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Physical-optics analysis of lightguides for augmented and mixed reality glasses

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*University of Jena, ** LightTrans GmbH. ***Wyrowski Photonics

Applied Computational Optics Group

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Applied Computational Optics Group and LightTrans

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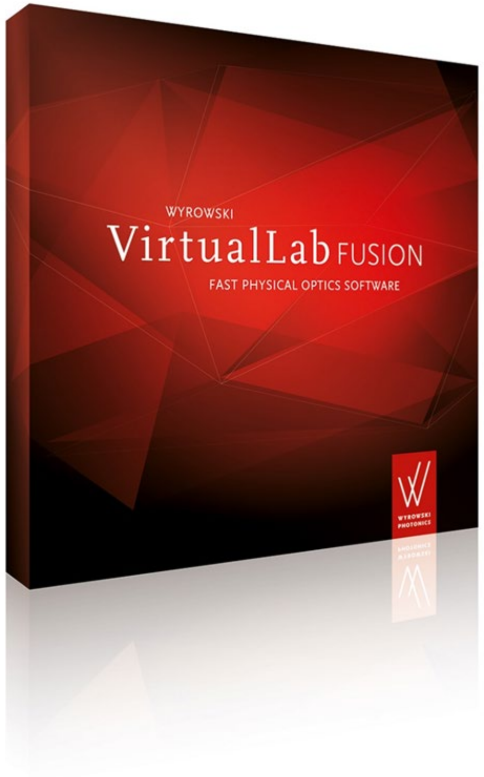
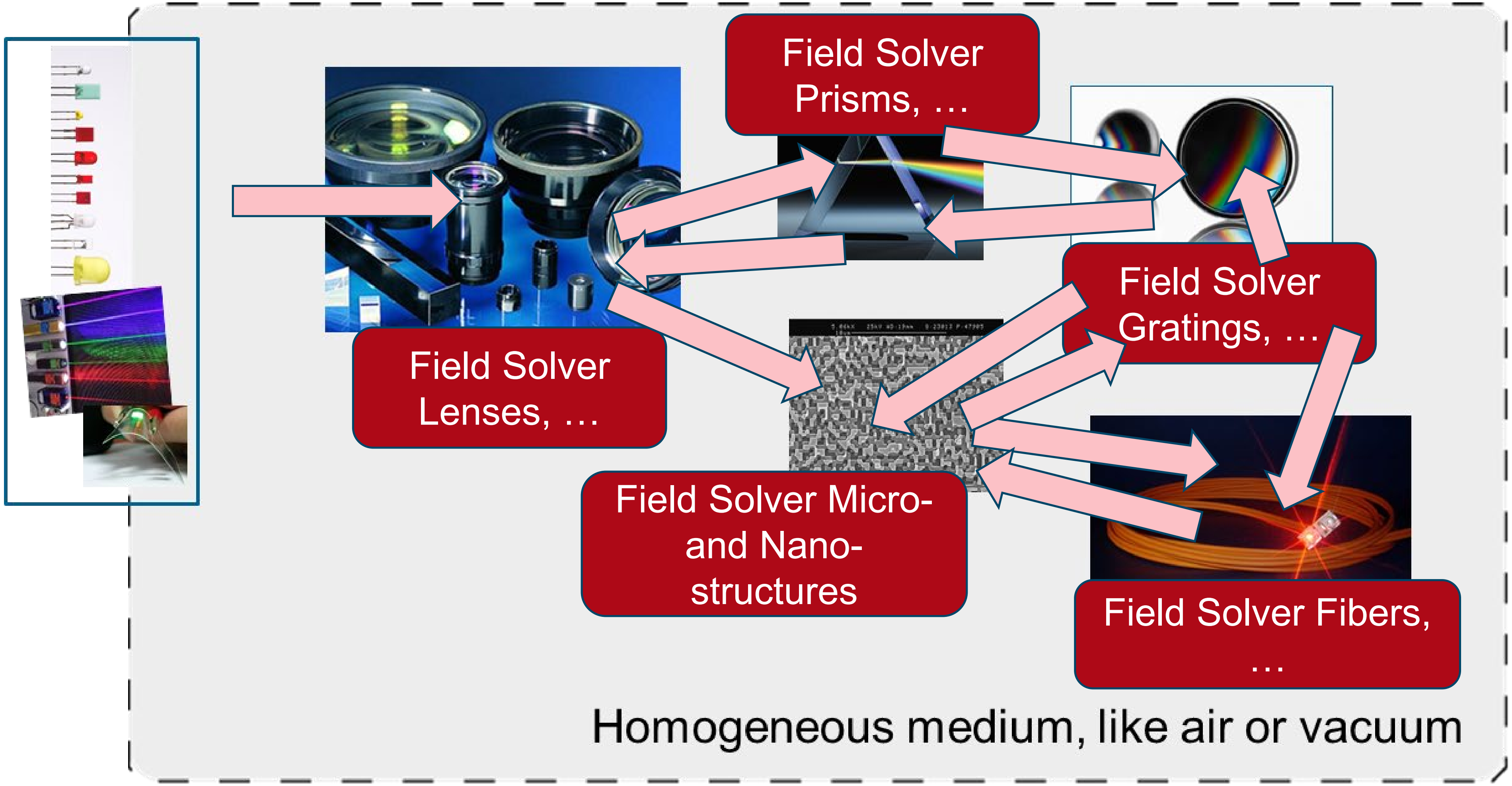
LightTrans

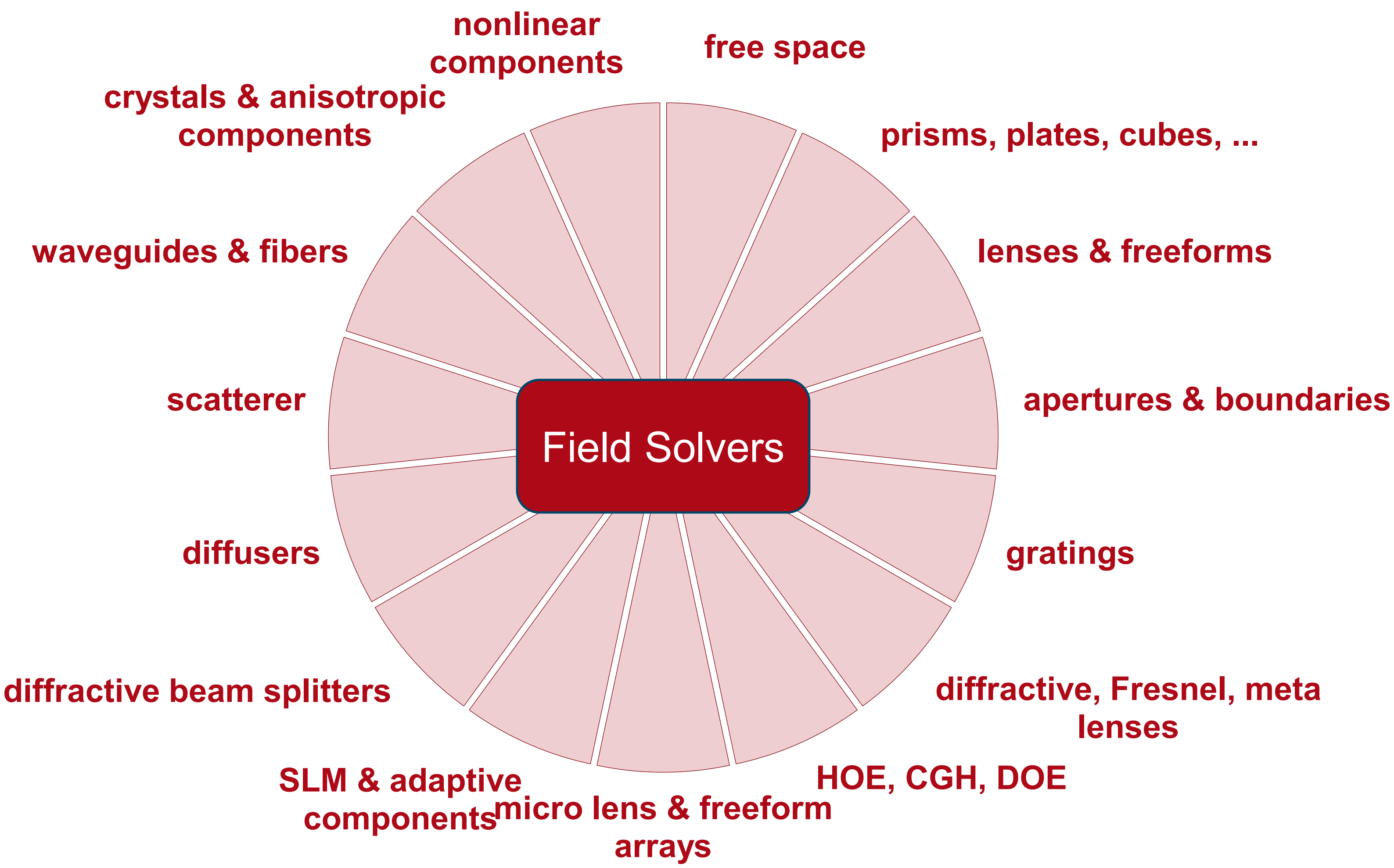


Connecting Optical Technologies

Physical-Optics System Modeling by Connecting Field Solvers

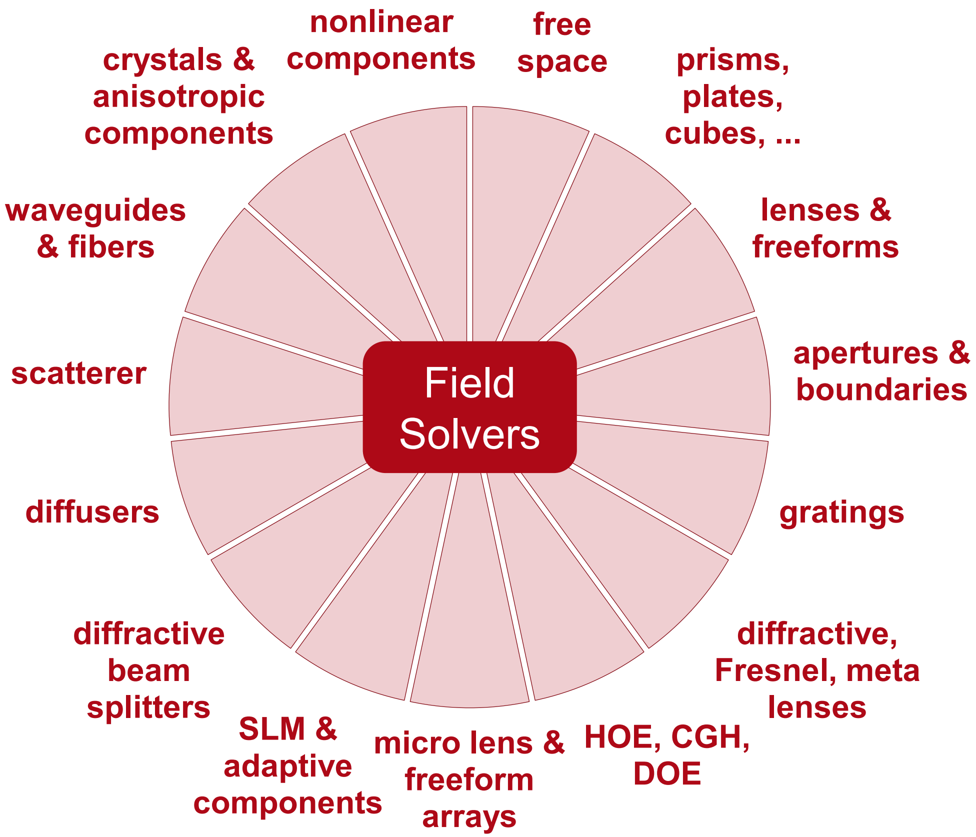


Physical-Optics System Modeling: Regional Field Solvers



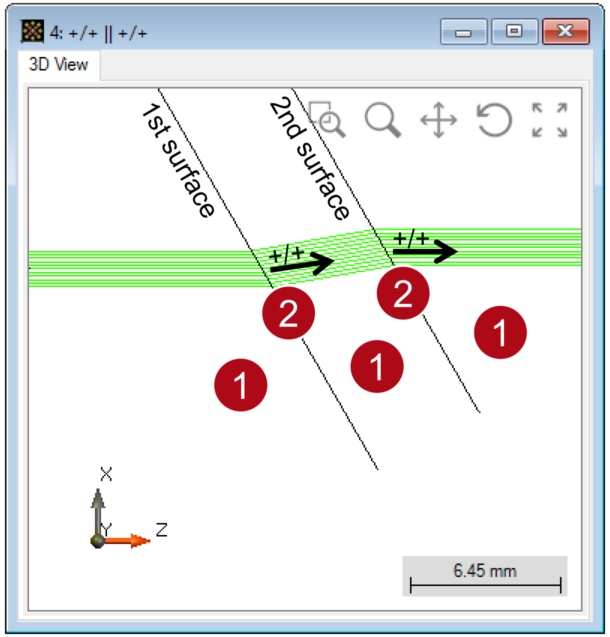
Physical-Optics System Modeling by Connecting Field Solvers

Connection of solvers via I/O channel concept which enables non-sequential physical-optics system modeling

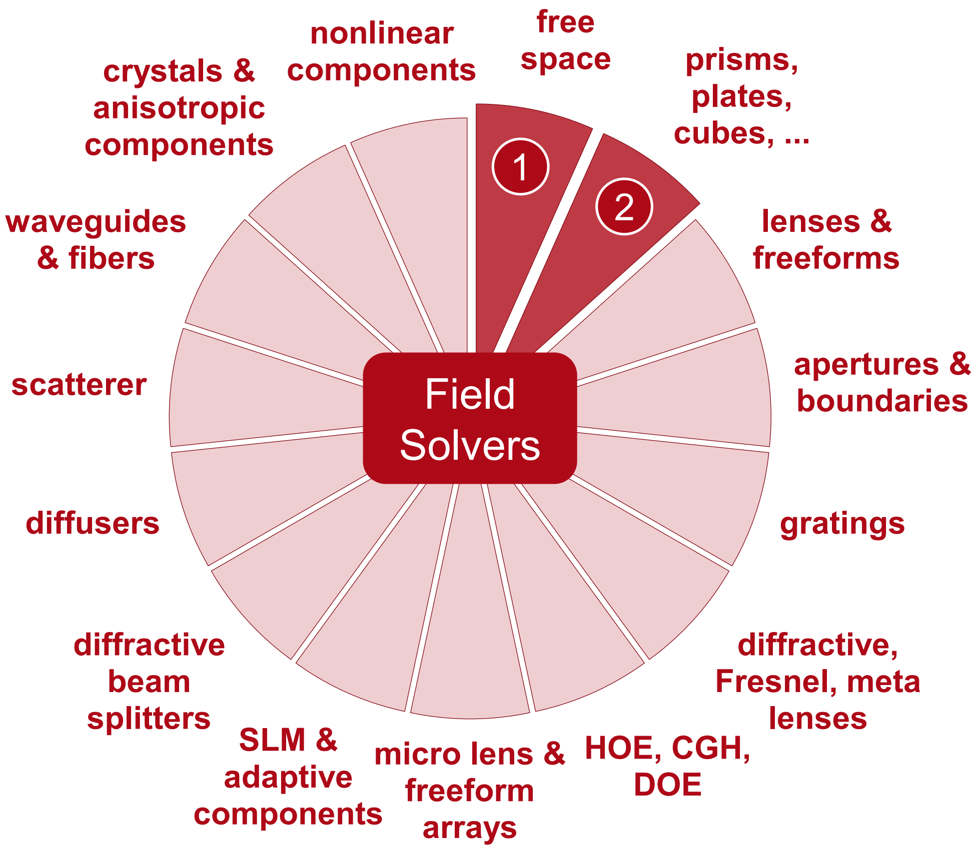


Surface Channels: Example of Plate/Etalon

Setting A

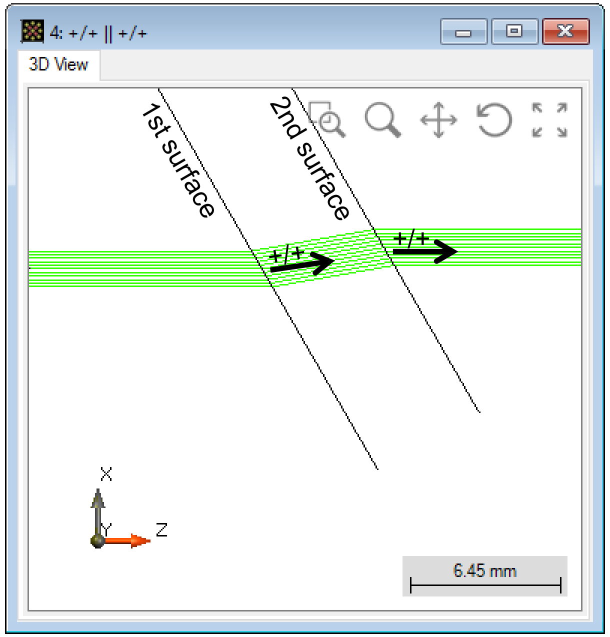


Surface	+/+	+/-	-/-	-/+
1st	×			
2nd	×			



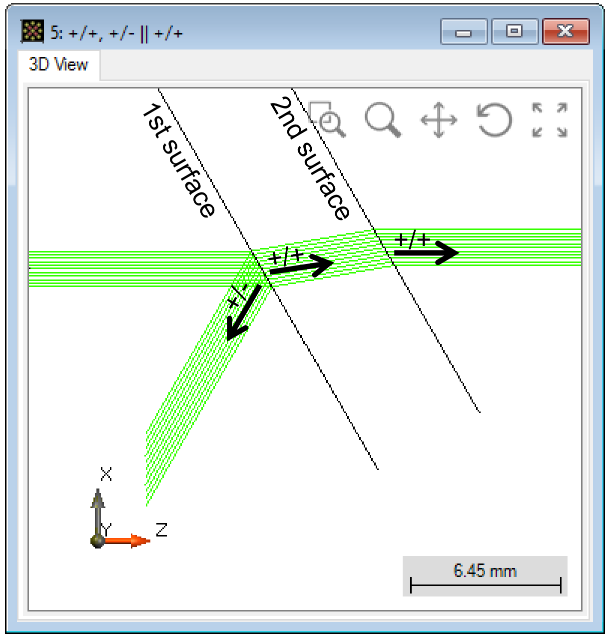
Surface Channels: Example of Plate/Etalon

