Laser – World of Photonics 2019, München

Physical-Optical Analysis of Lightguide Coupling Setup and Systematic Design Strategy

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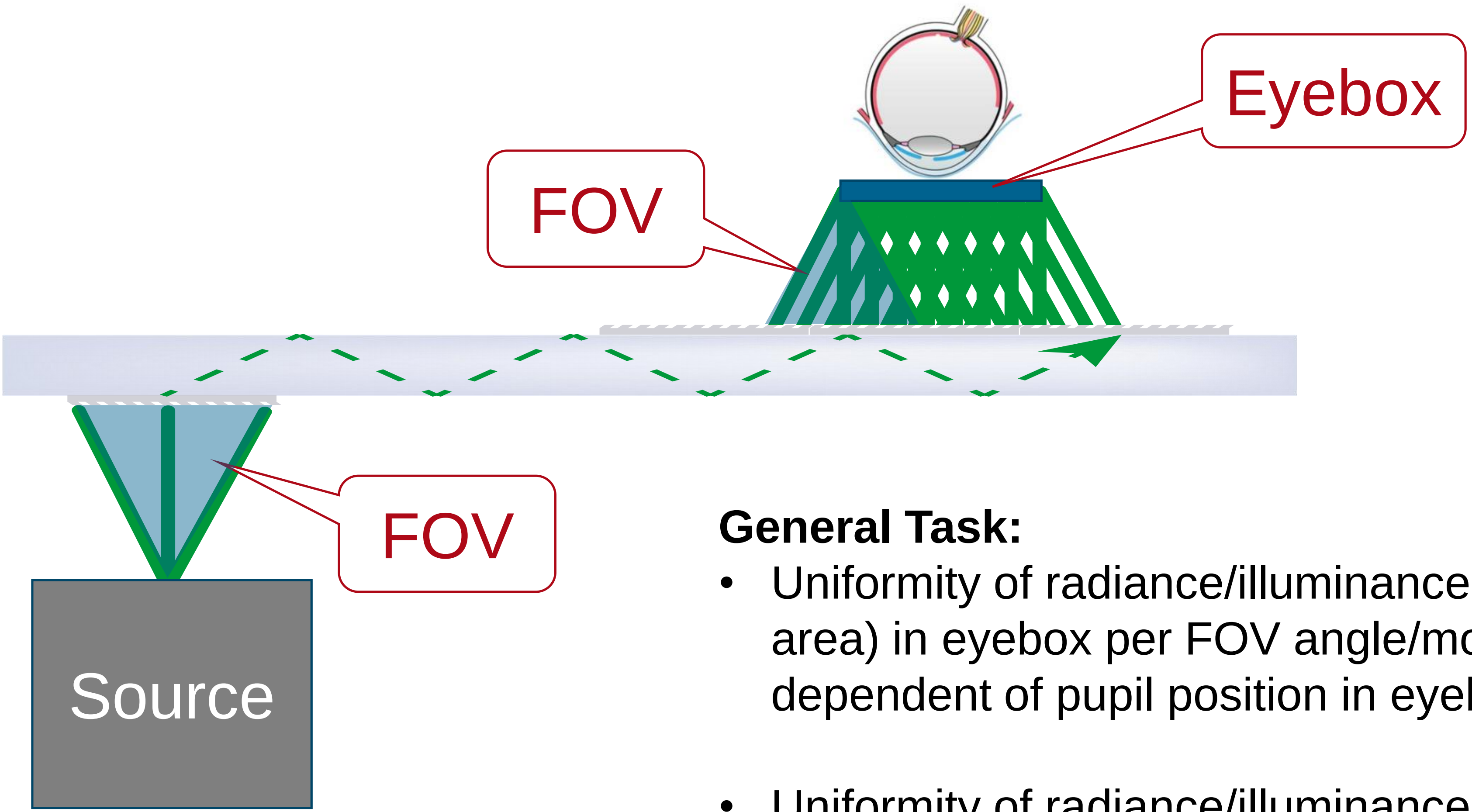
Lightguide Concept: Fundamental Design Criteria

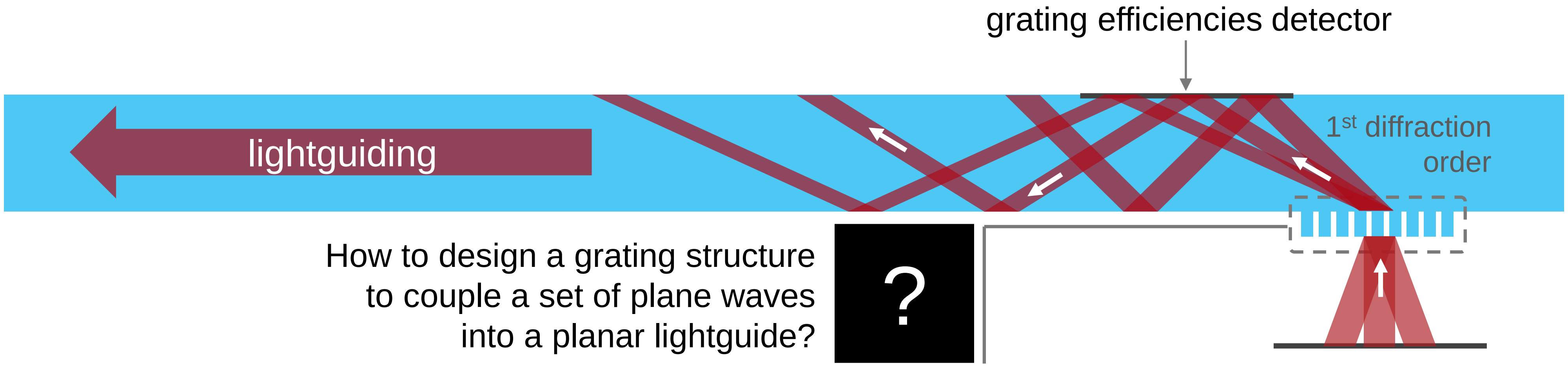


General Task:

- Uniformity of radiance/illuminance (per pupil area) in eyebox per FOV angle/mode dependent of pupil position in eyebox.

- Uniformity of radiance/illuminance per pupil position dependent of FOV angles.

Lightguide Coupling Approach

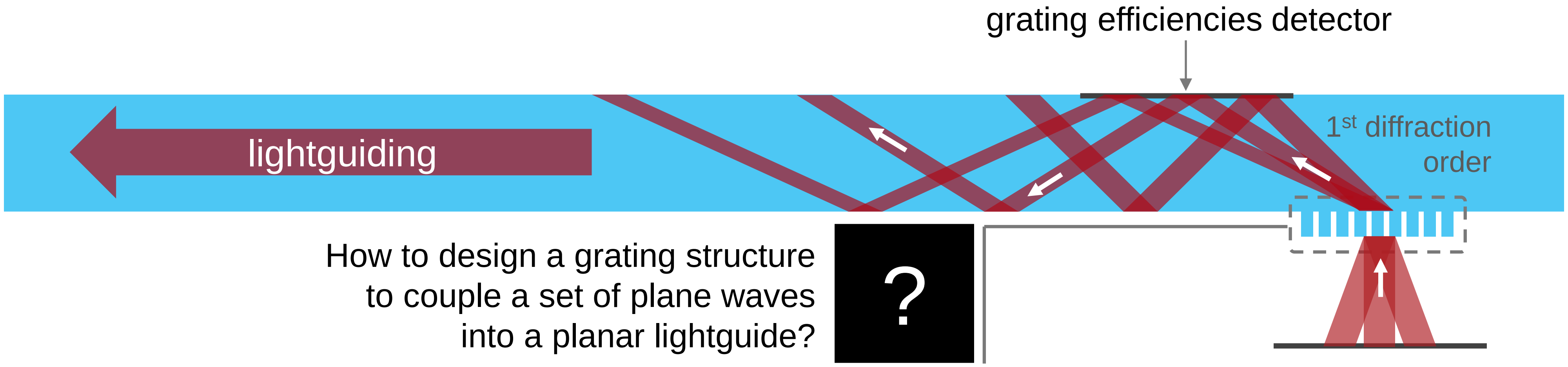


set of plane waves
- field of view (-15..15, -10..10)°
- wavelength 532 nm
- linearly polarized along x-axis

Workflow:
1. Determination of the grating vector (period and orientation) to fulfill the guiding condition of lightguides

2. Designing the structure profile of the incouple grating by an optimization approach

Lightguide Coupling Approach



How to design a grating structure to couple a set of plane waves into a planar lightguide?

set of plane waves

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Consideration of the k-Domain

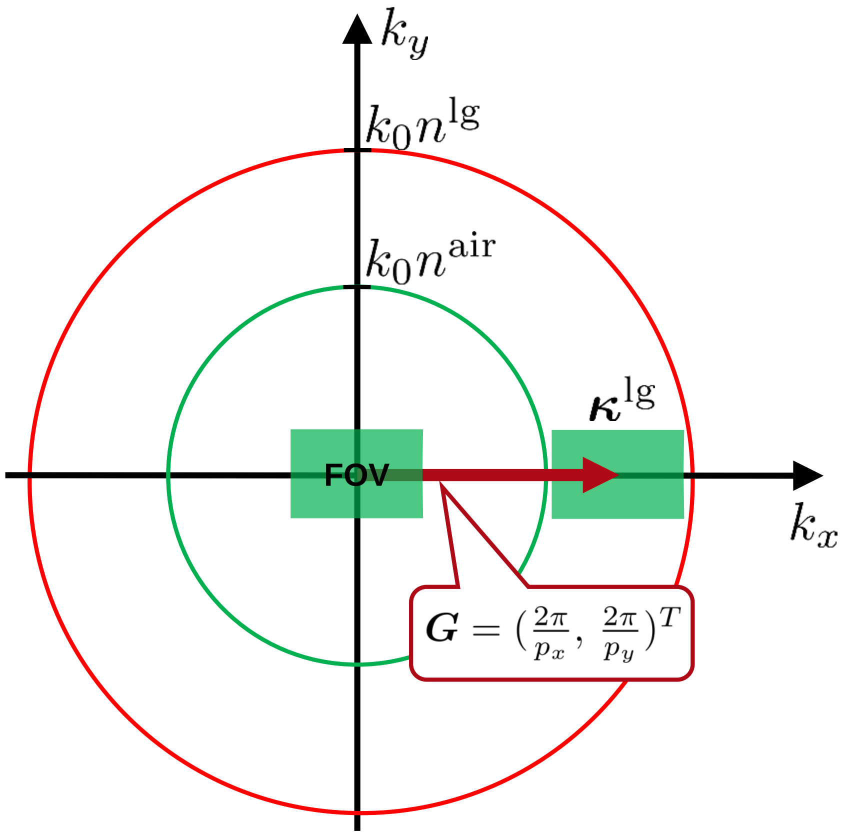
A grating is an elegant component for the coupling because the FOV is shifted in the k-domain under consideration of the grating vector $\boldsymbol{G}$.

$$k_0 n^{\mathrm{lg}} \geq \left|\boldsymbol{\kappa}^{\mathrm{in}} + \boldsymbol{m}\,\boldsymbol{G}\right| \geq k_0 n^{\mathrm{air}}$$

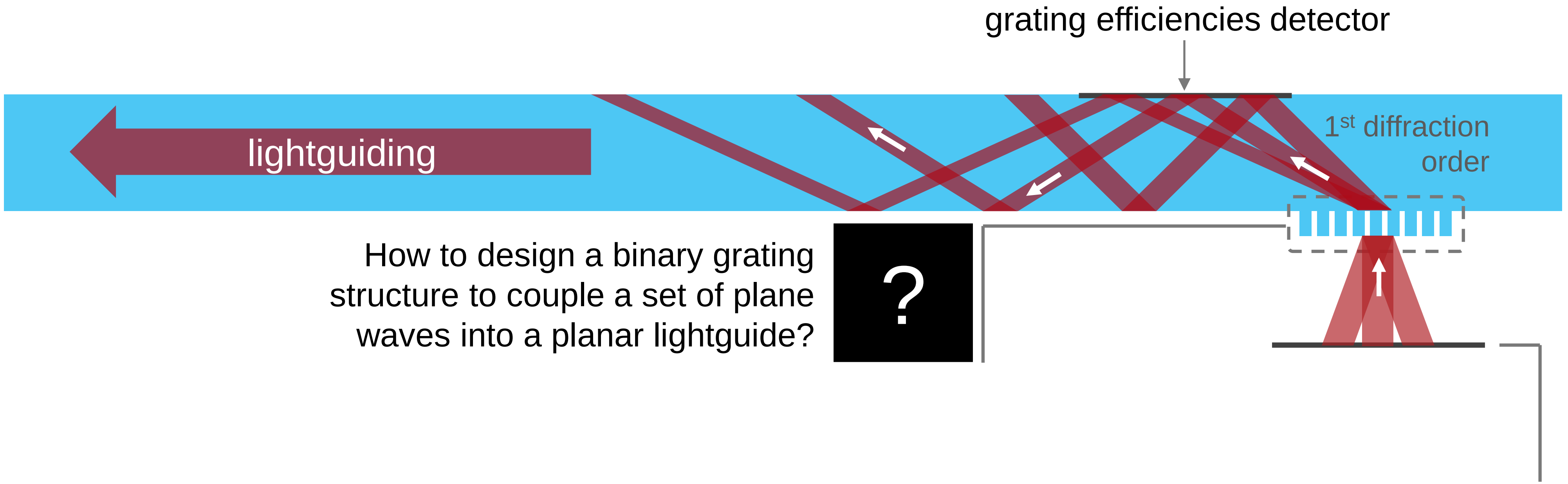
In general, the 2D-periodic grating vector has two components

$$\boldsymbol{G} = \left(\frac{2\pi}{p_x}, \frac{2\pi}{p_y}\right)^T$$

with period along the x- and y-axis (p_x, p_y) and the diffraction order $\boldsymbol{m} = (m_x, m_y)^T$.



