WOST, Weimar

Design and Optimization Strategy of Coupling Gratings for Near-Eye Displays

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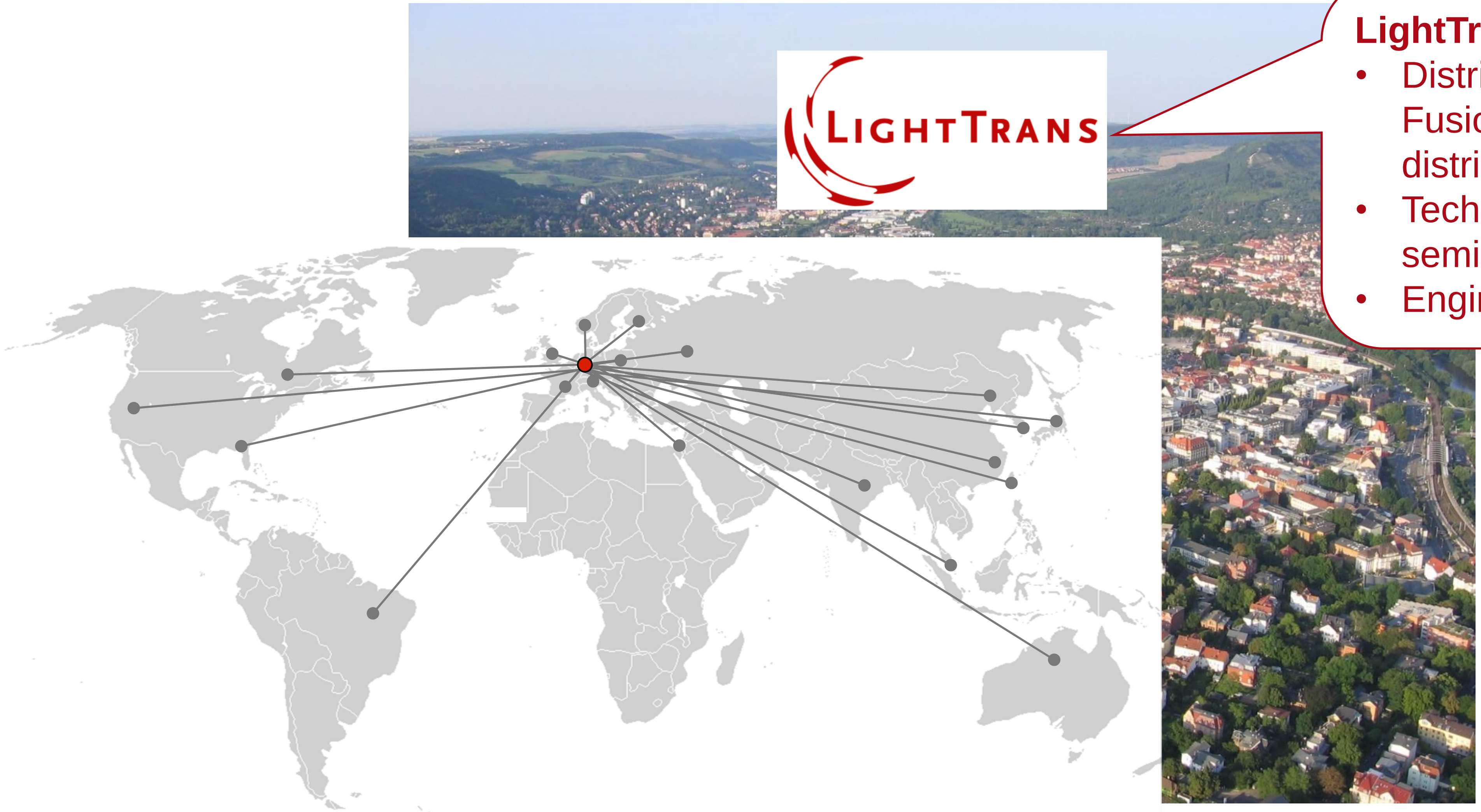
Jena, Germany

LightTrans International



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

Tim Cook on Augmented Reality

MASHABLE, OCT 04, 2016

https://mashable.com/2016/10/03/tim-cook-augmented-reality/

"**AR I think is going to become really big**," said Cook. "VR, I think, is not gonna be that big, compared to AR **… How long will it take? AR gonna take a little while, because there's some really hard technology challenges there. But it will happen. It will happen in a big way.** And we will wonder, when it does [happen], how we lived without it. Kind of how we wonder how we lived without our [smartphones] today."

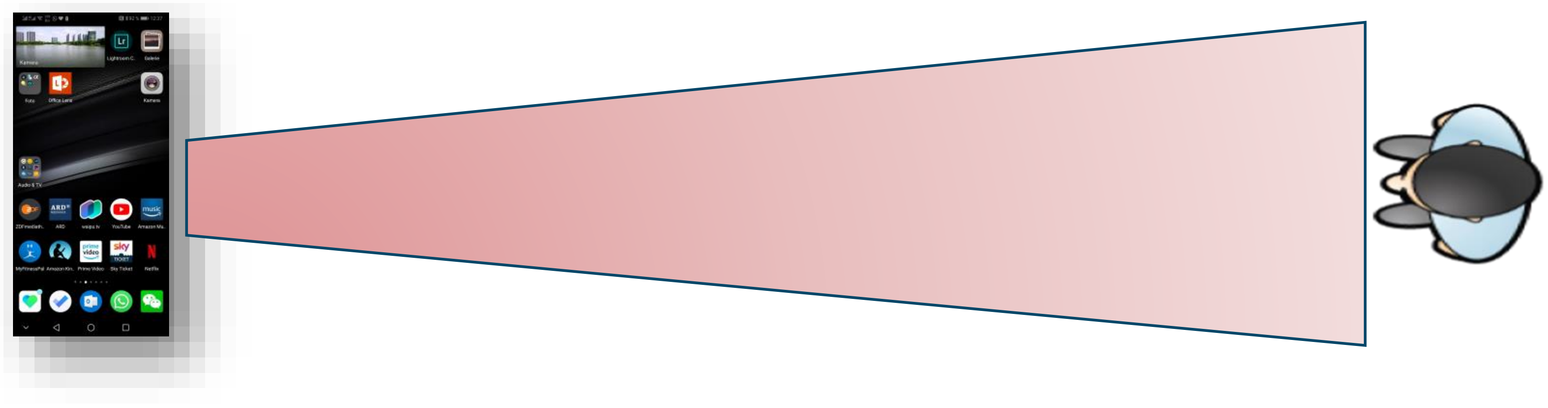
Tim Cook on AR Glasses

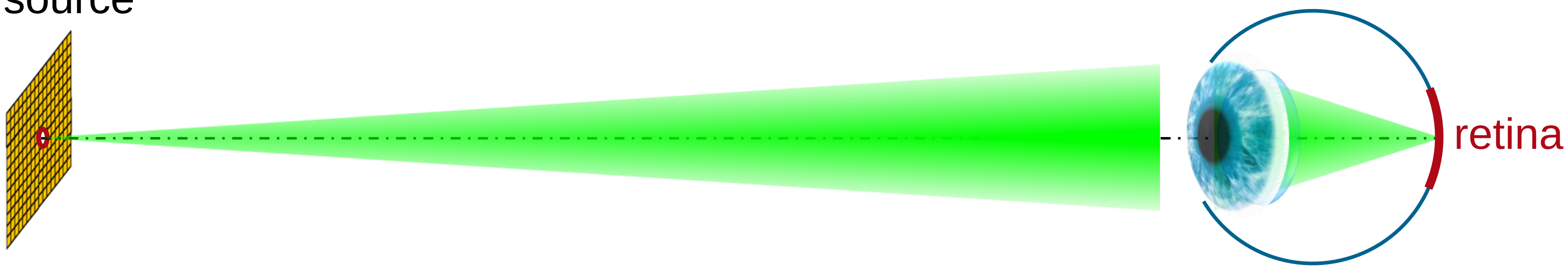
Independent, 10 October 2017

https://www.independent.co.uk/life-style/gadgets-and-tech/features/

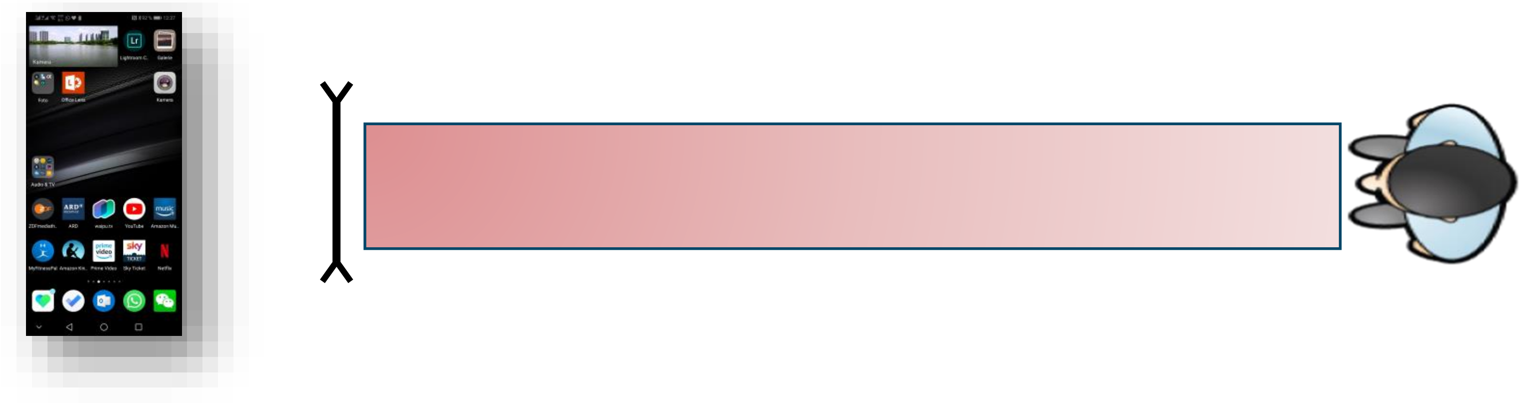
- "But today I can tell you the **technology itself doesn't exist to do that in a quality way**. The display technology required, as well as putting enough stuff around your face – there's huge challenges with that."
- "**The field of view, the quality of the display itself, it's not there yet**," he says. And as with all of its products, Apple will only ship something if it feels it can do it "in a quality way".

