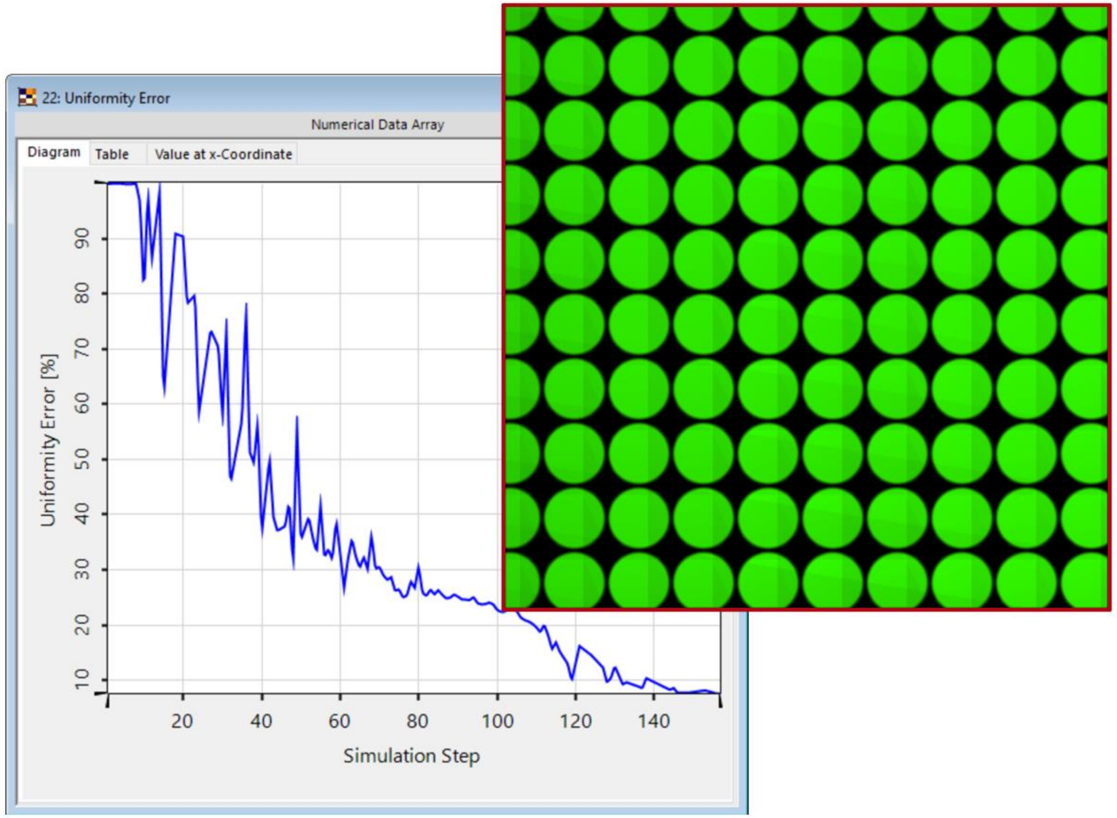
Fast Optimization of Grating-Based Waveguides Enabled by Efficient Single-Platform Interoperability

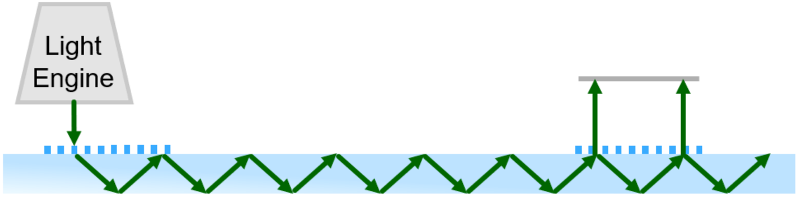
Abstract



In the design process of waveguide devices in the field of augmented and mixed reality applications (AR & MR), lateral uniformity (per field of view mode) and overall efficiency are two of the most important merit functions. In order to optimize the uniformity and efficiency in a lightguide system, it is necessary to allow for a lateral variation of the grating parameters, particularly in the expander and/or outcoupling region. For this purpose, VirtualLab Fusion enables the introduction of smoothly varying grating parameters in a grating region along with the necessary tools to run an optimization according to a defined merit function. Furthermore, for such complex optical setups, a flexible interoperability of modeling techniques on a single platform is key for an accurate and fast simulation. This use case demonstrates the analysis of accuracy and speed and the resulting fast optimization of a lightguide with continuously varied values of the fill factor in order to obtain an adequate uniformity.

Task Description

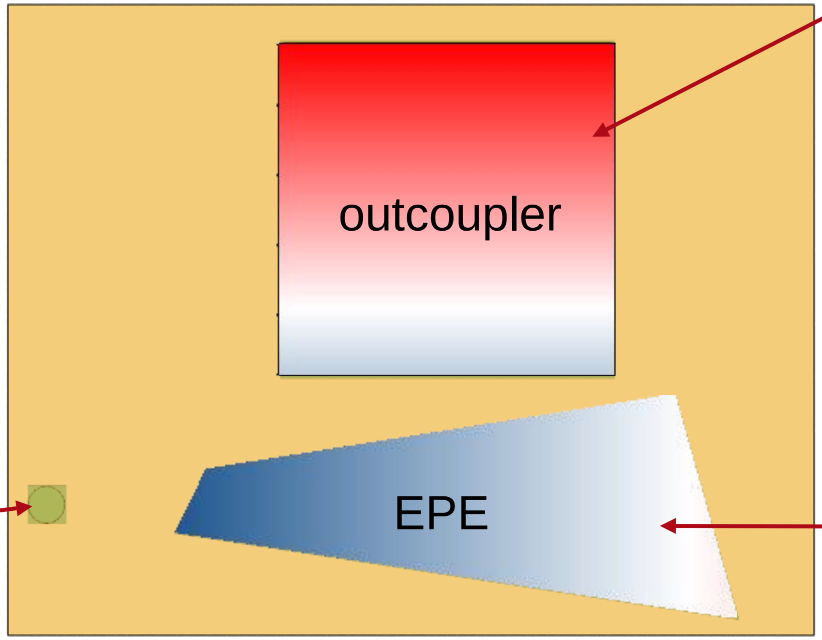
Task: Optimize lateral uniformity in the eyebox (e.g. for a single FOV mode) with an adequate balance of speed and accuracy?



Layout & initial parameters:

Incoupler

- slanted grating
- 380 nm period
- fill factor: 50%
- height: 300 nm
- slant angle: 45°



Outcoupler

- binary grating
- 380 nm period
- height: 165 nm
- linearly varying fill factor

Eye Pupil Expander

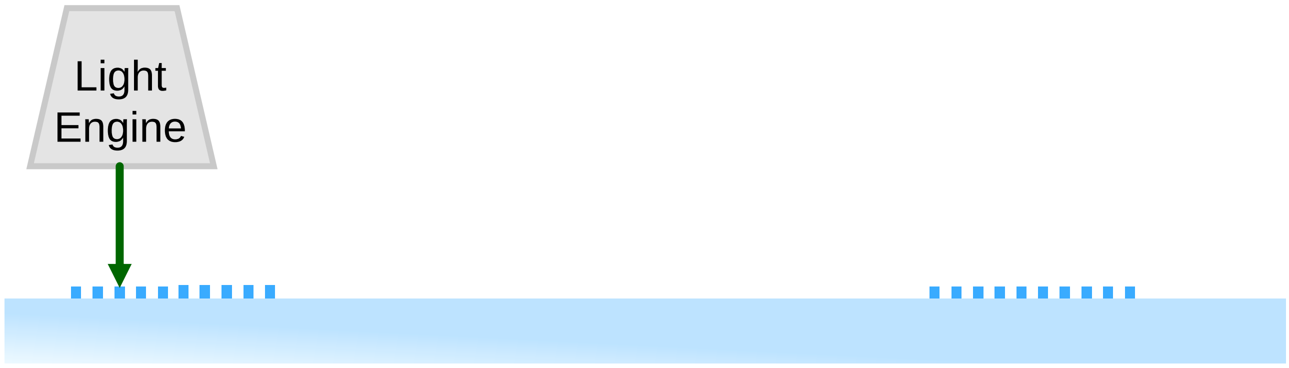
- binary grating
- 268.7 nm period
- height: 150 nm
- linearly varying fill factor

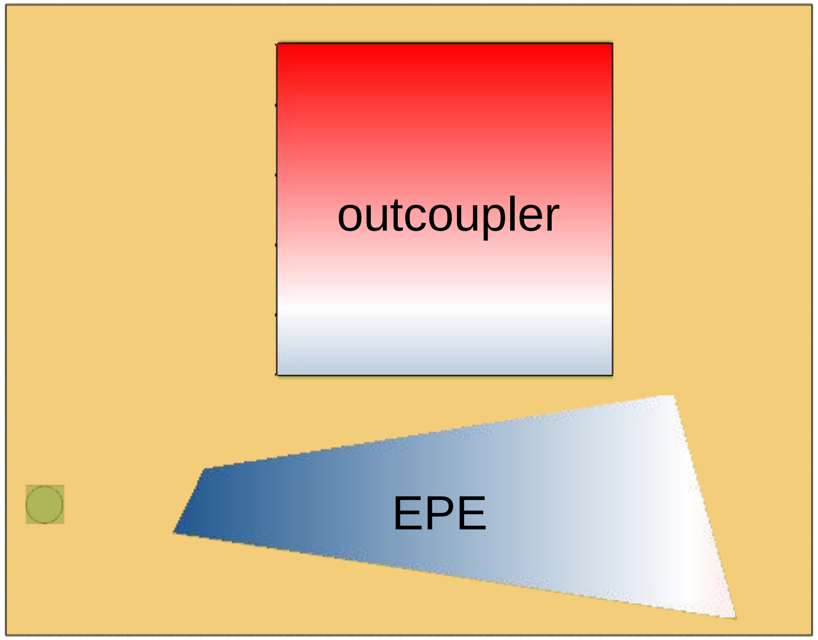
Simulation & Setup: Single Platform Interoperability

Connected Modeling Techniques: Source

Light Engine Model

- beam type: plane wave
- beam diameter: 1 mm (circular)
- polarization: linearly polarized
- wavelength: 532 nm

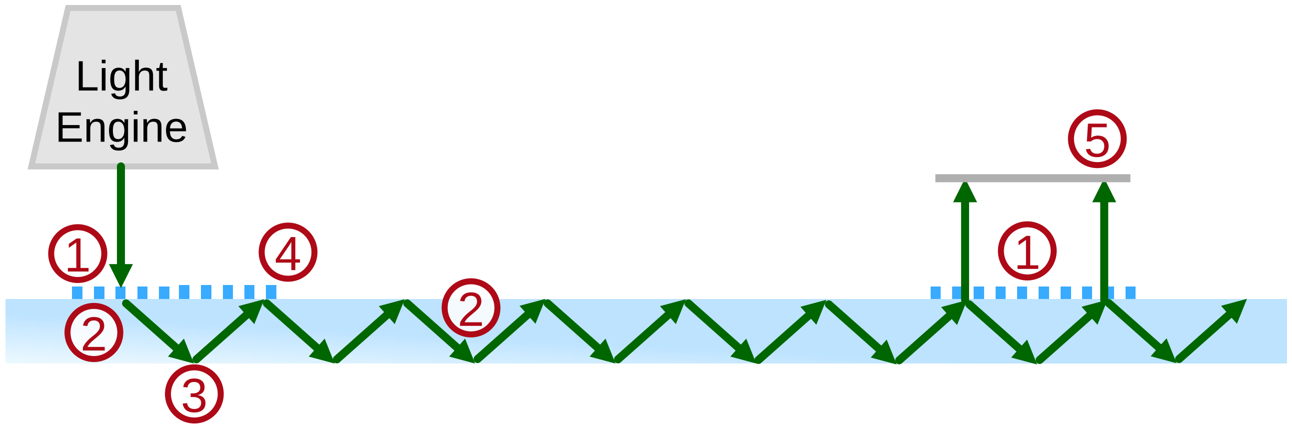


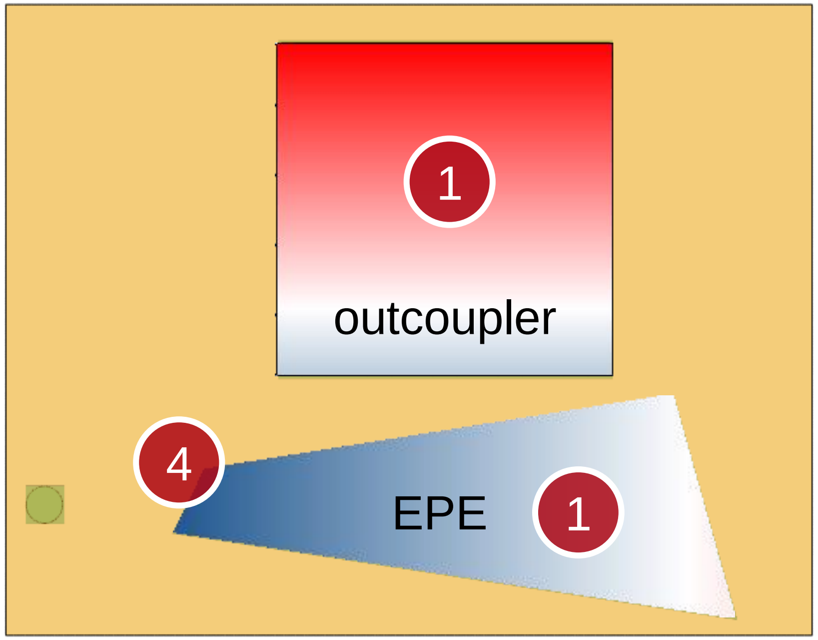


Connected Modeling Techniques: Beam Propagation

Each beam interacts with very different kinds of optical components while propagating through the complex system. Hence, an accurate model requires a seamless interoperability of algorithms to be able to handle all aspects that arise:

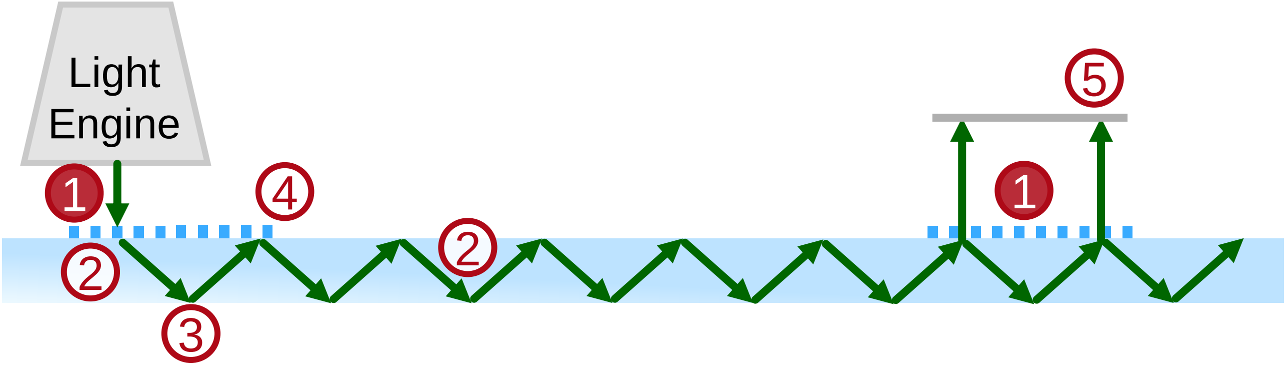
① gratings (incoupler, EPE, outcoupler)
② free-space (propagation inside the glass slab)
③ reflection at surfaces of glass slab
④ region boundaries (at boundaries of a grating)
⑤ detector (uniformity measurement in eye box)





Connected Modeling Techniques: Gratings

1. gratings (incoupler, EPE, outcoupler)
2. free-space (propagation inside the glass slab)
3. reflection at surfaces of glass slab
4. region boundaries (at boundaries of a grating)
5. detector (uniformity measurement in eye box)



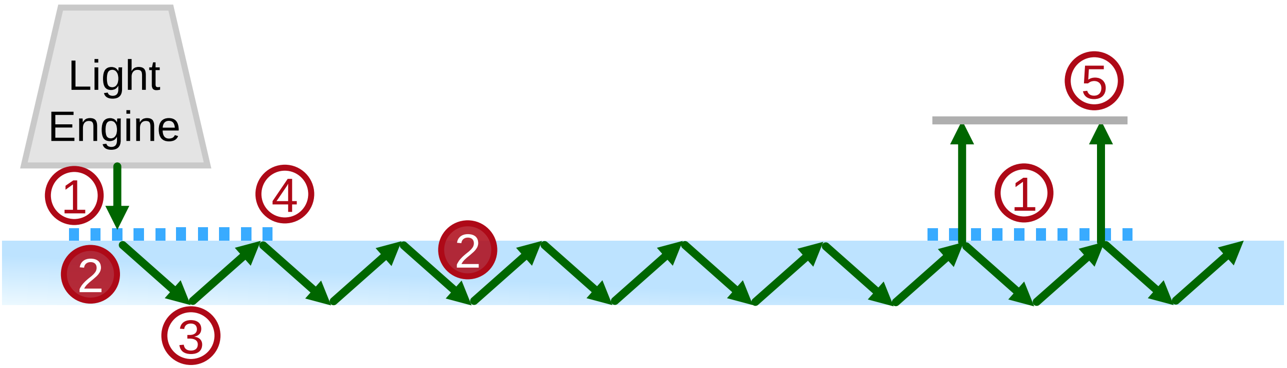
Available modeling techniques for periodic micro and nano structures:

Methods	Preconditions	Accuracy	Speed	Comments
Fourier Modal Method (FMM)	None	High	High	**Small periods**
Thin Grating Approximation	**Large periods & features, thin**	High	High	Thickness about wavelength; period & features larger than about ten wavelengths
	Otherwise	Low	High	
FMM in Kogelnik Approximation	**Thick volume gratings; Bragg condition**	High	Very high	Method is electromagnetic formulation of Kogelnik’s approach
	No Bragg condition	Low	Very high	

As a rigorous eigenmode solver, the Fourier modal method (also known as rigorous coupled wave analysis, RCWA) provides a very high accuracy. Due to the small periods in this setup, the calculation is speed is fast. Hence, FMM is the best compromise of accuracy and speed.

Connected Modeling Techniques: Inside Waveguide Slab

1. gratings (incoupler, EPE, outcoupler)
2. free-space (propagation inside the glass slab)
3. reflection at surfaces of glass slab
4. region boundaries (at boundaries of a grating)
5. detector (uniformity measurement in eye box)



Available modeling techniques for free-space propagation:

Methods	Preconditions	Accuracy	Speed	Comments
Rayleigh Sommerfeld Integral	None	High	Low	Rigorous solution
Fourier Domain Techniques	None	High	High	Rigorous mathematical reformulation of RS integral
Fresnel Integral	**Paraxial**	High	High	Assumes paraxial light; moderate speed for very short distances
	Non-paraxial	Low	High	
Geometric Propagation	**Low diffraction**	High	Very high	Neglects diffraction effects
	Otherwise	Low	Very high	

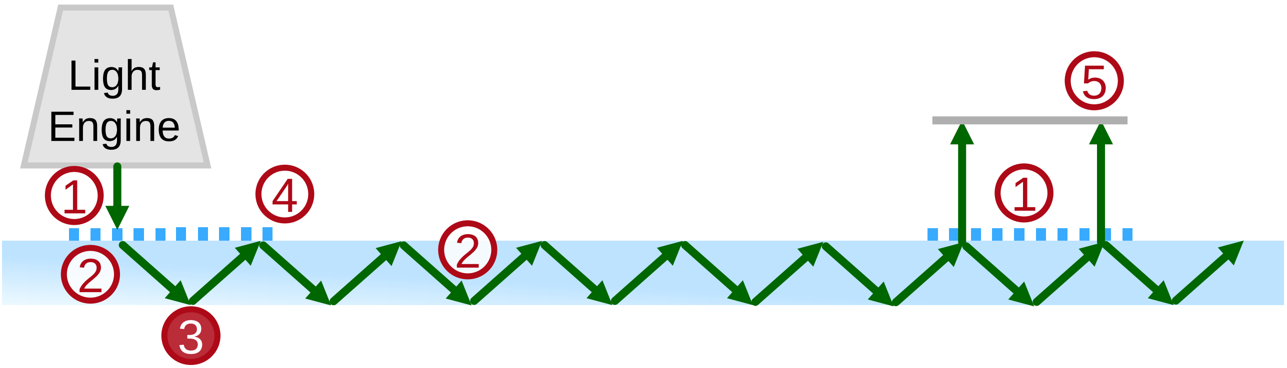
Two fast modeling techniques are available for calculating the propagation inside the glass plate:

- **Fourier Domain Techniques** (includes diffraction effects of boundaries and apertures)
- **Geometric Propagation** (neglects diffraction that arises from boundaries and apertures)

For choosing the adequate technique the results need to be considered!

Connected Modeling Techniques: Waveguide Surfaces

1. gratings (incoupler, EPE, outcoupler)
2. free-space (propagation inside the glass slab)
3. reflection at surfaces of glass slab
4. region boundaries (at boundaries of a grating)
5. detector (uniformity measurement in eye box)



Available modeling techniques interaction with surfaces:

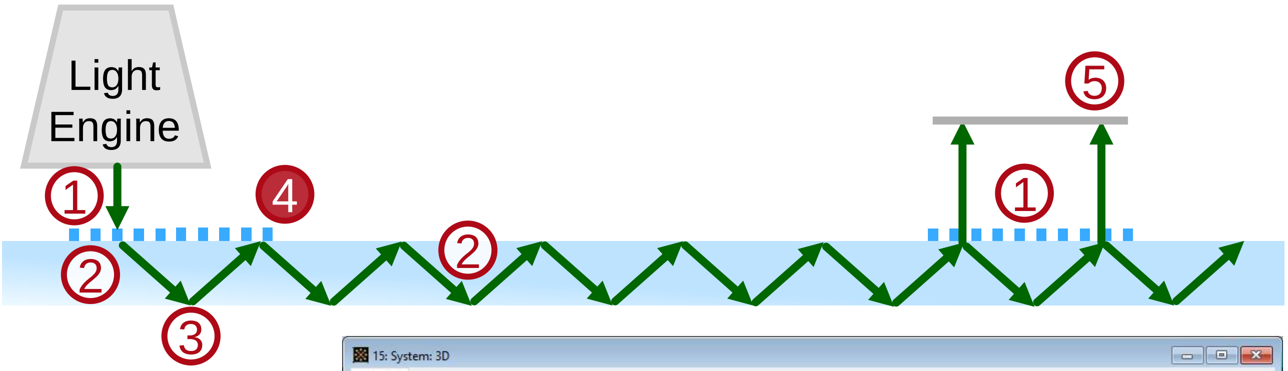
Methods	Preconditions	Accuracy	Speed	Comments
S matrix	Planar surface	High	Very High	Rigorous model; includes isotropic and birefringent coatings; k-domain
Local Planar Interface Approximation	Surface not in focal region of beam	High	Very High	Local application of S matrix; LPIA; x-domain

Two modeling techniques are available for calculating the interaction with the surfaces.

Due to both are very fast and the **Local Planar Interface Approximation** enables to consider curved surfaces (e.g. for tolerancing analysis), this technique is chosen.