Optimization Task: Binary Coupling Grating



How to design a binary grating structure to couple a set of plane waves into a planar lightguide?

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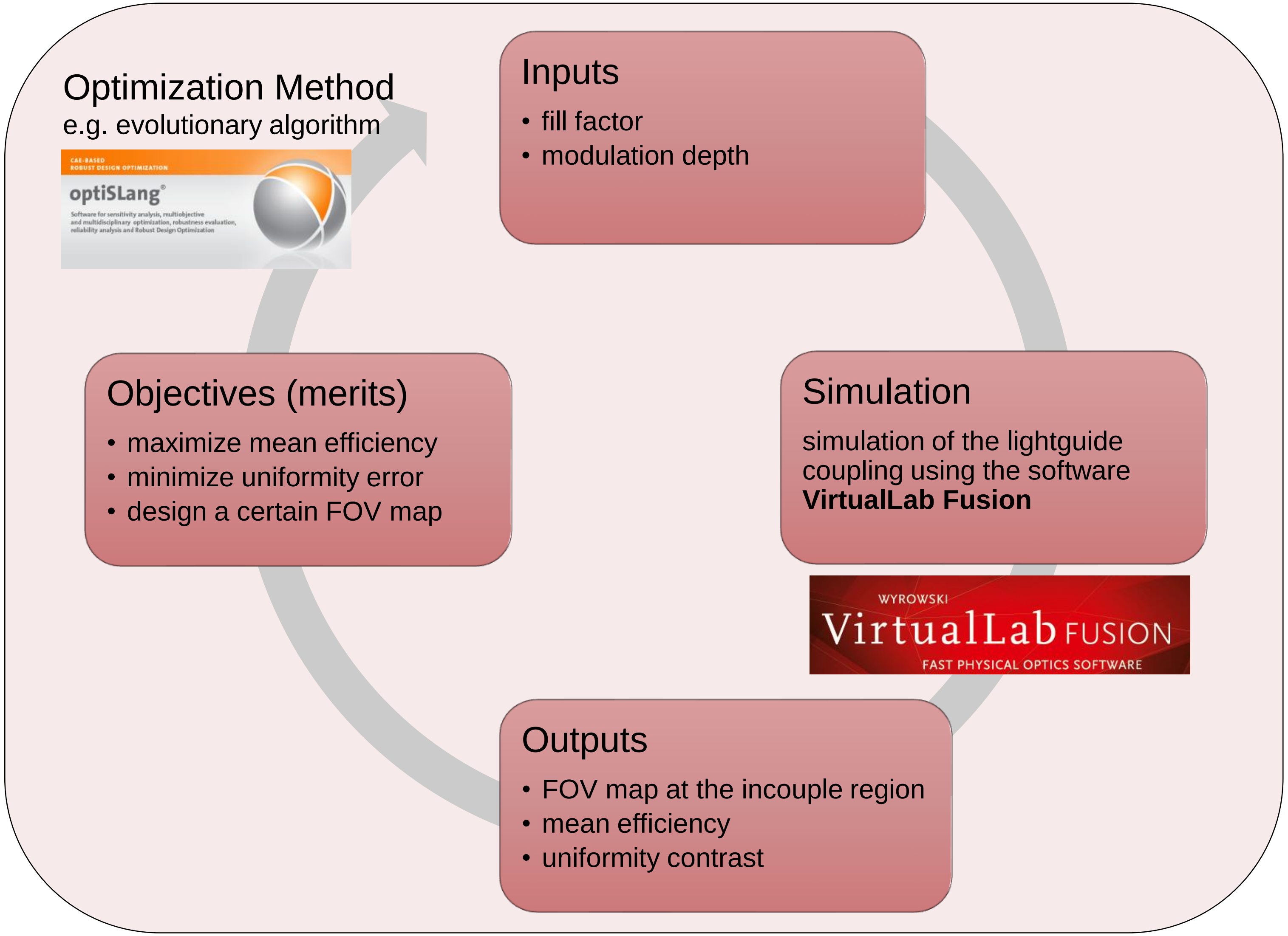
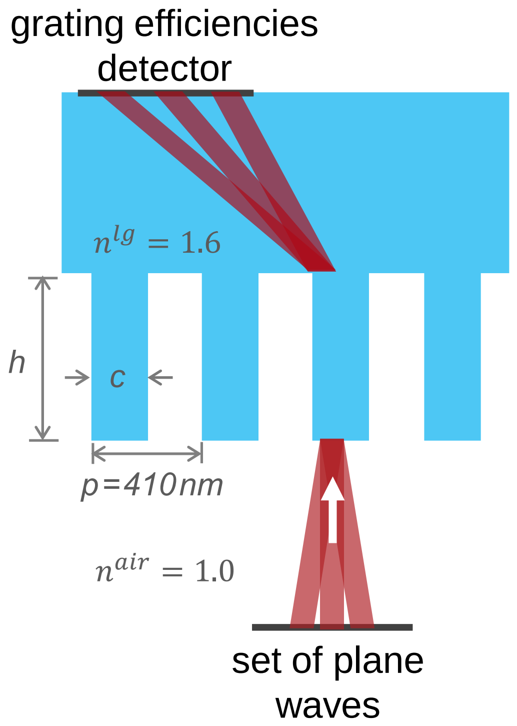
1. Determination of the grating vector (period and orientation) to fulfill the guiding condition of lightguides
2. Designing the structure profile of the incouple grating by an optimization approach

Optimization Workflow

- the following optimization workflow is applied to design a certain grating for a specific lightguide coupling:
  1. Define the inputs and their ranges, start with a reference input combination
  2. Perform the optimization with several simulations
  3. Calculate the corresponding outputs
  4. Evaluation of the defined objectives
  5. Next iteration with new inputs
- the optimization algorithm stops after certain iterations and/ or when no more improvement of the objectives can be achieved



Simulation Results and Configuration of the Merit Function



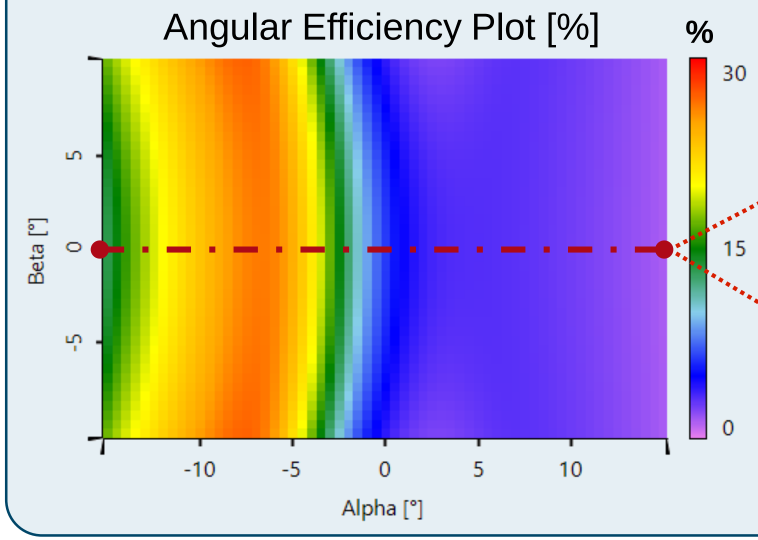
Inputs

- variation of the **fill factor** c/p with the slit width c and the period p
  - ➢ **0.1% to 99.9%**
- variation of the **modulation depth** h
  - ➢ **50 nm to 1500 nm**

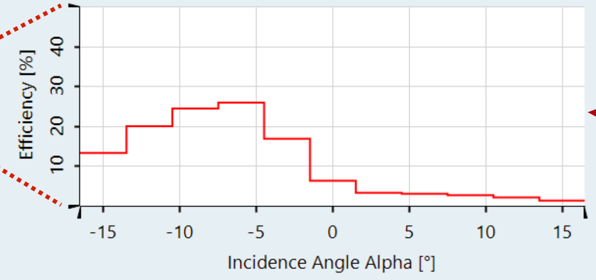
Initial Configuration of Grating	
fill factor	50.00%
modulation depth	400.00 nm
period	410 nm
operating order	1st transmitted

to be varied

Detector Result: Grating Efficiencies

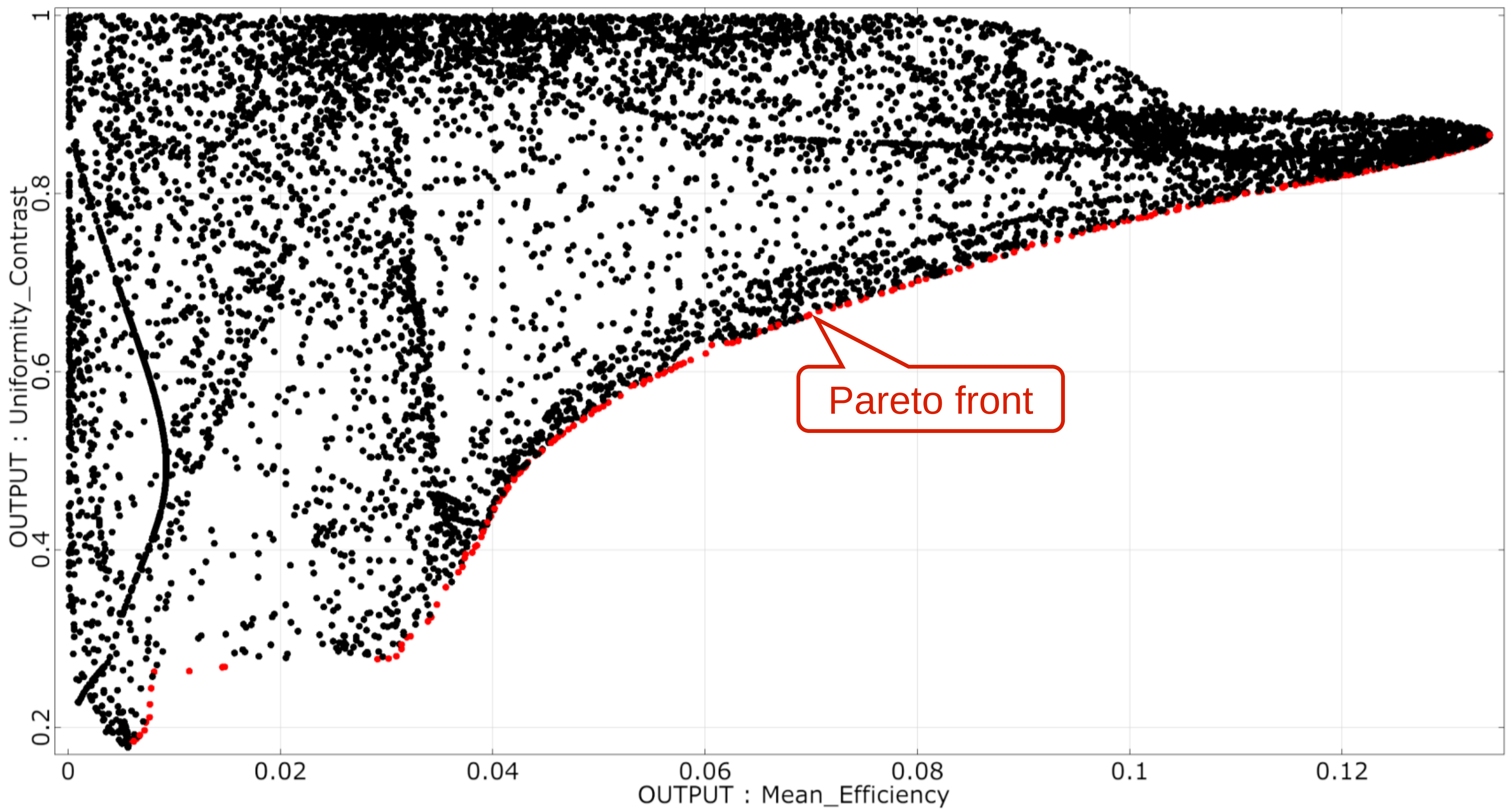


Mean Efficiency 10.96%
Uniformity Contrast 89.45%



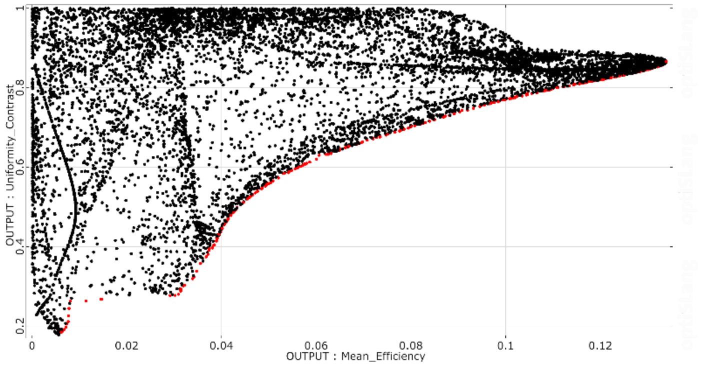
a roughly sampled evaluation of the incidence angles along the period is sufficient for the optimization