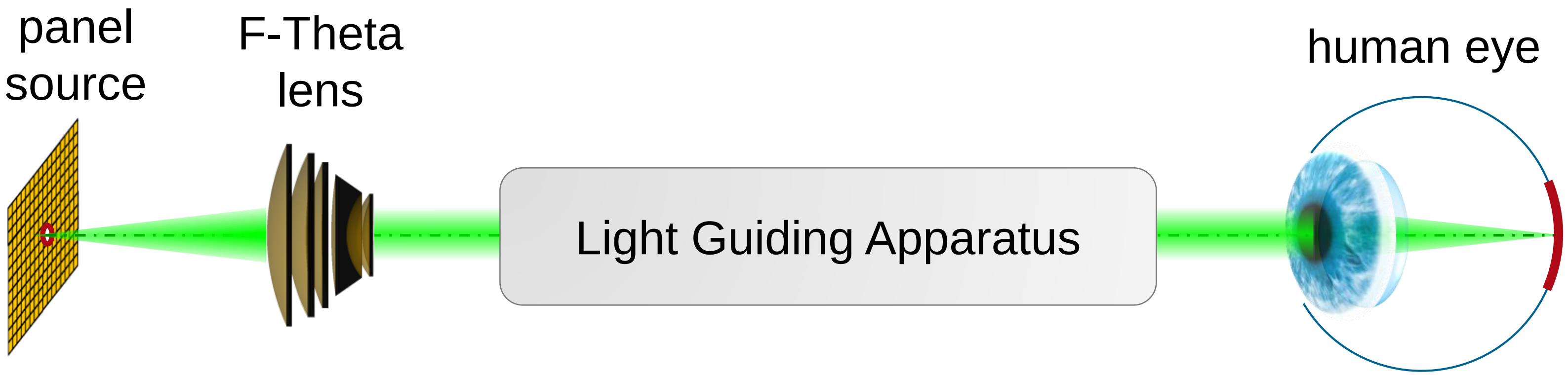
Typical Imaging Unit



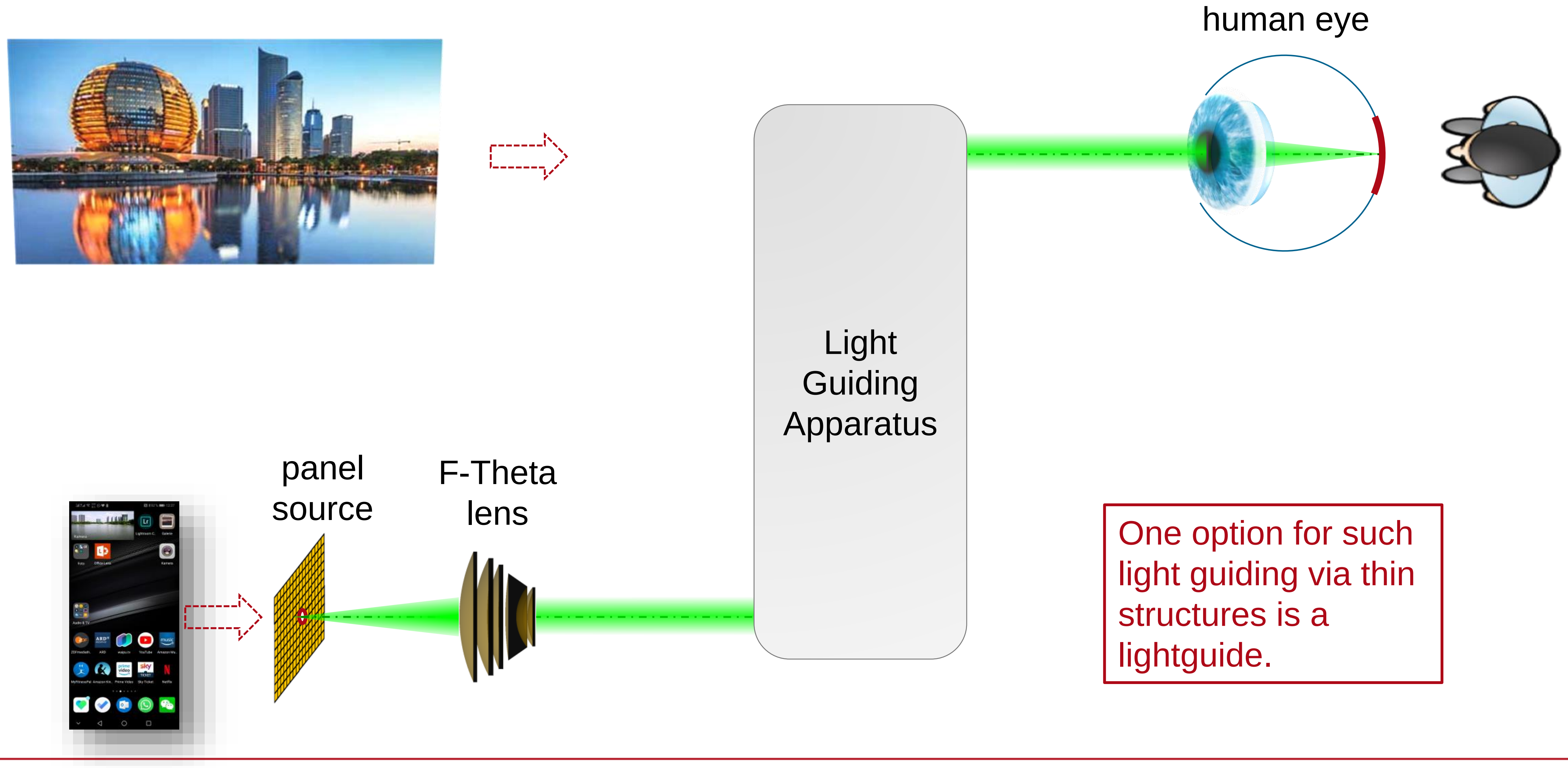


Typical Additions to Basic Setup



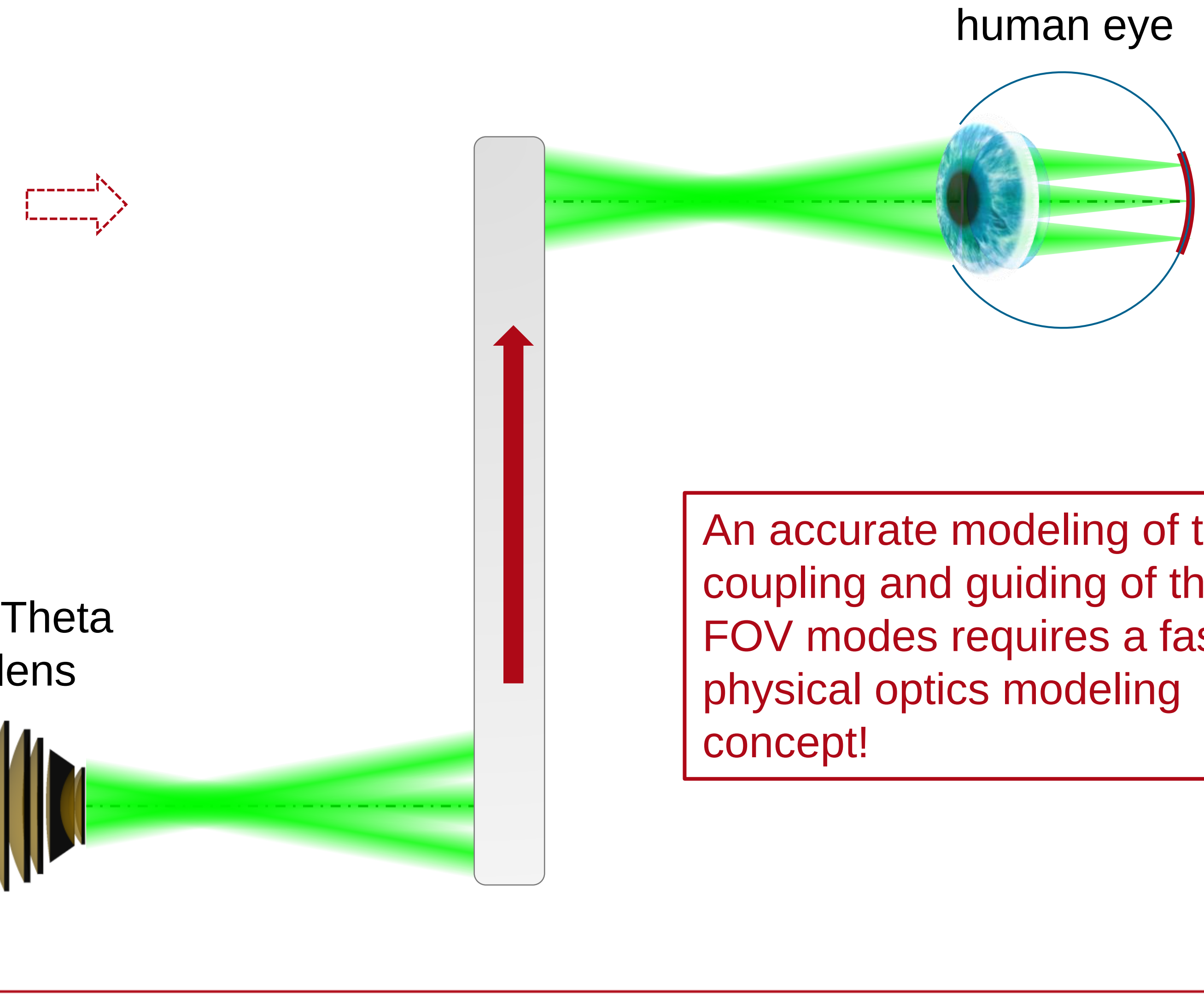


Redirection & Light Path Extension



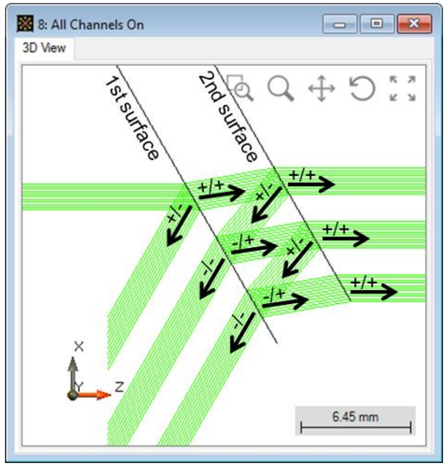
One option for such light guiding via thin structures is a lightguide.

Redirection & Light Path Extension

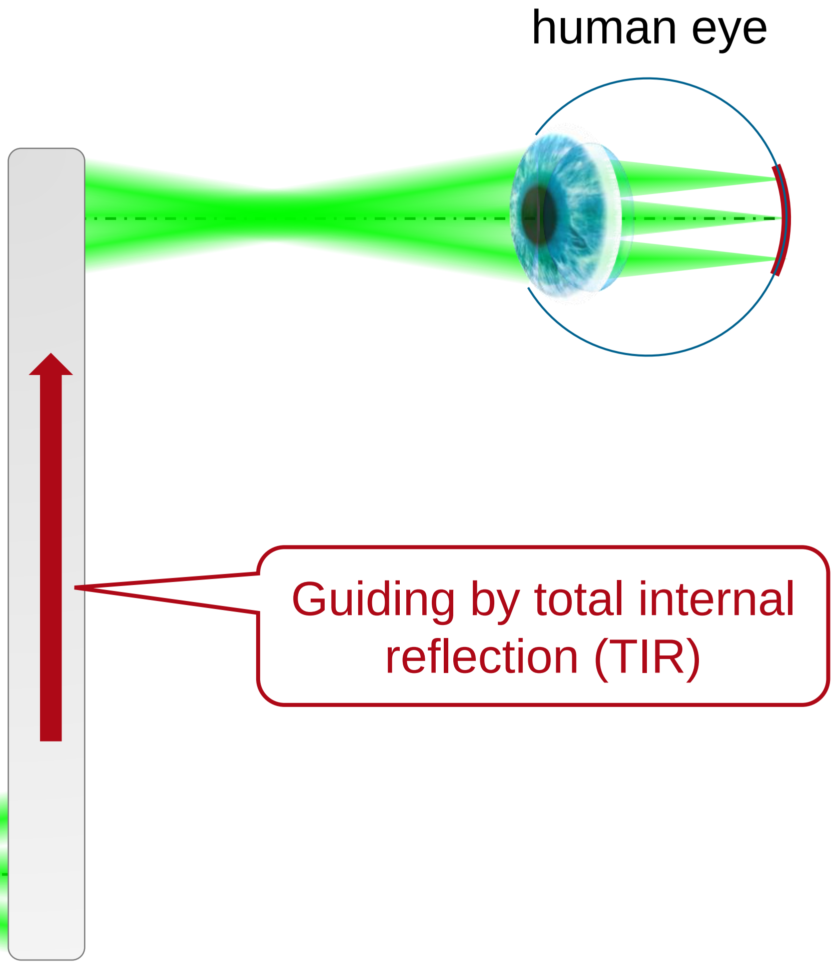


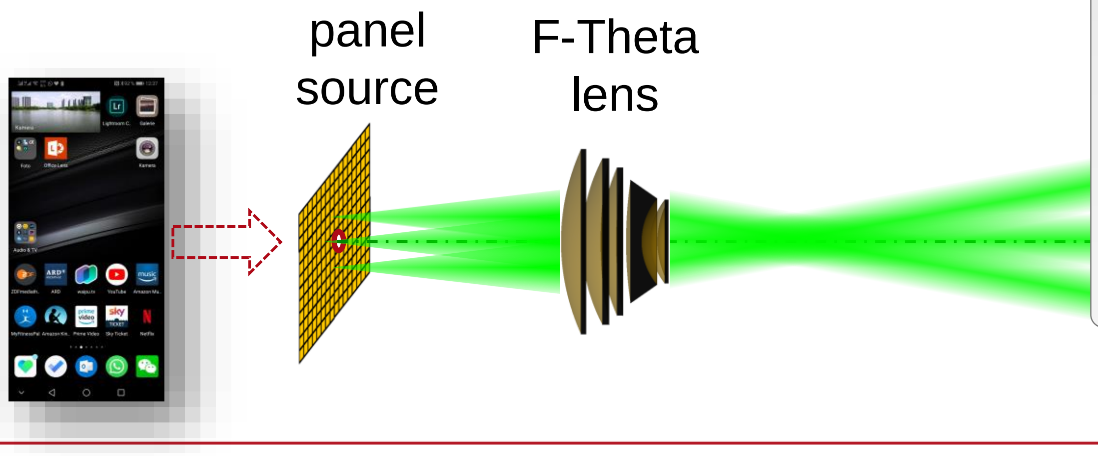
An accurate modeling of the coupling and guiding of the FOV modes requires a fast physical optics modeling concept!

