OASIS 180923

Optimization of Coupling Gratings for Lightguide-Based Displays

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Roberto Knoth[1], Stefan Steiner[1], Site Zhang[1], Yichen Liu[2], Christian Hellmann[3], and Frank Wyrowski[2]

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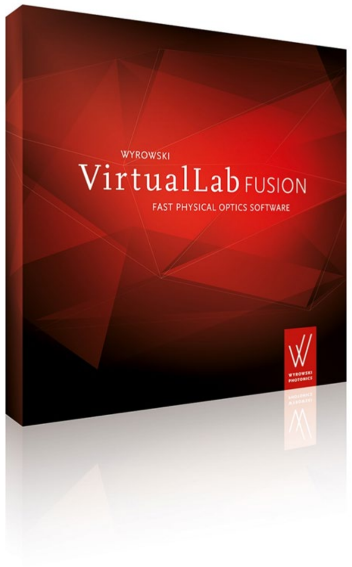
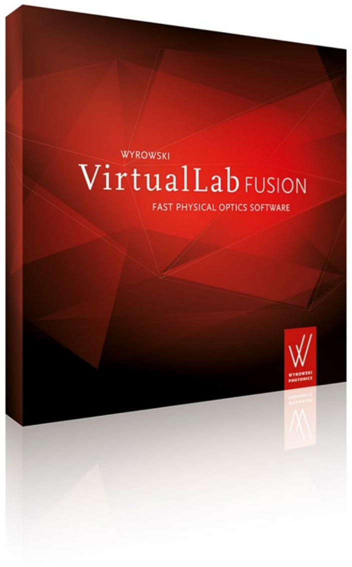
[3] Wyrowski Photonics GmbH

Jena, Germany



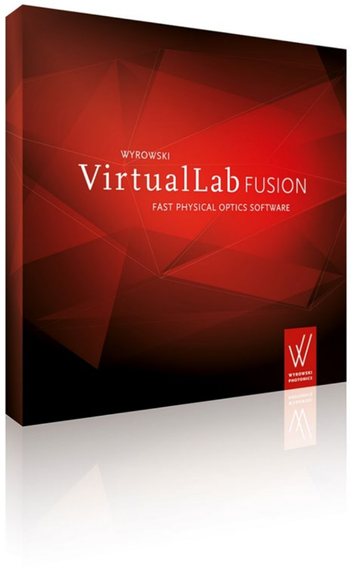
University of Jena

Applied Computational Optics Group R&D in optical modeling and design with emphasis on physical optics



Wyrowski Photonics

Wyrowski Photonics
Development of fast physical optics software VirtualLab Fusion



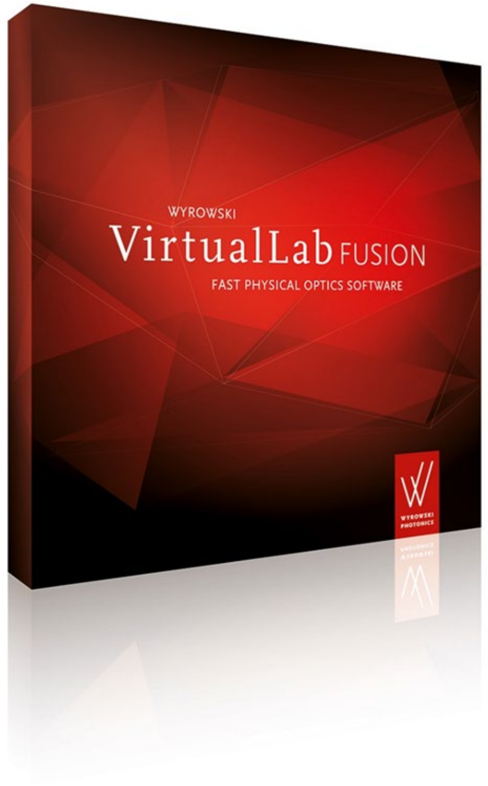
LightTrans International

LightTrans

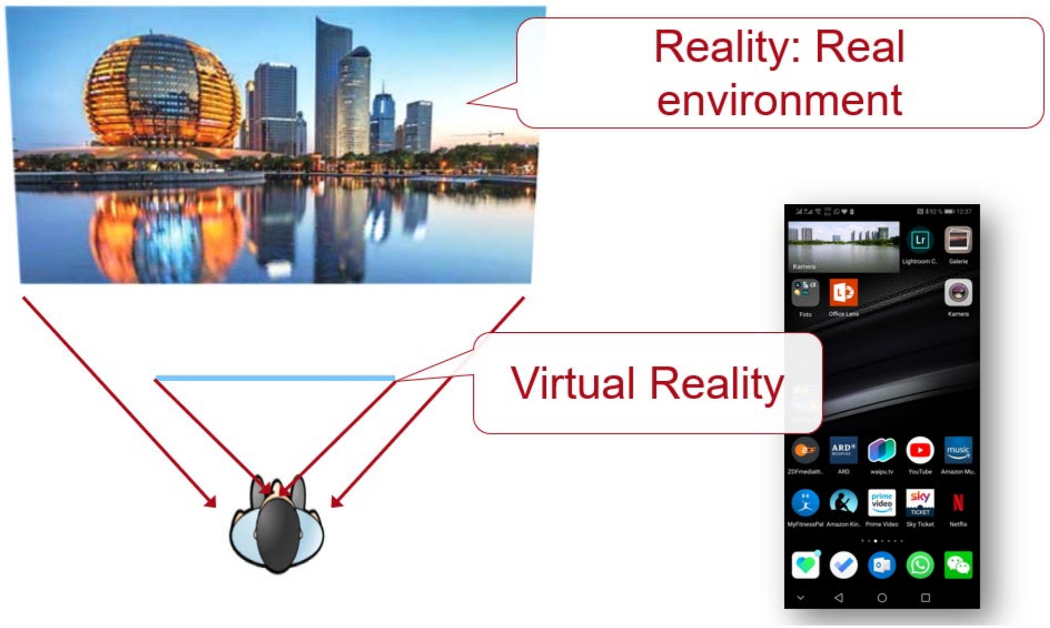
- Distribution of VirtualLab Fusion, together with distributors worldwide
- Technical support, seminars, and trainings
- Engineering projects

