

# **Analysis and Design of Highly Efficient Polarization Independent Transmission Gratings**

# Abstract

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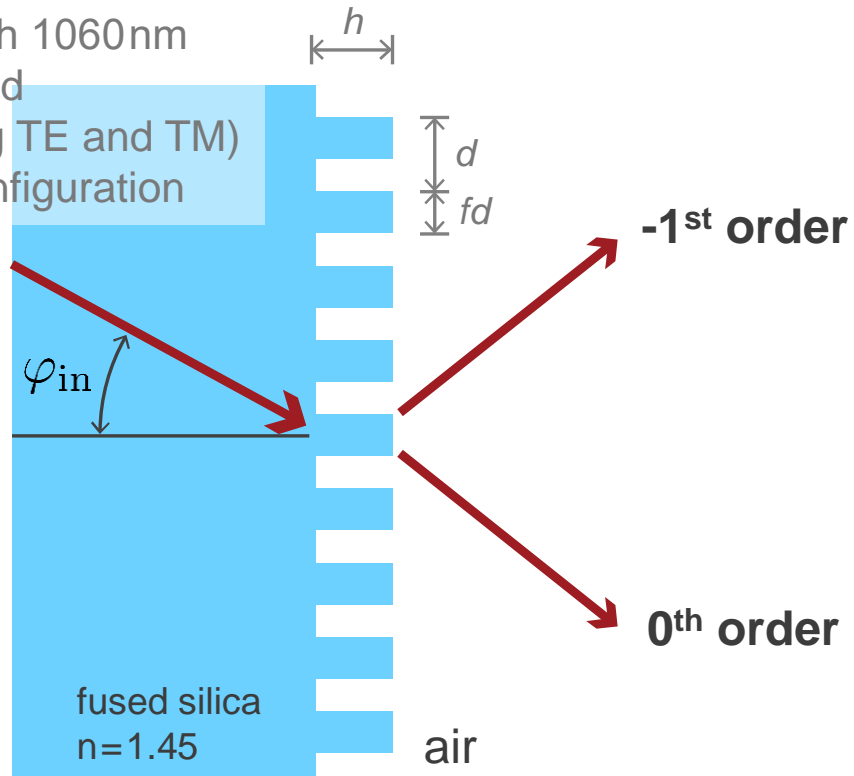


Gratings, especially those with feature size comparable to the wavelength, are known to possess polarization-dependent optical properties. That makes it difficult to design gratings with high diffraction efficiencies for arbitrary polarizations. Following the concept reported in literature [T. Clausnitzer, *et al.*, Proc. SPIE **5252**, 174-182 (2003)], we show how to analyze the polarization-dependent property of gratings rigorously, as well as how to use parametric optimization to design polarization-independent gratings with high diffraction efficiency.

# Design Task

## plane wave

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



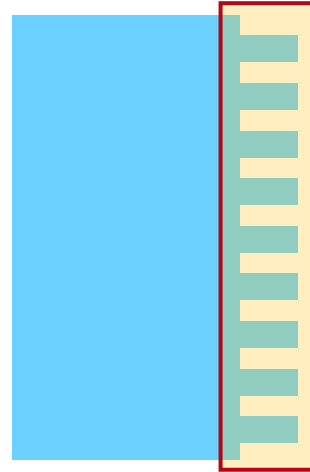
How to optimized the grating structure parameters so to maximize the diffraction efficiency of  $-1^{st}$  transmission order, for unpolarized input light?

?

Parameter	Value Range
grating depth $h$	0.1 - 10 $\mu$ m
grating period $d$	550 - 1350nm
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)

# Connected Modeling Techniques: Grating Structure



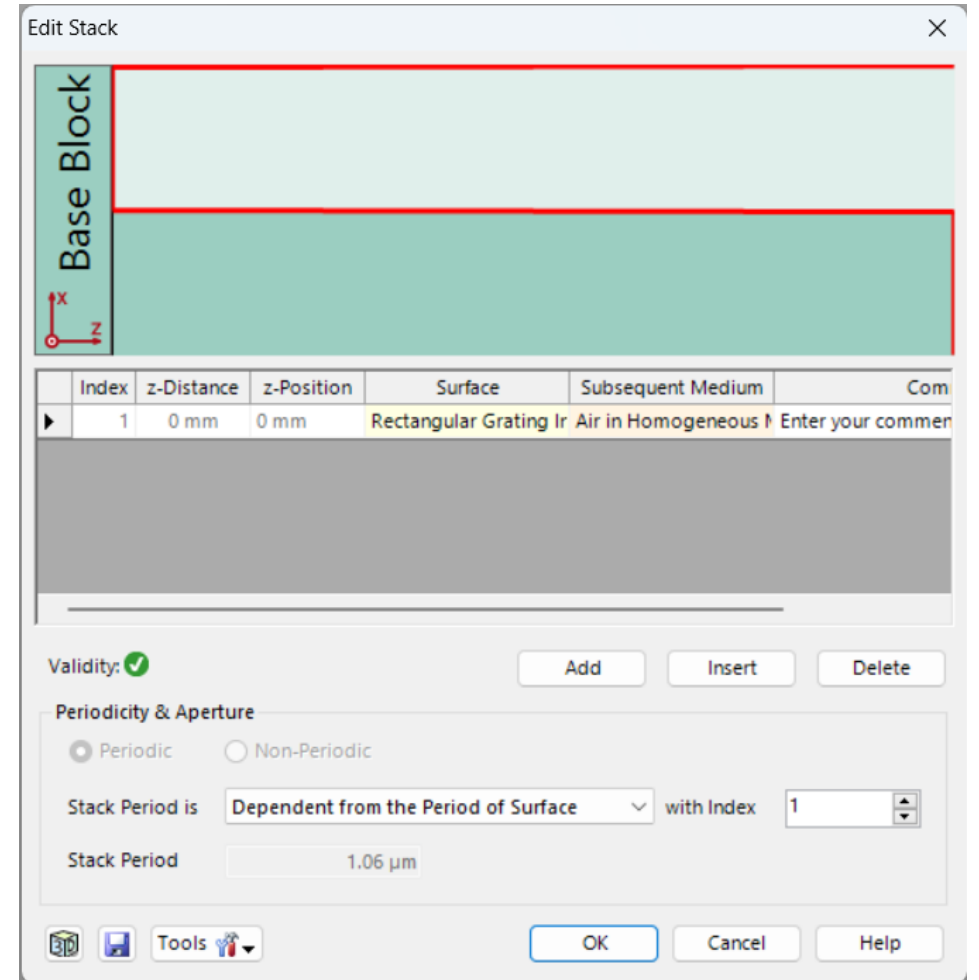
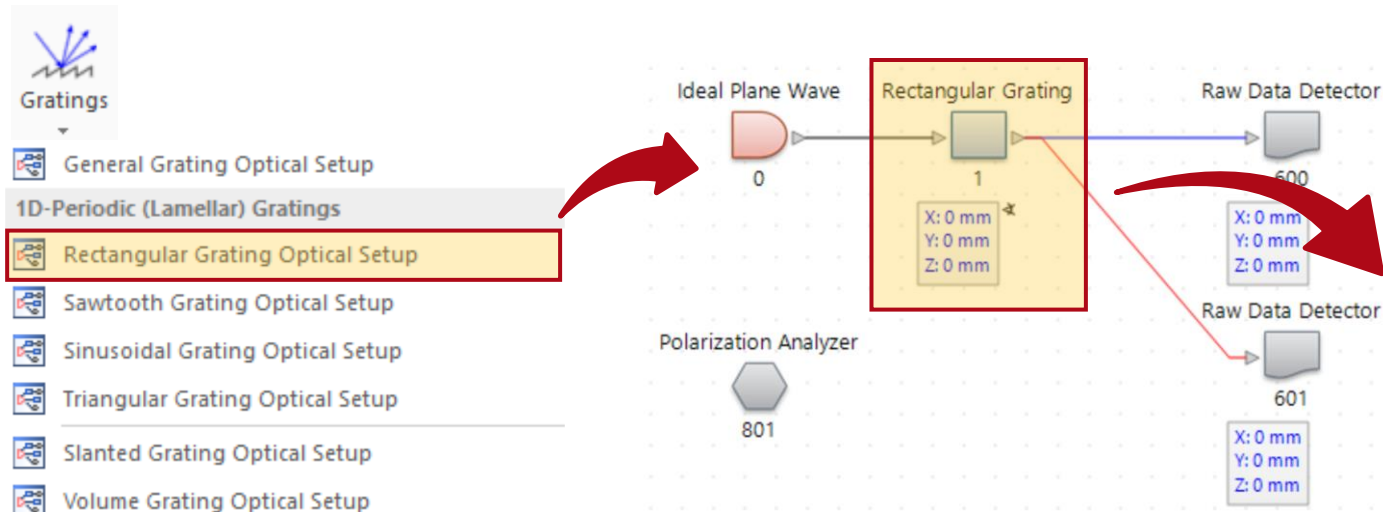
Available modeling techniques for microstructures:

