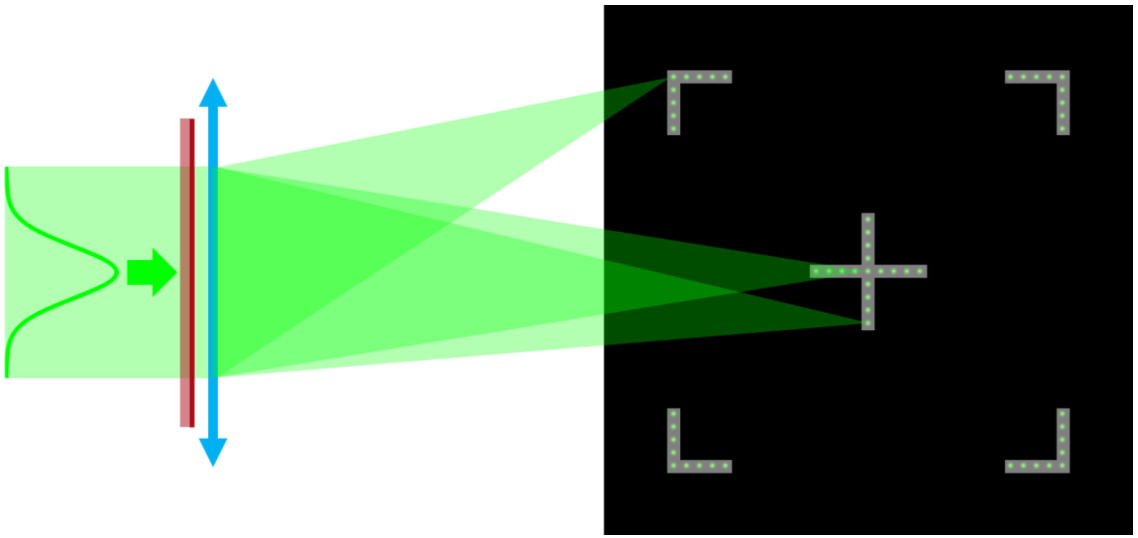
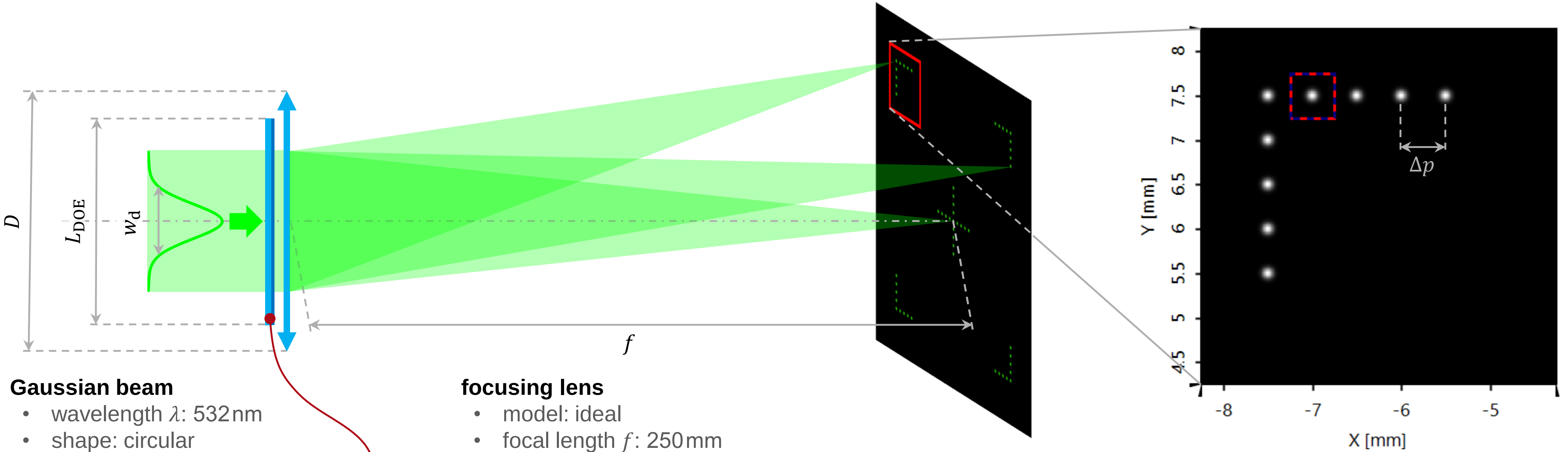
Design & Analysis of Diffractive Splitter Generating a Light Mark

Abstract



Separate (focused) beams or light points are of interest for a wide range of applications, whether for manufacturing processes, for special fiber coupling, for face recognition systems or light marker generation. Each of these applications has different and very specific requirements. VirtualLab Fusion offers you a powerful yet easy-to-use software package to design, simulate and analyze such beam splitter systems. Using a simple diffractive beam splitter system to generate a paraxial light mark, we will present a typical workflow and describe and demonstrate various design, modeling, simulation and analysis aspects that maybe relevant for such tasks.

Task



Gaussian beam

- wavelength λ: 532 nm
- shape: circular
- 1/e² waist diameter w_{d}: 1.0 mm
- linearly polarized in x

focusing lens

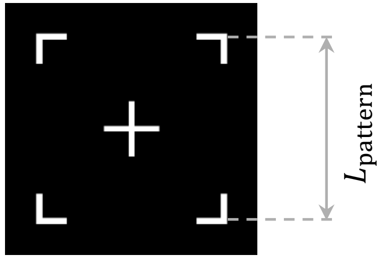
- model: ideal
- focal length f: 250 mm
- shape: circular
- diameter D: 5.0 mm

diffractive beam splitting element

- type: binary
- aperture shape: square
- side length L_{DOE} : 3 mm
- thickness: 1 mm
- substrate material: fused silica
- structure on 2nd surface
- further requirements on later slide

spot pattern to be generated

- shape: light mark with center cross and corner markings (given by bitmap file)
- distance of neighbor spot positions Δp: 500 µm
- side length L_{pattern}: 15 mm
- 1/e² diameter of spots: 170 µm (already given by focusing system)



Requirements

Geometry

- beam splitting element with binary structure (e.g. to reduce the cost)
- smallest feature size: 2.5 µm (to ensure that the intended structure design method is within its validity range(*))
- highest positioning accuracy: 10 nm (possible capabilities of manufacturer)
- manufacturing data of mask via bitmap file

Merit Functions(**)

The following conditions should be maintained considering an etching depth tolerance of ±2%:

- conversion efficiency (CE) > 60%
- maximum relative(***) intensity of stray light (SL) < 5%
- uniformity error (UE) < 5%

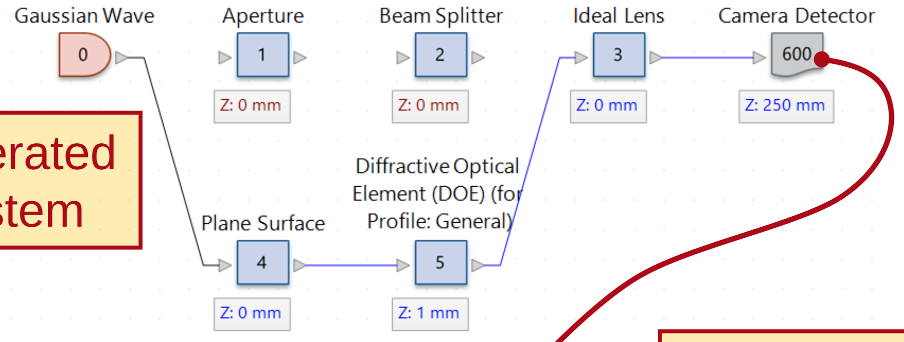
(*) For the conversion from the functional design data to a structured data the conventional thin element approximation (TEA) is applied.

(**) The formulas can be found in the help/manual of VirtualLab Fusion.

(***) "relative" refers to the average value of the desired working orders' efficiencies.

Result Preview

generated system



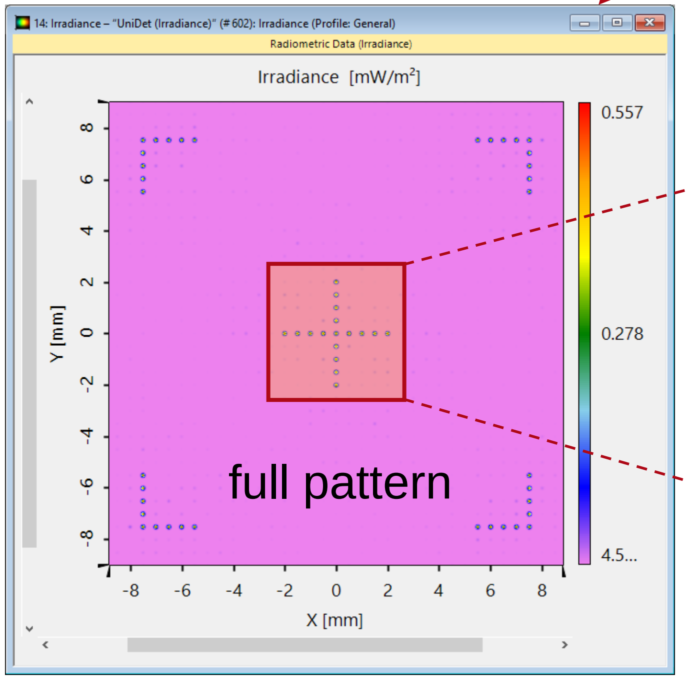
evaluated merit functions

fulfilled requirements

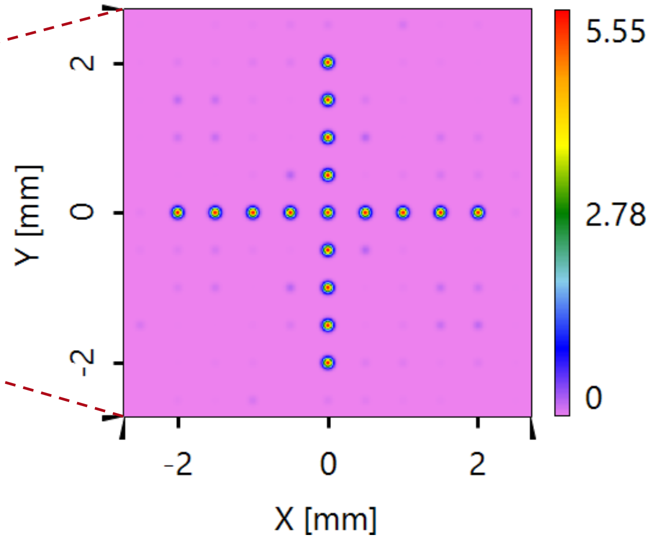
conversion efficiency ~63%
max. rel. eff. of stray light <5%