Setting A



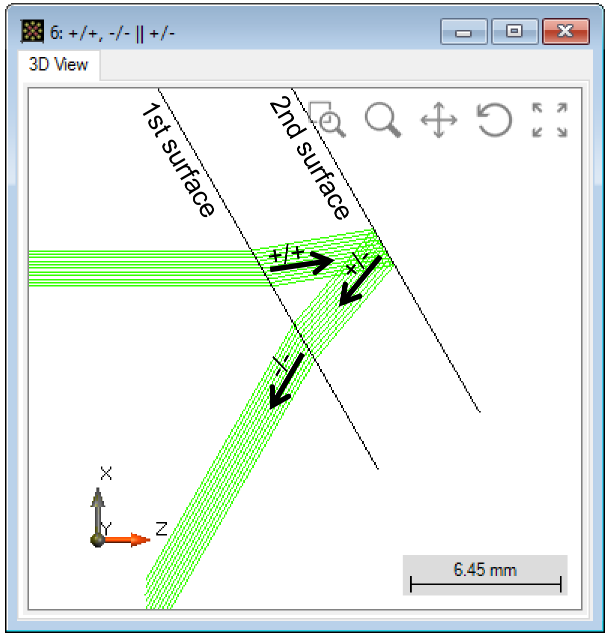
Surface	+/+	+/-	-/-	-/+
1st	×			
2nd	×			

Setting B



Surface	+/+	+/-	-/-	-/+
1st	×	×		
2nd	×			

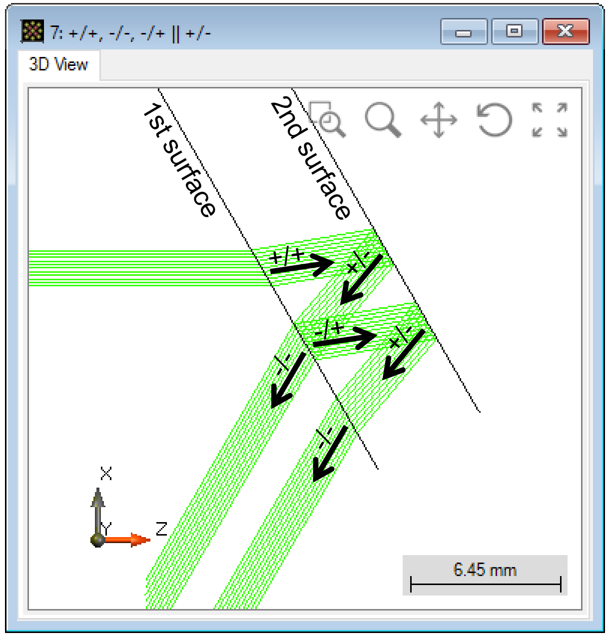
Setting C



Surface	+/+	+/-	-/-	-/+
1st	×		×	
2nd		×		

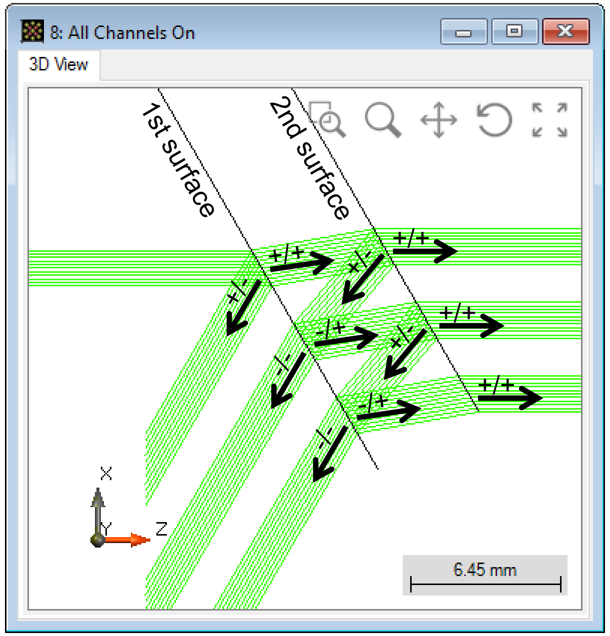
Surface Channels: Example of Plate/Etalon

Setting D



Surface	+/+	+/-	-/-	-/+
1st	×		×	×
2nd		×		

Setting E

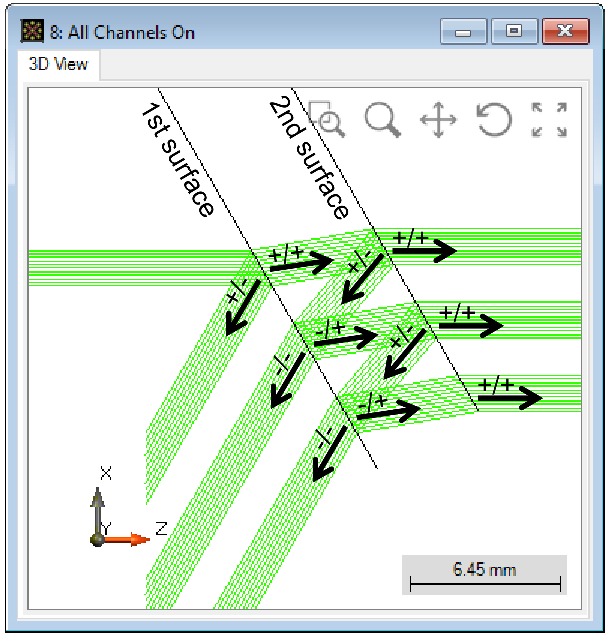


Surface	+/+	+/-	-/-	-/+
1st	×	×	×	×
2nd	×	×	×	×

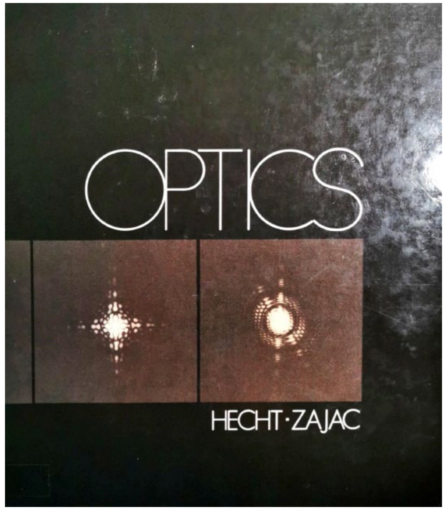
Surface Channels: Example of Plate/Etalon

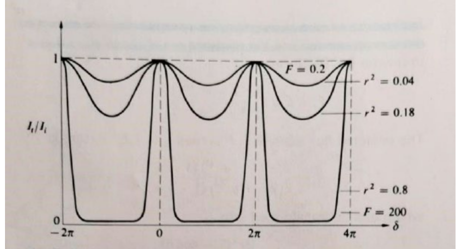
planar-planar (parallel)

- **varying thickness from 100 to 99µm**



Surface	+/+	+/-	-/-	-/+
1st	×	×	×	×
2nd	×	×	×	×





306 Interference

Fig. 9.45 Airy function.

density emerging from the film. It follows from Eqs. (9.33) and (9.34), that this is indeed the case, that is

$$I_i = I_r + I_t \qquad (9.35)$$

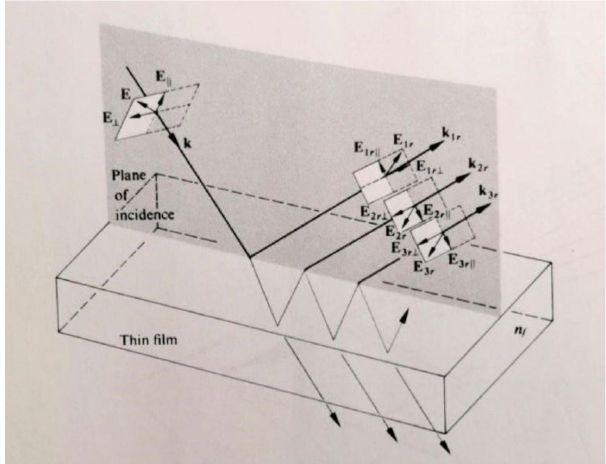


Fig. 9.41 Phase shifts arising purely from the reflections (internal $\theta_i < \theta_p'$).

at point P, is then

$$E_{0r} = E_0 r - (E_0 t r' t' + E_0 t r'^3 t' + E_0 t r'^5 t' + \cdots)$$

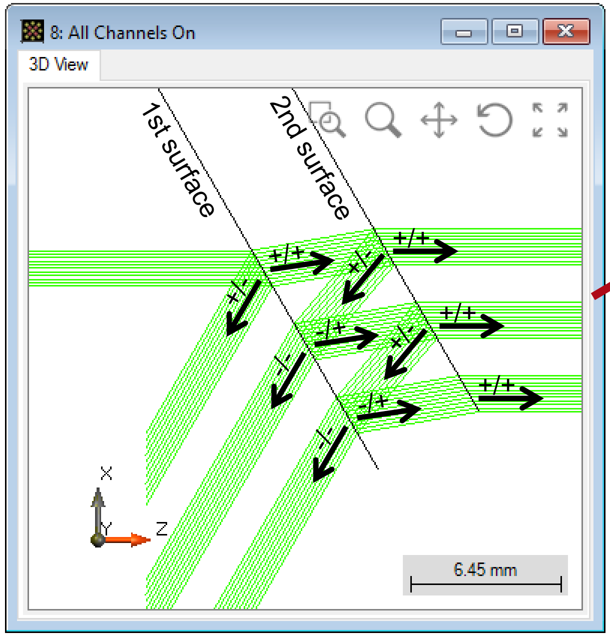
or

$$E_{0r} = E_0 r - E_0 t r' t' (1 + r^2 + r^4 + \cdots),$$

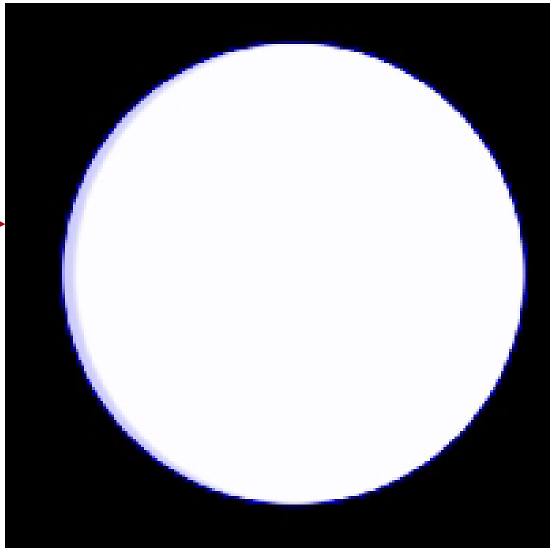
Surface Channels: Example of Plate/Etalon

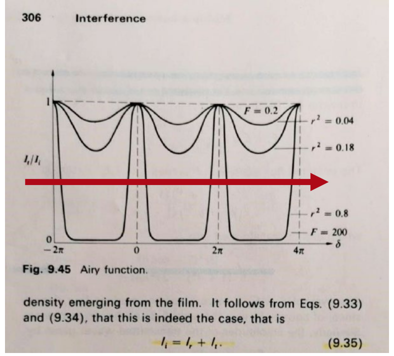
planar-planar (parallel)

- **varying thickness from 100 to 99µm**



Surface	+/+	+/-	-/-	-/+
1st	×	×	×	×
2nd	×	×	×	×



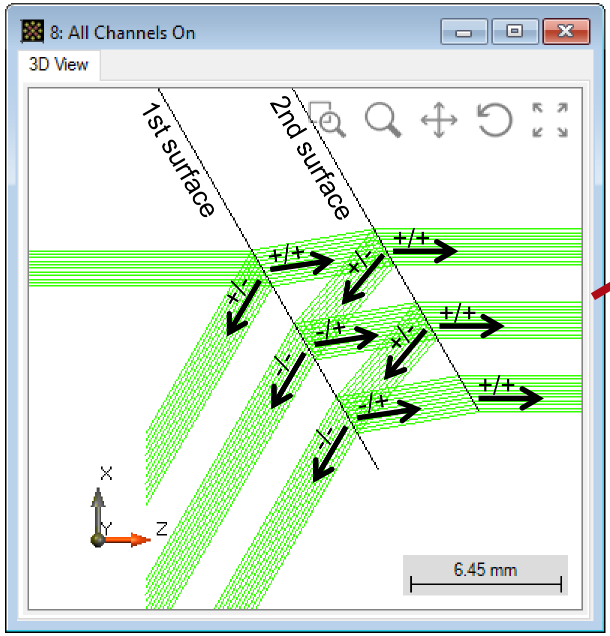


Constructive and destructive interference alternatively shows up when the thickness of plate varies.

