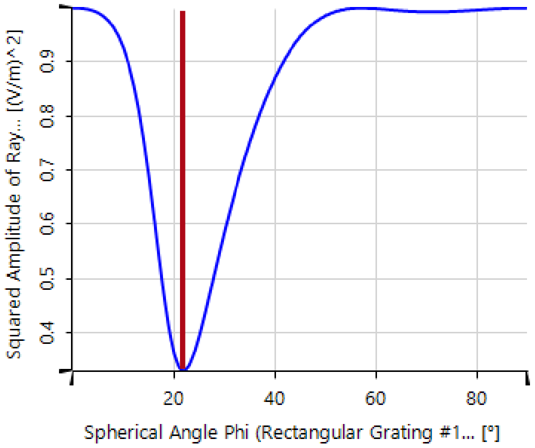


Resulting Polarization States

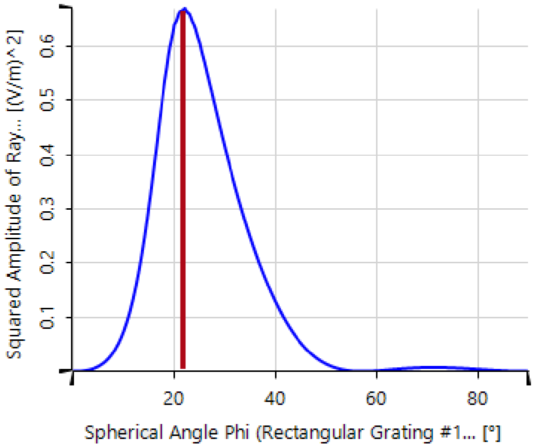
efficiency η

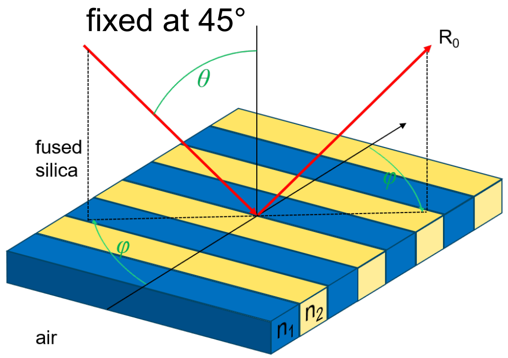


$\left|R_0^{\mathrm{TE}}\right|^2$



$\left|R_0^{\mathrm{TM}}\right|^2$





The Rayleigh coefficients now disclose the polarization information:

- In case of non-conical incidence (φ = 0), $\left|R_0^{\mathrm{TE}}\right|^2$ is 1 (V/m)^2, whereas $\left|R_0^{\mathrm{TM}}\right|^2$ is 0. This means the diffracted light is TE-polarized, entirely.
- For φ = 22° there is a minimum of $\left|R_0^{\mathrm{TE}}\right|^2$ yielding a value of 0.33 (V/m)^2 and a maximum of $\left|R_0^{\mathrm{TM}}\right|^2$ with 0.67 (V/m)^2. In this case, 67% of the light are TM polarized.
- For φ > 50° the coefficients are almost constant, and thus the polarization as well.

Further Example

- In the work by Passilly *et al*. the polarization state of light diffracted at a subwavelength grating was investigated and optimized in order to receive a high conversion between different states.
- Thus they compared simulated results with measurement data of fabricated sample.

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Polarization conversion by dielectric subwavelength gratings in conical mounting

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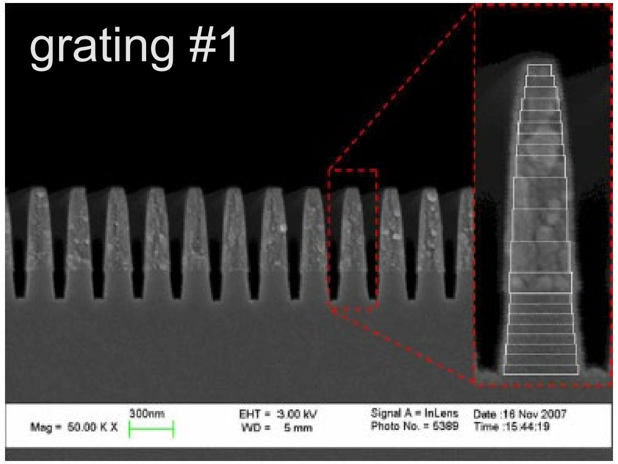
Subwavelength dielectric gratings are examined in total-internal-reflection configuration. It is demonstrated experimentally that such elements, fabricated in TiO_2, can perform full polarization conversion from incident TE to TM with nearly 100% efficiency. The dependence of the polarization conversion on the angle of incidence is analyzed. Rigorous diffraction theory is used to cross check the experimental results. [DOI: 10.2971/jeos.2008.08009]

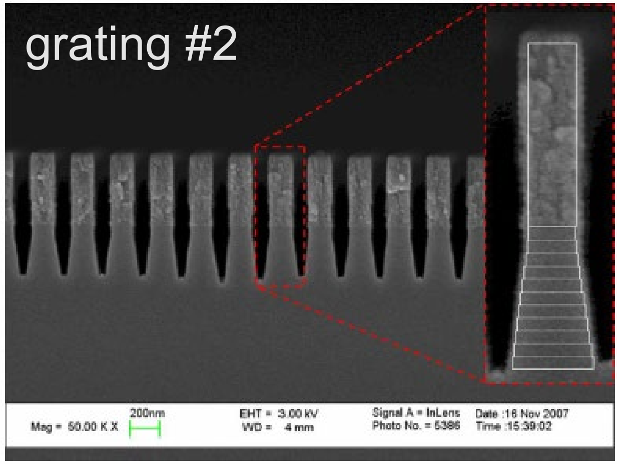
Keywords: Diffraction gratings, polarization, form birefringence

Grating Structure Parameters

- In the cited work, two different fabricated grating structured were investigated.
- Caused by the applied fabrication strategy, the structures exhibit some deviations compared to the desired binary shape.: under-etching in the substrate and deviating shapes of ridges.
- Due to missing details about the fabricated structure, it is simplified for the realization in VirtualLab.
- Nevertheless, if the data is available, the complex shape of the grating could be analyzed in detail.

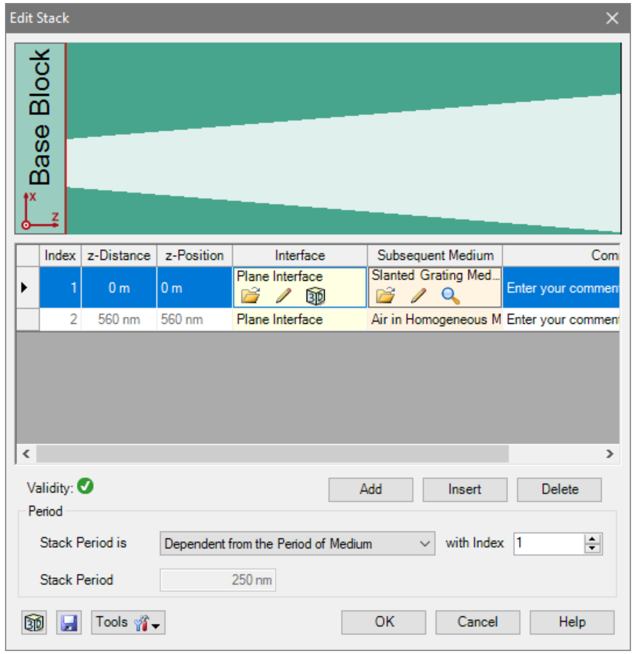


Passilly *et al.* (2008)



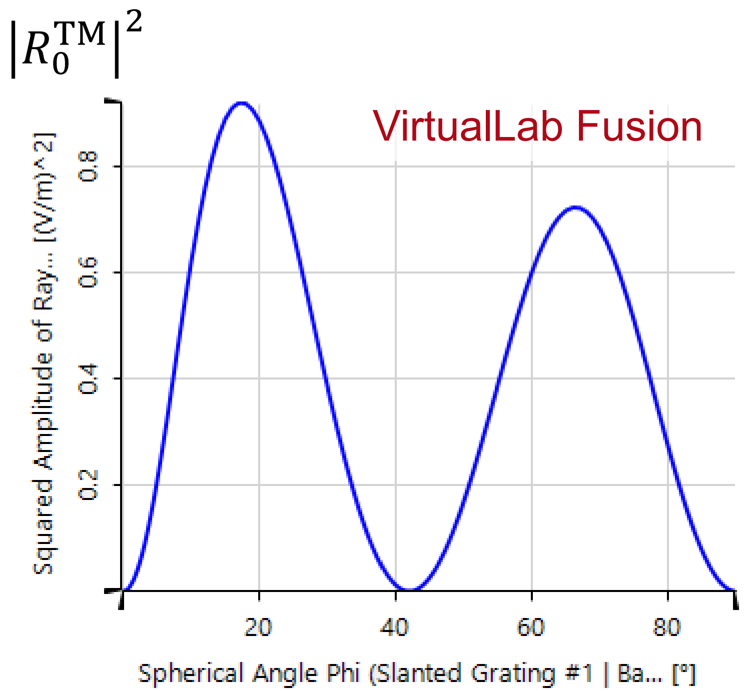
Grating #1 Parameters

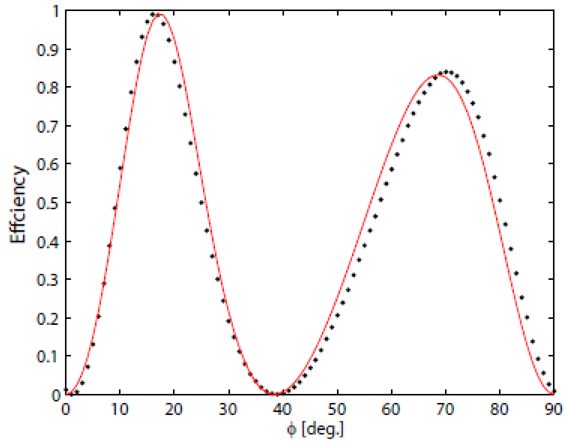
- The sidewalls are assumed to exhibit a linear slope.
- The under-etched part in the substrate is neglected.
- In order to realize the trapezoidal shape of the grating ridges, the slanted grating medium was applied.
  - grating period: 250 nm
  - grating height: 660 nm
  - fill factor: 0.75 (bottom)
  - angles of sidewalls: ±6°
  - n_1: 1.46
  - n_2: 2.08



Grating #1 Results

- In comparison, both figures exhibit a very good match, especially the course of the graph.
- There are some small deviations, caused by the simplification of the grating structure compared to the reference. The simplifications were necessary due to the lack of data of the complex grating structure.

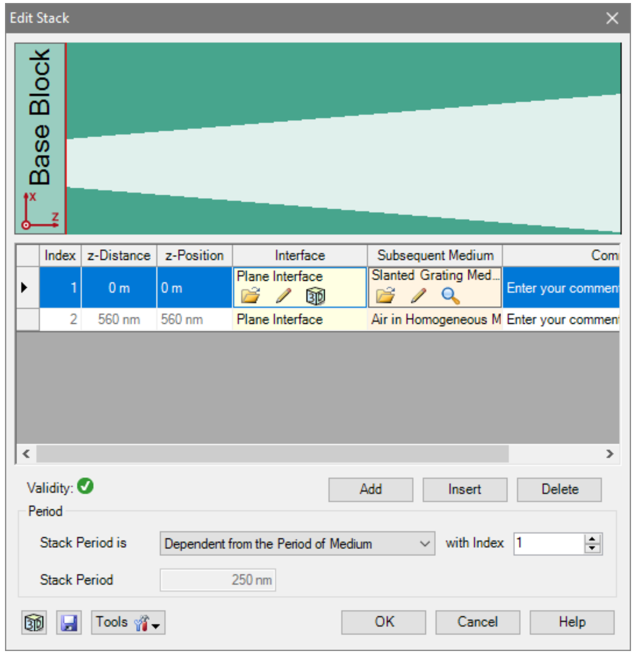




Passilly *et al.* (2008)

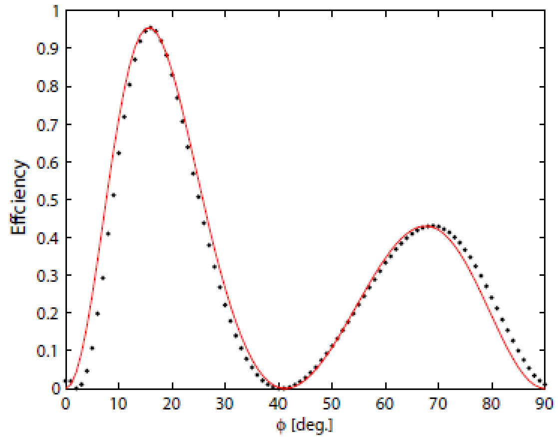
Grating #2 Parameters

- The grating is to be assumed to have a rectangular shape.
- The under-etched part in the substrate is neglected.
- A rectangular grating is sufficient to present such kind of grating structure.
  - grating period: 250 nm
  - grating height: 490 nm
  - fill factor: 0.5
  - n_1: 1.46
  - n_2: 2.08

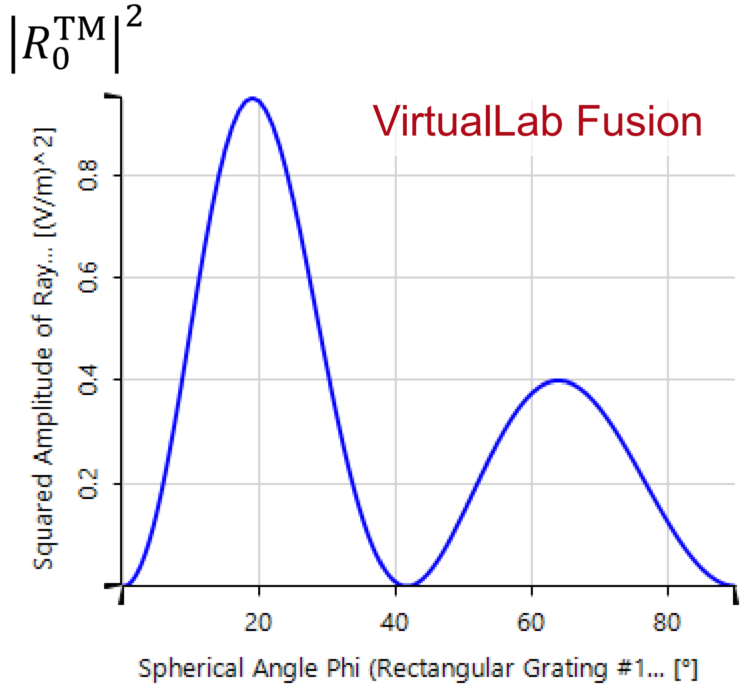


Grating #2 Results

- In comparison, both figures show again a very good match, especially the course of the graph.
- There are some small deviations, caused by the simplification of the grating structure compared to the reference and the lack of some grating parameters.



Passilly *et al*. (2008)



Document Information

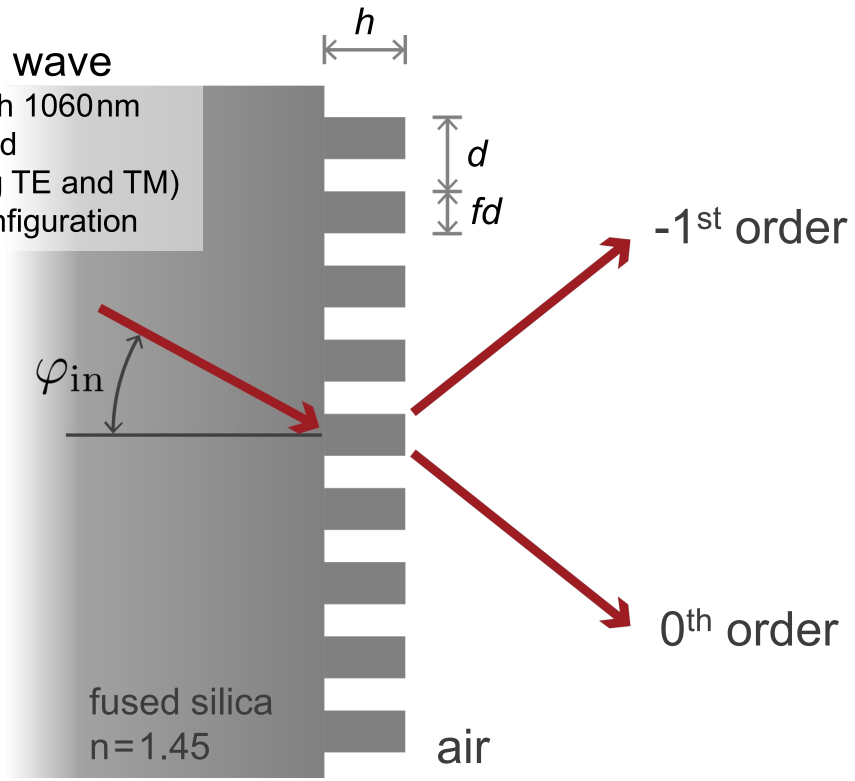
title	Investigation of Polarization State of Diffraction Orders
document code	GRT.0008
version	1.1
toolbox(es)	Grating Toolbox
VL version used for simulations	7.4.0.49
category	Feature Use Case
further reading	- Ultra-Sparse Dielectric Nano-Wire Grid Polarizers - Rigorous Analysis and Design of Anti-Reflective Moth-Eye Structures

Analysis and Design of Highly Efficient Polarization Independent Transmission Gratings

Polarization Independent Grating …

Design Task

input plane wave
- wavelength 1060 nm
- unpolarized (averaging TE and TM)
- Littrow configuration



How to optimized the grating structure parameters so to maximize the diffraction efficiency of -1st transmission order, for unpolarized input light?

?

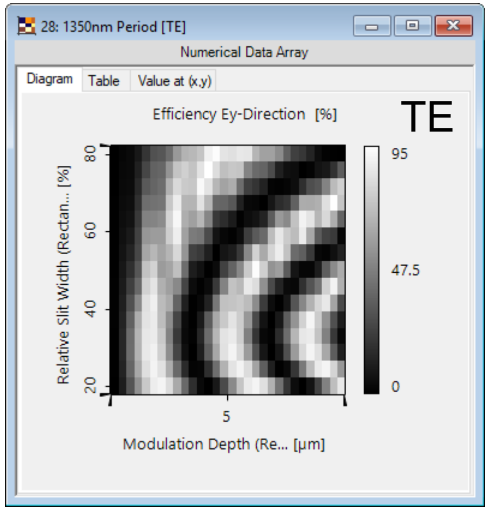
Parameter	Value Range
grating depth *h*	0.1-10 µm
grating period *d*	550-1350 nm
fill factor *f*	20-80%

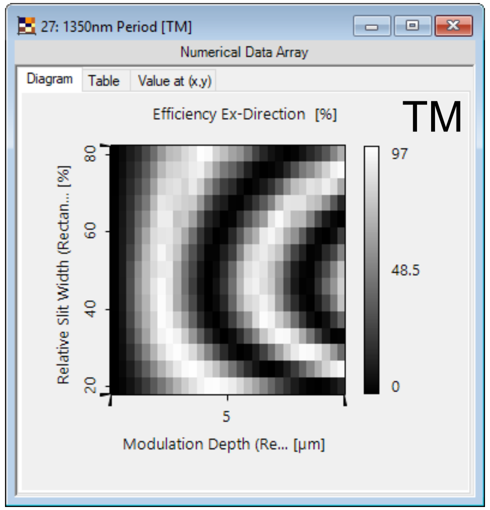
reference: T. Clausnitzer, *et al.*, „Highly efficient polarization independent transmission gratings for pulse stretching and compression,“Proc. SPIE **5252**, 174-182 (2003)

Rigorous Analysis of Grating Property vs. Parameters

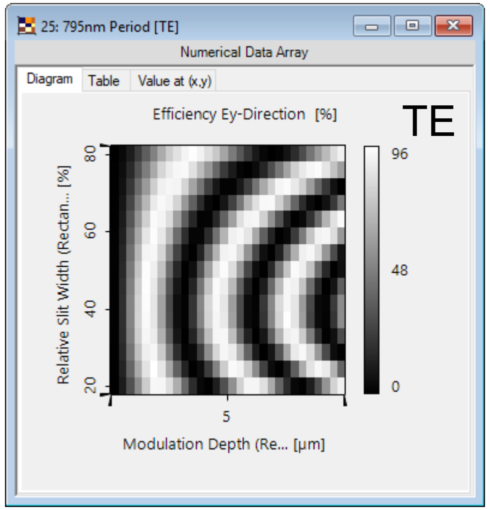
Diffraction Efficiency @ Different Grating Periods

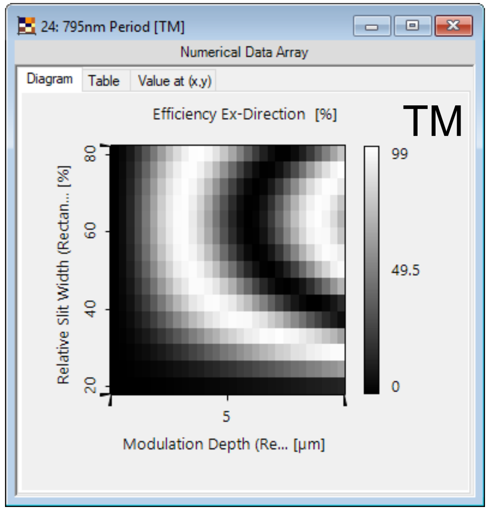
period=1350nm



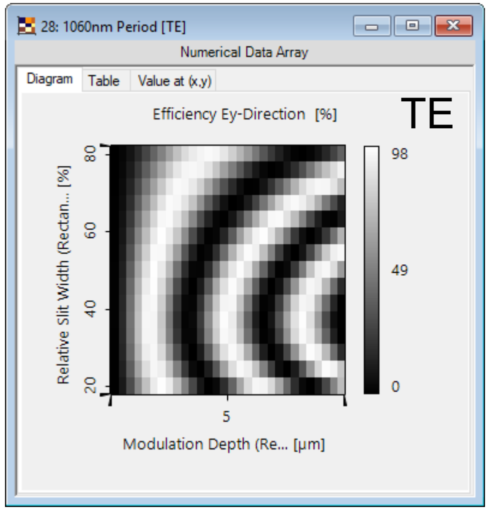


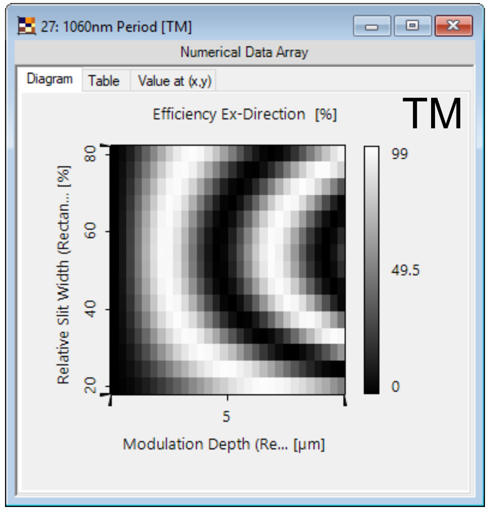
period=795nm



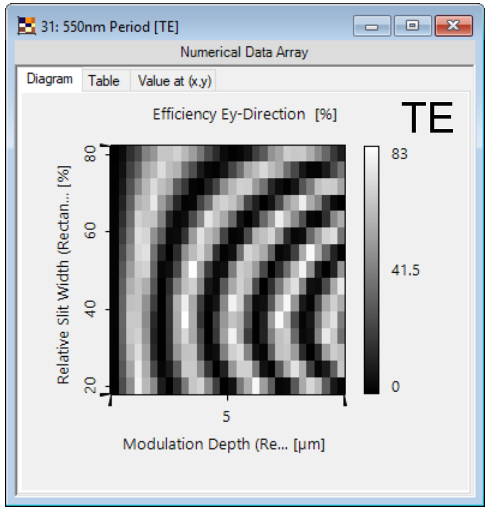


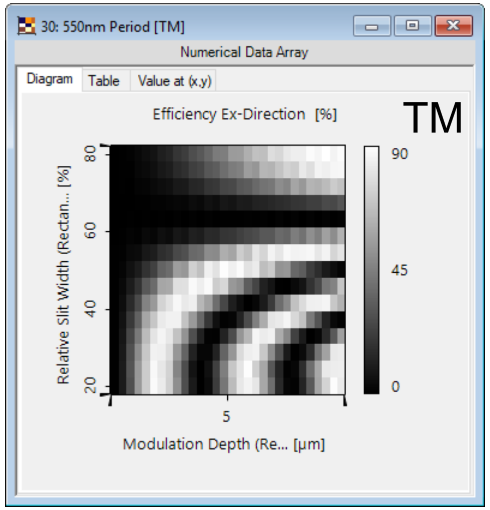
period=1060nm





period=550nm





Considerations on Grating Period Choice

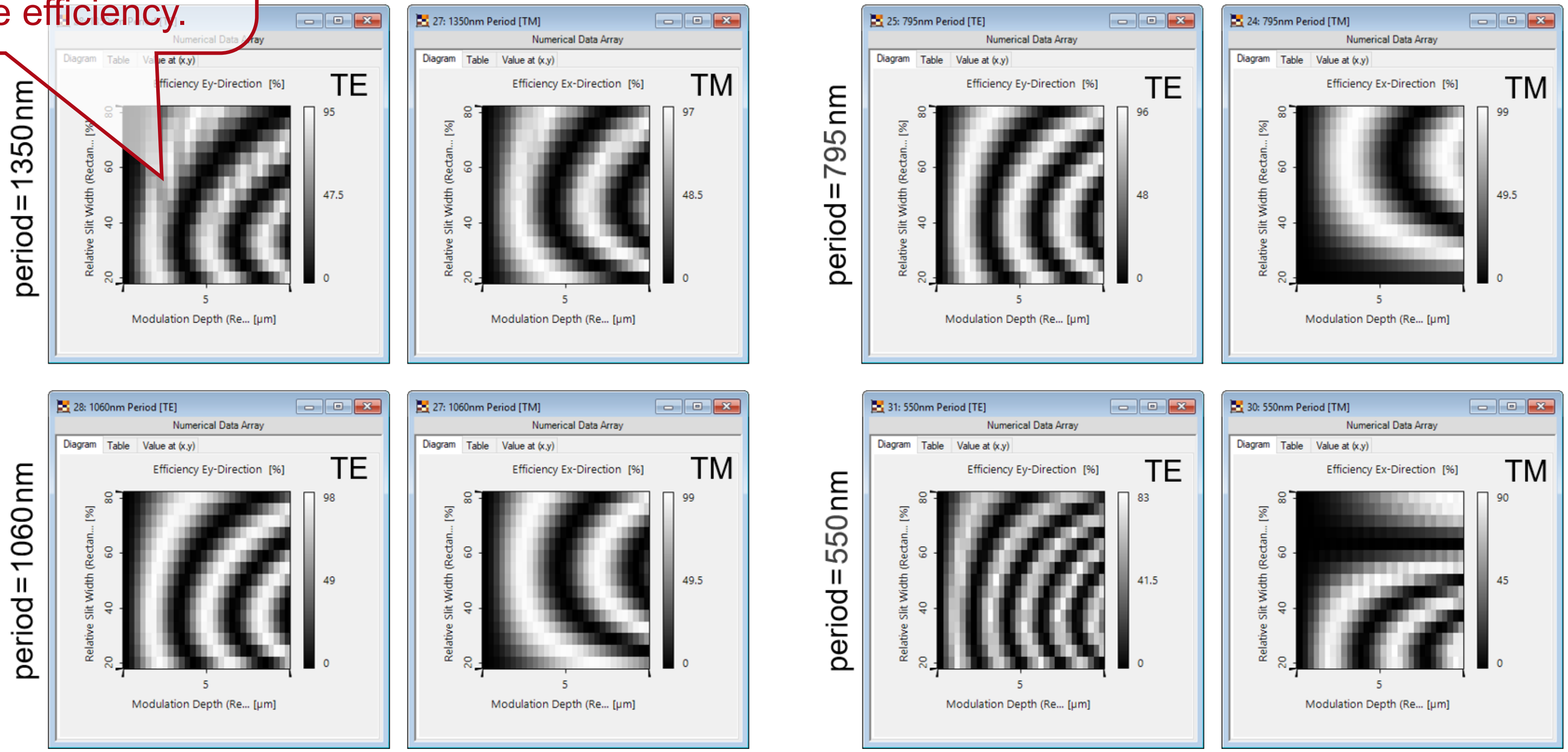
Large period leads to higher diffraction orders in the substrate, and causes additional modulation in the efficiency.

Similar analysis can be found in T. Clausnitzer, *et al.*, Proc. SPIE **5252**, 174-182 (2003).

