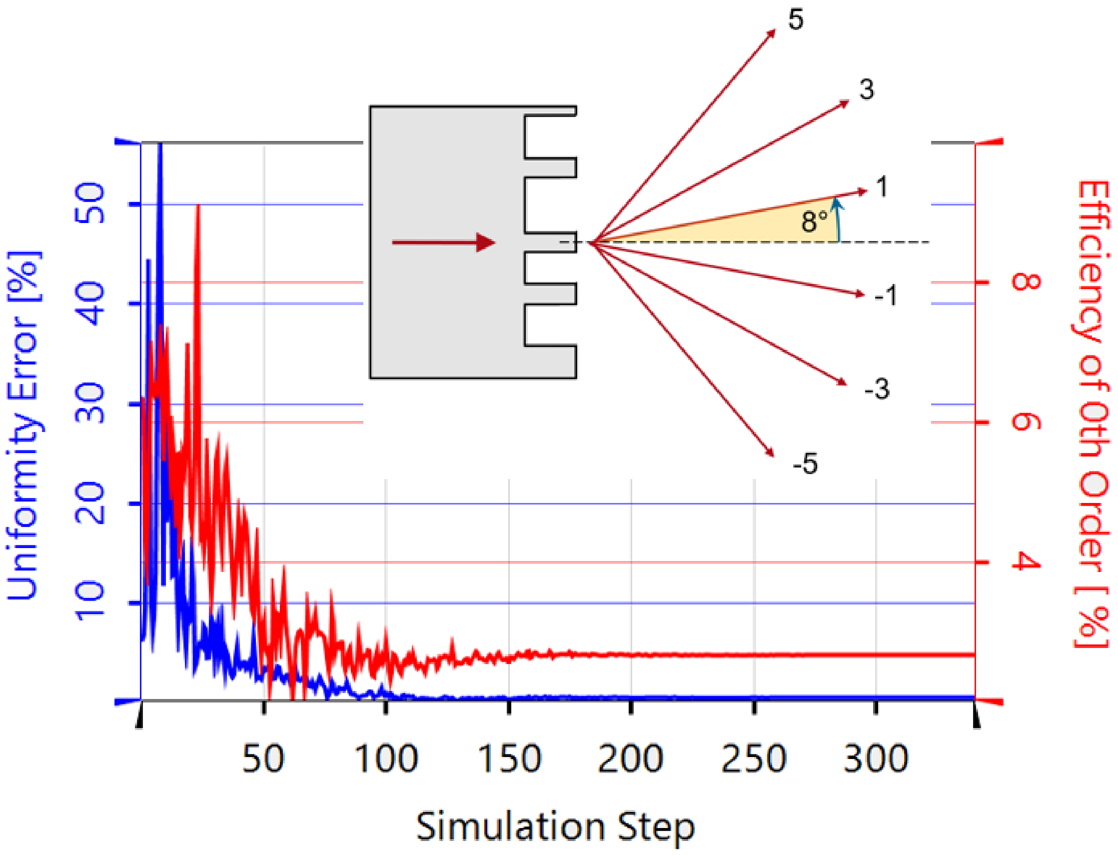
High-NA Beam Splitter Optimization with User-Defined Merit Functions

Abstract



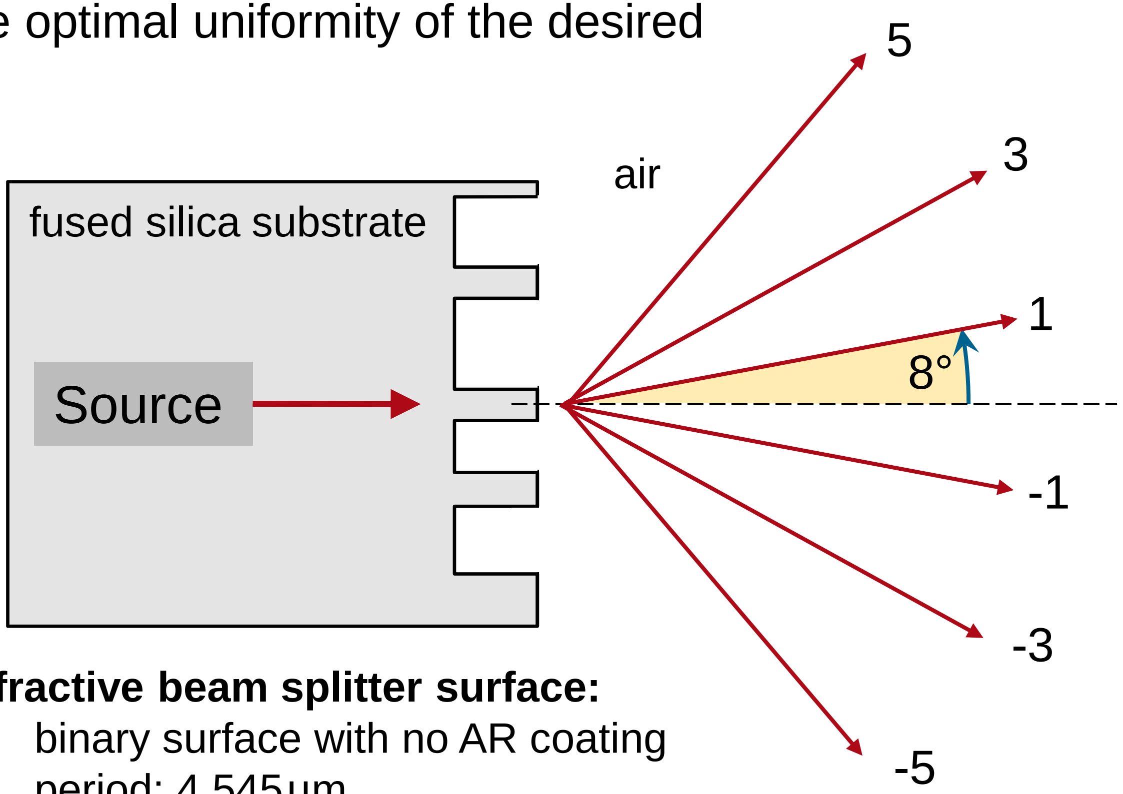
Diffractive beam splitters are often designed by applying certain paraxial approximations due to the direct relation between phase and structure and vice versa, which these algorithms provide. In case of non-paraxial or even high-NA splitters these approximations will introduce some inaccuracy and hence at least a rigorous analysis is advised, if not an additional rigorous post-optimization. In this use case, such rigorous evaluations are performed for an exemplary binary 1:6 splitter, using the odd diffraction orders. For this purpose, the structure of the initial system is parametrized, and a set of user-defined merit functions are defined via the Programmable Grating Analyzer. For the parametric optimization and subsequent tolerance analysis, the rigorous Fourier Modal Method (FMM) is used.

Modeling Task

How to optimize the surface profile of the following diffractive high-NA 1:6 beam splitter to achieve optimal uniformity of the desired working orders?

light parameters

- wavelength: 632.63 nm
- polarization: along x-direction

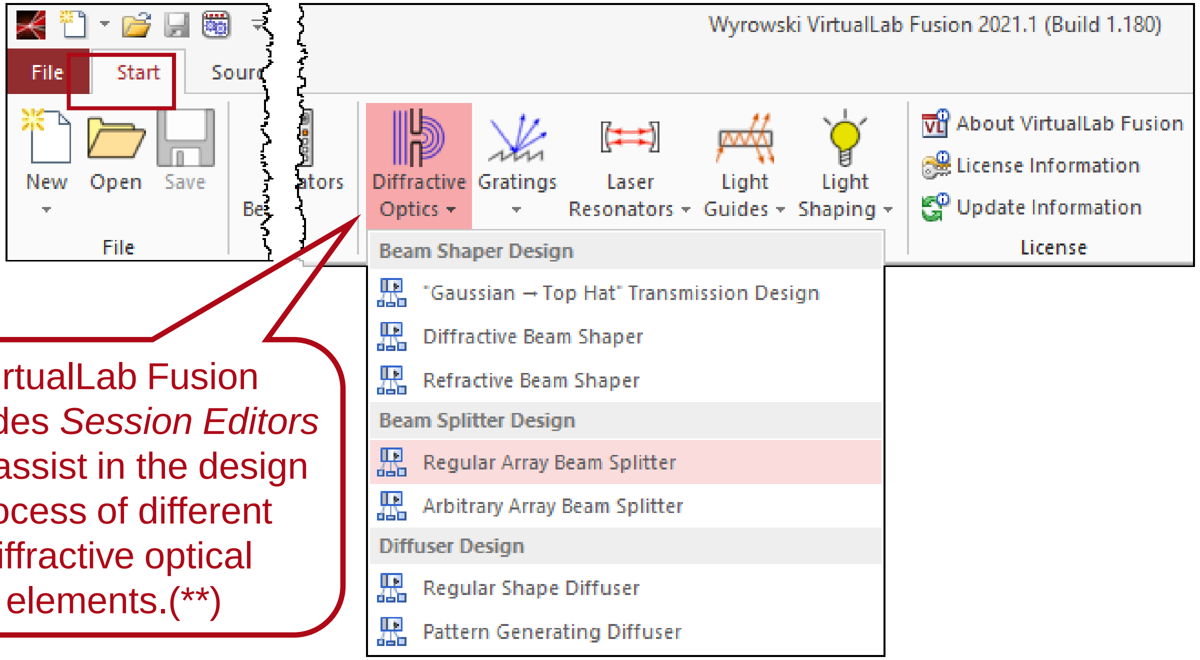


6 diffraction orders with uniform diffraction efficiencies

diffractive beam splitter surface:

- binary surface with no AR coating
- period: 4.545 µm
- minimum feature size: 431 nm

Initial Design of Diffractive Beam Splitter Surface(*)



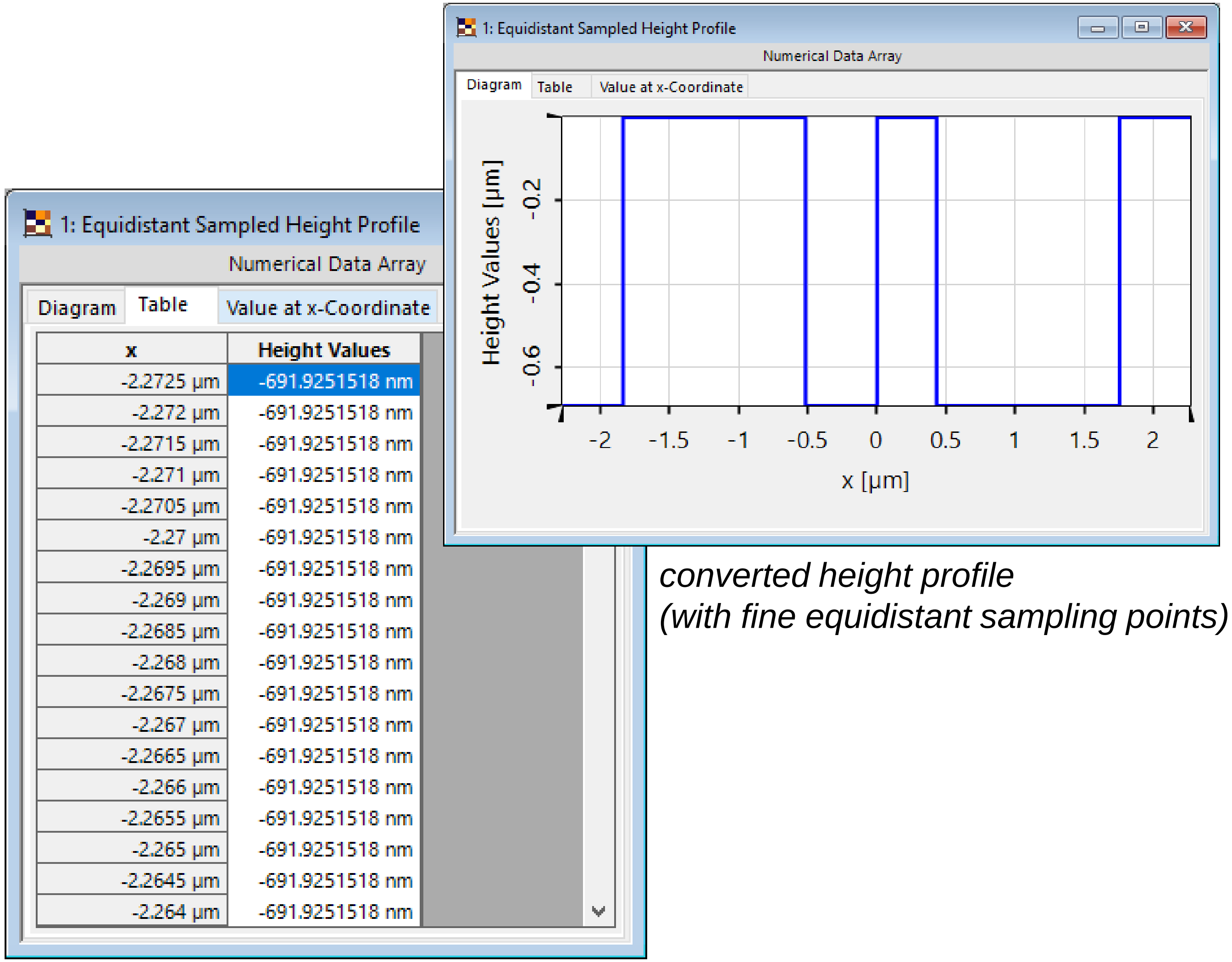
VirtualLab Fusion provides *Session Editors* that assist in the design process of different diffractive optical elements.(**)

1. The initial beam splitter phase function was calculated by VirtualLab Fusion's Iterative Fourier Transform Algorithm (IFTA) design tool.
2. For the conversion to a height profile, a structure design based on the Thin Element Approximation (TEA) was applied.

(*) not part of this use case

(**) These Session Editors are available with the Diffractive Optics Toolbox Silver.

Limitations of TEA and an Equidistant Sampled Structure

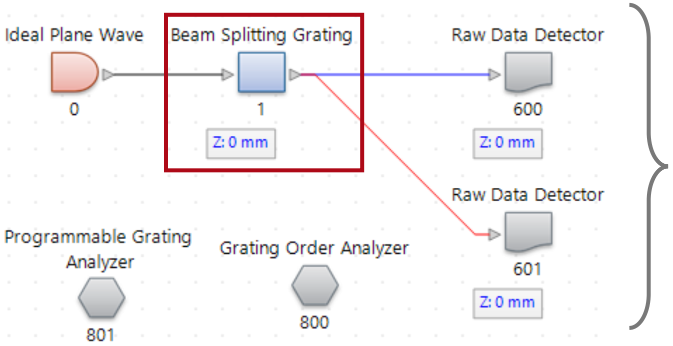


x	Height Values
-2.2725 µm	-691.9251518 nm
-2.272 µm	-691.9251518 nm
-2.2715 µm	-691.9251518 nm
-2.271 µm	-691.9251518 nm
-2.2705 µm	-691.9251518 nm
-2.27 µm	-691.9251518 nm
-2.2695 µm	-691.9251518 nm
-2.269 µm	-691.9251518 nm
-2.2685 µm	-691.9251518 nm
-2.268 µm	-691.9251518 nm
-2.2675 µm	-691.9251518 nm
-2.267 µm	-691.9251518 nm
-2.2665 µm	-691.9251518 nm
-2.266 µm	-691.9251518 nm
-2.2655 µm	-691.9251518 nm
-2.265 µm	-691.9251518 nm
-2.2645 µm	-691.9251518 nm
-2.264 µm	-691.9251518 nm

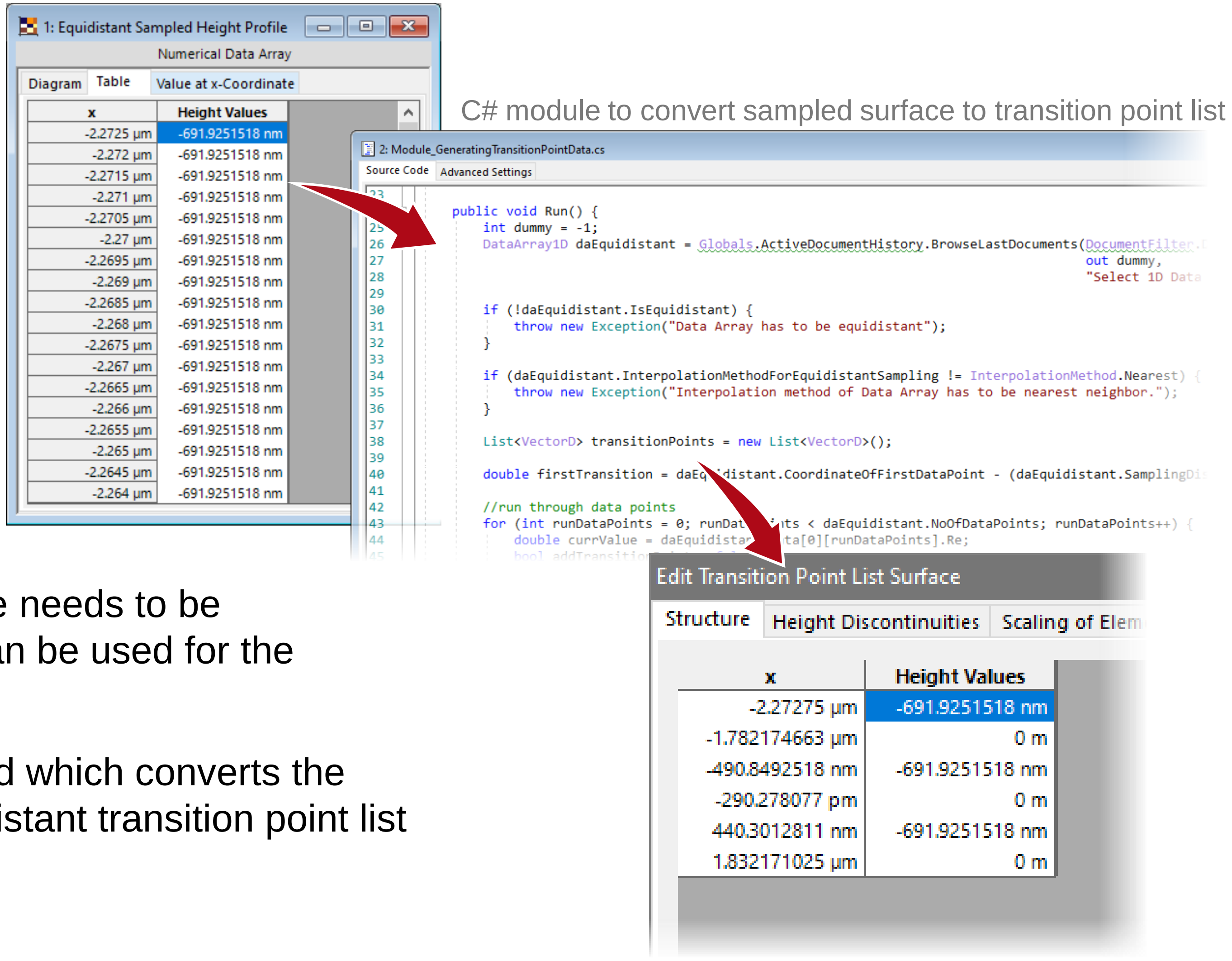
converted height profile
(with fine equidistant sampling points)

- TEA is well suited if the smallest feature sizes are not smaller than ~5 times the wavelength. If this is not the case, the amplitude/phase distribution after interacting with the designed height profile might exhibit relevant deviations from the desired values.
- Thus, a rigorous evaluation is needed.
- And for a parametric optimization, the structure data needs to be defined differently.