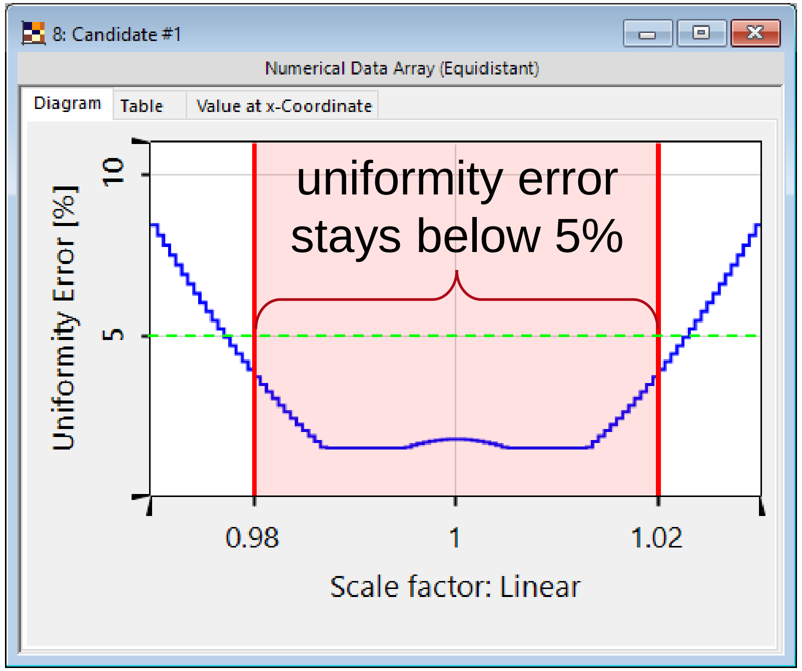
stable over tolerance range

generated irradiance pattern in false color



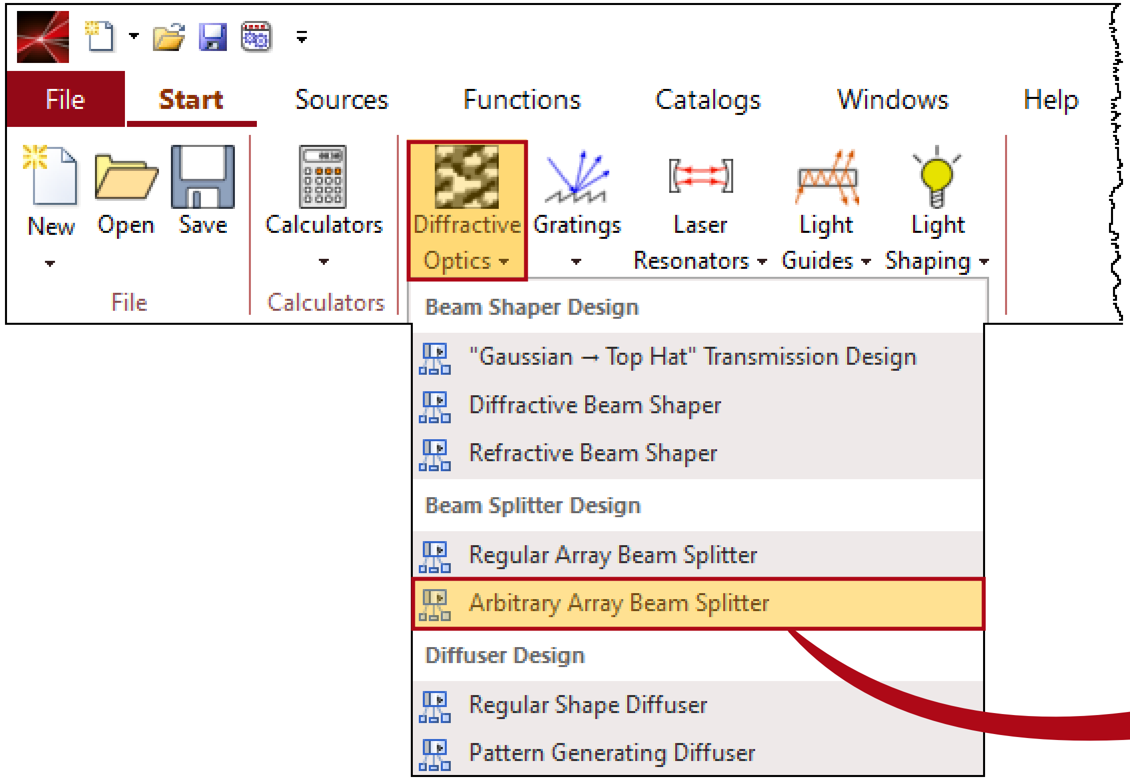
full pattern

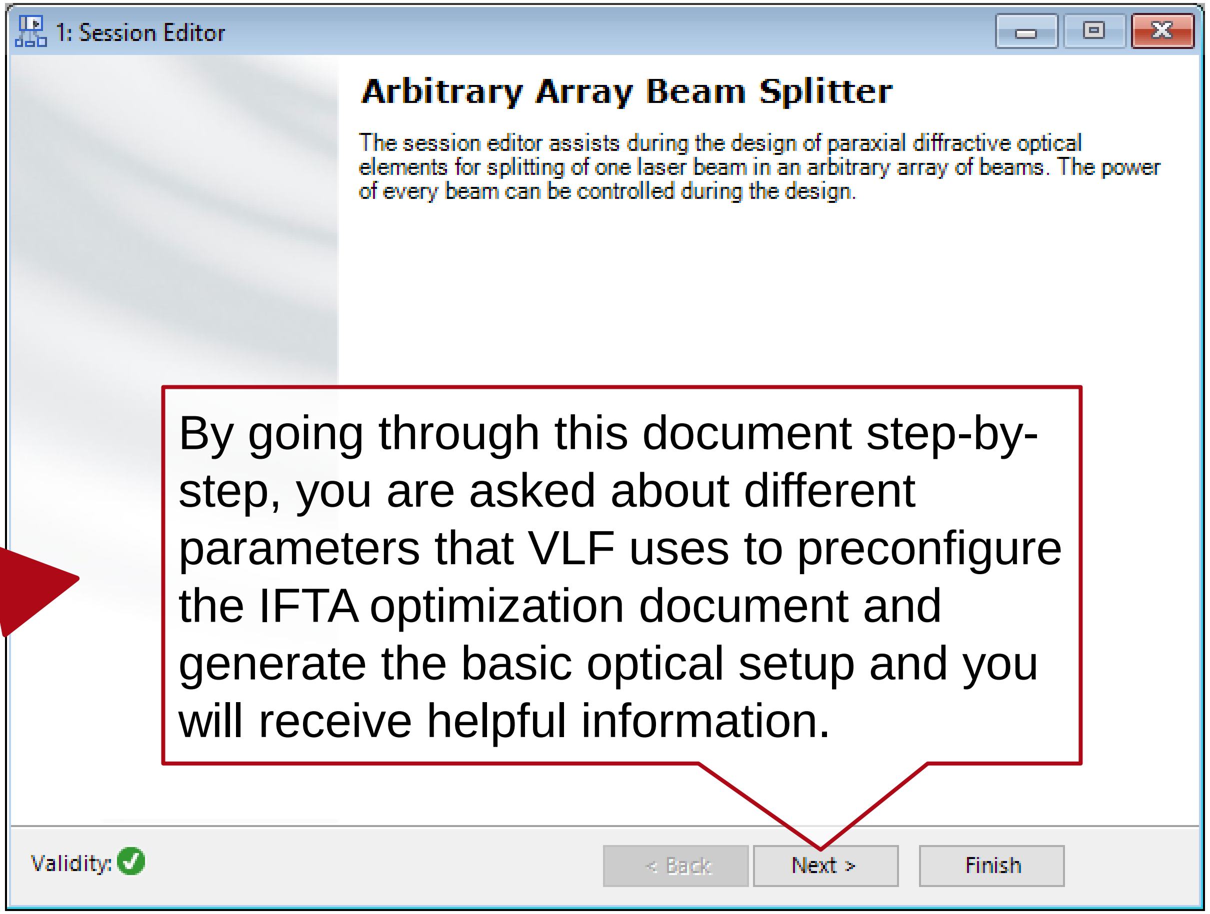




uniformity error stays below 5%

Start (Session Editor)



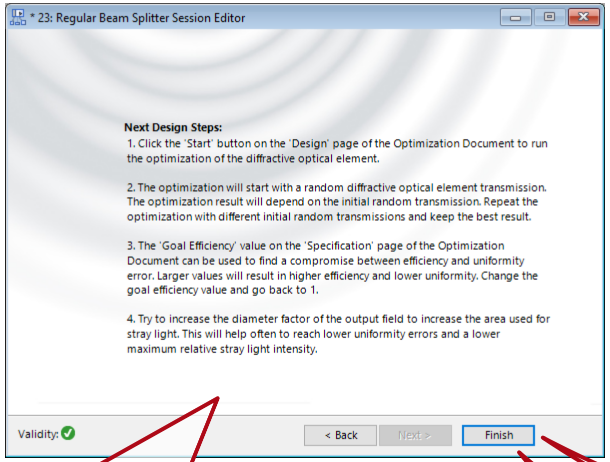


Arbitrary Array Beam Splitter

The session editor assists during the design of paraxial diffractive optical elements for splitting of one laser beam in an arbitrary array of beams. The power of every beam can be controlled during the design.

By going through this document step-by-step, you are asked about different parameters that VLF uses to preconfigure the IFTA optimization document and generate the basic optical setup and you will receive helpful information.

Presenting Preconfigured System and Design Document



Next Design Steps:

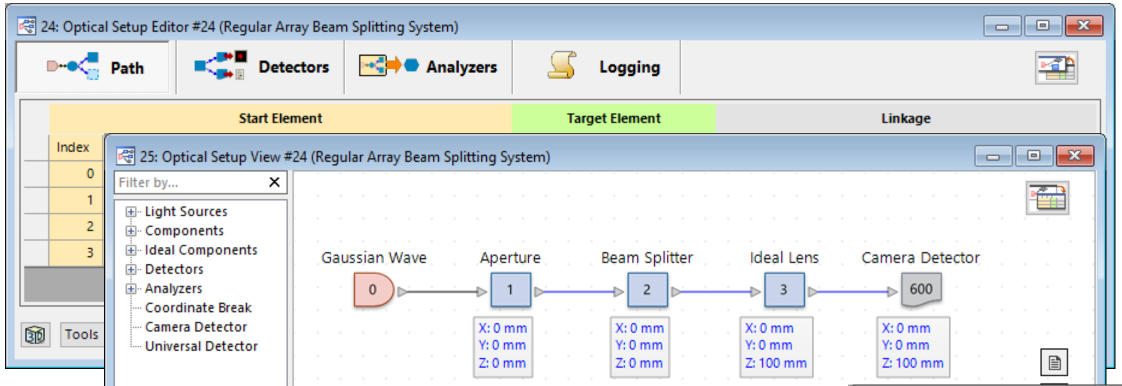
1. Click the 'Start' button on the 'Design' page of the Optimization Document to run the optimization of the diffractive optical element.

2. The optimization will start with a random diffractive optical element transmission. The optimization result will depend on the initial random transmission. Repeat the optimization with different initial random transmissions and keep the best result.

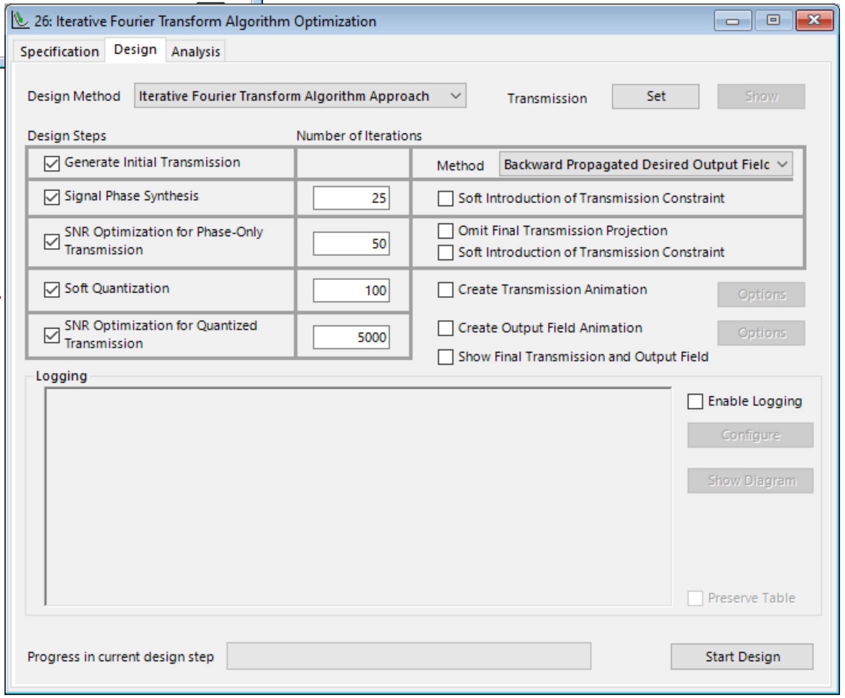
3. The 'Goal Efficiency' value on the 'Specification' page of the Optimization Document can be used to find a compromise between efficiency and uniformity error. Larger values will result in higher efficiency and lower uniformity. Change the goal efficiency value and go back to 1.

4. Try to increase the diameter factor of the output field to increase the area used for stray light. This will help often to reach lower uniformity errors and a lower maximum relative stray light intensity.

On the last page of the session editor, you will be givensome tipsfor the next steps.



Aperture	Beam Splitter	Ideal Lens	Camera Detector
X: 0 mm Y: 0 mm Z: 0 mm	X: 0 mm Y: 0 mm Z: 0 mm	X: 0 mm Y: 0 mm Z: 100 mm	X: 0 mm Y: 0 mm Z: 100 mm



Design Method: Iterative Fourier Transform Algorithm Approach

Design Steps	Number of Iterations	
☑ Generate Initial Transmission		Method: Backward Propagated Desired Output Fielc
☑ Signal Phase Synthesis	25	☐ Soft Introduction of Transmission Constraint
☑ SNR Optimization for Phase-Only Transmission	50	☐ Omit Final Transmission Projection ☐ Soft Introduction of Transmission Constraint
☑ Soft Quantization	100	☐ Create Transmission Animation
☑ SNR Optimization for Quantized Transmission	5000	☐ Create Output Field Animation ☐ Show Final Transmission and Output Field

Logging

☐ Enable Logging

☐ Preserve Table

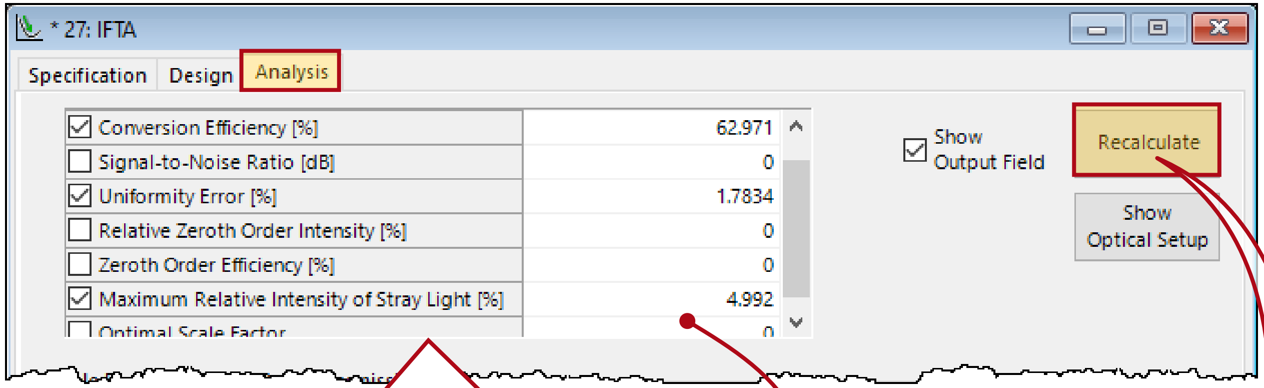
Progress in current design step

By clicking *"Finish"* in the session editor, VLF presents the user

- a preset optical setup (OS)
- a preset IFTA optimization document

for the actual design and simulation.

First Impression: Light Mark & Its Merit Functions



☑ Conversion Efficiency [%] 62.971
☐ Signal-to-Noise Ratio [dB] 0
☑ Uniformity Error [%] 1.7834
☐ Relative Zeroth Order Intensity [%] 0
☐ Zeroth Order Efficiency [%] 0
☑ Maximum Relative Intensity of Stray Light [%] 4.992
☐ Optimal Scale Factor 0

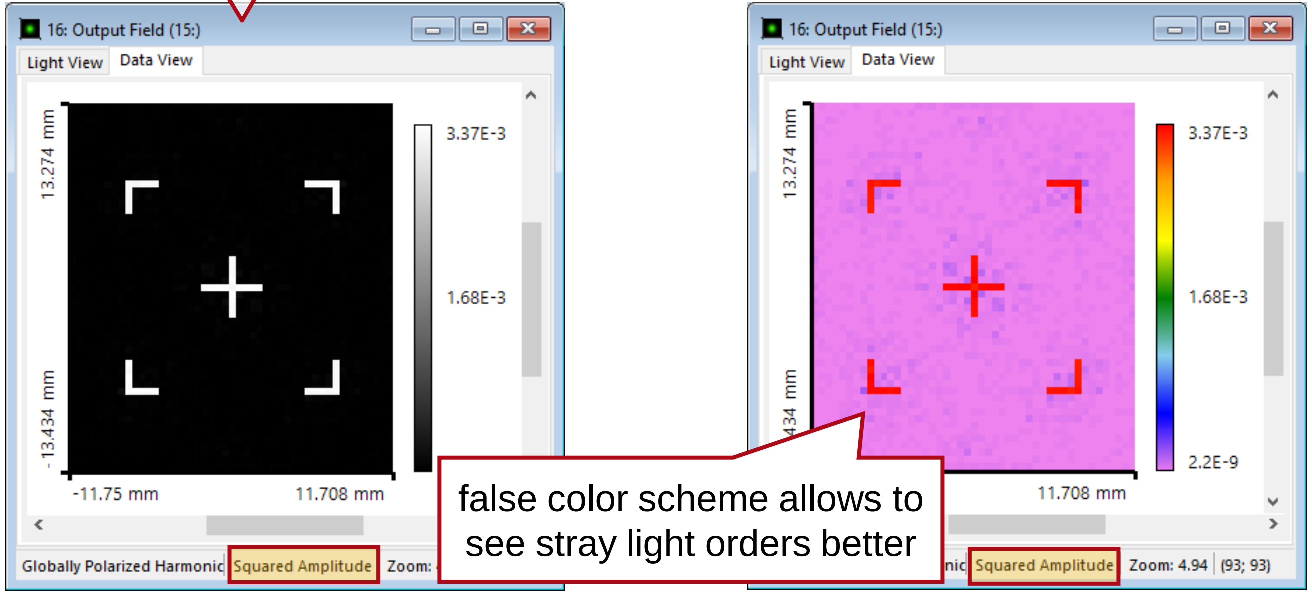
☑ Show Output Field

No system simulation is needed for evaluating the merit functions.

Merit Function	Result Value
Conversion Efficiency (CE) / %	63.0
Uniformity Error (UE) / %	1.8
Maximum Relative Intensity of Stray Light (SL) / %	5.0

Clicking *"Recalculate"* on the *Analysis* tab outputs

- the checked merit function values
- the output field in its mathematical representation. For most designs, this means that each pixel of the output field corresponds to a diffraction order whose squared amplitude value is proportional to its efficiency.