Connected Modeling Techniques: Region Boundaries

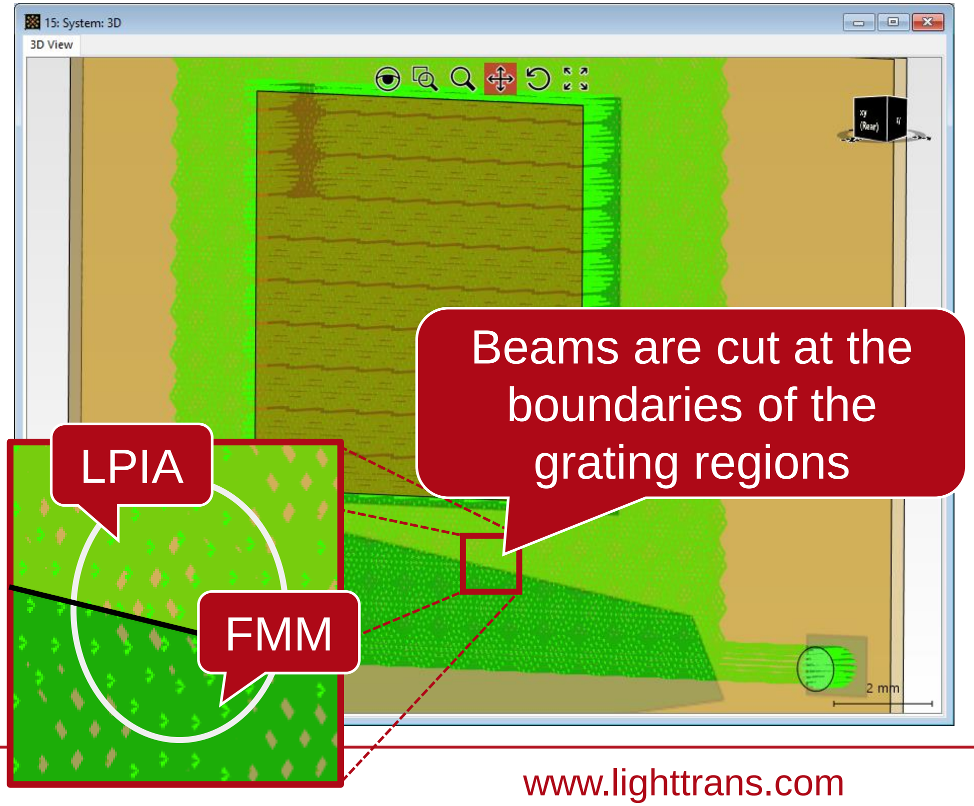
1. gratings (incoupler, EPE, outcoupler)
2. free-space (propagation inside the glass slab)
3. reflection at surfaces of glass slab
4. region boundaries (at boundaries of a grating)
5. detector (uniformity measurement in eye box)



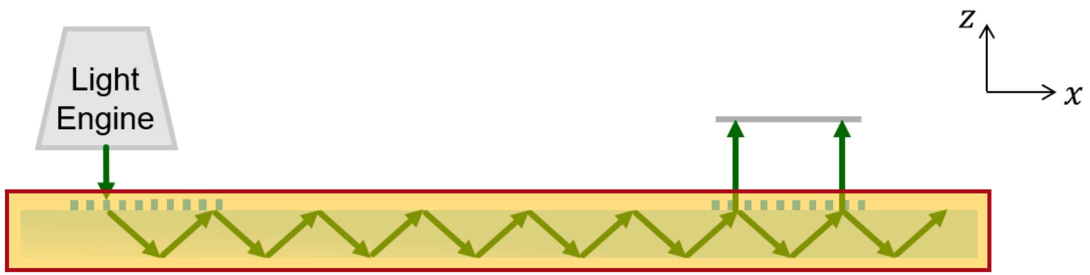
Available modeling techniques for interaction with region boundaries:

Methods	Preconditions	Accuracy	Speed	Comments
Local application of LPIA and FMM	Region extent not close to a few wavelengths	High	Very High	Beam profile cut along region boundaries; **high resolution**

The local application of LPIA and FMM enables to take into account the interaction with the boundaries of grating regions.

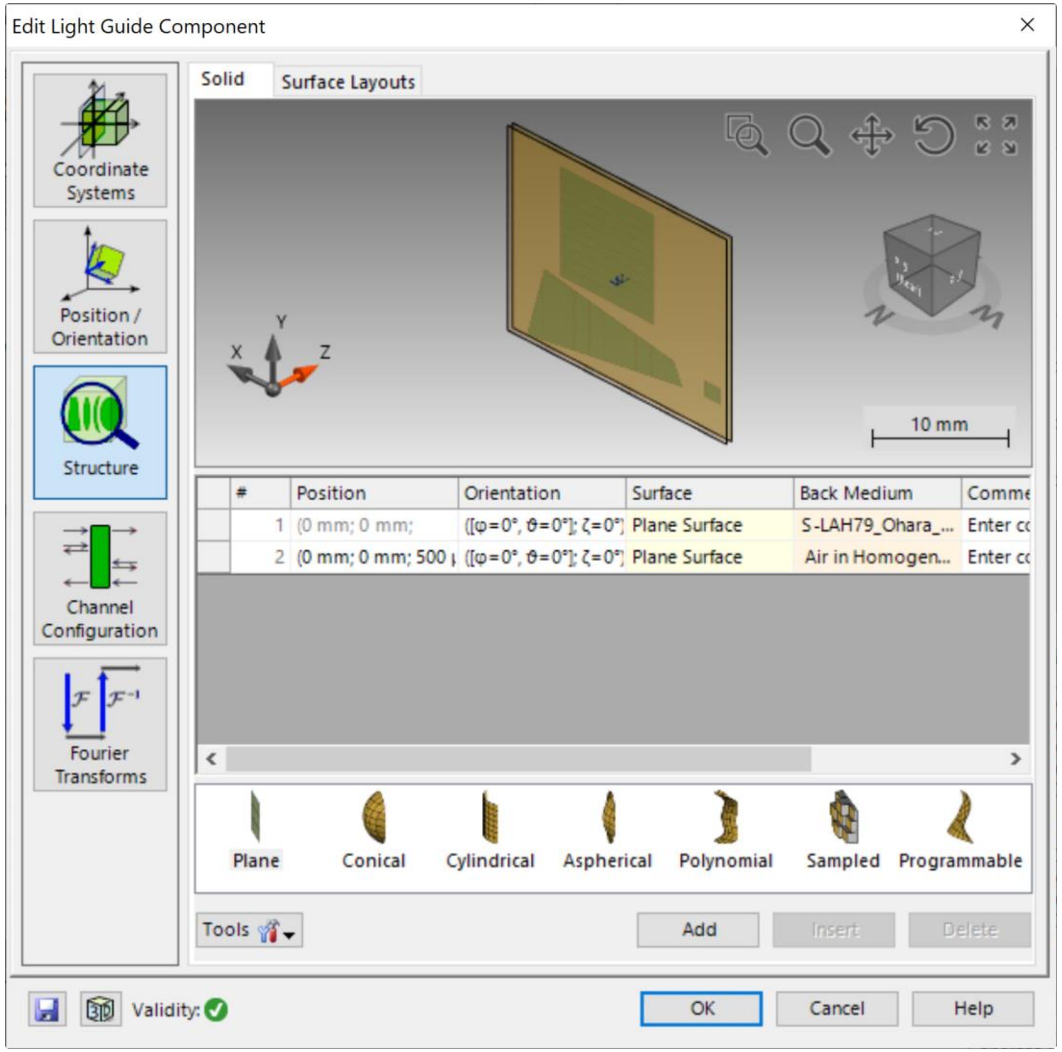


Light Guide Component

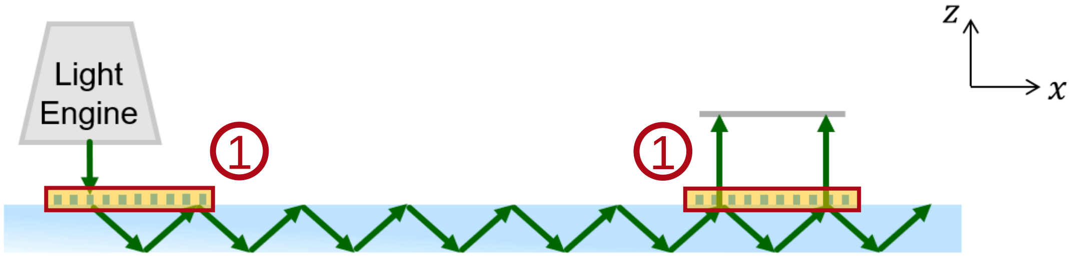


Modeling techniques ① to ④ are combined in the *Light Guide Component.* With this element, grating-based lightguide systems with complex-shaped grating regions can easily be defined. Furthermore, these regions can be equipped with idealized or real grating structures to act as incoupler, outcoupler or exit pupil expanders. More information under:

Construction of a Light Guide

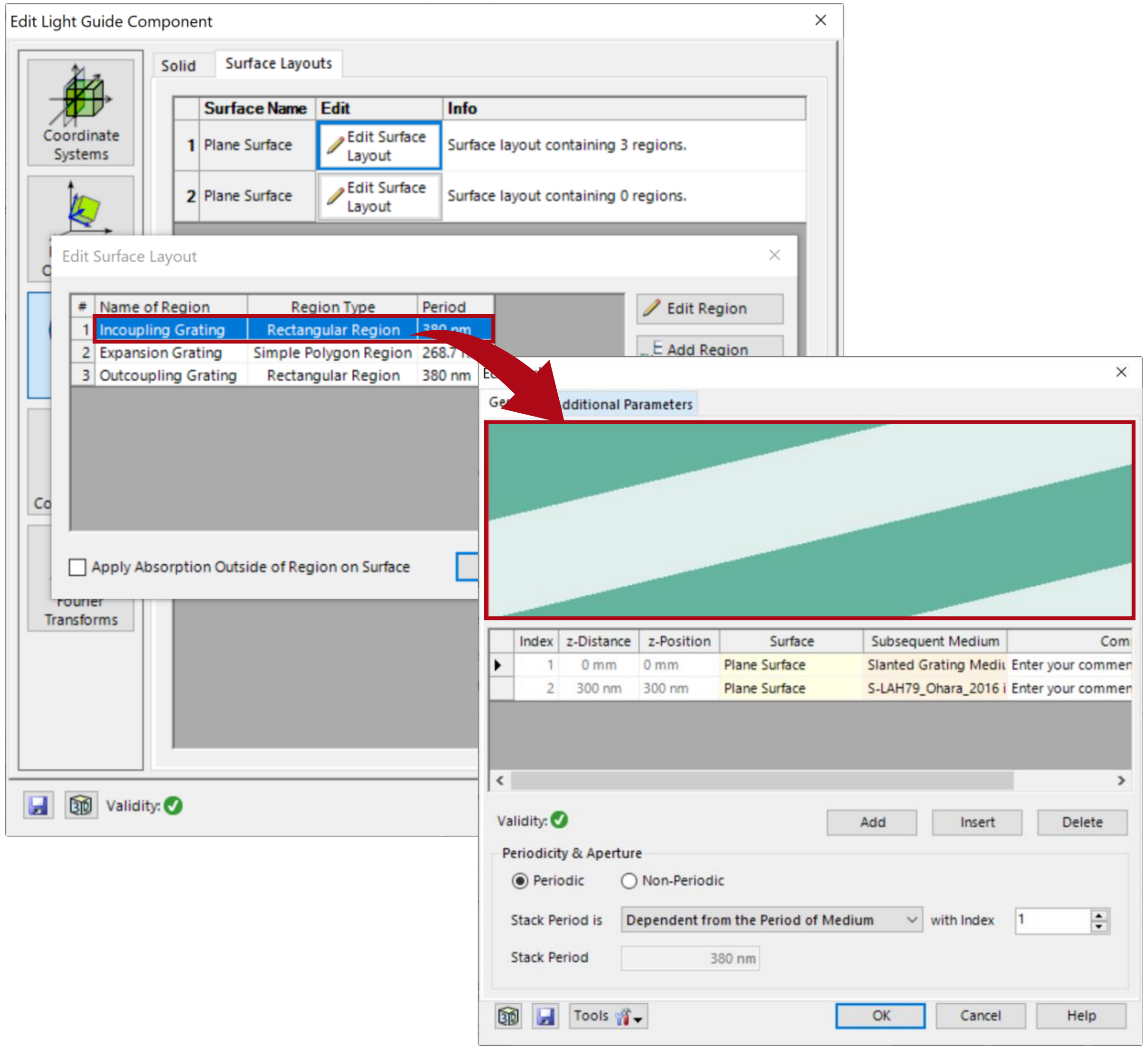


Grating Regions



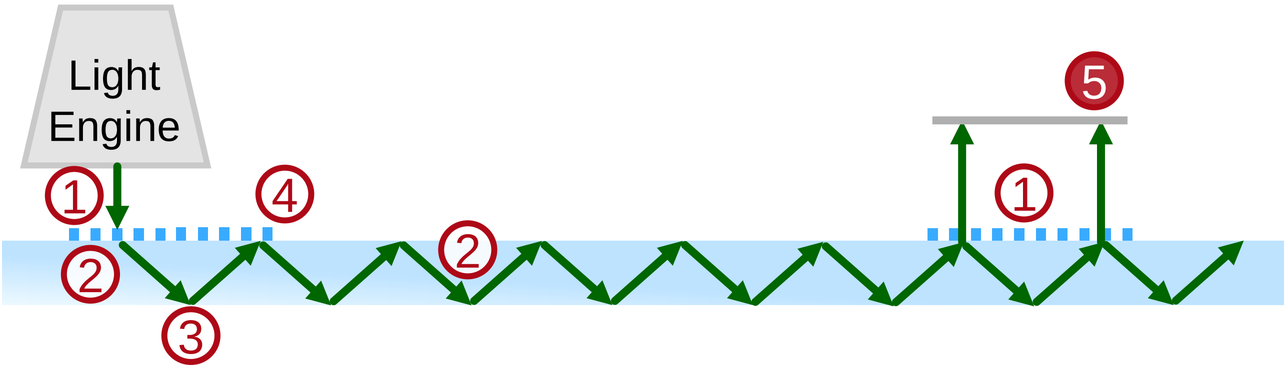
For the incoupler, outcoupler and eye pupil expander (EPE) real gratings were used. Their Rayleigh matrices and the corresponding efficiencies are calculated rigorously with FMM (RCWA). You can find more information on how to set this up under:

[How to Set Up a Lightguide with Real Grating Structures]



Connected Modeling Techniques: Detector Eyebox

1. grating (incoupler)
2. free space (propagation inside the glass slab)
3. reflection at surfaces of glass slab
4. region boundaries (boundaries of a grating)
5. detector (uniformity measurement in eye box)



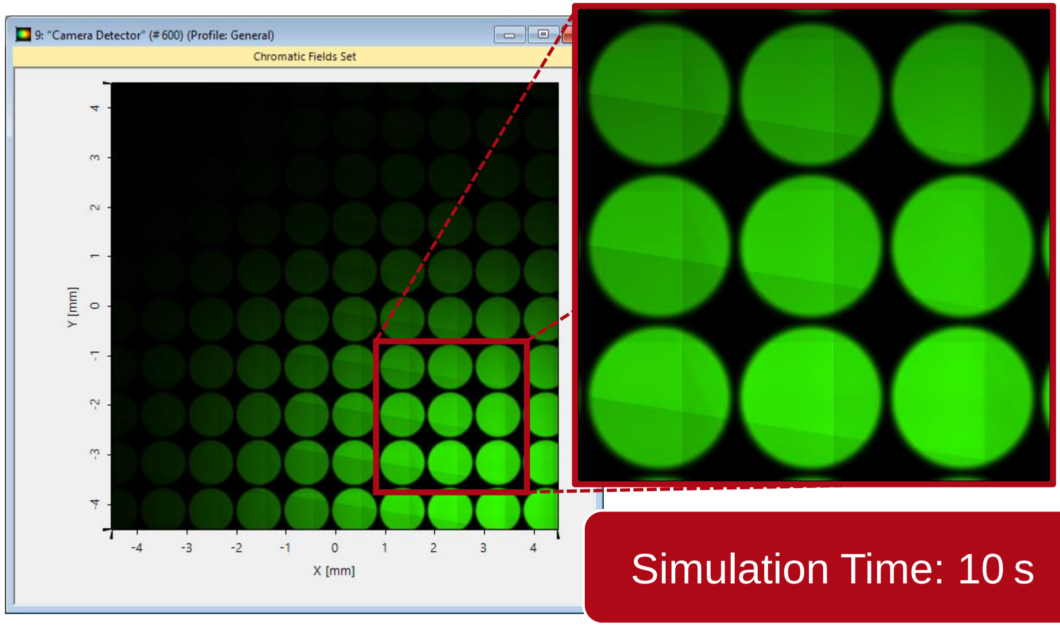
Full flexibility in detector modeling:

- Radiometry, e.g., irradiance per FOV or all FOVs, radiance
- Photometry, e.g., illuminance per FOV or all FOVs, luminance
- Uniformity measures

Diffraction Inside Waveguide: Irradiance Eyebox

1 grating (incoupler)
2 free-space (propagation inside the glass slab)

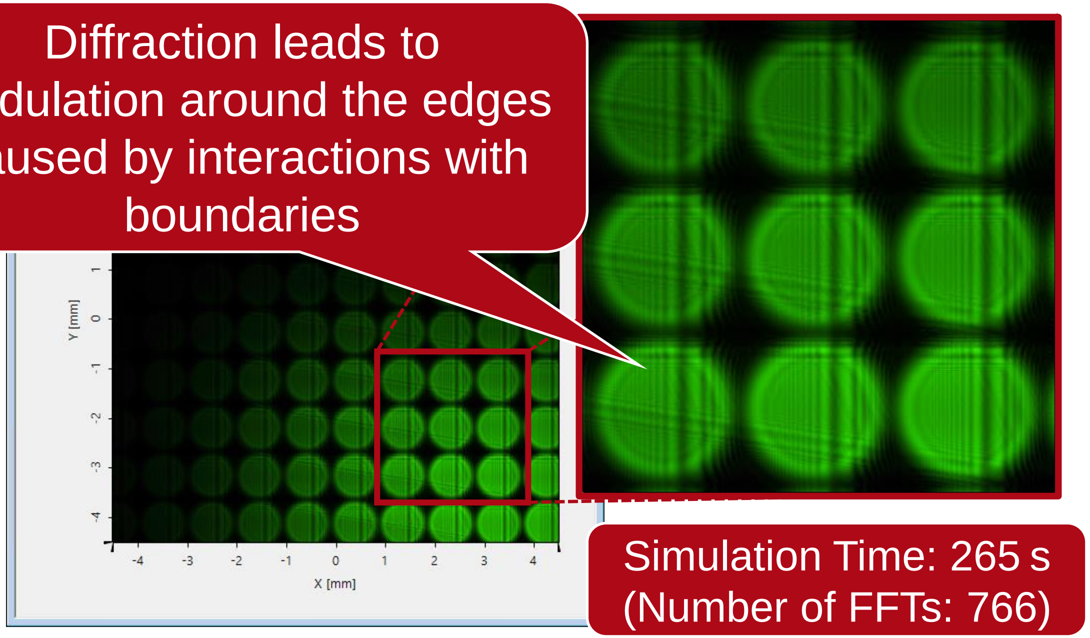
result without diffraction:



Simulation Time: 10 s

Methods	Preconditions	Accuracy	Speed	Comments
Fourier Domain Techniques	None	High	High	Rigorous mathematical reformulation of RS integral
Geometric Propagation	**Low diffraction**	High	Very high	Neglects diffraction effects
	Otherwise	Low	Very high	

result with diffraction:



Diffraction leads to modulation around the edges caused by interactions with boundaries

Simulation Time: 265 s (Number of FFTs: 766)

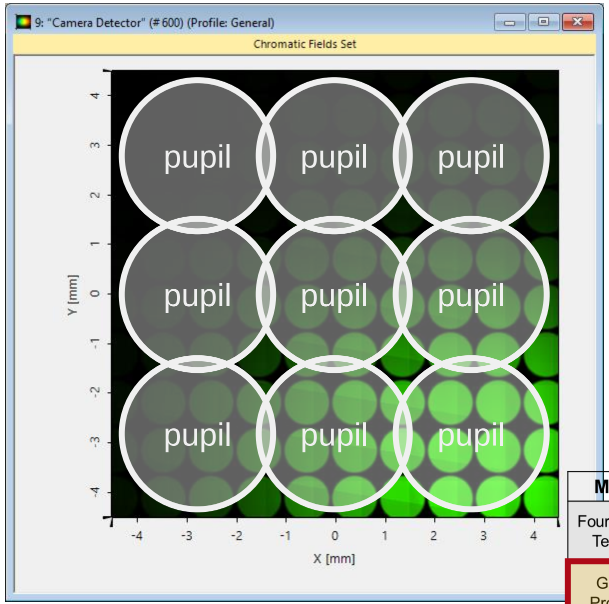
Methods	Preconditions	Accuracy	Speed	Comments
Fourier Domain Techniques	None	High	High	Rigorous mathematical reformulation of RS integral
Geometric Propagation	**Low diffraction**	High	Very high	Neglects diffraction effects
	Otherwise	Low	Very high	

Diffraction Inside Waveguide: Uniformity Measurement

1 grating (incoupler)

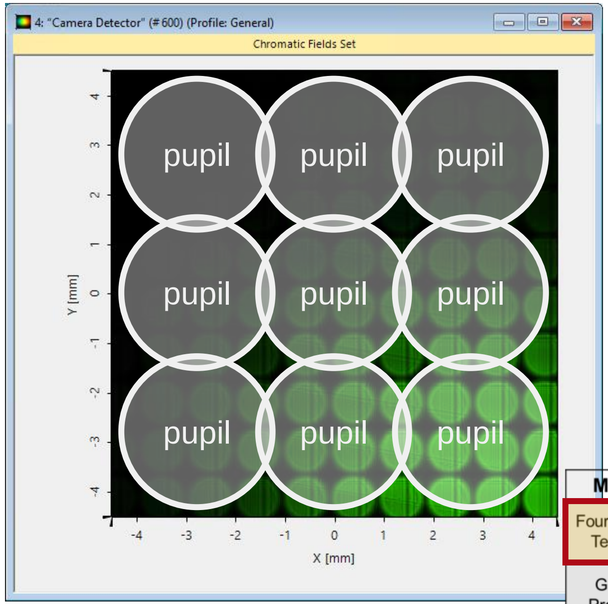
2 free-space (propagation inside the glass slab)

result without diffraction:



Methods	Preconditions	Accuracy	Speed	Comments
Fourier Domain Techniques	None	High	High	Rigorous mathematical reformulation of RS integral
Geometric Propagation	**Low diffraction**	High	Very high	Neglects diffraction effects
	Otherwise	Low	Very high	

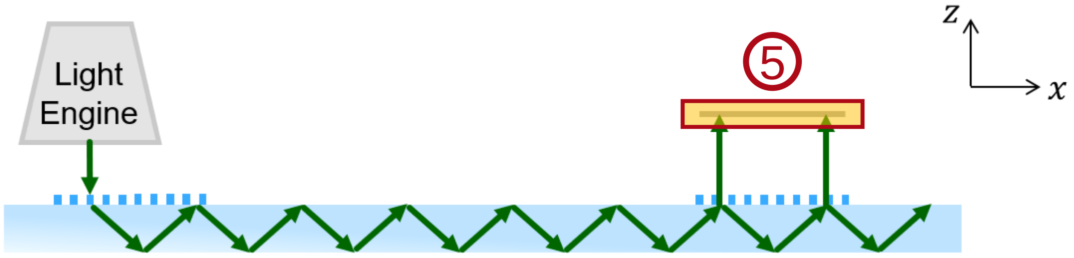
result with diffraction:

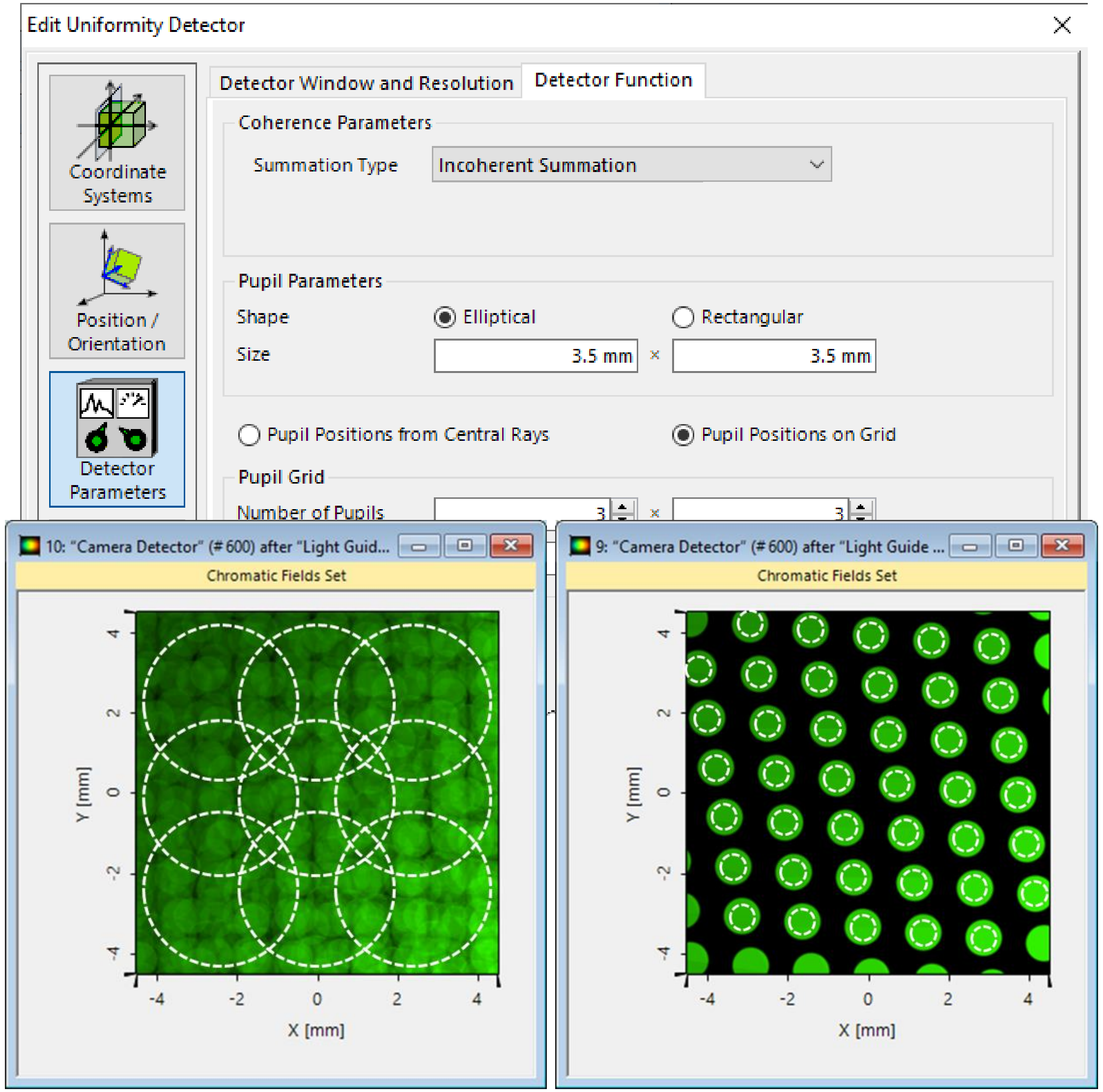


Methods	Preconditions	Accuracy	Speed	Comments
Fourier Domain Techniques	None	High	High	Rigorous mathematical reformulation of RS integral
Geometric Propagation	**Low diffraction**	High	Very high	Neglects diffraction effects
	Otherwise	Low	Very high	

Conclusion: Due to a similar pattern and distribution in the eye box for both results, which is caused by the general function of the waveguide in combination with the averaging inside the chosen pupils, **diffraction can be neglected** for the optimization of the (lateral) uniformity. Hence, the accuracy of the faster technique is sufficient for this purpose.

Uniformity Detector





The *Uniformity Detector* is used to measure the lateral uniformity. This detector evaluates the impinging intensity in configured local areas, which are called pupils. Each pupil is defined by its size ($dx \times dy$) and shape, which can be set either elliptical or rectangular.

You can find more information on how to set this up under:

Uniformity Detector for Lightguide Systems

Lightguide Design Workflow

General Workflow with Additional Guidance

1. Configuration of basic optical lightguide setup (not part of this use case)

2. Application of the *Footprint and Grating Analysis* tool including the generation of the optical setup equipped with all requirements for the parameter modulation

3. Definition of desired modulation of grating parameters

4. Select variables and define merit functions to optimize the modulated grating parameters.

The starting point is an existing, executable lightguide system, where the basic geometries (desired distances and positioned grating regions) and grating specifications (orientation, period, orders) are already included. This example is taken from:

- Construction of a Light Guide [Use Case]
- Light Guide Layout Design Tool [Use Case]

The real grating structures of the grating regions are configured, a necessary step before applying a continuous or smooth variation of the grating parameters:

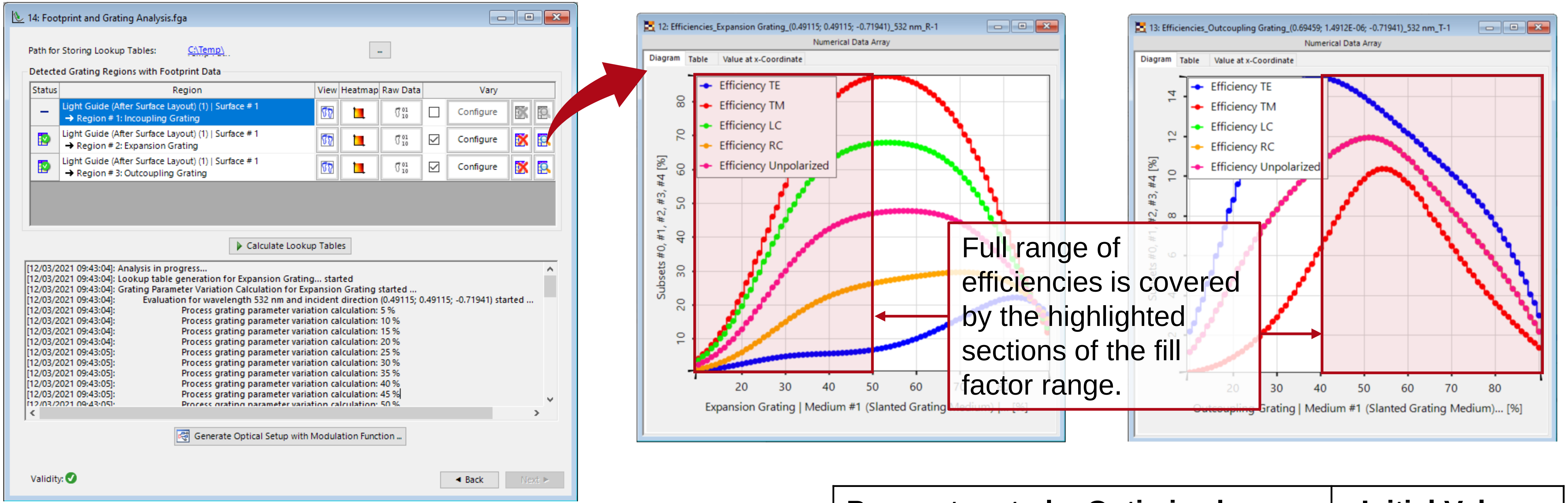
- How to Set Up a Lightguide with Real Grating Structures [Use Case]
- Simulation of 1D-1D Pupil Expander with Real Gratings [Use Case]

The *Footprint and Grating Analysis* tool is used to specify the desired range for the variation of the grating parameters and to pre-calculate the according Rayleigh coefficients for the specific conditions (wavelength and directions). As a next step, an optical setup is generated, where the smooth parameter variation can be defined:

- Footprint Analysis of Lightguides for AR/MR Applications [Use Case]
- Grating Analysis and Smoothly Modulated Grating Parameters on Lightguides [Use Case]

Note:
The grating modulation is defined for individual grating regions.

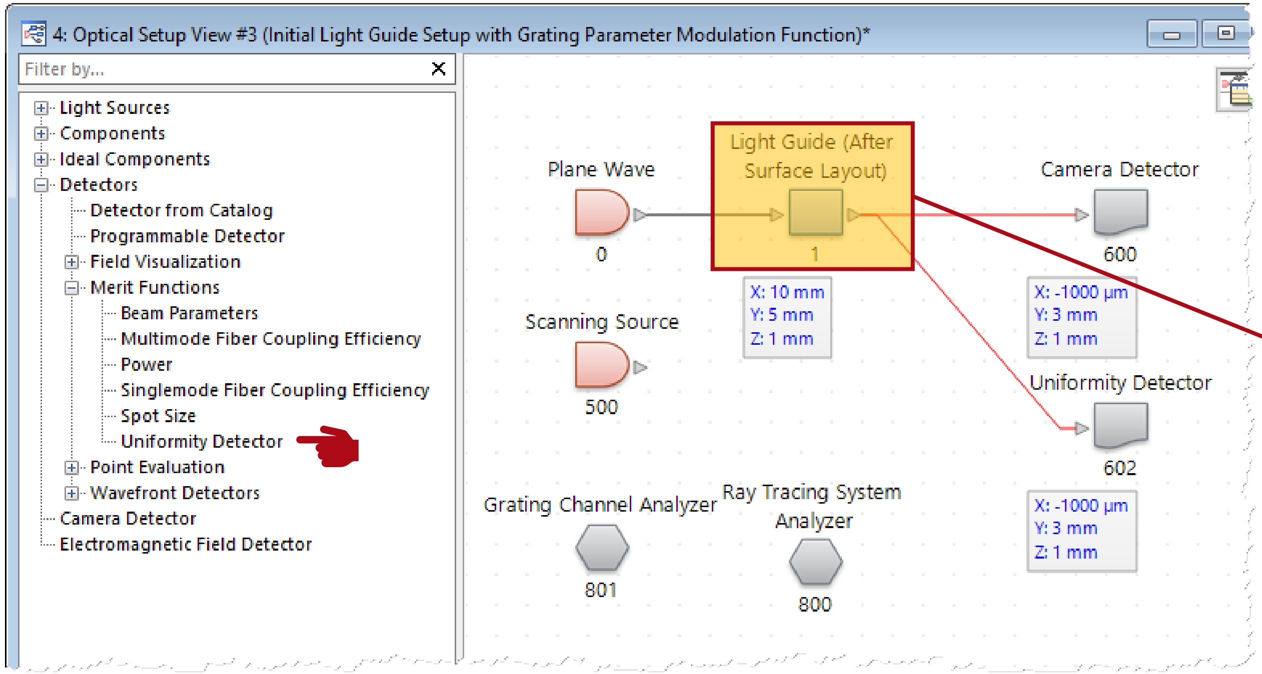
Footprint & Grating Analysis

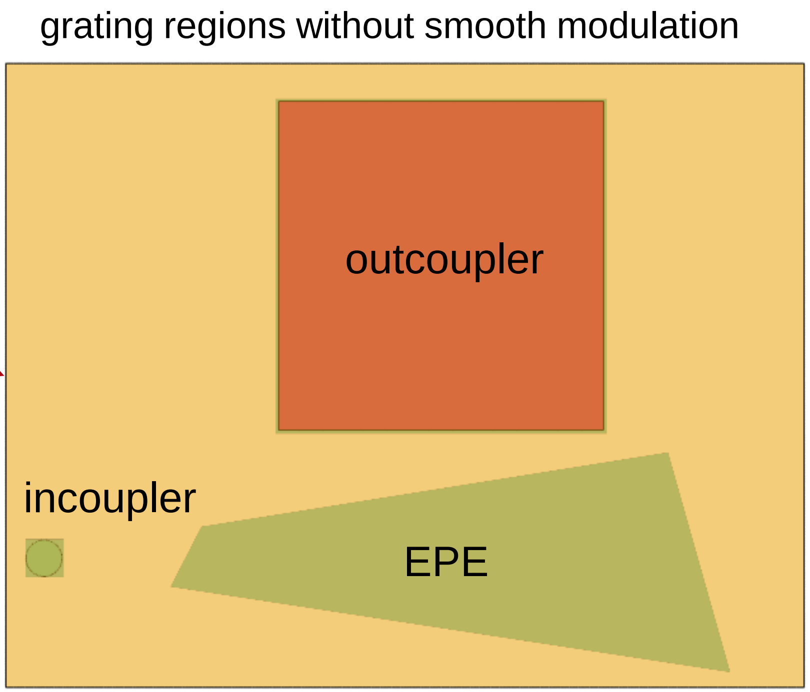


With the help of the *Footprint & Grating Analysis Tool*, the grating characteristics (complex valued) are pre-calculated and stored in lookup tables for a specified range of the chosen parameter (e.g. fill factor). The initial range of the fill factor is chosen according to the range of available efficiency modulation. More information can be found in: [Grating Analysis and Smoothly Modulated Grating Parameters on Lightguides]

