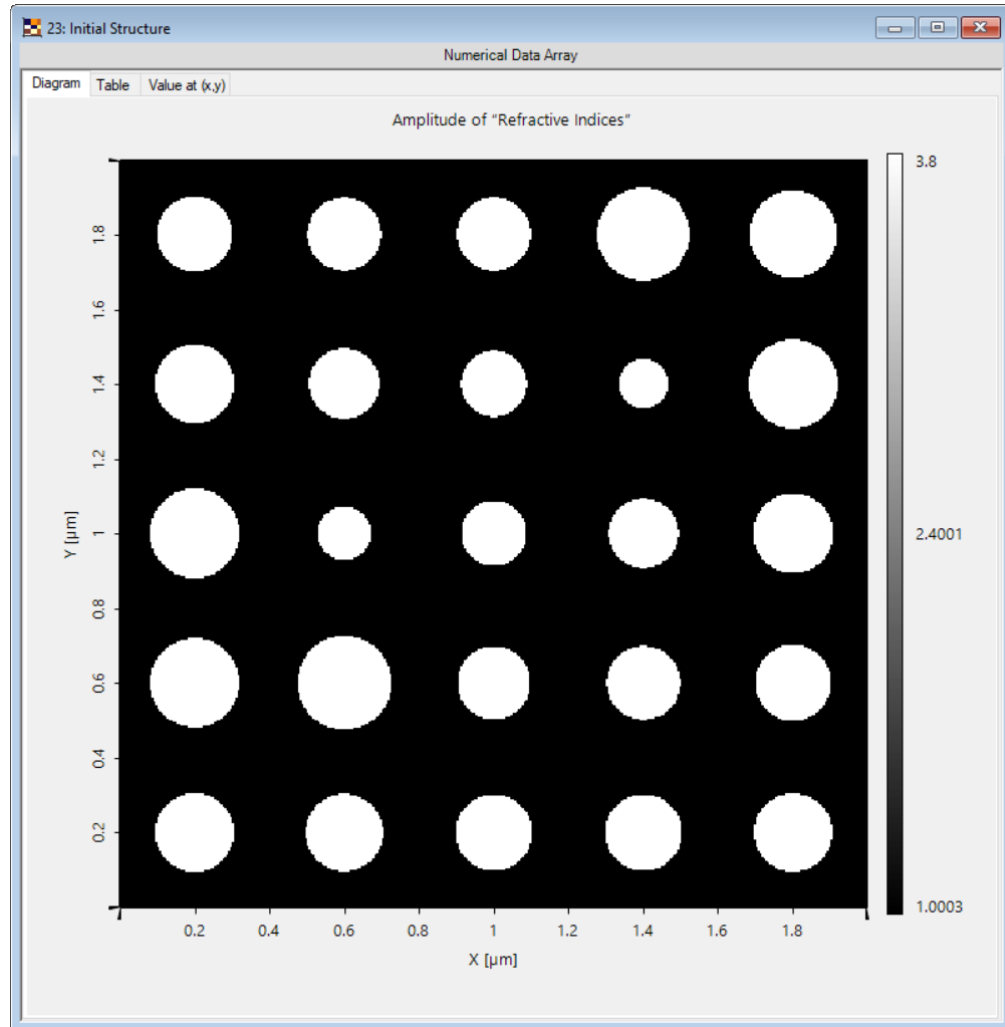


Two-Dimensional Meta-Gratings Modeling and Design

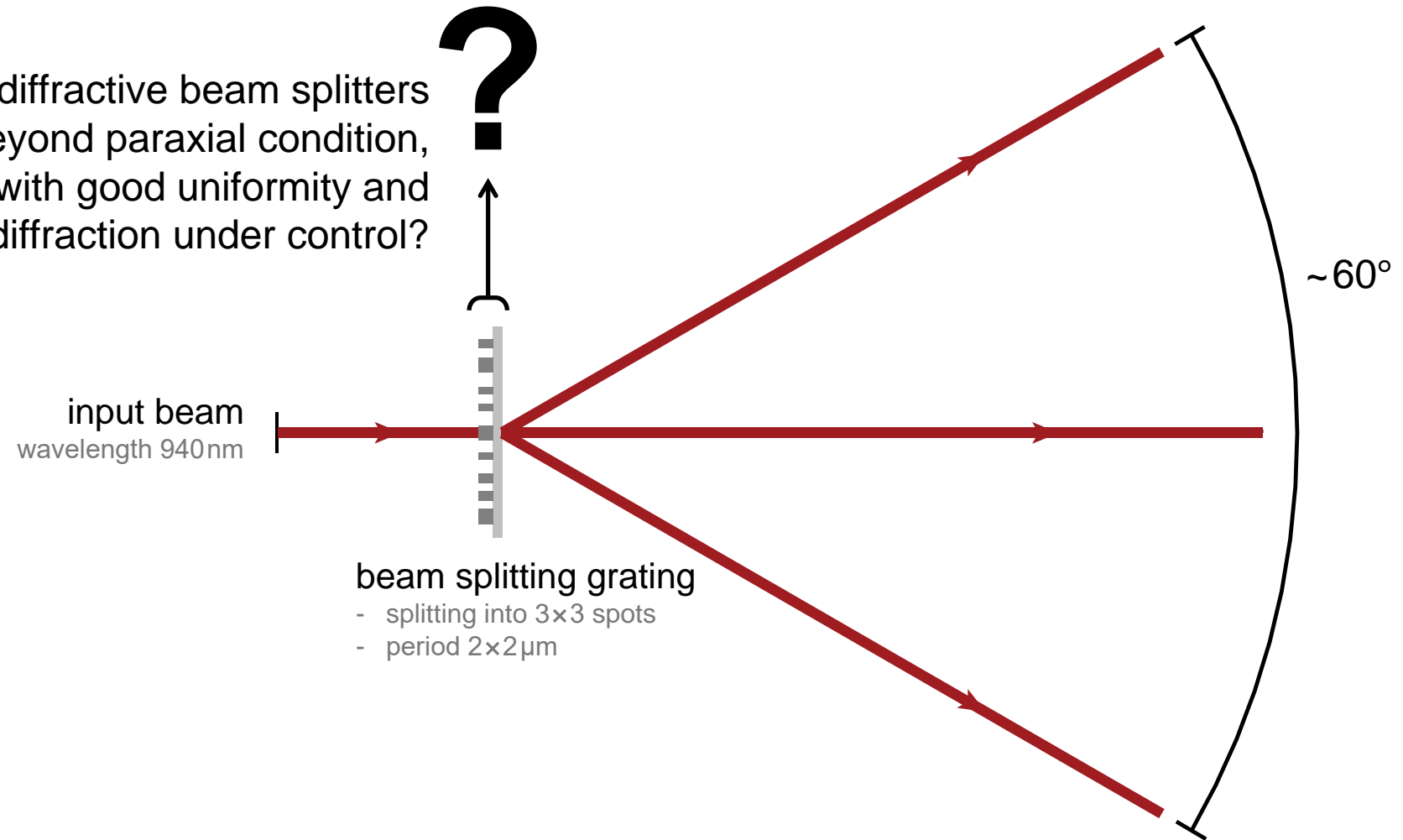
Abstract



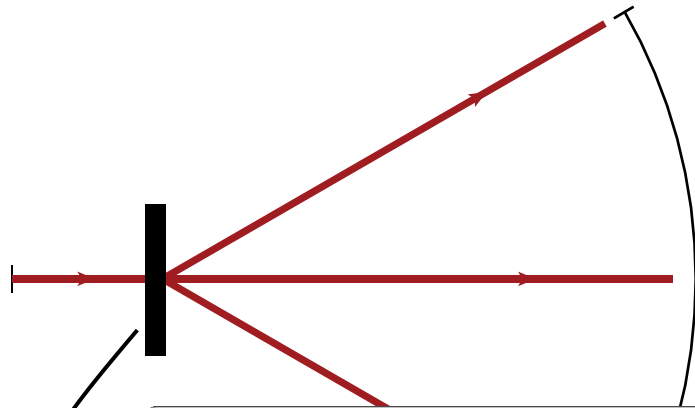
We demonstrate the design of 2D meta-gratings as large-angle beam splitters and how to further optimization with the rigorous Fourier modal method (FMM, also known as RCWA) and parametric optimization algorithm.

Design Task

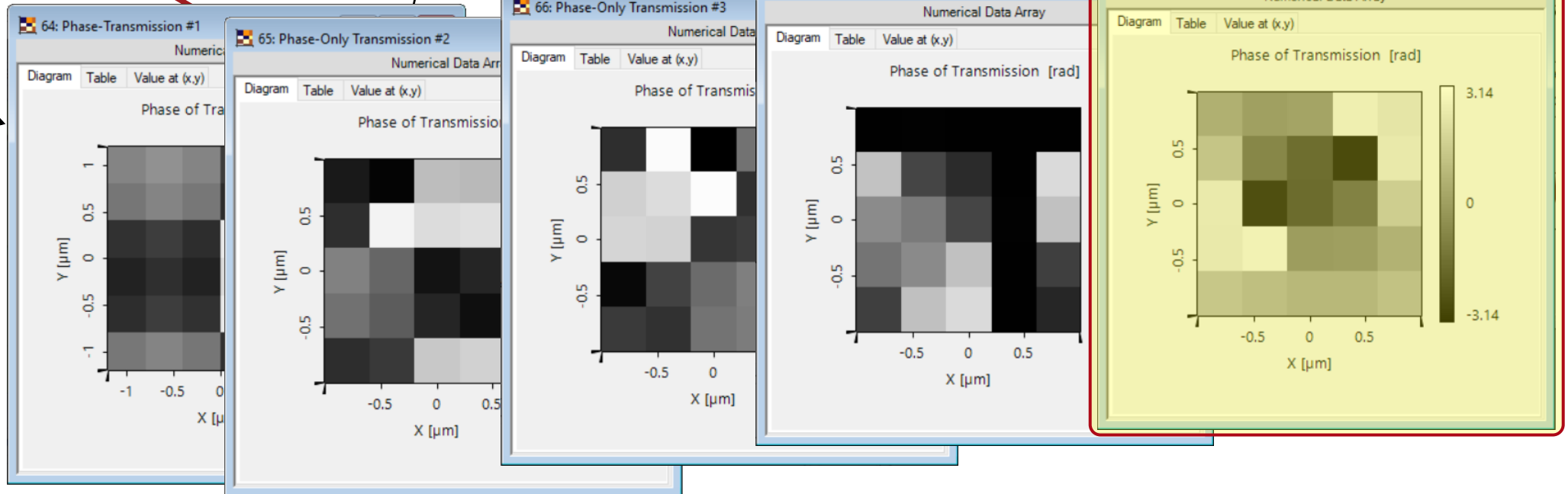
How to design diffractive beam splitters that work beyond paraxial condition, especially with good uniformity and zeroth-order diffraction under control?



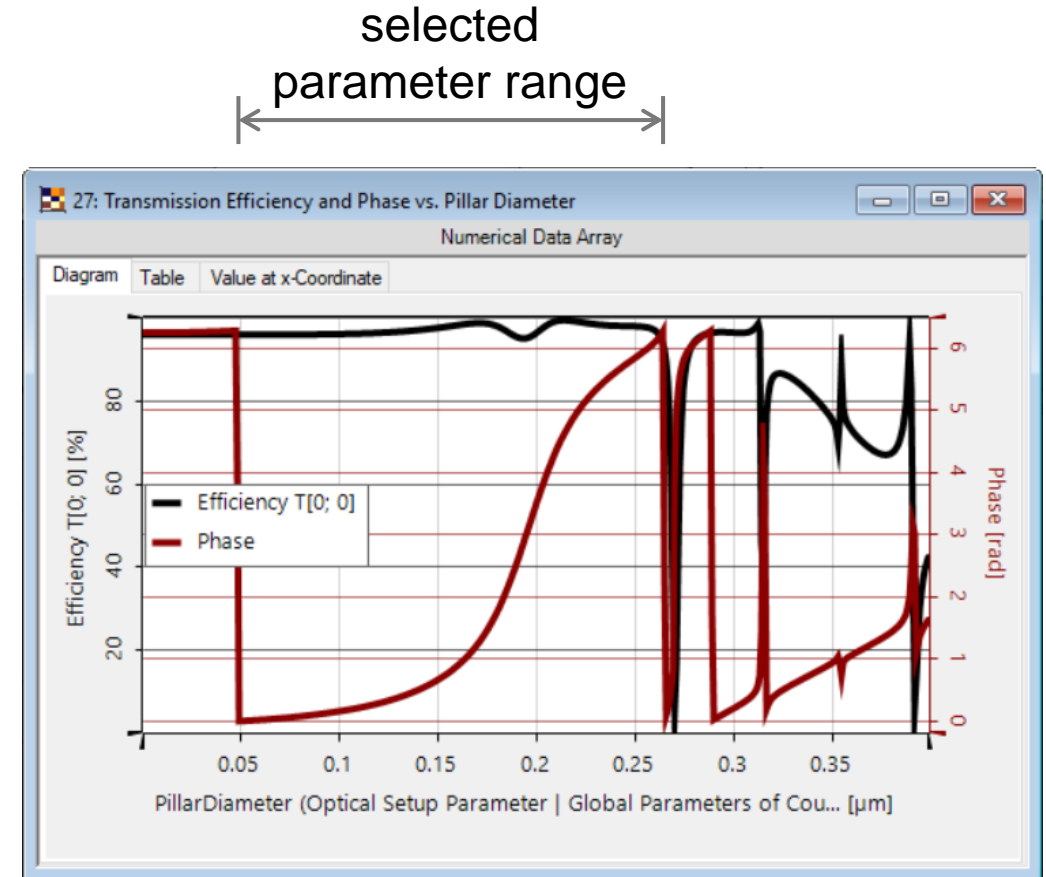
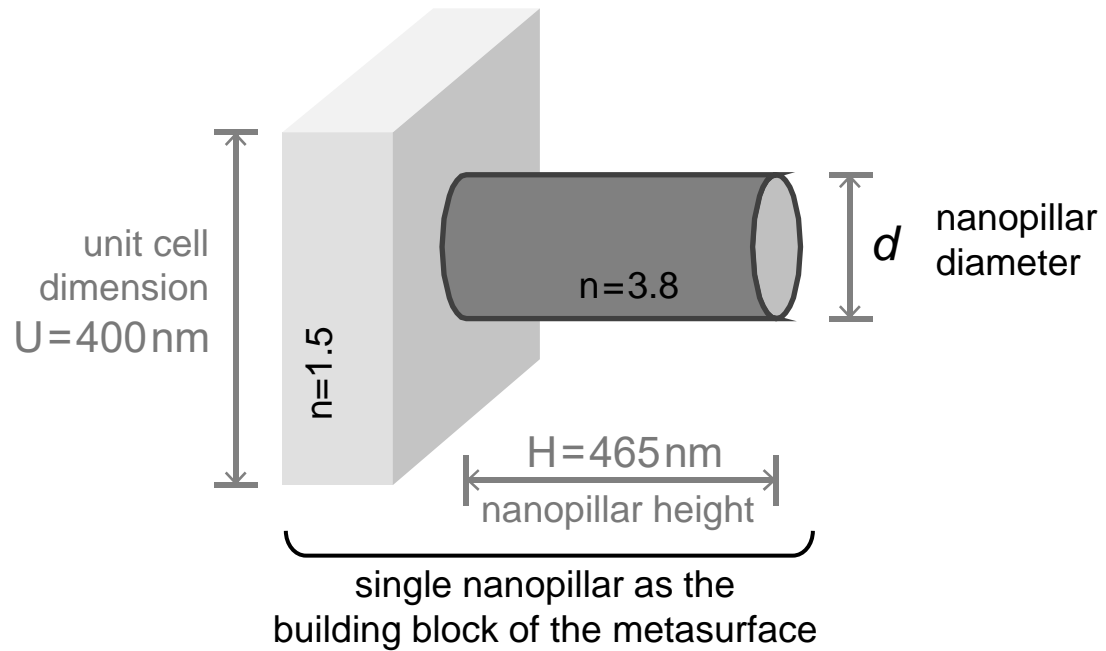
Phase-Only Transmission Design (IFTA)



With differently random phase distributions as starting points, IFTA calculates different possible design results.

