FRIEDRICH-SCHILLER-UNIVERSITÄT JENA

DGaO 2019, Darmstadt, June 13, 2019

Challenges and Solutions in the Design of Lightguides for XR Glasses

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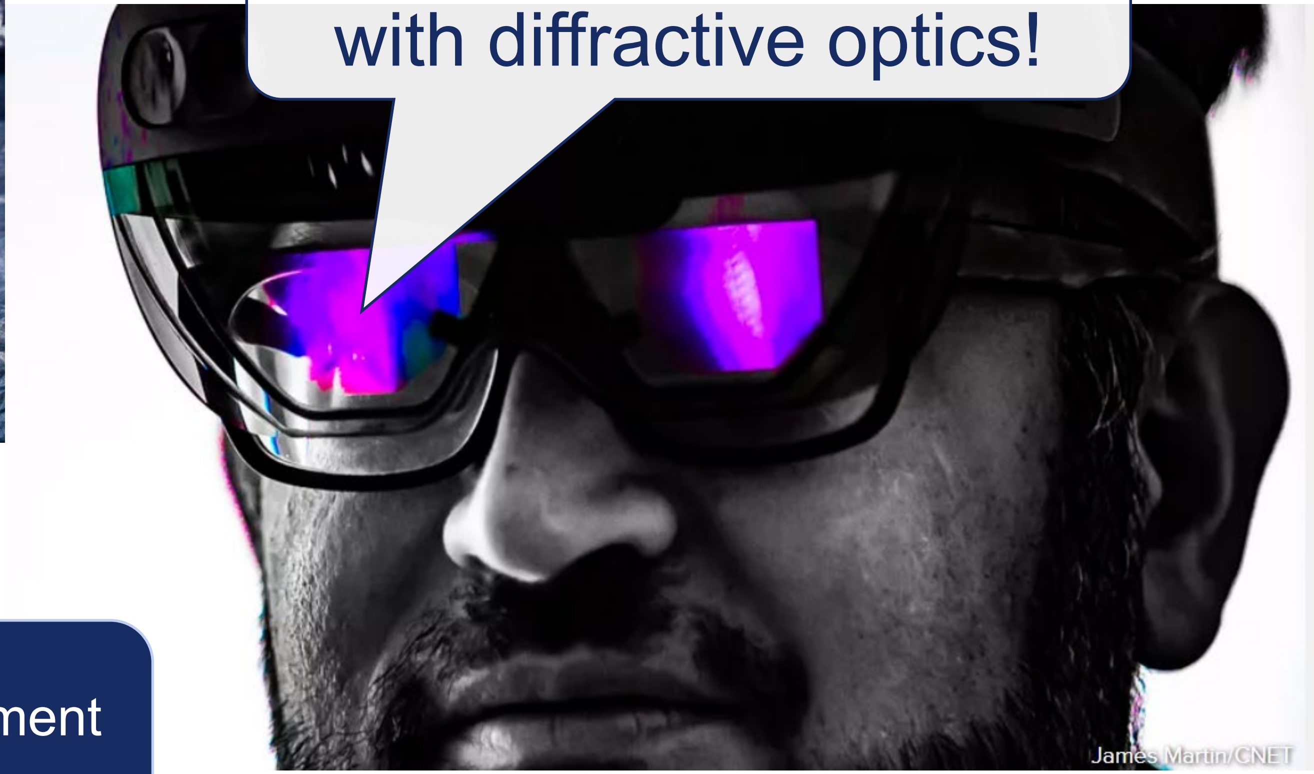
*University of Jena, ** LightTrans GmbH

Microsoft HoloLens 2 Presented Sunday, February 24, 2019

Lightguide technology
with diffractive optics!



Microsoft has invested in the development
for 10 years with huge resources.

HoloLens V1 and V2: Comparison

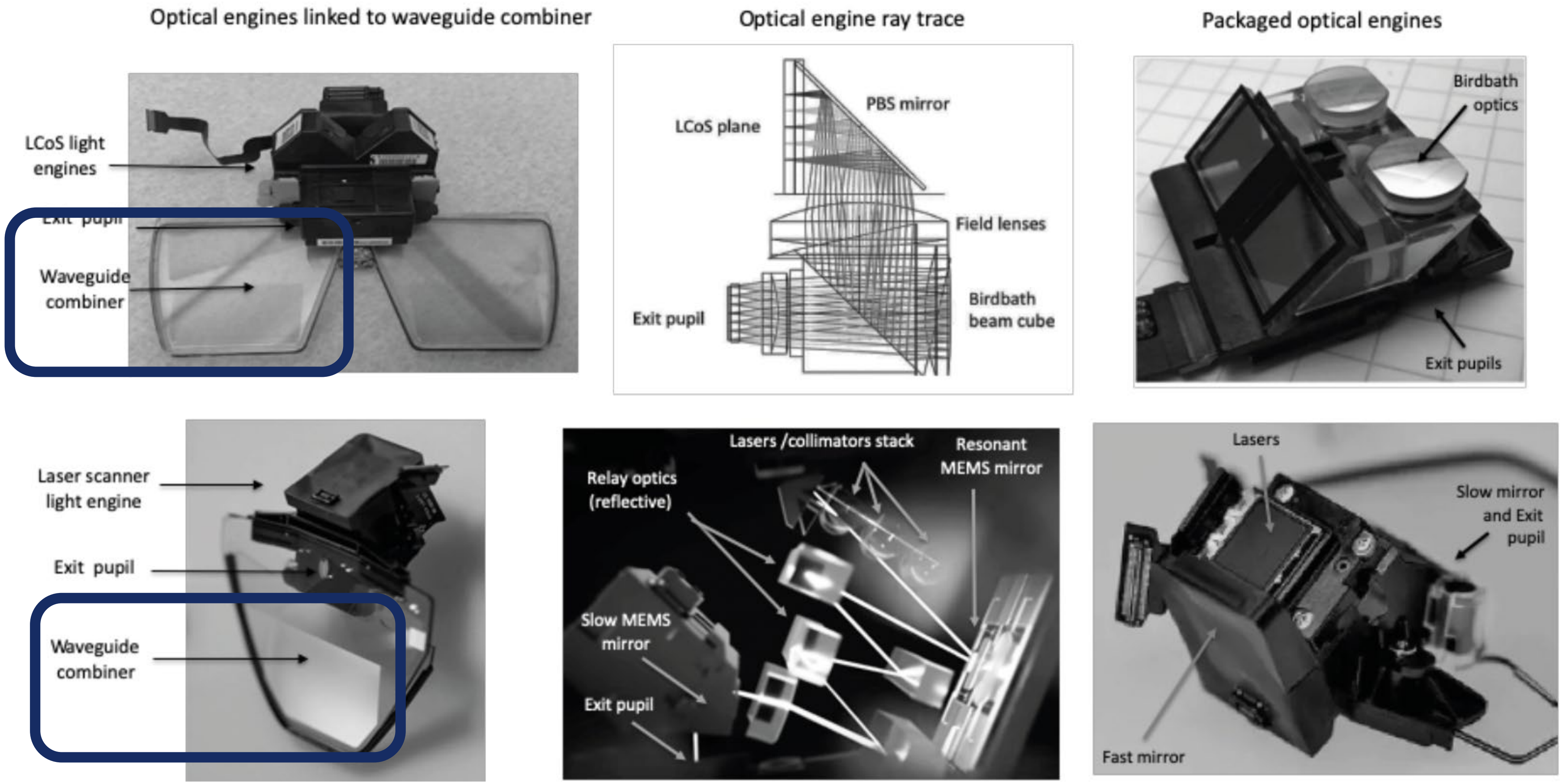
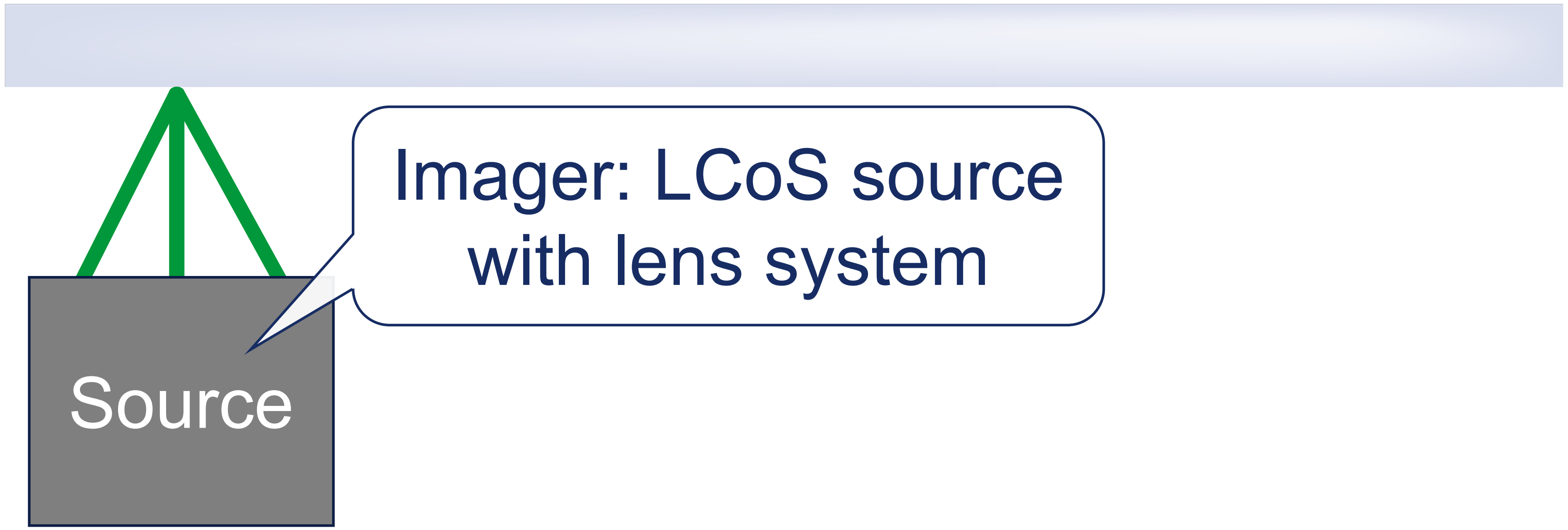


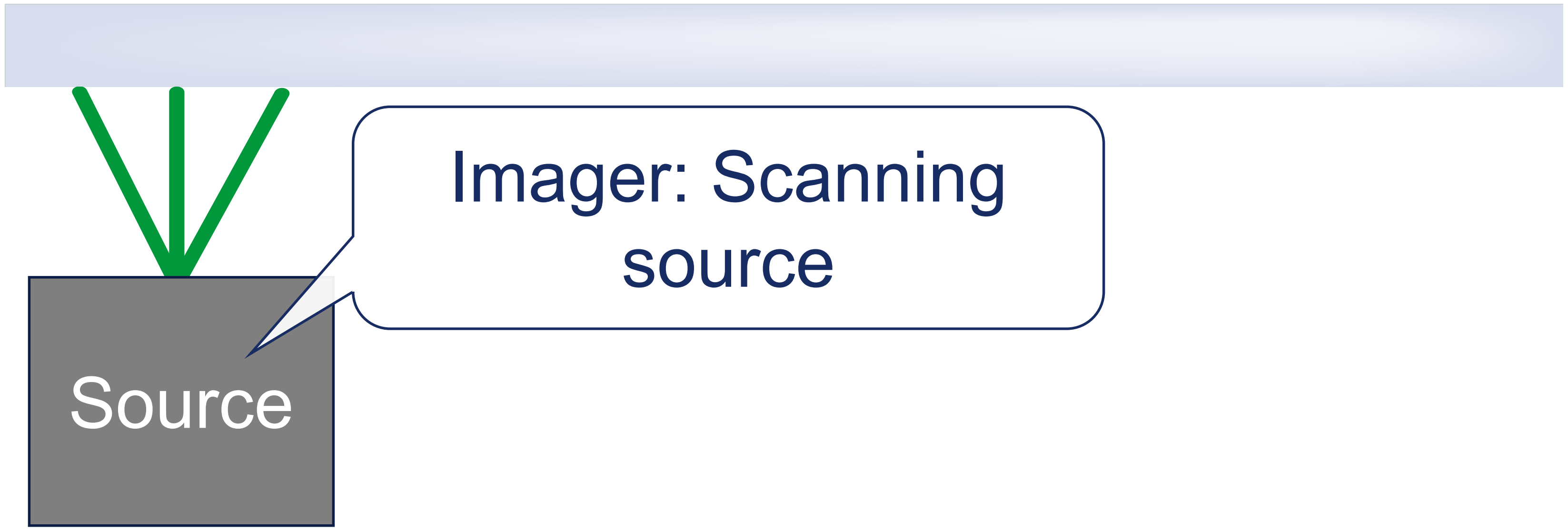
Figure 30: Display engines based on LCoS imager as in HoloLens V1 (top, 2016) and laser MEMS scanner as in HoloLens V2 (bottom, 2019).

Courtesy Bernard Kress

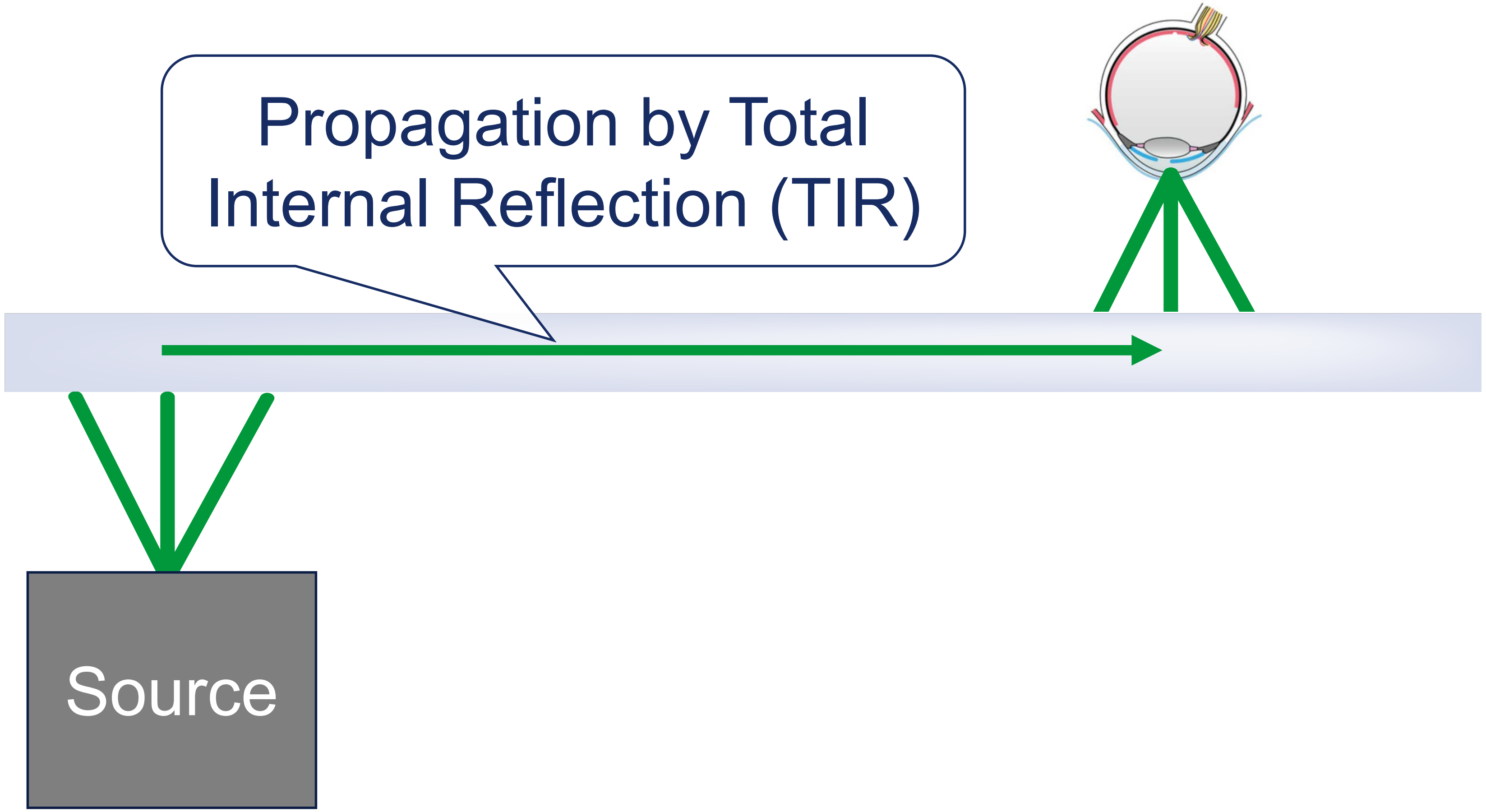
Lightguide Concept: Light Engine



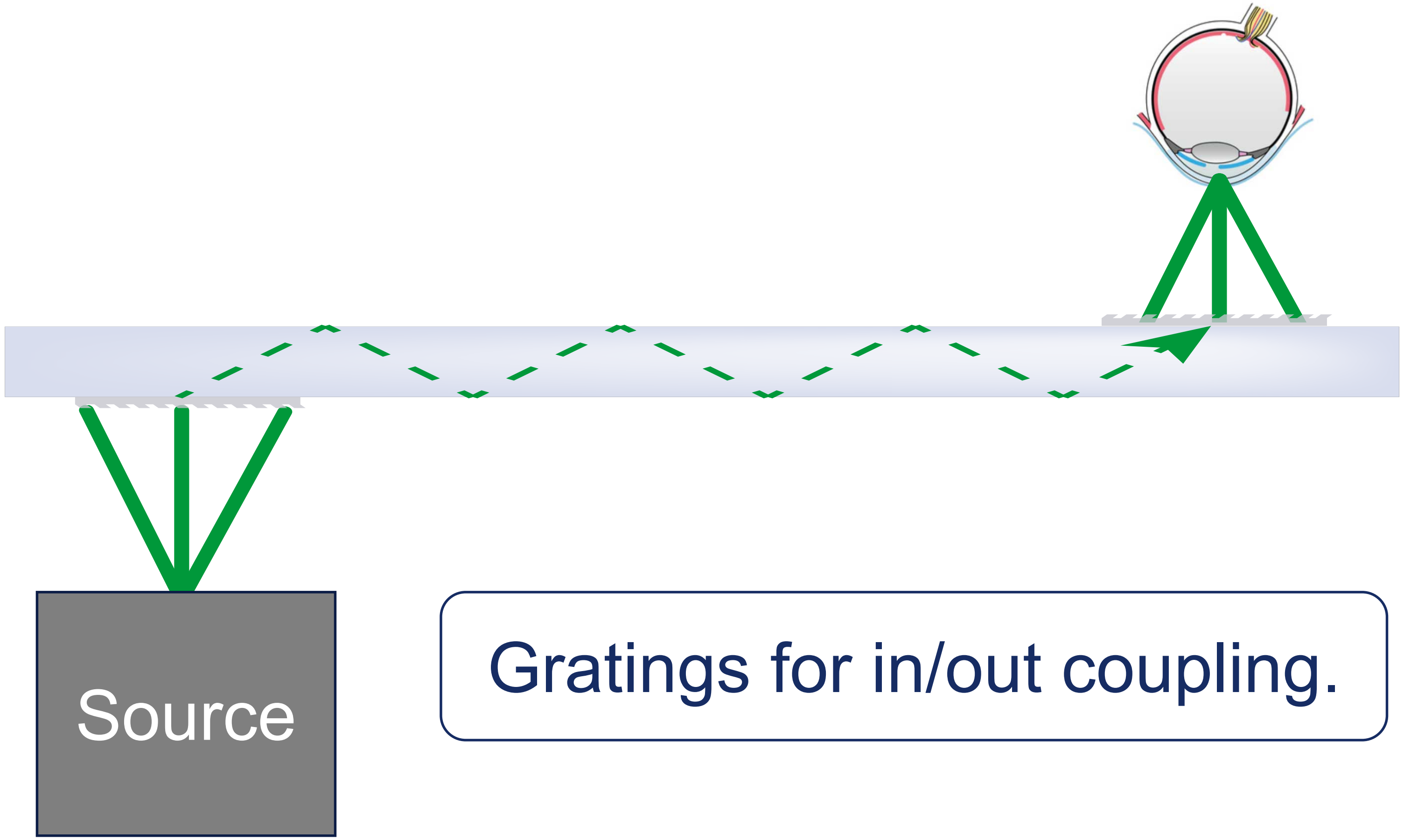
Lightguide Concept: Light Engine



Lightguide Concept: In/Out Coupling

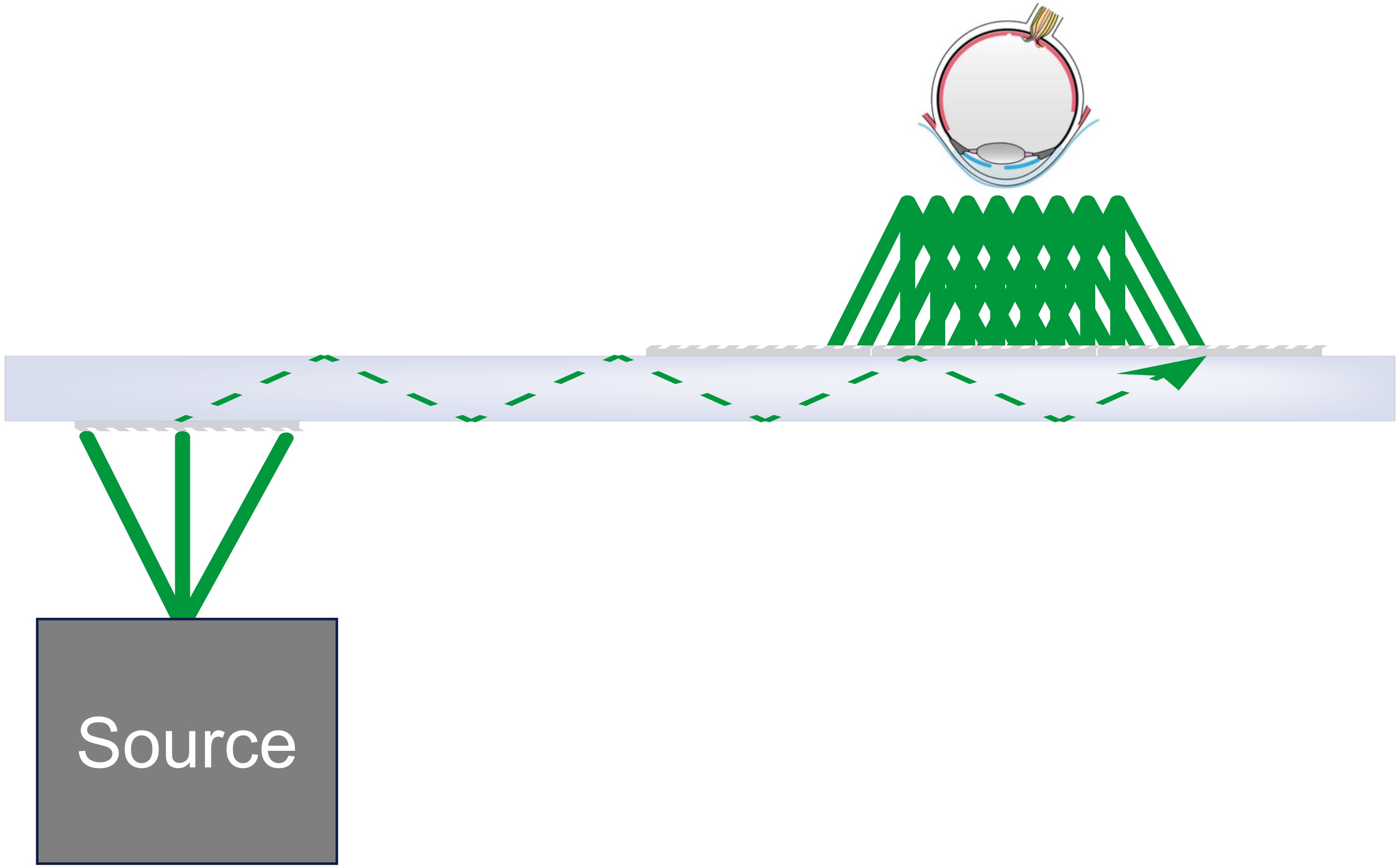


Lightguide Concept: In/Out Coupling

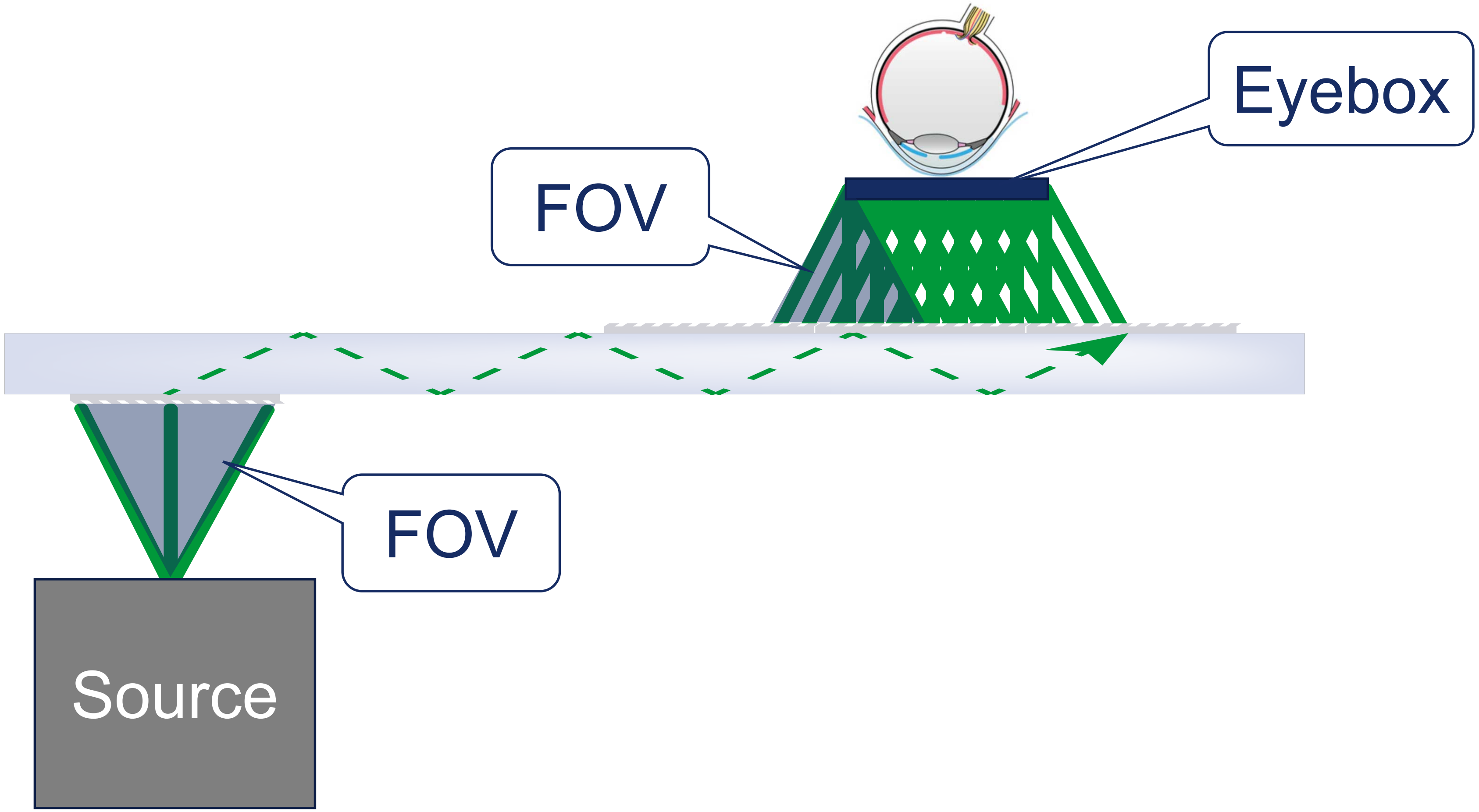


Gratings for in/out coupling.