Optical Design Software and Services

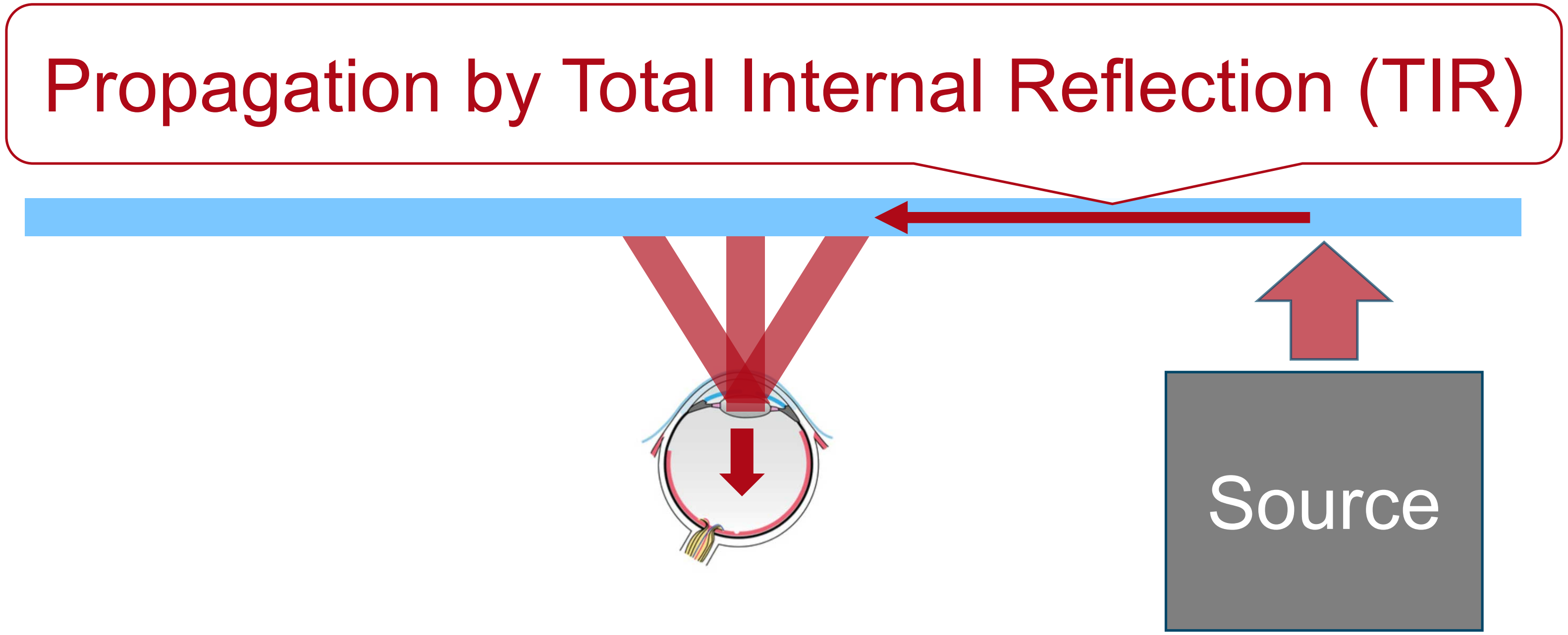
booth 17



Augmented / Mixed Reality by Lightguide-Based Displays



Lightguide Approach



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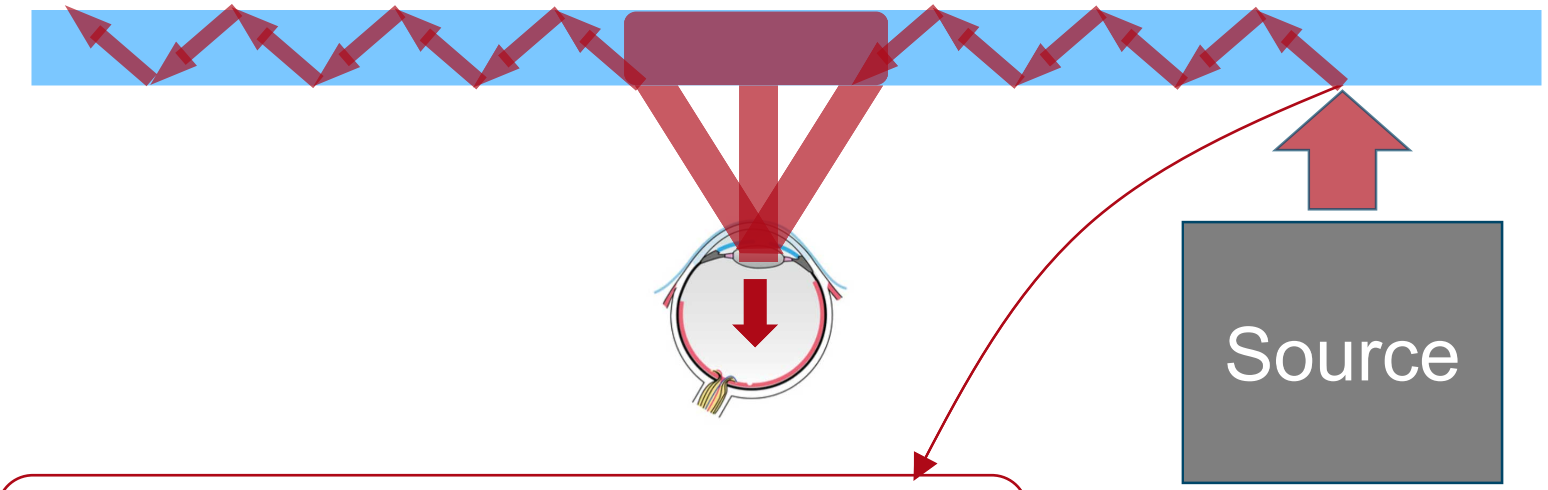
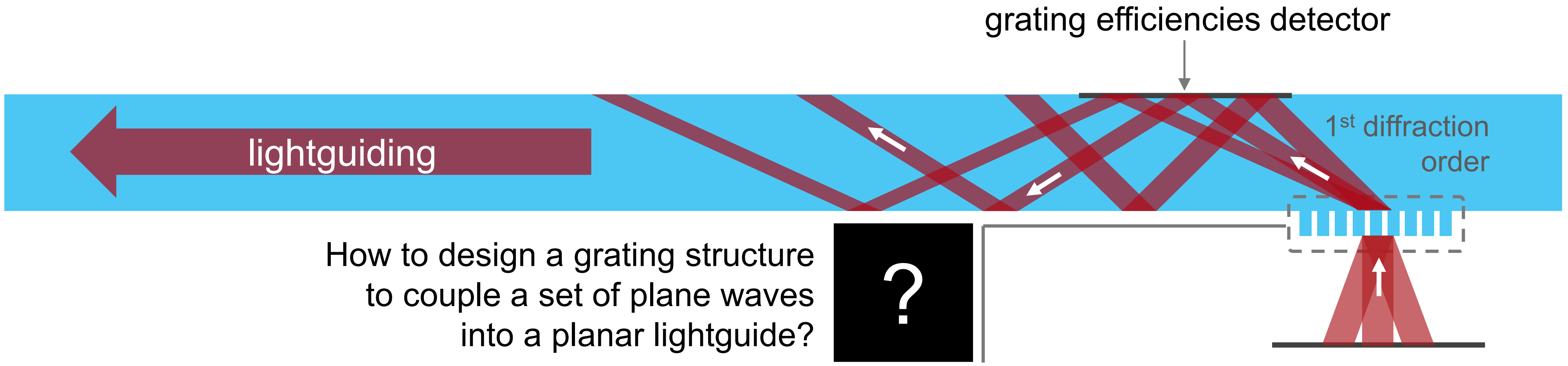


Electromagnetic modeling of surface or volume gratings.

Task: Workflow of designing coupling grating with considering a certain field of view (FOV).

Lightguide Approach



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

Workflow:
- decide the period of grating by k-domain thinking
- parametric optimization of the grating to achieve high coupling efficiency and uniform efficiency over FOV

Mathematical Modeling: Direction Vector and *k*-Domain

- Field of View (FOV) angles denoted by the Cartesian angles θ_x and θ_y.
- This defines a unit direction vector according to

$$\hat{\boldsymbol{s}} \stackrel{\text{def}}{=} \frac{(\tan\theta_x, \tan\theta_y, 1)}{\sqrt{1+\tan^2\theta_x+\tan^2\theta_y}}$$

plane wave with largest inclined angle (θ_x, θ_y)

- The vector $\boldsymbol{k}$ of a plane wave is defined by

$$\boldsymbol{k} = k_0 n \hat{\boldsymbol{s}},$$

with $k_0 = 2\pi/\lambda$ and the refractive index n of the medium in which we consider the wave.

$\boldsymbol{\kappa} = (k_x, k_y)$

$k_z = \sqrt{(k_0 n)^2 - (k_x^2 + k_y^2)}$

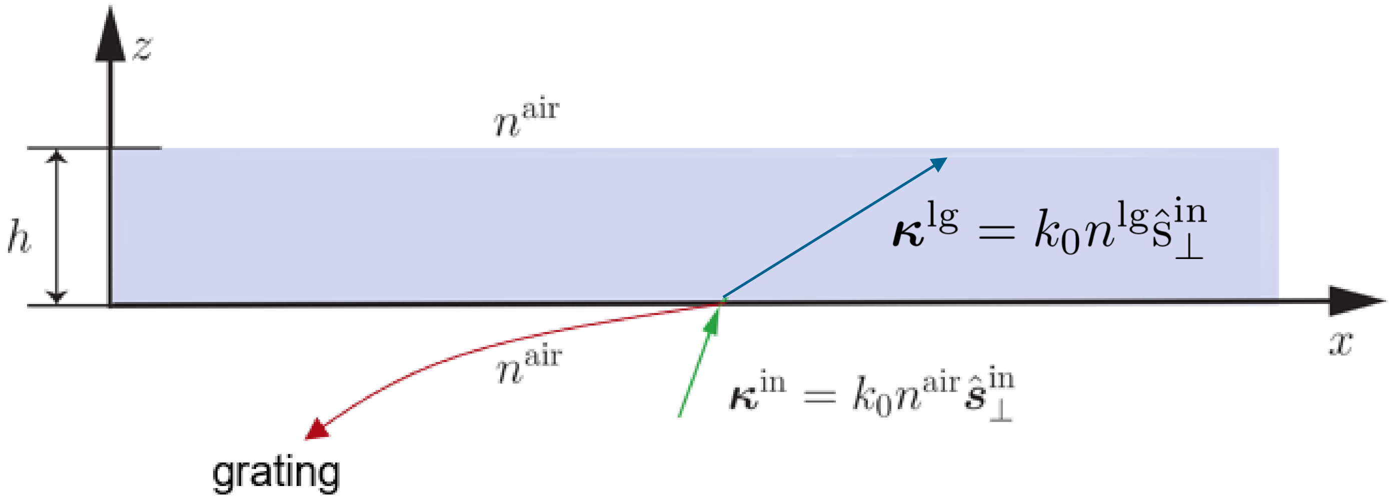
For propagating wave,

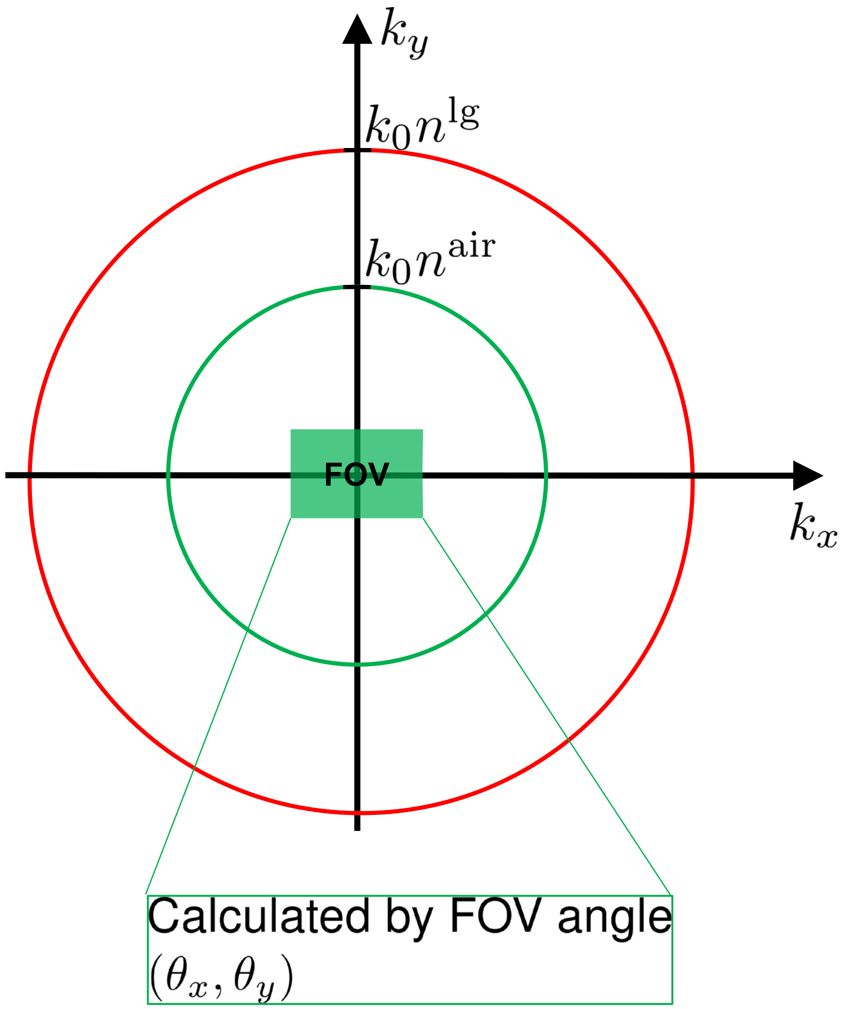
$k_x^2 + k_y^2 \leqslant (k_0 n)^2$

Lightguide Coupling by Gratings

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

$$k_0 n^{\mathrm{lg}} \geq |\boldsymbol{\kappa}^{\mathrm{lg}}| \geq k_0 n^{\mathrm{air}}$$