To ensure -1st transmission order exist (in air) and to avoid higher diffraction orders (in substrate), the grating period follows

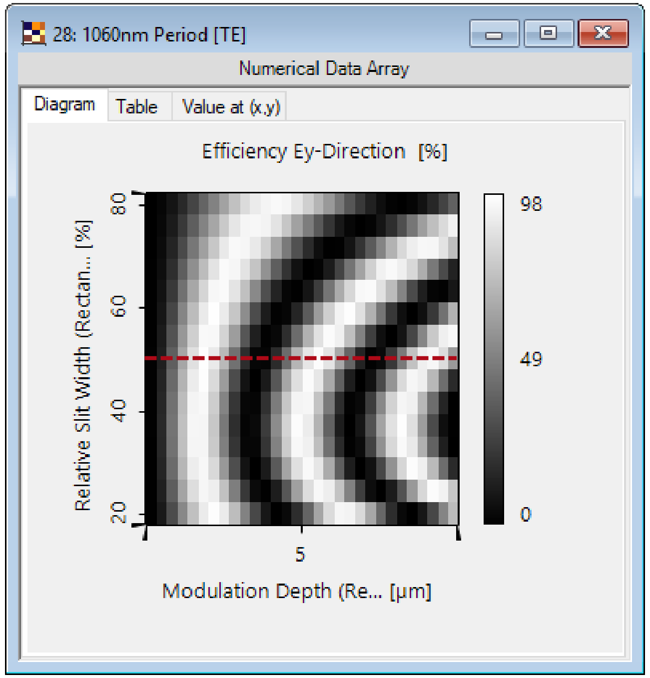
$$\lambda/2 < d < 3\lambda/2n$$

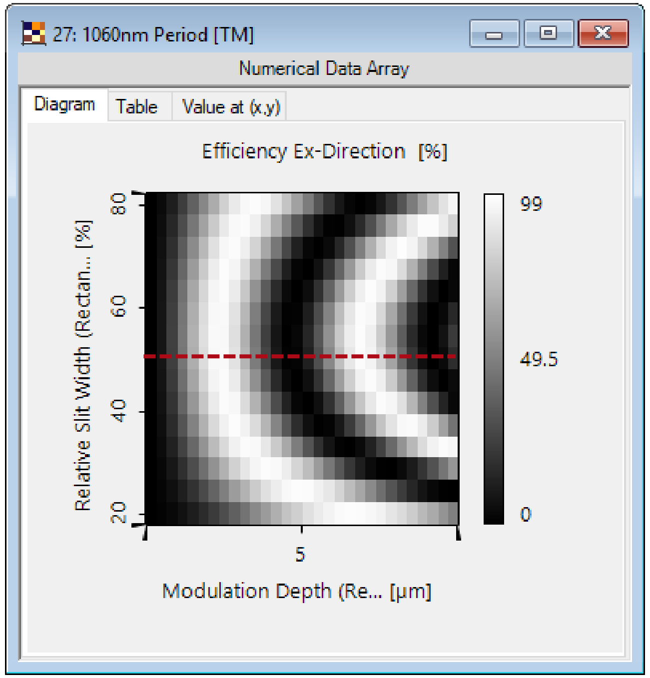
where n is the refractive index of the substrate.



Polarization-Dependent Diffraction Property

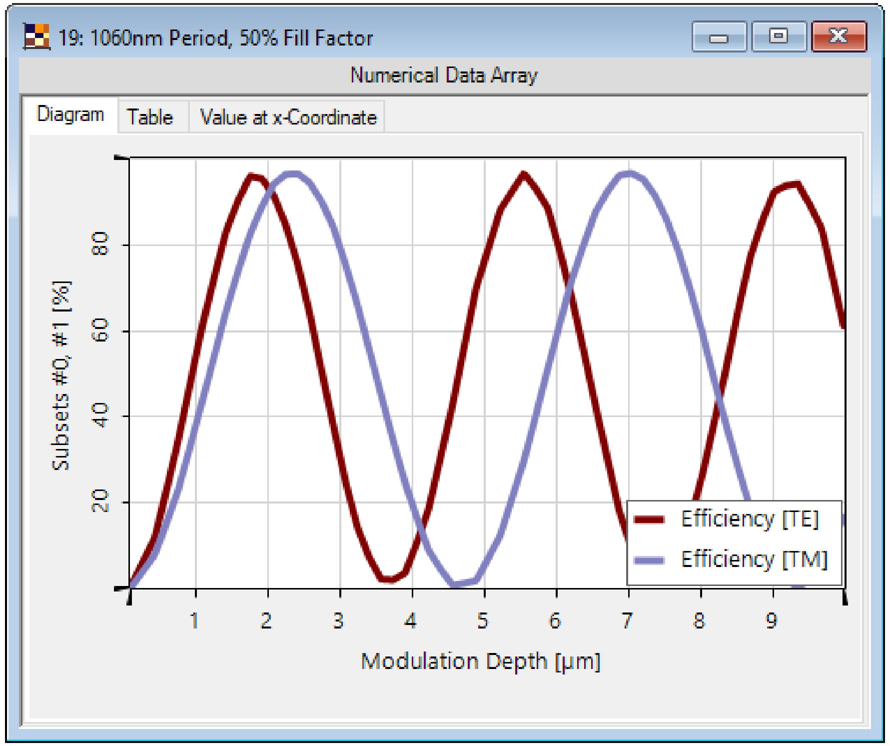
diffraction efficiency analysis for given period 1060 nm





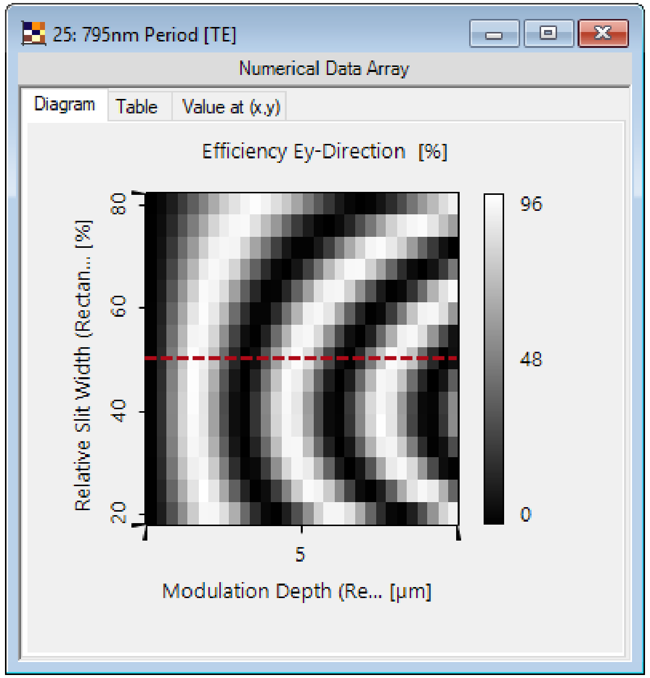
Parameter	Value
grating depth *h*	0.1-10 µm
grating period *d*	**1060 nm**
fill factor *f*	20-80%

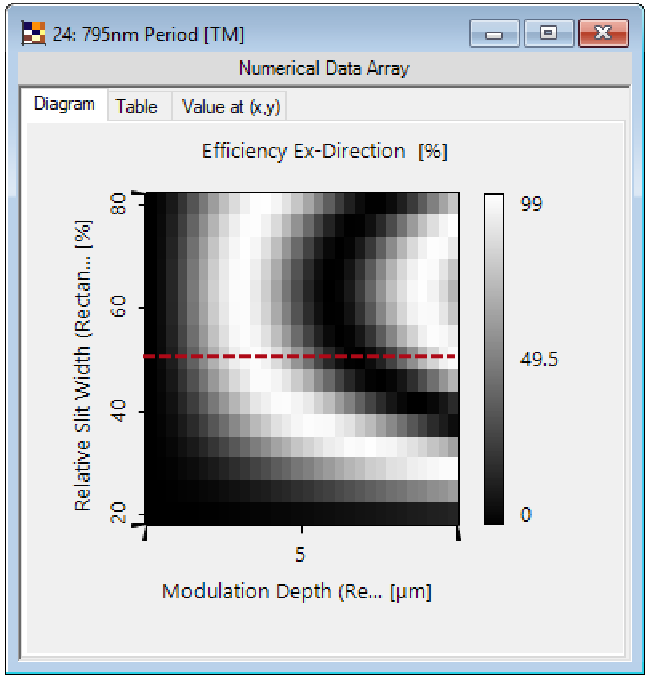
diffraction efficiencies vs. grating depth
(grating period = 1060 nm, fill factor = 50%)



Polarization-Dependent Diffraction Property

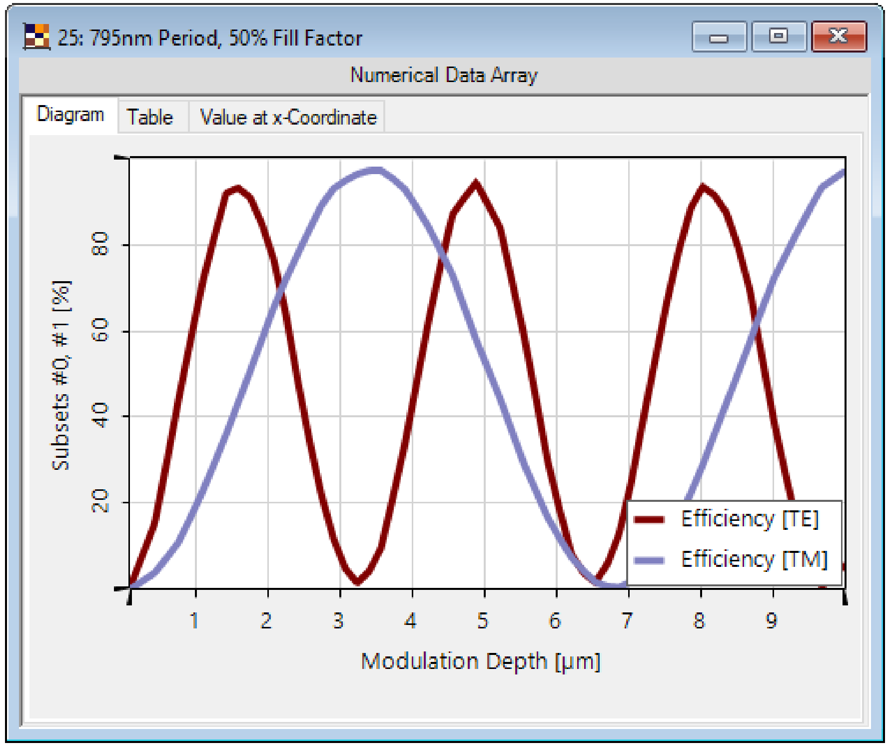
diffraction efficiency analysis for given period 795 nm





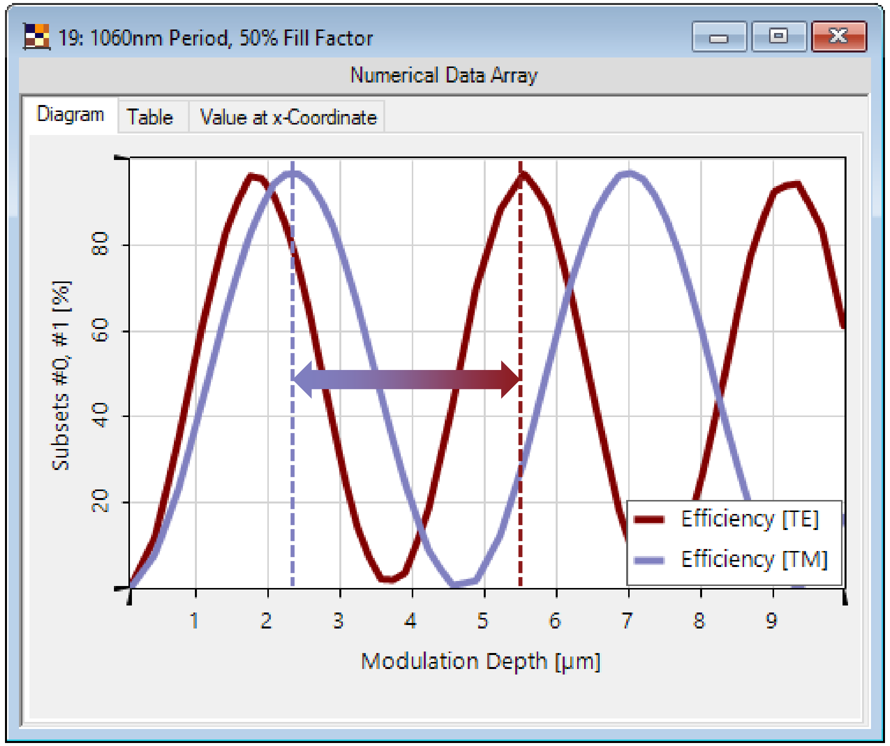
Parameter	Value
grating depth *h*	0.1-10 µm
grating period *d*	**795 nm**
fill factor *f*	20-80%

analysis of diffraction efficiency with fixed fill factor 50%

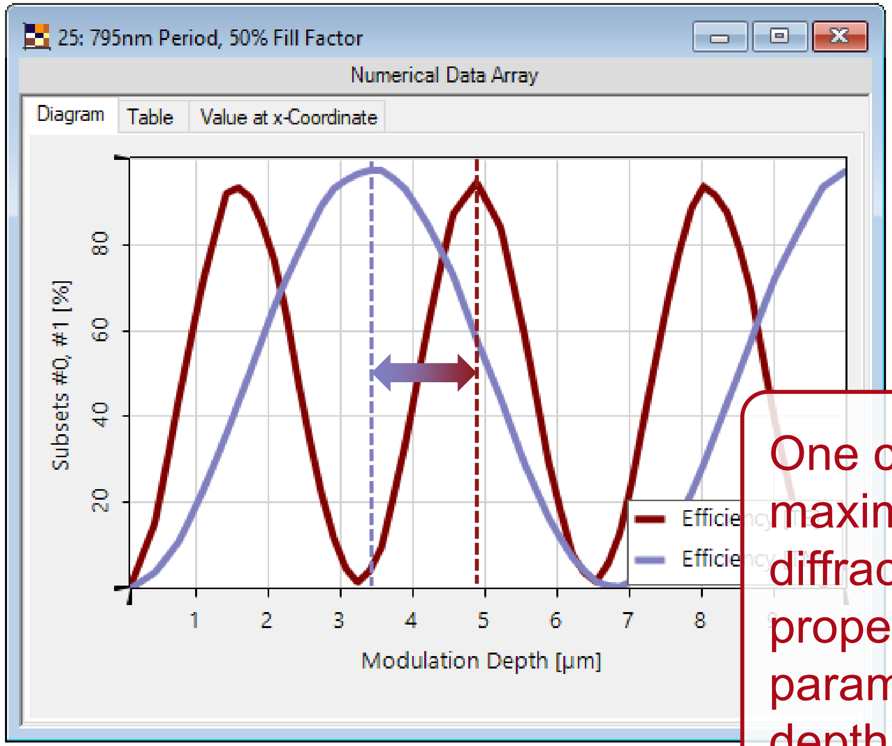


Polarization-Dependent Diffraction Property

diffraction efficiencies vs. grating depth
(grating period=**1060 nm**, fill factor=50%)



diffraction efficiencies vs. grating depth
(grating period=**795 nm**, fill factor=50%)



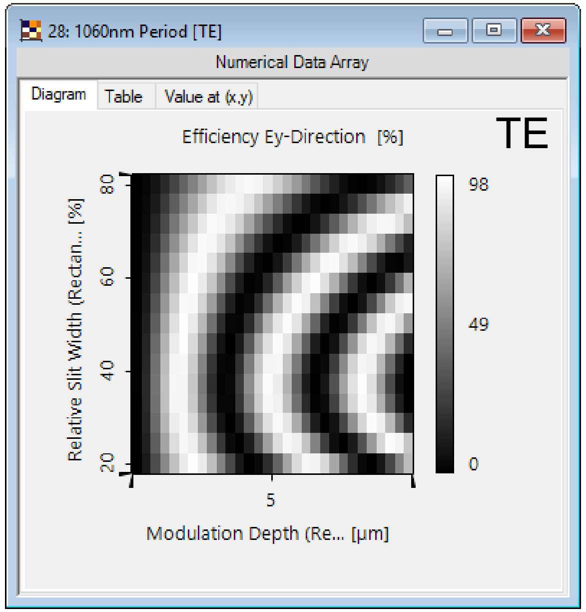
One could simultaneously maximize the TE and TM diffraction efficiencies by proper choice of grating parameters, e.g., period, depth, and fill factor.

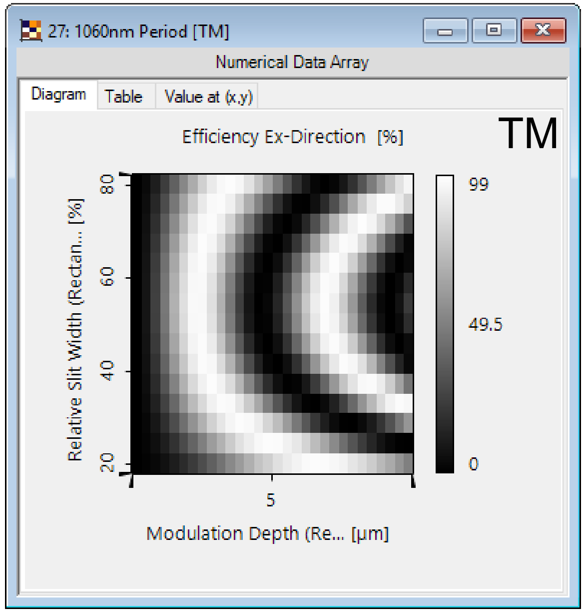
When grating period changes from 1060nm to 795nm
- the TE peak efficiency position shifts toward right i.e. larger grating depth;
- the TM peak efficiency position shifts toward left i.e. smaller grating depth.

Grating Design by Parametric Optimization

2D Parametric Optimization with Fixed Period

We use fixed period of 1060 nm, with grating depth and fill factor as variables, and try to optimize the averaged diffraction efficiency.





The average diffraction efficiency can be defined as

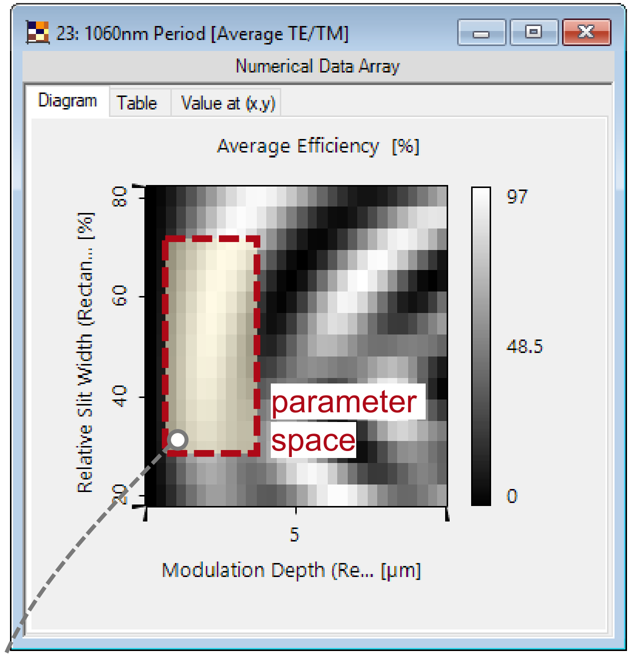
$$\eta^{\mathrm{avg}} = \frac{1}{2}\left(\eta^{\mathrm{TE}} + \eta^{\mathrm{TM}}\right) ,$$

and it is to be maximized within the following parameter range

Parameter	Value Range
grating depth *h*	0.5-3.5 μm
fill factor *f*	30-70%
grating period *d*	**1060 nm (fixed)**

To keep a relatively low aspect ratio, we defined a reduced variation range of the grating depth and fill factor for design.

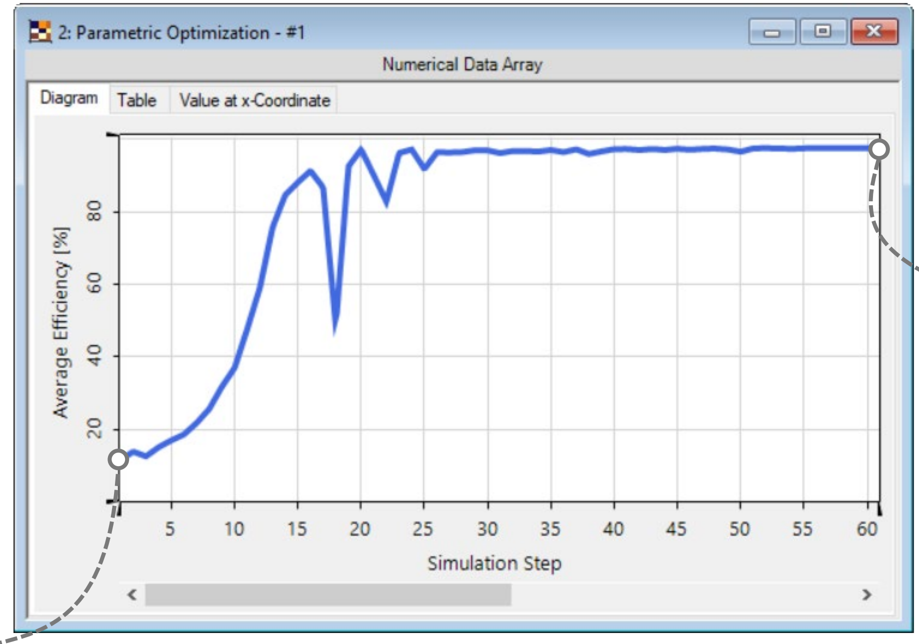
2D Parametric Optimization – Design #1



initial parameters

Parameter	Value
grating depth *h*	0.5 µm
fill factor *f*	30 %
grating period *d*	**1060 nm (fixed)**

parametric optimization – downhill simplex

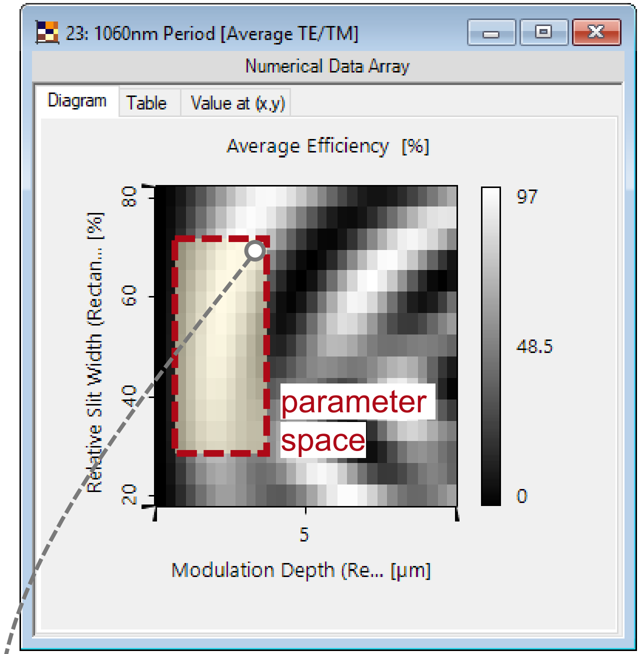


Diffraction efficiency in each optimization step is calculated using Fourier modal method (FMM, also known as RCWA).

optimized parameters

Parameter	Value
grating depth *h*	2.22 µm
fill factor *f*	59 %
grating period *d*	**1060 nm (fixed)**

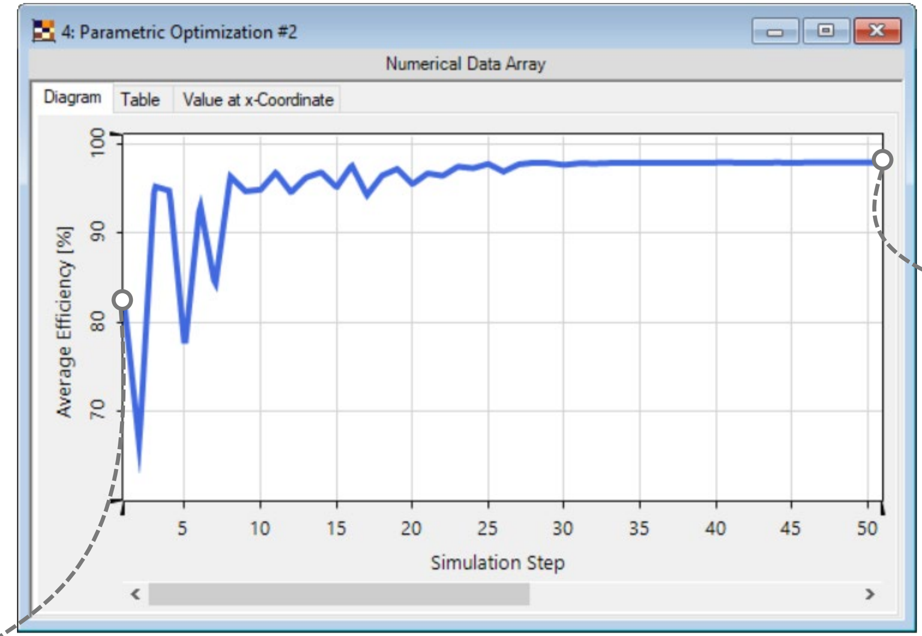
2D Parametric Optimization – Design #2



initial parameters

Parameter	Value
grating depth *h*	3.5 µm
fill factor *f*	70 %
grating period *d*	**1060 nm (fixed)**

parametric optimization – downhill simplex



Diffraction efficiency in each optimization step is calculated using Fourier modal method (FMM, also known as RCWA).

optimized parameters

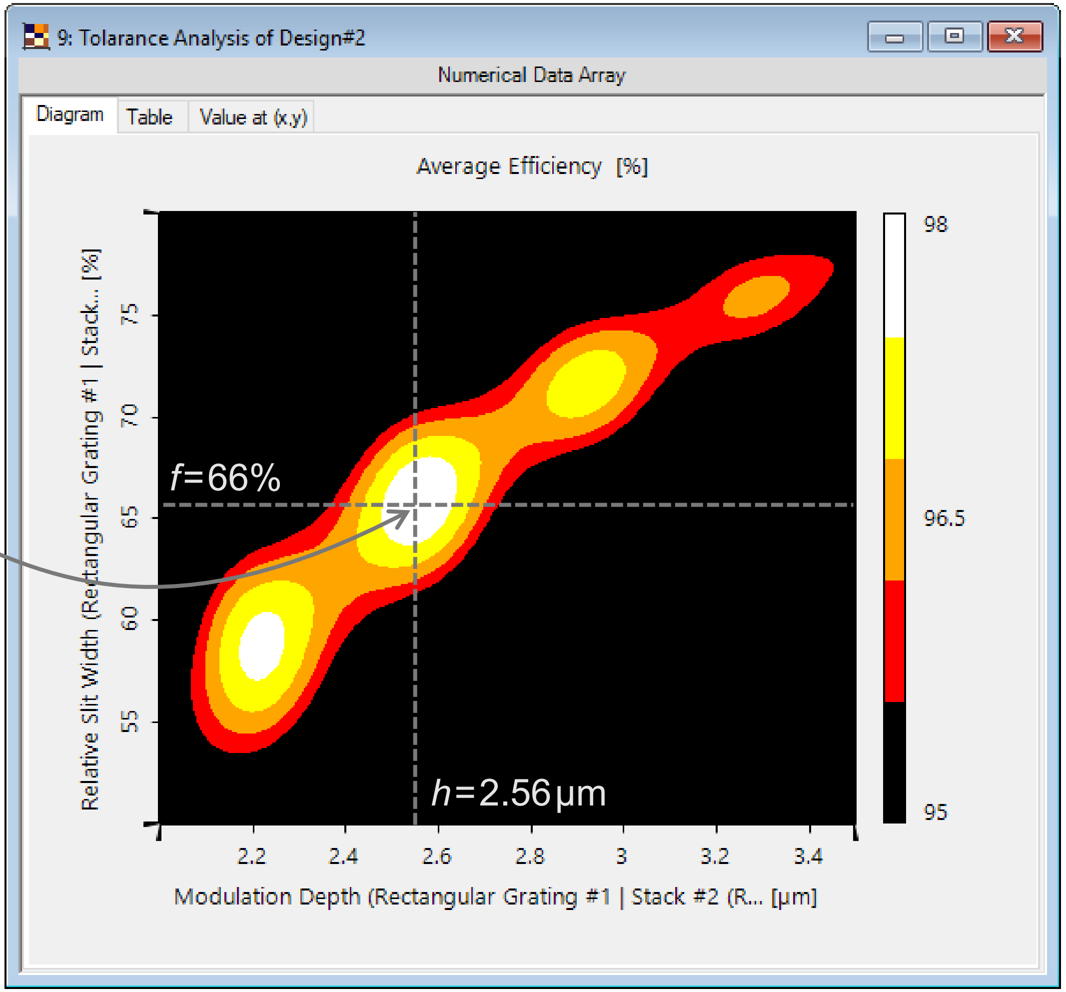
Parameter	Value
grating depth *h*	2.56 µm
fill factor *f*	66 %
grating period *d*	**1060 nm (fixed)**

The same resulting parameters can be found in T. Clausnitzer, *et al.*, Proc. SPIE **5252**, 174-182 (2003).