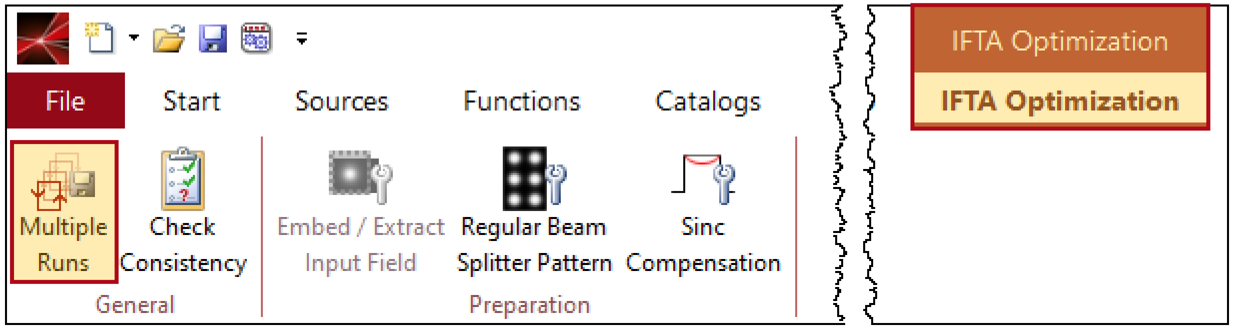
false color scheme allows to see stray light orders better

Design Selection

multiple designs and tolerance checks
with IFTA document

Multiple Run & Best Result Candidates

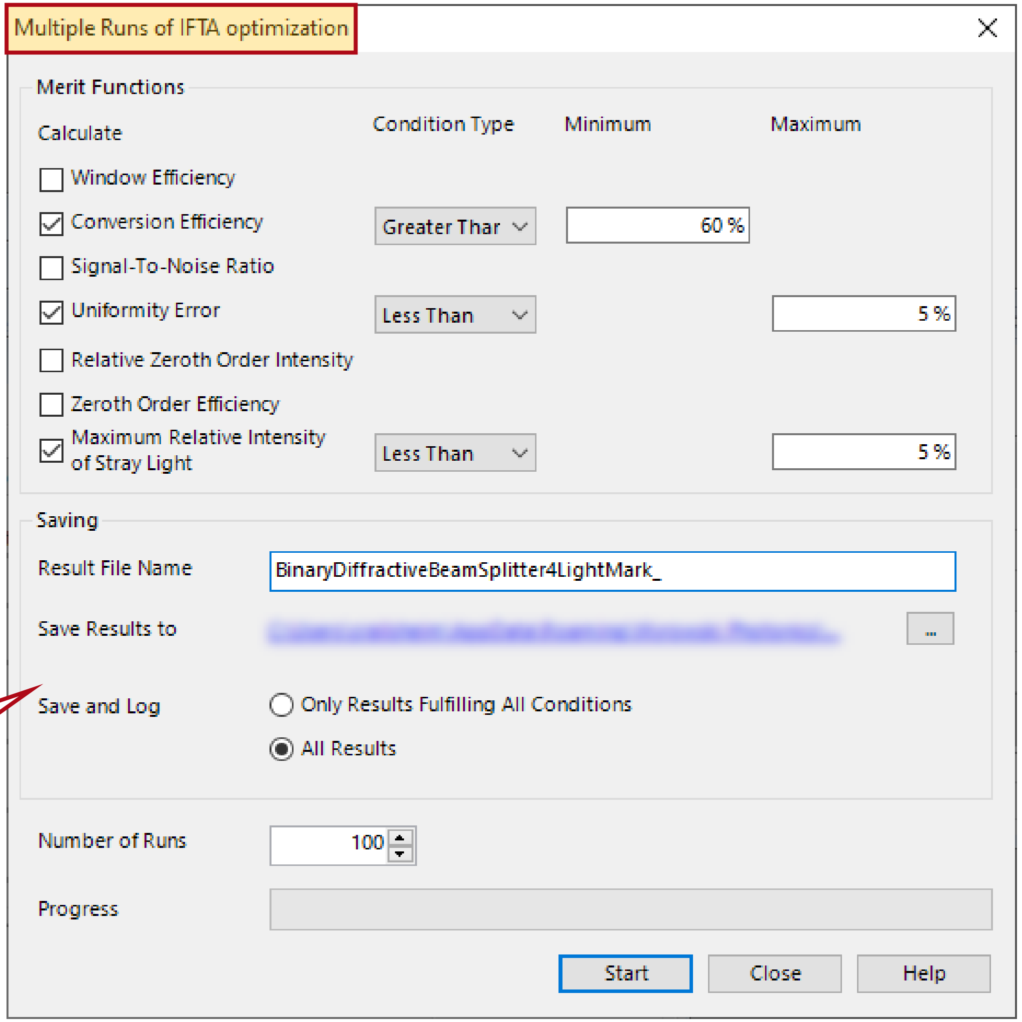
VLF offers you the *Multiple Run* document for automatic generation & evaluation of many designs with preset result filters.



For this use case the following filters were used:

- Conversion Efficiency (CE) > 60%
- Uniformity Error (UE) < 5%
- Maximum Relative Intensity of Stray Light (SL) < 5%

The multiple run document saves the CA2 files of the designed transmission functions together with an overview CSV file.
Selected transmission functions can be set in the IFTA document for some tolerance evaluations.



Multiple Runs of IFTA optimization

Merit Functions

Calculate	Condition Type	Minimum	Maximum
☐ Window Efficiency			
☑ Conversion Efficiency	Greater Thar	60 %	
☐ Signal-To-Noise Ratio			
☑ Uniformity Error	Less Than		5 %
☐ Relative Zeroth Order Intensity			
☐ Zeroth Order Efficiency			
☑ Maximum Relative Intensity of Stray Light	Less Than		5 %

Saving

Result File Name: BinaryDiffractiveBeamSplitter4LightMark_

Save Results to

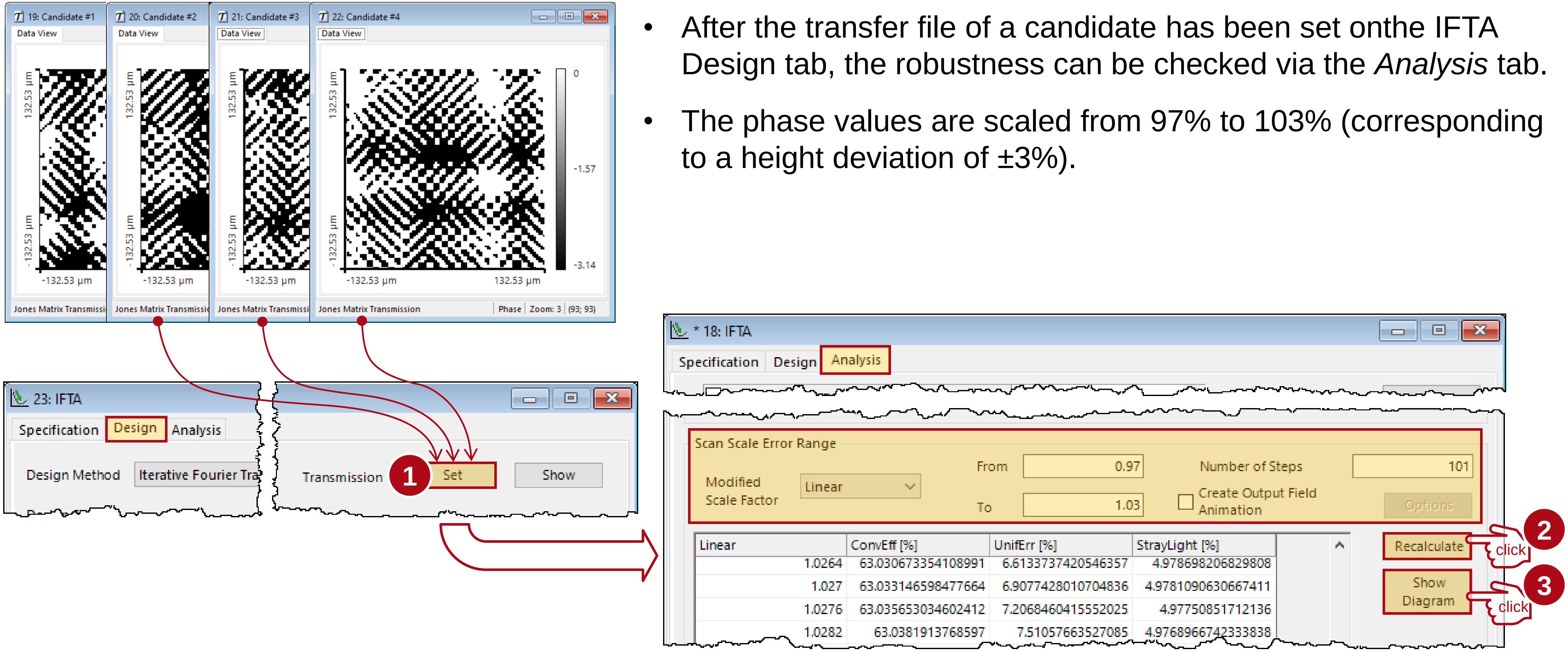
Save and Log: ○ Only Results Fulfilling All Conditions ● All Results

Number of Runs: 100

Progress

Perform Tolerance Evaluations for Other Design Candidates

- After the transfer file of a candidate has been set onthe IFTA Design tab, the robustness can be checked via the *Analysis* tab.
- The phase values are scaled from 97% to 103% (corresponding to a height deviation of ±3%).



Design Method: Iterative Fourier Tra

Transmission: Set

Scan Scale Error Range

Modified Scale Factor: Linear

From: 0.97

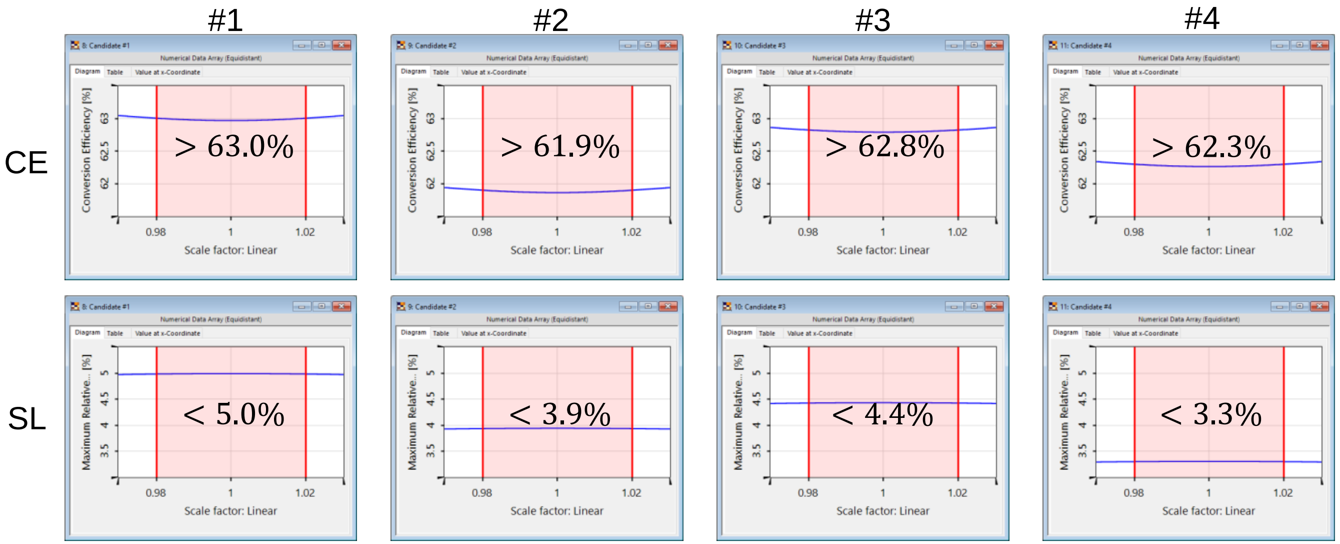
To: 1.03

Number of Steps: 101

☐ Create Output Field Animation

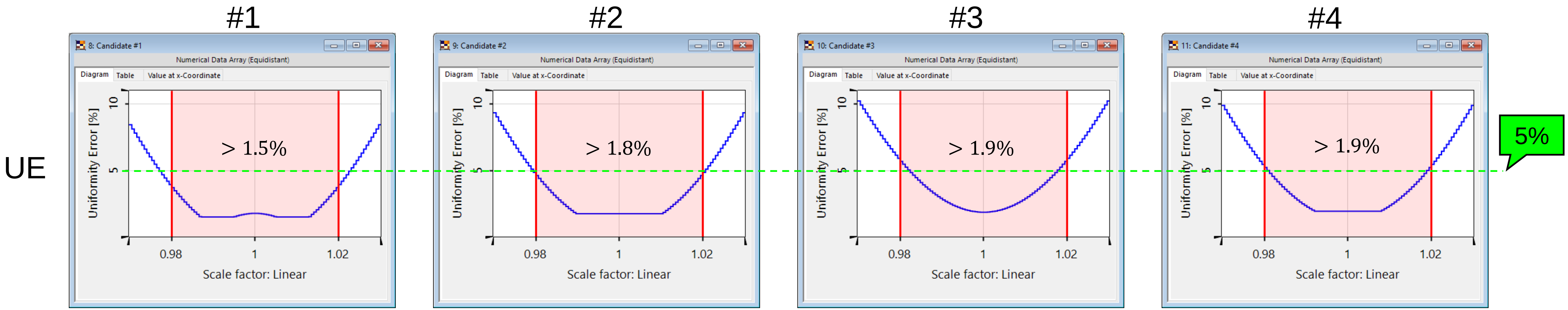
Linear	ConvEff [%]	UnifErr [%]	StrayLight [%]
1.0264	63.030673354108991	6.6133737420546357	4.978698206829808
1.027	63.033146598477664	6.9077428010704836	4.9781090630667411
1.0276	63.035653034602412	7.2068460415552025	4.97750851712136
1.0282	63.0381913768597	7.51057663527085	4.9768966742333838

Tolerance Checks & Selection of Design Candidate



The adjacent figures show the possible merit functions in case of an inaccuracy due to an etching depth tolerance (±2% range is marked in red).

- The Conversion Efficiency (CE) and the Maximum Stray Light (SL) do not vary significantly. They even get better for deviating depths.
  But the Uniformity Error (UE) does change for the worse!
- Candidate #1 & #2 keep a Uniformity Error below 5%. Candidate #1 plays it safer, thus for the following simulations candidate #1 is chosen.



System Simulation

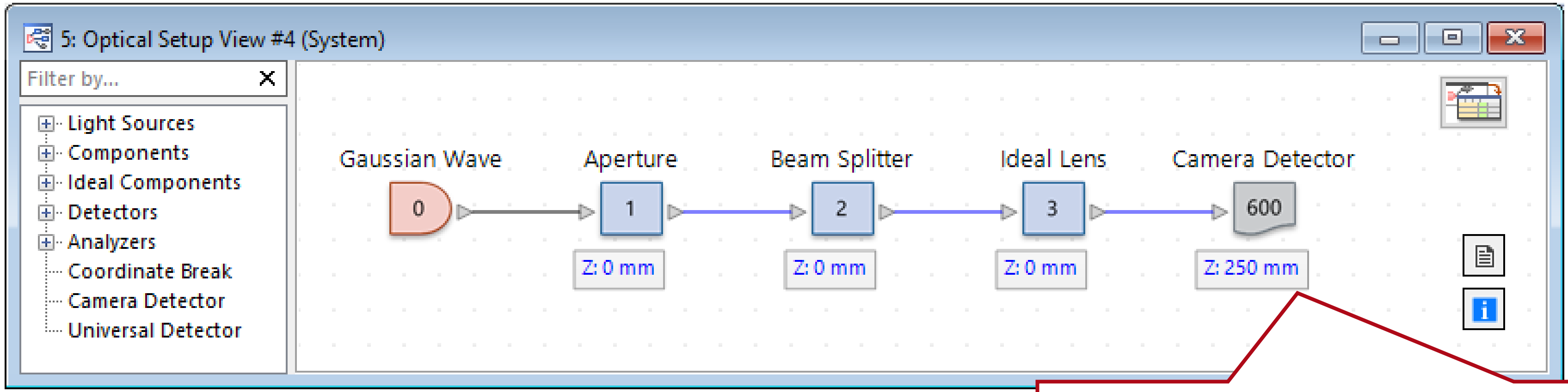
initial adjustments & first impression

Initial Optical Setup

Apart from the IFTA document, the session editor has prepared a preconfigured system, the optical setup (OS).