Non-Sequential Light Propagation

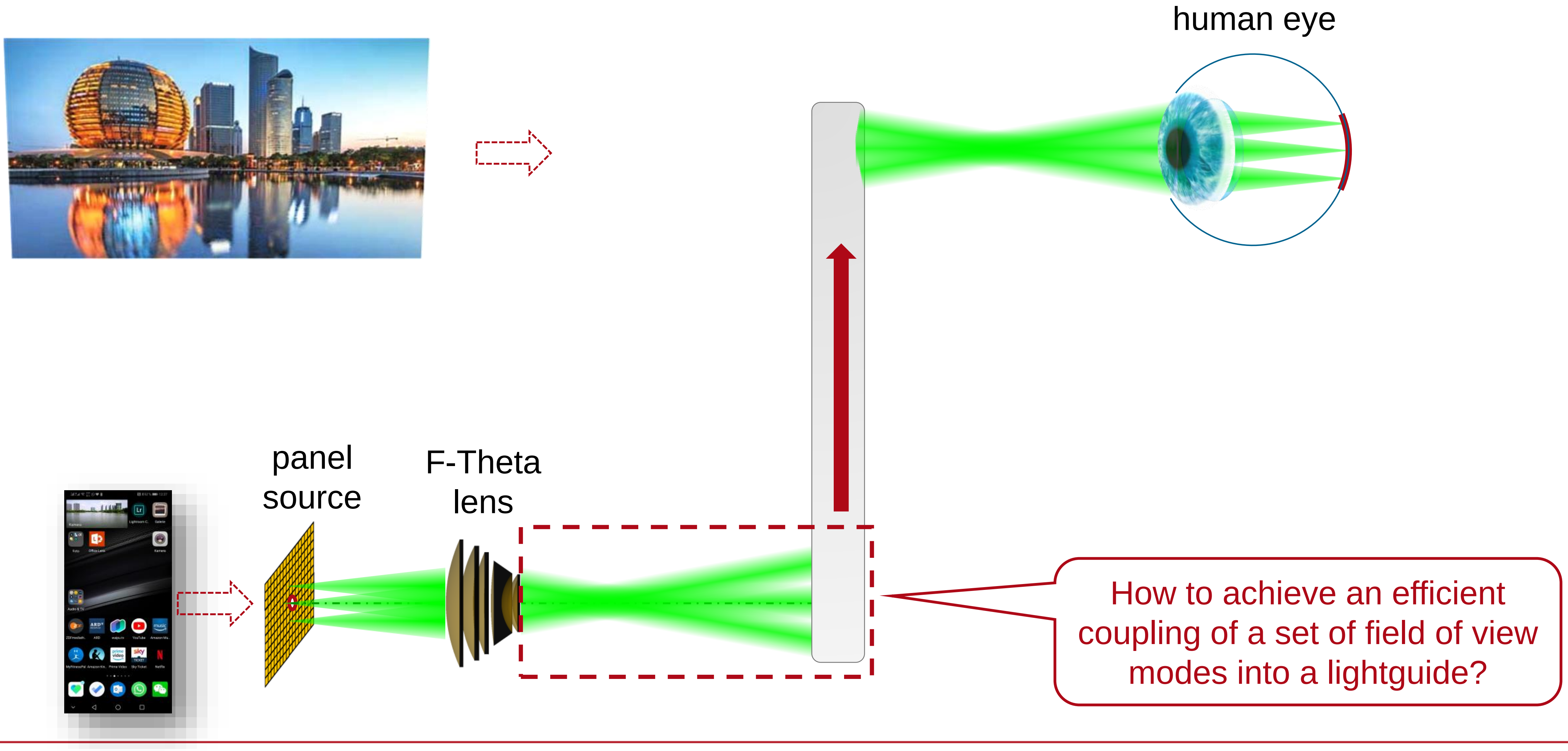


Lightguide simulations require a good **non-sequential** light propagation capability!

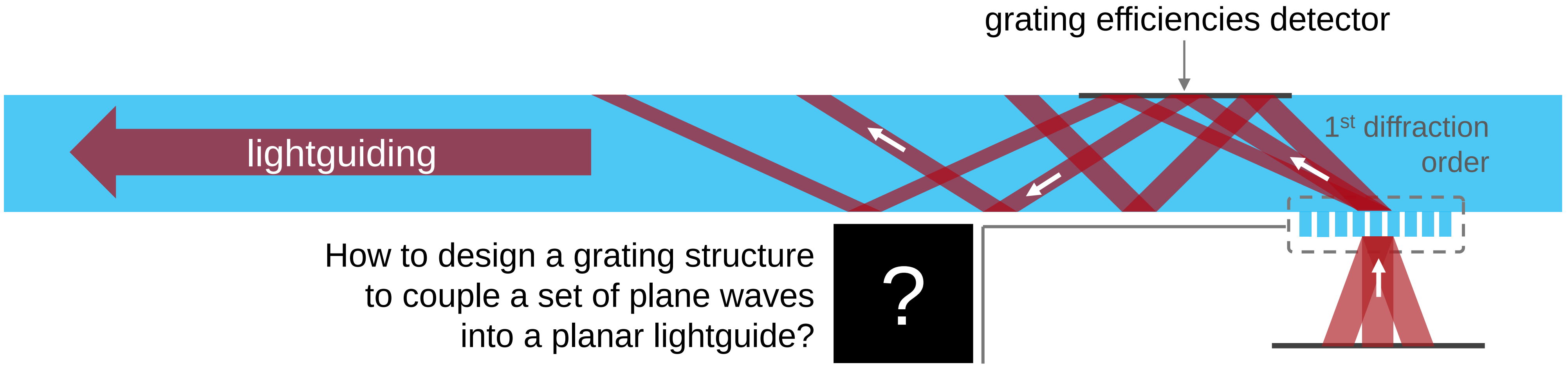




Lightguide Coupling Approach



Lightguide Coupling Approach



set of plane waves

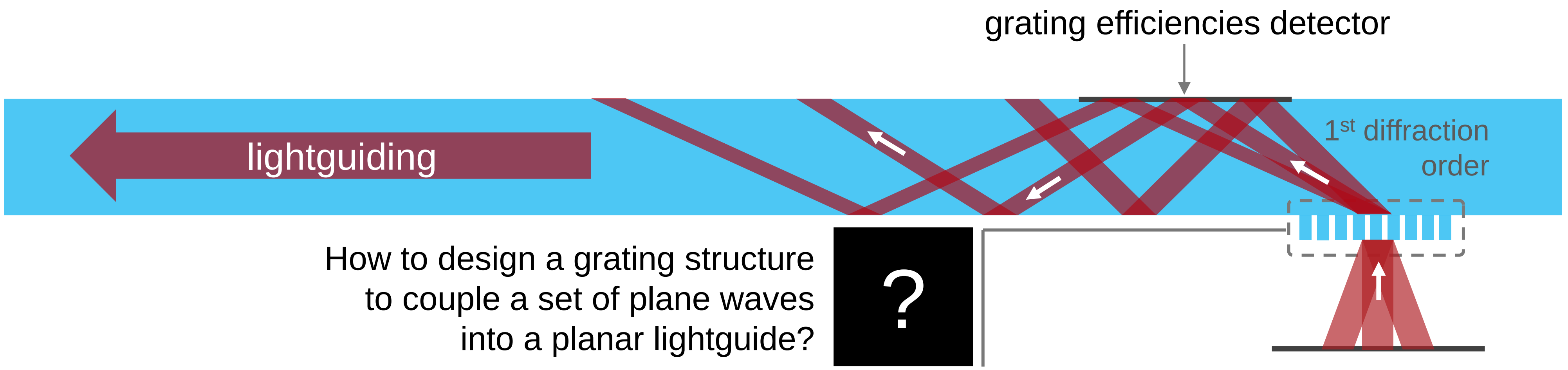
- field of view (-15..15, -10..10)°
- wavelength 532 nm
- linearly polarized along x-axis

Workflow:

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

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

Lightguide Coupling Approach



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Mathematical Modeling: Direction Vector and *k*-Domain

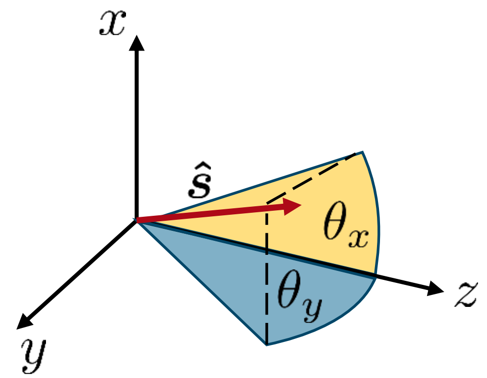
- Field of View (FOV) angles denoted by the Cartesian angles θ_x and θ_y.
- This defines a unit direction vector according to

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

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

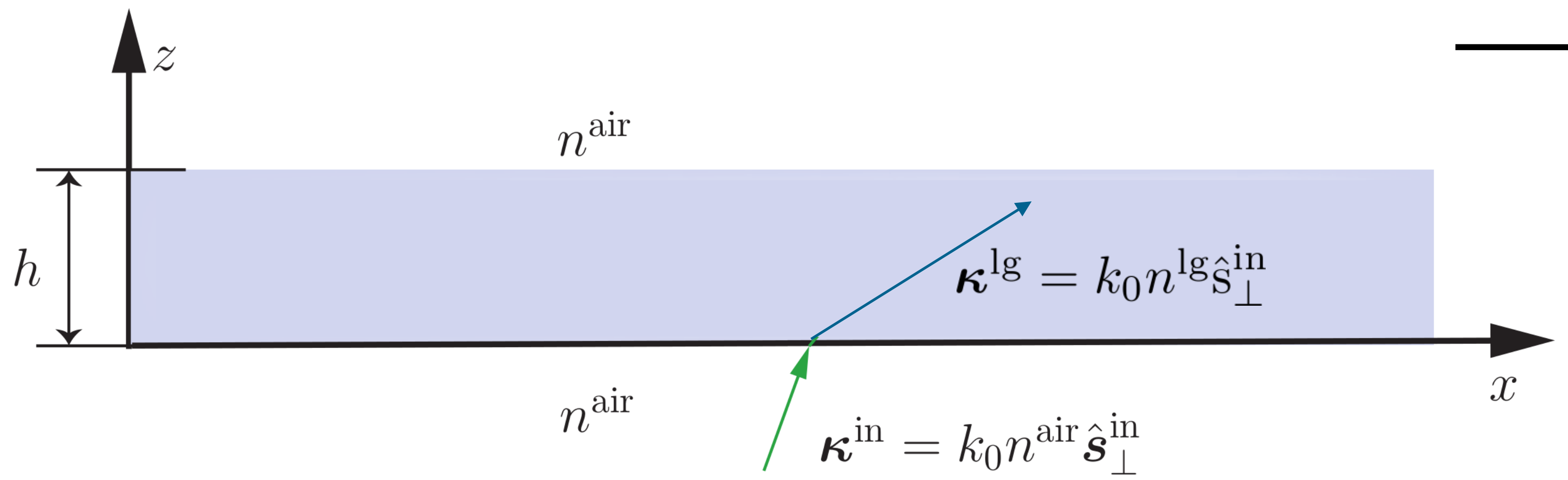
$$\boldsymbol{k} = k_0 n \hat{\boldsymbol{s}},$$

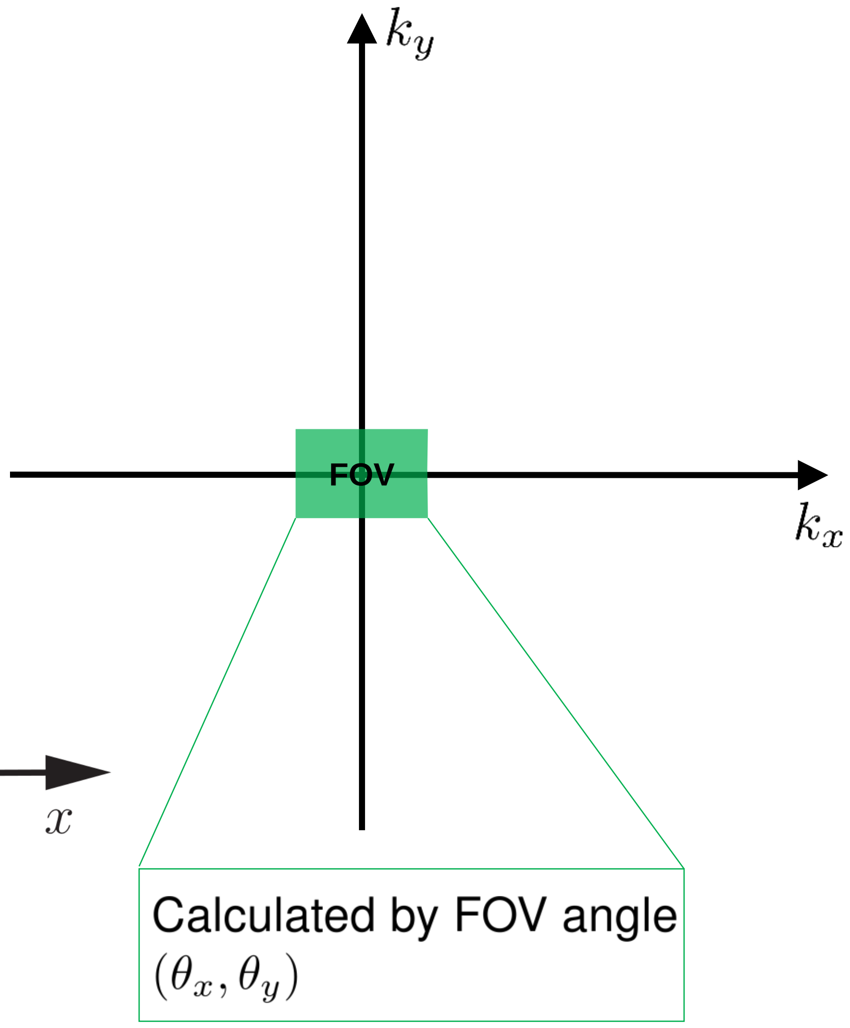
with $k_0 = 2\pi/\lambda$ and the refractive index n of the medium in which we consider the wave.