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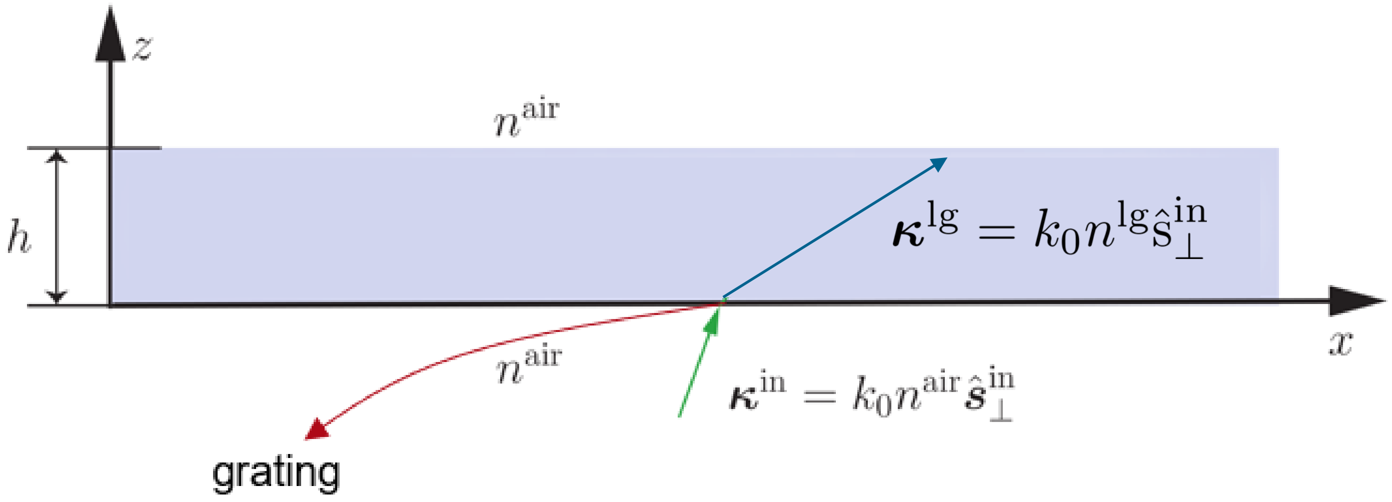
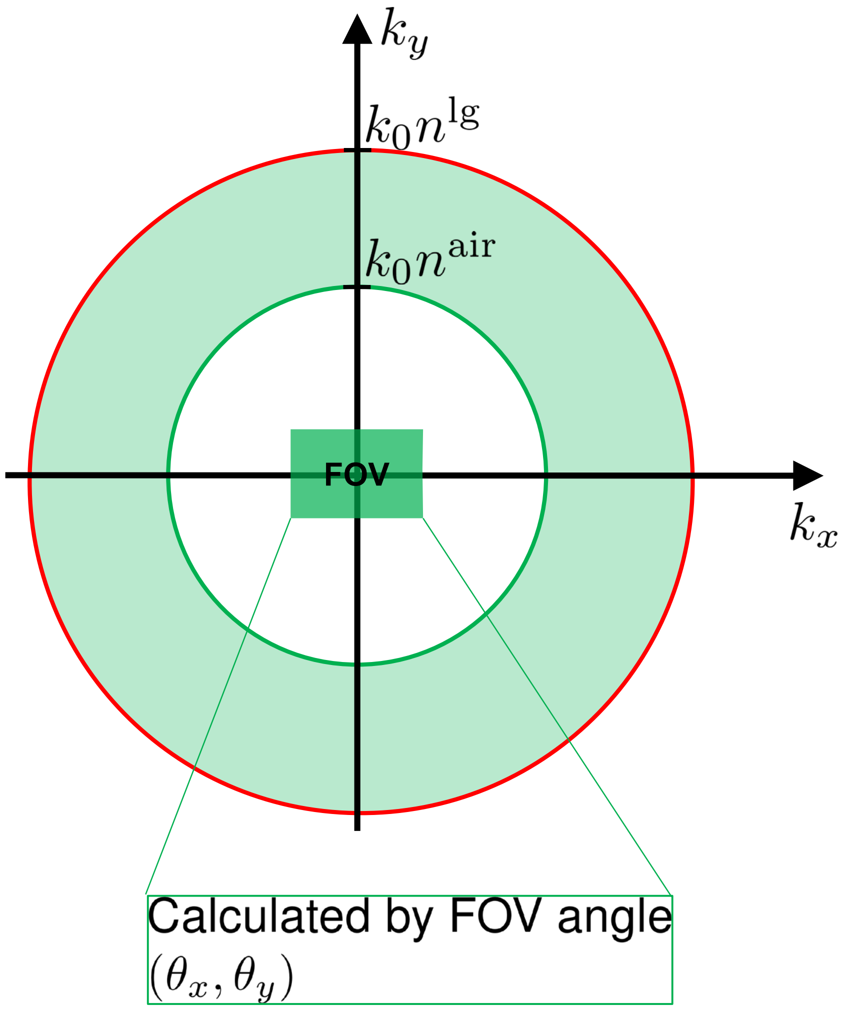




Lightguide Coupling by Gratings

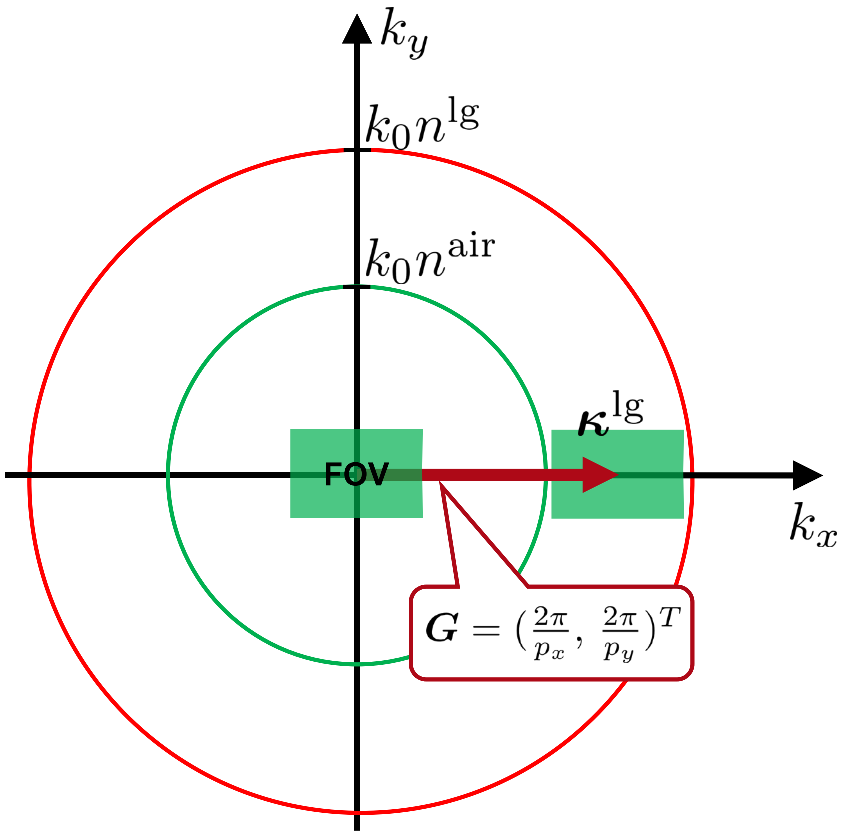
A grating is an elegant component for the coupling because the FOV is shifted in the k-domain under consideration of the grating vector $\boldsymbol{G}$.

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

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 $\boldsymbol{m} = (m_x, m_y)^T$.

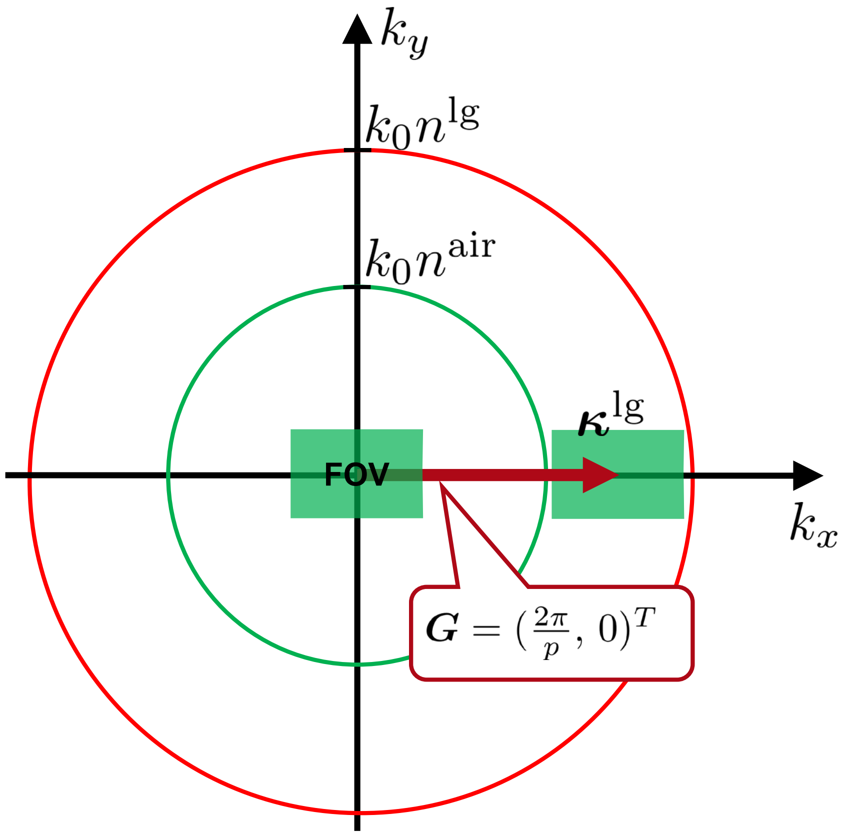


Tool: Period Calculation According to Guiding Condition

- In case of 1D-periodic gratings one component of the grating vector becomes zero, so that $G_y = 0$ without loosing of generality.

