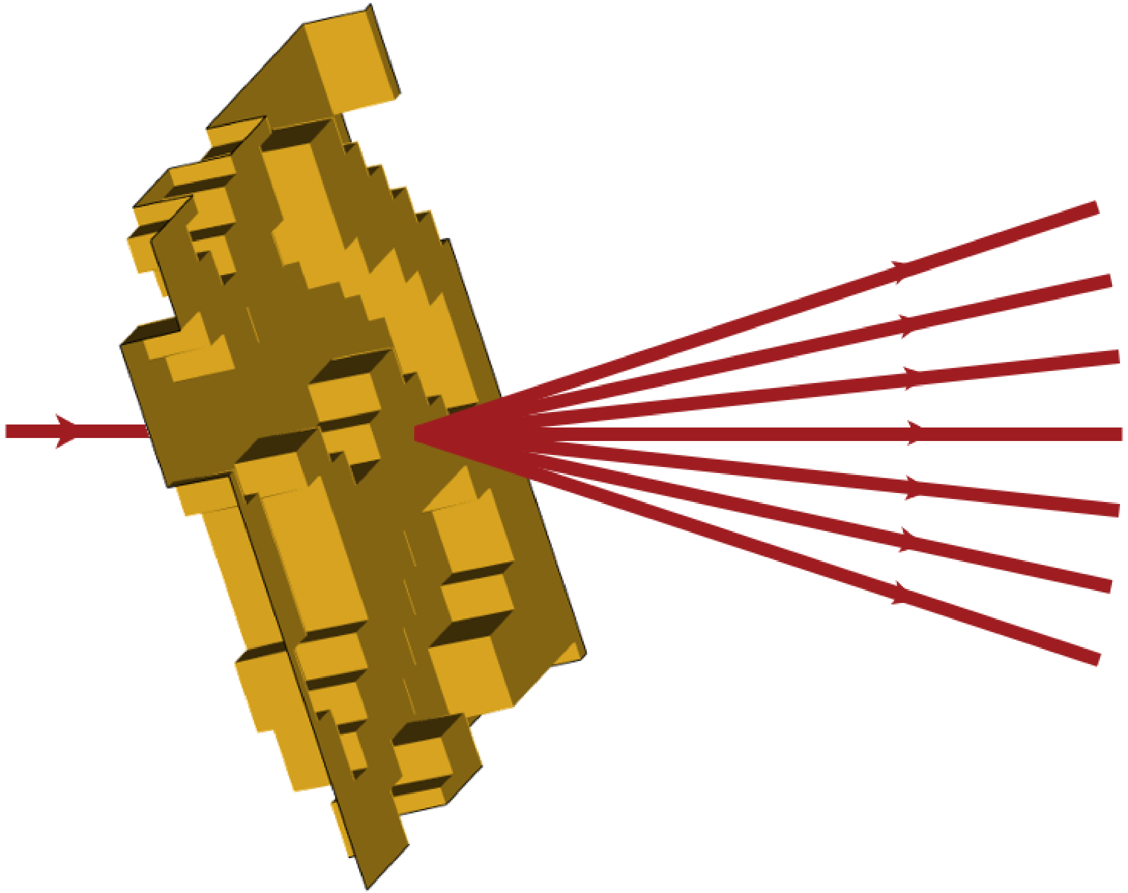
Design and Rigorous Analysis of Non-Paraxial Diffractive Beam Splitter

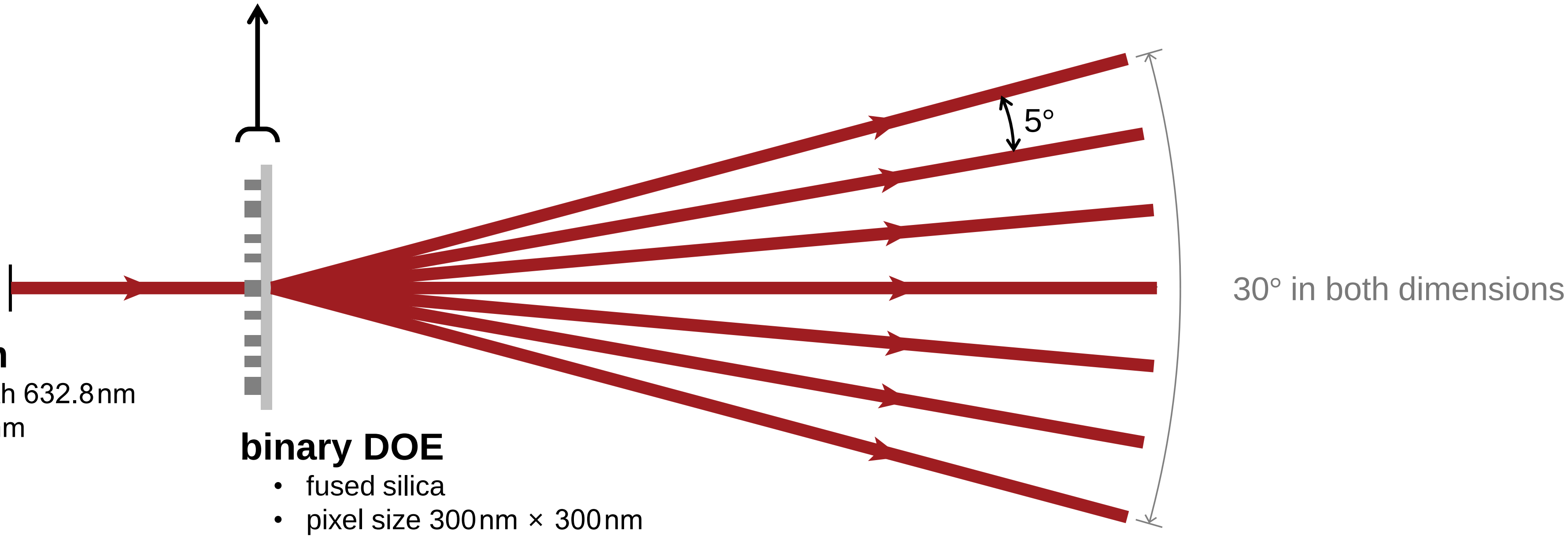
Abstract



The direct design of non-paraxial diffractive beam splitters is still a challenge. Due to the quite large diffraction angle, the feature size of the element is in the same order of magnitude as the working wavelength. Hence, the design process is beyond paraxial modeling approaches. Thus, in this example, the Iterative Fourier Transform Algorithm (IFTA) and the Thin Element Approximation (TEA) are used for the initial design of the diffractive element structures, and the Fourier Modal Method (FMM) is applied afterwards for a rigorous performance evaluation, including the investigation of merit function changes in the case of height variations.

Design Task

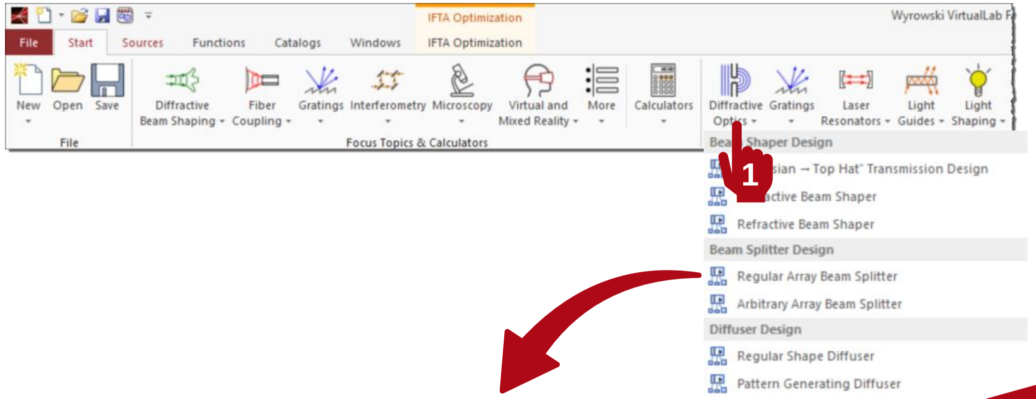
- initial design of a diffractive 1:7×7 beam splitter using a paraxial approximation
- performance analysis and further optimization of uniformity and influence of zeroth order by using rigorous analyses