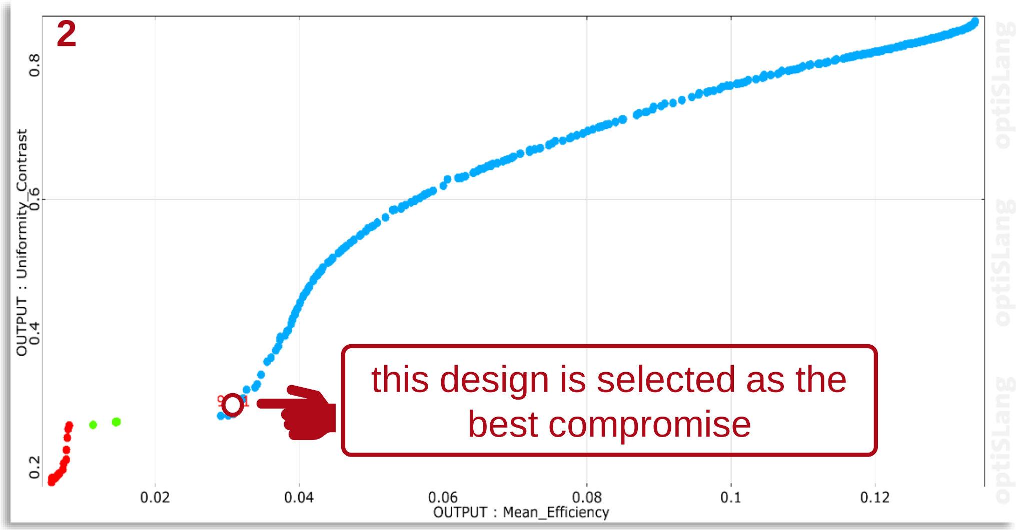
Optimization Results of optiSLang



- the optimization results are plotted as a function of the merit functions
  - mean efficiency
  - uniformity contrast
- the Pareto front indicates the optimum compromise between the two merit functions (highlighted)
- any optimization result at the pareto front might selected depending on the needs of the optical designer

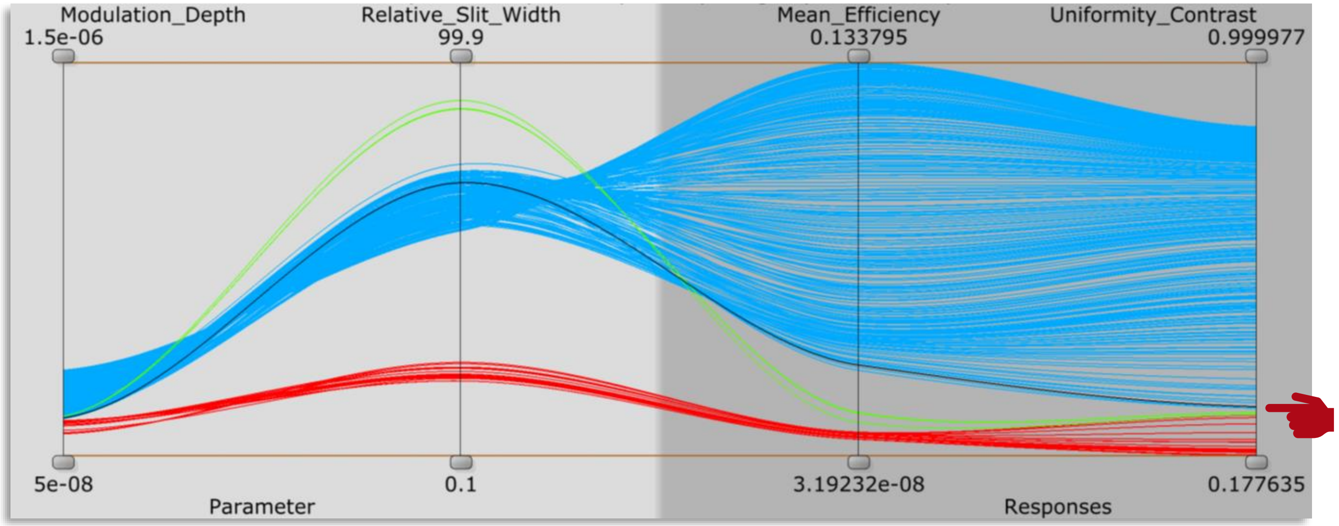
Advanced Evaluation of the Optimization Results



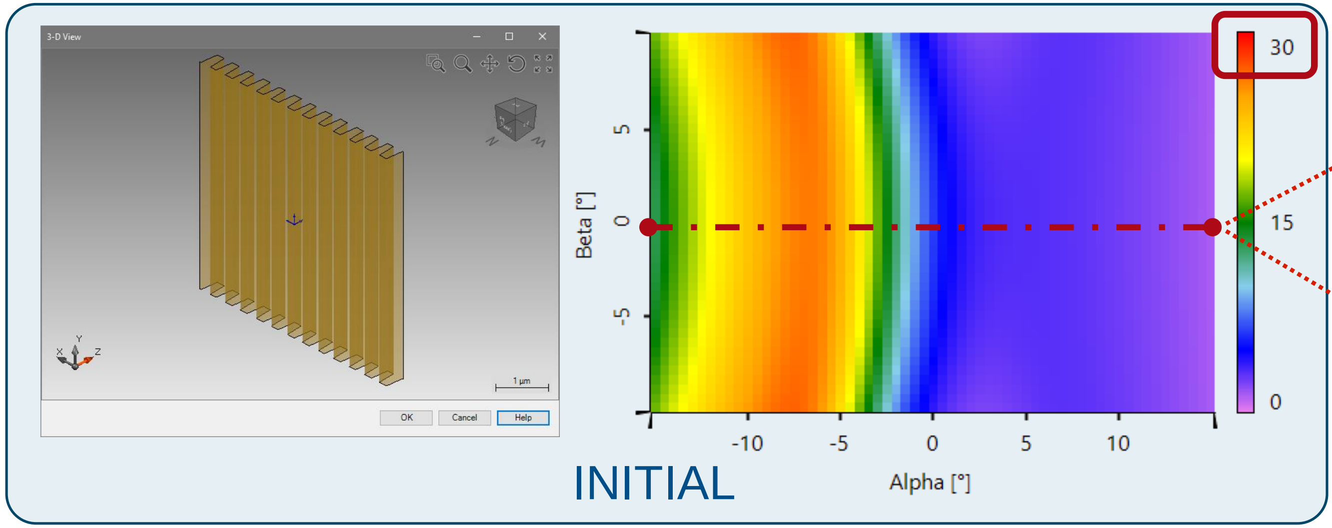


- as a result, a design is selected, which is the best compromise for a prioritized low uniformity contrast and an acceptable mean efficiency including manufacturable grating parameters

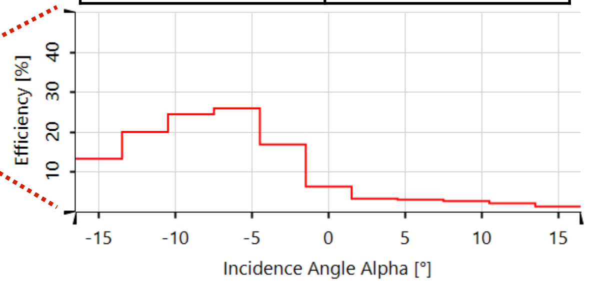
- the *Parallel Coordinates Plot* illustrates the corresponding input parameter combination for this design (black curve)



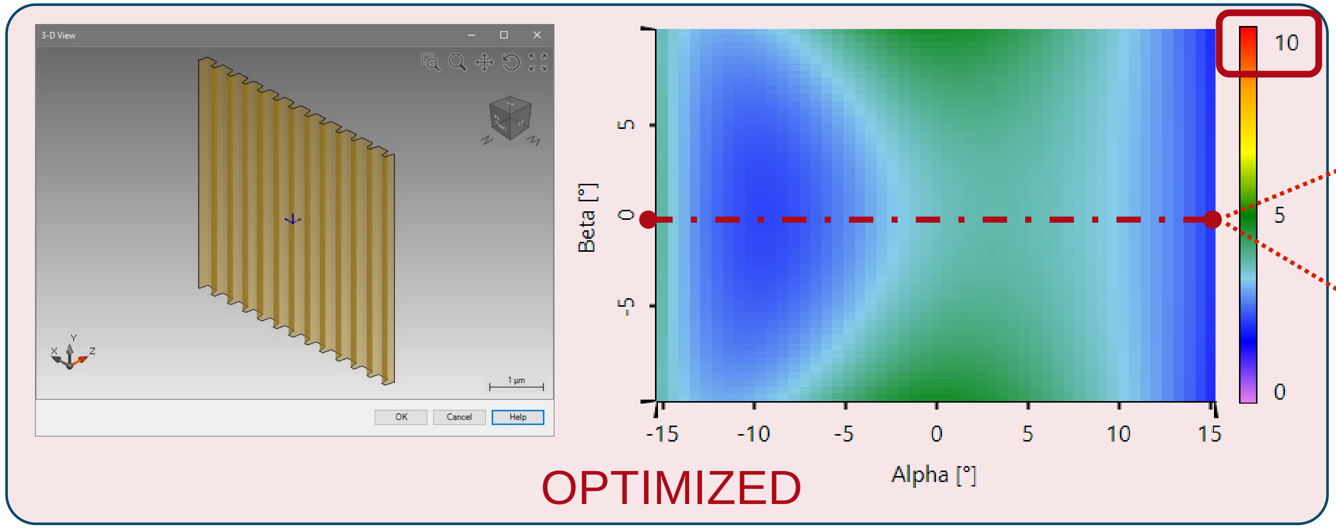
Analysis of Coupling Efficiency for Optimization Result



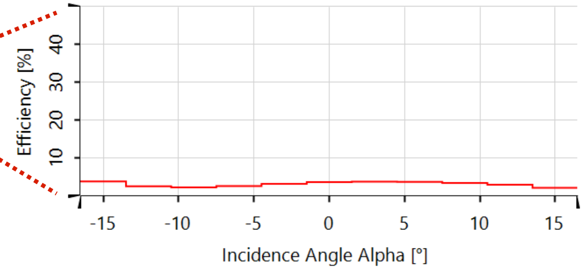
fill factor	50.00%
modulation depth	400.00nm



Mean Efficiency 10.96%
Uniformity Contrast **89.45%**



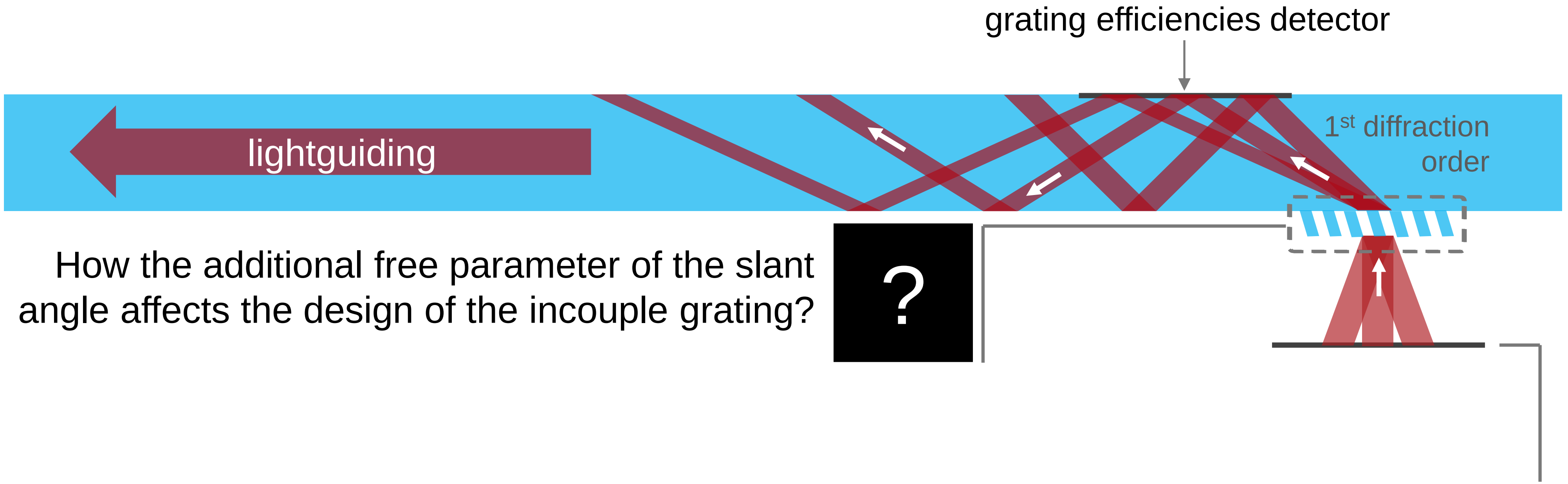
fill factor	68.43%
modulation depth	187.18nm



Mean Efficiency 3.08%
Uniformity Contrast **28.02%**

- finally, the optimization result is analyzed regarding the coupling efficiency using the software VirtualLab Fusion
- as a result, the uniformity contrast was significantly reduced but to the cost of the entire efficiency