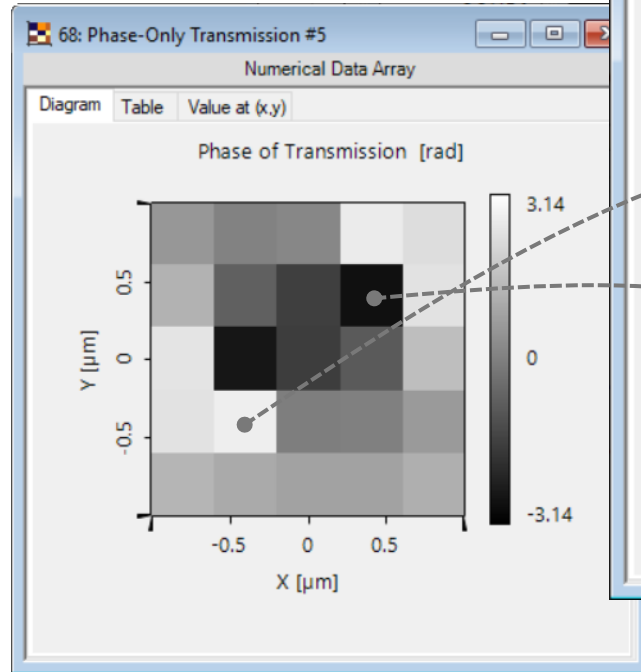


Metasurface Building Block / Unit Cell

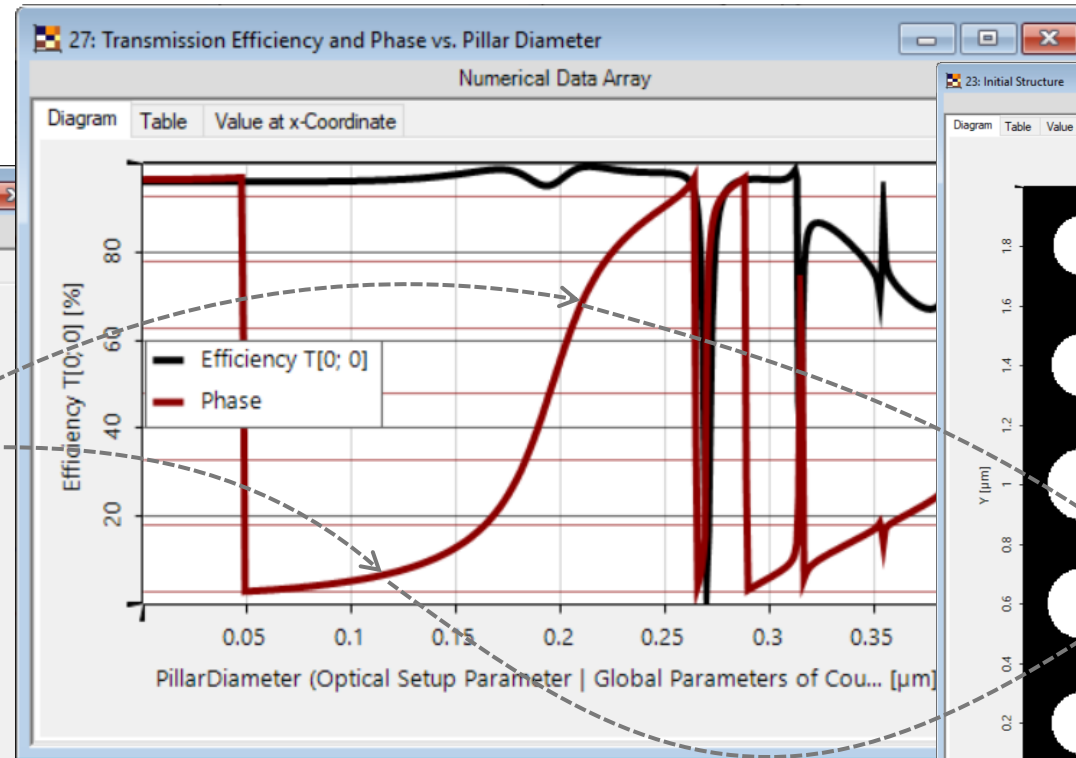


Phase Distribution → Metasurface Structure

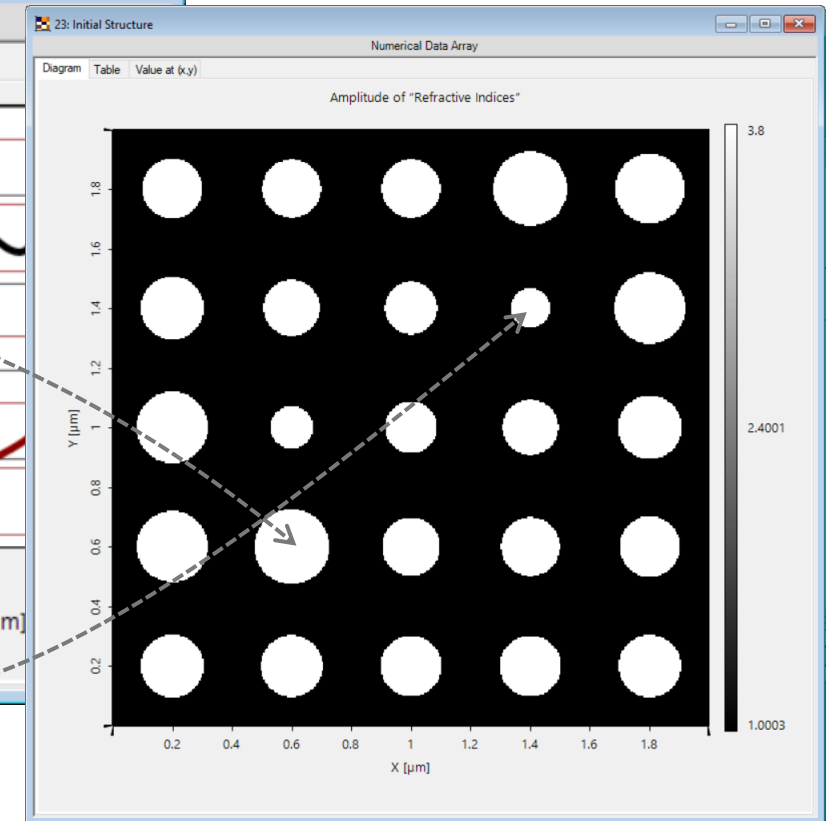
phase-only transmission



phase-diameter map / library

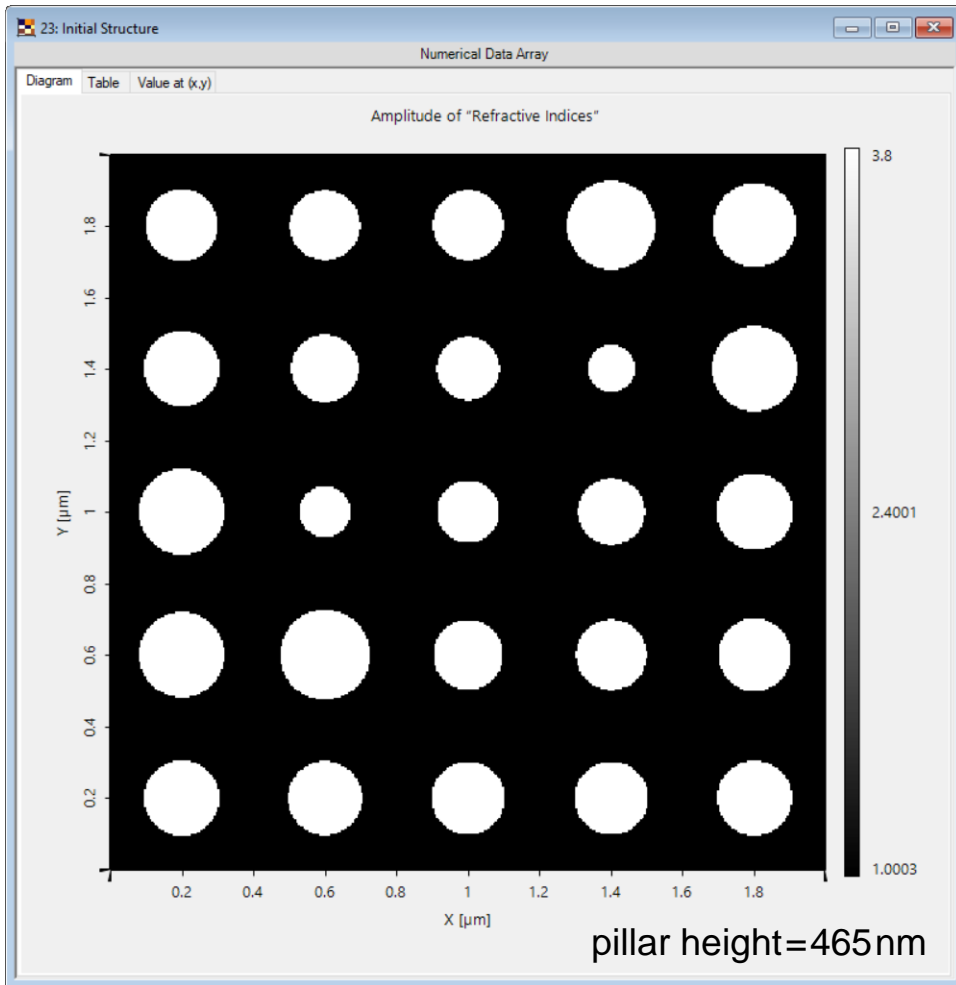


metasurface structure

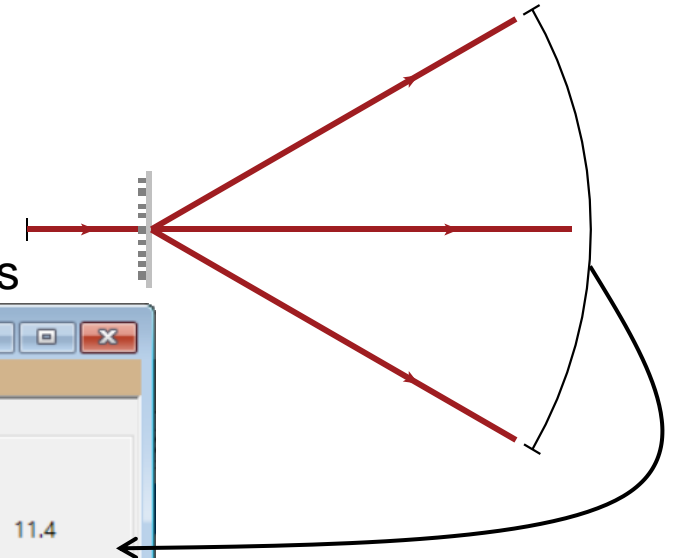
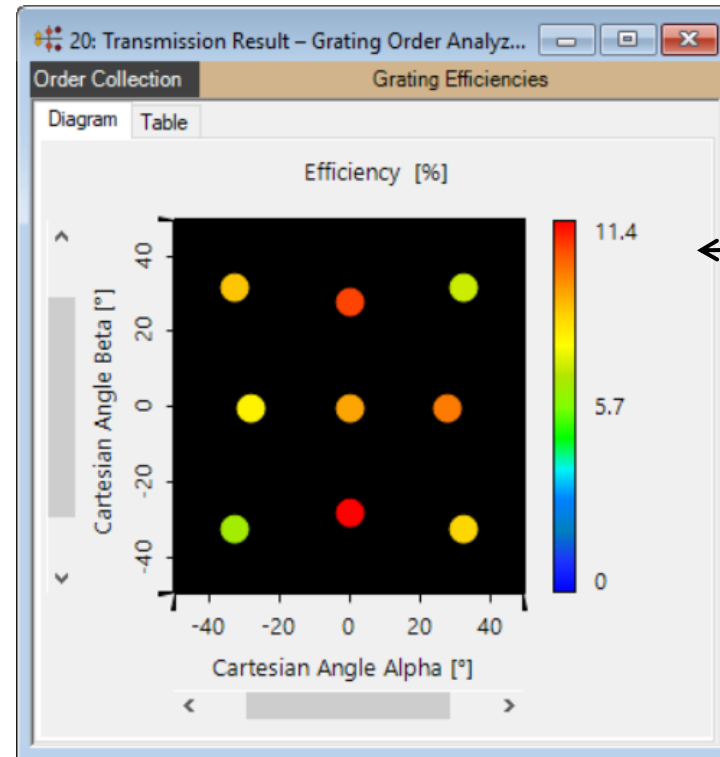


