SPIE AR VR MR 2020, San Francisco, February 2020

Innovative systematic design approach for lightguide devices for AR & MR-applications (11310-16)

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Teams

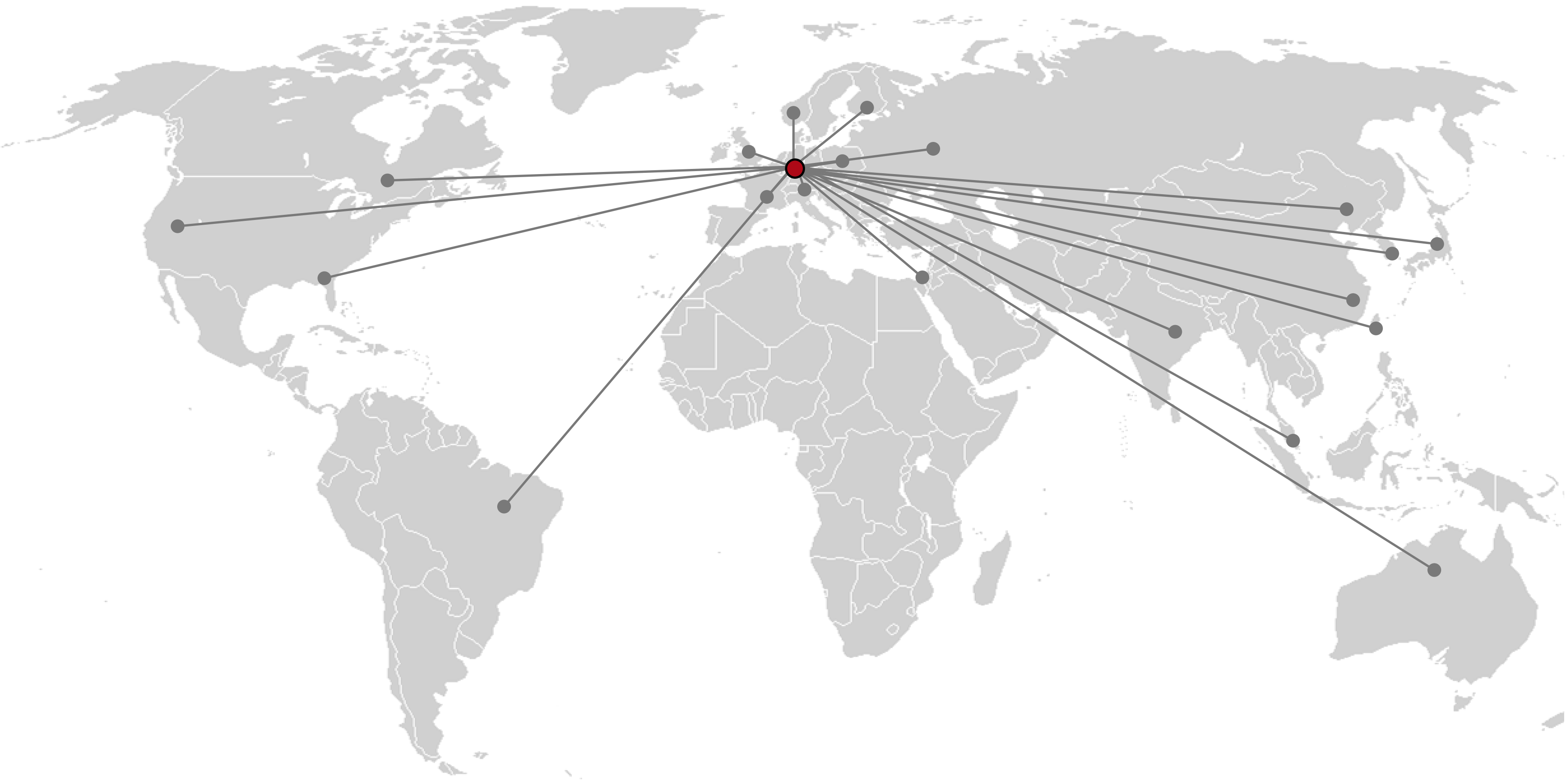
LightTrans (since 1999)

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

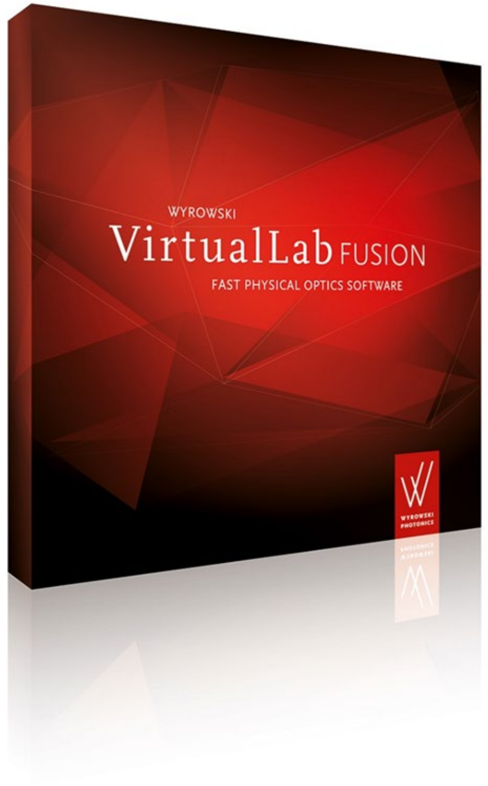
(since 2014)

photo from wikitravel

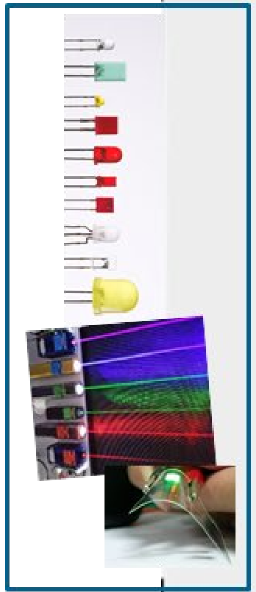
Optical Design Software and Services

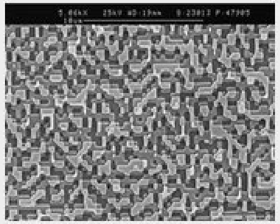


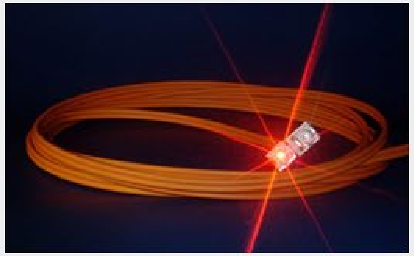
Booth #4545 (German pavilion)



Physical-Optics System Modeling





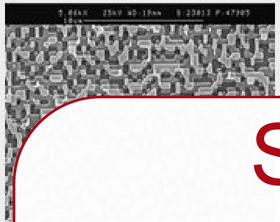


Name	Integral equations	Differential equations
Gauss's law	$\oint\!\!\oint_{\partial\Omega} \mathbf{E}\cdot \mathrm{d}\mathbf{S} = \frac{1}{\varepsilon_0}\iiint_{\Omega} \rho\,\mathrm{d}V$	$\nabla\cdot\mathbf{E} = \frac{\rho}{\varepsilon_0}$
Gauss's law for magnetism	$\oint\!\!\oint_{\partial\Omega} \mathbf{B}\cdot \mathrm{d}\mathbf{S} = 0$	$\nabla\cdot\mathbf{B} = 0$
Maxwell–Faraday equation (Faraday's law of induction)	$\oint_{\partial\Sigma} \mathbf{E}\cdot \mathrm{d}\boldsymbol{\ell} = -\frac{d}{dt}\iint_{\Sigma} \mathbf{B}\cdot \mathrm{d}\mathbf{S}$	$\nabla\times\mathbf{E} = -\frac{\partial\mathbf{B}}{\partial t}$
Ampère's circuital law (with Maxwell's addition)	$\oint_{\partial\Sigma} \mathbf{B}\cdot \mathrm{d}\boldsymbol{\ell} = \mu_0\iint_{\Sigma} \mathbf{J}\cdot \mathrm{d}\mathbf{S} + \mu_0\varepsilon_0\frac{d}{dt}\iint_{\Sigma} \mathbf{E}\cdot \mathrm{d}\mathbf{S}$	$\nabla\times\mathbf{B} = \mu_0\left(\mathbf{J} + \varepsilon_0\frac{\partial\mathbf{E}}{\partial t}\right)$

Homogeneous medium, like air or vacuum

Solve Maxwell's equations for given source field and components.

Physical-Optics System Modeling



Name	Integral equations	Differe
Gauss's law	$\oiint_{\partial\Omega} \mathbf{E} \cdot d\mathbf{S} = \frac{1}{\varepsilon_0} \iiint_{\Omega} \rho \, dV$	∇
Gauss's law for magnetism	$\oiint_{\partial\Omega} \mathbf{B} \cdot d\mathbf{S} = 0$	∇
Maxwell–Faraday equation (Faraday's law of induction)	$\oint_{\partial\Sigma} \mathbf{E} \cdot d\boldsymbol{\ell} = -\frac{d}{dt} \iint_{\Sigma} \mathbf{B} \cdot d\mathbf{S}$	$\nabla \times$
Ampère's circuital law (with Maxwell's addition)	$\oint_{\partial\Sigma} \mathbf{B} \cdot d\boldsymbol{\ell} = \mu_0 \iint_{\Sigma} \mathbf{J} \cdot d\mathbf{S} + \mu_0 \varepsilon_0 \frac{d}{dt} \iint_{\Sigma} \mathbf{E} \cdot d\mathbf{S}$	$\nabla \times \mathbf{B} =$

Homogeneous medium, like air or vacuum

Solution of Maxwell's equations with one field solver, e.g. FEM, FMM, or FDTD, for entire system not feasible because of numerical effort!

Physical-Optics System Modeling

Name	Integral equations
Gauss's law	$\oint\!\!\!\oint_{\partial\Omega} \mathbf{E}\cdot \mathrm{d}\mathbf{S} = \frac{1}{\varepsilon_0}\iiint_\Omega \rho\, \mathrm{d}V$
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Homogeneous medium, like air or vacuum

How to obtain a reliable and fast physical optics solution - whenever possible?

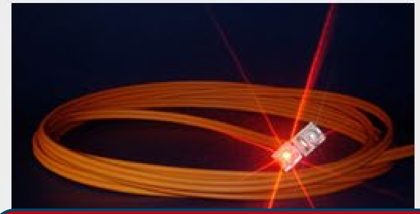
Connecting Optical Technologies / Maxwell Solvers

Field Solver Lenses, …

Field Solver Prisms, …

Field Solver Gratings, …

Field Solver micro- and nano-structures



Field Solver fibers, …

Homogeneous medium, like air or vacuum

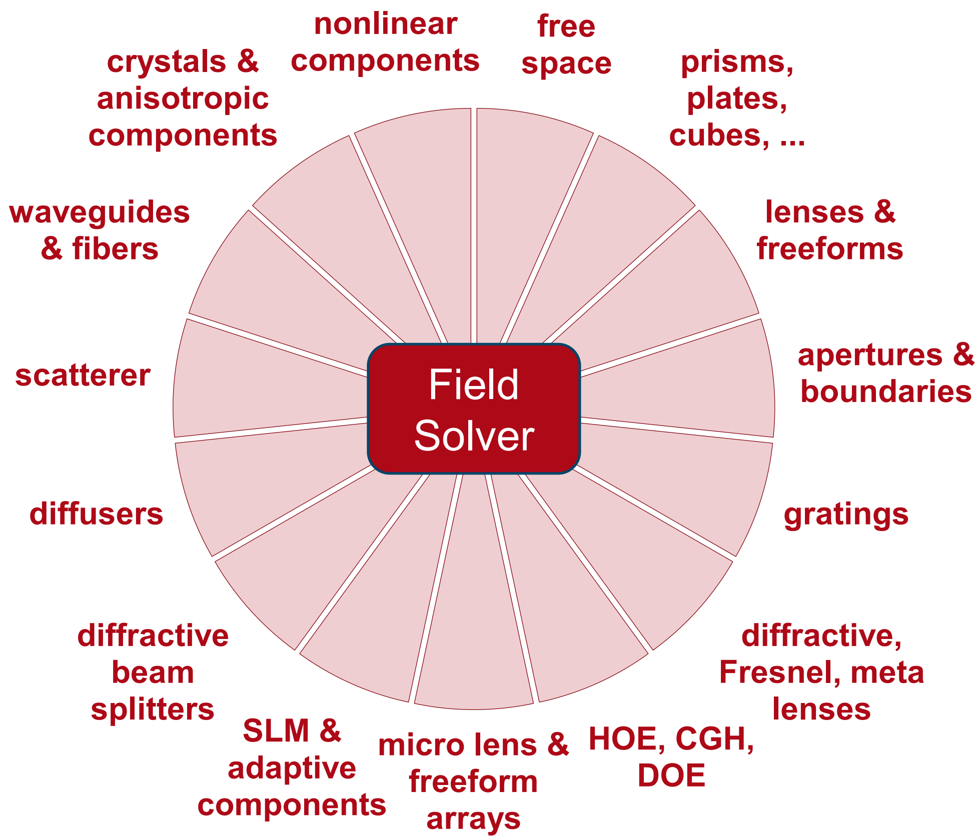
Connecting Optical Technologies / Maxwell Solvers

Problem:

Application of a single field solver, e.g. FEM or FDTD, to the entire system: **Unrealistic numerical effort**

Solution:

- Decomposition of system and application of regional field solvers.
- Interconnection of different solvers and so to solve the complete system.



Connecting Optical Technologies / Maxwell Solvers

Problem:

Application of
FEM or FDT
Unrealistic

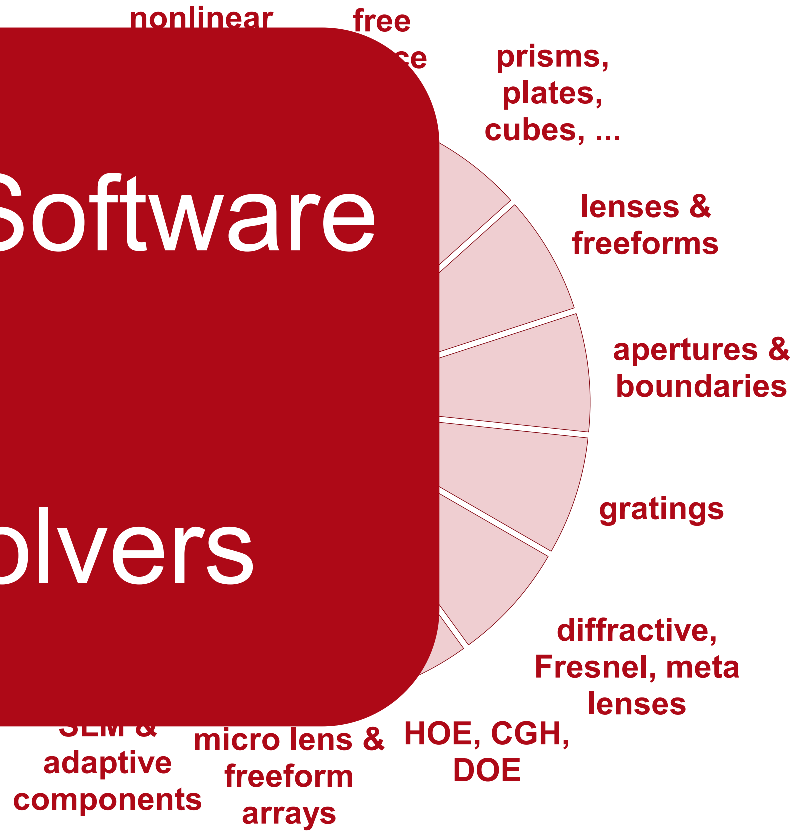
Solution:

- Decompo
  applicatio
- Interconne
  and so to solve the complete system.

Fast Physical Optics Software

by

Connecting Field Solvers



Lightguide Modeling and Design

AR&VR in VirtualLab Fusion

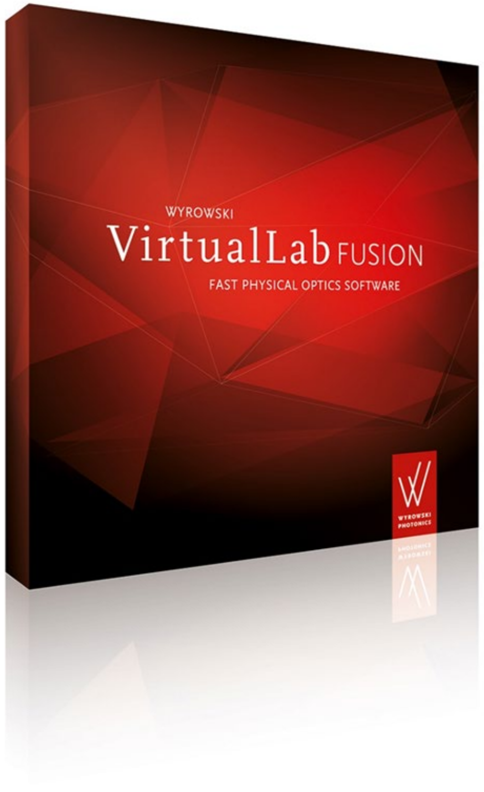
System configuration

Lightguide modeling

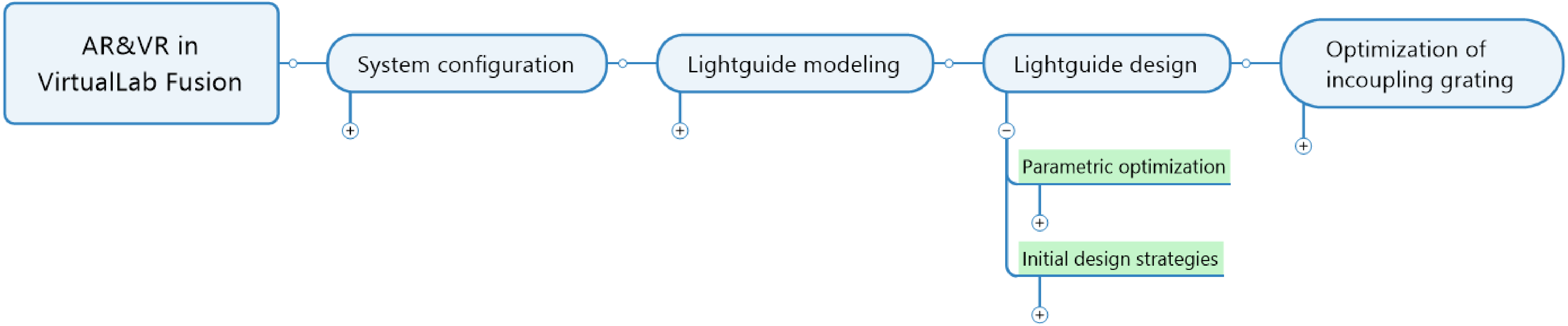
Lightguide design

Optimization of incoupling grating

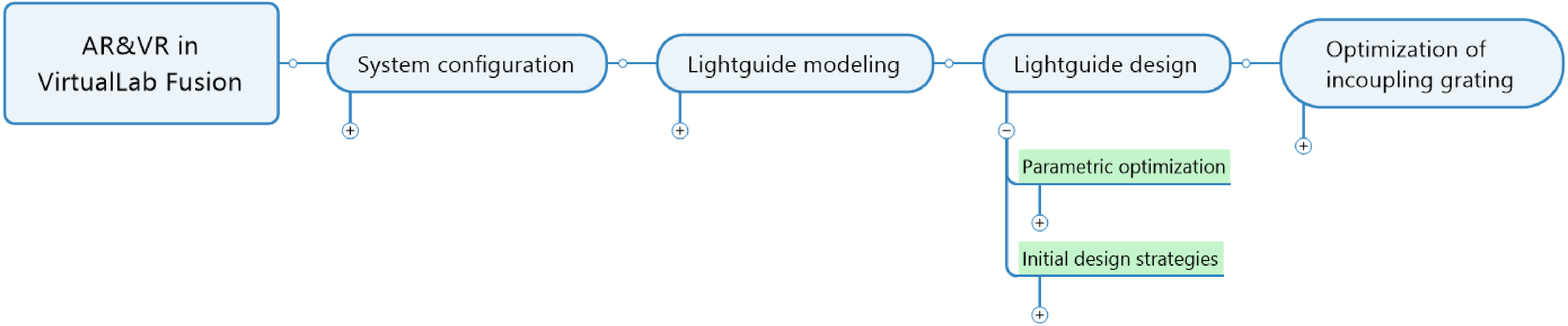
Today 4:10 pm: **Physical-optics analysis of lightguides for augmented and mixed reality glasses**



Lightguide Modeling and Design

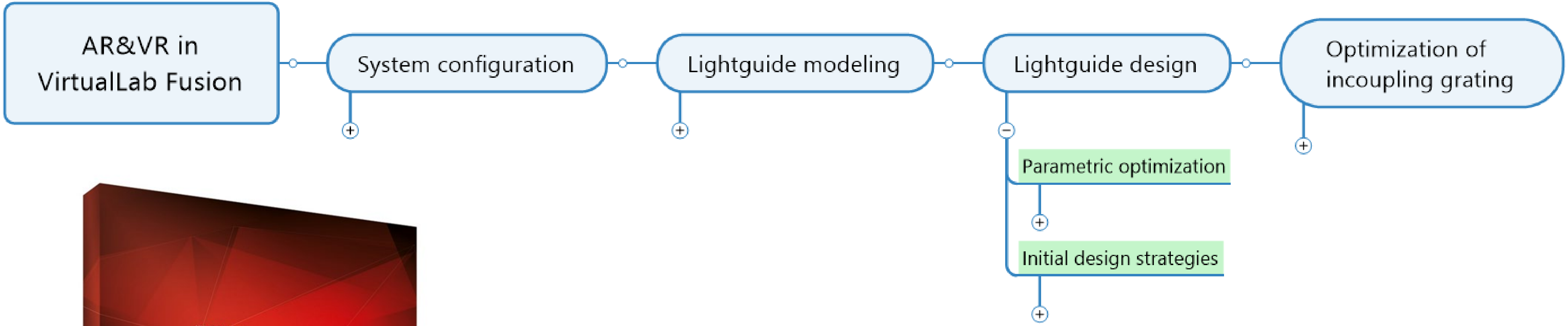


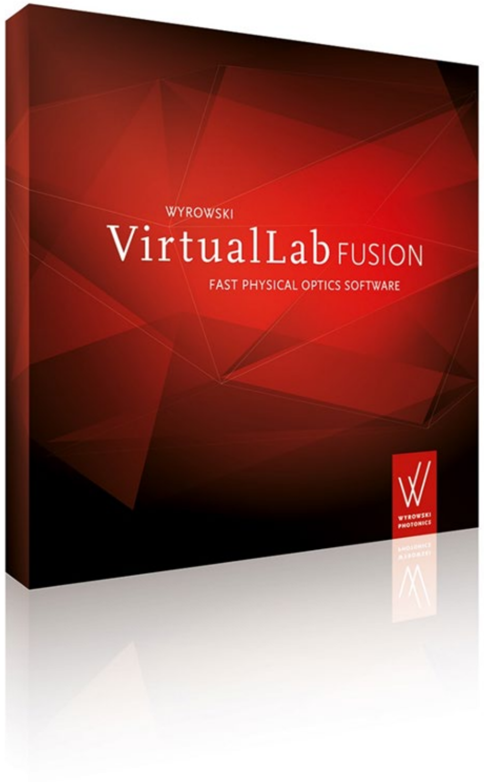
Lightguide Modeling and Design



Design demands & constraints: e.g.
- Constraints of lateral layout & dimensions
- Desired optical parameters (e.g. FoV, wavelength)
- Desired optical performance (efficiency & uniformity)
- Type of gratings and range of parameters

Lightguide Modeling and Design



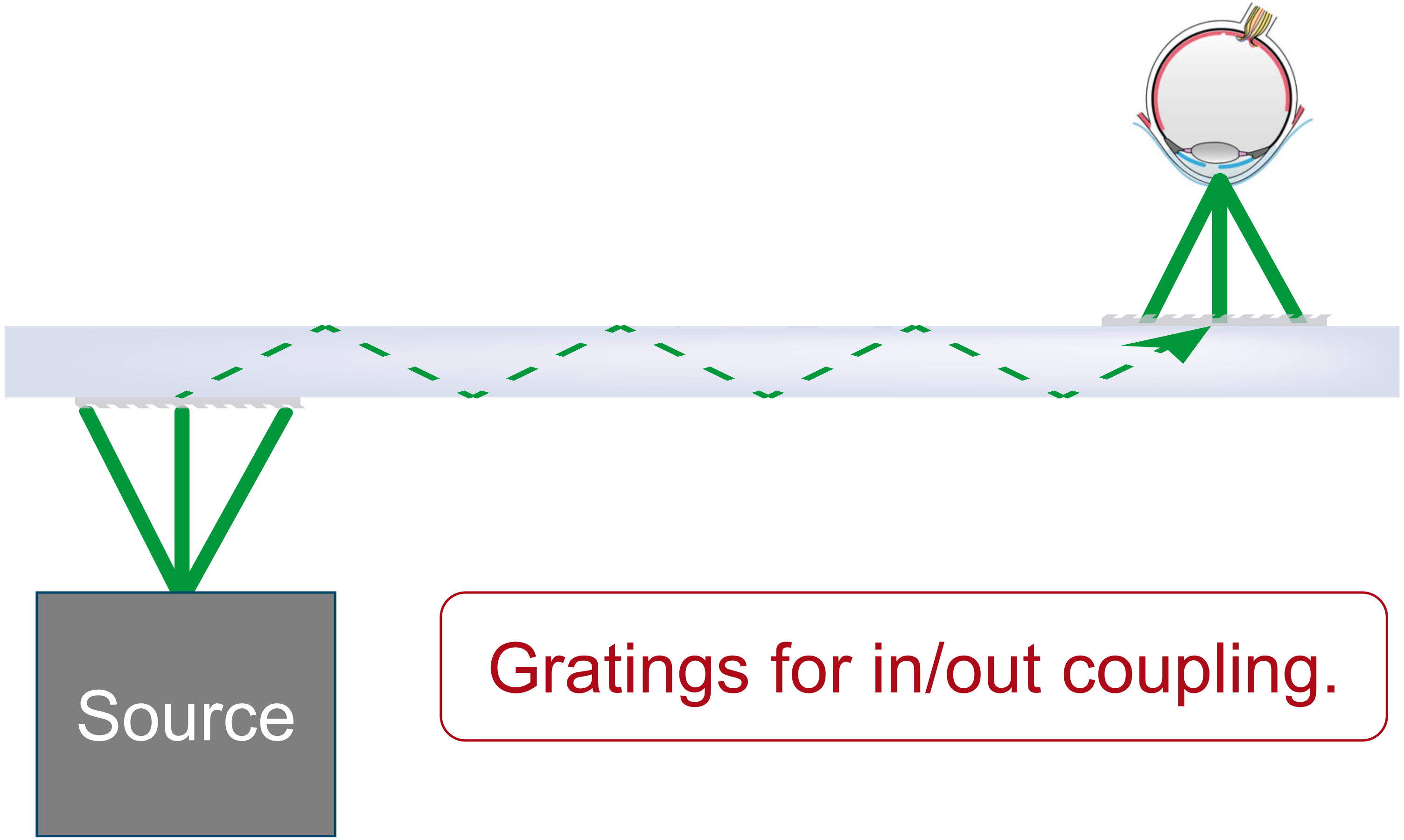


Design demands & constraints: e.g.

- Constraints of lateral layout & dimensions
- Desired optical parameters (e.g. FoV, wavelength)
- Desired optical performance (efficiency & uniformity
- Type of gratings and range of parameters

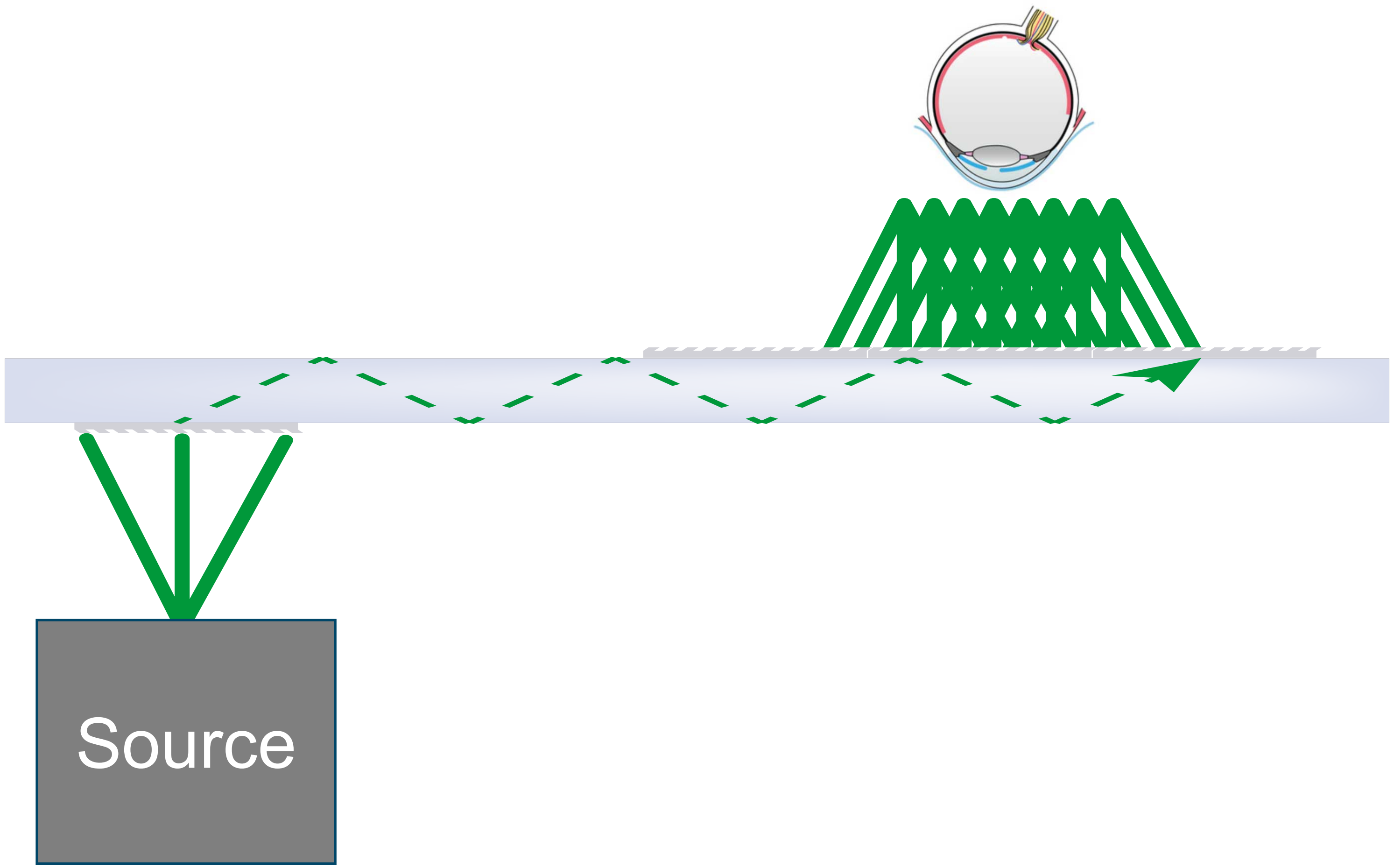
Selection of design criteria?

Lightguide Concept: In/Out Coupling

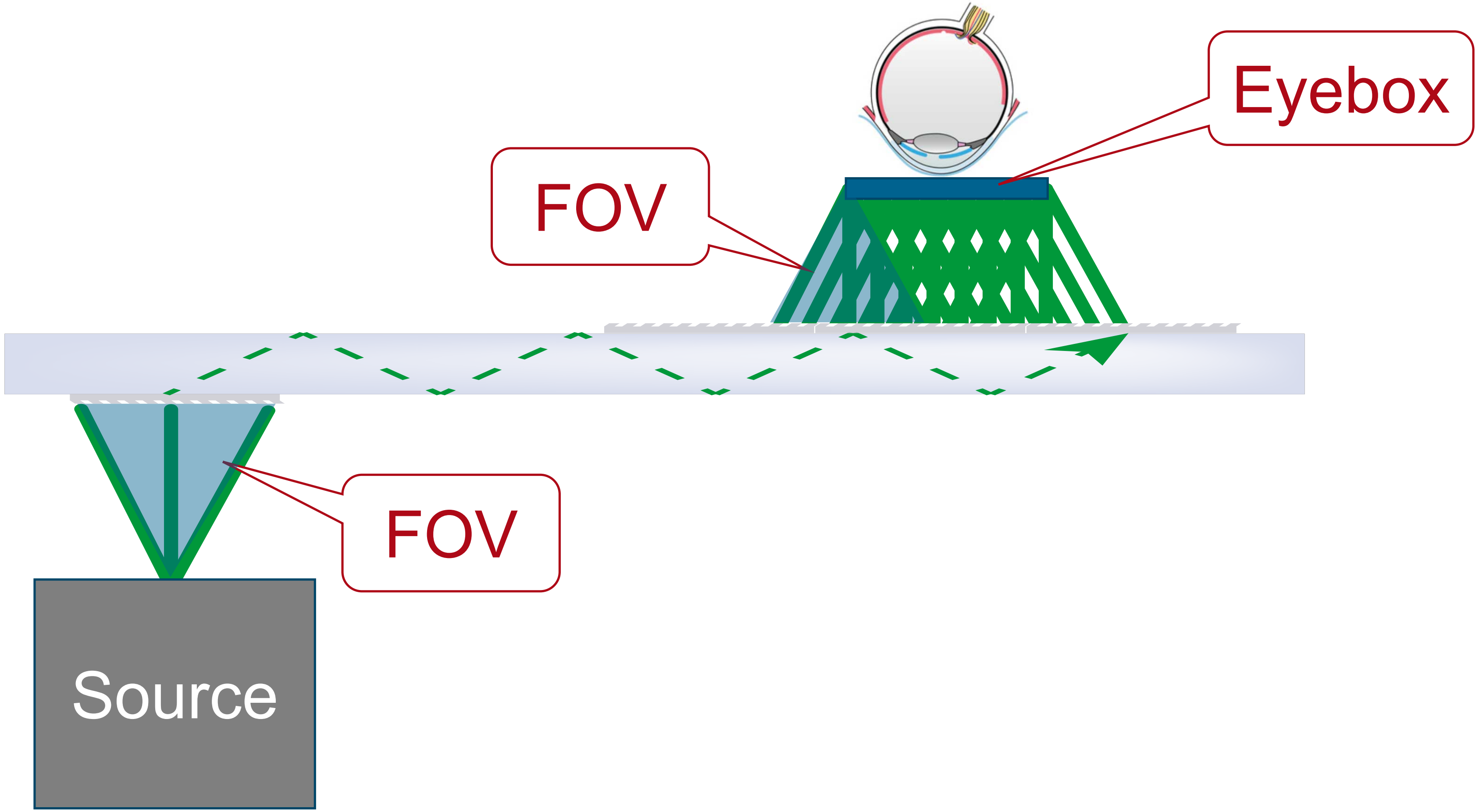


Gratings for in/out coupling.