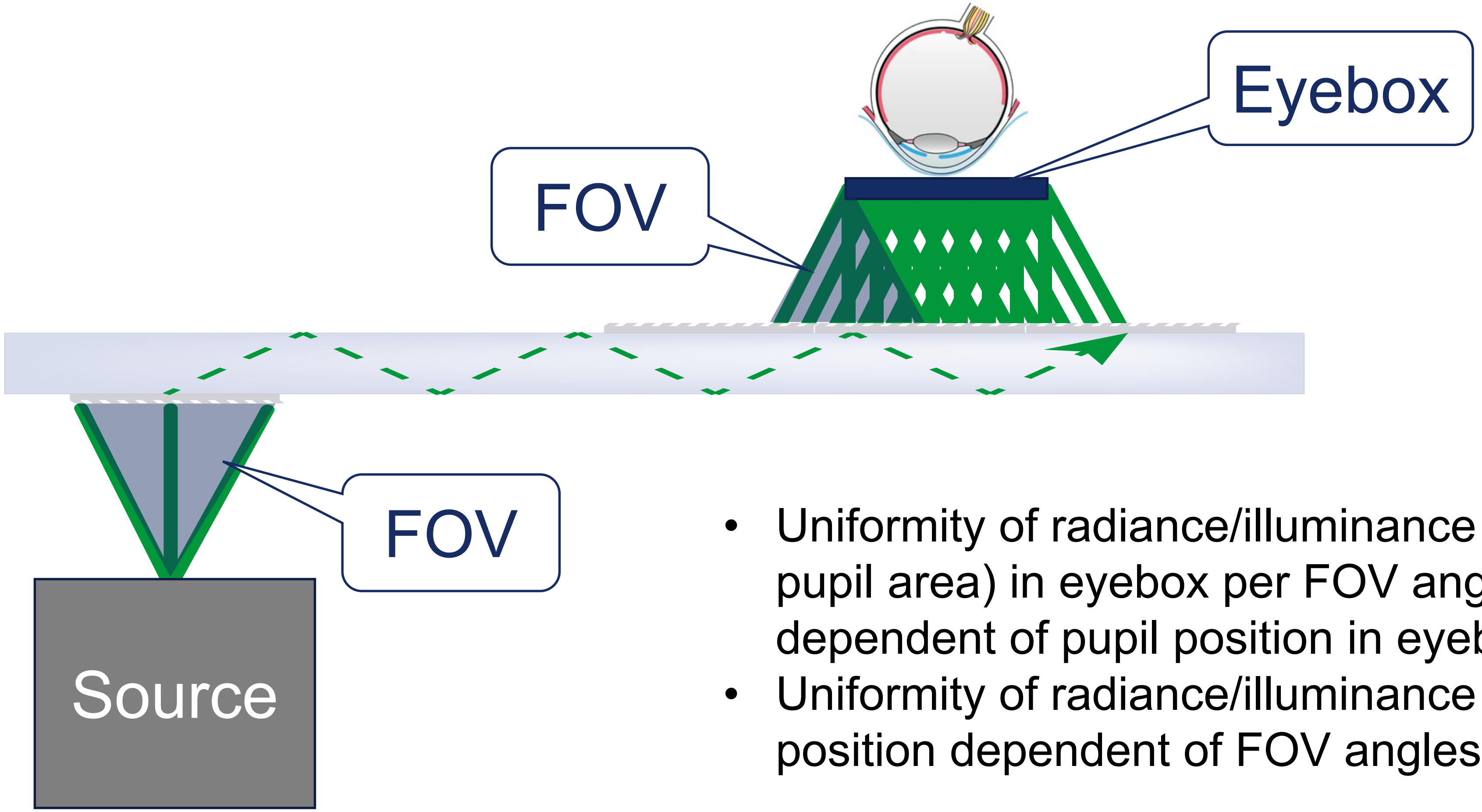
Lightguide Concept: Exit Pupil Expansion



Lightguide Concept: Exit Pupil Expansion

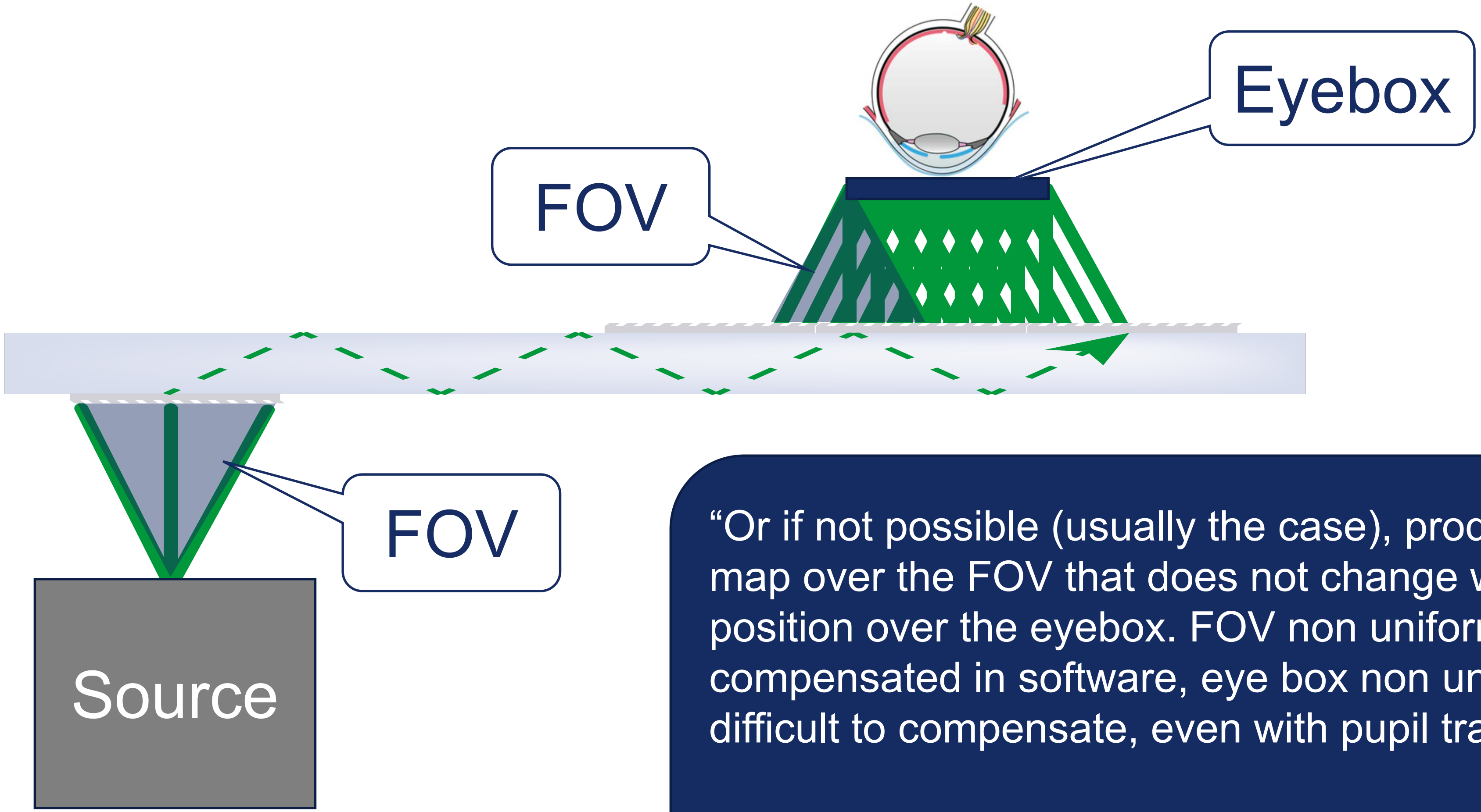


Lightguide Concept: Fundamental Design Criteria



- Uniformity of radiance/illuminance (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.

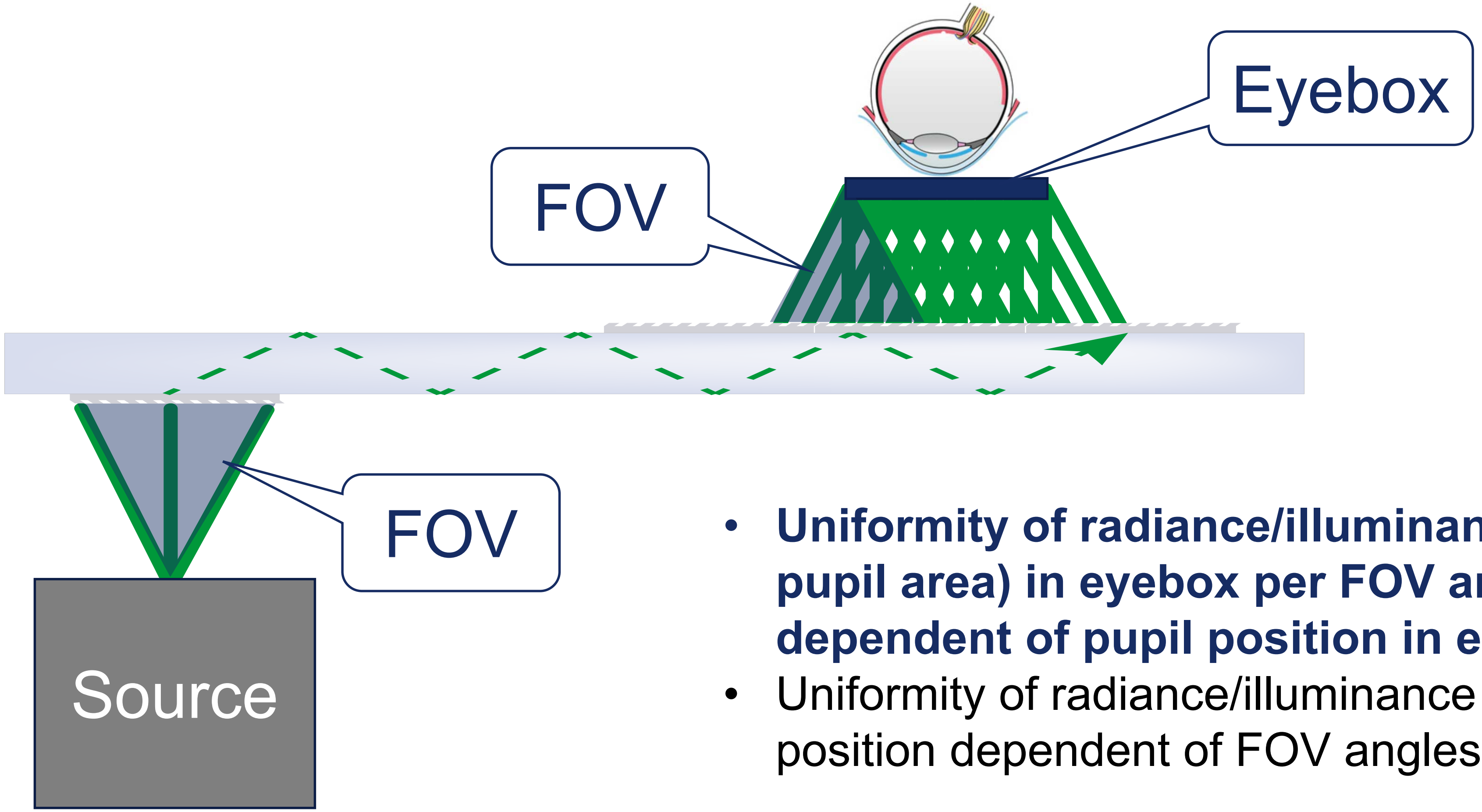
Lightguide Concept: Fundamental Design Criteria



"Or if not possible (usually the case), produce a non uniform map over the FOV that does not change with the pupil position over the eyebox. FOV non uniformity can be compensated in software, eye box non uniformity is very difficult to compensate, even with pupil tracking."

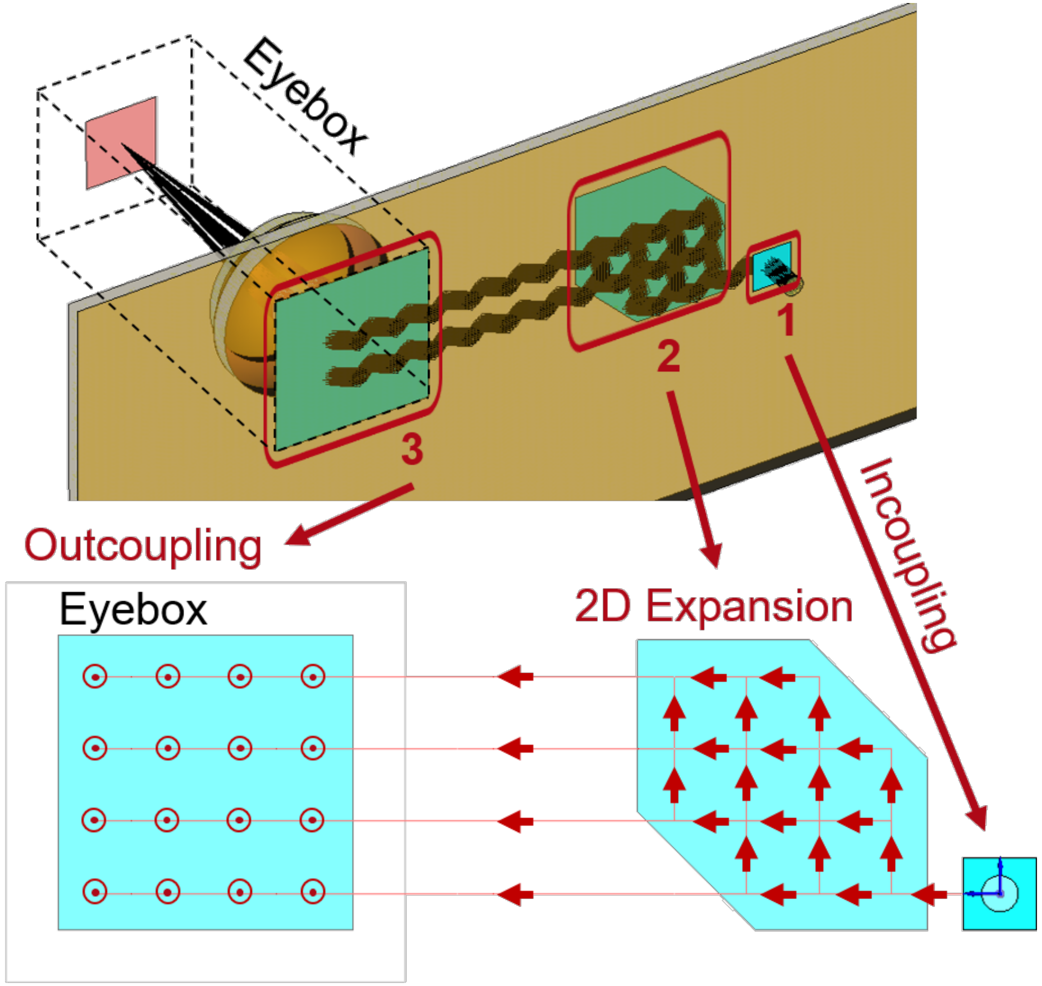
Bernard Kress, Microsoft

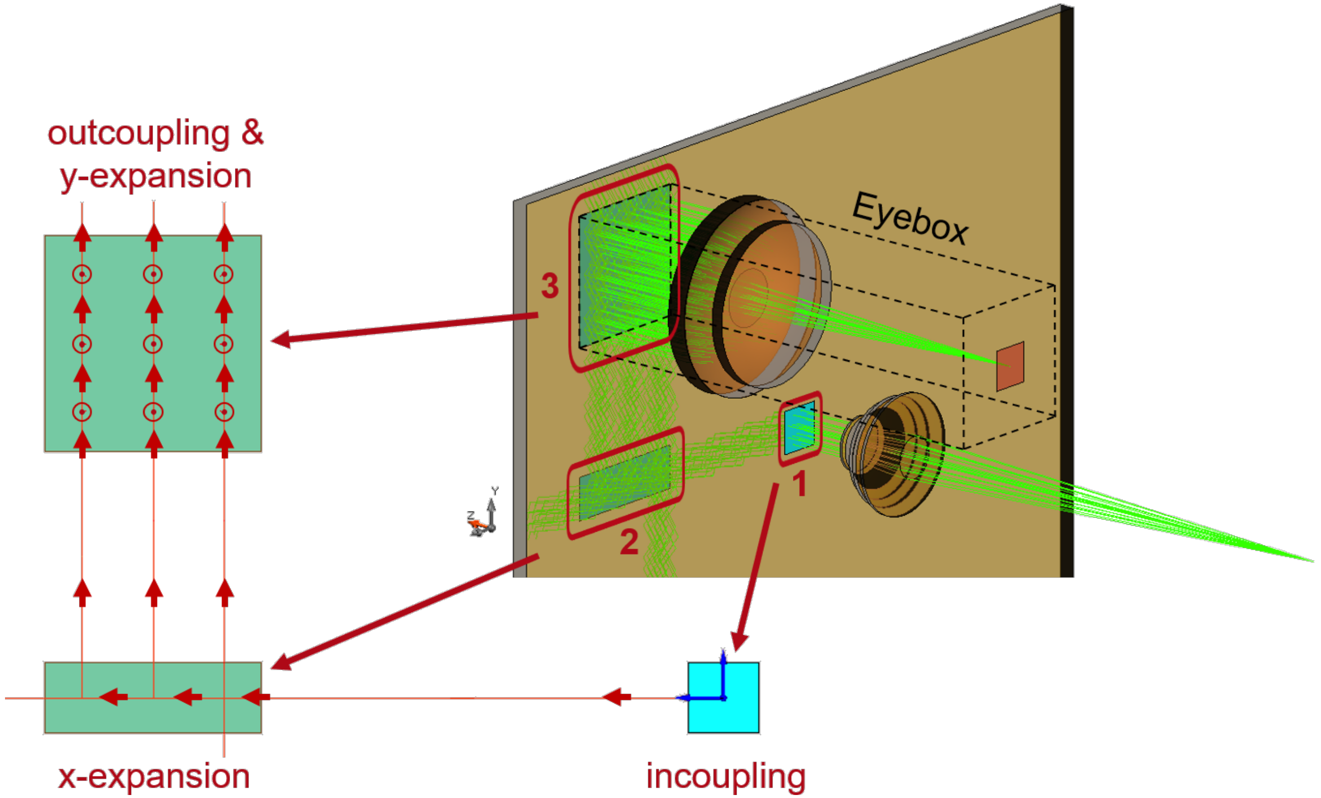
Lightguide Concept: Fundamental Design Criteria



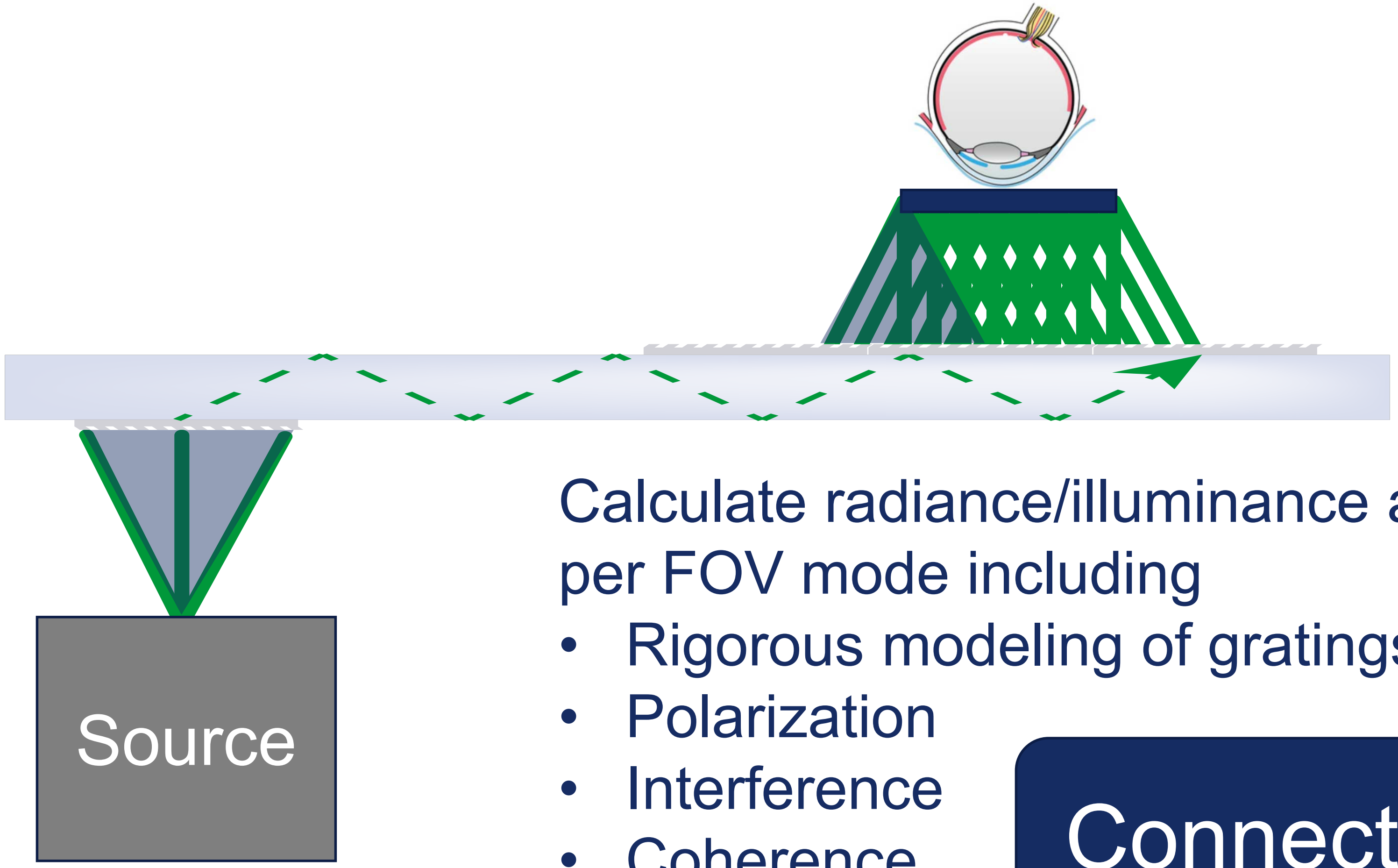
- **Uniformity of radiance/illuminance (per pupil area) in eyebox per FOV angle/mode dependent of pupil position in eyebox.**
- Uniformity of radiance/illuminance per pupil position dependent of FOV angles.