Data Preparation (Parametrization) for Post-Optimization

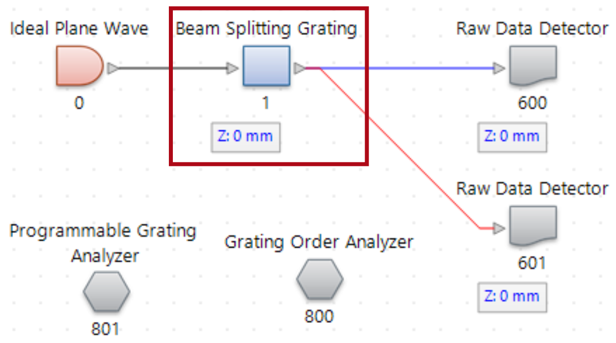


special optical setup for grating evaluations



- For a rigorous analysis with the Fourier Modal Method (FMM), the sampled height profile from the structure design can directly be used.
- However, for a parametric optimization, the structure needs to be parametrized so that a suitable set of parameters can be used for the optimization.
- For this purpose, a VirtualLab Fusion module is used which converts the equidistantly sampled surface data into a non-equidistant transition point list (included in attached sample files).

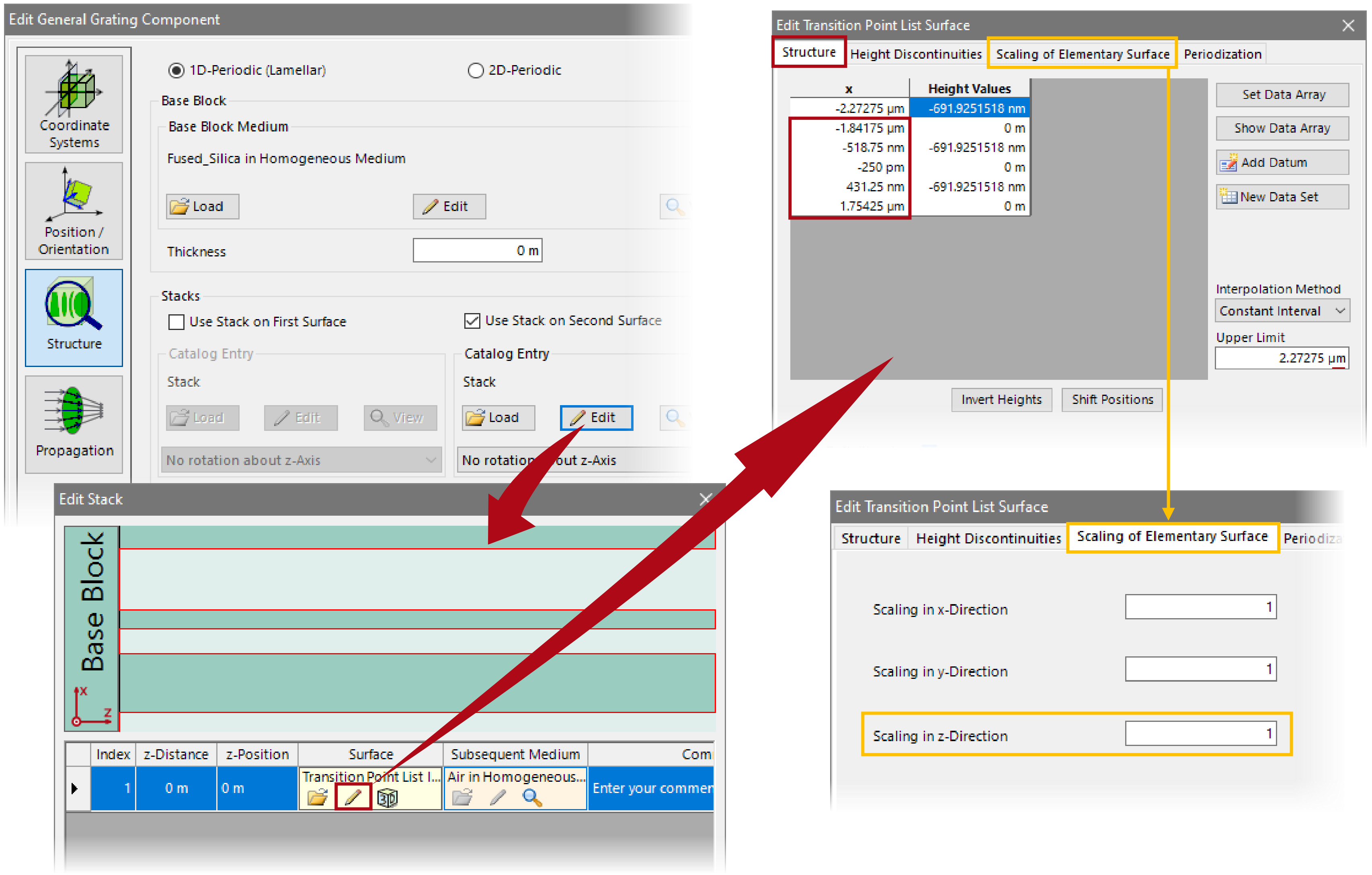
Diffractive Beam Splitter Surface for Further Optimization



For the parametric optimization we plan to use

- the position of the transition points(*)
- and the z-scaling factor (i.e. the profile height)

as free parameters.



(*) except for the first one, which defines the border or the element

Which Merit Functions for Which Diffraction Orders?

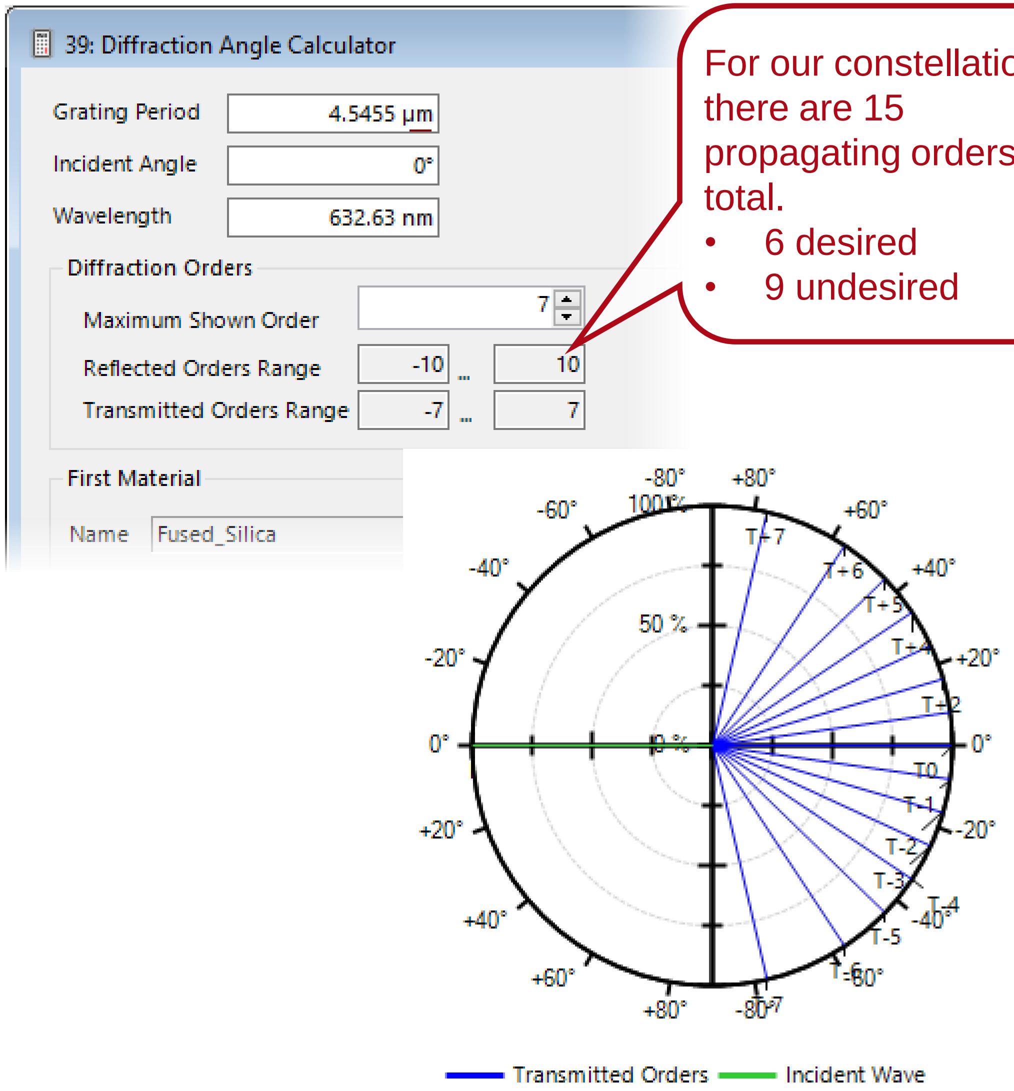
For the optimization it is not just relevant to have a well-parametrized structure, it is also important to define suitable merit functions, which are calculated based on distinct diffraction order results.