VirtualLab Fusion (VLF) allows to balance between speed and accuracy:

- For this scenario, the general profile simulation engine automatically selects the most accurate propagation method.
- However, we adjust the settings to use a generalized Debye integral method that provides a very good approximation result in less than 1/3 of the simulation time.

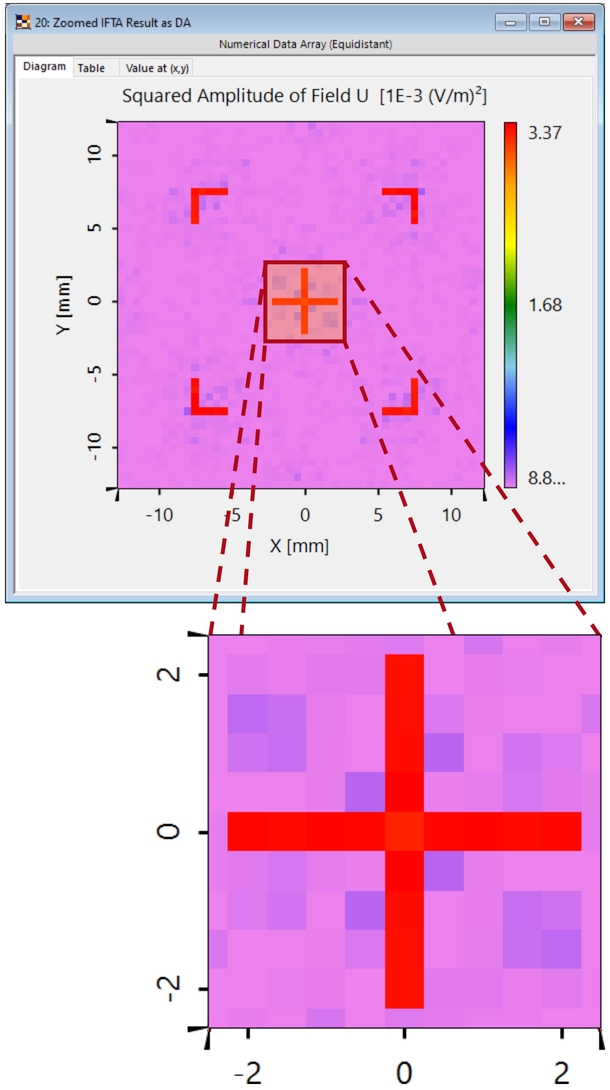


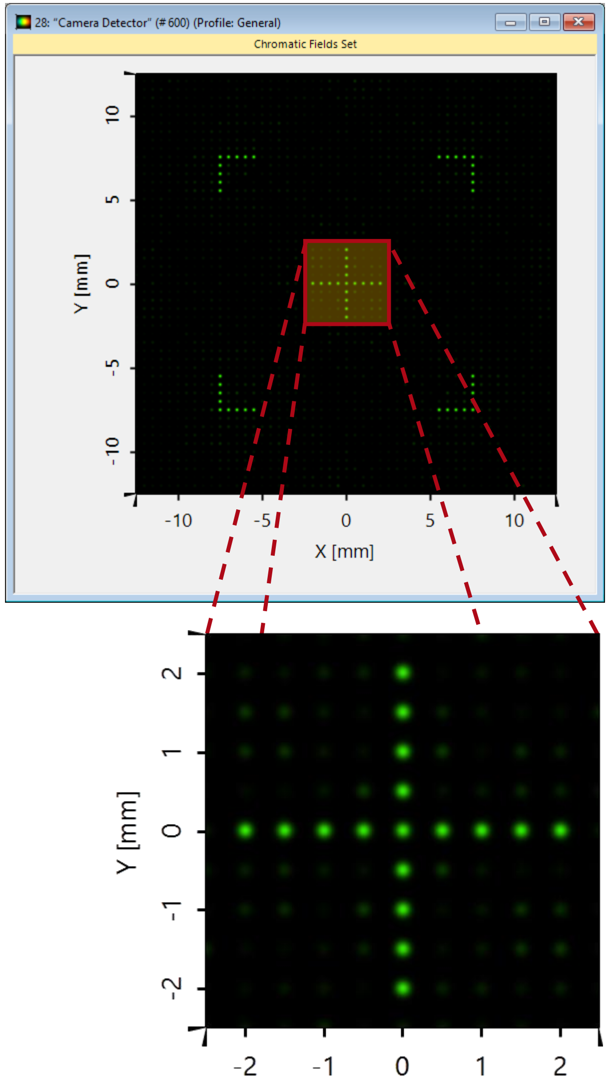
Accuracy Speed Balance (Propgation Method)

For more info follow this link into the appendix.

Result from IFTA vs System Simulation

IFTA result display
with single pixel
per diffraction order



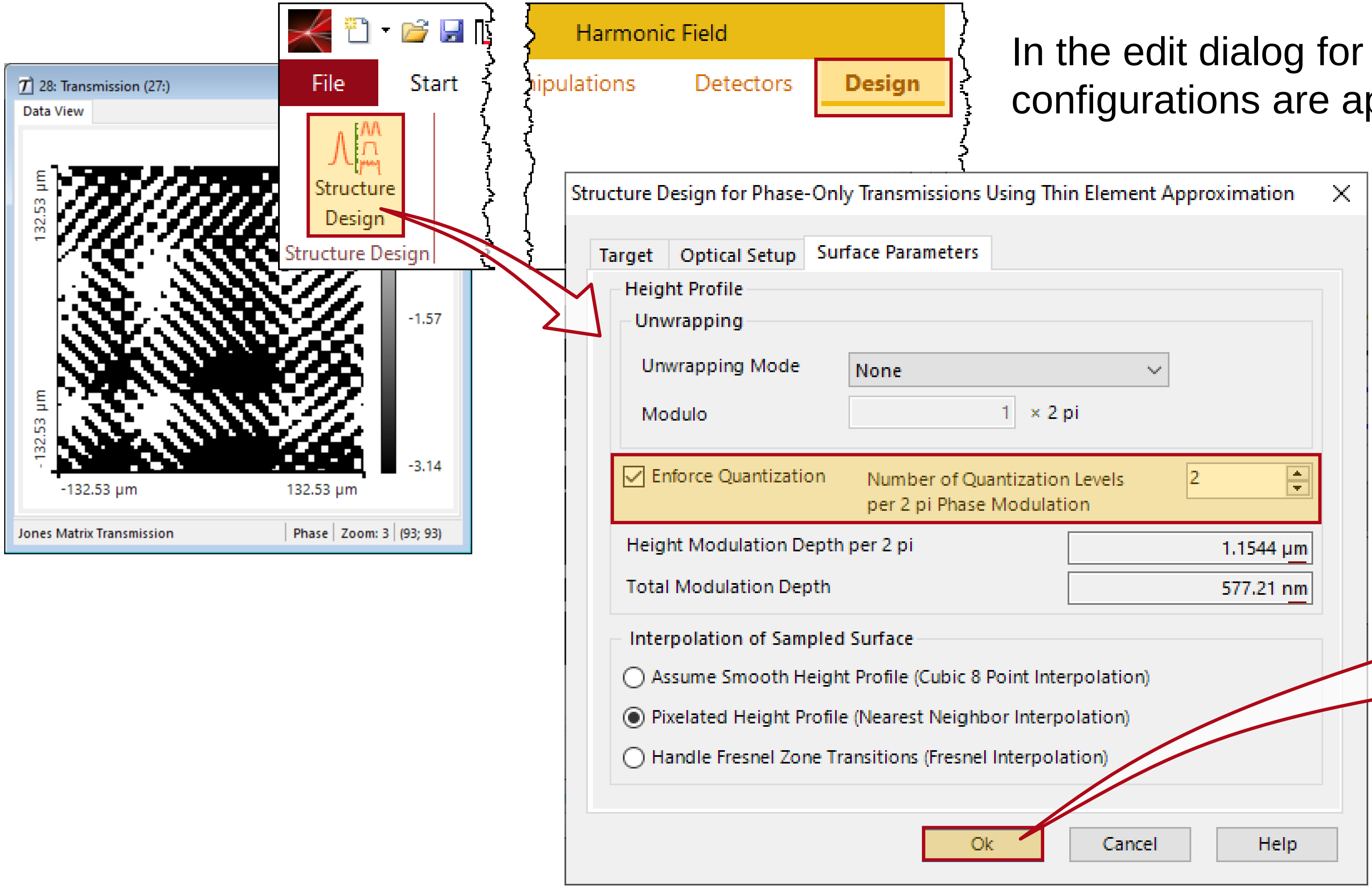


system result display
with Gaussian beams
per diffraction order

Structure Design

conversion of designed phase to height distribution

Structure Design



Structure Design for Phase-Only Transmissions Using Thin Element Approximation

Target | Optical Setup | Surface Parameters

Height Profile

Unwrapping

Unwrapping Mode: None

Modulo: 1 × 2 pi

☑ Enforce Quantization — Number of Quantization Levels per 2 pi Phase Modulation: 2

Height Modulation Depth per 2 pi: 1.1544 µm

Total Modulation Depth: 577.21 nm

Interpolation of Sampled Surface

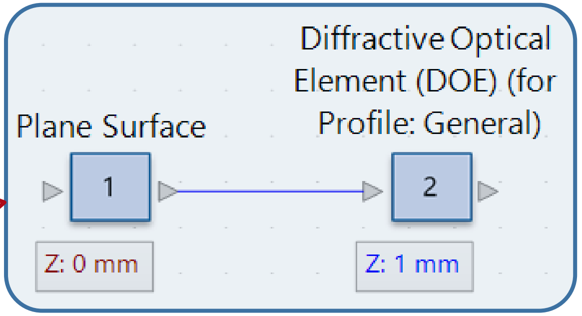
○ Assume Smooth Height Profile (Cubic 8 Point Interpolation)

● Pixelated Height Profile (Nearest Neighbor Interpolation)

○ Handle Fresnel Zone Transitions (Fresnel Interpolation)

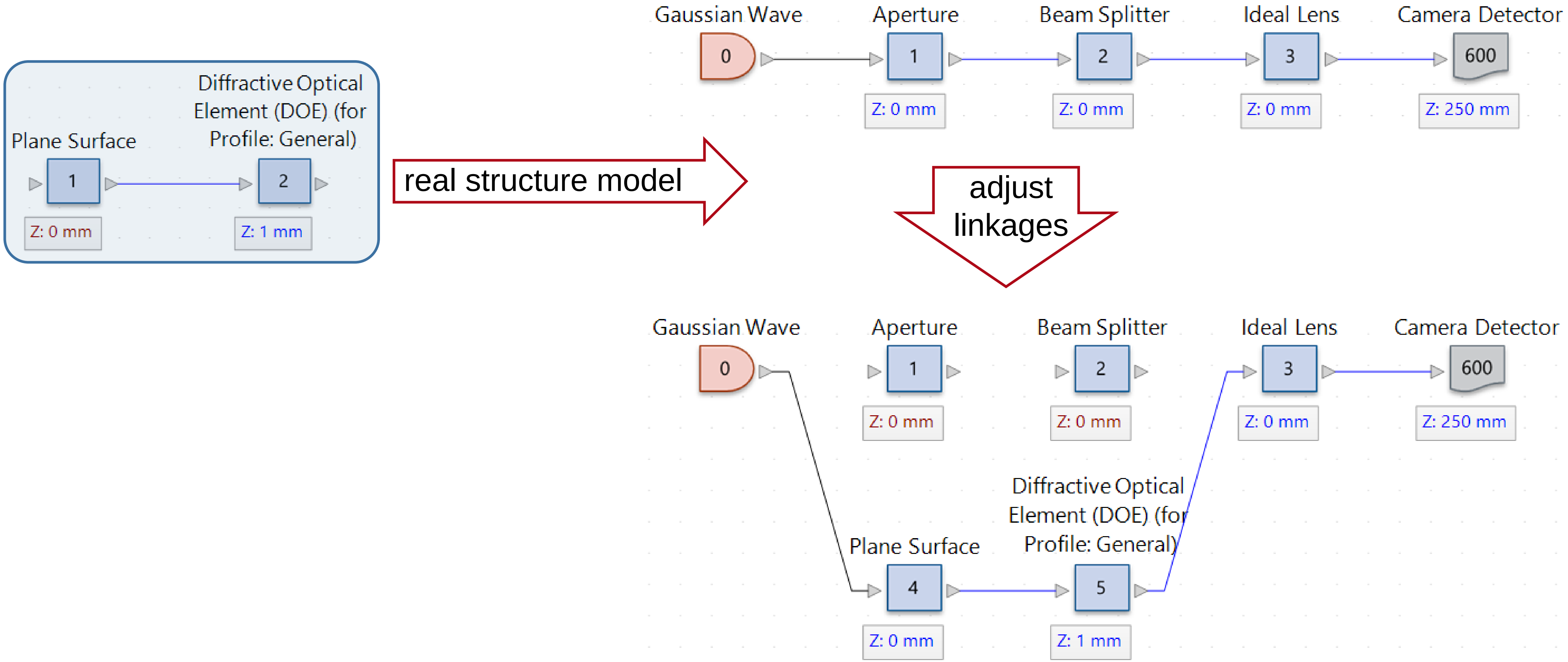
In the edit dialog for the structure design, the following configurations are applied:

- transparent plate (no mirror)
- thickness of substrate: 1 mm
- substrate material: fused silica
- embedding material: air
- design wavelength: 532 nm
- enforce quantization: 2 levels
- pixelated height profile



real model of diffractive binary beam splitter (with 2 surfaces and material)