Optimization Task: Slanted Coupling Grating

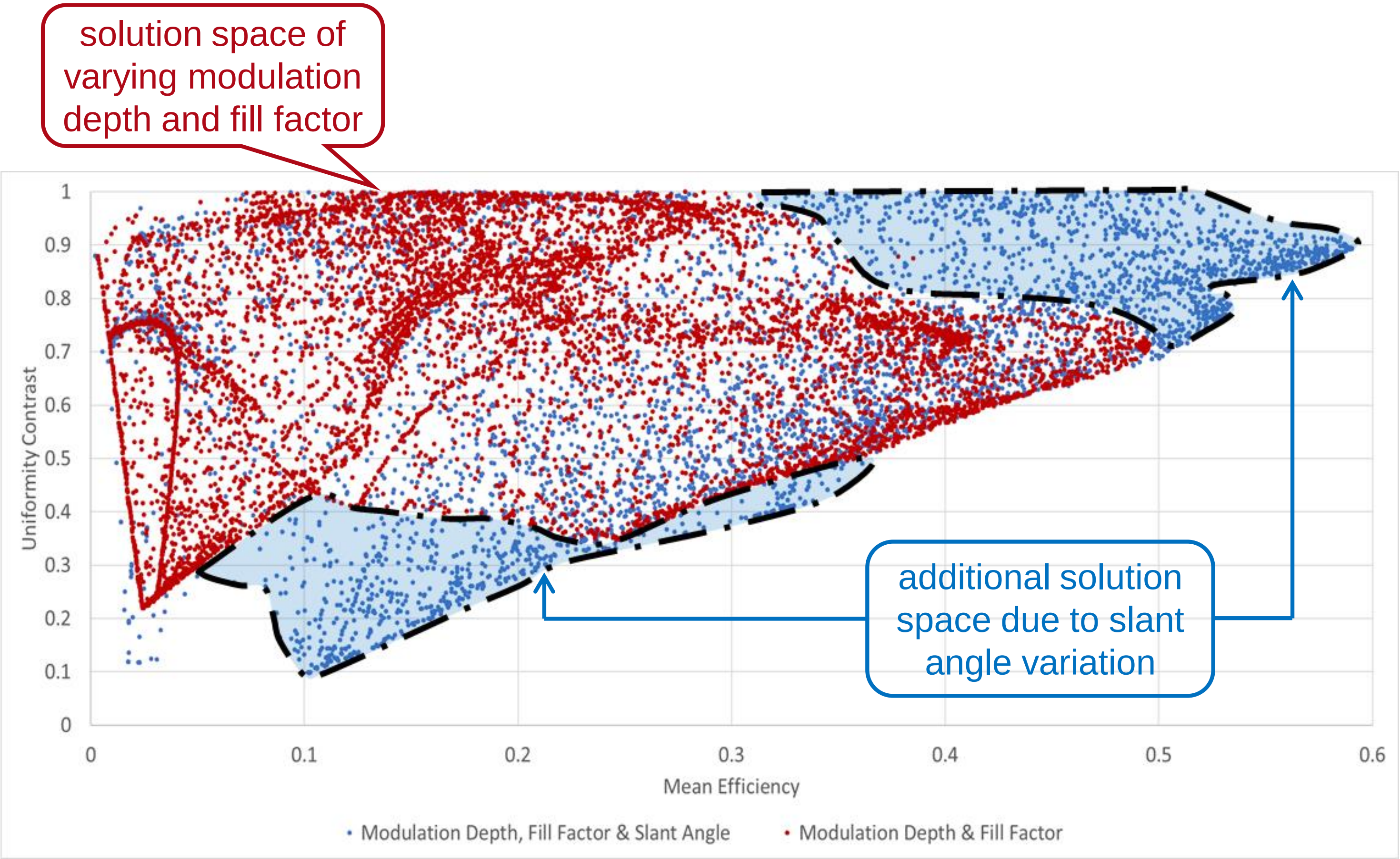


How the additional free parameter of the slant angle affects the design of the incouple grating?

set of plane waves

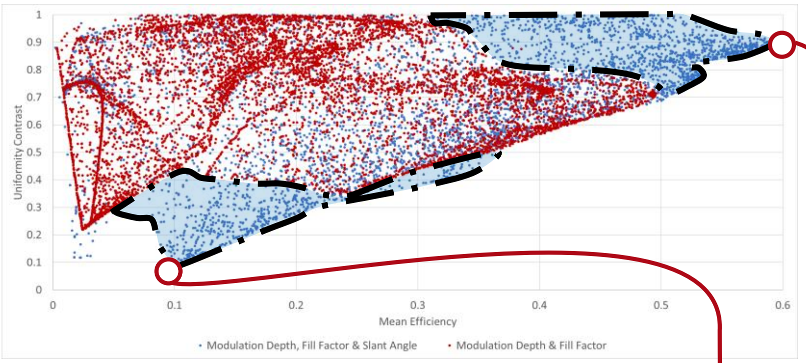
- **field of view (-30..30, -15..15)°**
- wavelength 532 nm
- linearly polarized along x-axis

Optimization Result of optiSLang

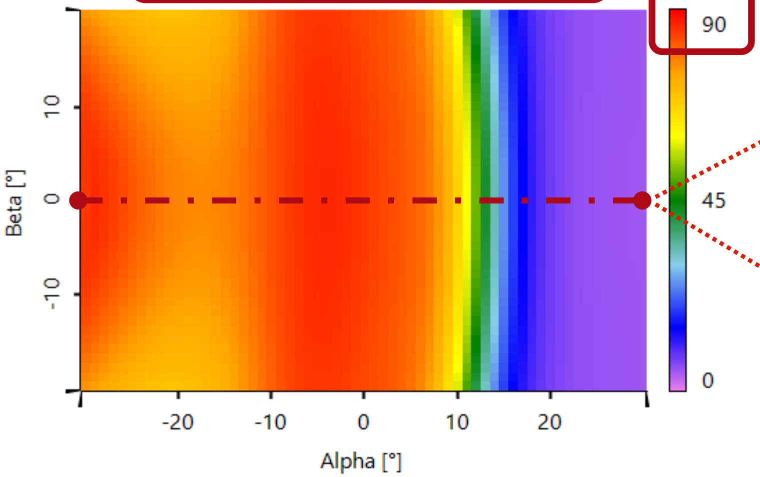


- the additional freedom of the slant angle provides additional solutions

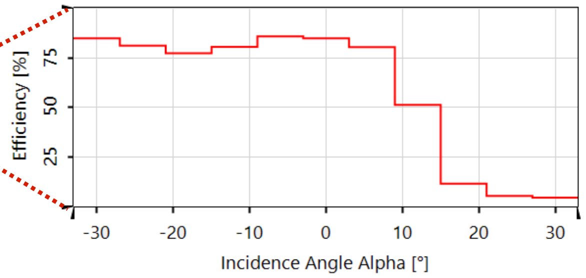
Analysis of Coupling Efficiency for Optimization Results



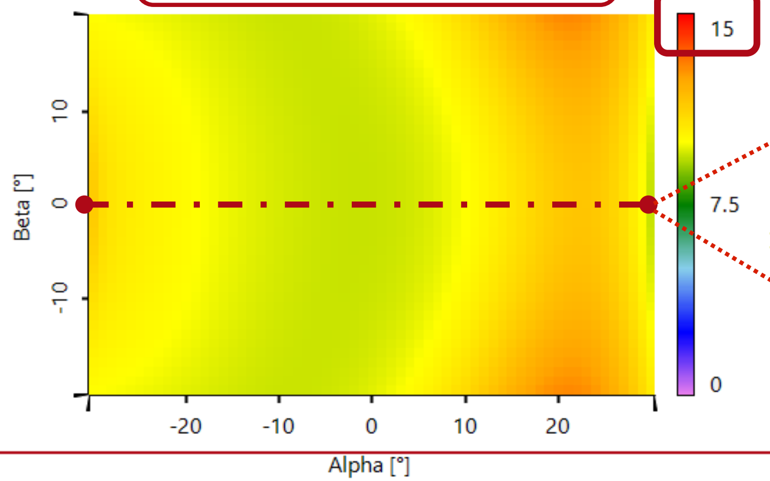
Mean Efficiency 58.74%
Uniformity Contrast 89.49%



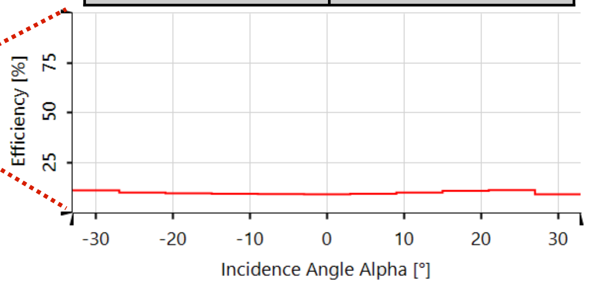
fill factor	70.82%
modulation depth	381.91 nm
slant Angle	24.58°



Mean Efficiency 10.34%
Uniformity Contrast 15.51%

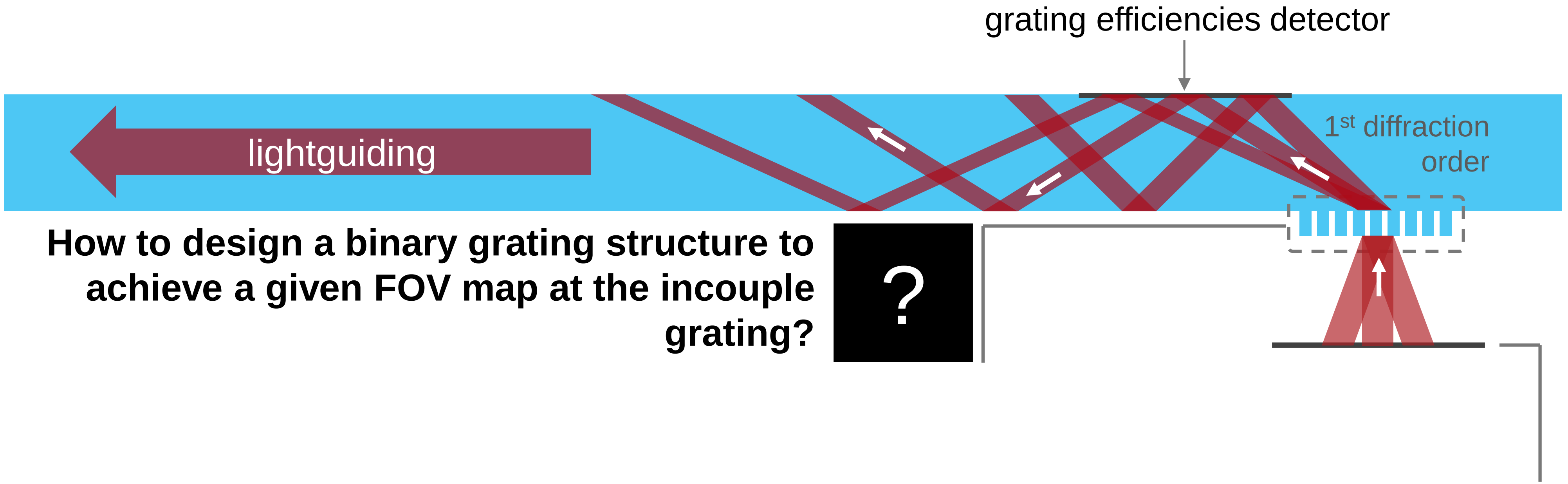


fill factor	90.00%
modulation depth	189.64 nm
slant Angle	14.57°



- an appropriate solution can be selected according specific constraints
- either uniformity contrast or mean efficiency might be prioritized

Optimization Task: Characteristic Curve Design

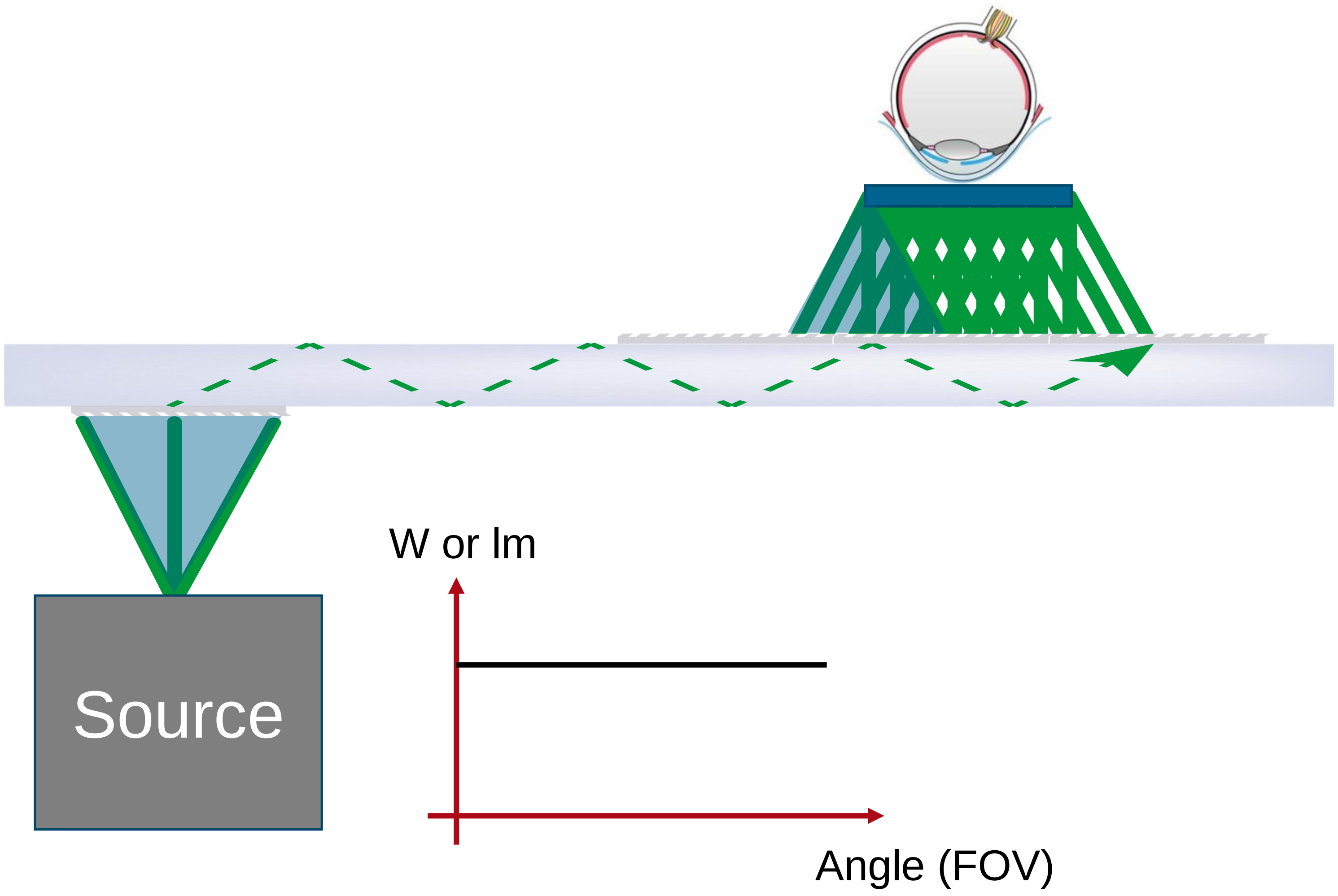


set of plane waves

- field of view (-15..15, -10..10)°
- wavelength 532 nm
- linearly polarized along x-axis