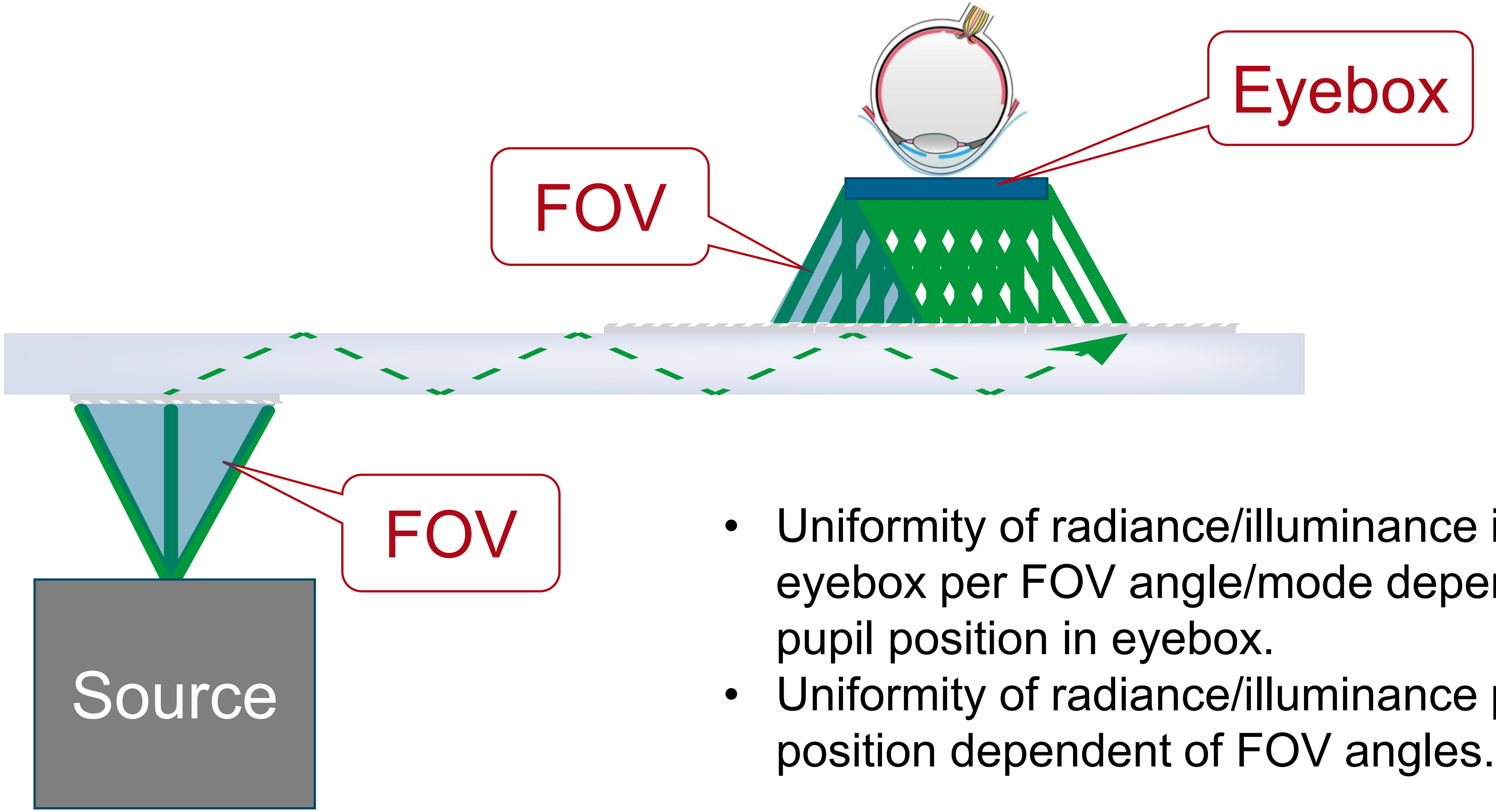
Lightguide Concept: Exit Pupil Expansion



Lightguide Concept: Exit Pupil Expansion

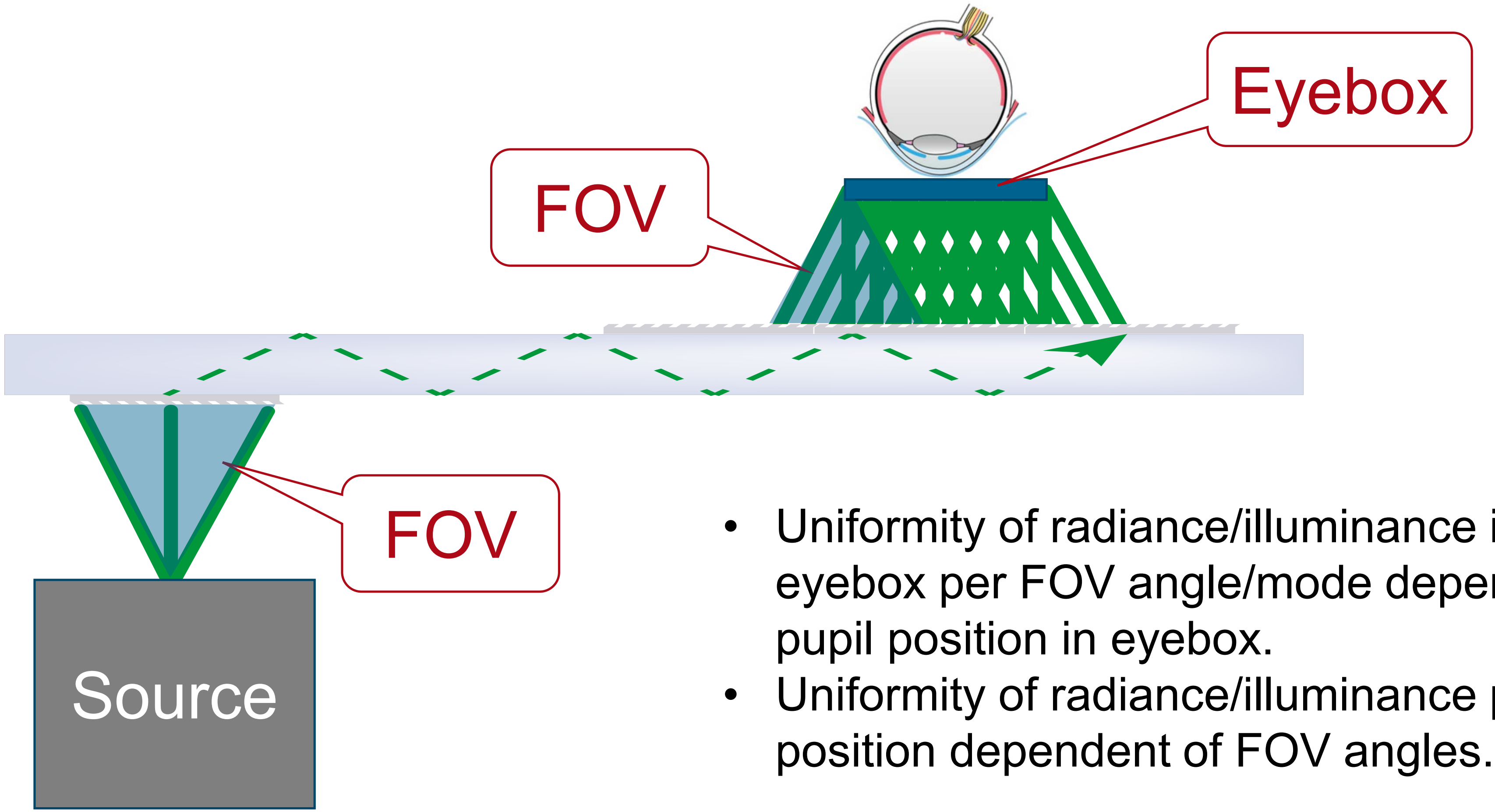


Lightguide Concept: Fundamental Design Criteria



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

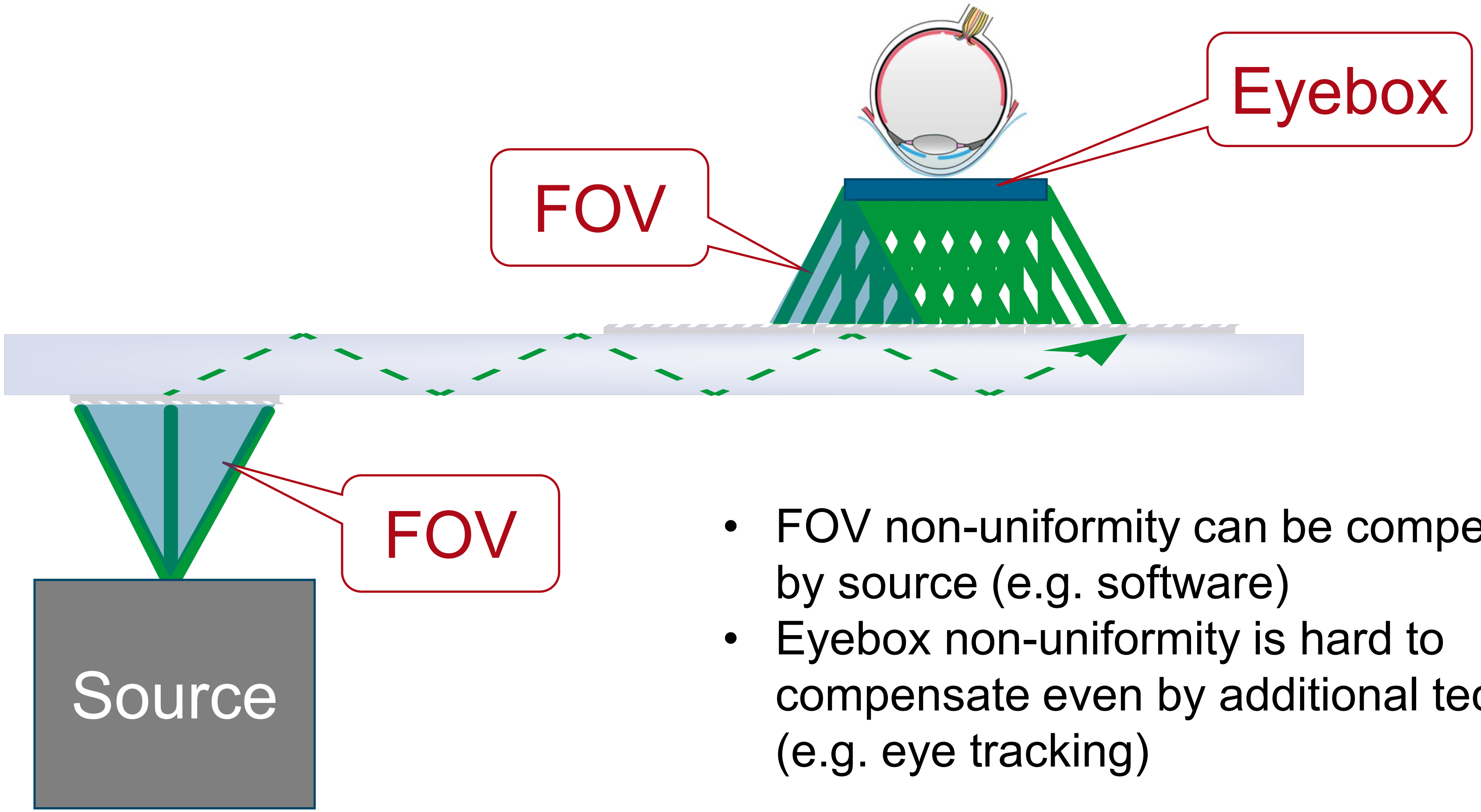
Lightguide Concept: Fundamental Design Criteria



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

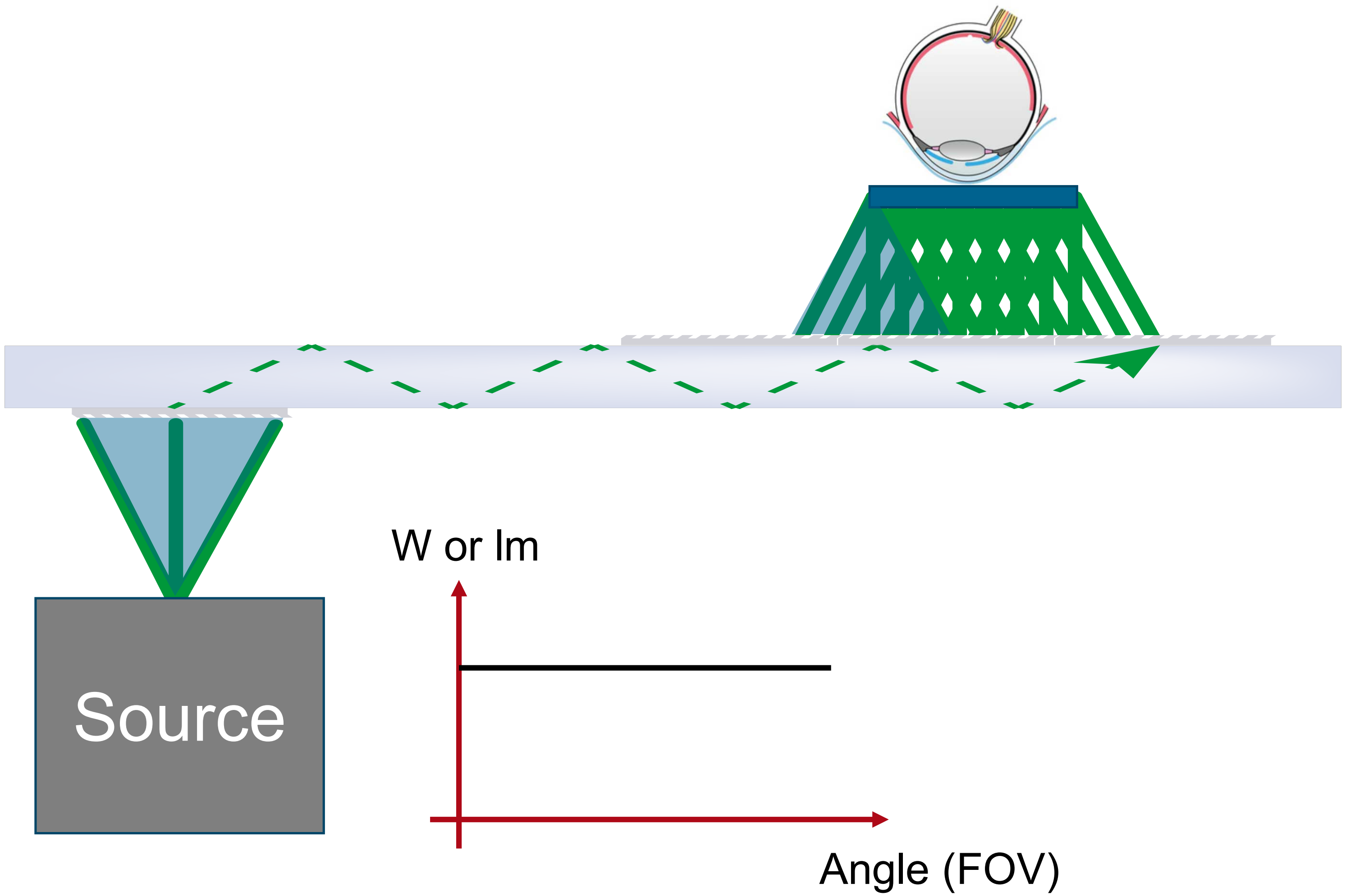
Which one is more critical and should be prioritized?

Lightguide Concept: Fundamental Design Criteria

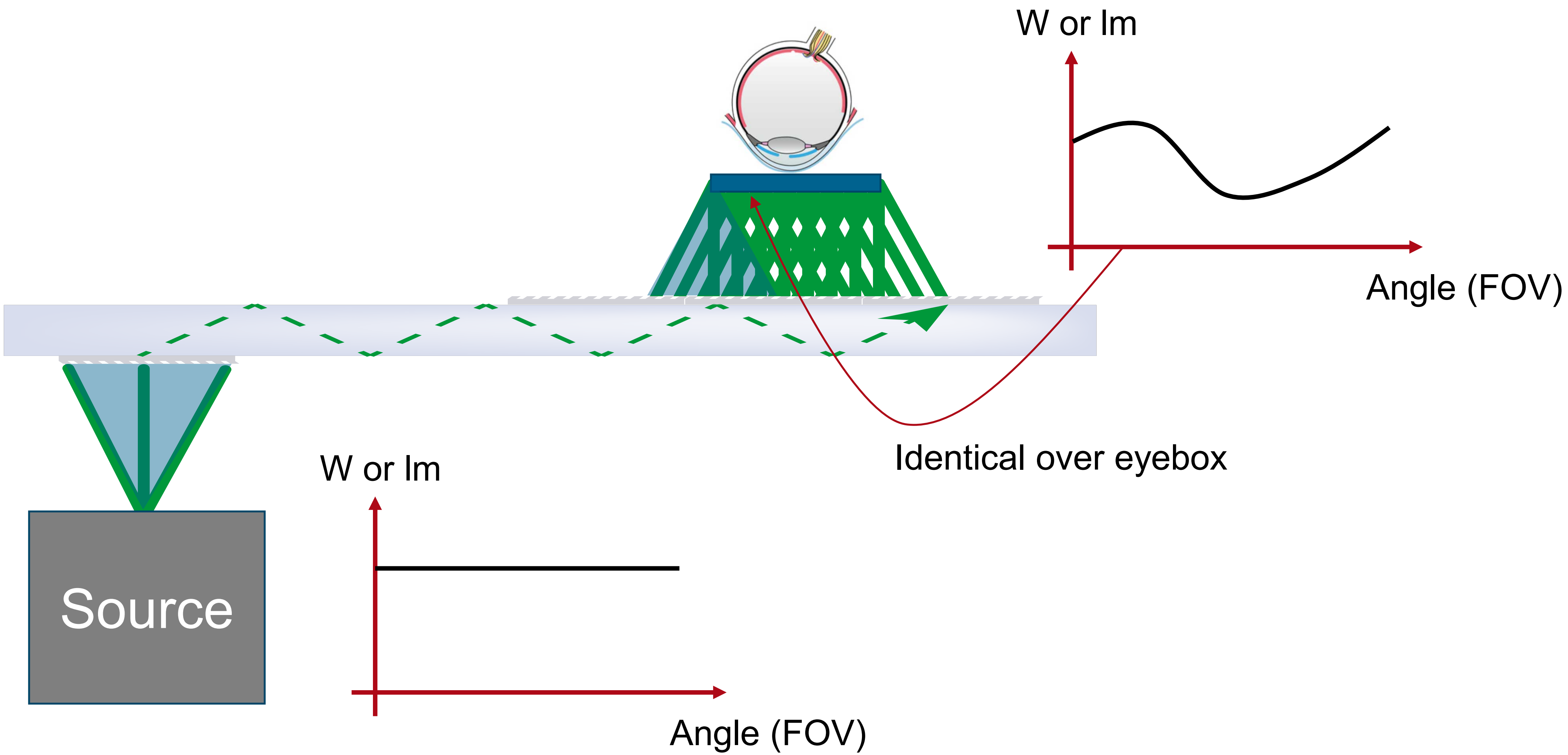


- FOV non-uniformity can be compensated by source (e.g. software)
- Eyebox non-uniformity is hard to compensate even by additional techniques (e.g. eye tracking)

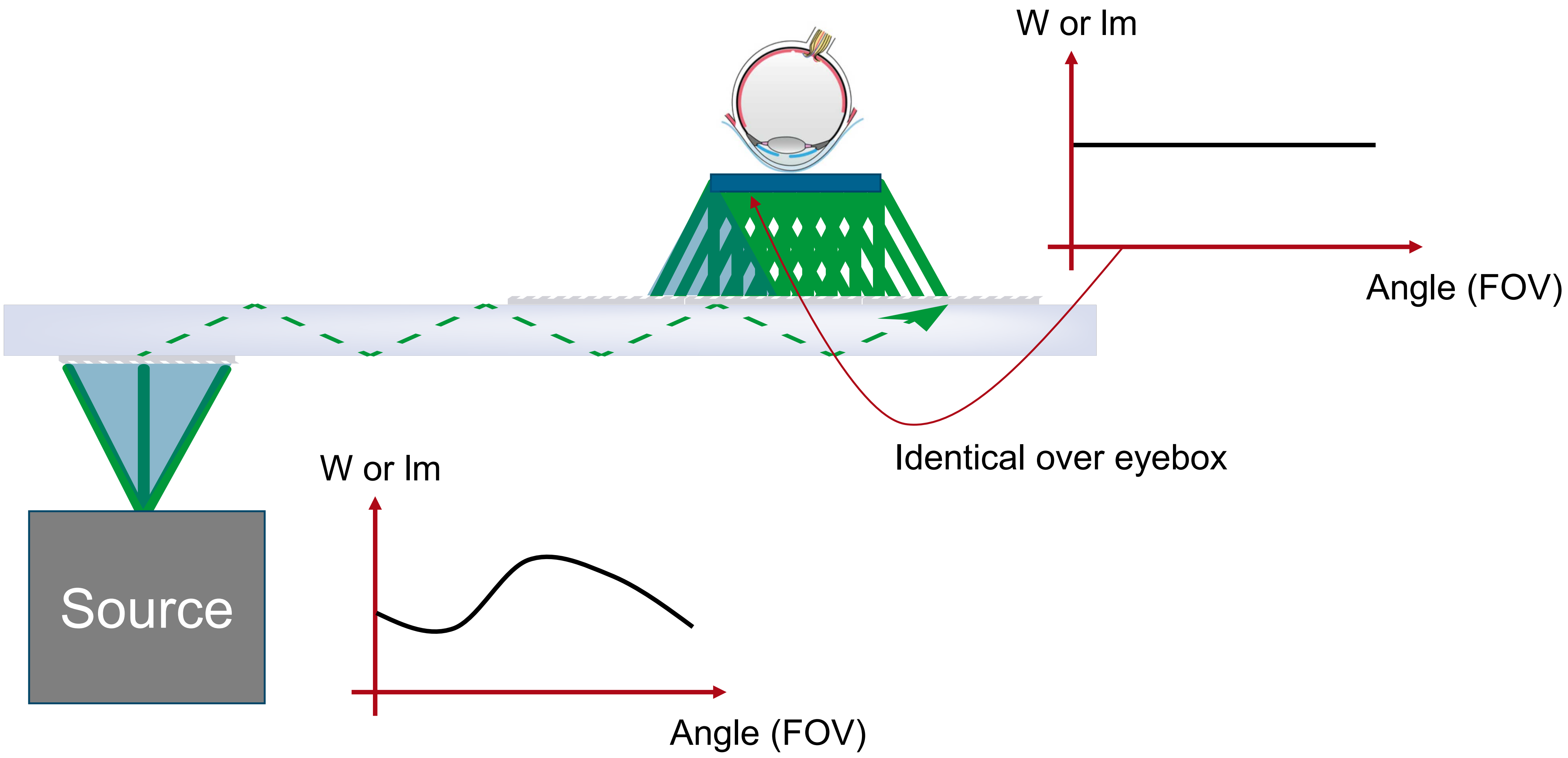
Lightguide Concept: Fundamental Design Criteria



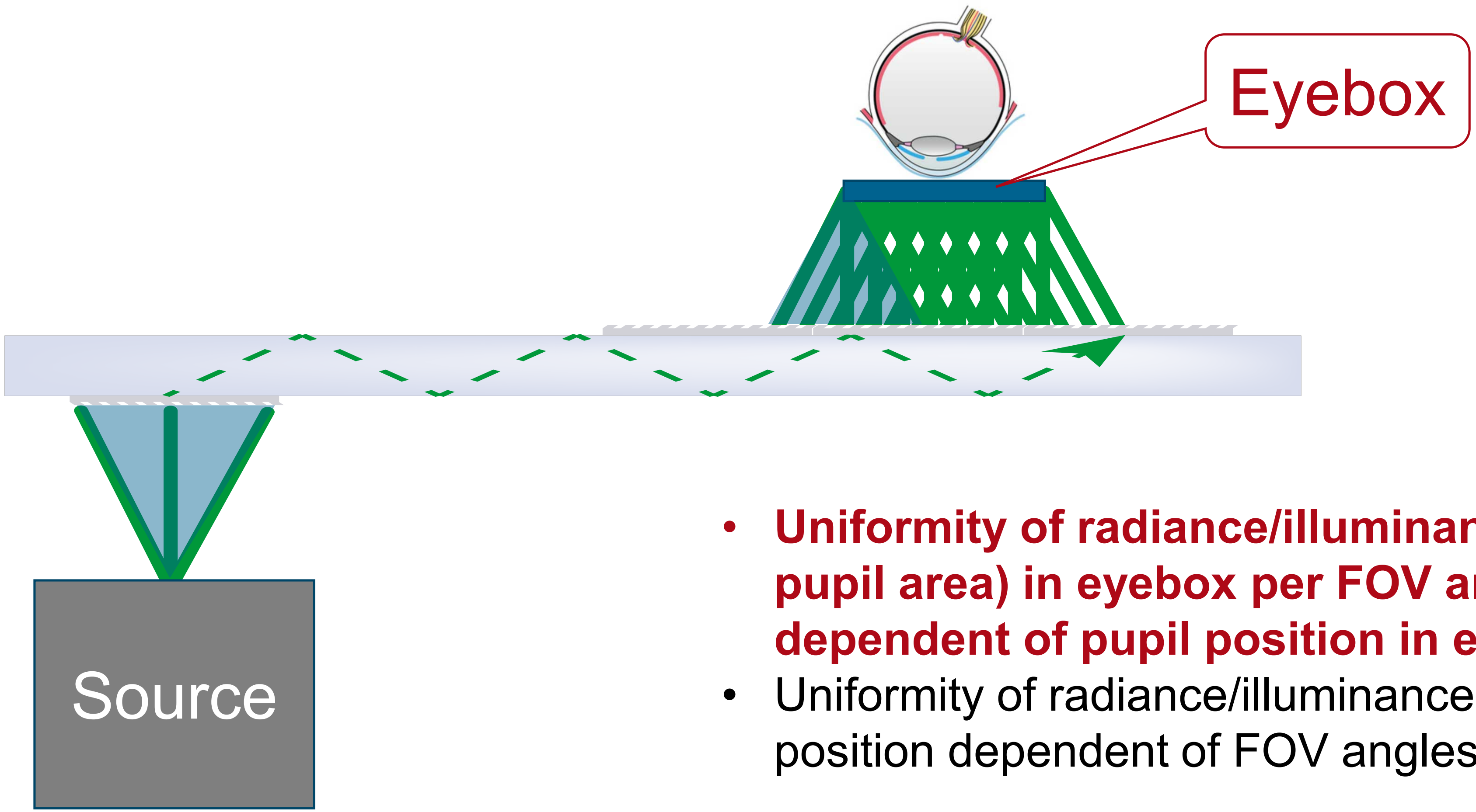
Lightguide Concept: Fundamental Design Criteria



Lightguide Concept: Fundamental Design Criteria

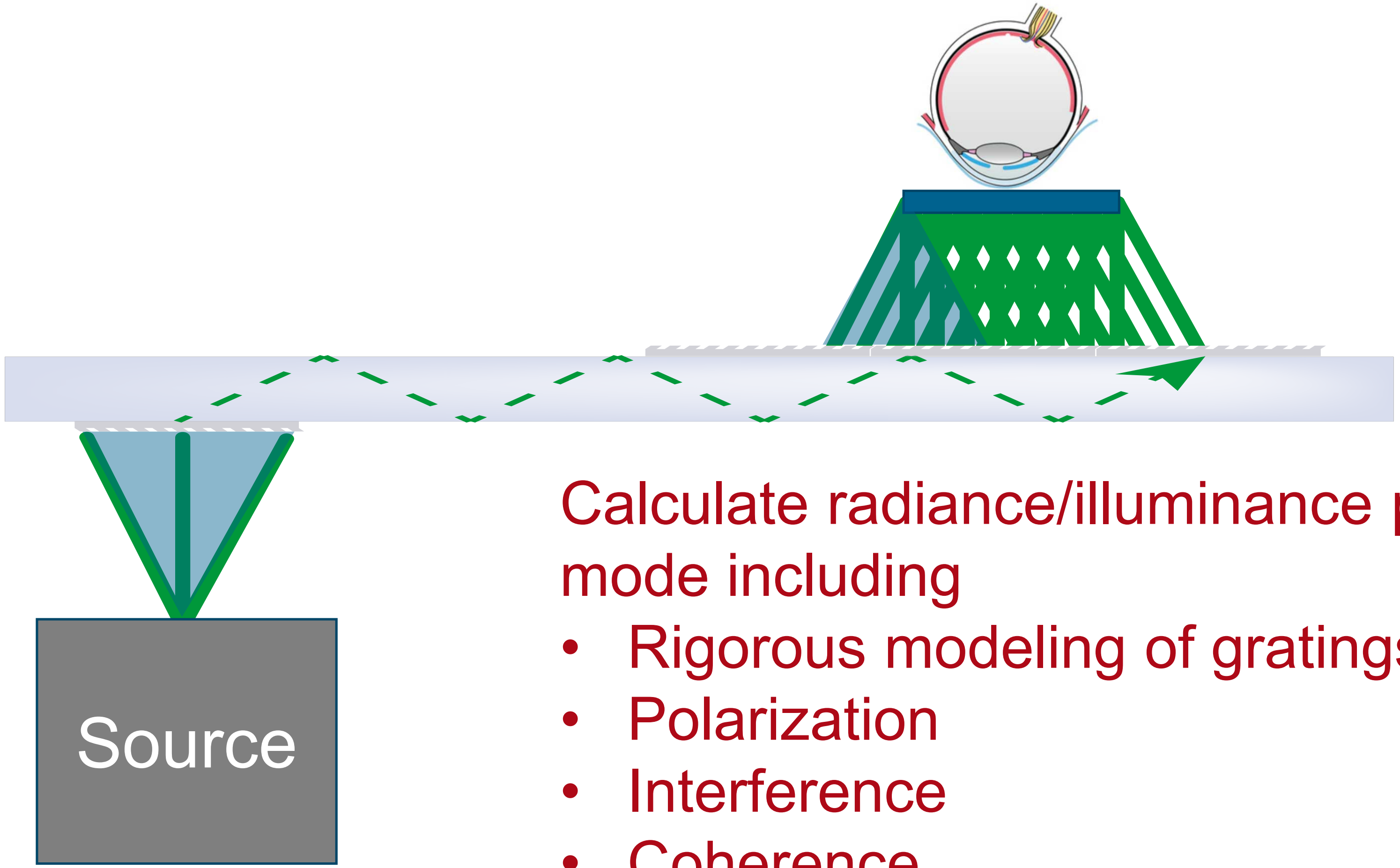


Lightguide Concept: Fundamental Design Criteria



- **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.

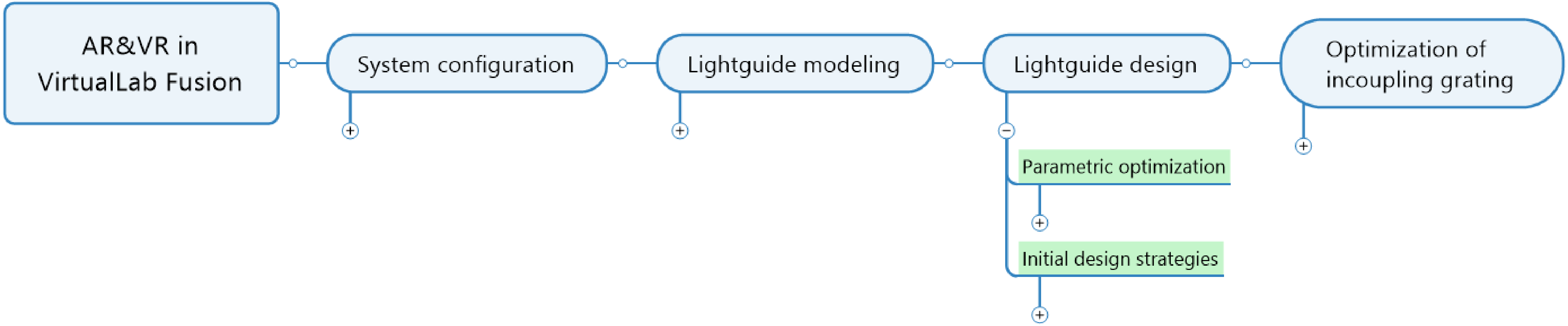
Lightguide Concept: Modeling Task



Calculate radiance/illuminance per FOV mode including

- Rigorous modeling of gratings
- Polarization
- Interference
- Coherence

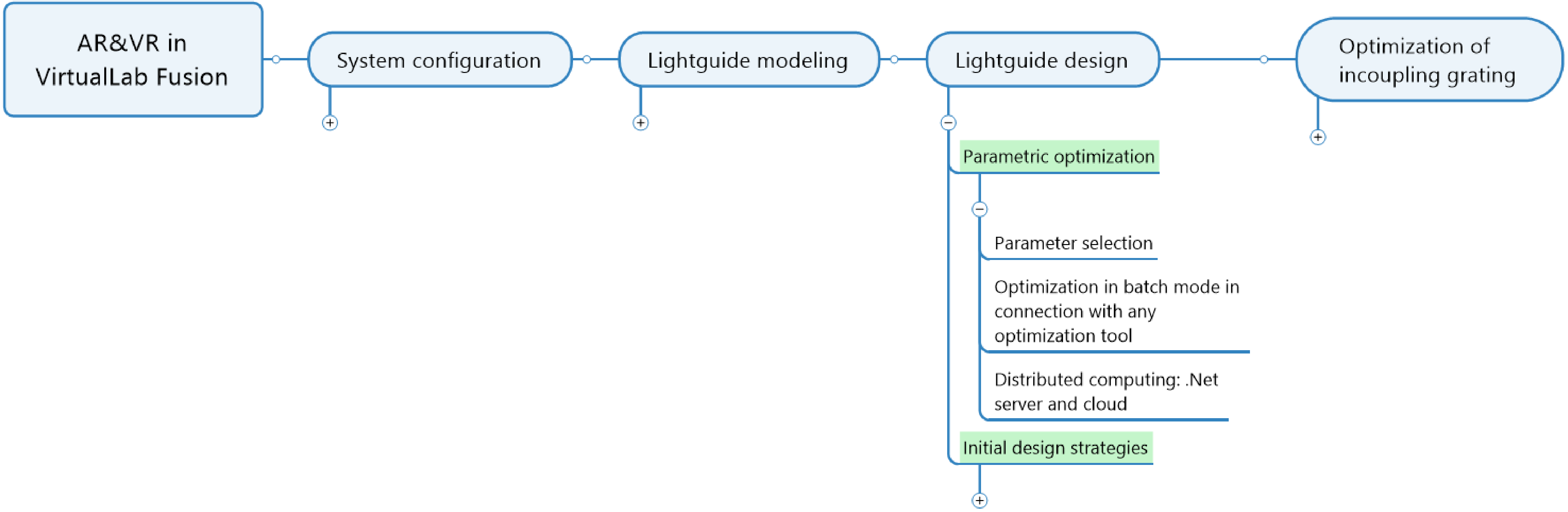
Lightguide Modeling and Design



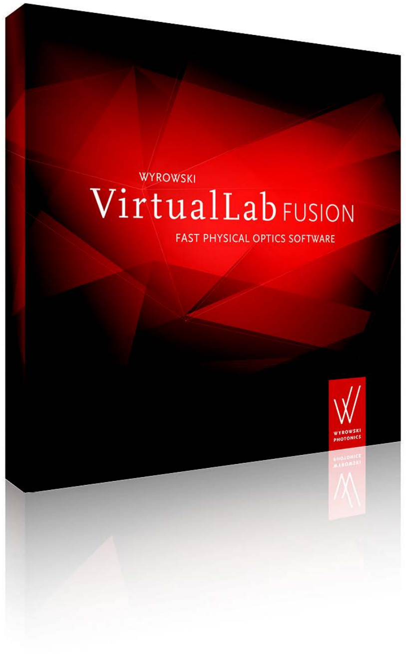
Parametric Optimization of Lightguide Parameters

Parametric optimization

Lightguide Modeling and Design



Parametric Optimization by VirtualLab & External Tools



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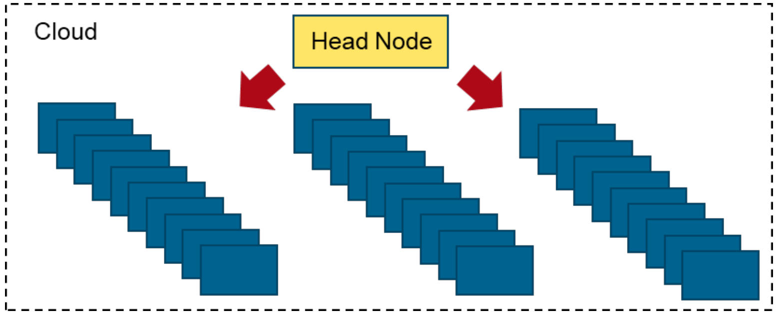
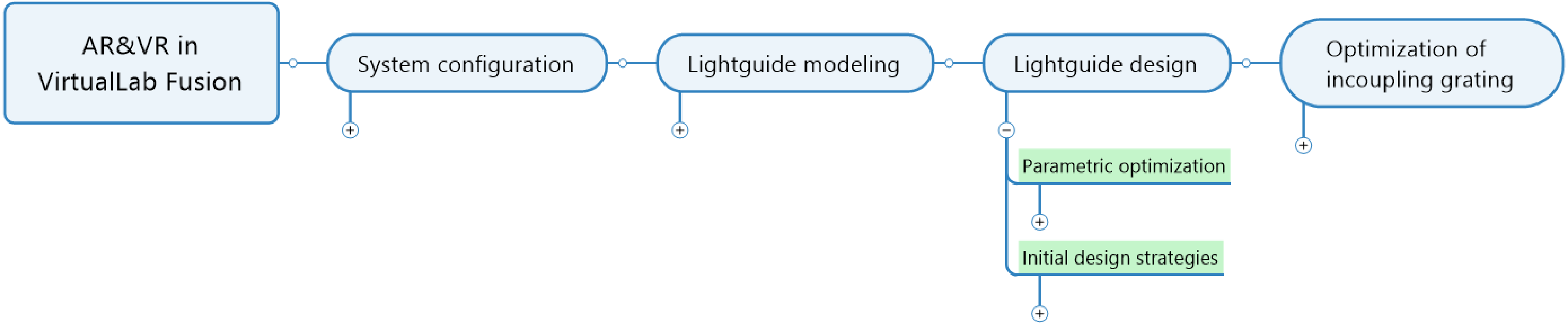


Provides full flexibility by a powerful combination of tools to find the best solution for your lightguide architecture

Lightguide Modeling and Design



Parametric Optimization and Initial Design

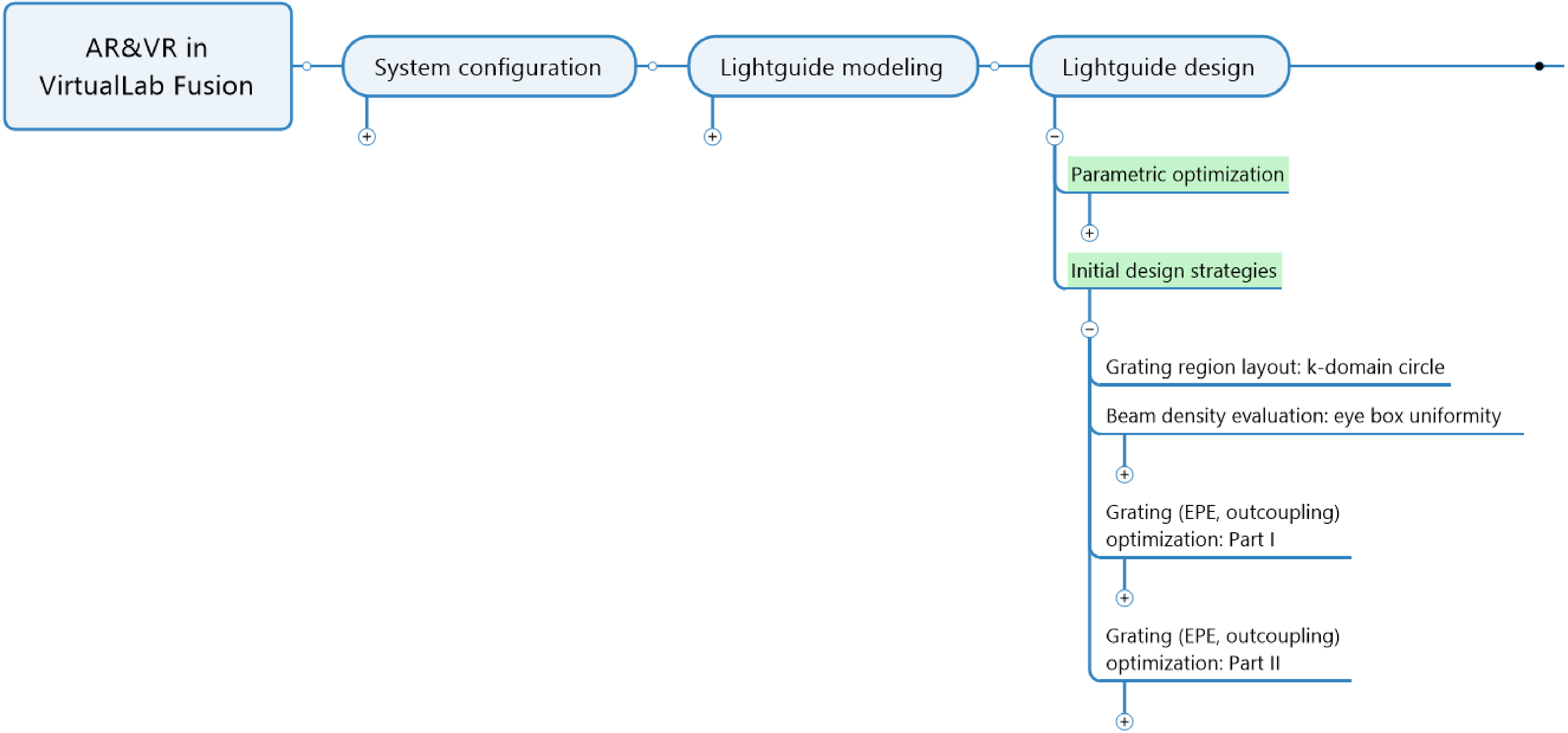
Initial design, e.g.