Fabrication Tolerance Analysis – Design #2

optimized parameters

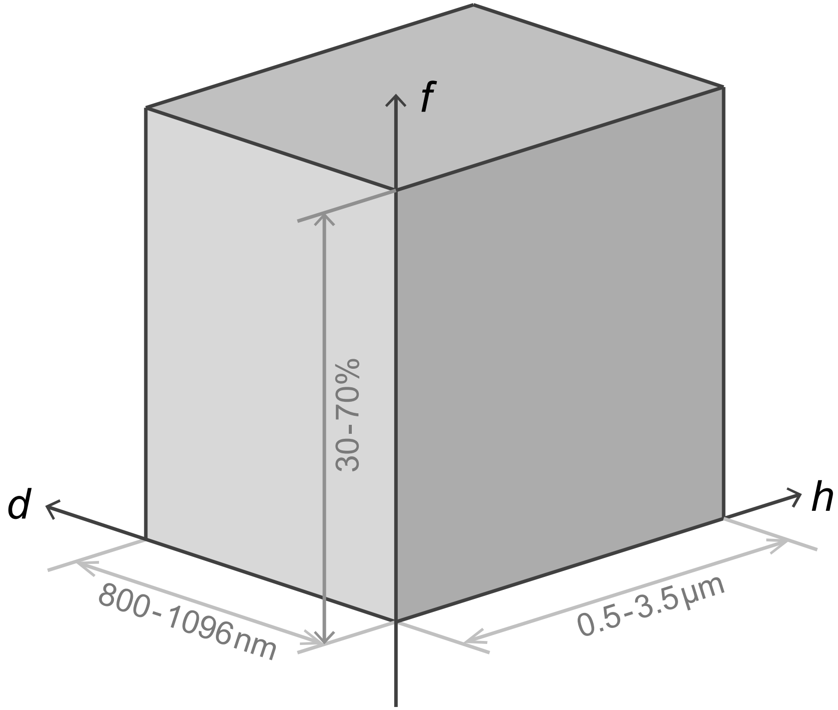
Parameter	**Value**
grating depth *h*	2.56 µm
fill factor *f*	66 %
grating period *d*	**1060 nm (fixed)**



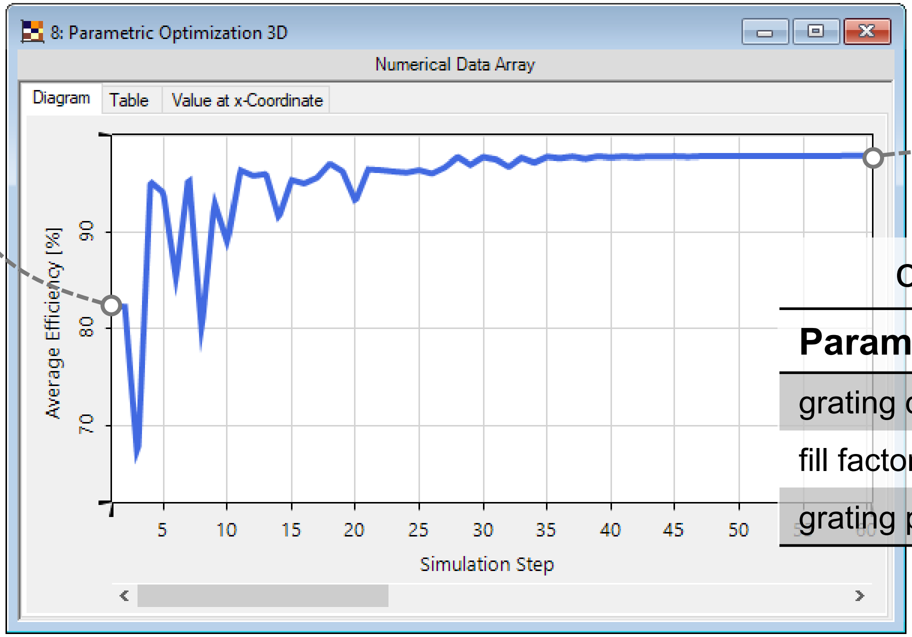
Diffraction efficiency within the region around the design parameters (efficiency value clipped above 95% only)

3D Parametric Optimization with Varying Grating Period

Parameter	Value Range	Initial Value
grating depth *h*	0.5-3.5µm	3.5µm
fill factor *f*	30-70%	70%
grating period *d*	800-1096nm	1060nm



parametric optimization – downhill simplex



optimized parameters

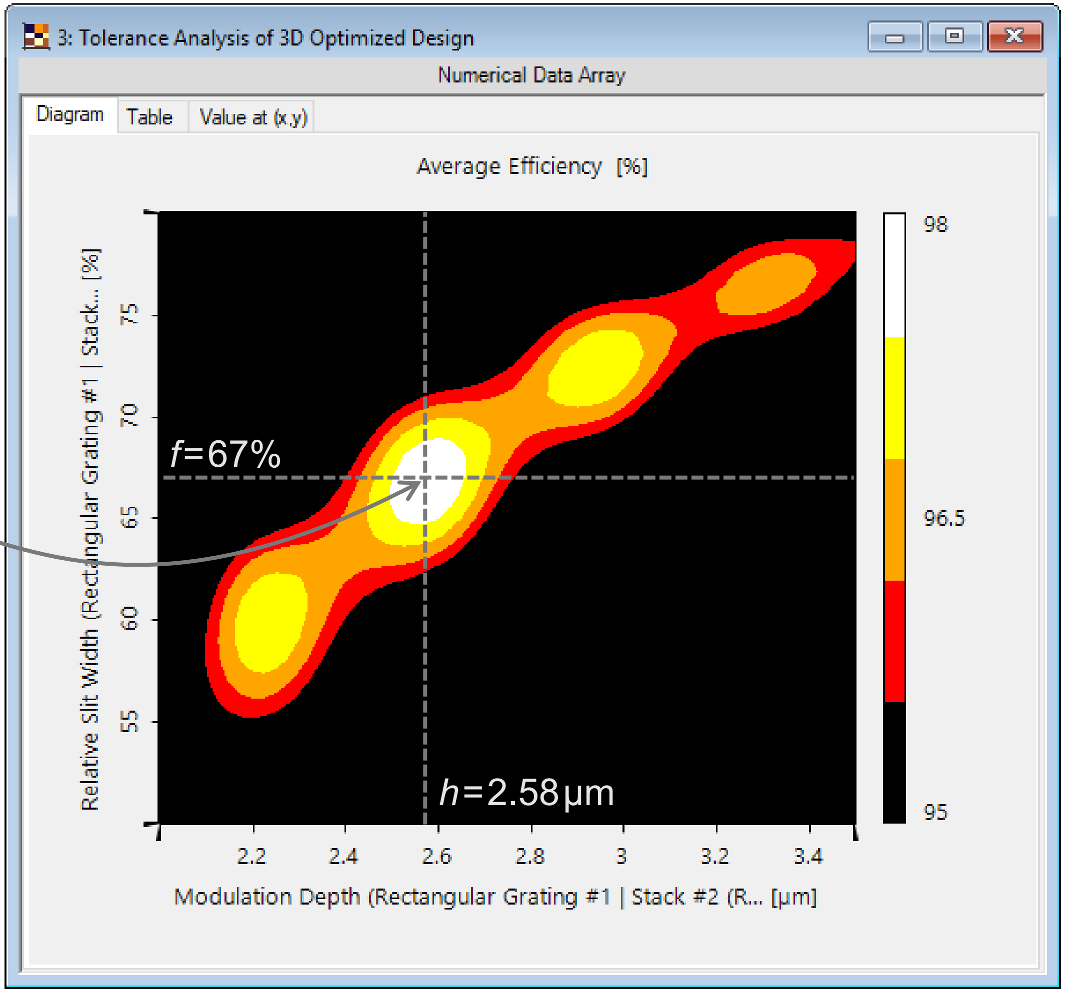
Parameter	Value
grating depth *h*	2.58µm
fill factor *f*	67%
grating period *d*	1024nm

Diffraction efficiency in each optimization step is calculated using Fourier modal method (FMM, also known as RCWA).

Fabrication Tolerance Analysis

optimized parameters

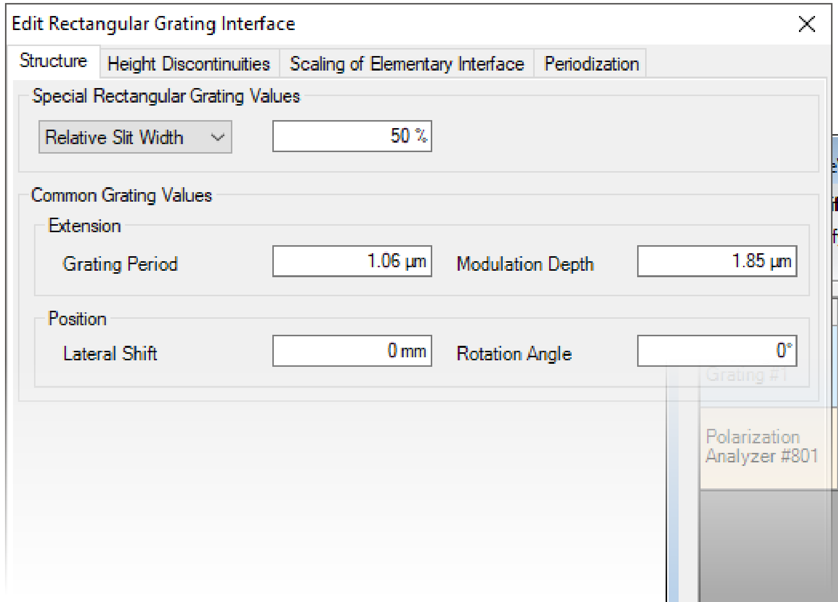
Parameter	Value
grating depth *h*	2.58 µm
fill factor *f*	67 %
grating period *d*	1024 nm (fixed)



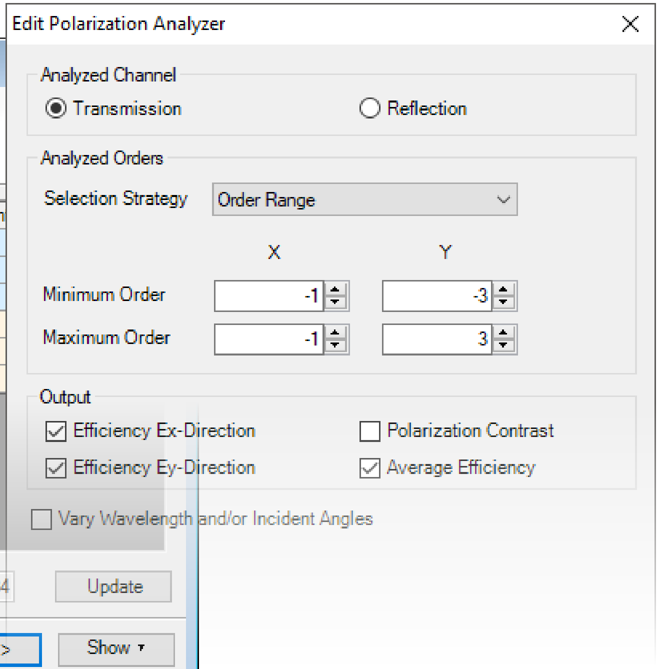
Diffraction efficiency within the region around the design parameters (efficiency value clipped above 95% only)

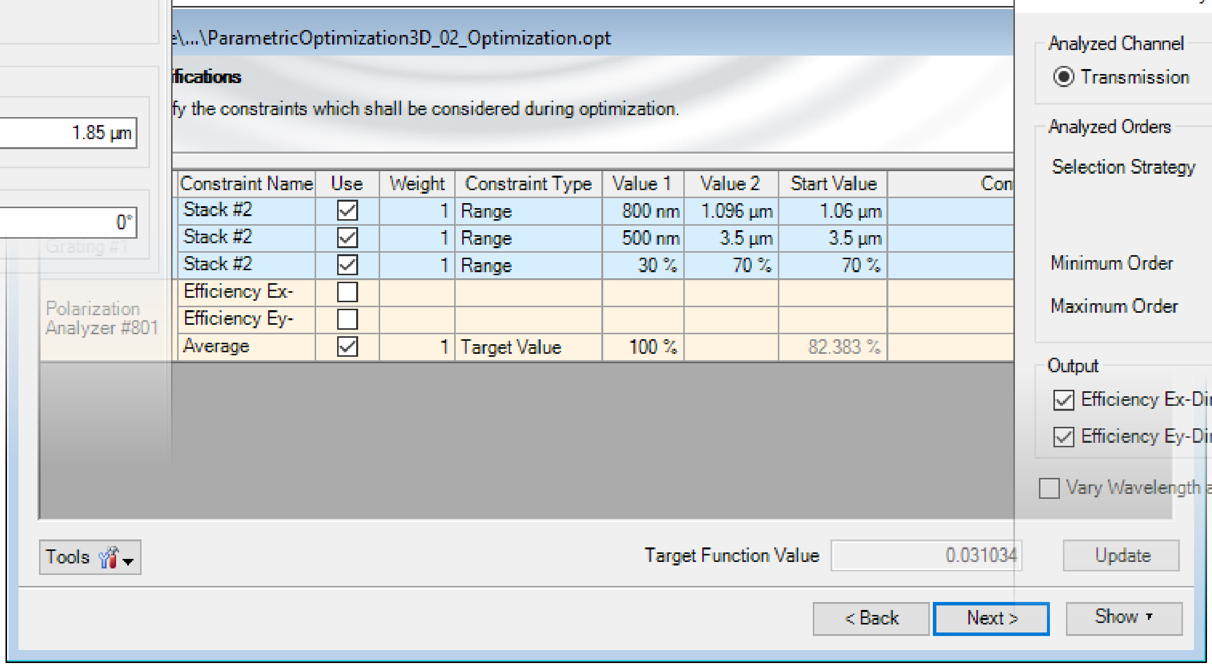
Peek into VirtualLab Fusion

intuitive grating parameters specification



special detector for polarization-related quantity analysis

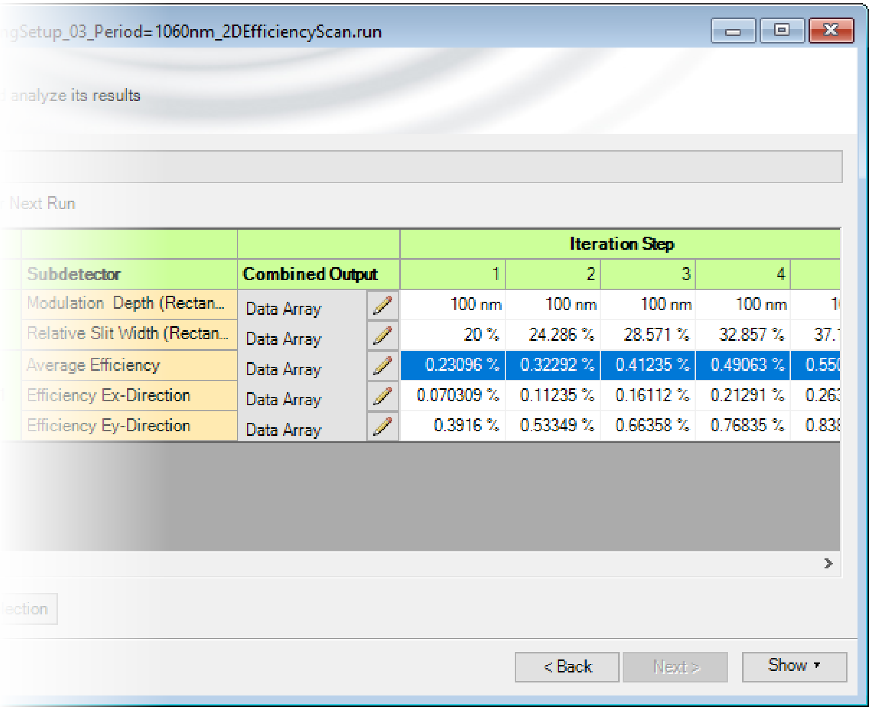




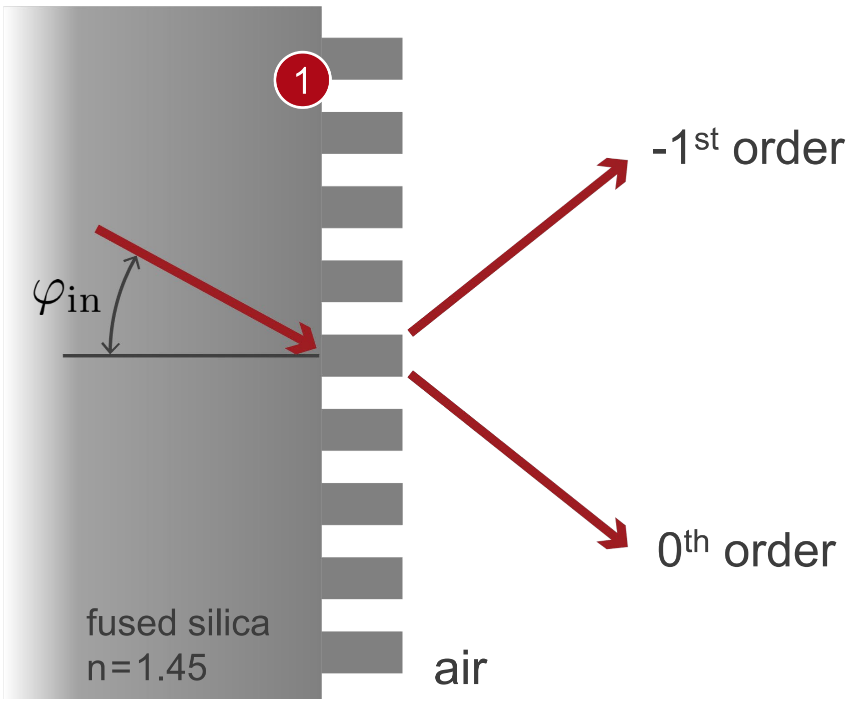
parametric optimization tools with friendly user interface

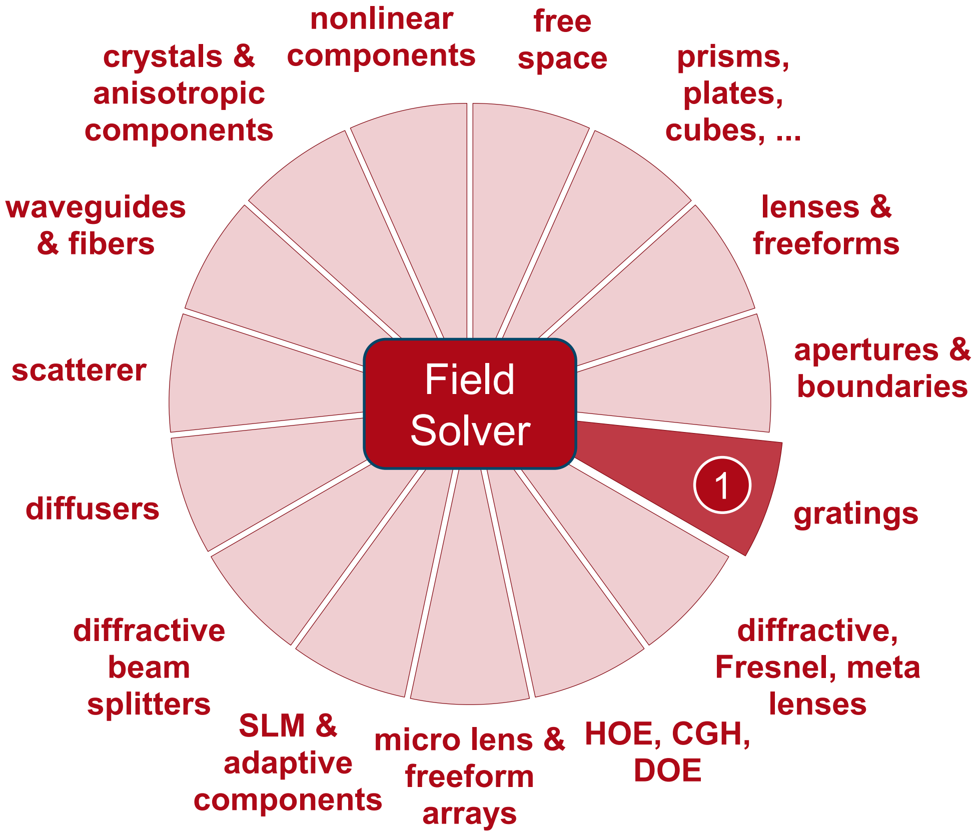
Workflow in VirtualLab Fusion

- Construct grating structure
  - Configuration of Grating Structures by Using Interfaces [Use Case]
- Analyze grating diffraction efficiency
  - Grating Order Analyzer [Use Case]
- Search for initial solutions with Parameter Run
  - Usage of the Parameter Run Document [Use Case]
- Find final design with Parametric Optimization



VirtualLab Fusion Technologies





Document Information

title	Analysis and Design of Highly Efficient Polarization Independent Transmission Gratings
document code	GRT.0015
version	1.0
toolbox(es)	Grating Toolbox
VL version used for simulations	7.5.0.158
category	Application Use Case
further reading	- Ultra-Sparse Dielectric Nano-Wire Grid Polarizers - Rigorous Analysis of Nanopillar Metasurface Building Block - Parametric Optimization and Tolerance Analysis of Slanted Gratings

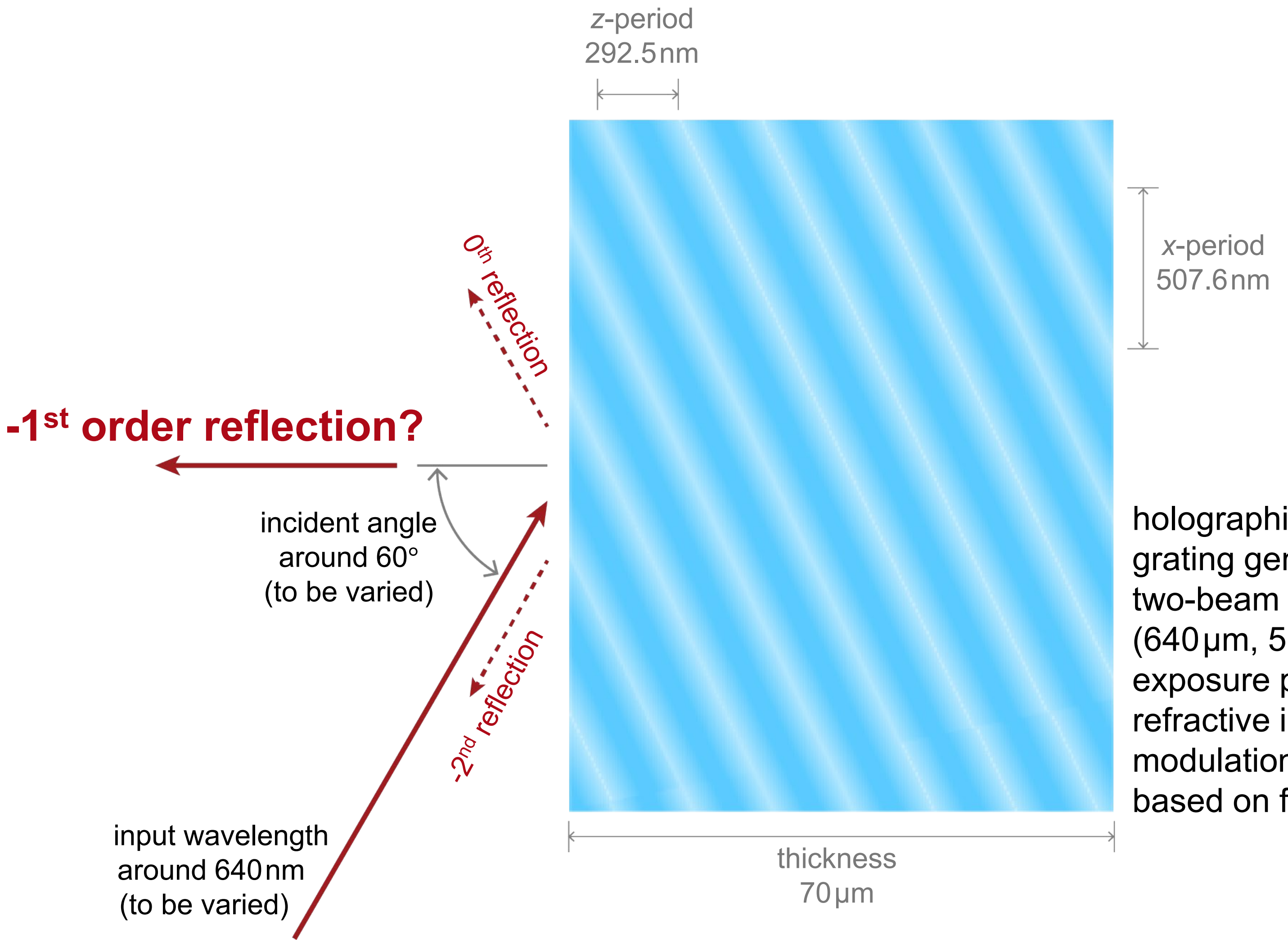
Introduction

- How to construct grating structures
- Modeling and design of surface-relief gratings, like slanted ones
- Analysis of polarization-dependent effects and optimization
- **Properties of holographic volume gratings**
- Investigation of two-dimensional periodic structures, like nanopillars

Rigorous Simulation of Holographic Generated Volume Grating

VolumeGrating_...