- practically, the incouple grating can be used to compensate the non-uniformity of the FOV map within the lightguide
- therefore, a strategy is shown how to achieve a desired FOV map by a parametric optimization approach of the incouple grating

Lightguide Concept: Fundamental Design Criteria



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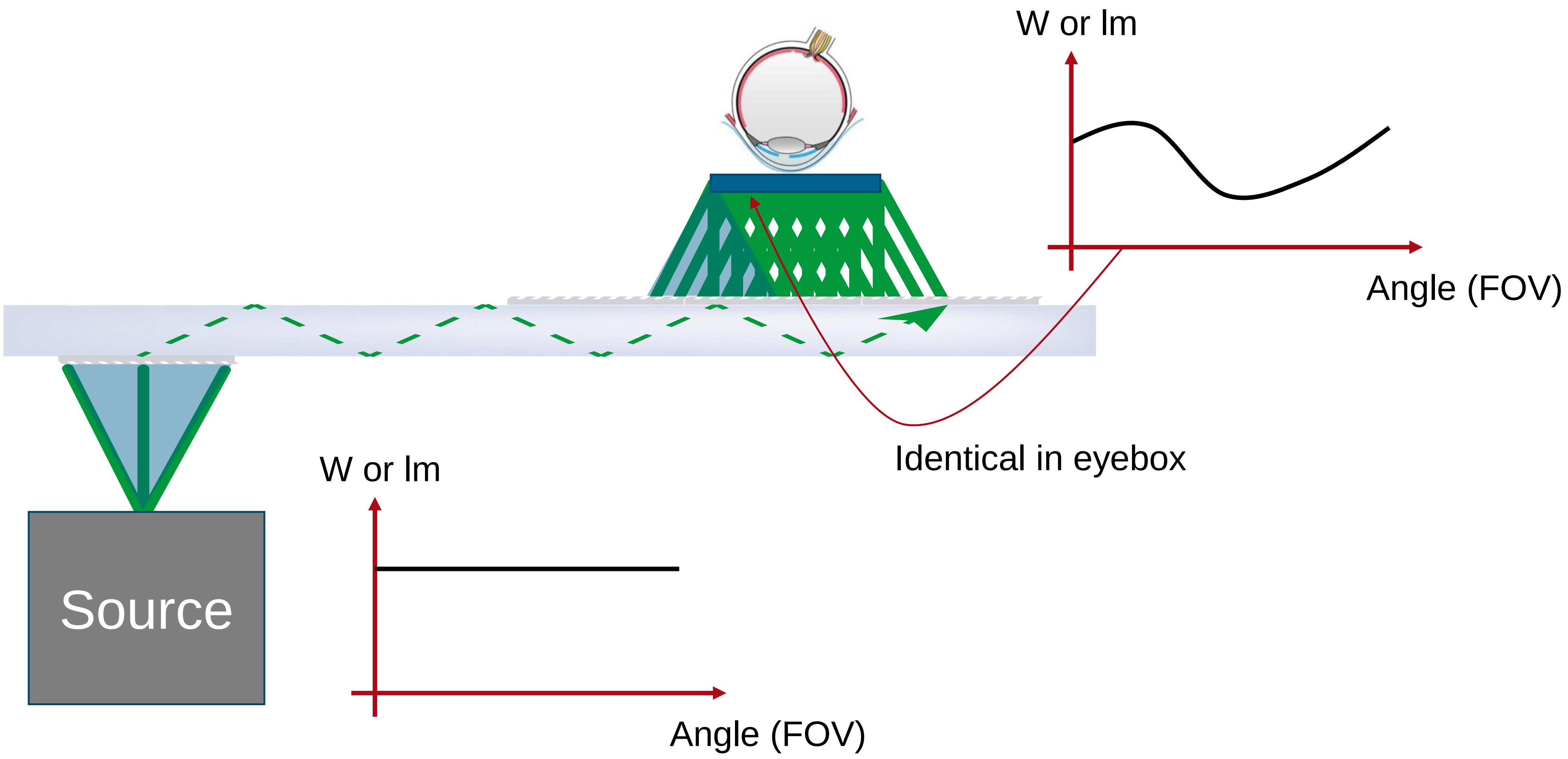
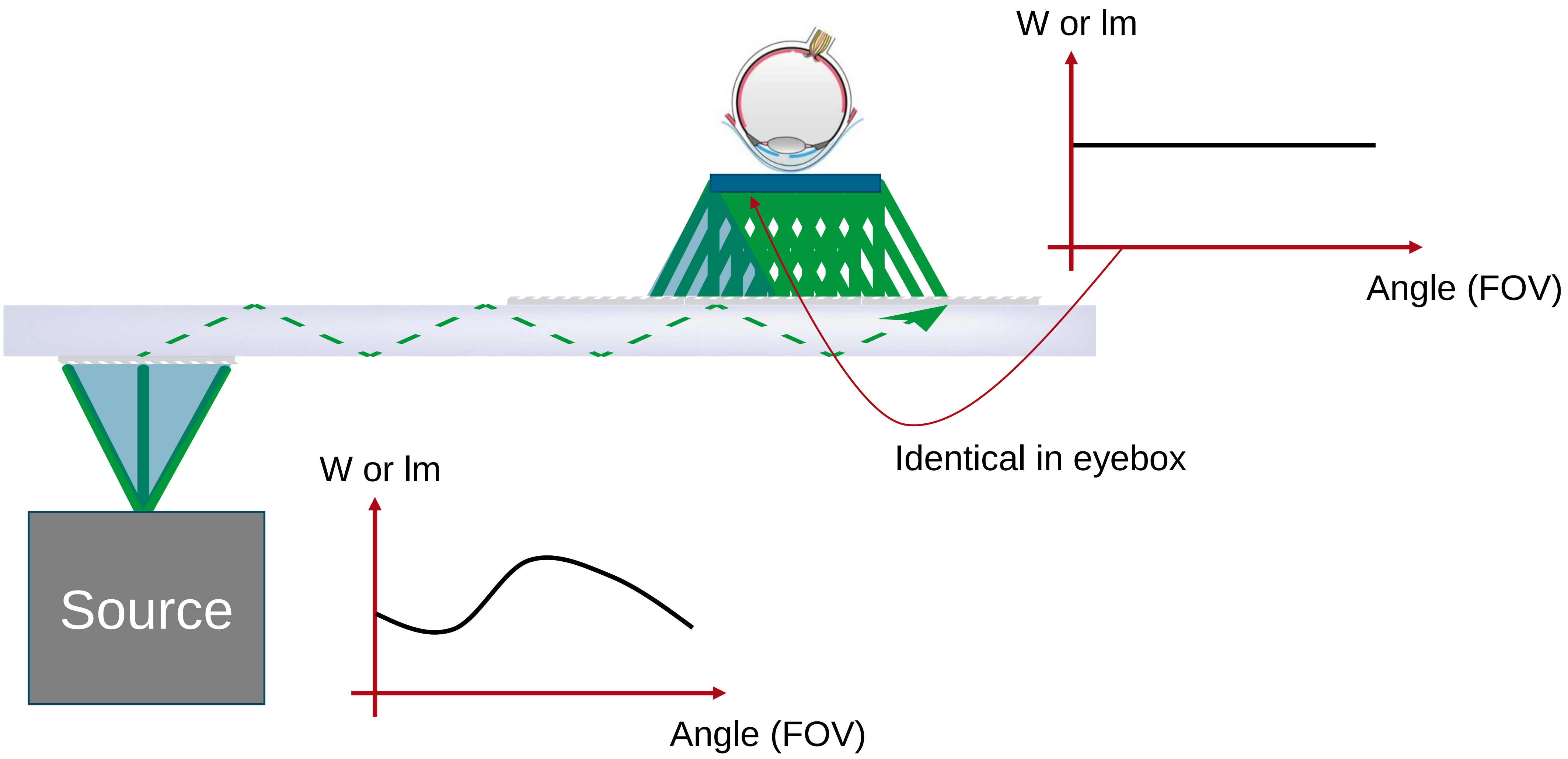
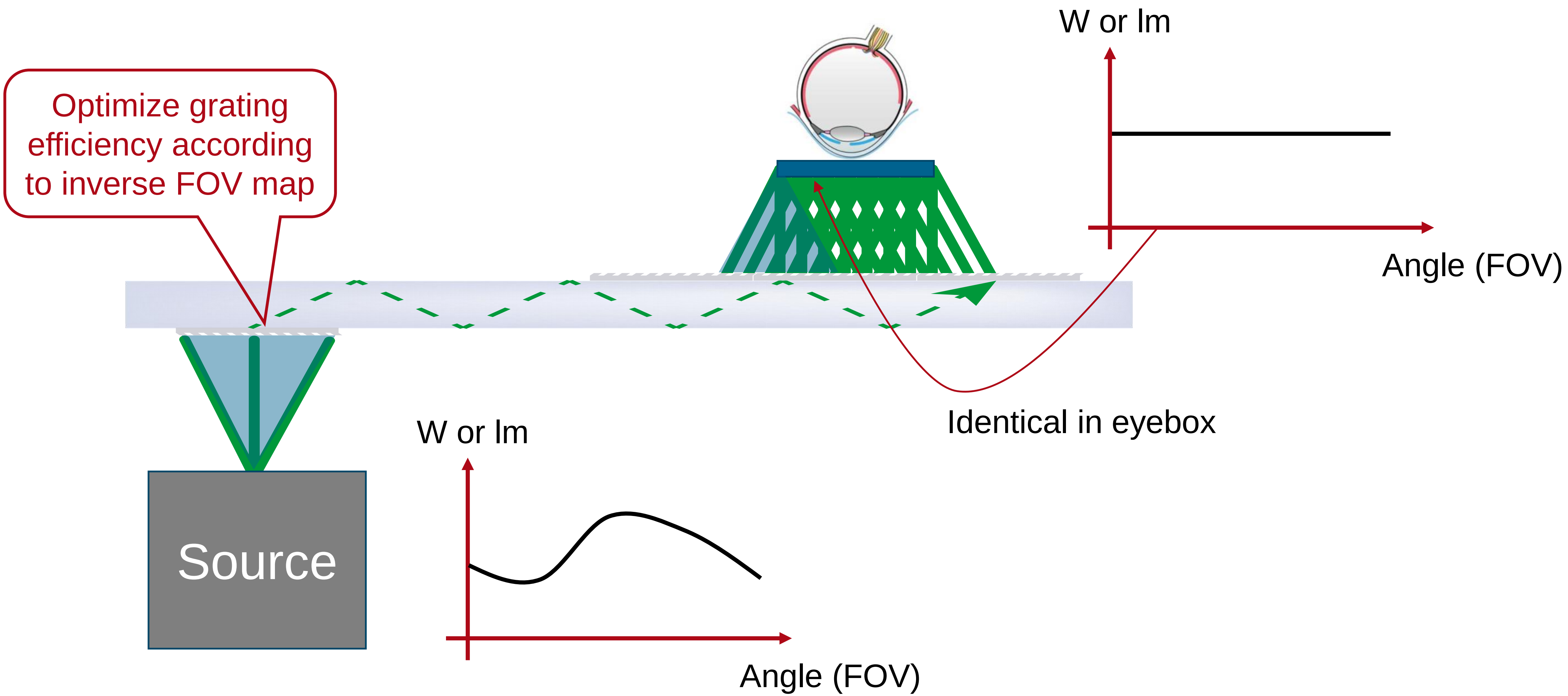


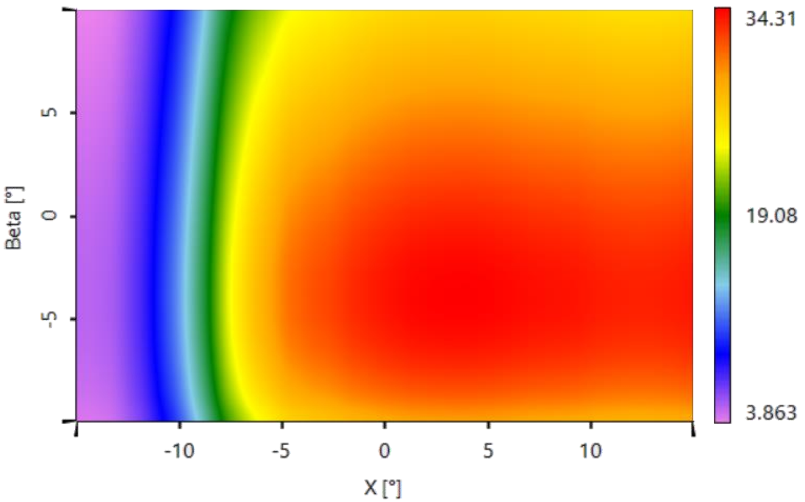
Lightguide Concept: Fundamental Design Criteria