- Inverse approaches
- Functional design

In suitable combination

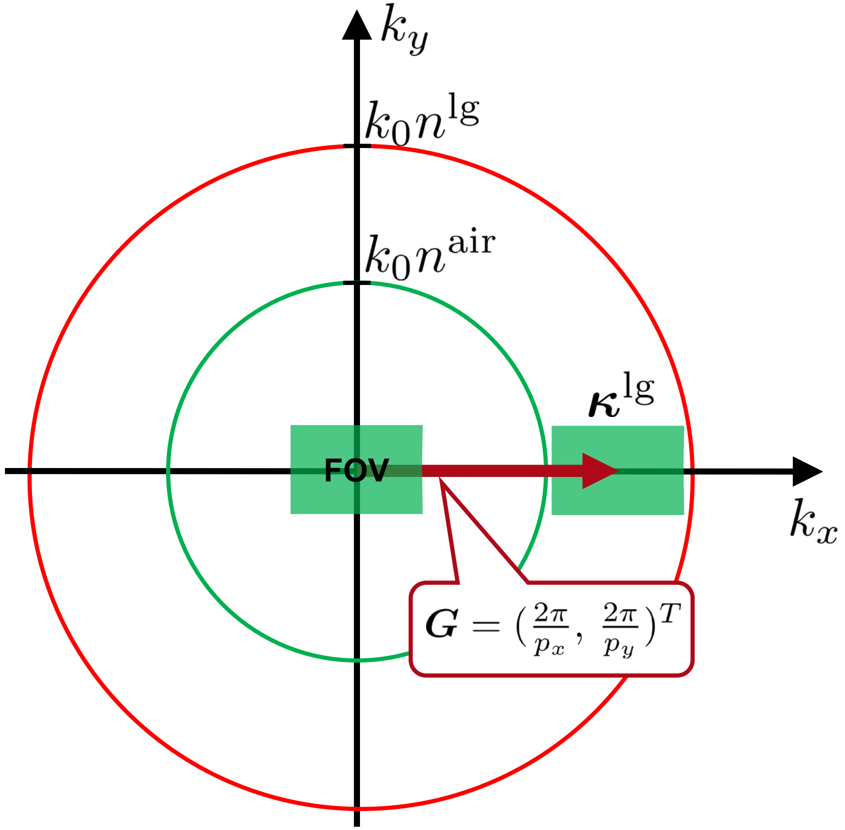
Parametric optimization

Lightguide Modeling and Design



Lightguide Modeling and Design

- AR&VR in VirtualLab Fusion
- System configuration
- Lightguide modeling
- Lightguide design
  - Parametric optimization
  - Initial design strategies
    - Grating region layout: k-domain circle
    - Beam density evaluation: eye box uniformity
    - Grating (EPE, outcoupling) optimization: Part I
    - Grating (EPE, outcoupling) optimization: Part II



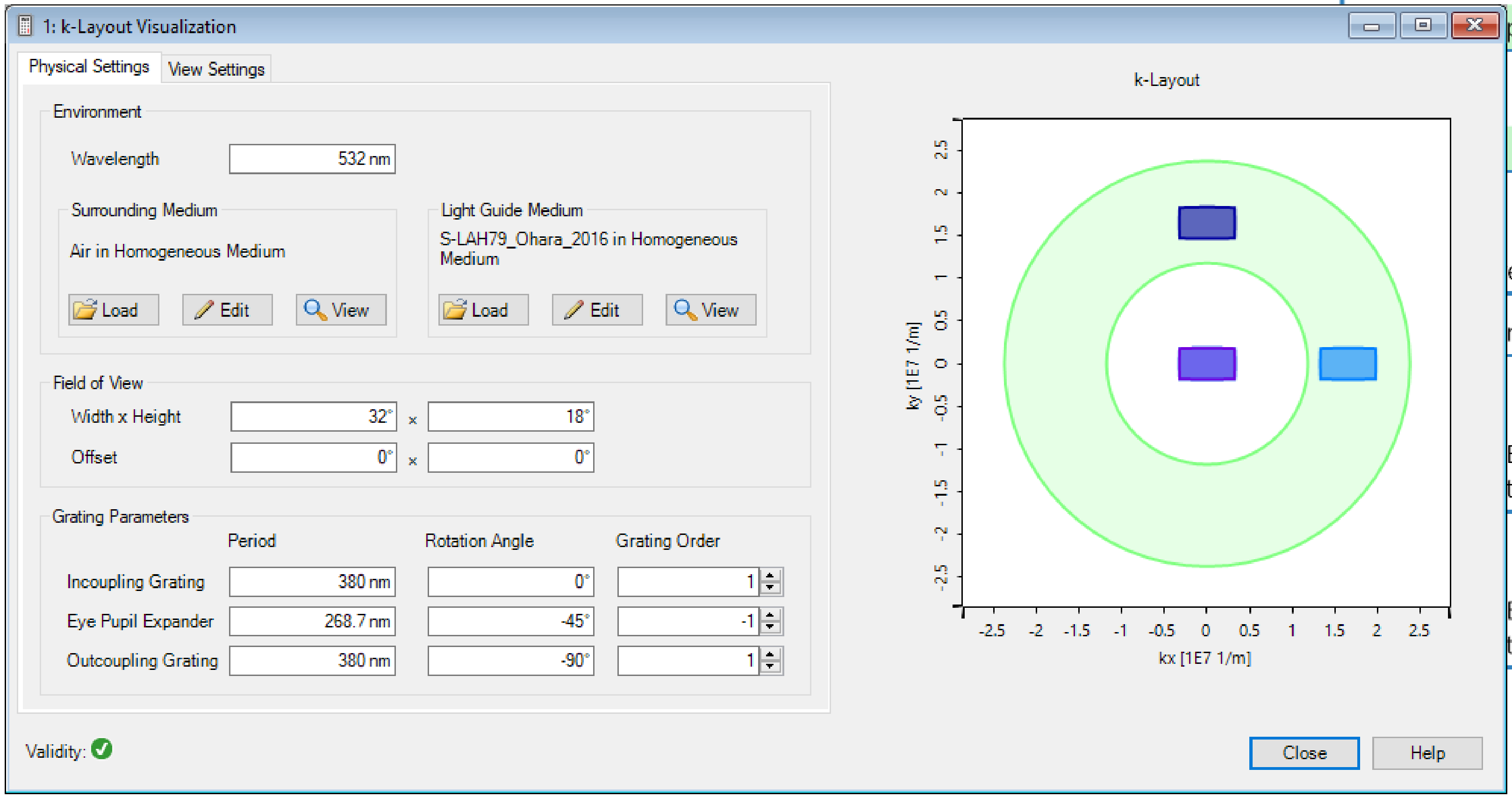
Lightguide Modeling and Design

AR&VR in VirtualLab Fusion

System configuration

Lightguide modeling

Lightguide design



ptimization

strategies

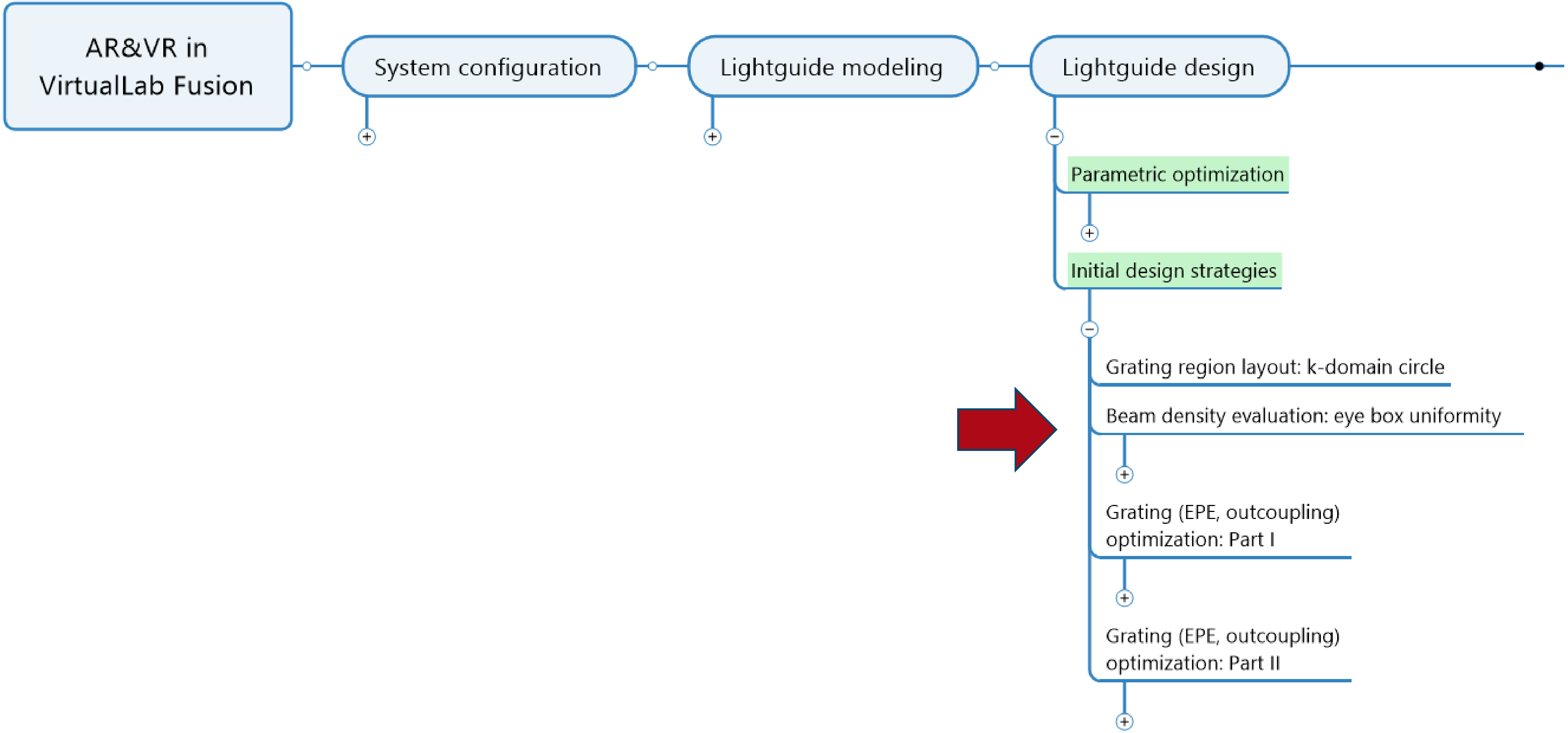
egion layout: k-domain circle

nsity evaluation: eye box uniformity

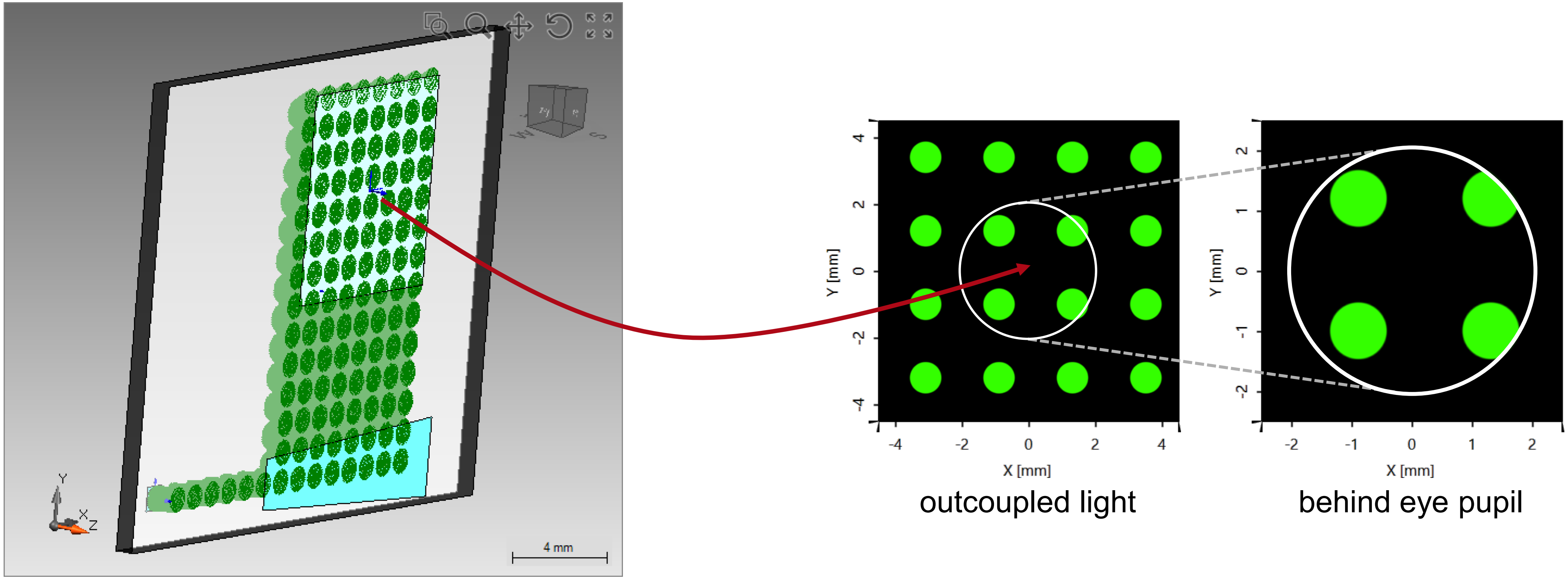
EPE, outcoupling)
tion: Part I

EPE, outcoupling)
tion: Part II

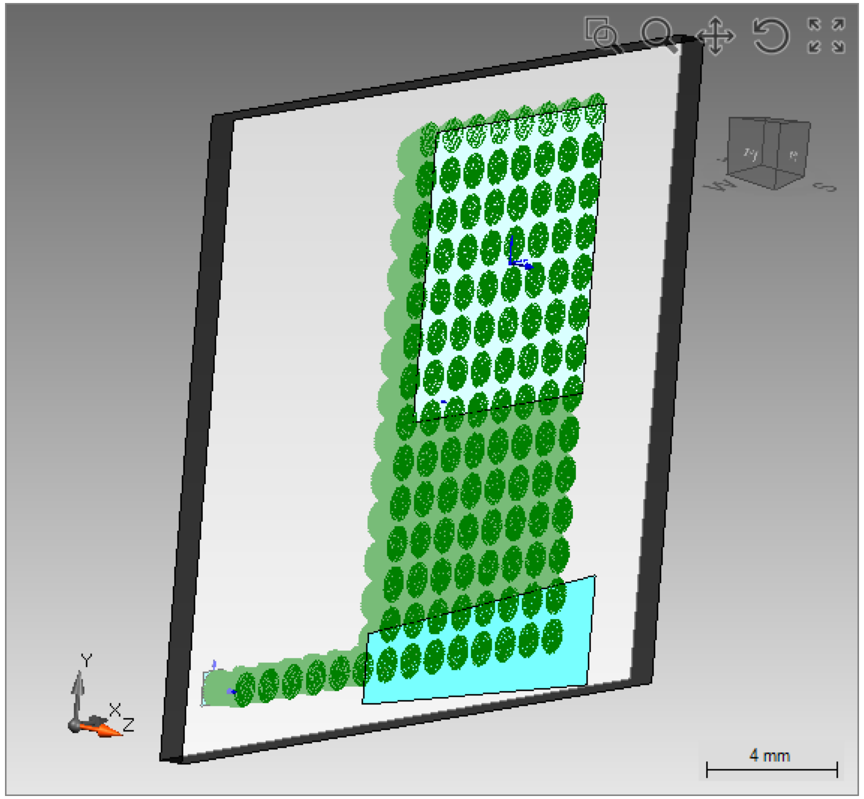
Lightguide Modeling and Design



Eyebox Uniformity vs. Beam Density



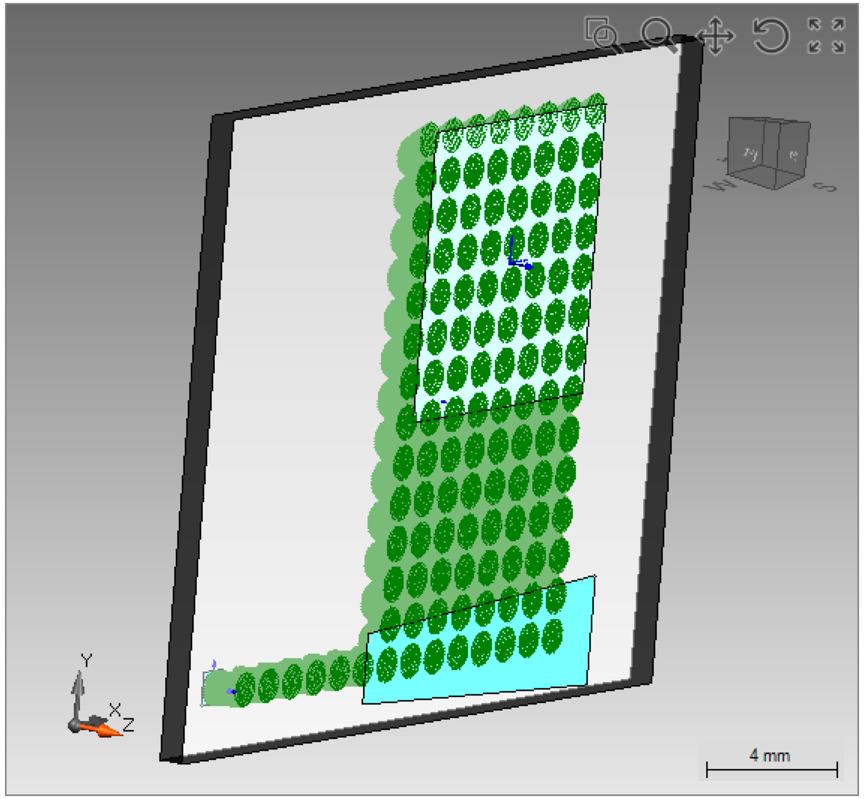
Eyebox Uniformity vs. Beam Density



- Per eye position (x, y) in eyebox the flux into the eye per FOV angle (θ_x, θ_y) is calculated, which represents the radiance L_e.
- The uniformity error $\Omega(\theta_x, \theta_y)$ is defined as the contrast of L_e:

$$\Omega(\theta_x, \theta_y) = \frac{\max_{(x,y)} L_e(\theta_x, \theta_y; x, y) - \min_{(x,y)} L_e(\theta_x, \theta_y; x, y)}{\max_{(x,y)} L_e(\theta_x, \theta_y; x, y) + \min_{(x,y)} L_e(\theta_x, \theta_y; x, y)}$$

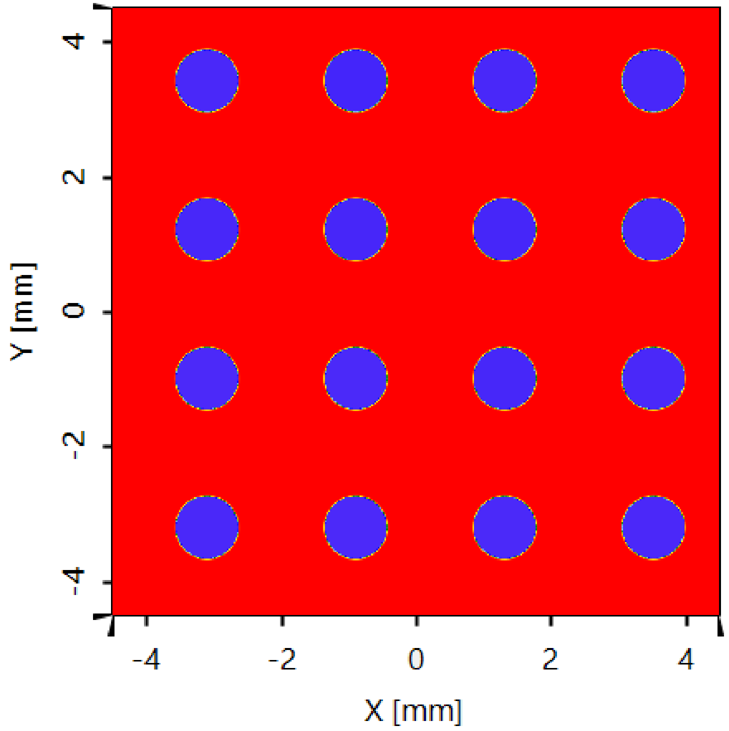
Eyebox Uniformity vs. Beam Density



Initial investigation:

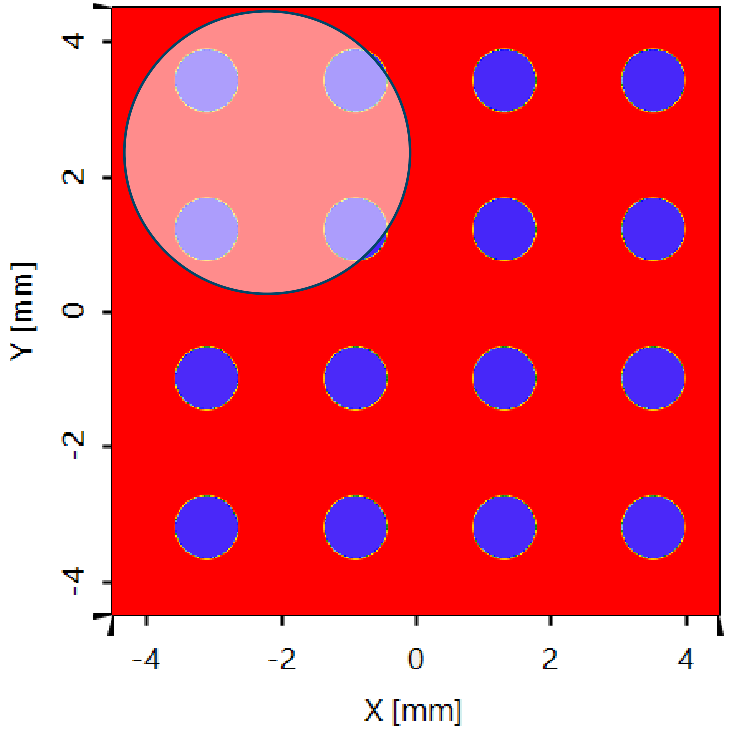
- Assume ideal gratings which provide perfectly uniform beams.
- Concentrate on beam density vs.
    - Thickness of lightguide
    - Beam size (light engine)
    - Off-axis angle incoupling

Eyebox Uniformity vs. Beam Density



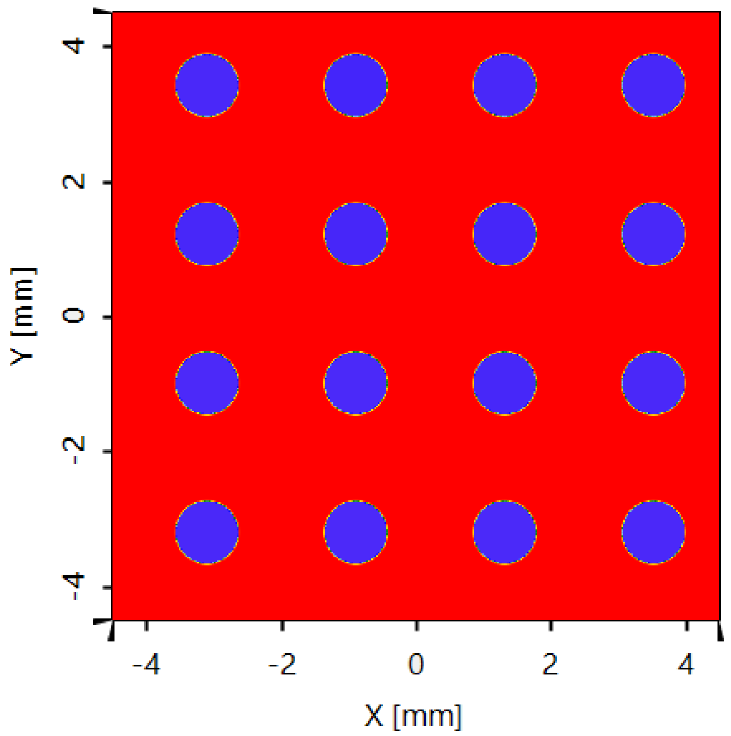
Irradiance in eyebox: FOV (0°, 0°)

Eyebox Uniformity vs. Beam Density

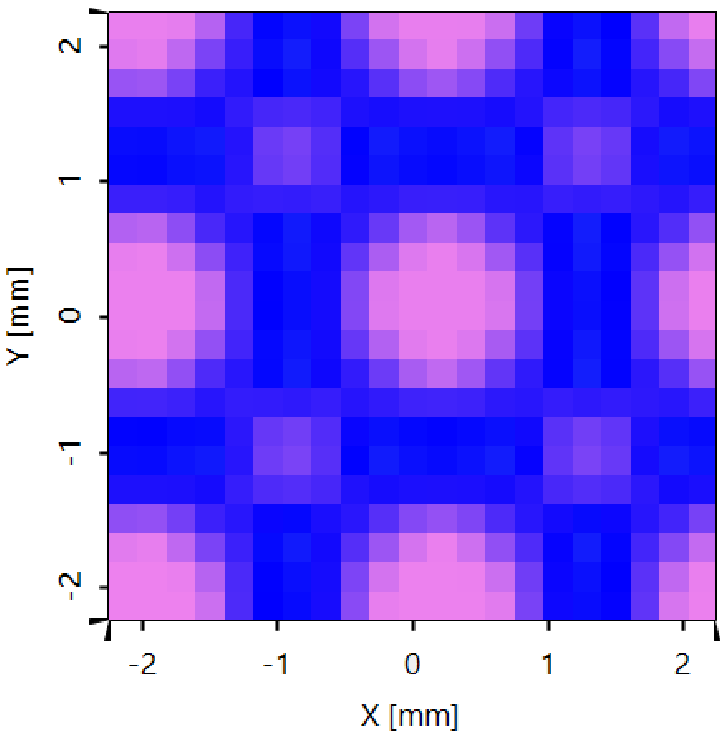


Irradiance in eyebox: FOV (0°, 0°)

Eyebox Uniformity vs. Beam Density



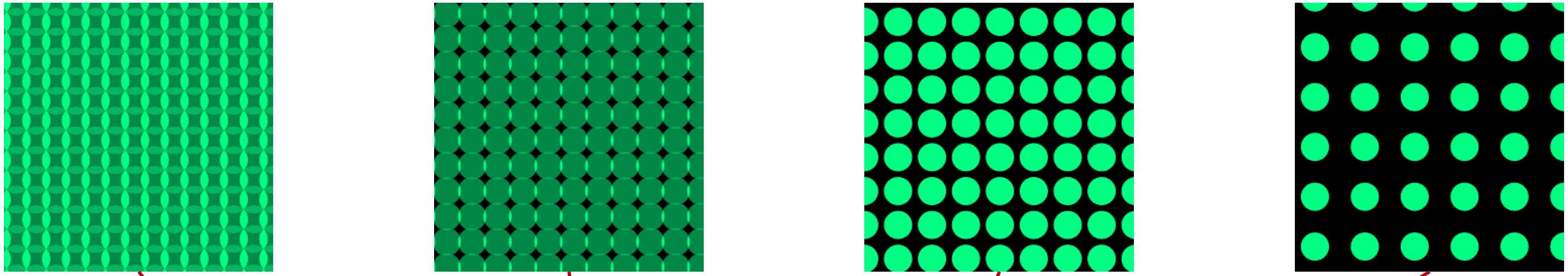
Irradiance in eyebox: FOV (0°, 0°)

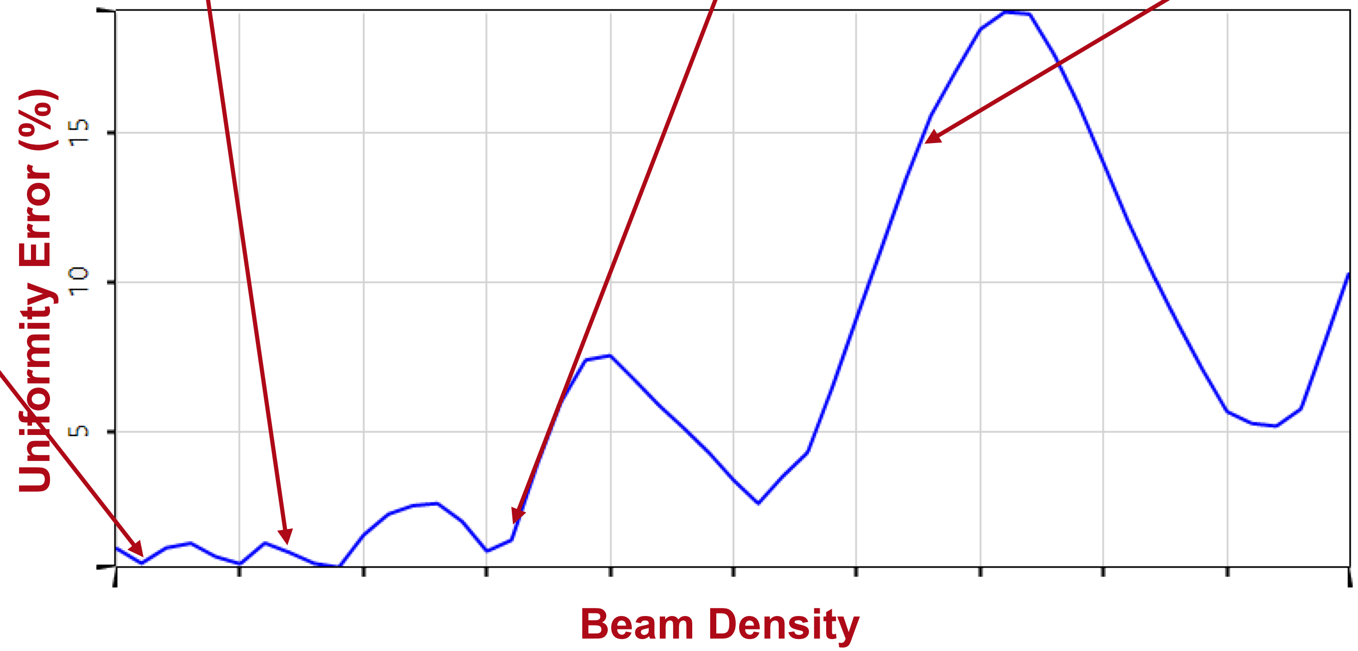


Radiance FOV (0°, 0°)

Uniformity: 10.5%

Eyebox Uniformity vs. Beam Density: Single Wavelength

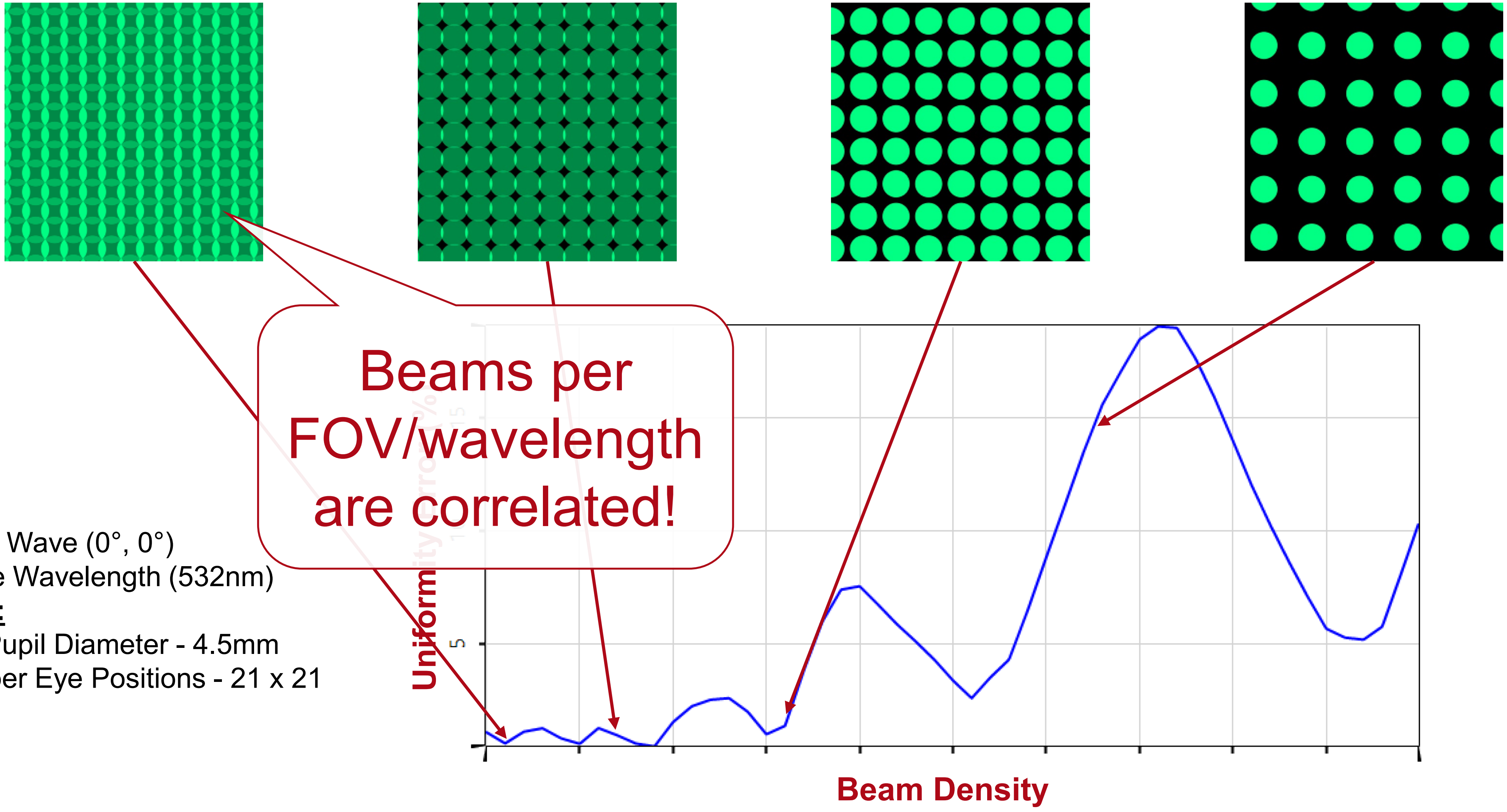




Source
- Plane Wave (0°, 0°)
- Single Wavelength (532nm)

Detector:
- Eye Pupil Diameter - 4.5mm
- Number Eye Positions - 21 x 21

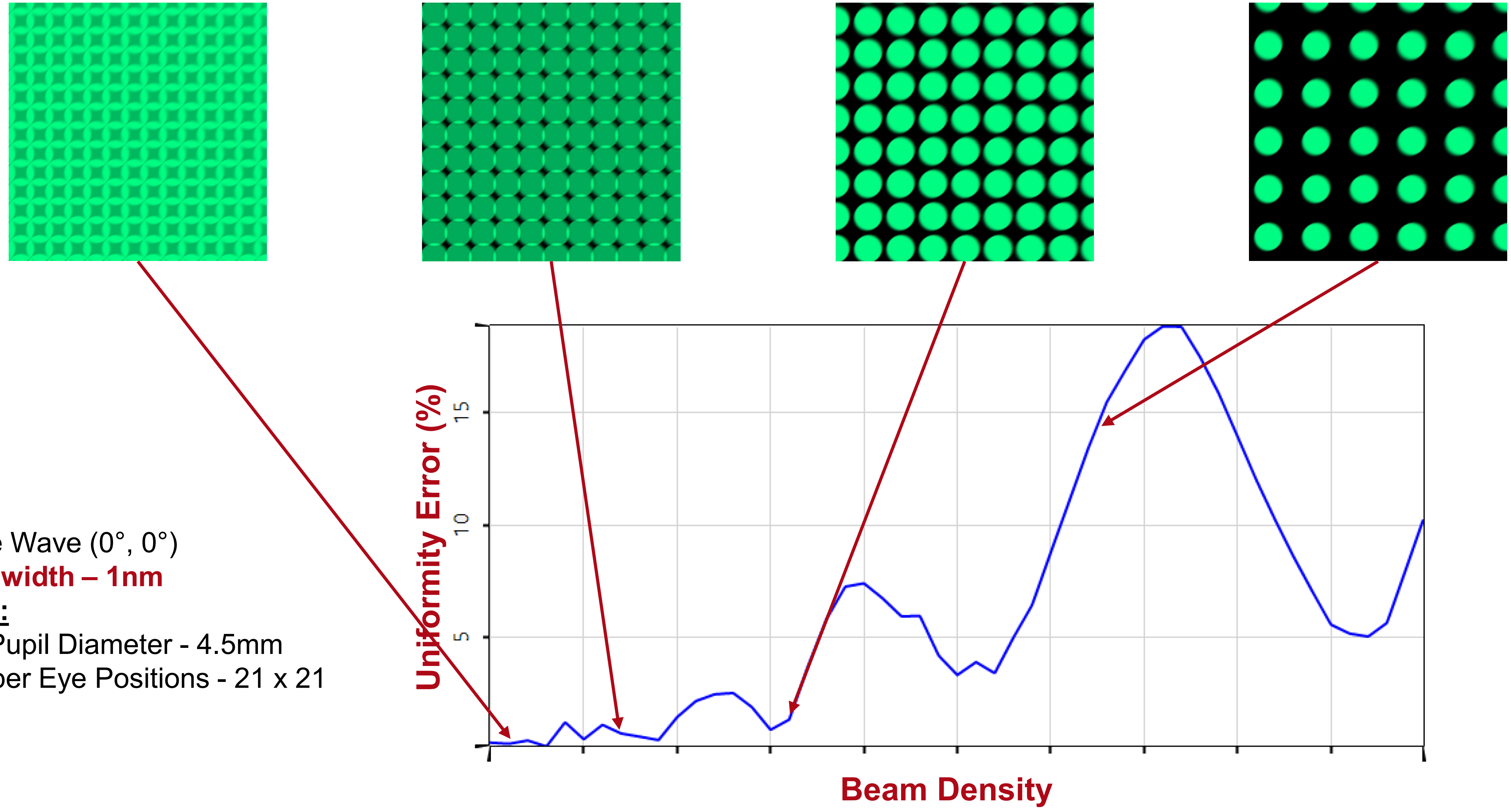
Eyebox Uniformity vs. Beam Density: Single Wavelength



Source
- Plane Wave (0°, 0°)
- Single Wavelength (532nm)

Detector:
- Eye Pupil Diameter - 4.5mm
- Number Eye Positions - 21 x 21

Eyebox Uniformity vs. Beam Density: Bandwidth 1nm



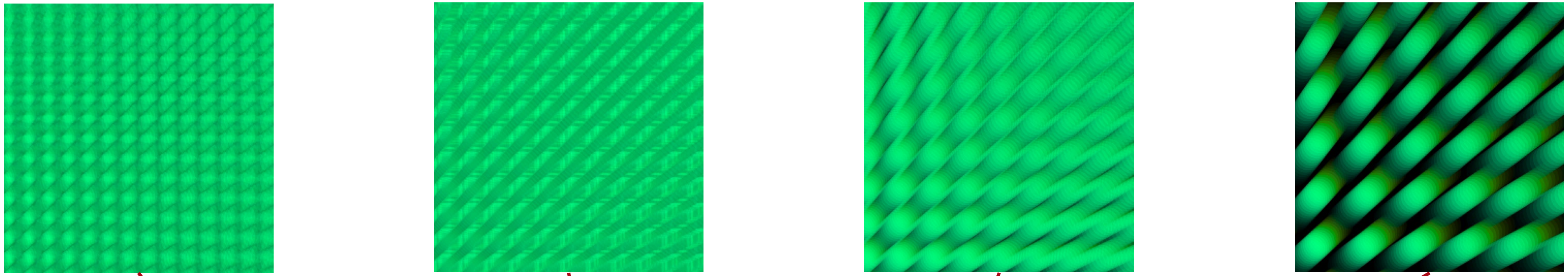
Source

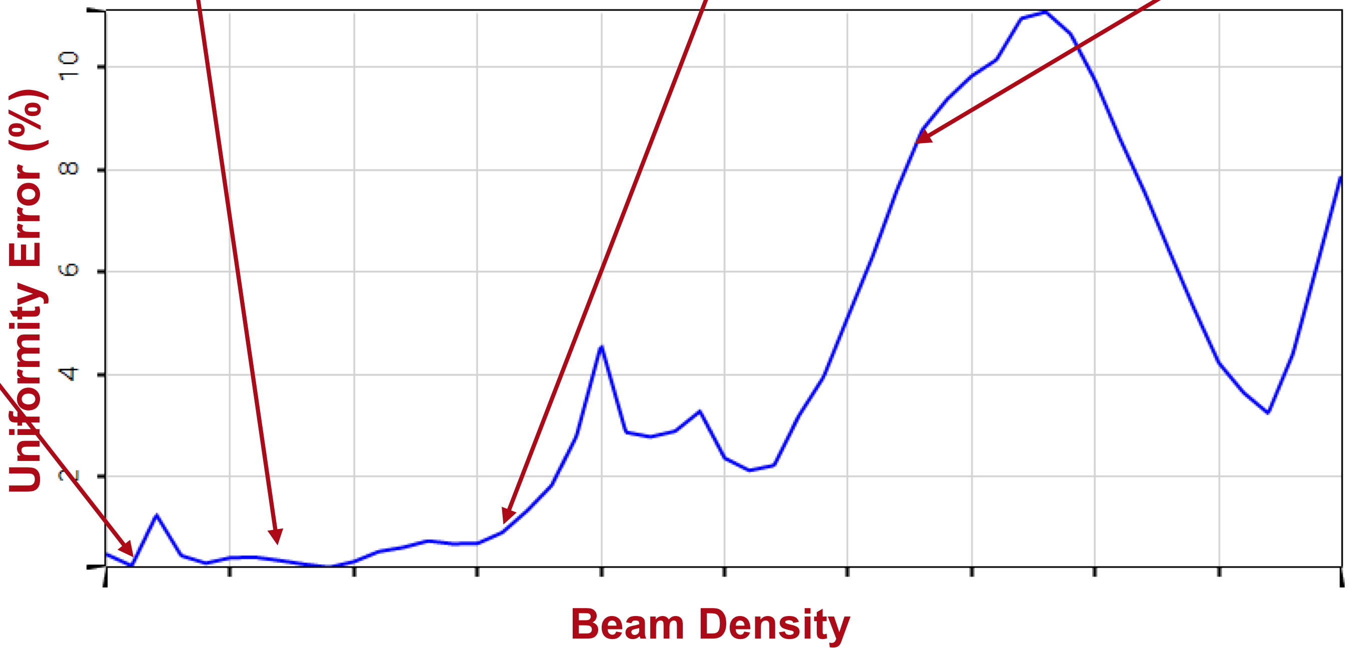
- Plane Wave (0°, 0°)
- **Bandwidth – 1nm**

Detector:

- Eye Pupil Diameter - 4.5mm
- Number Eye Positions - 21 x 21

Eyebox Uniformity vs. Beam Density: Bandwidth 10nm

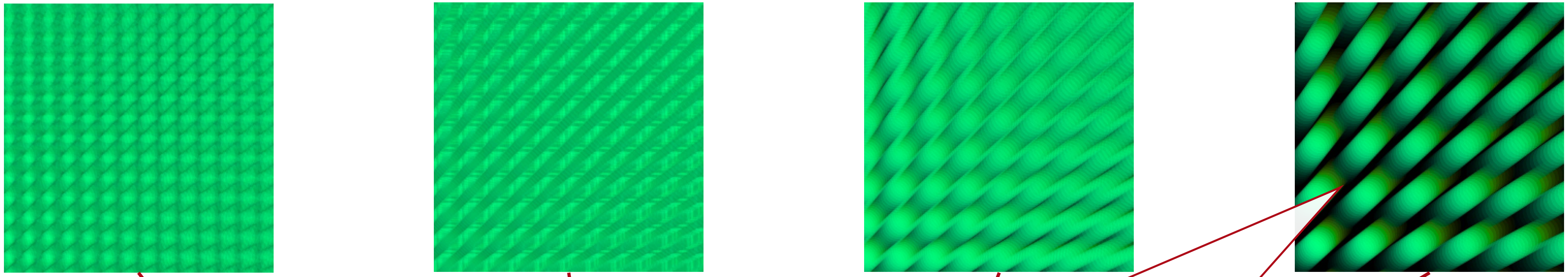




Source
- Plane Wave (0°, 0°)
- **Bandwidth – 10nm**

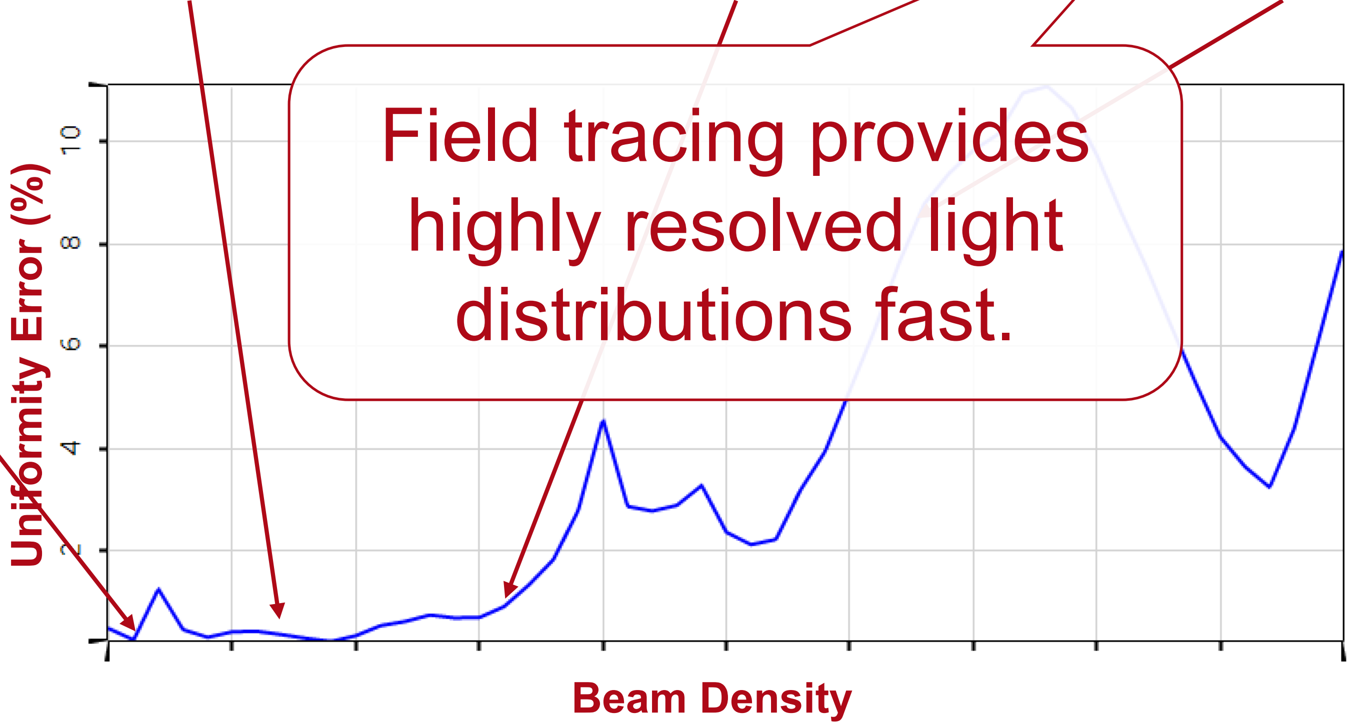
Detector:
- Eye Pupil Diameter - 4.5mm
- Number Eye Positions - 21 x 21

Eyebox Uniformity vs. Beam Density: Bandwidth 10nm

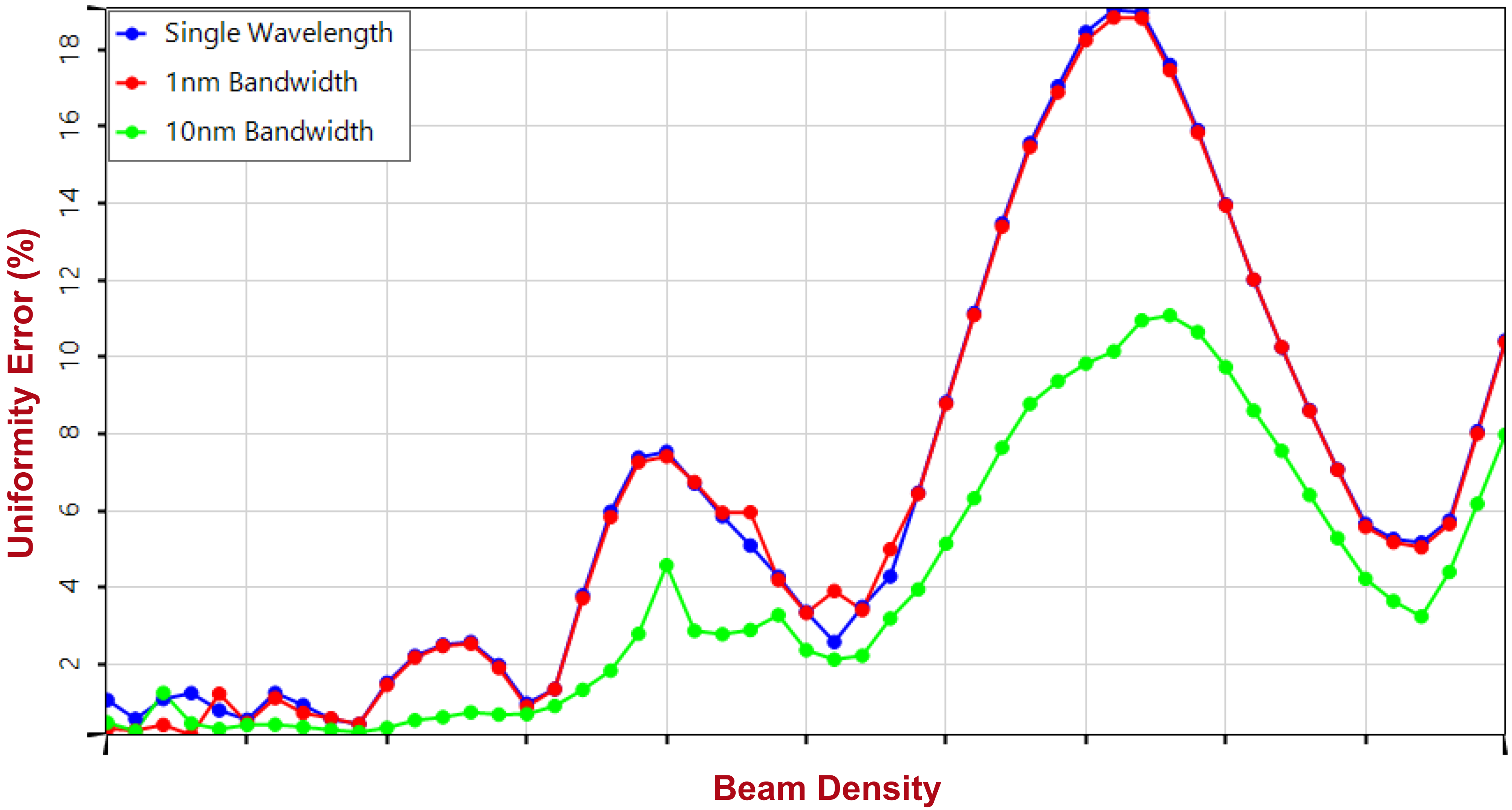


Source
- Plane Wave (0°, 0°)
- **Bandwidth – 10nm**

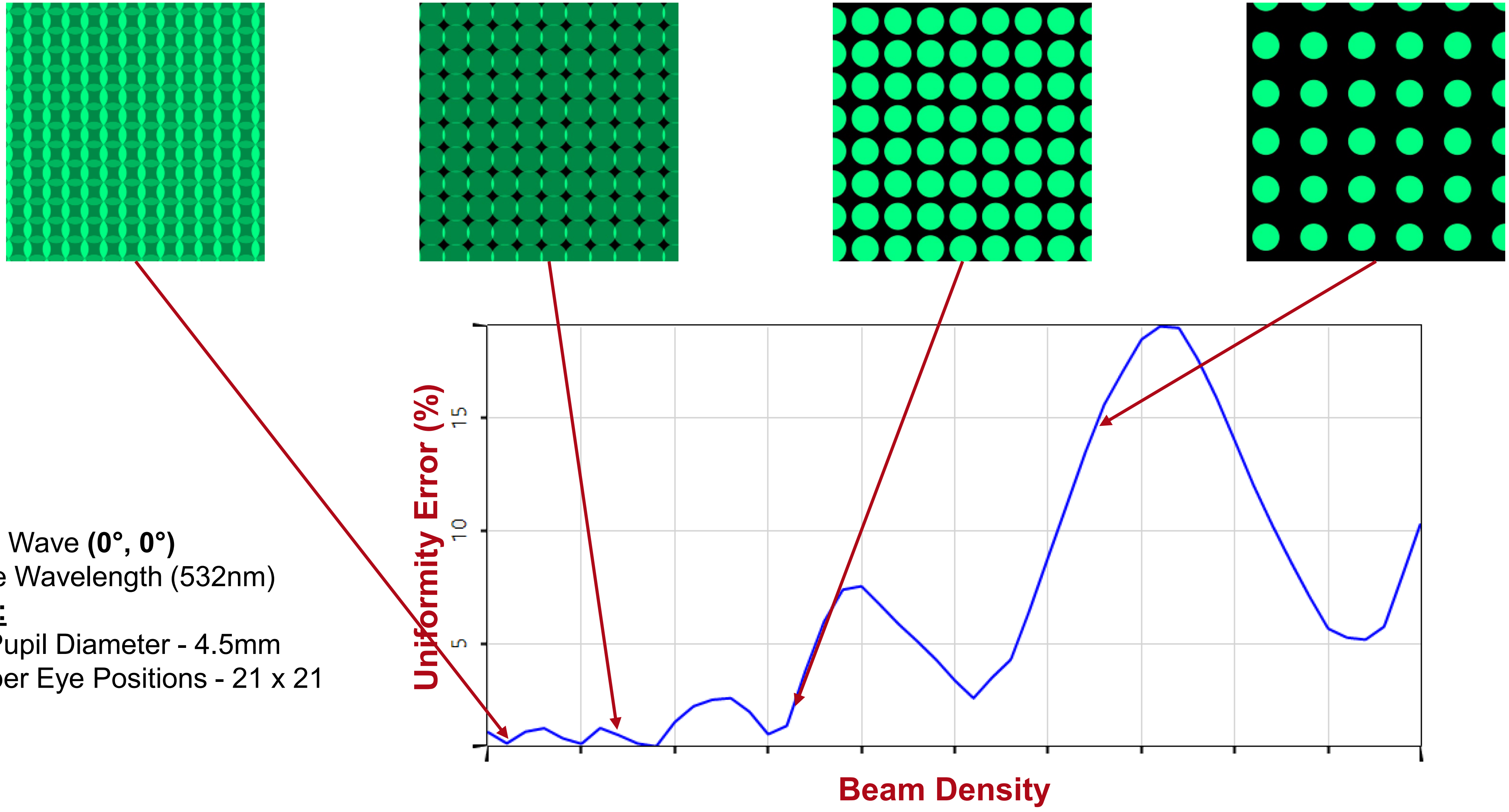
Detector:
- Eye Pupil Diameter - 4.5mm
- Number Eye Positions - 21 x 21



Uniformity vs. Beam Density – Comparison Bandwidths



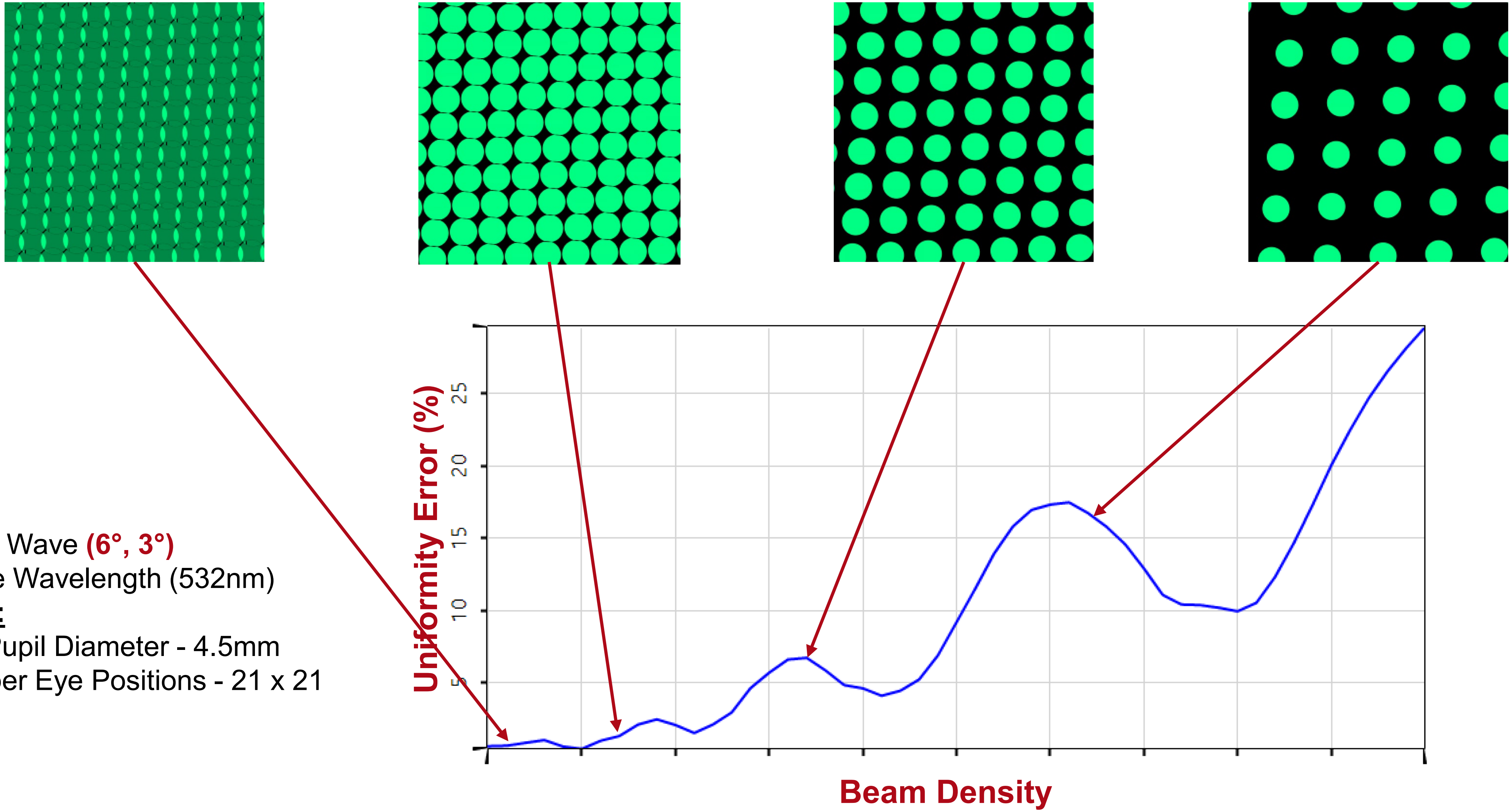
Eyebox Uniformity vs. Beam Density: FOV 1



Source
- Plane Wave **(0°, 0°)**
- Single Wavelength (532nm)

Detector:
- Eye Pupil Diameter - 4.5mm
- Number Eye Positions - 21 x 21

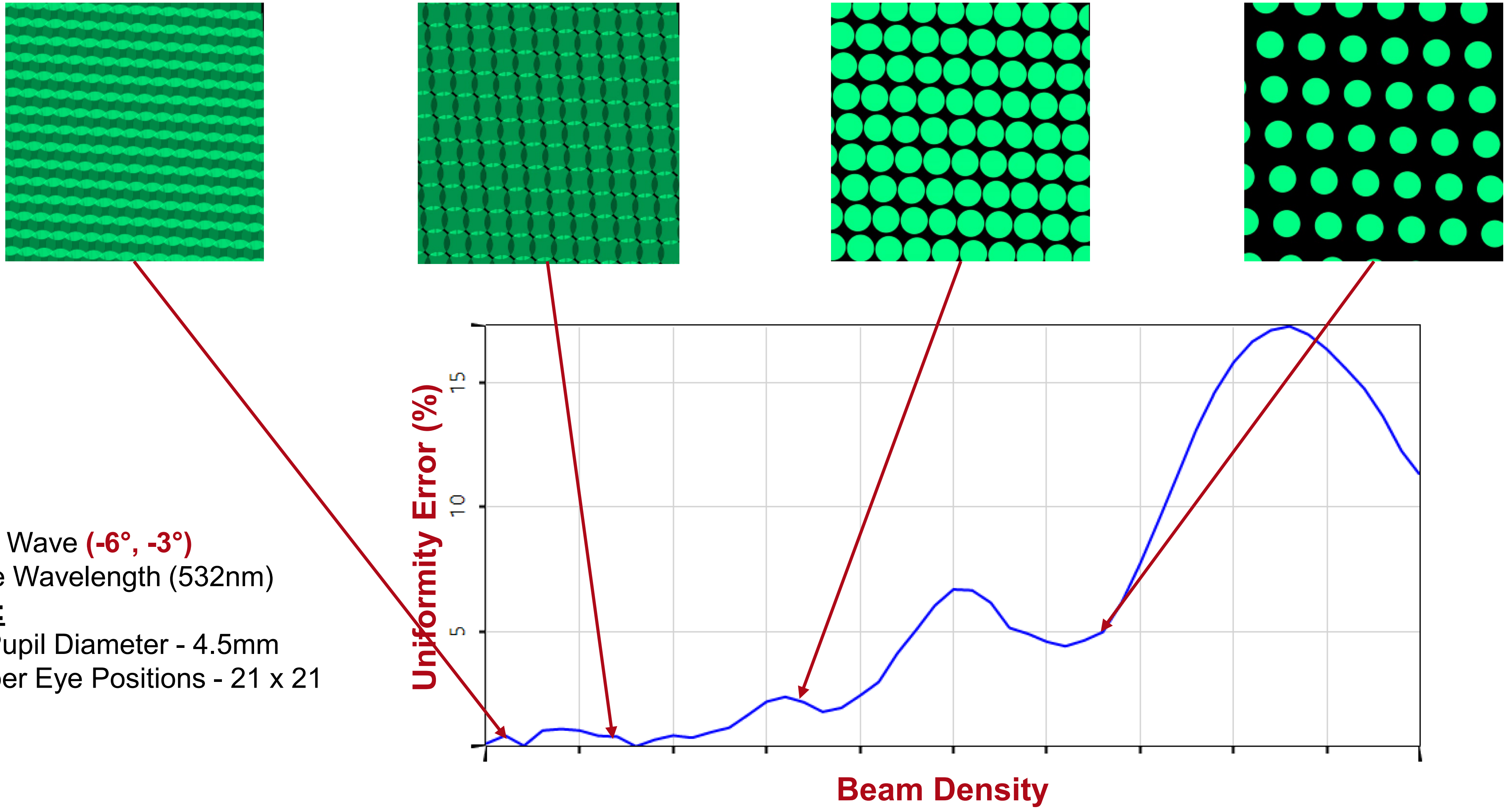
Eyebox Uniformity vs. Beam Density: FOV 2



Source
- Plane Wave **(6°, 3°)**
- Single Wavelength (532nm)

Detector:
- Eye Pupil Diameter - 4.5mm
- Number Eye Positions - 21 x 21

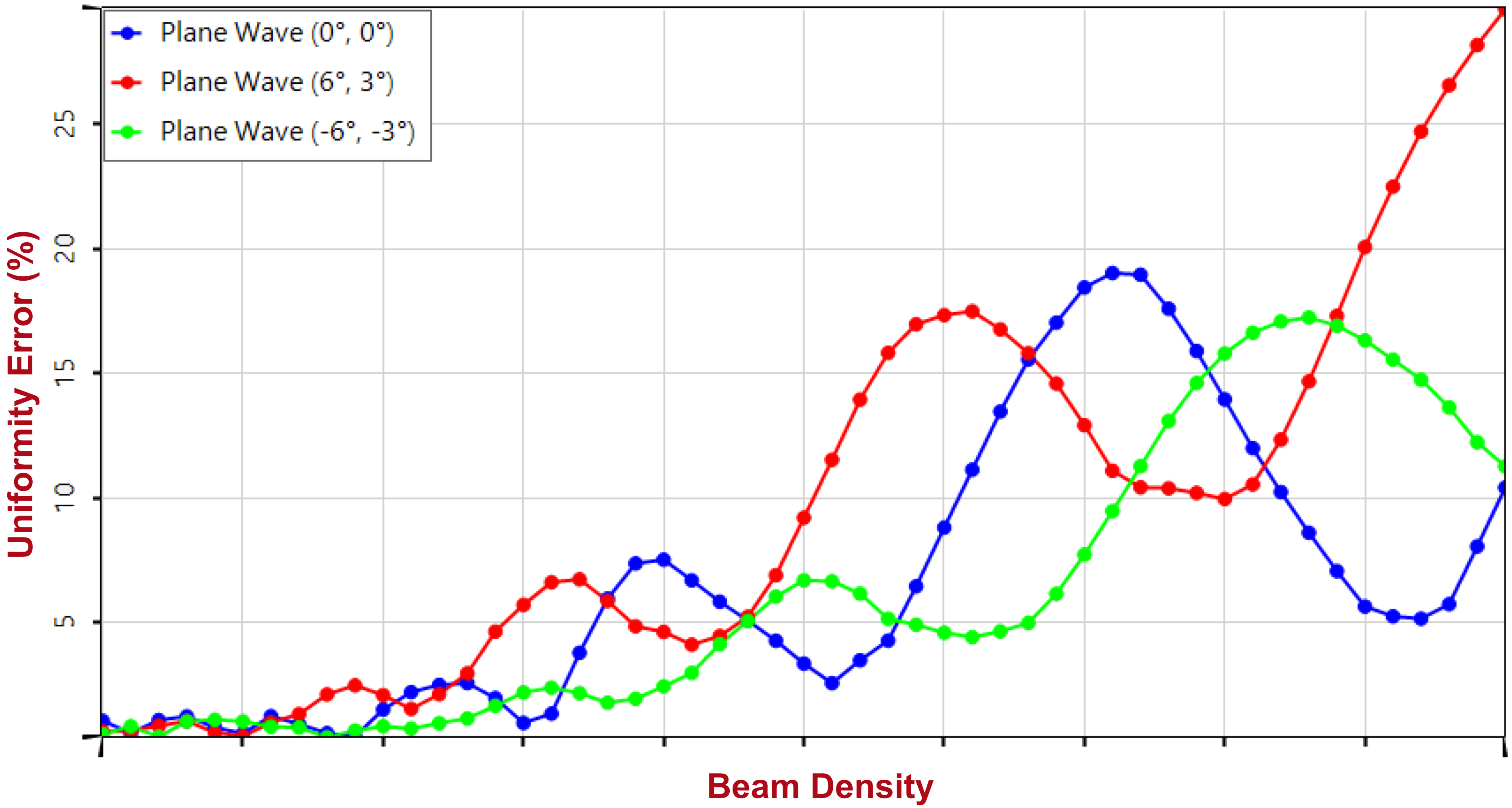
Eyebox Uniformity vs. Beam Density: FOV 3



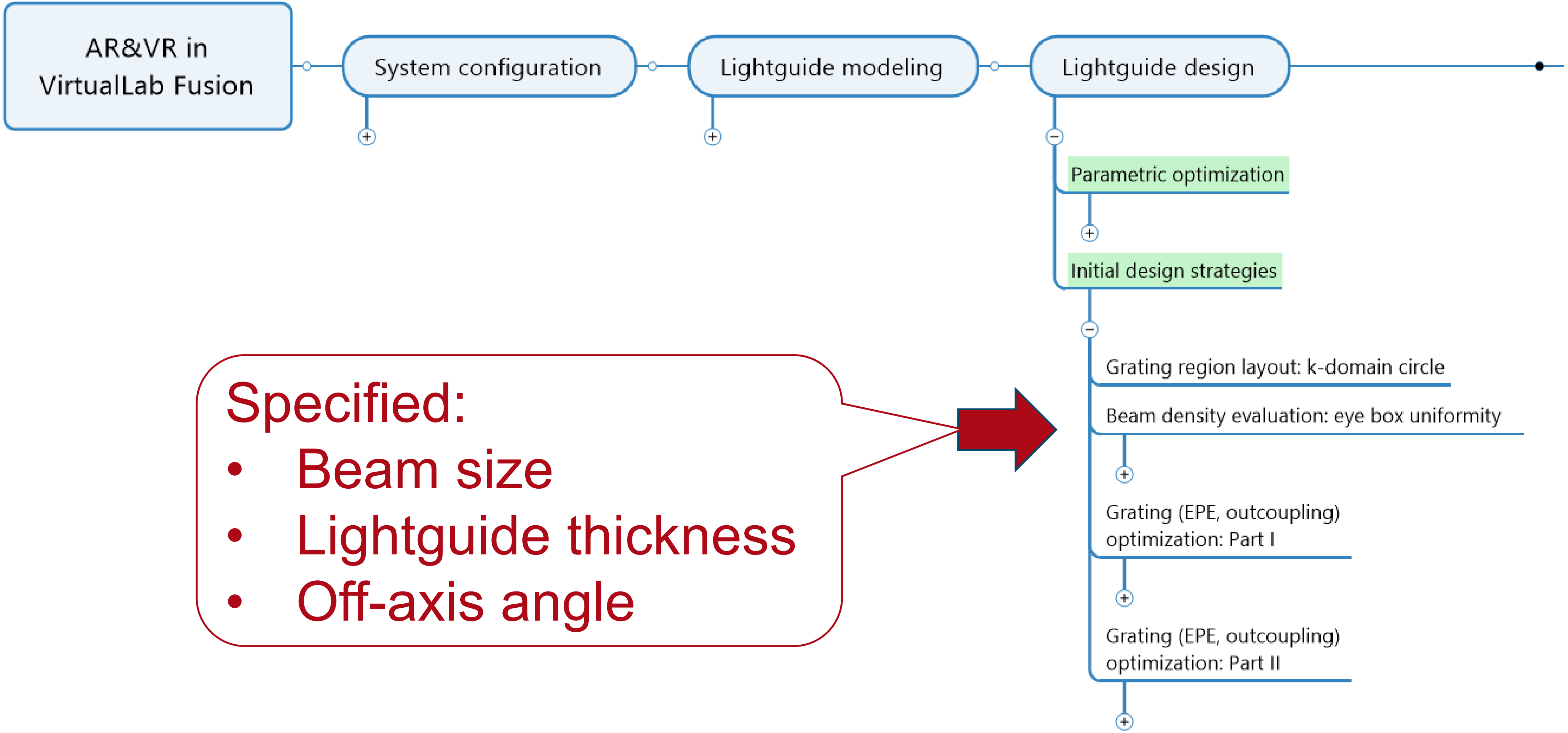
Source
- Plane Wave **(-6°, -3°)**
- Single Wavelength (532nm)

Detector:
- Eye Pupil Diameter - 4.5mm
- Number Eye Positions - 21 x 21

Uniformity vs. Beam Density: Comparison Different FOVs



Lightguide Modeling and Design: Grating Optimization



Specified:

- Beam size
- Lightguide thickness
- Off-axis angle

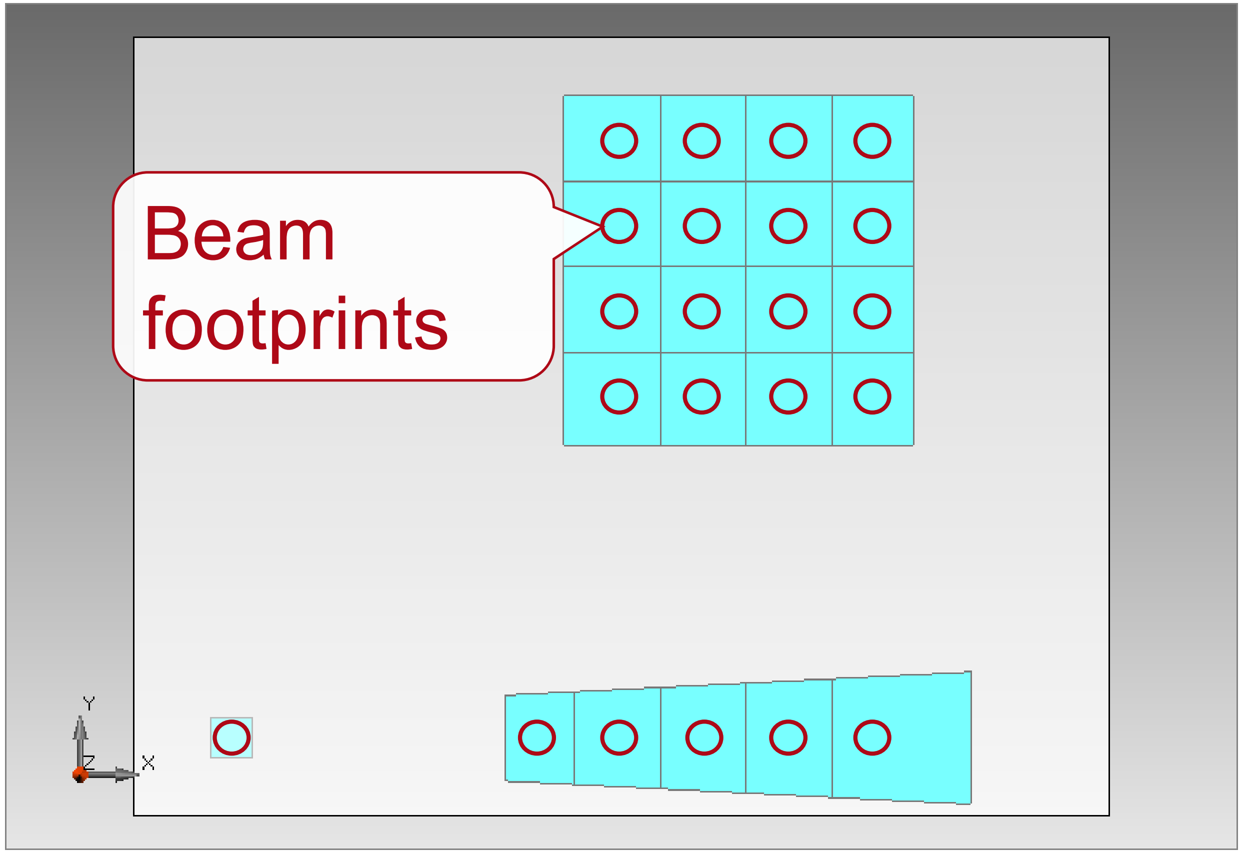
Lightguide Modeling and Design: Grating Optimization

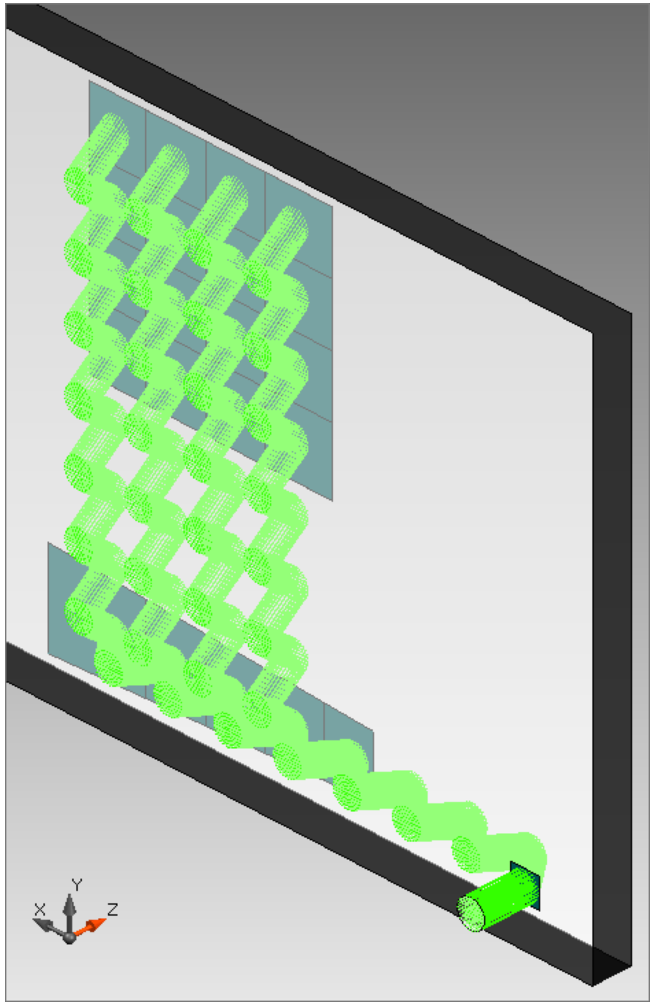
- AR&VR in VirtualLab Fusion
  - System configuration
  - Lightguide modeling
  - Lightguide design
    - Parametric optimization
    - Initial design strategies
      - Grating region layout: k-domain circle
      - Beam density evaluation: eye box uniformity
      - Grating (EPE, outcoupling) optimization: Part I
        - Direct design for selected FOV modes
        - Combination of results
      - Grating (EPE, outcoupling) optimization: Part II

Strategy:

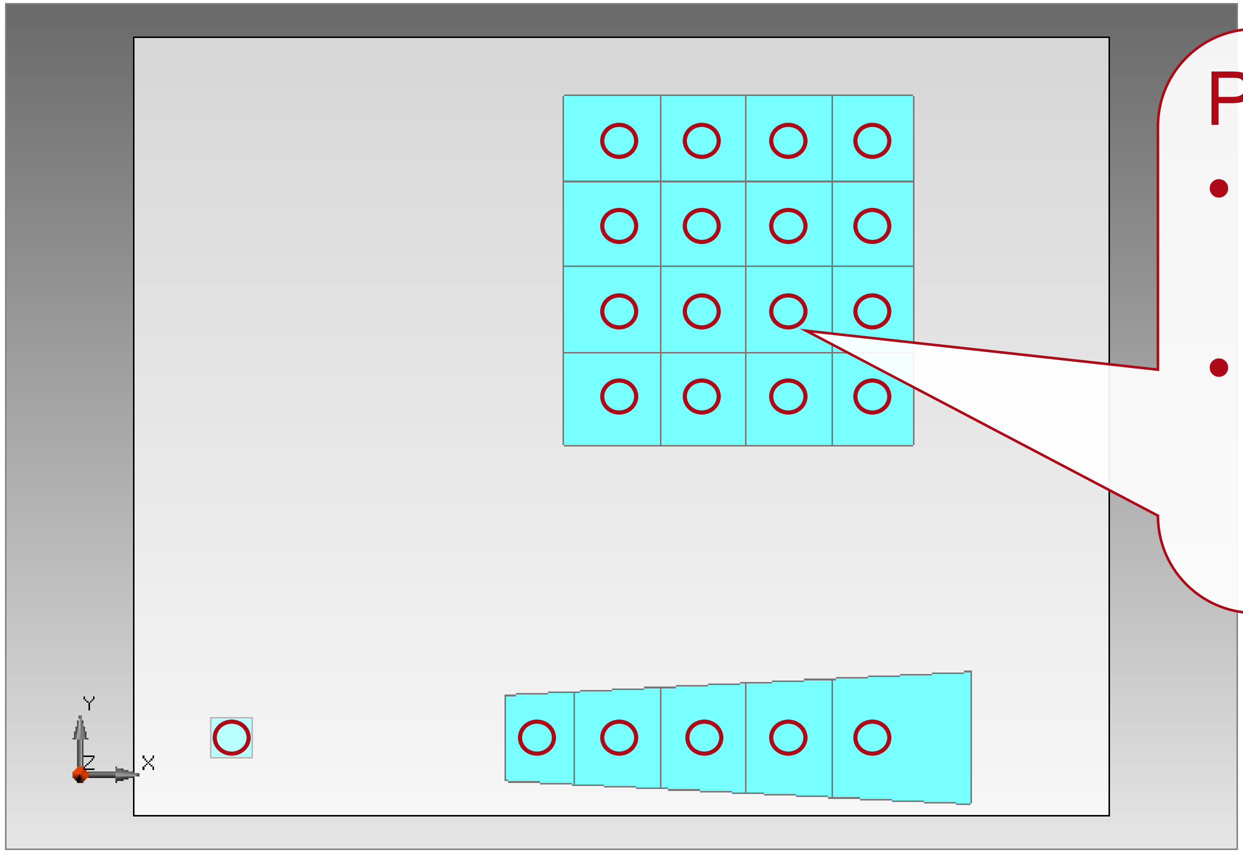
- Optimize grating parameters per FOV angle
- Combine results

Grating Design for FOV Angle (0°, 0°)





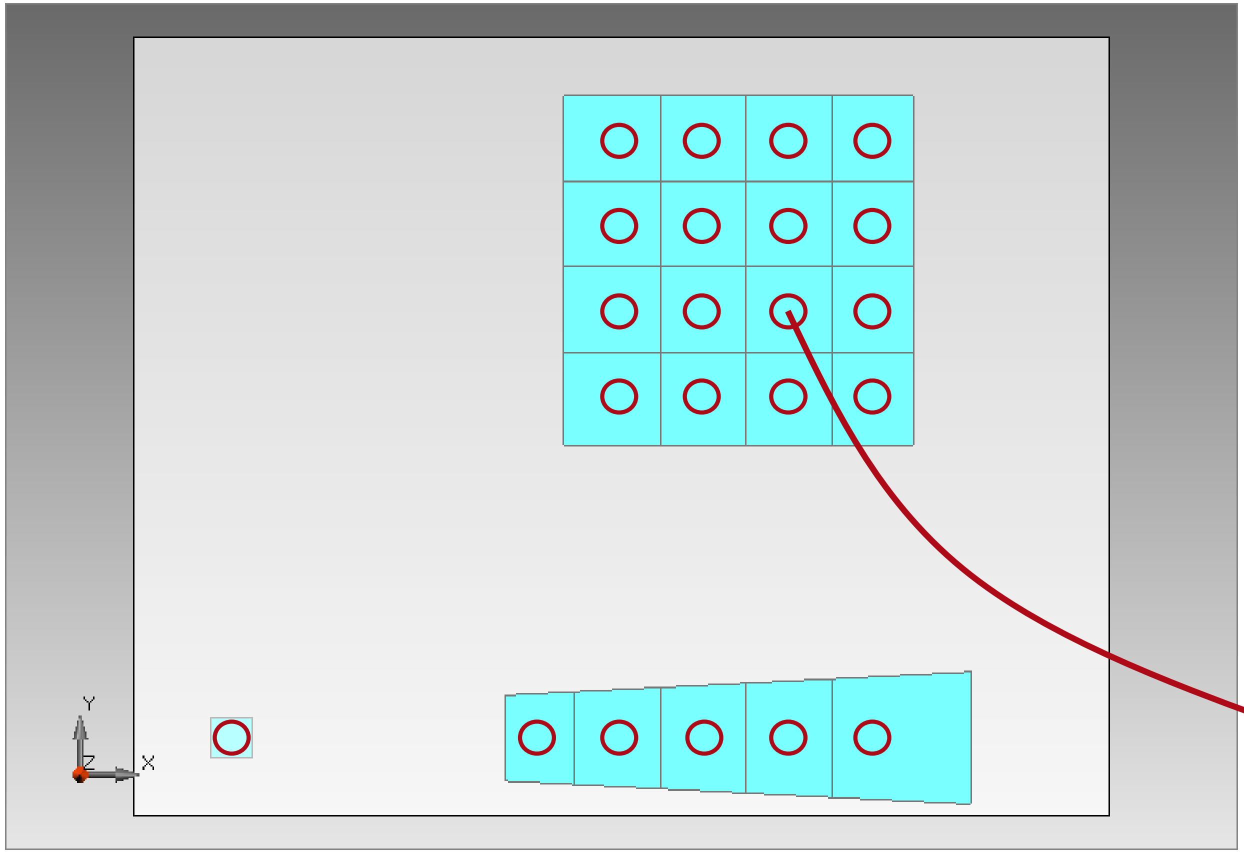
Grating Design per FOV Angle: Flux Control