Evaluation of Initial Metasurface Design

metasurface structure



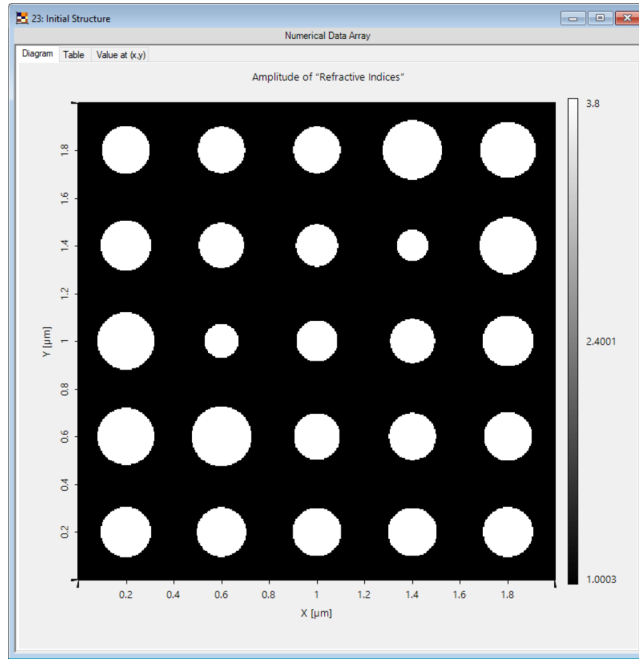
diffraction efficiencies



Overall efficiency	79%
Uniformity error (PV)	29%
Uniformity error (RMS)	18%

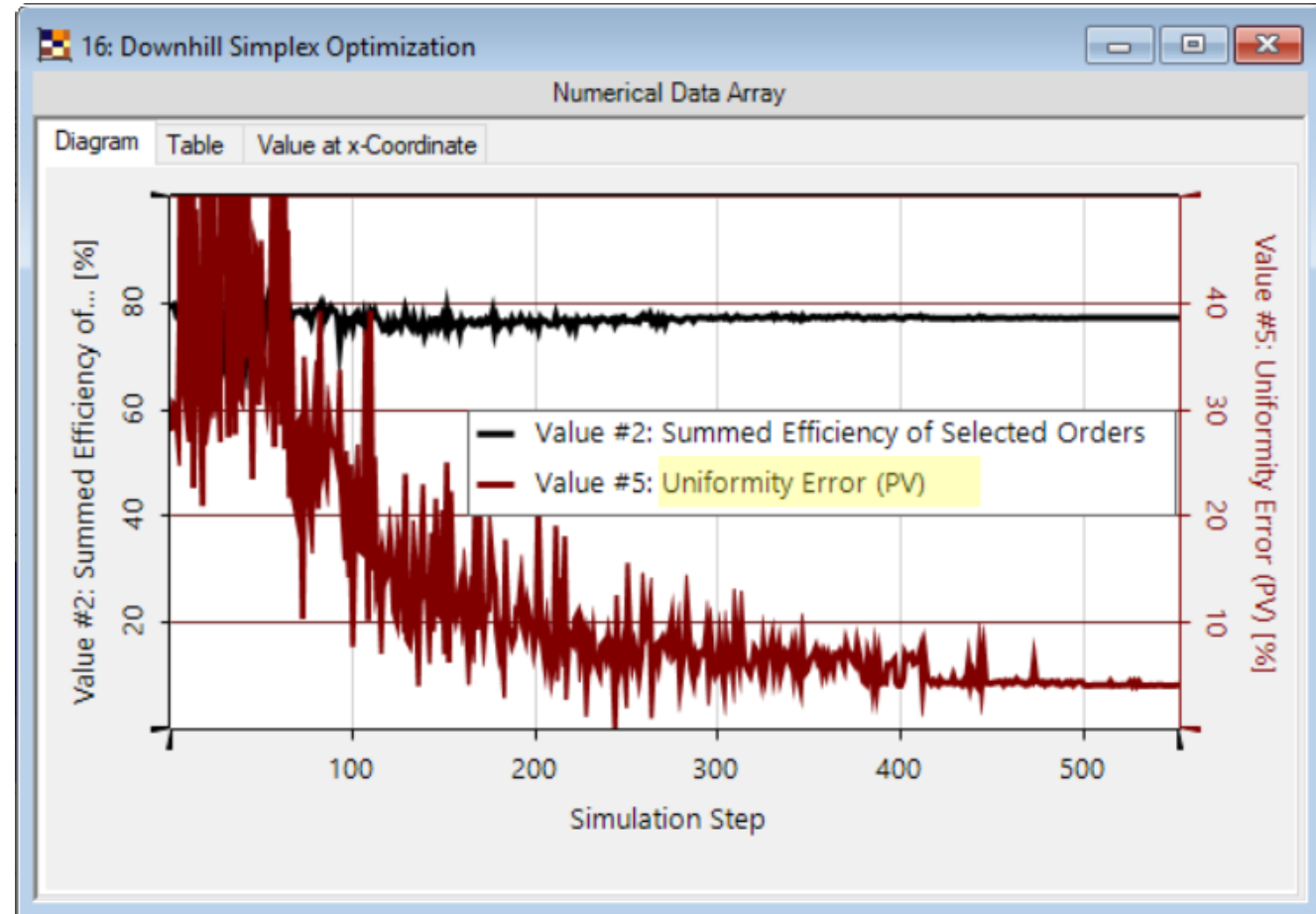
Parametric Optimization

initial structure



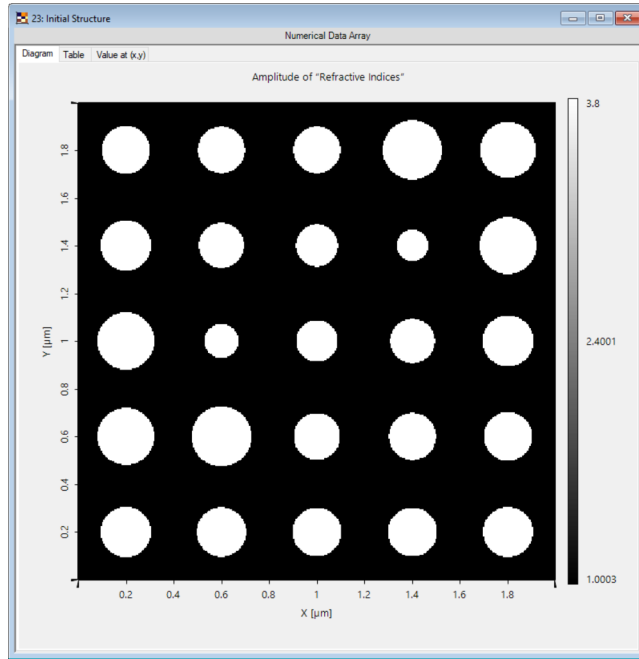
- keep pillar positions
- varying pillar diameters
- vary overall height
- 26 variables in total

downhill simplex optimization with FMM/RCWA for grating analysis



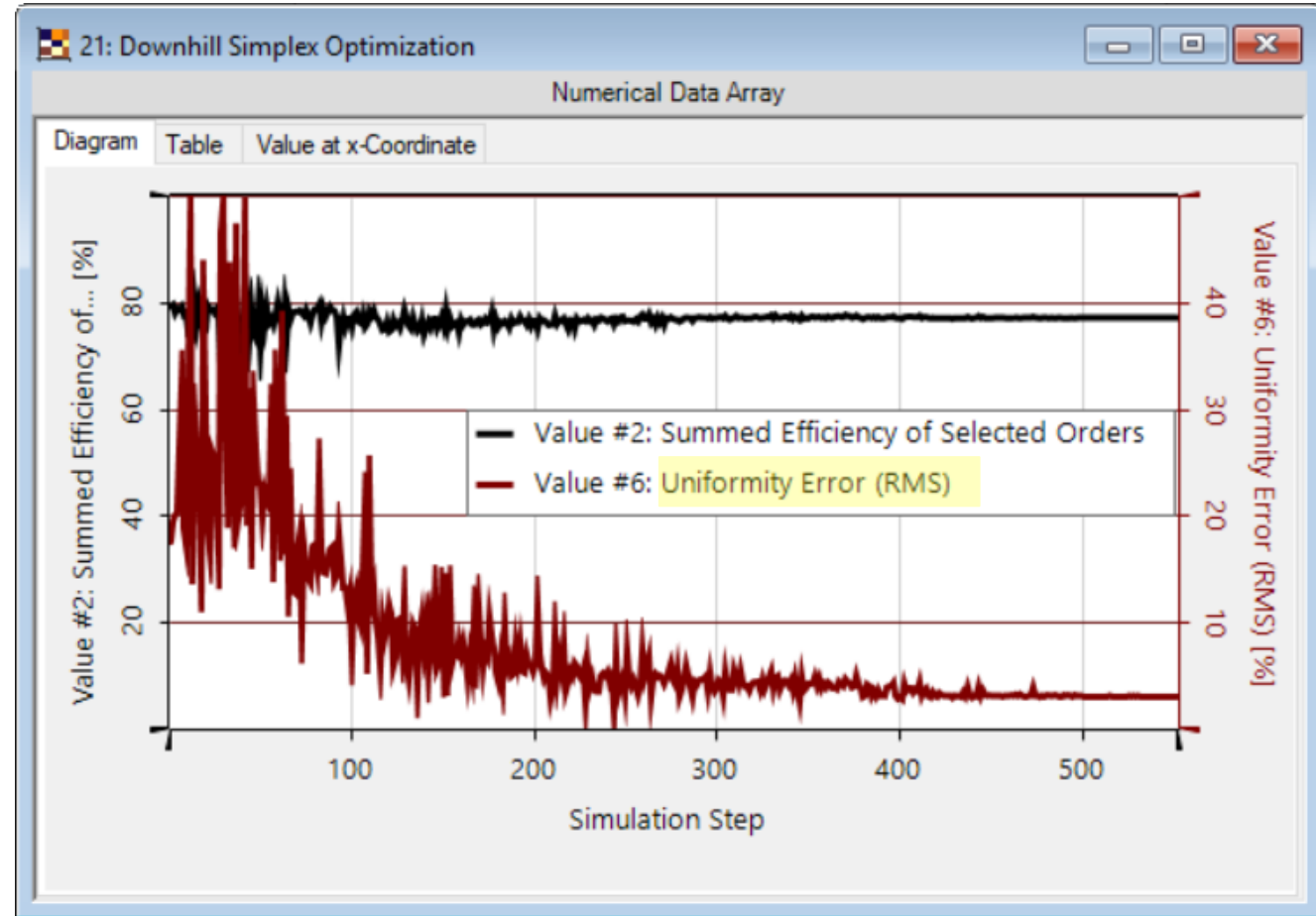
Parametric Optimization

initial structure



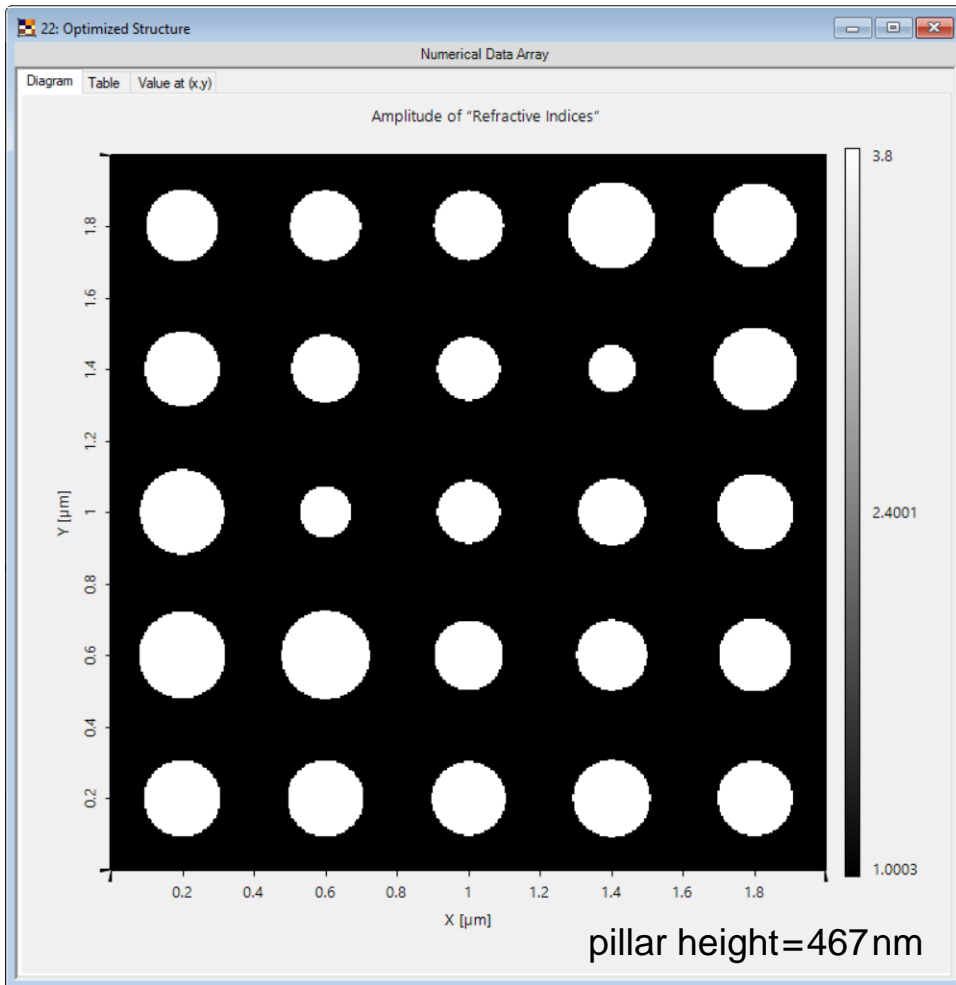
- keep pillar positions
- varying pillar diameters
- vary overall height
- 26 variables in total

downhill simplex optimization with FMM/RCWA for grating analysis

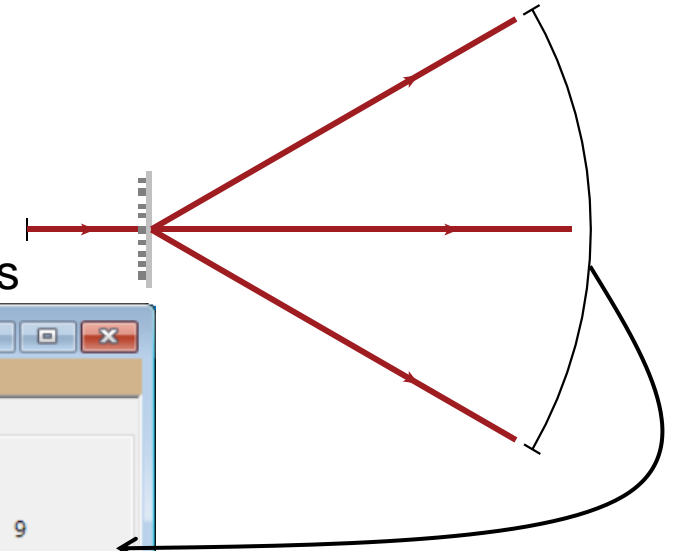
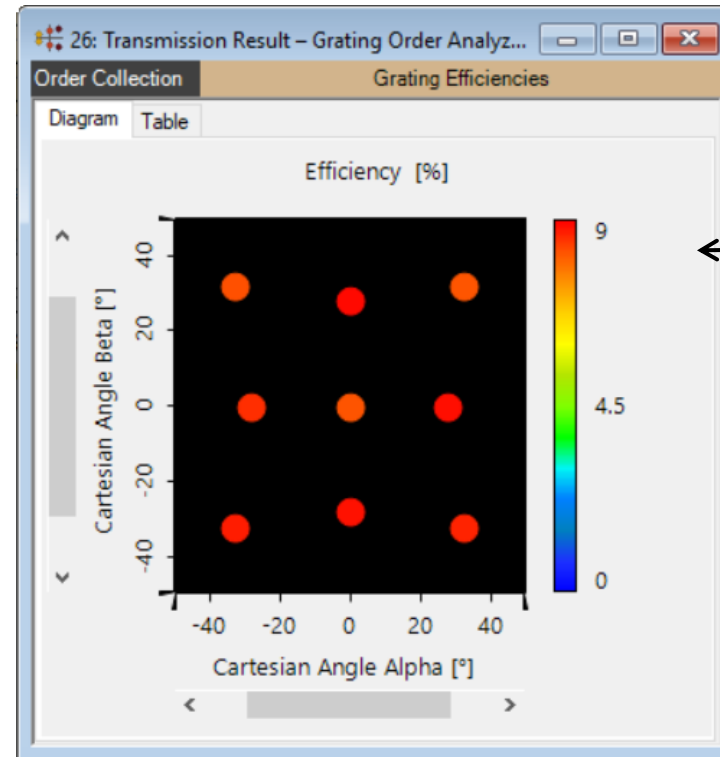