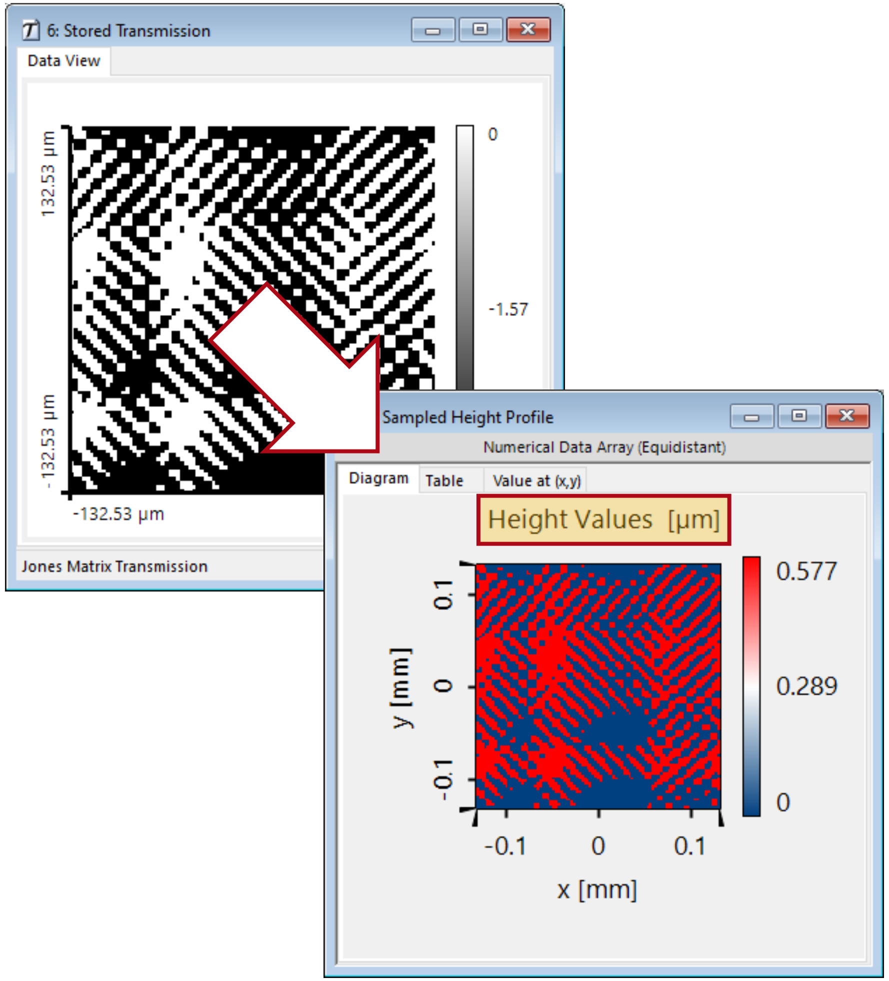
Integrate Real Splitter Model to System

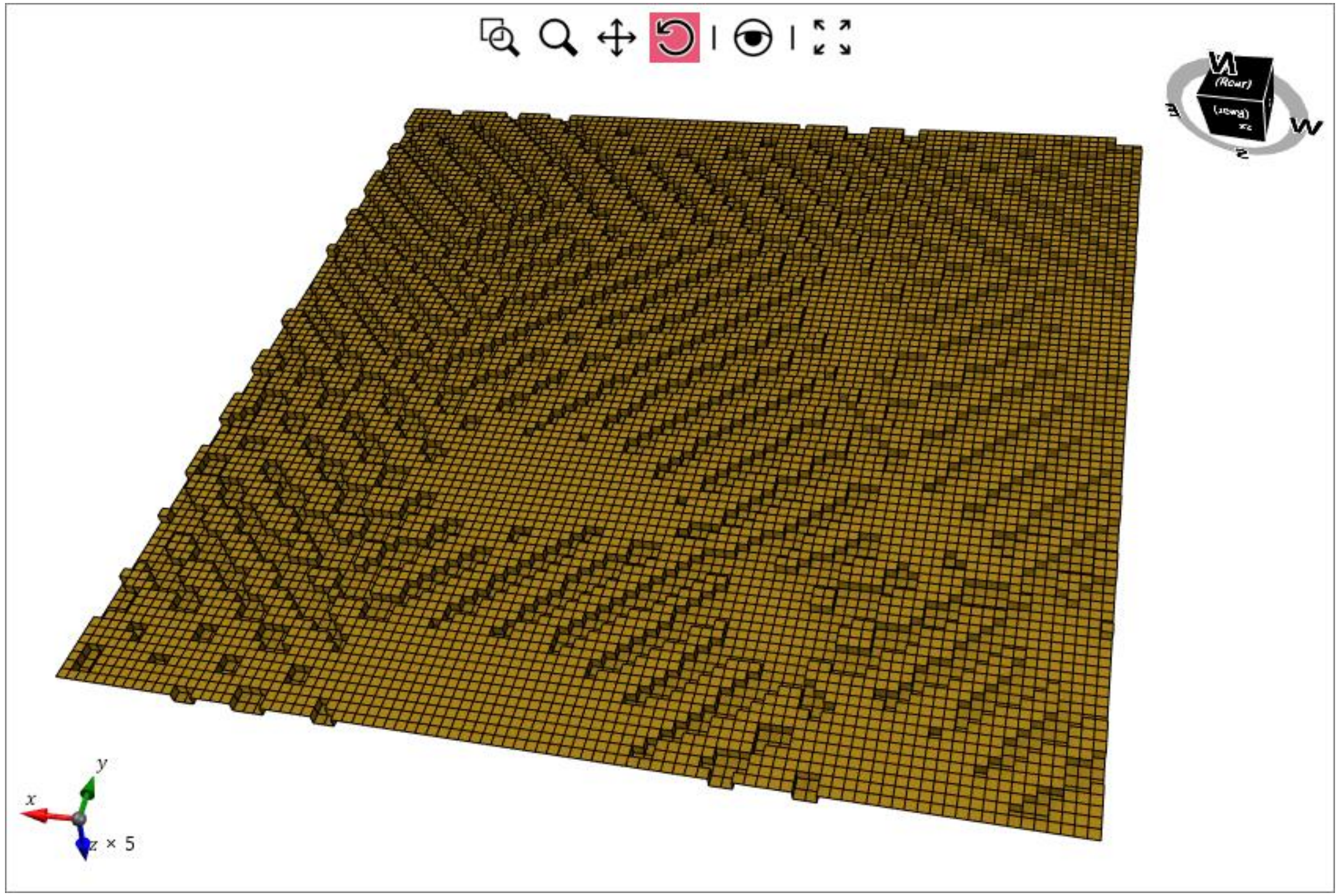


real structure model

adjust linkages

Structure Representation



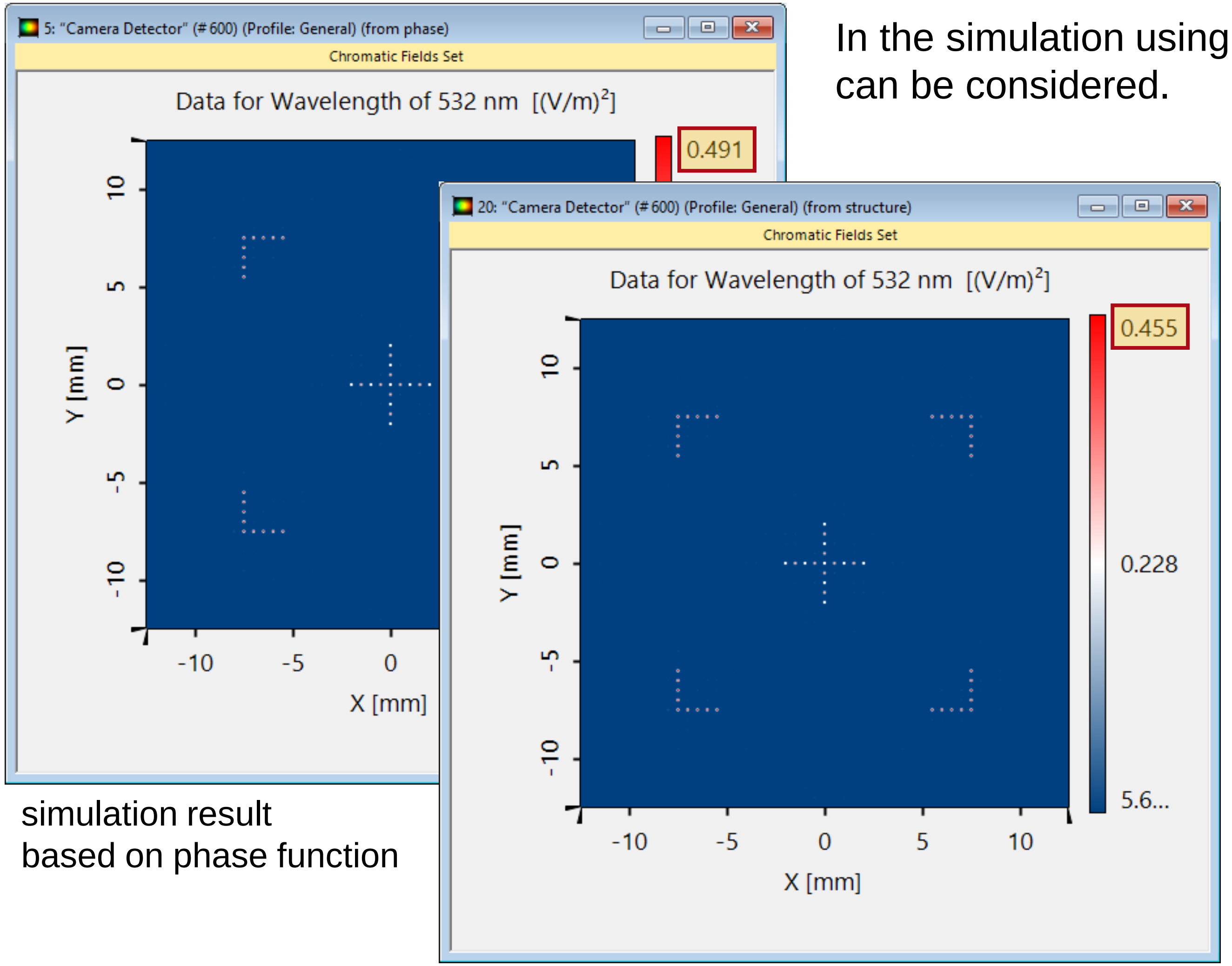


for clearer view of height structure,
the modulation depth was scaled by a factor of 5

Simulation Difference for Phase vs Structure: Fresnel Effects

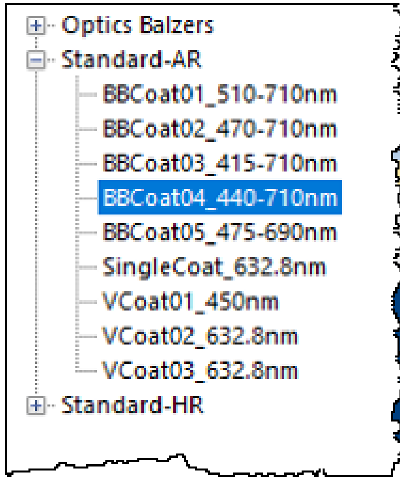
In the simulation using real structures and materials effects like Fresnel reflection can be considered.

- Adjacent figures show, that the maximum in the result based on the phase function (0.491 (V/m)²) is higher than the result's maximum from the structure simulation (0.461 (V/m)²).
- Typically, you would apply anti reflection (AR) coatings to reduce this effect.
- By applying the AR coating BBCoat04_440-710nm from VLF's catalog, the reflection losses are gone.

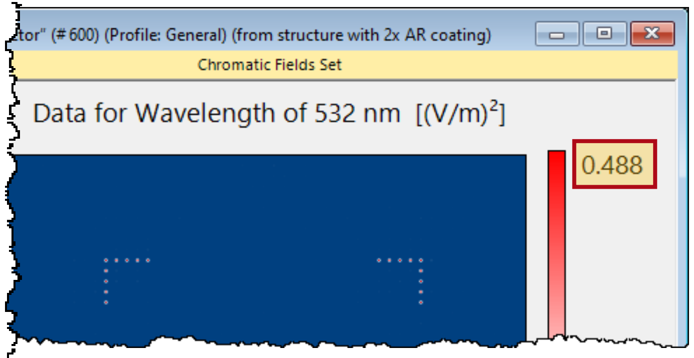


simulation result based on phase function

simulation result based on structure profile



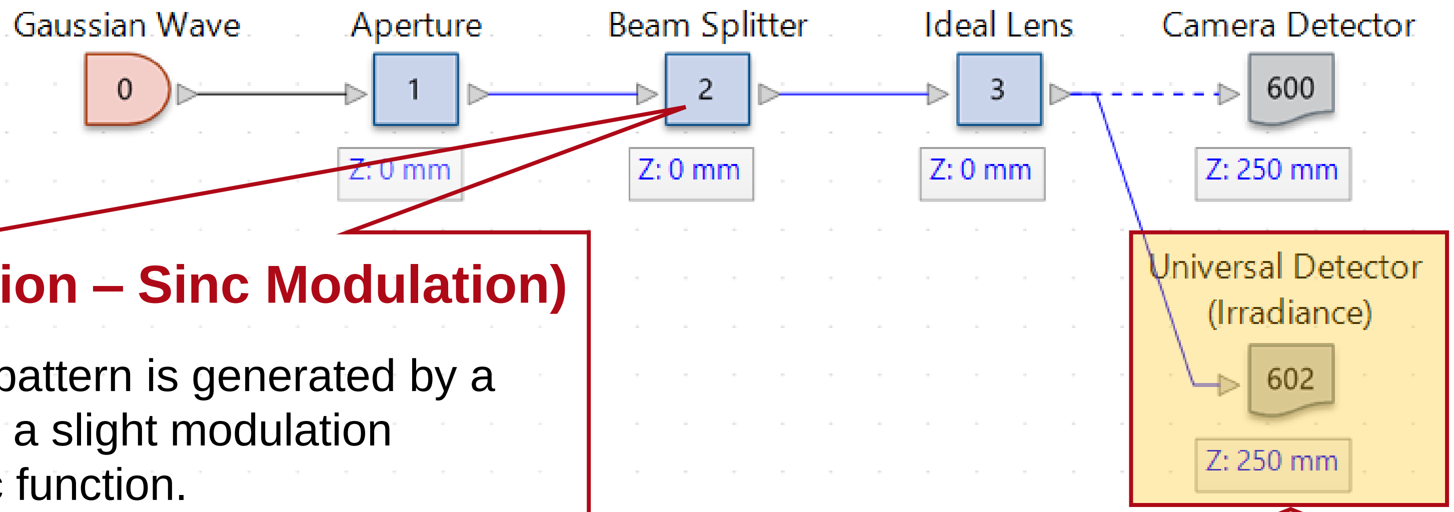
simulation result based on structure profile with 2x AR coating



Final System Simulations

pixelation factor and irradiance detection

Final Adjustments to the System



Accuracy Speed Balance (Pixelation – Sinc Modulation)

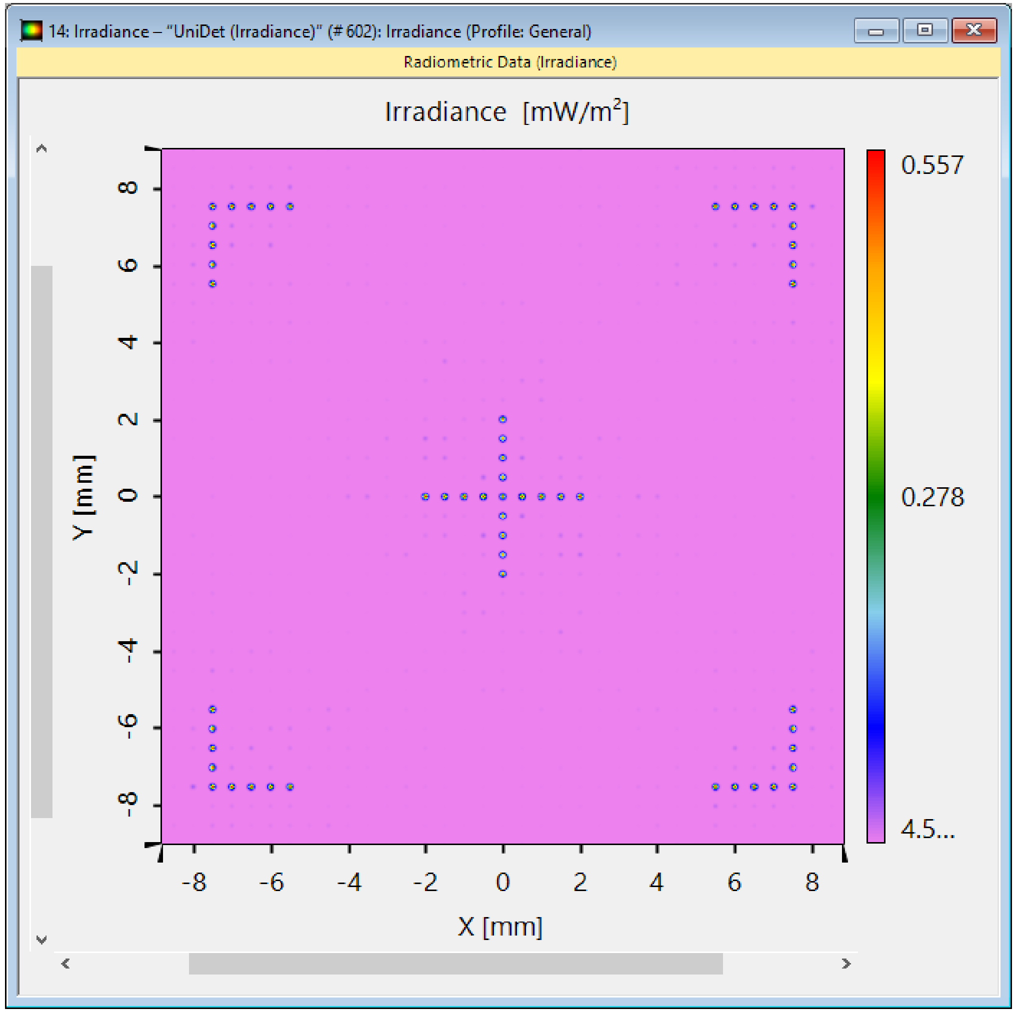
- There exists a physical effect, that if a pattern is generated by a pixelated structure, the pattern exhibits a slight modulation according to the center region of a sinc function.
- This effect will be considered in the simulation if the so-called pixelation factor is set larger than the default 1×1.
- For the final simulation we used a pixelation factor of 5×5.
- This increases the simulation duration but also the accuracy. So, again, VLF offers the customer the option to get quick first results and to include more physics by increasing the accuracy.