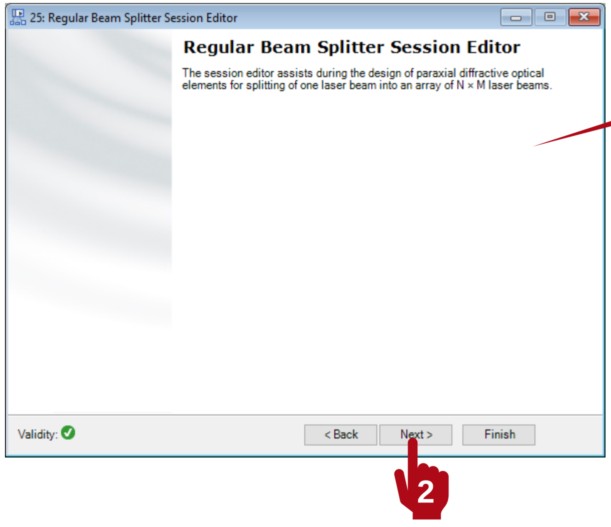


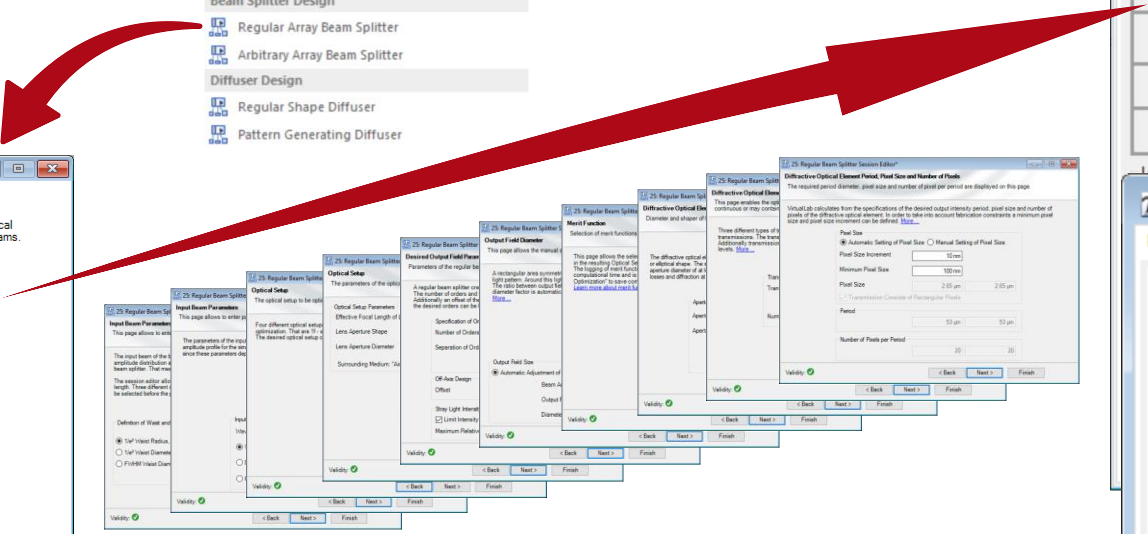
input beam
- wavelength 632.8 nm
- 1 mm × 1 mm

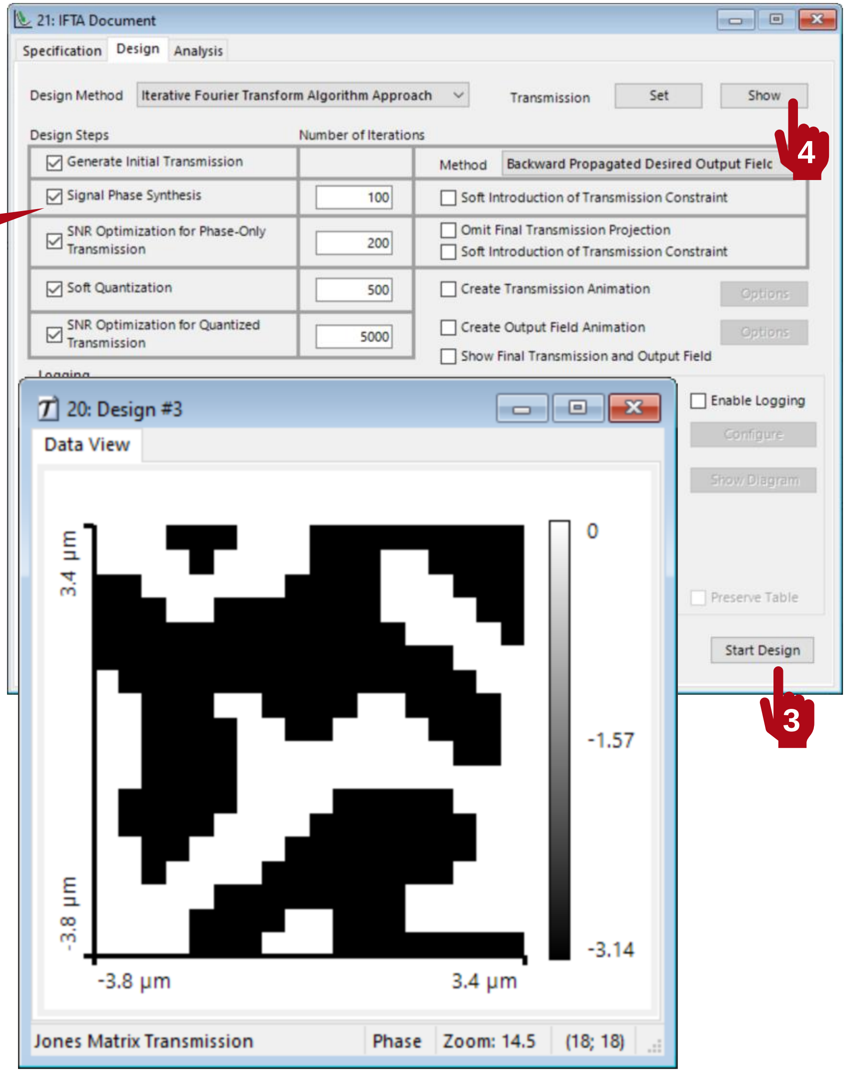
binary DOE
- fused silica
- pixel size 300 nm × 300 nm
- 1 mm thickness

Iterative Fourier Transform Algorithm (IFTA)





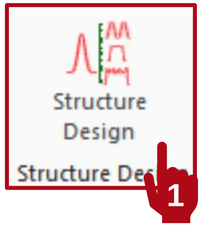


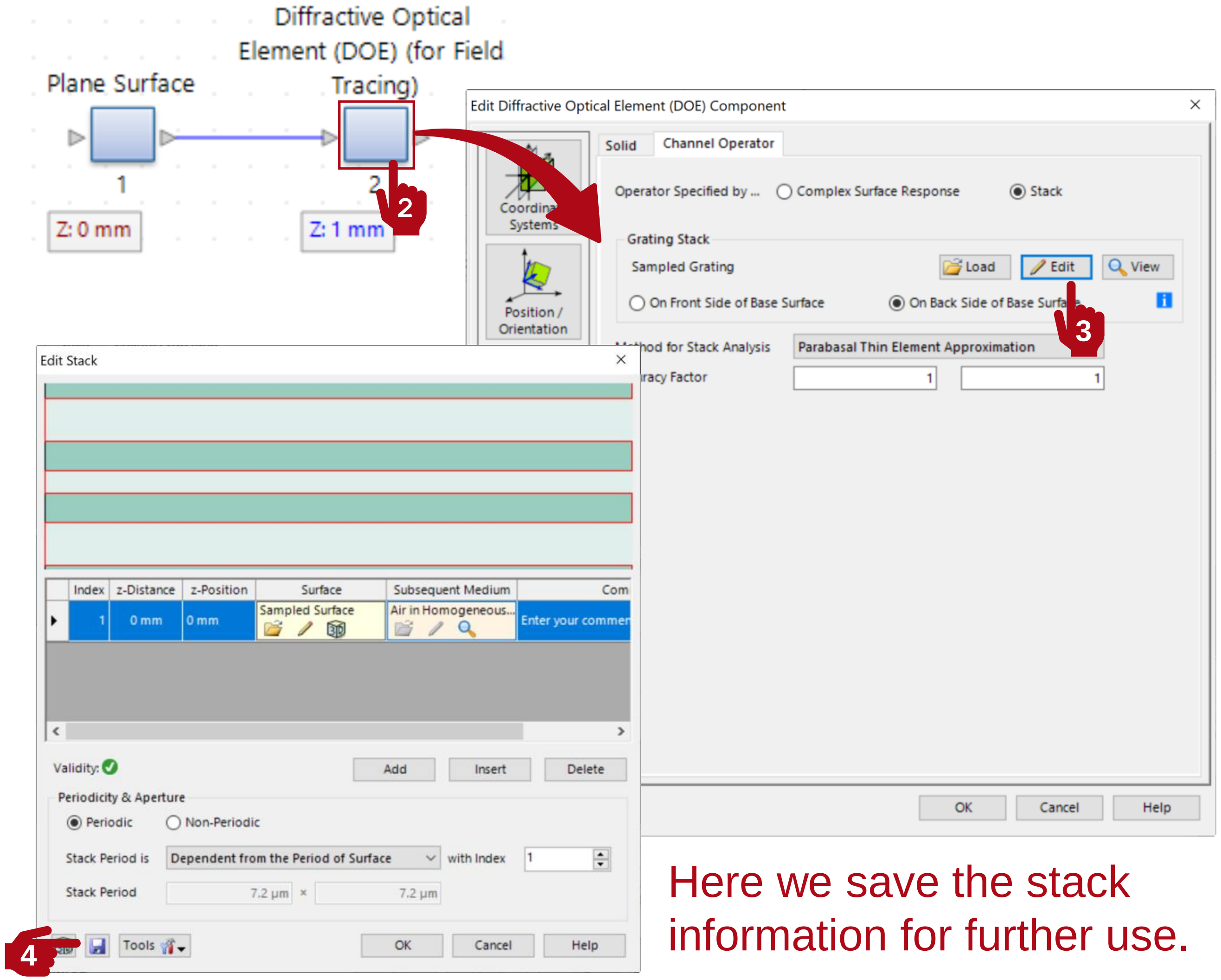


With the *Regular Beam Splitter Session Editor*, VirtualLab Fusion offers a guided tool that allows the user to specify step-by-step all parameters that influence the beam splitter design.