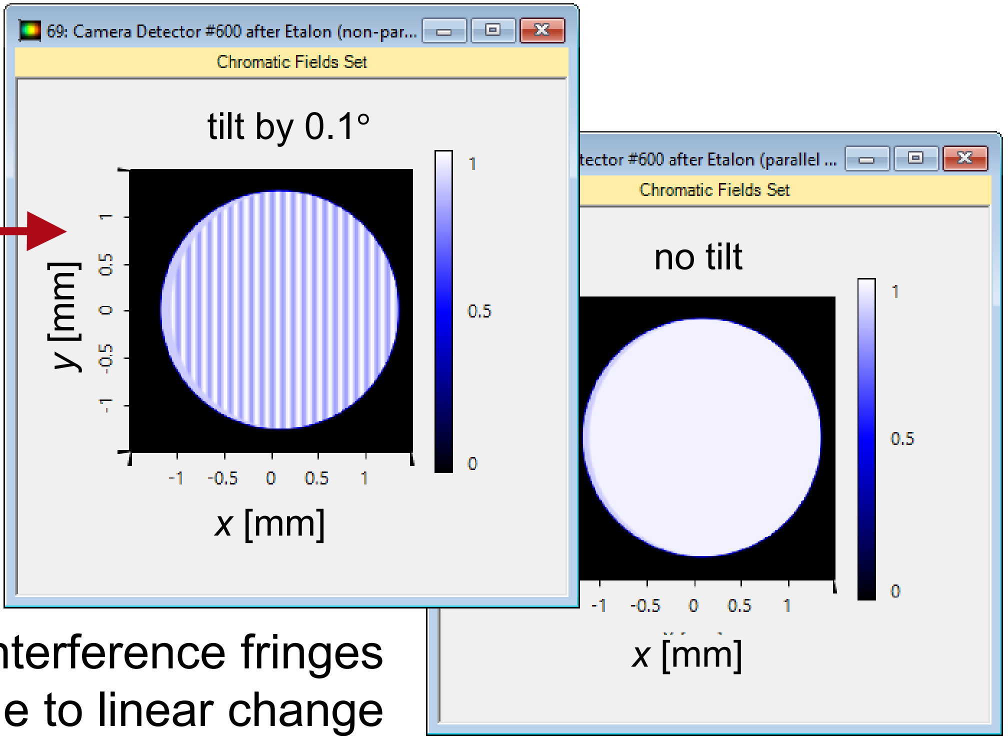
Surface Channels: Example of Plate

planar-planar (non-parallel)

- center thickness 100 µm
- **tilt of first surface**



Surface	+/+	+/-	-/-	-/+
1st	×	×	×	×
2nd	×	×	×	×

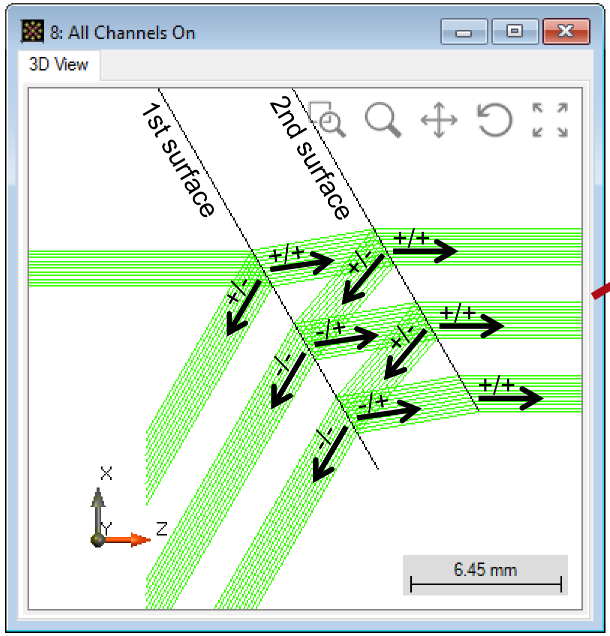


Linear interference fringes appear due to linear change of etalon thickness.

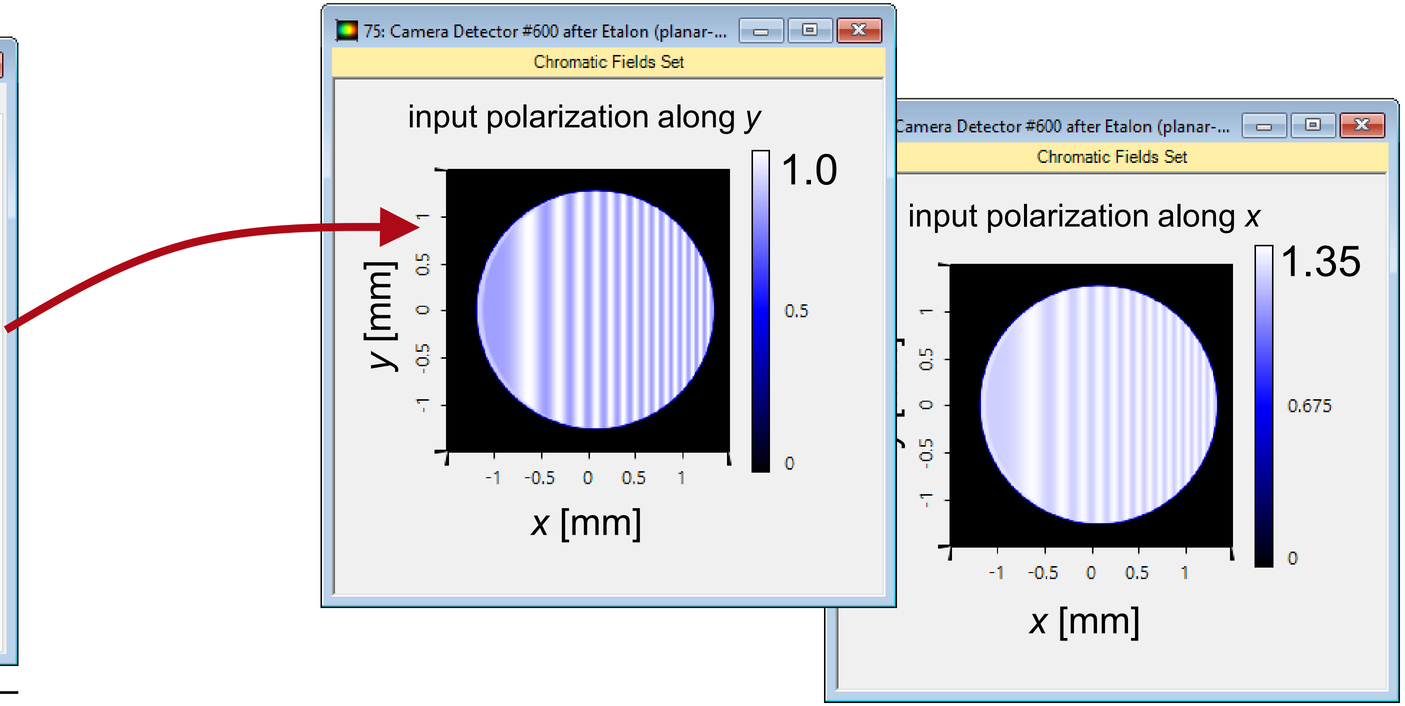
Surface Channels: Example of Plate

cylindrical-planar

- center thickness 100 µm
- **cylindrical surface radius 1 m**



Surface	+/+	+/-	-/-	-/+
1st	×	×	×	×
2nd	×	×	×	×

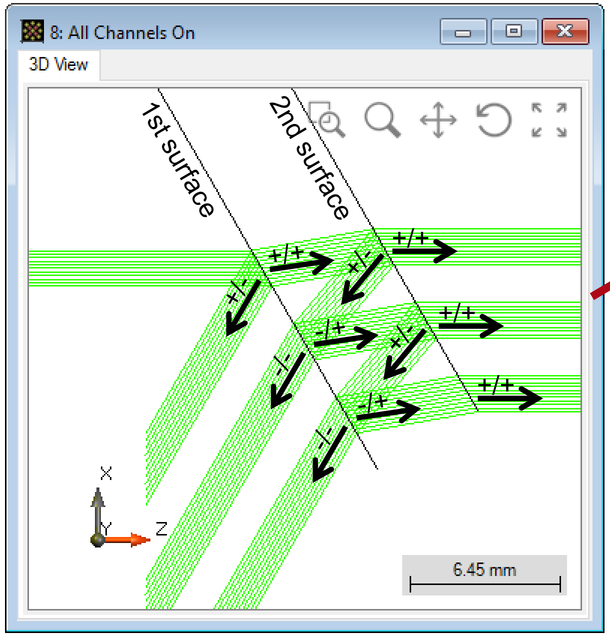


Polarization-dependent effect on the interference is considered.

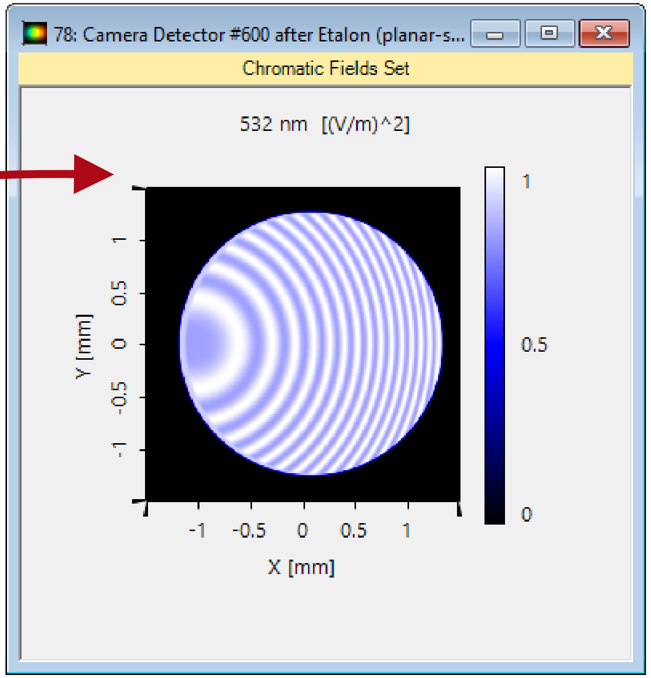
Surface Channels: Example of Plate

planar-spherical

- center thickness 100 µm
- **spherical surface radius -1 m**



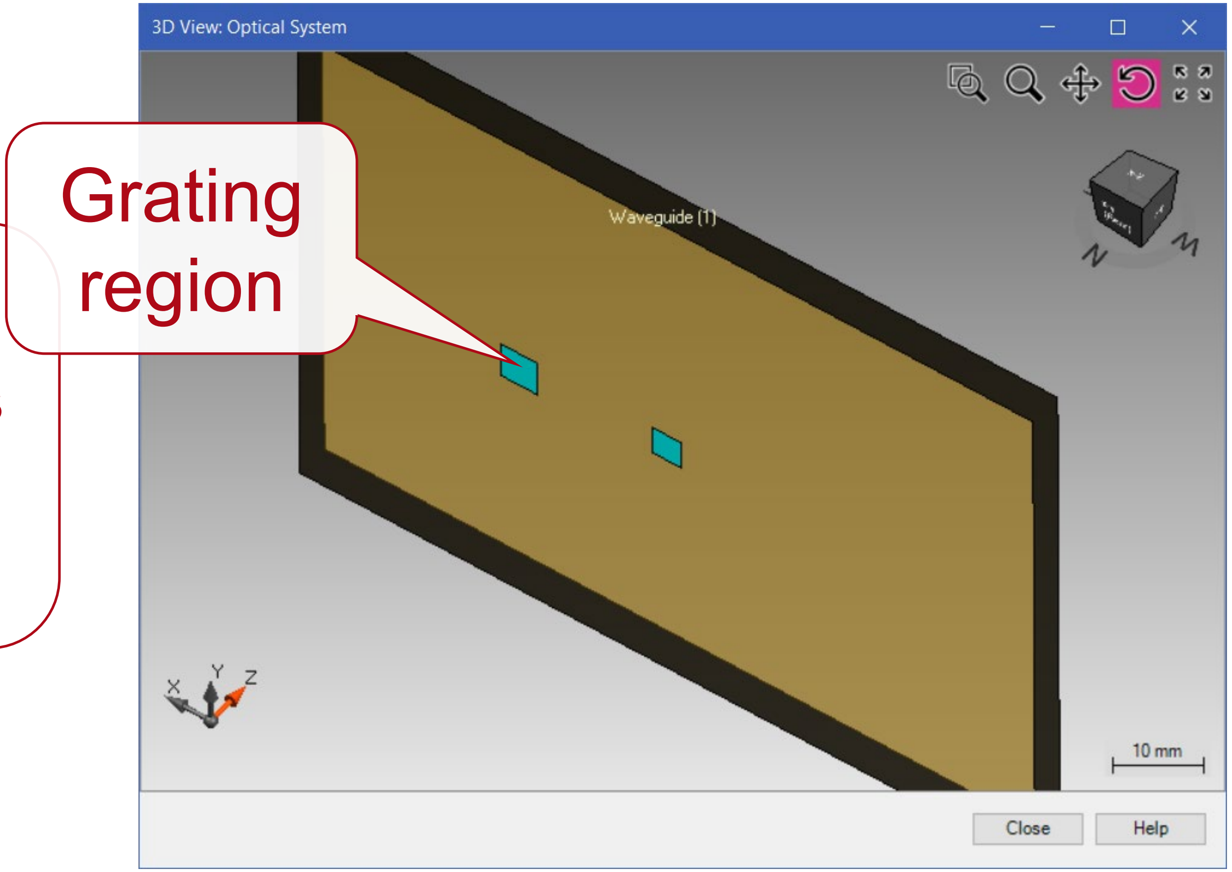
Surface	+/+	+/-	-/-	-/+
1st	×	×	×	×
2nd	×	×	×	×



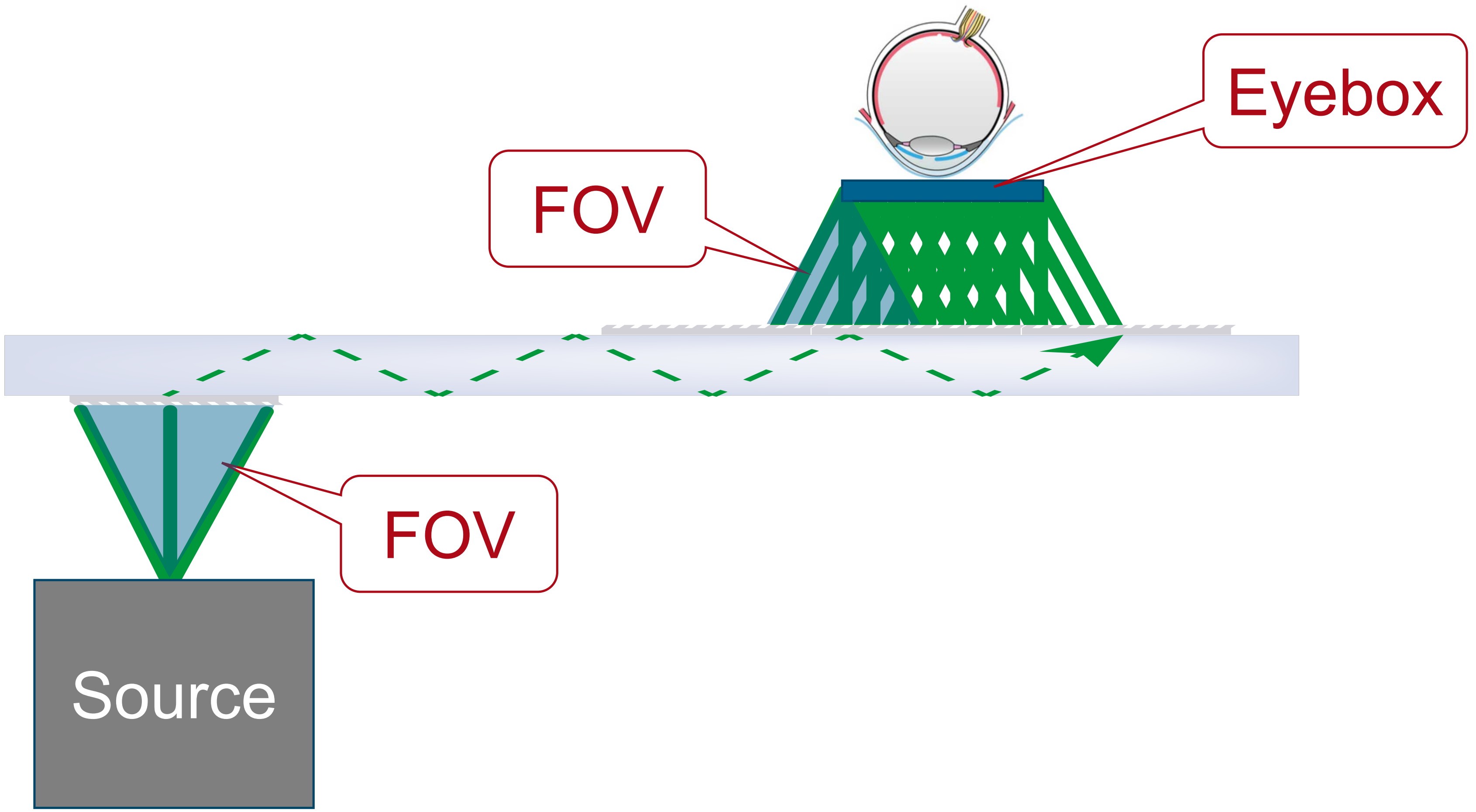
Non-sequential simulation time of etalon with curved surfaces: few seconds and less