Mathematical Modeling: k-Domain Consideration

The consideration of the coupling and guiding situation of the FOV modes in the spatial frequency domain is much more convenient than in the space or angular domain!

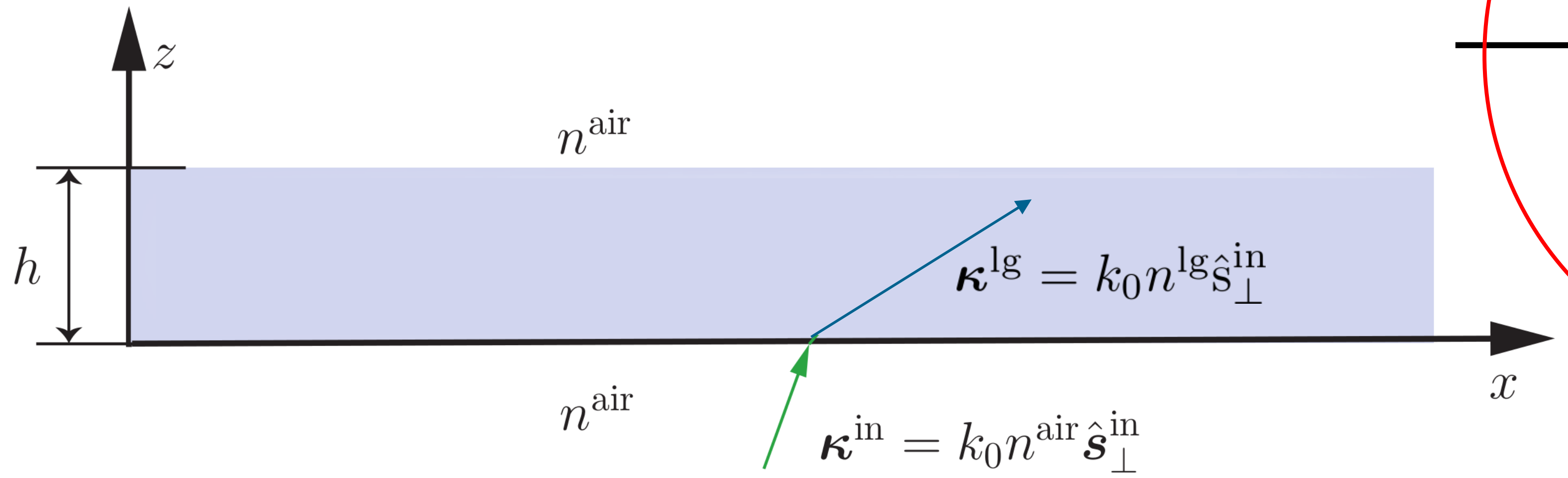


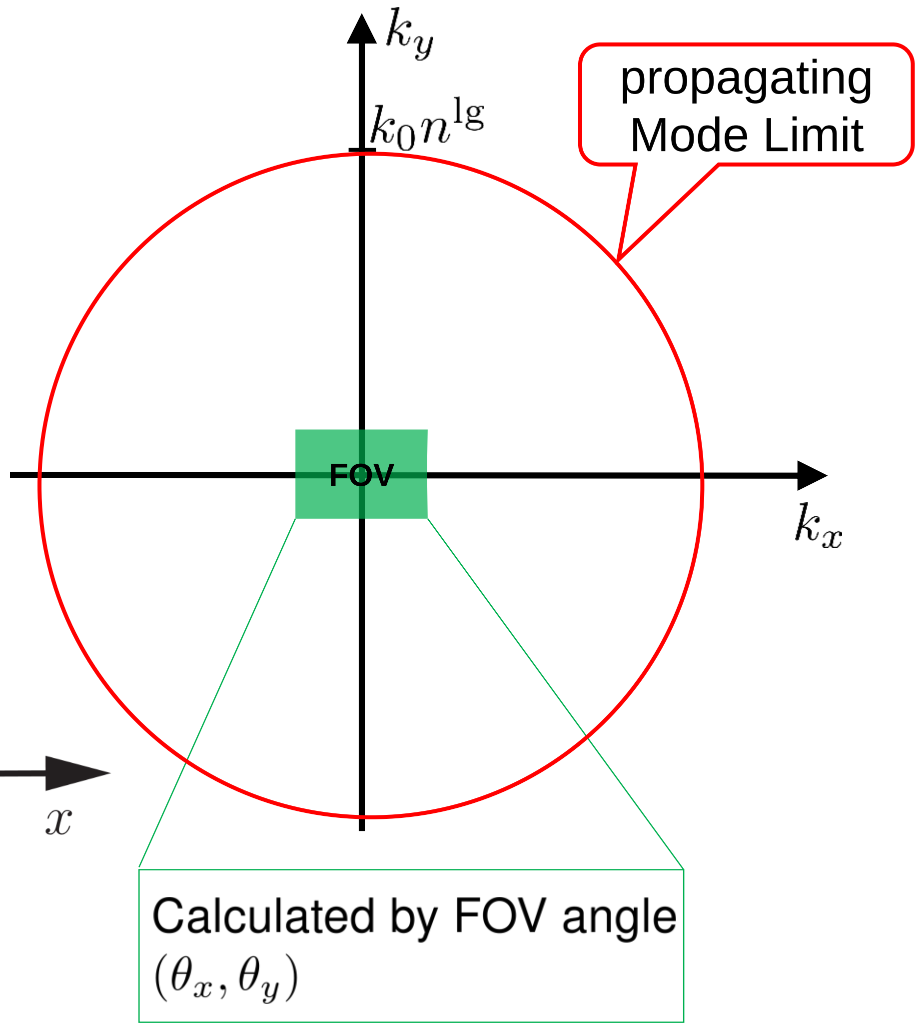


Mathematical Modeling: Propagating Mode Condition

A guided mode must be a propagating mode

$$\kappa^{\mathrm{lg}} \leq k_0 n^{\mathrm{lg}}$$

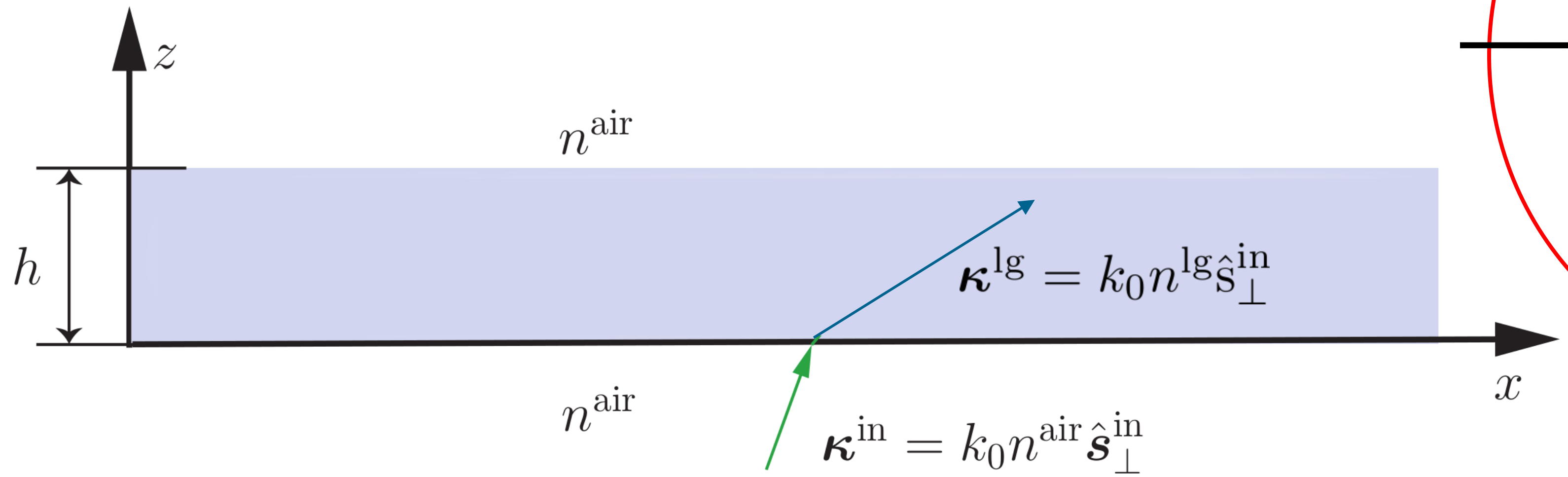


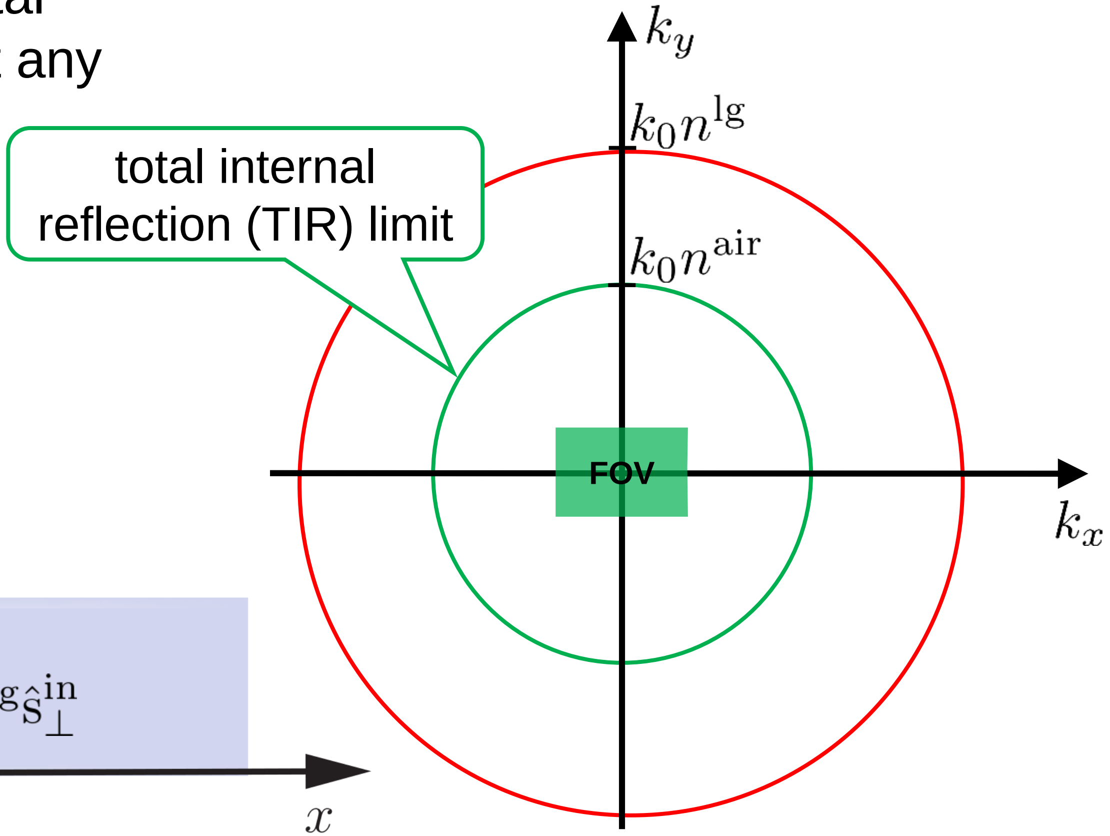


Mathematical Modeling: TIR Condition

Furthermore, the guided mode must fulfill the total internal reflection condition to propagate without any losses