Parameters to be Optimized	**Initial Values**
varied range of fill factor (EPE)	10% – 50%
varied range of fill factor (outcoupler)	40% – 90%

Generation of the Initial System

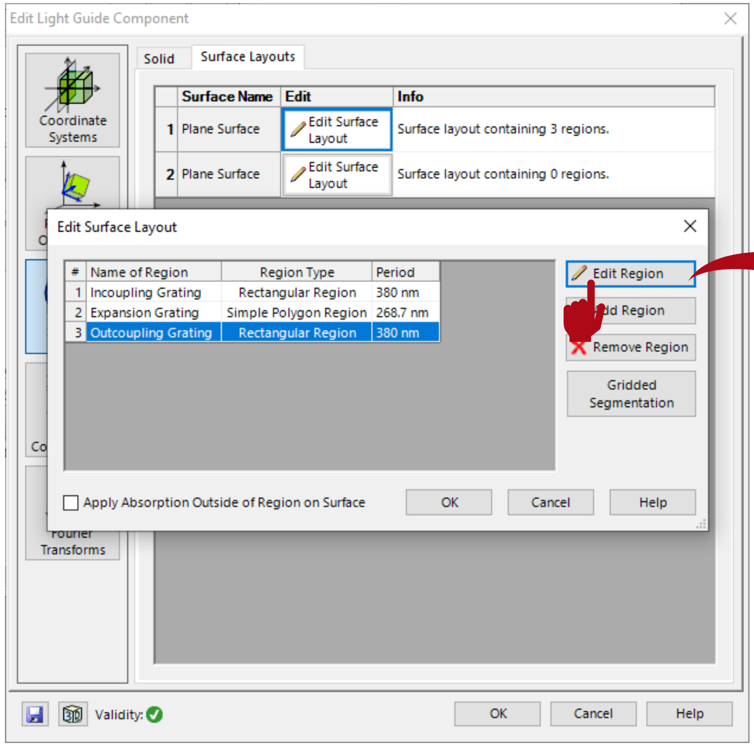


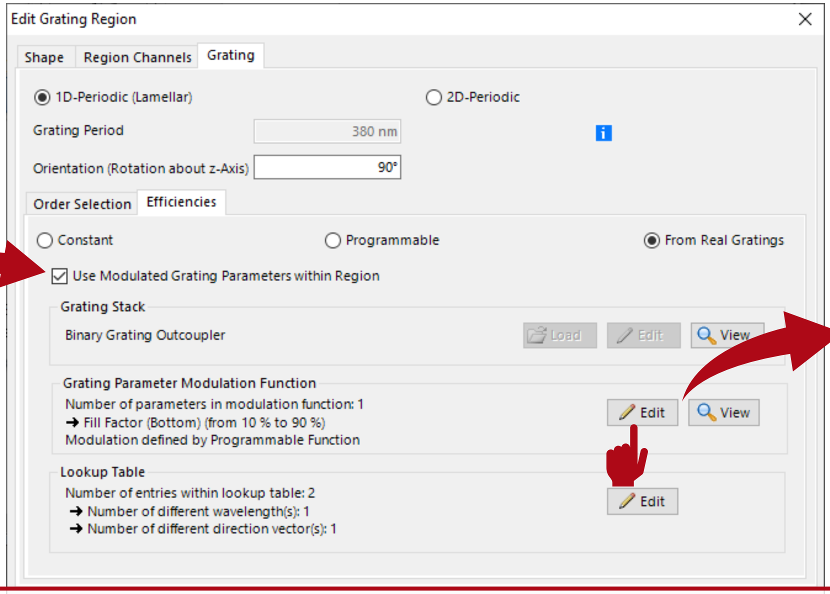


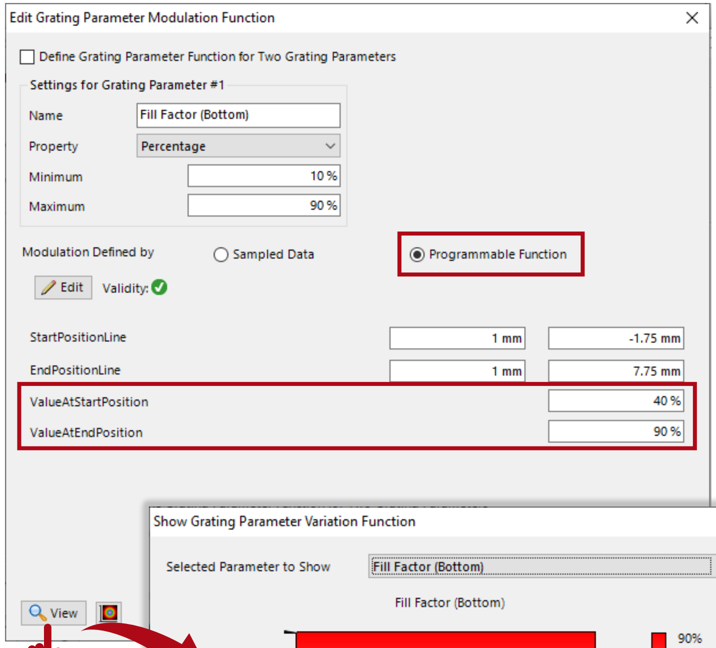
- A lightguide setup with a so-called grating parameter modulation function is generated from the *Footprint & Grating Analysis Tool* (including the grating characteristics).

- The *Uniformity Detector* is used to define the merit function for the optimization.

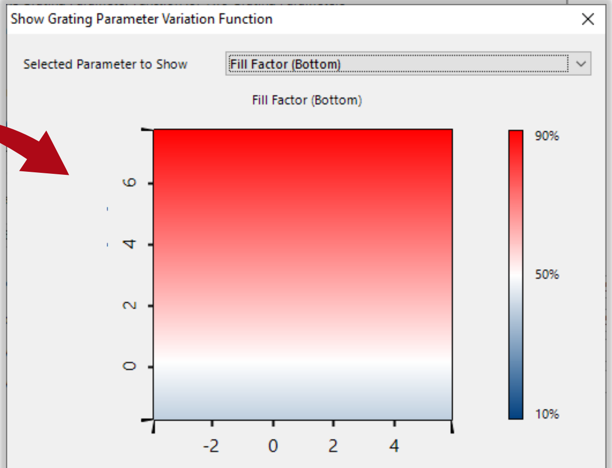
Define Modulation Function of the Grating Region







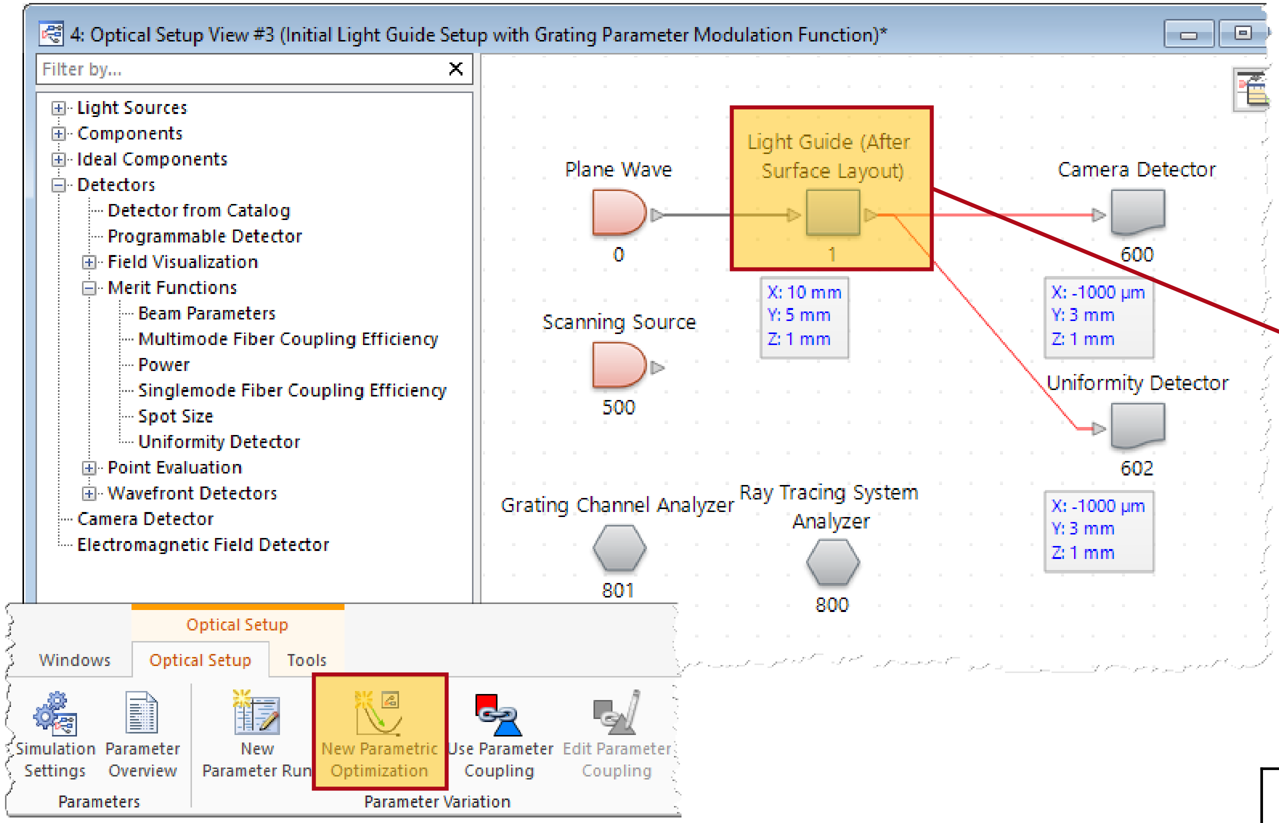
See the full use case for setting up a smooth modulation based on mathematical function: [Grating Analysis and Smoothly Modulated Grating Parameters on Lightguides]



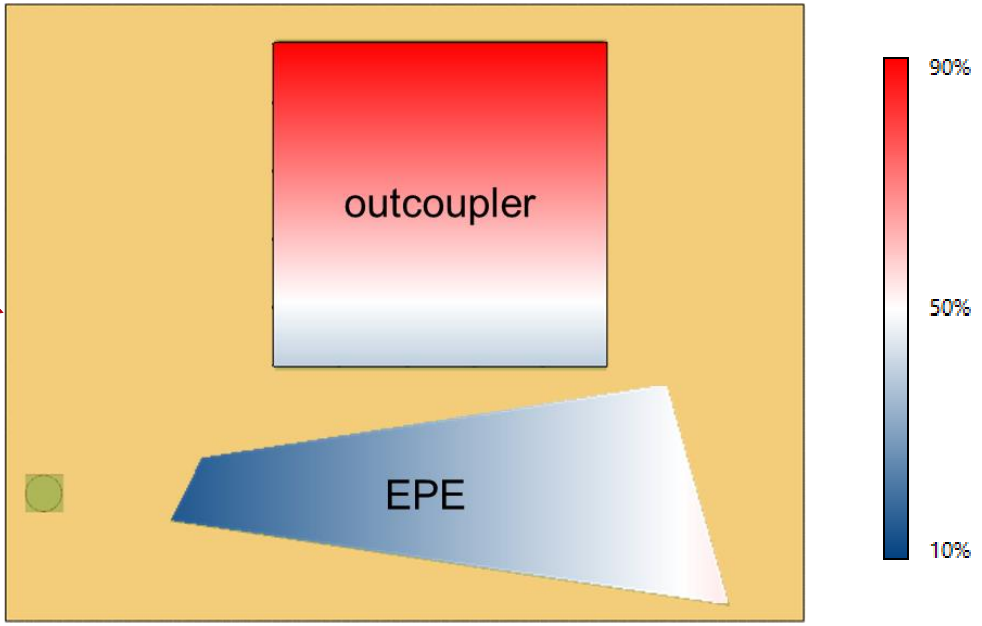
linear modulation for outcoupler

- Open the edit dialogue of the region in the lightguide component; the grating characteristics and the lookup tables are stored in the grating regions.
- Edit the *Grating Parameter Modulation Function* so that it's defined as a programmable function, the intended linear modulation of the grating parameters is defined by the value at the start and end position (left to right border for EPE & top to bottom for the outcoupler).