Physical-Optics System Modeling by Connecting Field Solvers

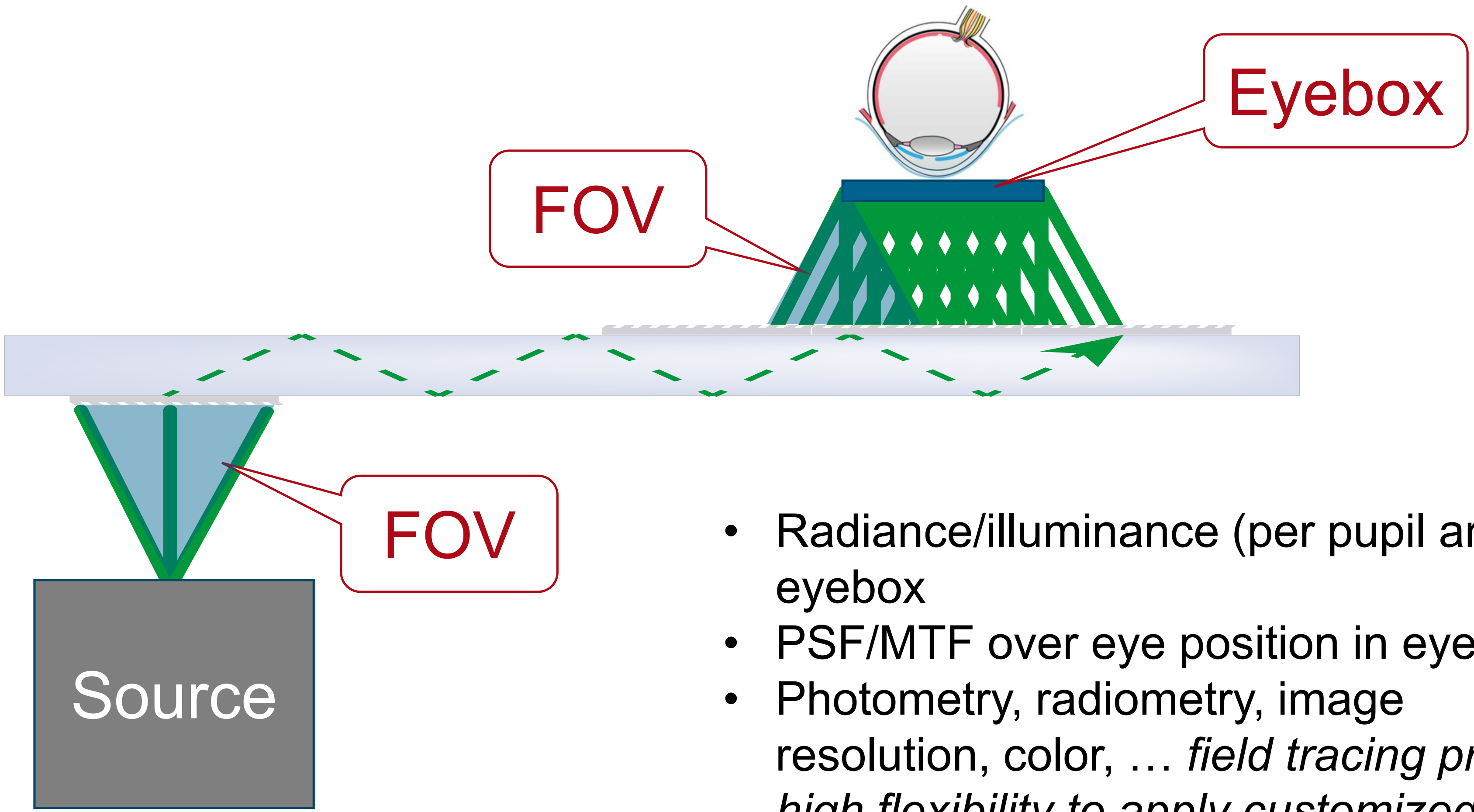
Connection of solvers via I/O channel concept which enables non-sequential physical-optics system modeling



Lightguide Concept

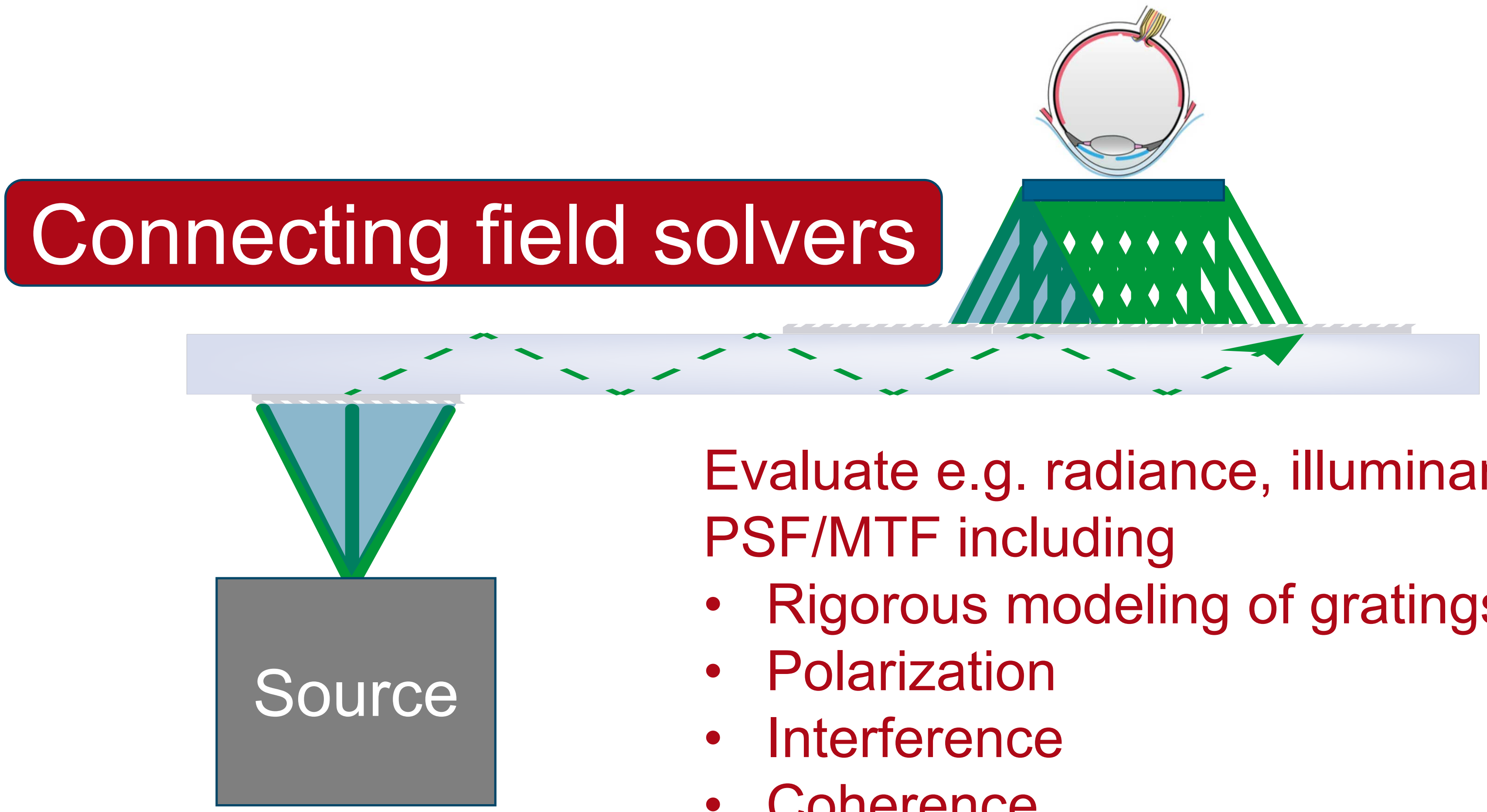


Lightguide Concept: Fundamental Detectors



- Radiance/illuminance (per pupil area) in eyebox
- PSF/MTF over eye position in eyebox
- Photometry, radiometry, image resolution, color, … *field tracing provides high flexibility to apply customized detector functions*

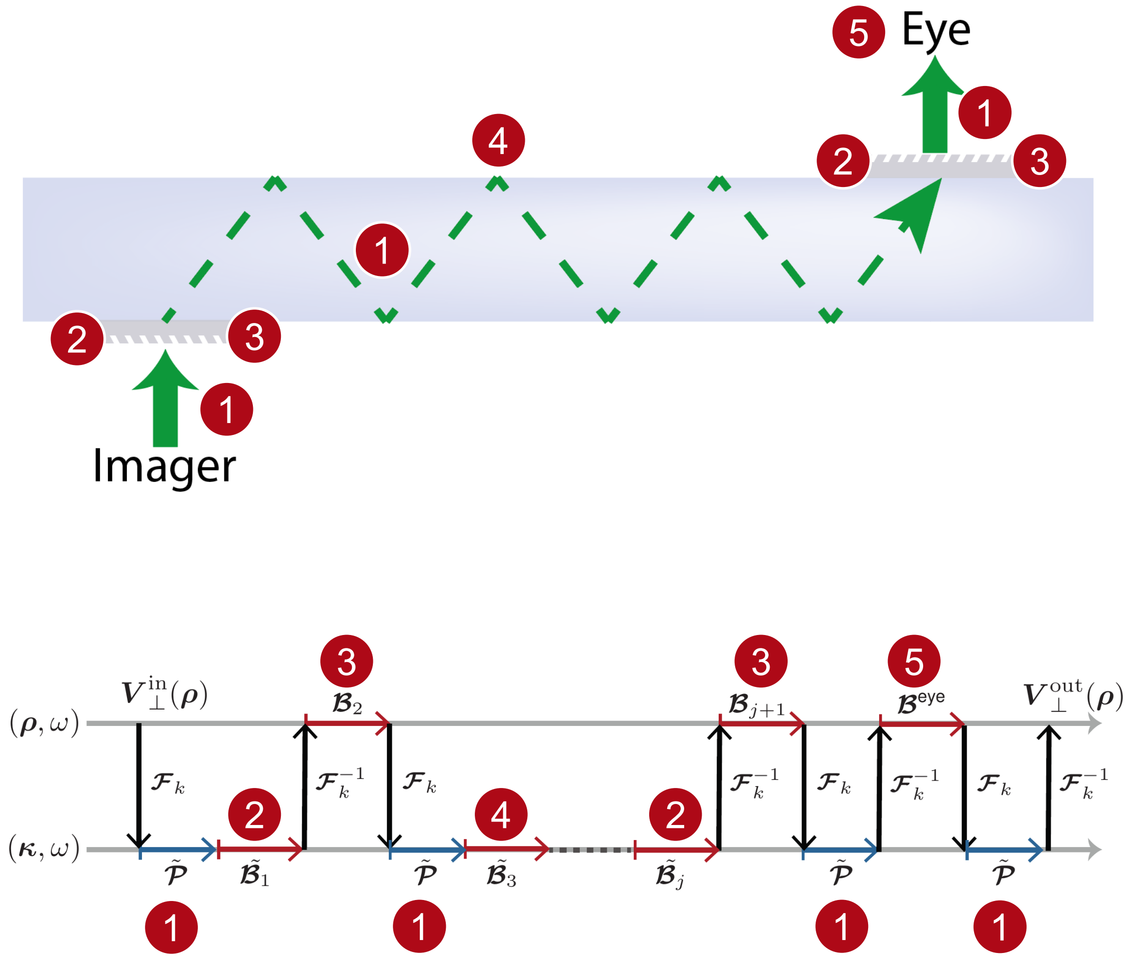
Lightguide Concept: Modeling Task

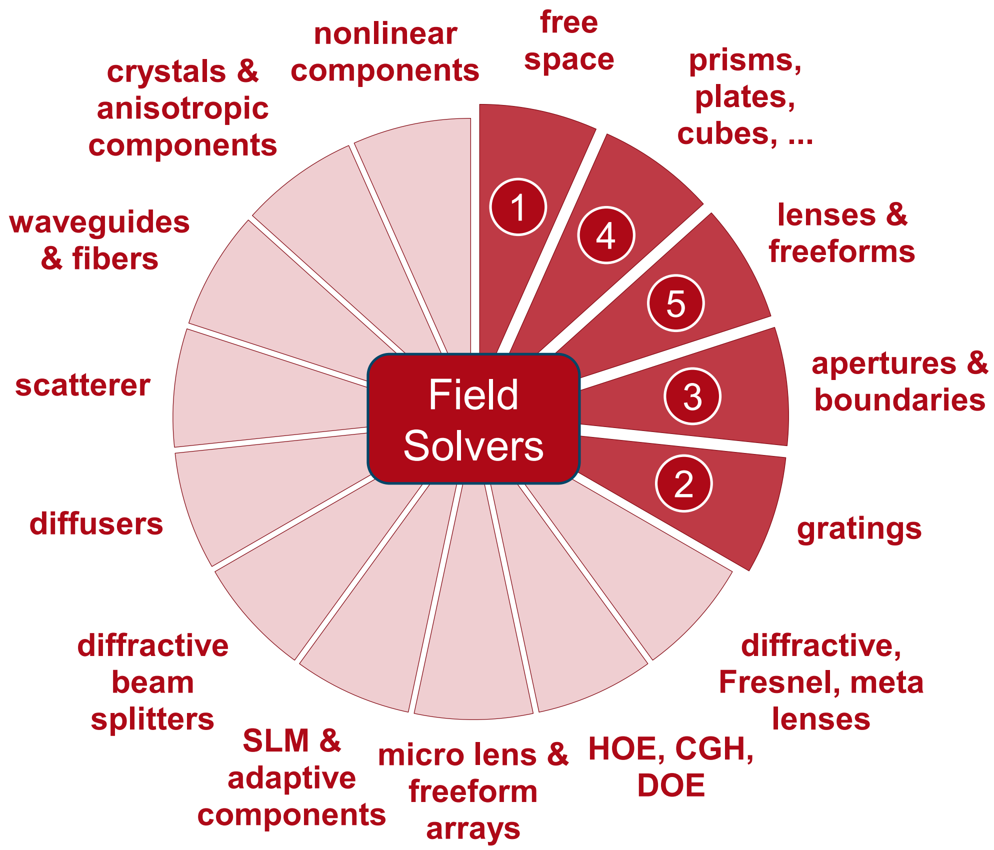


Evaluate e.g. radiance, illuminance, PSF/MTF including

- Rigorous modeling of gratings
- Polarization
- Interference
- Coherence

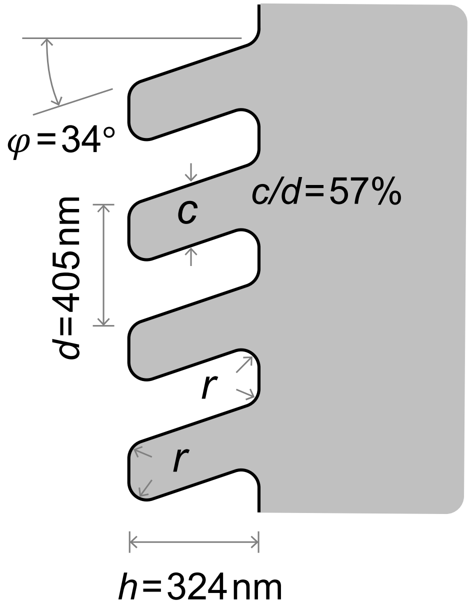
Typical Modeling Situation for AR&MR Lightguide



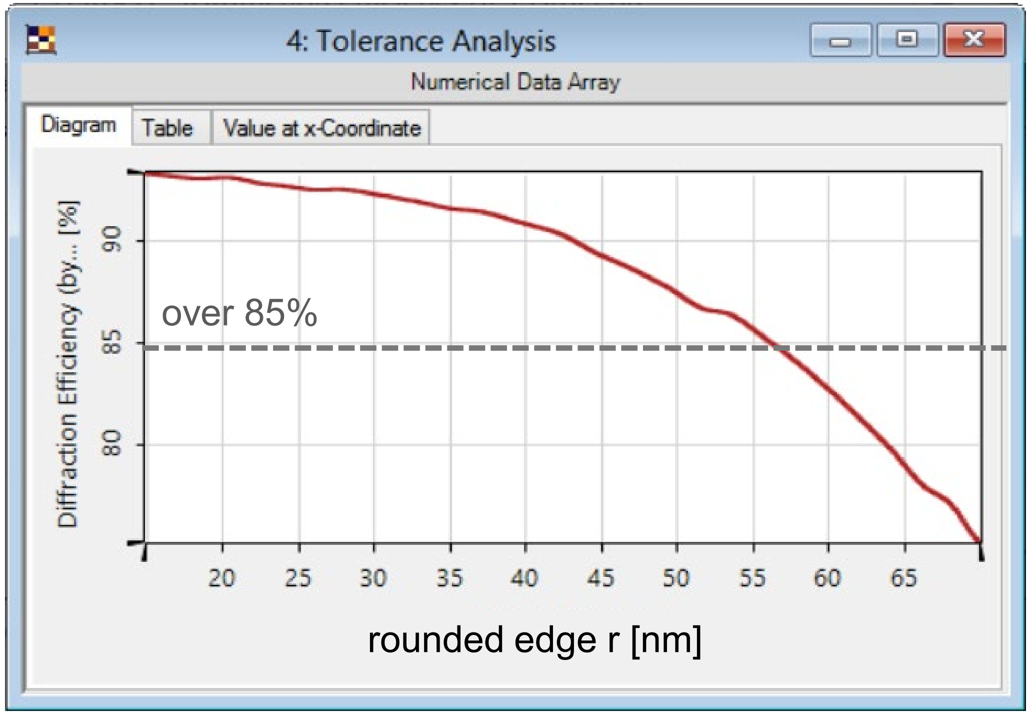


Tolerance Analysis by Integral Method

The fabricated slanted gratings often shows a deviation from the perfect parallel grating lines. The rounded edges should be taken into account for the tolerance analysis.



