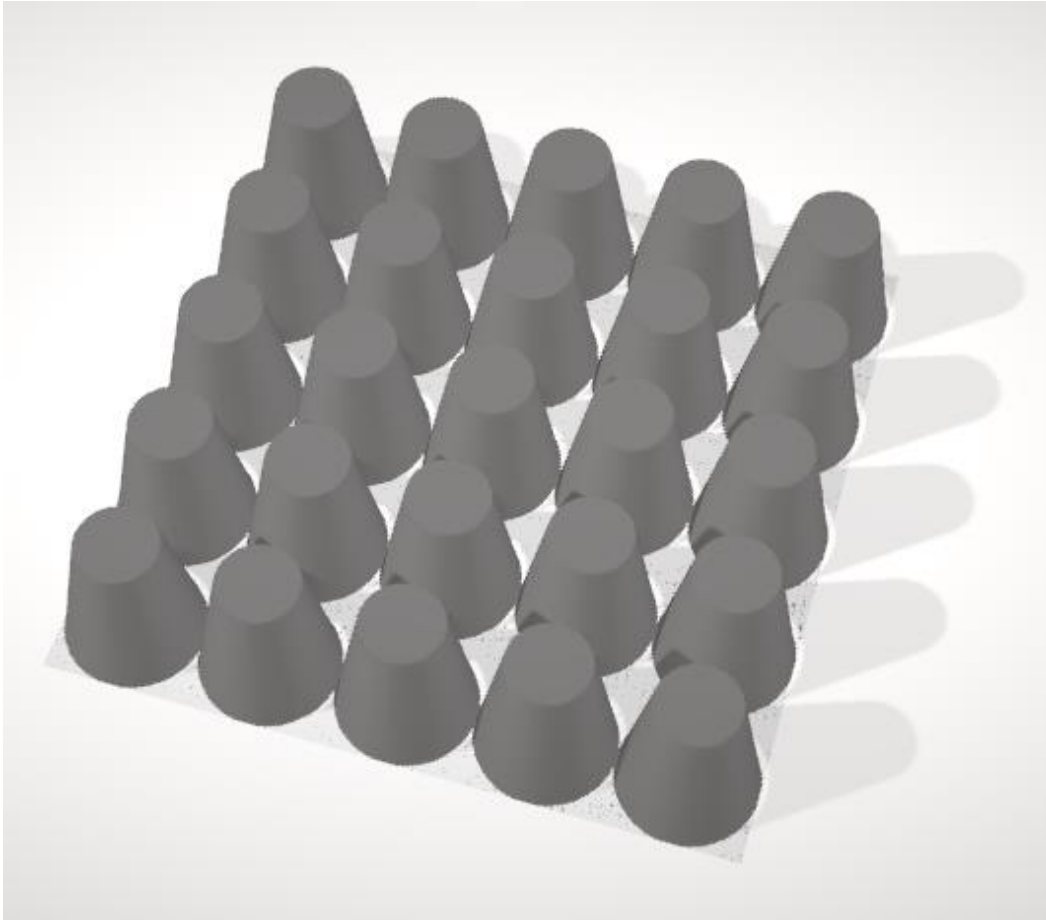


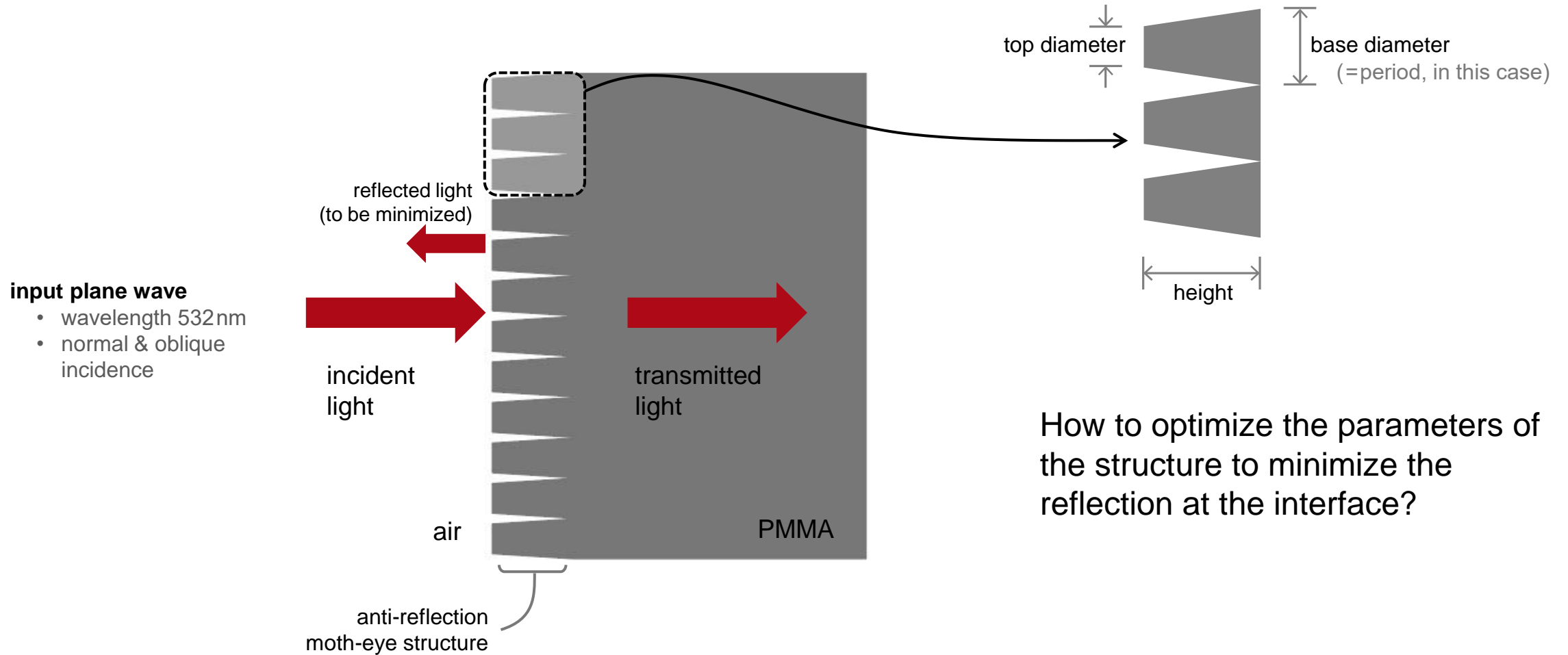
# **Rigorous Analysis and Design of Anti-Reflective Moth-Eye Structures**

# Abstract

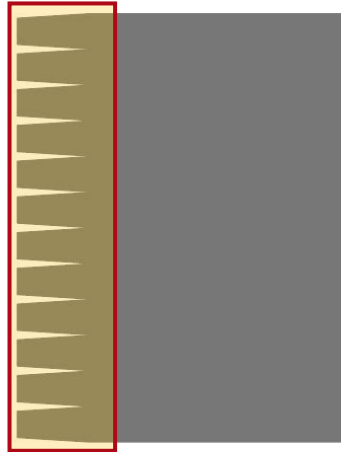


The suppression of reflection at surfaces of components is of interest for numerous optical applications. One very interesting approach to controlling the reflection at surfaces is the use of anti-reflective nano- and micro-structures, which are motivated by nature (moth-eye). These structures with feature sizes in the sub-wavelength domain exhibit unique properties concerning wavelength and angular dependency. In this document, the analysis and design of deterministic anti-reflective structures in VirtualLab Fusion is presented.