In this use case the following merit functions are defined:

1. Efficiency of Desired (Working) Orders
2. Uniformity Error of Desired (Working) Orders
3. Maximum Efficiency of Undesired Orders (excl. 0th)
4. Efficiency of Undesired 0th Order
5. Efficiency of Undesired Orders

The six desired (working) orders are: -5, -3, -1, 1, 3, 5

How many undesired orders are to be considered?
→ We used VirtualLab Fusion's *Diffraction Angle Calculator* to ascertain the number of propagating orders.



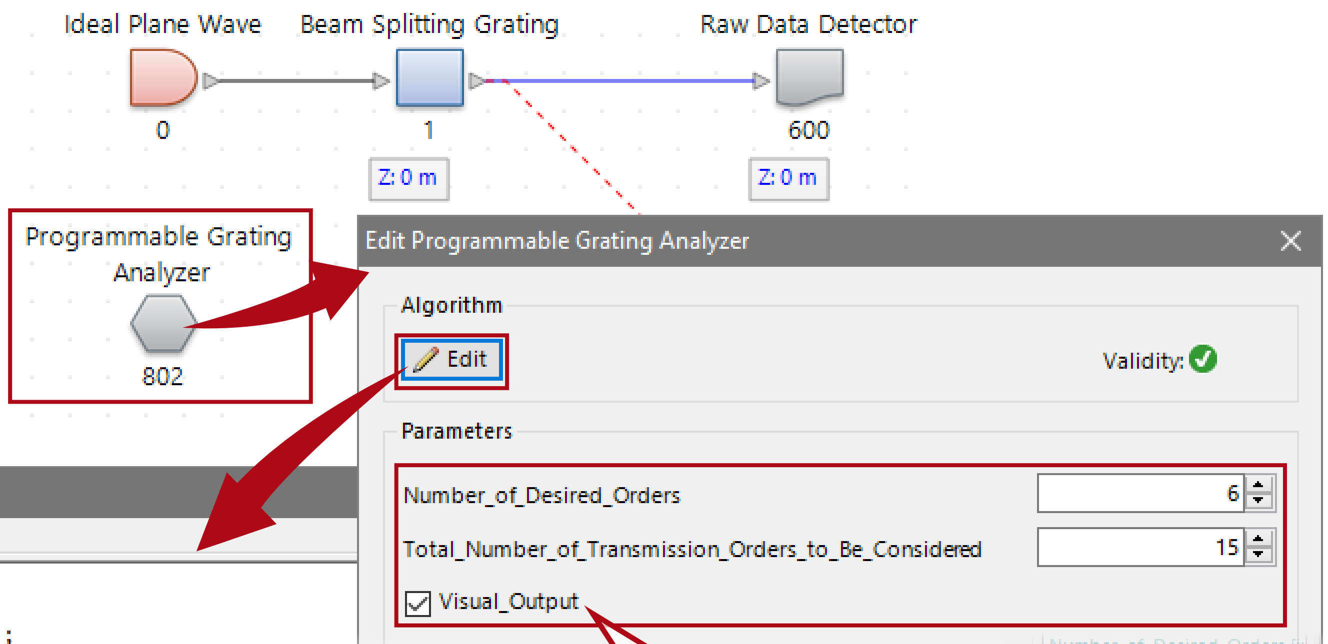
For our constellation, there are 15 propagating orders in total.

- 6 desired
- 9 undesired

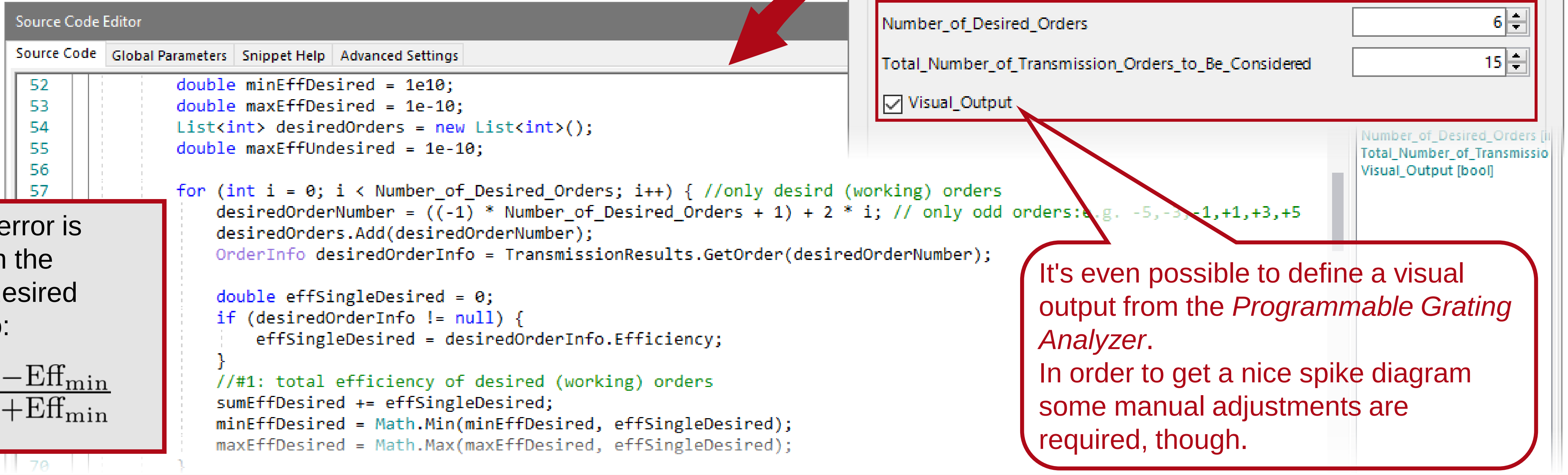
Using the Programmable Grating Analyzer

The standard *Grating Order Analyzer* is a great tool for displaying all the efficiencies of interest in manifold ways.

But for defining arbitrary desired merit functions the *Programmable Grating Analyzer* is the most suitable tool.



C# code of *Programmable Grating Analyzer*

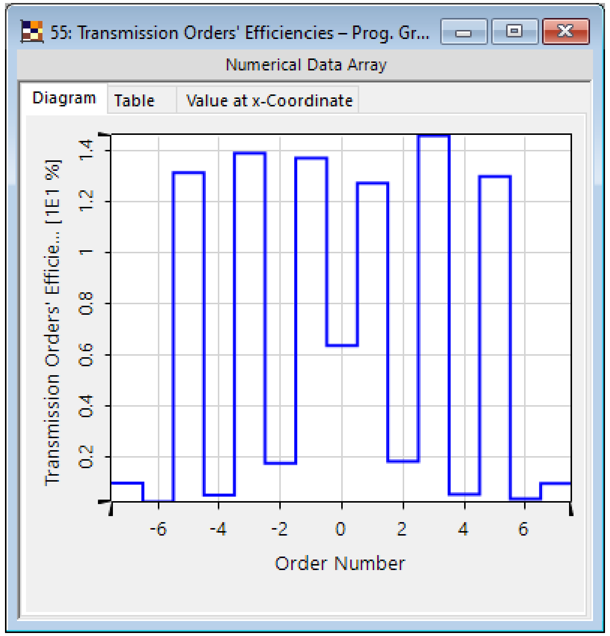


E.g. the uniformity error is evaluated based on the efficiencies of the desired orders according to:

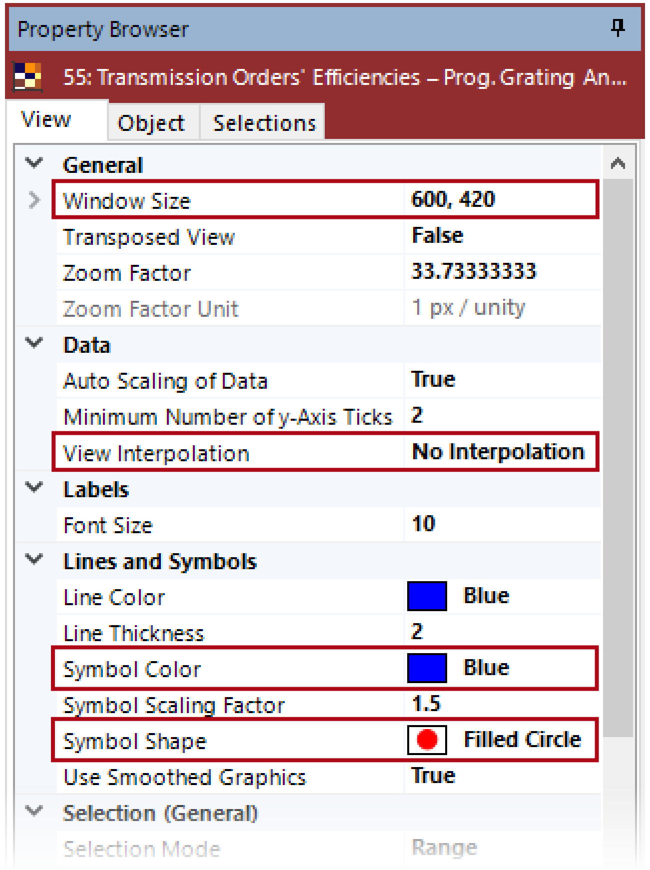
$$\mathrm{UE} = \frac{\mathrm{Eff}_{\max} - \mathrm{Eff}_{\min}}{\mathrm{Eff}_{\max} + \mathrm{Eff}_{\min}}$$

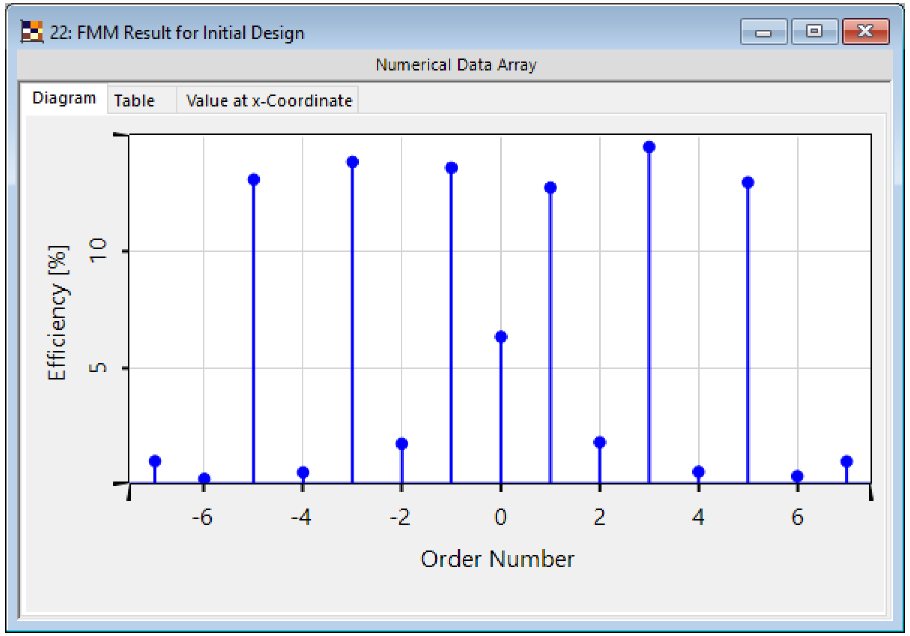
It's even possible to define a visual output from the *Programmable Grating Analyzer*.
In order to get a nice spike diagram some manual adjustments are required, though.

Rigorous Analysis of Initial Beamsplitter Design



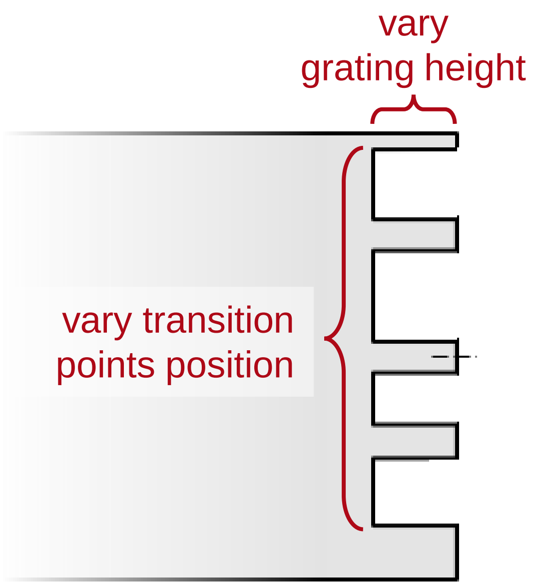
adjustments via *Property Browser*

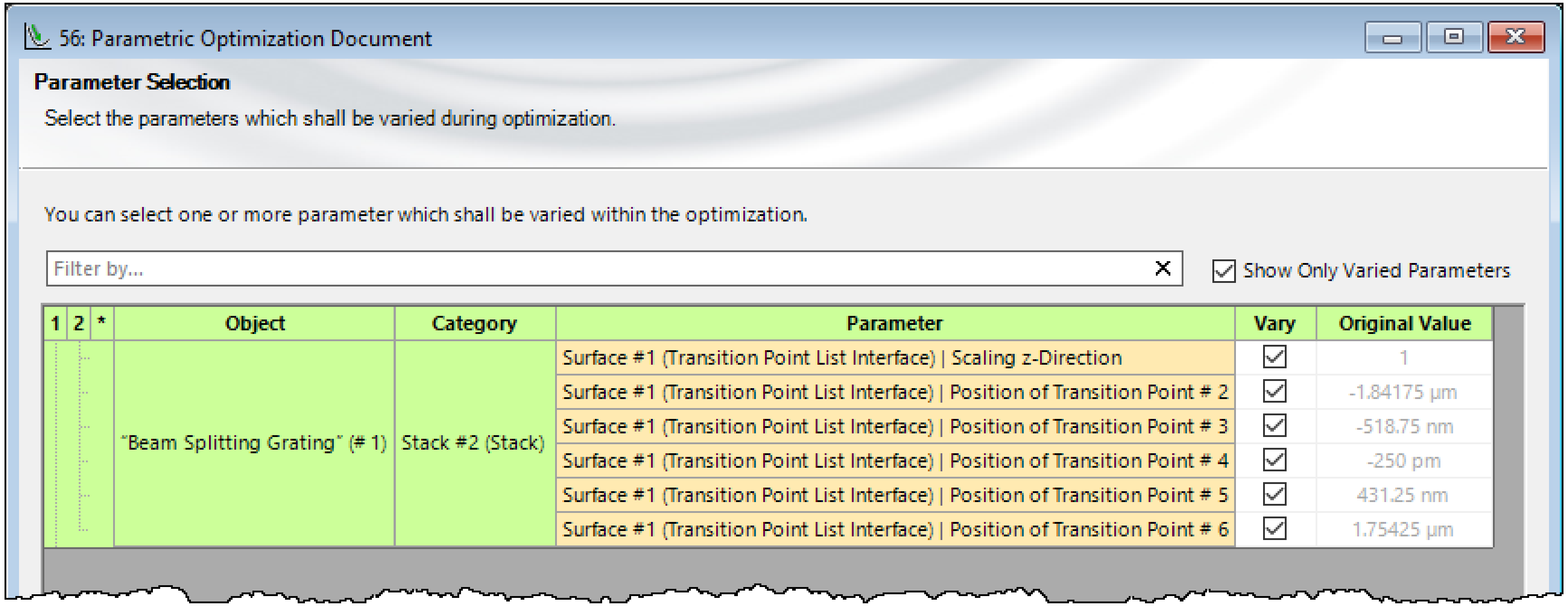




Merit Function	Result
Efficiency of Desired (Working) Orders	80.9%
Uniformity Error of Desired (Working) Orders	6.8%
Maximum Efficiency of Undesired Orders (excl. 0th)	1.8%
Efficiency of Undesired 0th Order	6.4%
Efficiency of Undesired Orders	13.4%

Set the Optimization Parameters





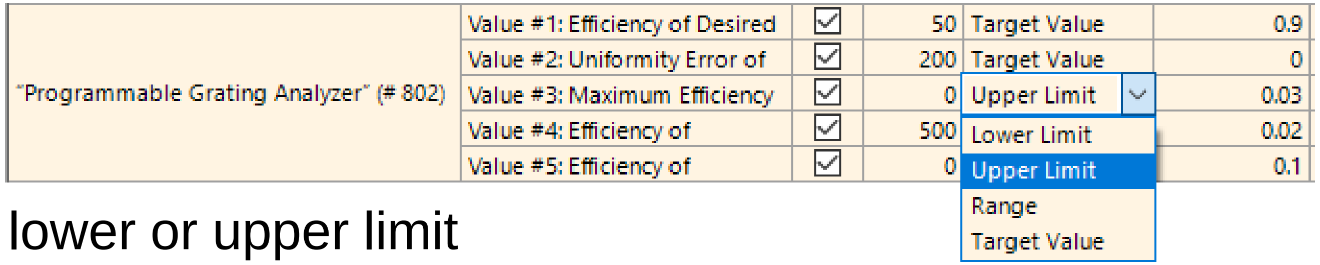
1	2	*	Object	Category	Parameter	Vary	Original Value
			"Beam Splitting Grating" (# 1)	Stack #2 (Stack)	Surface #1 (Transition Point List Interface) | Scaling z-Direction	☑	1
					Surface #1 (Transition Point List Interface) | Position of Transition Point # 2	☑	-1.84175 µm
					Surface #1 (Transition Point List Interface) | Position of Transition Point # 3	☑	-518.75 nm
					Surface #1 (Transition Point List Interface) | Position of Transition Point # 4	☑	-250 pm
					Surface #1 (Transition Point List Interface) | Position of Transition Point # 5	☑	431.25 nm
					Surface #1 (Transition Point List Interface) | Position of Transition Point # 6	☑	1.75425 µm

specified free parameters for the optimization

Two Optimization Processes for Comparison

In this use case we demonstrate two optimizations with differently configured aims and constraints:

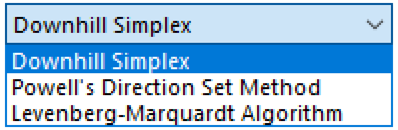
- In **optimization #1**, the uniformity error is prioritized.
- In **optimization #2**, the 0th order should be minimized as well.