Methods	Preconditions	Accuracy	Speed	Comments
Functional Approach	-	low	very high	diffraction angles acc. to grating equation; manual efficiencies
Thin Element Approximation (TEA)	smallest features $> \sim 10\lambda$	high	very high	inaccurate for larger NA and thick elements; x-domain
	smallest features $< \sim 2\lambda$	low	very high	
Fourier Modal Method (FMM)	period $< \sim (5\lambda \times 5\lambda)$	very high	high	rigorous solution; fast for structures and periods similar to the wavelength; more demanding for larger periods; k-domain
	period $> \sim (15\lambda \times 15\lambda)$	very high	slow	



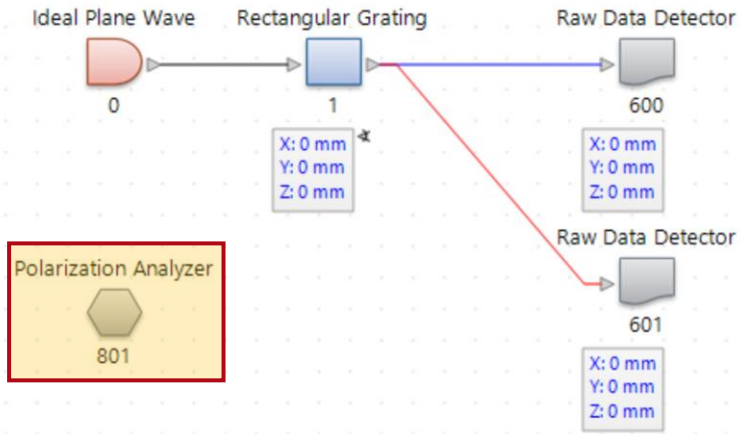
Due to the small feature sizes (in the order of magnitude of the wavelength), the **Fourier Modal Method (FMM)** provides a very accurate and fast solution and hence is used for the analysis.

# Grating Optical Setup



With the *Grating Package*, the user gains access to the grating specific optical setup that allows for a deeper investigation of different kind of gratings by applying the Fourier Modal method (FMM), which is also known as rigorous coupled wave analysis (RCWA).

# Polarization Analyzer



One of these tools is the *Polarization Analyzer*, which allows for the definition of different coordinate systems and has an inbuilt *Parameter Run* function.

More Information under:

 [Polarization Analyzer](#)

Transmission  Reflection

Analyzed Orders  
 Selection Strategy: Order Range

	X	Y
Minimum Order	-1	-3
Maximum Order	-1	3

Polarization Refers to: TE-TM Coordinate System

Output  
 Efficiency for TM-Polarization  Polarization Contrast  
 Efficiency for TE-Polarization  Average Efficiency

Vary Wavelength and/or Orientation  
 Orientation Definition Type: Cartesian Angles

Parameter	Vary	From	To	Steps	Step Size
Wavelength	<input checked="" type="checkbox"/>	193 nm	3.71 $\mu\text{m}$	2	3.517 $\mu\text{m}$
Cartesian Angle Alpha	<input checked="" type="checkbox"/>	-180°	180°	2	360°
Cartesian Angle Beta	<input checked="" type="checkbox"/>	-180°	180°	2	360°
Angle Zeta	<input type="checkbox"/>	-1e+300°	1e+300°	1	2e+300°

Advanced Output  
 Diagram  Minimum  
 Uniformity Error  Maximum

OK Cancel Help

Transmission  Reflection

Analyzed Orders  
 Selection Strategy: Order Range

	X	Y
Minimum Order	-1	-3
Maximum Order	-1	3

Polarization Refers to:
 

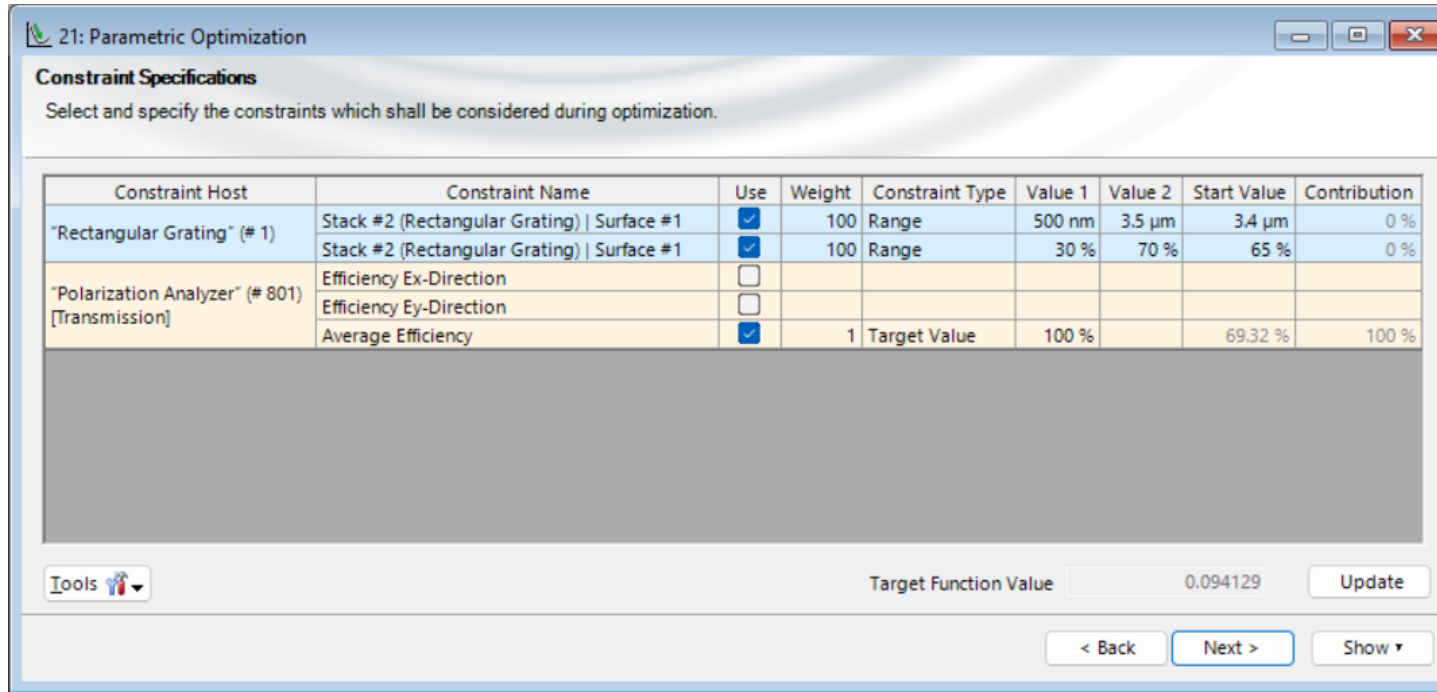
- TE-TM Coordinate System
- Coordinate System of Grating
- Coordinate System of Light Source
- p-s Coordinate System**
- TE-TM Coordinate System