Example Geometries of Lightguide Systems





Lightguide Concept: Modeling Task

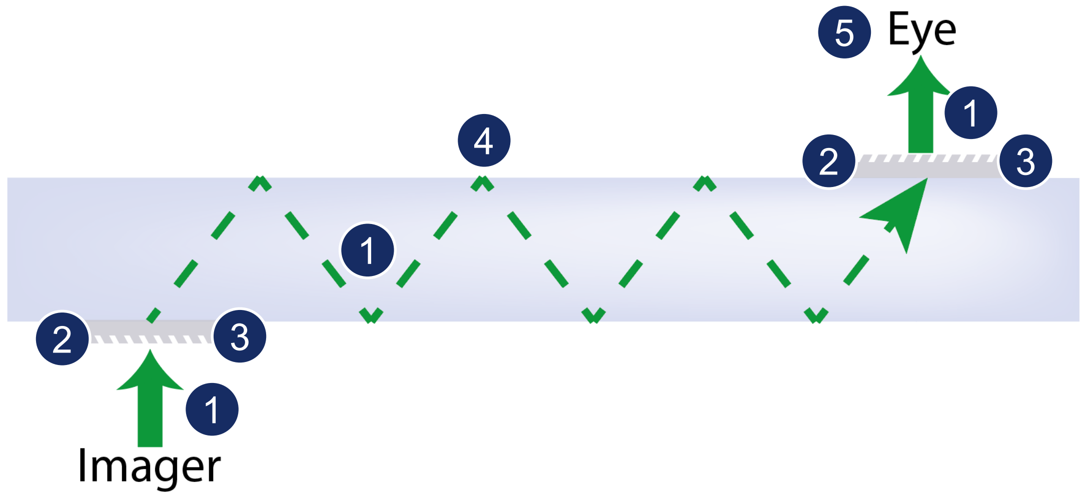


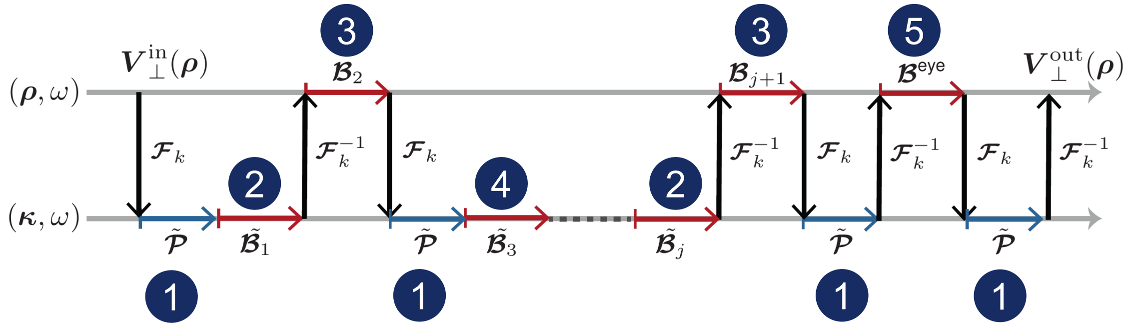
Calculate radiance/illuminance and MTF per FOV mode including

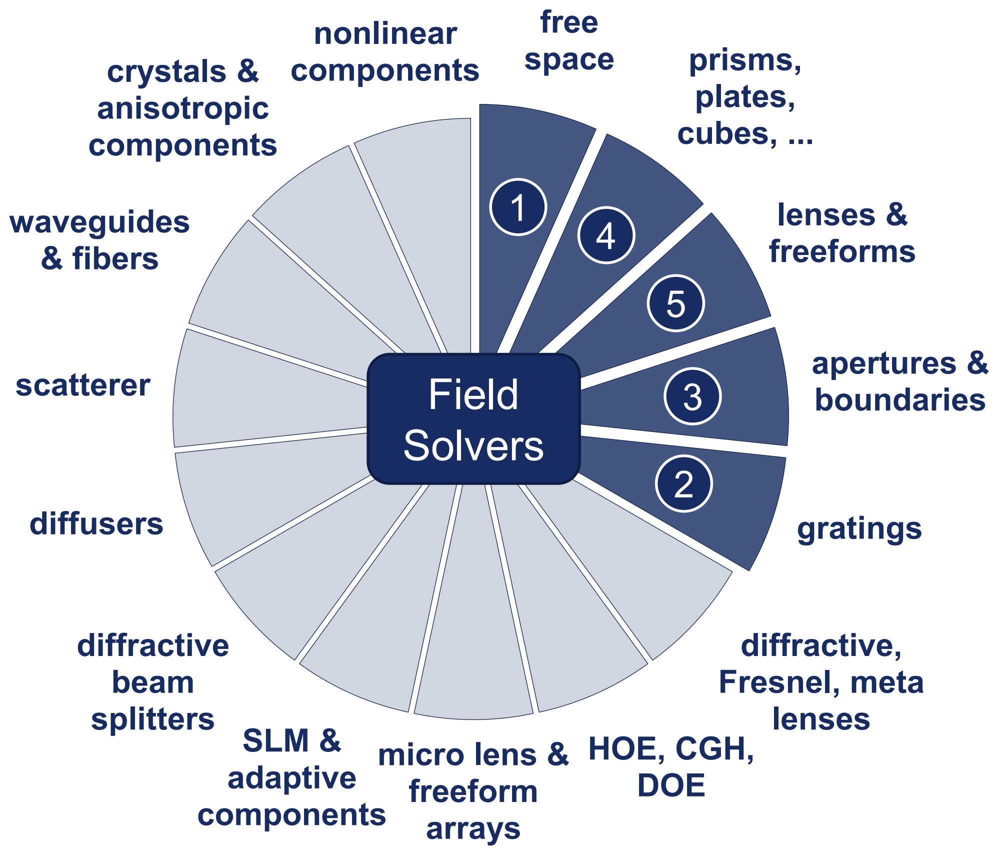
- Rigorous modeling of gratings
- Polarization
- Interference
- Coherence

Connecting field solvers

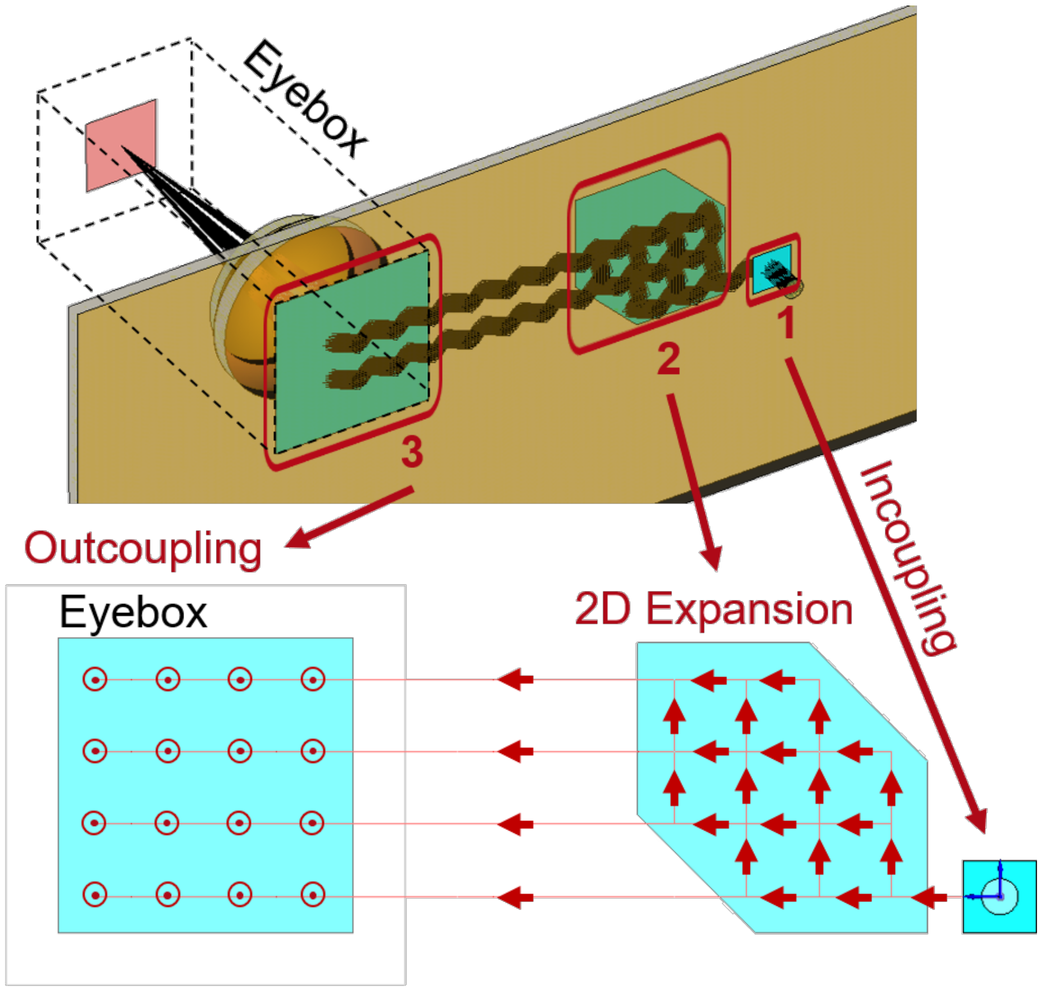
Typical Modeling Situation for AR&MR Lightguide

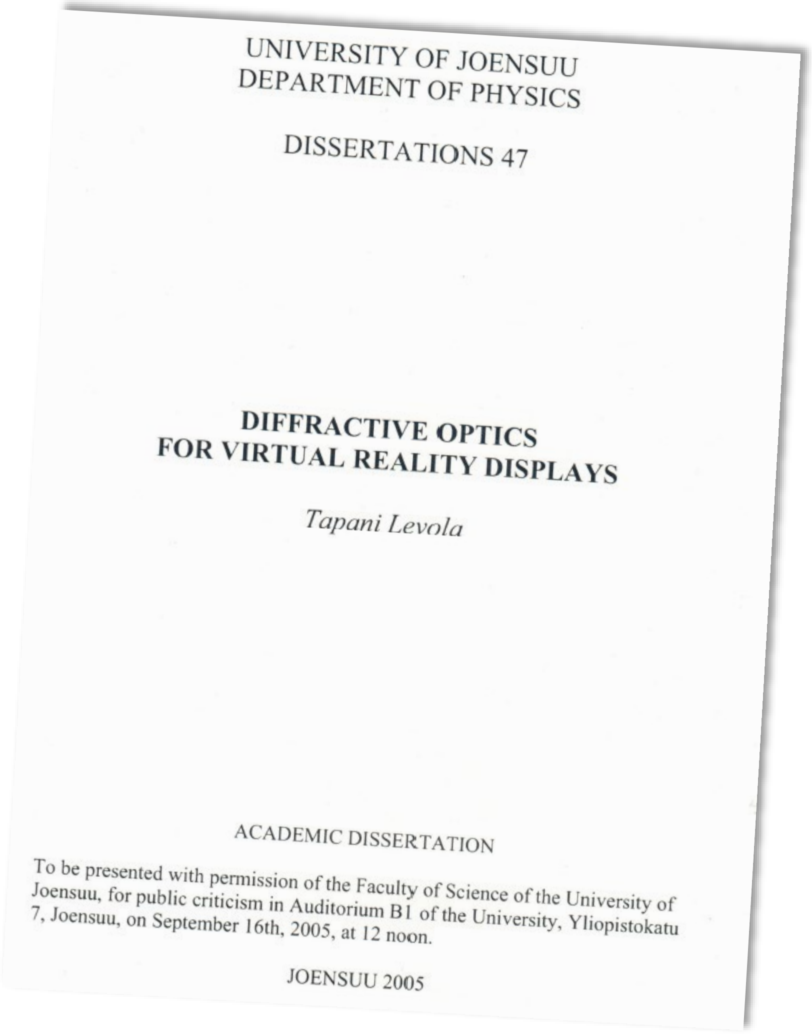






Levola Type Geometry of Eye Pupil Expansion (EPE)




UNIVERSITY OF JOENSUU
DEPARTMENT OF PHYSICS

DISSERTATIONS 47

DIFFRACTIVE OPTICS FOR VIRTUAL REALITY DISPLAYS

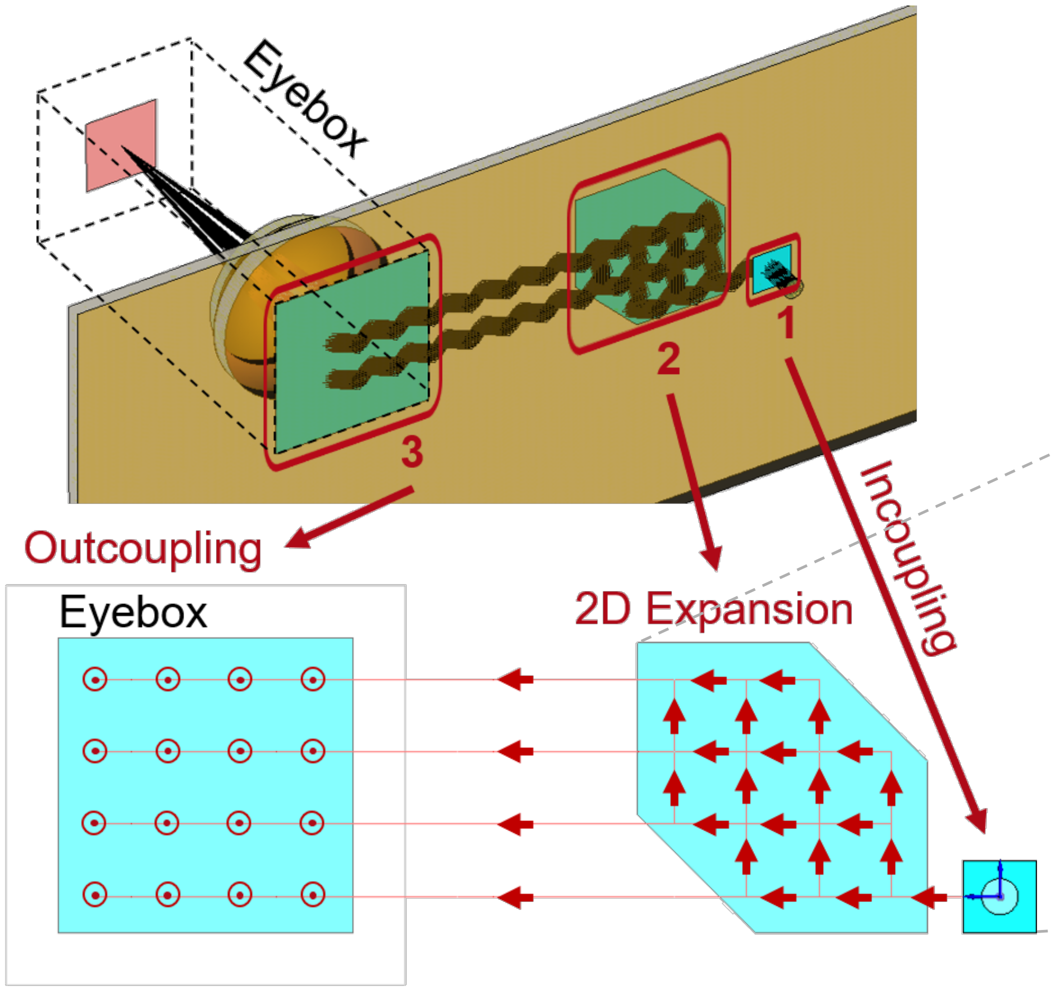
Tapani Levola

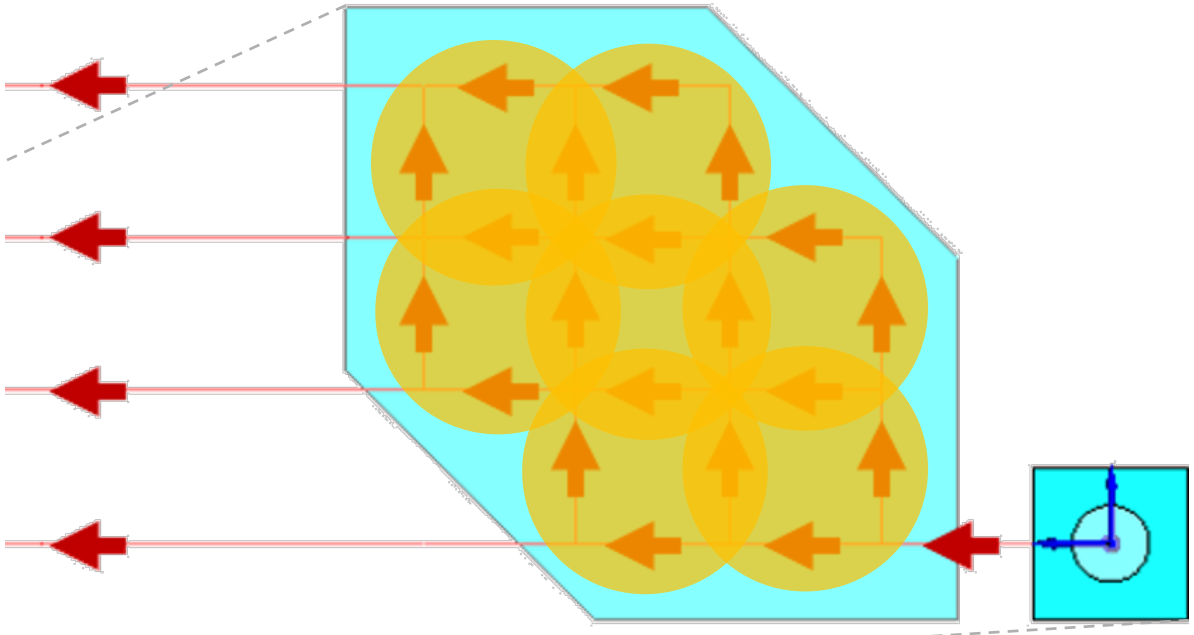
ACADEMIC DISSERTATION

To be presented with permission of the Faculty of Science of the University of Joensuu, for public criticism in Auditorium B1 of the University, Yliopistokatu 7, Joensuu, on September 16th, 2005, at 12 noon.

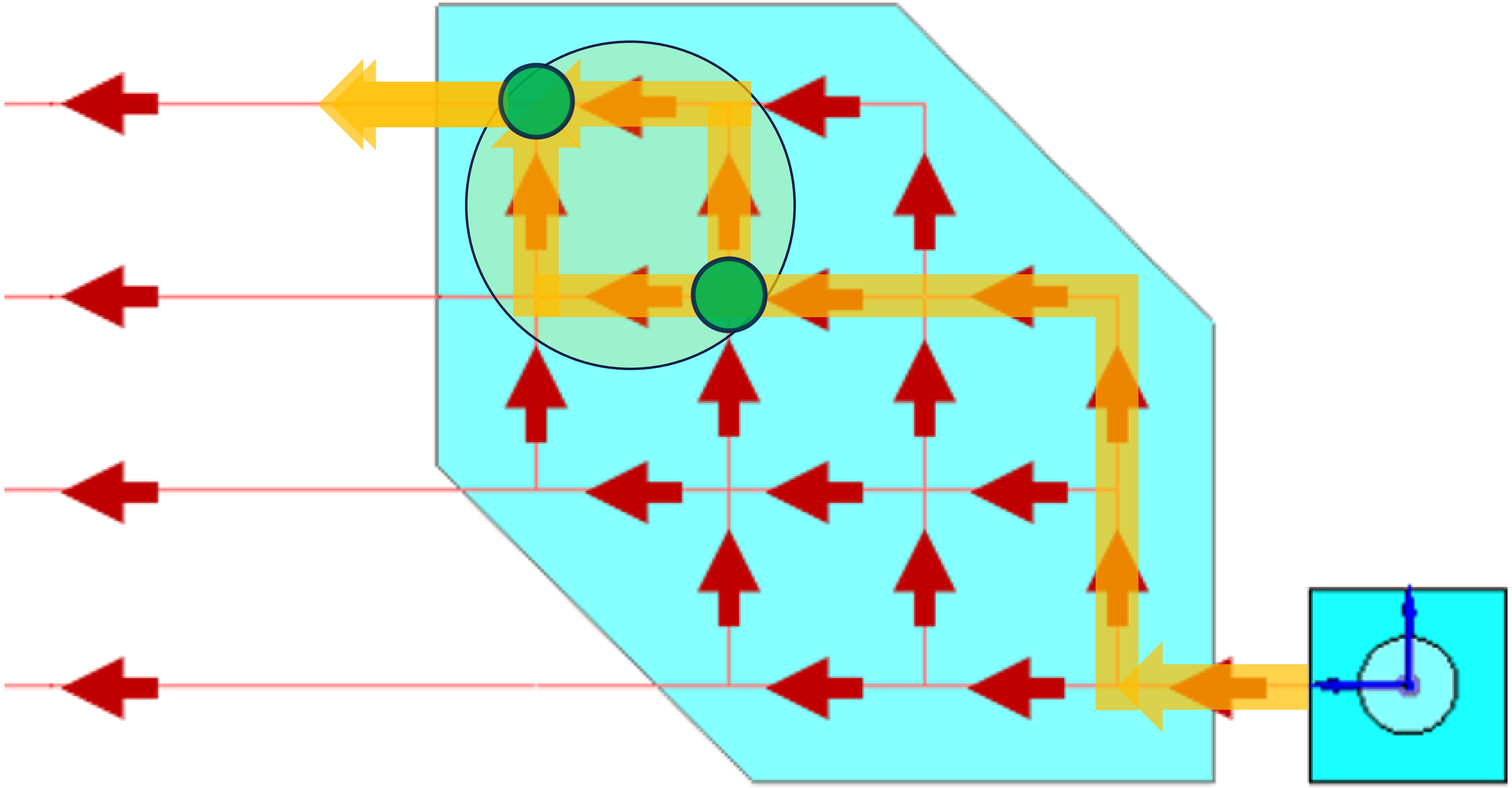
JOENSUU 2005

Levola Type Geometry of Eye Pupil Expansion (EPE)

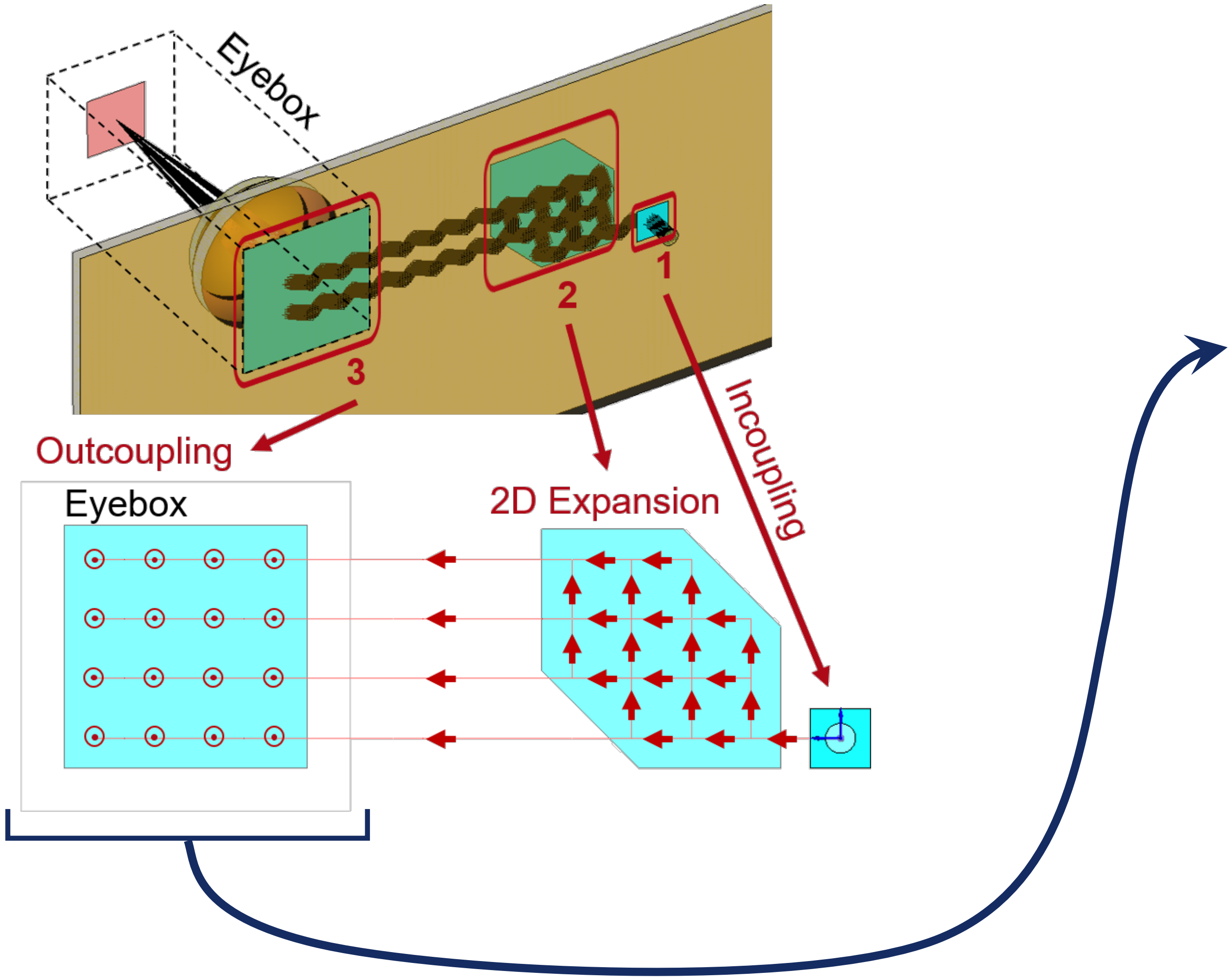


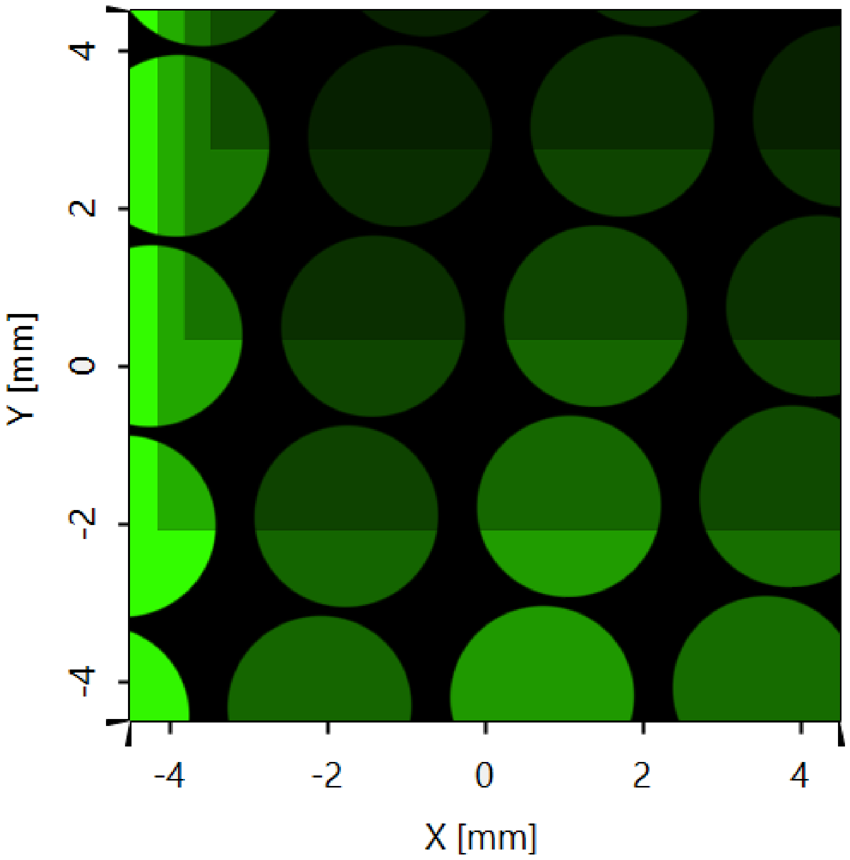


Demo of Mini Mach-Zehnder Inferferometer Lightpaths



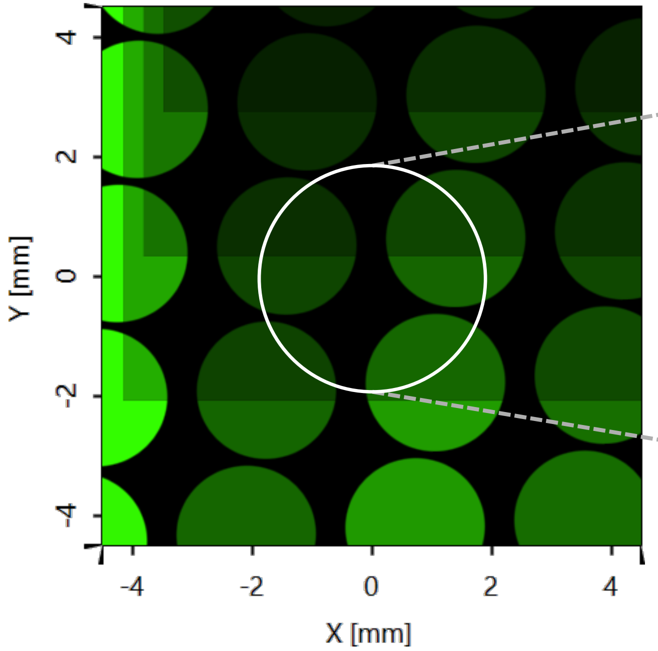
Lightguide Setup & Evaluation of Outcoupled Light