# Design Task



# Connected Modeling Techniques: Moth-Eye Structure



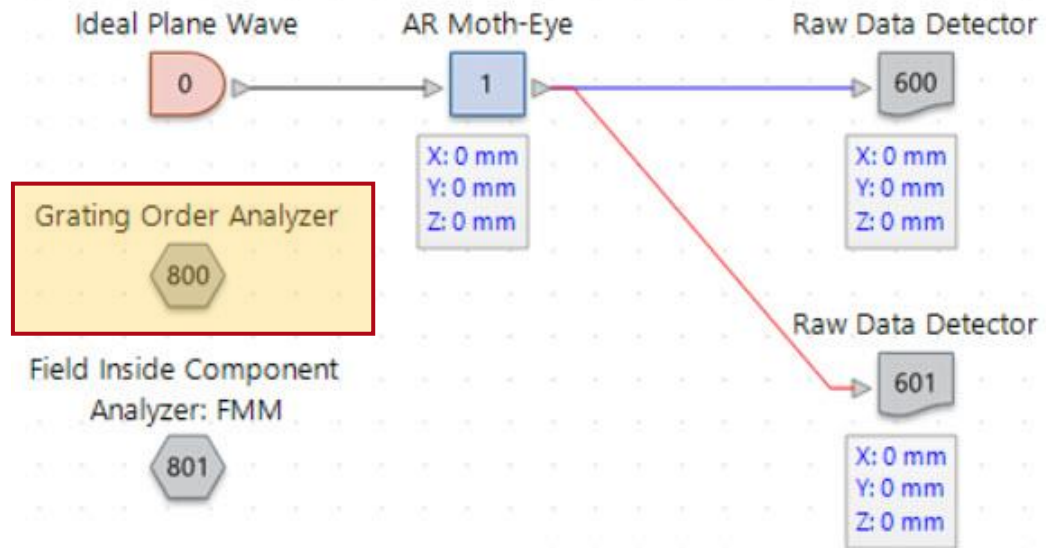
Available modeling techniques for microstructures:

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	



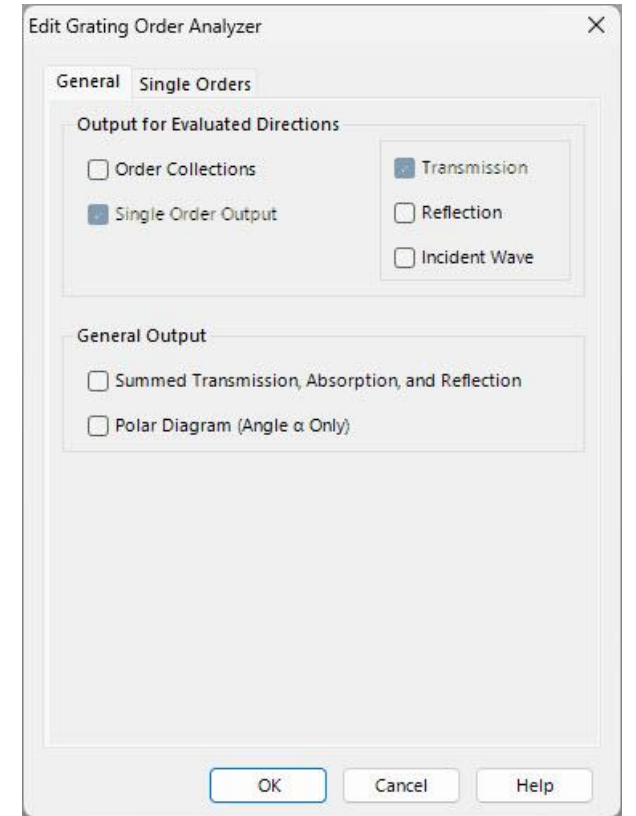
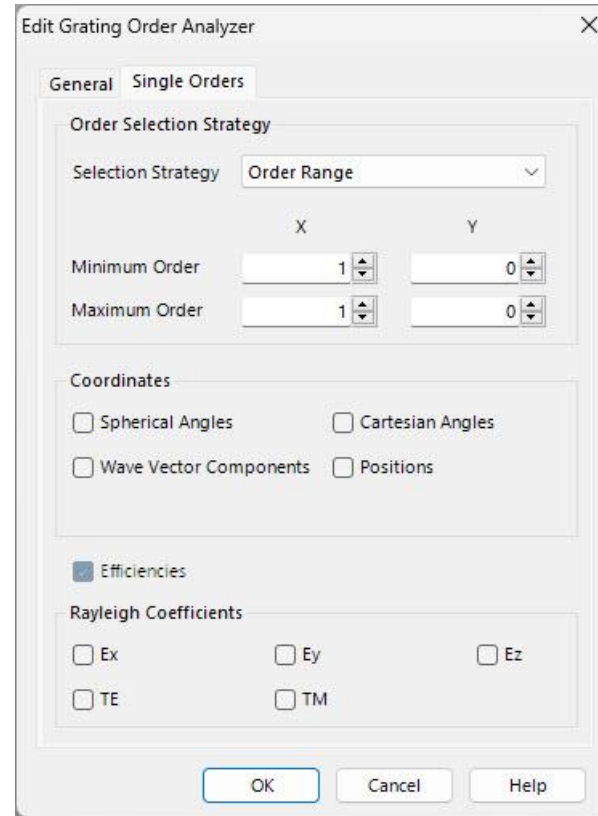
Due to the small feature sizes (in the order of magnitude of the wavelength), the **Fourier Modal Method (FMM)** provides a very accurate and fast solution and hence is used for the analysis.

# Grating Order Analyzer

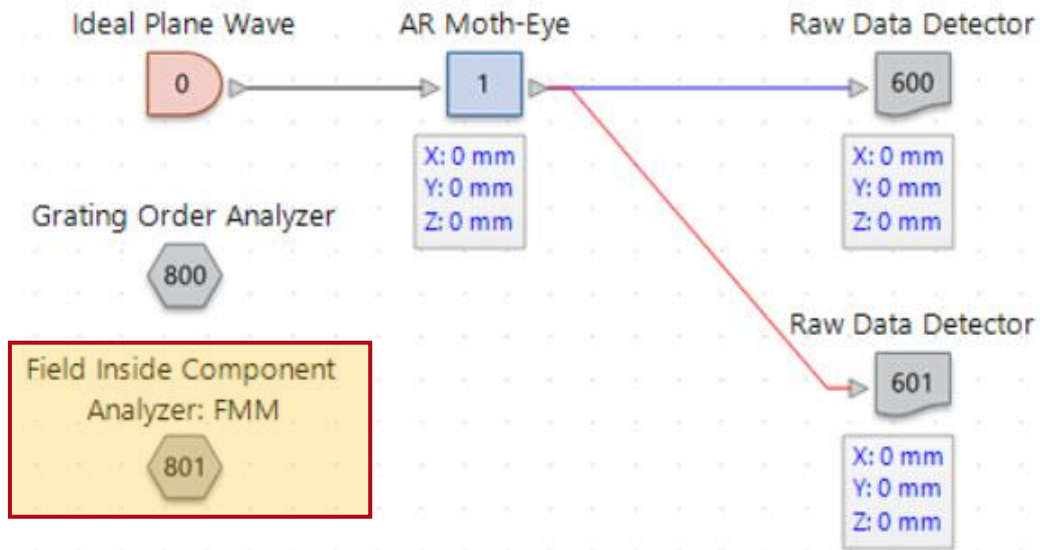


The *Grating Order Analyzer* can be used to investigate the order efficiencies of any given grating. Find more information under:

[Grating Order Analyzer](#)