Output  
 Efficiency for TM-Polarization  Polarization Contrast  
 Efficiency for TE-Polarization  Average Efficiency

Vary Wavelength and/or Orientation

OK Cancel Help


# Optimization



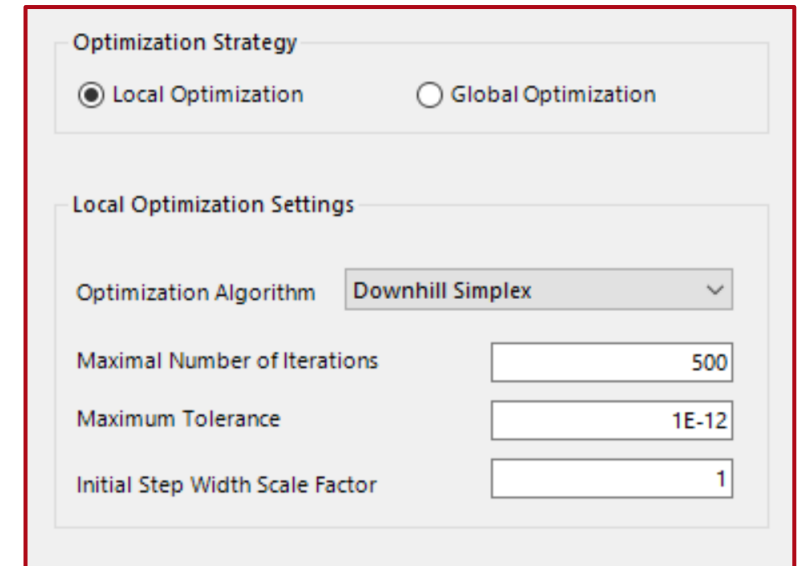
21: Parametric Optimization

**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
"Rectangular Grating" (# 1)	Stack #2 (Rectangular Grating)   Surface #1	<input checked="" type="checkbox"/>	100	Range	500 nm	3.5 $\mu\text{m}$	3.4 $\mu\text{m}$	0 %
	Stack #2 (Rectangular Grating)   Surface #1	<input checked="" type="checkbox"/>	100	Range	30 %	70 %	65 %	0 %
"Polarization Analyzer" (# 801) [Transmission]	Efficiency Ex-Direction	<input type="checkbox"/>						
	Efficiency Ey-Direction	<input type="checkbox"/>						
	Average Efficiency	<input checked="" type="checkbox"/>	1	Target Value	100 %		69.32 %	100 %

Tools  Target Function Value: 0.094129 Update

< Back Next > Show ▾



**Optimization Strategy**

Local Optimization  Global Optimization

**Local Optimization Settings**

Optimization Algorithm: Downhill Simplex ▾

Maximal Number of Iterations:

Maximum Tolerance:

Initial Step Width Scale Factor:

In order to find optimized grating parameters, the *Optimization* document enables the definition of parameter constraints and weights for the target values. Find more information under

[!\[\]\(9dfdaff1d86ba3c1f8353b4d1b61b8c5\_img.jpg\) Introduction to the Parametric Optimization Document](#)

# Parameter Run

22: Parameter Run

Parameter Specification

Set up the parameter(s) to be varied.

You can select one or more parameters which shall be varied as well as the resulting number of iterations. Several [modes](#) are available specifying how the parameters are varied per iteration.

Usage Mode: **Scanning** Number of Iterations: 1891

Filter by...

1	2	*	Object	Category	Parameter	Vary	From	To	Steps	Step Size
			"Rectangular Grating" (# 1)	Stack #2 (Rectangular Grati...	Surface #1 (Rectangular Grating Interf...	<input checked="" type="checkbox"/>	2 μm	3.5 μm	61	25 nm
					Surface #1 (Rectangular Grating Interf...	<input checked="" type="checkbox"/>	50 %	80 %	31	1 %

Iteration Step									
3	4	5	6	7	8	9	10	11	
2 μm	2 μm	2 μm	2 μm	2 μm	2 μm	2 μm	2 μm	2 μm	2 μm
52 %	53 %	54 %	55 %	56 %	57 %	58 %	59 %	60 %	
94.202 %	94.348 %	94.404 %	94.367 %	94.239 %	94.015 %	93.69 %	93.259 %	92.716 %	
93.407 %	93.522 %	93.566 %	93.541 %	93.449 %	93.291 %	93.065 %	92.768 %	92.399 %	
94.996 %	95.174 %	95.241 %	95.194 %	95.029 %	94.738 %	94.315 %	93.75 %	93.033 %	

< Back Next > Show ▾

The *Parameter Run* is designed to help the optical engineer investigate the effect of varying parameters and manufacturing deviations. It is possible to define which parameters shall be varied and to either investigate all possible combinations by choosing *Scanning* mode or to only randomly pick a sample by choosing *Random* mode. As in this example only a few parameters are varied, *Scanning* mode was chosen.