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

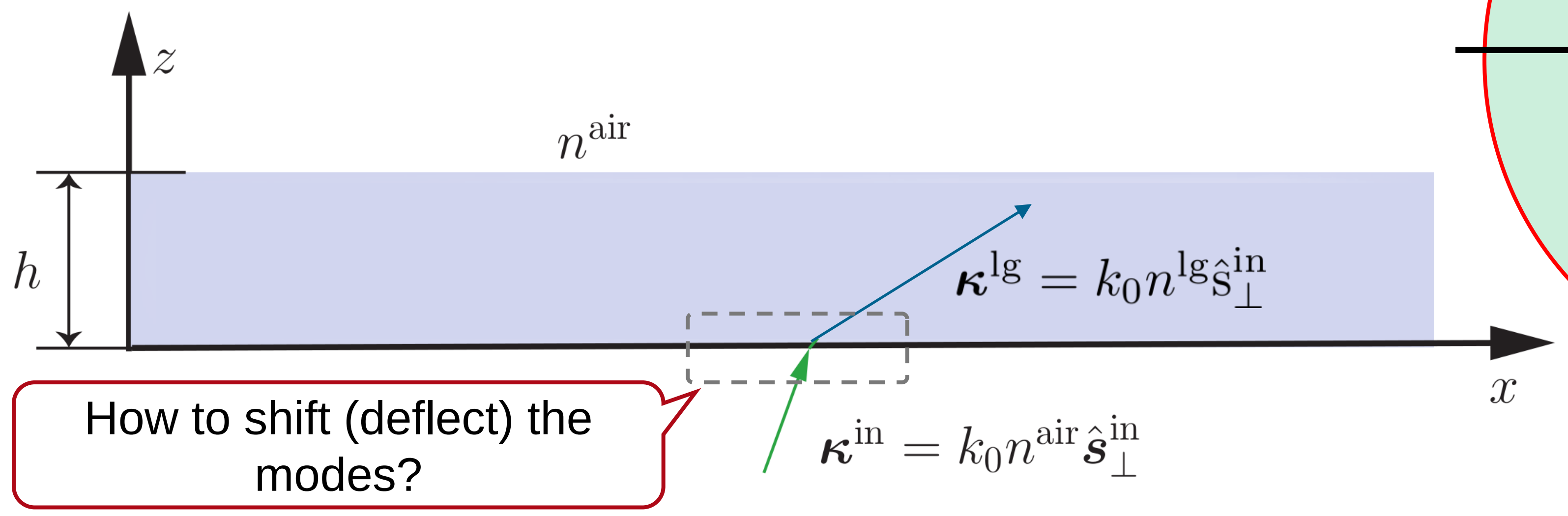


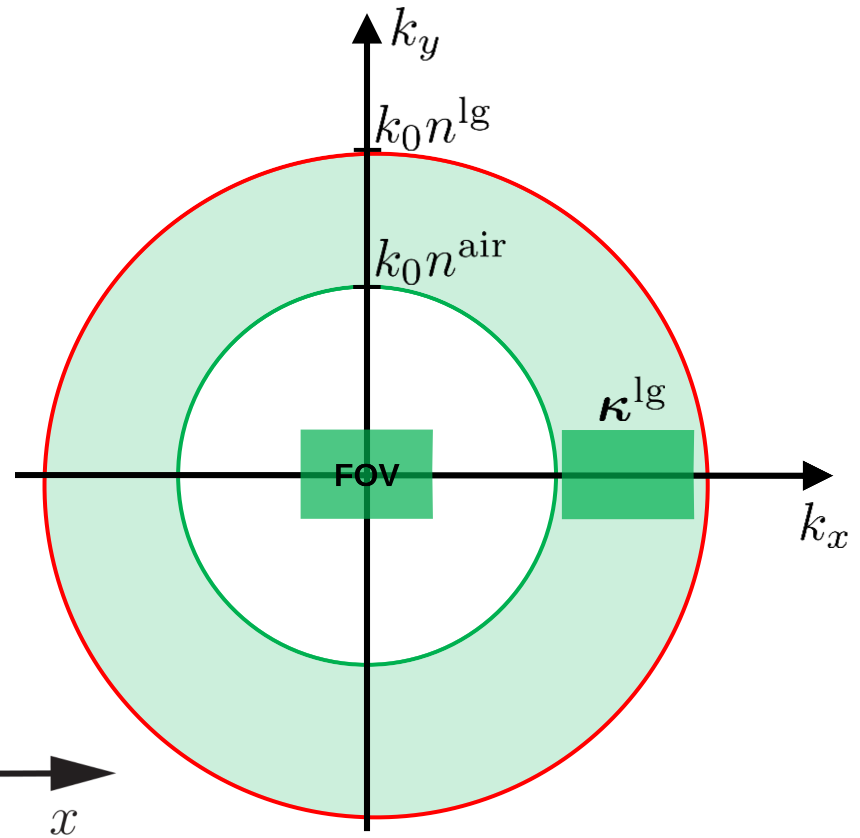


Mathematical Modeling: Guiding Condition

These both condition lead to the guiding condition of lightguides

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





Lightguide Coupling by Gratings

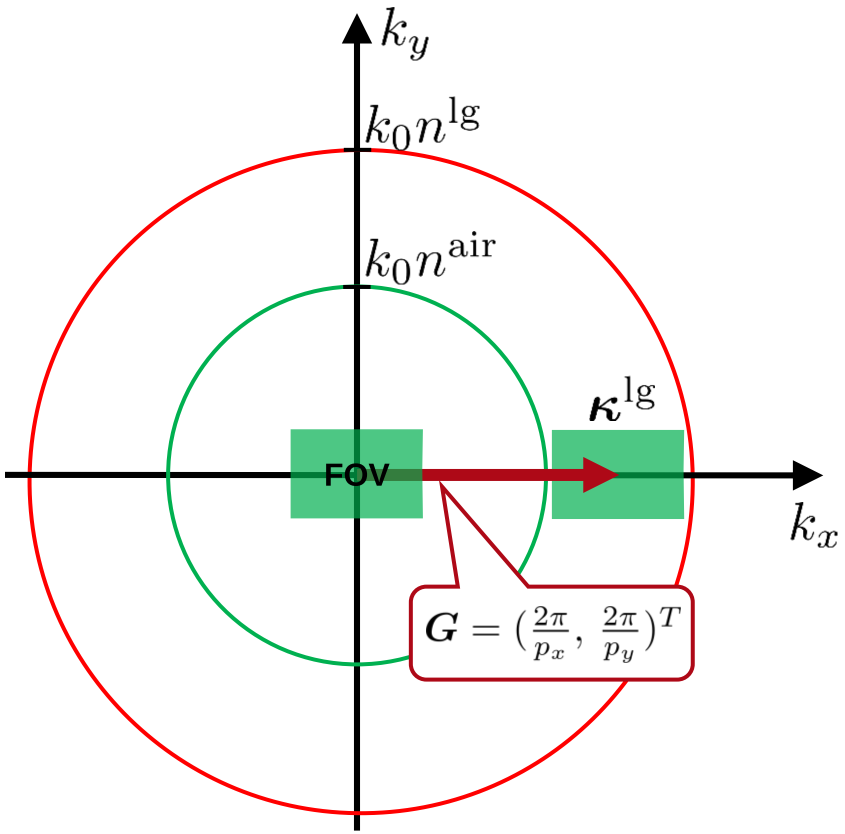
A grating is an elegant component for the coupling because the FOV is shifted in the k-domain under consideration of the grating vector $\boldsymbol{G}$.

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

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

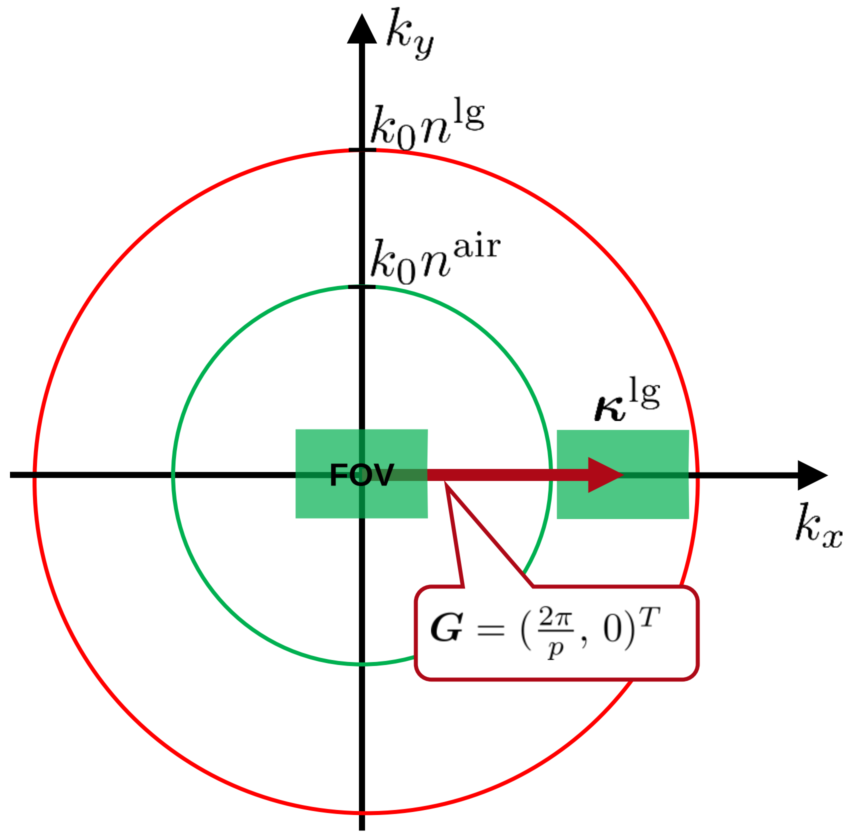


Period Calculation According to Guiding Condition

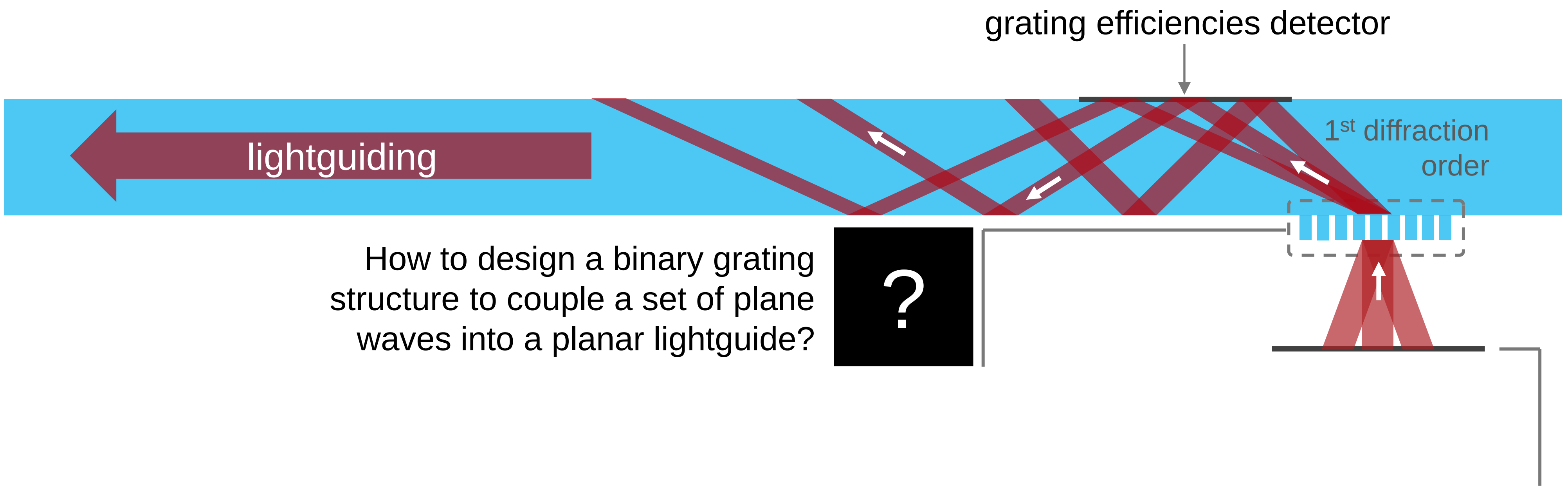
- In case of 1D-periodic gratings one component of the grating vector becomes zero, so that $G_y = 0$ without loosing of generality.