- fixed average slant angle $\varphi = 34°$
- fixed filling factor c/d=57%
- varying *r* from 15nm 70nm

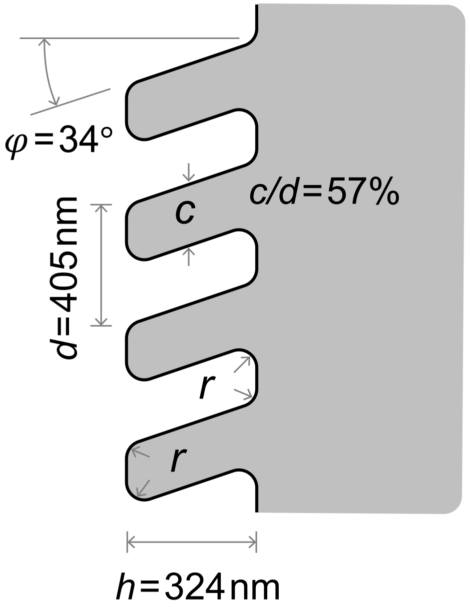


Rigorous simulation with Integral Method (IM), for tolerance analysis over 30 steps, takes 9 seconds.

Tolerance Analysis by Integral Method

Two rigorous grating modeling techniques available in VirtualLab Fusion:

- Fourier Modal Method (FMM)
- Integral Method (IM)



- fixed average slant angle $\varphi = 34°$
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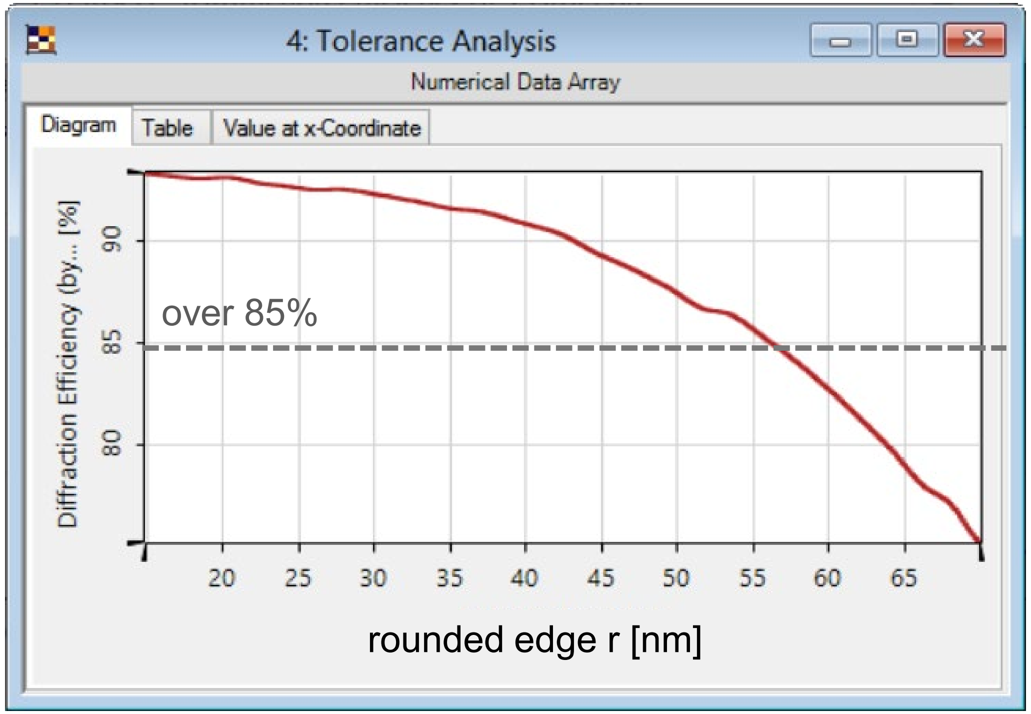

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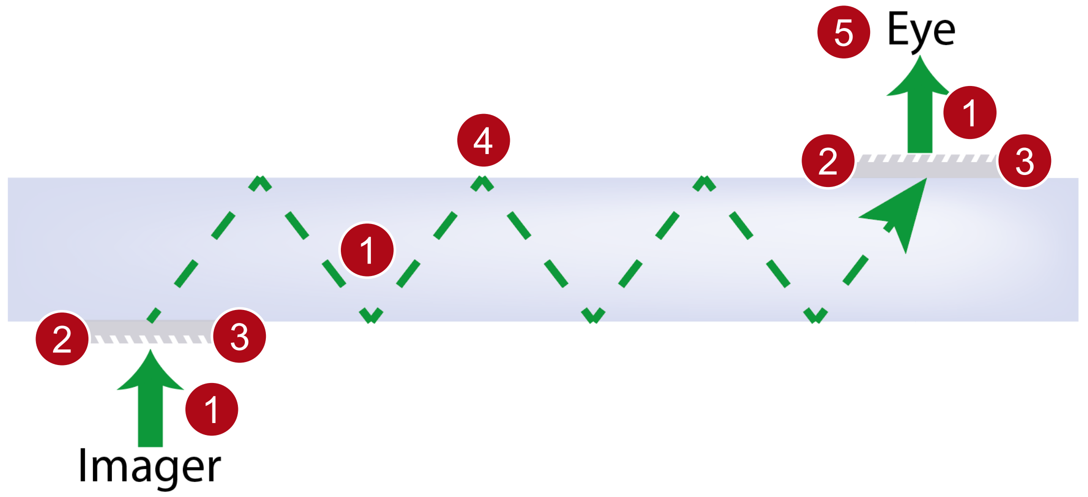
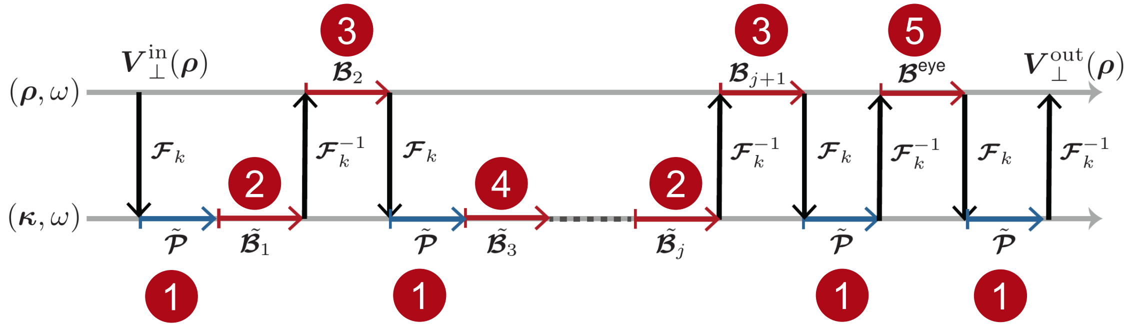
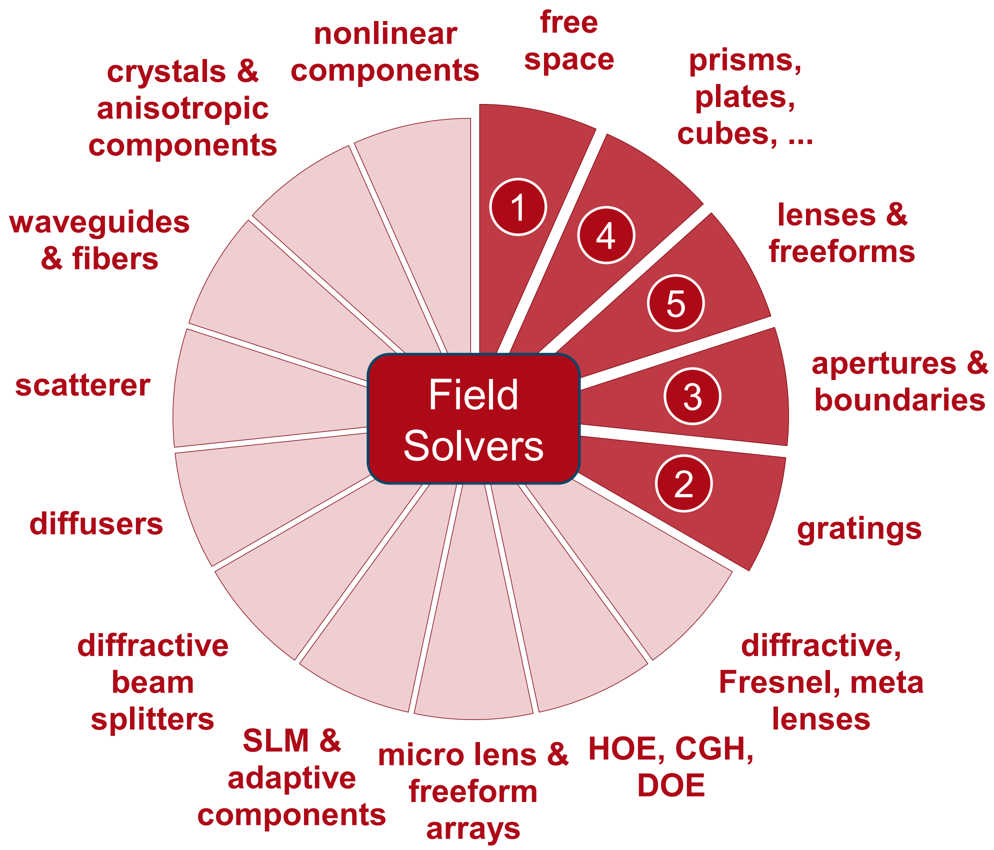
Typical Modeling Situation for AR&MR Lightguide