Evaluation of Optimized Metasurface Design

metasurface structure

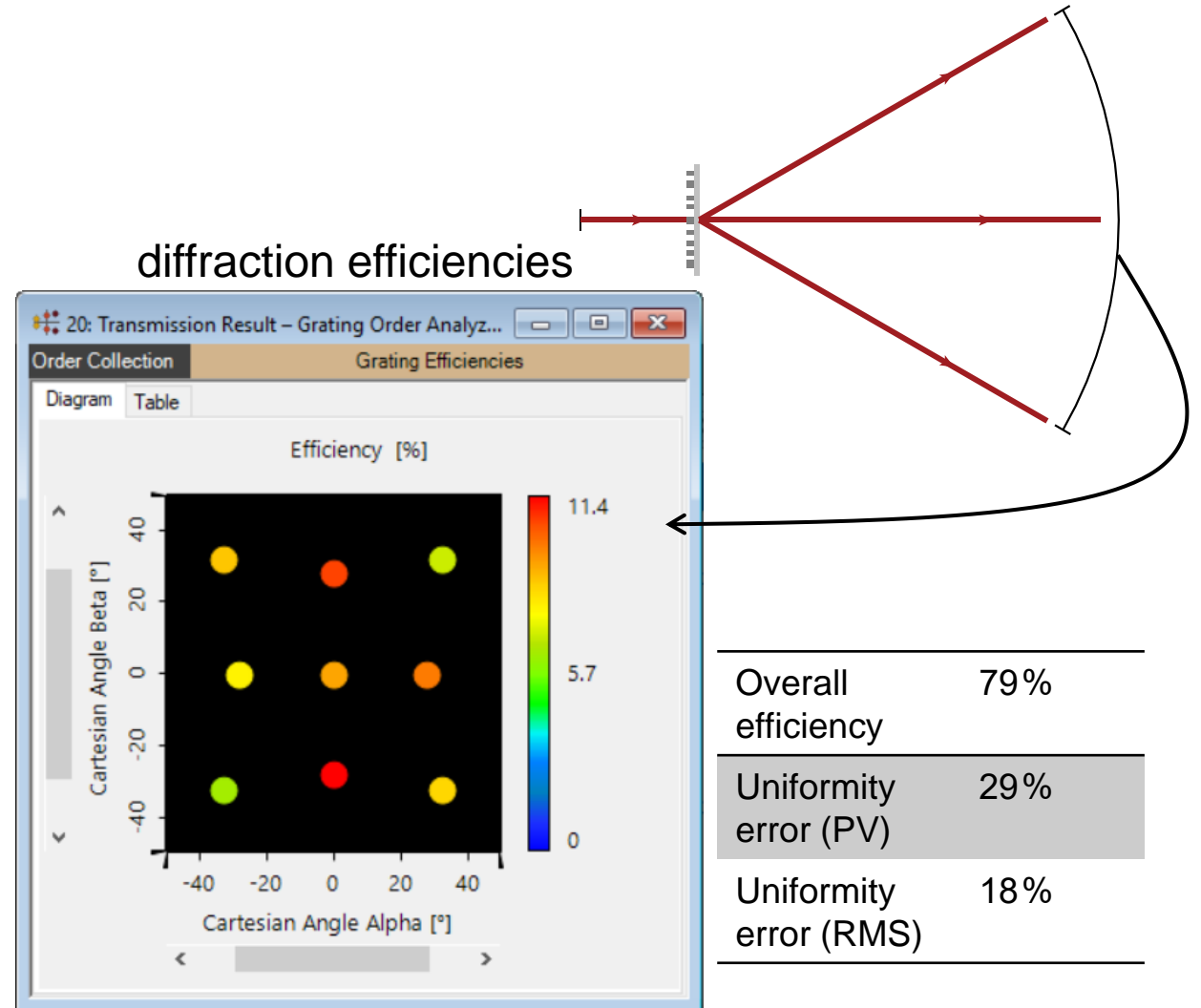
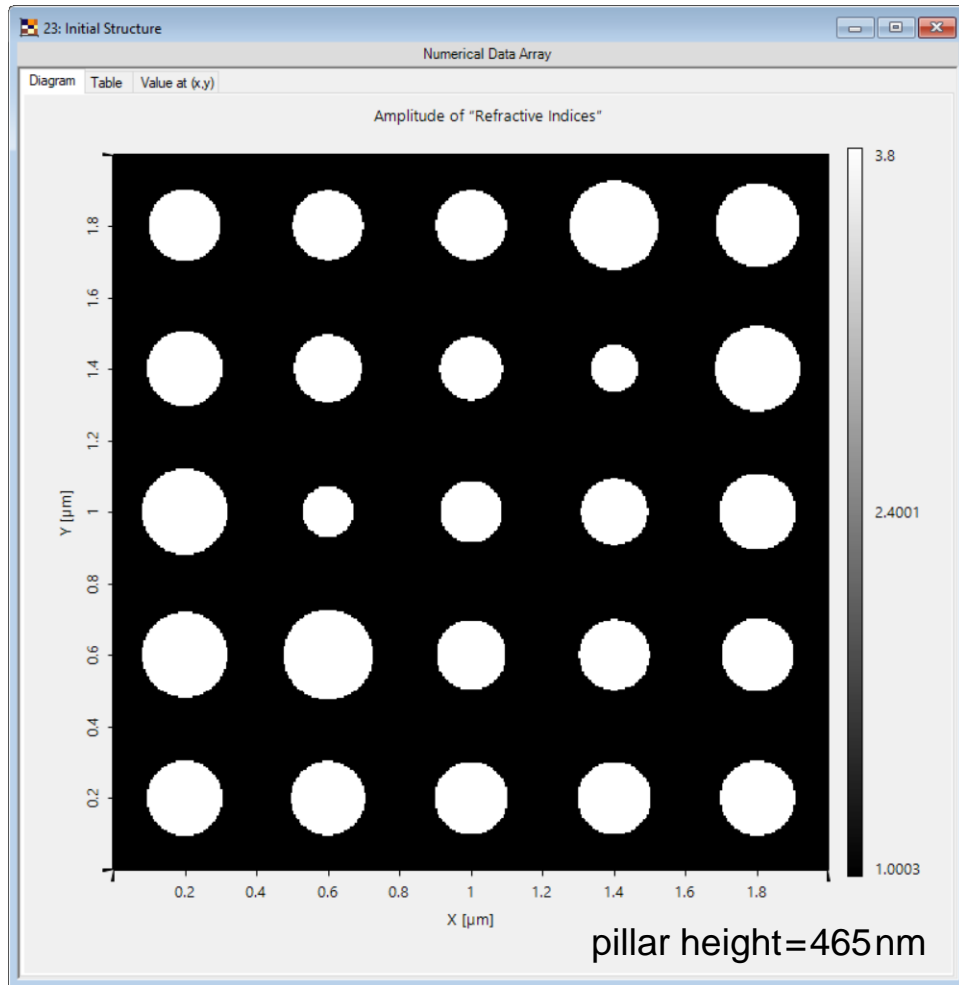


diffraction efficiencies



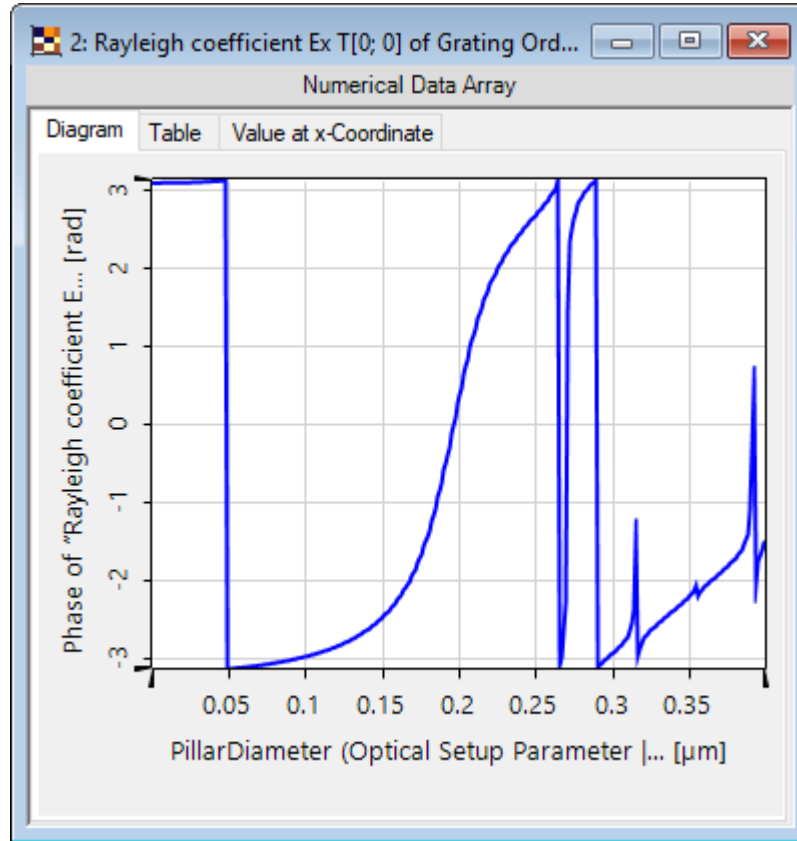
Overall efficiency	77%
Uniformity error (PV)	4.1%
Uniformity error (RMS)	3.2%

Meta-Grating Design – Initial Structure (for Comparison)



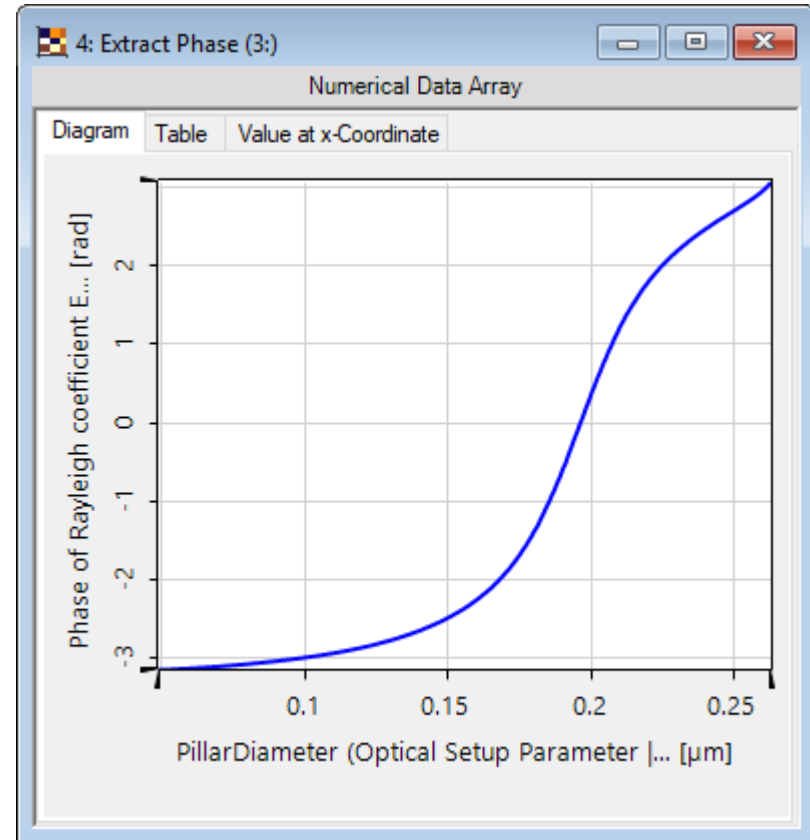
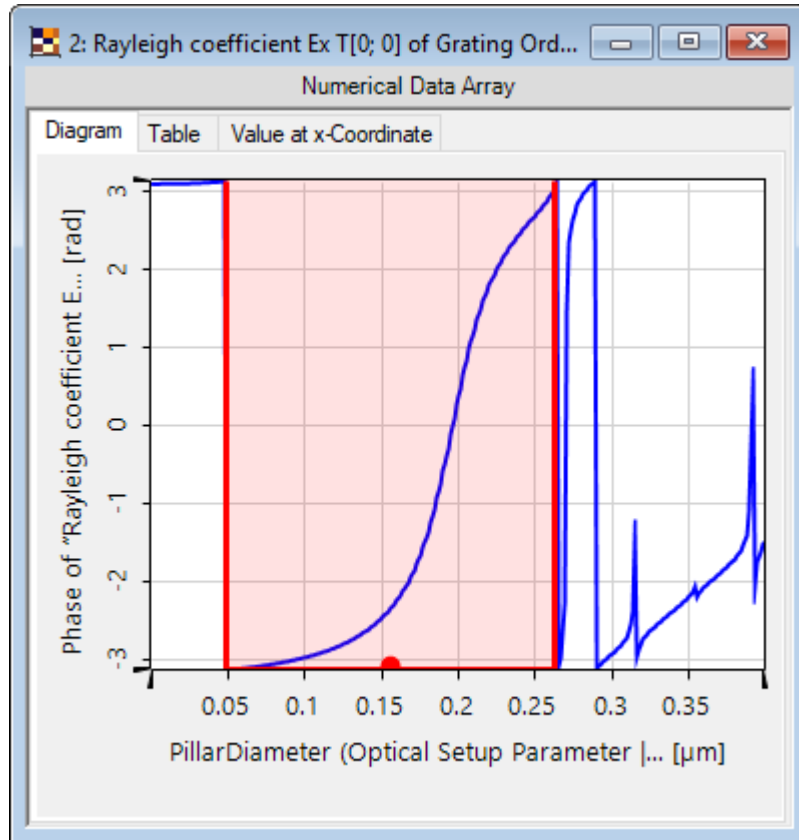
Brief Instruction on Workflow in VirtualLab Fusion