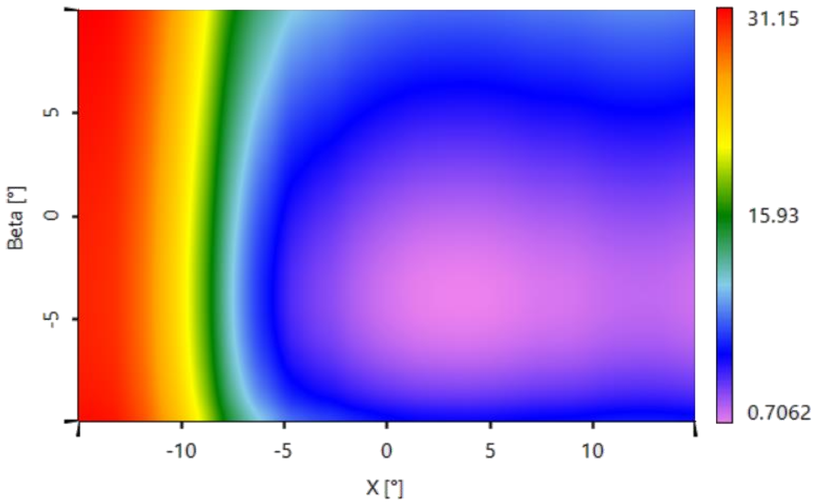
Incoupling Grating Design: Pre-Compensate FOV Map



Compensation of Non-Uniformity by the Incoupling Grating



Calculated Angular Efficiency at Eye-Box

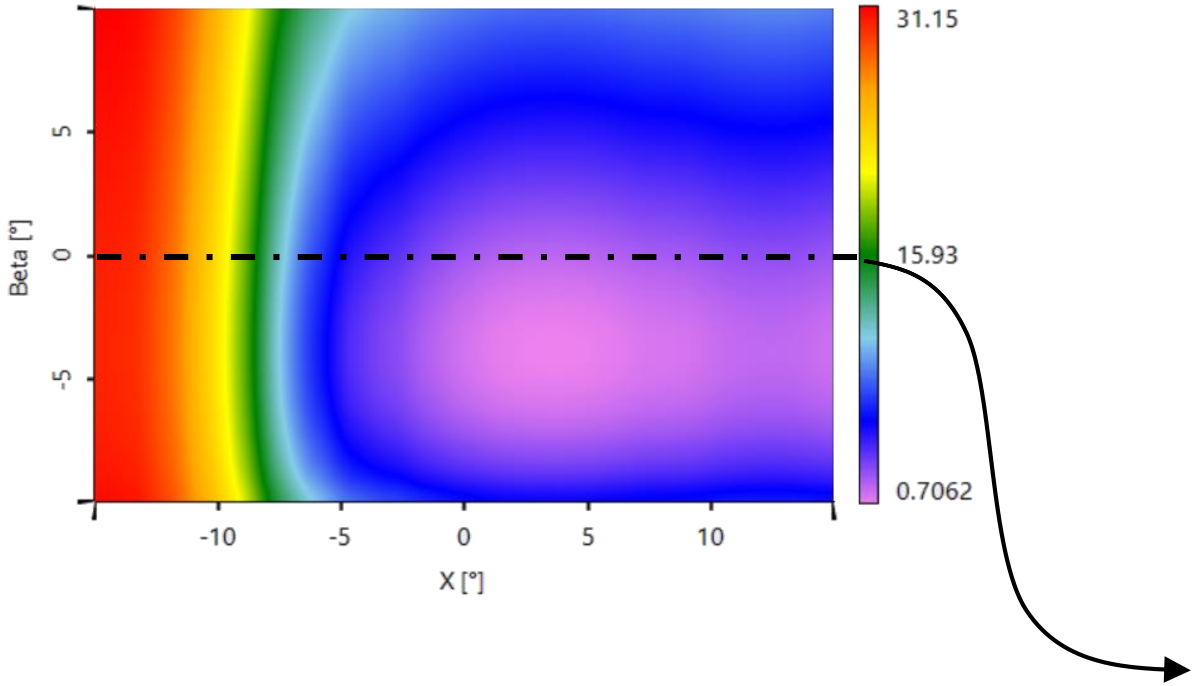


Assumed Desired Angular Efficiency at Incouple Region

- as an example, the desired FOV map at the incouple region **<u>is assumed</u>** to be simply the inverted FOV map at the eye-box

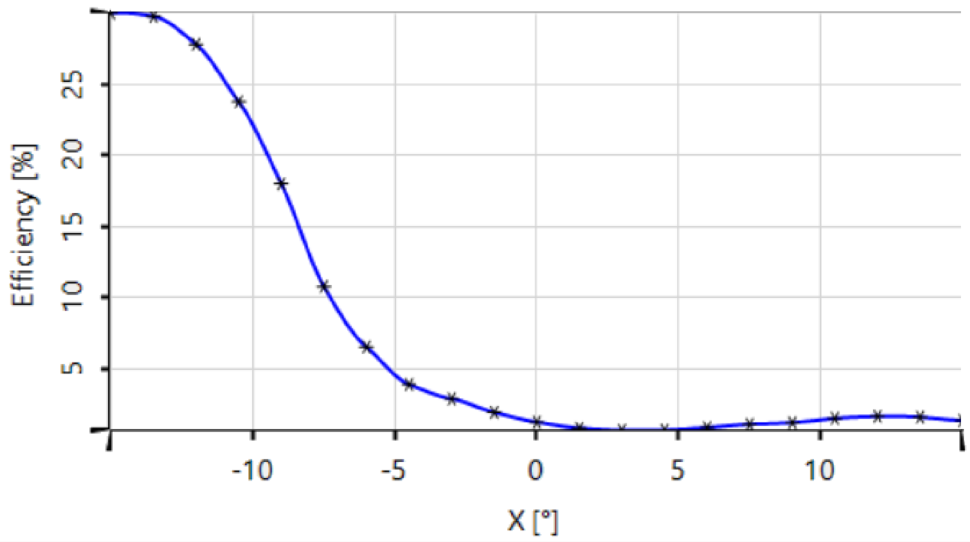
One-dimensional Investigation of the FOV Map

2D Angular Efficiency [%]

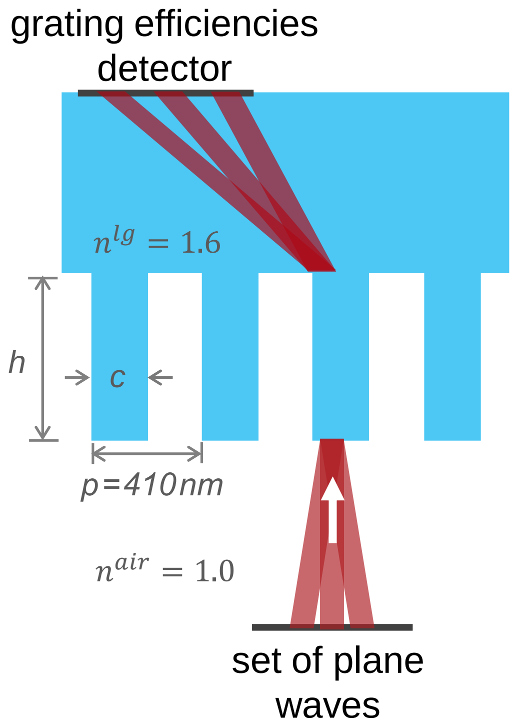


- for this example, a one-dimensional design approach of the FOV map was chosen
- hence, the angular efficiency along the grating period was used for analysis and optimization

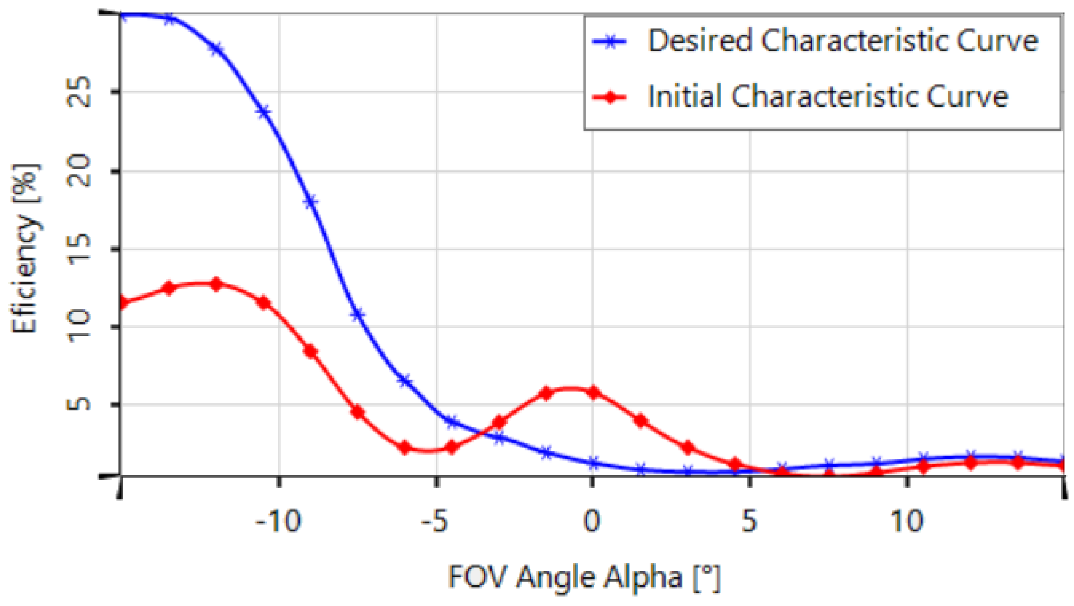
Characteristic Curve [%]



Definition of the Merit Function for the FOV Map Design

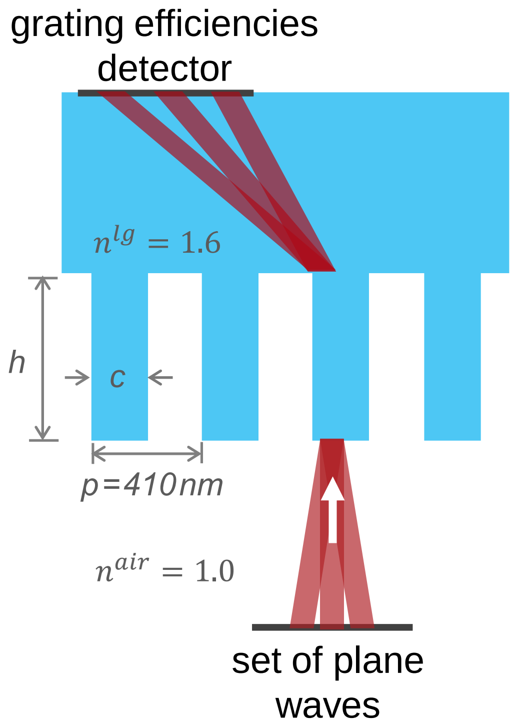


Initial Configuration of Grating	
fill factor	50.00%
modulation depth	500.00 nm



- two parameters are used to evaluate the match of the FOV map to the desired one
  - ➢ scaling factor
  - ➢ sum of deviation per FOV angle

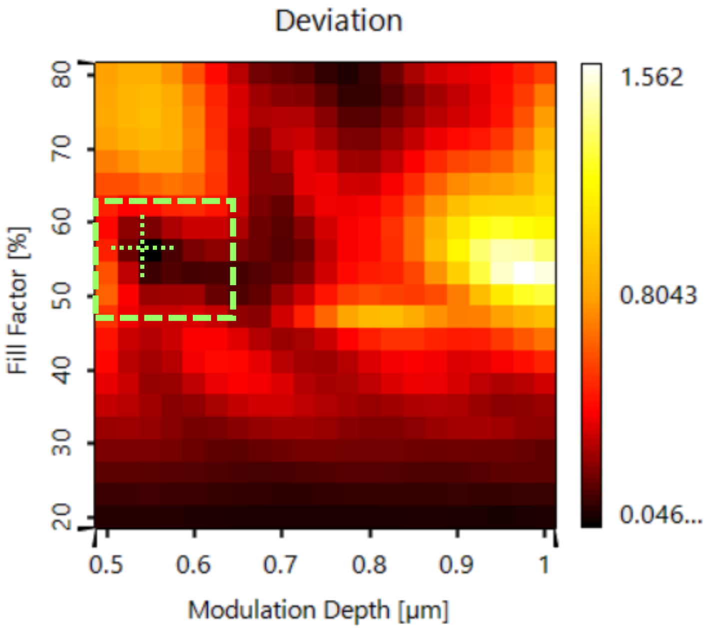
Investigation of the Grating for Angular Efficiency Design