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

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



Optimization Task



Workflow:

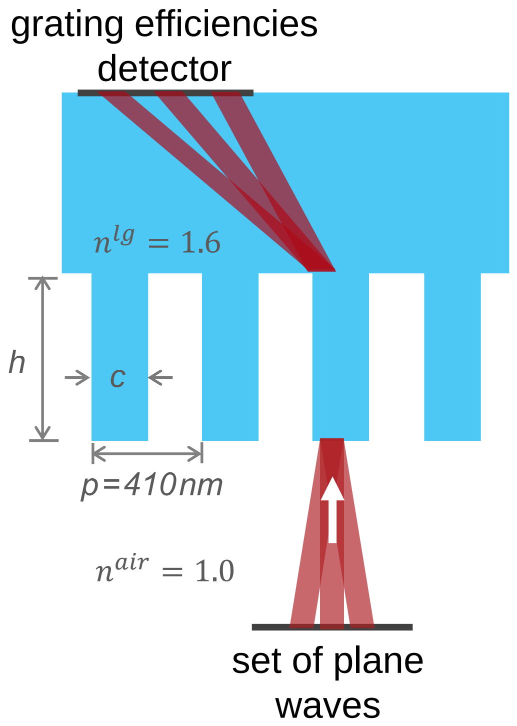
1. Determination of the grating vector (period and orientation) to fulfill the guiding condition of lightguides

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

set of plane waves

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

Simulation Results and Configuration of the Merit Function



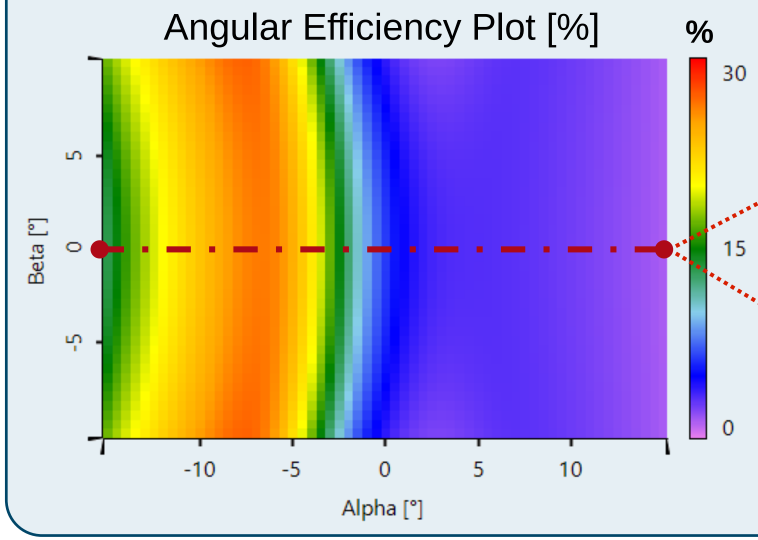
Inputs

- 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**

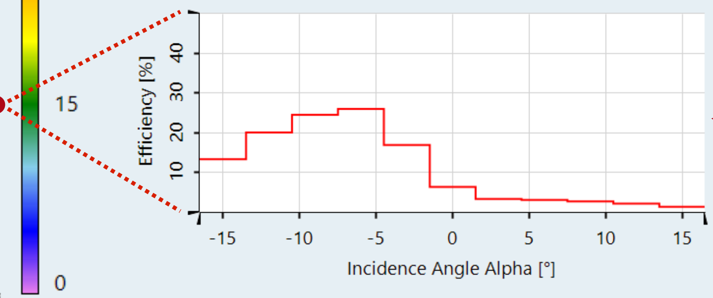
Initial Configuration of Grating	
fill factor	50.00%
modulation depth	400.00 nm
period	410 nm
operating order	1st transmitted

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

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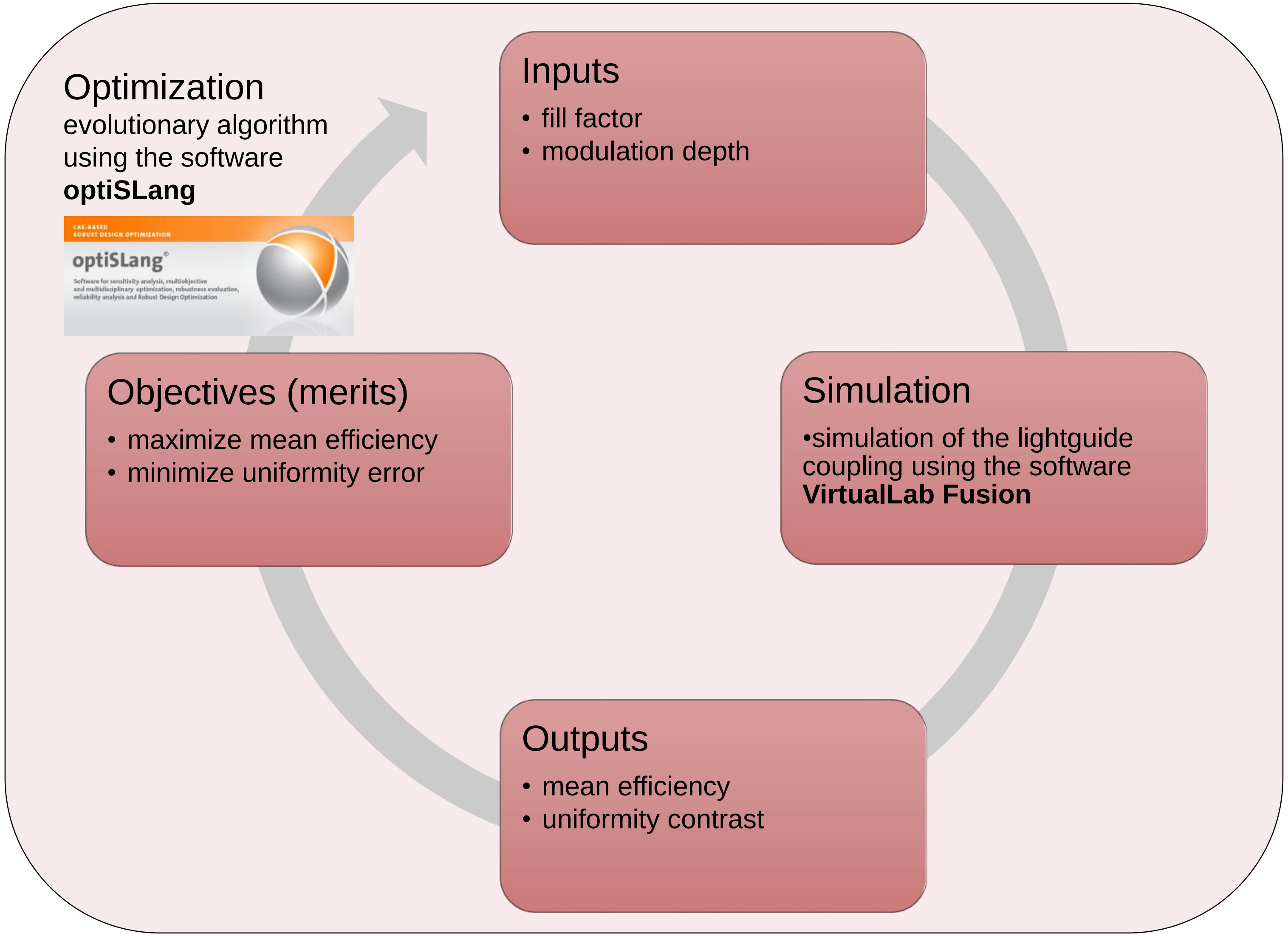
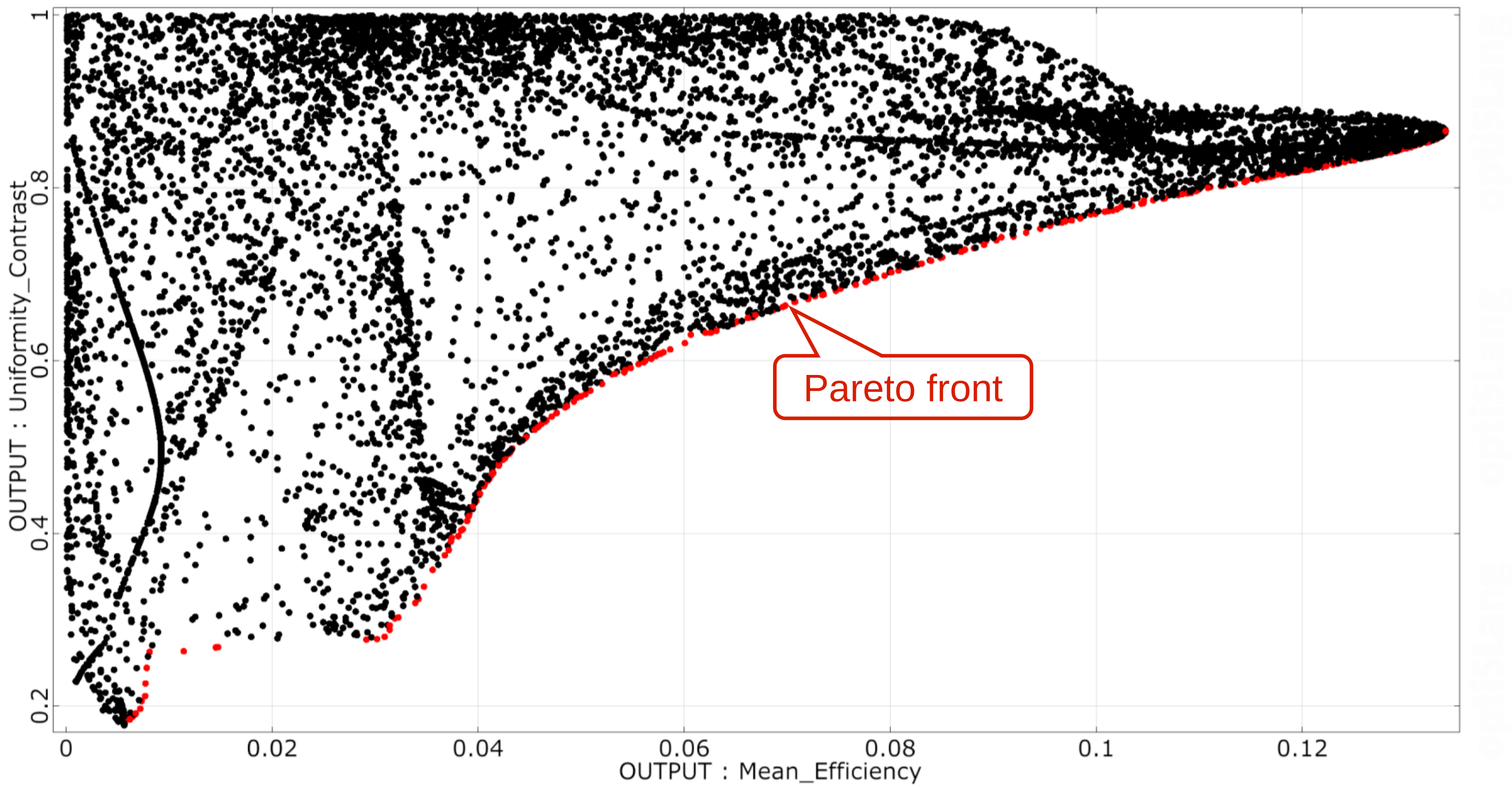
Optimization Workflow

- 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

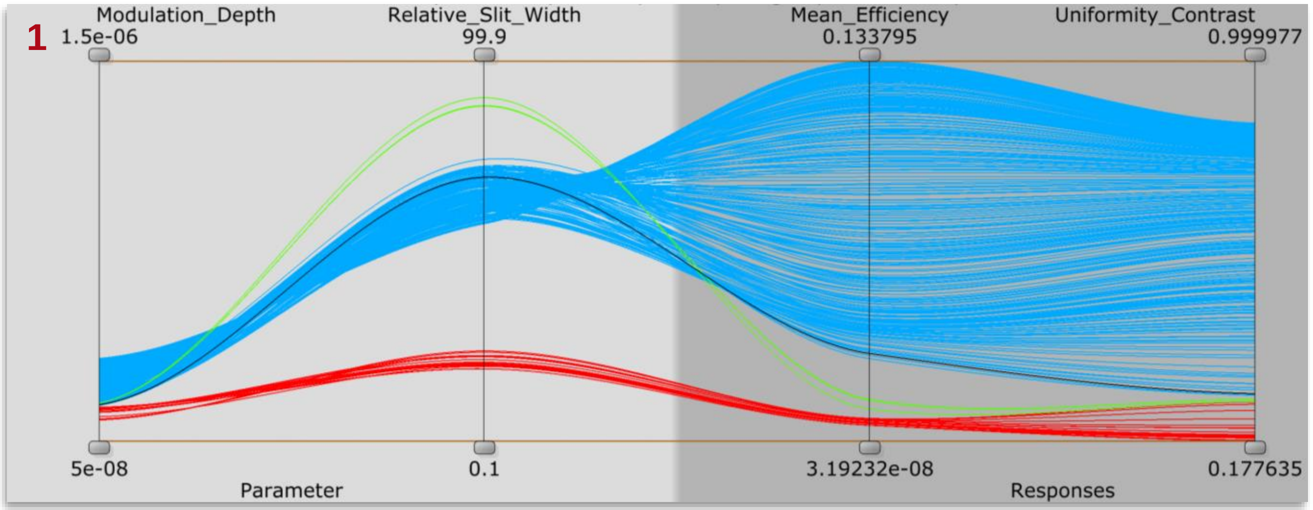


Optimization Results of optiSLang



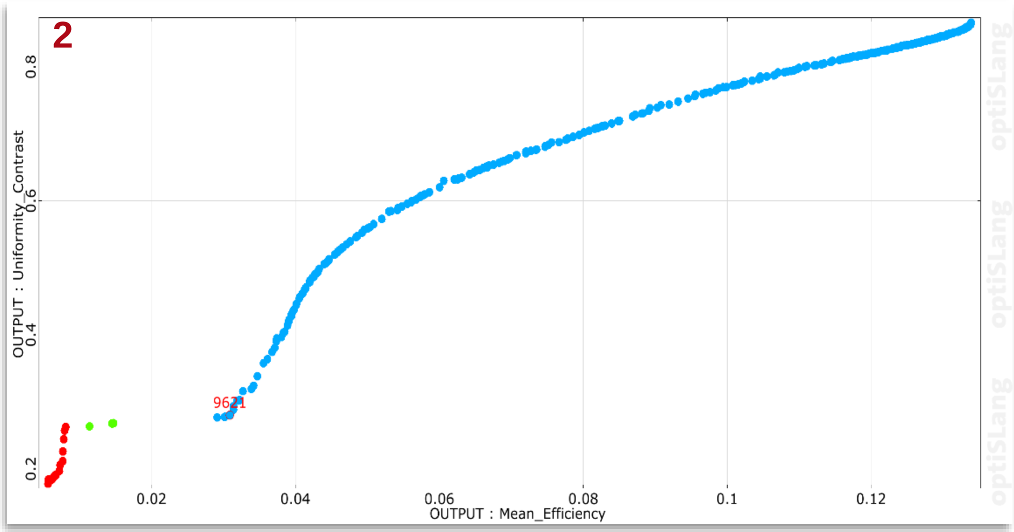
- the optimization results are plotted as a function of the merit functions
  - mean efficiency
  - uniformity contrast
- the Pareto front indicates the optimum compromise between the two merit functions (highlighted)
- any optimization result at the pareto front might selected depending on the needs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