Convert Transmission Function To Structure

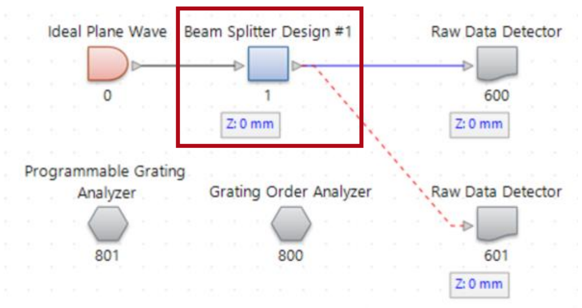
- The resulting transmission function can be converted into a structure profile by applying *Structure Design* from the *Design* ribbon.
- For this conversion, the Thin Element Approximation (TEA) is used. The resulting structure is hence proportional to the initial phase function.
- VirtualLab Fusion delivers the calculated structure data in the form of already preset elements of an optical setup.
- To use this structure in different simulation scenarios either the actual sampled surface or the specified stack needs to be taken from within the component.



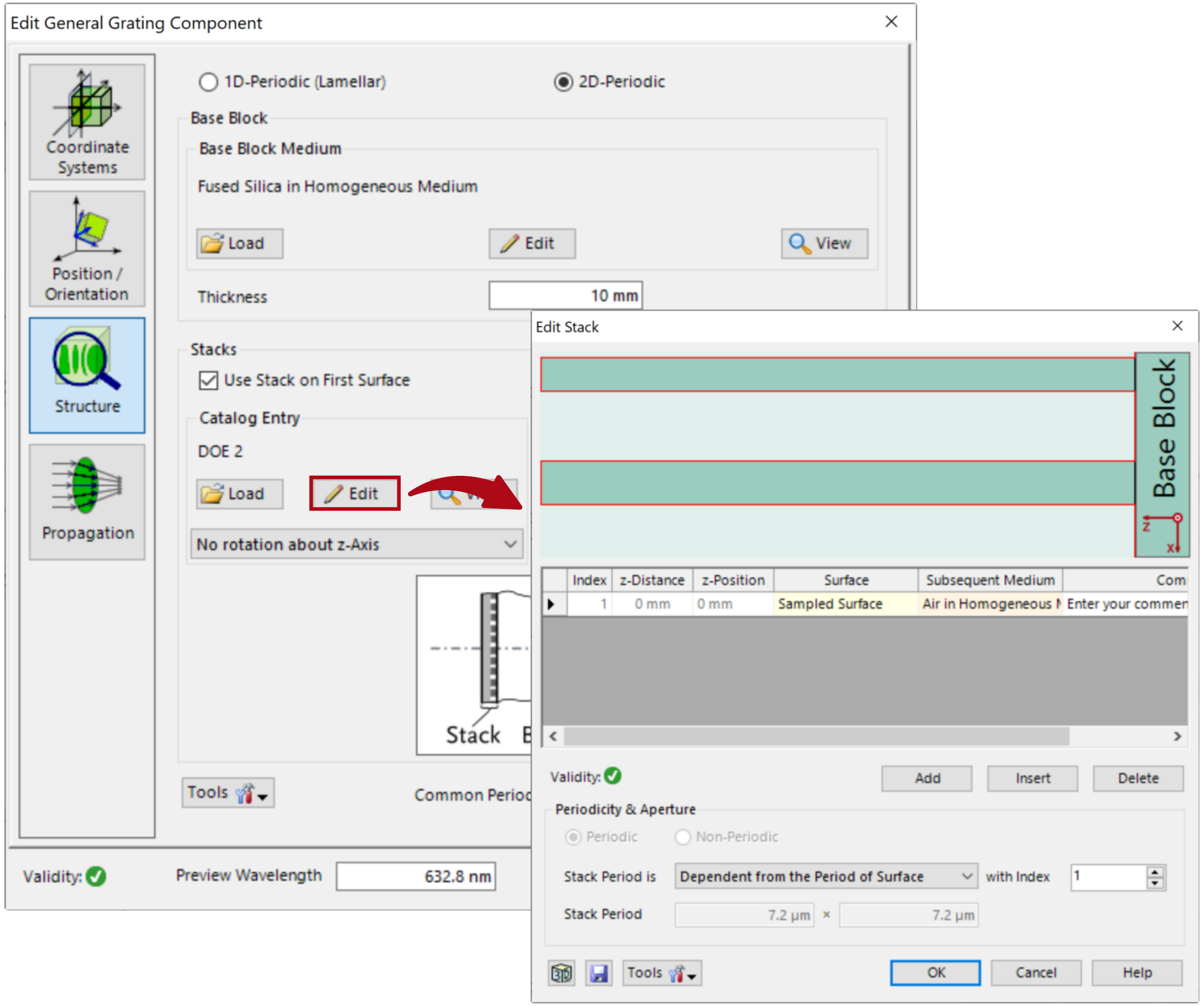


Here we save the stack information for further use.

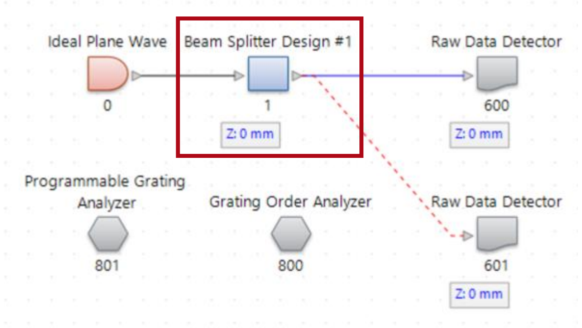
Diffractive Beam Splitter Surface



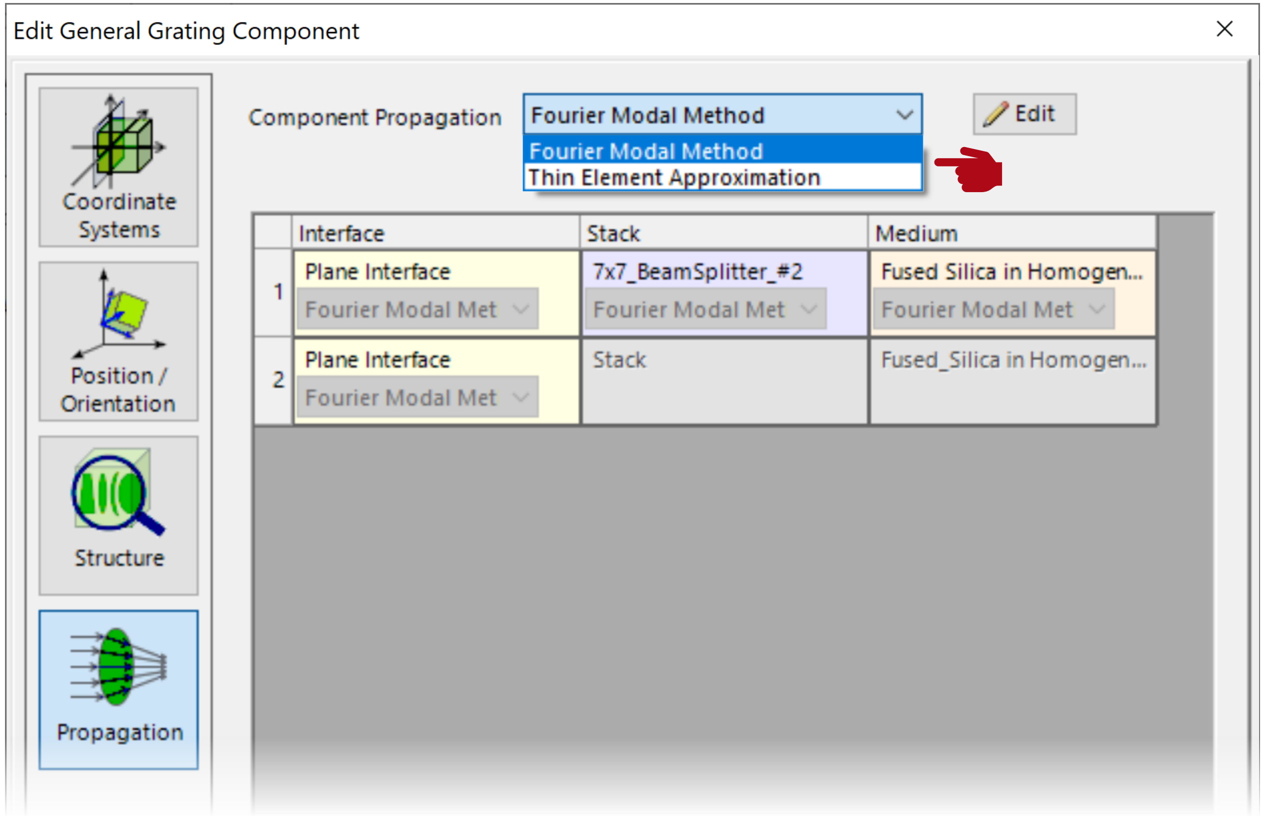
For further evaluation, a *General Grating Optical Setup is used,* where load the previously saved stack is loaded. The *Grating Optical Setup* offers unique tools, components and analyzers to further investigate the characteristics and performance of a given periodic structure.