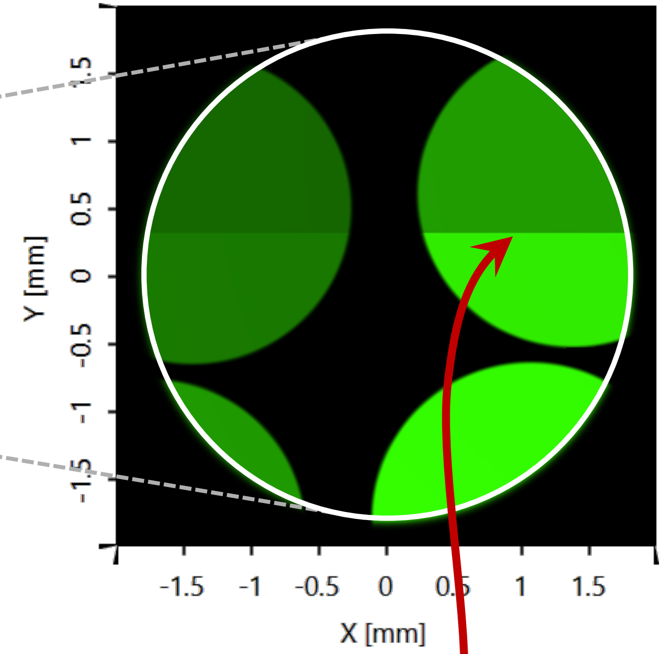
Exemplary
Outcoupled Light

Outcoupled Light Modes Passing Through Eye Pupil



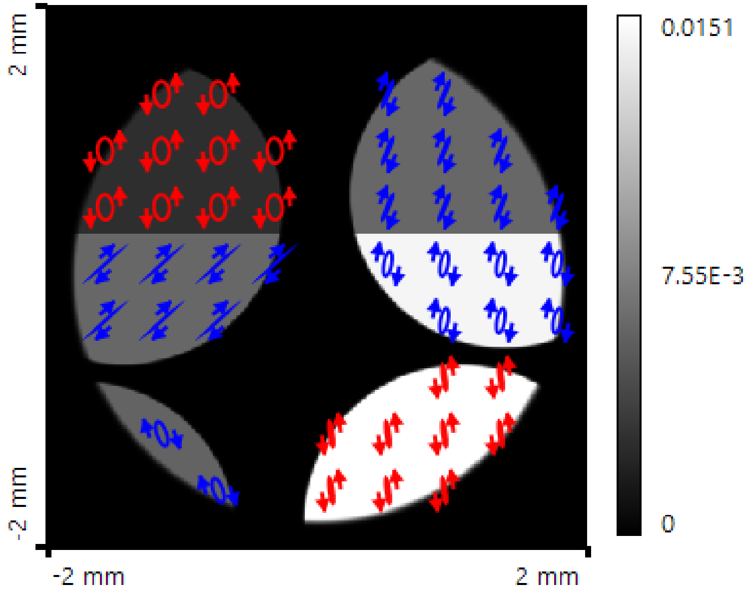
marginal area
of outcouling grating region

due to beams hitting the edge of any grating region, the further propagation varies for the different light portions; this causes these segmented beam footprints



light passing the eye pupil

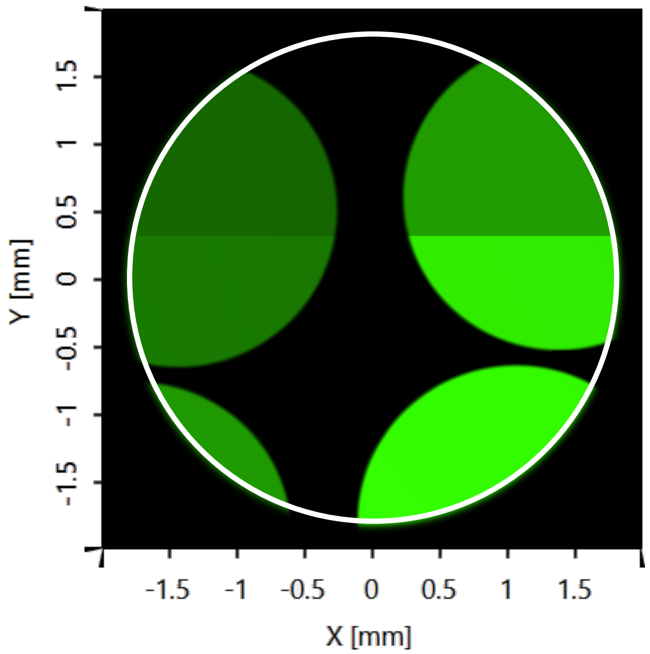
each of these beam footprints derives from multiple light modes from different light paths



locally varying polarizations

due to the different light paths whose beams have encountered different grating incidents

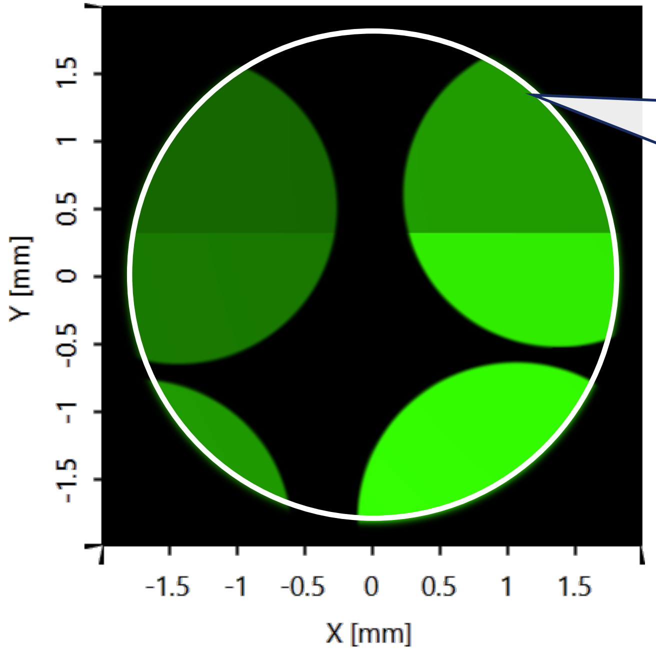
Outcoupled Light Modes Passing Through Eye Pupil



light passing the eye pupil

Eye pupil is (partly) filled with numerous modes with specific but varying mutual correlation

Outcoupled Light Modes Passing Through Eye Pupil

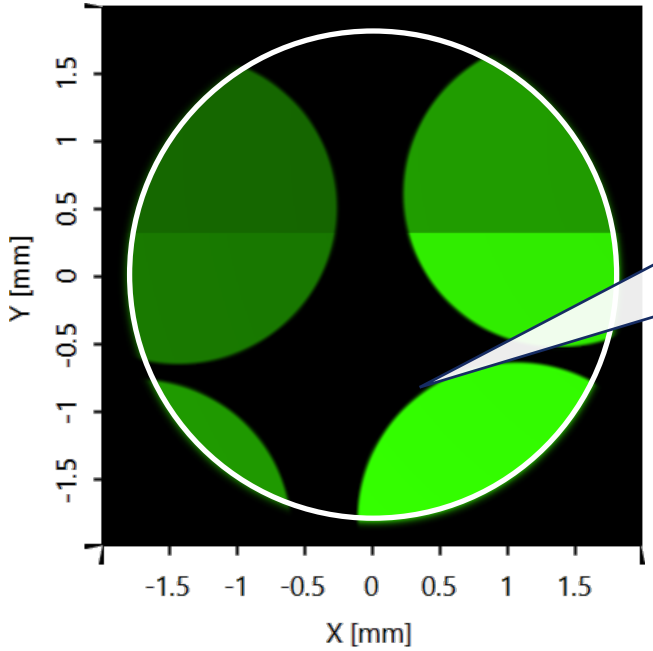


light passing the eye pupil

Boundary effects should be included in high resolution

Eye pupil is (partly) filled with numerous modes with specific but varying mutual correlation

Outcoupled Light Modes Passing Through Eye Pupil



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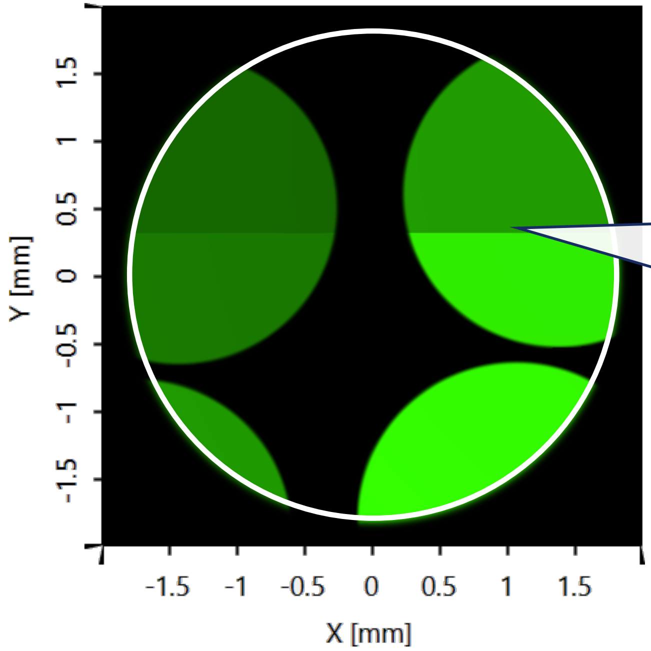
Outcoupled Light Modes Passing Through Eye Pupil

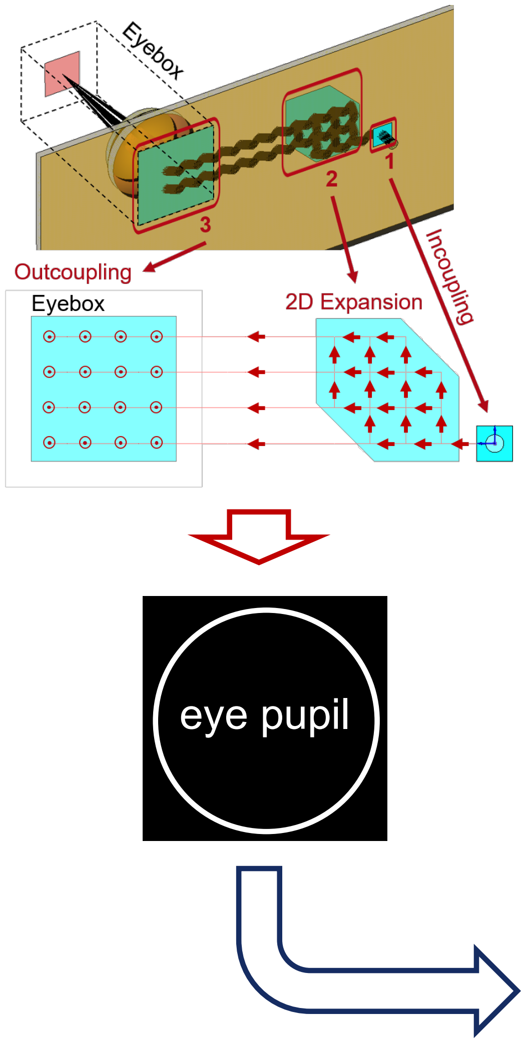


light passing the eye pupil

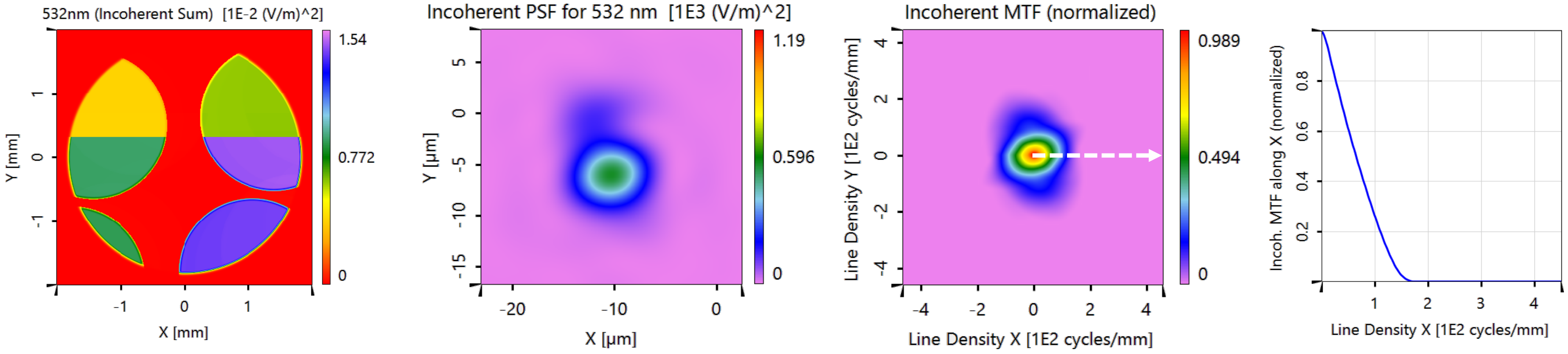
Boundary effects should be included in high resolution

Eye pupil is (partly) filled with numerous modes with specific but varying mutual correlation

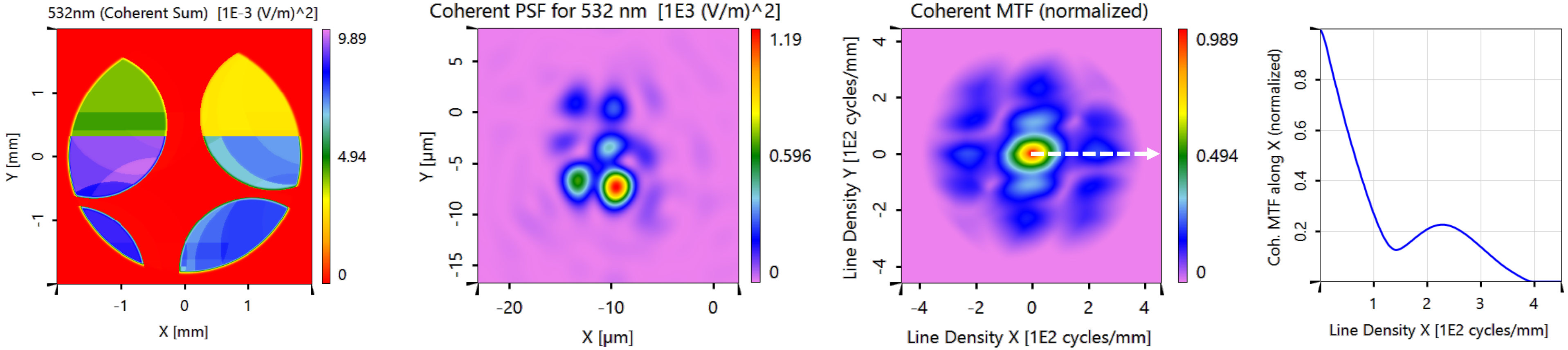
Coherent & Incoherent PSF & MTF Evaluation (Pupil to Retina)



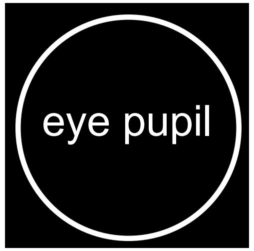
Incoherent Evaluation



Coherent Evaluation



Physical-Optics Modeling

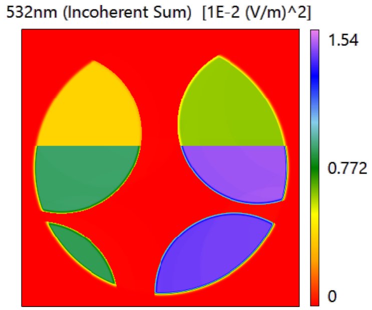


The light passing the eye pupil typically consists of
- differently truncated & polarized beams
- different wavelength & lateral light modes
    - coherent
    - incoherent
    - partially coherent

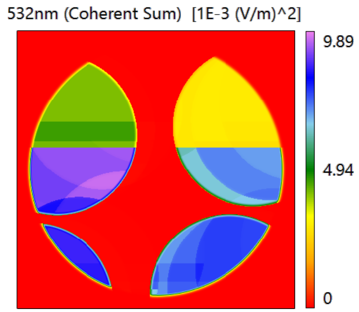
For the different numerical circumstances, VirtualLab provides **approximated and rigorous bandwidth modeling techniques!**

→ **Thus, this light could also look like the following ...**

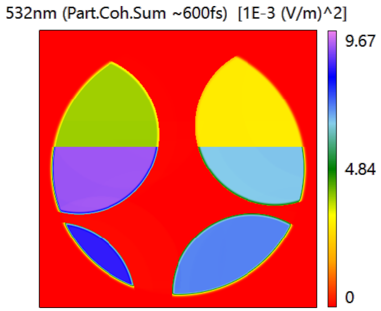
with different evaluation modes



incoherent



coherent



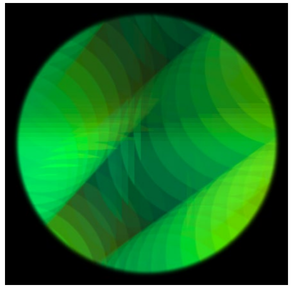
partially coherent
(bandwidth 1 nm)

with typical source bandwidths ...

...of a
laser diode (~1 nm)

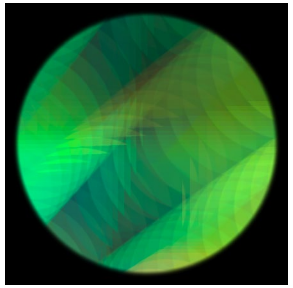
24 wavelength samples

...of a
VCSEL (~20 nm)



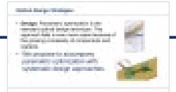
24 wavelength samples

...of an
LED (~40 nm)



48 wavelength samples

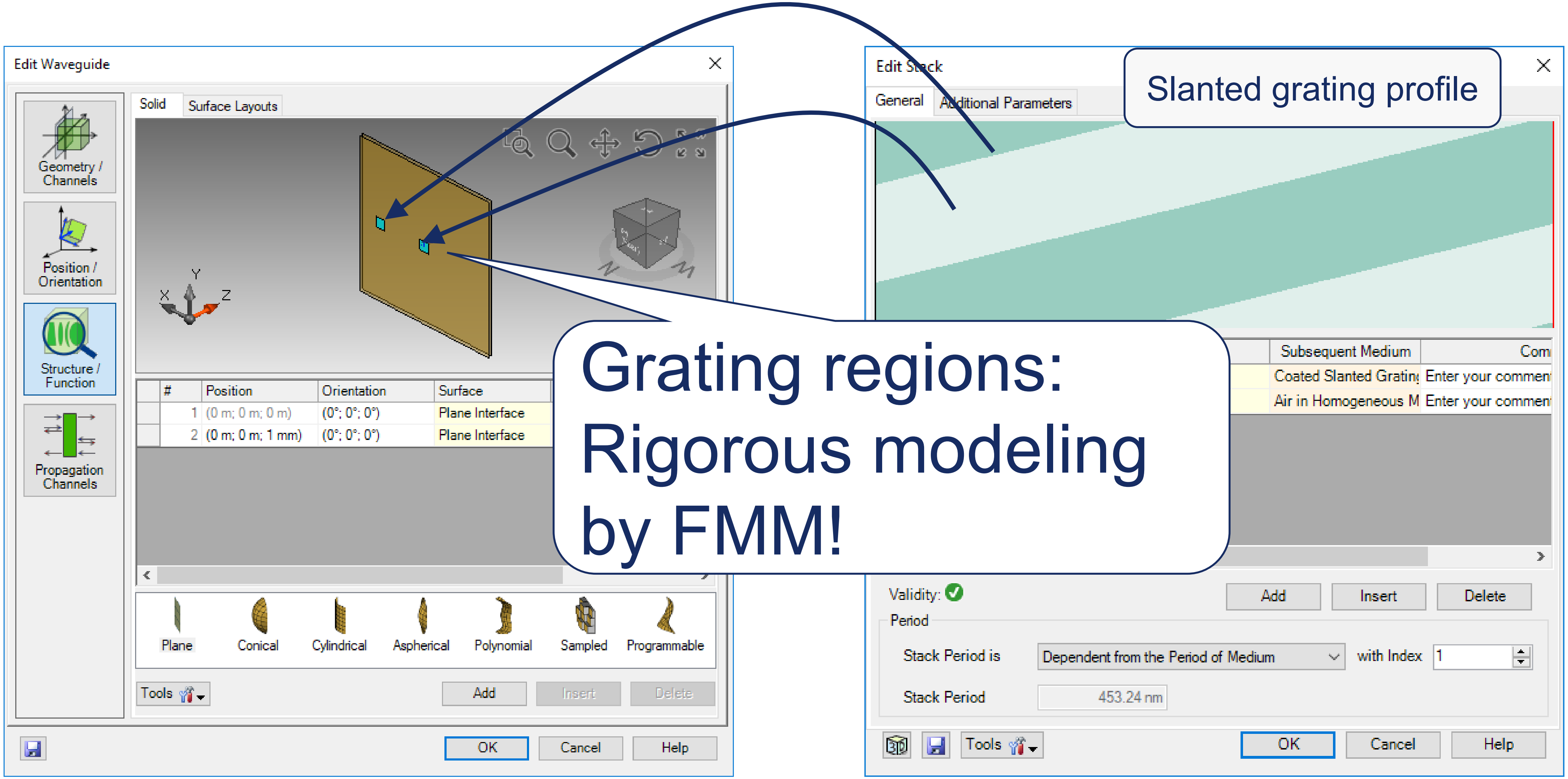
the beam's diffraction angles strongly depend on the wavelengths



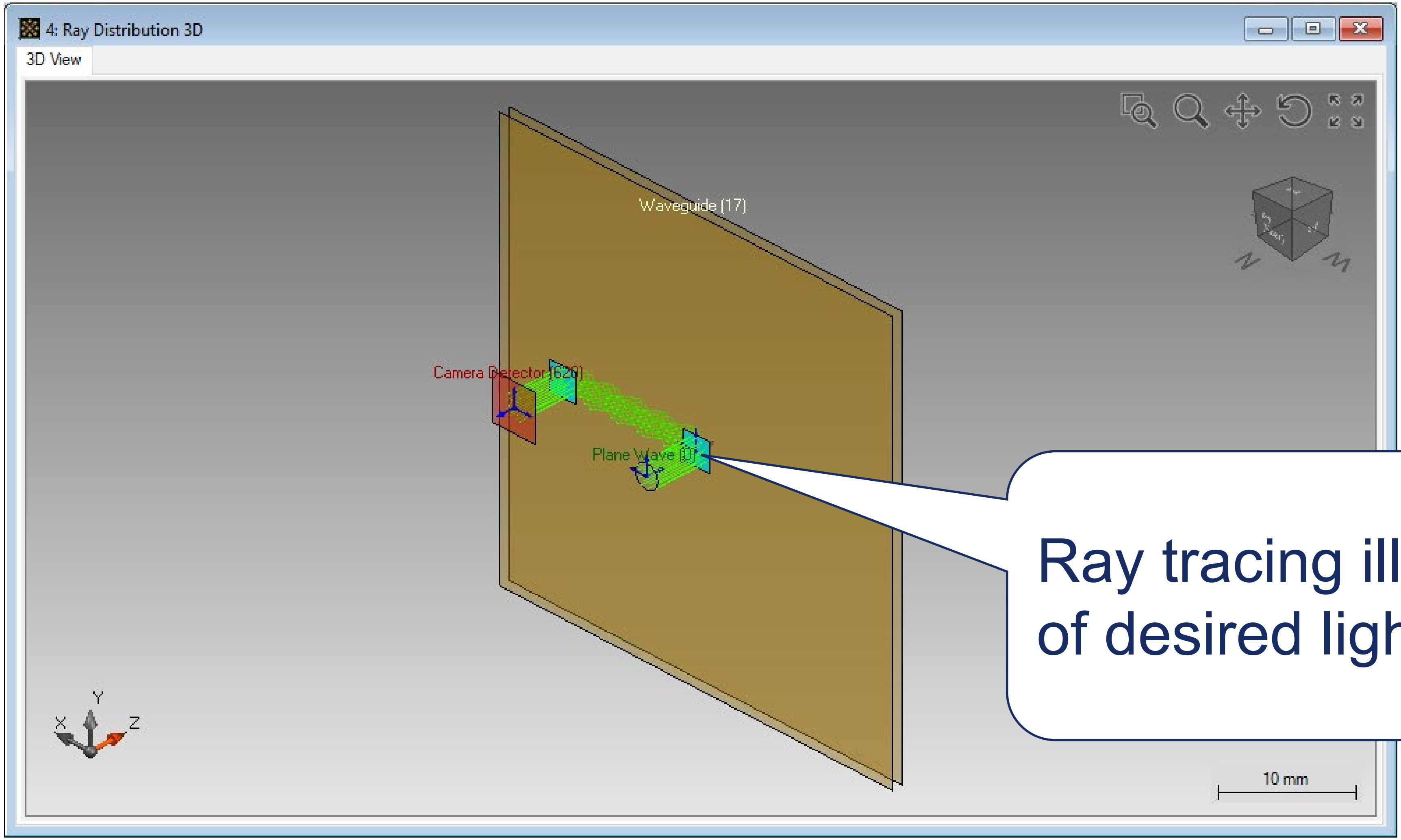
Energy conservation

Ultimate test: Evaluation of overall flux through all surfaces of waveguide must provide efficiency close to 100%

Modeling Task: In- and Outcoupling

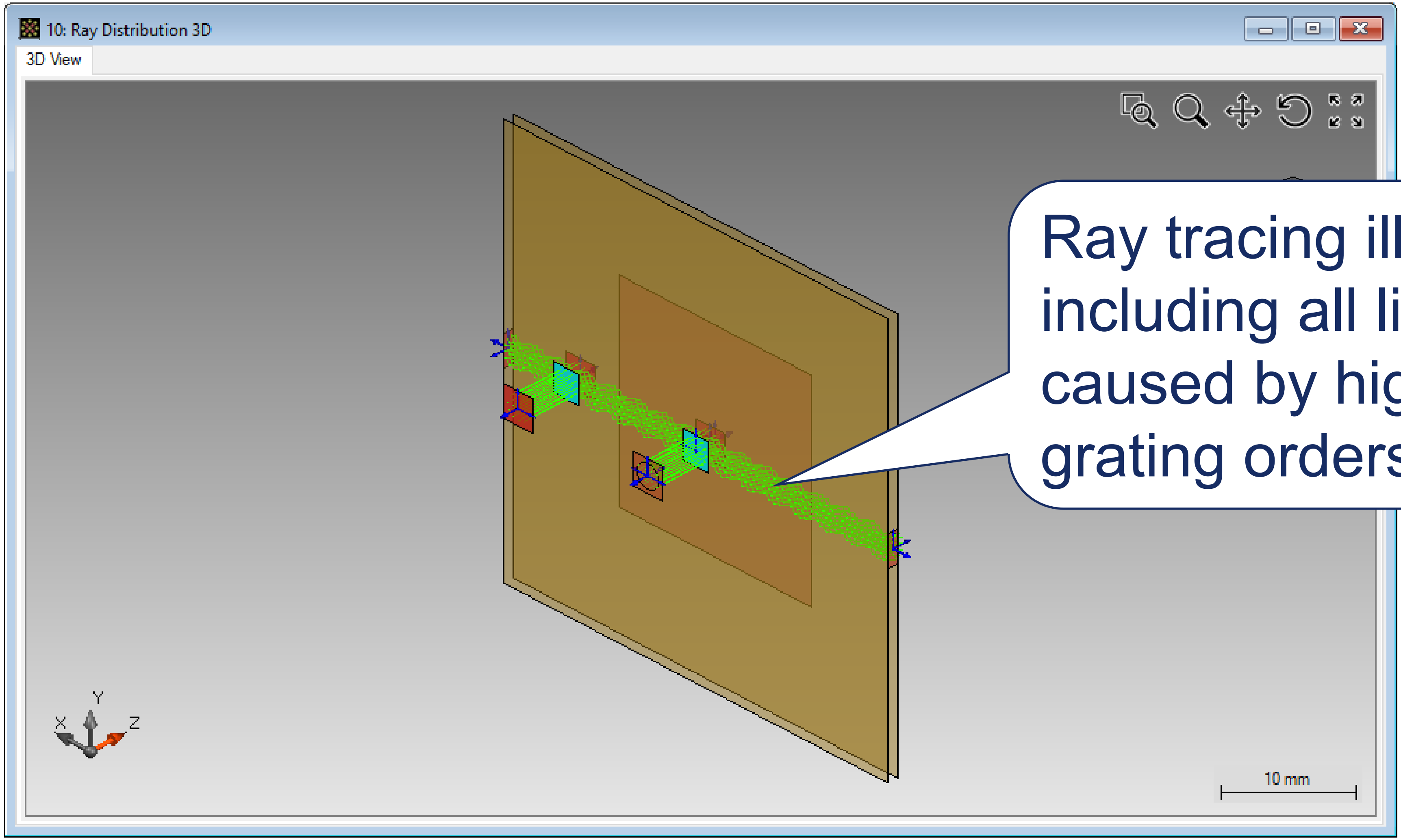


Result by 3D Ray Tracing (Working Orders)



Ray tracing illustration of desired lightpath.