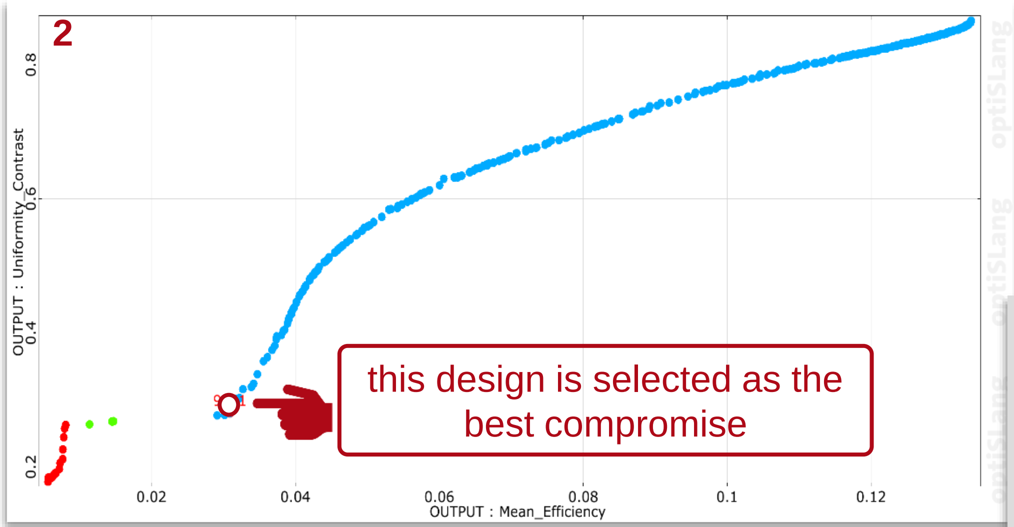
- furthermore, the same colors are visualized on the Pareto front (2) to visualize the clusters (here: the impact of the slit width on both objectives)
- therefrom, the optical designer is able to select a robust design with the best compromise between the input parameters and the output parameters

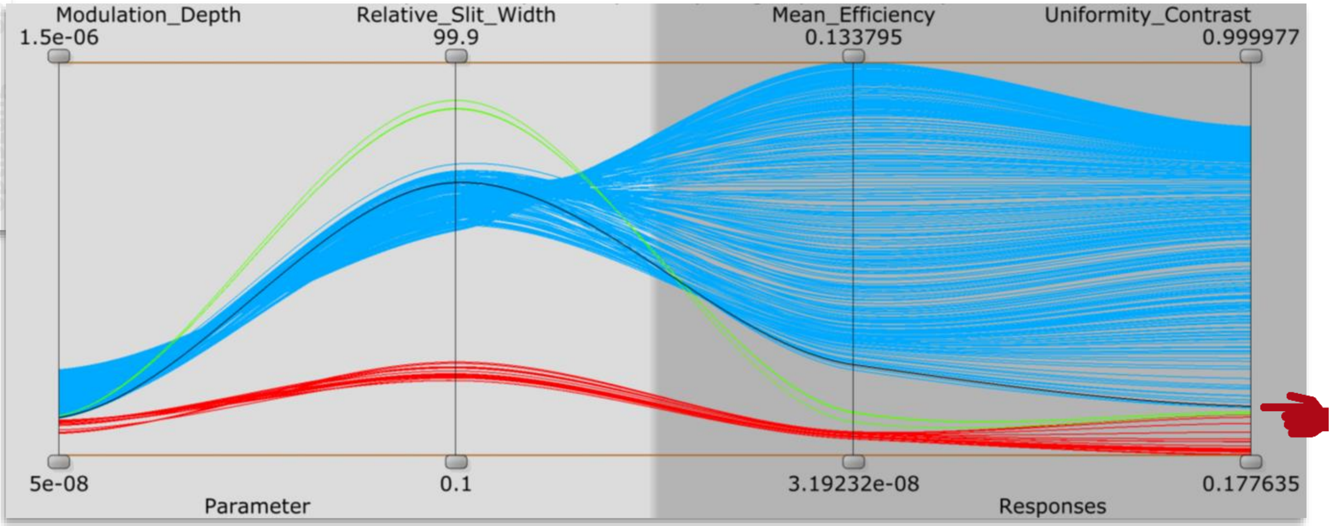


Advanced Evaluation of the Optimization Results

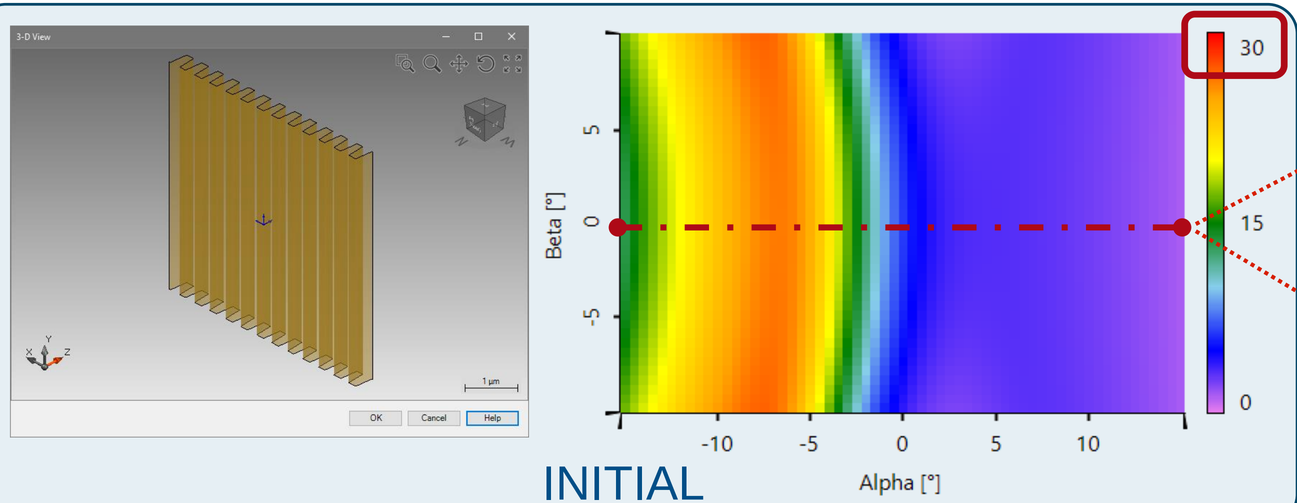
- as a result, a design is selected, which is the best compromise for a prioritized low uniformity contrast and an acceptable mean efficiency including manufacturable grating parameters

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



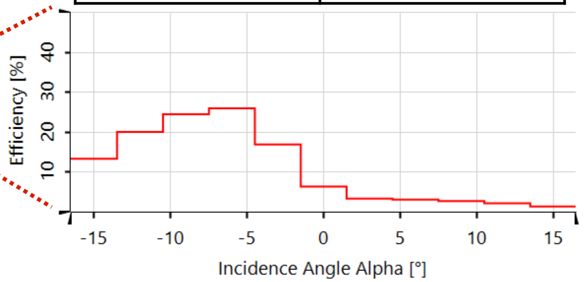


Analysis of Coupling Efficiency for Optimization Result

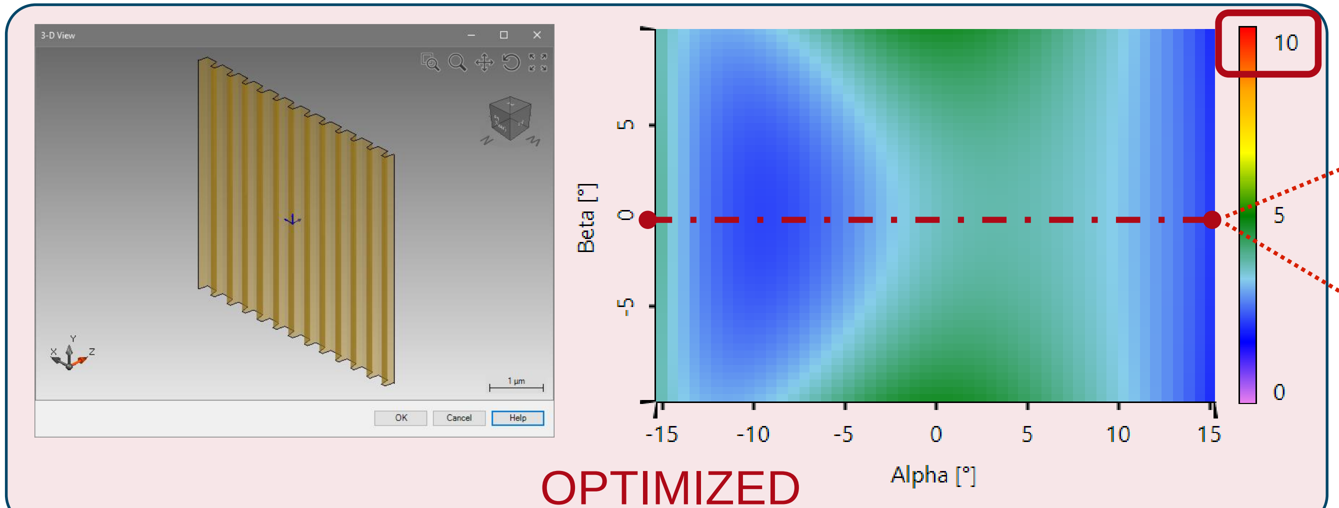


INITIAL

fill factor	50.00%
modulation depth	400.00nm

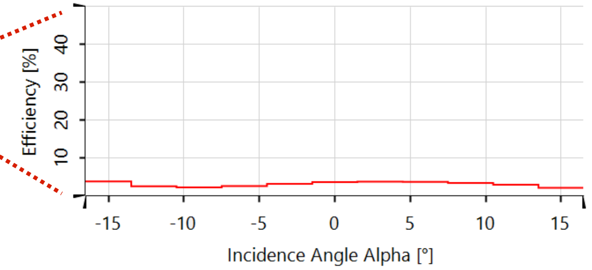


Mean Efficiency 10.96%
Uniformity Contrast **89.45%**



OPTIMIZED

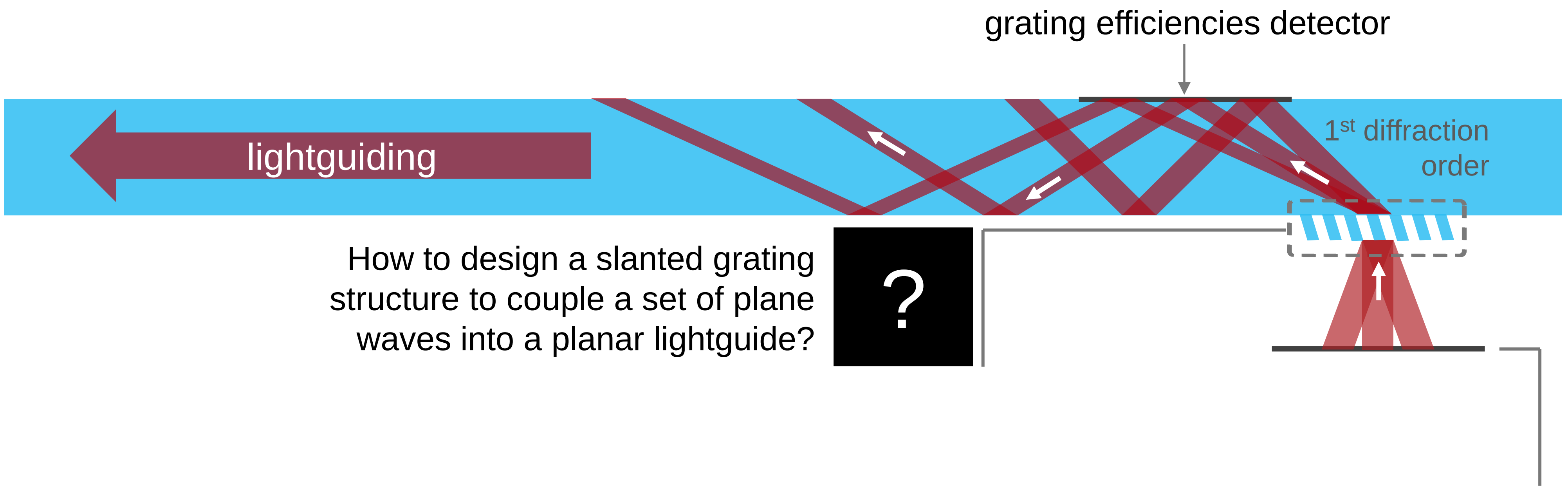
fill factor	68.43%
modulation depth	187.18nm