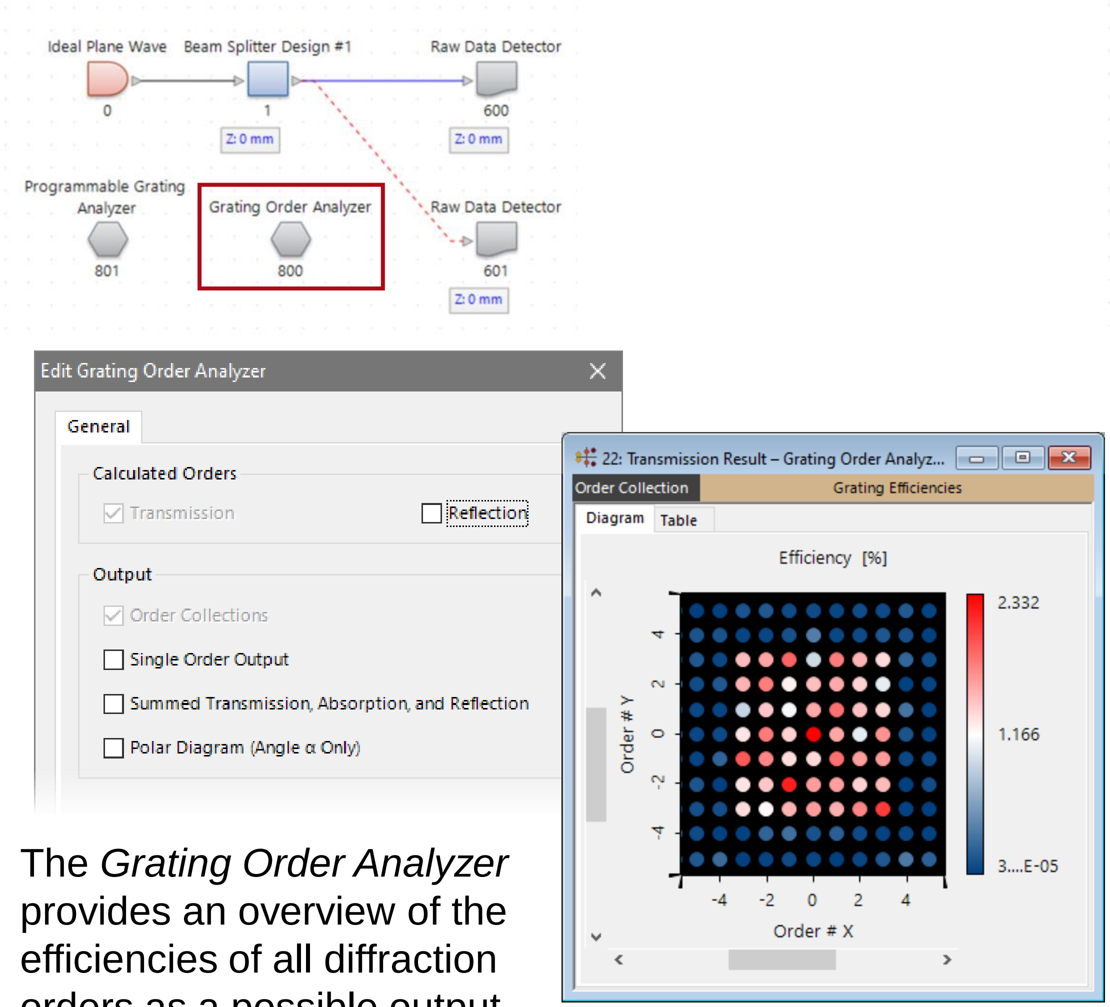
Diffractive Beam Solvers – Thin Element Approximation (TEA)



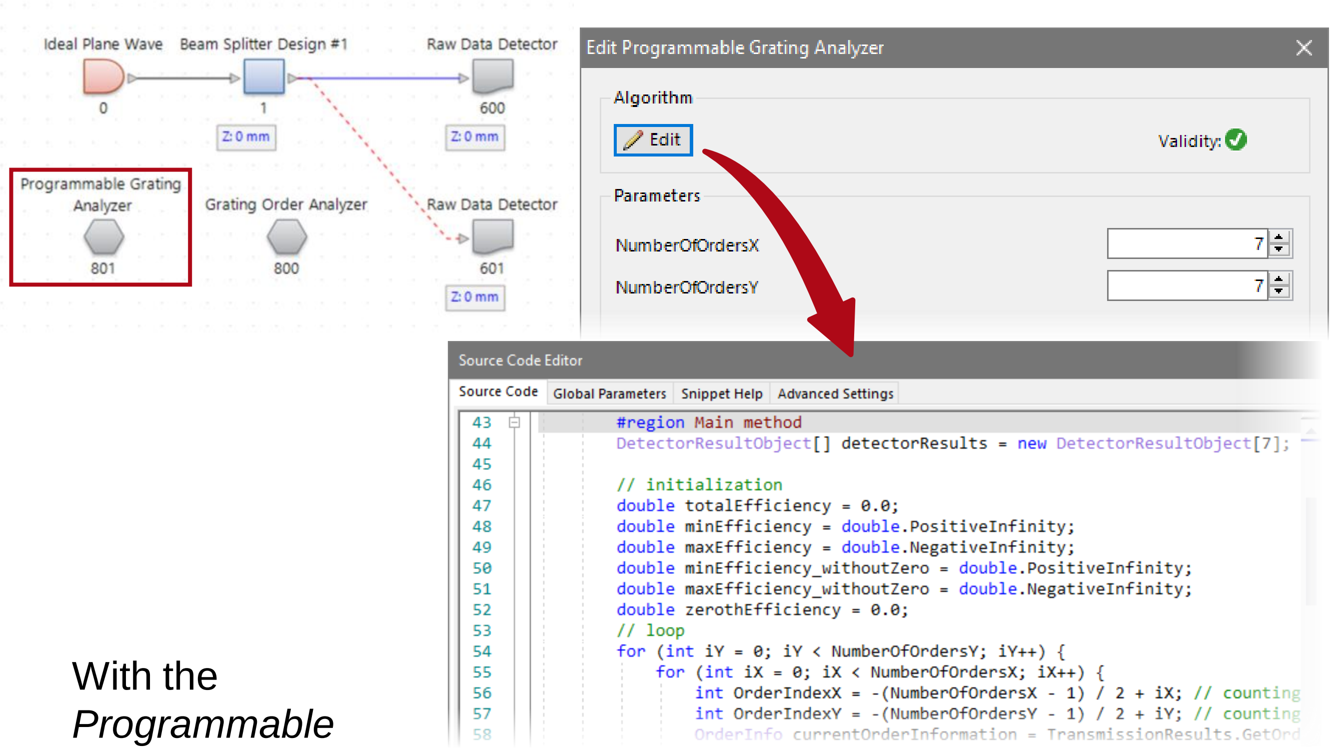
- The *General Grating Component* offers the *Thin Element Approximation (TEA)* and the *Fourier Modal Method (FMM)* as solvers to model the given grating.
- The *Thin Element Approximation* normally produces results faster but may have accuracy issues, when the structures are smaller than approx. 5 times the wavelength.
- The *Fourier Modal Method* allows for a rigorous simulation but requires a higher numerical effort.



Grating Order & Programmable Grating Analyzer



The *Grating Order Analyzer* provides an overview of the efficiencies of all diffraction orders as a possible output among many.