Result by 3D Ray Tracing (All Orders)



Ray tracing illustration including all lightpaths caused by higher grating orders.

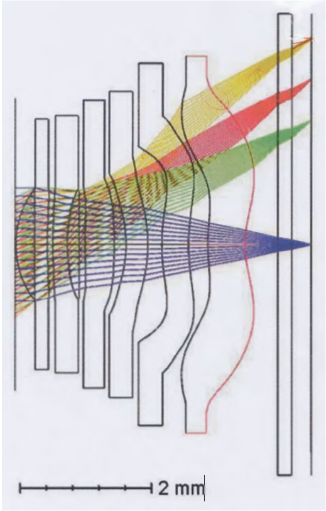
Rigorous Overall Efficiency Evaluation

- Physical-optics analysis of all lightpaths.
- Combination including polarization and coherence!

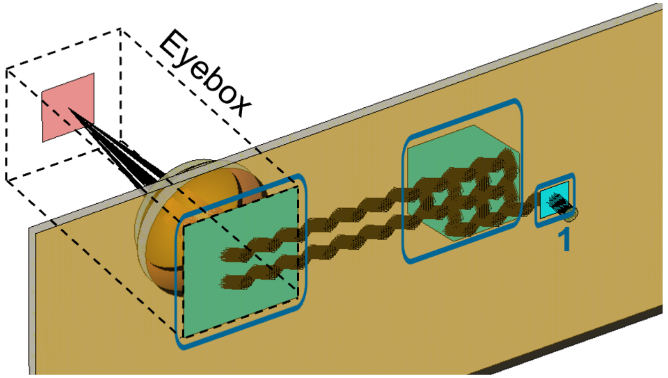
Detector	Calculated Efficiency
Transmission @ Incoupling	0.416%
Reflection @ Incoupling	11.997%
Side Wall #1	1.194%
Side Wall #2	6.778%
Reflection @ Outcoupling	77.983%
Transmission @ Outcoupling	1.546%
Total	**99.915%**

Optical Design Strategies

- **Design:** Parametric optimization is the standard optical design technique. This approach fails in ever more cases because of the growing complexity of components and systems.



- We propose to accompany parametric optimization with systematic design approaches.



Parametric Optimization and Systematic Design

Parametric optimization

How to find a good initial system for final parametric optimization?

Parametric Optimization and Systematic Design

Functional design

Where and what should be done with incident light to obtain a desired function?

Parametric optimization

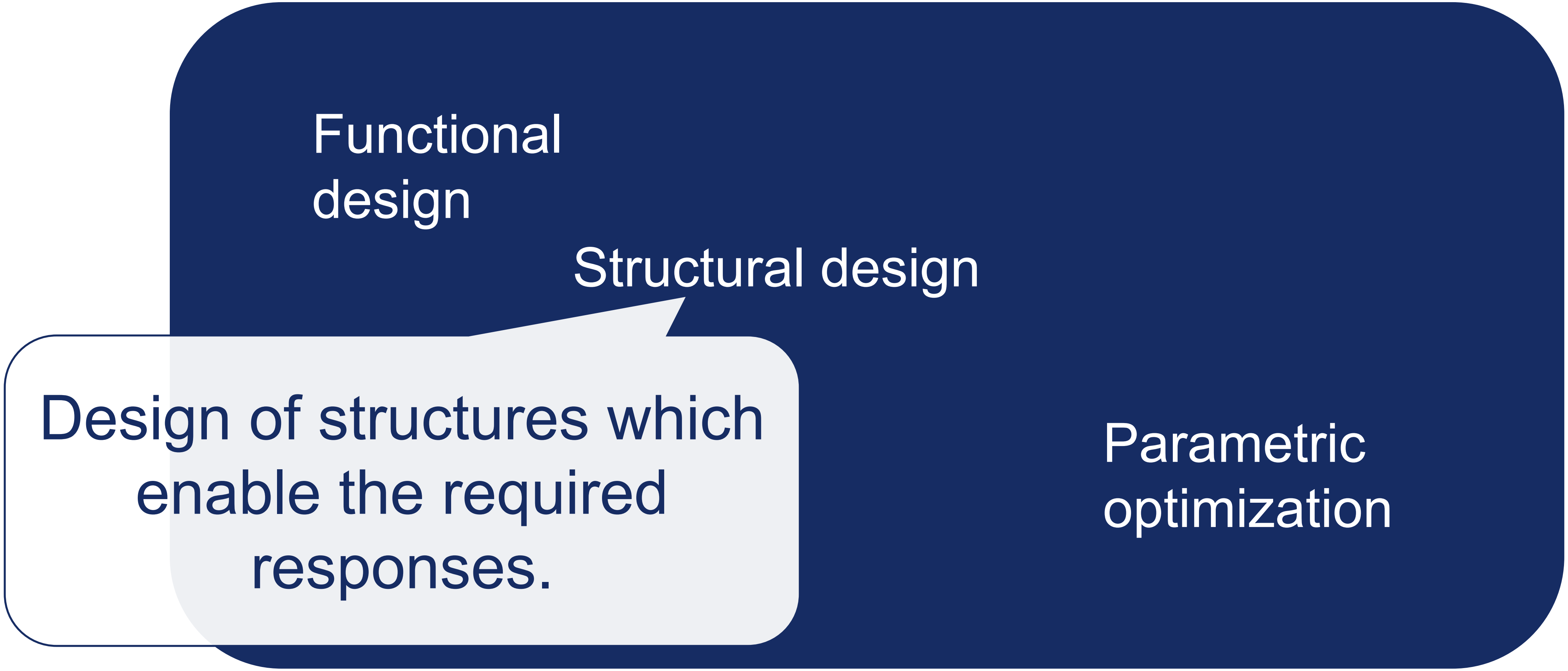
Parametric Optimization and Systematic Design

Functional design

Result: Set of positions and ideal responses of optical components.

Parametric optimization

Parametric Optimization and Systematic Design



Parametric Optimization and Systematic Design

Functional design

In suitable combination

Structural design

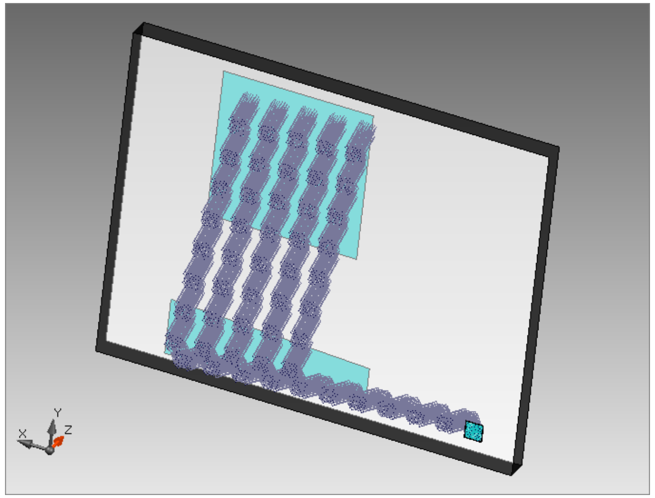
- Diffractive surfaces
- Metalayers
- Volume holograms

Parametric optimization

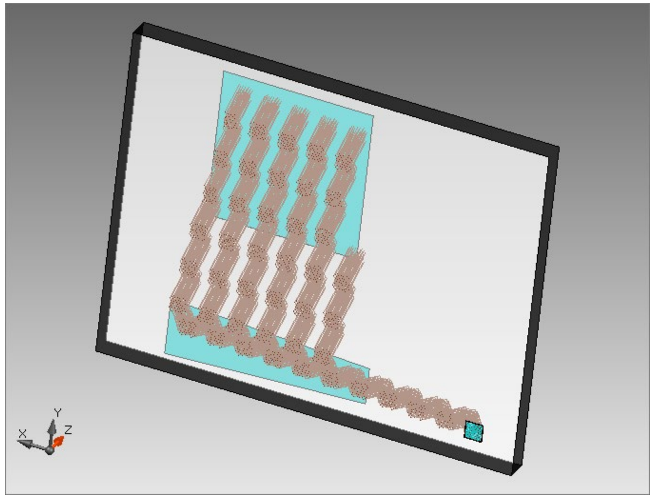
Per FOV mode and in combination of all source modes!

Systematic Waveguide Design Example

Ray Tracing Illustration of Typical Paths Through Lightguide



α= -10°;
β= -3.5°



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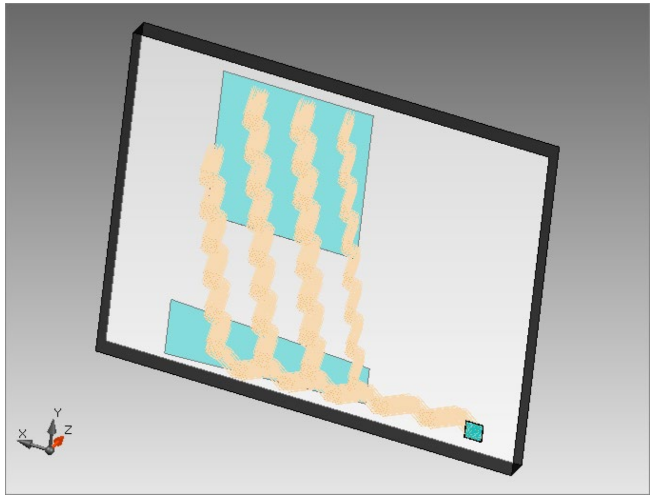

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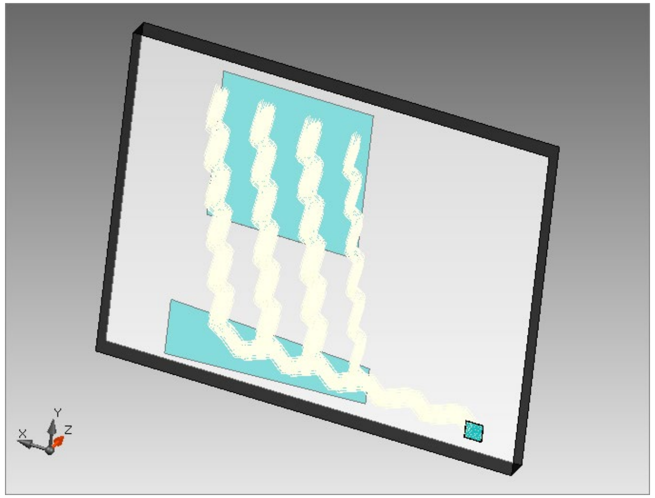

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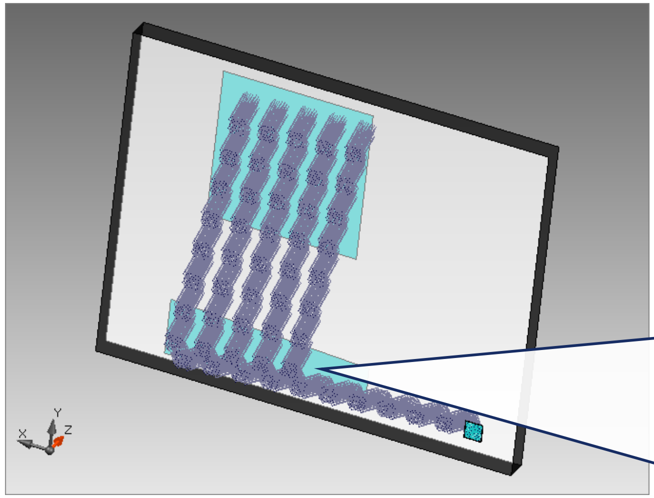
Ray Tracing Illustration of Typical Paths Through Lightguide



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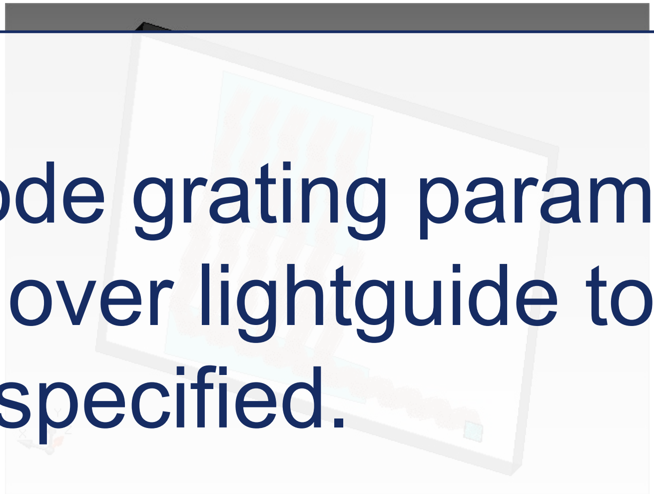
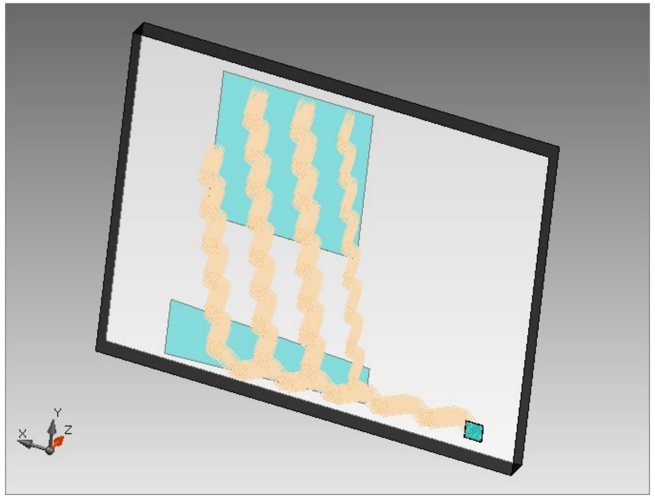


α= -10°;
β= 3.5°

Per FOV mode grating parameter modulation over lightguide to be specified.



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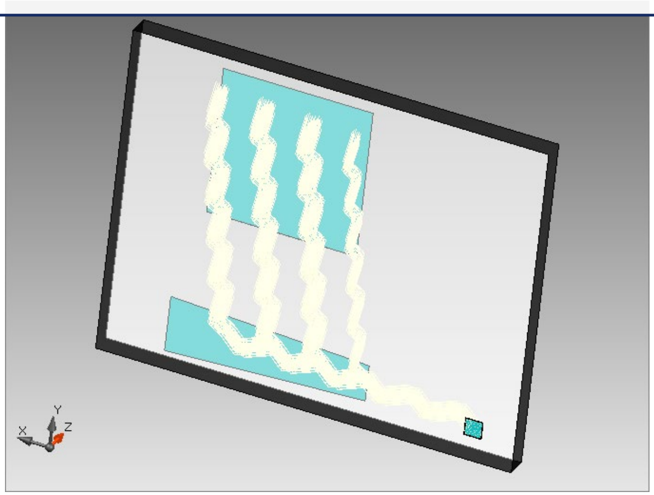

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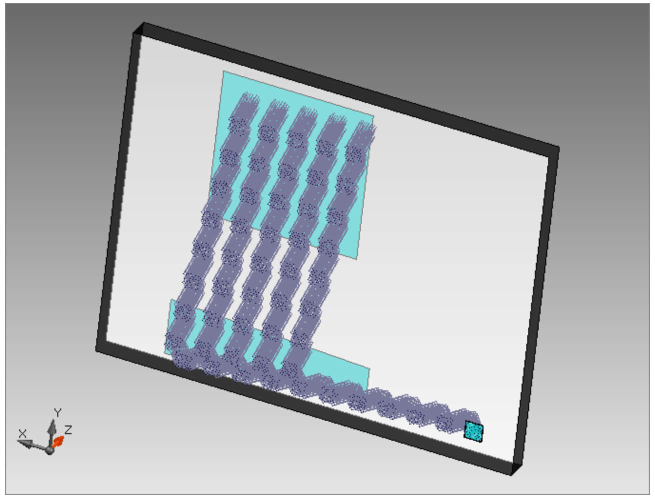
Ray Tracing Illustration of Typical Paths Through Lightguide



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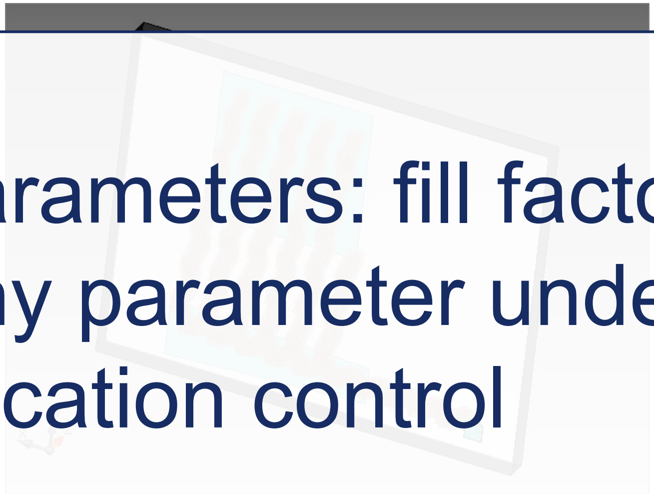
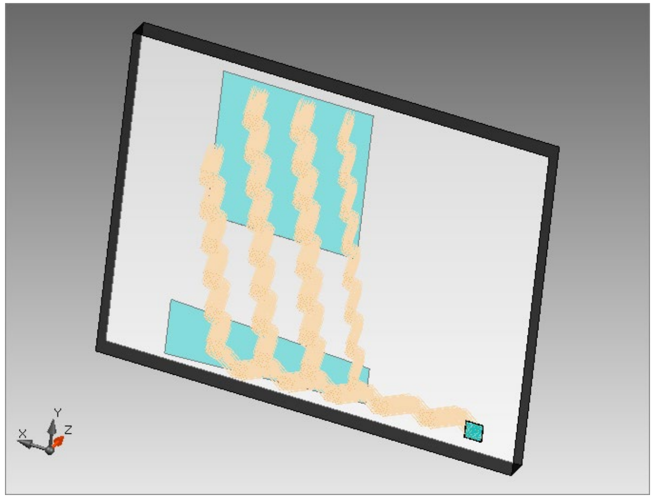
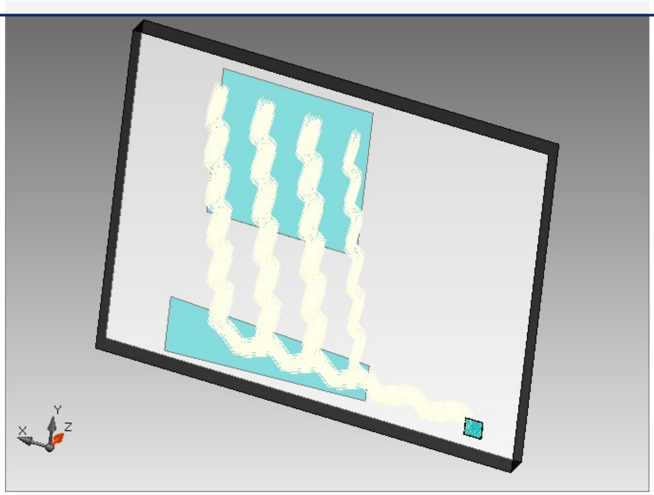


α= -10°;
β= 3.5°

Grating parameters: fill factor, height, any parameter under fabrication control

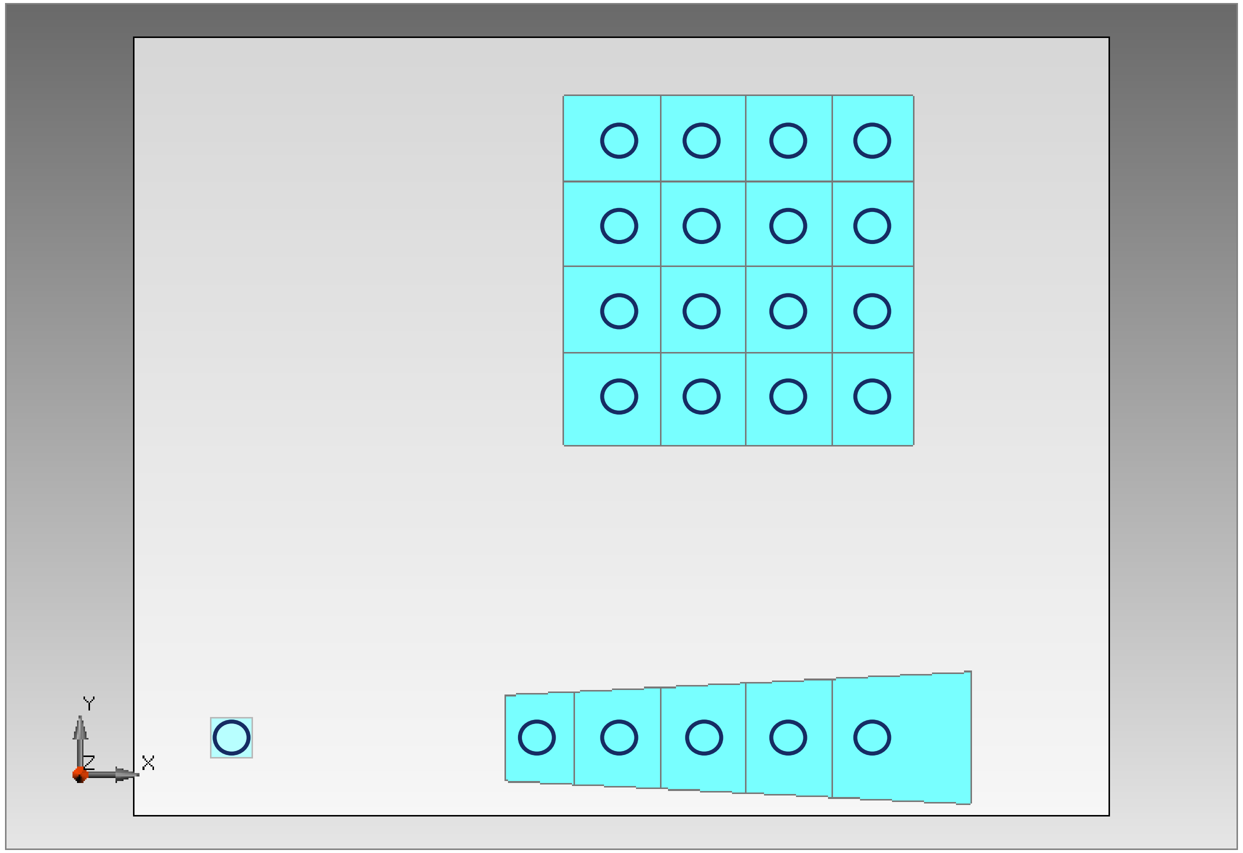


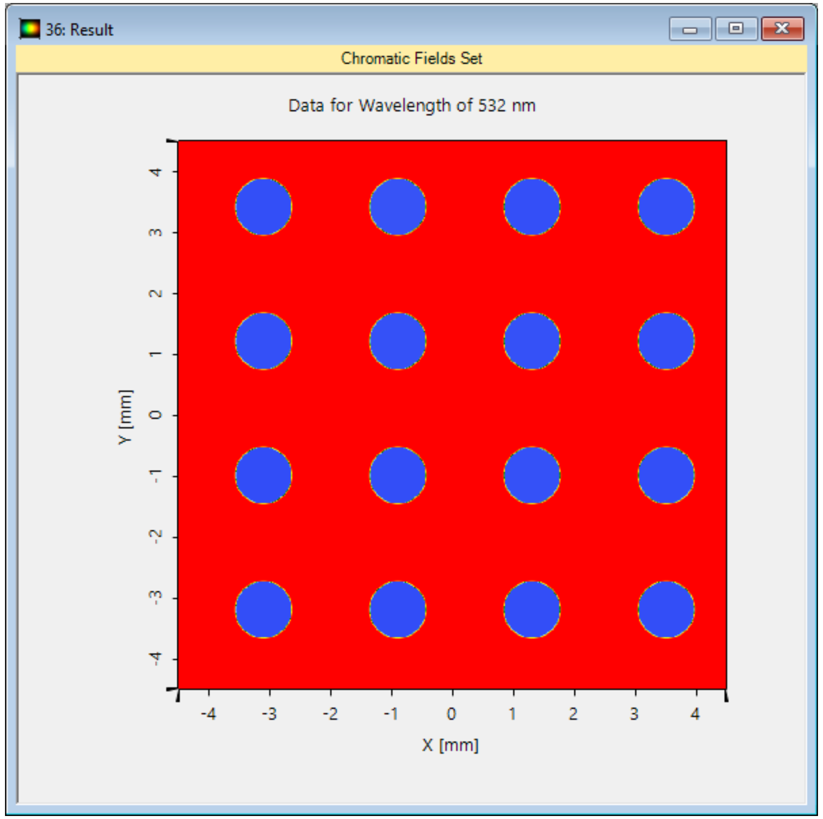
α= 10°;
β= -3.5°



α= 10°;
β= 3.5°

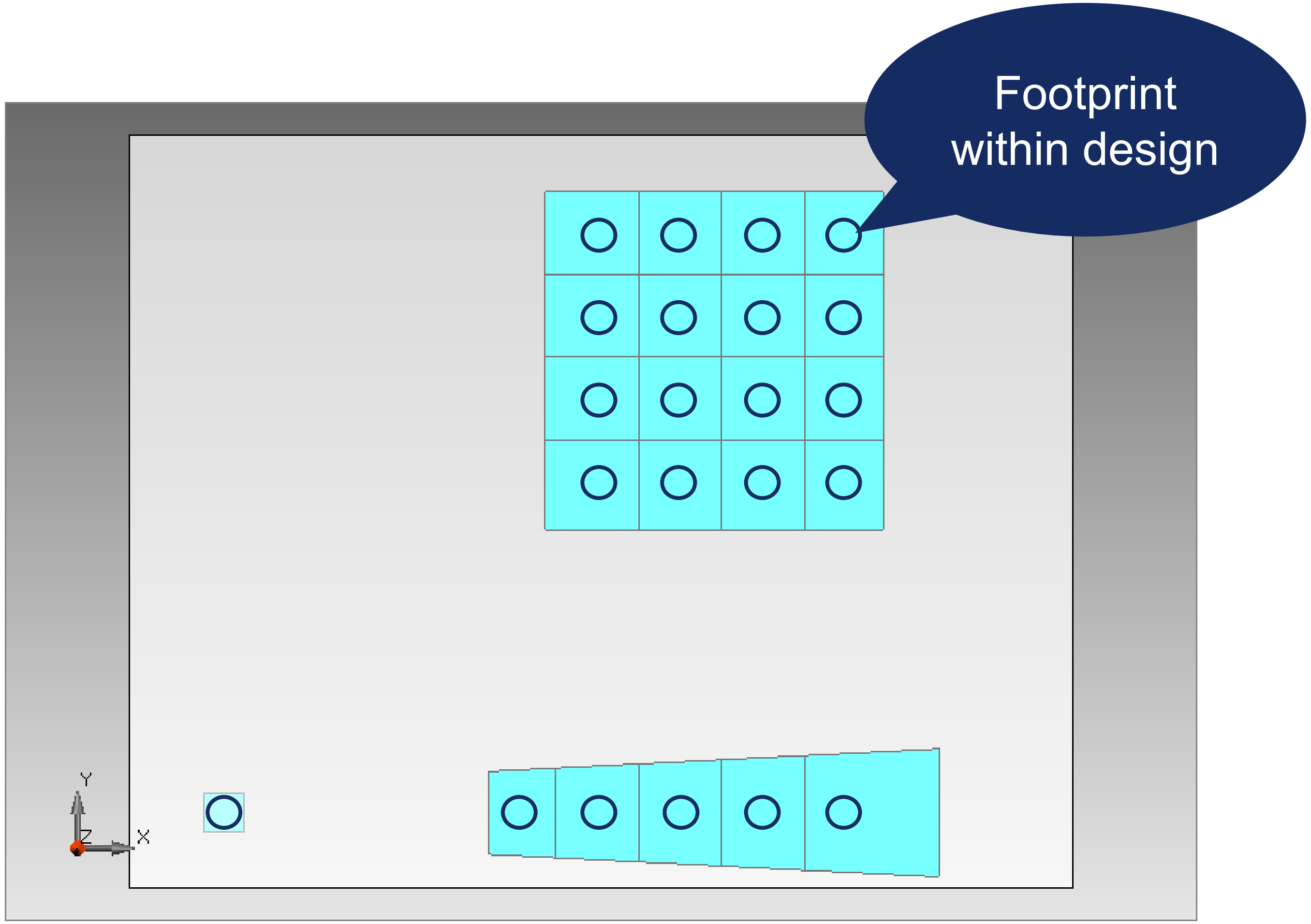
Grating Design for FOV Angle (0°, 0°)