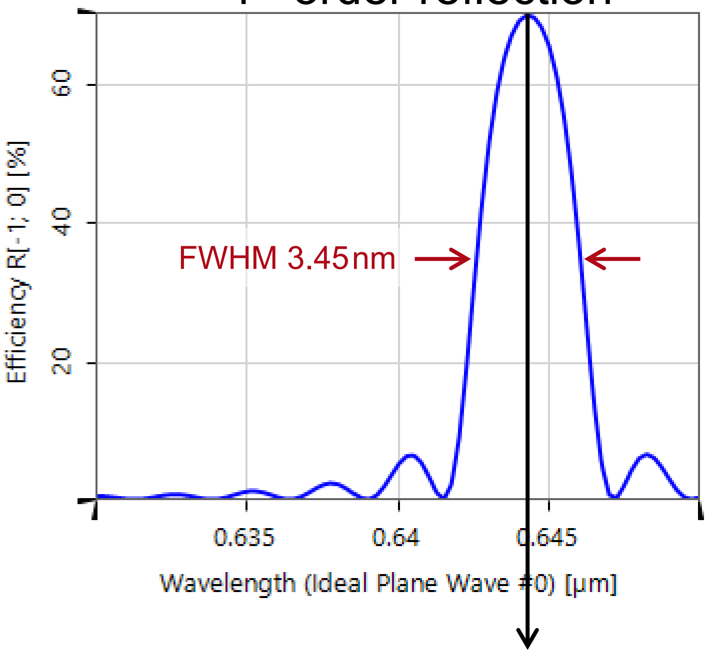
Modeling Task



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

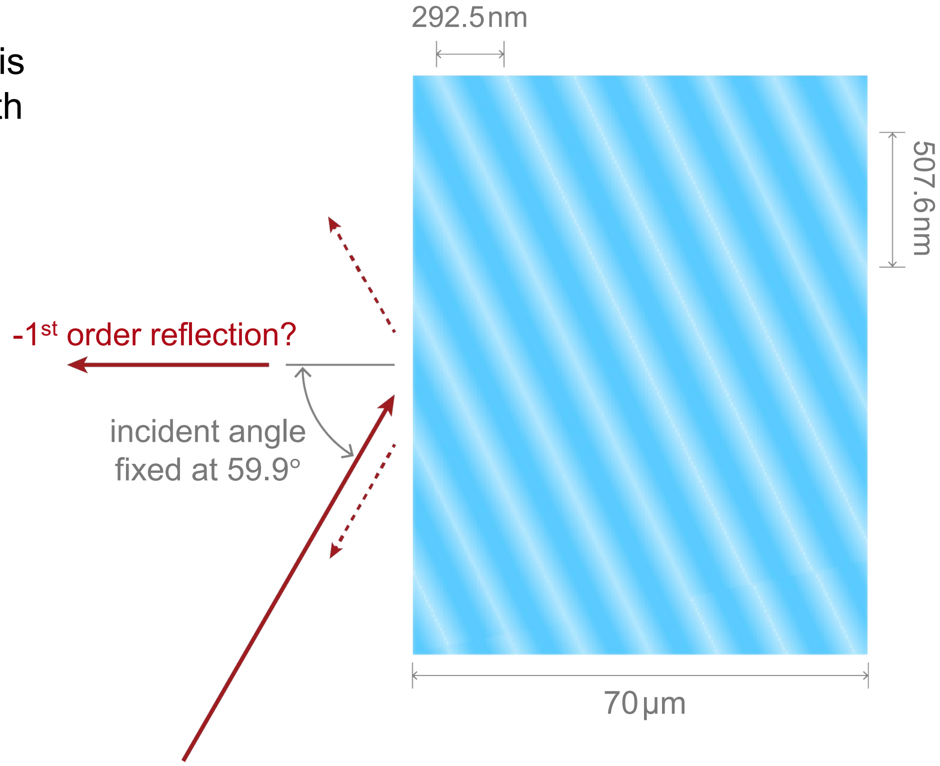
Diffraction Efficiency vs. Wavelength

-1st order reflection



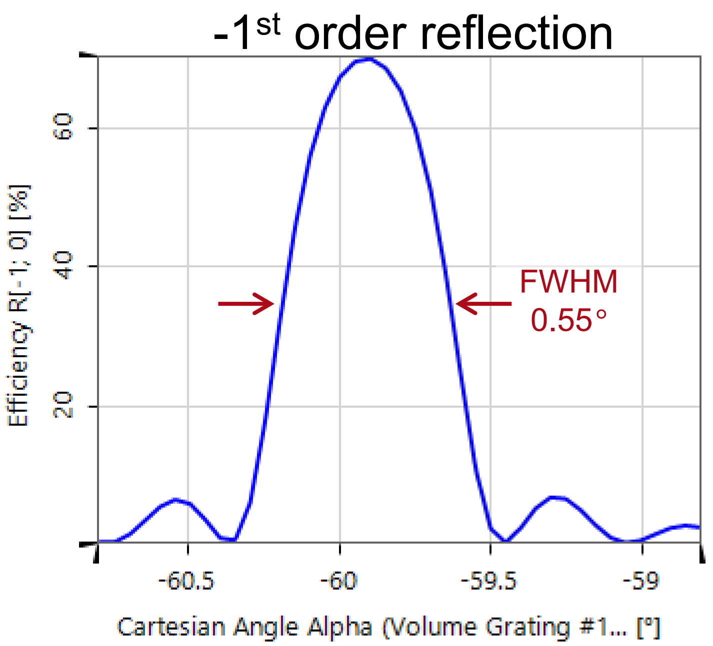
shift of wavelength dependent reflection due to locally increased effective refraction index

rigorous FMM analysis for varying wavelength

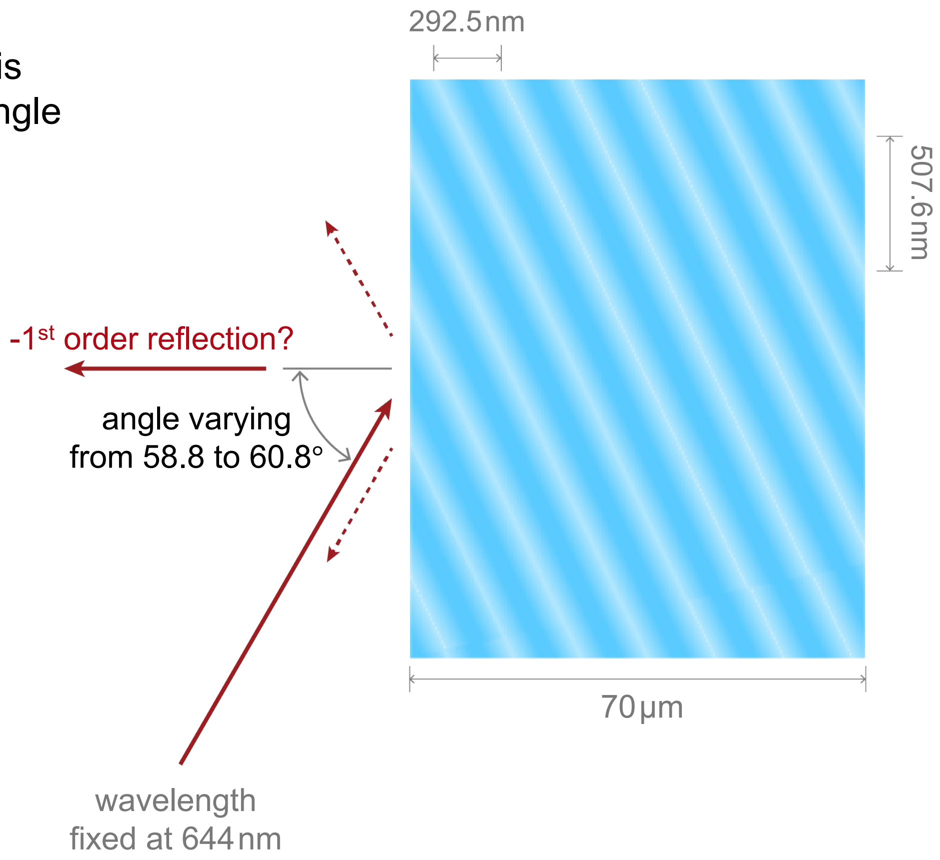


wavelength varying from 630 to 650nm

Diffraction Efficiency vs. Angle of Incidence



rigorous FMM analysis
for varying incident angle



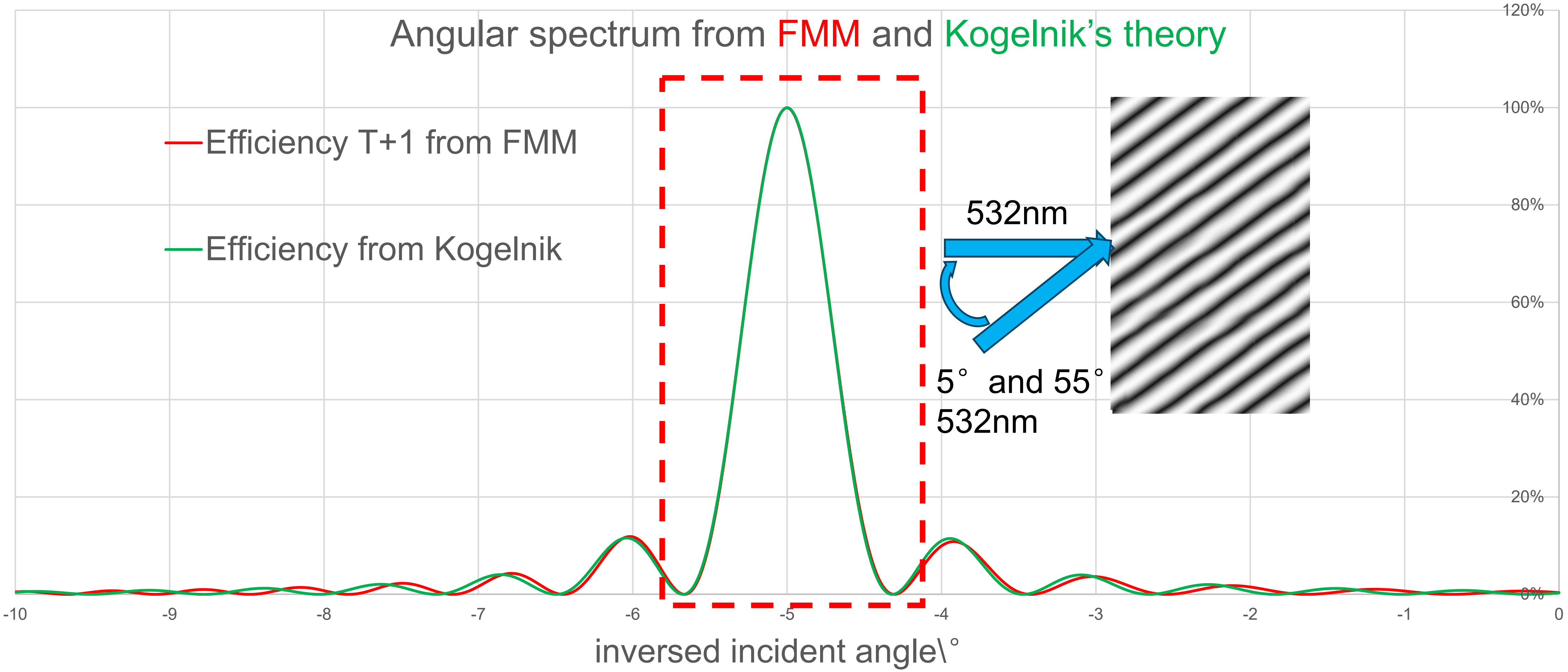
Document Information

title	Rigorous Simulation of Holographic Generated Volume Grating
document code	GRT.0003
version	1.1
toolbox(es)	Grating Toolbox
VL version used for simulations	7.5.0.158
category	Application Use Case
further reading	- Configuration of Grating Structures by Using Special Media

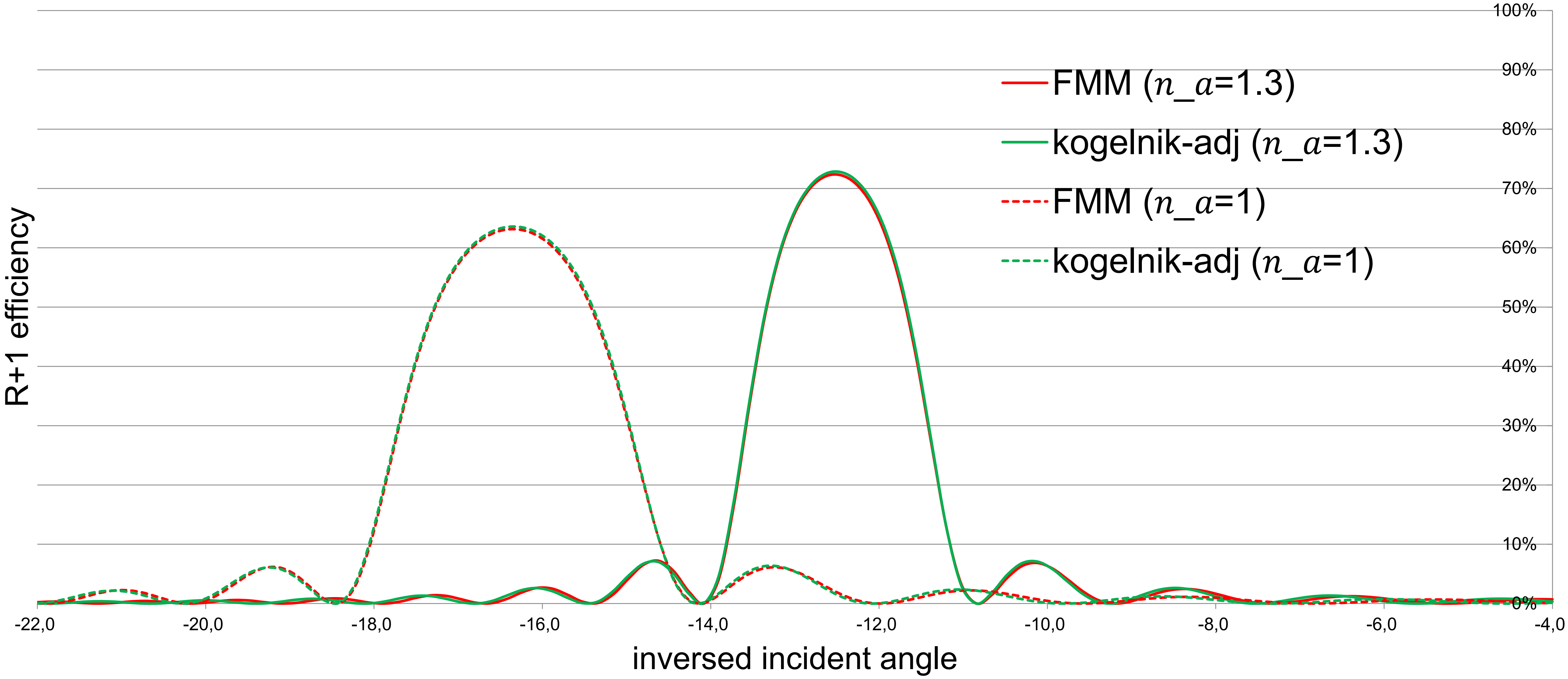
Using Kogelnik Theory for Volume Holographic Grating Simulation

Coming feature for grating simulation

Comparing Kogelnik Theory with FMM



Reflection Grating Example



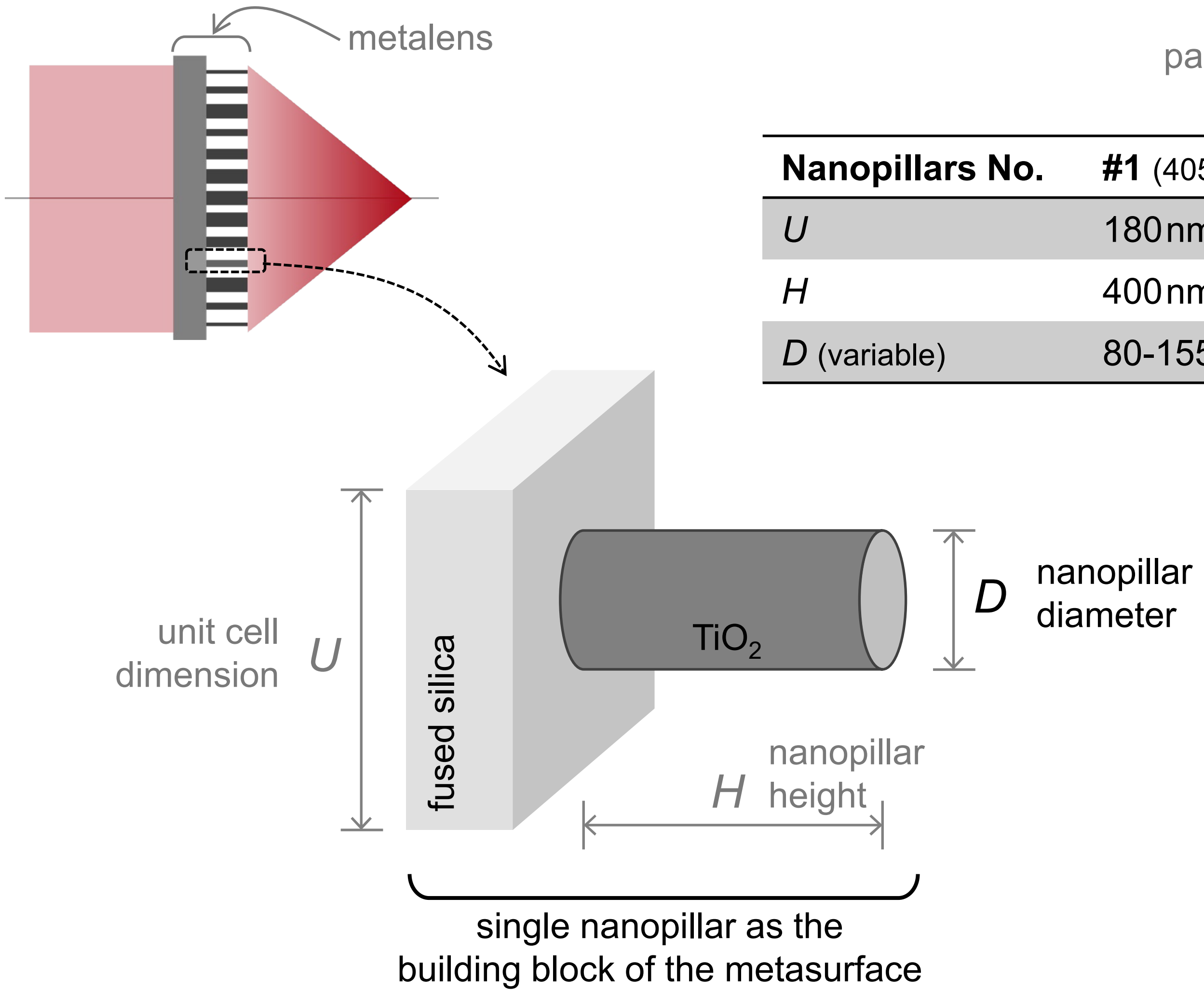
Introduction

- How to construct grating structures
- Modeling and design of surface-relief gratings, like slanted ones
- Analysis of polarization-dependent effects and optimization
- Properties of holographic volume gratings
- **Investigation of two-dimensional periodic structures, like nanopillars**

Rigorous Analysis of Nanopillar Metasurface Building Block

TiO2 Nanopillar_...

Modeling Task



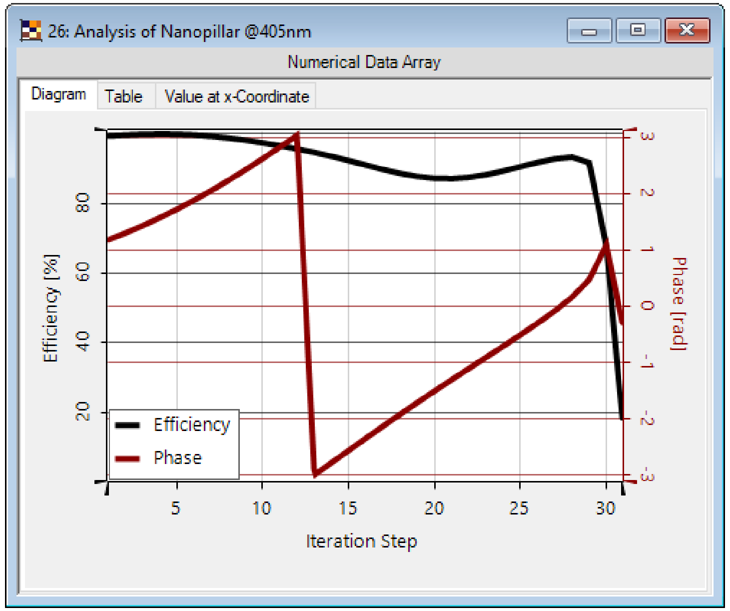
parameters from M. Khorasaninejad,
Nano Lett. 2016, 16, 7229-7234

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

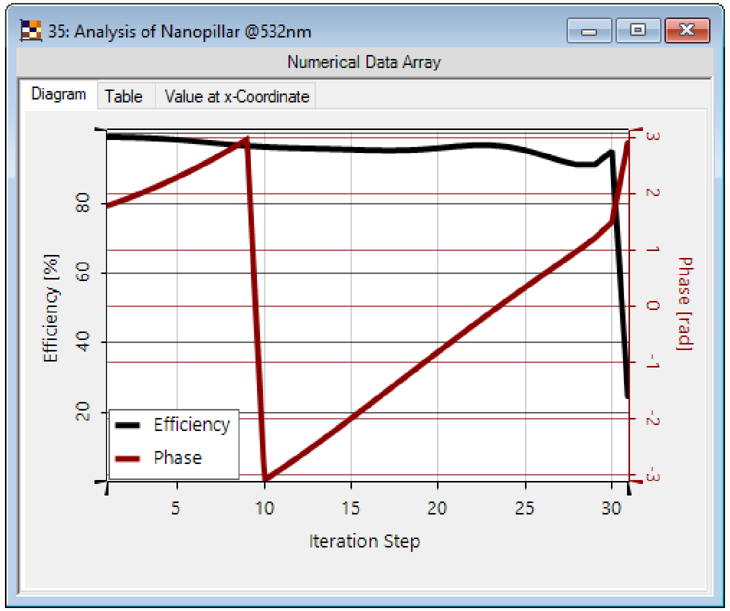
By varying the nanopillar diameter, the metasurface building block is supposed to have phase modulation covering 2π. How to evaluate such nanopillar structure rigorously?

Nanopillar Analysis vs. Pillar Diameter

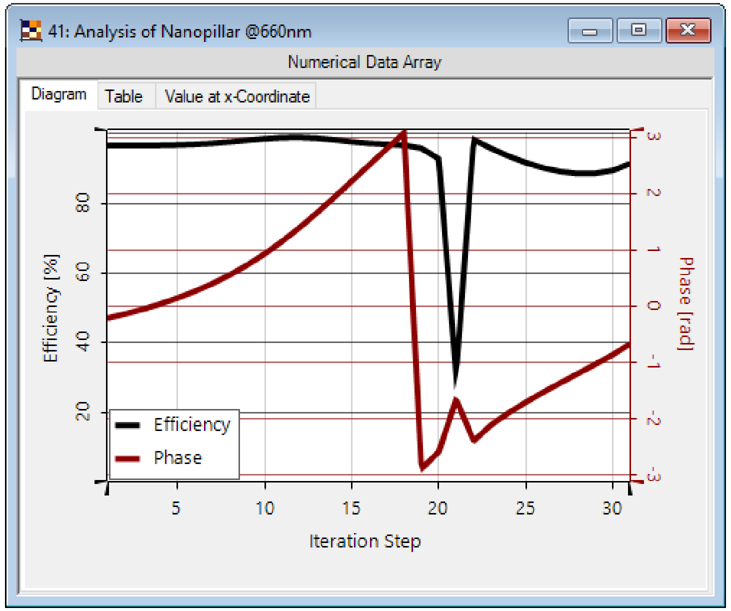
nanopillar #1



nanopillar #2



nanopillar #3

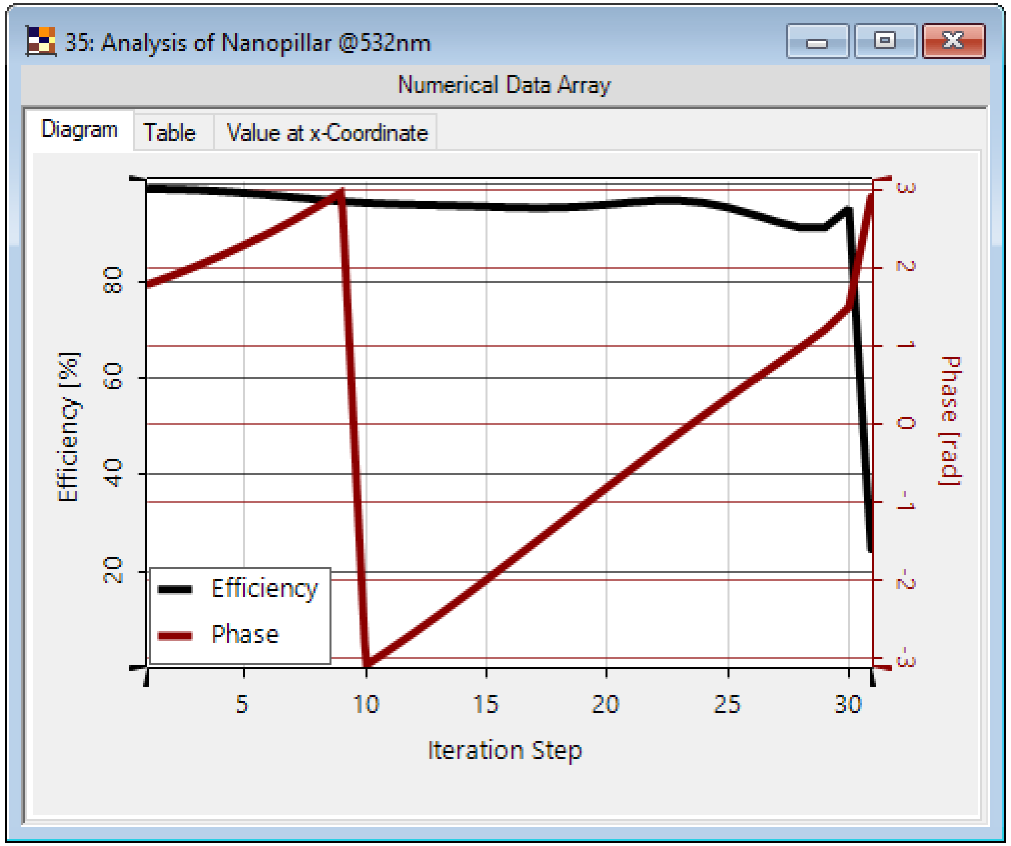


Nanopillars No.	**#1** (405 nm)	**#2** (532 nm)	**#3** (660 nm)
U	180 nm	250 nm	350 nm
H	400 nm	600 nm	600 nm
D (variable)	80-155 nm	100-220 nm	100-320 nm

Nanopillar Analysis vs. Pillar Diameter

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

nanopillar #2



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

Appendix: Refractive Index of TiO_2

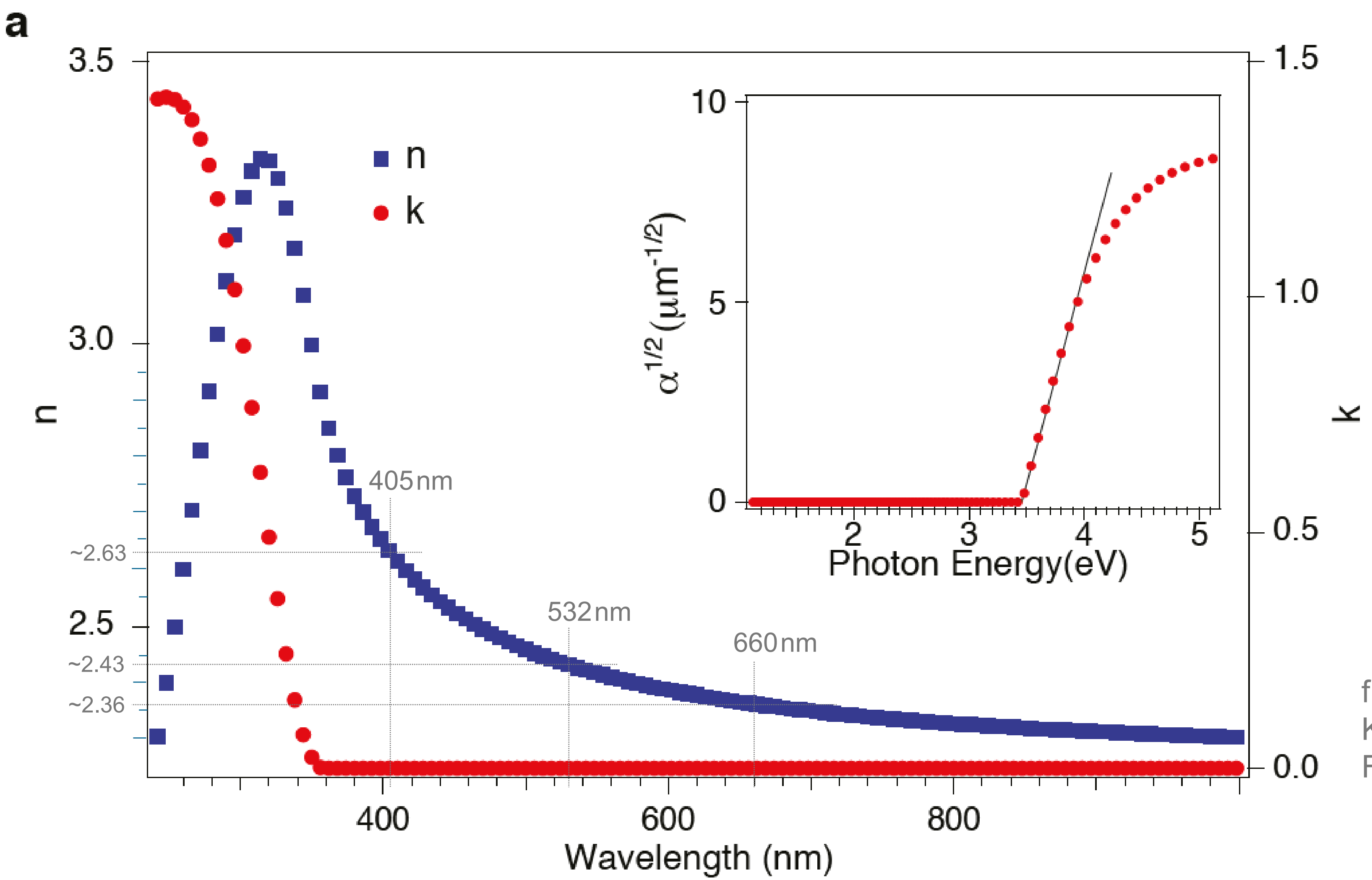
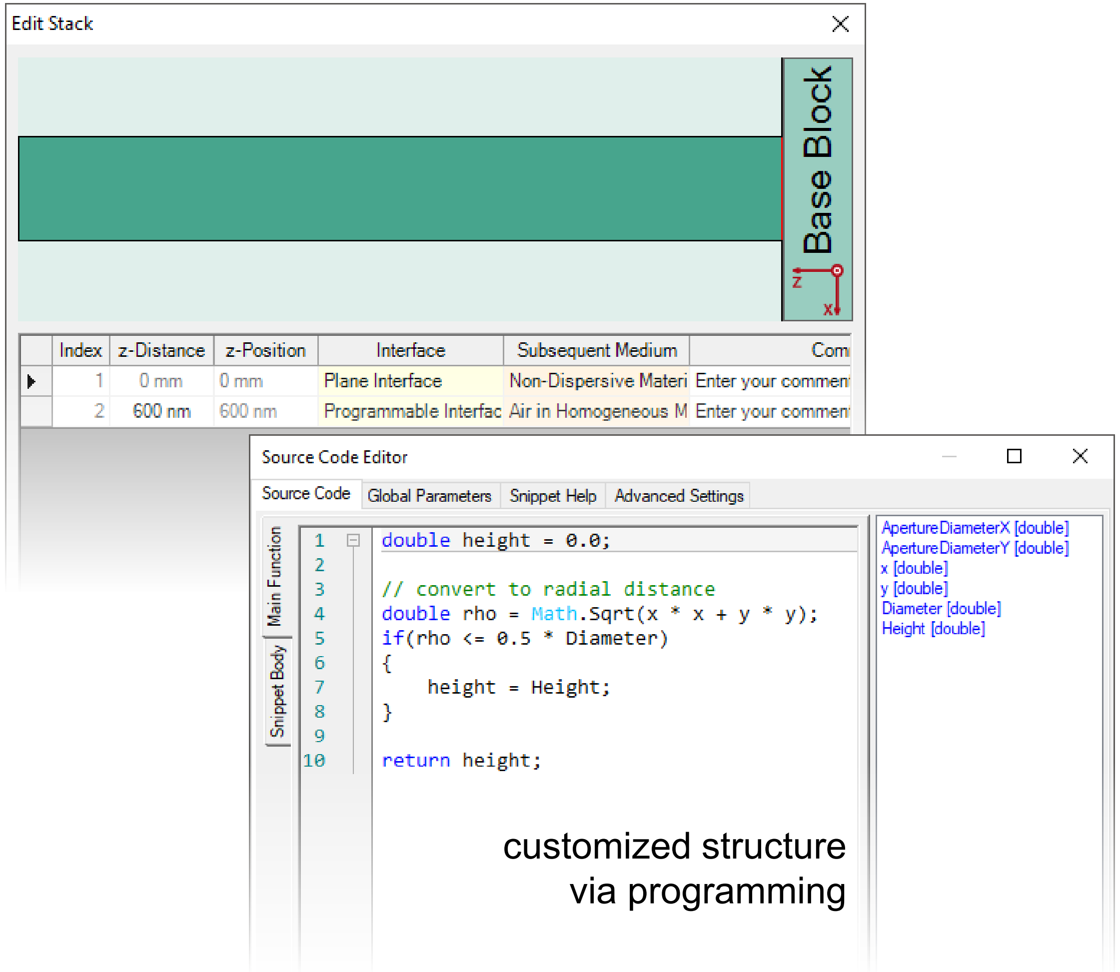