With the *Programmable Grating Analyzer* the user can specify what values shall be calculated, e.g.:

- *Total Efficiency*
- *Uniformity Error*
- *0^{th} Order Efficiency*

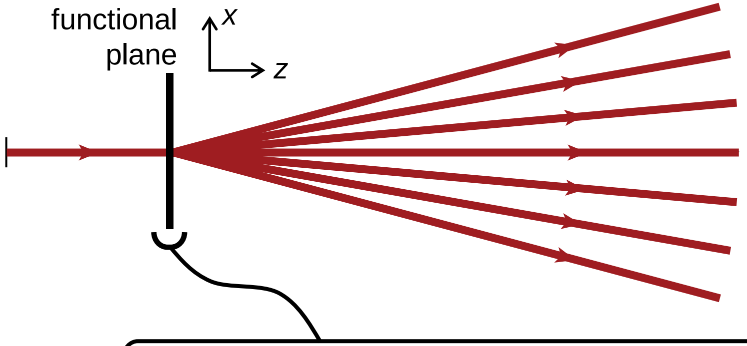
Detector	Sub - Detector	Result
Grating Analyzer	Value #6: Uniformity Error (RMS)	67.453014 %
Grating Analyzer	Value #5: Zeroth Order Error	451.46414 %
Grating Analyzer	Value #4: Zeroth Efficiency	7.9549562 %
Grating Analyzer	Value #3: Average Efficiency without Zeroth Order	1.3068398 %
Grating Analyzer	Value #2: Average Efficiency	1.4425156 %
Grating Analyzer	Value #1: Total Efficiency	70.683265 %

Design & Evaluation Results

- Phase Function Design
- Structure Design
- TEA Evaluation
- FMM Evaluation
- Height Scaling (Tolerancing)

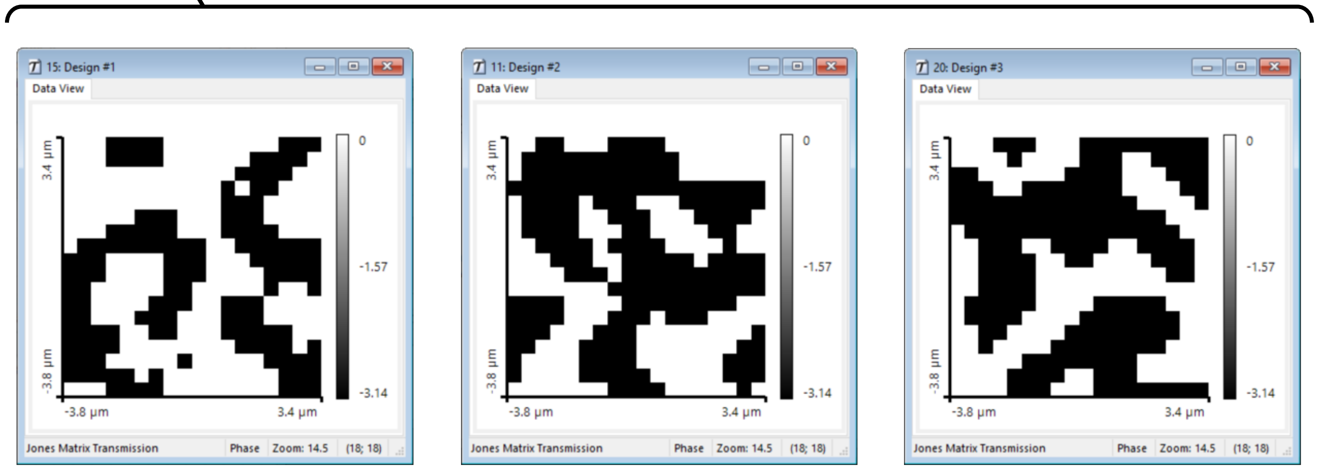
Phase-Only Transmission Design

In this step, the Iterative Fourier Transform Algorithm (IFTA) is applied fot a binary phase-only transmission design



VirtualLab Fusion provides the *Multiple Run* document, which allows the user to perform an arbitrary number of designs with an option to filter the results according to certain criteria.
The following three results were obtained this way; we will evaluate them further.

phase functions

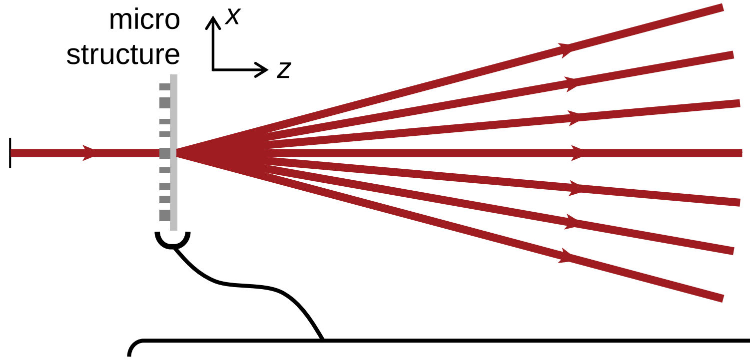


design #1 design #2 design #3

...

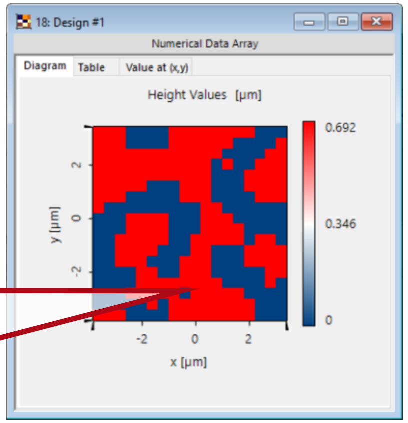
Structure Design

Next, the Thin Element Approximation (TEA) is used for the structure design, means under a paraxial assumption (the phase function and the resulting height profile are therefore proportional)

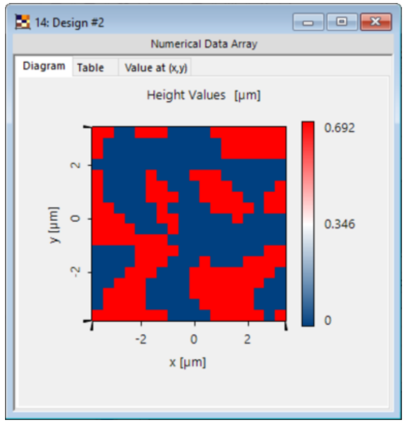


Automatic conversion from phase-only transmission to structure height profile, according to given wavelength and material

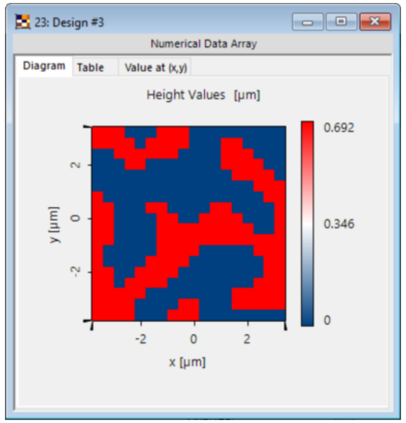
height profiles



design #1



design #2

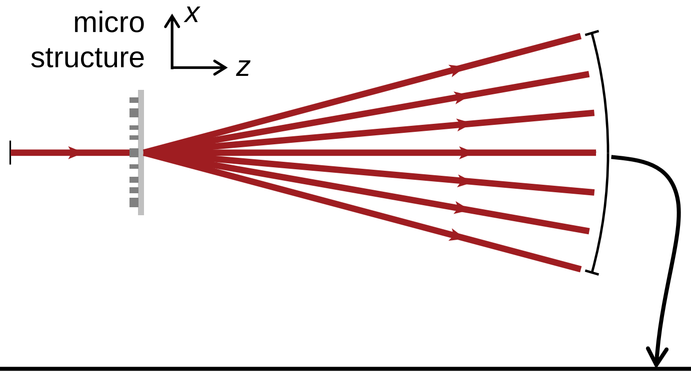


design #3

Note: Such small features might cause issues for achieving good results and for fabrication.