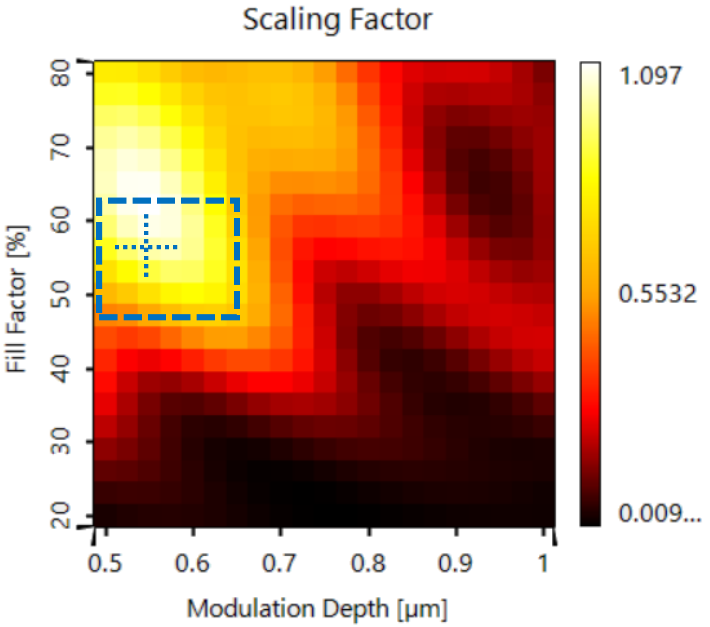


Parameter Scan

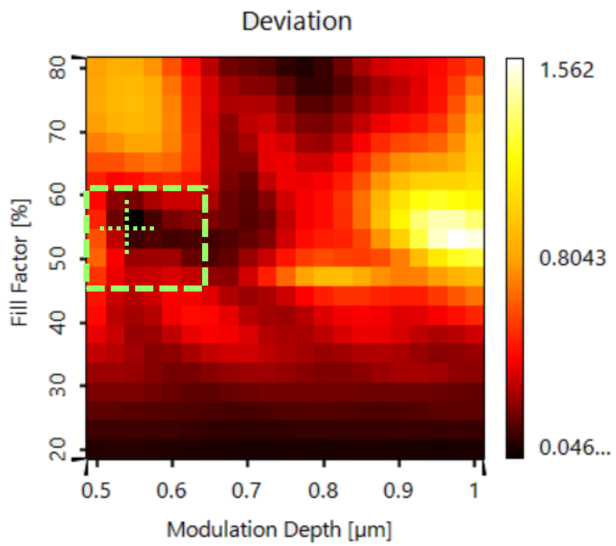
- variation of the **fill factor** c/p with the slit width c and the period p
  - ➢ **20% to 80%**
- variation of the **modulation depth** h
  - ➢ **500 nm to 1000 nm**

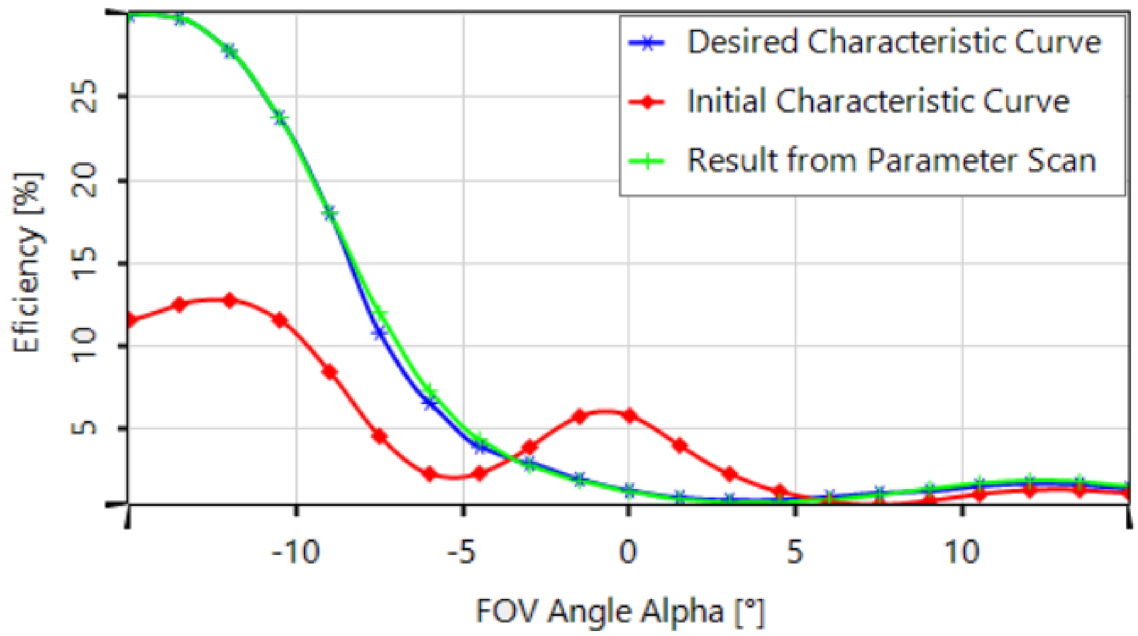
- first, a parameter scan is performed to determine an initial setup for a local optimization method
- in addition, an appropriate range of the parameters for the further optimization can be found





Result of the Parameter Scan

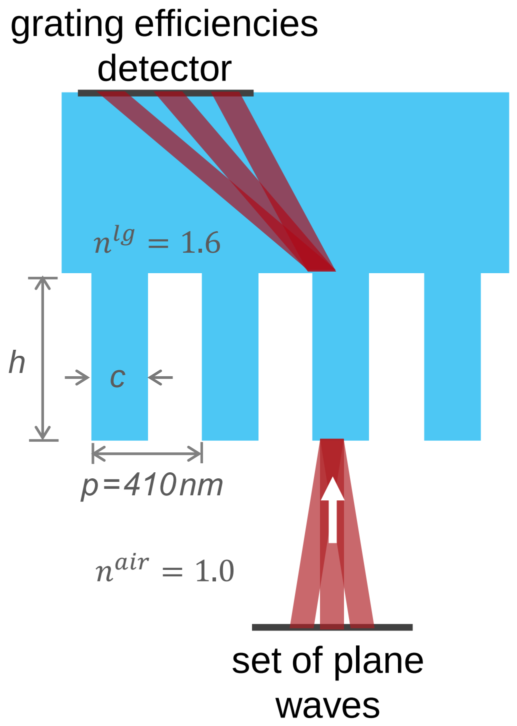




Configuration of Grating found by Parameter Scan	
fill factor	56.00%
modulation depth	550 nm

- as a result, a grating configuration with a minimum deviation and a scaling factor near to one is selected
- the configuration already fits quite well to the desired characteristic curve

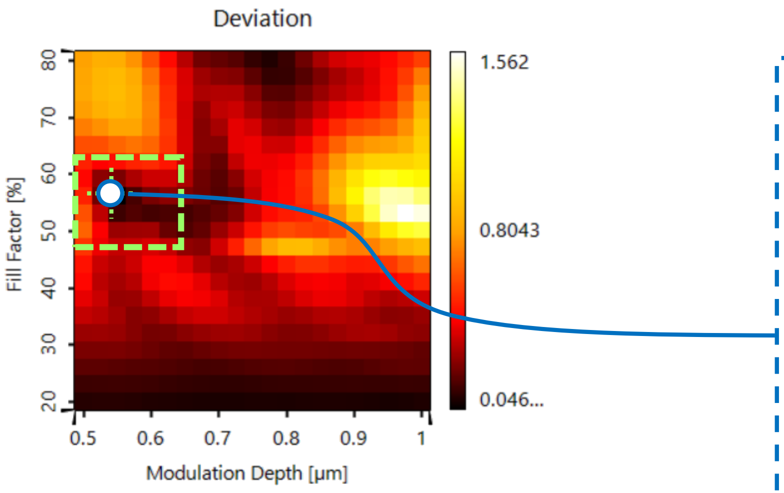
Downhill Simplex Optimization for Characteristic Curve Design



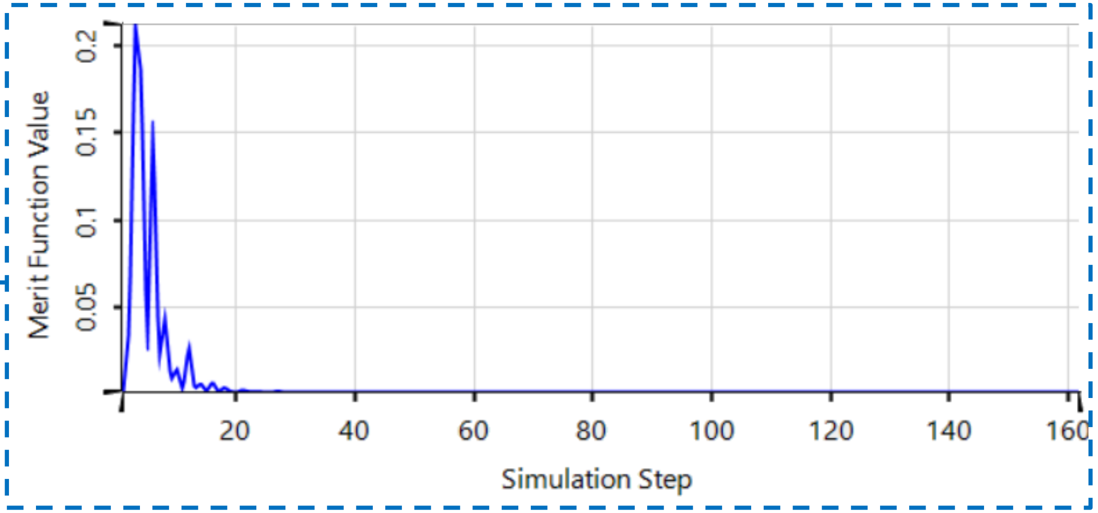
Local Optimization in Selection

- variation of the **fill factor** *c*/*p* with the slit width *c* and the period *p*
  - ➢ **47% to 62%**
- variation of the **modulation depth** *h*
  - ➢ **500 nm to 650 nm**

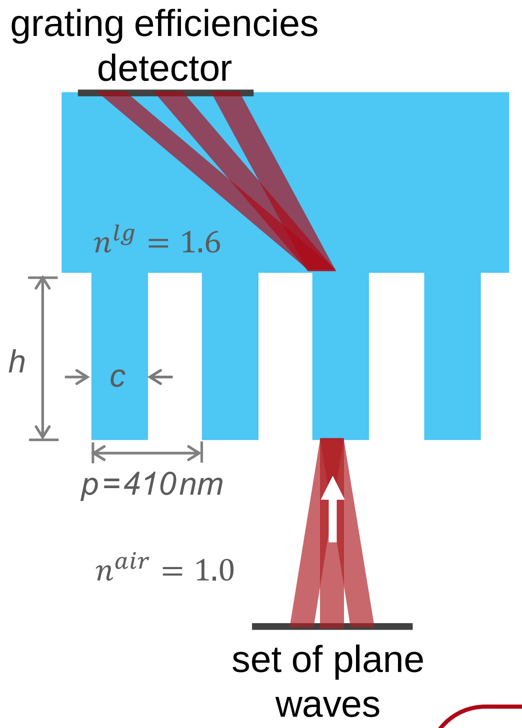
- as a second step, a local optimization is performed to find the best configuration for the desired characteristic curve



Convergence of the Merit Function



Result of Optimization

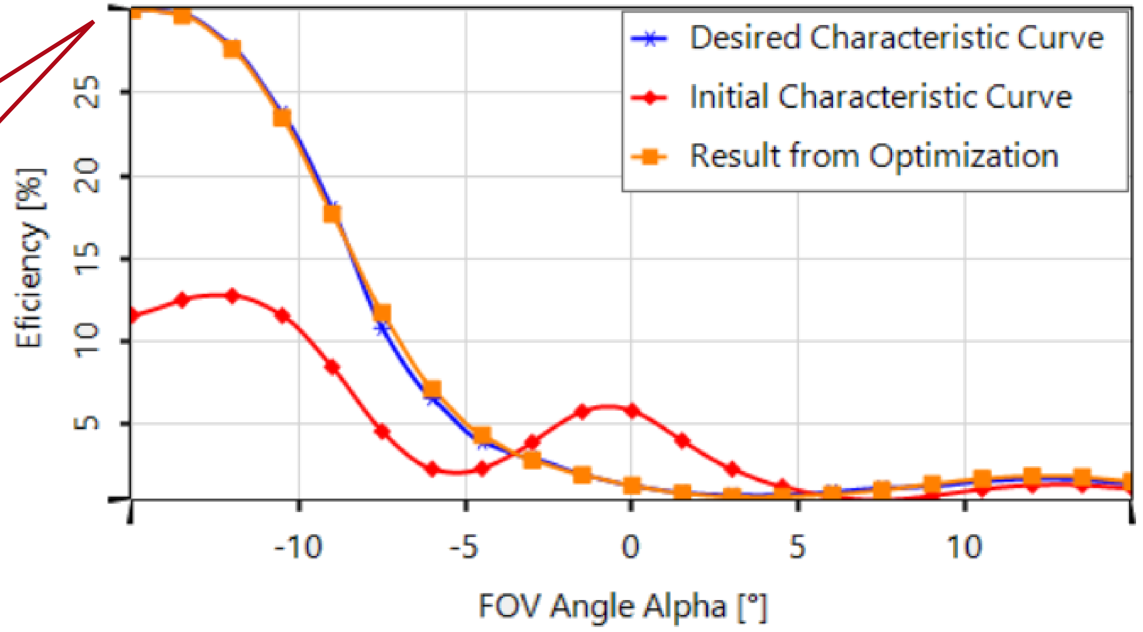


Local Optimization in Selection

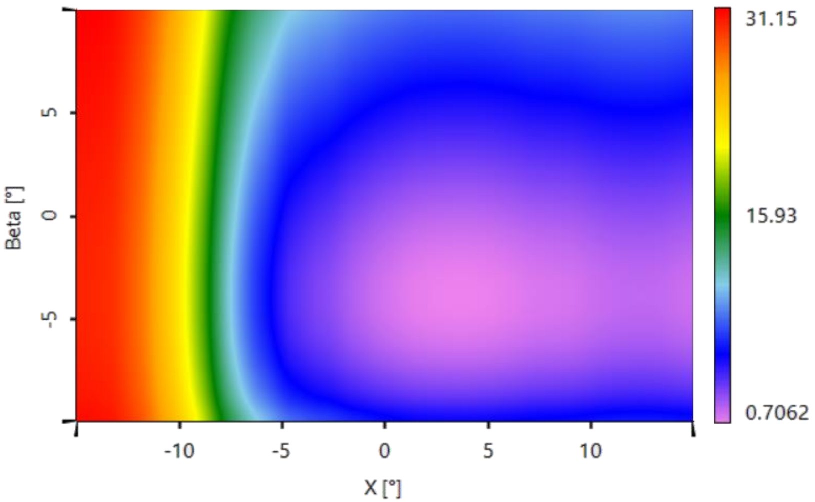
- variation of the **fill factor** *c/p* with the slit width *c* and the period *p*
  - ➢ **47% to 62%**
- variation of the **modulation depth** *h*
  - ➢ **500 nm to 650 nm**