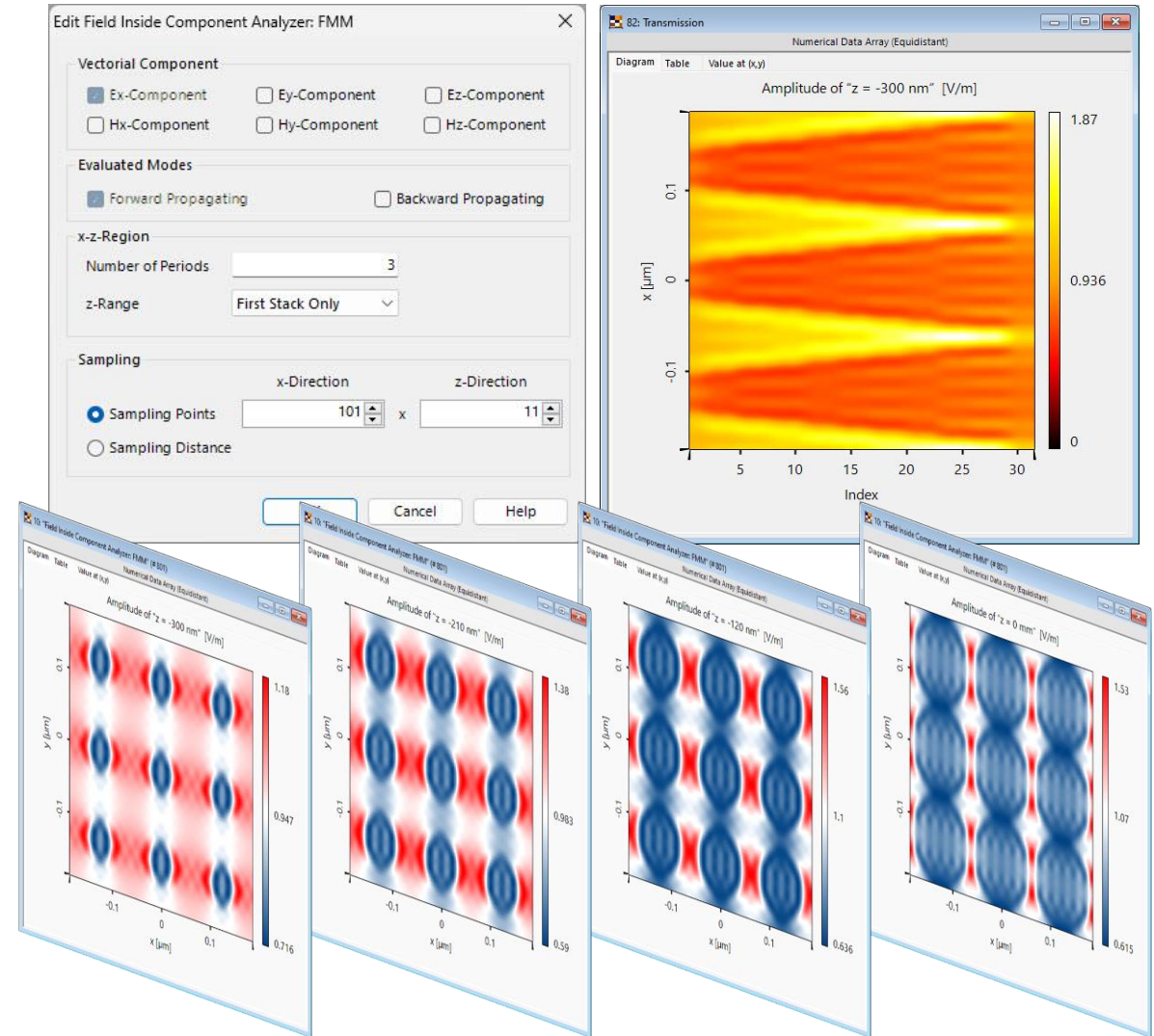


# Field Inside Component Analyzer: FMM

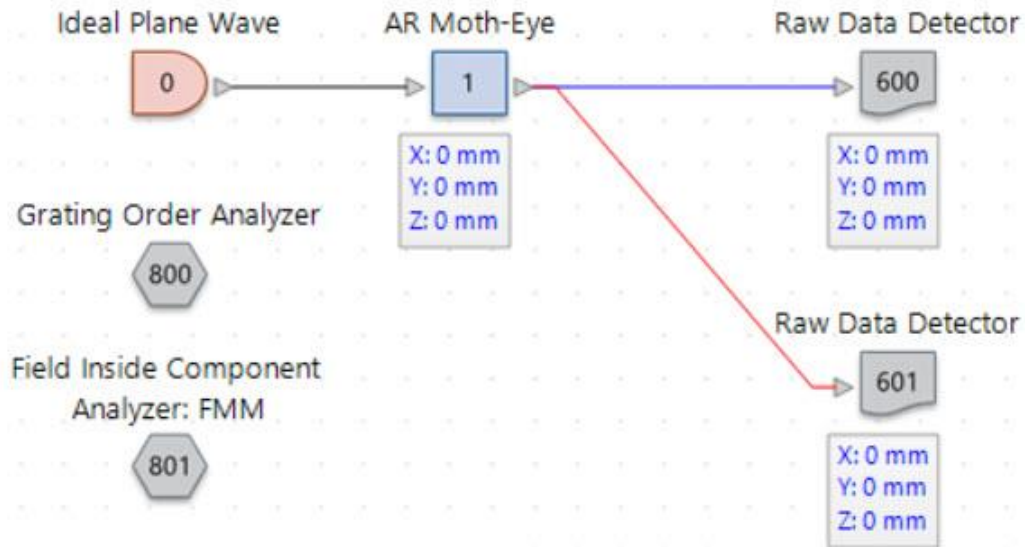


With the *Field Inside Component Analyzer: FMM*, the propagated field can be displayed in various planes inside the moth-eye structure. Find more information under:

[Field Inside Component Analyzer: FMM](#)



# Parameter Run



To analyze the behavior in the tolerance range envisaged for the device, a parameter sweep is performed with the Parameter Run document.

More information under:

[Usage of the Parameter Run Document](#)

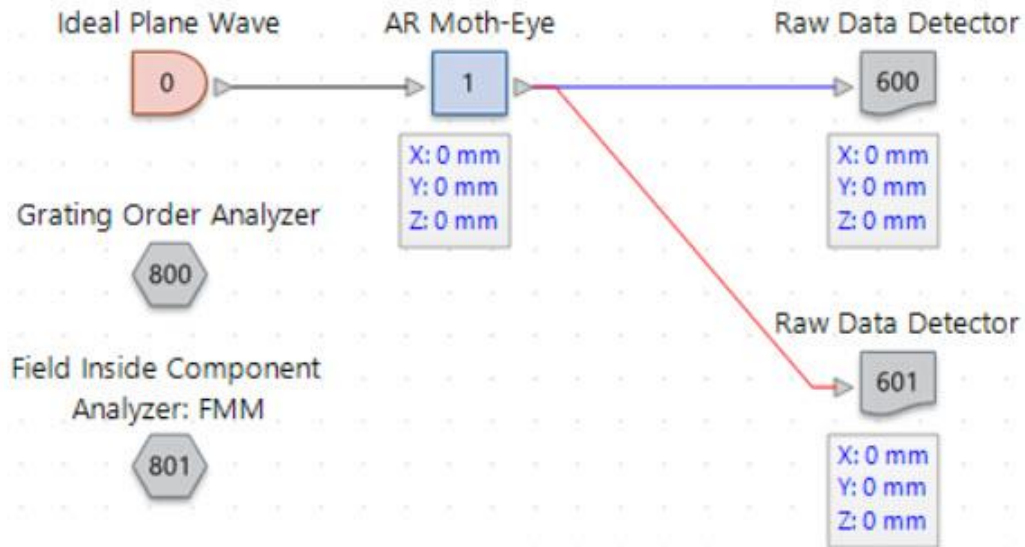
The screenshot displays the '49: Parameter Sweep' software interface. The top window shows 'Parameter Specification' with 'Usage Mode' set to 'Scanning' and 'Number of Iterations: 228'. The bottom window shows 'Results' with a table of data for various detectors and parameters over 8 iteration steps.