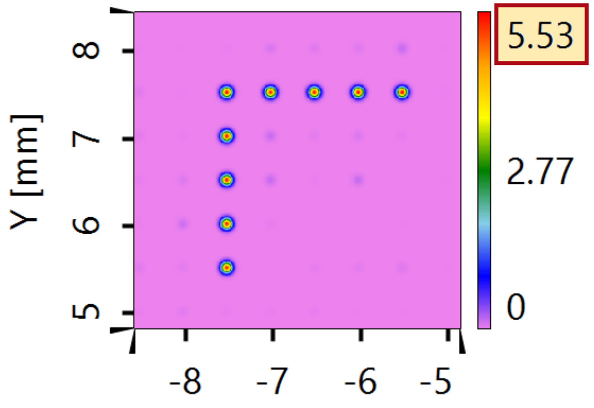
For more info follow this link into the appendix.

For the final evaluation we use the universal detector calculating the irradiance.

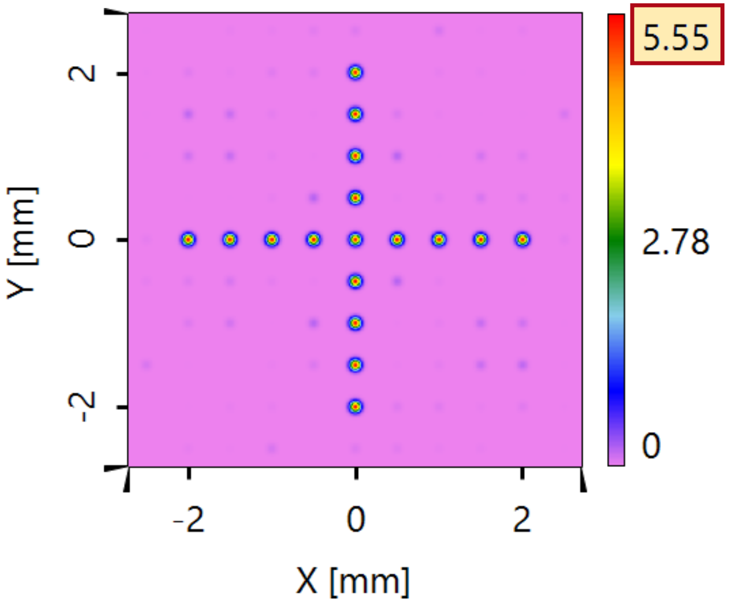
For more info follow this link into the appendix.

Irradiance Results from Simulation with Pixelation Factor of 5×5





This final simulation result shows very nicely the uniform spots achieved along the desired light mark.



Structure Export

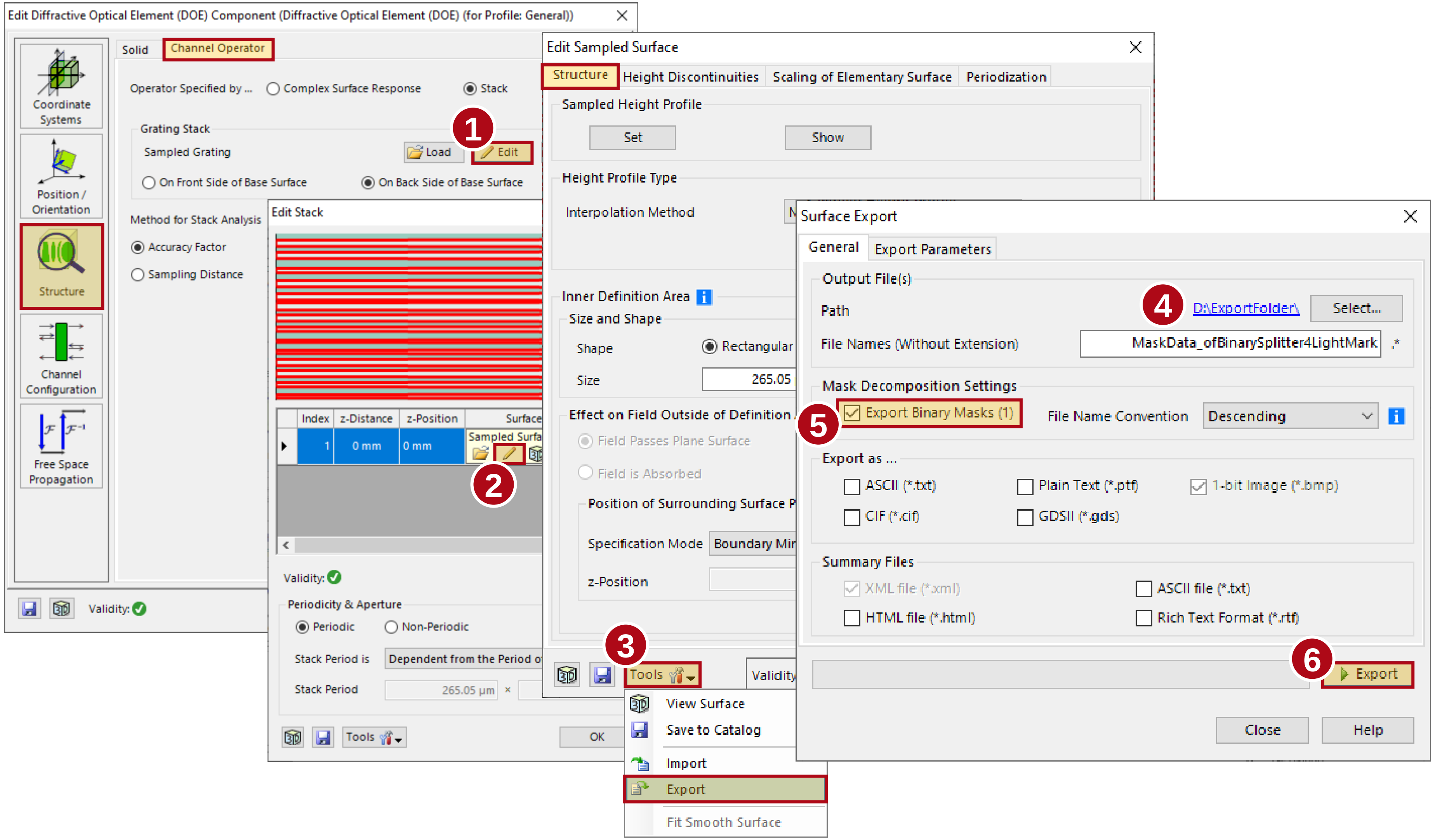
generate data for manufacturer

Export of Fabrication Data

The export is initiated directly from the surface edit dialog via the *Tools* button.

The export dialog provides the user with various options.

VLF will always generate a summary file which contains all relevant description for the manufacturer.



Edit Diffractive Optical Element (DOE) Component (Diffractive Optical Element (DOE) (for Profile: General))

Operator Specified by ... ○ Complex Surface Response ● Stack

Grating Stack: Sampled Grating

○ On Front Side of Base Surface ● On Back Side of Base Surface

Method for Stack Analysis: ● Accuracy Factor ○ Sampling Distance

Edit Stack

Index	z-Distance	z-Position	Surface
1	0 mm	0 mm	Sampled Surfa

Periodicity & Aperture: ● Periodic ○ Non-Periodic

Stack Period is: Dependent from the Period o

Stack Period: 265.05 µm

Edit Sampled Surface

Sampled Height Profile

Height Profile Type

Interpolation Method

Inner Definition Area

Size and Shape

Shape: ● Rectangular

Size: 265.05

Effect on Field Outside of Definition

○ Field Passes Plane Surface

○ Field is Absorbed

Position of Surrounding Surface P

Specification Mode: Boundary Mir

z-Position

Surface Export

Output File(s)

Path: D:\ExportFolder\

File Names (Without Extension): MaskData_ofBinarySplitter4LightMark .*

Mask Decomposition Settings

☑ Export Binary Masks (1)

File Name Convention: Descending

Export as ...

☐ ASCII (*.txt) ☐ Plain Text (*.ptf) ☑ 1-bit Image (*.bmp)

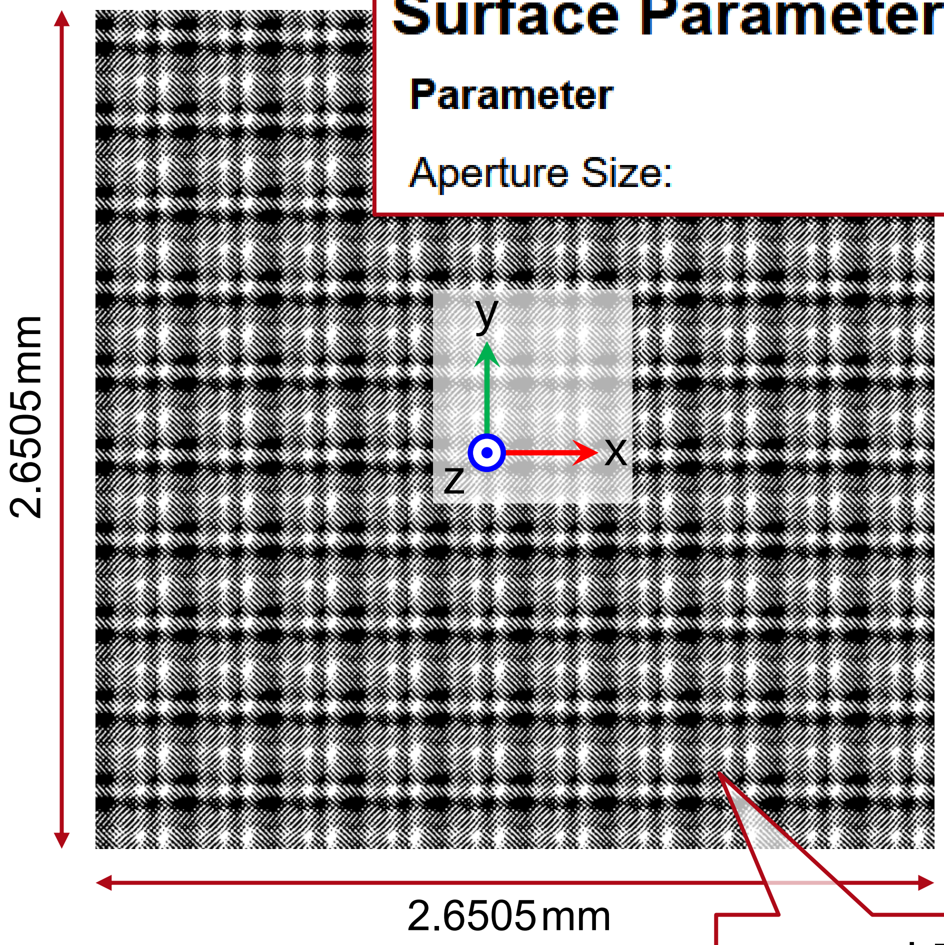
☐ CIF (*.cif) ☐ GDSII (*.gds)

Summary Files

☑ XML file (*.xml) ☐ ASCII file (*.txt)

☐ HTML file (*.html) ☐ Rich Text Format (*.rtf)

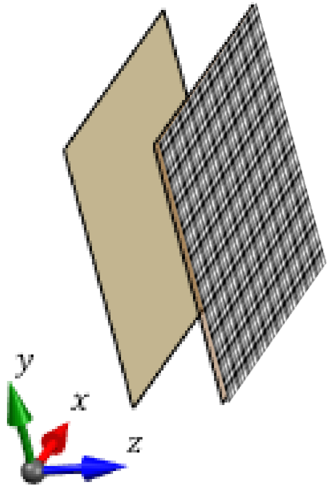
Exported Data



Surface Parameters

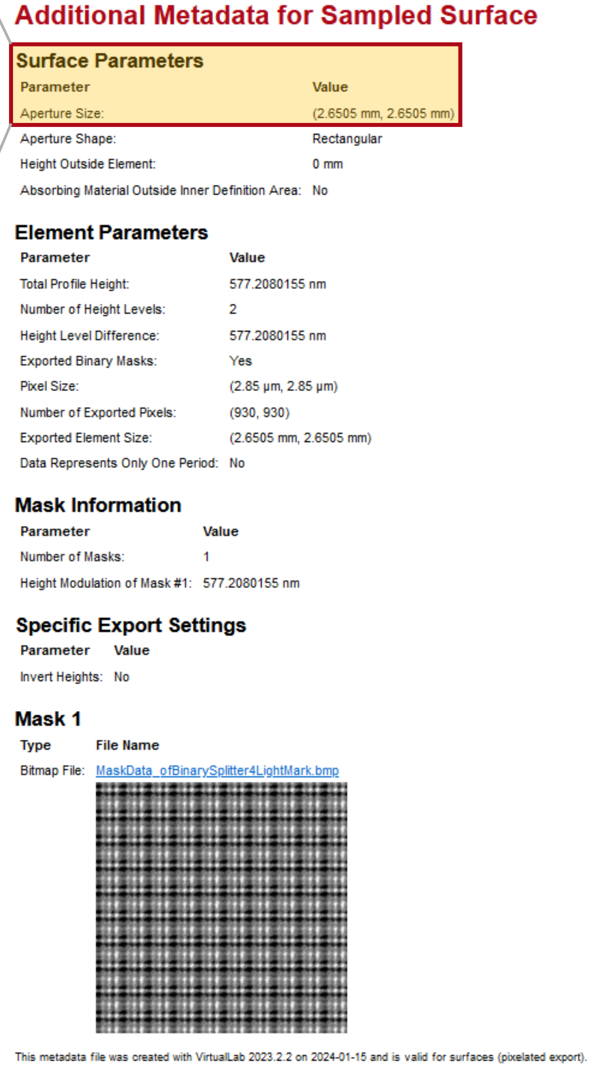
Parameter	Value
Aperture Size:	(2.6505 mm, 2.6505 mm)

The height definition is based on the coordinate system of the surface.



exported BMP of mask data

export summary in HTML format



Additional Metadata for Sampled Surface

Surface Parameters

Parameter	Value
Aperture Size:	(2.6505 mm, 2.6505 mm)
Aperture Shape:	Rectangular
Height Outside Element:	0 mm
Absorbing Material Outside Inner Definition Area:	No

Element Parameters

Parameter	Value
Total Profile Height:	577.2080155 nm
Number of Height Levels:	2
Height Level Difference:	577.2080155 nm
Exported Binary Masks:	Yes
Pixel Size:	(2.85 µm, 2.85 µm)
Number of Exported Pixels:	(930, 930)
Exported Element Size:	(2.6505 mm, 2.6505 mm)
Data Represents Only One Period:	No