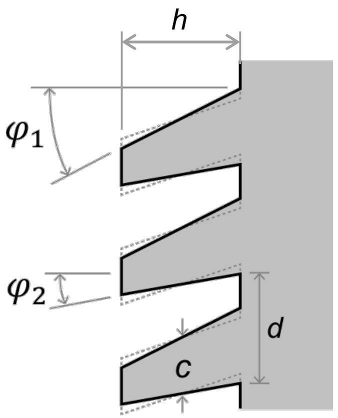


Per footprint of beam:

- Control percental flux into required directions
- Optimize local grating parameters to obtain required flux

Grating Design per FOV Angle: Grating Analysis and Selection





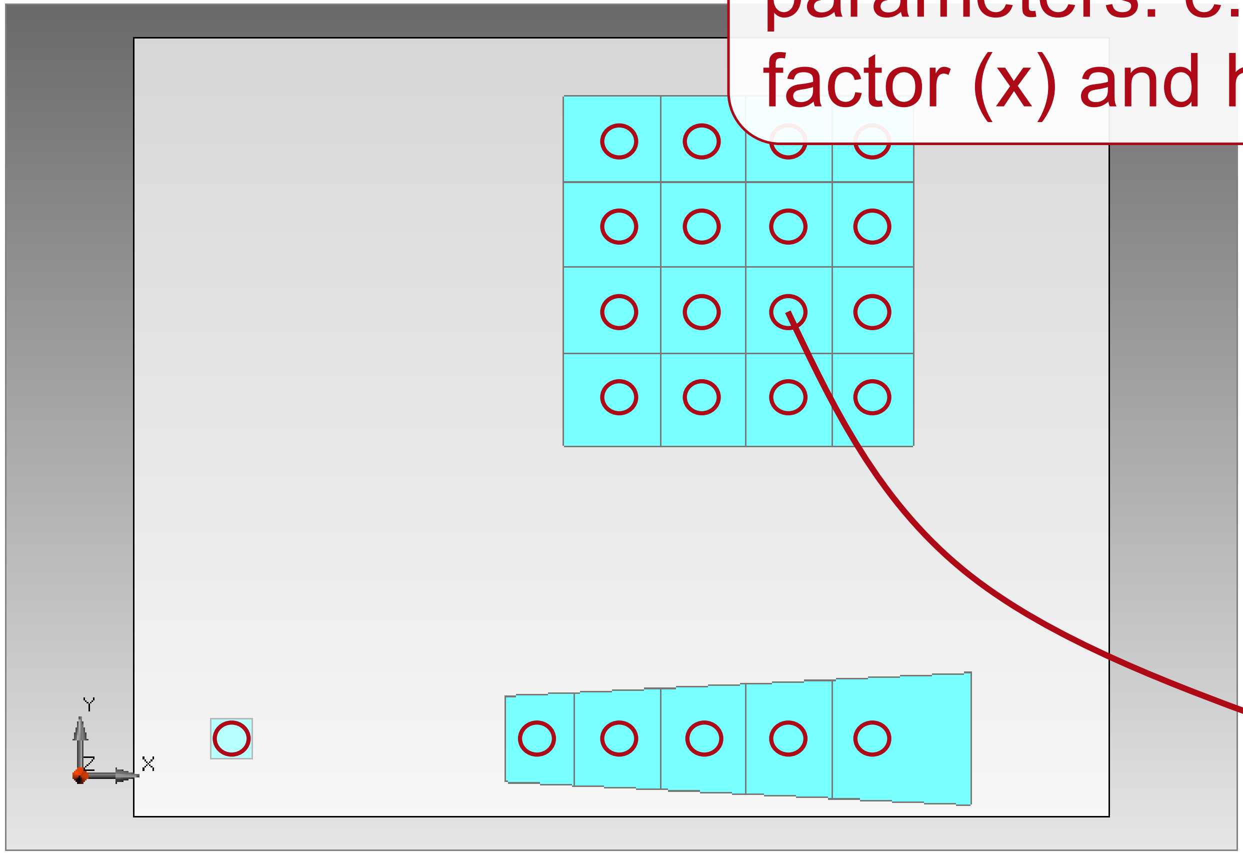
example slanted grating structure

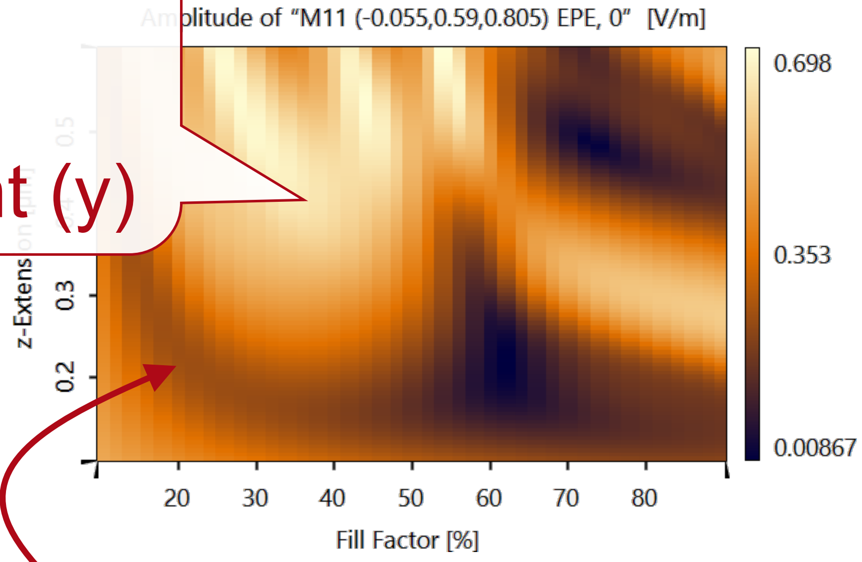
Calculation of Rayleigh matrix for given input beam parameters

$$\begin{pmatrix} E_{x,\text{out}} \\ E_{y,\text{out}} \end{pmatrix}_{k_{\text{out},m}} = \begin{bmatrix} R_{xx} & R_{yx} \\ R_{xy} & R_{yy} \end{bmatrix} \cdot \begin{pmatrix} E_{x,\text{arb,in}} \\ E_{y,\text{arb,in}} \end{pmatrix}_{k_{\text{in}}}$$

Grating Design per FOV Angle: Grating Analysis and Selection

Scan of grating parameters: e.g. fill factor (x) and height (y)

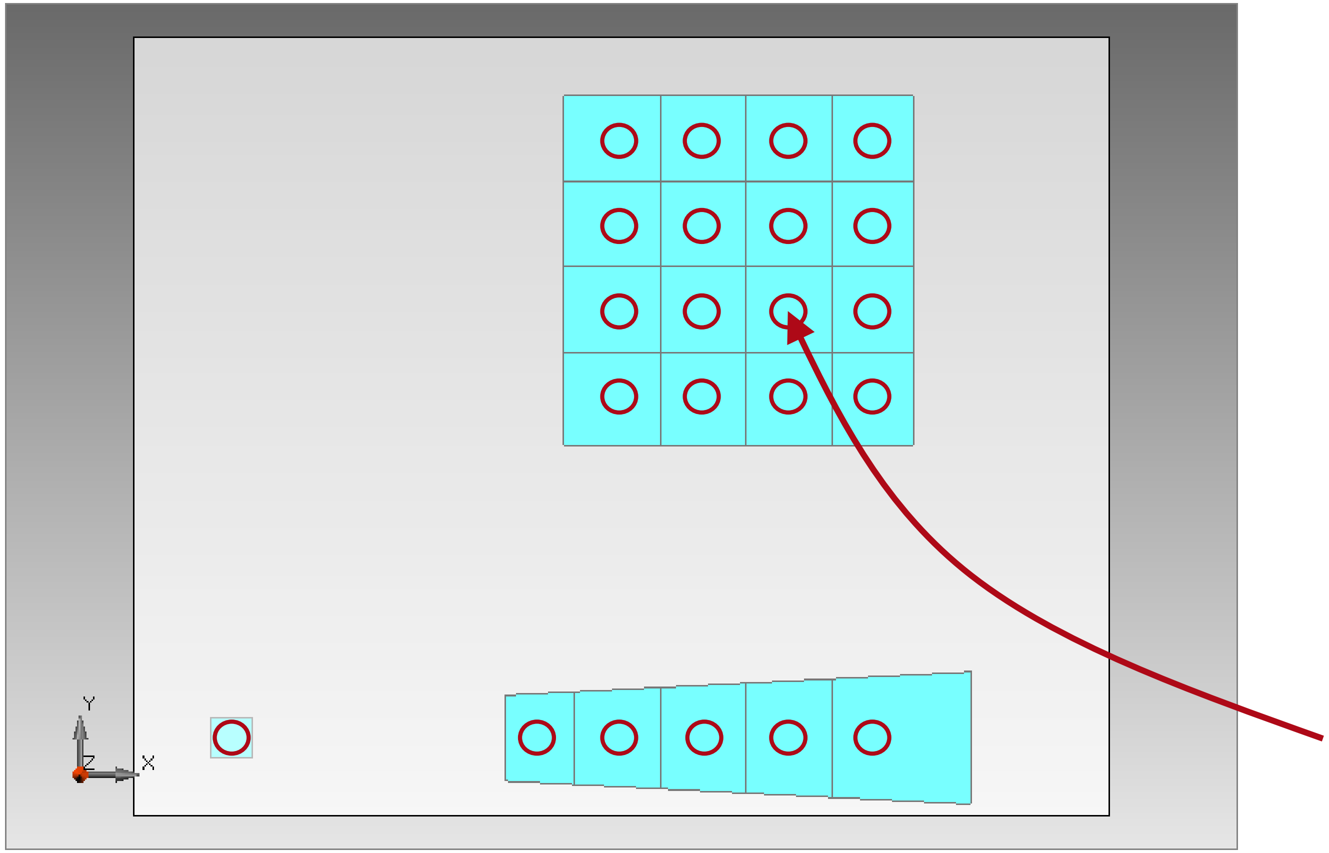




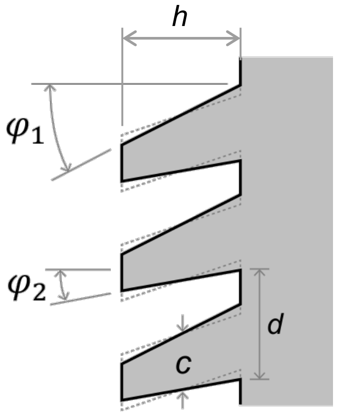
Calculation of Rayleigh matrix for given input beam parameters

$$\begin{pmatrix} E_{x,\mathrm{out}} \\ E_{y,\mathrm{out}} \end{pmatrix}_{k_{\mathrm{out},m}} = \begin{bmatrix} R_{xx} & R_{yx} \\ R_{xy} & R_{yy} \end{bmatrix} \cdot \begin{pmatrix} E_{x,\mathrm{arb,in}} \\ E_{y,\mathrm{arb,in}} \end{pmatrix}_{k_{\mathrm{in}}}$$

Grating Design per FOV Angle: Grating Analysis and Selection

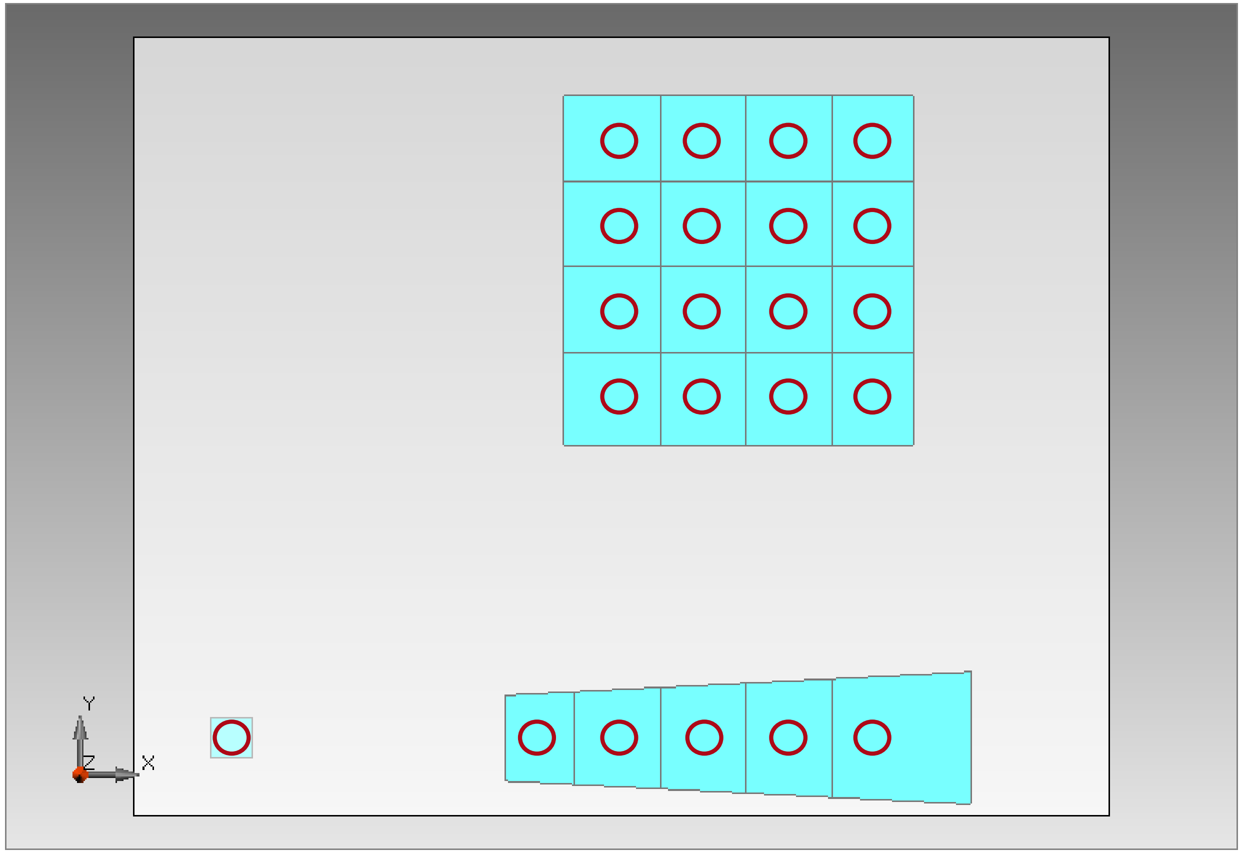


- Selection of grating parameters per footprint to obtain required fluxes.



example slanted grating structure

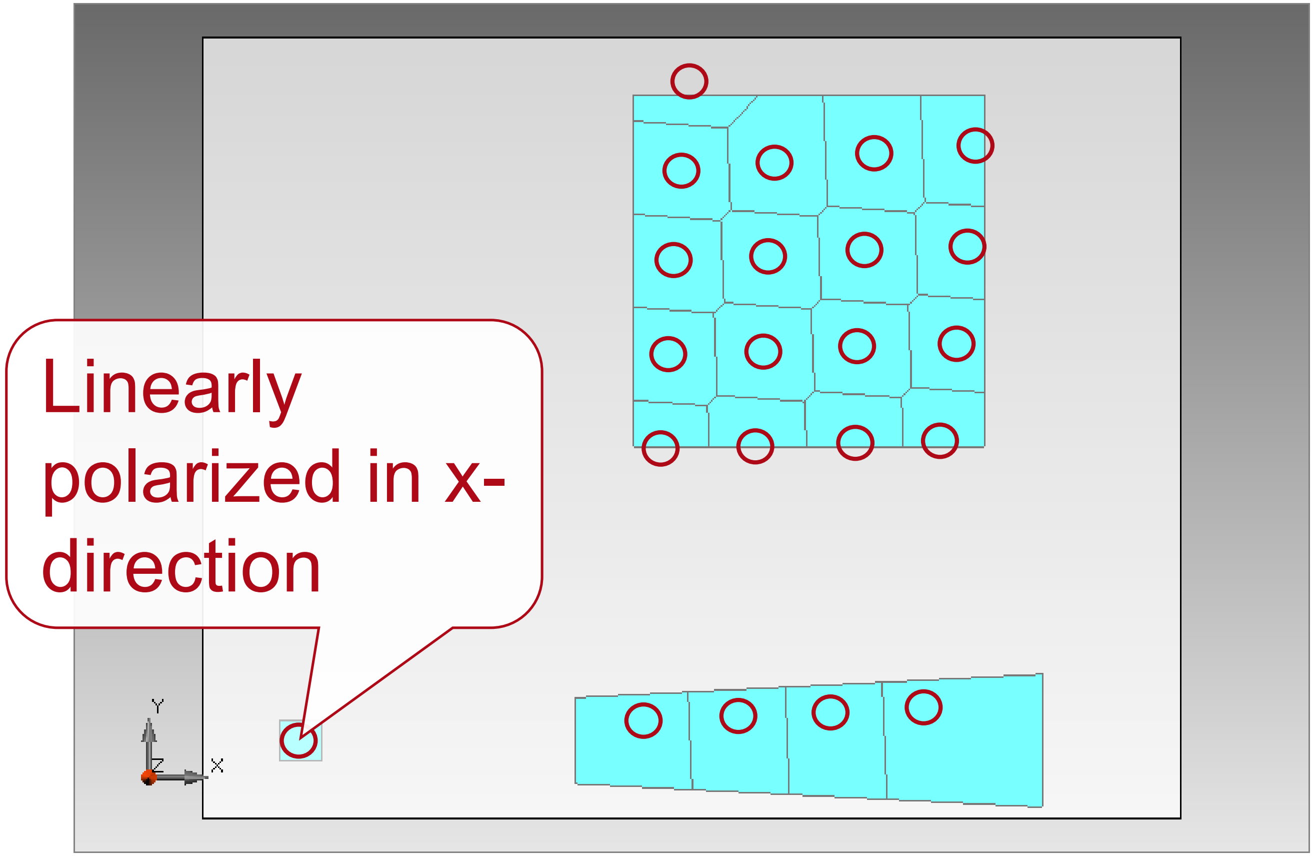
Grating Design per FOV Angle: Grating Analysis and Selection



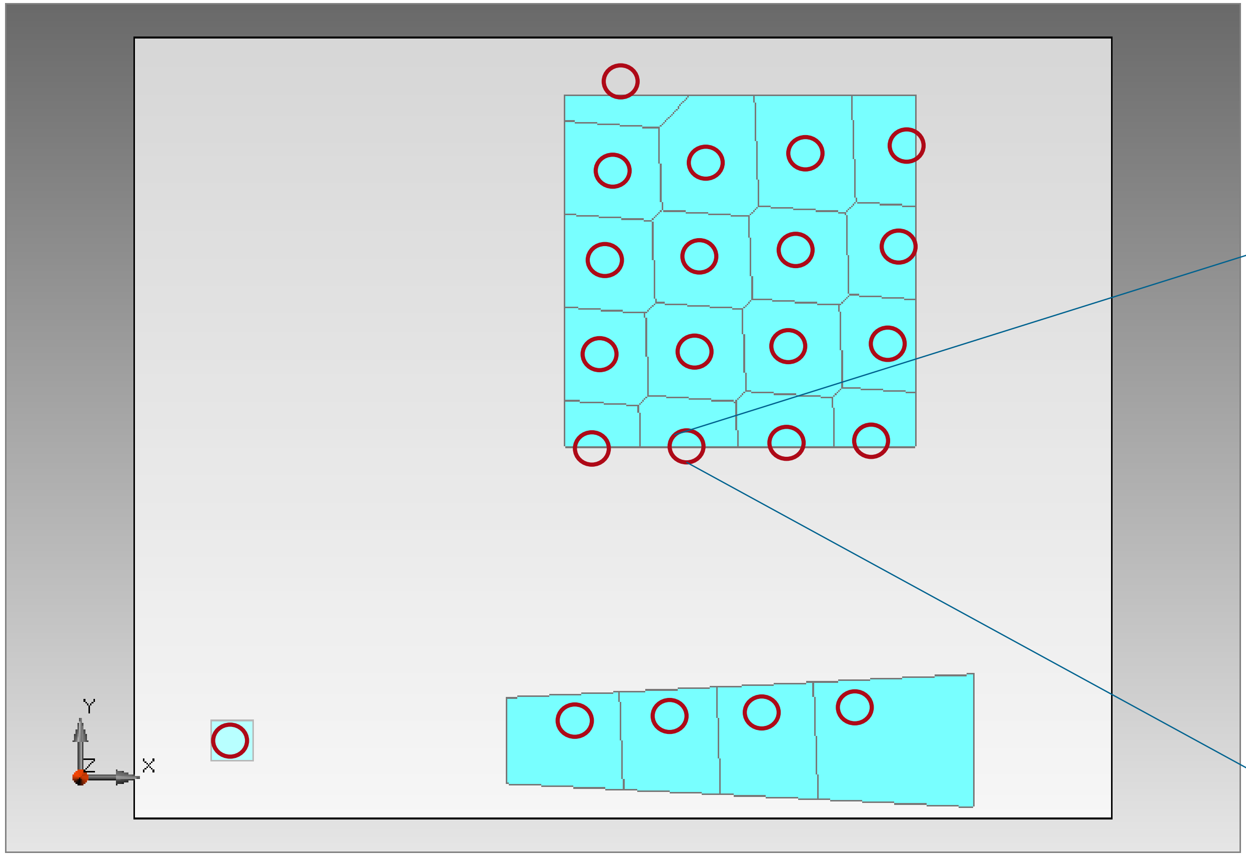
$$\begin{pmatrix} E_{x,\mathrm{out}} \\ E_{y,\mathrm{out}} \end{pmatrix}_{k_{\mathrm{out},m}} = \begin{bmatrix} R_{xx} & R_{yx} \\ R_{xy} & R_{yy} \end{bmatrix} \cdot \begin{pmatrix} E_{x,\mathrm{arb,in}} \\ E_{y,\mathrm{arb,in}} \end{pmatrix}_{k_{\mathrm{in}}}$$

- Storage of Rayleigh matrices in lookup table.
- Can be applied to arbitrary polarization for optimizing grating parameters.

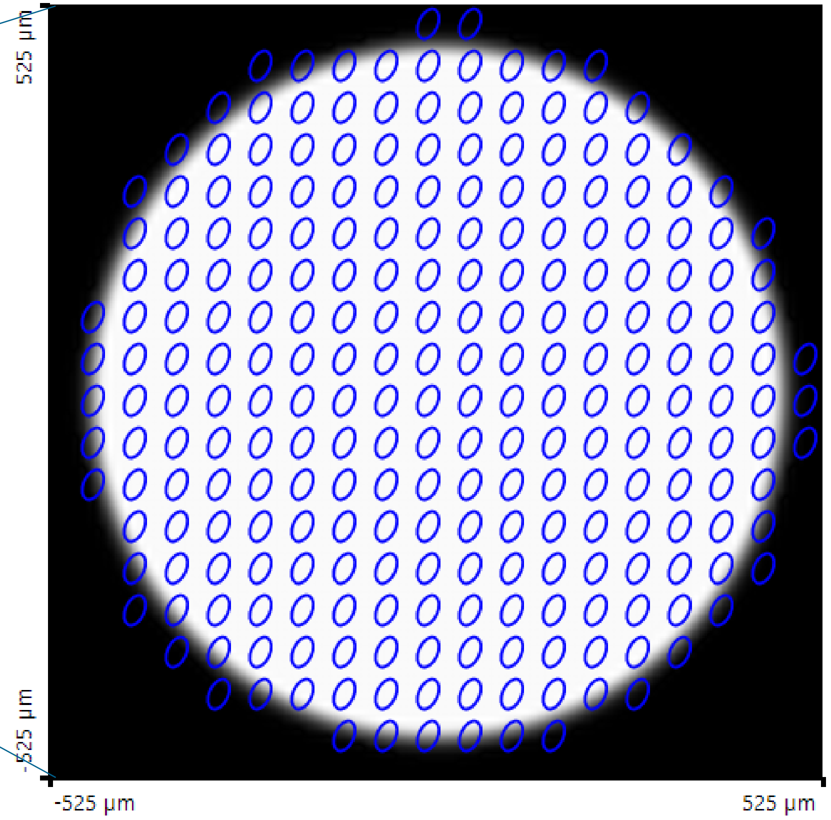
Grating Design for FOV Angle (5°, 3°) – Polarization Evaluation



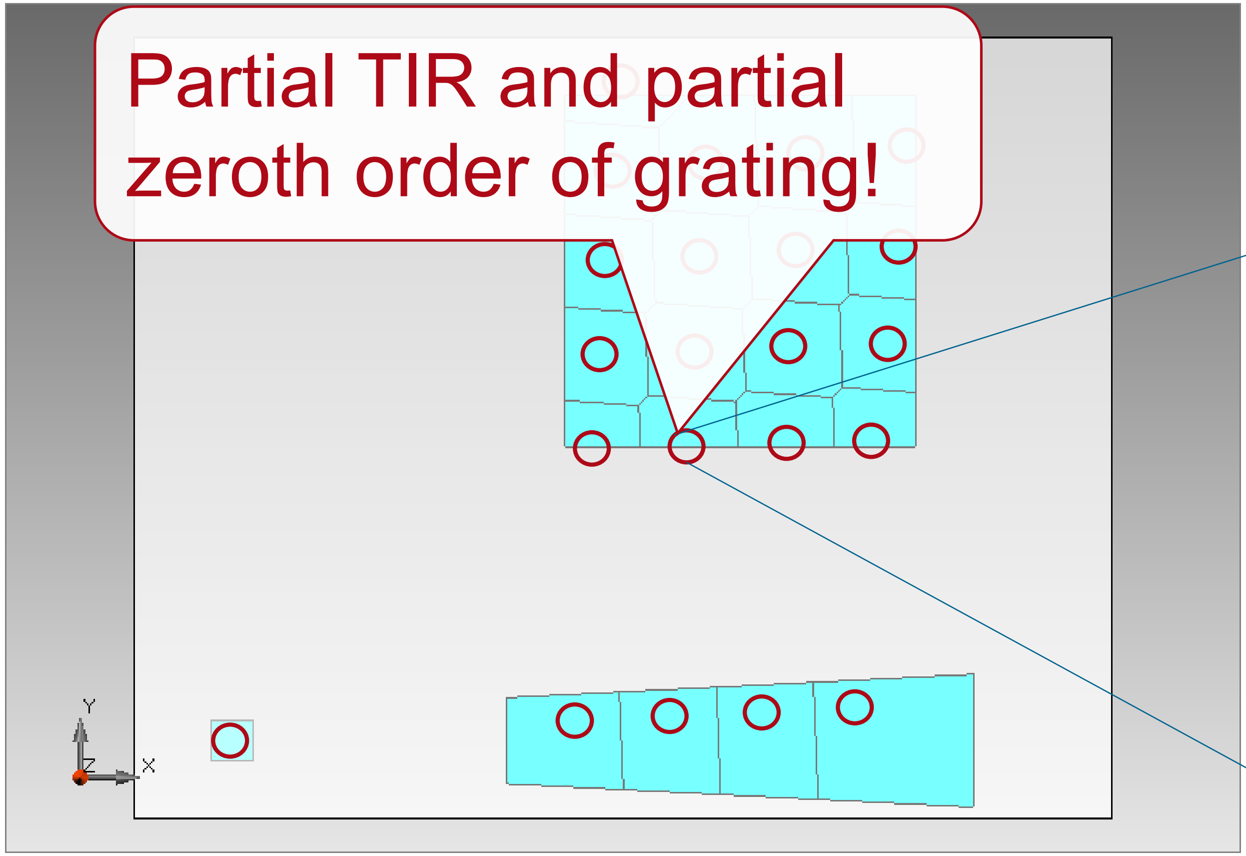
Grating Design for FOV Angle (5°, 3°) – Polarization Evaluation



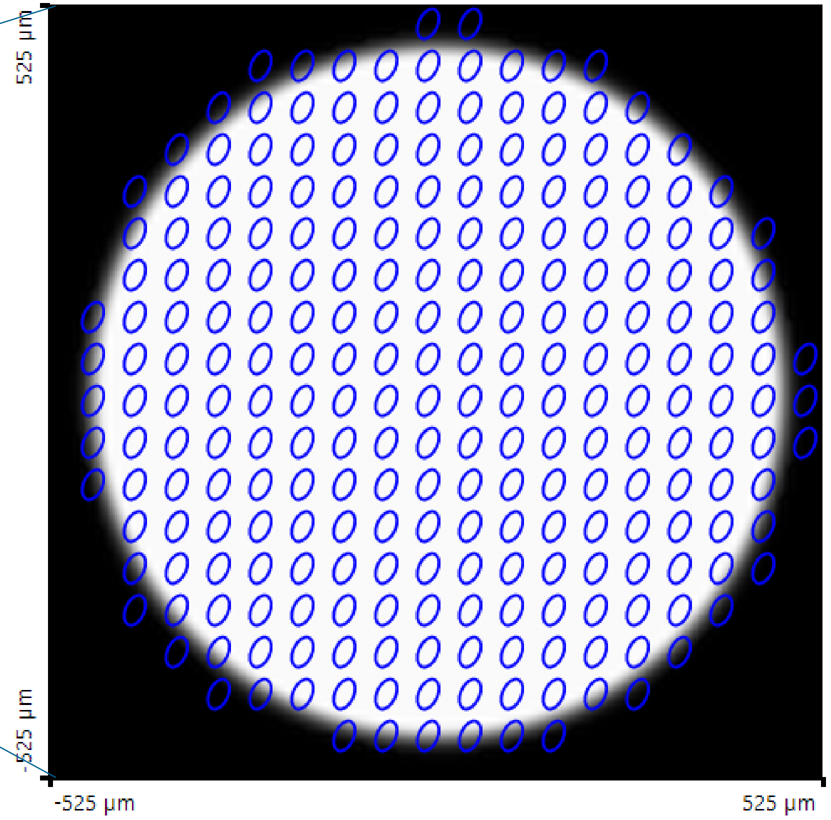
Incident light at grating interaction (uniform polarization)



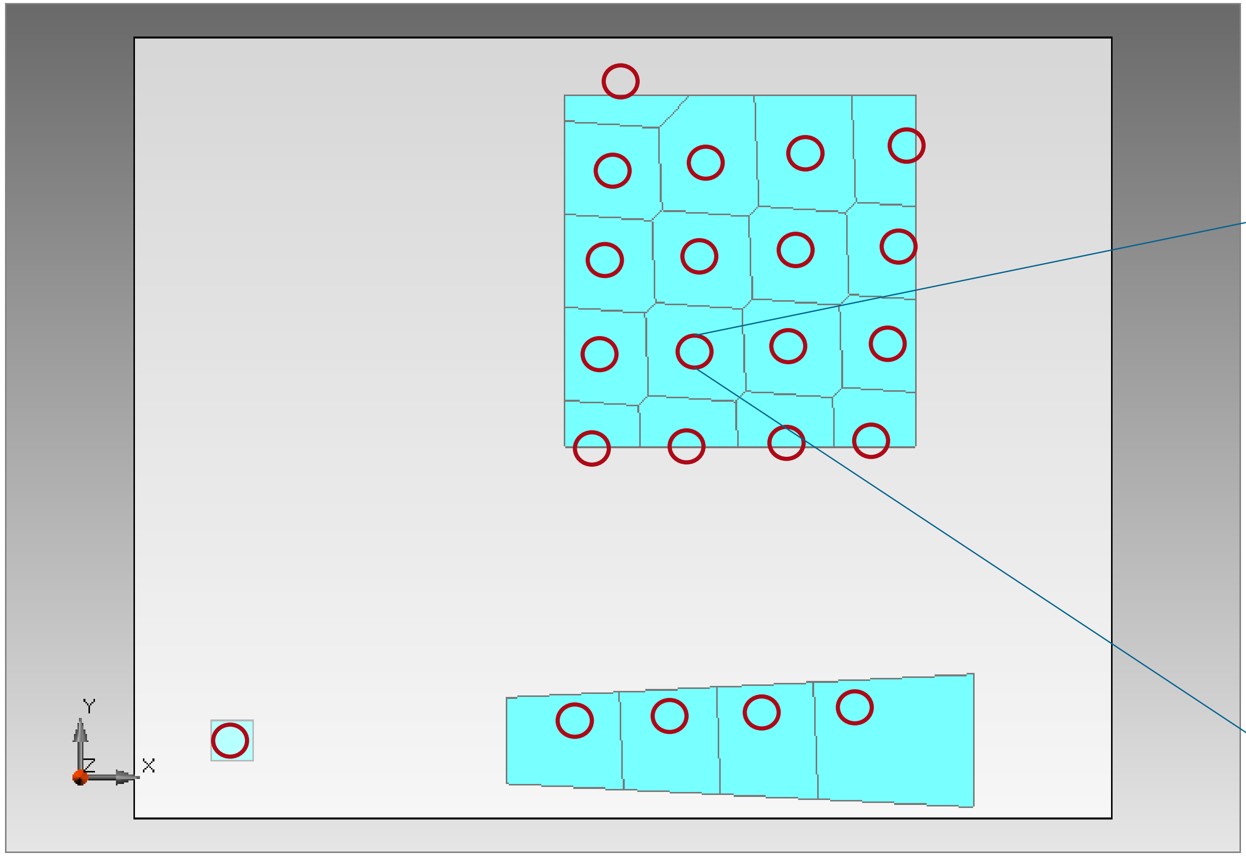
Grating Design for FOV Angle (5°, 3°) – Polarization Evaluation



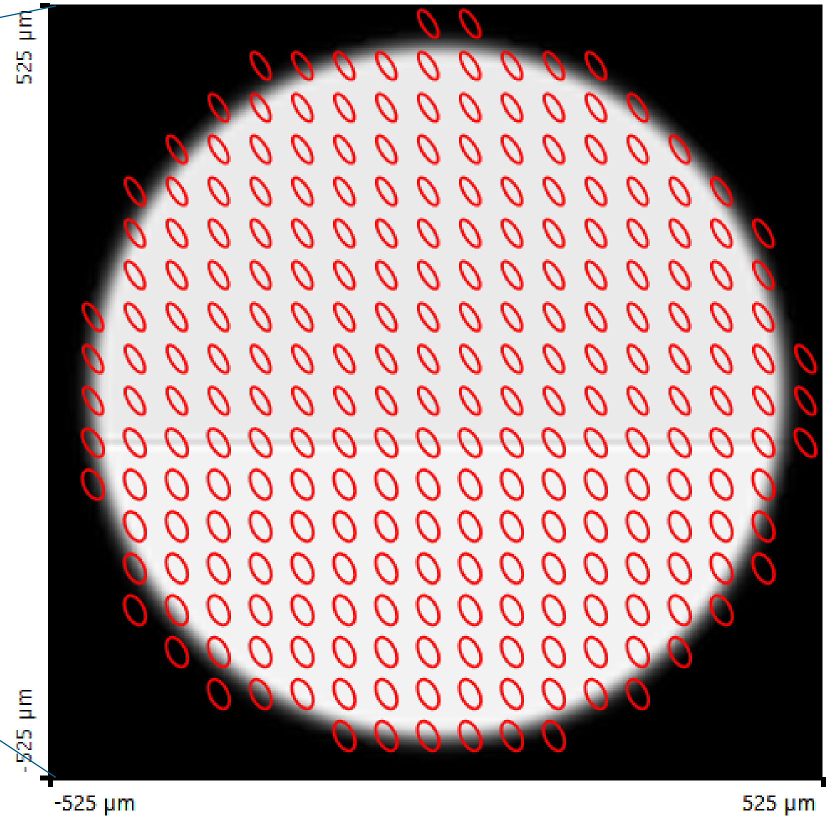
Incident light at grating interaction (uniform polarization)



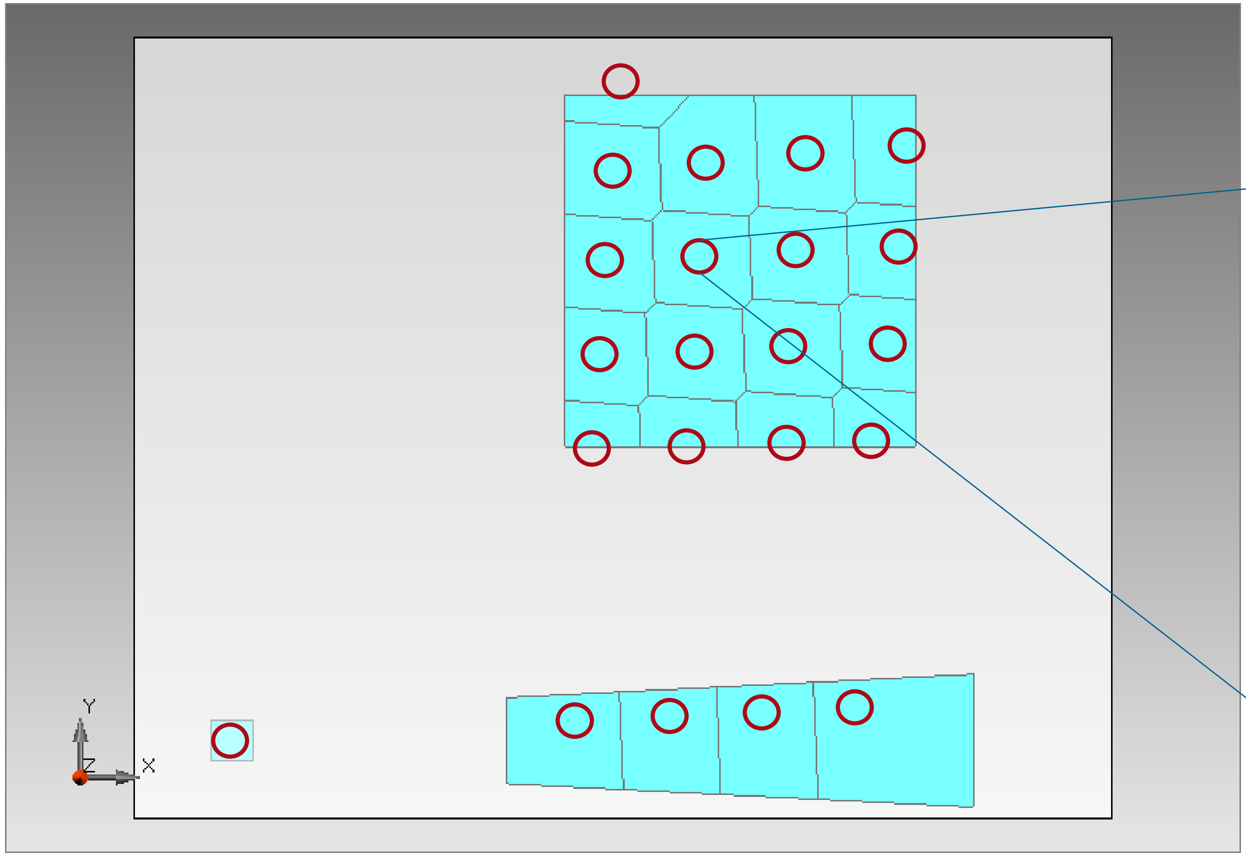
Grating Design for FOV Angle (5°, 3°) – Polarization Evaluation