Concerning the merit function constraints, the user can specify

- what is the individual target value, range, lower or upper limit
- and via a weight, what the contributions of these should be.

For the optimization, the inbuilt *Down-Hill Simplex* algorithm is applied.



Configuration of the Merit Function Constraints

Optimization #1

Contributions of Considered Merit Functions	
Efficiency of desired Orders	0.2%
Uniformity Error of des. Ord.	99.8%

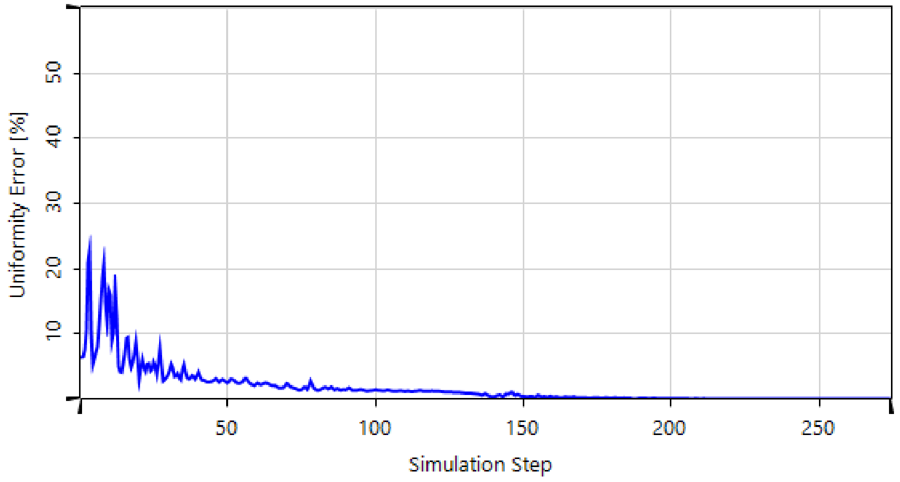
Constraint Host	Constraint Name	Use	Weight	Constraint Type	Value 1	Value 2	Start Value	Contribution
"Beam Splitting Grating" (# 1)	Stack #2 (Stack) | Surface #1 (Transition Point List	☑	1	Range	0.5	1.5	1	0 %
	Stack #2 (Stack) | Surface #1 (Transition Point List	☑	1	Range	-2.27275 µm	2.27275 µm	-1.84175 µm	0 %
	Stack #2 (Stack) | Surface #1 (Transition Point List	☑	1	Range	-2.27275 µm	2.27275 µm	-518.75 nm	0 %
	Stack #2 (Stack) | Surface #1 (Transition Point List	☑	1	Range	-2.27275 µm	2.27275 µm	-250 pm	0 %
	Stack #2 (Stack) | Surface #1 (Transition Point List	☑	1	Range	-2.27275 µm	2.27275 µm	431.25 nm	0 %
	Stack #2 (Stack) | Surface #1 (Transition Point List	☑	1	Range	-2.27275 µm	2.27275 µm	1.75425 µm	0 %
"Programmable Grating Analyzer" (# 802)	Value #1: Efficiency of Desired (Working) Orders	☑	1	Target Value	0.9		0.8093572324	0.1983999243 %
	Value #2: Uniformity Error of Desired (Working)	☑	1000	Target Value	0		0.06428818407	99.80160008 %
	Value #3: Maximum Efficiency of Undesired Orders	☑	0	Upper Limit	0.03		0.01796733629	0 %
	Value #4: Efficiency of Undesired Zeroth Order	☑	0	Upper Limit	0.03		0.06340706733	0 %
	Value #5: Efficiency of Undesired Orders	☑	0	Upper Limit	0.1		0.1340061047	0 %
"Beam Splitting	Transition Point List Surface # 1 | Minimum Feature	☑	1	Lower Limit	300 nm		431 nm	0 %

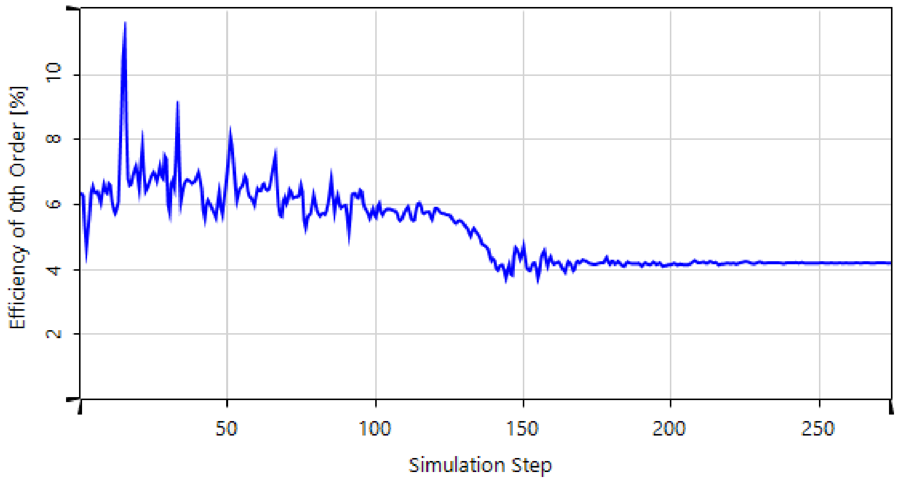
Optimization #2

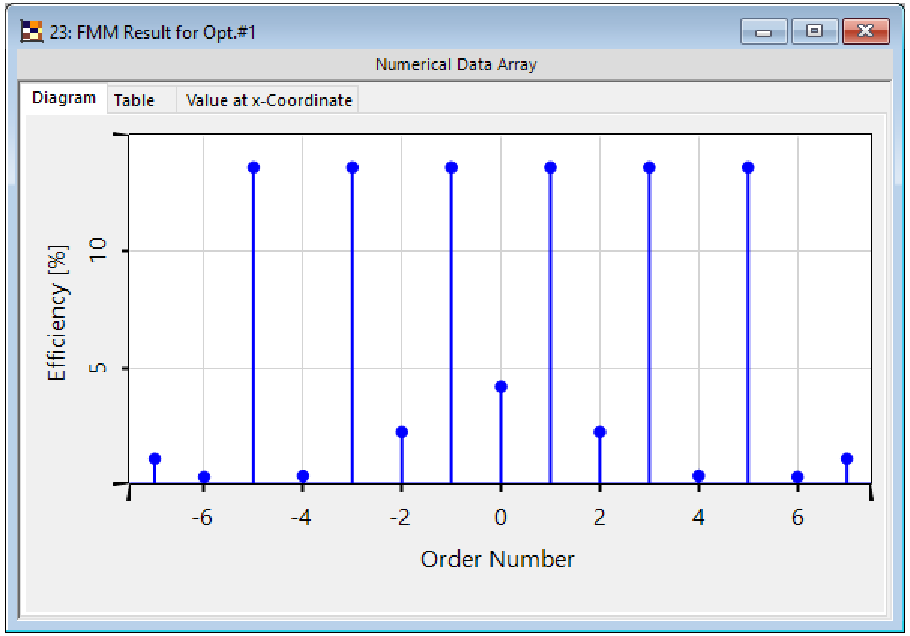
Contributions of Considered Merit Functions	
Efficiency of Desired Orders	18.8%
Uniformity Error of Des. Ord.	37.9%
Efficiency of Undesired 0th Ord.	43.2%

Constraint Host	Constraint Name	Use	Weight	Constraint Type	Value 1	Value 2	Start Value	Contribution
"Beam Splitting Grating" (# 1)	Stack #2 (Stack) | Surface #1 (Transition Point List	☑	1	Range	0.5	1.5	1	0 %
	Stack #2 (Stack) | Surface #1 (Transition Point List	☑	1	Range	-2.27275 µm	2.27275 µm	-1.84175 µm	0 %
	Stack #2 (Stack) | Surface #1 (Transition Point List	☑	1	Range	-2.27275 µm	2.27275 µm	-518.75 nm	0 %
	Stack #2 (Stack) | Surface #1 (Transition Point List	☑	1	Range	-2.27275 µm	2.27275 µm	-250 pm	0 %
	Stack #2 (Stack) | Surface #1 (Transition Point List	☑	1	Range	-2.27275 µm	2.27275 µm	431.25 nm	0 %
	Stack #2 (Stack) | Surface #1 (Transition Point List	☑	1	Range	-2.27275 µm	2.27275 µm	1.75425 µm	0 %
"Programmable Grating Analyzer" (# 802)	Value #1: Efficiency of Desired (Working) Orders	☑	50	Target Value	0.9		0.8093572324	18.84873241 %
	Value #2: Uniformity Error of Desired (Working)	☑	200	Target Value	0		0.06428818407	37.9260962 %
	Value #3: Maximum Efficiency of Undesired Orders	☑	0	Upper Limit	0.03		0.01796733629	0 %
	Value #4: Efficiency of Undesired Zeroth Order	☑	500	Upper Limit	0.02		0.06340706733	43.22517139 %
	Value #5: Efficiency of Undesired Orders	☑	0	Upper Limit	0.1		0.1340061047	0 %
"Beam Splitting	Transition Point List Surface # 1 | Minimum Feature	☑	1	Lower Limit	300 nm		431 nm	0 %