Mask Information

Parameter	Value
Number of Masks:	1
Height Modulation of Mask #1:	577.2080155 nm

Specific Export Settings

Parameter	Value
Invert Heights:	No

Mask 1

Type	File Name
Bitmap File:	MaskData_ofBinarySplitter4LightMark.bmp

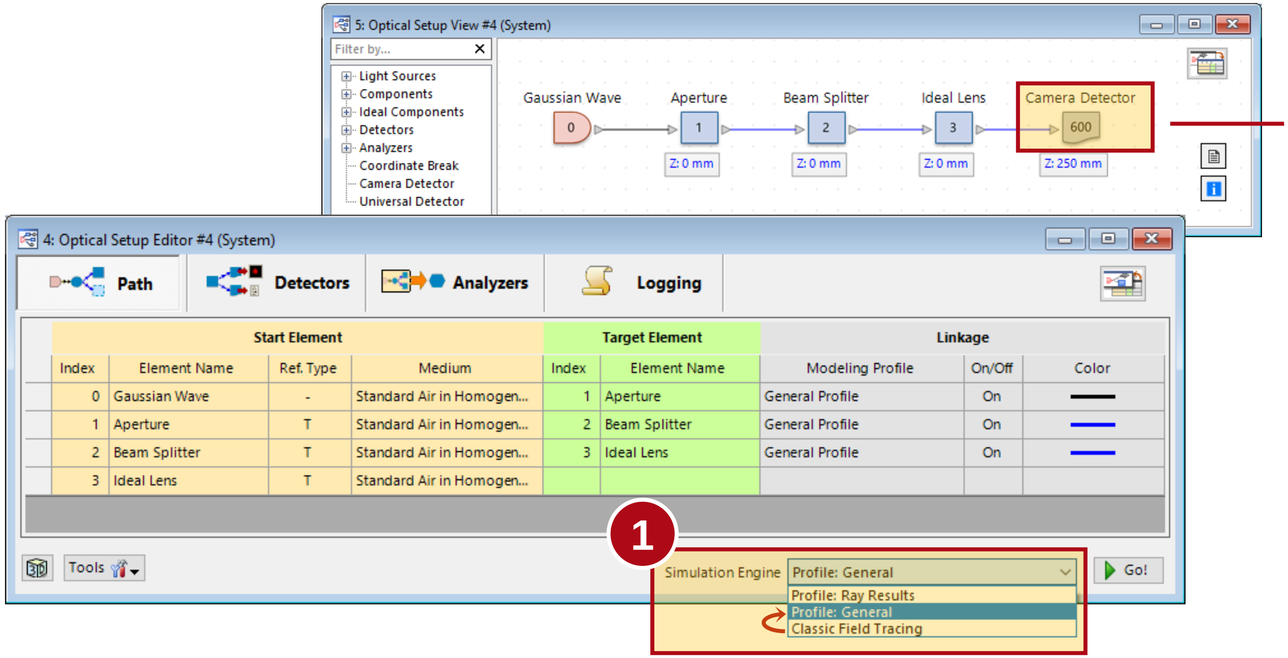
This metadata file was created with VirtualLab 2023.2.2 on 2024-01-15 and is valid for surfaces (pixelated export).

Document Information

title	Design & Analysis of Diffractive Splitter Generating a Light Mark
document code	DOE.0002
document version	3.0
required packages	• Diffractive Optics
software version	2023.2 (2.30)
category	Application Use Case
further reading	

Appendix

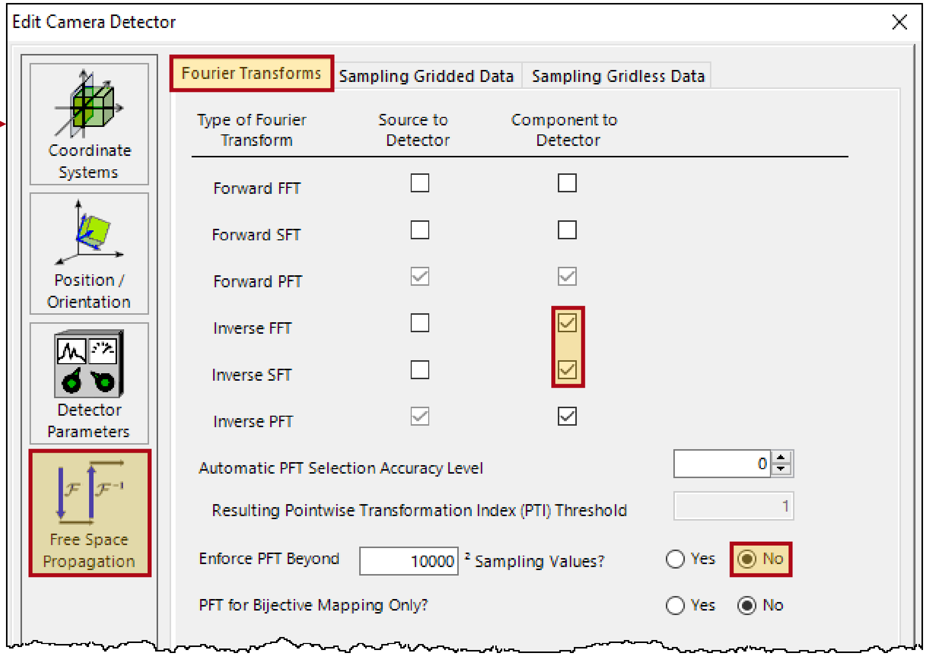
Info & Adjustments of Initially Output Optical Setup



Start Element				Target Element		Linkage		
Index	Element Name	Ref. Type	Medium	Index	Element Name	Modeling Profile	On/Off	Color
0	Gaussian Wave	-	Standard Air in Homogen...	1	Aperture	General Profile	On	—
1	Aperture	T	Standard Air in Homogen...	2	Beam Splitter	General Profile	On	—
2	Beam Splitter	T	Standard Air in Homogen...	3	Ideal Lens	General Profile	On	—
3	Ideal Lens	T	Standard Air in Homogen...					

Simulation Engine: Profile: General

Profile: Ray Results
Profile: General
Classic Field Tracing



Type of Fourier Transform	Source to Detector	Component to Detector
Forward FFT	☐	☐
Forward SFT	☐	☐
Forward PFT	☑	☑
Inverse FFT	☐	☑
Inverse SFT	☐	☑
Inverse PFT	☑	☑

Automatic PFT Selection Accuracy Level: 0

Resulting Pointwise Transformation Index (PTI) Threshold: 1

Enforce PFT Beyond 10000 ² Sampling Values? ○ Yes ● No

PFT for Bijective Mapping Only? ○ Yes ● No

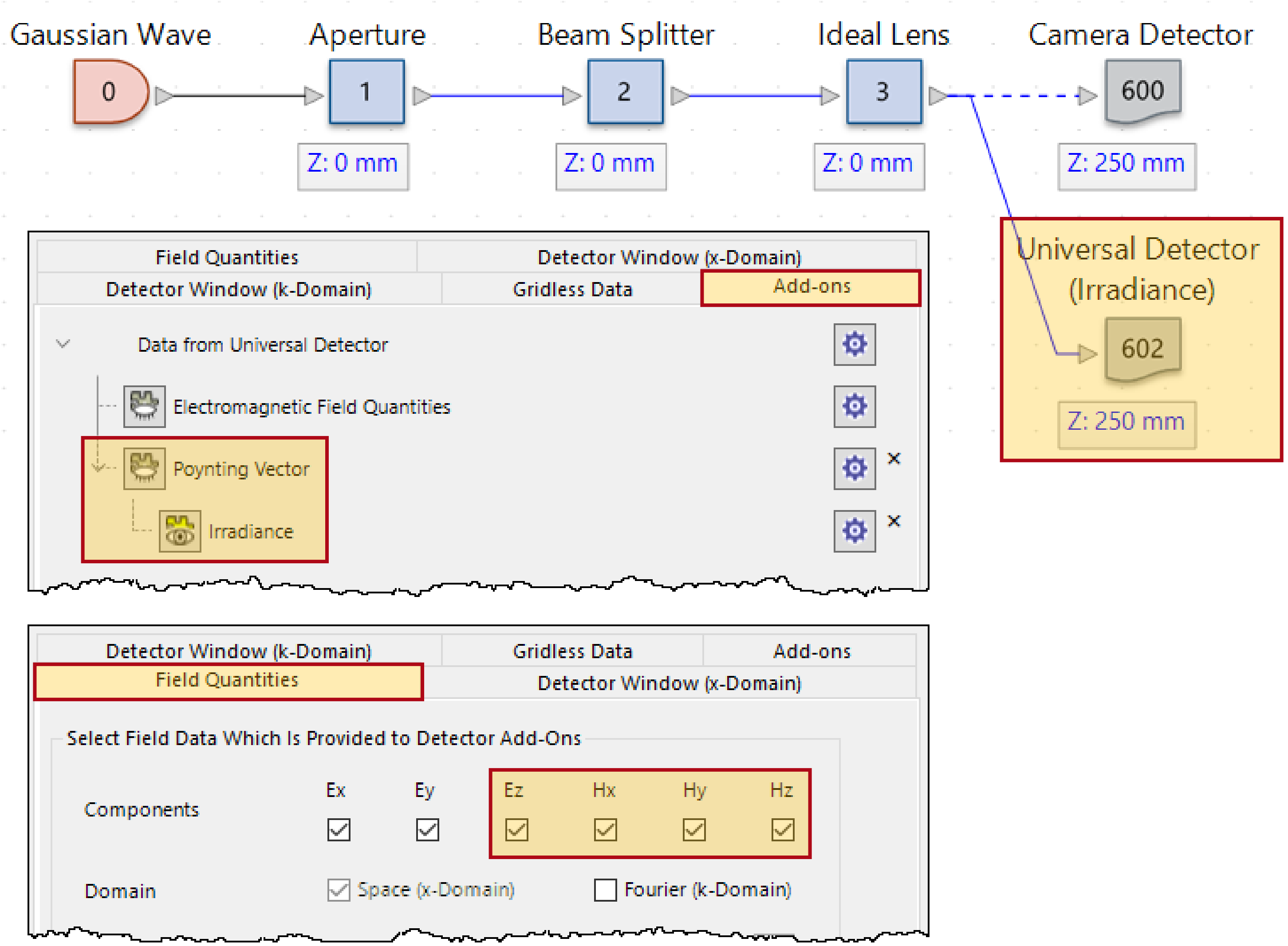
1. Currently the preset simulation engine is still "Classic Field Tracing (CFT)", but the newer General Profile option is already the better choice for most setups. Thus, the simulation engine is switched to *"Profile: General".*

2. Furthermore, as this scenario can be assumed to be paraxial, where we do not expect distorted off-axis spots, and the light is propagated into a Fourier plane, we choose the Fourier transforms "pointwise" & "inverse integral"; this corresponds to the generalized Debye method.
By default, the automatisms of VLF with version 2023.2 (build 2.30) are a bit stricter and would select a rigorous propagation method which would take about 3× longer, with similar result.

question of balance between speed and accuracy

Configuring of Radiometric Evaluation

- The camera detector outputs the components of the **E** field. Typically, one is interested in radiometric or photometric quantities.
- In the optical setup (OS) we have prepared two Universal Detectors for that purpose. One for the general pattern impression and one for a detail of it.
- Here we configure the detection of the radiometric quantity "Irradiance" which is derived from the Poynting vector.
- As a consequence all 6 EM field components have to be evaluated to calculate the Poynting vector and then the irradiance.
- For such a paraxial system, the summed squared amplitudes and the irradiance result are proportional.



Field Quantities | Detector Window (x-Domain) | Detector Window (k-Domain) | Gridless Data | Add-ons

Data from Universal Detector
- Electromagnetic Field Quantities
  - Poynting Vector
    - Irradiance

Detector Window (k-Domain) | Gridless Data | Add-ons | Field Quantities | Detector Window (x-Domain)

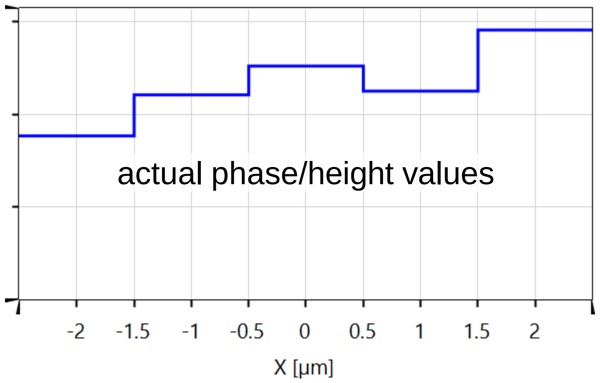
Select Field Data Which Is Provided to Detector Add-Ons

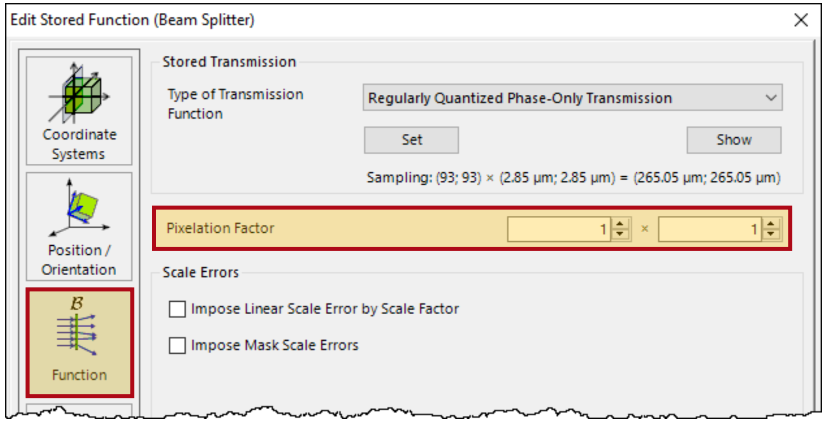
	Ex	Ey	Ez	Hx	Hy	Hz
Components	☑	☑	☑	☑	☑	☑

Domain ☑ Space (x-Domain) ☐ Fourier (k-Domain)

Simulate Pixelated DOE

- The first system simulations neglected the pixelated nature of the phase or height distribution.
- By introducing a pixelation factor larger than 1×1 per we "tell" VLF to sample each phase (and structure) pixel (respectively) by multiple points.