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

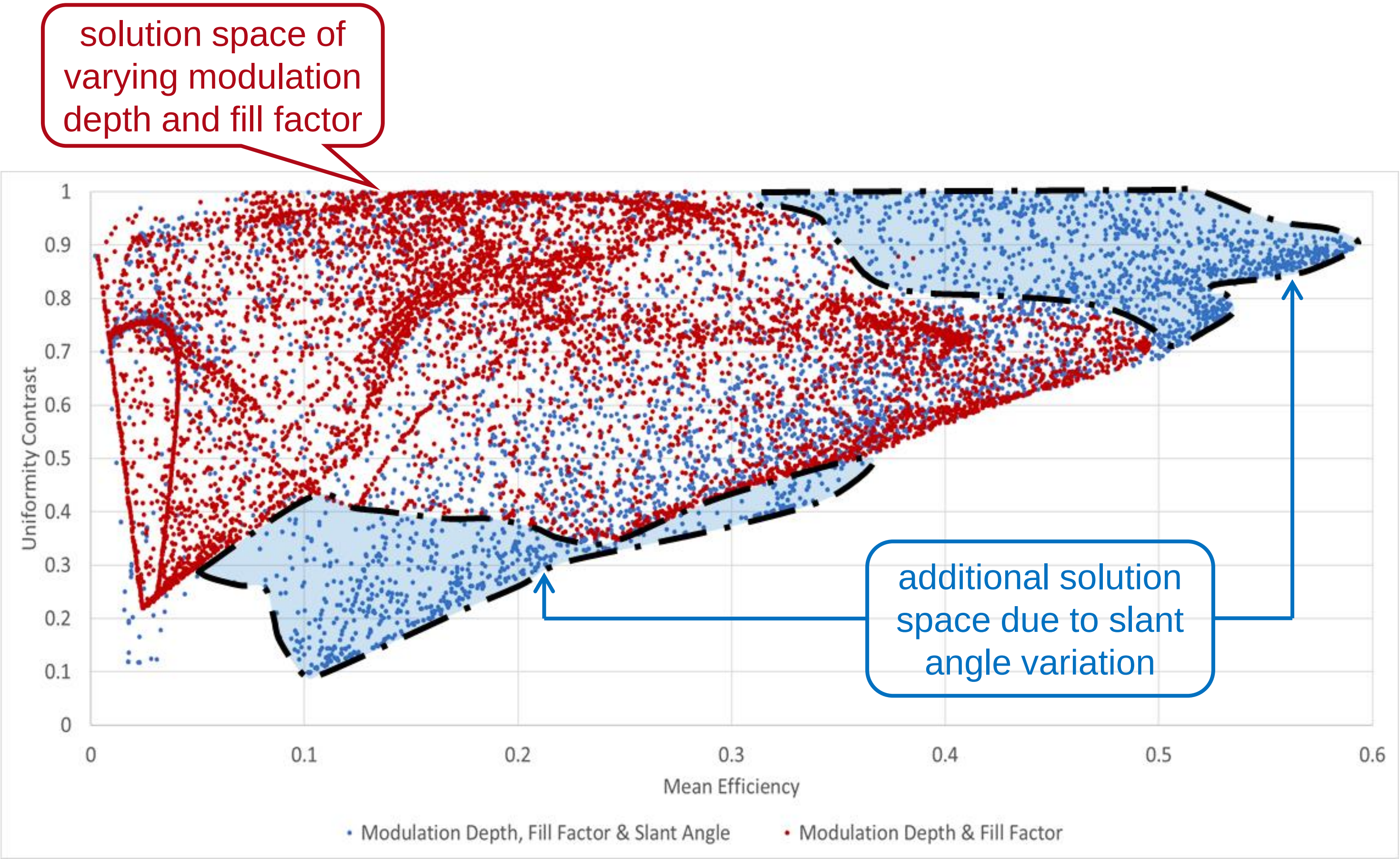
- field of view (-30..30, -15..15)°
- wavelength 532 nm
- linearly polarized along x-axis

Workflow:

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

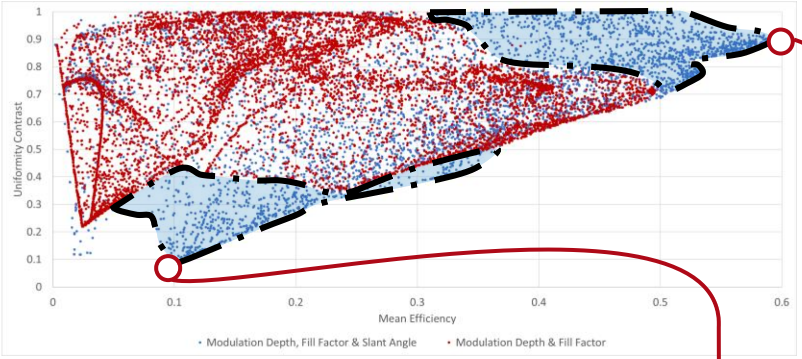
2. Designing the structure profile of the incoupling grating by an optimization approach

Optimization Result of optiSLang

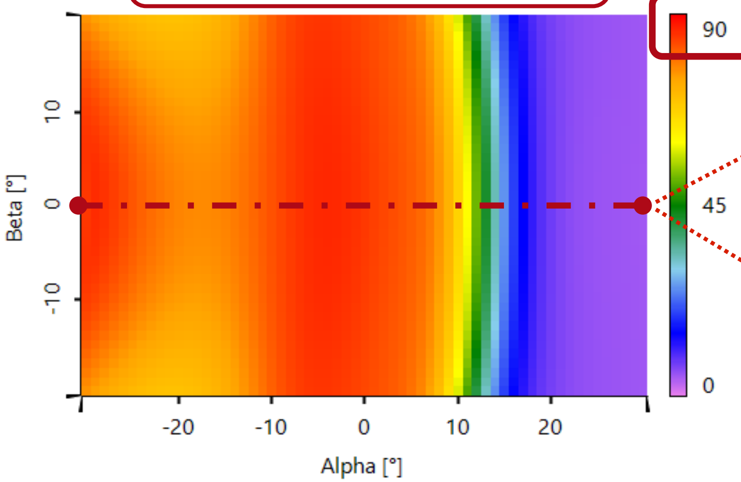


- an evolutionary optimization algorithm is applied using the optimization software optiSLang
- the additional freedom of the slant angle provides additional solutions

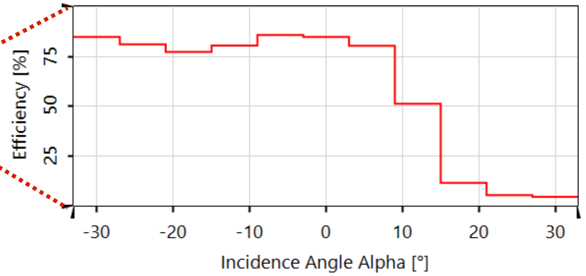
Analysis of Coupling Efficiency for Optimization Results



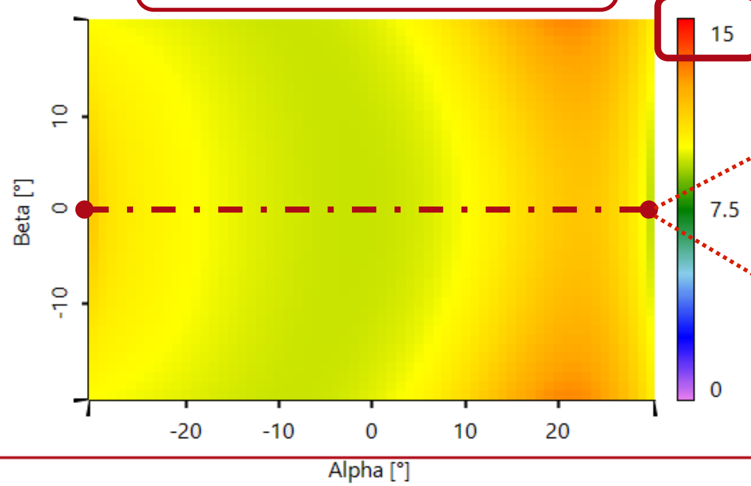
Mean Efficiency 58.74%
Uniformity Contrast 89.49%



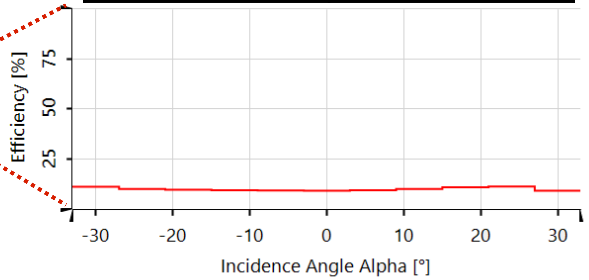
fill factor	70.82%
modulation depth	381.91 nm
slant Angle	24.58°



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

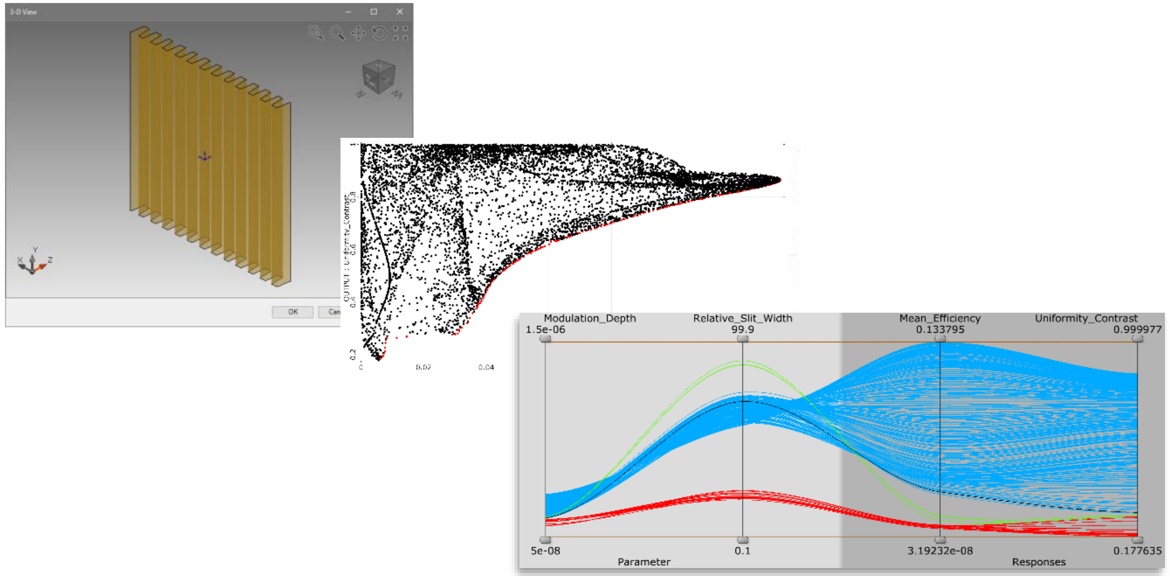
Conclusion

Inputs
- fill factor
- modulation depth

Simulation
- simulation of the lightguide coupling using the software **VirtualLab Fusion**

Outputs
- mean efficiency
- uniformity contrast

Objectives (merits)
- maximize mean efficiency
- minimize uniformity error



- VirtualLab Fusion interconnects various field tracing solvers to enable fast physical optics modeling
- optiSLang is a software for sensitivity analysis, multiobjective and multidisciplinary optimization, robustness evaluation, reliability analysis and robust design optimization
- both were used for the design of an optical grating to couple an FOV field into a planar lightguide setup for AR&VR applications

Thank you for your attention!