Step 1: Unit Cell Analysis



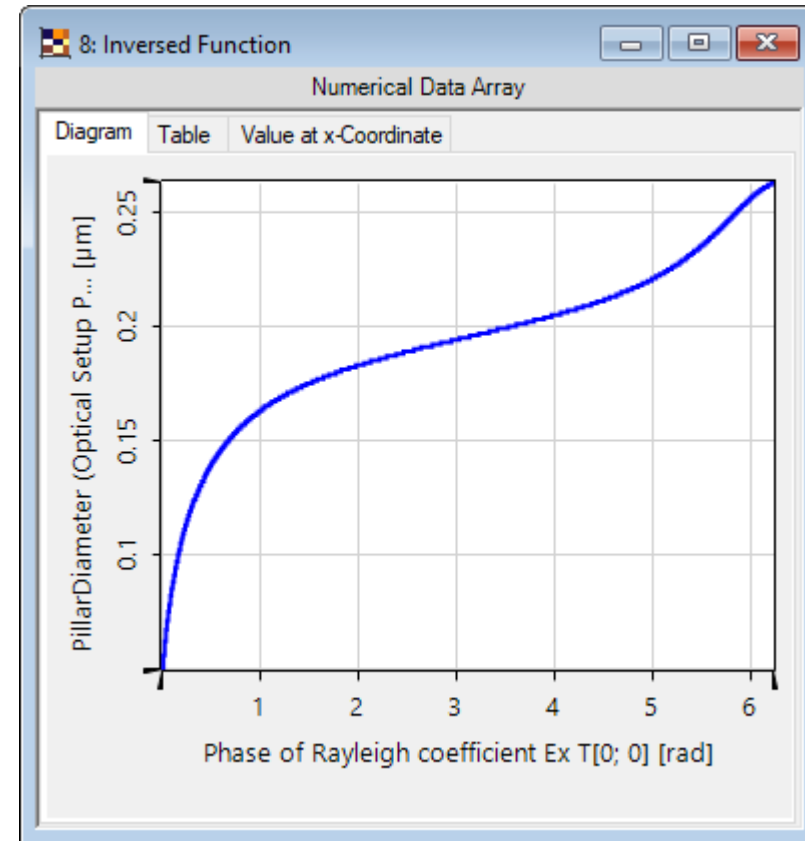
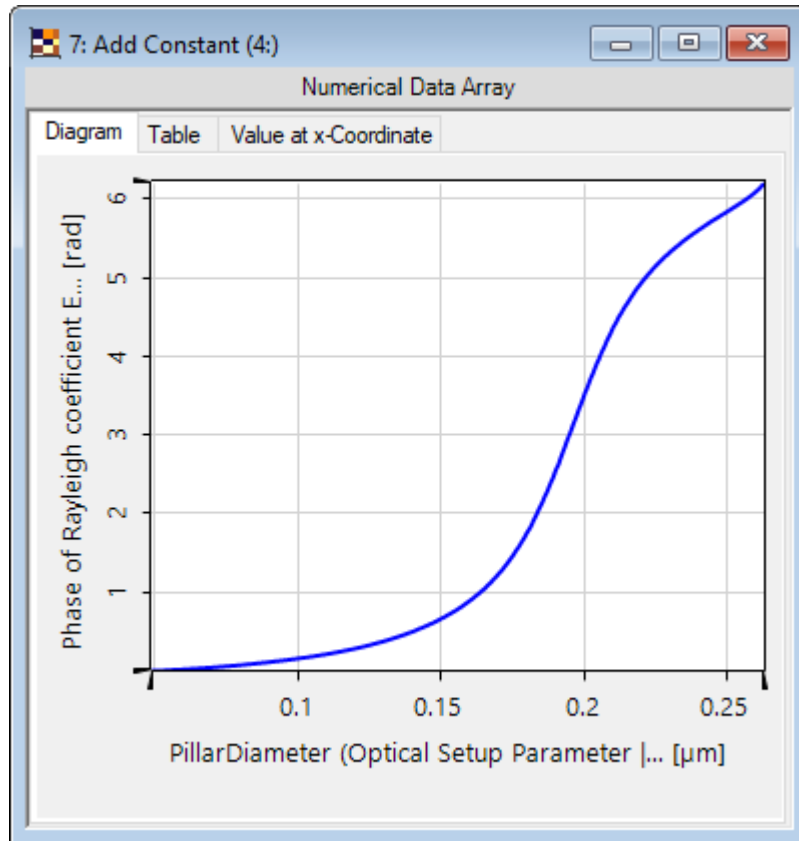
- Vary the pillar diameter and obtain the phase-diameter characteristic curve.
- Note that the phase value is wrapped within $[-\pi, +\pi]$, and it may contain certain dips.
- In this case, one can find a smooth phase function that covers 2π range, and that will be used for constructing the meta-grating.
- In case of irregular phase behavior, one can regularize it as shown in the blazed meta-grating example.

Step 2: Select Valid Pillar Diameter Range



(This step is very similar to the 1D grating case)

Step 3: Define Diameter – Phase Mapping Relation



(This step is very similar to the 1D grating case)

Step 4: Calculate Phase-Only Transmission

9: D:\OneDrive\...\Step_04_Phase-Only Transmission Design_IFTA_400nm Pixel .dp

Specification Design Analysis

Input Field

Wavelength

Constant Input Field Arbitrary Input Field

Transmission

Sampling Points x

Sampling Distance x

Type of Transmission

Number of Quantization Levels

Output Field Requirements

Desired Output Field

Optimization Region

Sample Optimization Region from Desired Output Field

Allow Phase Freedom

Allow Scale Freedom

Limit Scale Factor According to Goal Efficiency

Propagation

Type of Propagation

Propagation Distance

Embed Frame Width

Pixelation Factor

Simulate Pixelation Exactly

Output Plane Sampling

Sampling Points x

Sampling Distance x

Field Size x

Use Angular Coordinates

Limit Stray Light

Maximum Relative Intensity of Stray Light

Limit Feature Size

Minimum Feature Size

Maximum Stray Light Intensity for Higher Frequencies

9: D:\OneDrive\...\Step_04_Phase-Only Transmission Design_IFTA_400nm Pixel .dp*

Specification Design Analysis

Design Method Transmission

Design Steps

Design Steps	Number of Iterations	Method
<input checked="" type="checkbox"/> Generate Initial Transmission		<input type="text" value="Backward Propagated Desired Output Field (Ri)"/>
<input checked="" type="checkbox"/> Signal Phase Synthesis	<input type="text" value="25"/>	<input type="checkbox"/> Soft Introduction of Transmission Constraint
<input checked="" type="checkbox"/> SNR Optimization for Phase-Only Transmission	<input type="text" value="50"/>	<input type="checkbox"/> Omit Final Transmission Projection
<input type="checkbox"/> Soft Quantization	<input type="text" value="100"/>	<input type="checkbox"/> Soft Introduction of Transmission Constraint
<input type="checkbox"/> SNR Optimization for Quantized Transmission	<input type="text" value="5000"/>	<input type="checkbox"/> Create Transmission Animation <input type="button" value="Options"/>
		<input type="checkbox"/> Create Output Field Animation <input type="button" value="Options"/>
		<input type="checkbox"/> Show Final Transmission and Output Field

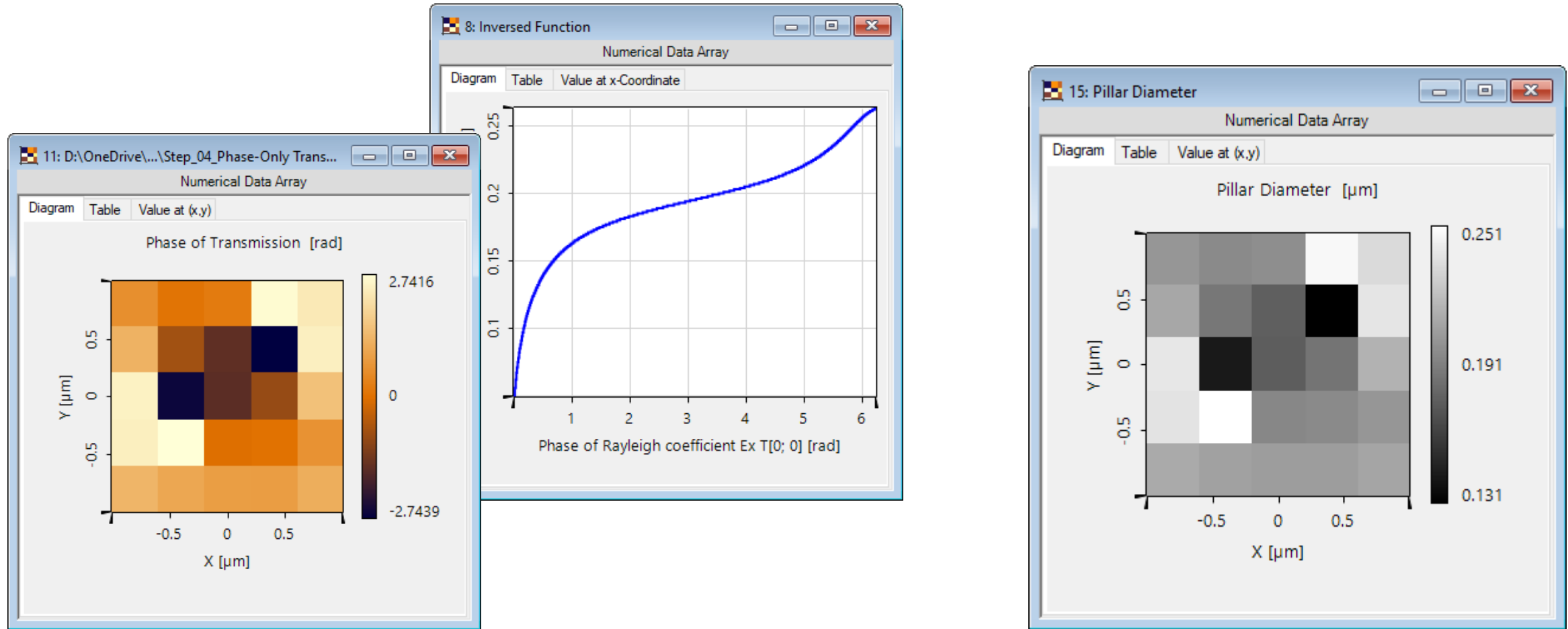
Logging

Enable Logging

Preserve Table

Progress in current design step

Step 5: From Phase Profile to Structure



Step_05_Calculate Pillar Diameters from Phase Profile_2D Regular Array.cs

Step 6: Load Meta-Grating Structure in FMM Simulation

Edit Stack

Index	z-Distance	z-Position	Interface	Subsequent Medium
1	0 mm	0 mm	Plane Interface	Cylinder Pillars (2D...)
2	465 nm	465 nm	Plane Interface	Air in Homogeneous M...

Index Modulation

Snippet defines Index Modulation Index Distribution

Definition:

Parameters:

- SideWallSlopeAngle:
- RoundedEdgeRadiusTop:
- RoundedEdgeRadiusBottom:
- PillarPositionDeviationX:
- PillarPositionDeviationY:
- PillarMaterial: "ConstantIndexMaterial"
- EmbedMaterial: "Air"

Buttons:

Annotations:

- Red arrow pointing to the 'Edit' button in the 'Cylinder Pillars (2D...)' section: "Load the pillar diameter information here"
- Red arrow pointing to the 'Edit' buttons for 'PillarPositionDeviationX' and 'PillarPositionDeviationY': "Define pillar position deviations here"

Step 7a: Optimization of Pillar Height

1: D:\OneDrive\...\Step_07a_Meta-Grating Rigorous Analysis_Optimizing Pillar Height.opt

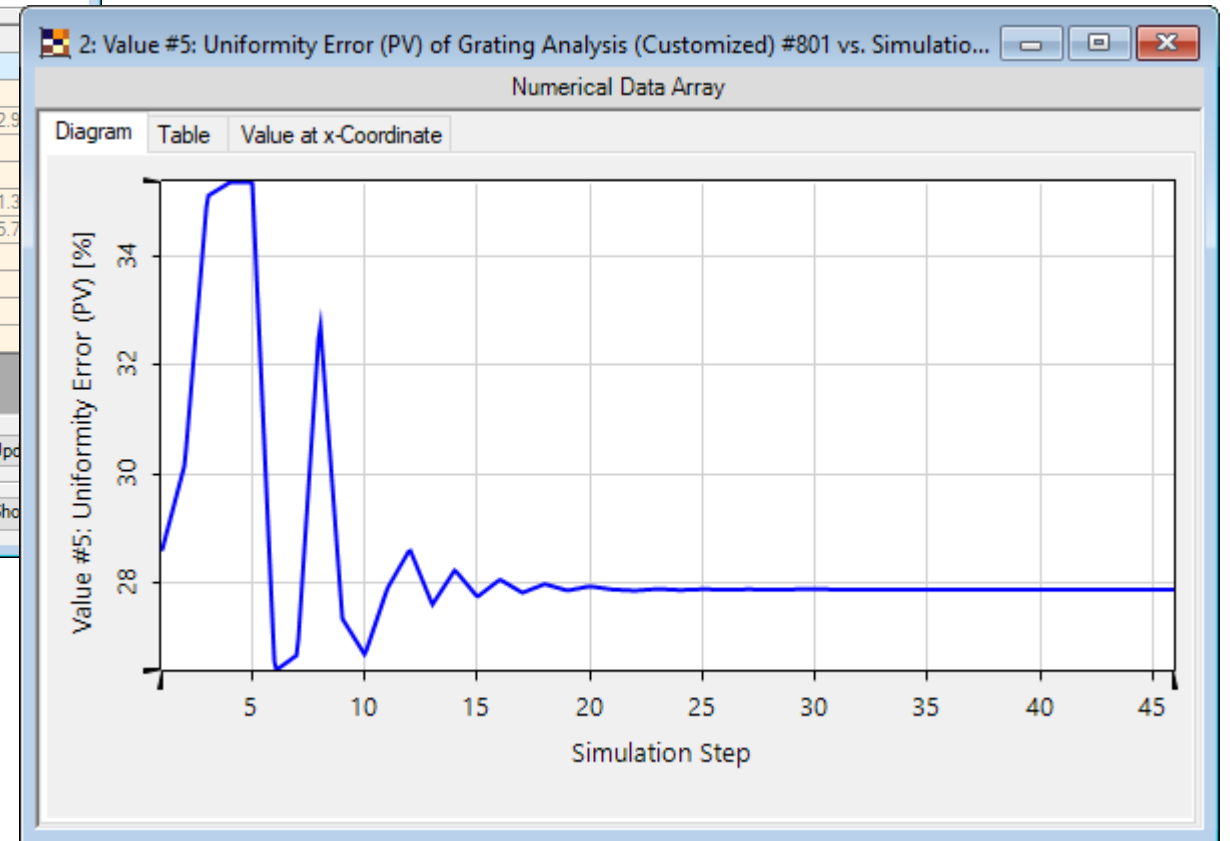
Constraint Specifications
Select and specify the constraints which shall be considered during optimization.