Object	Category	Parameter	Vary	From	To	Steps	Step Size	Original Value
"AR Moth-Eye" (#1)	Stack #1 (Stack)	Surface #1 (Truncated Cone Grating Interface)   Height	<input checked="" type="checkbox"/>	50 nm	500 nm	19	25 nm	300 nm
		Surface #1 (Truncated Cone Grating Interface)   TopDia...	<input checked="" type="checkbox"/>	10 nm	120 nm	12	10 nm	50 nm

Detector	Subdetector	Combined Output	Iteration Step							
			1	2	3	4	5	6	7	8
Varied Parameters	Height ("AR Moth-Eye" (#1))	Data Array	50 nm	50 nm	50 nm	50 nm	50 nm	50 nm	50 nm	50 nm
	TopDiameter ("AR Moth-Ey...	Data Array	10 nm	20 nm	30 nm	40 nm	50 nm	60 nm	70 nm	80 nm
	Absorption	Data Array	0 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %
"Grating Order Analyzer" (#800)	Overall Reflection and Tran...	Data Array	100 %	100 %	100 %	100 %	100 %	100 %	100 %	100 %
	Overall Reflection Efficiency	Data Array	3.4097 %	3.3218 %	3.2293 %	3.1202 %	3.0084 %	2.8953 %	2.7859 %	2.6888 %
	Overall Transmission Efficie...	Data Array	96.59 %	96.678 %	96.771 %	96.88 %	96.992 %	97.105 %	97.214 %	97.311 %

# Parametric Optimization



Then, the grating structure can be optimized using the in-built *Parametric Optimization*. A reflection efficiency of 0 (to minimize this value) is used as target for the optimization.

More information under:

[Introduction to the Parametric Optimization Document](#)

The screenshot displays the Parametric Optimization software interface. The top window, titled "Parameter Selection", shows a table of parameters to be varied during optimization. The bottom window, titled "Constraint Specifications", shows a table of constraints to be considered during optimization.

**Parameter Selection**

Select the parameters which shall be varied during optimization.

You can select one or more parameter which shall be varied within the optimization.

Filter by...  Show Only Varied Parameters

1	2	*	Object	Category	Parameter	Vary	Original Value
			"AR Moth-Eye" (# 1)	Stack #1 (Stack)	Surface #1 (Truncated Cone Grating Interface)   Height	<input checked="" type="checkbox"/>	150 nm
					Surface #1 (Truncated Cone Grating Interface)   TopDiameter	<input checked="" type="checkbox"/>	70 nm

**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
"AR Moth-Eye" (# 1)	Stack #1 (Stack)   Surface #1 (Truncated	<input checked="" type="checkbox"/>	1	Range	130 nm	170 nm	150 nm	0 %
	Stack #1 (Stack)   Surface #1 (Truncated	<input checked="" type="checkbox"/>	1	Range	50 nm	90 nm	70 nm	0 %
"Grating Order Analyzer" (# 800)	Overall Reflection Efficiency	<input type="checkbox"/>						
	Overall Transmission Efficiency	<input type="checkbox"/>						
	Overall Reflection and Transmission Absorption	<input type="checkbox"/>						

Target Function Value: 1.5851e-08



# Simulation Results

# Reference Measurement by Calculator

In this example, we want to minimize the reflection at the surface of a substrate, which consists of PMMA (polymethylmethacrylat).

The *Fresnel Effects Calculator* can be used to get information of the reflectance and transmittance at an interface between air and PMM (3.93% without any anti-reflection).

Learn more about the *Fresnel Effects Calculator* under:

[Fresnel Curves on a Plane Surface](#)

94: Fresnel Effects Calculator

First Material  
Name: Air  
Catalog Material: [dropdown]  
State of Matter: Gas or Vacuum

Second Material  
Name: PolyMethylMethAcrylate-PMMA  
Catalog Material: [dropdown]  
State of Matter: Solid

Coating  
Name: No Coating

Wavelength: 532 nm  
Angle of Incidence: 0°

Intensity Coefficients

	TE	TM
Reflectance	0.039276	0.039276
Transmittance	0.96072	0.96072

Complex Fresnel Coefficients

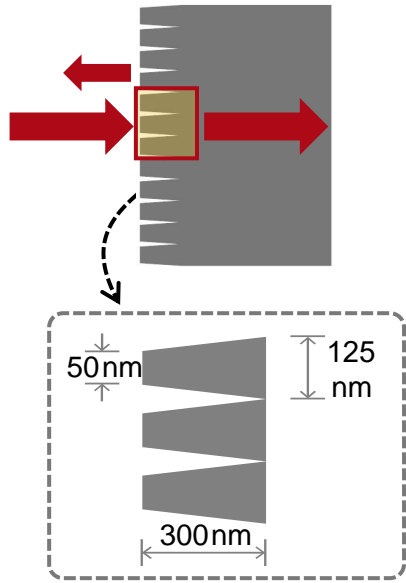
	TE	TM
Reflection	0.19818 $\cdot \exp(-3.1416 \text{ rad } i)$	0.19818 $\cdot \exp(0 \text{ rad } i)$
Transmission	0.80182 $\cdot \exp(0 \text{ rad } i)$	0.80182 $\cdot \exp(0 \text{ rad } i)$

Validity:

Close Help

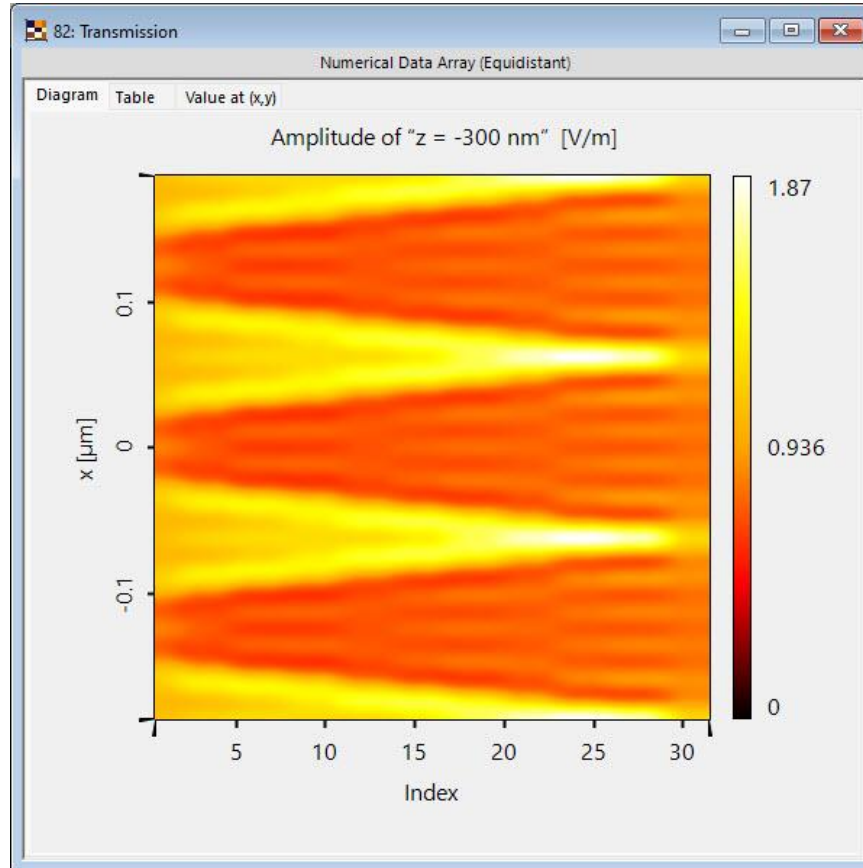
Diagram: First Material | Second Material. Incident wave (in), reflected wave (R), transmitted wave (T).