Generation of the Initial System



grating regions after smoothly modulation

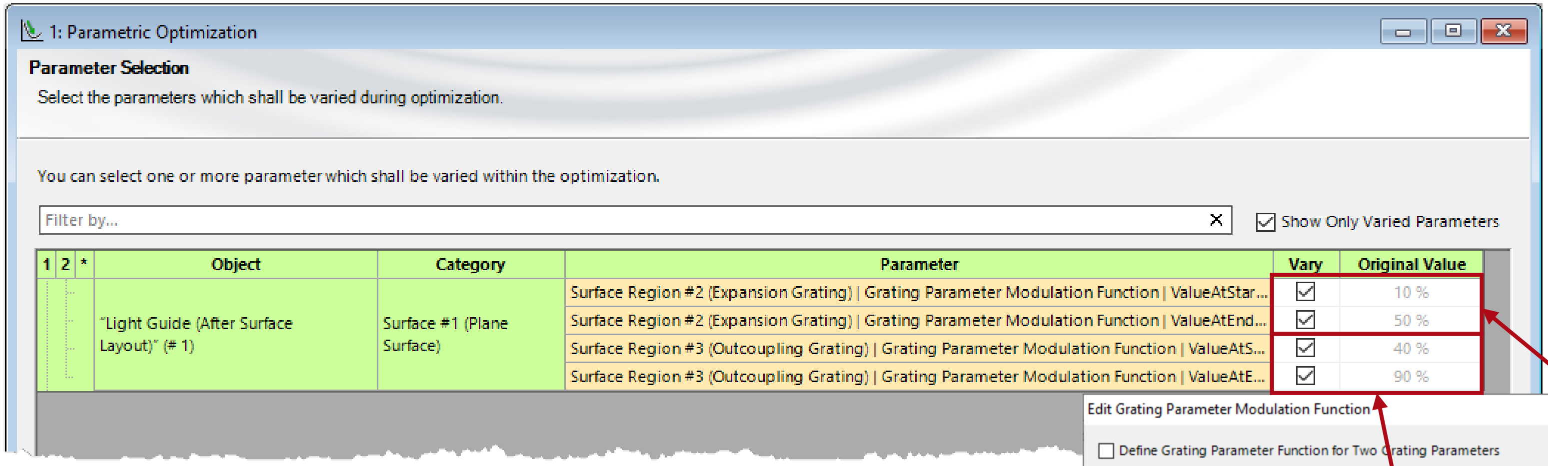


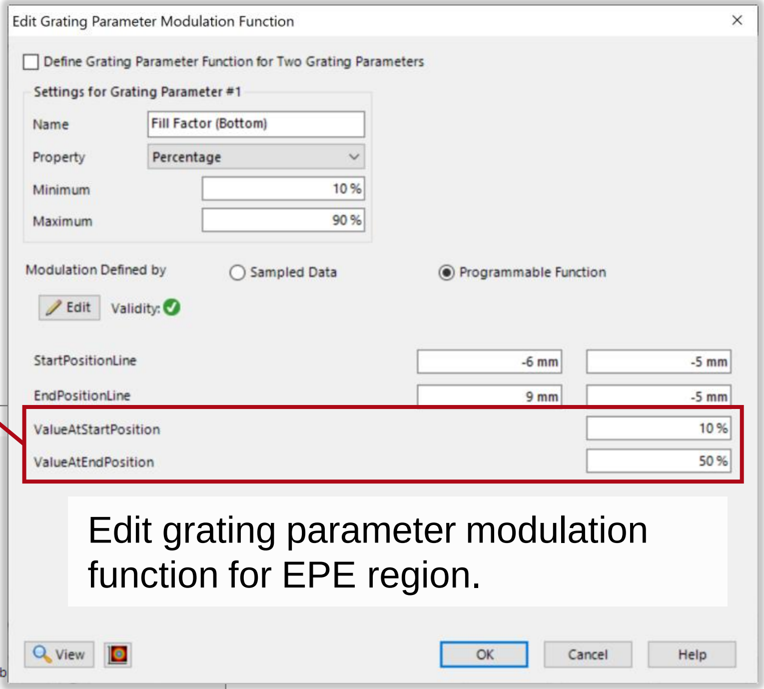
After defining the modulation for the EPE and outcoupler respectively, the *Parametric Optimization* document can be started via *Optical Setup > New Parameter Optimization.*

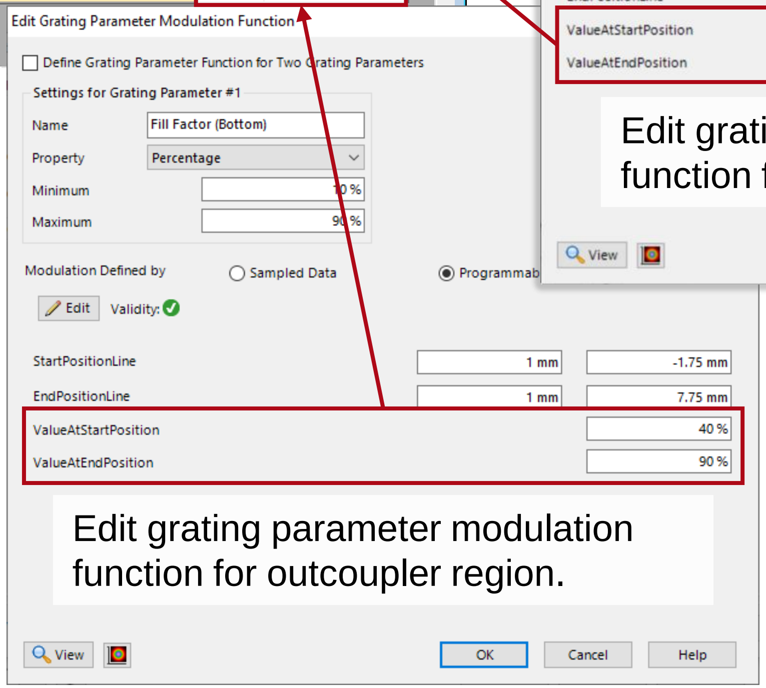
Parameters to be Optimized	**Initial Values**
varied range of fill factor (EPE)	10% – 50%
varied range of fill factor (outcoupler)	40% – 90%

Optimization

Optimization Settings – Select Parameters

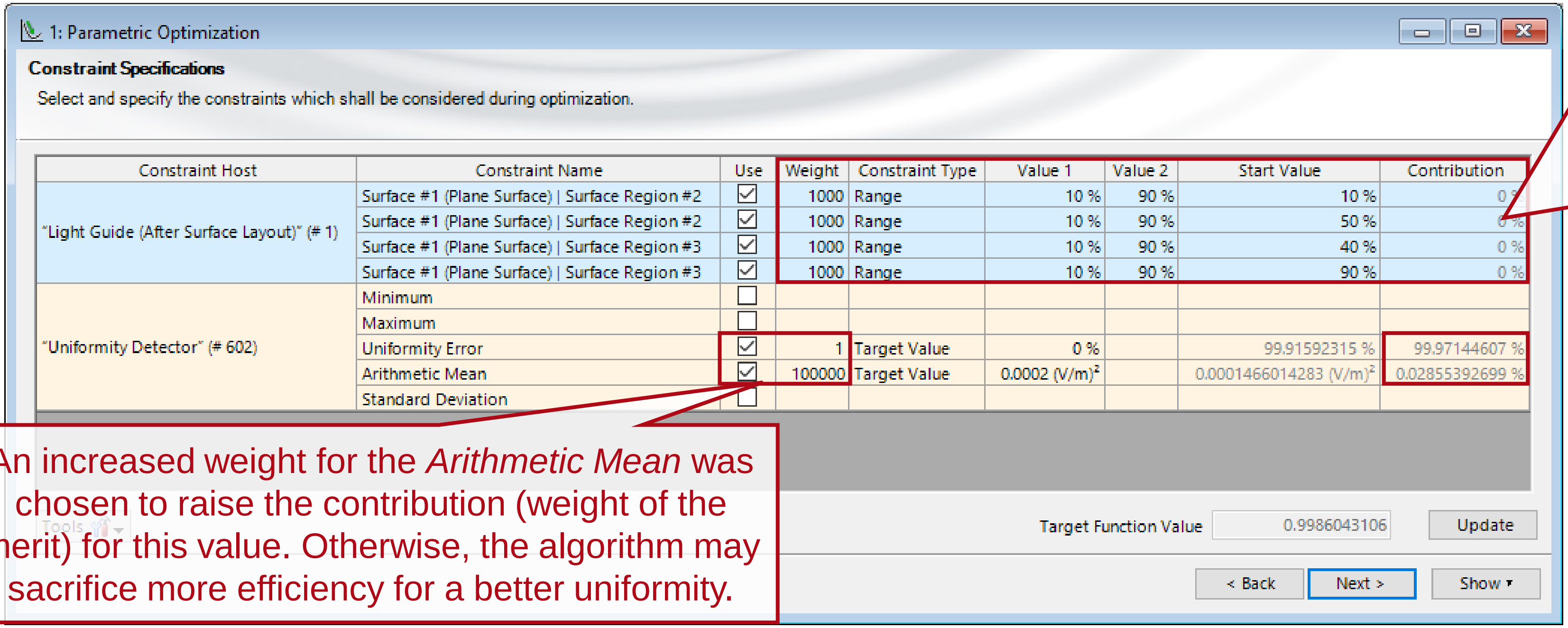






- Select the value of the fill factor at the start and end positions of the modulation for the EPE and outcouple gratings, respectively.
- The initial values are automatically filled in according to the settings in the modulation function editor.

Optimization Settings – Specify Constraints



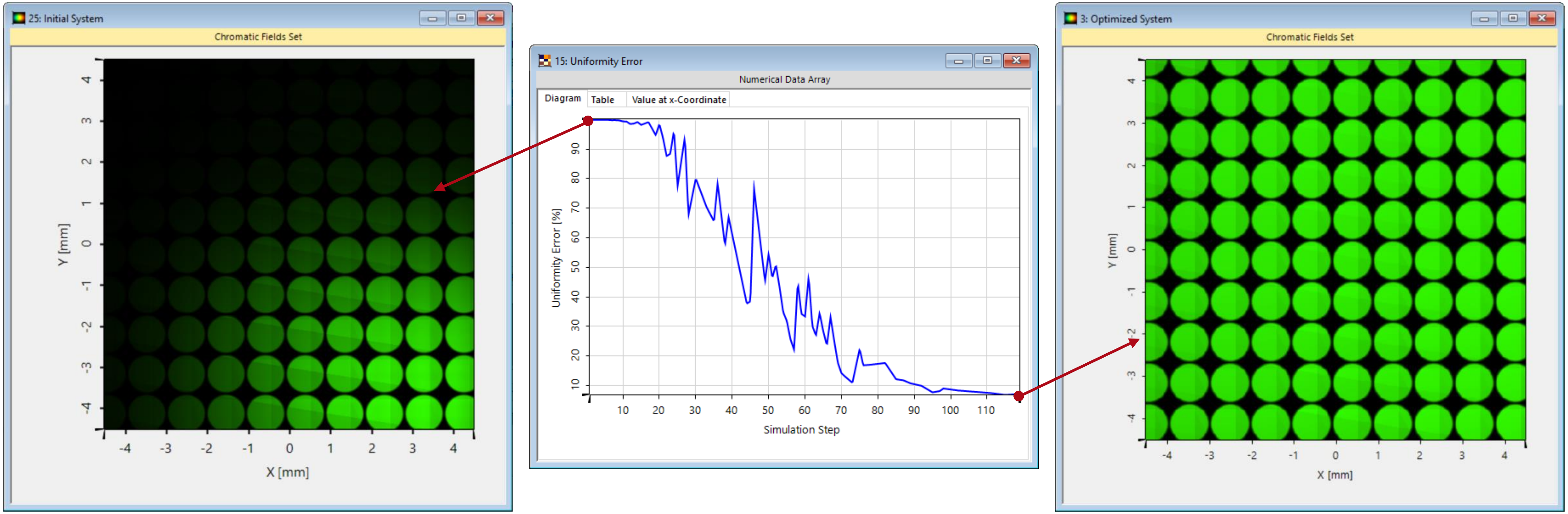
An increased weight for the *Arithmetic Mean* was chosen to raise the contribution (weight of the merit) for this value. Otherwise, the algorithm may sacrifice more efficiency for a better uniformity.