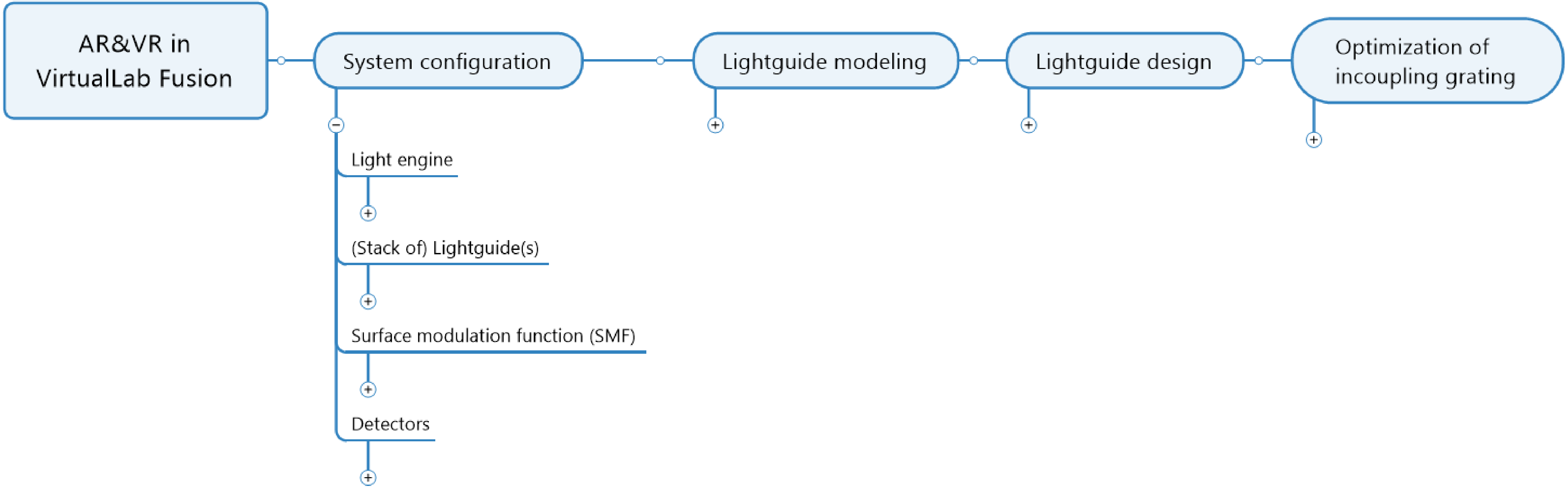


Coherence effects

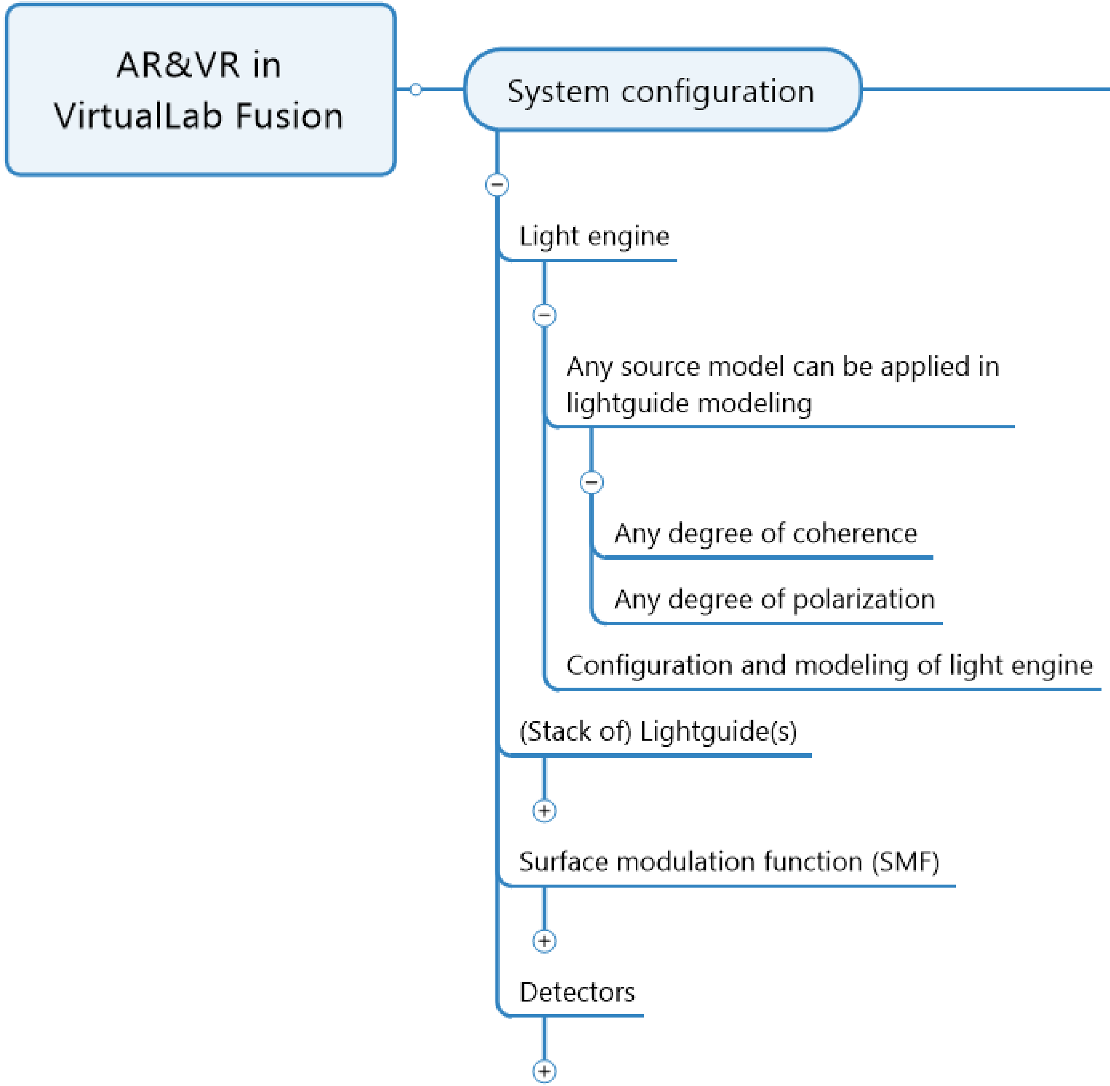
Correlation between Modes in Modeling

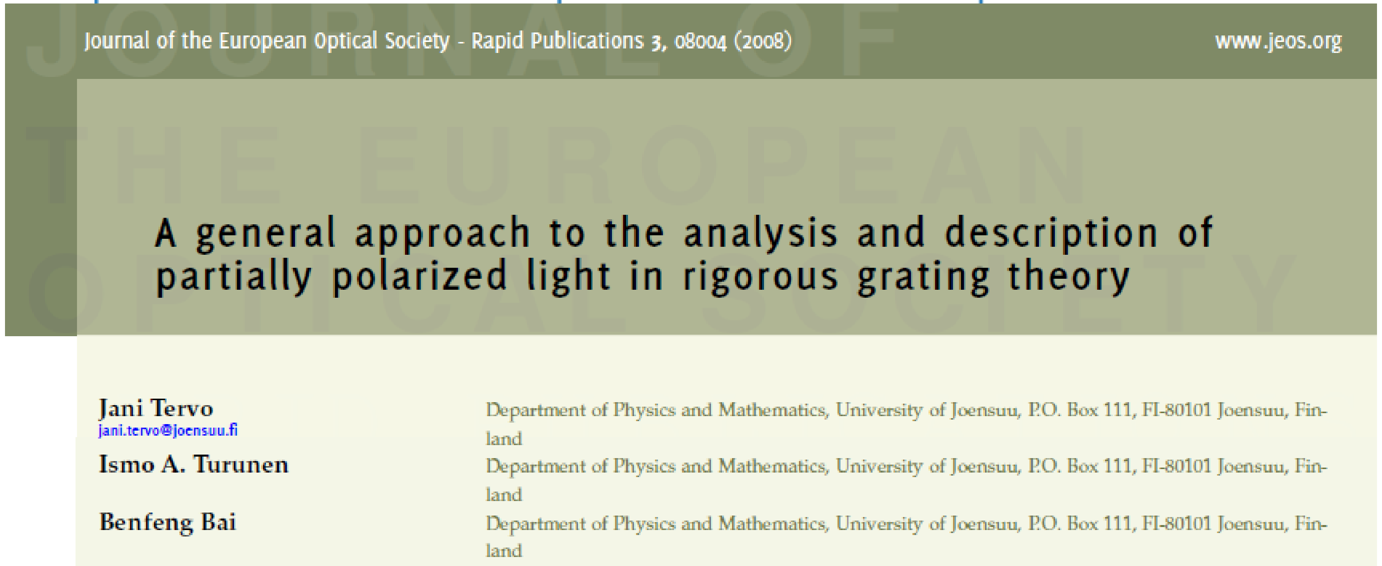
- FOV mode (one image pixel) represents electromagnetic field which consists of
  - Fully coherent modes per wavelength: spectral modes
  - Stationary sources: Spectral modes are mutually uncorrelated
  - Degree of polarization: Representation by two uncorrelated modes per spectral mode
- Each spectral mode propagates through lightguide and is split numerous times:
  - Channel modes (beams in eyebox)
  - Channel modes per spectral mode are mutually correlated!

Lightguide Modeling and Design



Lightguide Modeling and Design




Journal of the European Optical Society - Rapid Publications 3, 08004 (2008) www.jeos.org

A general approach to the analysis and description of partially polarized light in rigorous grating theory

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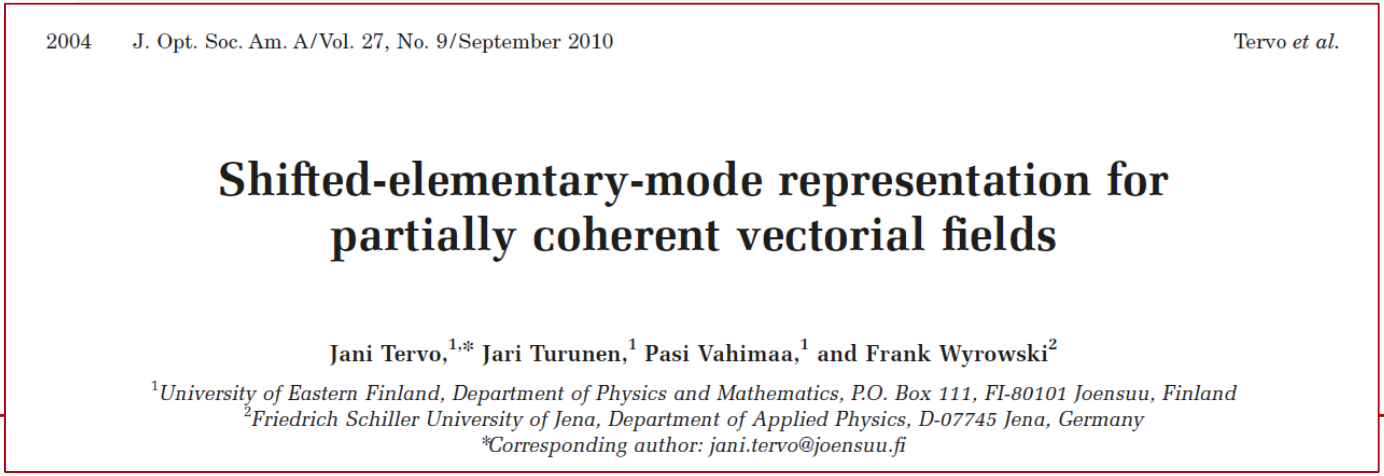
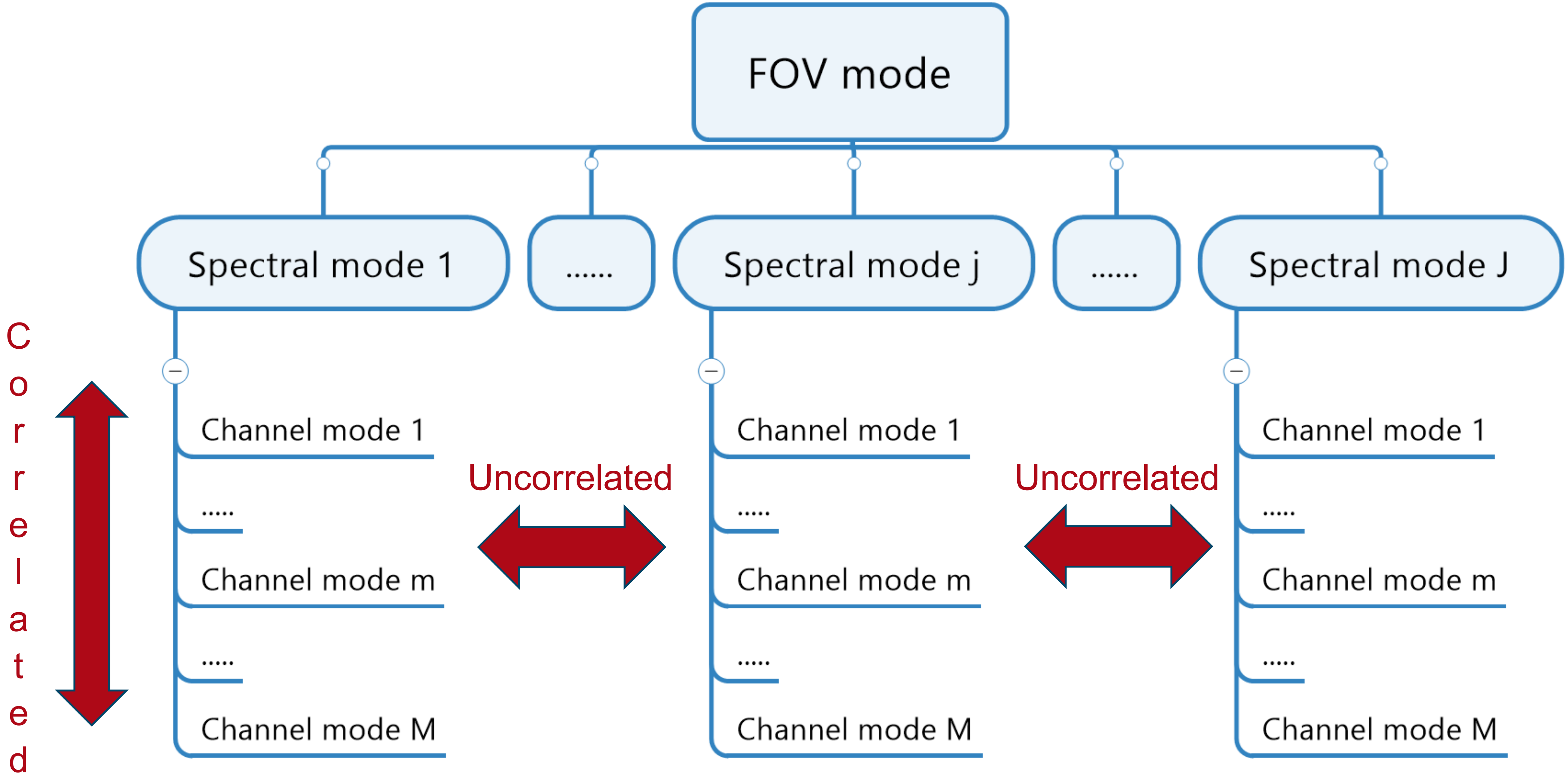
Ismo A. Turunen Department of Physics and Mathematics, University of Joensuu, P.O. Box 111, FI-80101 Joensuu, Finland
Benfeng Bai Department of Physics and Mathematics, University of Joensuu, P.O. Box 111, FI-80101 Joensuu, Finland


2004 J. Opt. Soc. Am. A/Vol. 27, No. 9/September 2010 Tervo *et al.*

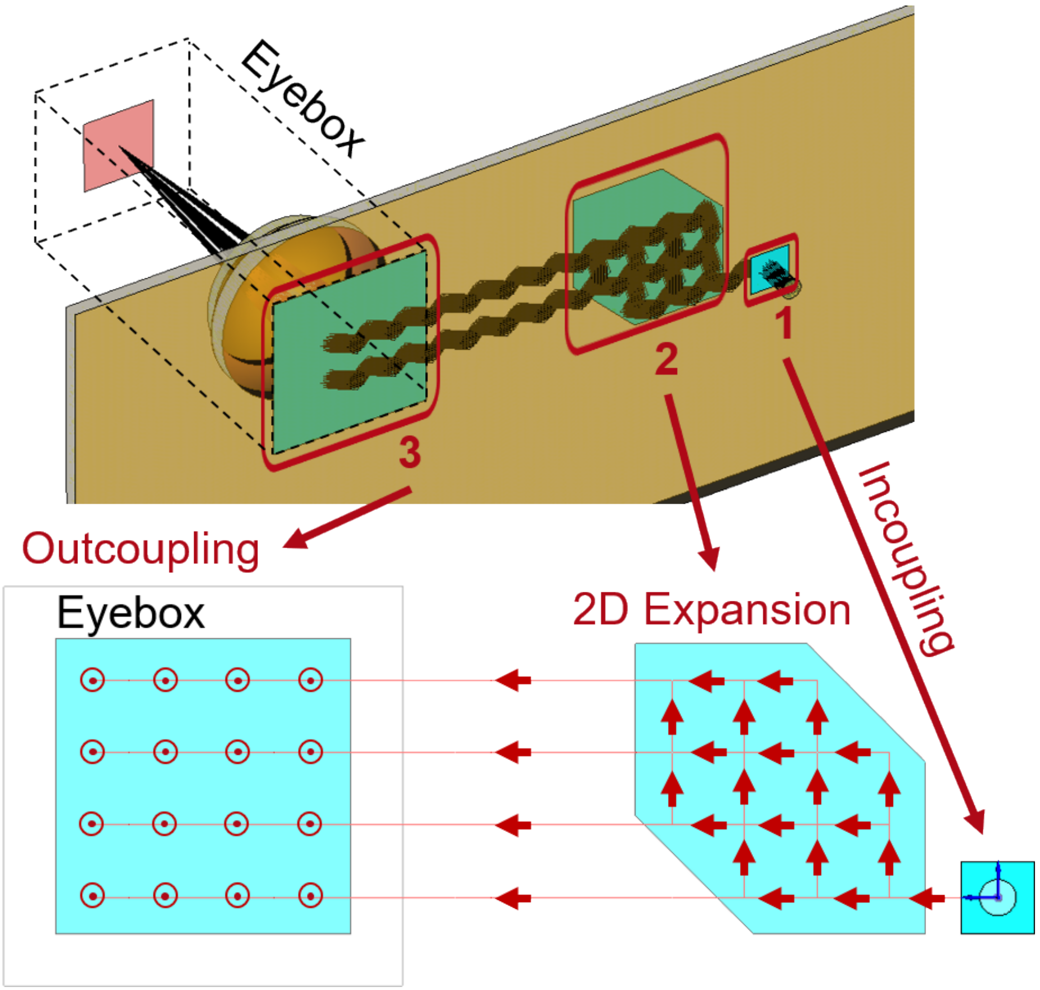
Shifted-elementary-mode representation for partially coherent vectorial fields

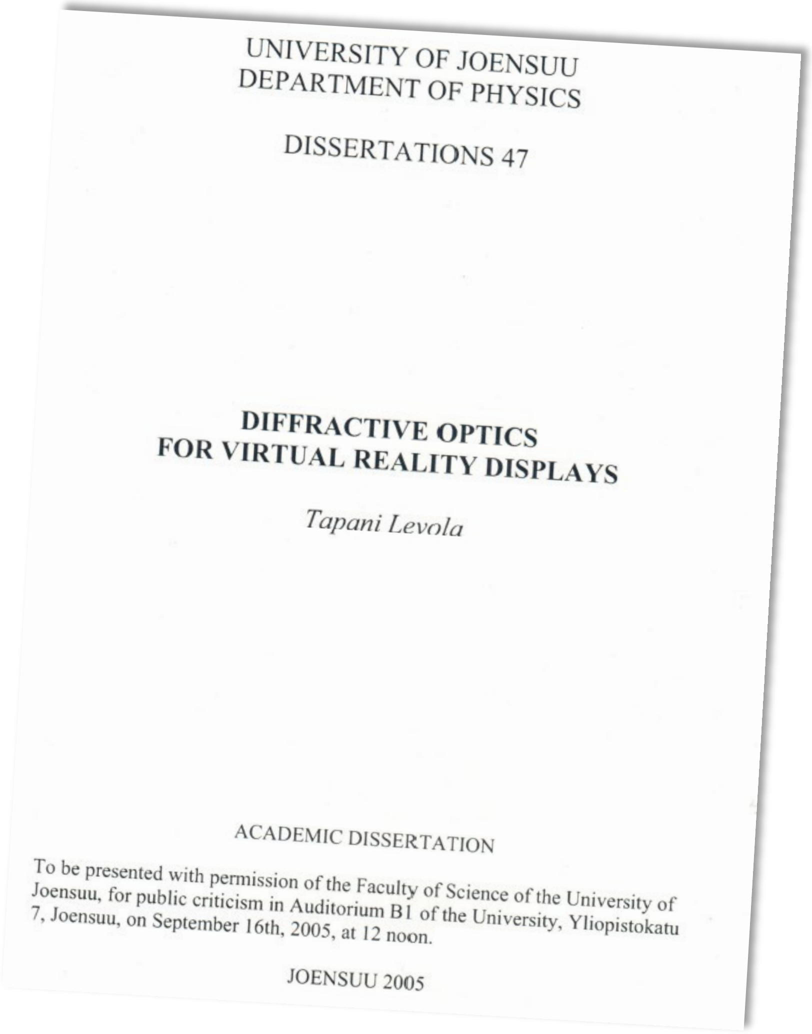
Jani Tervo,[1,*] Jari Turunen,[1] Pasi Vahimaa,[1] and Frank Wyrowski[2]
[1]*University of Eastern Finland, Department of Physics and Mathematics, P.O. Box 111, FI-80101 Joensuu, Finland*
[2]*Friedrich Schiller University of Jena, Department of Applied Physics, D-07745 Jena, Germany*
**Corresponding author: jani.tervo@joensuu.fi*