# Field Inside Structure

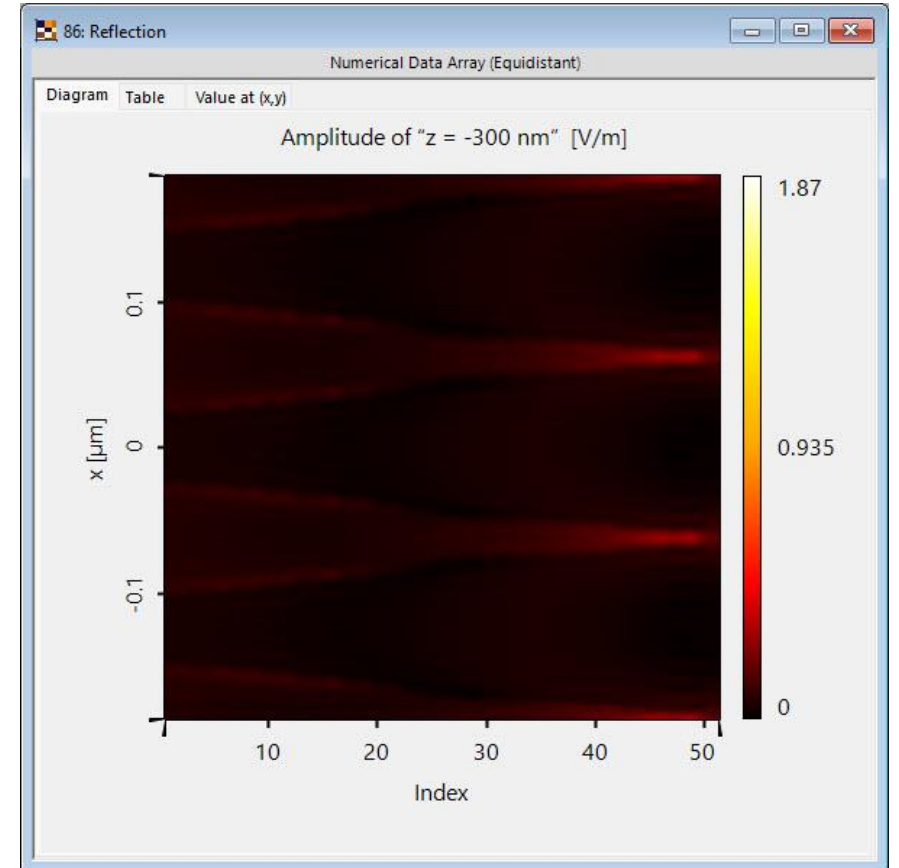


An investigation of the field distribution reveals, that most of the light seems to be reflected by the bottom part of the structure. Hence, in a next step, the parameters are further improved by optimization.

The structure inspired by a moth-eye reduces the reflection by a factor of ten. When using the mentioned parameters, the resulting reflectance is 0.38%.

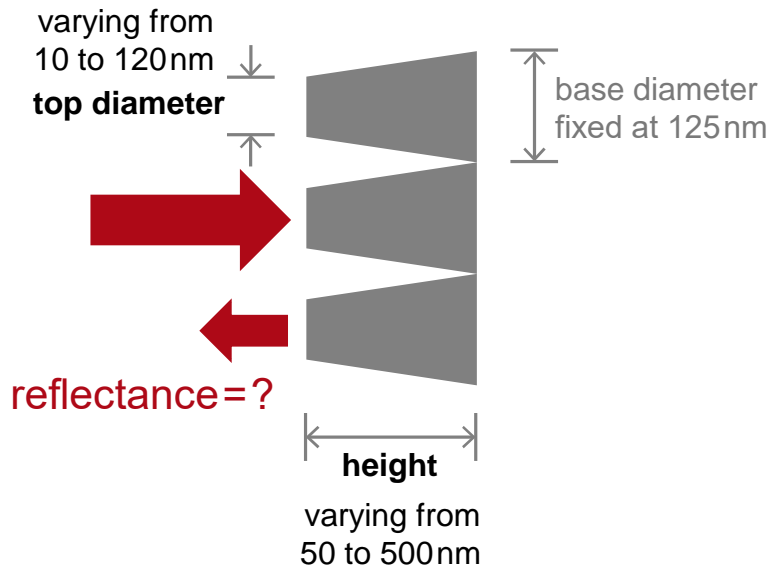


incident field

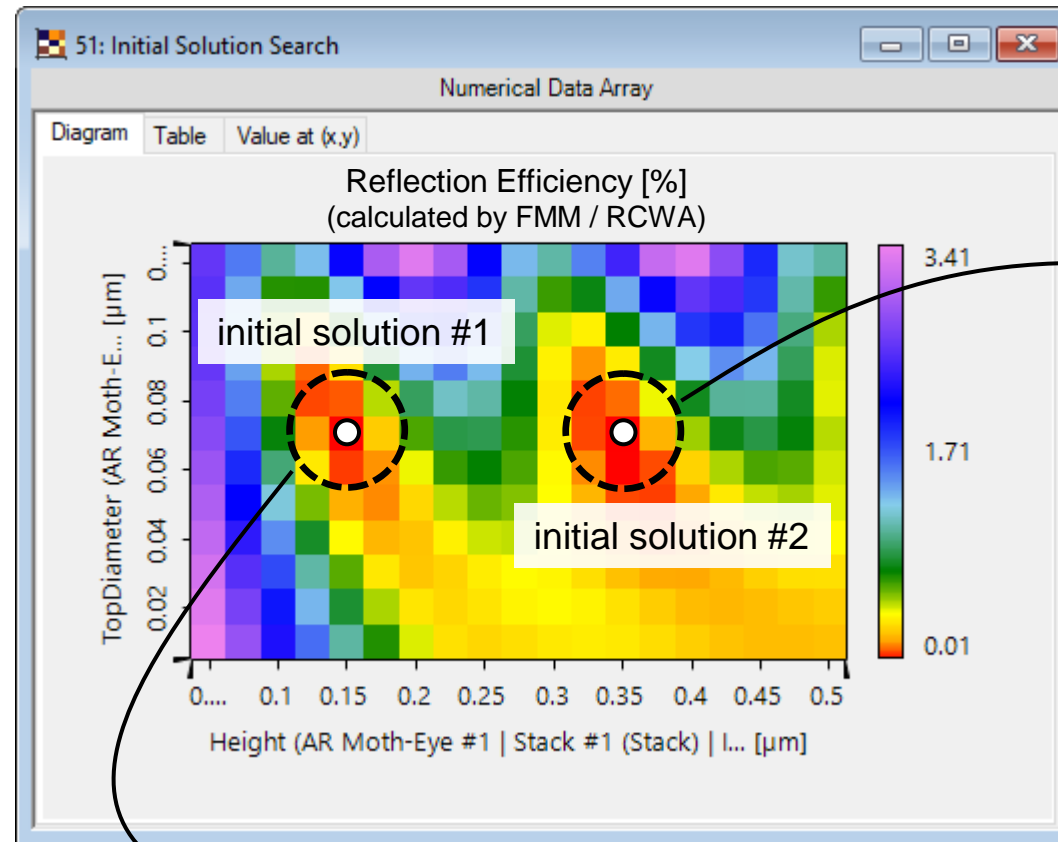


reflected field

# Scanning over Parameter Space for Initial Solutions



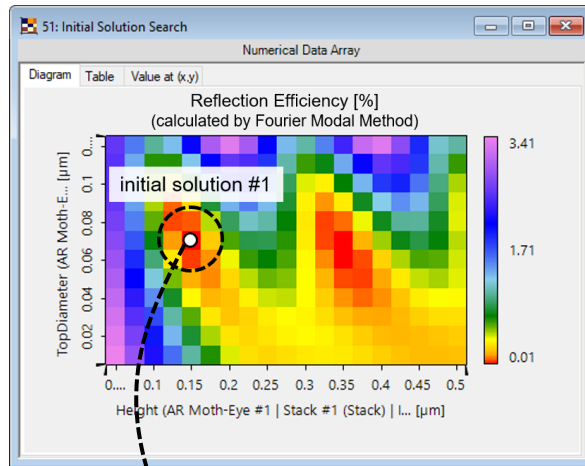
A parameter sweep is performed in order to find an adequate initial solution for the optimization.