Optimization #1 (Priority = Uniformity Error)

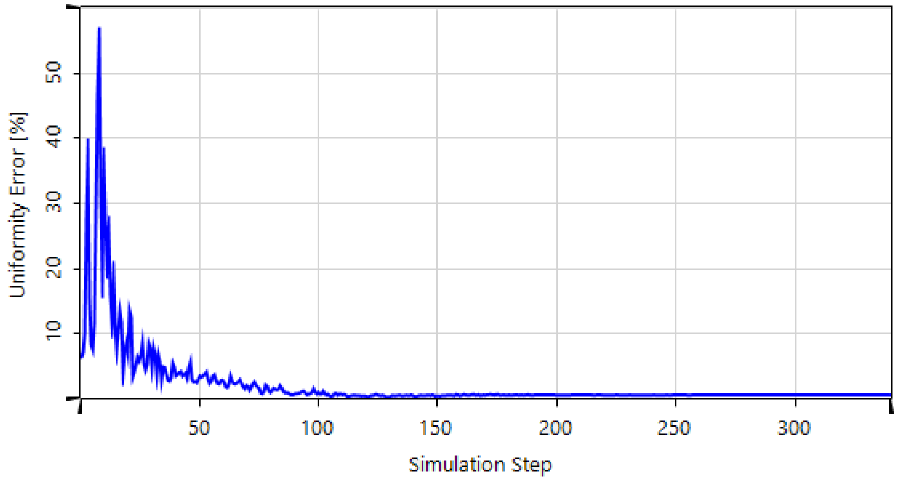


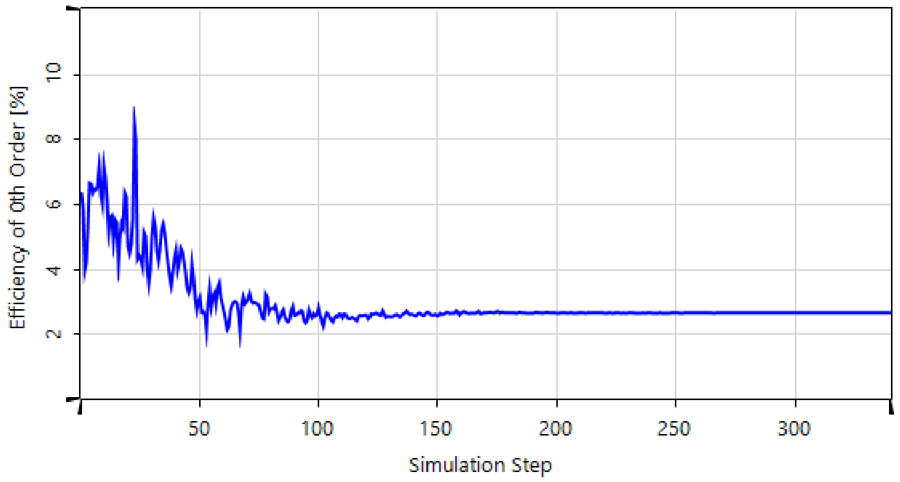


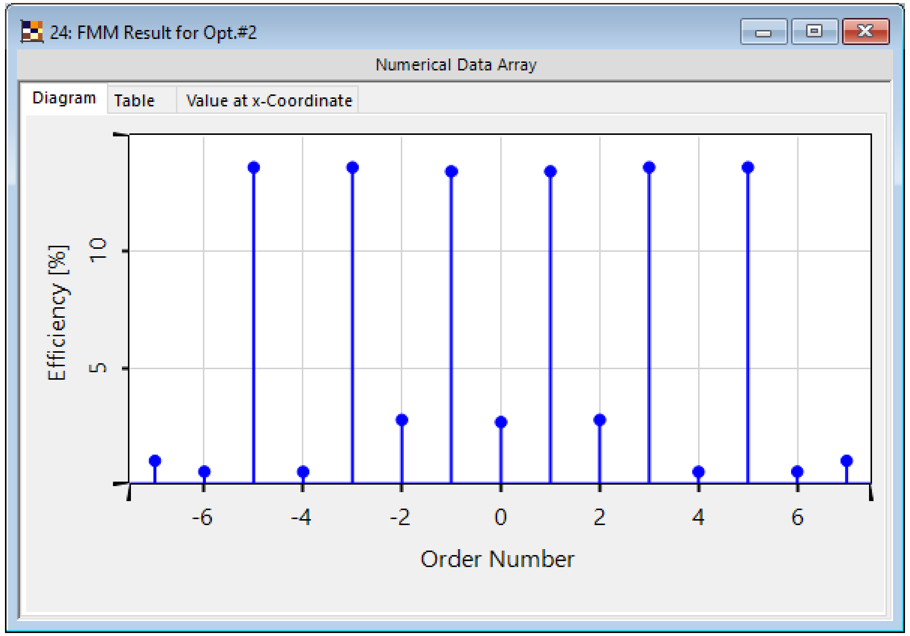


Merit Function	Result
Efficiency of Desired (Working) Orders	81.8%
Uniformity Error of Desired (Working) Orders	0.0%
Maximum Efficiency of Undesired Orders (excl. 0th)	2.3%
Efficiency of Undesired 0th Order	4.2%
Efficiency of Undesired Orders	12.3%

Optimization #2 (Priority = Uniformity Error & Low 0th Order)



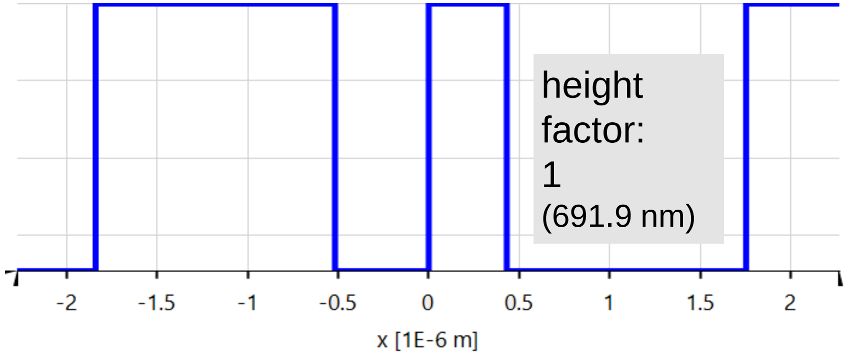




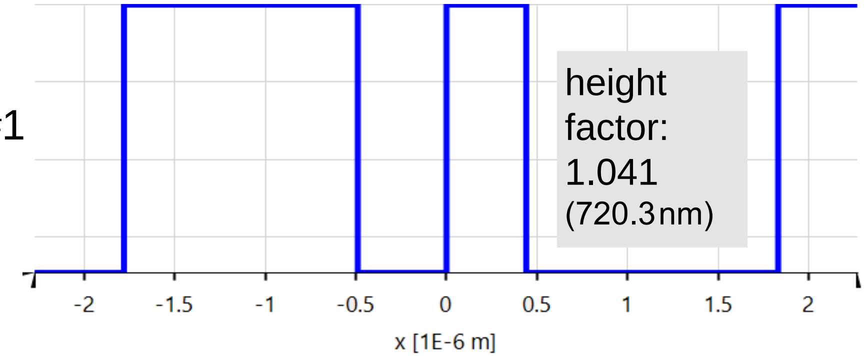
Merit Function	Result
Efficiency of Desired (Working) Orders	81.5%
Uniformity Error of Desired (Working) Orders	0.6%
Maximum Efficiency of Undesired Orders (excl. 0th)	2.8%
Efficiency of Undesired 0th Order	2.7%
Efficiency of Undesired Orders	12.3%

Comparison of Rigorous Results (Initial – Opt.#1 – Opt.#2)