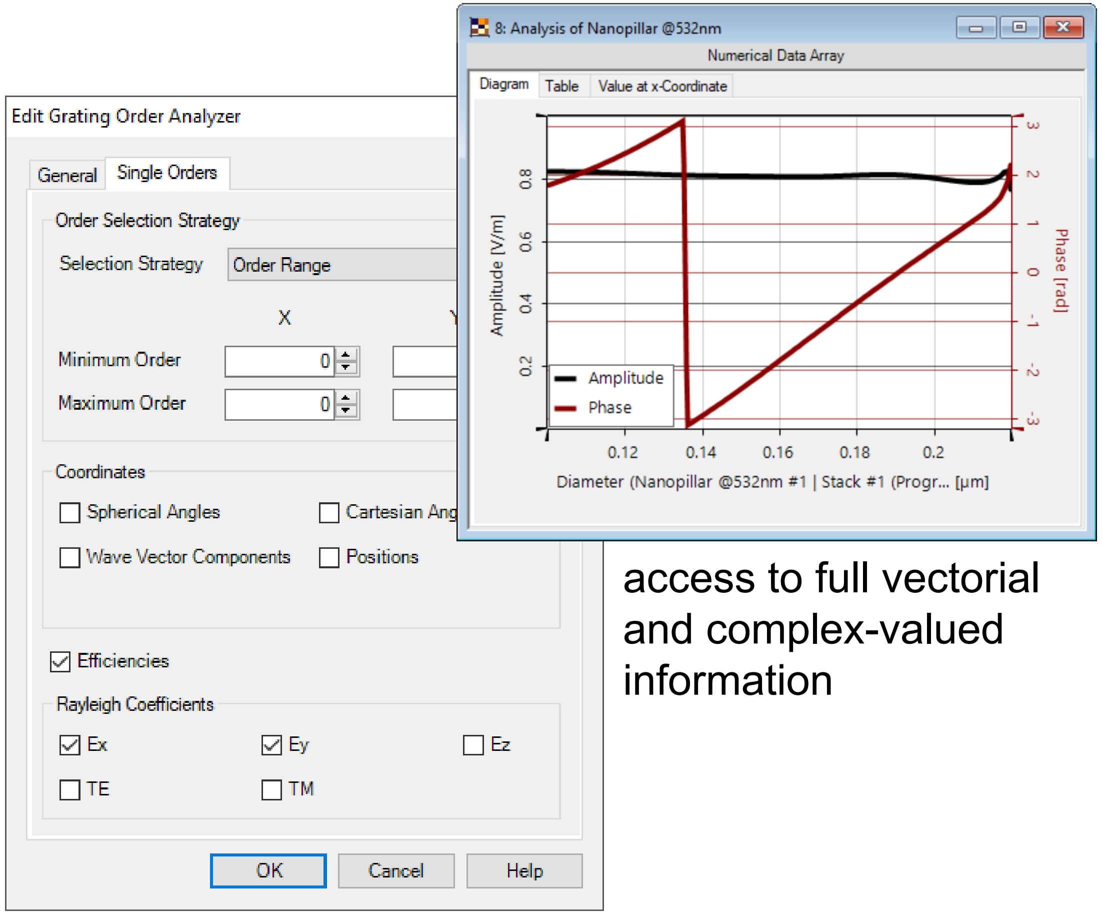
figure from R. C. Devlin, M. Khorasaninejad, W.-T. Chen, J. Oh, F. Capasso, arXiv:1603.02735 (2016)

Peek into VirtualLab Fusion

flexible pillar structure definition



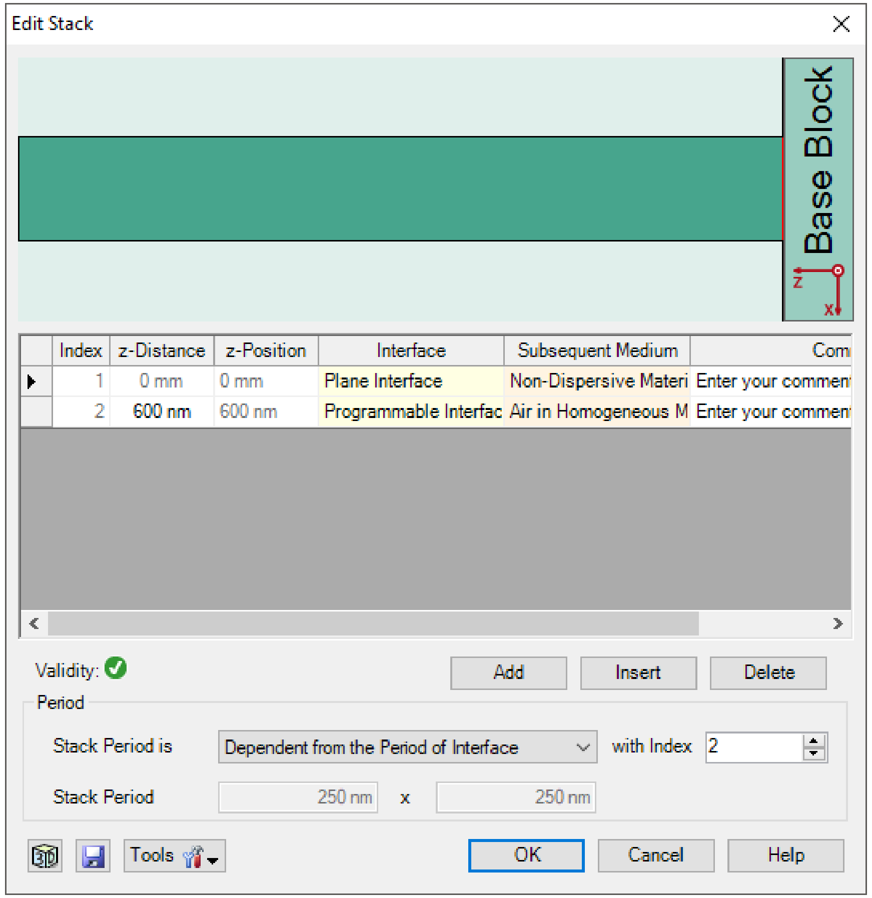
customized structure
via programming



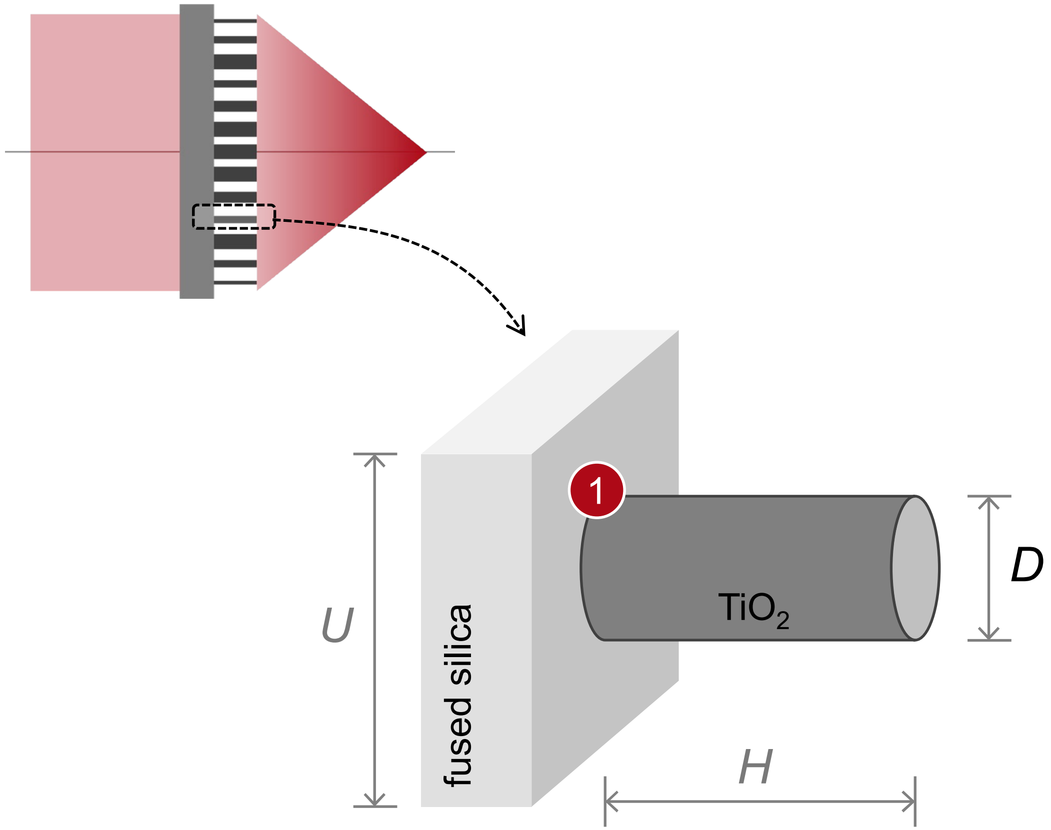
access to full vectorial and complex-valued information

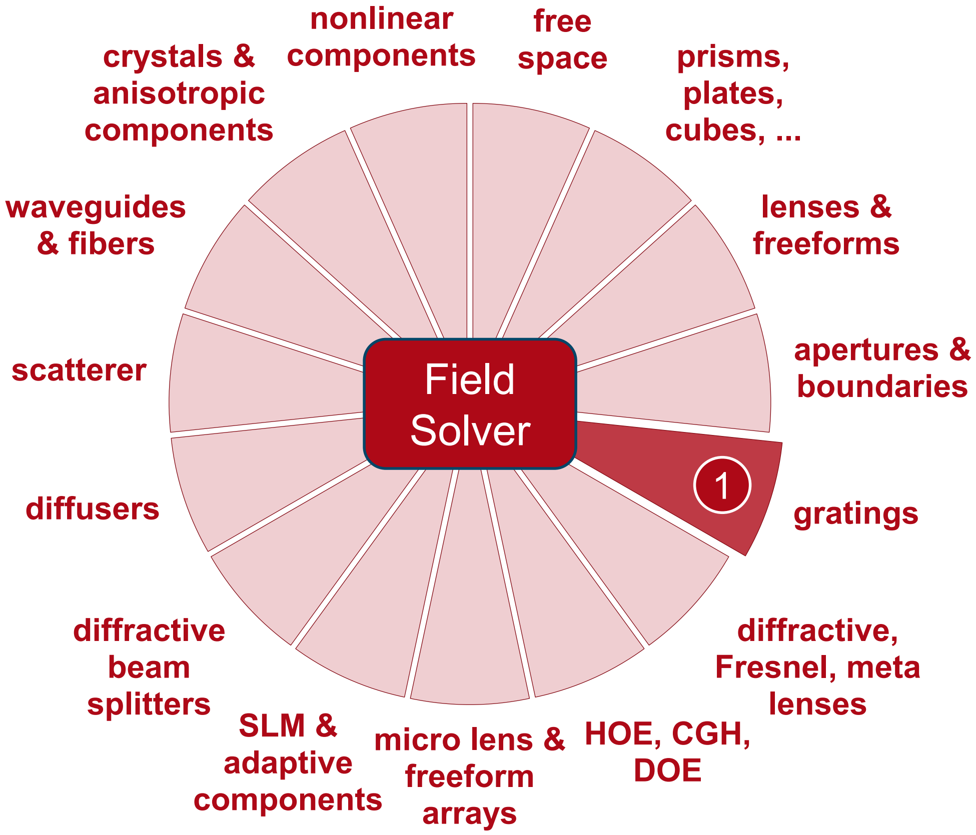
Workflow in VirtualLab Fusion

- Construct grating structure
  - Configuration of Grating Structures by Using Interfaces [Use Case]
  - Configuration of Grating Structures by Using Special Media [Use Case]
- Analyze grating diffraction efficiency
  - Grating Order Analyzer [Use Case]
- Check influence from specific parameters with Parameter Run
  - Usage of the Parameter Run Document [Use Case]



VirtualLab Fusion Technologies





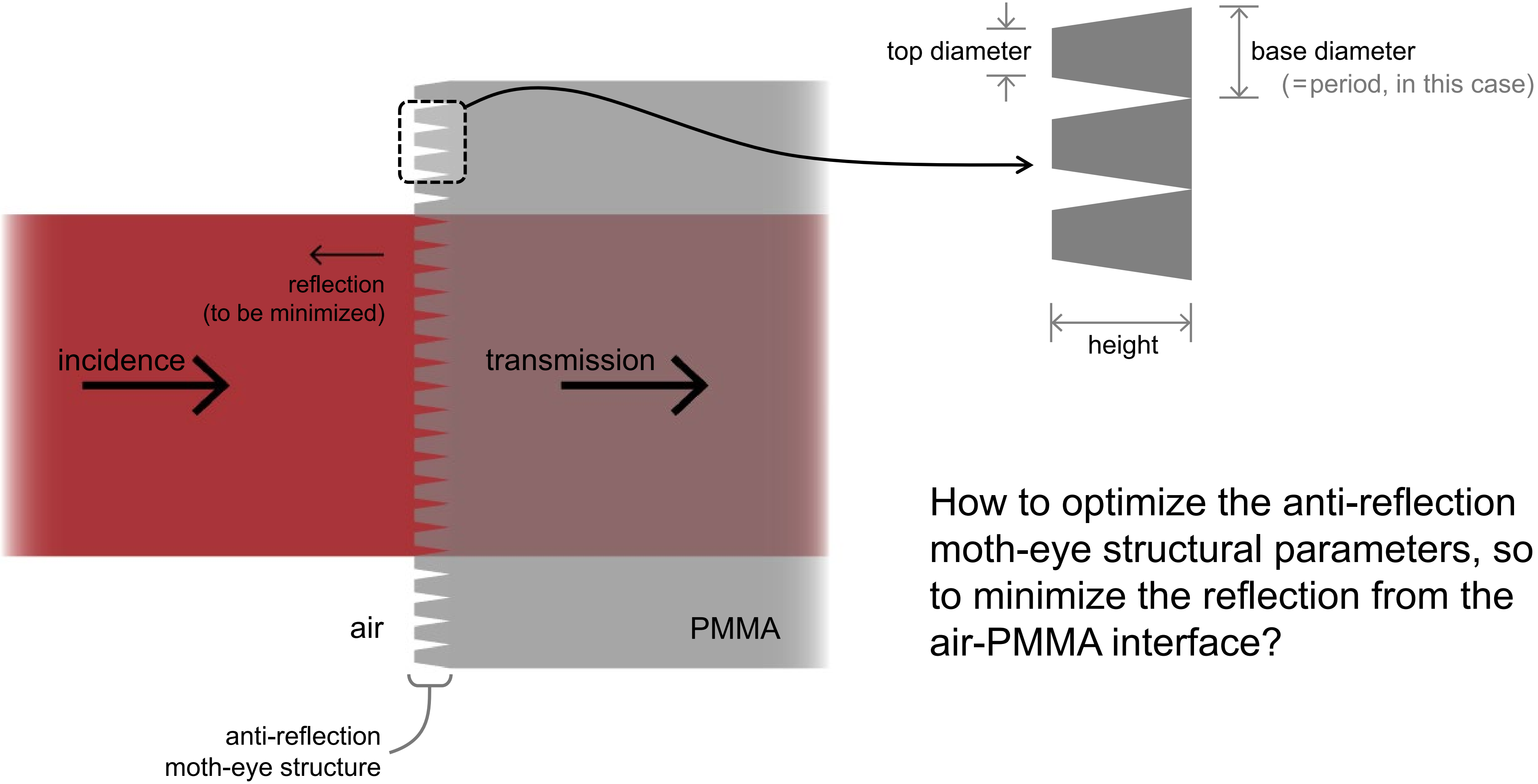
Document Information

title	Rigorous Analysis of Nanopillar Metasurface Building Block
document code	GRT.0012
version	1.0
toolbox(es)	Grating Toolbox
VL version used for simulations	7.4.0.49
category	Application Use Case
further reading	- Ultra-Sparse Dielectric Nano-Wire Grid Polarizers - Investigation of Polarization State of Diffraction Orders - Rigorous Analysis and Design of Anti-Reflective Moth-Eye Structures

Rigorous Analysis and Design of Anti-Reflective Moth-Eye Structures

AR Moth Eye_...

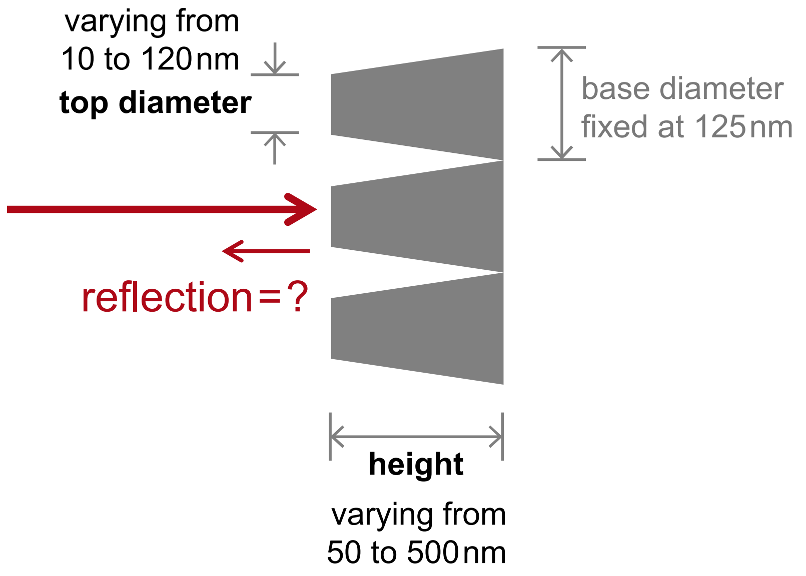
Design Task

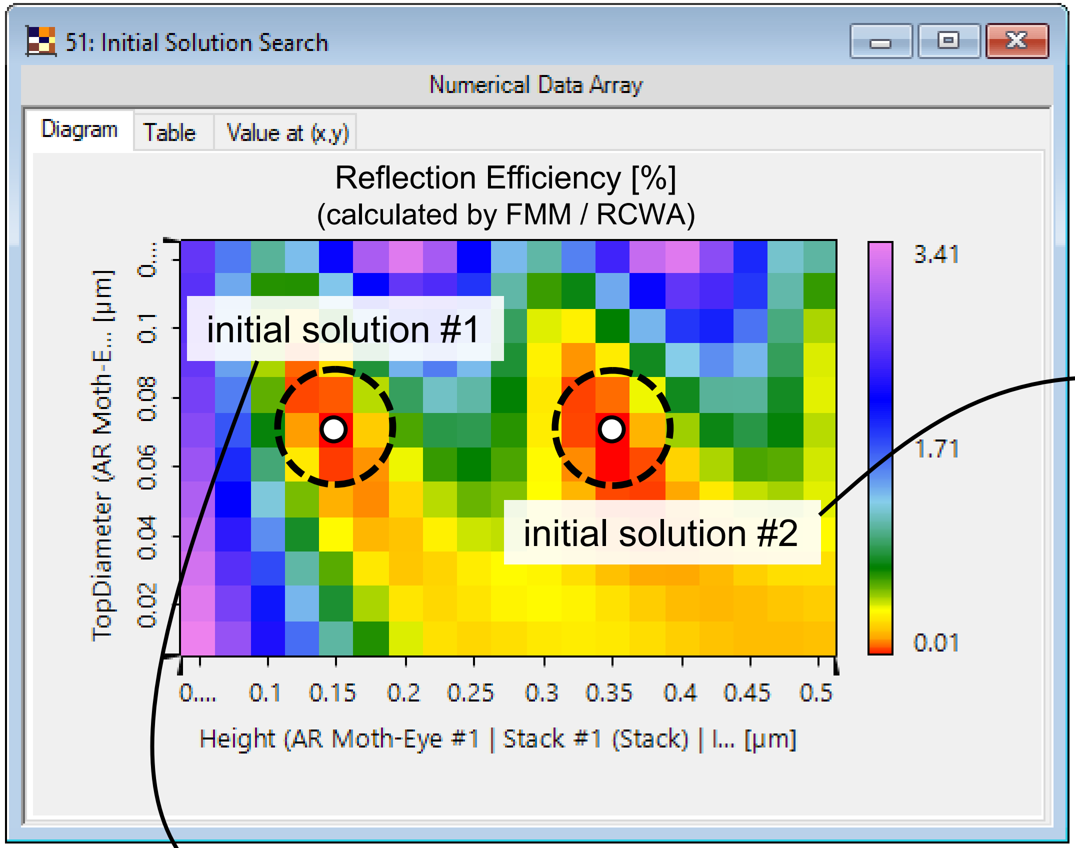


input plane wave
- wavelength 532 nm
- normal incidence

How to optimize the anti-reflection moth-eye structural parameters, so to minimize the reflection from the air-PMMA interface?

Scanning over Parameter Space for Initial Solutions

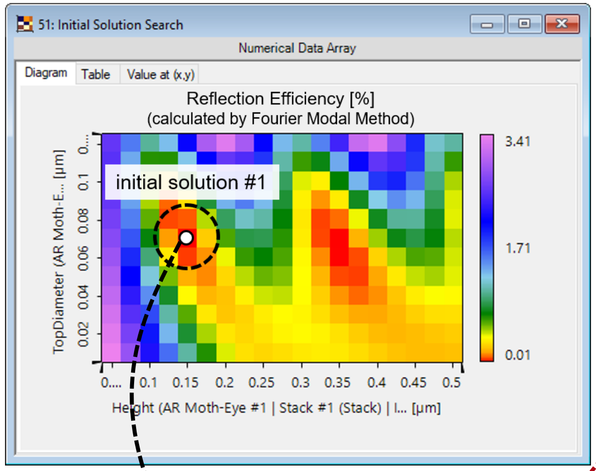


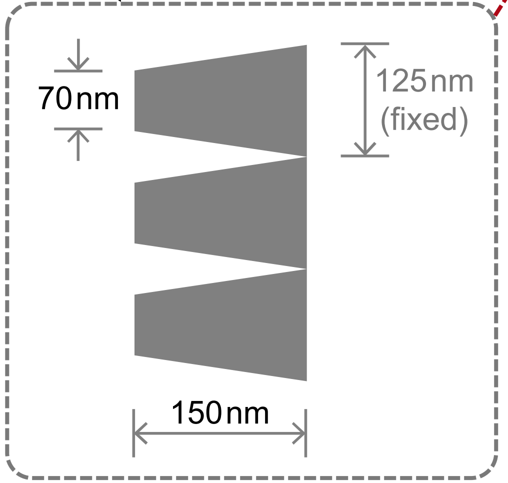


relatively higher aspect ratio and maybe not the first choice for fabrication

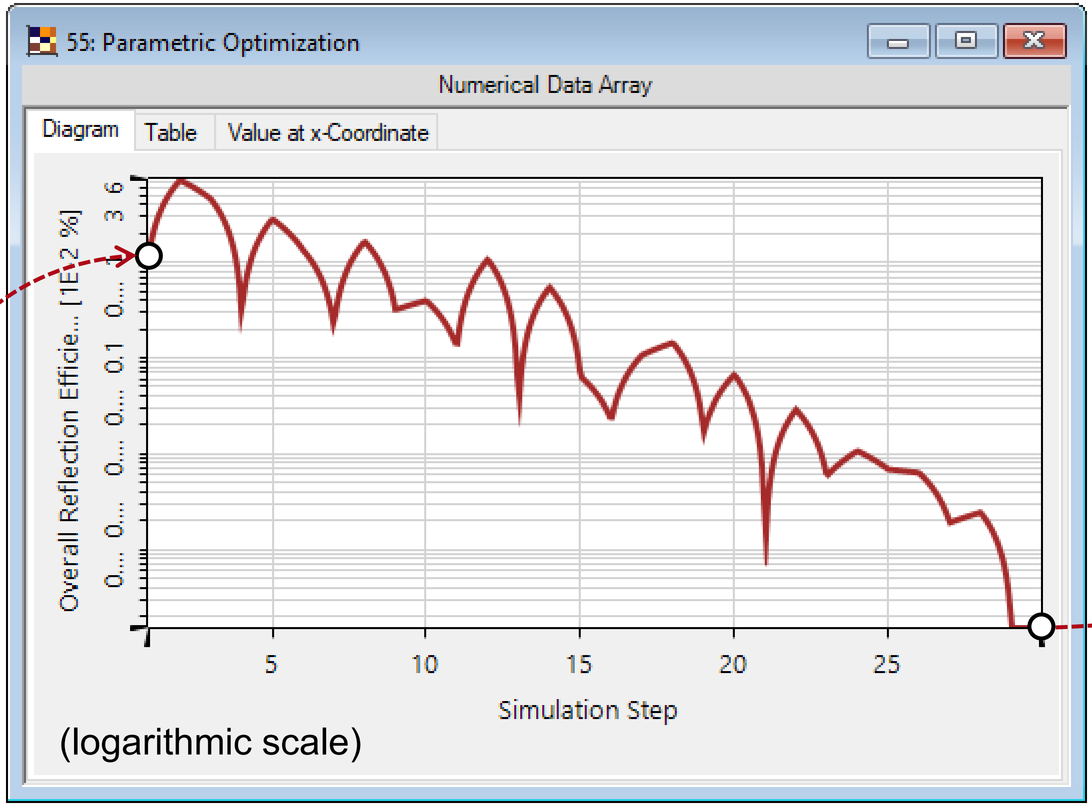
relatively smaller aspect ratio and therefore preferable for fabrication

Parametric Optimization for Initial Solution #1



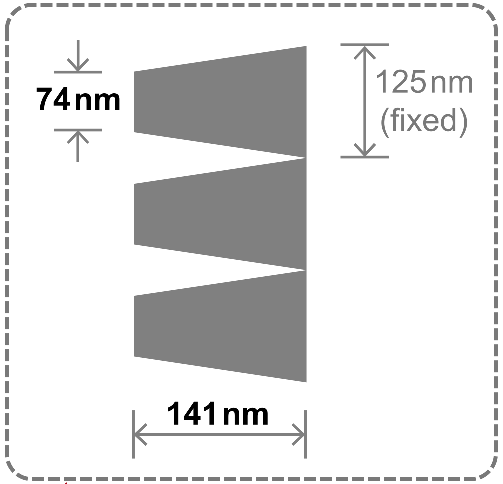


parametric optimization by downhill simplex method
(each iteration calculated by FMM / RCWA)