- From that follows the range of the period of a 1D-periodic grating geometry to couple a certain FOV into a waveguide:

$$\frac{2\pi}{\sqrt{(k_0 n^{\mathrm{air}})^2 - (k_y^{\mathrm{in}})^2} - k_x^{\mathrm{in}}} \geq p \geq \frac{2\pi}{\sqrt{(k_0 n^{\mathrm{lg}})^2 - (k_y^{\mathrm{in}})^2} - k_x^{\mathrm{in}}}.$$



Input to the VirtualLab Module

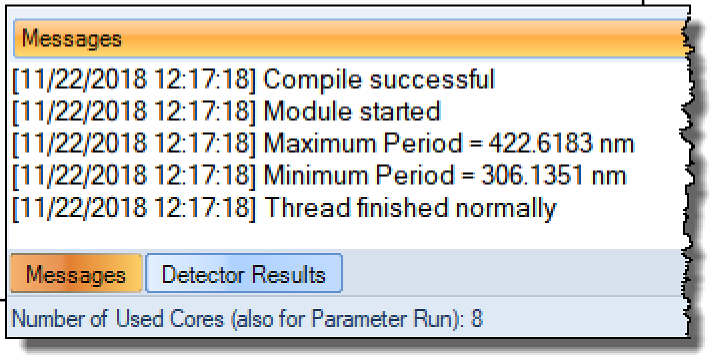
C# Module: Header

```
using System;

using VirtualLabAPI.Core.Common;
using VirtualLabAPI.Core.Modules;
using VirtualLabAPI.Core.Numerics;
using VirtualLabAPI.Core.SupportFunctions;

namespace OwnCode {
    public class VLModule : IVLModule {
        //define wavelength for evaluations
        double wavelength = 532e-9;
        //define refractive index of surrounding medium
        double refractiveIndexSurrounding = 1;
        //define refractive index of substrate
        double refractiveIndexSubstrate = 2;
        //define FOV rectangle (cartesian angles)
        VectorD FOV_CartesianAngles = new VectorD(30, 20);
```

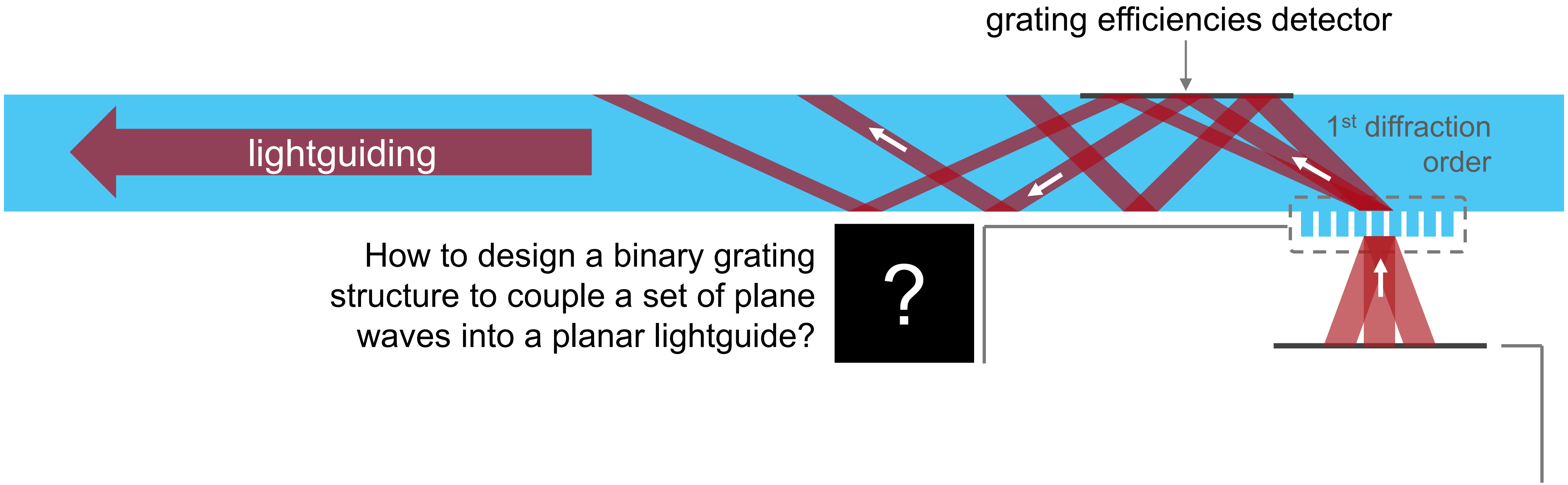
Output of the VirtualLab Module

C# Module: Output

```
public void Run() {
            […]

            //output of results
            if(minimumPeriod >= maximumPeriod){
                //log maximum period
                Globals.DataDisplay.LogMessage("The specified field of view can not be handled (completely coupled into the
                                               substrate) by the current media configuration.");
            }else{
                //log maximum period
                Globals.DataDisplay.LogMessage("Maximum Period = " + PhysicalUnits.FormatPhysicalUnit(maximumPeriod,
                                               PhysicalProperty.Length));
                //log minimum period
                Globals.DataDisplay.LogMessage("Minimum Period = " + PhysicalUnits.FormatPhysicalUnit(minimumPeriod,
                                               PhysicalProperty.Length));
            }
```



Optimization Task



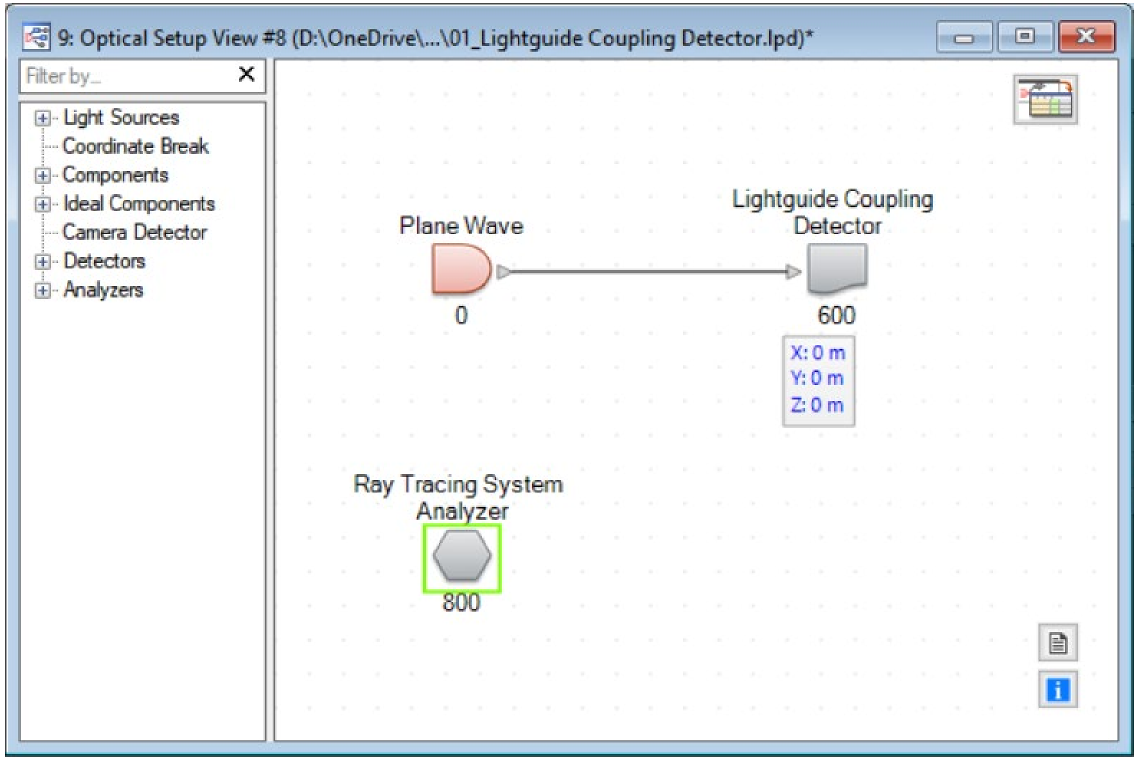
How to design a binary grating structure to couple a set of plane waves into a planar lightguide?

set of plane waves

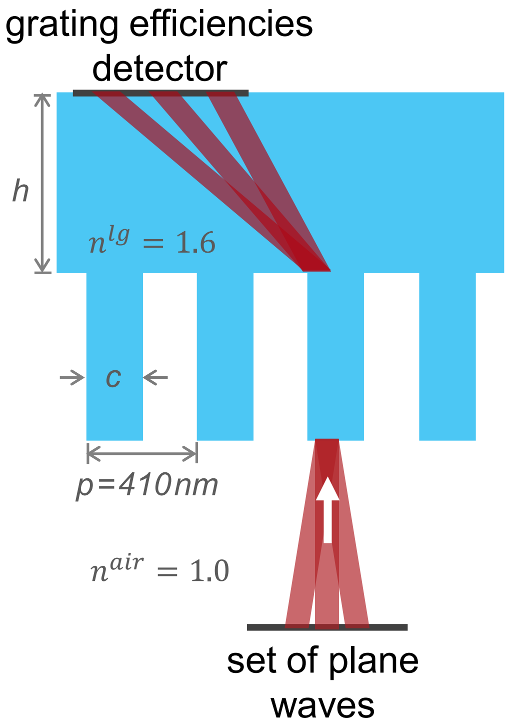
- field of view (-15..15, -10..10)°
- wavelength 532 nm
- linearly polarized along x-axis