Constraint Host	Constraint Name	Use	Weight	Constraint Type	Value 1	Value 2	Start Value	Contribution
Meta-Grating	Stack #2 (Pillar)	<input checked="" type="checkbox"/>	1	Range	0 mm	1 m	465 nm	
Grating Analysis (Customized) #801	Value #1:	<input type="checkbox"/>						
	Value #2:	<input checked="" type="checkbox"/>	2	Target Value	1		0.79269	32.9
	Value #3:	<input type="checkbox"/>						
	Value #4:	<input type="checkbox"/>						
	Value #5:	<input checked="" type="checkbox"/>	1	Target Value	0		0.28611	31.3
	Value #6:	<input checked="" type="checkbox"/>	3	Target Value	0		0.17627	35.7
	Value #7:	<input type="checkbox"/>						
	Value #8:	<input type="checkbox"/>						
	Value #9:	<input type="checkbox"/>						
	Value #10:	<input type="checkbox"/>						

Tools Target Function Value: 0.26102

< Back Next > Show

Not very effective on the optimization



Step 7b: Optimization of Pillar Diameters

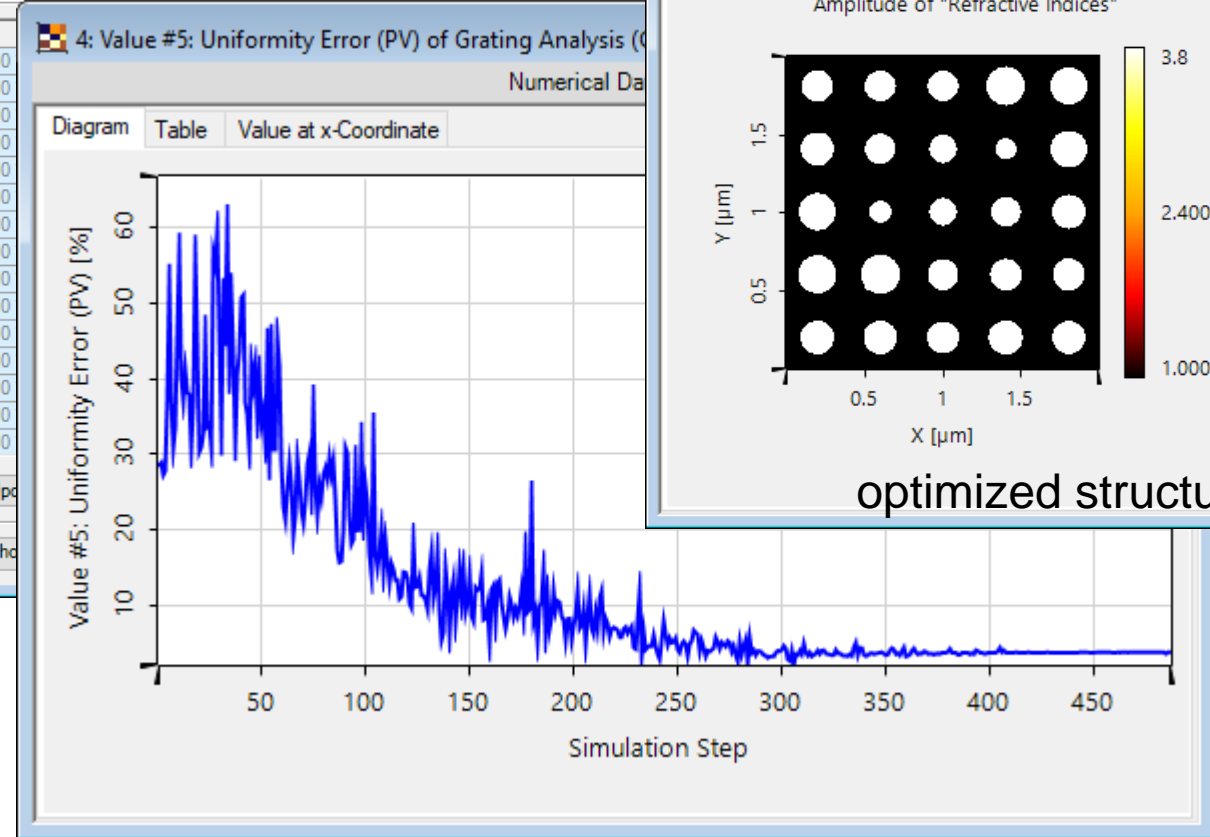
3: D:\OneDrive\...\Step_07b_Meta-Grating Rigorous Analysis_Optimizing Pillar Diameters.opt

Constraint Specifications
Select and specify the constraints which shall be considered during optimization.

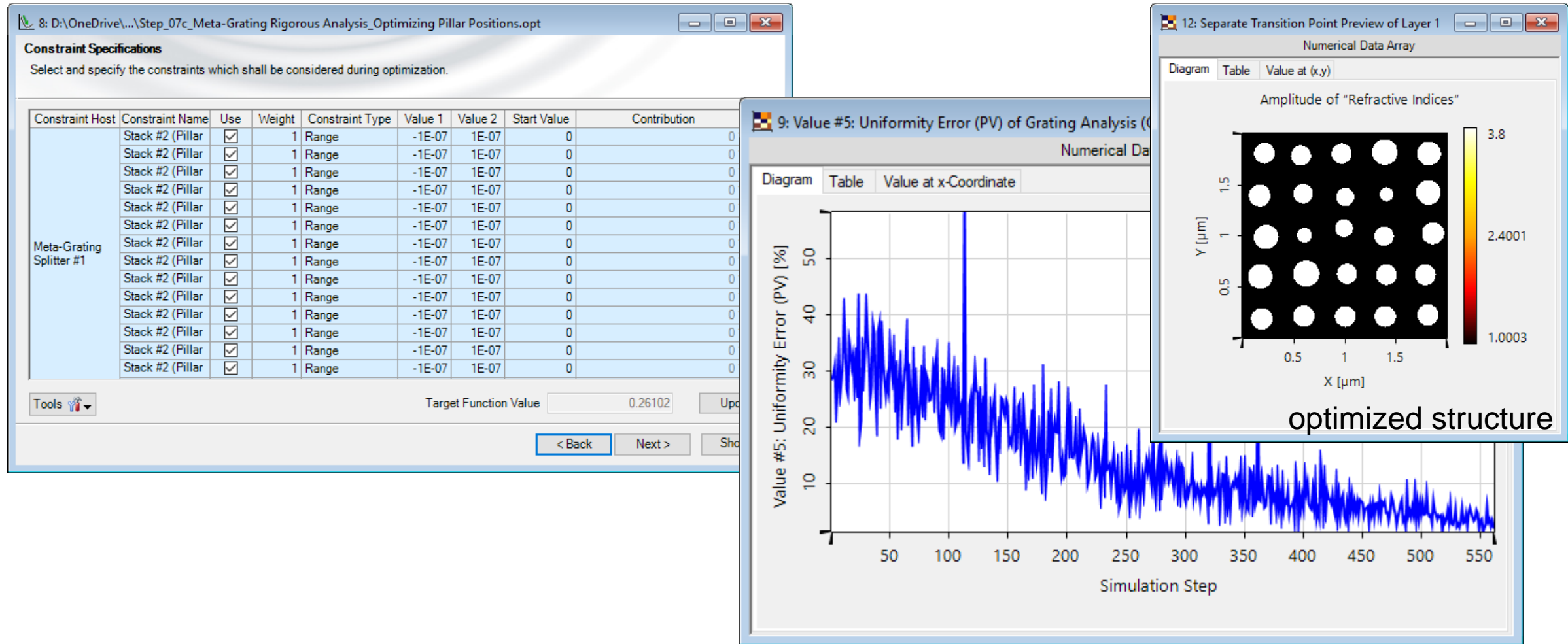
Constraint Host	Constraint Name	Use	Weight	Constraint Type	Value 1	Value 2	Start Value	Contribution
Meta-Grating Splitter #1	Stack #2 (Pillar)	<input checked="" type="checkbox"/>	1	Range	1E-07	3.6E-07	2.11E-07	0
	Stack #2 (Pillar)	<input checked="" type="checkbox"/>	1	Range	1E-07	3.6E-07	2.38E-07	0
	Stack #2 (Pillar)	<input checked="" type="checkbox"/>	1	Range	1E-07	3.6E-07	2.4E-07	0
	Stack #2 (Pillar)	<input checked="" type="checkbox"/>	1	Range	1E-07	3.6E-07	2.1E-07	0
	Stack #2 (Pillar)	<input checked="" type="checkbox"/>	1	Range	1E-07	3.6E-07	2.02E-07	0
	Stack #2 (Pillar)	<input checked="" type="checkbox"/>	1	Range	1E-07	3.6E-07	2.07E-07	0
	Stack #2 (Pillar)	<input checked="" type="checkbox"/>	1	Range	1E-07	3.6E-07	2.51E-07	0
	Stack #2 (Pillar)	<input checked="" type="checkbox"/>	1	Range	1E-07	3.6E-07	1.43E-07	0
	Stack #2 (Pillar)	<input checked="" type="checkbox"/>	1	Range	1E-07	3.6E-07	1.87E-07	0
	Stack #2 (Pillar)	<input checked="" type="checkbox"/>	1	Range	1E-07	3.6E-07	1.96E-07	0
	Stack #2 (Pillar)	<input checked="" type="checkbox"/>	1	Range	1E-07	3.6E-07	2.05E-07	0
	Stack #2 (Pillar)	<input checked="" type="checkbox"/>	1	Range	1E-07	3.6E-07	1.95E-07	0
	Stack #2 (Pillar)	<input checked="" type="checkbox"/>	1	Range	1E-07	3.6E-07	1.75E-07	0
	Stack #2 (Pillar)	<input checked="" type="checkbox"/>	1	Range	1E-07	3.6E-07	1.76E-07	0
Stack #2 (Pillar)	<input checked="" type="checkbox"/>	1	Range	1E-07	3.6E-07	1.98E-07	0	

Tools Target Function Value: 0.26102

< Back Next > Show



Step 7c: Optimization of Pillar Positions



Step 7d: Optimization of All Parameters

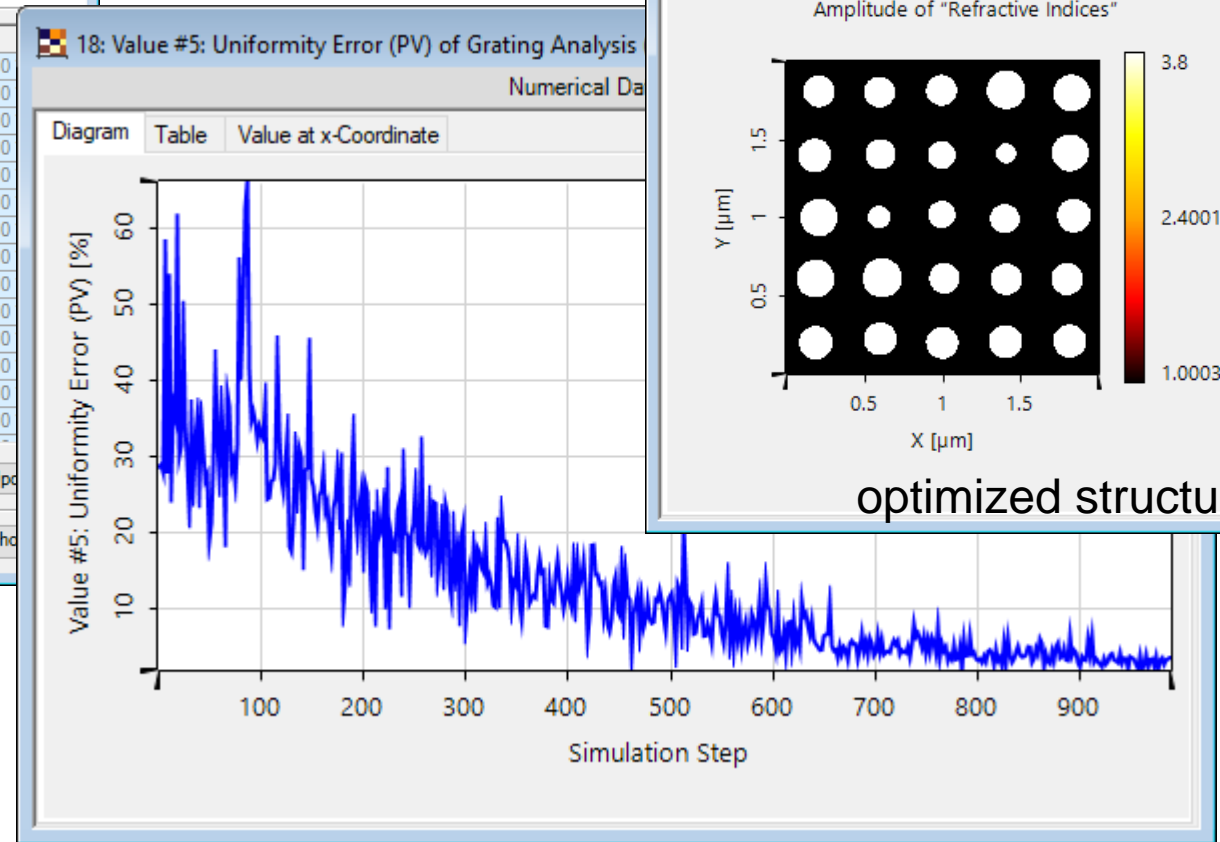
17: D:\OneDrive\...\Step_07d_Meta-Grating Rigorous Analysis_Optimizing All Parameters.opt

Constraint Specifications
Select and specify the constraints which shall be considered during optimization.

Constraint Host	Constraint Name	Use	Weight	Constraint Type	Value 1	Value 2	Start Value	Contribution
Meta-Grating Splitter #1	Stack #2 (Pillar)	<input checked="" type="checkbox"/>	1	Range	425 nm	500 nm	465 nm	0
	Stack #2 (Pillar)	<input checked="" type="checkbox"/>	1	Range	1E-07	3.6E-07	2.11E-07	0
	Stack #2 (Pillar)	<input checked="" type="checkbox"/>	1	Range	1E-07	3.6E-07	2.38E-07	0
	Stack #2 (Pillar)	<input checked="" type="checkbox"/>	1	Range	1E-07	3.6E-07	2.4E-07	0
	Stack #2 (Pillar)	<input checked="" type="checkbox"/>	1	Range	1E-07	3.6E-07	2.1E-07	0
	Stack #2 (Pillar)	<input checked="" type="checkbox"/>	1	Range	1E-07	3.6E-07	2.02E-07	0
	Stack #2 (Pillar)	<input checked="" type="checkbox"/>	1	Range	1E-07	3.6E-07	2.07E-07	0
	Stack #2 (Pillar)	<input checked="" type="checkbox"/>	1	Range	1E-07	3.6E-07	2.51E-07	0
	Stack #2 (Pillar)	<input checked="" type="checkbox"/>	1	Range	1E-07	3.6E-07	1.43E-07	0
	Stack #2 (Pillar)	<input checked="" type="checkbox"/>	1	Range	1E-07	3.6E-07	1.87E-07	0
	Stack #2 (Pillar)	<input checked="" type="checkbox"/>	1	Range	1E-07	3.6E-07	1.96E-07	0
	Stack #2 (Pillar)	<input checked="" type="checkbox"/>	1	Range	1E-07	3.6E-07	2.05E-07	0
	Stack #2 (Pillar)	<input checked="" type="checkbox"/>	1	Range	1E-07	3.6E-07	1.95E-07	0
	Stack #2 (Pillar)	<input checked="" type="checkbox"/>	1	Range	1E-07	3.6E-07	1.75E-07	0

Tools Target Function Value: 0.26102

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“Binary” Design Example

Step 1~3: Analysis of Single Pillar

- The procedure on finding proper pillar diameters is the same as in the previous example, and thus will not be repeated here.