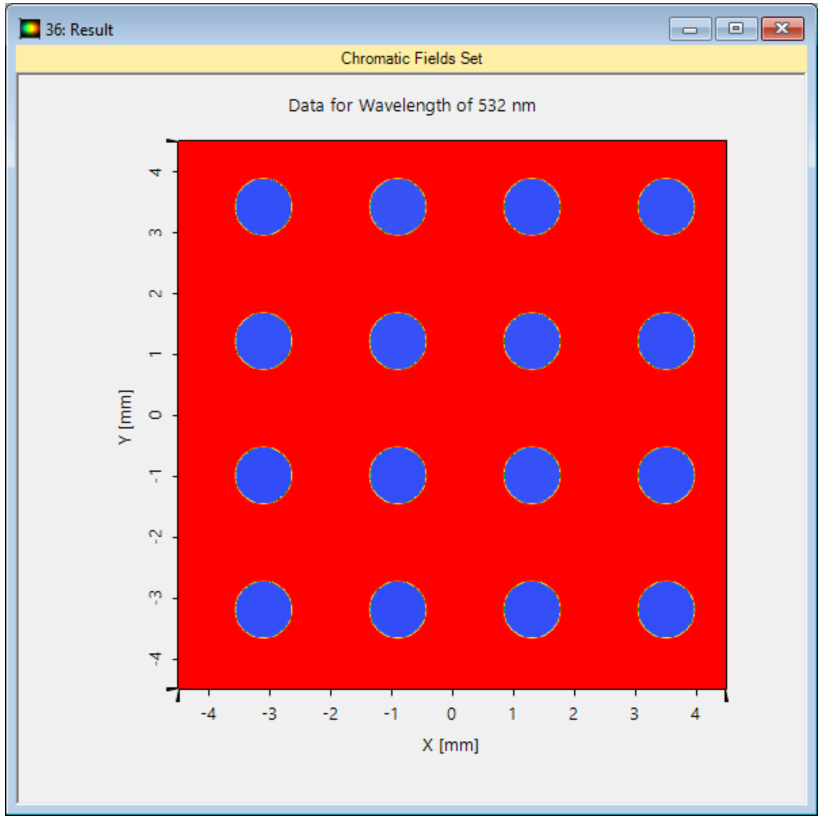




Merit Function	Value
FOV Angle	$\alpha = 0° \,;\, \beta = 0°$
Uniformity Error	**0.34%**

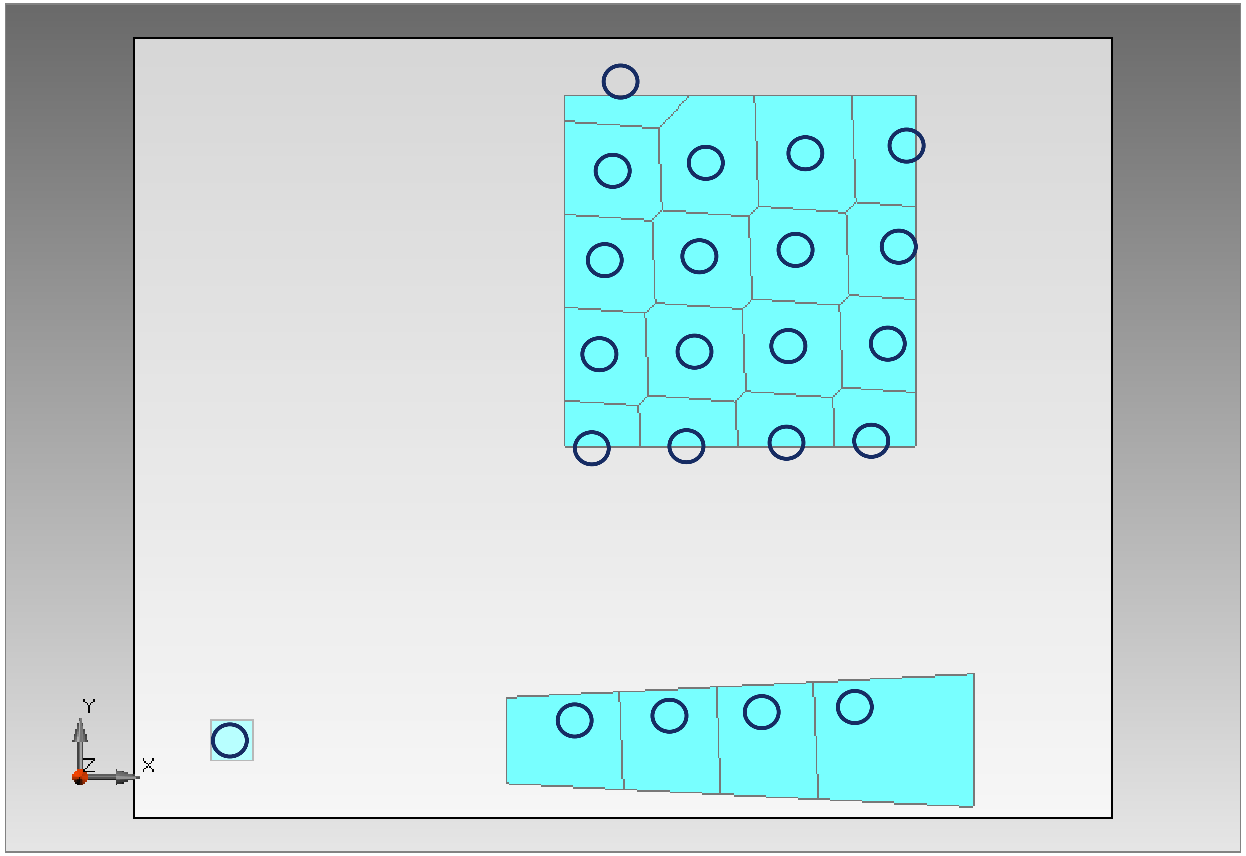
Grating Design for FOV Angle (0°, 0°)

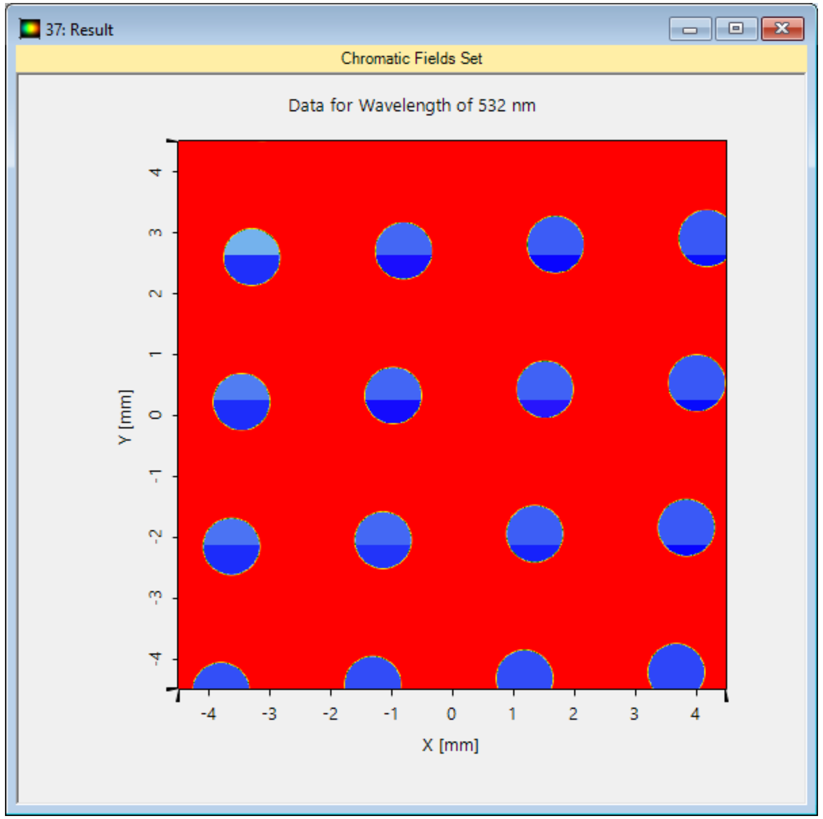




Merit Function	Value
FOV Angle	$\alpha = 0° ; \beta = 0°$
Uniformity Error	**0.34%**

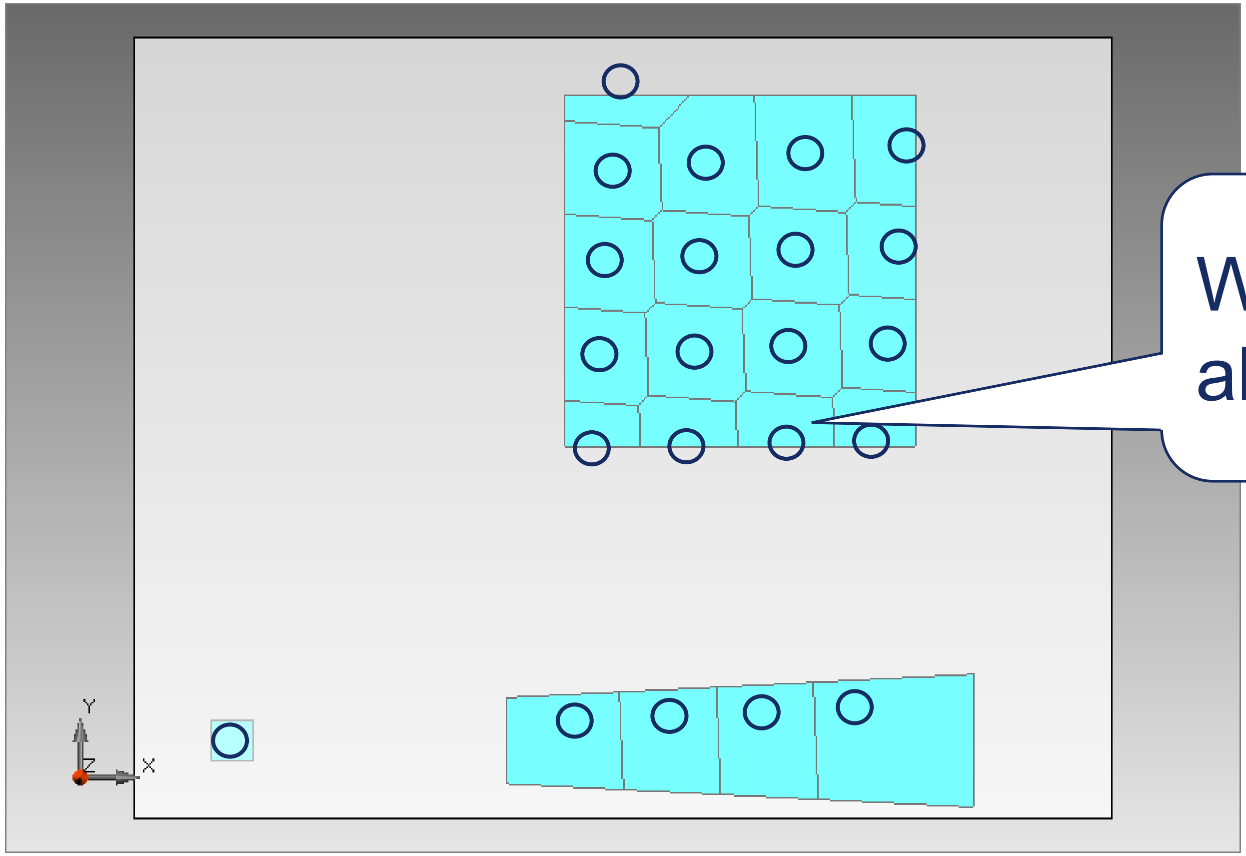
Grating Design for FOV Angle (5°, 3°)

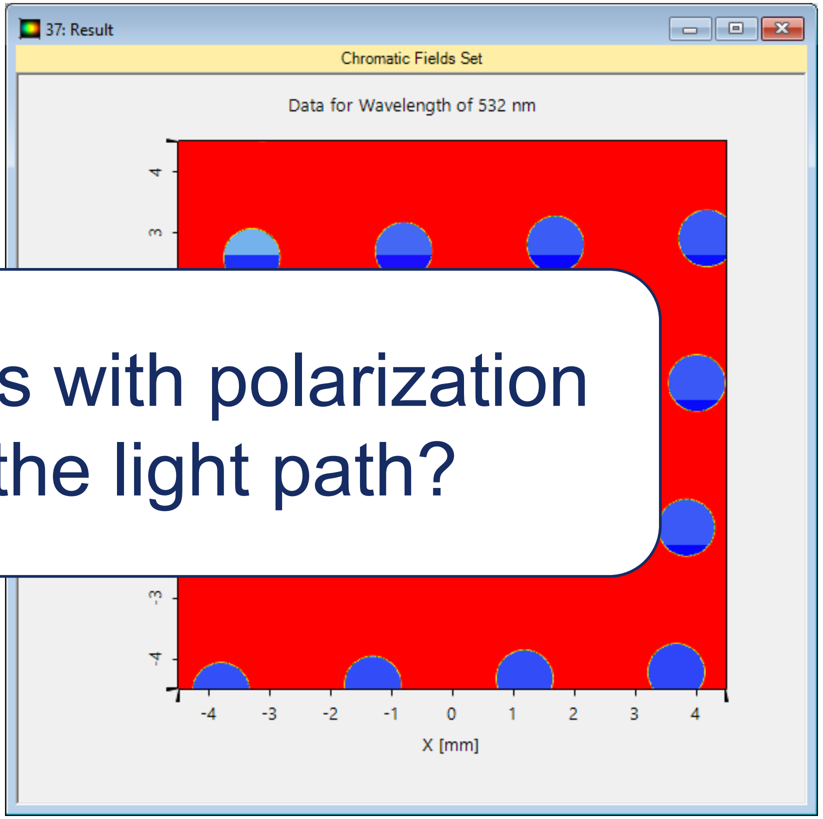




Merit Function	Value
FOV Angle	$\alpha = 5°; \beta = 3°$
Uniformity Error	**2.76%**

Grating Design for FOV Angle (5°, 3°)

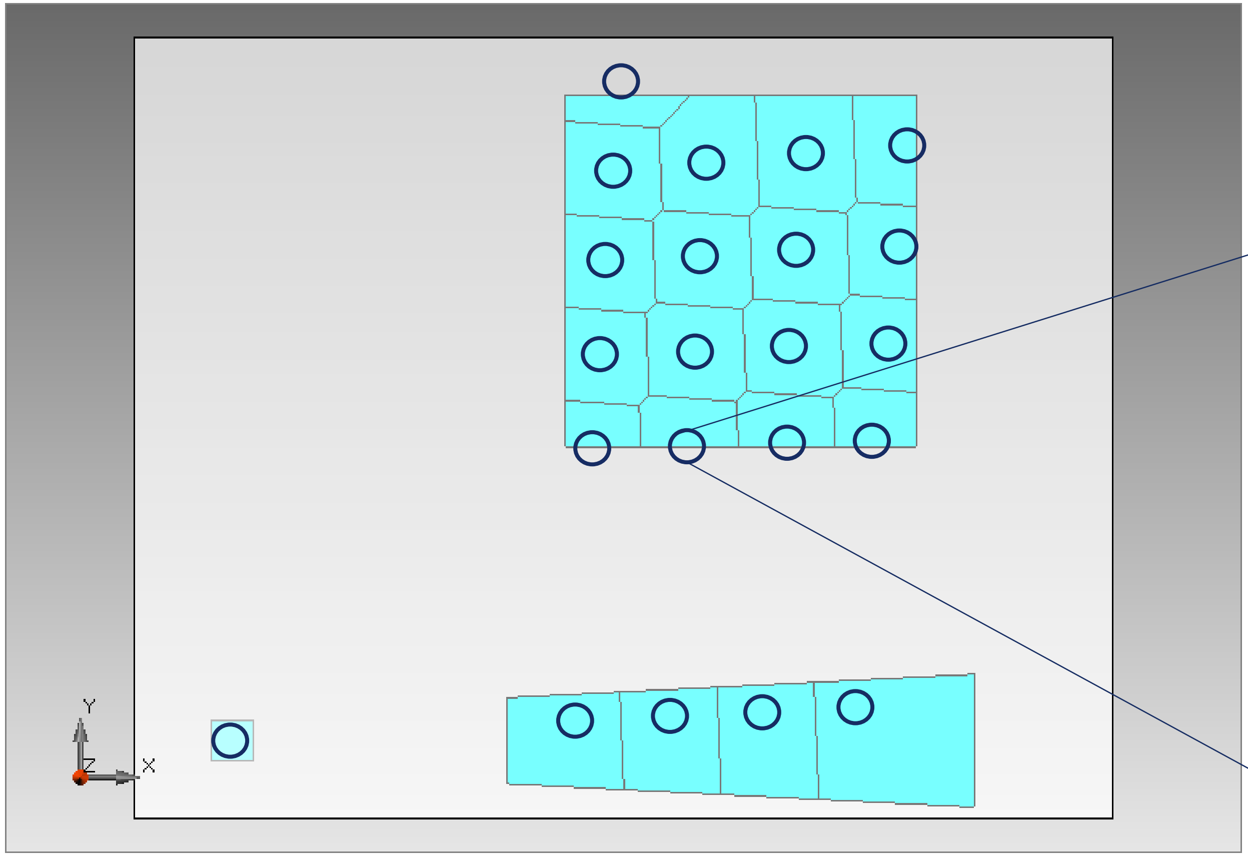




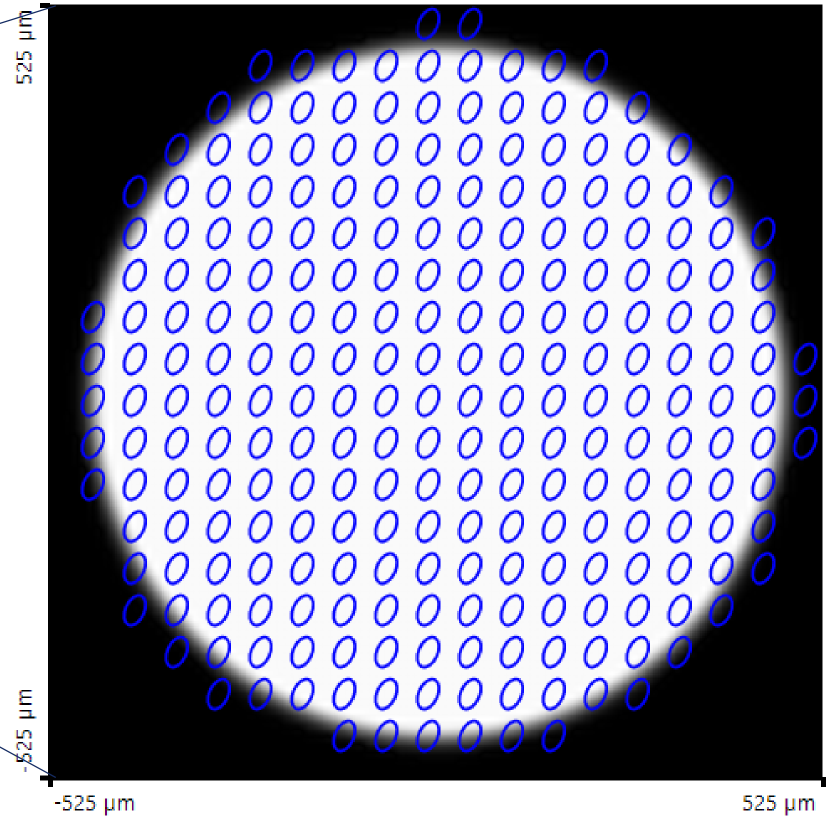
What is with polarization along the light path?