Initialization of the Optical Setup

- Initial Setup in VirtualLab Fusion
  - Select the structure of grating
  - Modeling technique of grating is selected: Fourier Modal Method (FMM)
  - The detector returns value of merit function
    - Mean efficiency
    - Efficiency contrast (uniform contrast) over FOV



Simulation Results and Configuration of the Merit Function



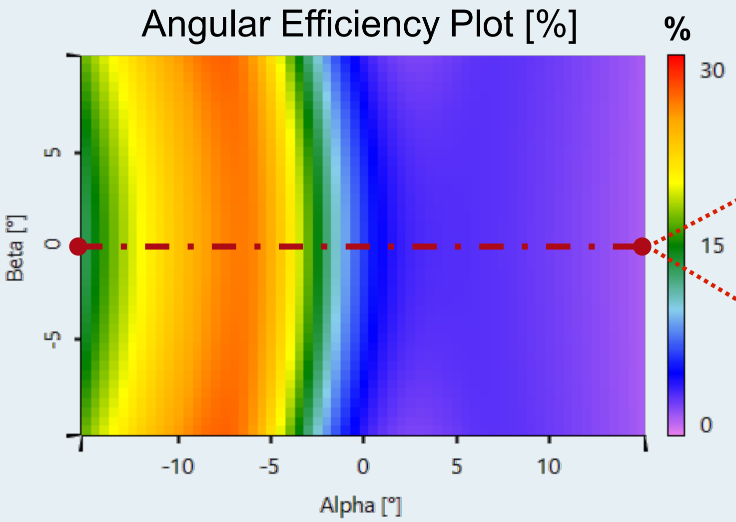
Inputs

- 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**

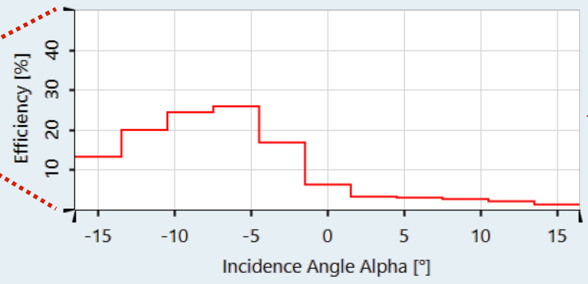
Initial Configuration of Grating	
fill factor	50.00%
modulation depth	400.00 nm
period	410 nm
operating order	1^{st} transmitted

to be varied

Detector Result: Grating Efficiencies



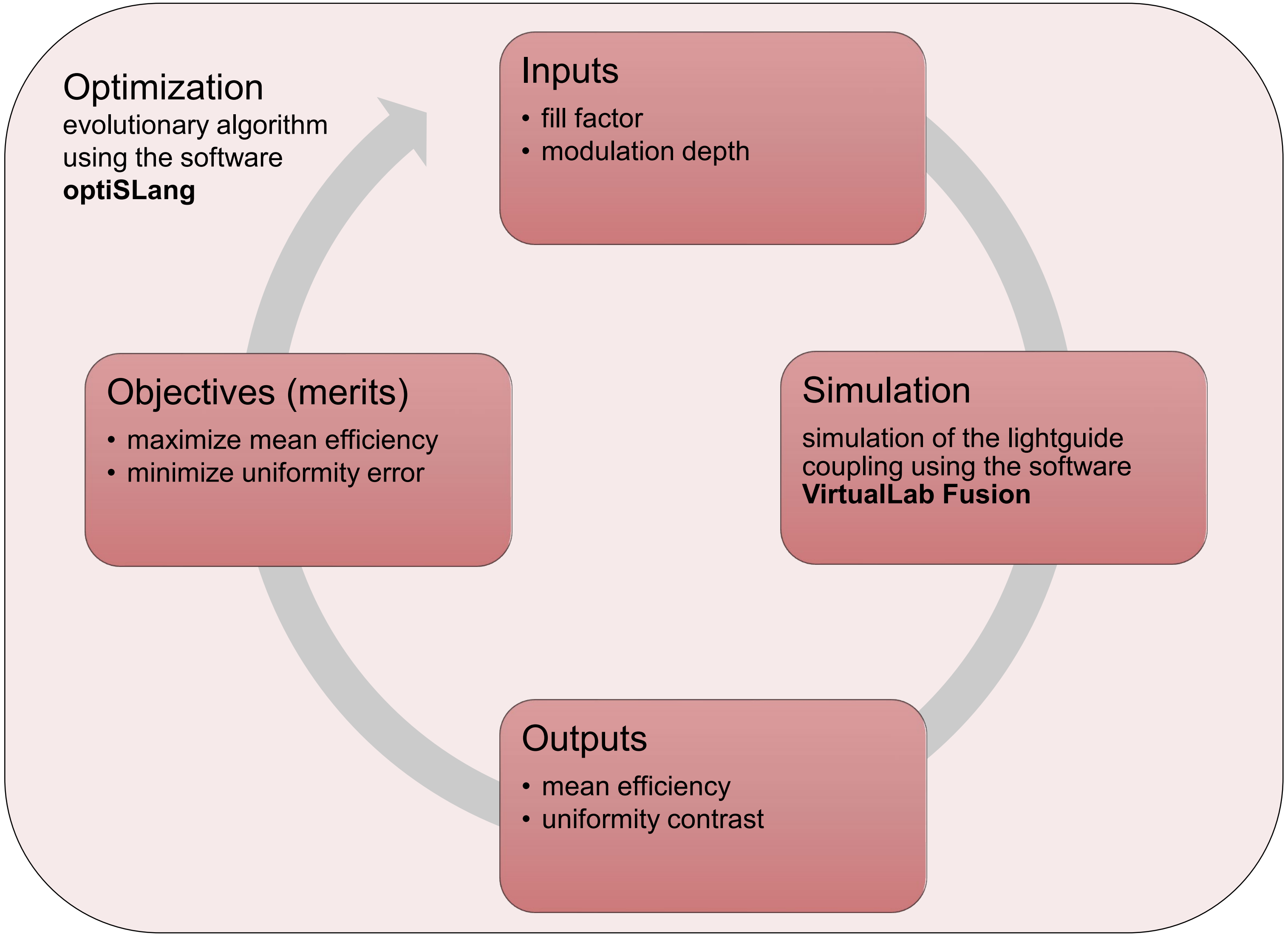
Mean Efficiency 10.96%
Uniformity Contrast 89.45%



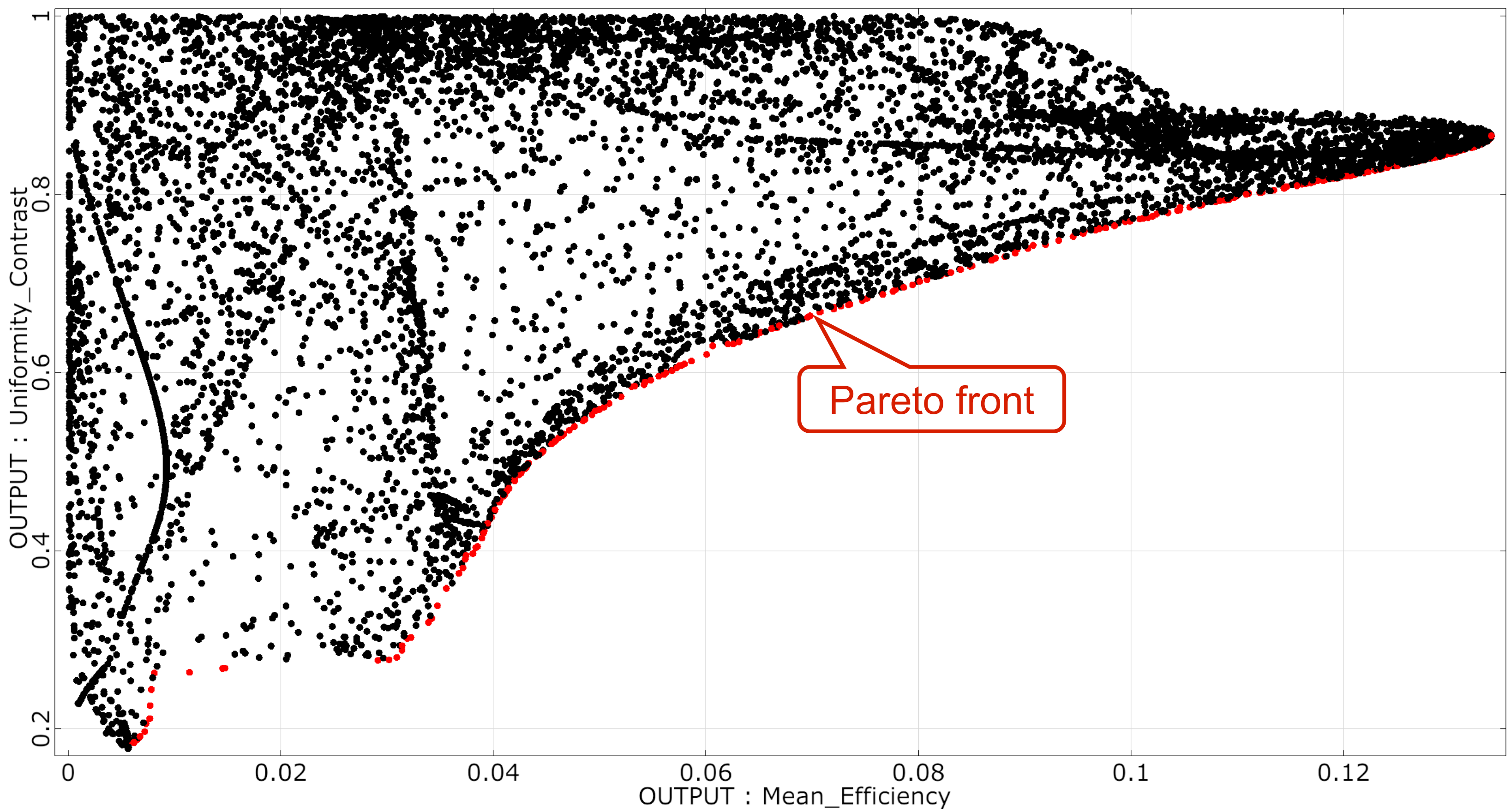
a roughly sampled evaluation of the incidence angles along the period is sufficient for the optimization