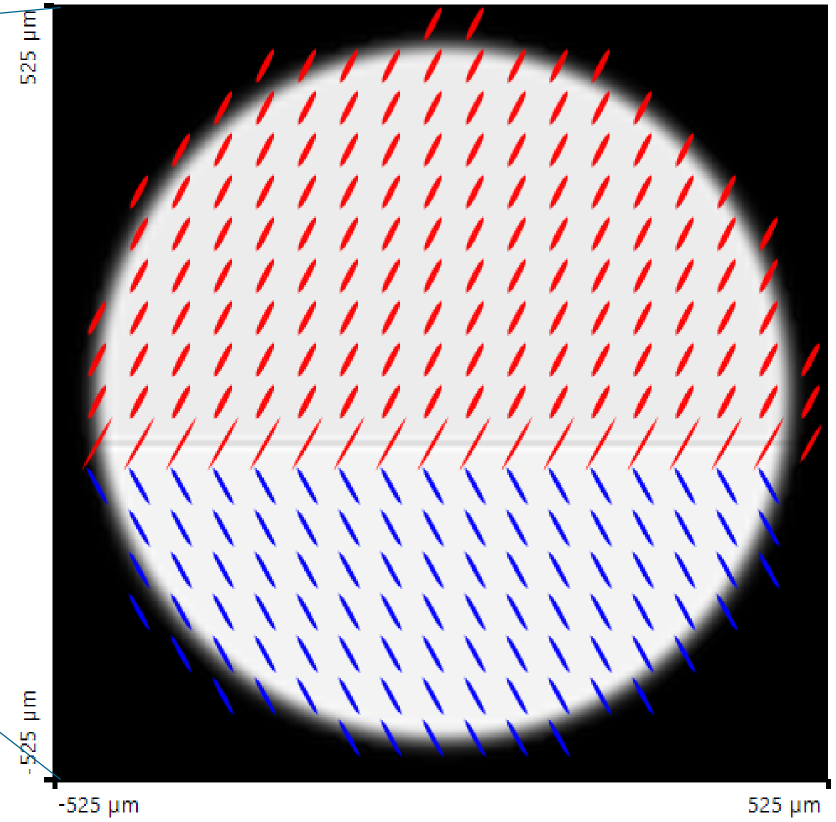
Incident light at grating interaction (non-uniform polarization)



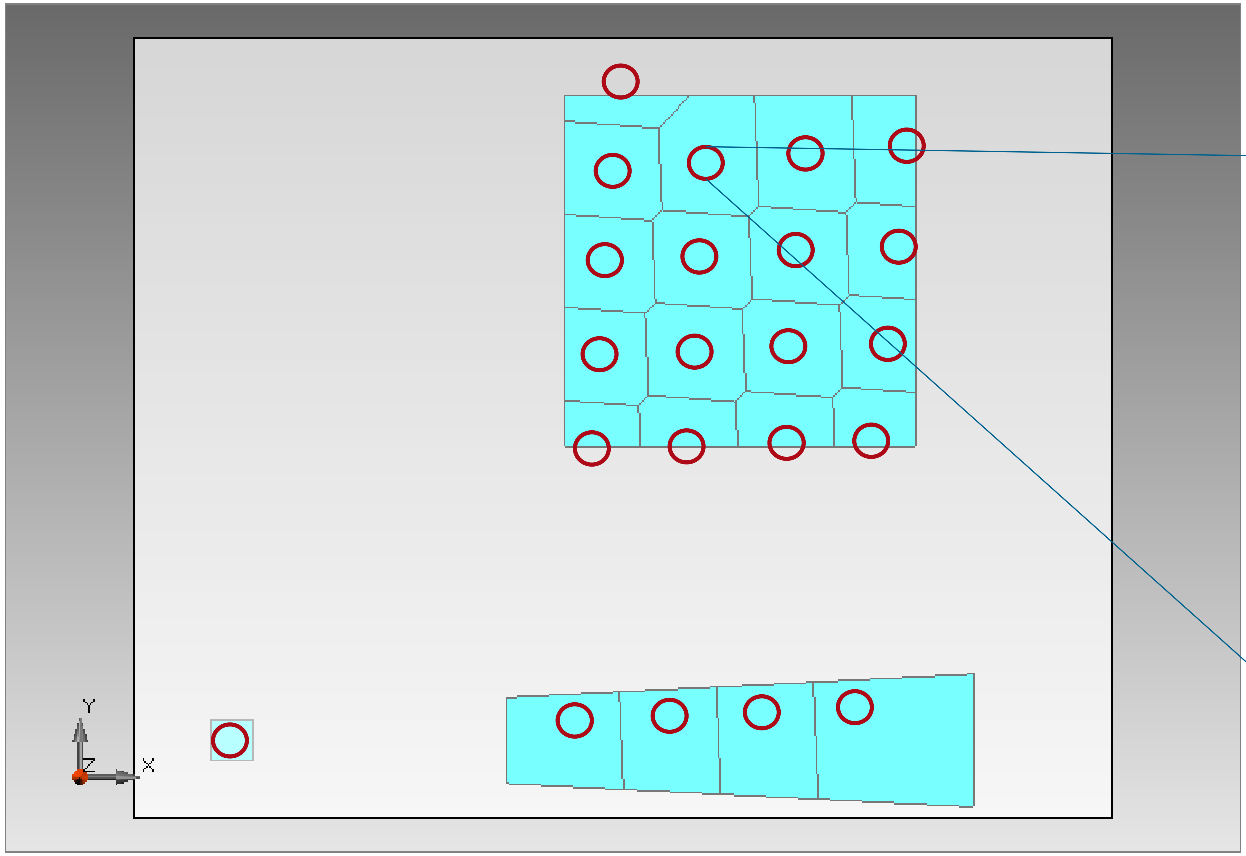
Grating Design for FOV Angle (5°, 3°) – Polarization Evaluation



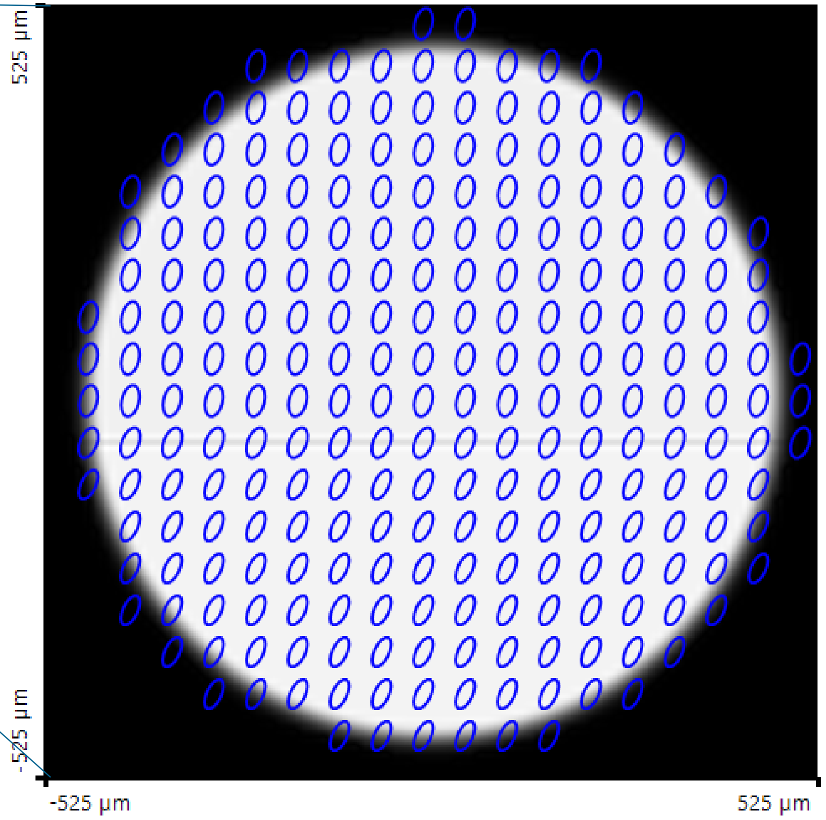
Incident light at grating interaction (non-uniform polarization)



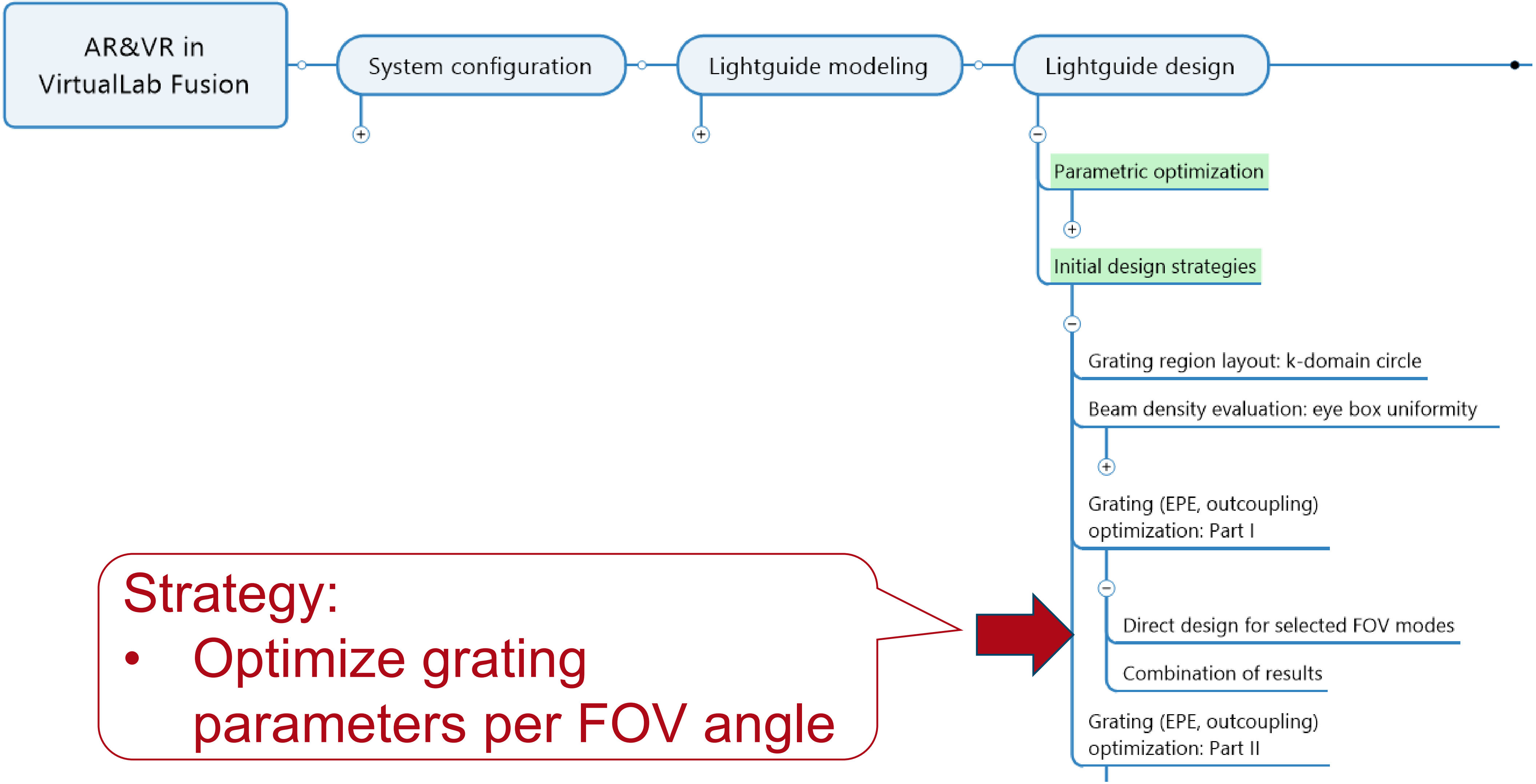
Grating Design for FOV Angle (5°, 3°) – Polarization Evaluation



Incident light at grating interaction
(non-uniform polarization)



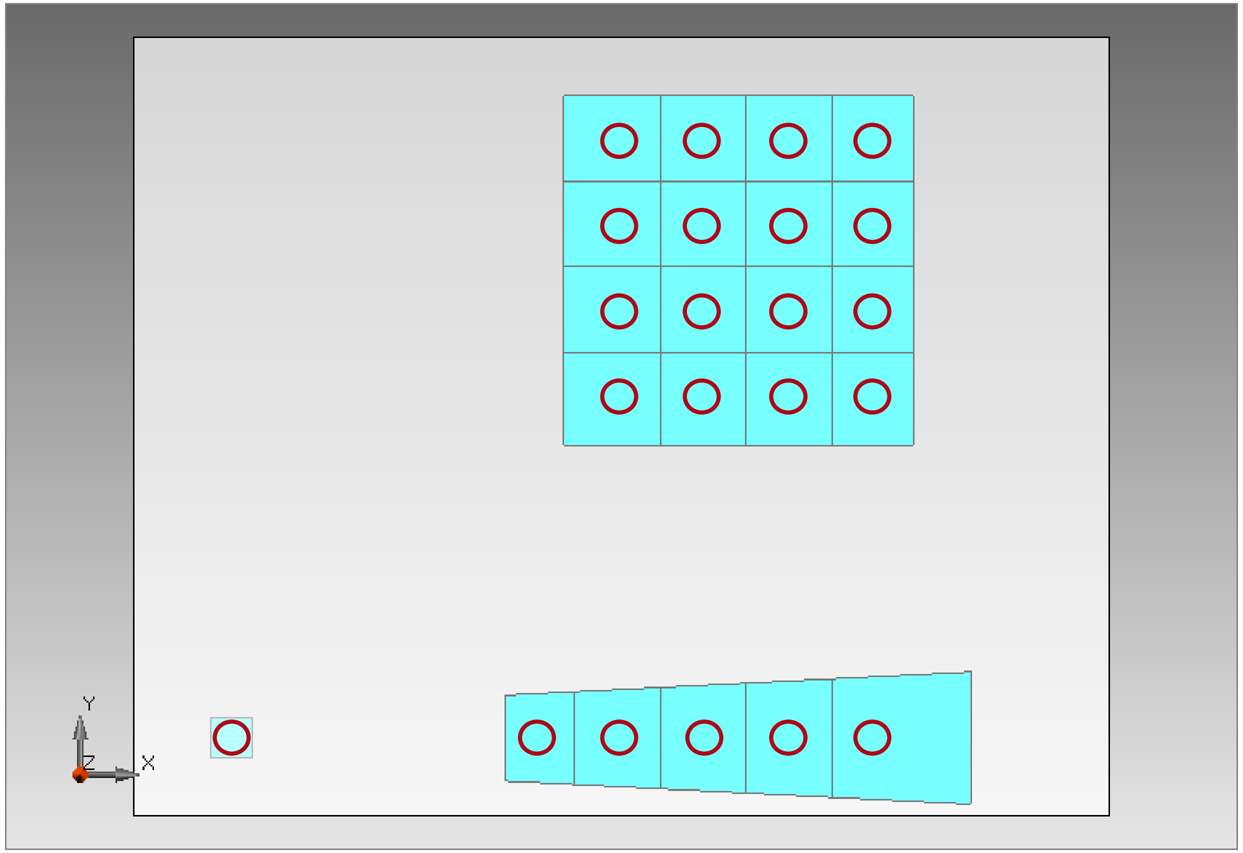
Lightguide Modeling and Design: Grating Optimization

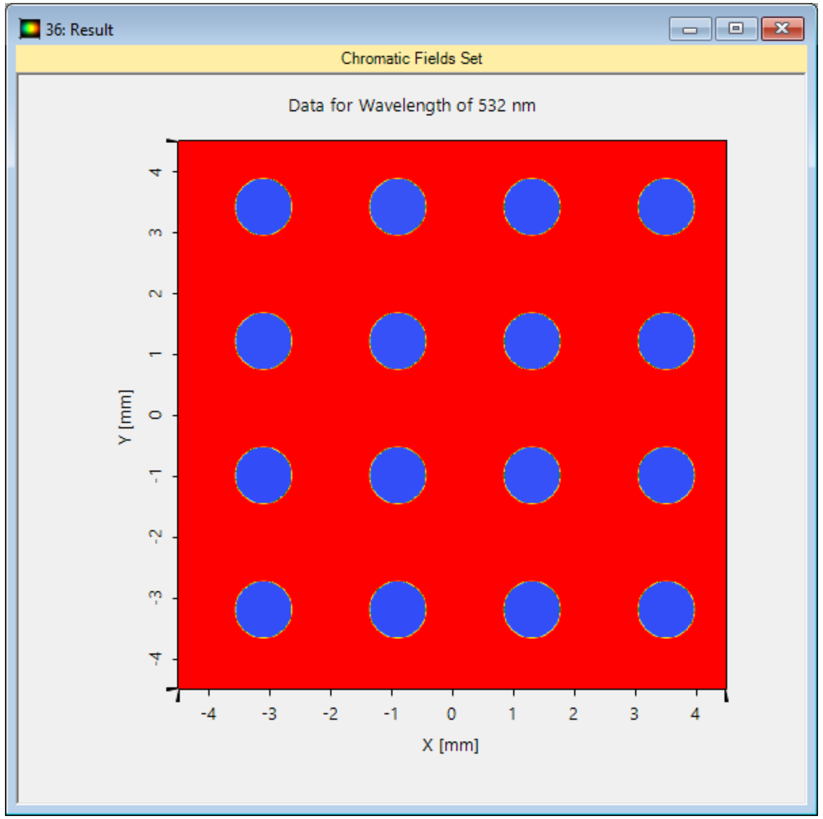


Strategy:

- Optimize grating parameters per FOV angle

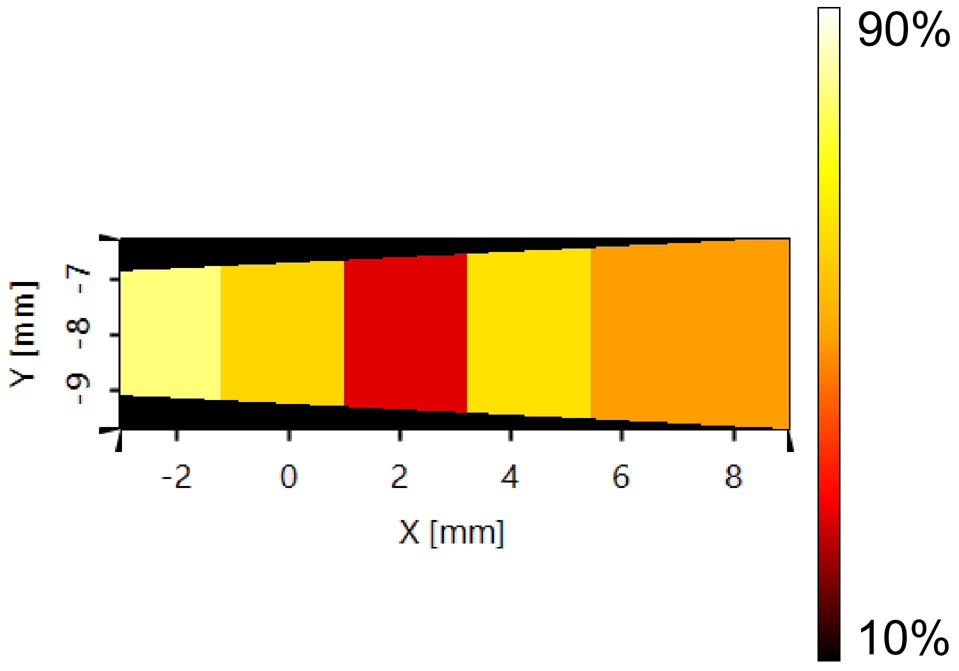
Grating Design for FOV Angle (0°, 0°)



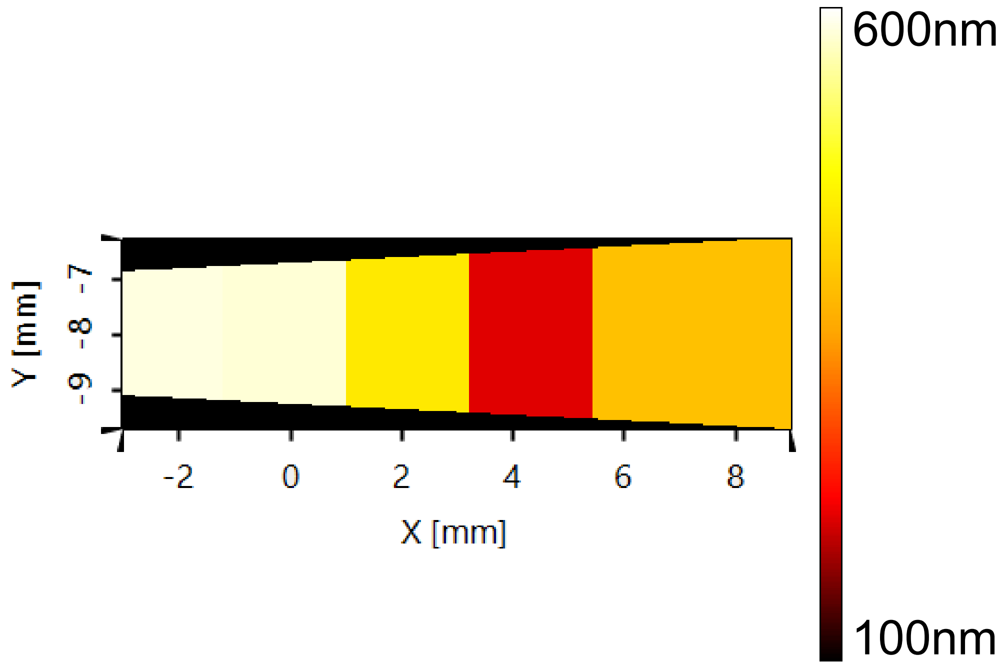


Merit Function	Value
FOV Angle	$\alpha = 0°\,;\,\beta = 0°$
Uniformity Error	**0.34%**

Optimized Grating Parameter EPE Grating

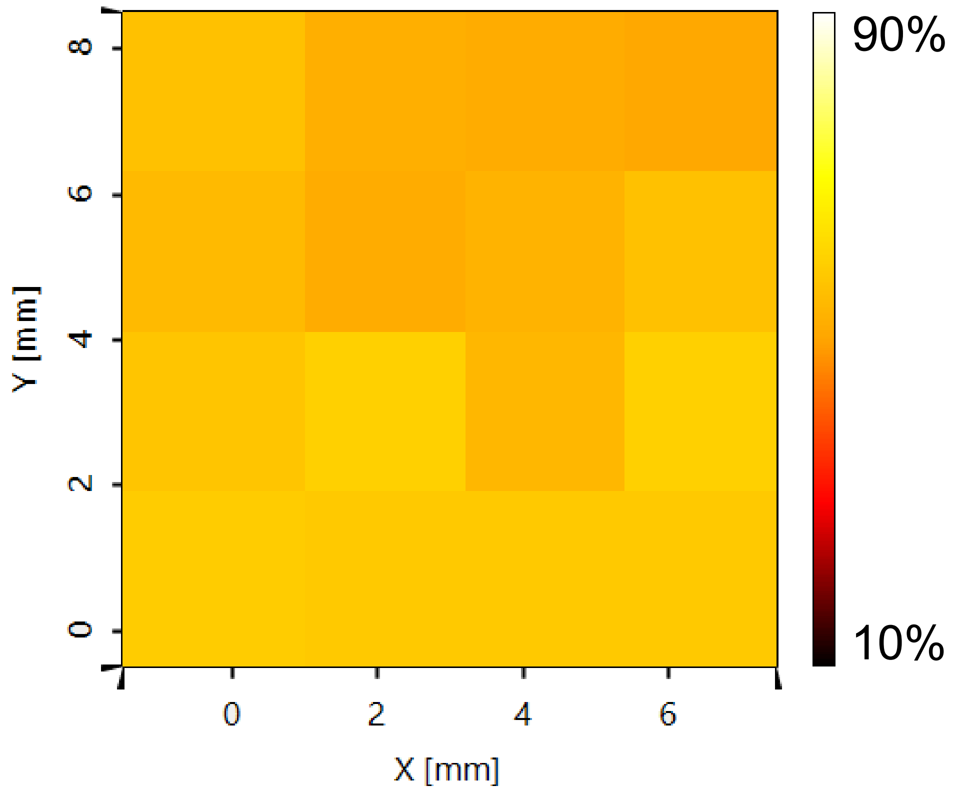


Optimized Fill Factors

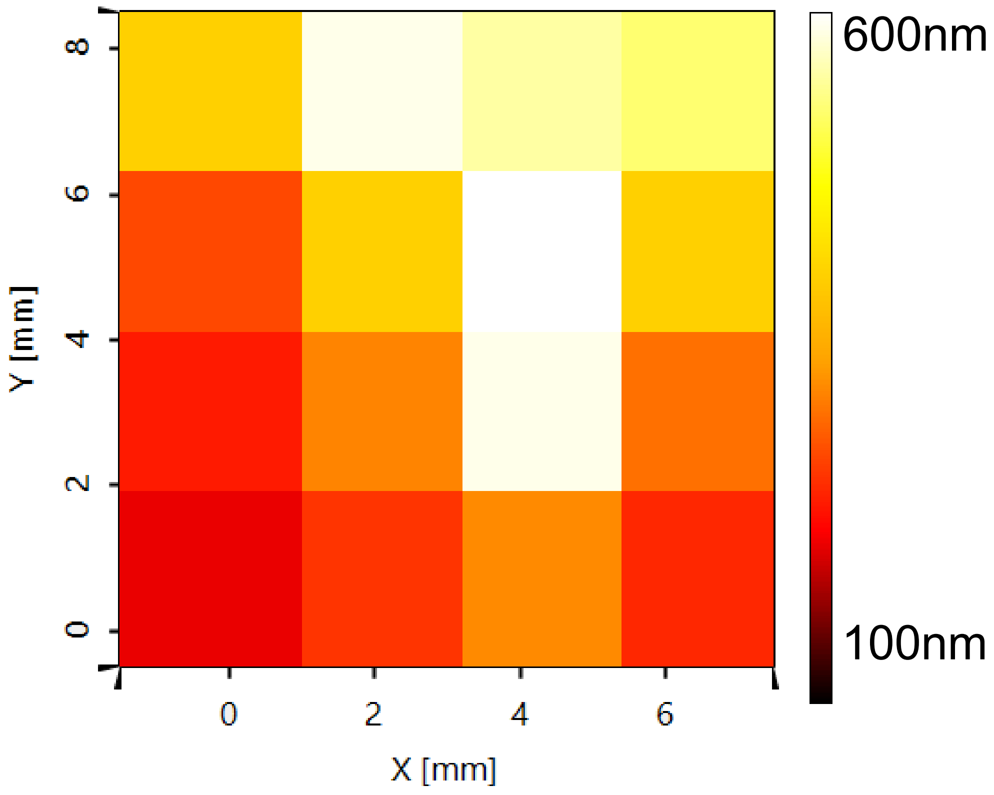


Optimized Modulation Depth

Optimized Grating Parameter Outcoupling Grating

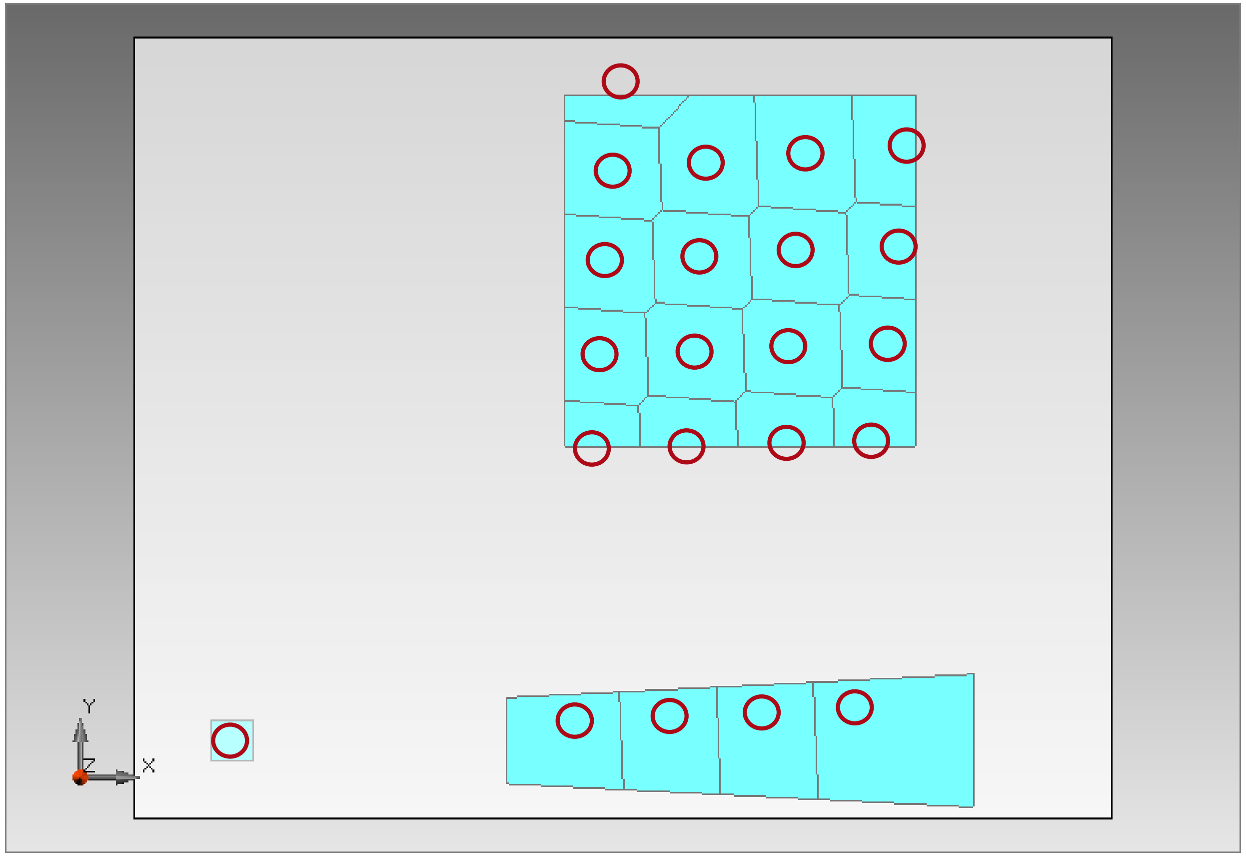


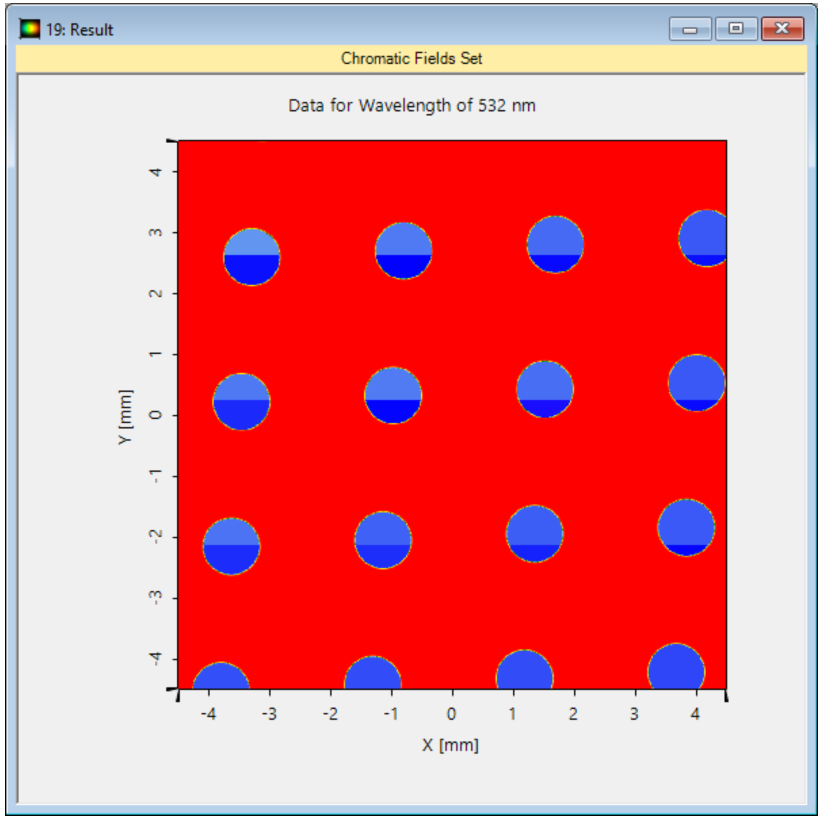
Optimized Fill Factors



Optimized Modulation Depth

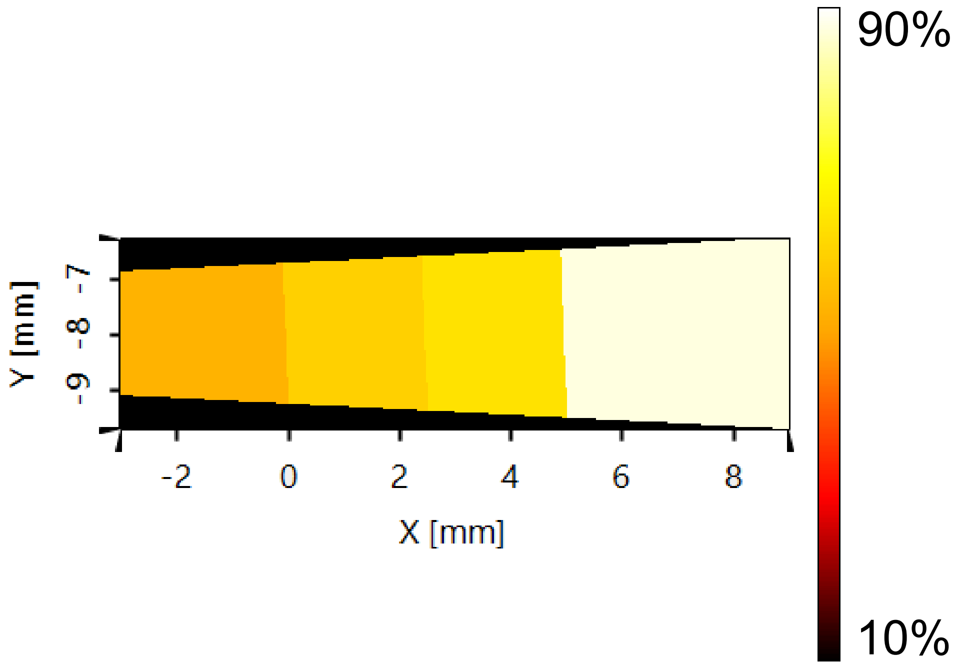
Grating Design for FOV Angle (5°, 3°)



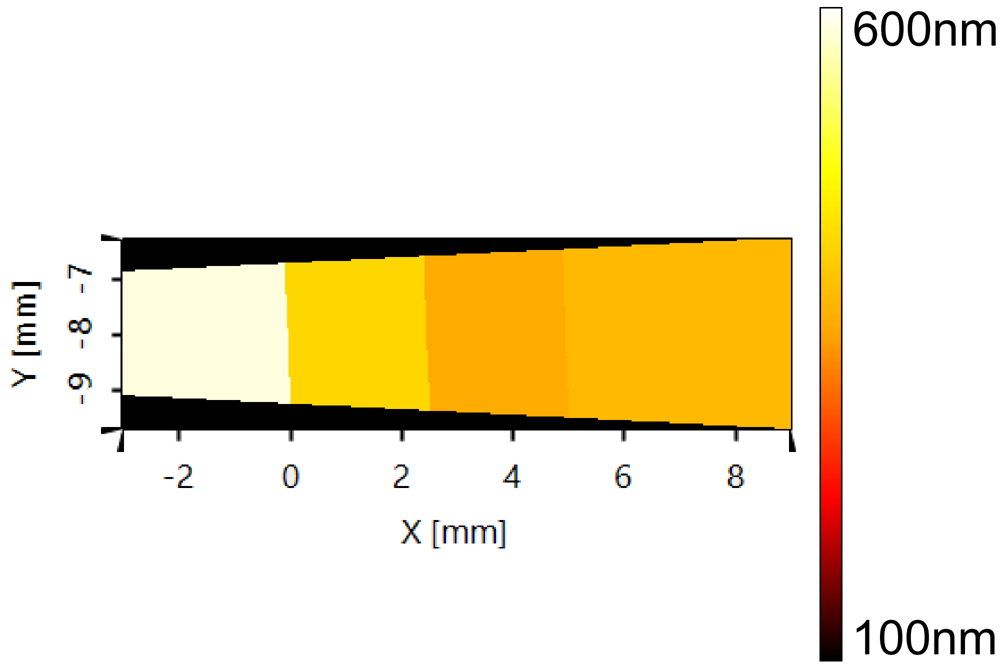


Merit Function	Value
FOV Angle	$\alpha = 5°; \beta = 3°$
Uniformity Error	**0.61%**