# Considerations on Grating Period Choice

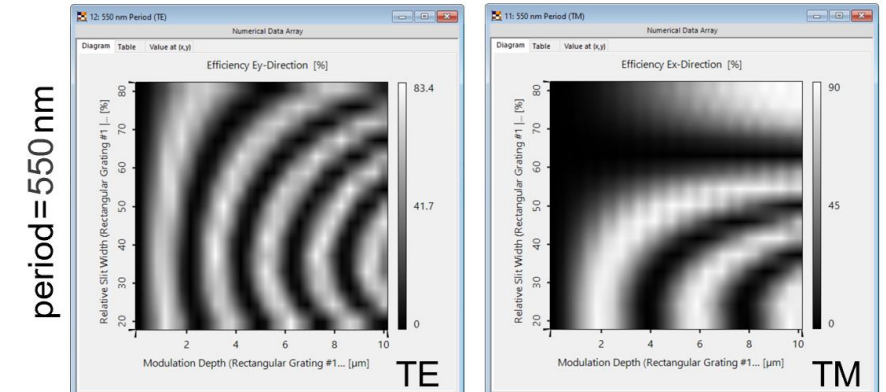
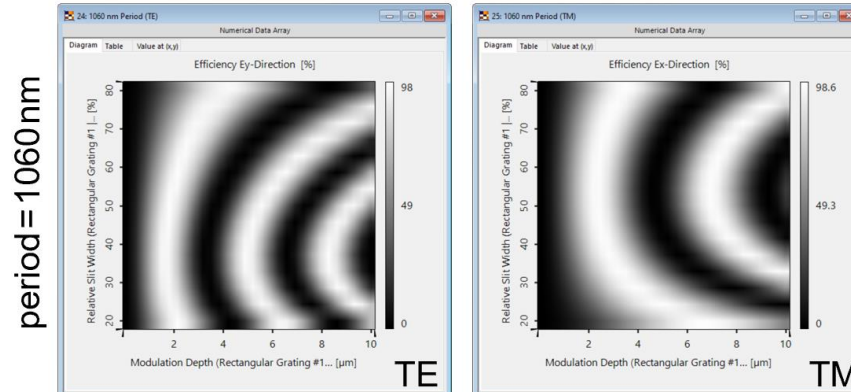
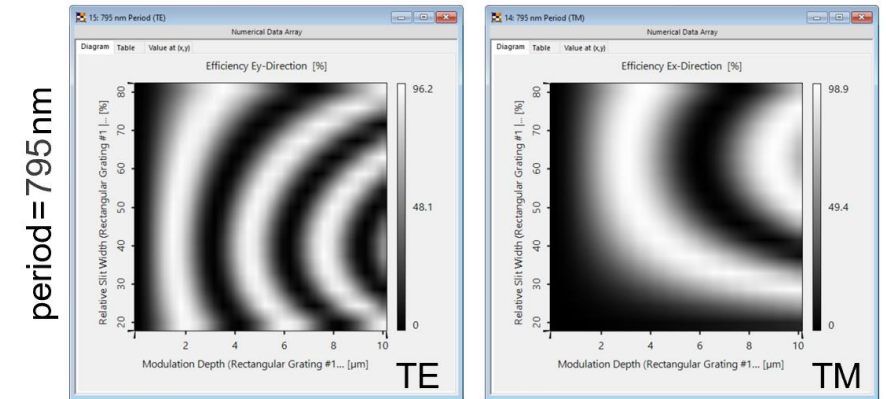
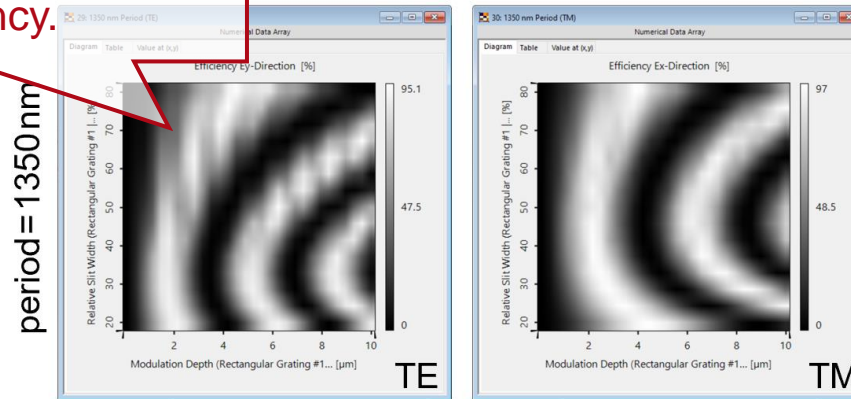
Large period leads to higher diffraction orders in the substrate, and causes additional modulation in the efficiency.

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

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

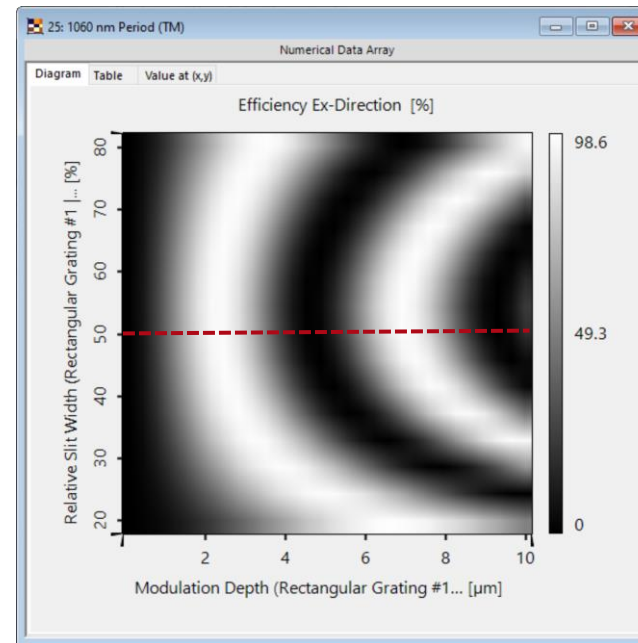
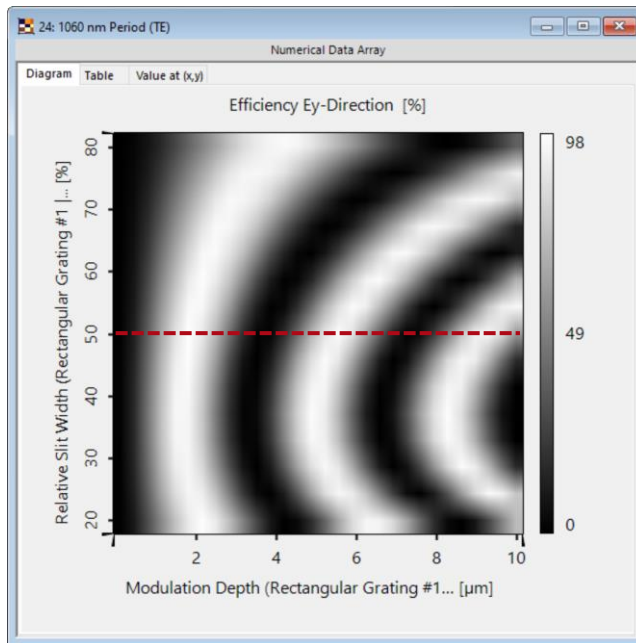
$$\lambda/2 < d < 3\lambda/2n$$

where  $n$  is the refractive index of the substrate.