Merit Function	Value
FOV Angle	$\alpha = 5°; \beta = 3°$
Uniformity Error	**2.76%**

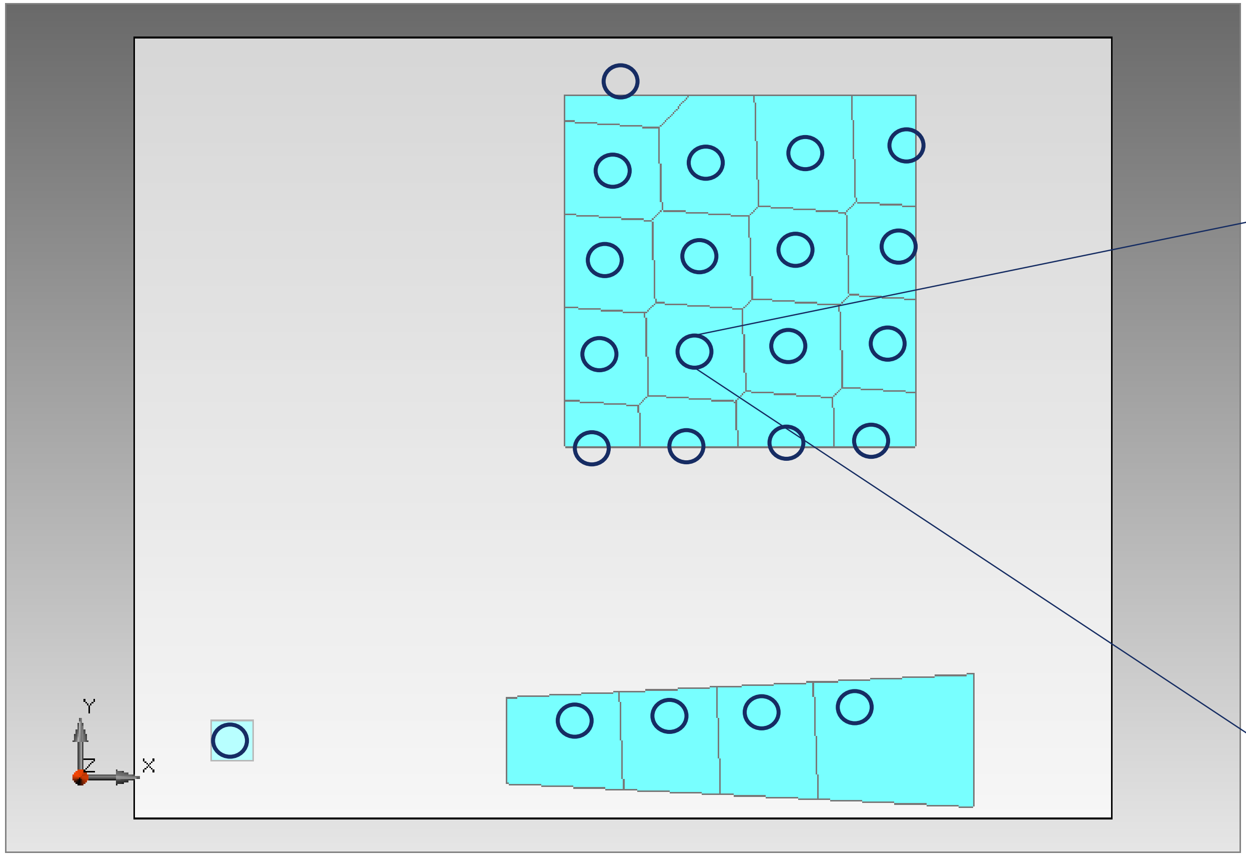
Grating Design for FOV Angle (5°, 3°) – Polarization Evaluation



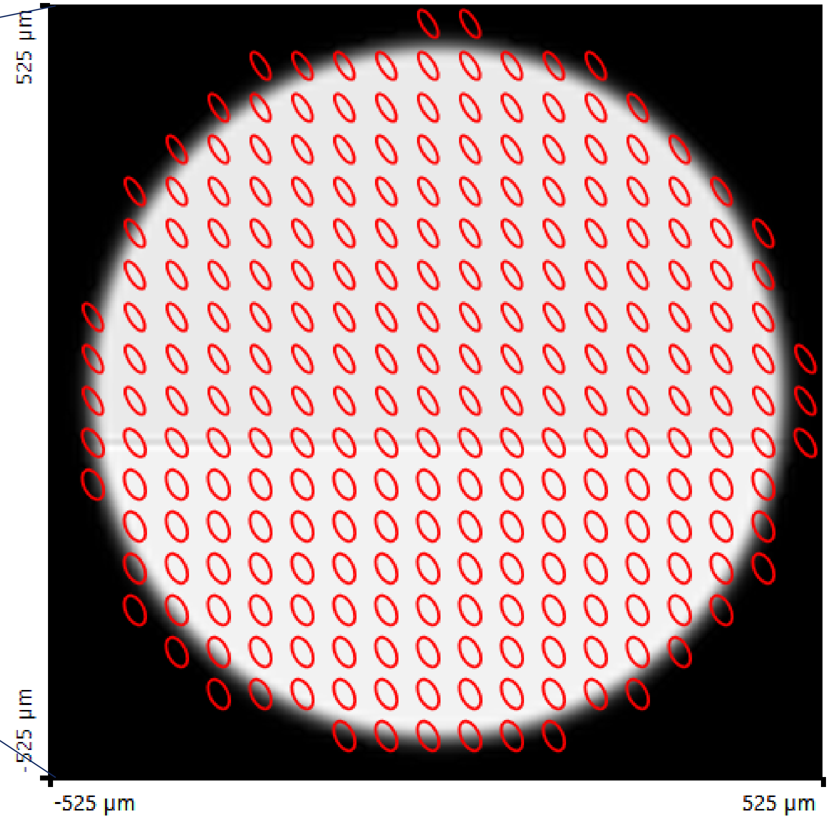
Incident light at grating interaction (globally polarized)



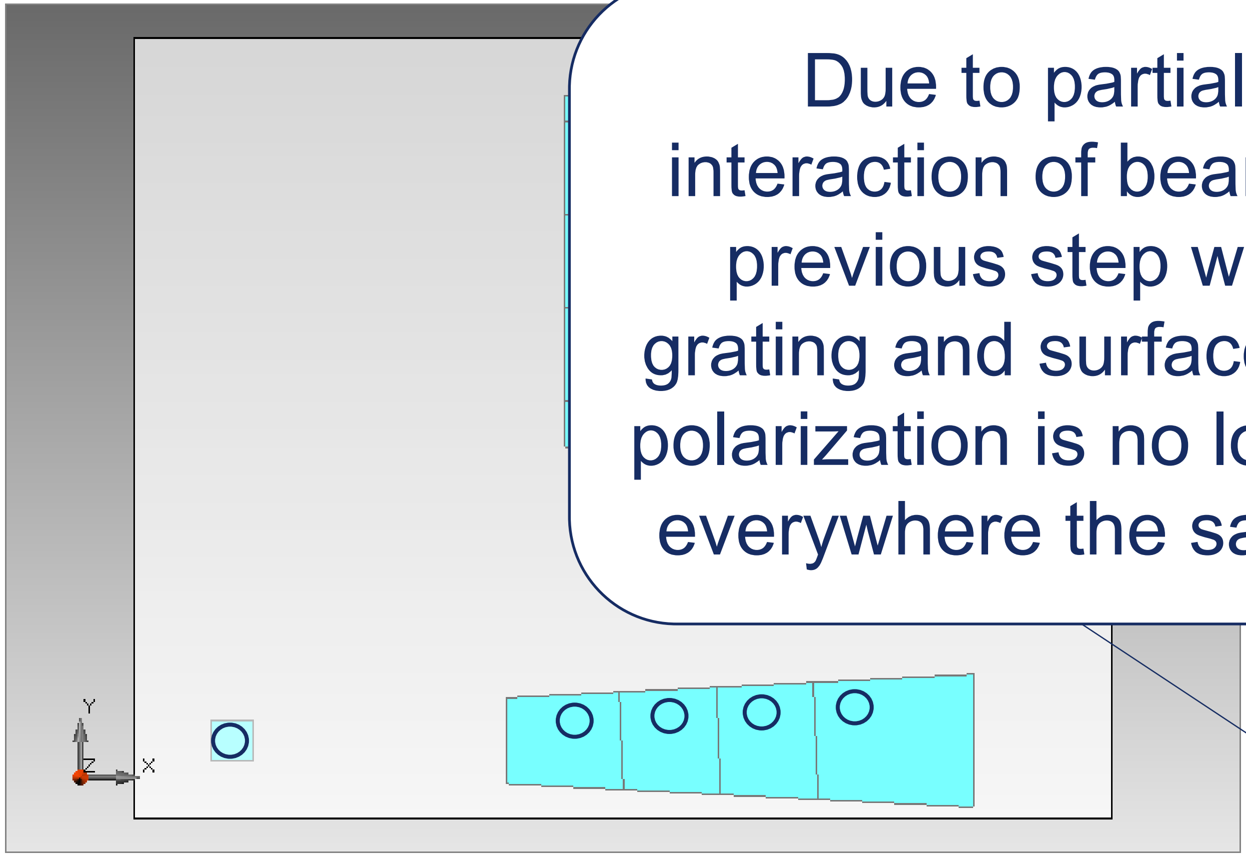
Grating Design for FOV Angle (5°, 3°) – Polarization Evaluation



Incident light at grating interaction (<u>locally</u> polarized)

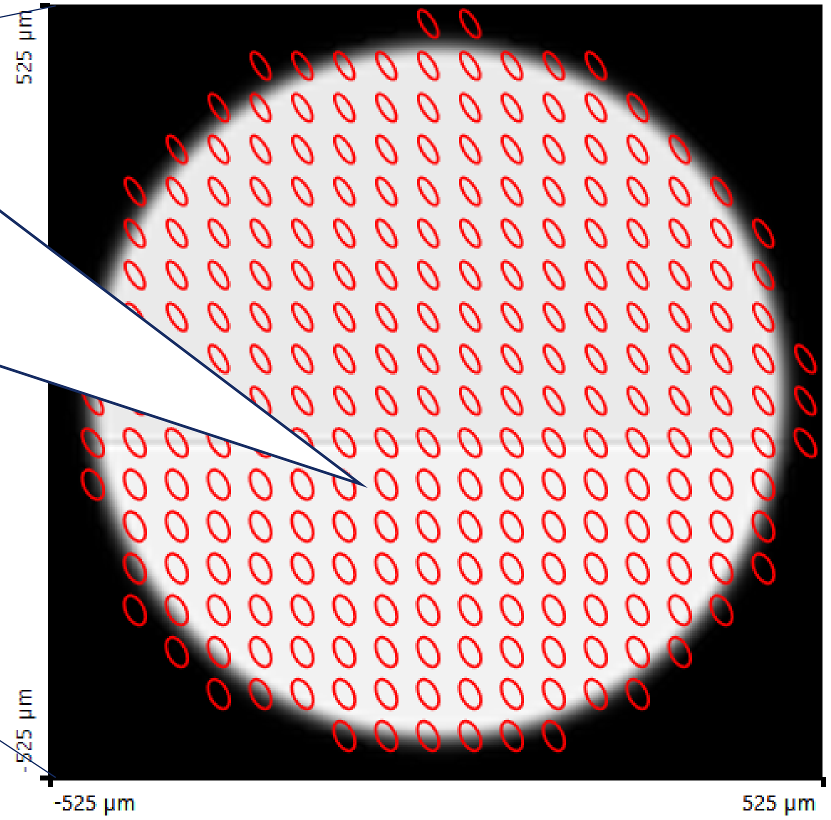


Grating Design for FOV Angle (5°, 3°) – Polarization Evaluation

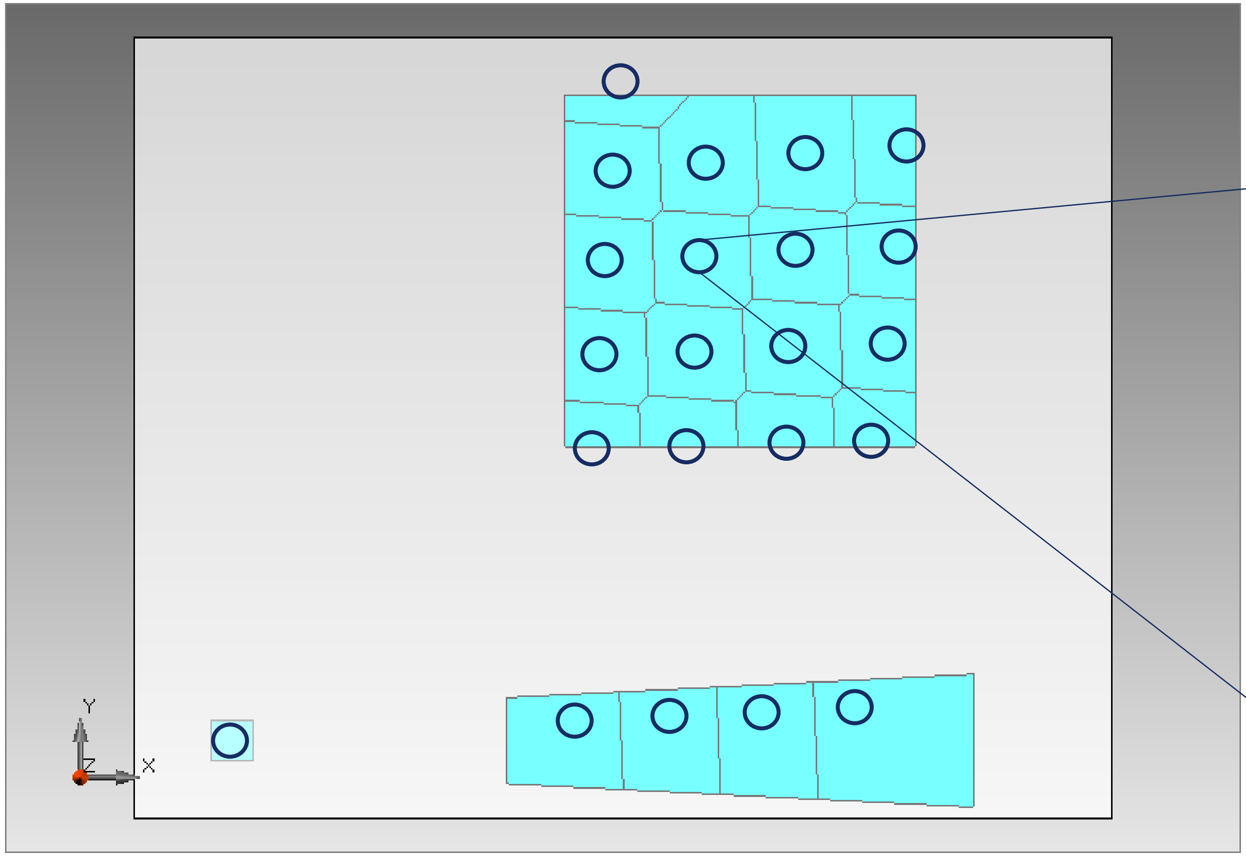


Due to partial interaction of beam in previous step with grating and surface the polarization is no longer everywhere the same.

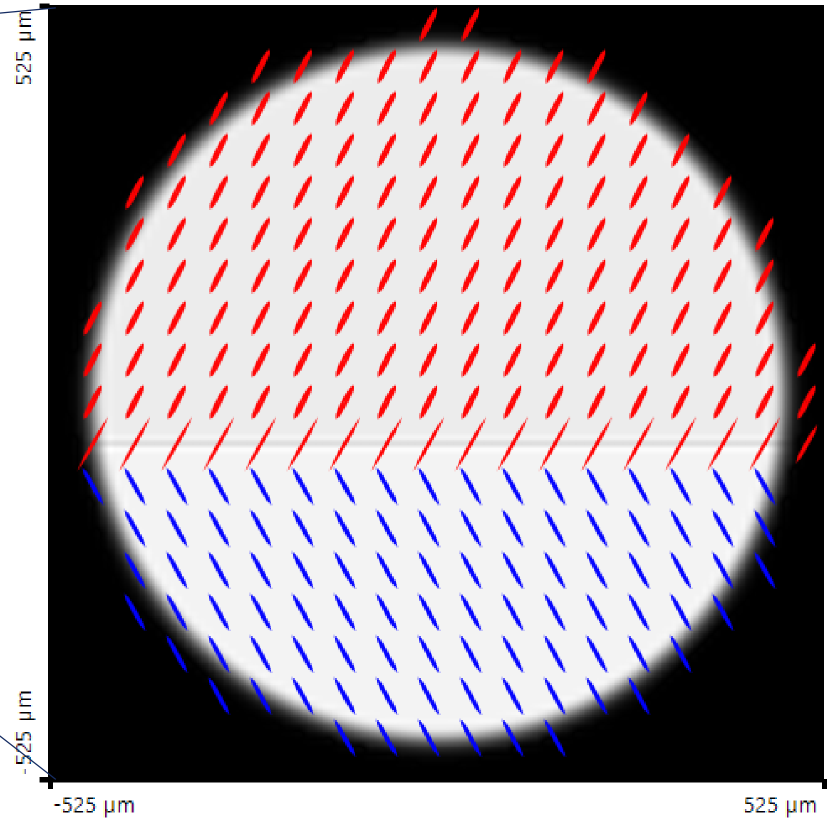
Incident light at grating interaction (locally polarized)



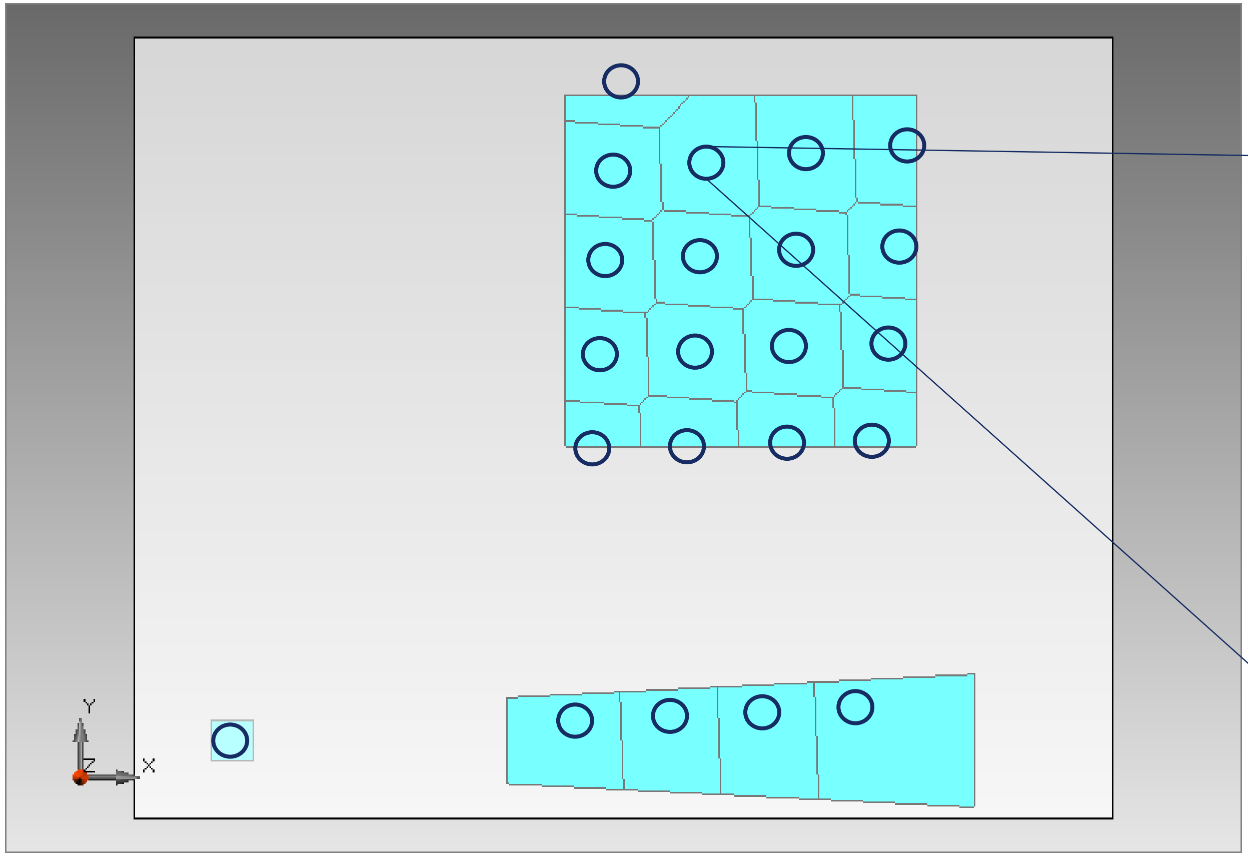
Grating Design for FOV Angle (5°, 3°) – Polarization Evaluation



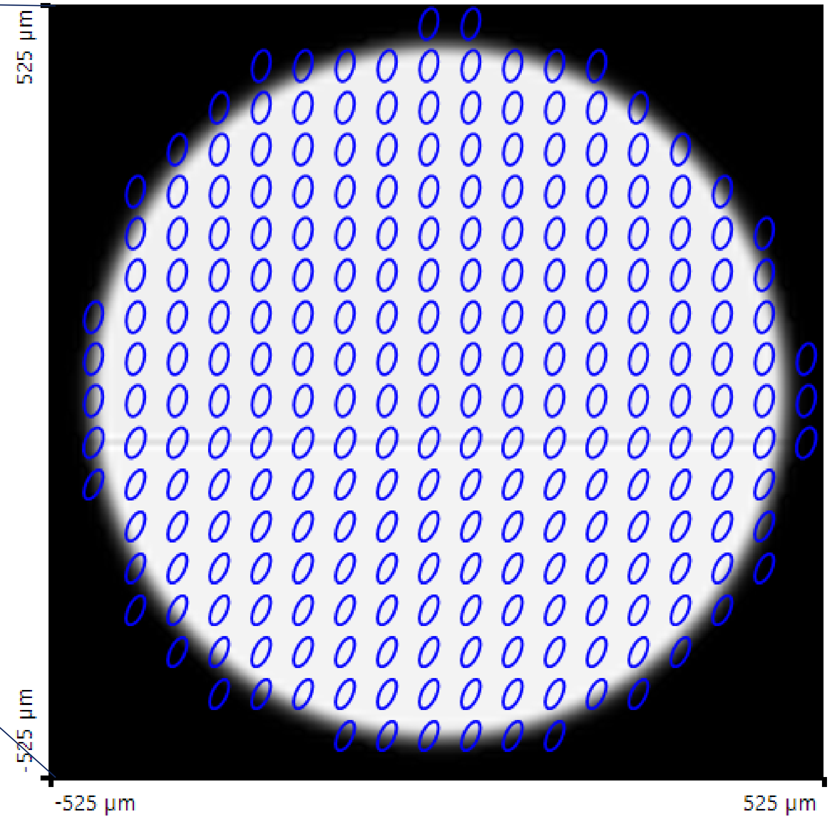
Incident light at grating interaction (<u>locally</u> polarized)



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

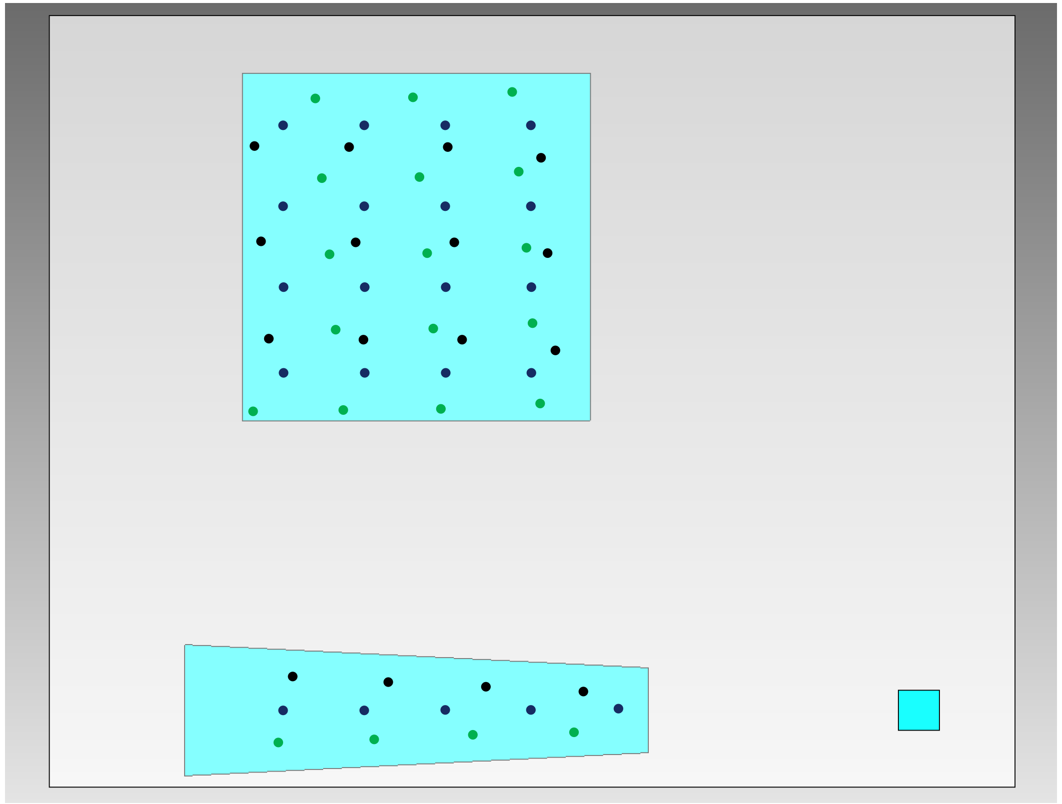


Incident light at grating interaction (locally polarized)



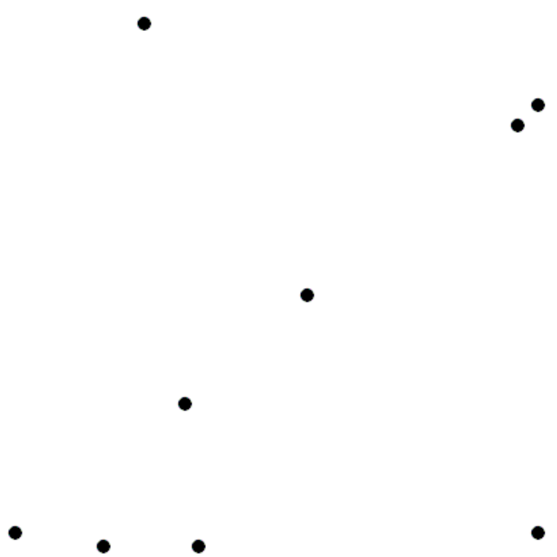
Combination of Different FOV Designs

- The basis for the design of a diffractive waveguide for different FOV angles is the capability to do the **design per angle**.
- Afterwards the designs of a set of FOV angles can be combined.