Optimization Workflow

- the following optimization workflow is applied to design a binary grating for efficient 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

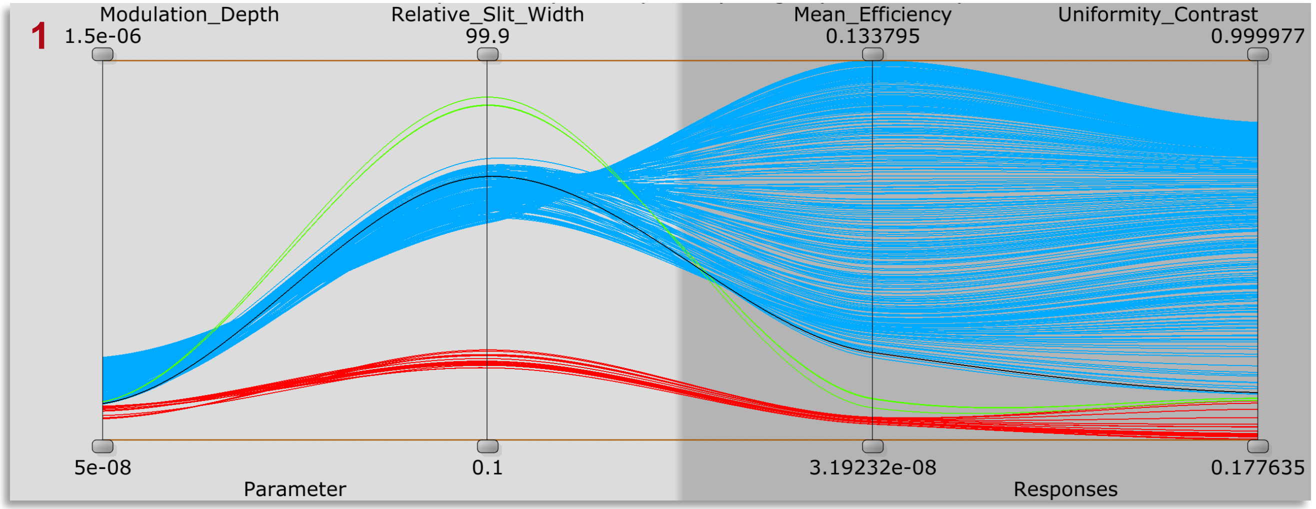


Optimization Results of optiSLang

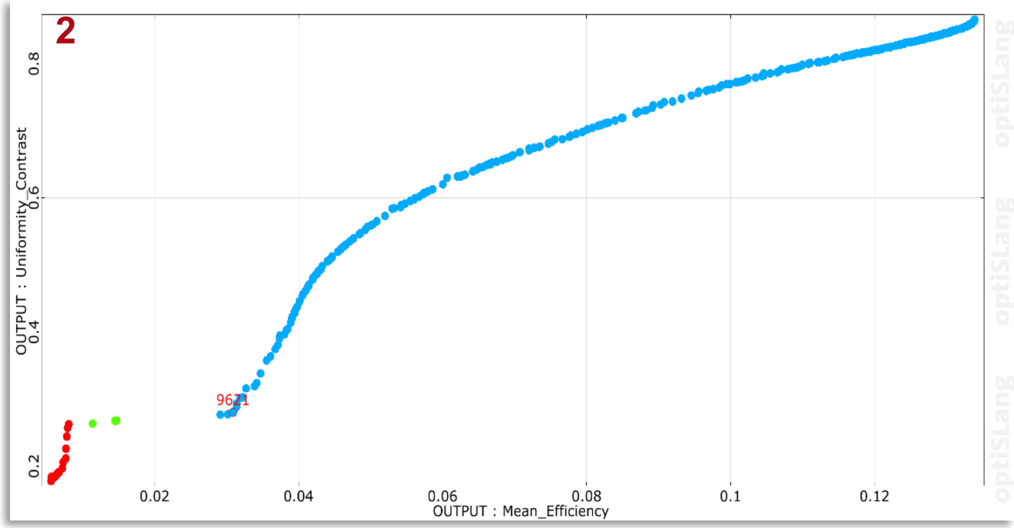


- the optimization results are plotted as a function of the merit functions
  - mean efficiency
  - uniformity contrast
- the Pareto front indicates the optimum compromise between the two merit functions (highlighted)
- any optimization result at the pareto front might selected depending on the needs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

Advanced Evaluation of the Optimization Results



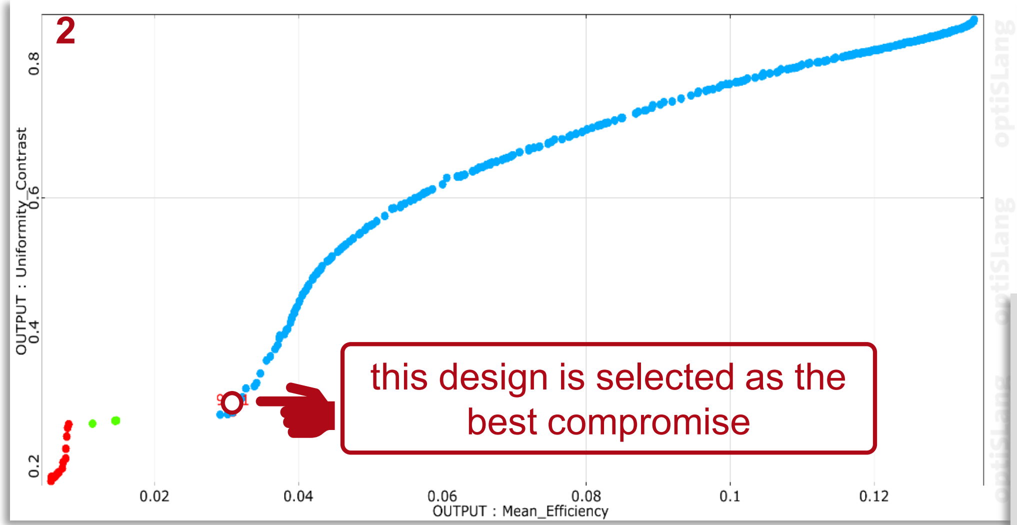
- for a better understanding how the input parameters are correlated to the output parameters, the Pareto front designs are visualized in a *Parallel Coordinates Plot* (1)
- in addition, a cluster analysis is performed to group a specific parameter (e.g. relative slit width) into colored clusters for highlighting the relationship of the input parameters to the output parameters
- for example, a low modulation depth and a low relative slit width (red cluster) lead to the best uniformity contrasts but to poor mean efficiencies on the other side
- furthermore, the same colors are visualized on the Pareto front (2) to visualize the clusters (here: the impact of the slit width on both objectives)
- therefrom, the optical designer is able to select a robust design with the best compromise between the input parameters and the output parameters

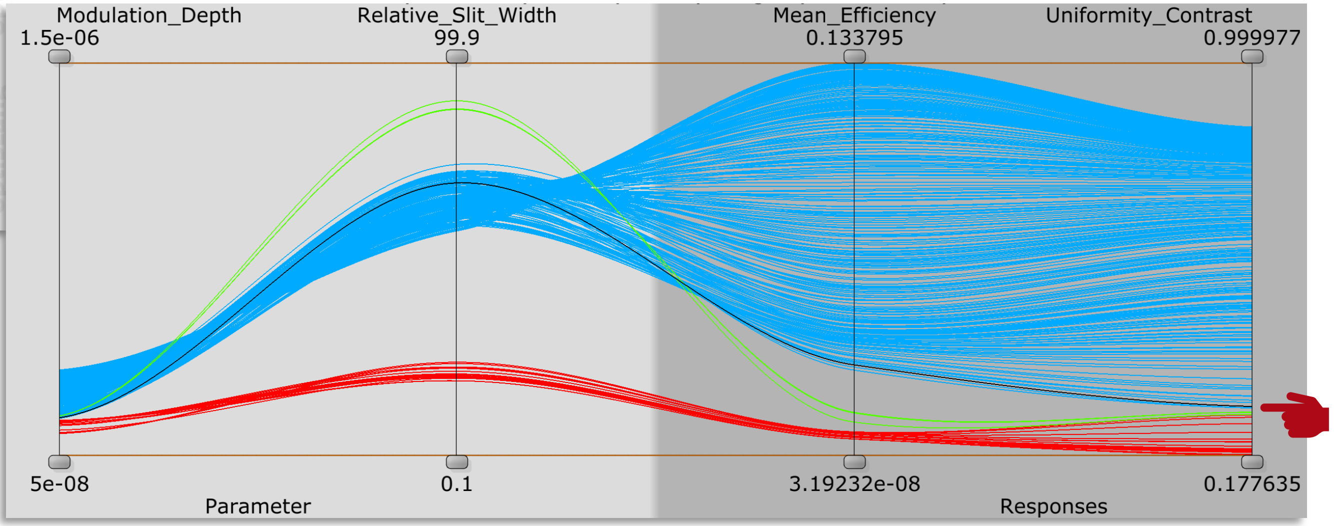


Advanced Evaluation of the Optimization Results

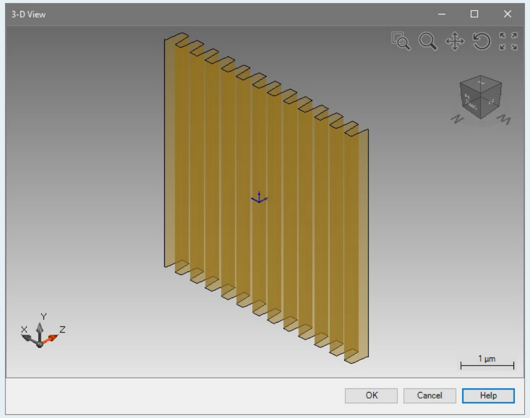
- as a result, a design is selected, which is the best compromise for a prioritized low uniformity contrast and an acceptable mean efficiency including manufacturable grating parameters