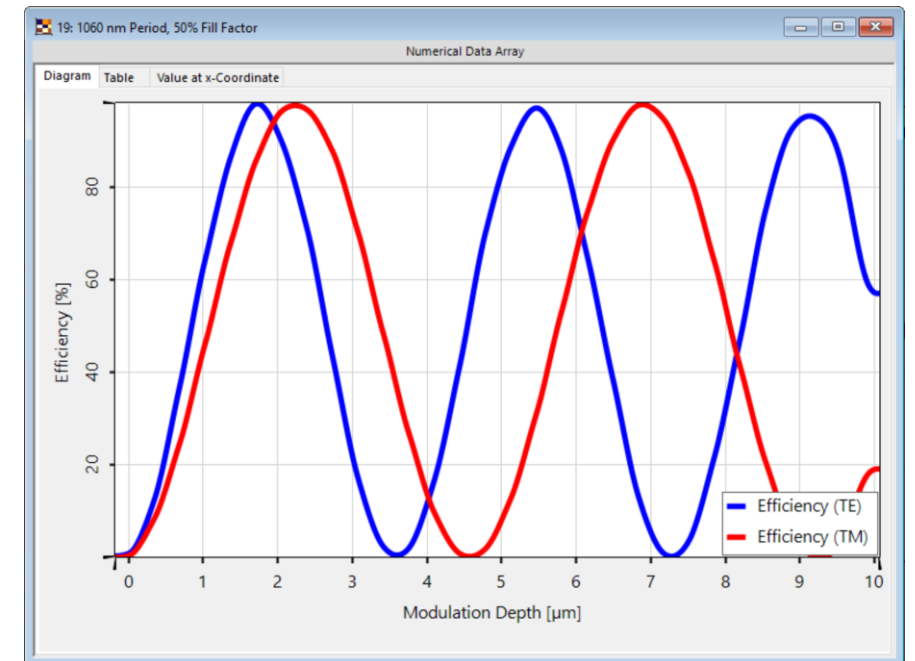


# Polarization-Dependent Diffraction Property

diffraction efficiency analysis for given period 1060nm



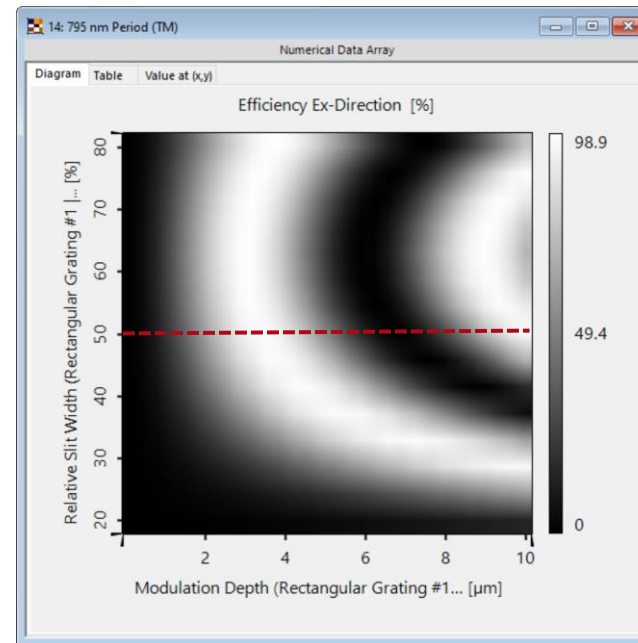
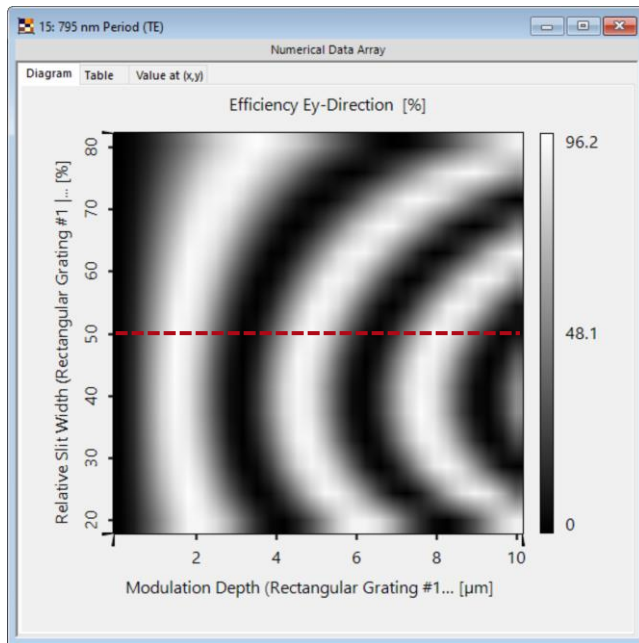
diffraction efficiencies vs. grating depth  
(grating period=1060nm, fill factor=50%)



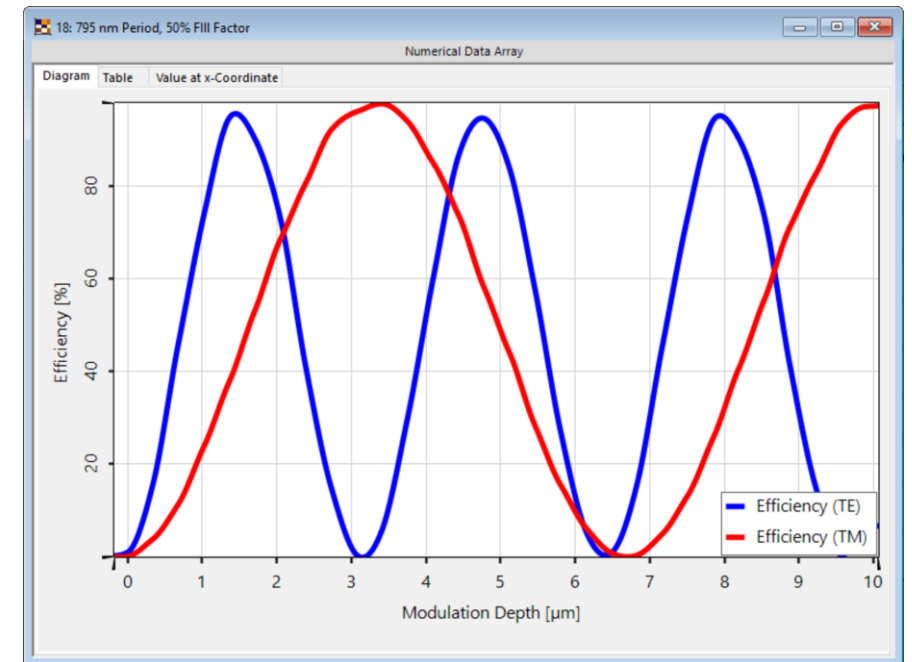
Parameter	Value
grating depth $h$	0.1-10μm
grating period $d$	<b>1060nm</b>
fill factor $f$	20-80%

# Polarization-Dependent Diffraction Property

diffraction efficiency analysis for given period 795 nm



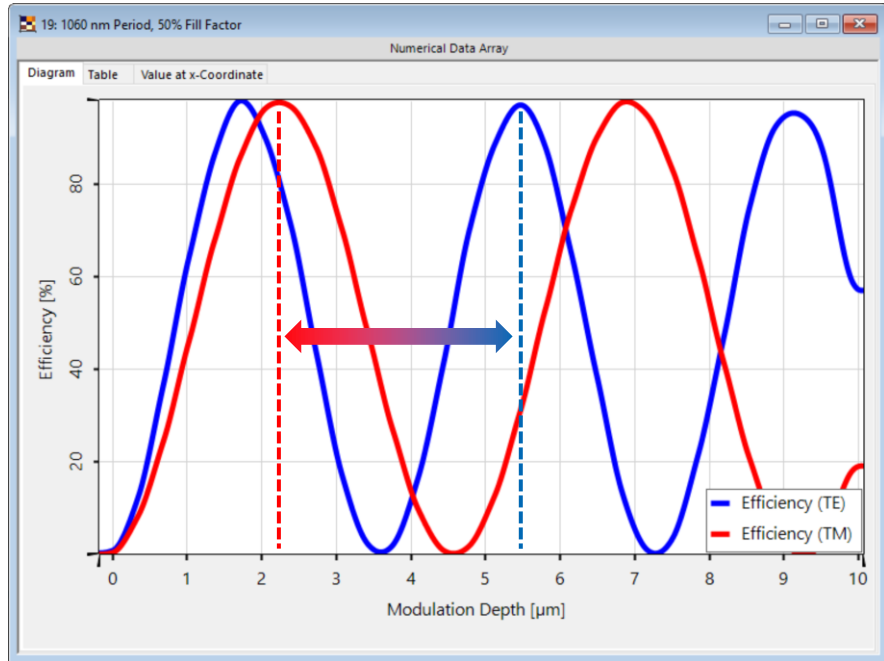
diffraction efficiencies vs. grating depth  
(grating period=795 nm, fill factor=50%)