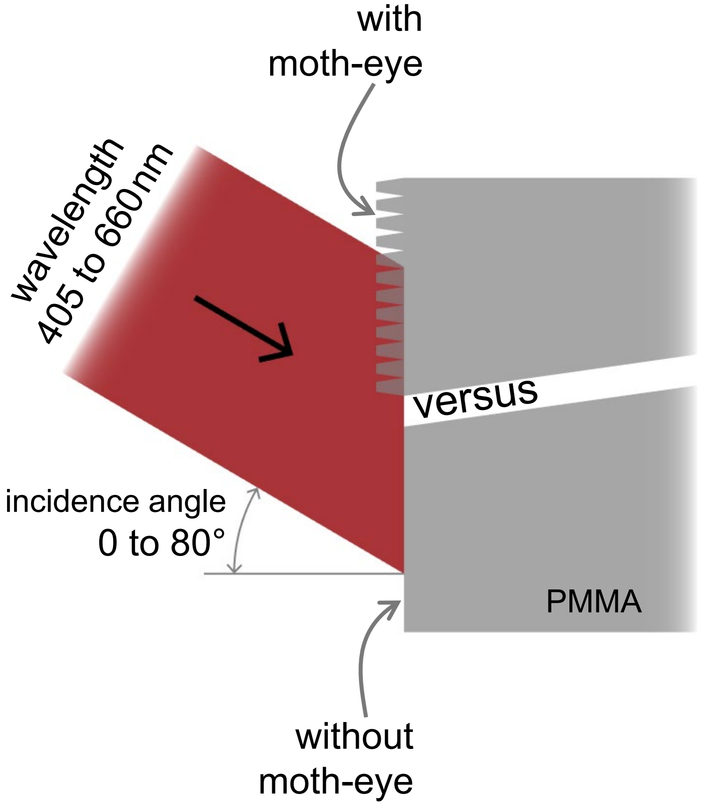


(logarithmic scale)

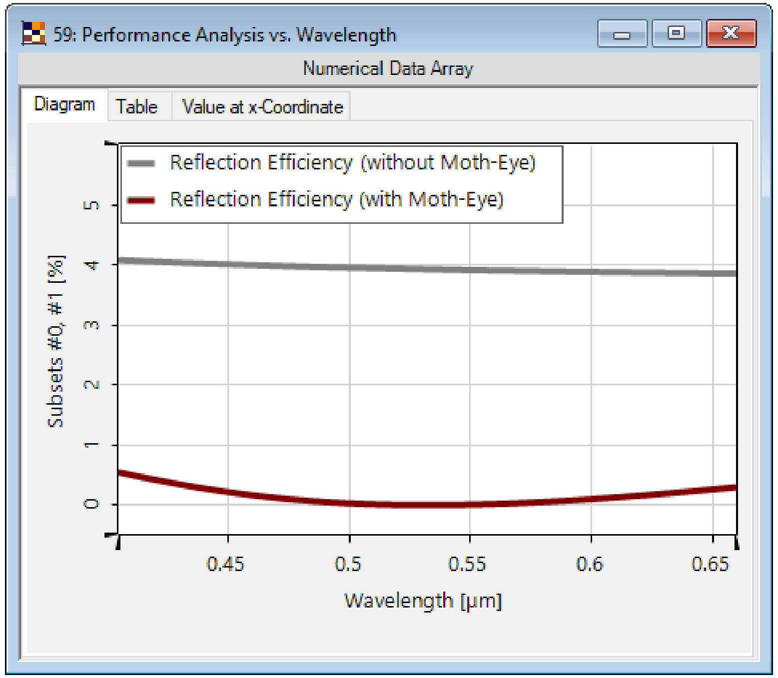
final design #1



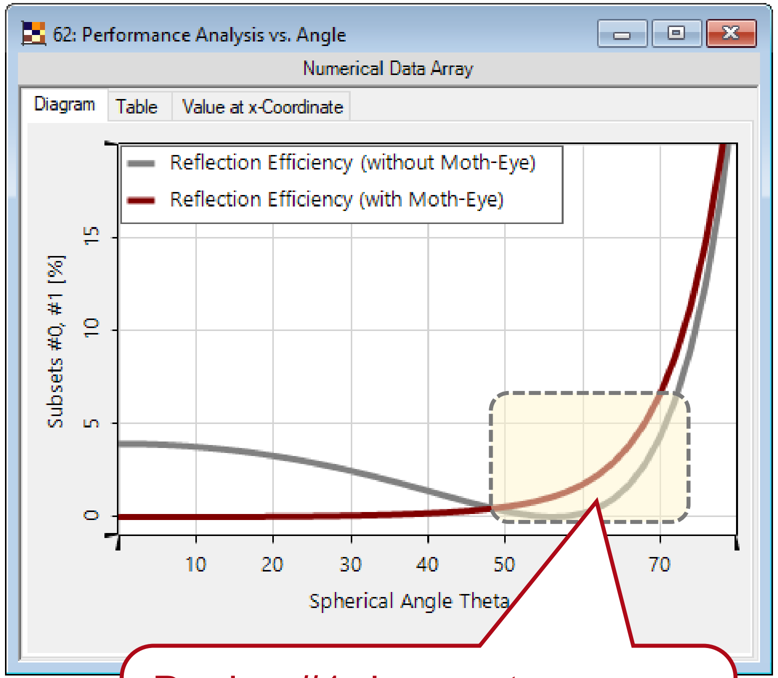
Performance Analysis of Final Design #1



reflection efficiency vs. wavelength
(at normal incidence)

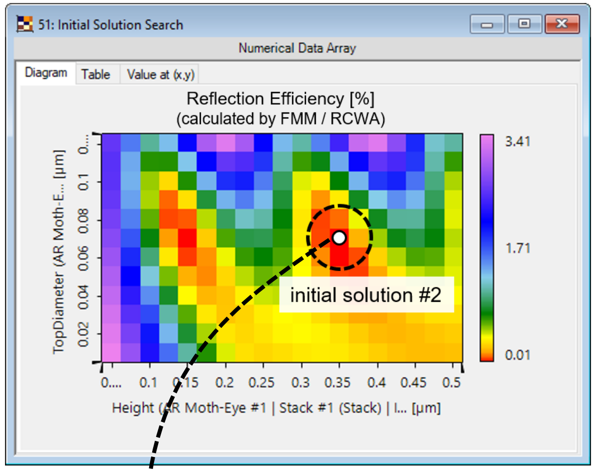


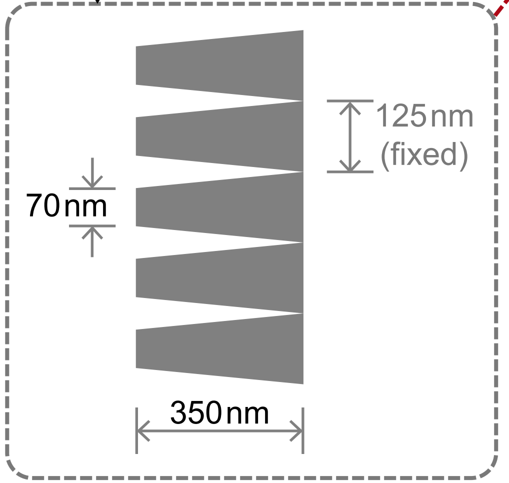
reflection efficiency vs. angle
(at 532 nm wavelength)



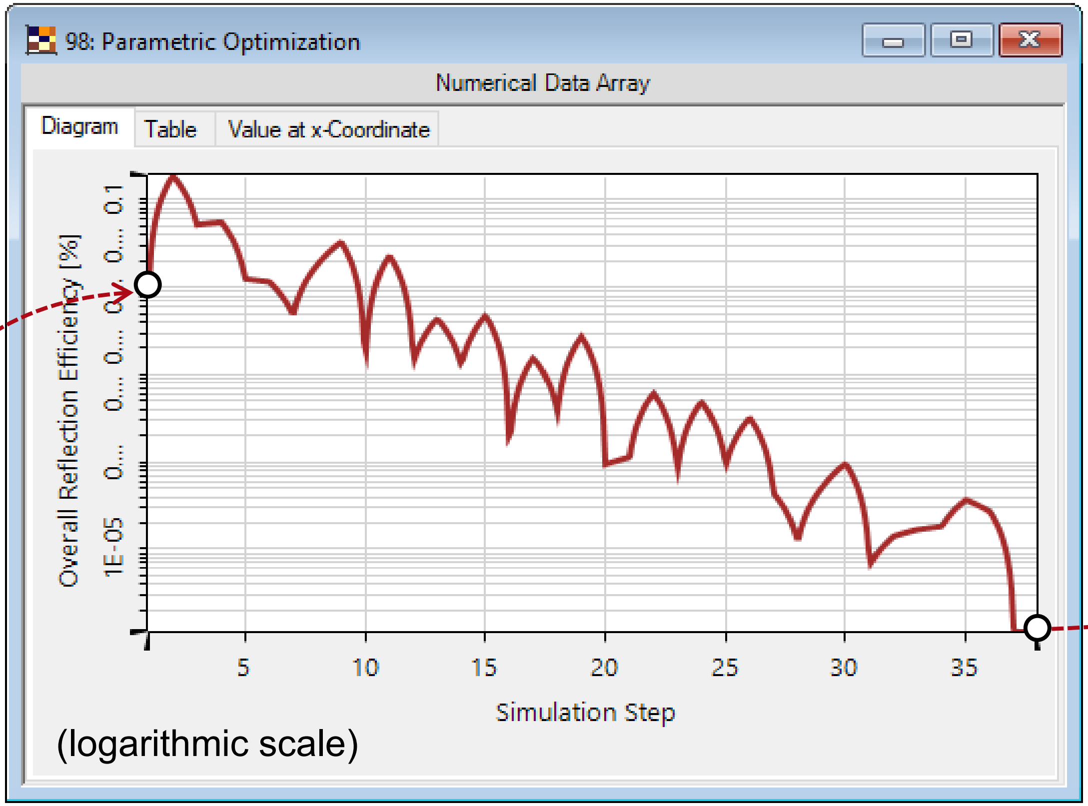
Design #1 does not suppress reflection effectively for incidence over 50°.

Parametric Optimization for Initial Solution #2

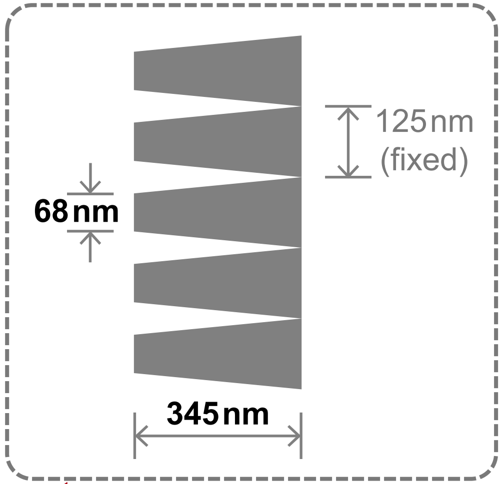




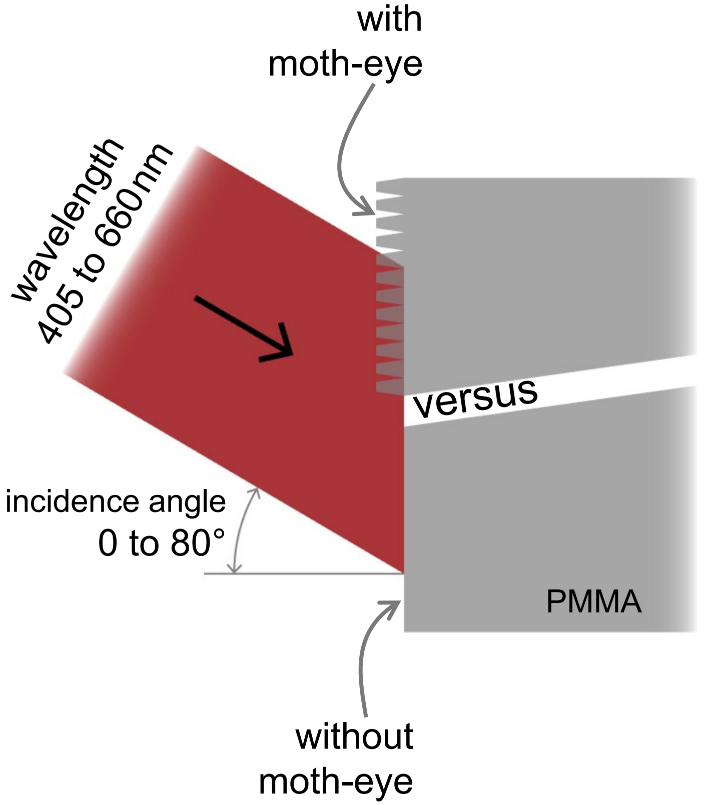
parametric optimization by downhill simplex method
(each iteration calculated by FMM / RCWA)



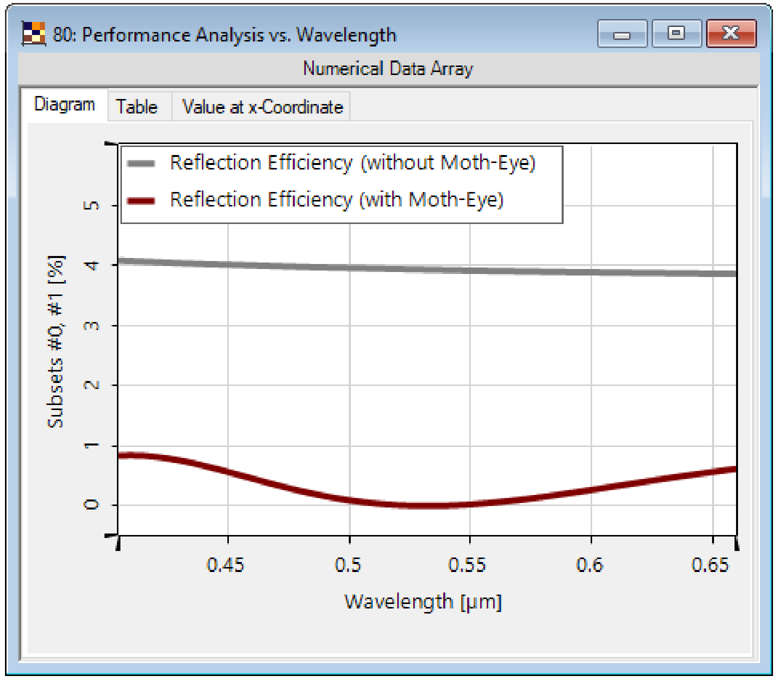
final design #2



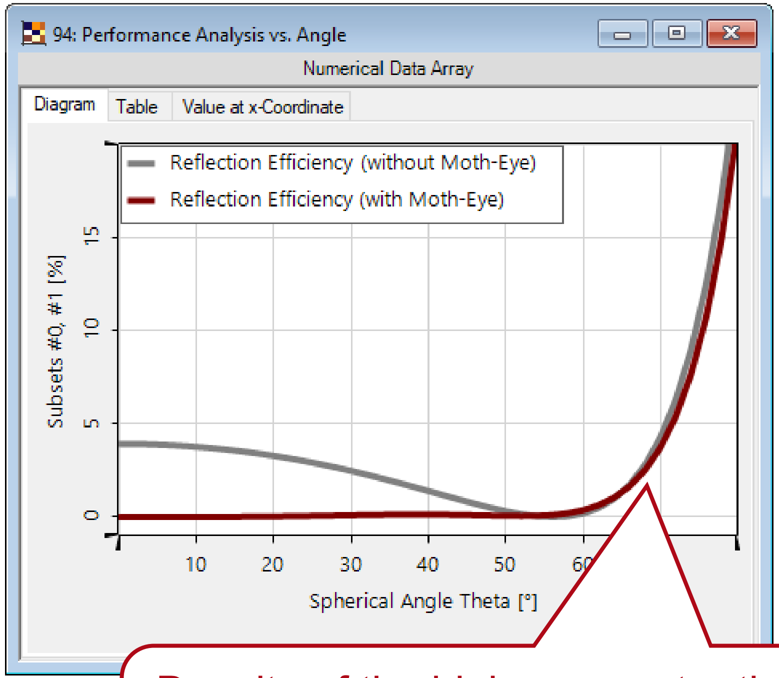
Performance Analysis of Final Design #2



reflection efficiency vs. wavelength
(at normal incidence)



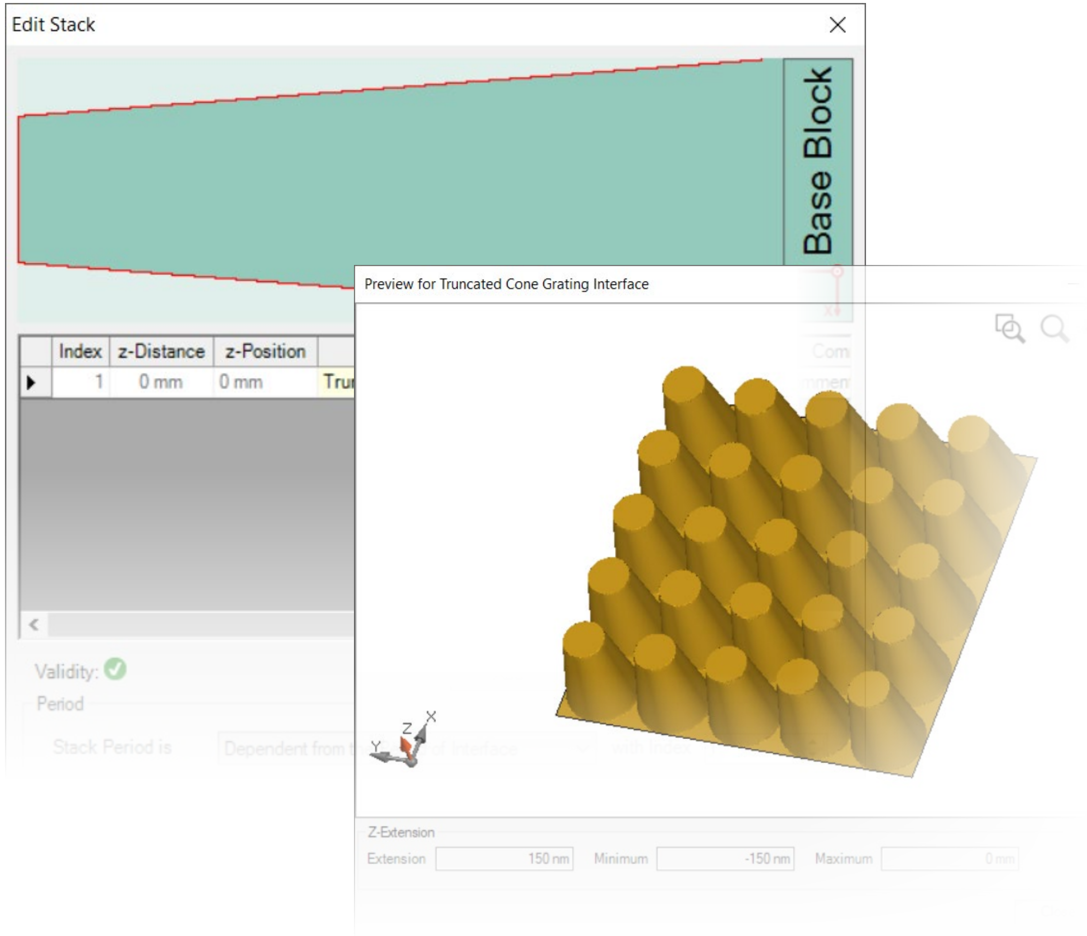
reflection efficiency vs. angle
(at 532 nm wavelength)



Despite of the higher aspect ratio, design #2 suppresses reflection better for higher incidence angles.

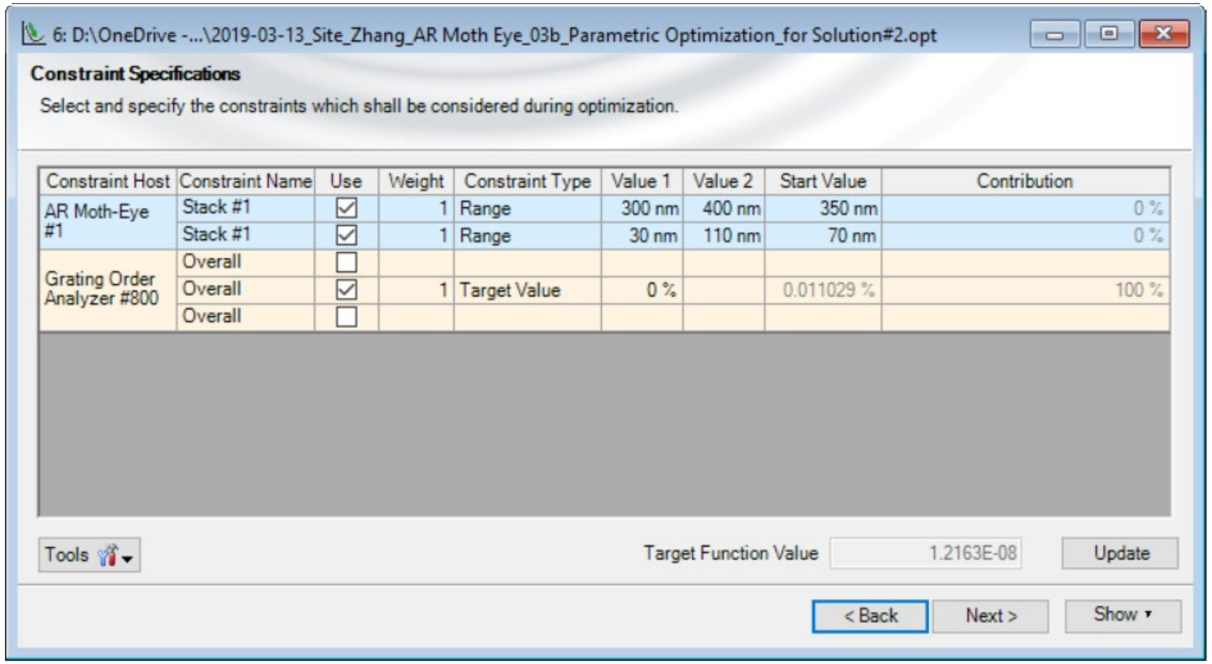
Peek into VirtualLab Fusion

grating structure editor with preview



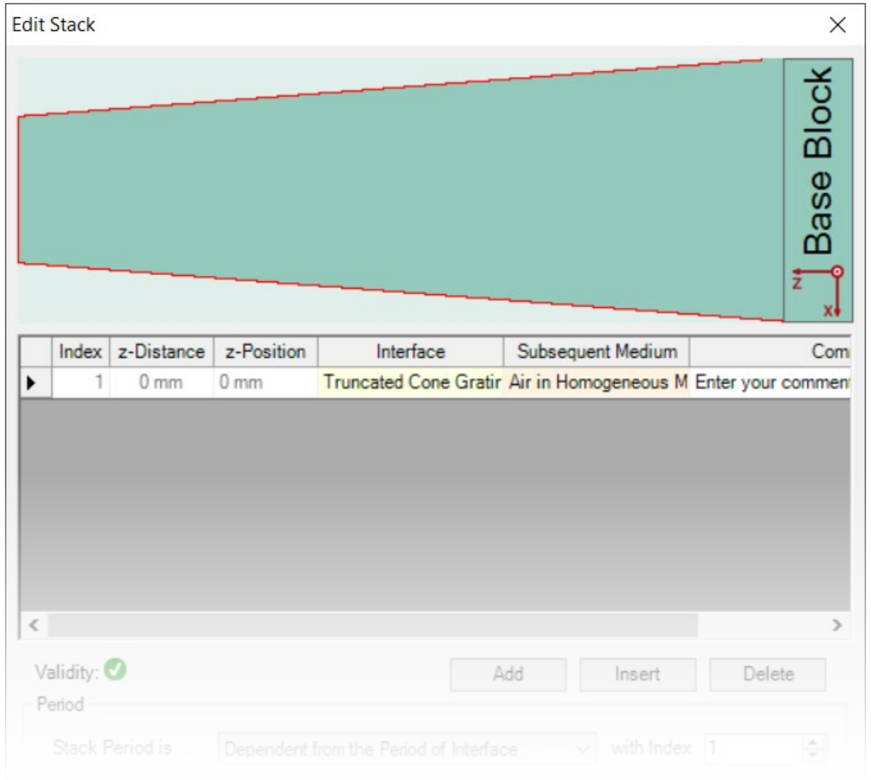
parametric optimization tools

with flexible variable and merit function definition

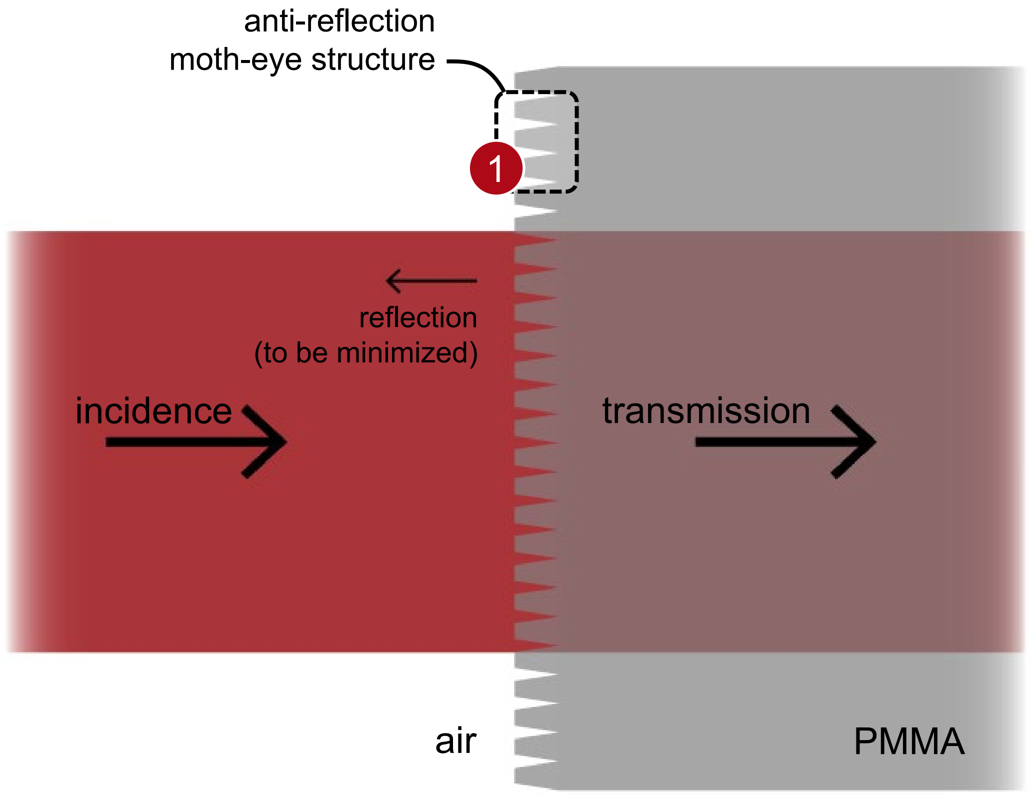


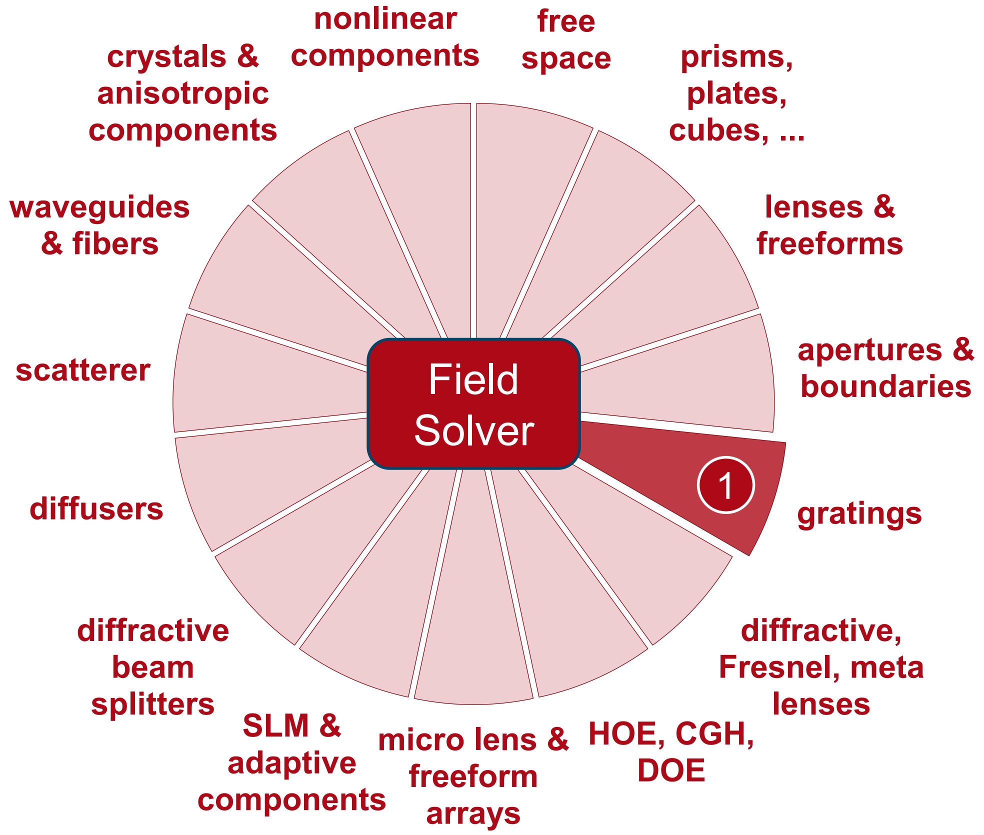
Workflow in VirtualLab Fusion

- Construct grating structure
  - Configuration of Grating Structures by Using Interfaces [Use Case]
  - Configuration of Grating Structures by Using Special Media [Use Case]
- Analyze grating diffraction efficiency
  - Grating Order Analyzer [Use Case]
- Search for initial solutions with Parameter Run
  - Usage of the Parameter Run Document [Use Case]
- Find final design with Parametric Optimization



VirtualLab Fusion Technologies





Document Information

title	Rigorous Analysis and Design of Anti-Reflective Moth-Eye Structures
document code	GRT.0011
version	1.0
toolbox(es)	Grating Toolbox
VL version used for simulations	7.4.0.49
category	Application Use Case
further reading	- Parametric Optimization and Tolerance Analysis of Slanted Gratings - Optimization of Lightguide Coupling Grating for Single Incidence Direction

Coming soon in VirtualLab Fusion Autumn Release!