+

Voronoi Segmentation



Source: www.wikipedia.com

Combination of Different FOV Designs

- The basis for the design of a diffractive waveguide for different FOV angles is the capability to do the **design per angle**.
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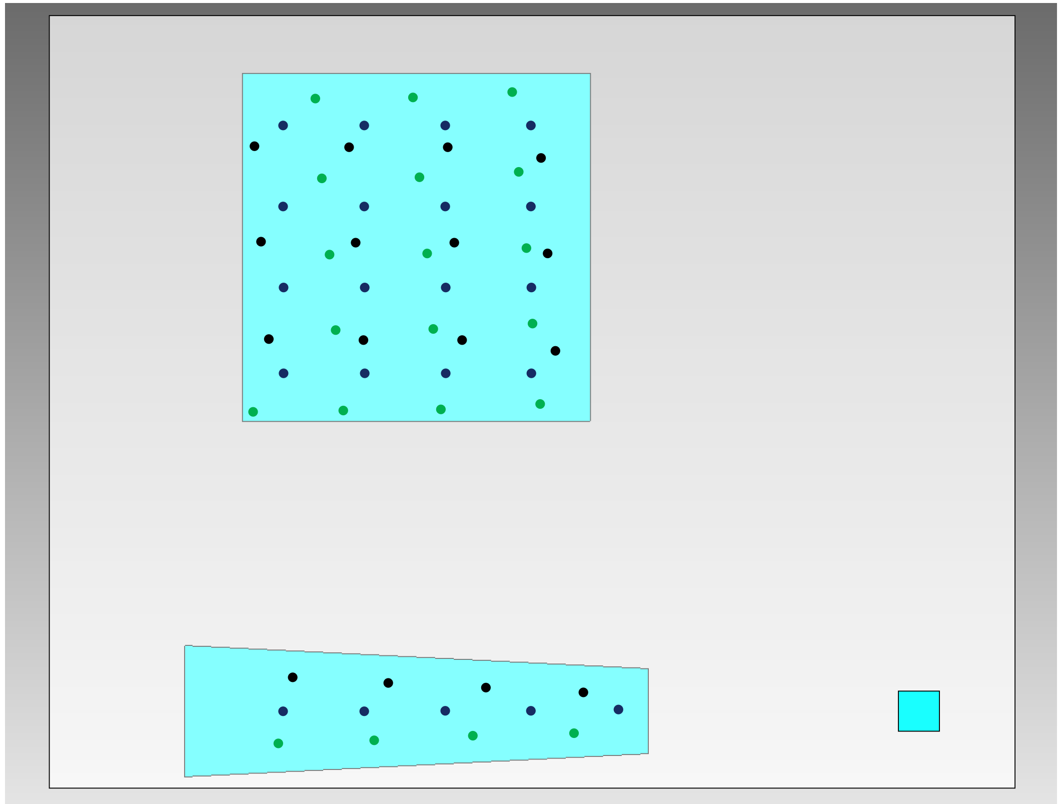
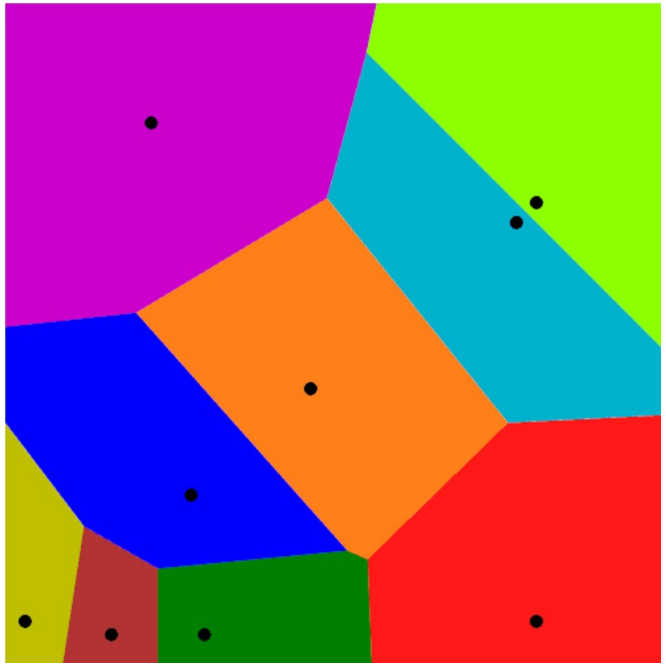


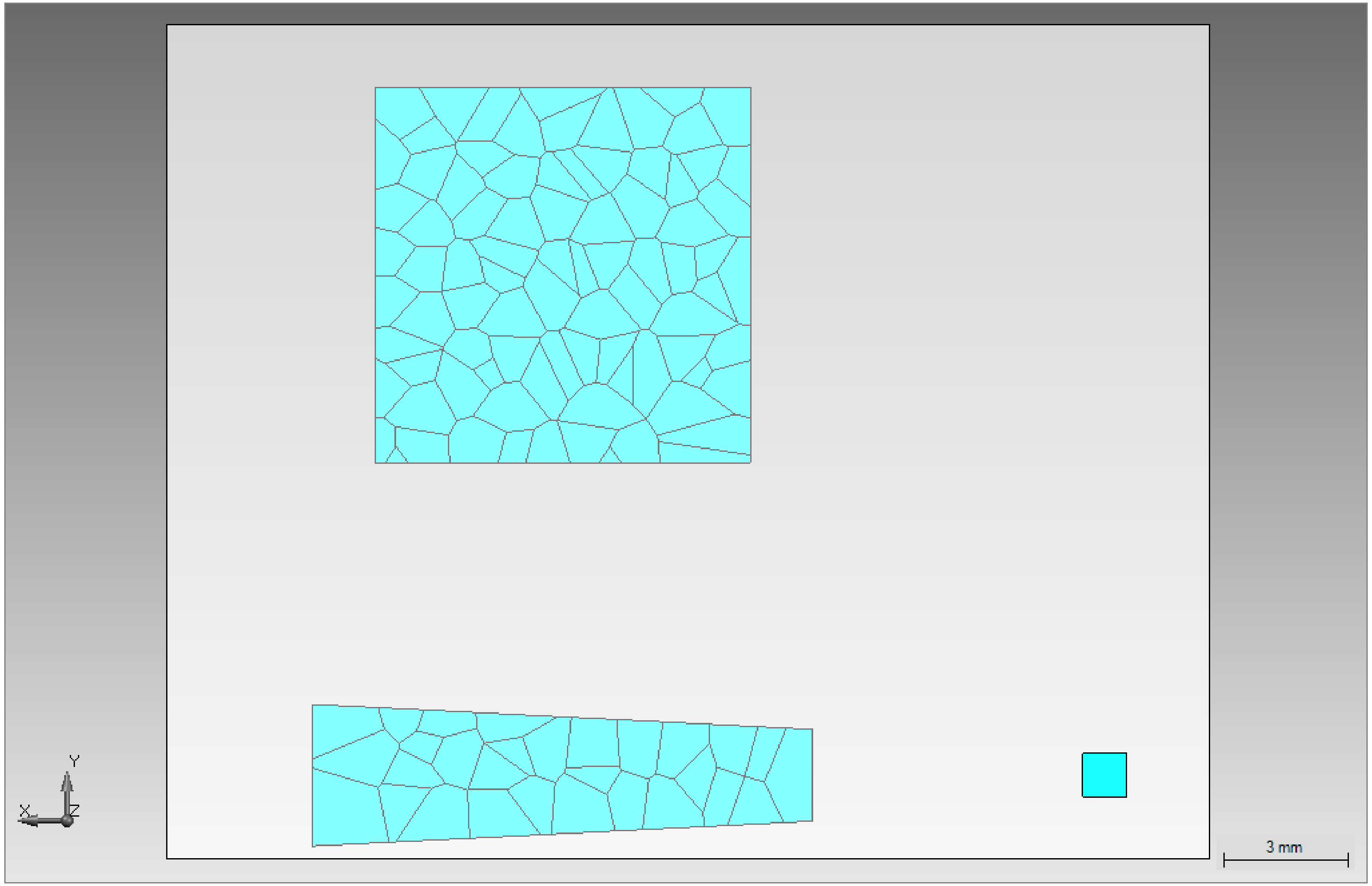
+

Voronoi Segmentation



Source: www.wikipedia.com

Combined Designed System Configuration



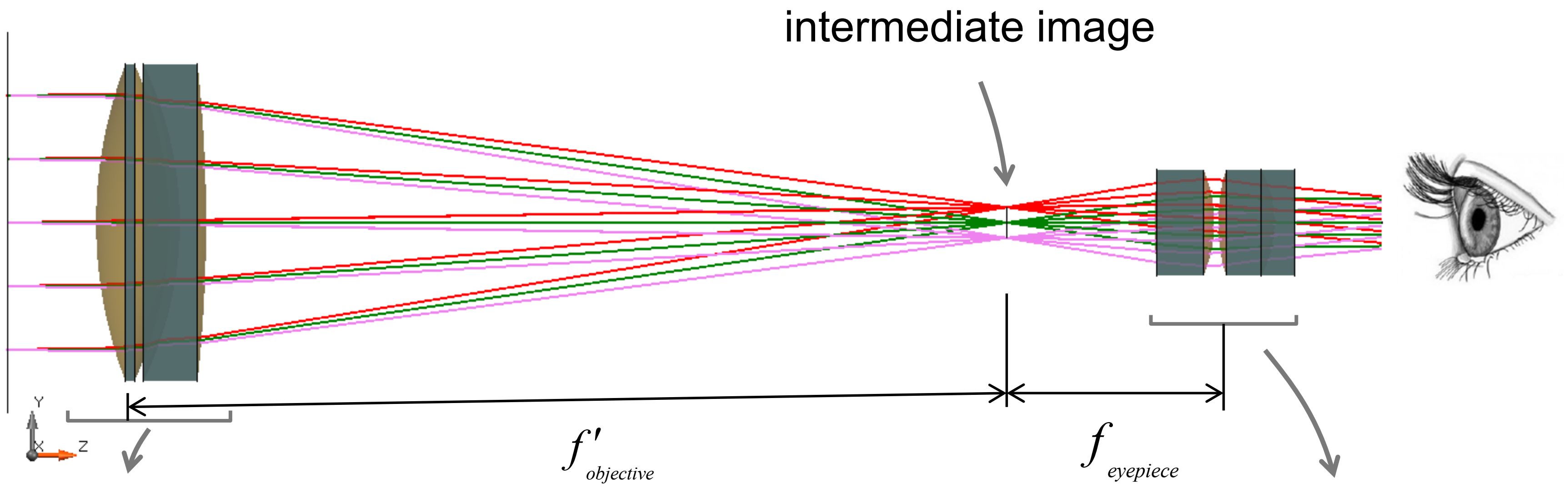
Telescope System

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

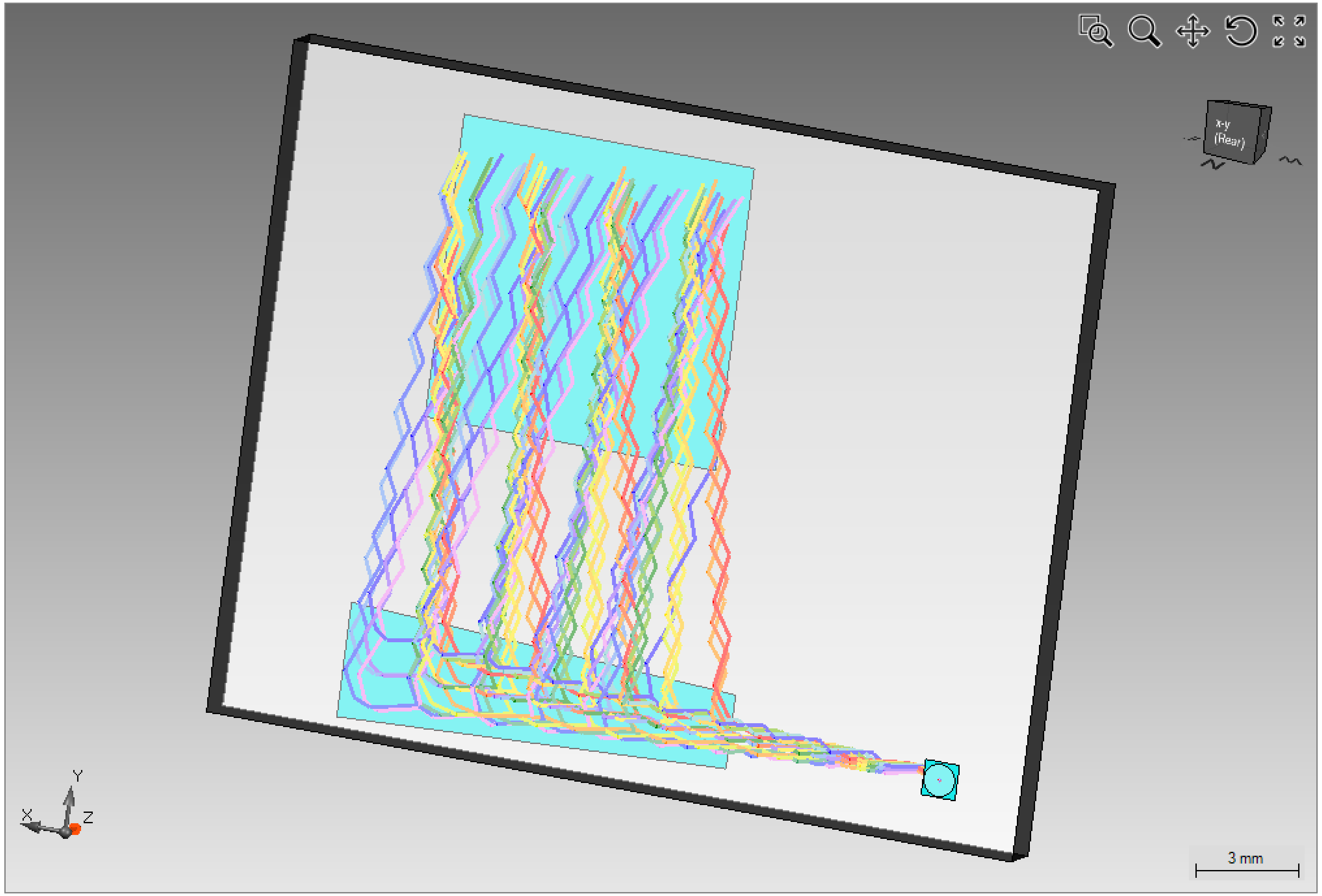


Objective group	
Focal length $f'_{objective}$	100 mm
F/#	2.8
number of lenses	4

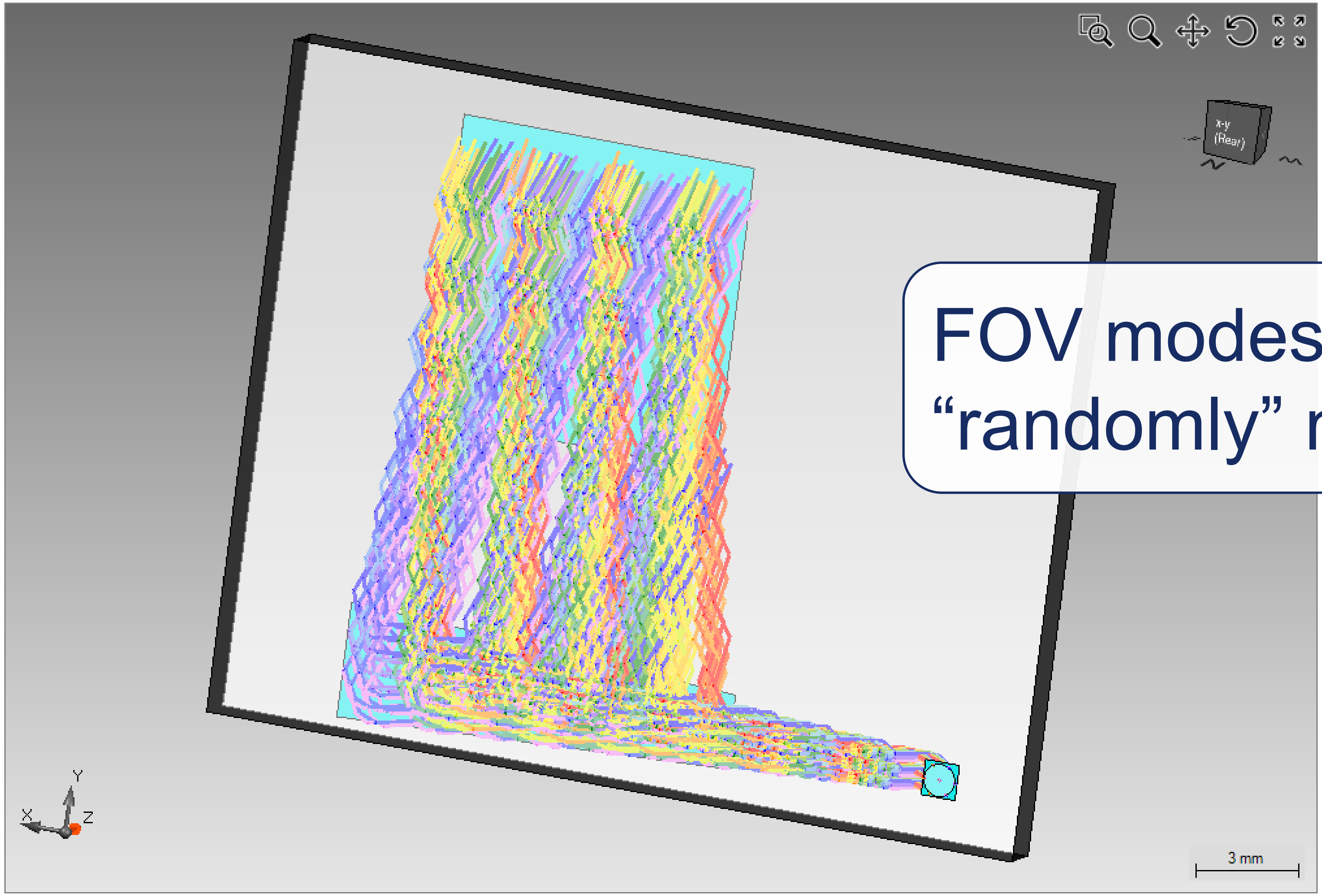
Eyepiece group	
Focal length $f_{eyepiece}$	18.3 mm
Exit Pupil Diameter	3.6 mm
number of lenses	5

Lens source: A_019 and C_001 in Zebase

Design for Multiple FOV Modes: Waveguide

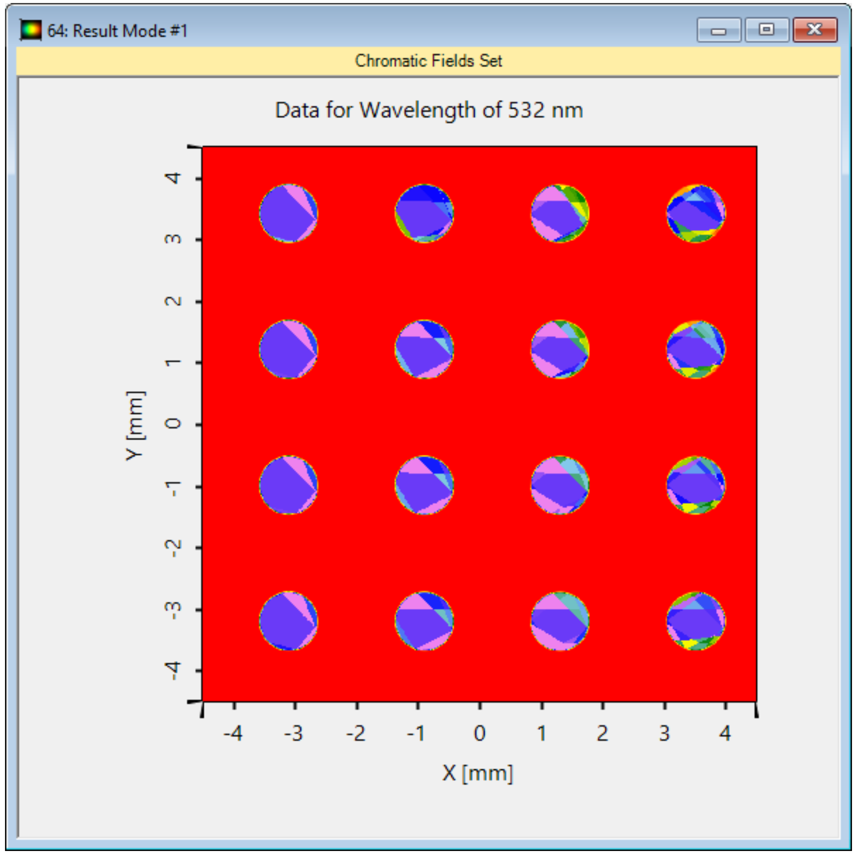


Design for Multiple FOV Modes: Waveguide

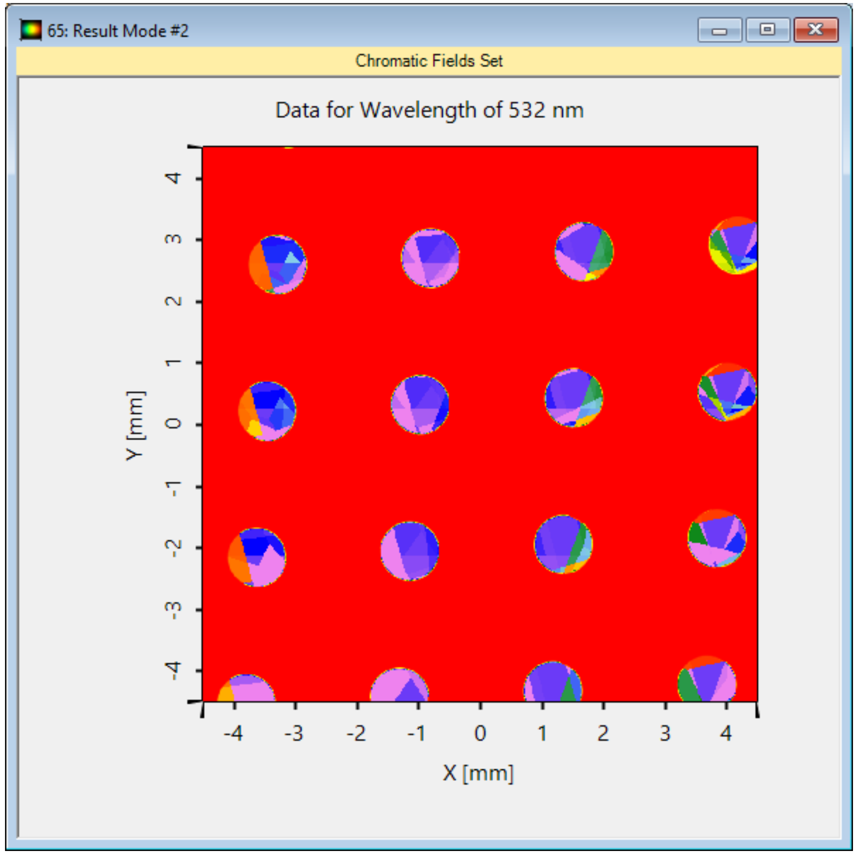


FOV modes laterally "randomly" mixed up

Final Design Results: Compromise

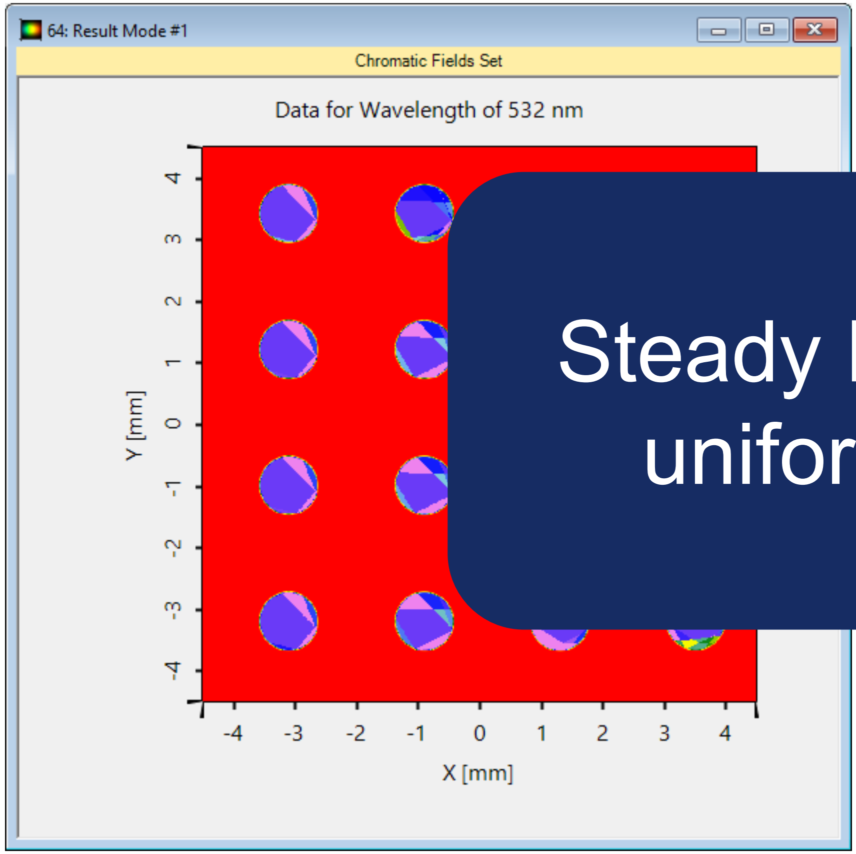


Mode	Merit Function	Value
#1	FOV Angle	$\alpha = 0°; \beta = 0°$
	Uniformity Error	**30.35%**

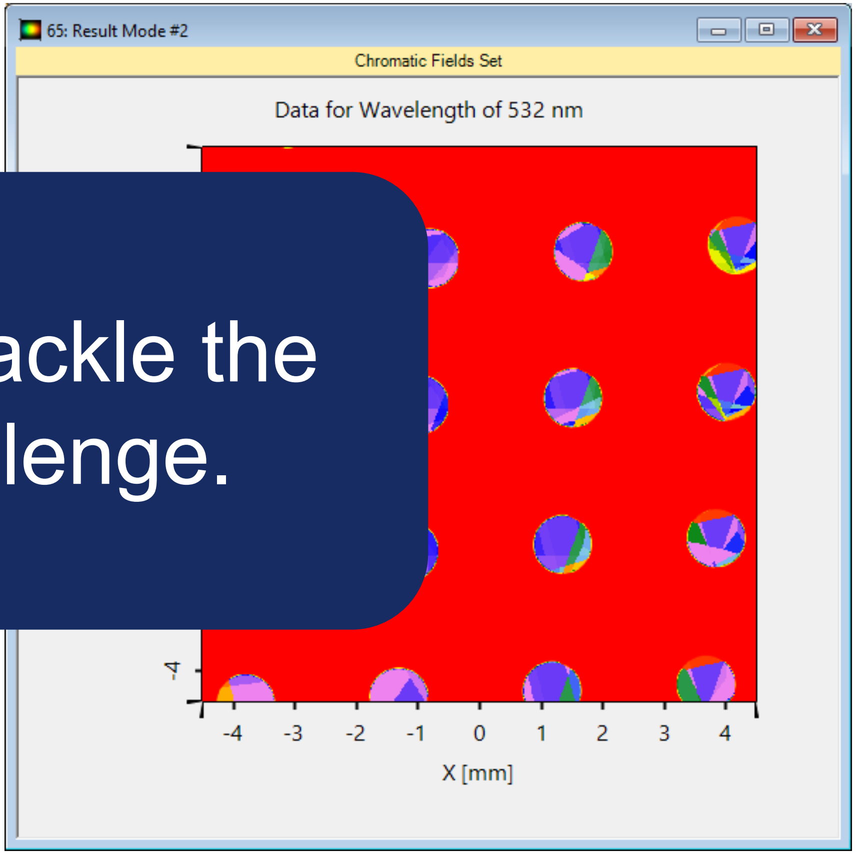


Mode	Merit Function	Value
#2	FOV Angle	$\alpha = 5°; \beta = 3°$
	Uniformity Error	**43.05%**

Final Design Results: Compromise



Steady R&D to tackle the uniformity challenge.



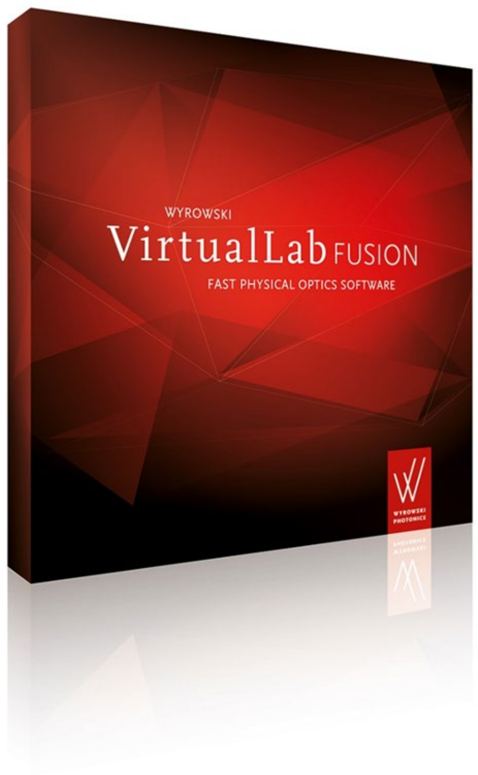
Mode	Merit Function	Value
#1	FOV Angle	$\alpha = 0°; \beta = 0°$
	Uniformity Error	**30.35%**

Mode	Merit Function	Value
#2	FOV Angle	$\alpha = 5°; \beta = 3°$
	Uniformity Error	**43.05%**

Conclusion

- Connecting field solvers enables practical physical-optics modeling of lightguides for AR&VR.
- VirtualLab Fusion provides all modeling techniques on one single platform.
- Parametric optimization must be combined with systematic design techniques, which includes inverse approaches.

Steady R&D in lightguide modeling and design.



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Andreas Erdmann, Fraunhofer IISB Erlangen, Germany

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Michael A. Golub, Tel Aviv University, Israel

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Thank You!