Performance Evaluation with TEA

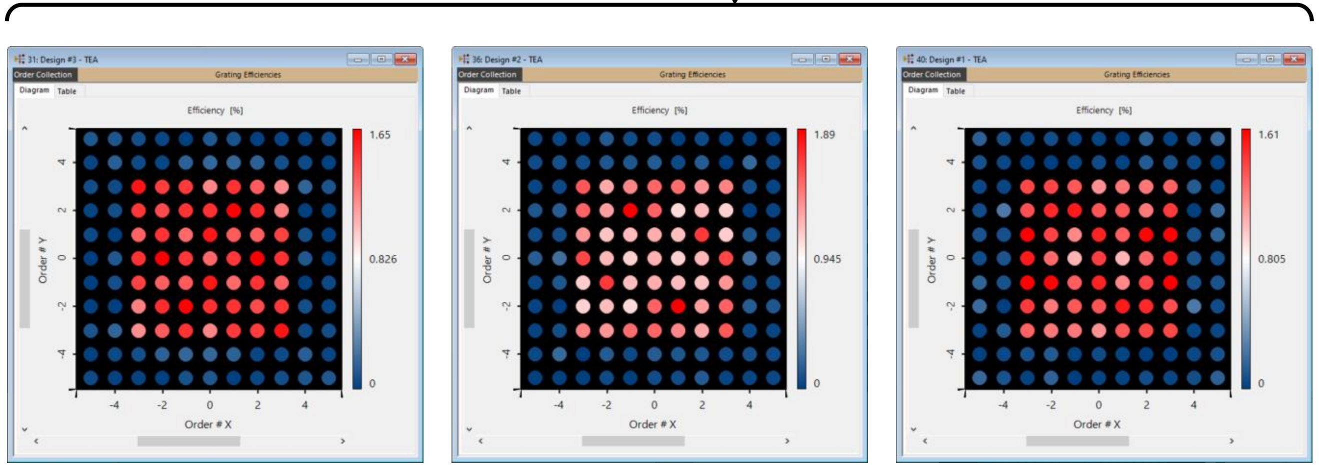
Now, the obtained microstructure is evaluation with TEA, which was also used for the structure design and which is accurate under paraxial conditions.



Merit Function	Design #1	Design #2	Design #3
Total Efficiency	66.7%	66.0%	70.0%
Average Efficiency (of working orders)	1.4%	1.3%	1.4%
Zeroth Order Efficiency	1.4%	1.2%	1.3%
Zeroth Order Error*	**3.4%**	8.8%	8.2%
Uniformity Error**	21.9%	27.4%	**16.4%**
Uniformity Error without 0th Order	21.9%	27.4%	16.4%

$$* \text{ Zeroth Order Error} = \frac{\text{Zeroth Efficiency} - \text{Average Efficiency}}{\text{Average Efficiency}}$$

$$** \text{ Uniformity Error} = \frac{\text{Max. Efficiency} - \text{Min.Efficiency}}{\text{Max. Efficiency} + \text{Min.Efficiency}}$$



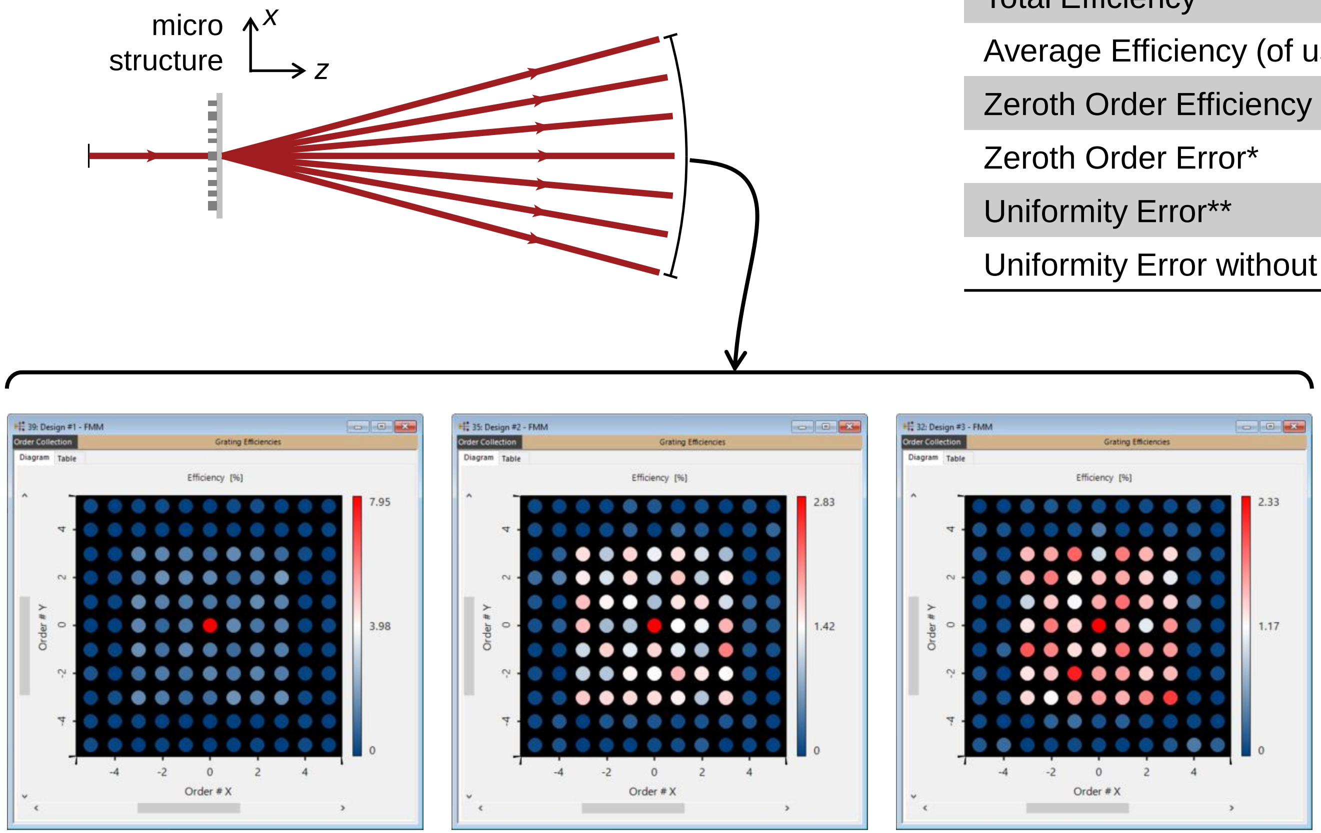
From the results with TEA the systems look very similar.

- Design #1 has the lowest zeroth order error.
- Design #3 has the lowest uniformity error.

But these values are not expected to be accurate, since the assumptions of the paraxial model do not hold.
A rigorous analysis is needed.

Performance Evaluation with FMM

After the investigation with TEA a rigorous analysis by using FMM is performed.



Merit Function	Design #1	Design #2	Design #3
Total Efficiency	70.7%	70.3%	74.3%
Average Efficiency (of use orders)	1.3%	1.4%	1.5%
Zeroth Order Efficiency	8.0%	2.8%	2.3%
Zeroth Order Error*	**451.5%**	97.4%	53.8%
Uniformity Error**	81.4%	51.6%	**43.9%**
Uniformity Error without 0^{th} Order	39.2%	40.0%	41.2%

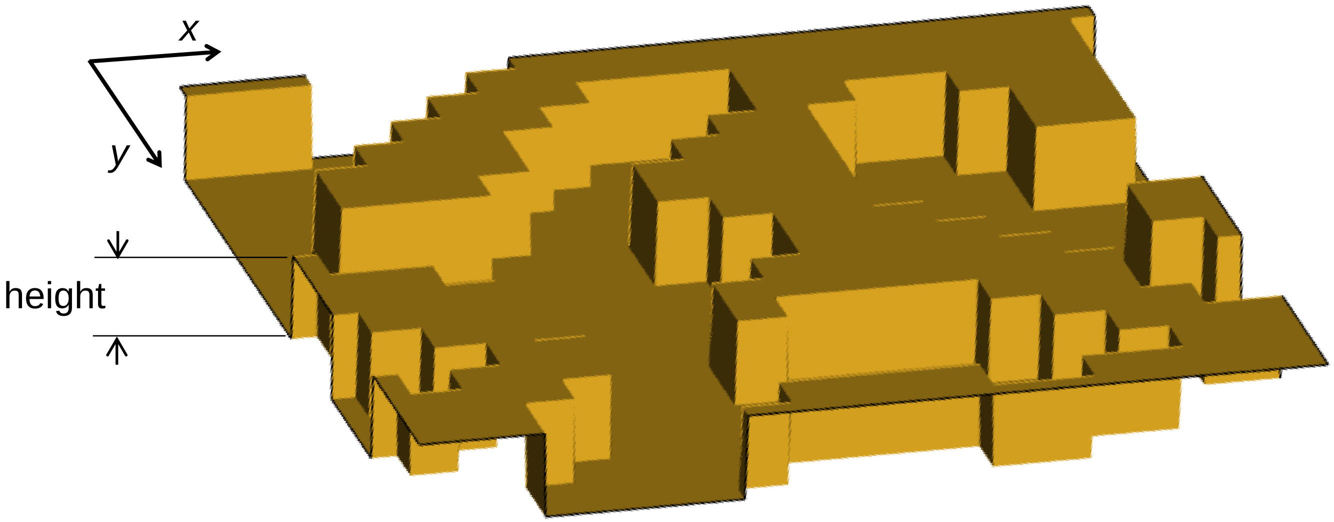
$$* \text{ Zeroth Order Error} = \frac{\text{Zeroth Efficiency} - \text{Average Efficiency}}{\text{Average Efficiency}}$$

$$** \text{ Uniformity Error} = \frac{\text{Max. Efficiency} - \text{Min.Efficiency}}{\text{Max. Efficiency} + \text{Min.Efficiency}}$$