Blazed Meta-Grating Composed of Square Pillars

P. Lalanne, *et al*., "Blazed binary subwavelength gratings with efficiencies larger than those of conventional échelette gratings," Opt. Lett. 23, 1081-1083 (1998)

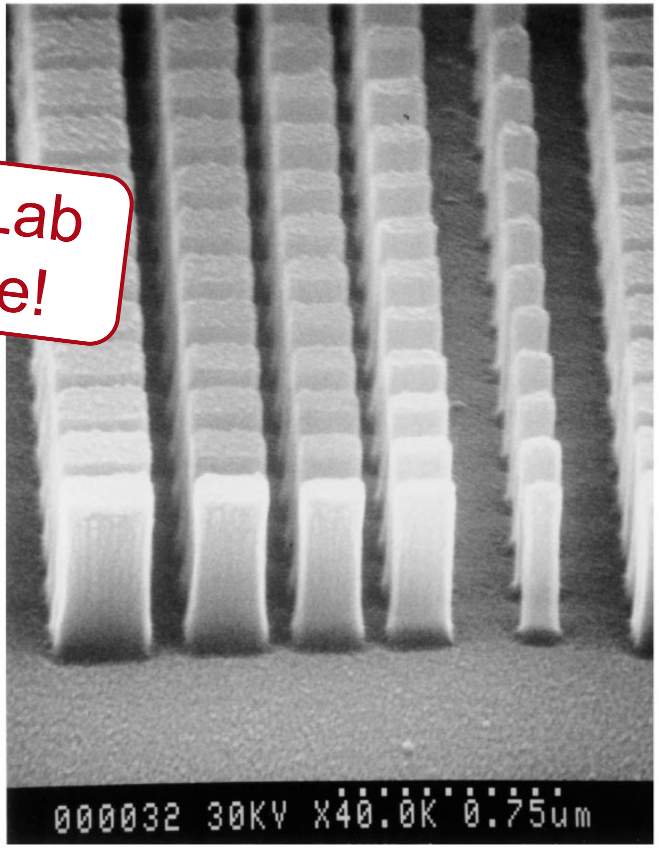
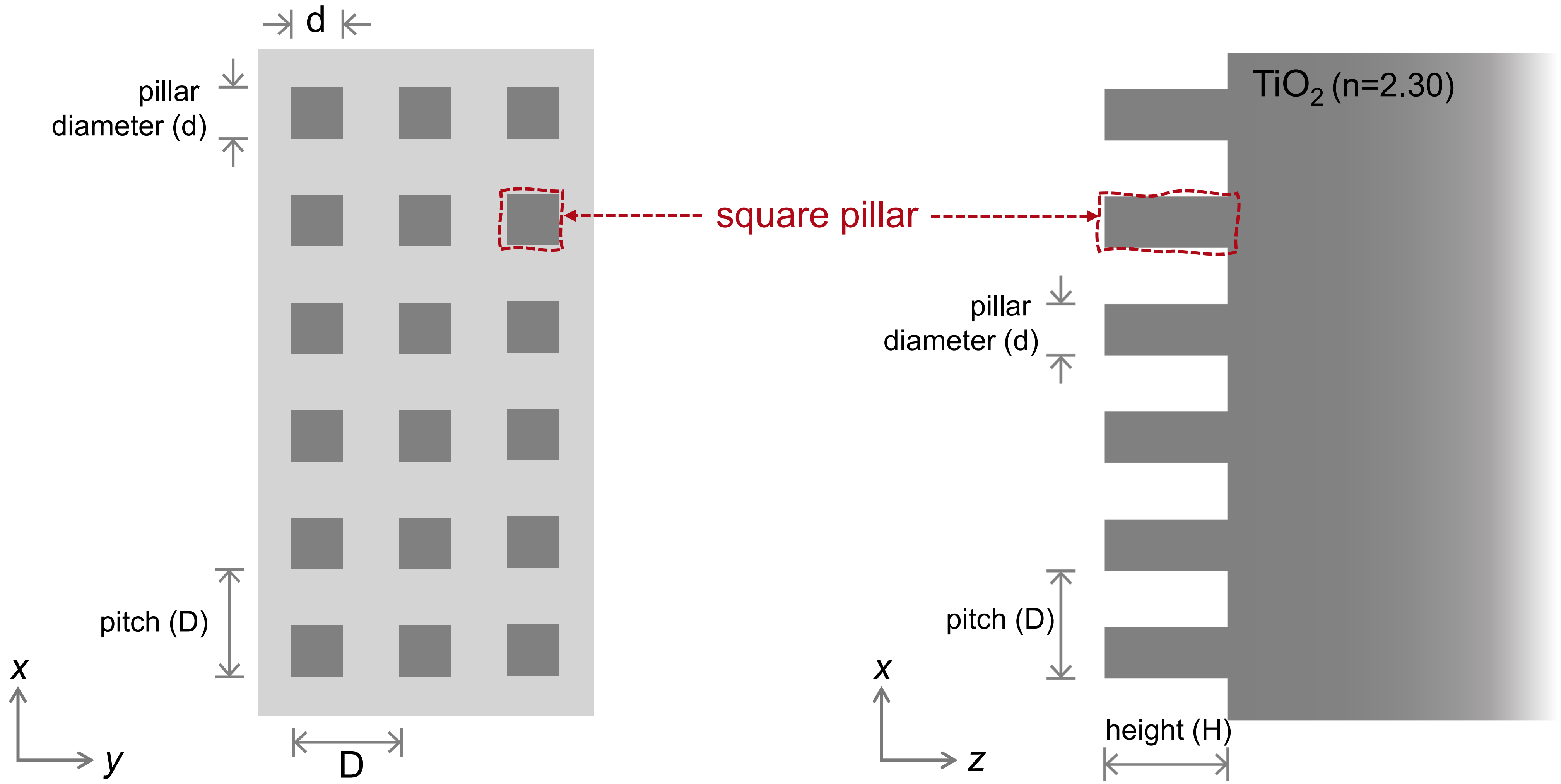
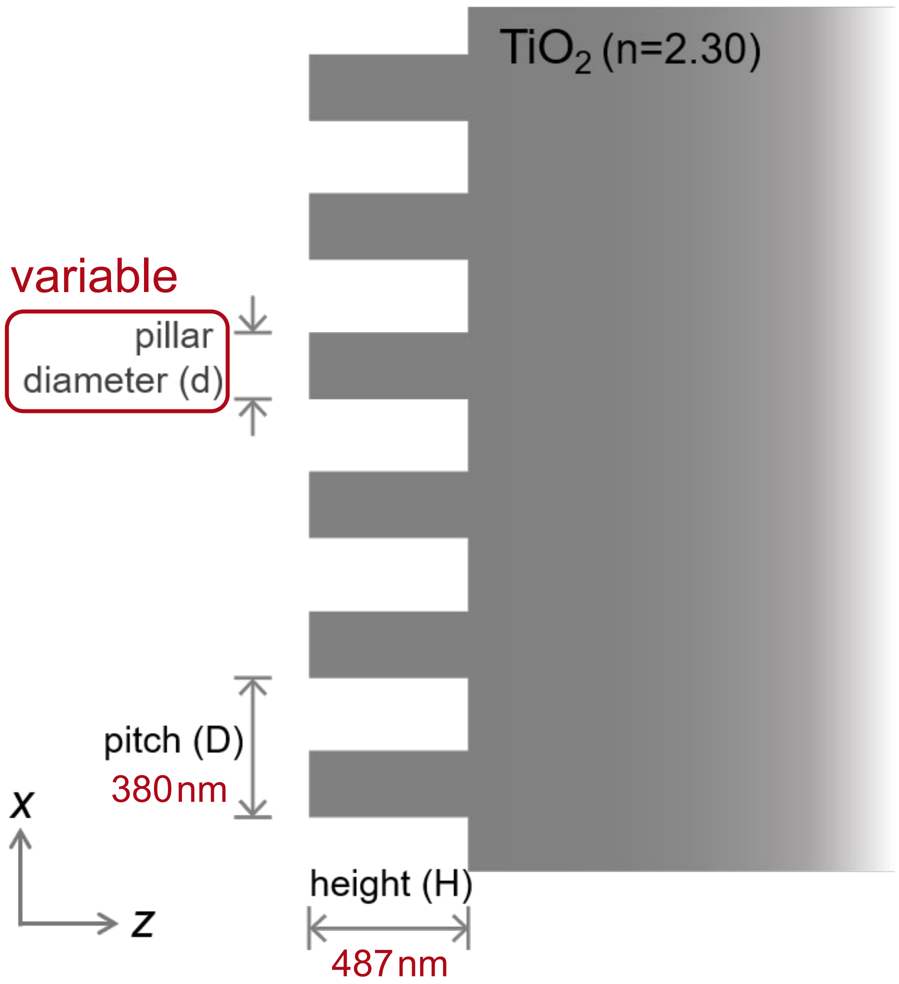


Fig. 2. Scanning-electron micrograph of the blazed binary subwavelength grating. The horizontal period (along the x axis) is 1.9 μm, and the period in the perpendicular direction (y axis) is equal to the sampling period (380 nm). The maximum pillar aspect ratio is 4.6.

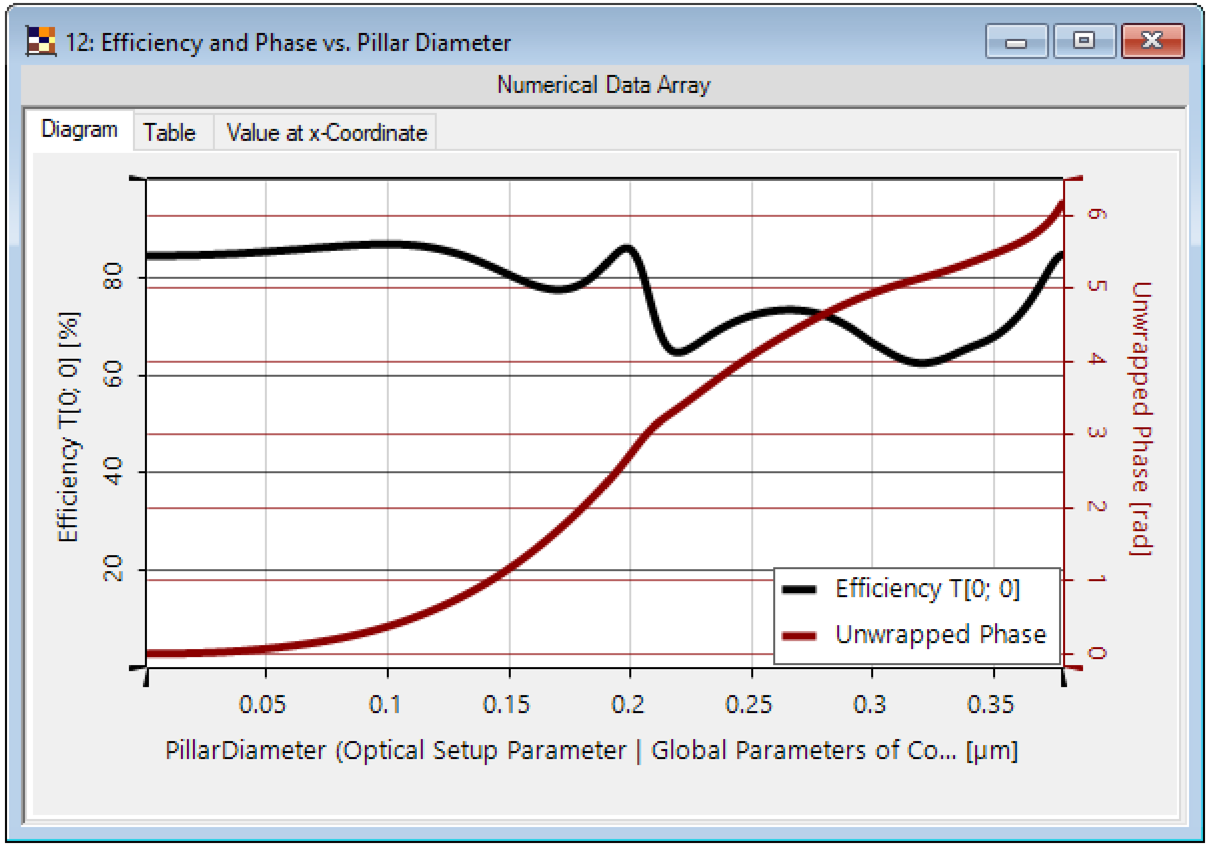
Building Block / Unit Cell Analysis (Index Matched)



Building Block / Unit Cell Analysis (Index Matched)



transmission amplitude/phase vs. pillar diameter (@633nm)



Building Block / Unit Cell Analysis (Index Matched)

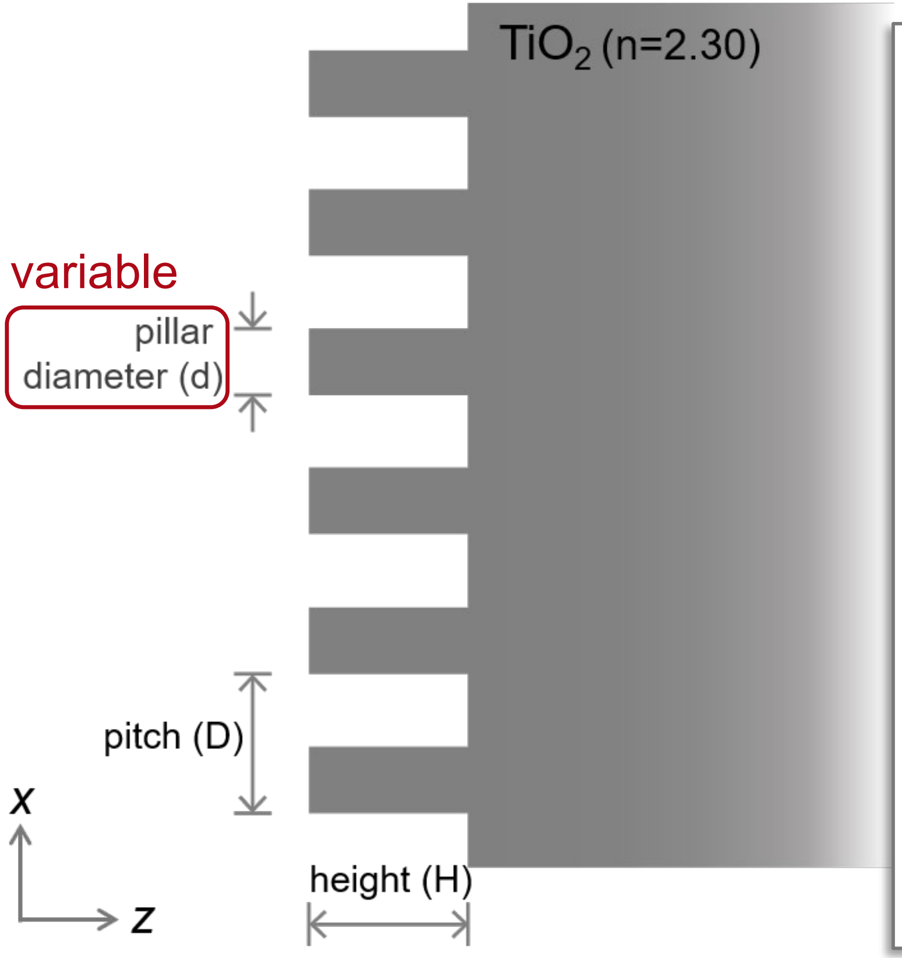


Figure 1 from P. Lalanne, *et al.*, Opt. Lett. 23, 1081-1083 (1998)

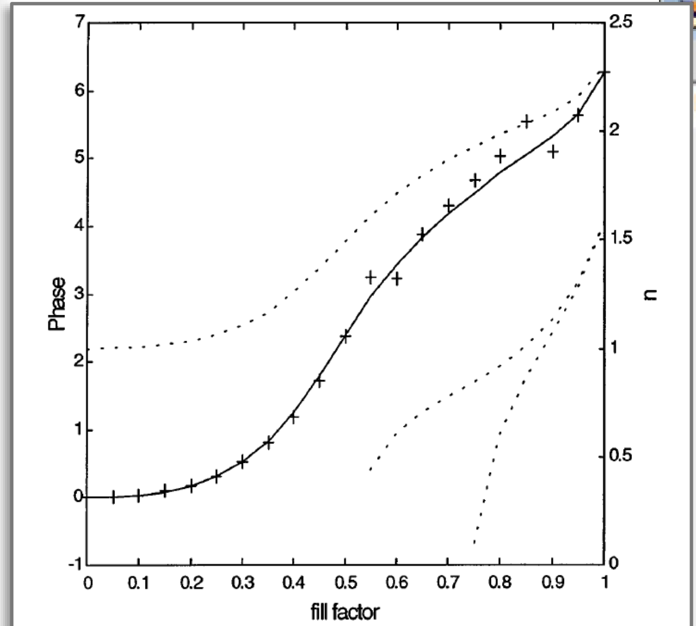
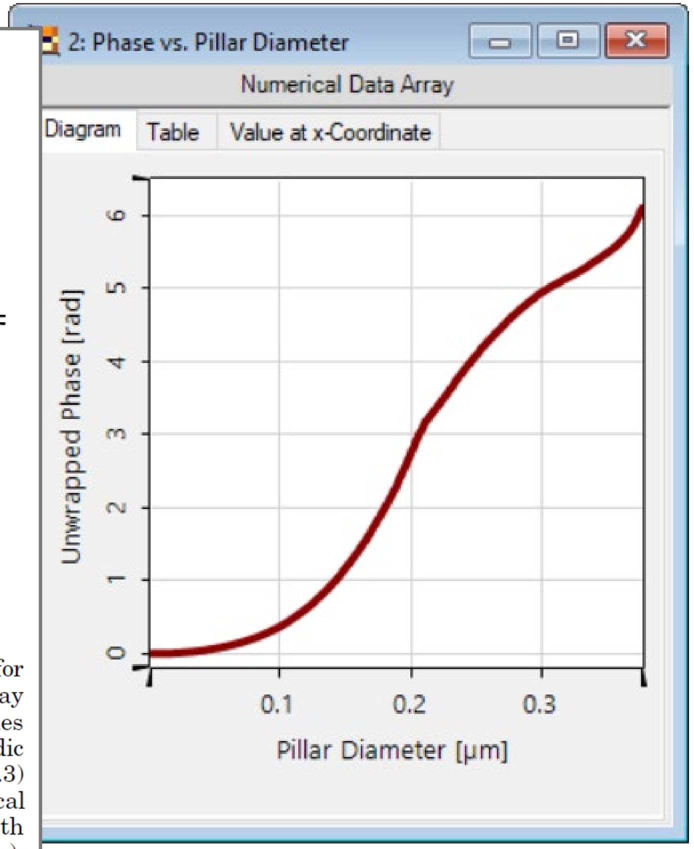
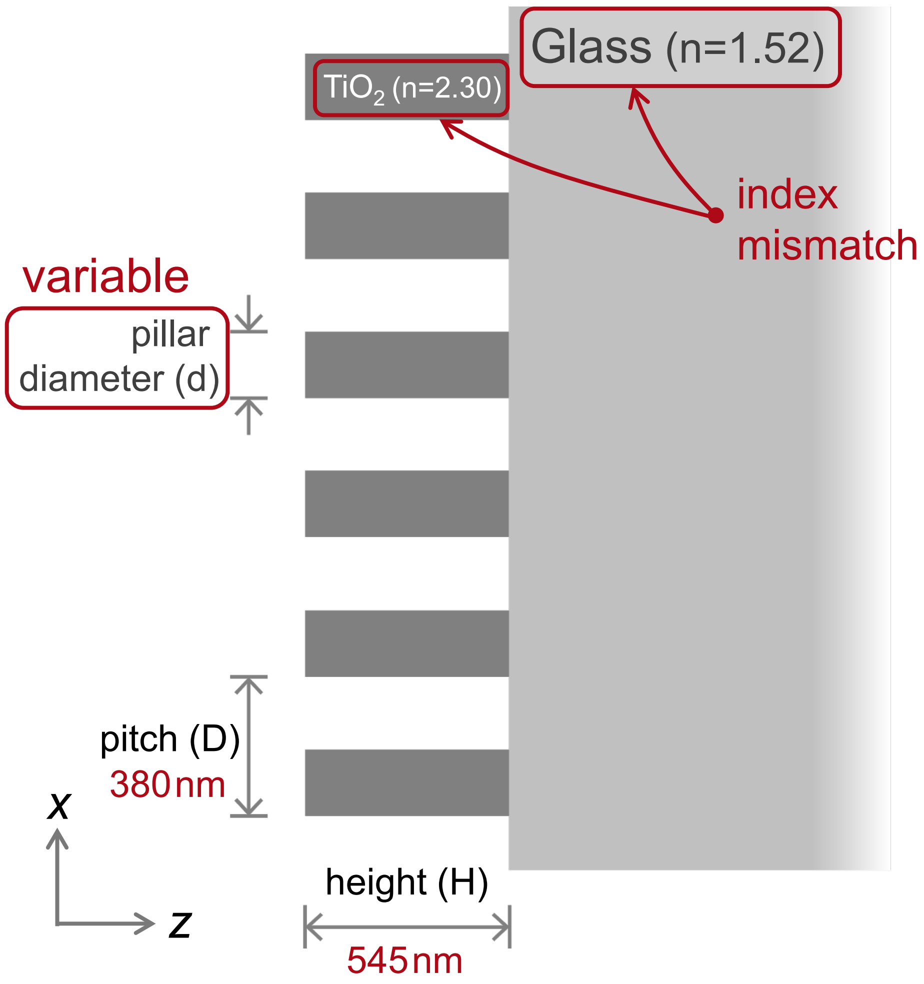


Fig. 1. Crosses, phases of the transmitted zeroth order for a 487-nm-thick grating composed of a 380-nm-period array of square pillars etched in TiO_2. Dotted curves, n values of all the propagating modes supported by the biperiodic structure. The uppermost curve (n varies from 1 to 2.3) corresponds to the grating effective index. Numerical results were obtained by the modal method of Ref. 10 with square truncation (17 orders are retained along each axis). Solid curve, phases of a plane wave transmitted through a 487-nm-thick homogeneous dielectric film whose refractive index is equal to the n value of the fundamental mode.

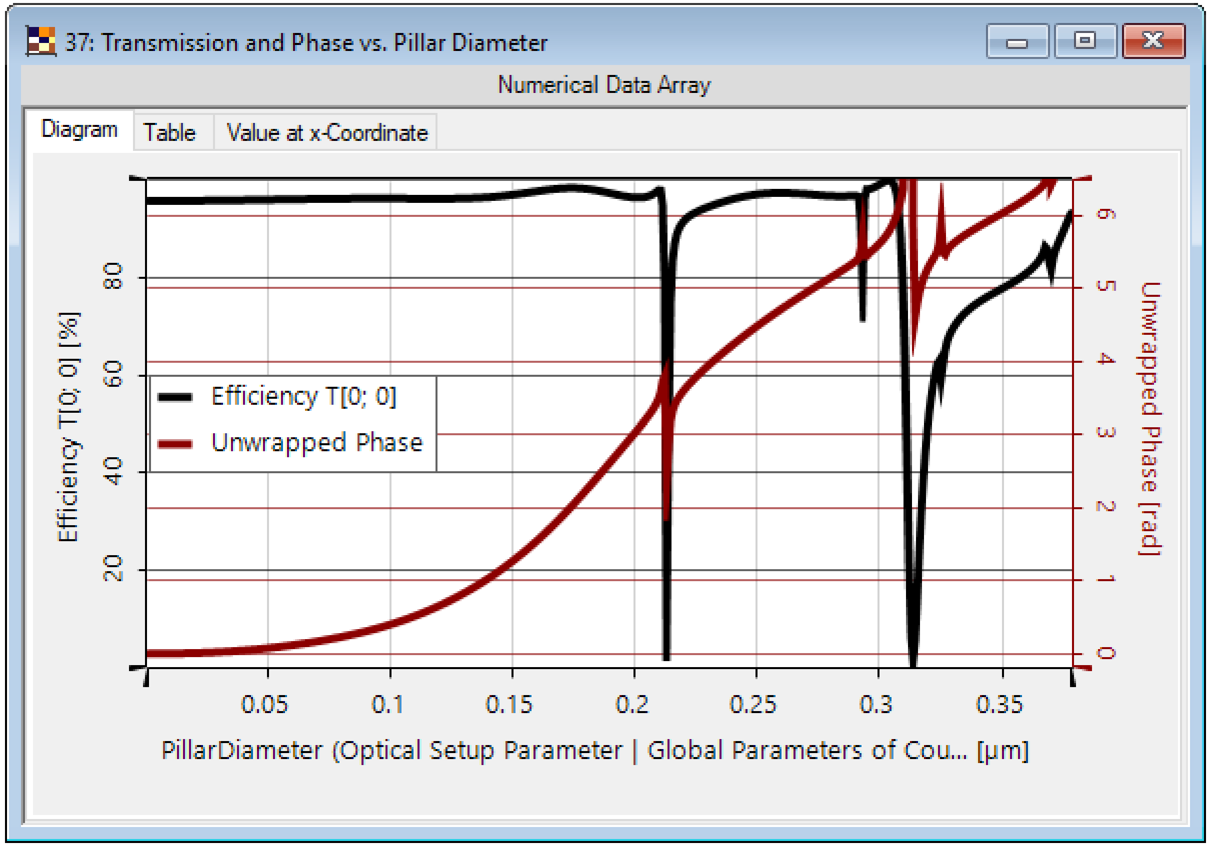


VirtualLab Fusion simulation

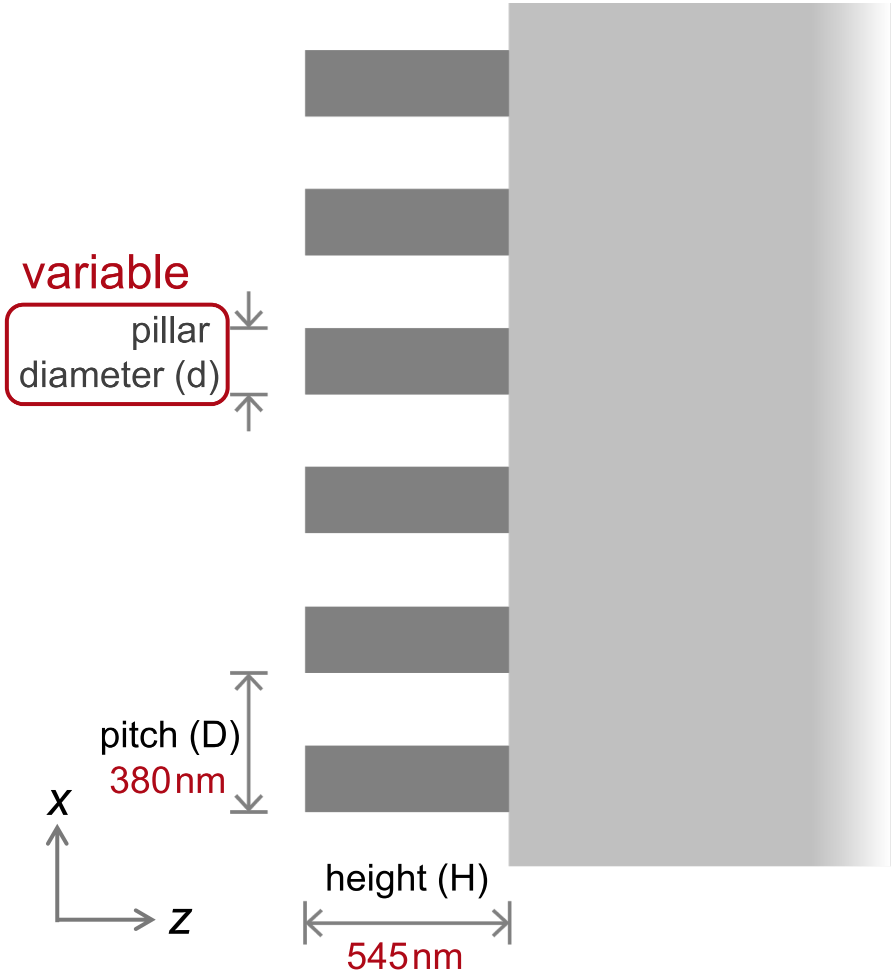
Building Block / Unit Cell Analysis (Glass Substrate)