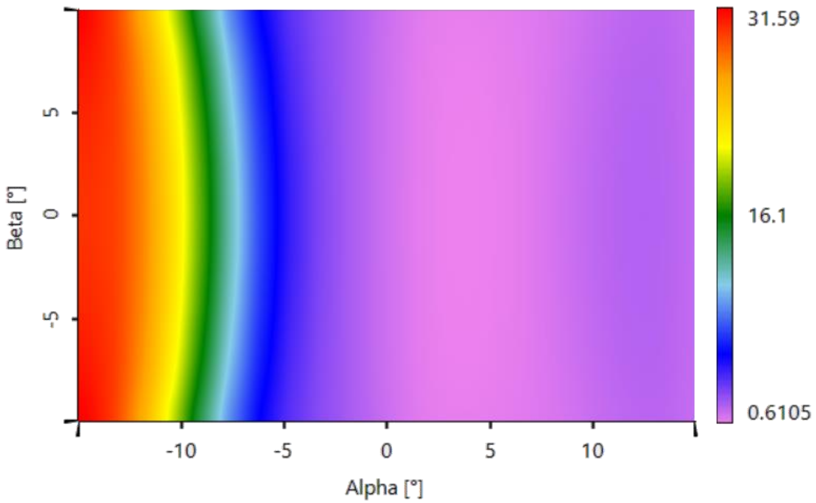
Configuration of Grating found by Optimization	
fill factor	**55.86%**
modulation depth	**549 nm**

This design strategy provides the best fit of the 1D angular efficiency to the desired characteristic curve by the structure of a binary grating



2D Analysis of the FOV map



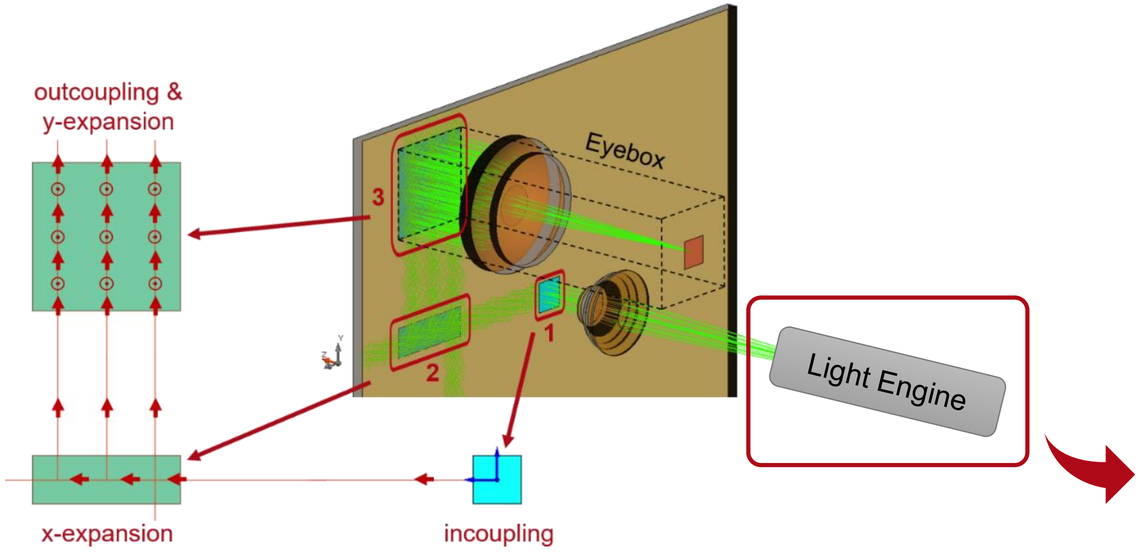


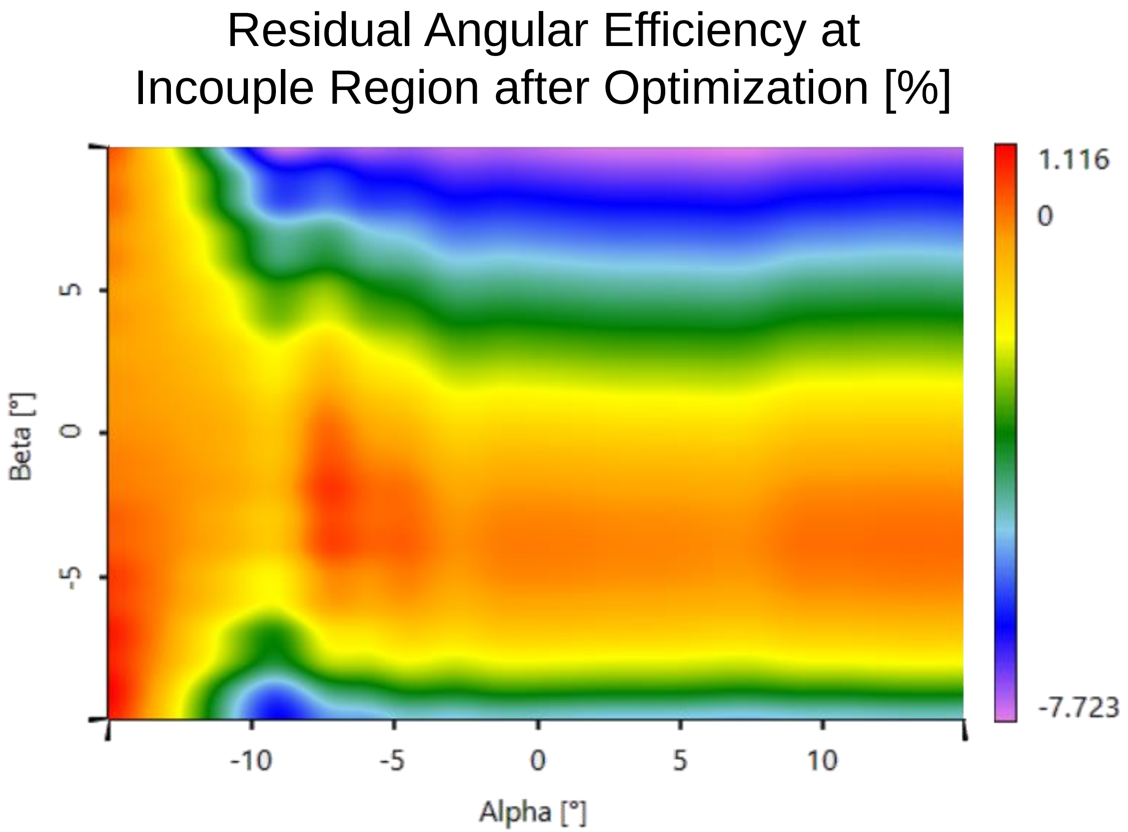
Desired Characteristic Efficiency Distribution at Incoupling Region

Achieved Characteristic Efficiency Distribution at Incoupling Region

- finally, the FOV map is analyzed two-dimensionally
- it is obvious, that the design strategy for 1D FOV map does not lead to perfect results in 2D case

Compensation of Residual Angular Efficiencies by Light Engine

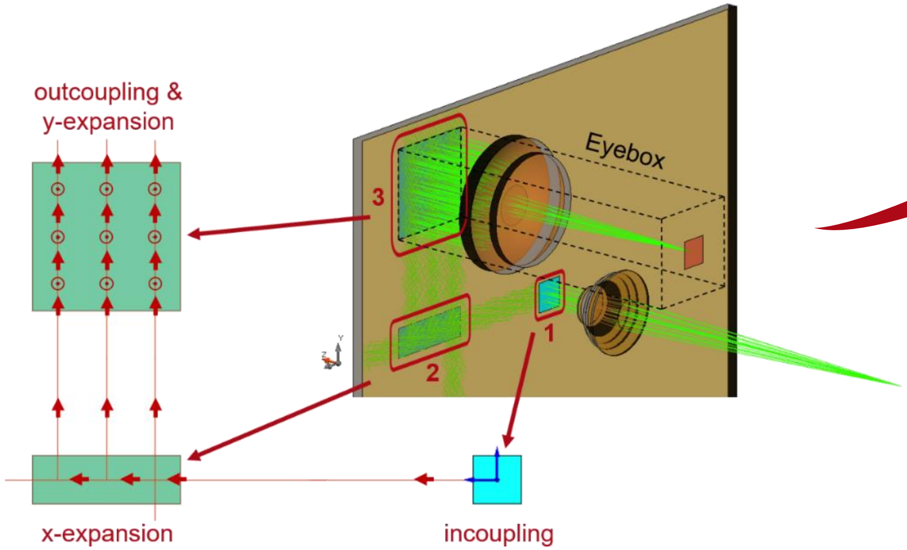


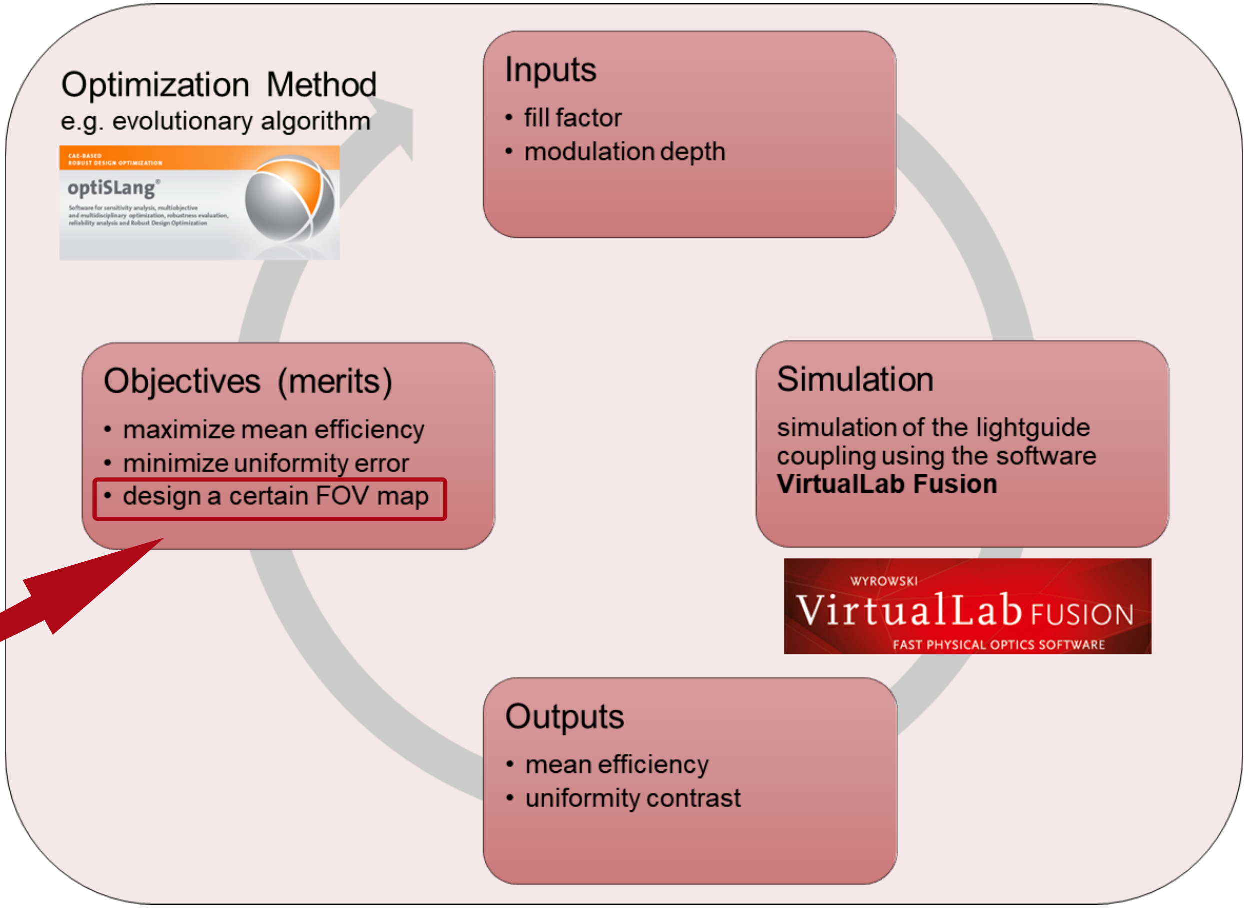


- the residual FOV map might be compensated by the dynamic characteristics of the light engine

Outlook

- the required angular efficiency at the incouple region is strongly dependent on the EPE and outcouple gratings
- hence, the incouple grating design is an iterative design process triggered by the systematic design approach of the lightguide





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