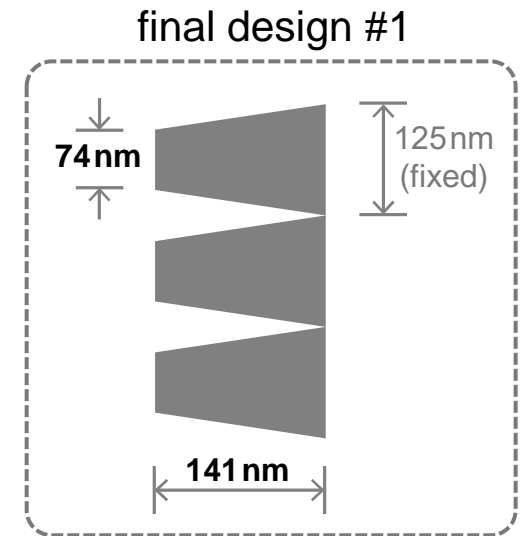
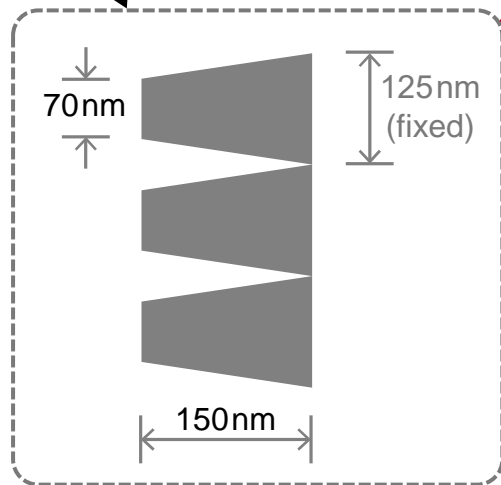
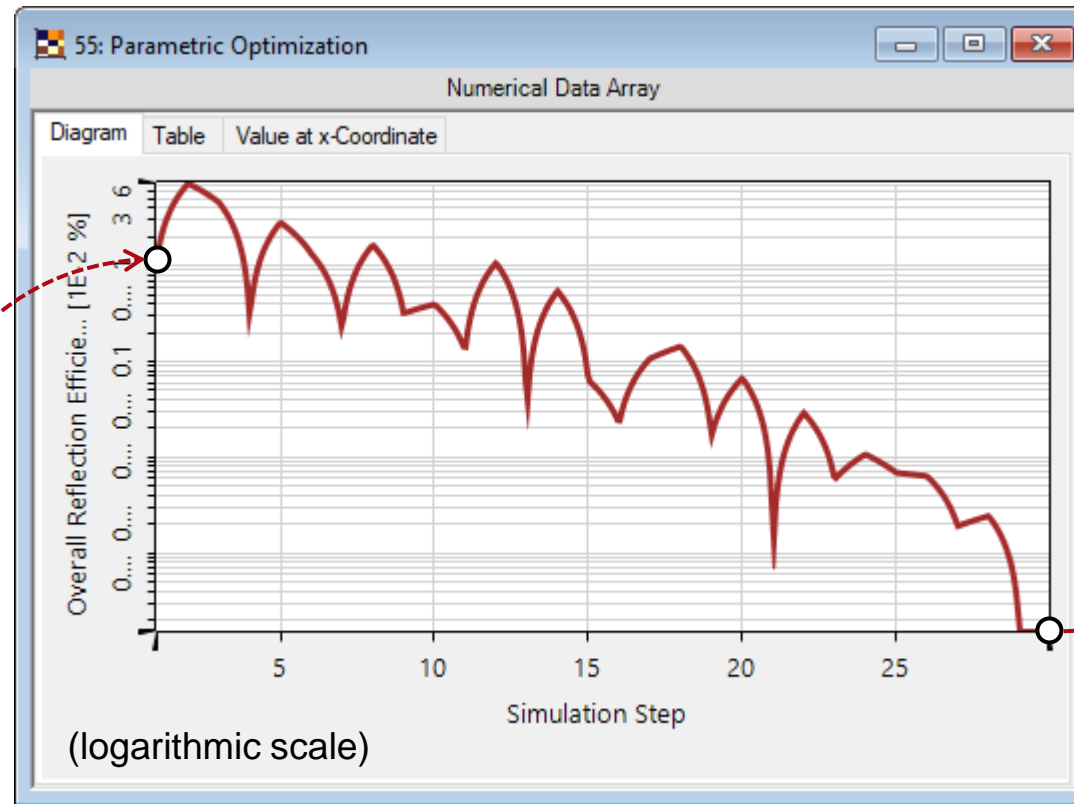
higher aspect ratio and maybe not the first choice for fabrication, but could be more robust

smaller aspect ratio and therefore preferable for fabrication

# Parametric Optimization for Initial Solution #1

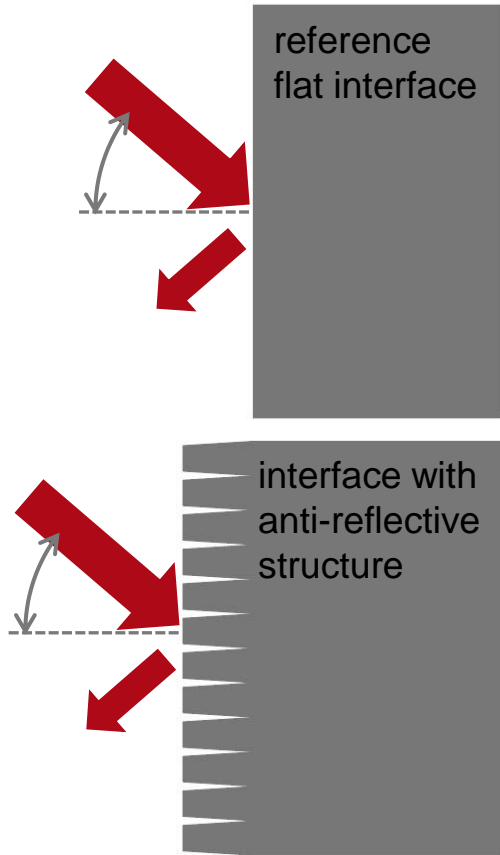


parametric optimization by downhill simplex method  
(each iteration calculated by FMM / RCWA)