Step 4: Calculate Phase-Only (3-Level) Transmission

8: D:\OneDrive\...\Step_04_Phase-Only Transmission Design_IFTA_400nm Pixel.dp

Specification Design Analysis

Input Field

Wavelength

Constant Input Field Arbitrary Input Field

Transmission

Sampling Points x

Sampling Distance x

Type of Transmission

Number of Quantization Levels

Output Field Requirements

Desired Output Field

Optimization Region

Sample Optimization Region from Desired Output Field

Allow Phase Freedom

Allow Scale Freedom

Limit Scale Factor According to Goal Efficiency

Propagation

Type of Propagation

Propagation Distance

Embed Frame Width

Pixelation Factor

Simulate Pixelation Exactly

Output Plane Sampling

Sampling Points x

Sampling Distance x

Field Size x

Use Angular Coordinates

Limit Stray Light

Maximum Relative Intensity of Stray Light

Limit Feature Size

Minimum Feature Size

Maximum Stray Light Intensity for Higher Frequencies

8: D:\OneDrive\...\Step_04_Phase-Only Transmission Design_IFTA_400nm Pixel.dp

Specification Design Analysis

Design Method Transmission

Design Steps

Design Steps	Number of Iterations	Method
<input checked="" type="checkbox"/> Generate Initial Transmission		<input type="text" value="Backward Propagated Desired Output Field (Ri)"/>
<input checked="" type="checkbox"/> Signal Phase Synthesis	<input type="text" value="25"/>	<input type="checkbox"/> Soft Introduction of Transmission Constraint
<input checked="" type="checkbox"/> SNR Optimization for Phase-Only Transmission	<input type="text" value="50"/>	<input type="checkbox"/> Omit Final Transmission Projection
<input checked="" type="checkbox"/> Soft Quantization	<input type="text" value="100"/>	<input type="checkbox"/> Soft Introduction of Transmission Constraint
<input checked="" type="checkbox"/> SNR Optimization for Quantized Transmission	<input type="text" value="5000"/>	<input type="checkbox"/> Create Transmission Animation <input type="button" value="Options"/>
		<input type="checkbox"/> Create Output Field Animation <input type="button" value="Options"/>
		<input type="checkbox"/> Show Final Transmission and Output Field

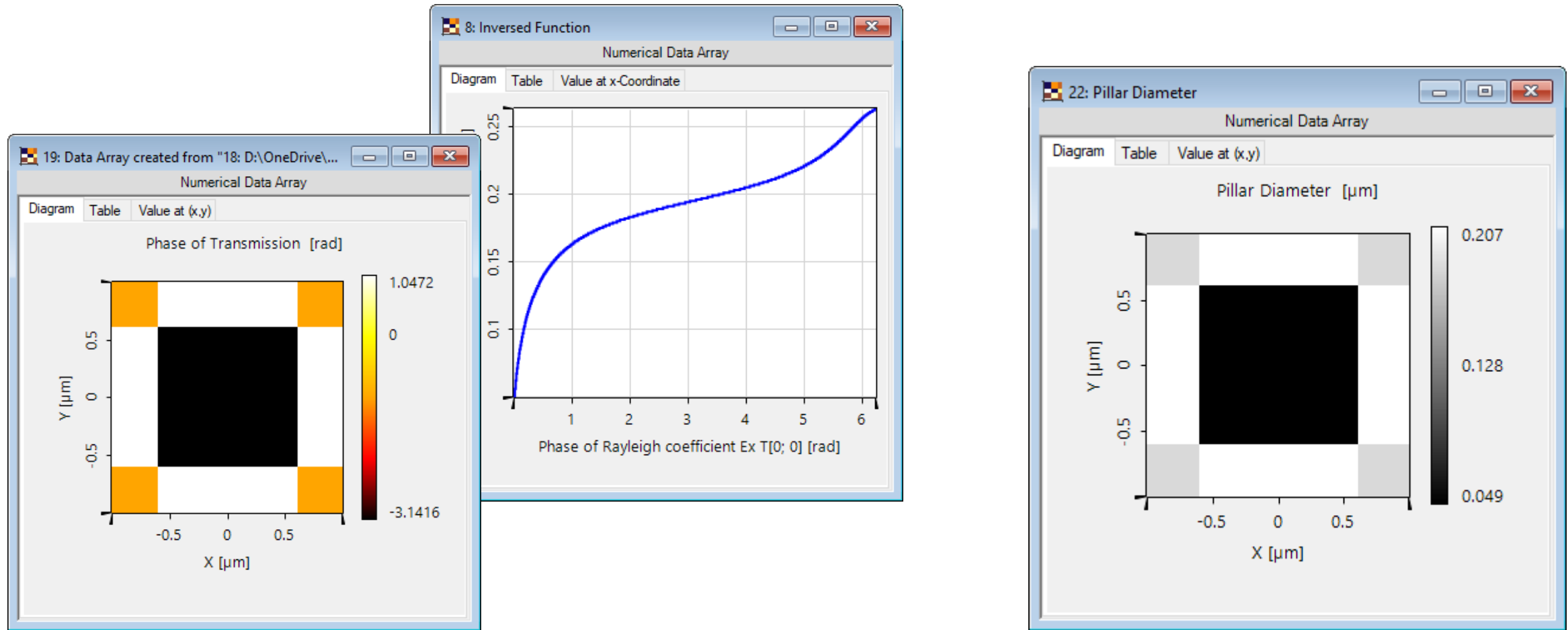
Logging

Enable Logging

Preserve Table

Progress in current design step

Step 5: From Phase Profile to Structure



Step_05_Calculate Pillar Diameters from Phase Profile_2D Regular Array.cs

Step 6: Load Meta-Grating Structure in FMM Simulation

The 'Edit Stack' dialog box displays a 3D visualization of a 'Base Block' with a meta-grating structure. The structure consists of a series of horizontal layers. The parameters for the meta-grating are as follows:

Index	z-Distance	z-Position	Interface	Subsequent Medium
1	0 mm	0 mm	Plane Interface	Cylinder Pillars [2D...]
2	465 nm	465 nm	Plane Interface	Air in Homogeneous M...

The 'Parameters' section for the 'Cylinder Pillars' includes:

- PillarHeight: 465 nm
- PitchX: 400 nm
- PitchY: 400 nm
- PillarDiameters: Edit...
- DiameterDefinitionMode: 0
- SideWallSlopeAngle: 90°
- RoundedEdgeRadiusTop: 0 mm

The 'Validity' section shows:

- Validity:
- Period: Stack Period is Independent from Interface/Media
- Stack Period: 2 μm

The 'Index Modulation' section includes:

- Snippet defines: Index Modulation
- Definition: Edit...
- Parameters: SideWallSlopeAngle (90°), RoundedEdgeRadiusTop (0 mm), RoundedEdgeRadiusBottom (0 mm), PillarPositionDeviationX (Edit...), PillarPositionDeviationY (Edit...), PillarMaterial: "ConstantIndexMaterial" (Load, Edit, View), EmbedMaterial: "Air" (Load, Edit, View)

Annotations:


- "Load the pillar diameter information here" points to the 'PillarDiameters' 'Edit...' button.
- "Define pillar position deviations here" points to the 'PillarPositionDeviationX' and 'PillarPositionDeviationY' 'Edit...' buttons.

Step 7a: Optimization of Pillar Height

23: D:\OneDrive\...\Step_07a_Meta-Grating Rigorous Analysis_Optimizing Pillar Height.opt

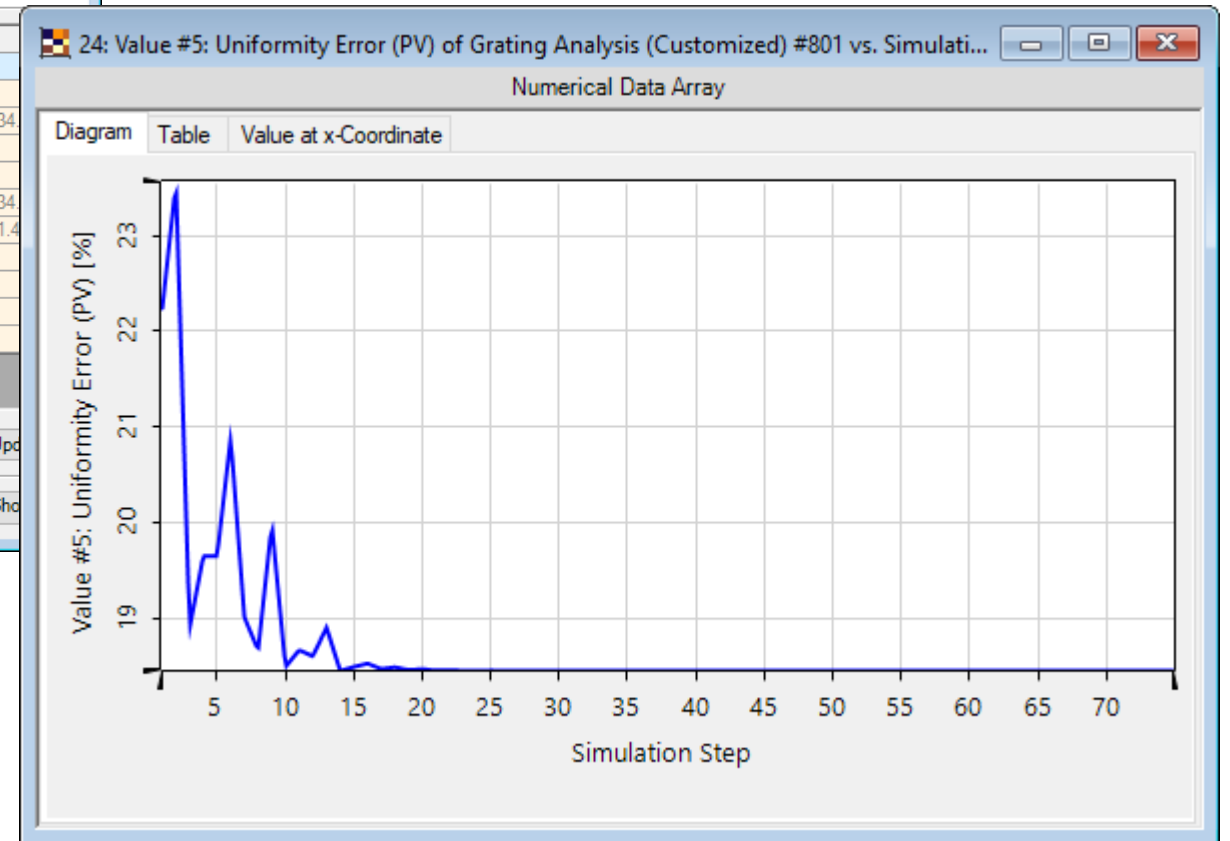
Constraint Specifications
Select and specify the constraints which shall be considered during optimization.

Constraint Host	Constraint Name	Use	Weight	Constraint Type	Value 1	Value 2	Start Value	Contribution
Meta-Grating	Stack #2 (Pillar)	<input checked="" type="checkbox"/>	1	Range	450 nm	480 nm	465 nm	
Grating Analysis (Customized) #801	Value #1:	<input type="checkbox"/>						
	Value #2:	<input checked="" type="checkbox"/>	1	Target Value	1		0.74415	34
	Value #3:	<input type="checkbox"/>						
	Value #4:	<input type="checkbox"/>						
	Value #5:	<input checked="" type="checkbox"/>	1.33	Target Value	0		0.22244	34
	Value #6:	<input checked="" type="checkbox"/>	3	Target Value	0		0.14178	31.4
	Value #7:	<input type="checkbox"/>						
	Value #8:	<input type="checkbox"/>						
	Value #9:	<input type="checkbox"/>						
	Value #10:	<input type="checkbox"/>						

Tools  Target Function Value: 0.19157

< Back Next > Show

Not very effective on the optimization



Step 7b: Optimization of Pillar Diameters

25: D:\OneDrive\...\Step_07b_Meta-Grating Rigorous Analysis_Optimizing Pillar Diameters.opt

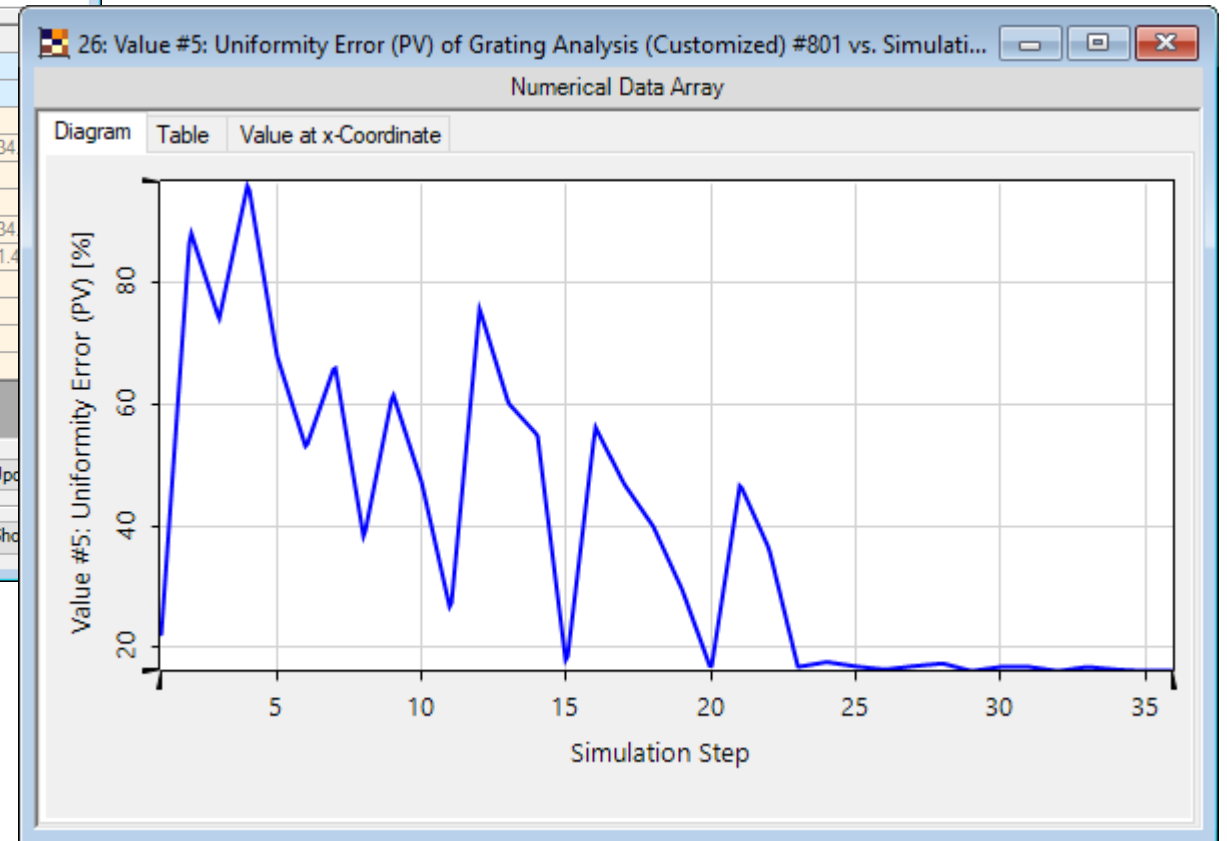
Constraint Specifications
Select and specify the constraints which shall be considered during optimization.