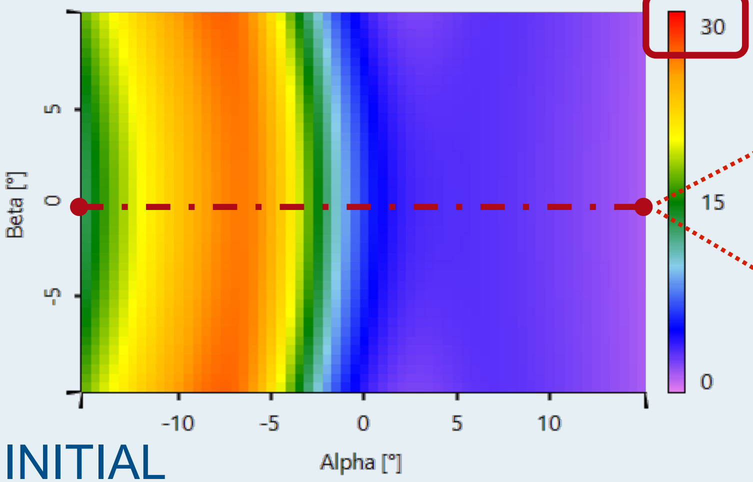
- the *Parallel Coordinates Plot* illustrates the corresponding input parameter combination for this design (black curve)





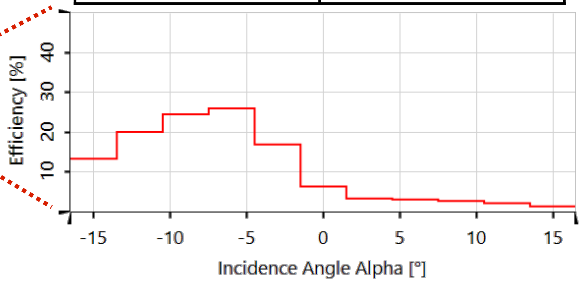
Analysis of Coupling Efficiency for Optimization Result



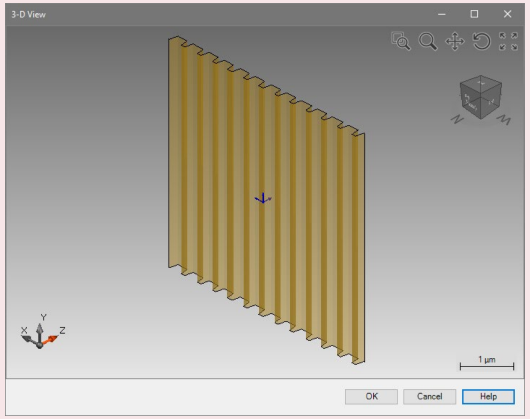


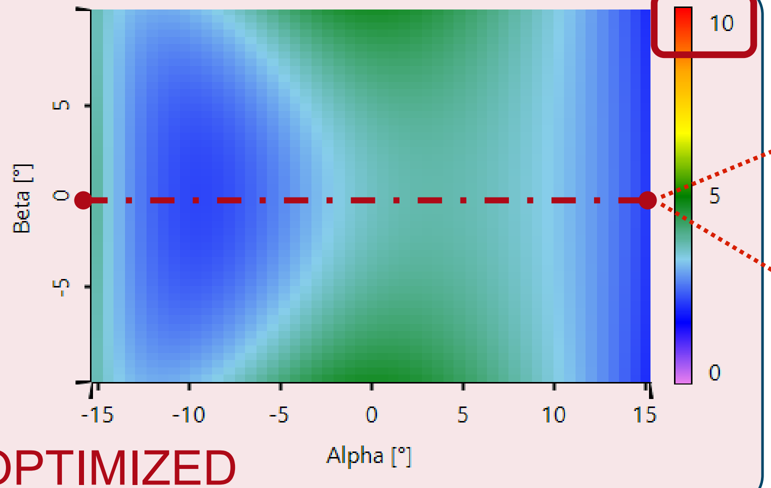
INITIAL

fill factor	50.00%
modulation depth	400.00nm



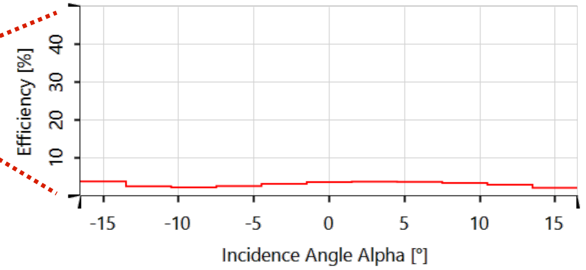
Mean Efficiency 10.96%
Uniformity Contrast **89.45%**





OPTIMIZED

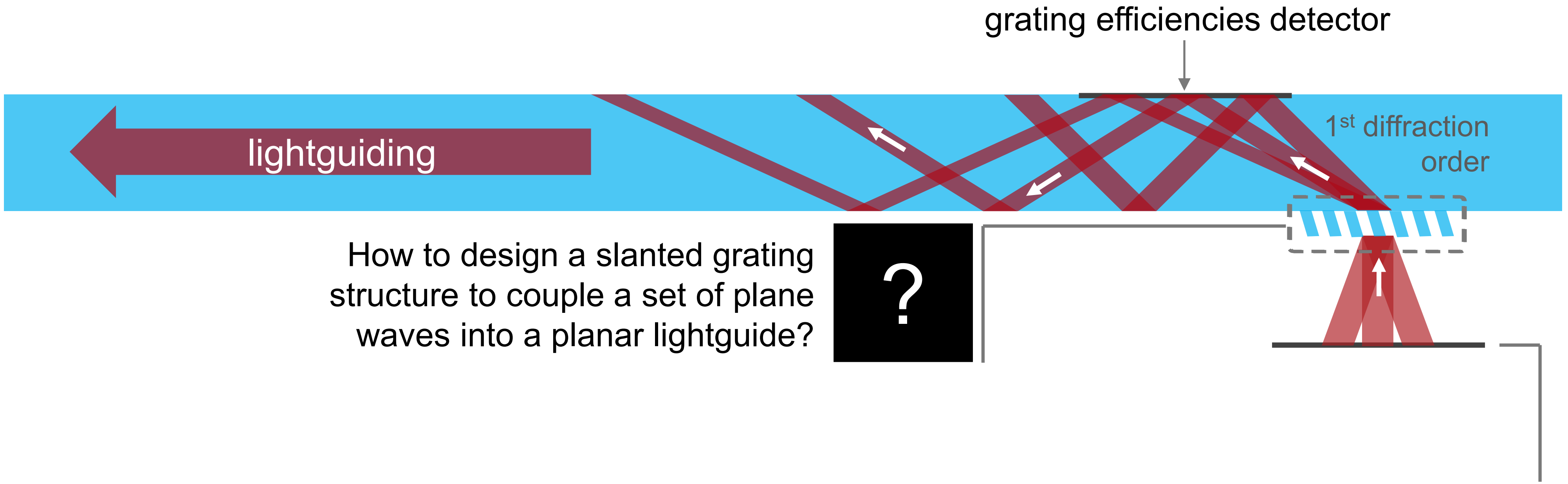
fill factor	68.43%
modulation depth	187.18nm