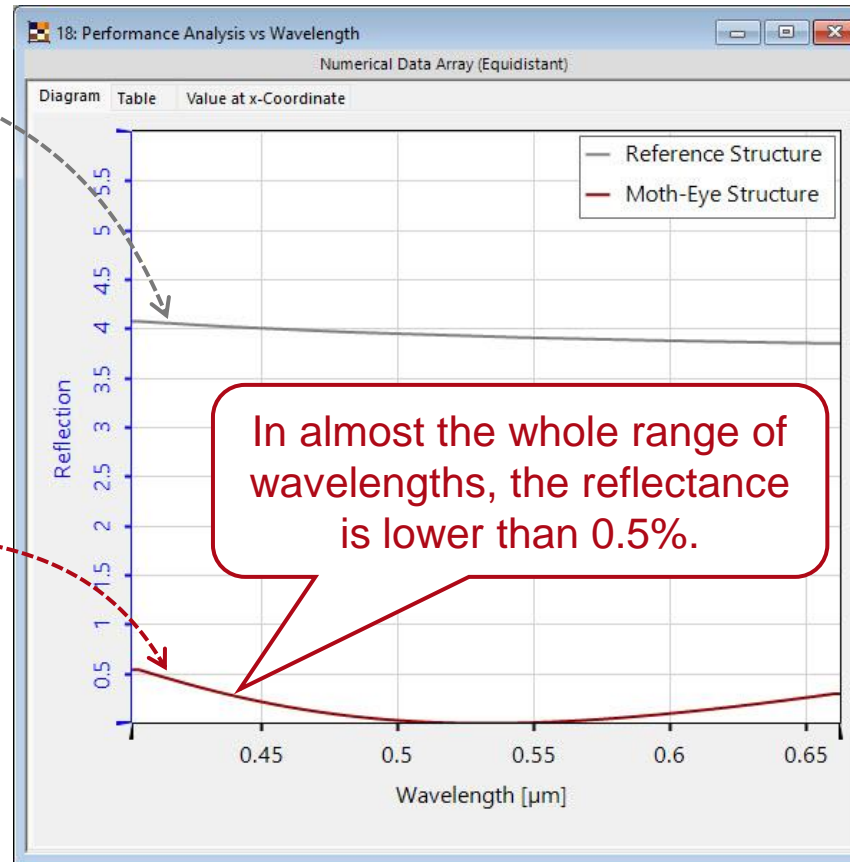


**optimized reflectance:**  
1.5E-6%

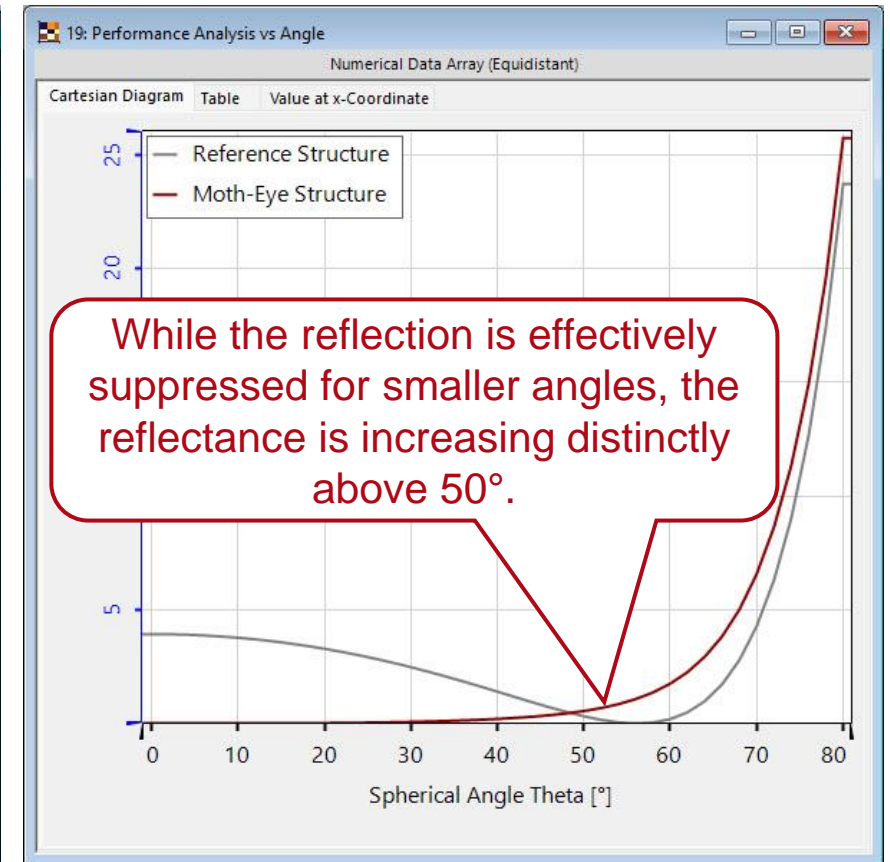
# Performance Analysis of Final Design #1



reflection efficiency vs. wavelength  
(at normal incidence)



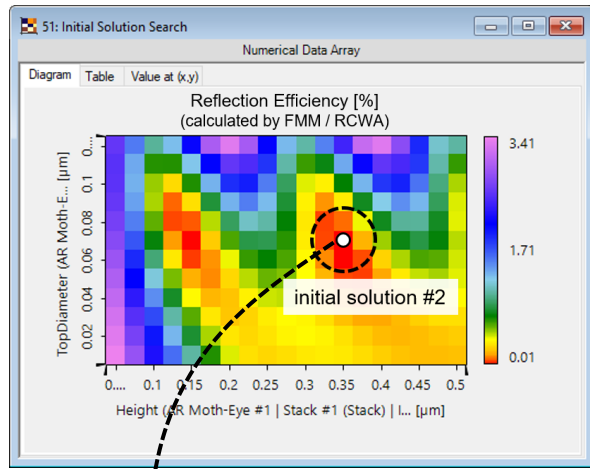
reflection efficiency vs. angle of incidence  
(at 532nm wavelength)



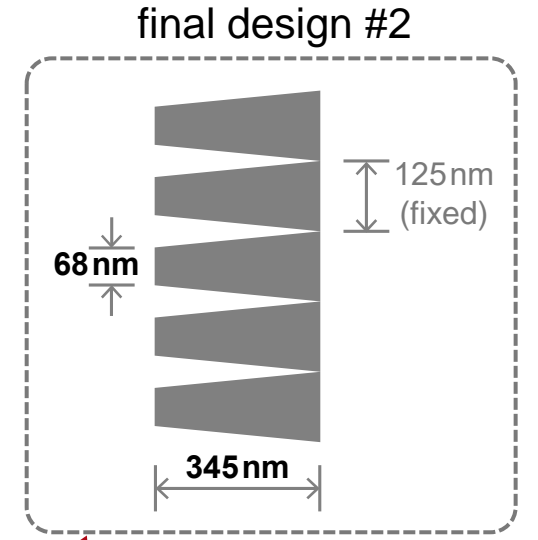
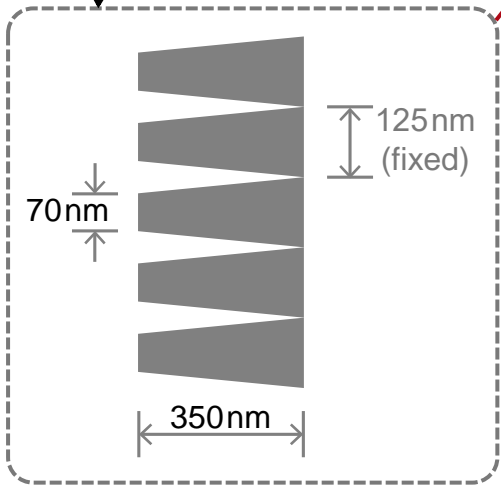
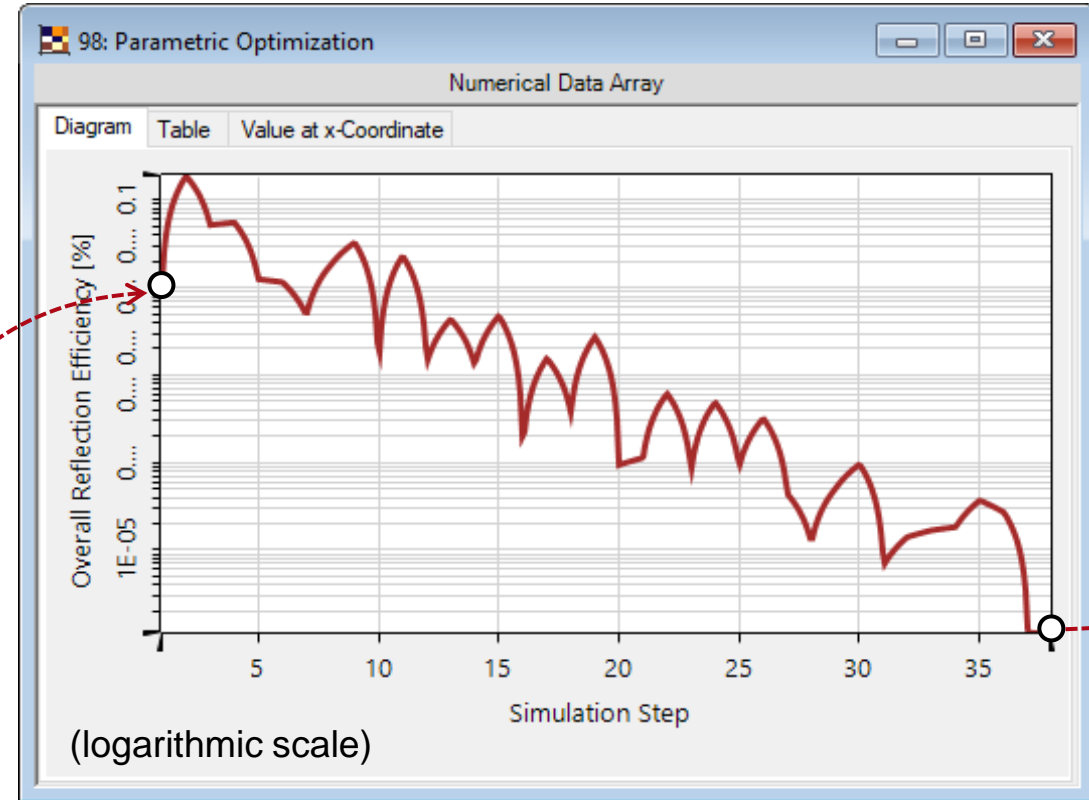
varying parameter:

- wavelength (405 to 660nm)
- incident angle ( $0^{\circ}$  to  $80^{\circ}$ )

# Parametric Optimization for Initial Solution #2

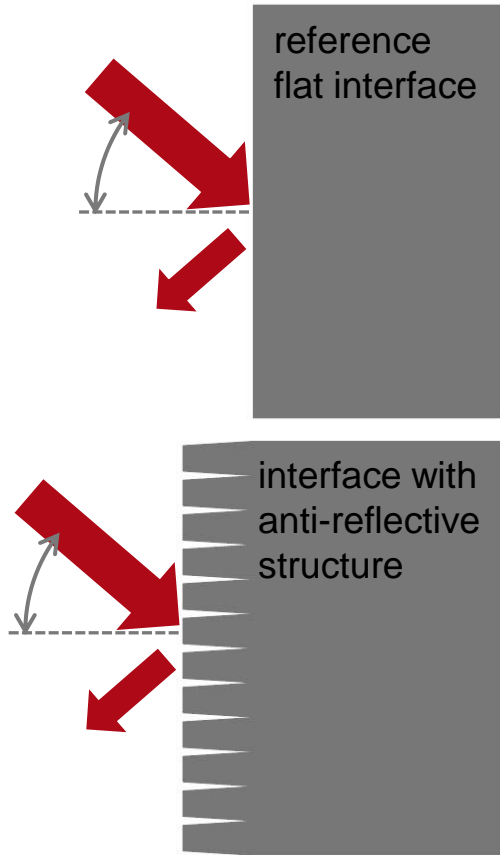


parametric optimization by downhill simplex method  
(each iteration calculated by FMM / RCWA)

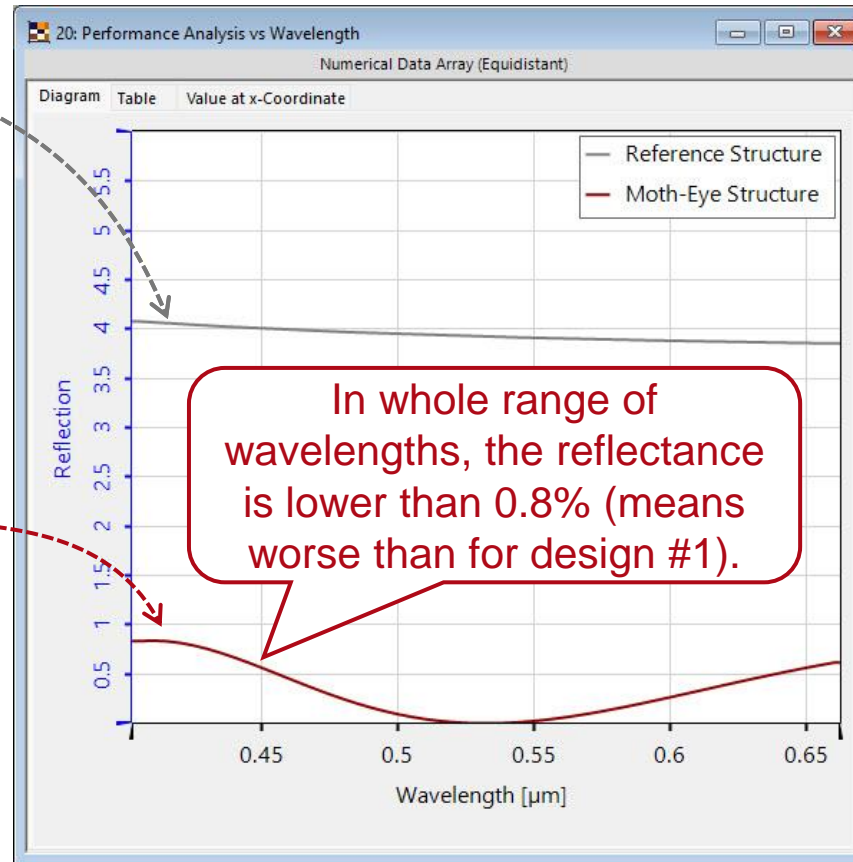


**optimized reflectance:**  
1.1E-6%

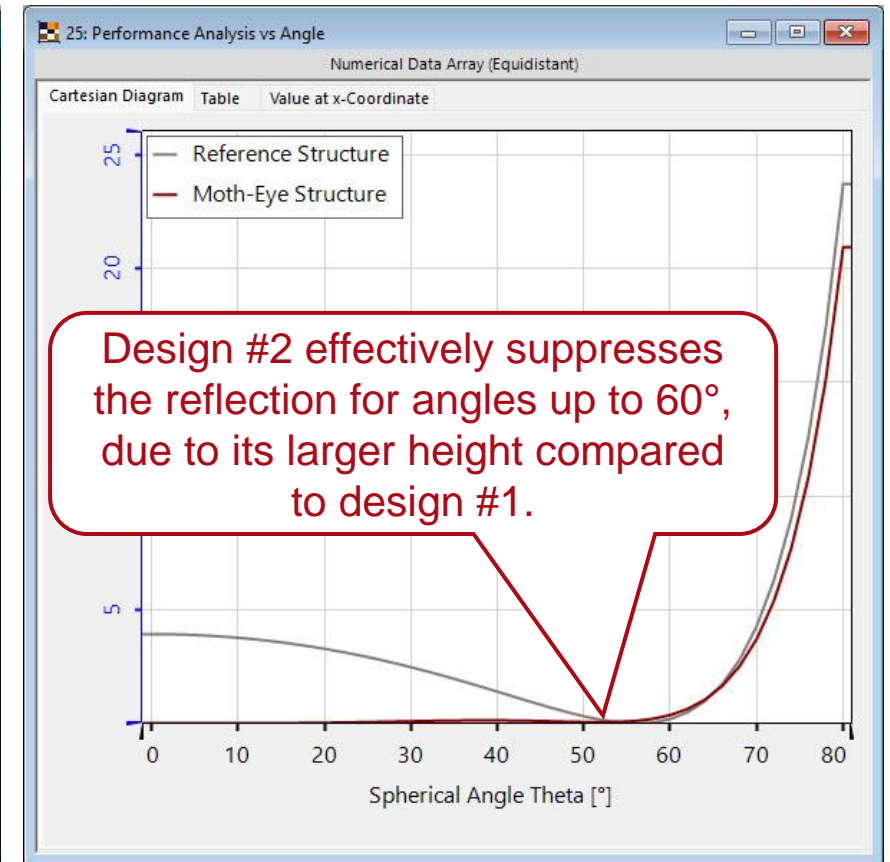
# Performance Analysis of Final Design #1



reflection efficiency vs. wavelength  
(at normal incidence)



reflection efficiency vs. angle of incidence  
(at 532nm wavelength)



varying parameter:

- wavelength (405 to 660nm)
- incident angle ( $0^\circ$  to  $80^\circ$ )



# Document Information

title	Rigorous Analysis and Design of Anti-Reflective Moth-Eye Structures
document code	GRT.0011
document version	2.0
software edition	<ul style="list-style-type: none"><li>• VirtualLab Fusion Standard</li><li>• Grating Package</li></ul>
software version	2023.2 (Build 1.242)
category	Feature Use Case
further reading	<ul style="list-style-type: none"><li>• <a href="#"><u>Thin Element Approximation (TEA) vs. Fourier Modal Method (FMM) for Grating Modeling</u></a></li><li>• <a href="#"><u>Parametric Optimization and Tolerance Analysis of Slanted Gratings</u></a></li><li>• <a href="#"><u>Field Inside Component Analyzer: FMM</u></a></li><li>• <a href="#"><u>Fresnel Curves on a Plane Surface</u></a></li></ul>