In this optimization, the initial values are quite close to the limits of the available range. Hence, the weights for the *Range* constraints are increased, in order to ensure that the values in the optimization stay inside the given range (the downhill-simplex does not provide hard boundaries for the parameter ranges). And because the *Start Values* are inside the allowed value range, the associated *Contribution* is regarded as 0%.

merit function	Values
Uniformity Error	0%
Arithmetic Mean	0.0002(V/m)²

- Define available range of the variables (here: fill factors of EPE and outcoupler).
- In order to achieve a low uniformity error with acceptable intensity distribution, the target value for the uniformity error is set to 0%, and a target value of the arithmetic mean is specified.
- By defining the weight value for the merit functions, the contribution (relevance or priority) for the optimization can be adapted.

Optimization Result



initial system

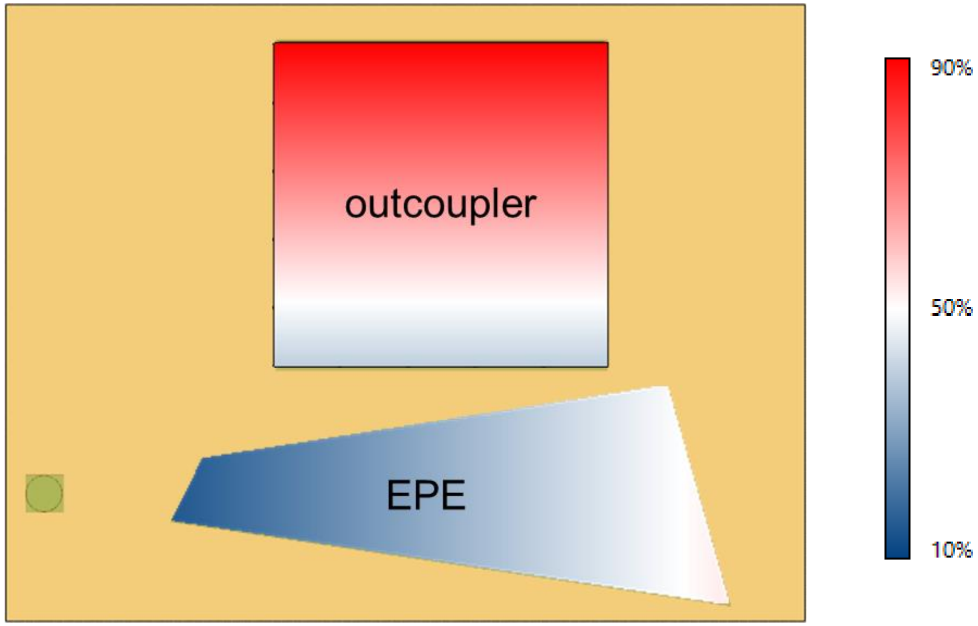
merit function	Values
Uniformity Error	99.92%
Arithmetic Mean	1.47E-04 $(V/m)^2$

optimized system

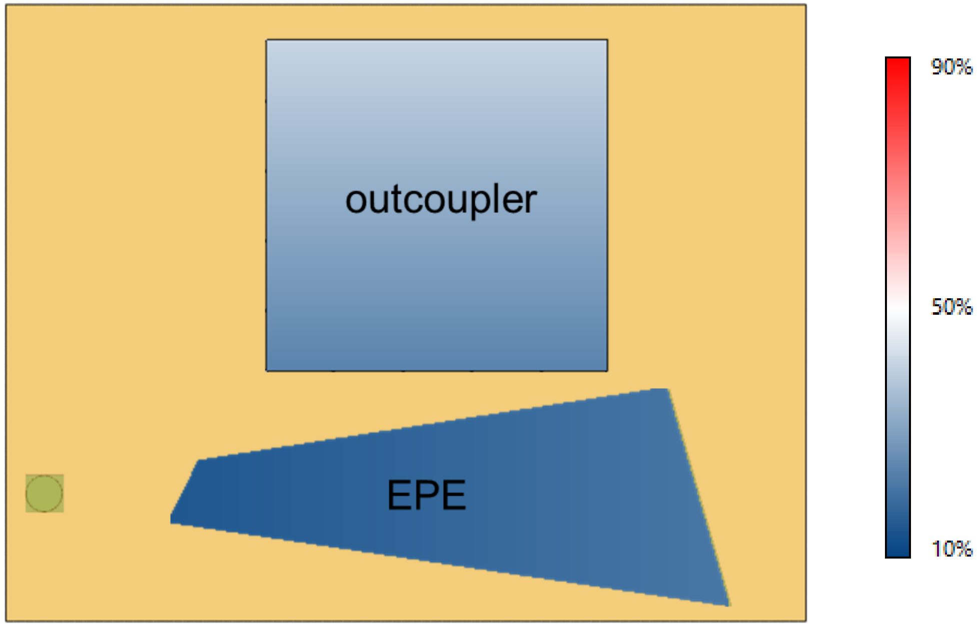
merit function	Values
Uniformity Error	6.84%
Arithmetic Mean	1.40E-04 $(V/m)^2$

Optimization Result

Initial System

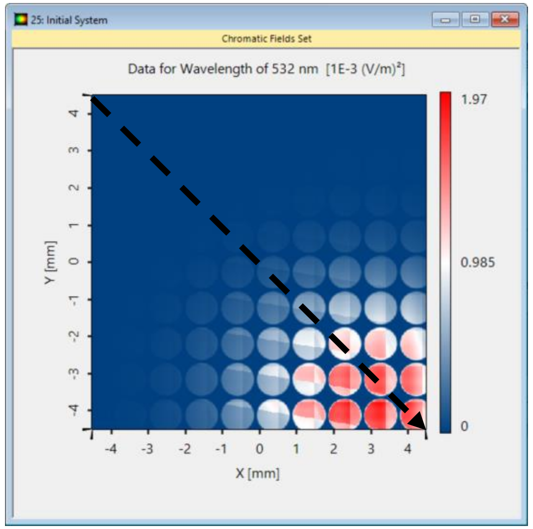


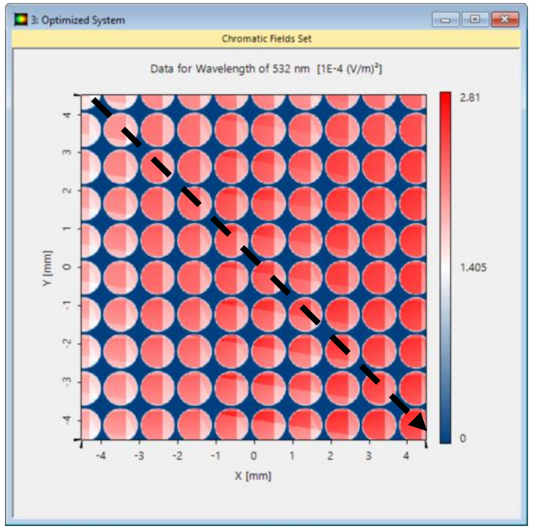
Opt. System



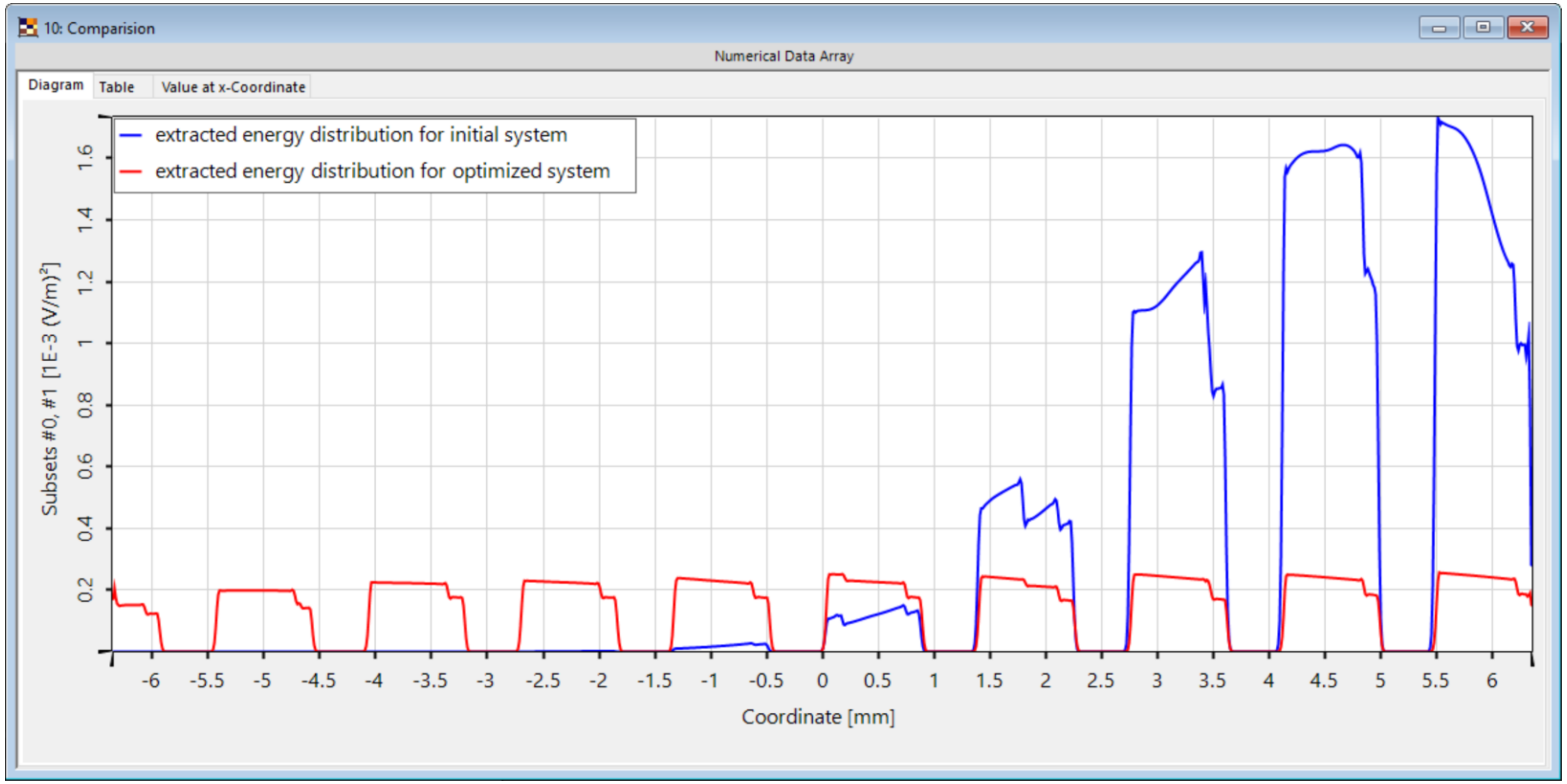
Parameters	Initial Values	Optimized Values
varied range of fill factor (EPE)	10% – 50%	10.0% – 17.1%
varied range of fill factor (Outcoupler)	40% – 90%	24.1% – 41.4%

Optimization Uniformity vs. Energy Density





The line scan through the eyebox for the initial and optimized systems reveals the difference in uniformity and local energy density.



Document Information

title	Fast Optimization of Grating-Based Waveguides Enabled by Efficient Single-Platform Interoperability
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software edition	• VirtualLab Fusion Advanced • Light Guide Toolbox Gold Edition
category	Application Use Case
further reading	• Grating Analysis and Smoothly Modulated Grating Parameters on Lightguides • Uniformity Detector for Lightguide Systems • Light Guide Layout Design Tool • Flexible Region Configuration • How to Set Up a Lightguide with Real Grating Structures