Optimized Grating Parameter EPE Grating

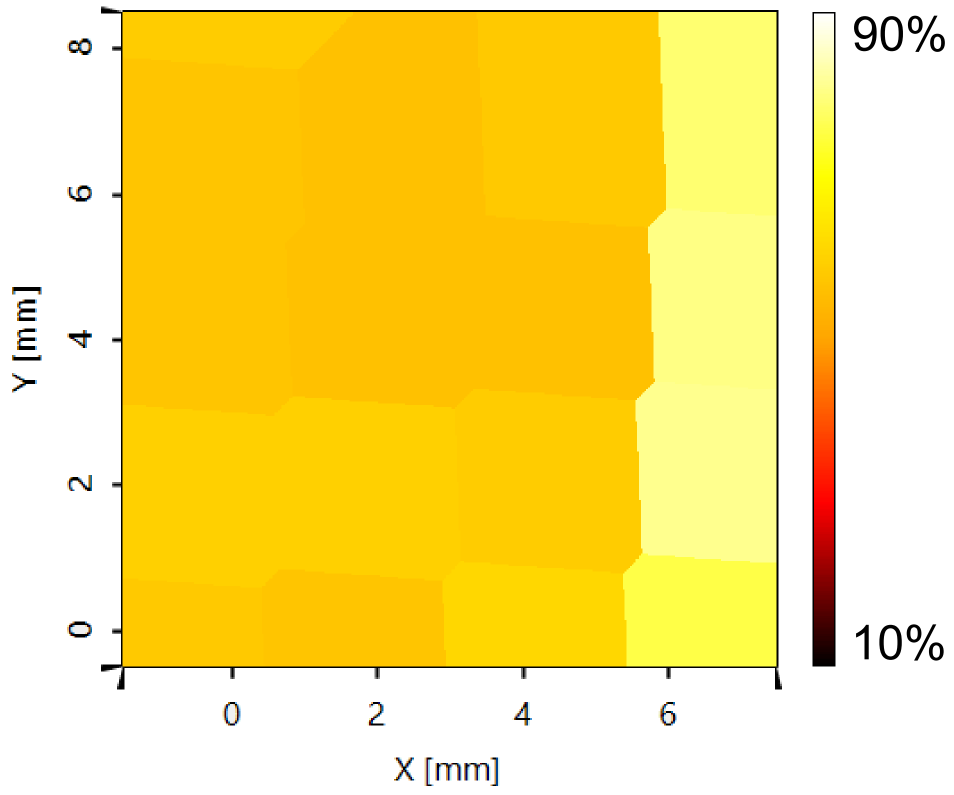


Optimized Fill Factors

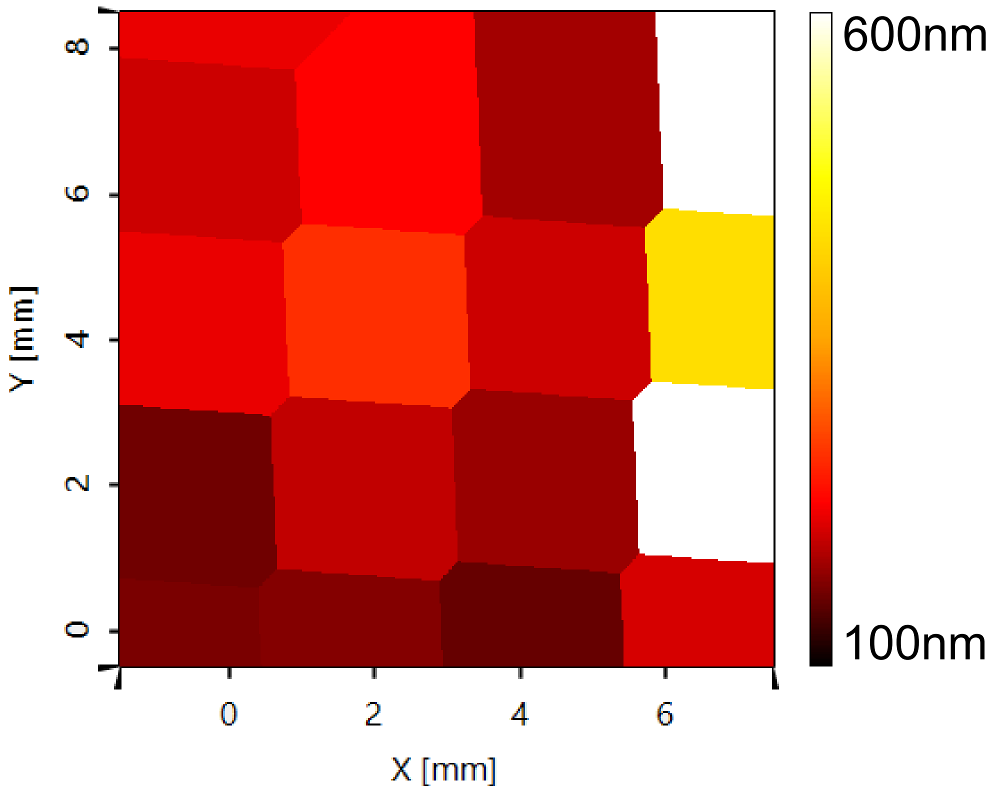


Optimized Modulation Depth

Optimized Grating Parameter Outcoupling Grating

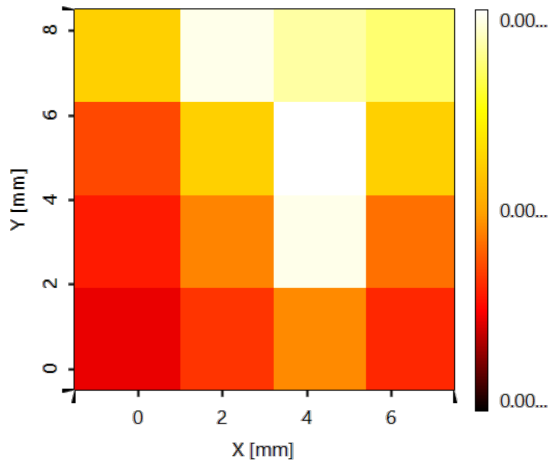


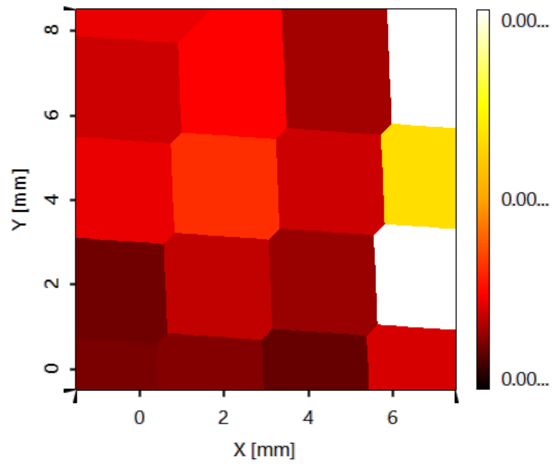
Optimized Fill Factors

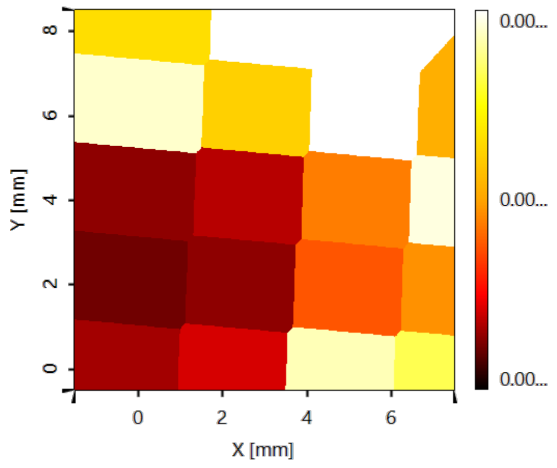


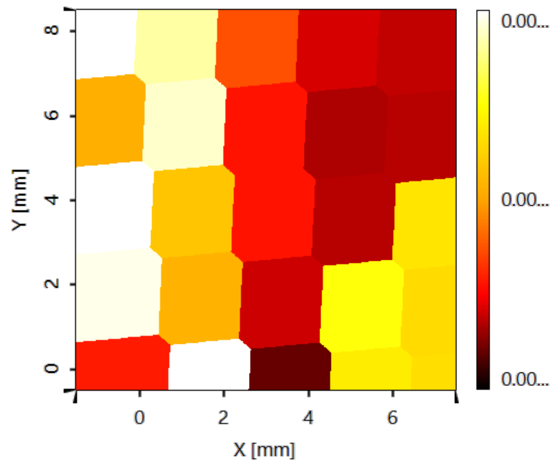
Optimized Modulation Depth

EPE Grating Design for Different FOV: Height

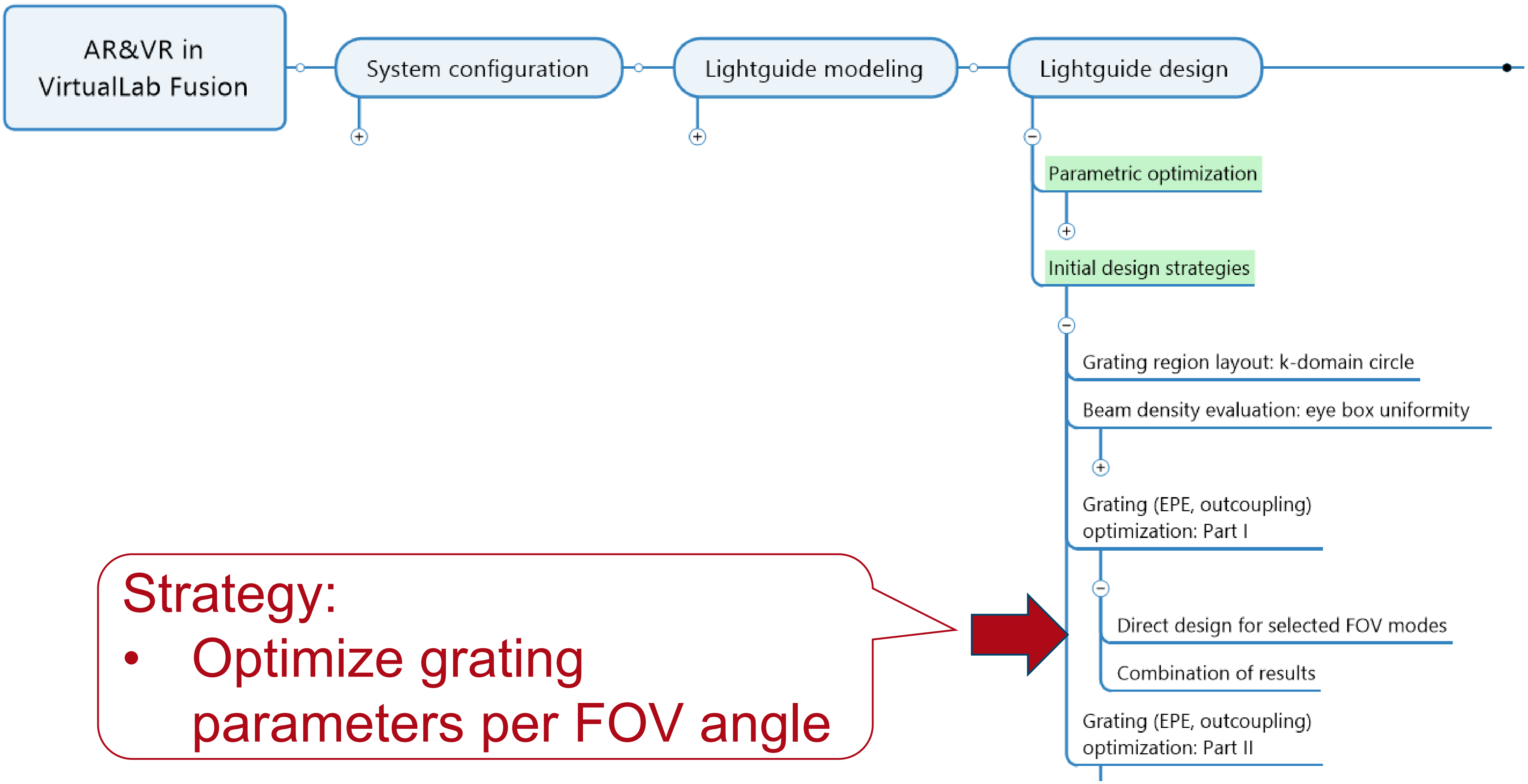








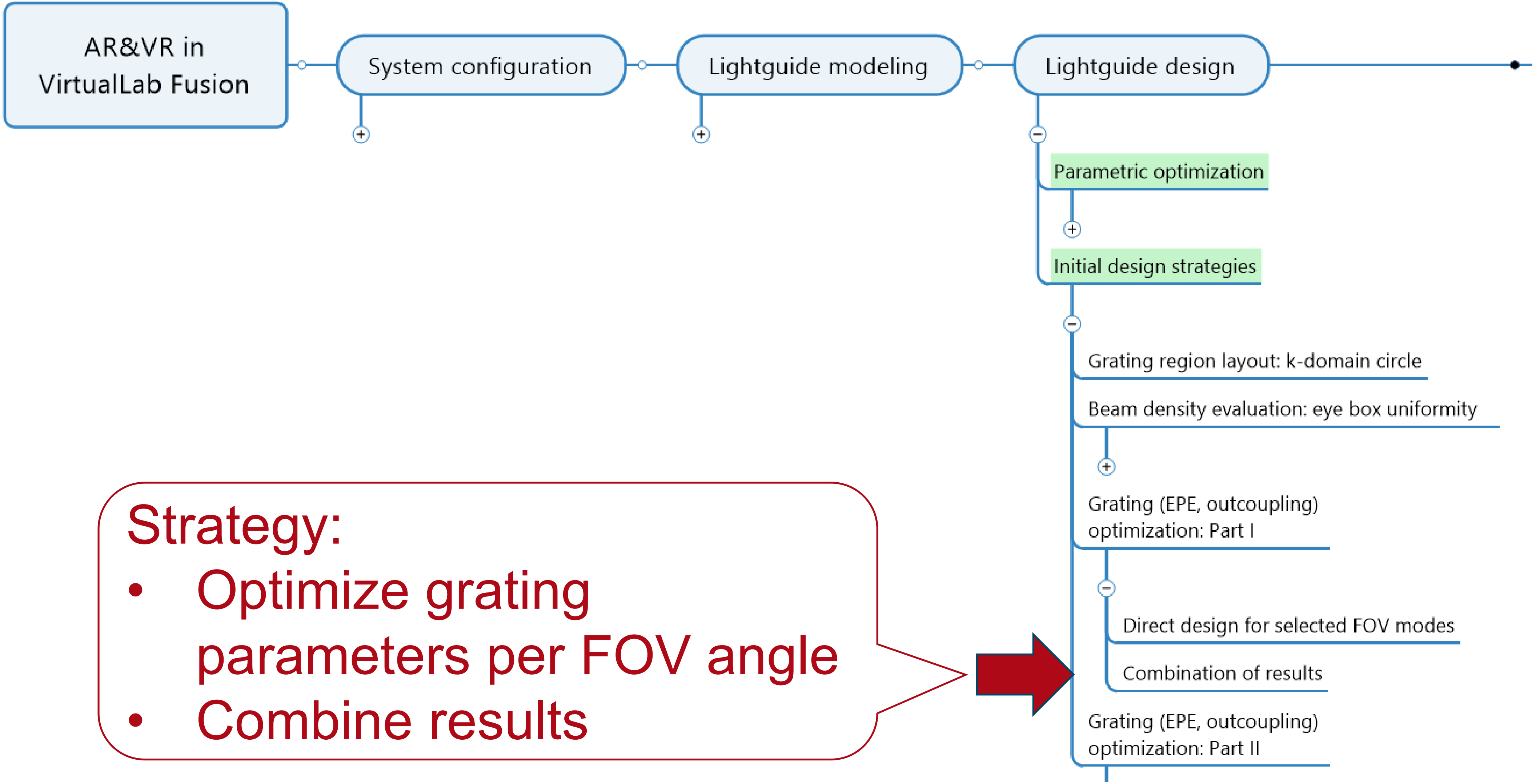
Lightguide Modeling and Design: Grating Optimization



Strategy:

- Optimize grating parameters per FOV angle

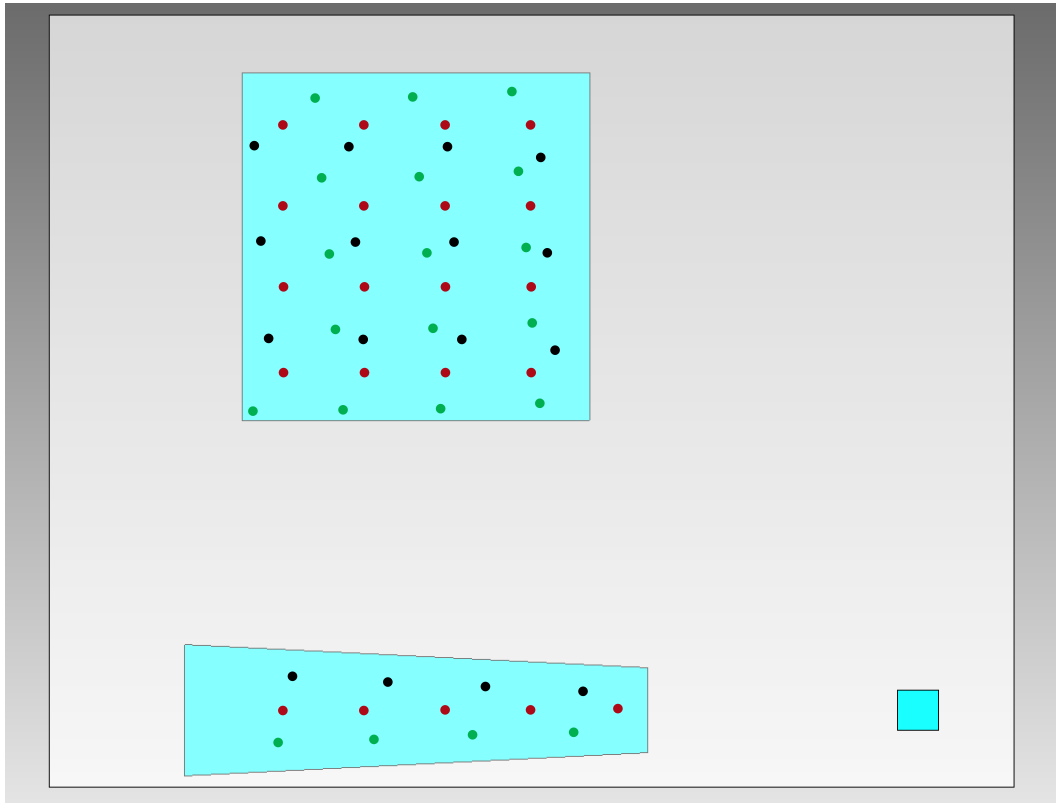
Lightguide Modeling and Design: Grating Optimization



Strategy:

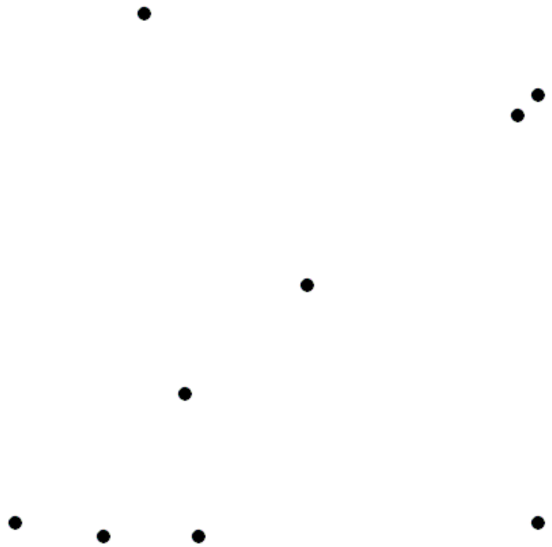
- Optimize grating parameters per FOV angle
- Combine results

Combination of Different FOV Designs



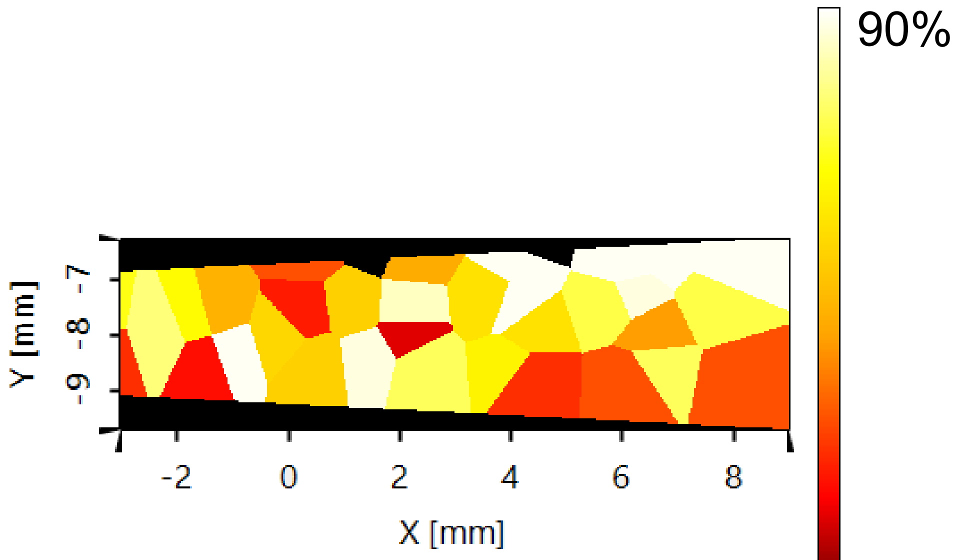
+

Voronoi Segmentation

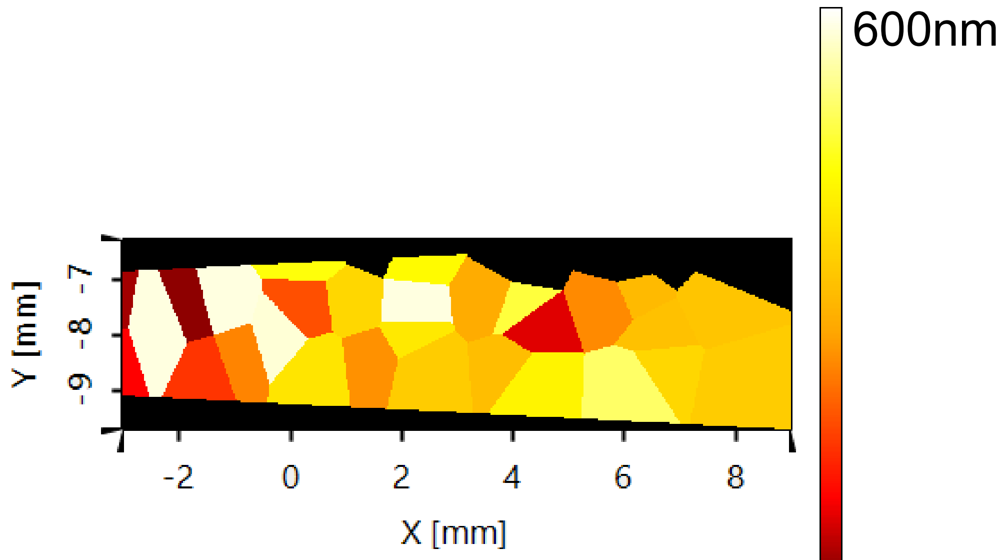


Source: www.wikipedia.com

Optimized Grating Parameter EPE Grating

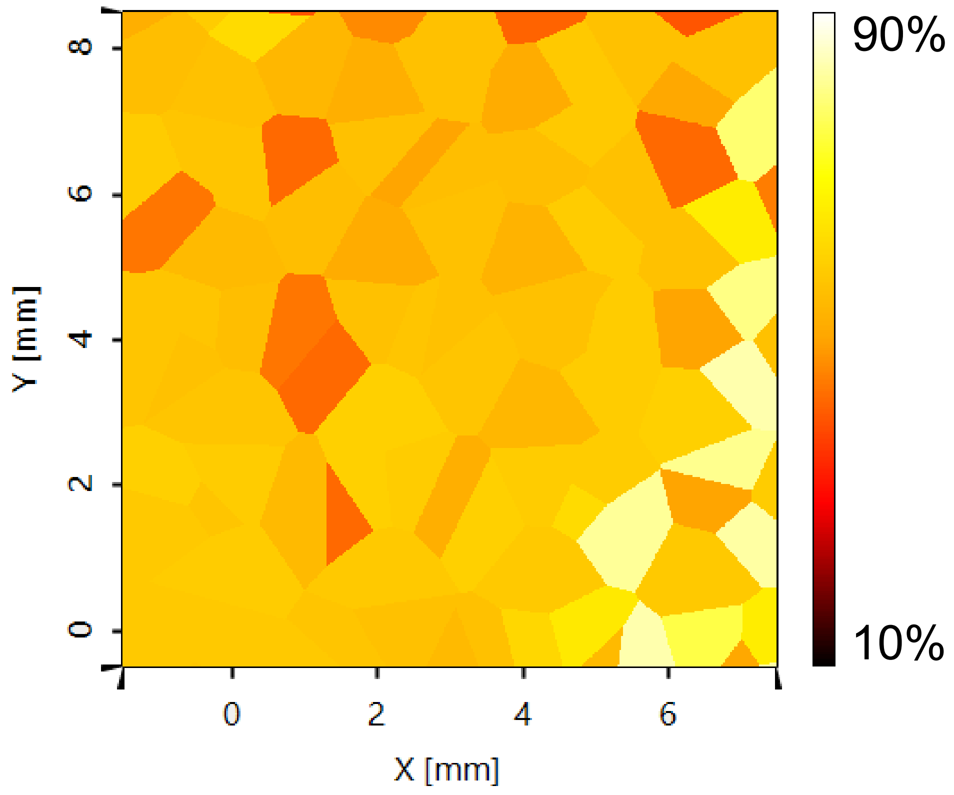


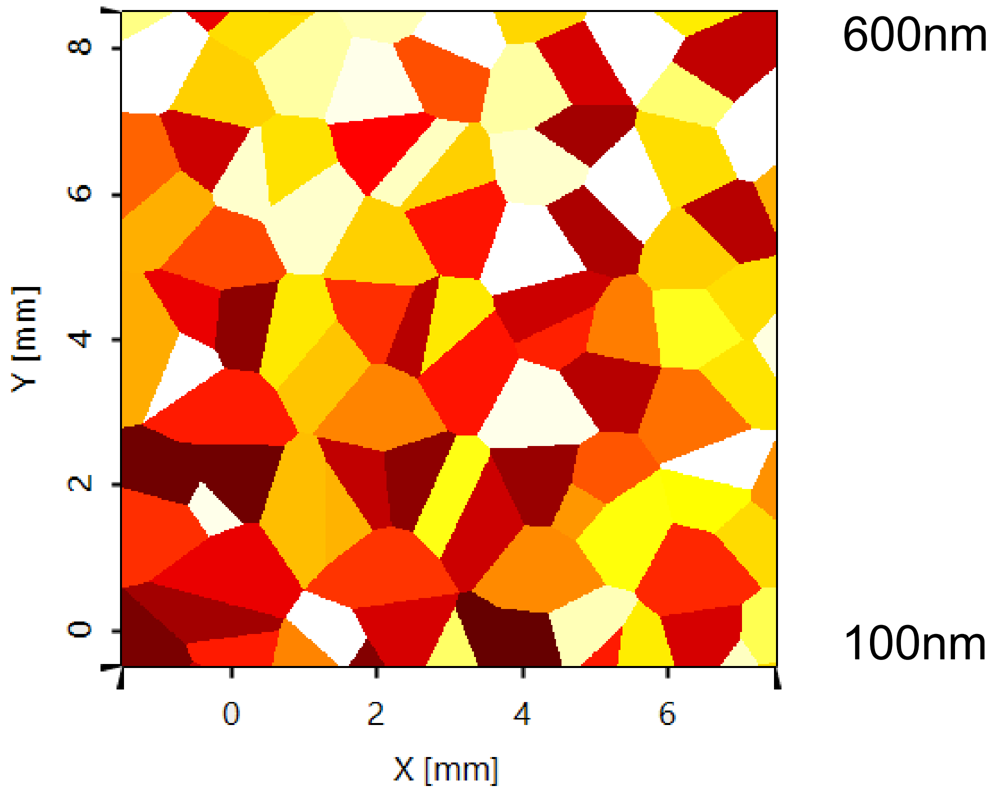
Optimized Fill Factors



Optimized Modulation Depth

Optimized Grating Parameter Outcoupling Grating

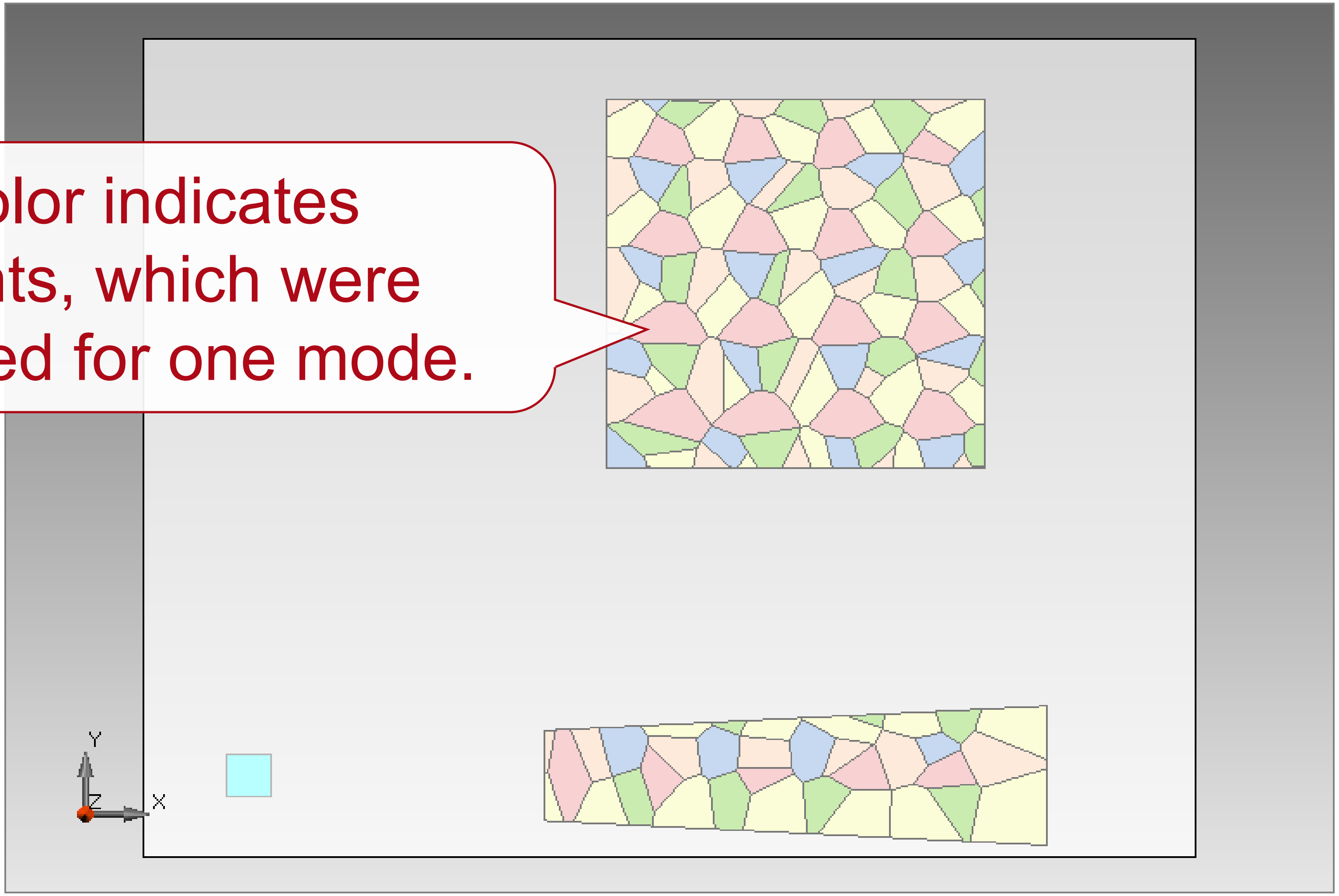




Optimized Fill Factors

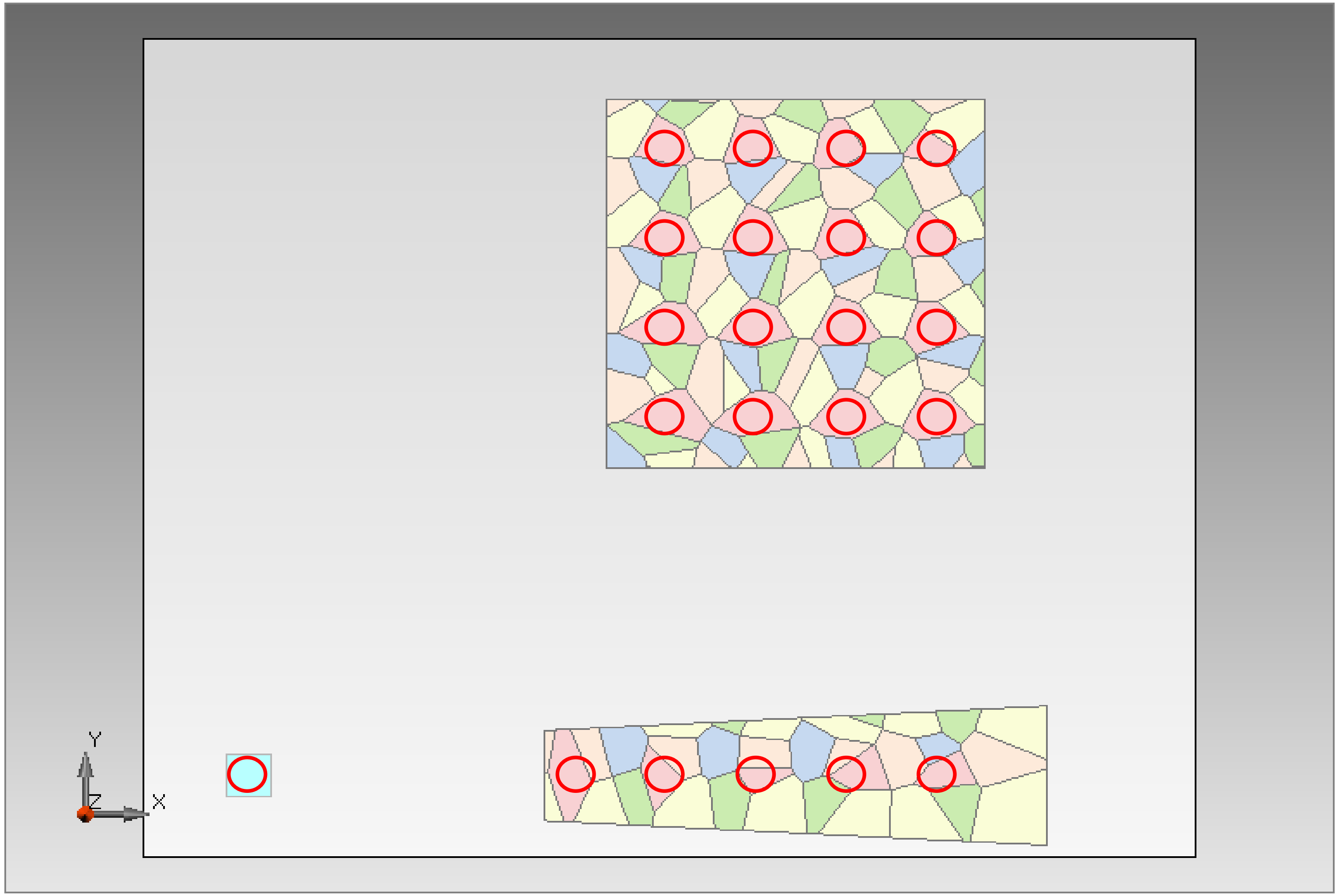
Optimized Modulation Depth

Result Combination of Modes (Segmentation)

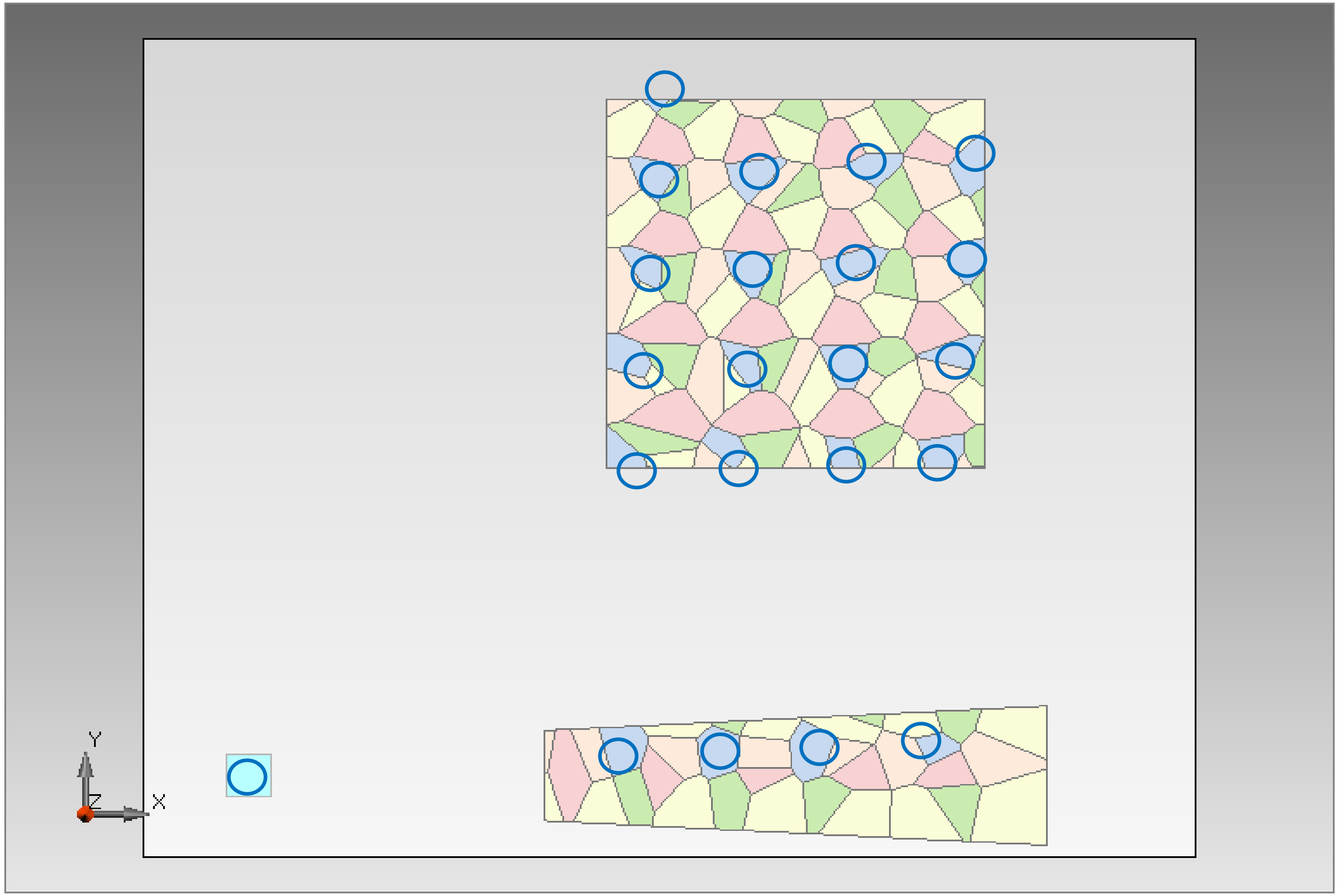


Each color indicates segments, which were optimized for one mode.