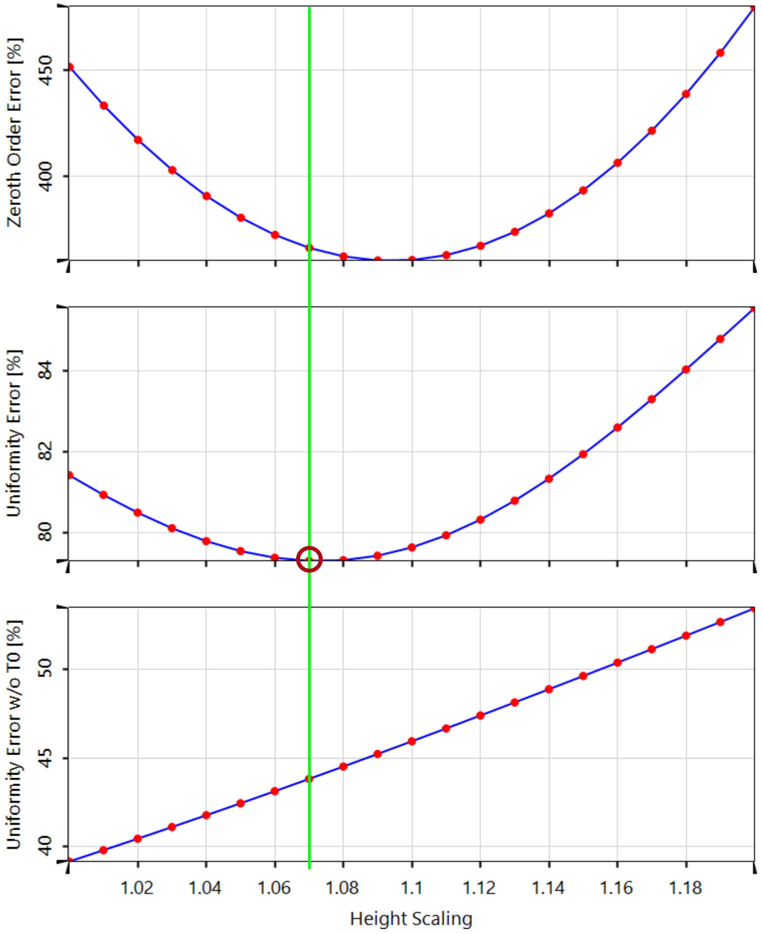
- With the rigorous Fourier Modal Method, it turns out that design #1 actually produces the strongest zeroth diffraction order, resulting in very poor uniformity.
- The designs seem to have a comparable (even lowest) *Uniformity Error* when the zeroth order is neglected.
- Therefore, an optimization to minimize the *Zeroth Order Error* may improve the performance.

Further Analyses

- A scaling of the height profile has a strong influence on the zero order.
- This can be exploited to correct an undesired efficiency of the zeroth order and thus also to improve the uniformity.
- The *Parameter Run* is the best suited tool to perform such investigations.



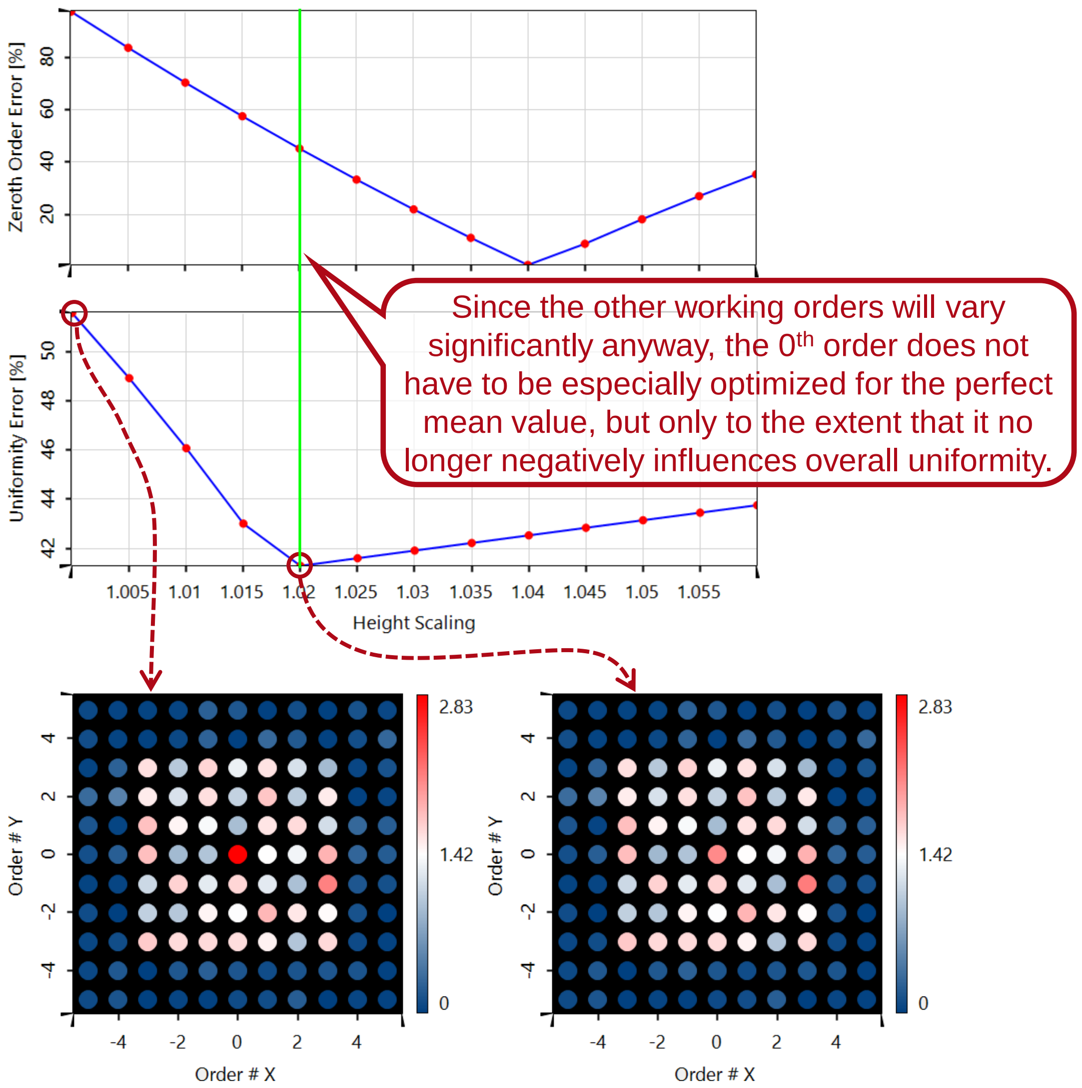
Further Optimization – Zeroth Order Tuning Design #1



- It turns out that a simple height scaling is not sufficient to compensate the quite high value of the *Zeroth Order Error* of design #1.
- It is worth noting that while the goal of the height scaling is to reduce the zeroth order and thus the *Uniformity Error*, other merit functions are also affected, but to a lesser degree.