Constraint Host	Constraint Name	Use	Weight	Constraint Type	Value 1	Value 2	Start Value	Contribution
Optical Setup Parameter	Global	<input checked="" type="checkbox"/>	1	Range	100 nm	330 nm	184 nm	
	Global	<input checked="" type="checkbox"/>	1	Range	100 nm	330 nm	208 nm	
Grating Analysis (Customized) #801	Value #1:	<input type="checkbox"/>						
	Value #2:	<input checked="" type="checkbox"/>	1	Target Value	1		0.74415	34
	Value #3:	<input type="checkbox"/>						
	Value #4:	<input type="checkbox"/>						
	Value #5:	<input checked="" type="checkbox"/>	1.33	Target Value	0		0.22244	34
	Value #6:	<input checked="" type="checkbox"/>	3	Target Value	0		0.14178	31.4
	Value #7:	<input type="checkbox"/>						
	Value #8:	<input type="checkbox"/>						
	Value #9:	<input type="checkbox"/>						
	Value #10:	<input type="checkbox"/>						

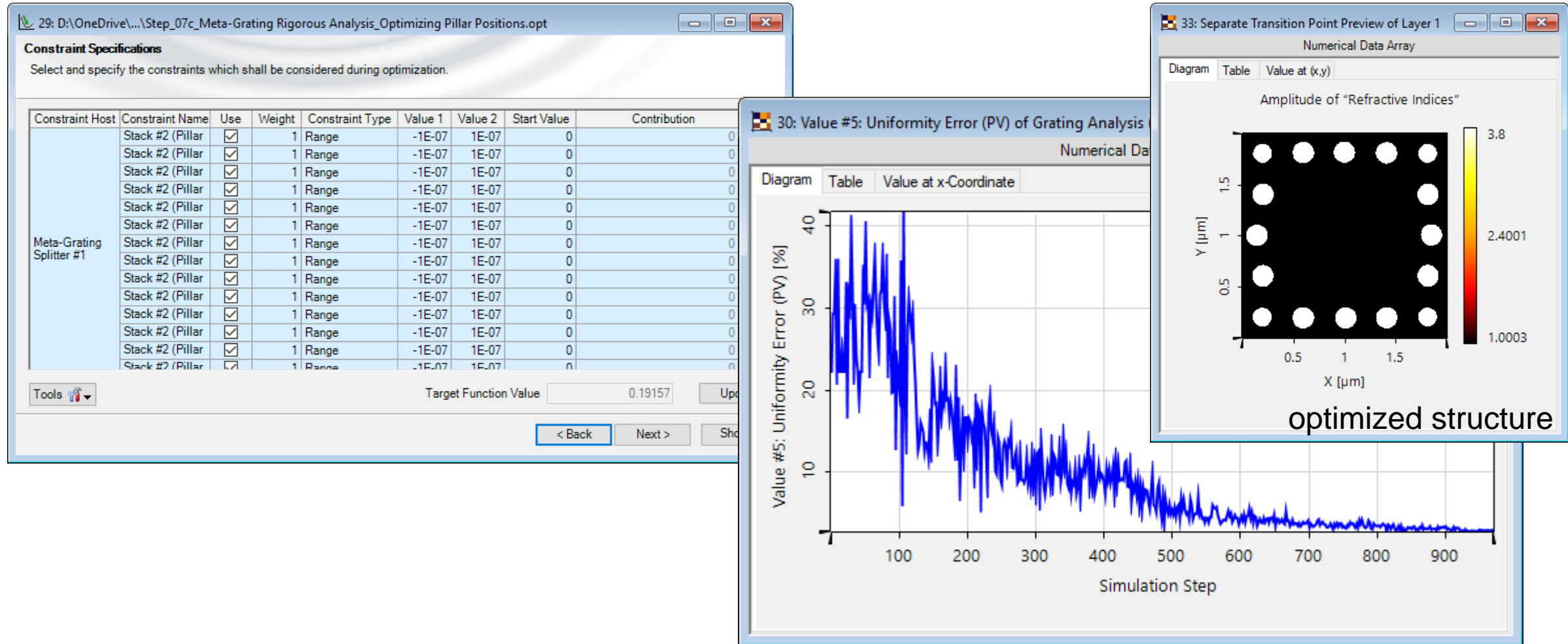
Tools Target Function Value: 0.19157

< Back Next > Show

Not very effective on the optimization



Step 7c: Optimization of Pillar Positions



Step 7d: Optimization of All Parameters

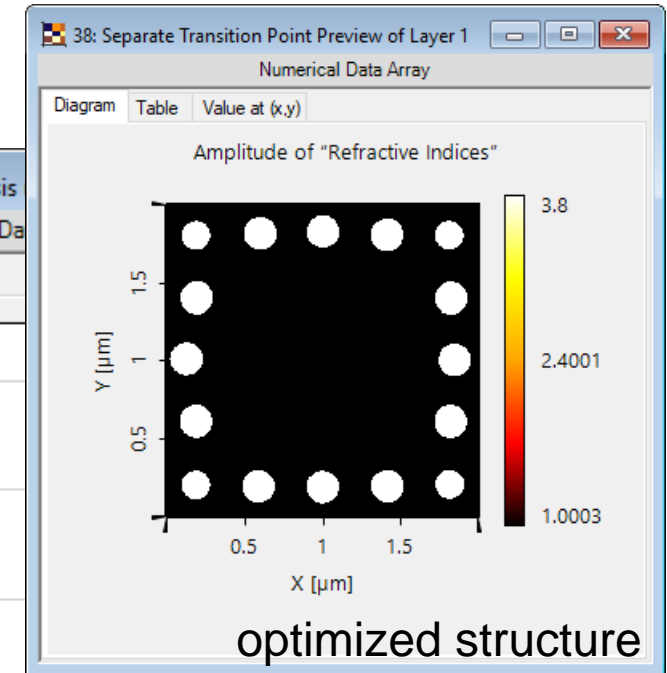
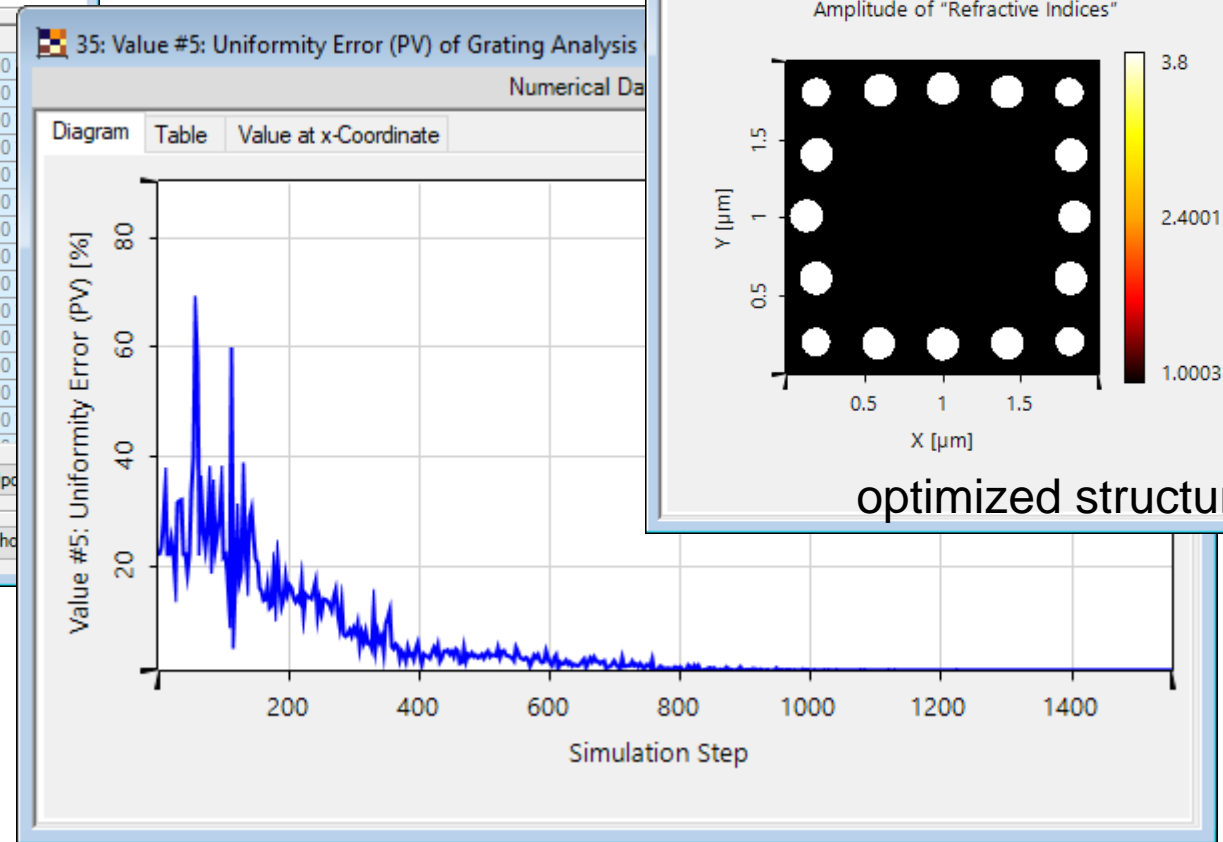
34: D:\OneDrive\...\Step_07d_Meta-Grating Rigorous Analysis_Optimizing All Parameters.opt

Constraint Specifications
Select and specify the constraints which shall be considered during optimization.

Constraint Host	Constraint Name	Use	Weight	Constraint Type	Value 1	Value 2	Start Value	Contribution
Optical Setup Parameter	Global	<input checked="" type="checkbox"/>	1	Range	100 nm	330 nm	184 nm	0
	Global	<input checked="" type="checkbox"/>	1	Range	100 nm	330 nm	208 nm	0
Meta-Grating Splitter #1	Stack #2 (Pillar)	<input checked="" type="checkbox"/>	1	Range	450 nm	480 nm	465 nm	0
	Stack #2 (Pillar)	<input checked="" type="checkbox"/>	1	Range	-1E-07	1E-07	0	0
	Stack #2 (Pillar)	<input checked="" type="checkbox"/>	1	Range	-1E-07	1E-07	0	0
	Stack #2 (Pillar)	<input checked="" type="checkbox"/>	1	Range	-1E-07	1E-07	0	0
	Stack #2 (Pillar)	<input checked="" type="checkbox"/>	1	Range	-1E-07	1E-07	0	0
	Stack #2 (Pillar)	<input checked="" type="checkbox"/>	1	Range	-1E-07	1E-07	0	0
	Stack #2 (Pillar)	<input checked="" type="checkbox"/>	1	Range	-1E-07	1E-07	0	0
	Stack #2 (Pillar)	<input checked="" type="checkbox"/>	1	Range	-1E-07	1E-07	0	0
	Stack #2 (Pillar)	<input checked="" type="checkbox"/>	1	Range	-1E-07	1E-07	0	0
	Stack #2 (Pillar)	<input checked="" type="checkbox"/>	1	Range	-1E-07	1E-07	0	0
	Stack #2 (Pillar)	<input checked="" type="checkbox"/>	1	Range	-1E-07	1E-07	0	0
	Stack #2 (Pillar)	<input checked="" type="checkbox"/>	1	Range	-1E-07	1E-07	0	0

Tools Target Function Value: 0.19157

< Back Next > Show



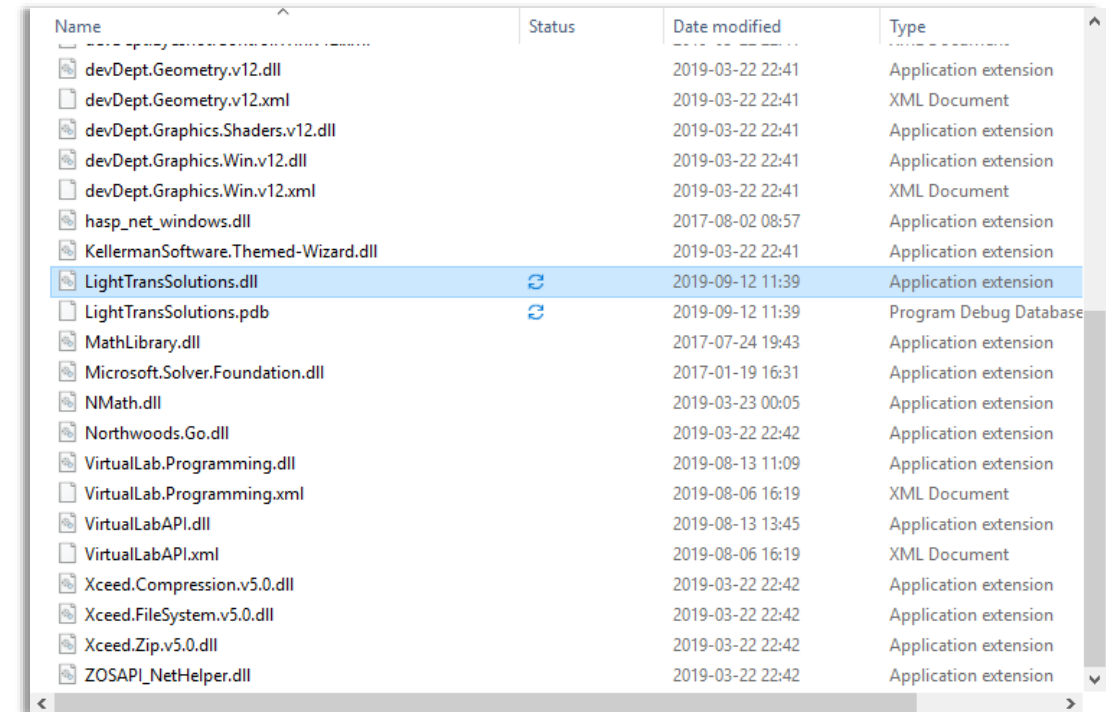
Appendix: How to Use LightTransSolutions.dll?



- Make a copy of

LightTransSolutions.dll

- Paste it into the installation location of VirtualLab Fusion, e.g.,

*C:\Program Files\Wyrowski
Photonics\VirtualLab Fusion (7.5.0)*



Name	Status	Date modified	Type
devDept.Geometry.v12.dll		2019-03-22 22:41	Application extension
devDept.Geometry.v12.xml		2019-03-22 22:41	XML Document
devDept.Graphics.Shaders.v12.dll		2019-03-22 22:41	Application extension
devDept.Graphics.Win.v12.dll		2019-03-22 22:41	Application extension
devDept.Graphics.Win.v12.xml		2019-03-22 22:41	XML Document
hasp_net_windows.dll		2017-08-02 08:57	Application extension
KellermanSoftware.Themed-Wizard.dll		2019-03-22 22:41	Application extension
LightTransSolutions.dll		2019-09-12 11:39	Application extension
LightTransSolutions.pdb		2019-09-12 11:39	Program Debug Database
MathLibrary.dll		2017-07-24 19:43	Application extension
Microsoft.Solver.Foundation.dll		2017-01-19 16:31	Application extension
NMath.dll		2019-03-23 00:05	Application extension
Northwoods.Go.dll		2019-03-22 22:42	Application extension
VirtualLab.Programming.dll		2019-08-13 11:09	Application extension
VirtualLab.Programming.xml		2019-08-06 16:19	XML Document
VirtualLabAPI.dll		2019-08-13 13:45	Application extension
VirtualLabAPI.xml		2019-08-06 16:19	XML Document
Xceed.Compression.v5.0.dll		2019-03-22 22:42	Application extension
Xceed.FileSystem.v5.0.dll		2019-03-22 22:42	Application extension
Xceed.Zip.v5.0.dll		2019-03-22 22:42	Application extension
ZOSAPI_NetHelper.dll		2019-03-22 22:42	Application extension

Document Information

title	Two-Dimensional Meta-Gratings Modeling and Design
document code	Demo.15
version	1.0
VL version used for simulations	VirtualLab Fusion Summer Release 2019 (7.6.1.18)
category	Demo
further reading	