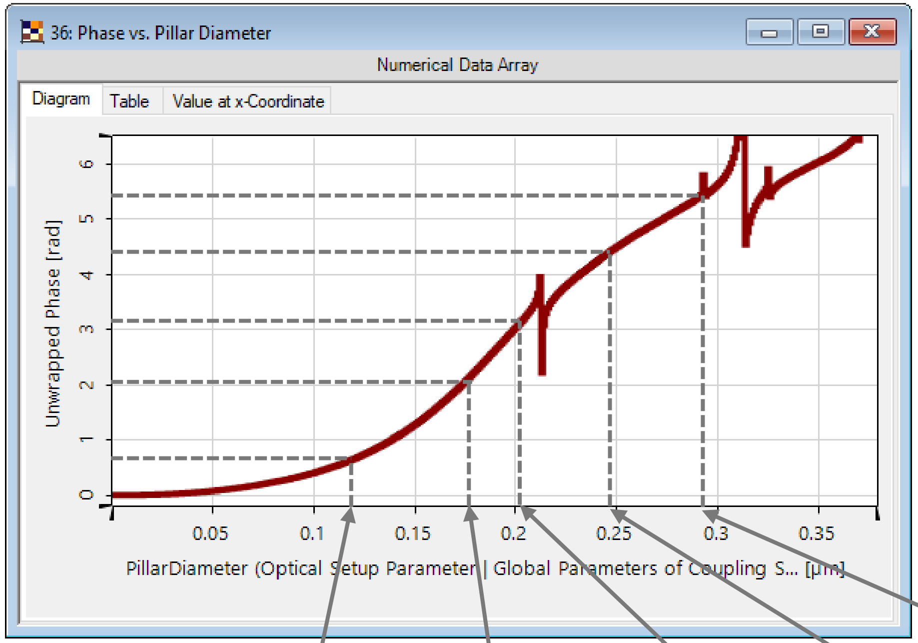


transmission amplitude/phase vs. pillar diameter (@633nm)



Selection of Unit Cells ➔ Linear Phase

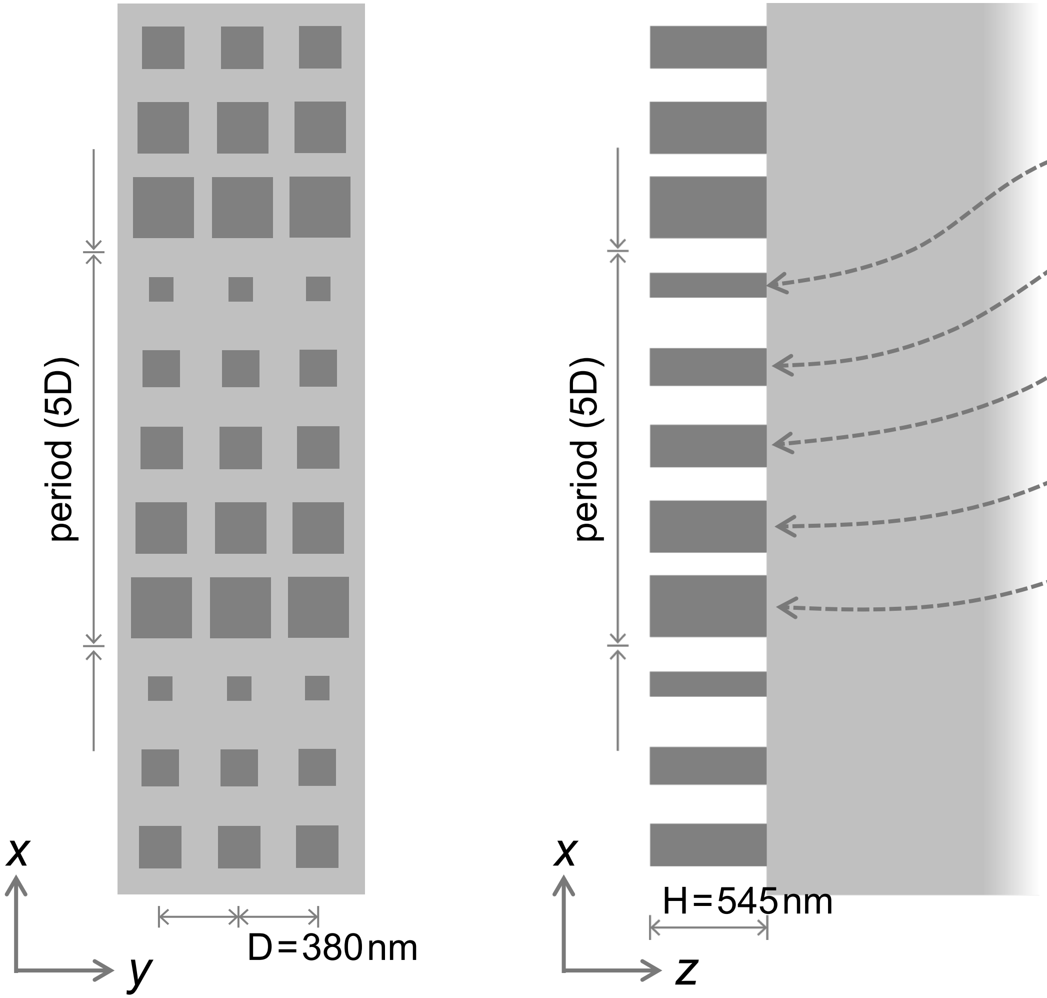




	#1	#2	#3	#4	#5
d	118nm	179nm	201nm	247nm	293nm
f=d/D	0.31	0.47	0.53	0.65	0.77
$\Delta\psi$	0.20π	0.69π	0.98π	1.40π	1.73π

Selection of pillar diameters follows from P. Lalanne, *et al*., Opt. Lett. 23, 1081-1083 (1998)

Initial Composition of the Blazed Grating



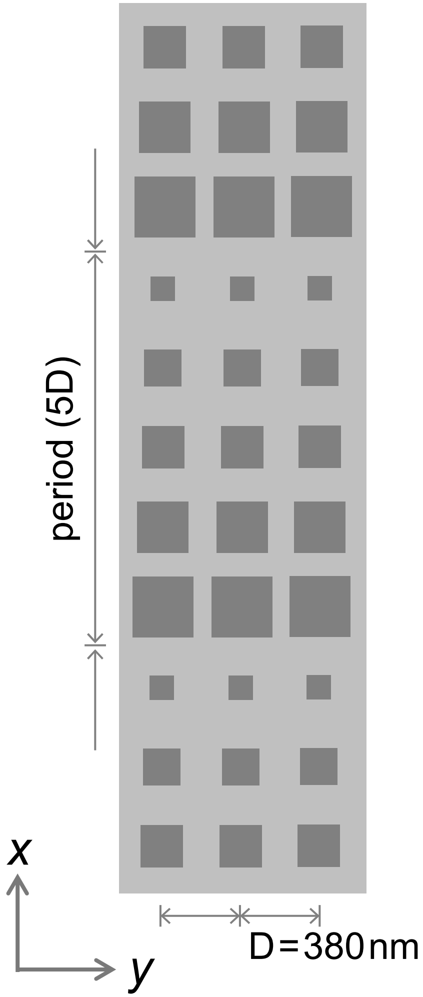
	#1	#2	#3	#4	#5
d	118nm	179nm	201nm	247nm	293nm
f=d/D	0.31	0.47	0.53	0.65	0.77
$\Delta\psi$	0.20π	0.69π	0.98π	1.40π	1.73π

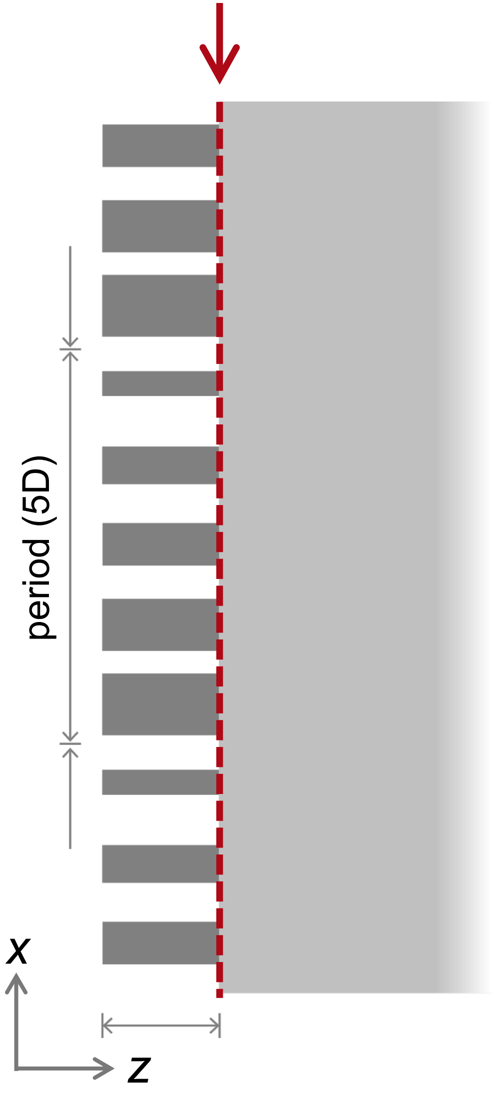
grating performance evaluation

	Efficiency
TE-polarization	79.6%
TM-polarization	74.5%
Average	**77.1%**

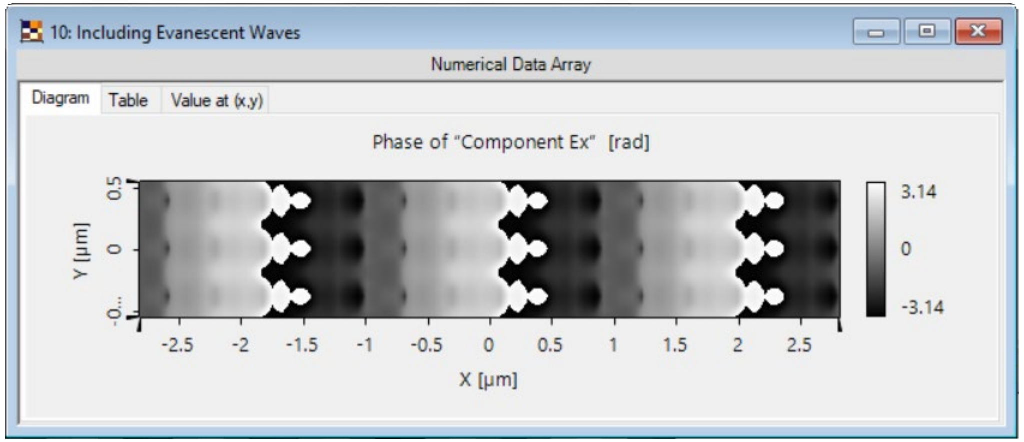
Same average efficiency value reported in
P. Lalanne, *et al.*, Opt. Lett. 23, 1081-1083 (1998)

Phase Distribution behind Blazed Meta-Grating

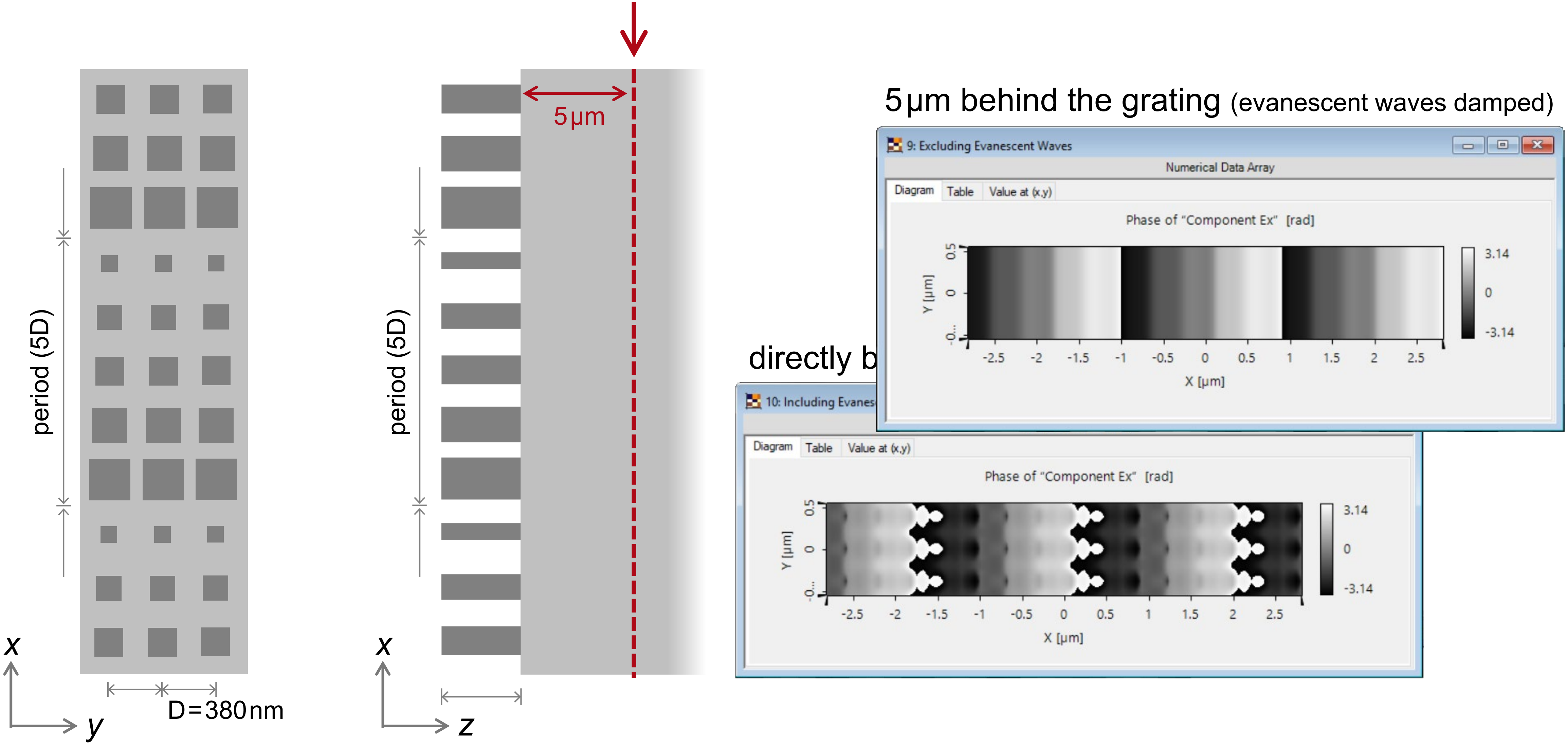




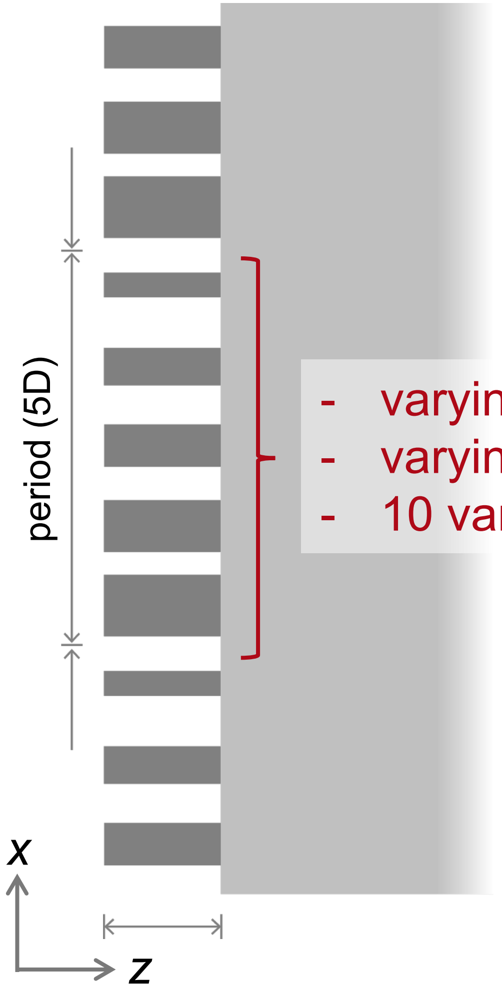
directly behind the grating



Phase Distribution behind Blazed Meta-Grating

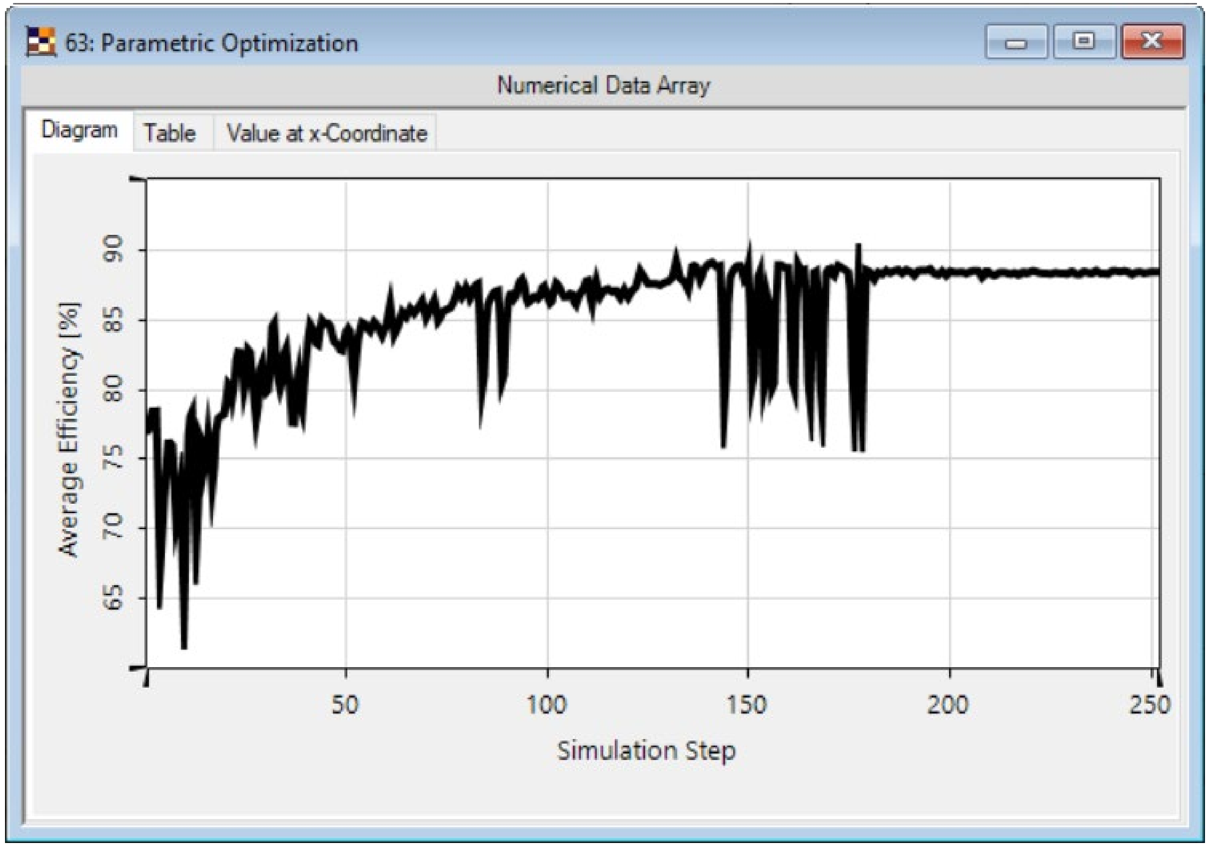


Further Optimization of Grating Structure

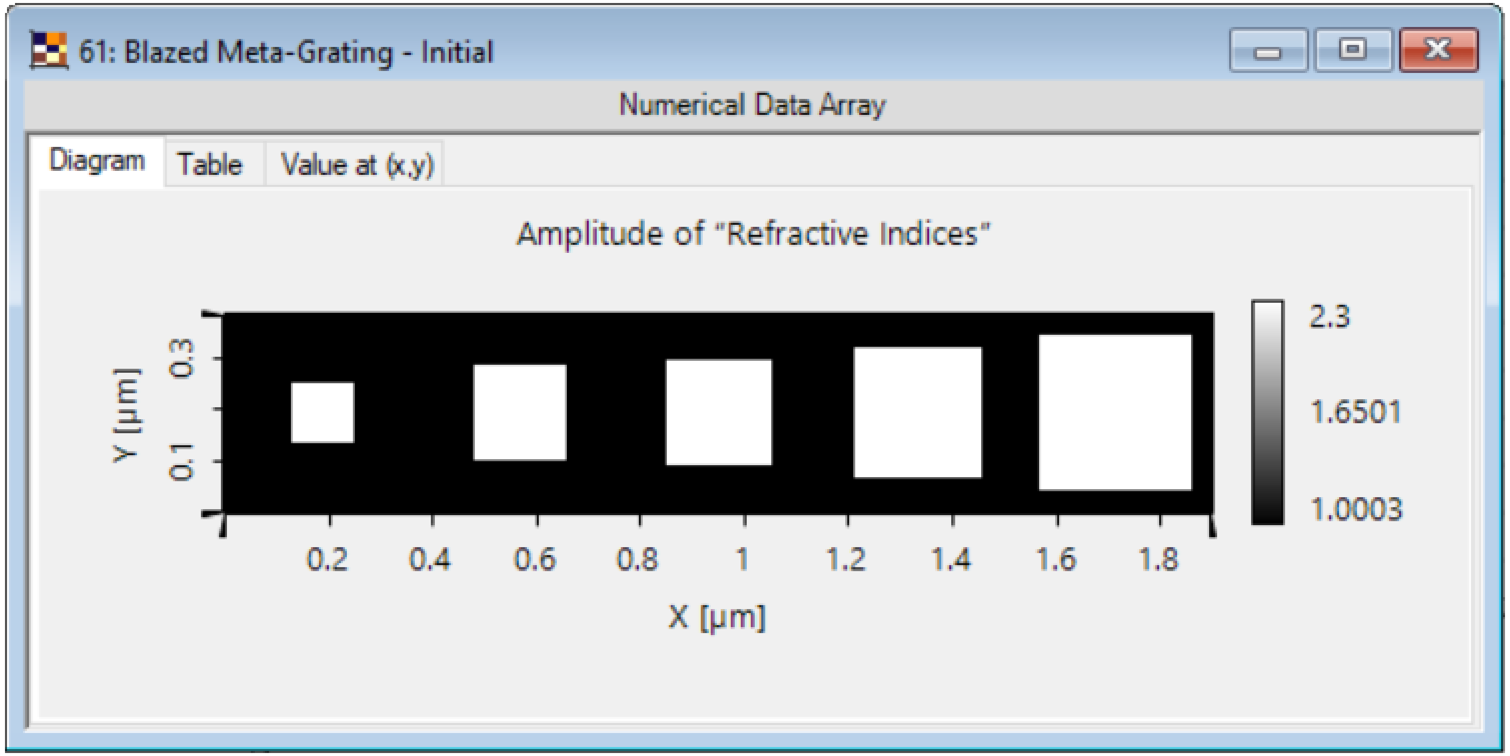


- varying pillar positions
- varying pillar diameters
- 10 variables in total

downhill simplex optimization with FMM/RCWA for grating analysis



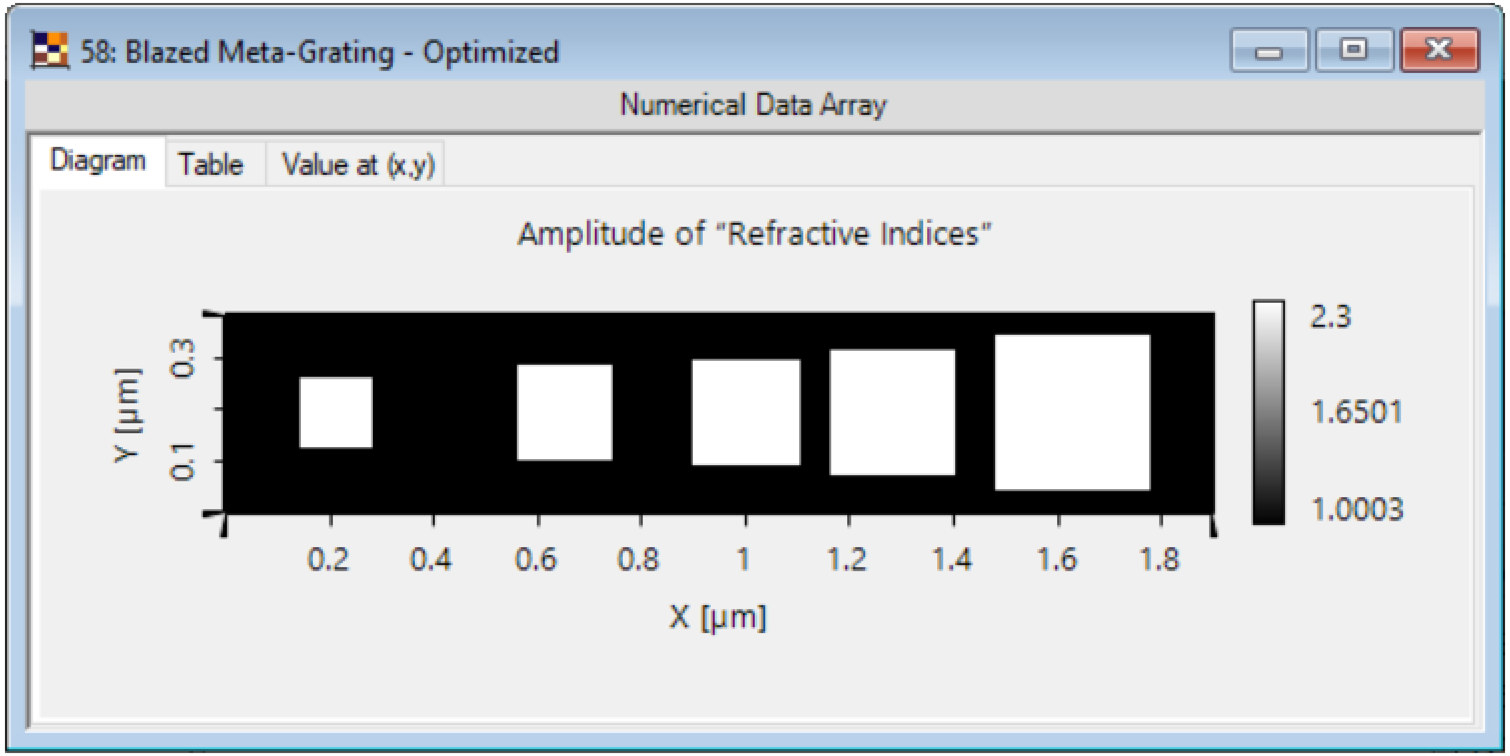
Blazed Meta-Grating Design – Initial Structure



grating performance evaluation

	Efficiency
TE-polarization	79.6%
TM-polarization	74.5%
Average	**77.1%**

Blazed Meta-Grating Design – After Optimization



grating performance evaluation

	Efficiency
TE-polarization	88.7%
TM-polarization	88.2%
Average	**88.5%**

Field Tracing Technologies – Gratings

Aim of this course:

- to be able to construct customized grating structure;
- to know grating modeling technologies;
- to use helpful tools for grating investigation and analysis;
- and, by applying the above to solve practical problems.

learning by examples!