Merit Function	**Design #1**	**with scaling factor 1.07**
Total Efficiency	70.7%	68.3%
Average Efficiency (of use orders)	1.3%	1.4%
Zeroth Order Efficiency	8.0%	6.5%
Zeroth Order Error	**451.5%**	**366.5%**
Uniformity Error	81.4%	79.3%
Uniformity Error without 0^{th} Order	39.2%	43.8%

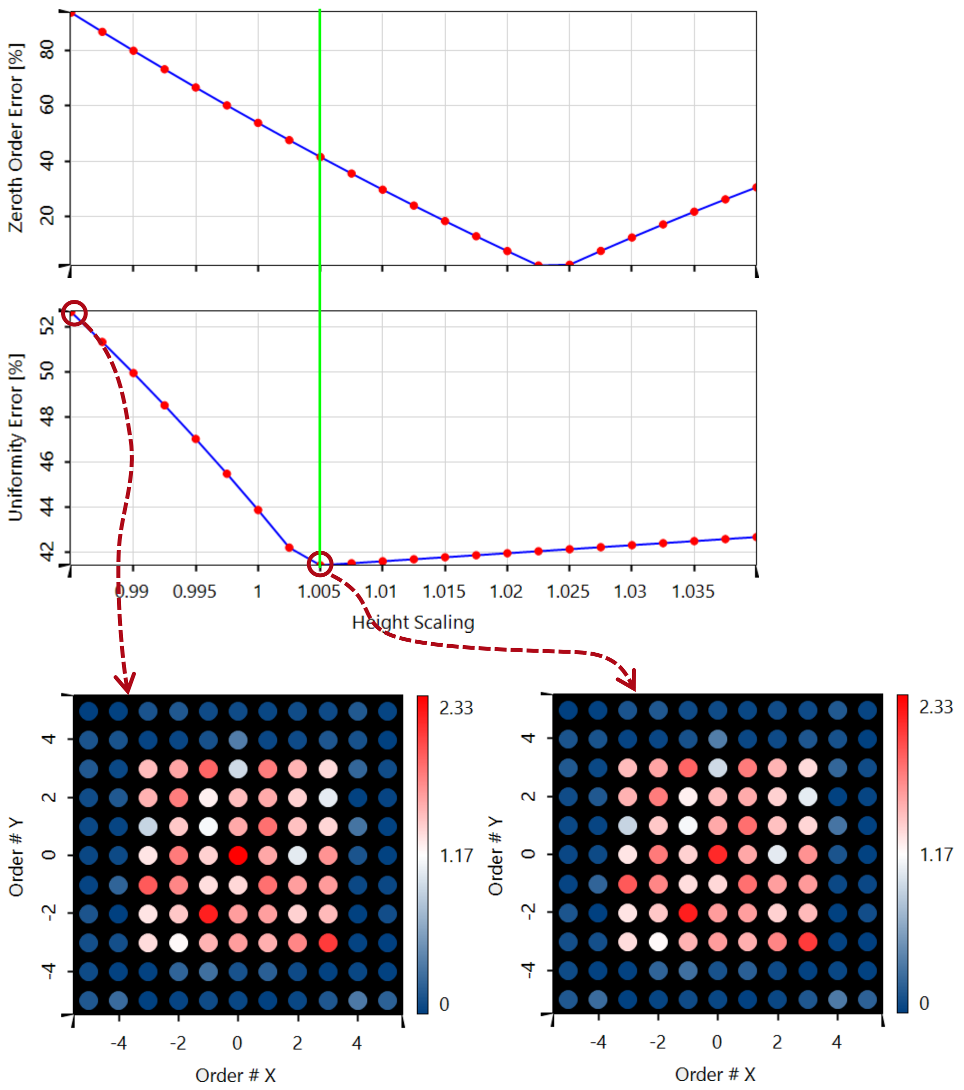
Further Optimization – Zeroth Order Tuning Design #2



- The zeroth order of design #2 is also distinctly higher but is not that dominant. Here a scaling might show more promising results.
- On the other hand, the height scaling won't optimize the *Uniformity Error without the 0th Order*. Hence in general, the best that can be expected is to get a similar overall uniformity of all working orders including the zeroth order.
- Typically, the other merit function values get worse, but not always. In any case, it is up to the optical engineer to decide which compromise is best.

Merit Function	Design #2	with scaling factor 1.02
Total Efficiency	70.3%	69.7%
Average Efficiency (of use orders)	1.4%	1.4%
Zeroth Order Efficiency	2.8%	2.1%
Zeroth Order Error	97.4%	45.2%
Uniformity Error	51.6%	41.3%
Uniformity Error without 0th Order	40.0%	41.3%

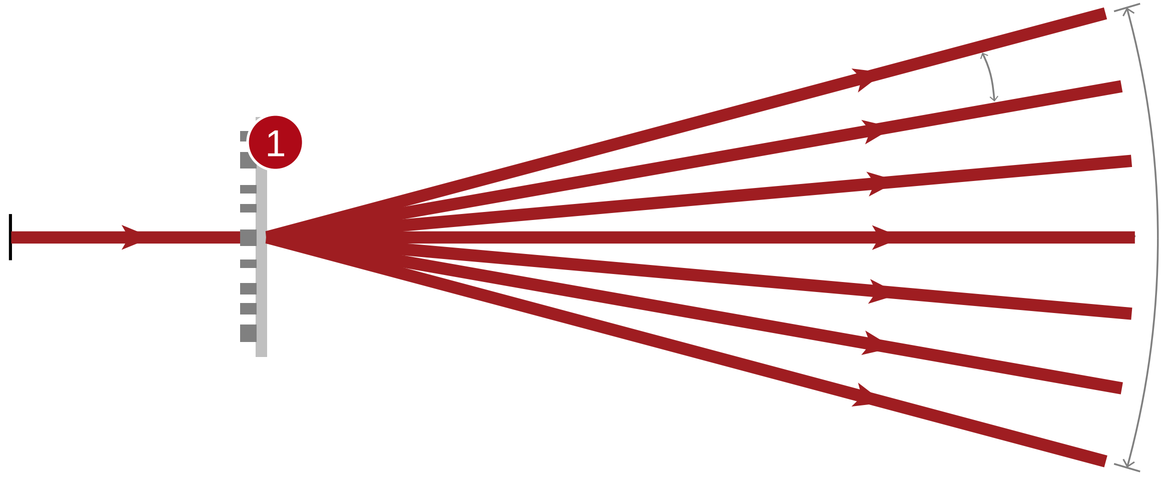
Further Optimization – Zeroth Order Tuning Design #3

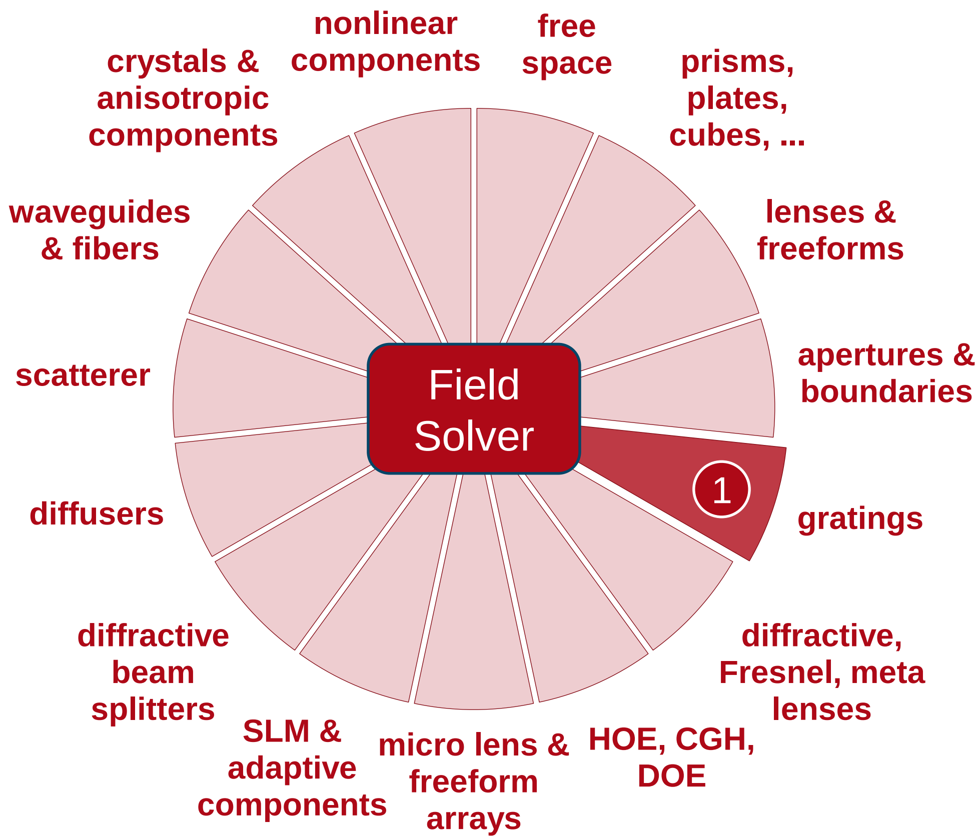


- The 0th order of design #3 was already quite similar to the other orders, so no big change is expected.
- Nevertheless, a variation of the height scaling is advised, as it gives some insight into how sensitive the design is regarding possible tolerances of the etching depth.

Merit Function	Design #3	with scaling factor 1.005
Total Efficiency	74.3%	74.1%
Average Efficiency (of use orders)	1.5%	1.5%
Zeroth Order Efficiency	2.3%	2.1%
Zeroth Order Error	53.8%	41.5%
Uniformity Error	43.9%	41.4%
Uniformity Error without 0^{th} Order	41.2%	41.4%

VirtualLab Fusion Technologies





Document Information

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further reading	- Grating Order Analyzer - Configuration of Grating Structures by Using Interfaces - Design of a High-NA Beam Splitter with 24000 Dots Random Pattern - Design of Diffractive Beam Splitters for Generating a 2D Light Mark - High NA Splitter Optimization with User-Defined Merit Functions