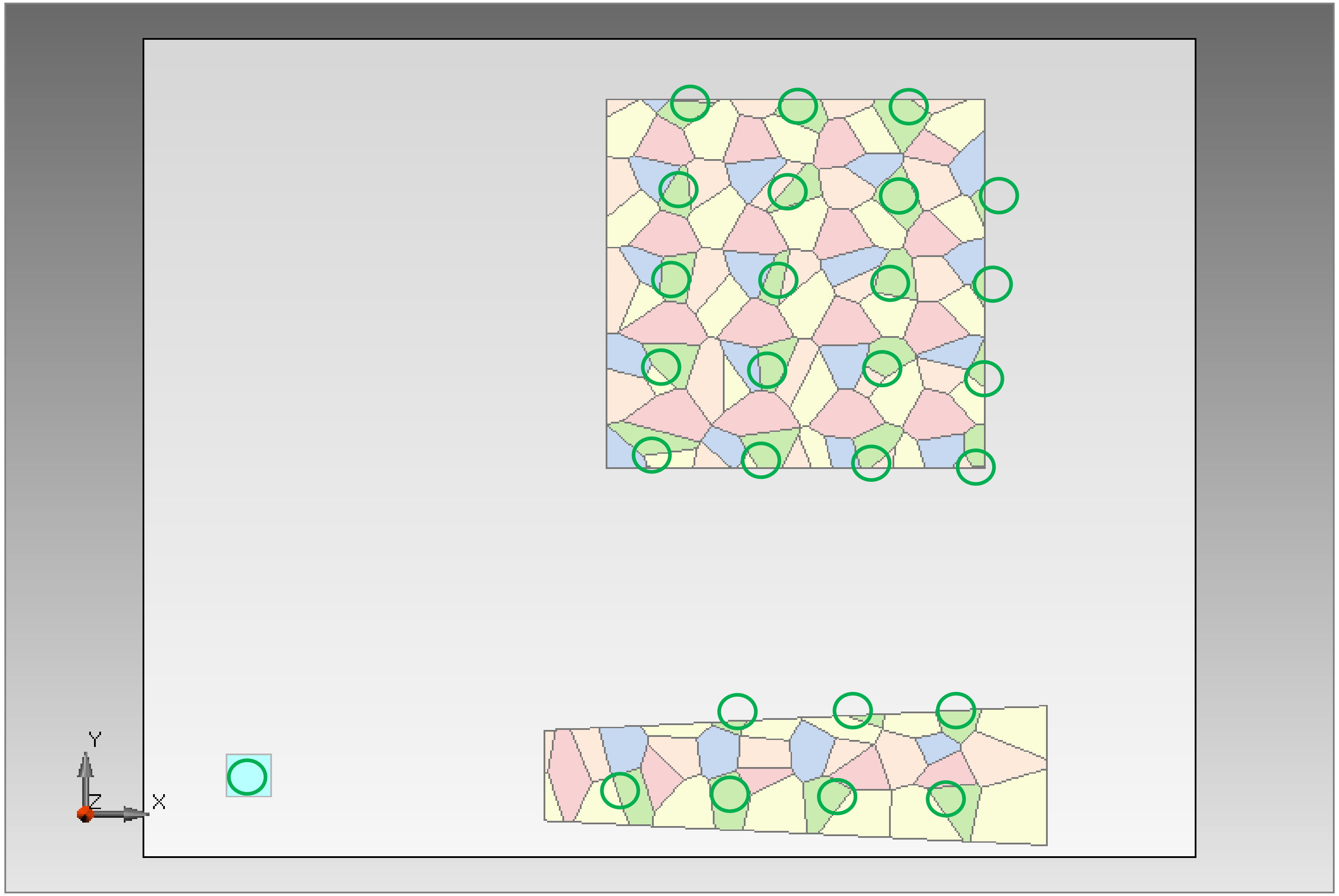
Result Combination of Modes (Segmentation)



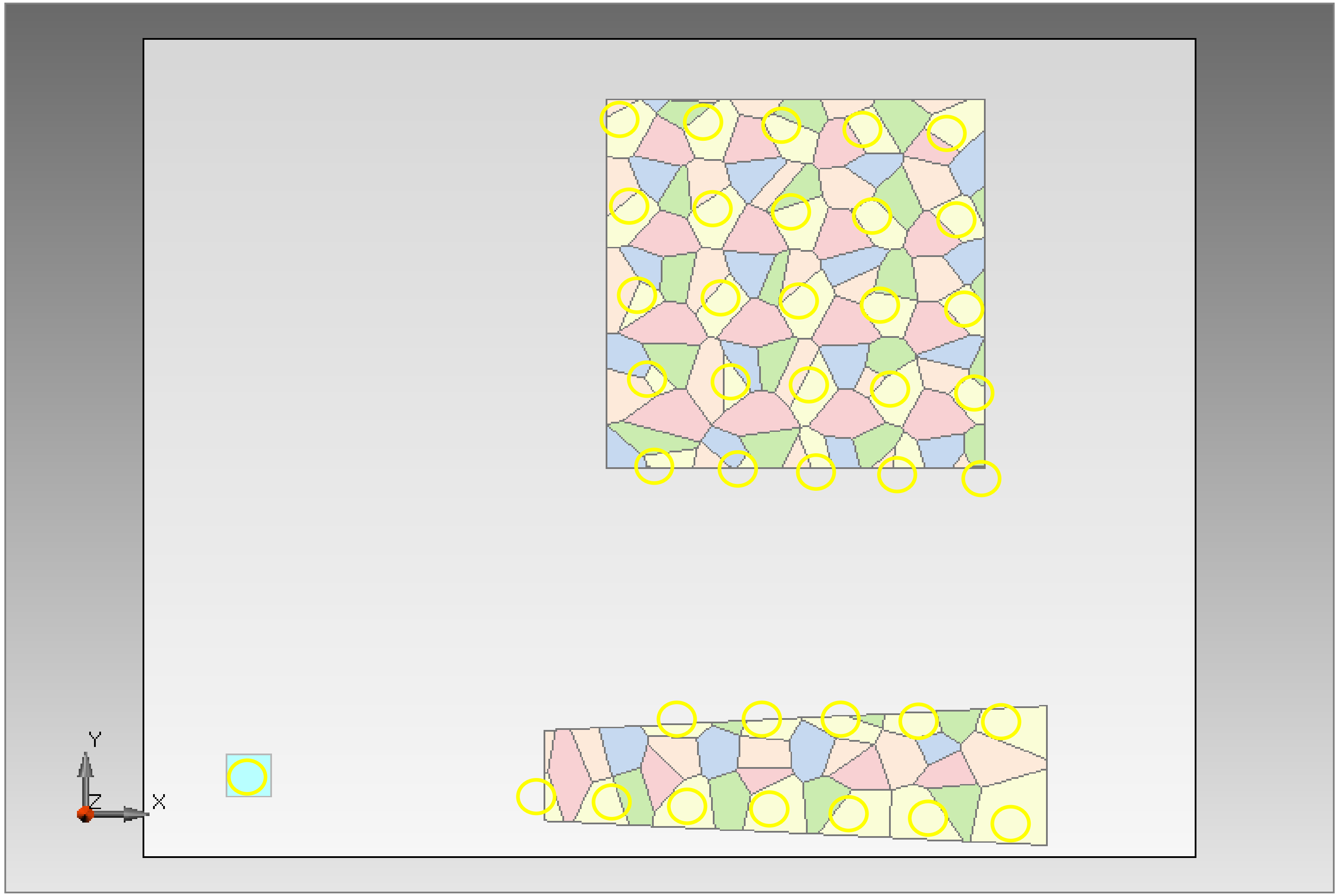
Result Combination of Modes (Segmentation)



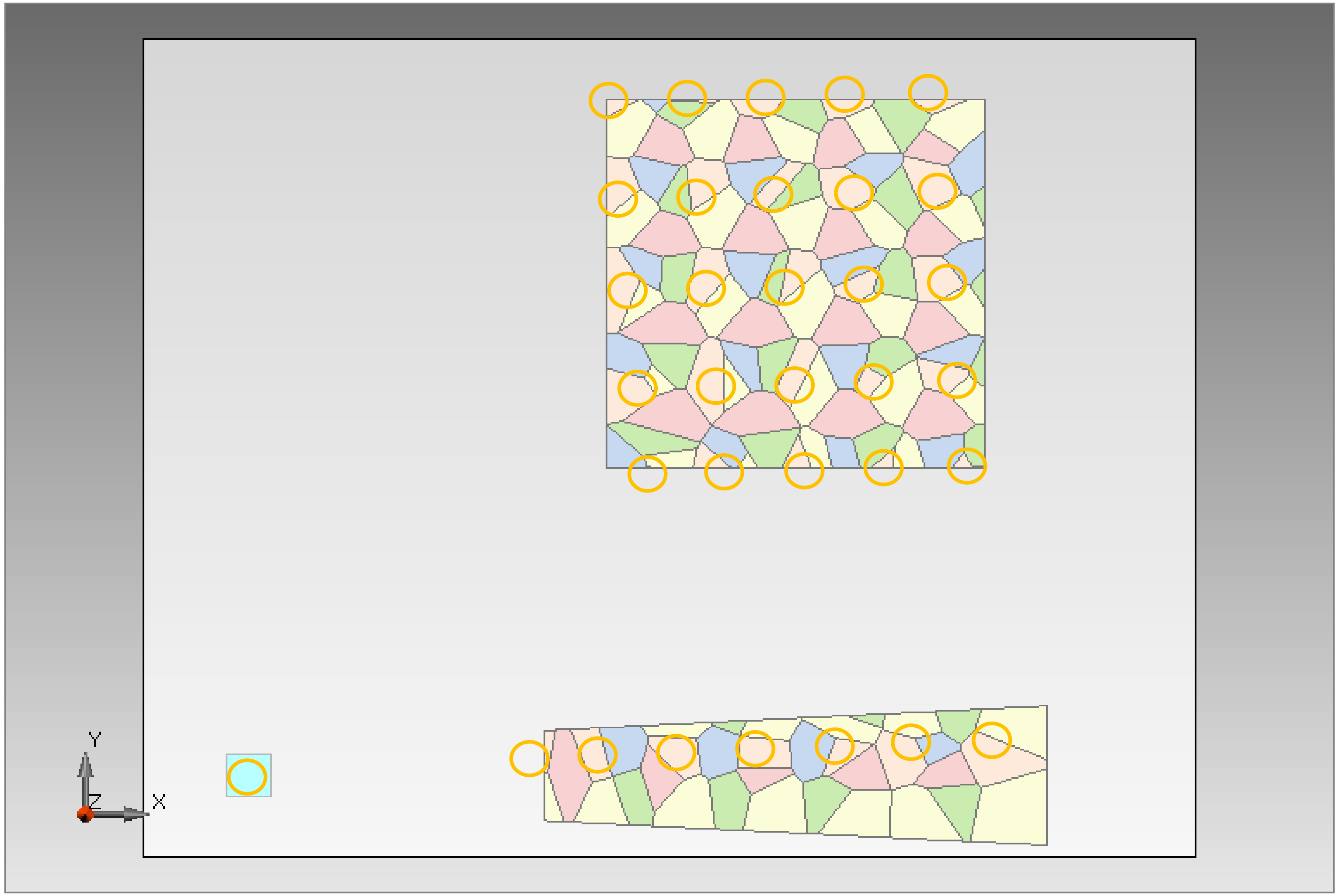
Result Combination of Modes (Segmentation)



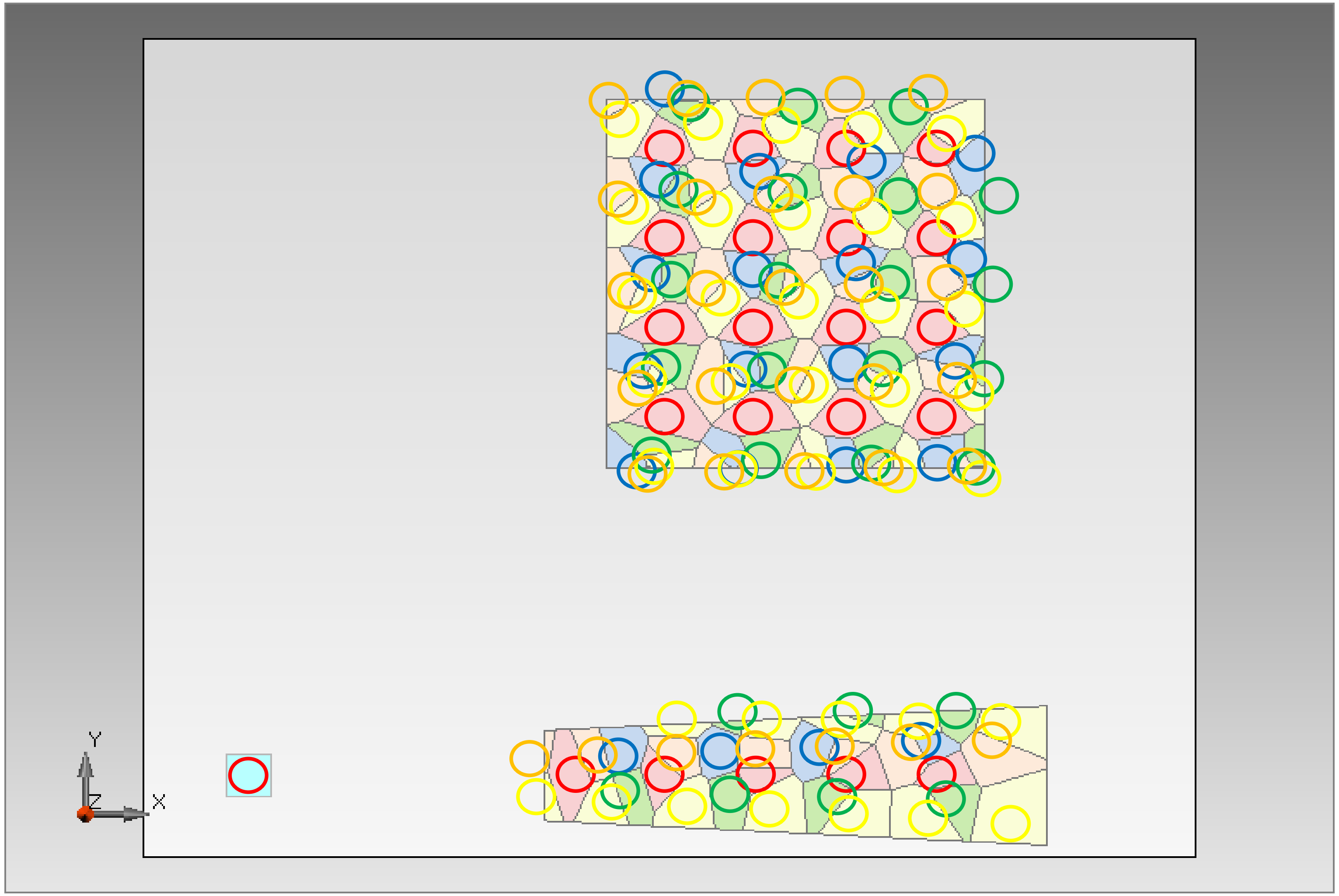
Result Combination of Modes (Segmentation)



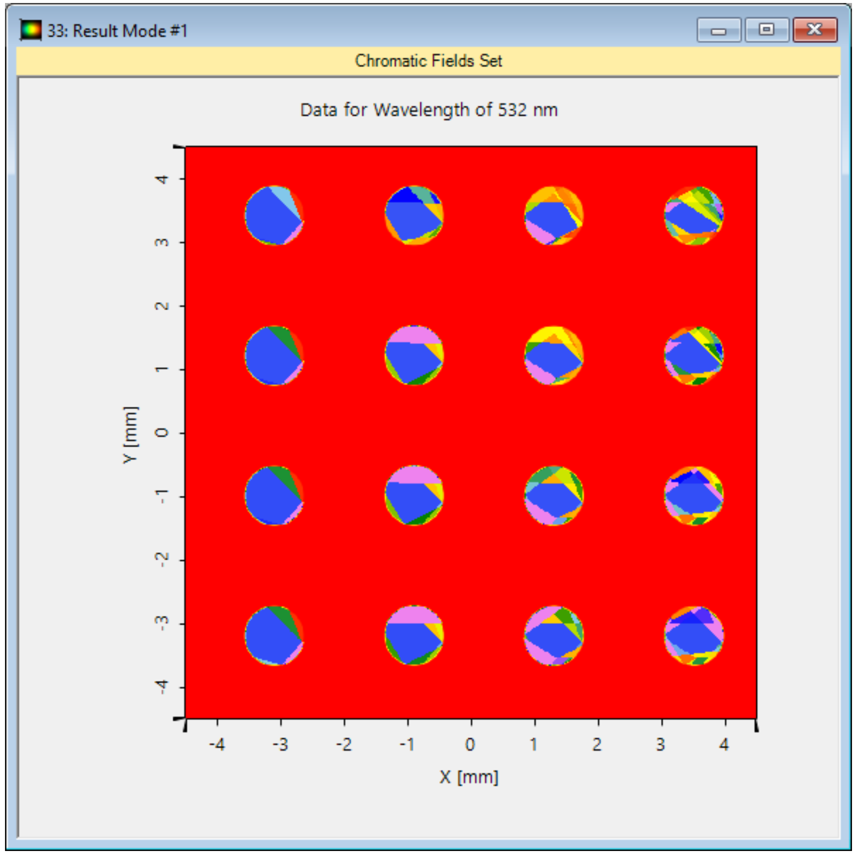
Result Combination of Modes (Segmentation)



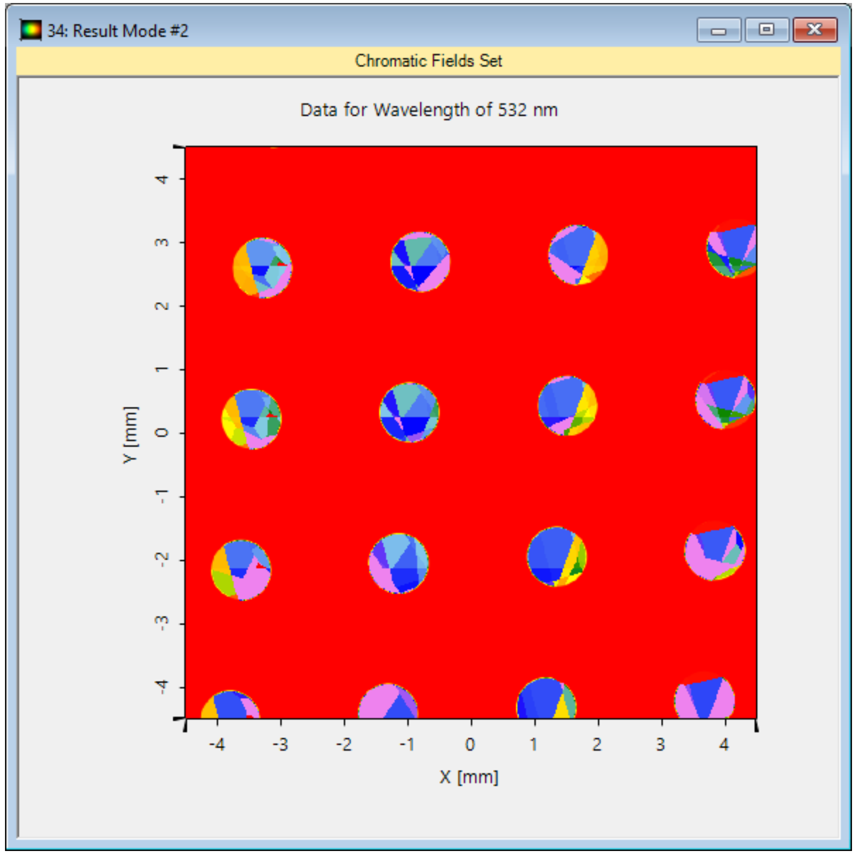
Result Combination of Modes (Segmentation)



Final Design Results Mode #1 + #2

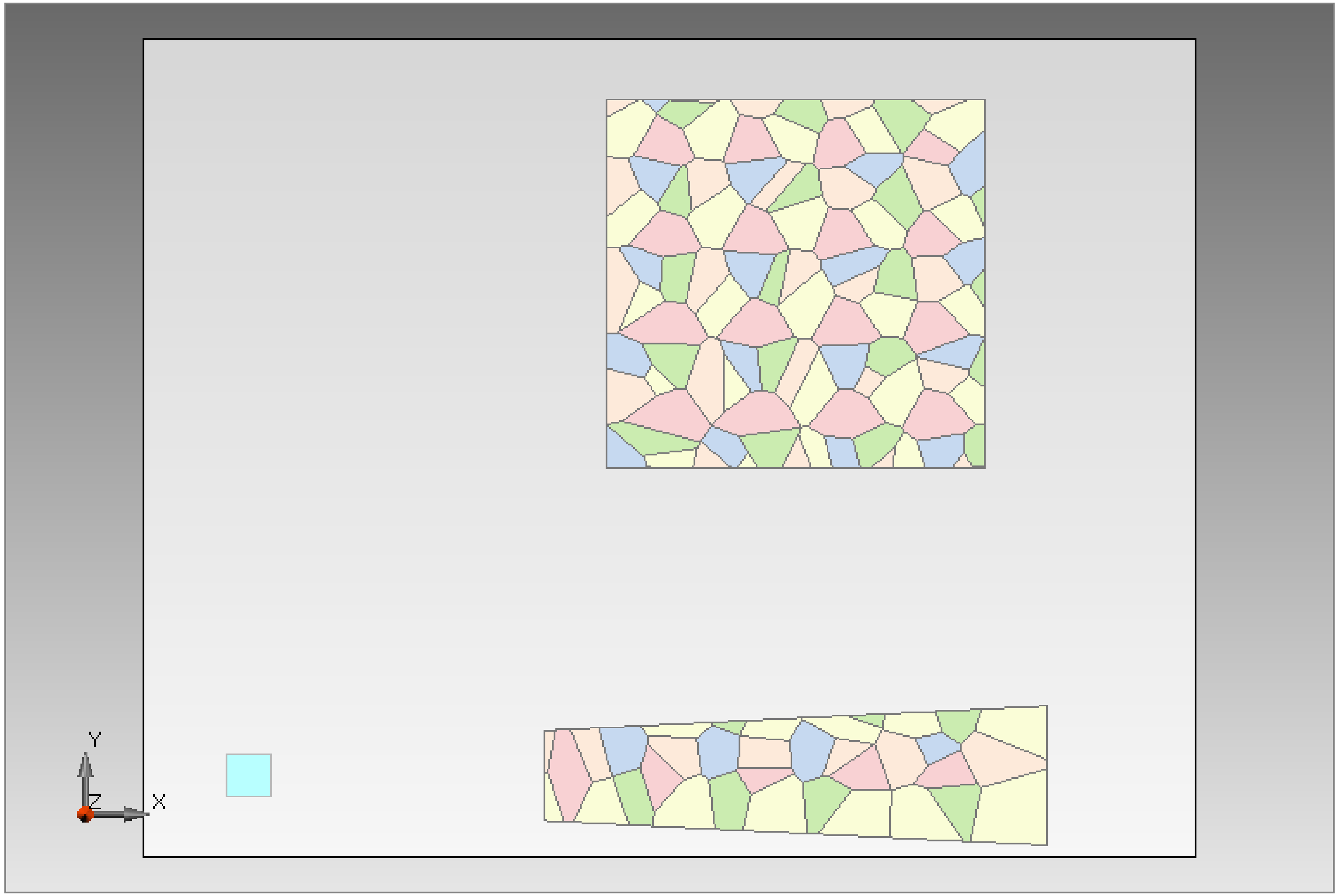


Mode	Merit Function	Value
#1	FOV Angle	$\alpha = 0°; \beta = 0°$
	Uniformity Error	**43.90%**



Mode	Merit Function	Value
#2	FOV Angle	$\alpha = 5°; \beta = 3°$
	Uniformity Error	**45.61%**

Result Combination of Modes (Segmentation)



Parametric Optimization and Initial Design

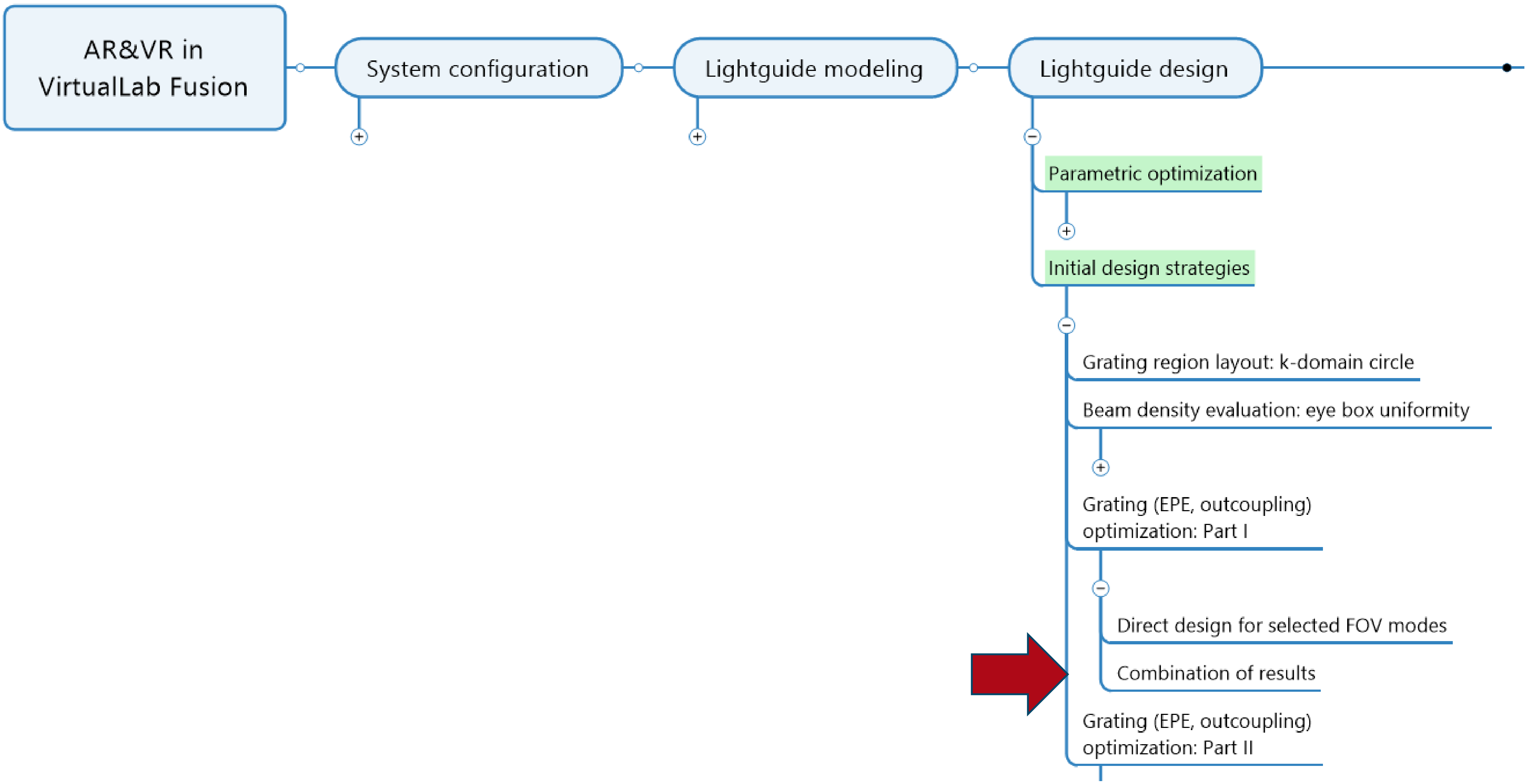
Initial design, e.g.

- Inverse approaches
- Functional design

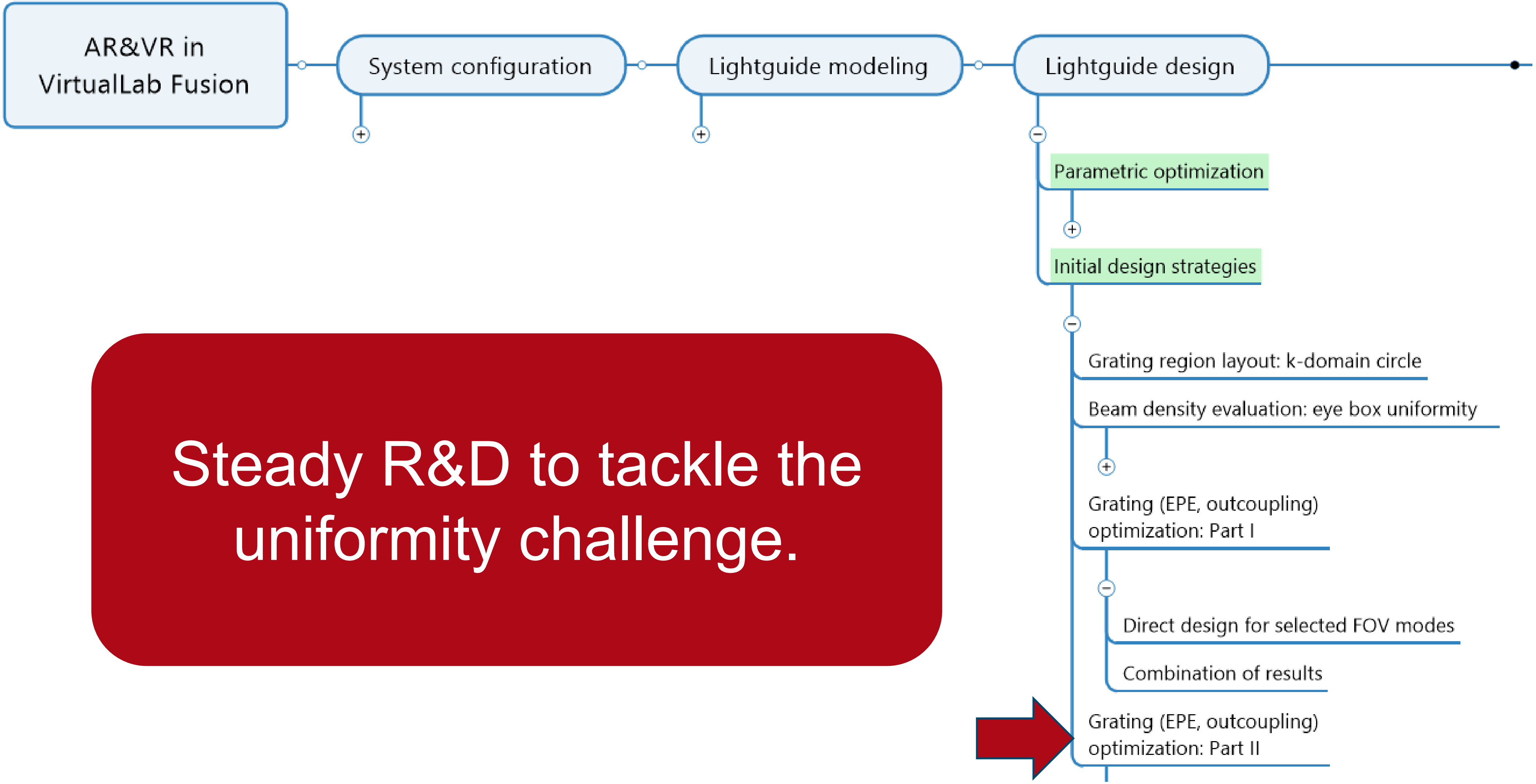
In suitable combination

Parametric optimization

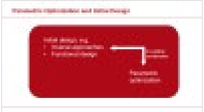
Lightguide Modeling and Design



Lightguide Modeling and Design

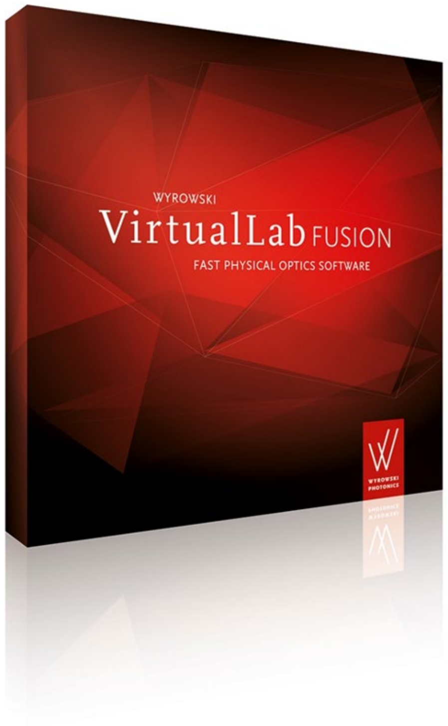


Steady R&D to tackle the uniformity challenge.



Conclusion

- Physical-optics modeling of lightguides enables the consideration of all effects that have to be taken into account during the design development
- Parametric optimization can be done but is often slow due to lack of good initial solution and numerous parameters of the system
- VirtualLab allows for new systematic design concepts for lightguide devices, which provide a strategy to obtain appropriate initial system configurations
- The combination of physical-optical modeling, systematic design and parametric optimization will provide the optimal system design



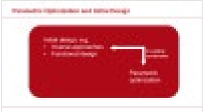
Thank You!

Lightguide Modeling and Design

- AR&VR in VirtualLab Fusion
- System configuration
- Lightguide modeling
- Lightguide design
  - Parametric optimization
  - Initial design strategies
    - Grating region layout: k-domain circle
    - Beam density evaluation: eye box uniformity
    - Grating (EPE, outcoupling) optimization: Part I
      - Direct design for selected FOV modes
      - Combination of results
    - Grating (EPE, outcoupling) optimization: Part II

Steady R&D to tackle the uniformity challenge.

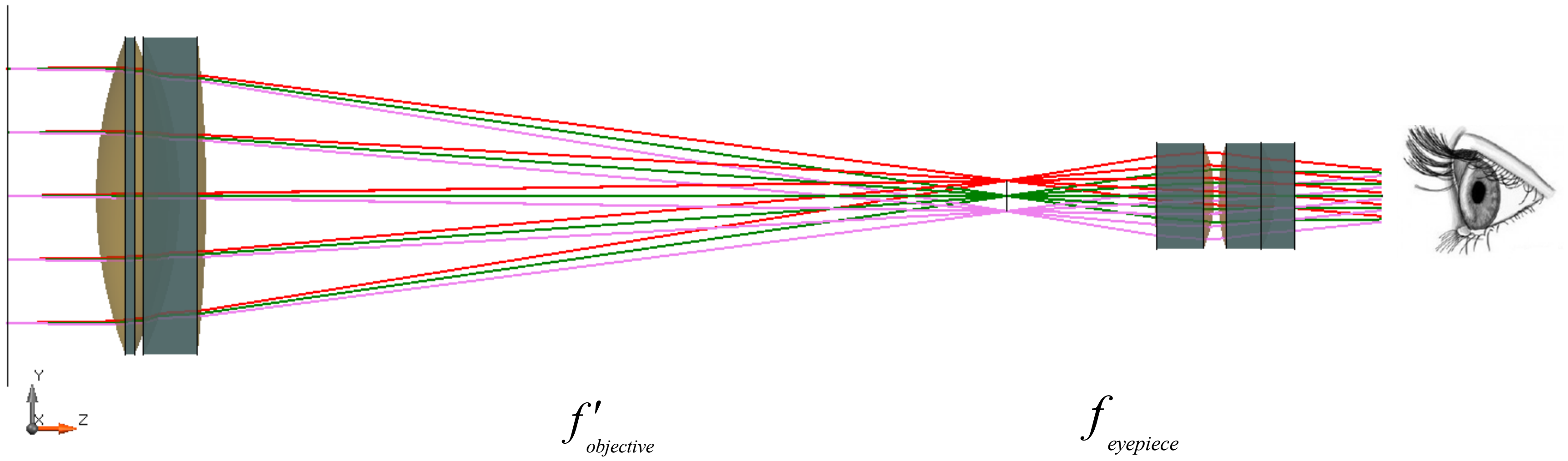
Why this task is so complex?



Telescope System

FOV modes behave somehow well-sorted

System parameters	
Magnification	5.5X
Field of view	4°



$$F/\# = f'/D'$$

where, D ′is the diameter of the entrance pupil

Objective group

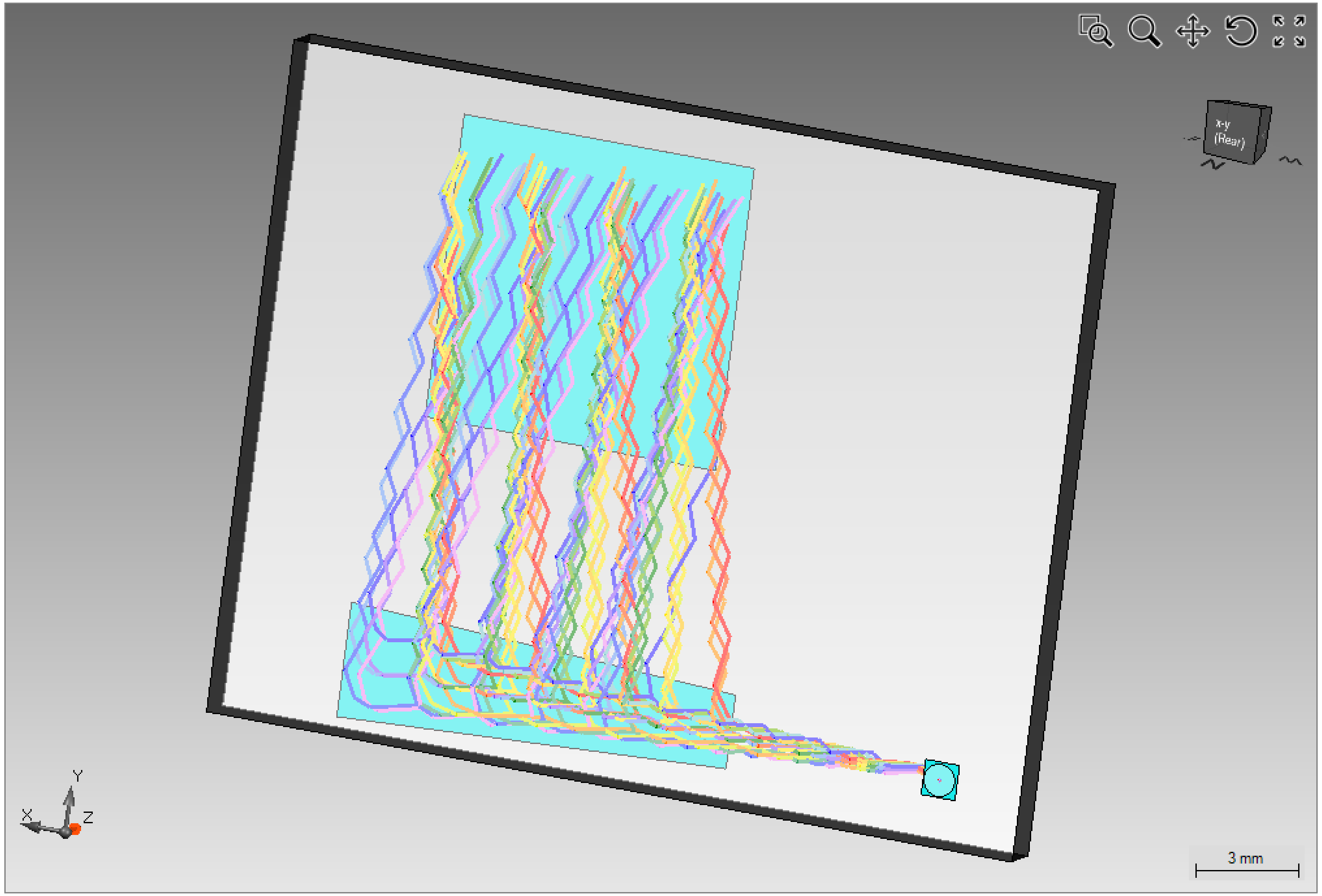
Focal length $f'_{objective}$	100 mm
F/#	2.8
number of lenses	4

Eyepiece group

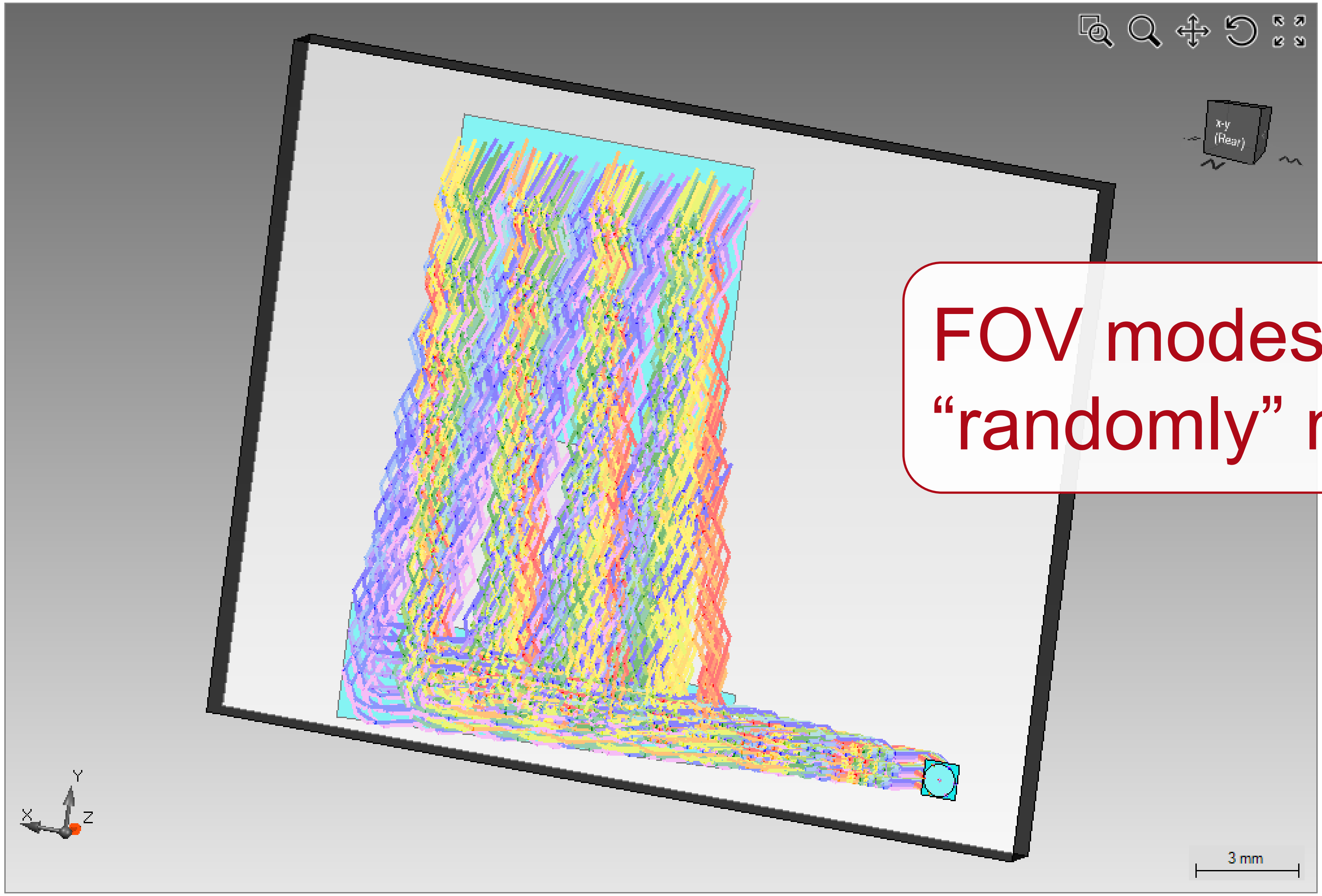
Focal length $f_{eyepiece}$	18.3 mm
Exit Pupil Diameter	3.6 mm
number of lenses	5

Lens source: A_019 and C_001 in Zebase

Design for Multiple FOV Modes: Waveguide



Design for Multiple FOV Modes: Waveguide



FOV modes laterally "randomly" mixed up

Parametric Optimization and Initial Design

Initial design, e.g.

- Inverse approaches
- Functional design

In suitable combination

Parametric optimization