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

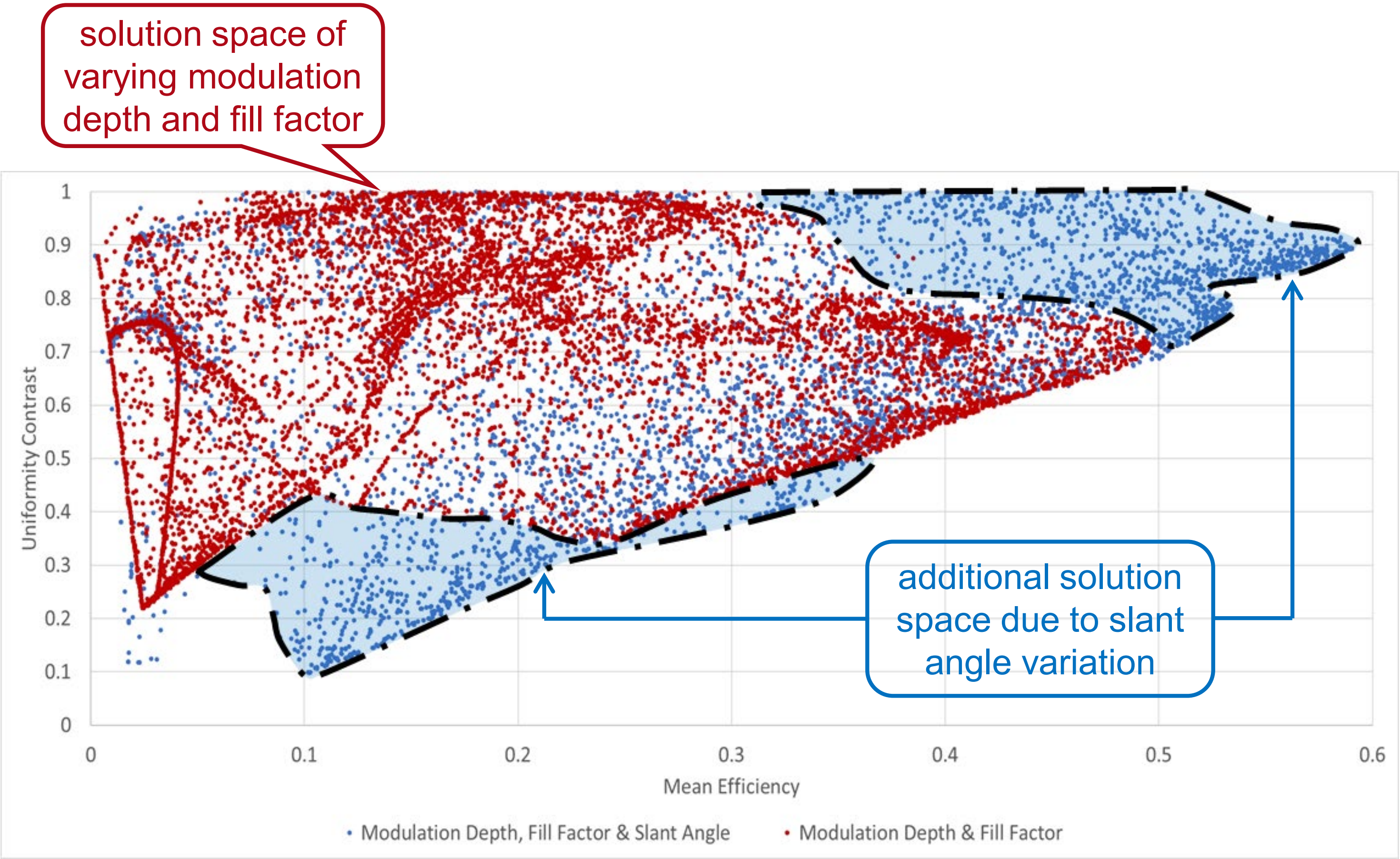


How to design a slanted grating structure to couple a set of plane waves into a planar lightguide?

set of plane waves

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

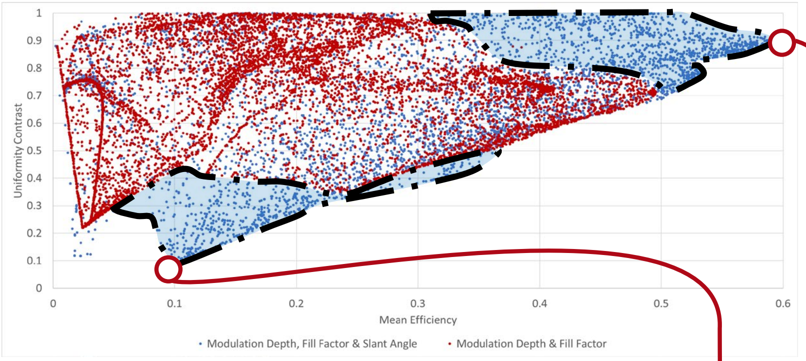
Optimization Result of optiSLang



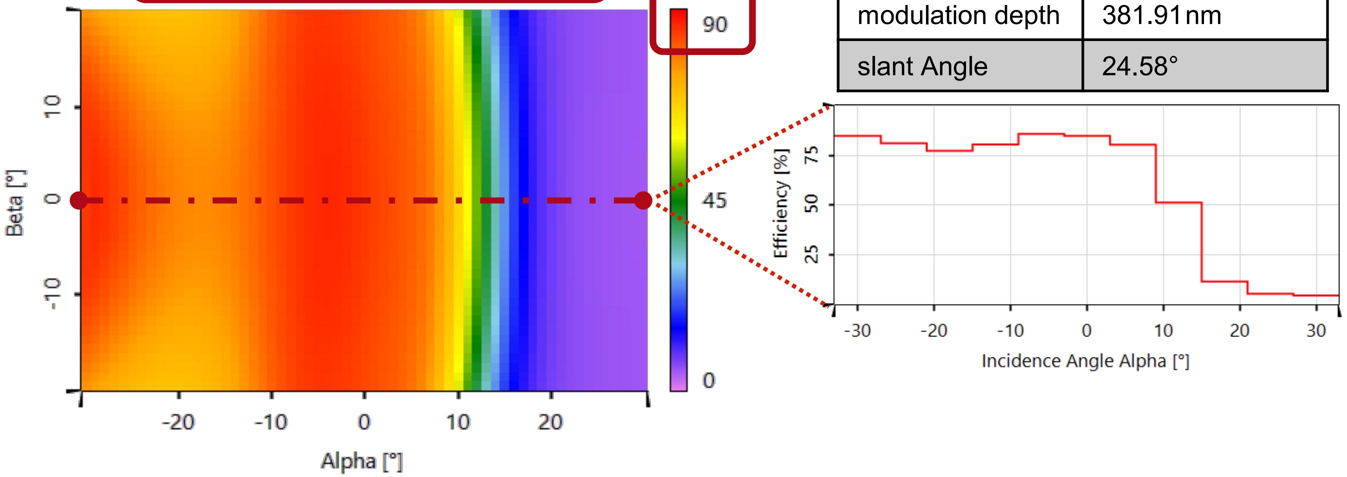
- an evolutionary optimization algorithm is applied using the optimization software optiSLang

- the additional freedom of the slant angle provides additional solutions

Analysis of Coupling Efficiency for Optimization Results

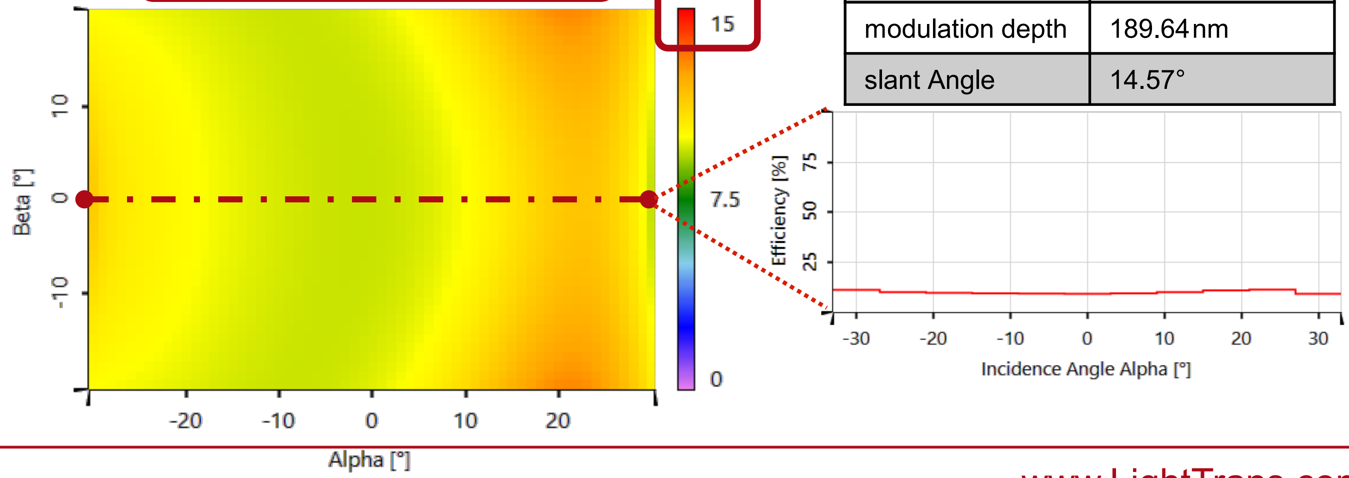


Mean Efficiency 58.74%
Uniformity Contrast 89.49%



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

Mean Efficiency 10.34%
Uniformity Contrast 15.51%



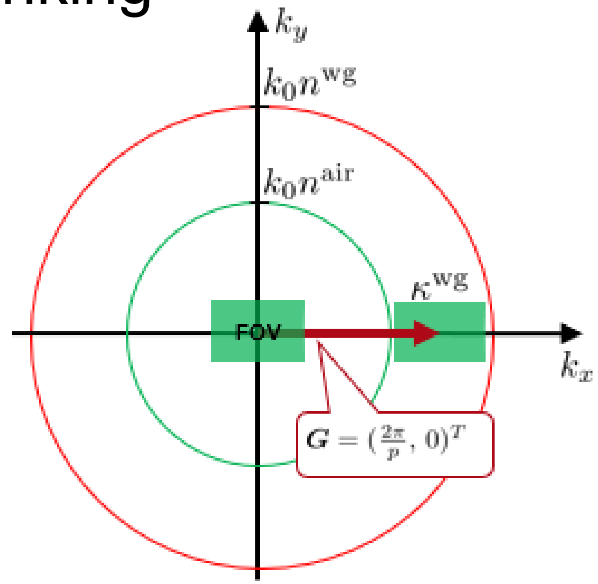
fill factor	90.00%
modulation depth	189.64 nm
slant Angle	14.57°

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

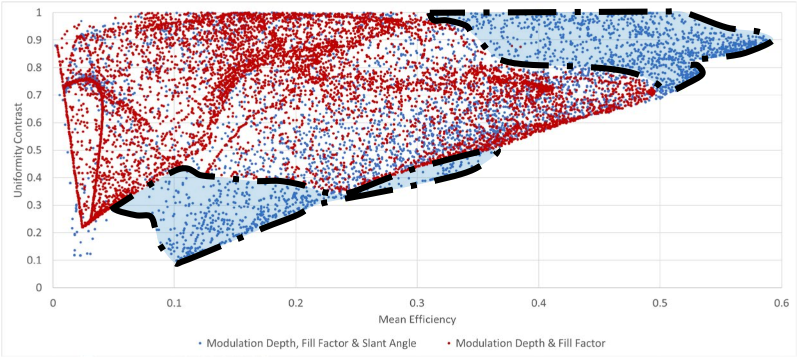
Conclusion

- Workflow of designing a coupling grating of lightguide, with considering a certain field of view (FOV)

  - fix the period of grating by using k-domain thinking



  - parametric optimization to achieve a high effciency which is uniform over desired FOV



Thank you!