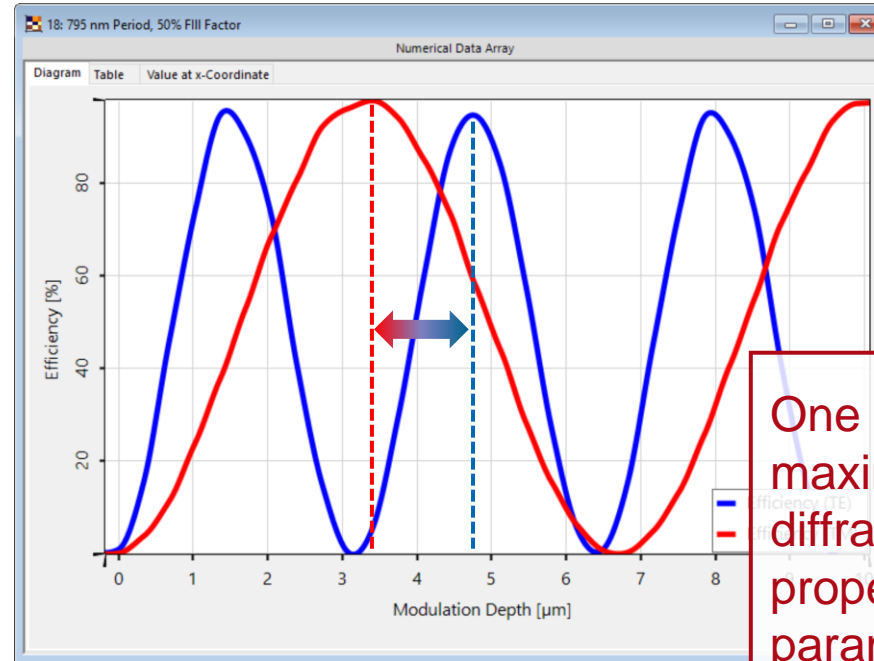
Parameter	Value
grating depth $h$	0.1-10 μm
grating period $d$	<b>795 nm</b>
fill factor $f$	20-80%

# Polarization-Dependent Diffraction Property

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



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



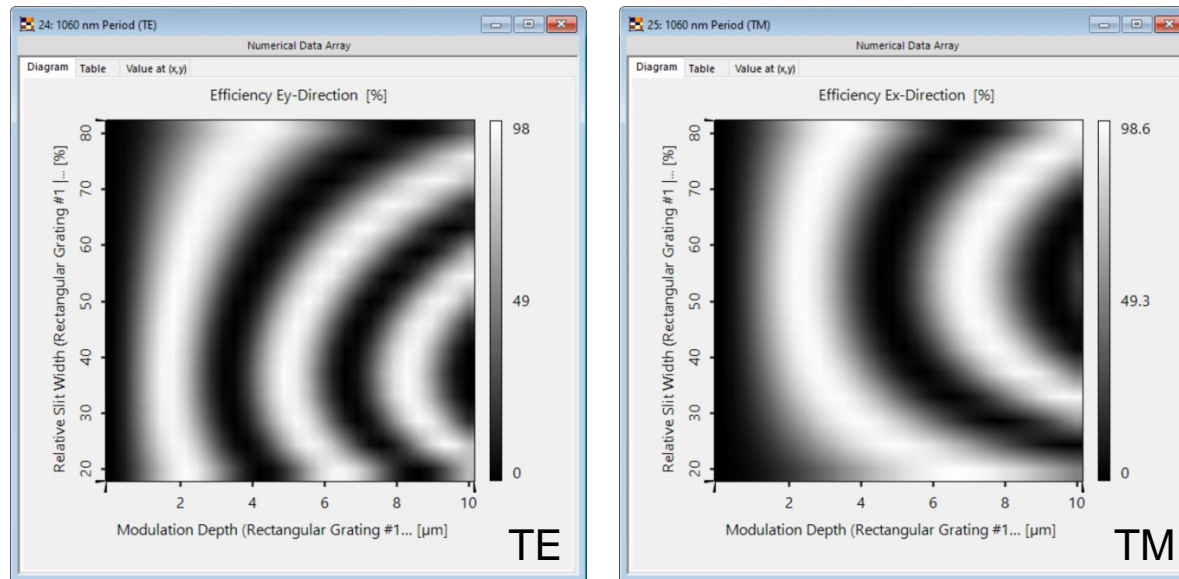
One could simultaneously maximize the TE and TM diffraction efficiencies by proper choice of grating parameters, e.g., period, depth, and fill factor.

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.

# 2D Parametric Optimization with Fixed Period

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



The average diffraction efficiency can be defined as

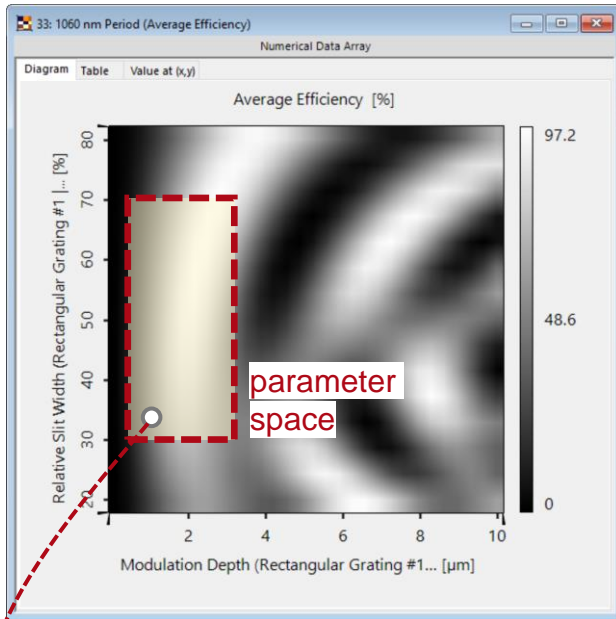
$$\eta^{\text{avg}} = \frac{1}{2} (\eta^{\text{TE}} + \eta^{\text{TM}}) ,$$

and it is to be maximized within the following parameter range

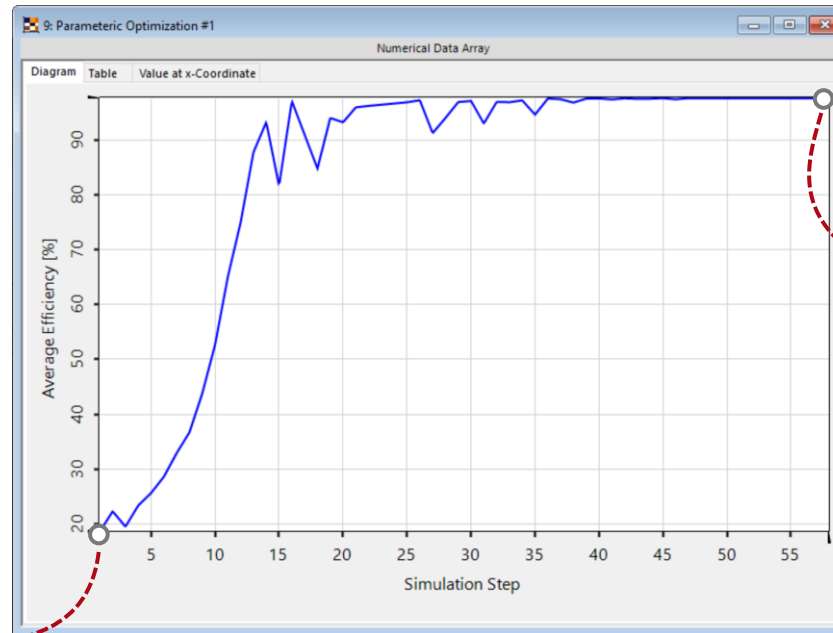
Parameter	Value Range
grating depth $h$	0.5-3.5 $\mu\text{m}$
fill factor $f$	30-70%
grating period $d$	1060nm (fixed)