Edit Stored Function (Beam Splitter)

Stored Transmission

Type of Transmission Function: Regularly Quantized Phase-Only Transmission

Sampling: (93; 93) × (2.85 µm; 2.85 µm) = (265.05 µm; 265.05 µm)

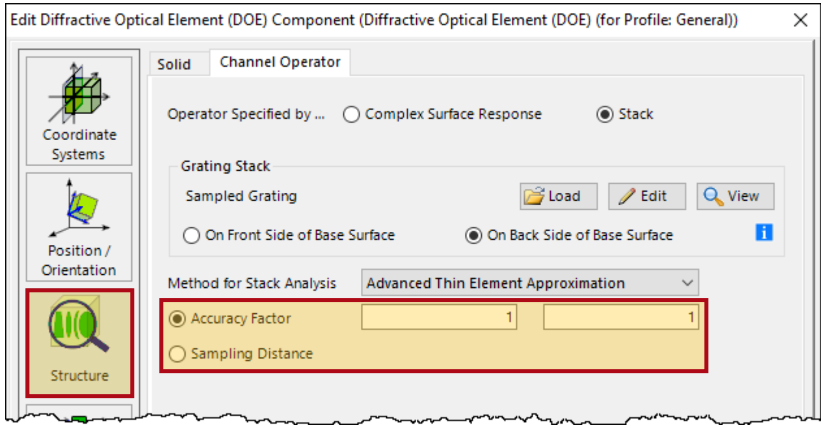
Pixelation Factor 1 × 1

Scale Errors

☐ Impose Linear Scale Error by Scale Factor

☐ Impose Mask Scale Errors

increase sampling for phase element


Edit Diffractive Optical Element (DOE) Component (Diffractive Optical Element (DOE) (for Profile: General))

Operator Specified by ... ○ Complex Surface Response ● Stack

Grating Stack

Sampled Grating

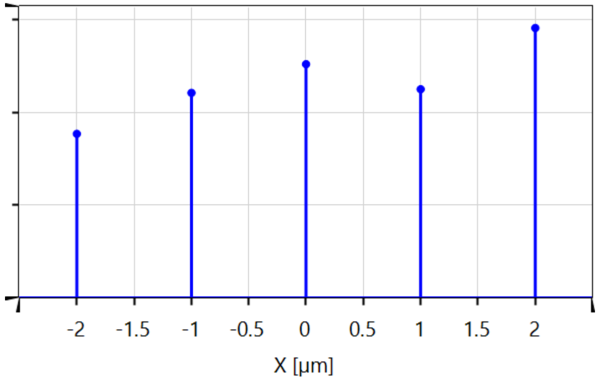
○ On Front Side of Base Surface ● On Back Side of Base Surface

Method for Stack Analysis: Advanced Thin Element Approximation

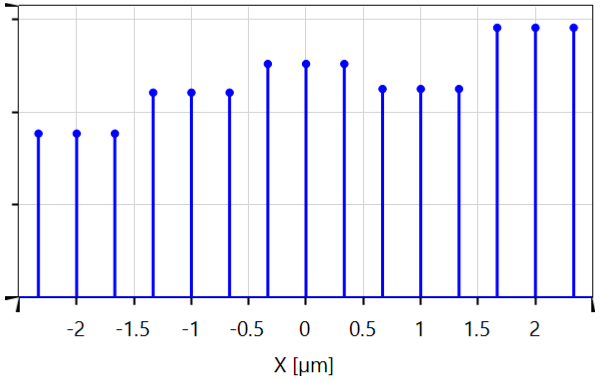
● Accuracy Factor 1 1

○ Sampling Distance

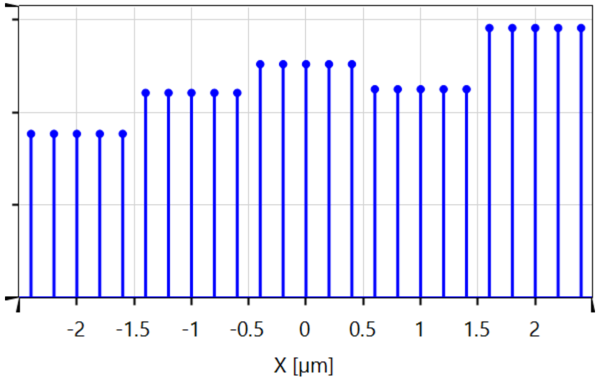
increase sampling for structure element



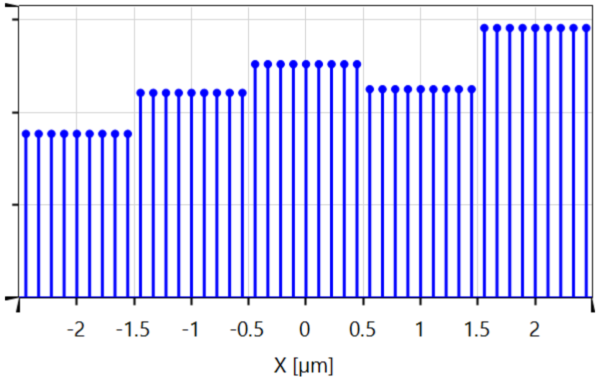
1 simulation point per pixel



3 simulation points per pixel

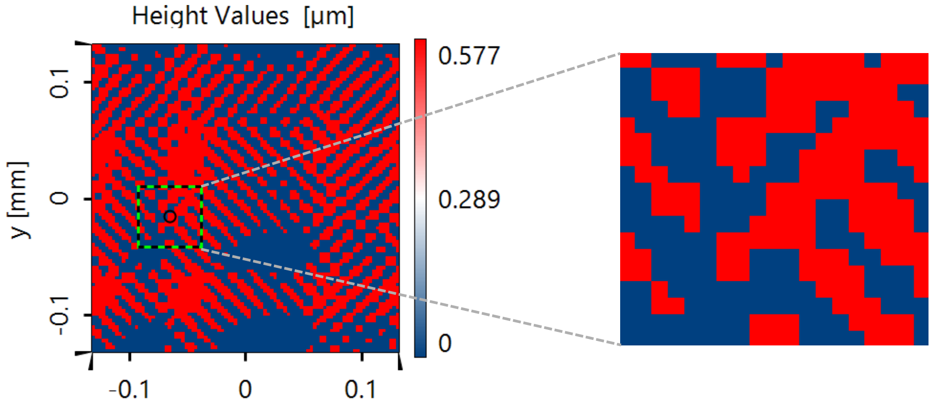


5 simulation points per pixel



9 simulation points per pixel

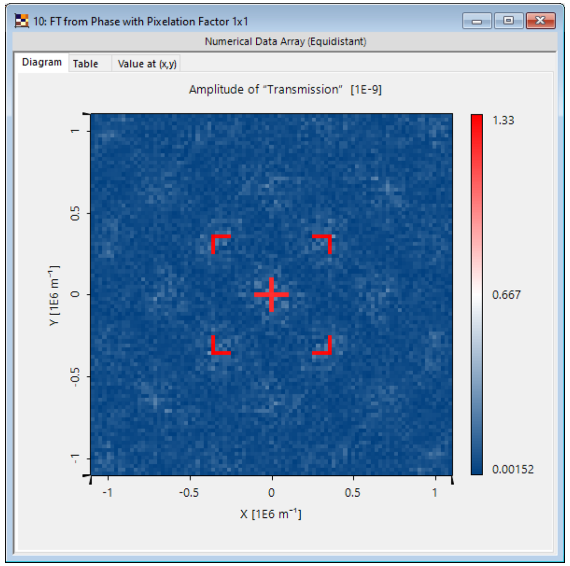
Higher Sinc Orders Due to Structure Pixelation

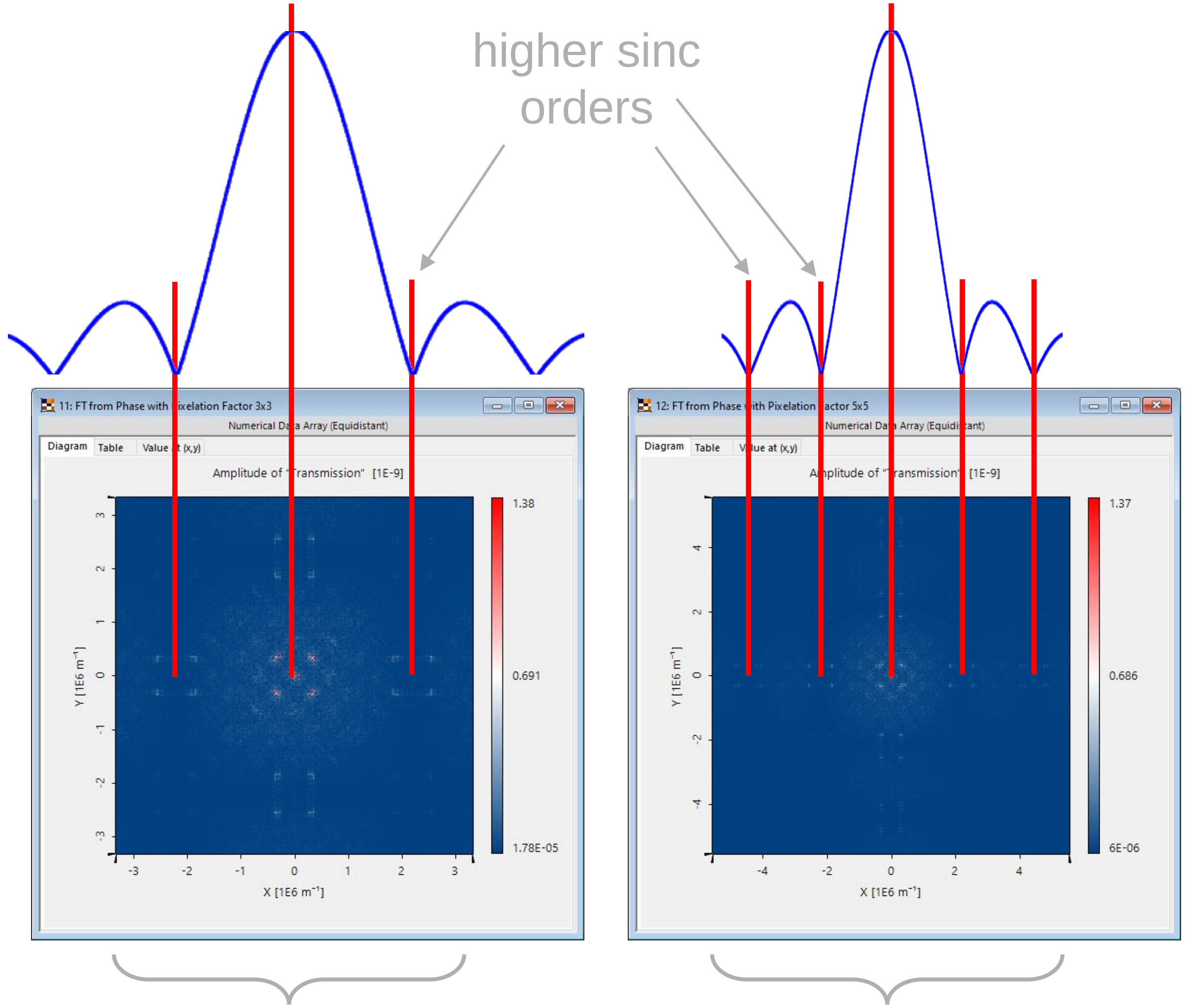


When light interacts with equidistant rectangular height plateaus (pixels), the generated diffraction order energies are globally modulated according to a sinusoidal function.

And the equidistance represents an additional period, which yields the so-called higher sinc diffraction orders.

The IFTA design counteracts the unwanted sinc modulation.

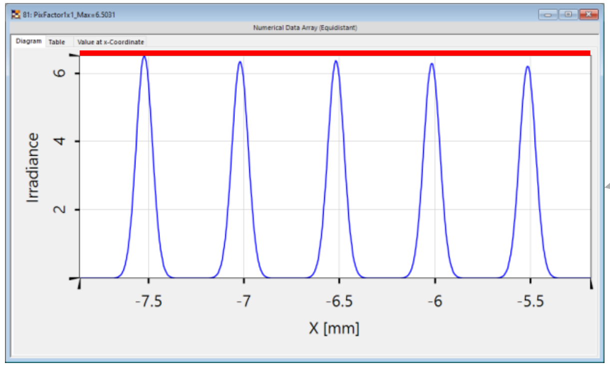




output field size × 3

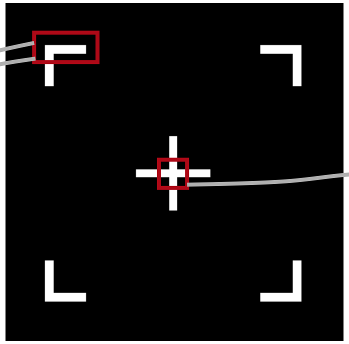
output field size × 5

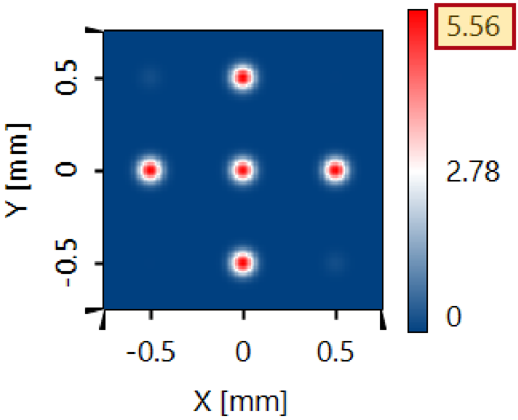
Convergence Check for Pixelation Factor



1×1 → non-uniform with Max@6.50

6.5 W/m²

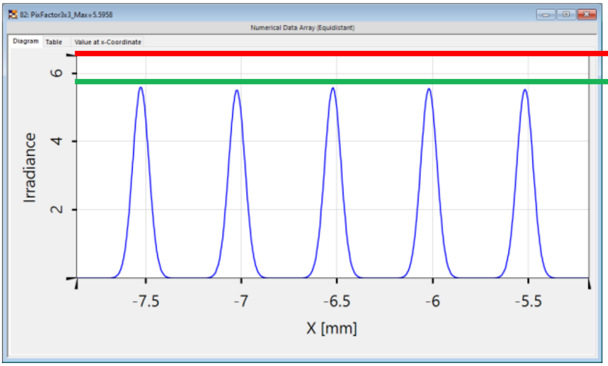




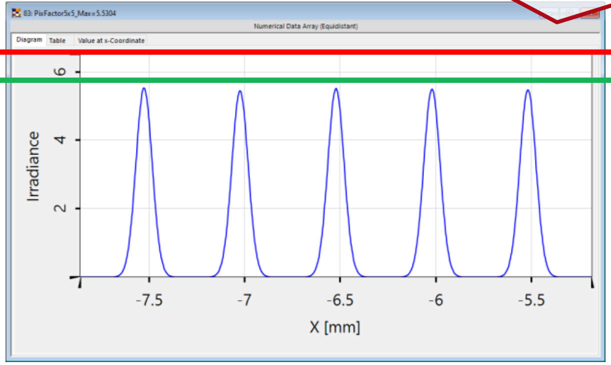
With a pixelation factor of 1×1 in the optical system, the sinc modulation due to the pixelated structure does not occur. Due to the IFTA compensation an irradiance difference of 5.56 W/m² to 6.5 W/m² between the center and the marginal spots remains.

Only when the simulation is allowed to "see" the rectangular pixels by using a higher pixelation factor does the compensation show its compensating effect.

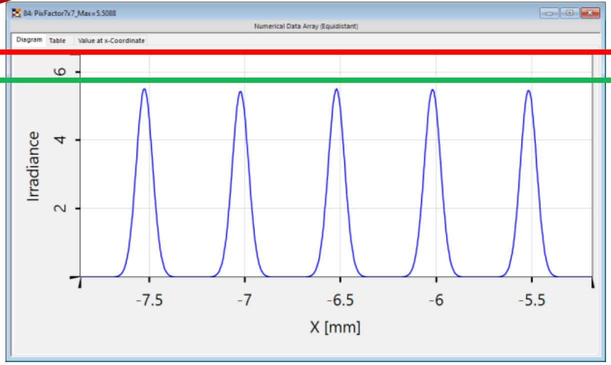
5.6 W/m²



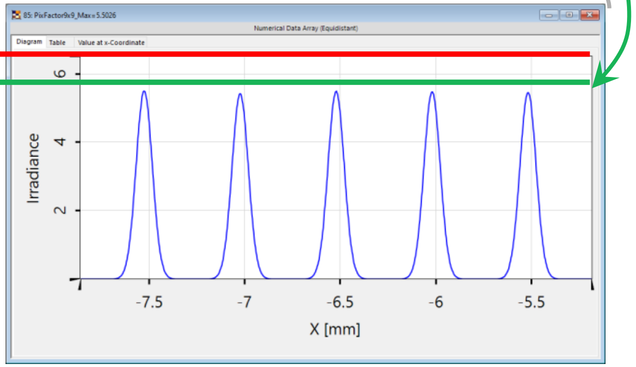
3×3 → uniform with max@5.60



5×5 → uniform with max@5.53



7×7 → uniform with max@5.51



9×9 → uniform with max@5.50

The difference of the maximum value between the simulation with a pixelation factor of 5×5 and 9×9 is only 0.5%.
It is a question of compromise between accuracy and calculation time.