Correlation between Modes in Modeling



Levola Type Geometry of Eye Pupil Expansion (EPE)




UNIVERSITY OF JOENSUU
DEPARTMENT OF PHYSICS

DISSERTATIONS 47

DIFFRACTIVE OPTICS
FOR VIRTUAL REALITY DISPLAYS

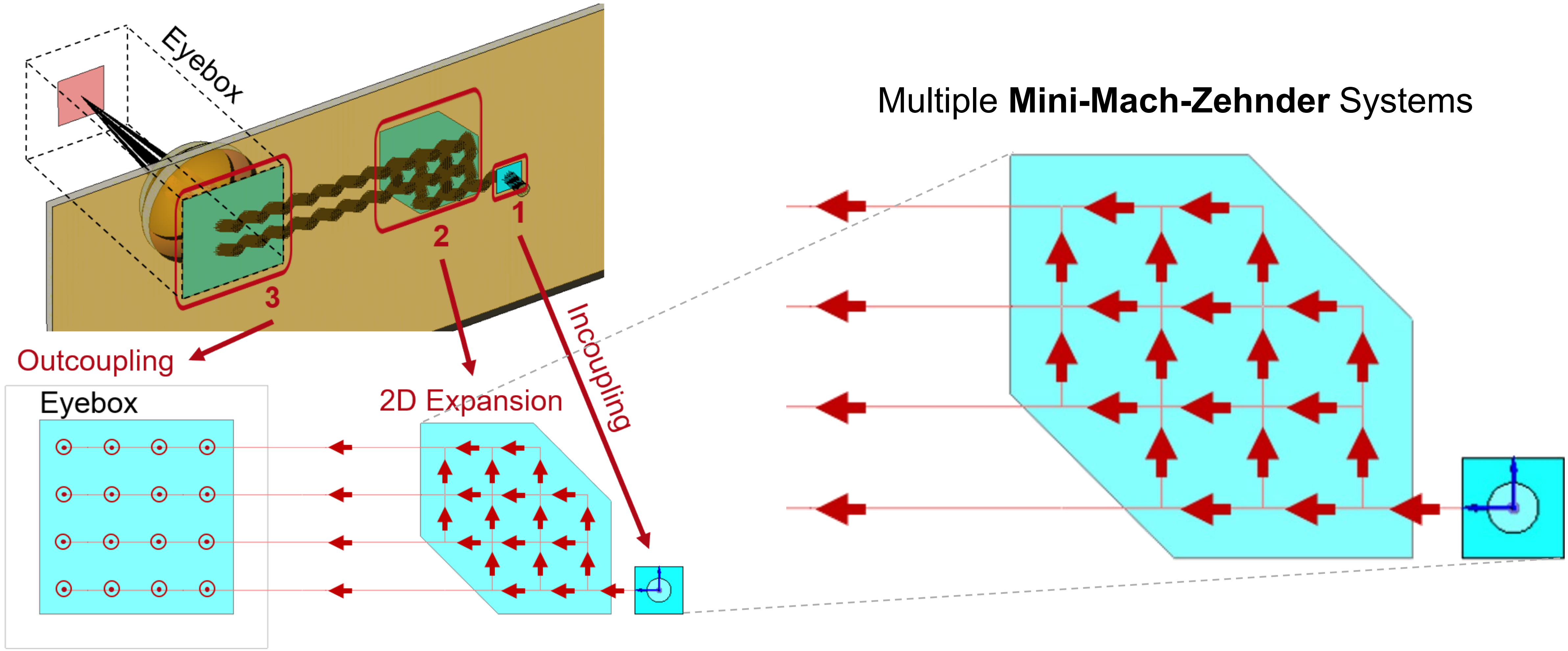
Tapani Levola

ACADEMIC DISSERTATION

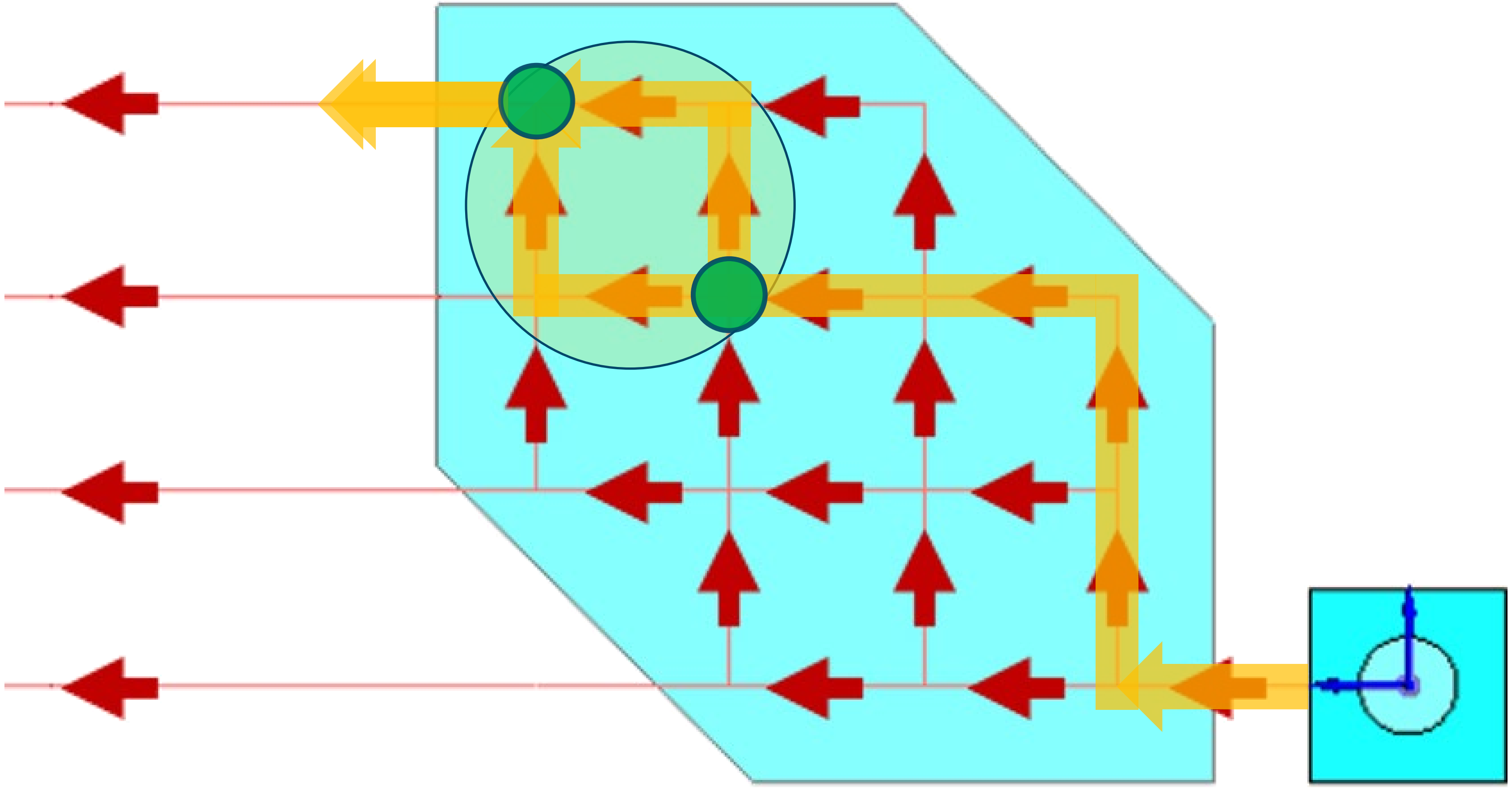
To be presented with permission of the Faculty of Science of the University of Joensuu, for public criticism in Auditorium B1 of the University, Yliopistokatu 7, Joensuu, on September 16th, 2005, at 12 noon.

JOENSUU 2005

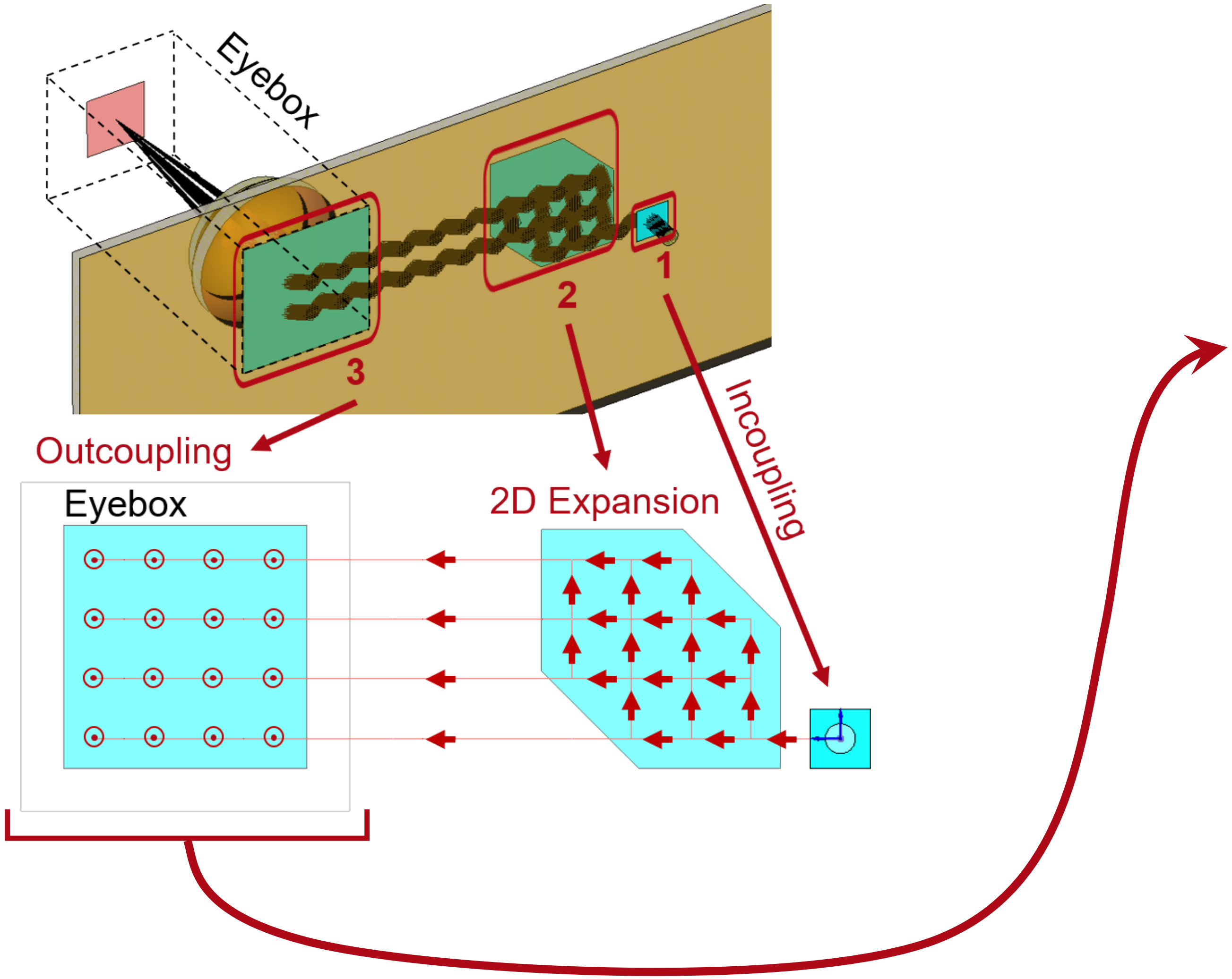
Levola Type Geometry of Eye Pupil Expansion (EPE)

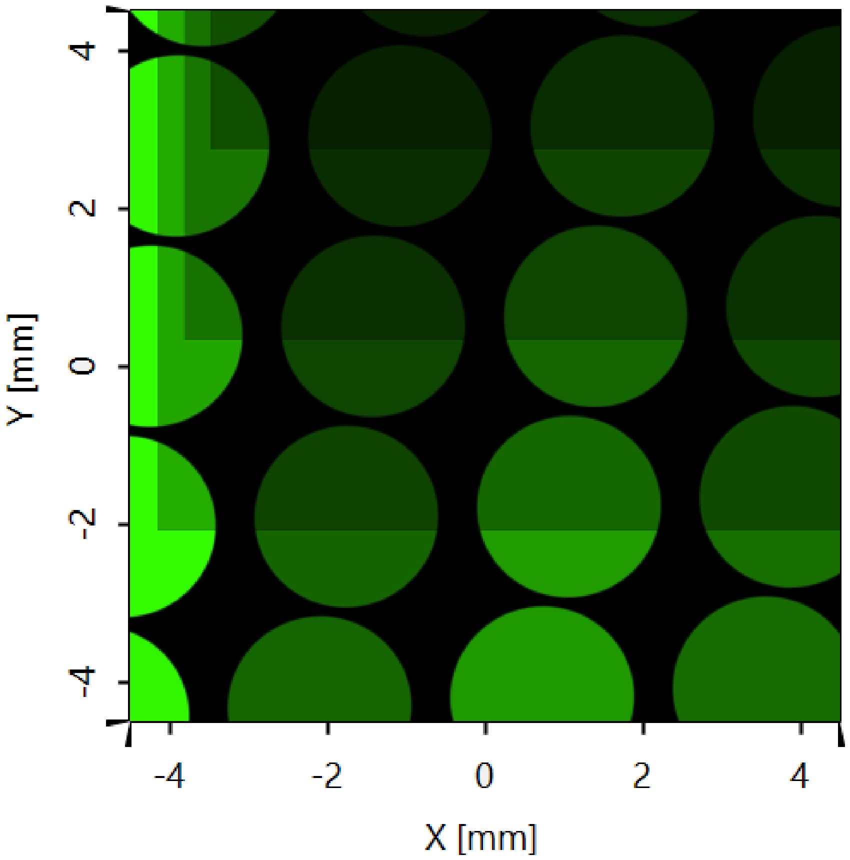


Mini Mach-Zehnder Inferferometer Lightpaths: Channel Modes



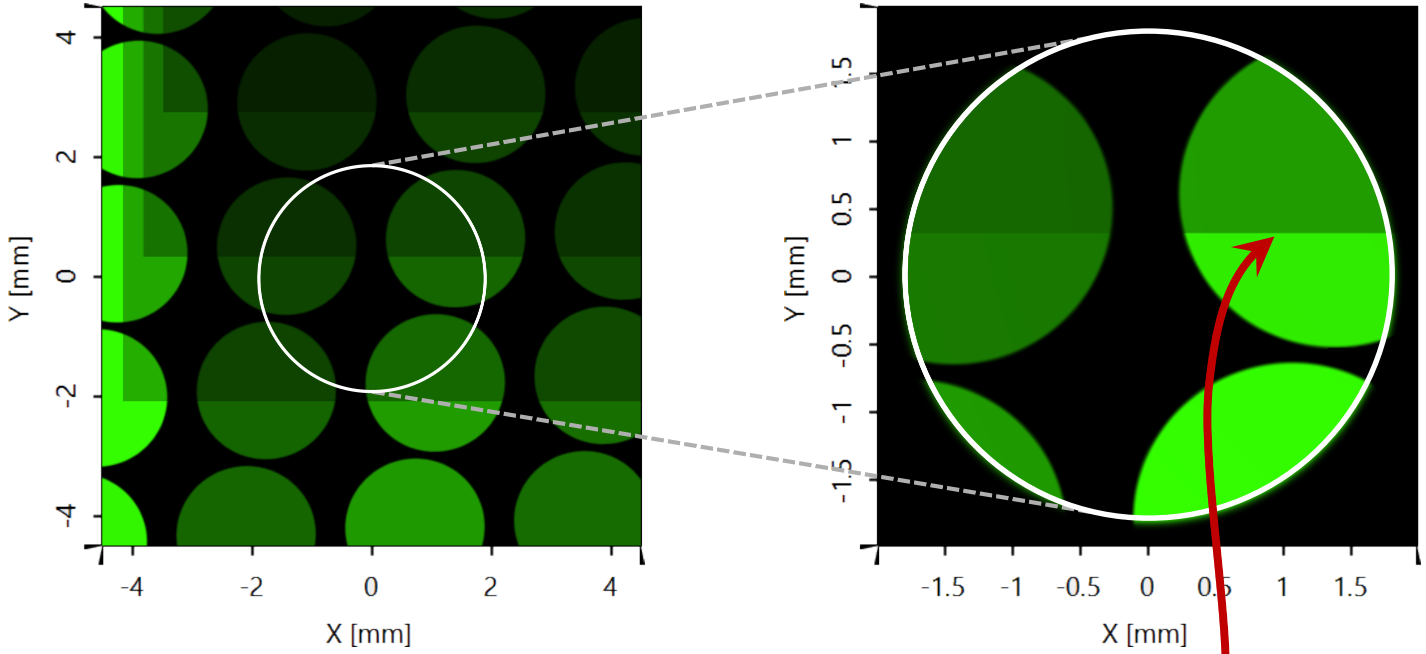
Lightguide Setup & Evaluation of Outcoupled Light