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



parametric optimization – downhill simplex



optimized parameters

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

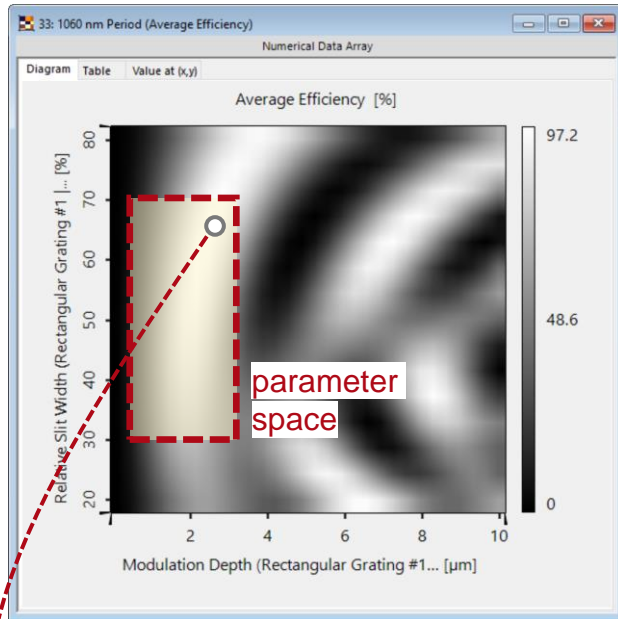
initial parameters

Parameter	Value
grating depth $h$	0.6 μm
fill factor $f$	35%
grating period $d$	1060nm (fixed)

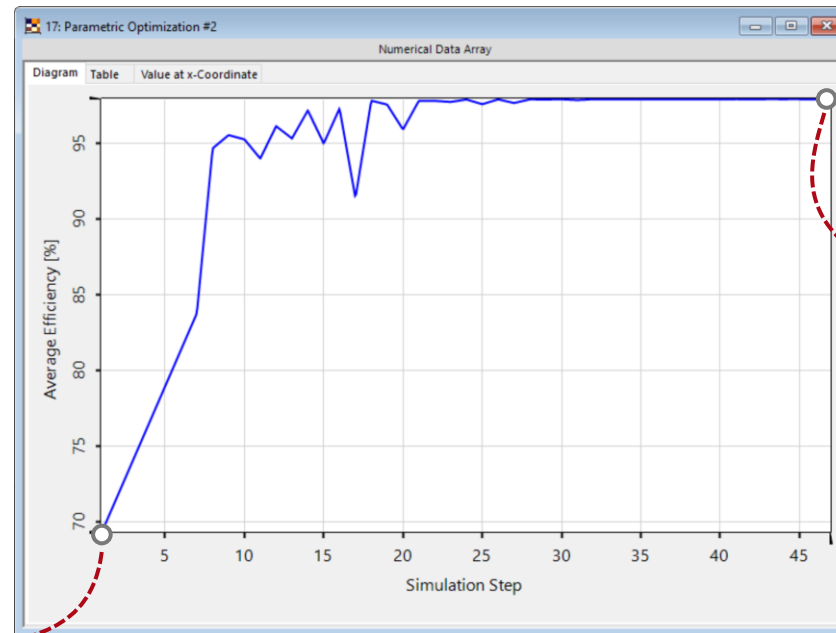
Diffraction efficiency in each optimization step is calculated using Fourier modal method (FMM, also known as RCWA).

# 2D Parametric Optimization – Design #2

Note: To ensure that the chosen initial parameters do not lead to a local maximum we performed a second optimization with initial parameters from the other side of the parameter space.



parametric optimization – downhill simplex



initial parameters

Parameter	Value
grating depth $h$	3.4 $\mu\text{m}$
fill factor $f$	65%
grating period $d$	1060nm (fixed)

optimized parameters

Parameter	Value
grating depth $h$	2.56 $\mu\text{m}$
fill factor $f$	66%
grating period $d$	1060nm (fixed)

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

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

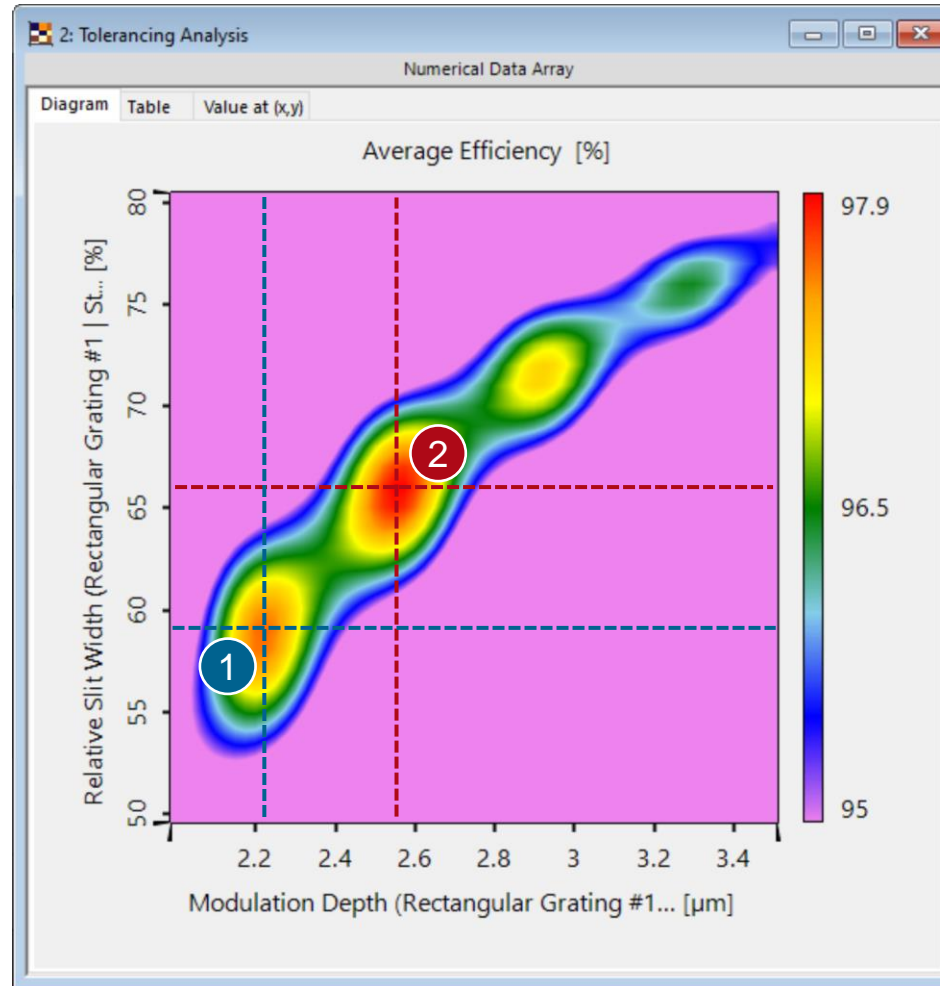
# Fabrication Tolerance Analysis

optimized parameters #2 ②

Parameter	Value
grating depth $h$	2.56 $\mu\text{m}$
fill factor $f$	66%
grating period $d$	1060nm (fixed)

optimized parameters #1 ①

Parameter	Value
grating depth $h$	2.23 $\mu\text{m}$
fill factor $f$	59%
grating period $d$	1060nm (fixed)