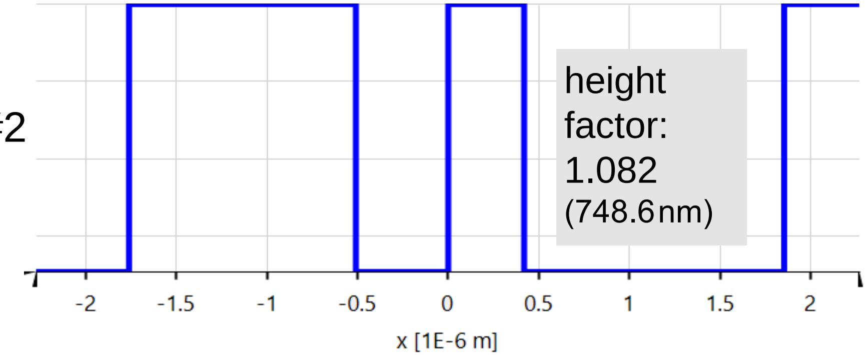
initial



opt.#1



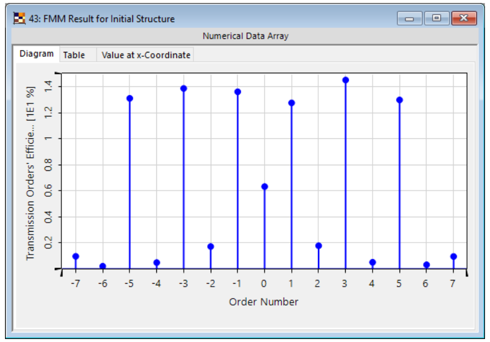
opt.#2

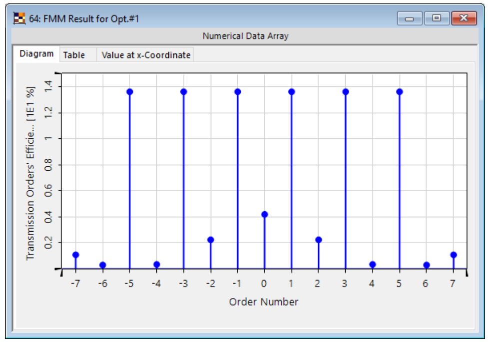


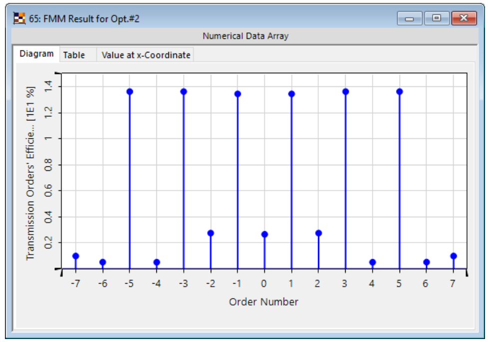
Merit Function	Initial	Opt.#1	Opt.#2
Total Efficiency	80.9%	81.8%	81.5%
Uniformity Error	6.8%	0.0%	0.6%
Max. Stray Light (excl. 0th)	1.8%	2.3%	2.8%
Efficiency of 0th Order	6.4%	4.2%	2.7%
Efficiency of Stray Light	13.4%	12.3%	12.3%

Note

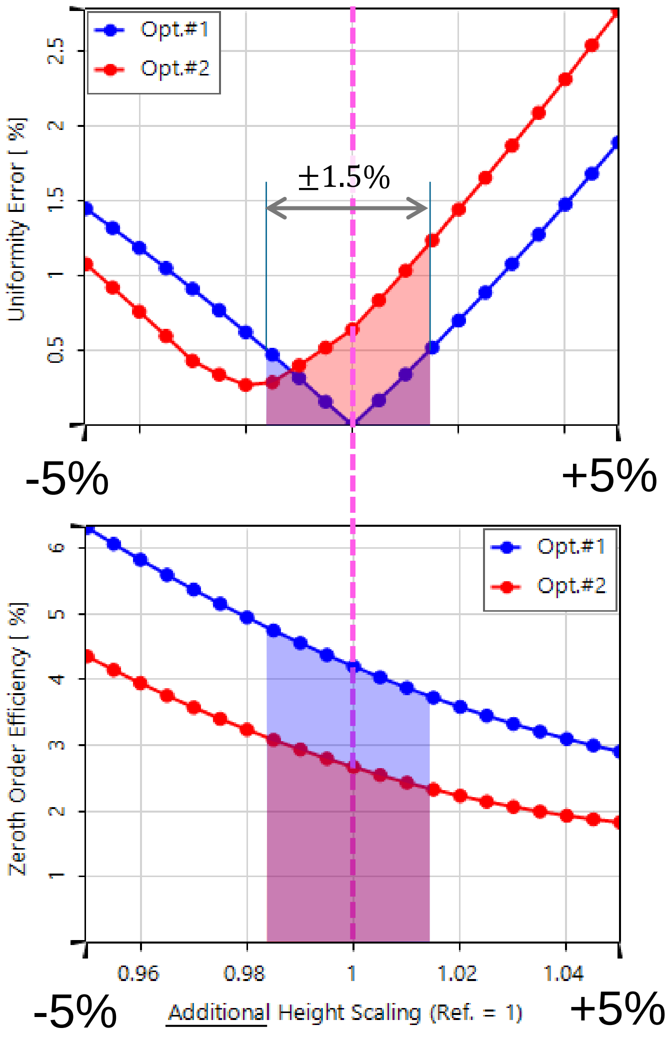
Since the rigorous results of a high-NA beam splitter might deviate considerably from the approximate results, consideration should be given to investigating and, if necessary, reoptimizing supposedly inferior initial designs.







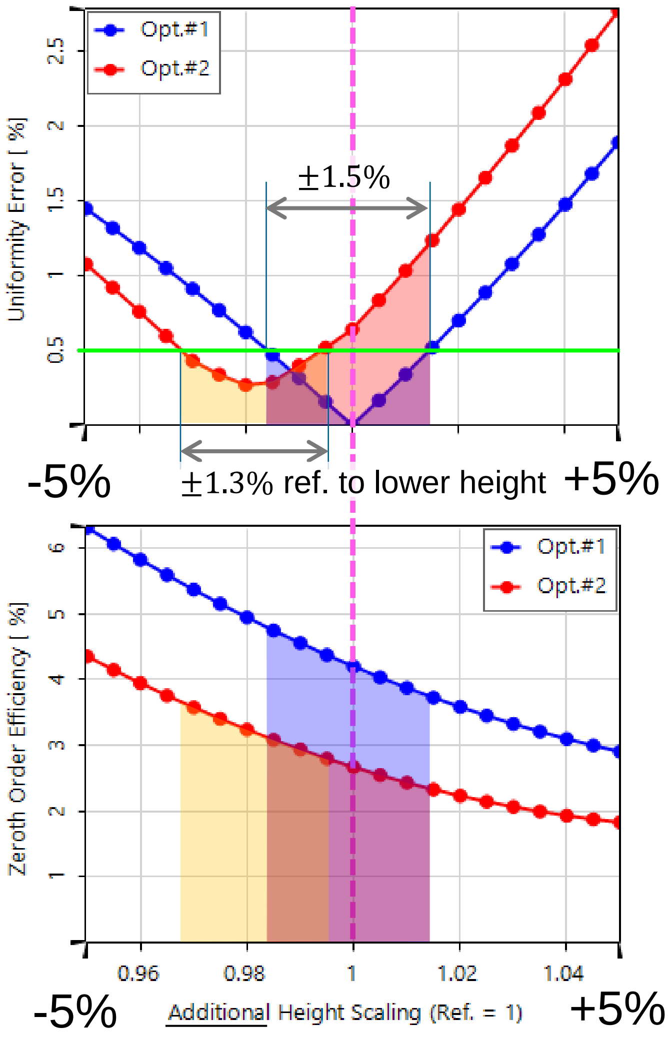
Results from Tolerance Simulations



- It was investigated how the quality functions behave for possibly height tolerances during production in the range of $\pm 5\%$.
- In most parts of the tolerancing range regarding an etching depth error of approx. $\pm 1.5\%$ (length of blue & red areas), the design from the 2nd optimization exhibits a distinctly worse uniformity.
- At first glance, it may seem strange for optimization #2 the minimal uniformity error (red curve @0%) is not centered. This is because low 0th order efficiency was prioritized in optimization #2 and some uniformity was sacrificed to achieve this aim.
- As a result, the structure of the 2nd optimization has always a distinct lower 0th order for the whole envisaged range of the tolerancing analysis.

Note:
The reference value 1 in the tolerance simulation results always refers to the individually optimized height of the examined structure (indicated by the purple line).

Conclusion from Tolerance Simulations



- Tolerance testing provides a better information base for deciding what is the most suitable structure for the desired application.
- It can be seen, that the structure of the 2nd optimization yields uniformity errors below 0.5% (green line) over a similar tolerancing range of ±1.3% (length of yellow area) if the height with the lowest uniformity error is used.
- Thus, the 2nd optimization result with an additional height scaling of 0.9825 (707.7 nm) might pose a good solution with an overall suitable performance.
  In below table the according results are shown in the last column titled "Opt.#2b".

Merit Function	Initial	Opt.#1	Opt.#2	Opt.#2b
Total Efficiency	80.9%	81.8%	81.5%	81.6%
Uniformity Error	6.8%	0.0%	0.6%	0.2%
Max. Stray Light (excl. 0th)	1.8%	2.3%	2.8%	2.6%
Efficiency of 0th Order	6.4%	4.2%	2.7%	3.2%
Efficiency of Stray Light	13.4%	12.3%	12.3%	12.3%

Document Information

title	High NA Beam Splitter Optimization with User-Defined Merit Functions
document code	DOE.0005
document version	1.0
software version	2021.1 (Build 1.180)
software edition	VirtualLab Fusion Advanced
category	Application Use Case
further reading	- Programmable Grating Analyzer - Design and Rigorous Analysis of Non-Paraxial Diffractive Beam Splitter - Design of Diffractive Beam Splitters for Generating a 2D Light Mark