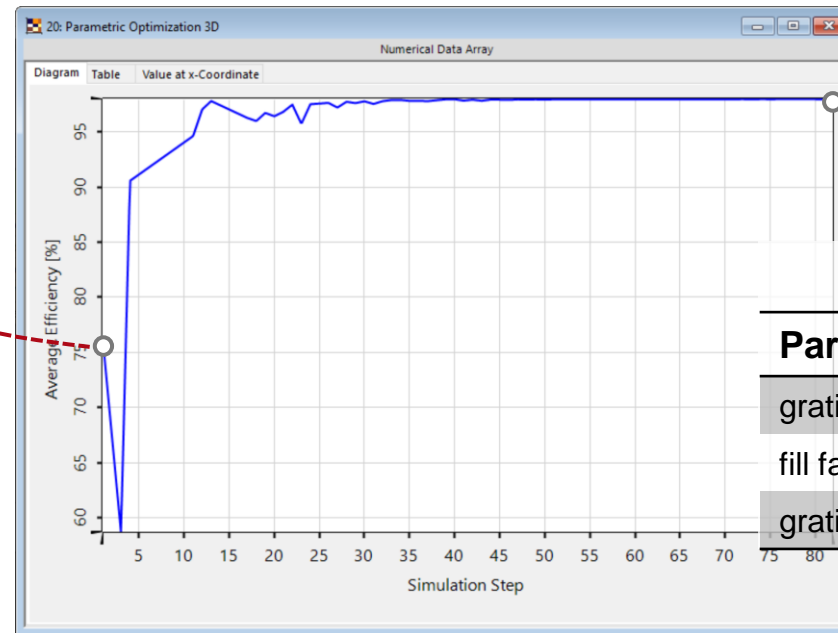
Diffraction efficiency within the region around the design parameters (efficiency value clipped above 95% only)



# 3D Parametric Optimization with Varying Grating Period

Parameter	Value Range	Initial Value
grating depth $h$	0.5-3.5 $\mu\text{m}$	3.0 $\mu\text{m}$
fill factor $f$	30-70%	60%
grating period $d$	800-1096nm	1060nm

parametric optimization – downhill simplex



optimized parameters

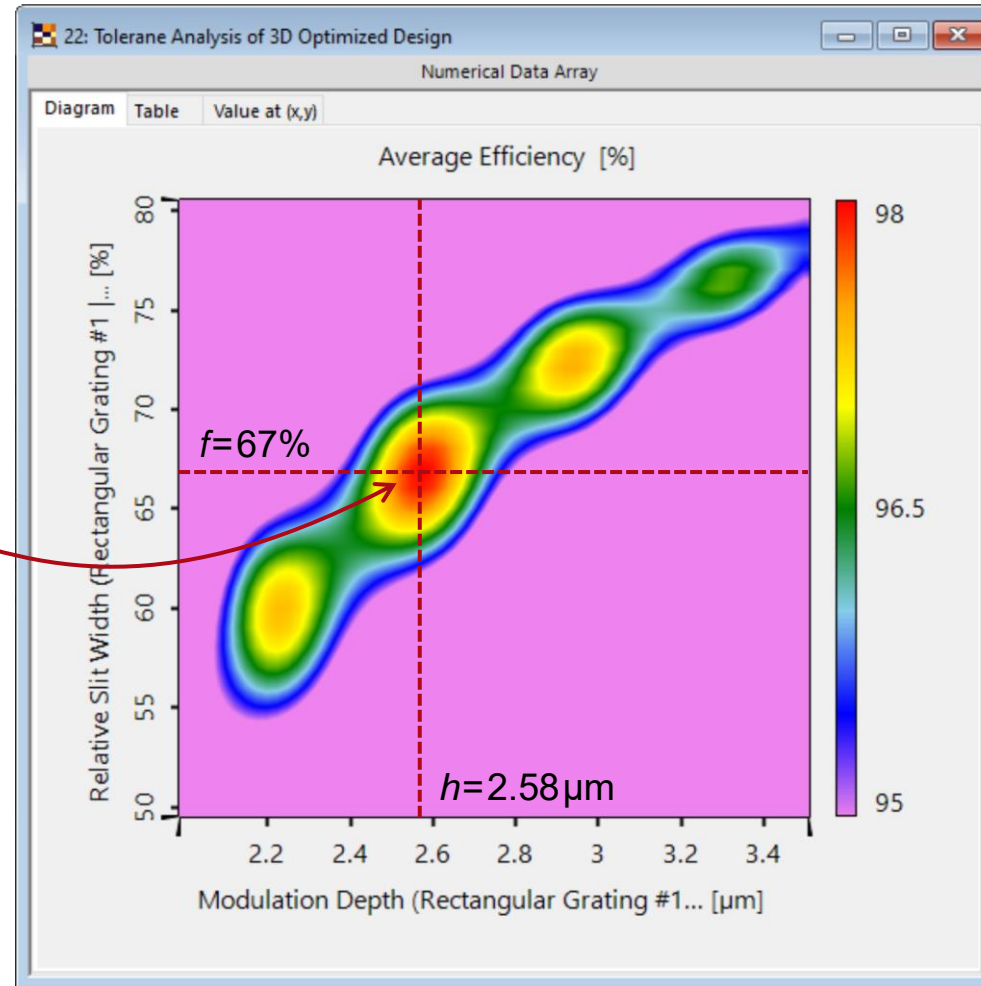
Parameter	Value
grating depth $h$	2.58 $\mu\text{m}$
fill factor $f$	67%
grating period $d$	1024nm

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 $h$	$2.58\mu\text{m}$
fill factor $f$	67%
grating period $d$	1024nm (fixed)



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

# Document Information

title	Analysis and Design of Highly Efficient Polarization Independent Transmission Gratings
document code	GRT.0015
document version	1.3
required packages	Grating Package
software version	2023.2 (Build 1.242)
category	Application Use Case
further reading	<ul style="list-style-type: none"><li>• <a href="#"><u>Ultra-Sparse Dielectric Nano-Wire Grid Polarizers</u></a></li><li>• <a href="#"><u>Rigorous Analysis of Nanopillar Metasurface Building Block</u></a></li><li>• <a href="#"><u>Parametric Optimization and Tolerance Analysis of Slanted Gratings</u></a></li><li>• <a href="#"><u>Polarization Analyzer</u></a></li><li>• <a href="#"><u>Configuration of Grating Structures by Using Interfaces</u></a></li></ul>