Exemplary
Outcoupled Light

Outcoupled Light Modes Passing Through Eye Pupil



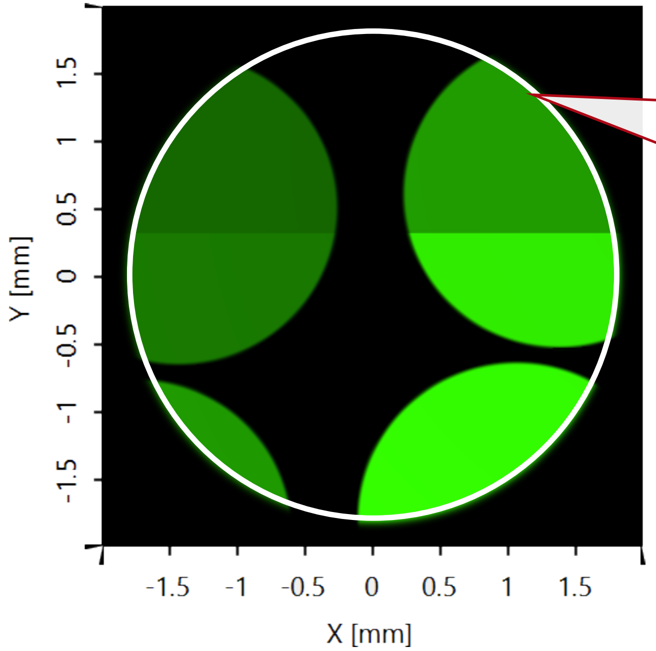
marginal area
of outcouling grating region

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

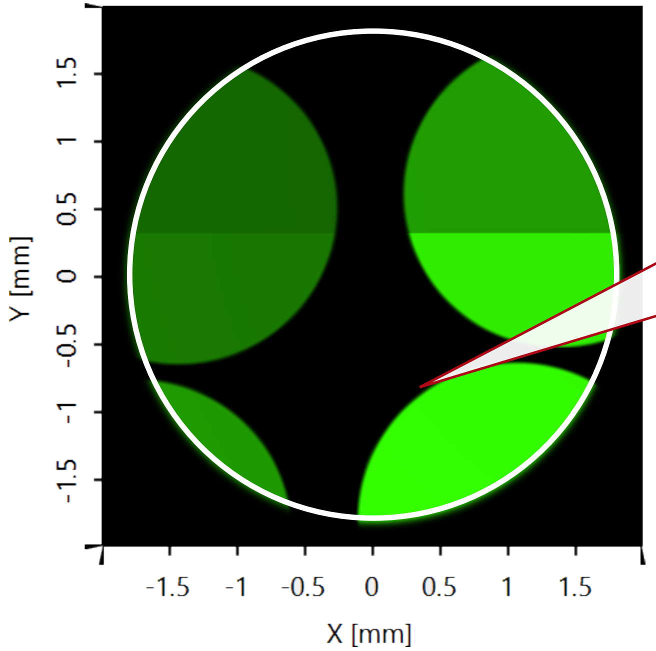
Outcoupled Light Modes Passing Through Eye Pupil



light passing the eye pupil

Boundary effects should be included in high resolution

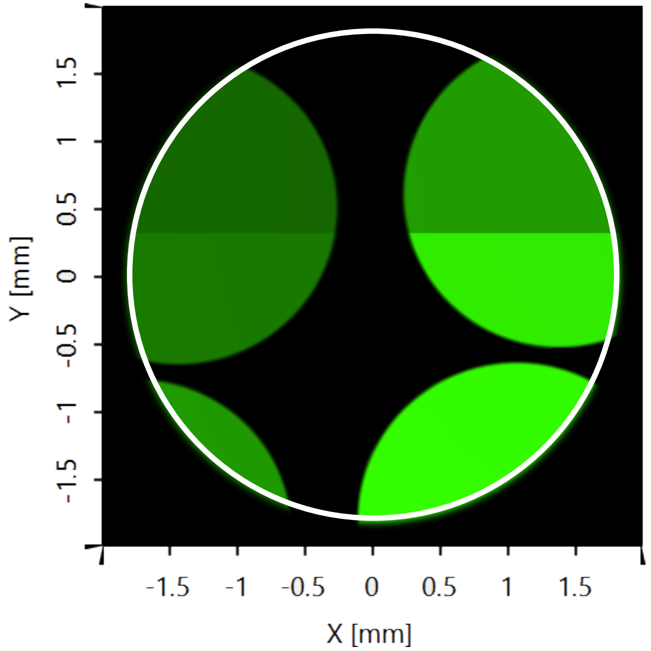
Outcoupled Light Modes Passing Through Eye Pupil



light passing the eye pupil

Boundary effects should be included in high resolution

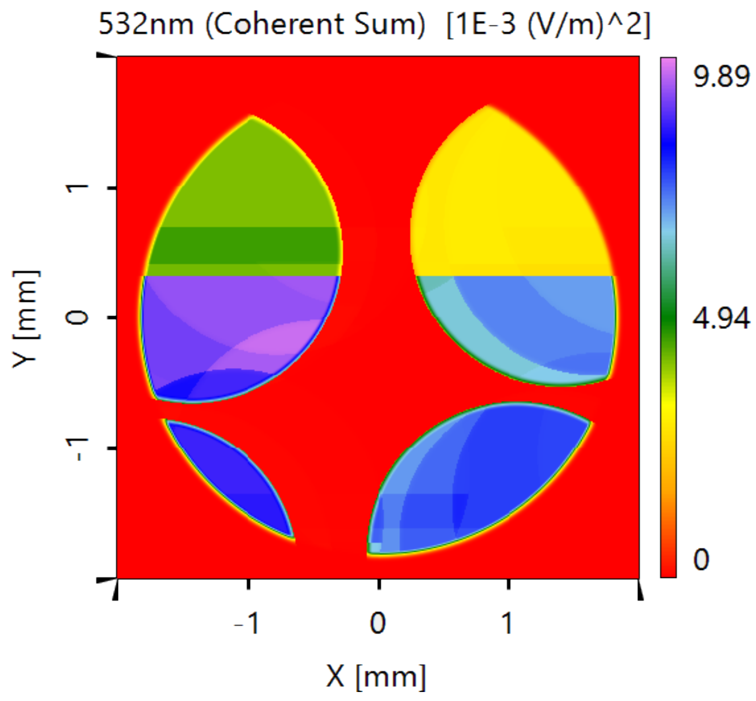
Outcoupled Light Modes Passing Through Eye Pupil



light passing the eye pupil

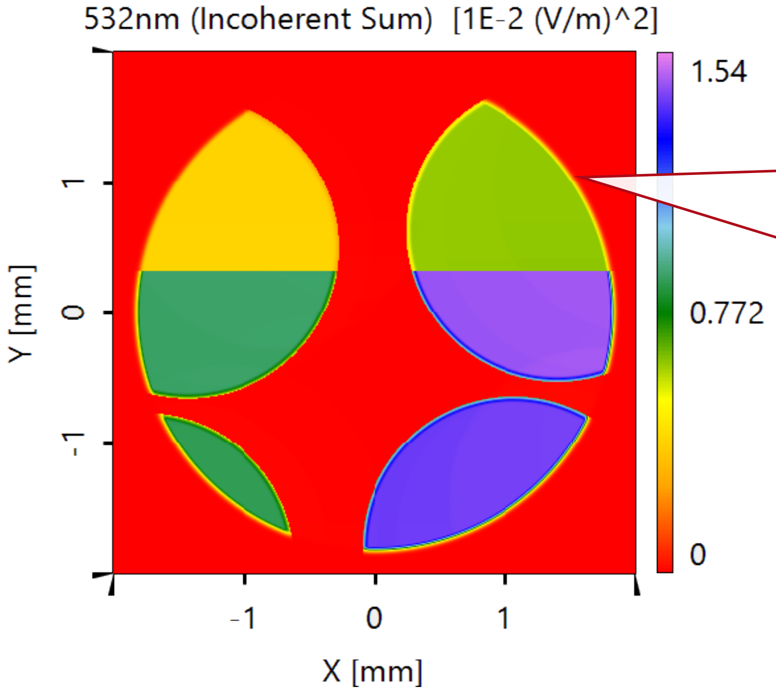
For one wavelength and one FOV the pupil is partly filled with mutually correlated channel modes.

Outcoupled Light Modes Passing Through Eye Pupil



For one wavelength and one FOV the pupil is partly filled with mutually correlated channel modes.

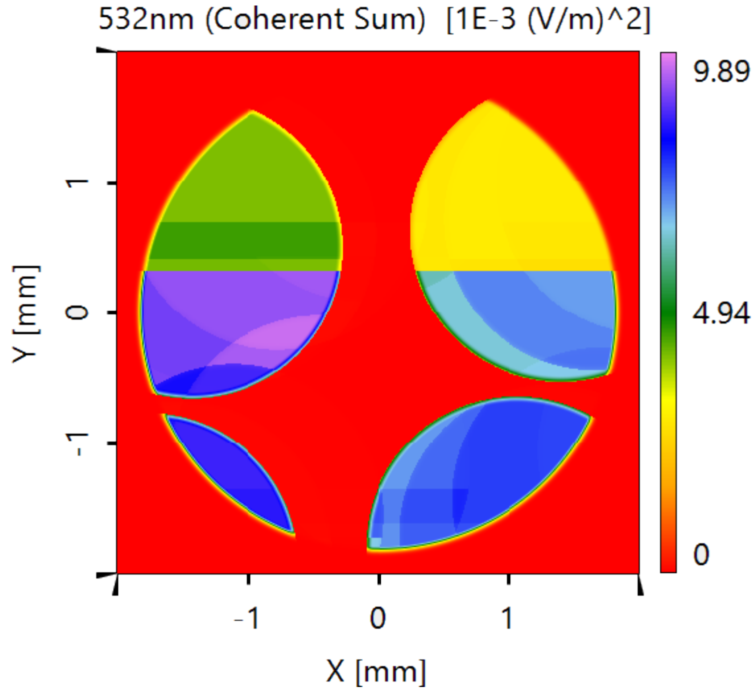
Outcoupled Light Modes Passing Through Eye Pupil



Assumption of uncorrelated modes leads to wrong result!

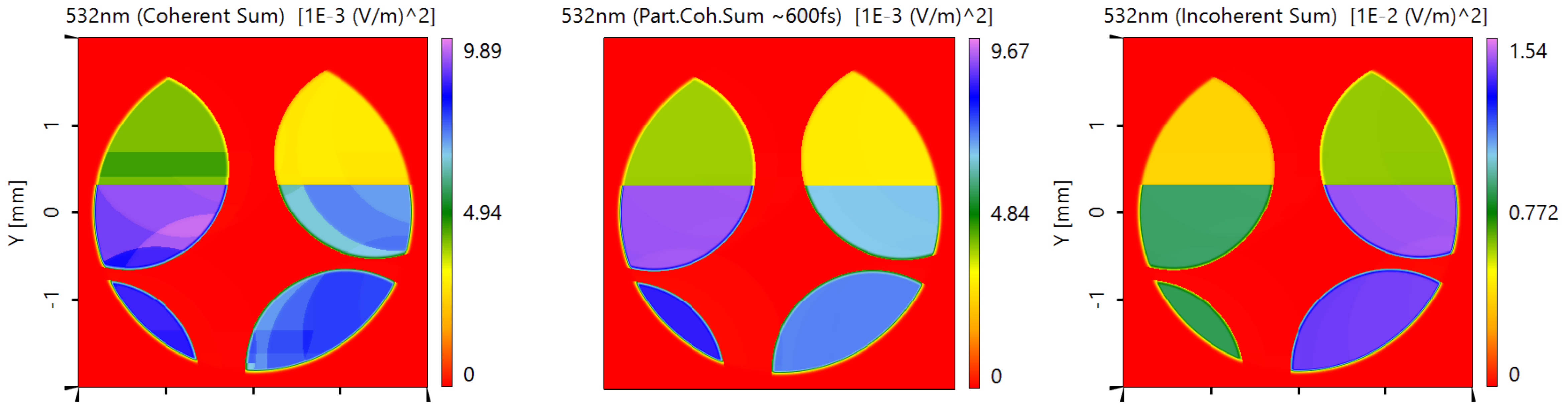
For one wavelength and one FOV the pupil is partly filled with mutually correlated channel modes.

Light Modes Passing Through Eye Pupil: Single Spectral Mode



For one wavelength and one FOV the pupil is partly filled with mutually correlated channel modes.

Light Modes Passing Through Eye Pupil: 1nm Bandwidth



Coherent

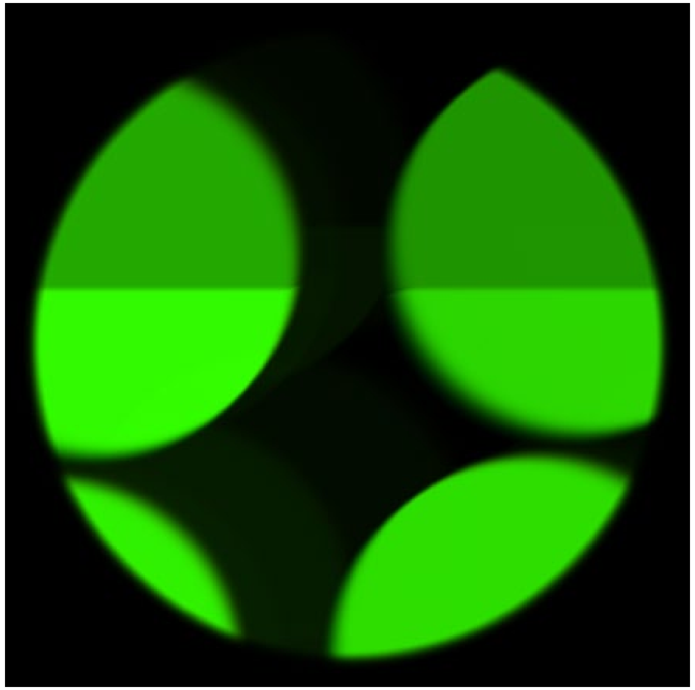
Partially Coherent

Incoherent

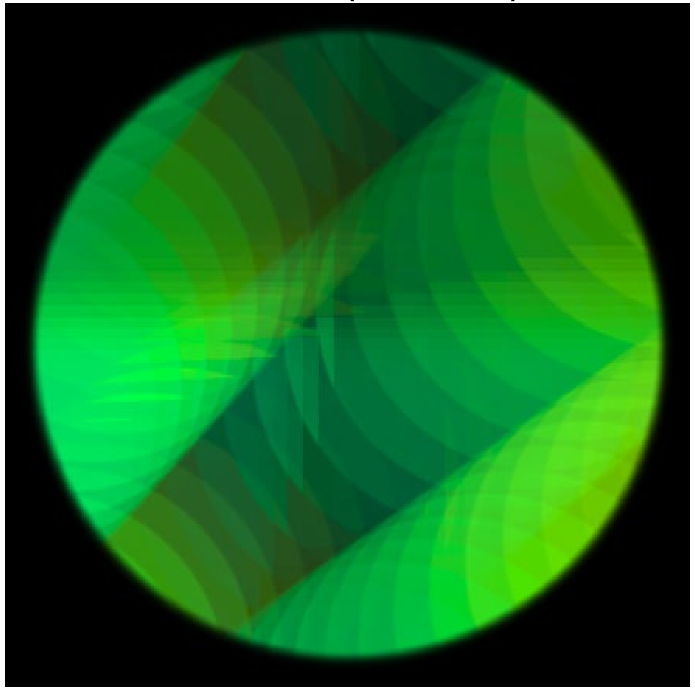
Pupil is partly filled with mutually correlated channel modes per uncorrelated spectral modes.

Light Modes Passing Through Eye Pupil

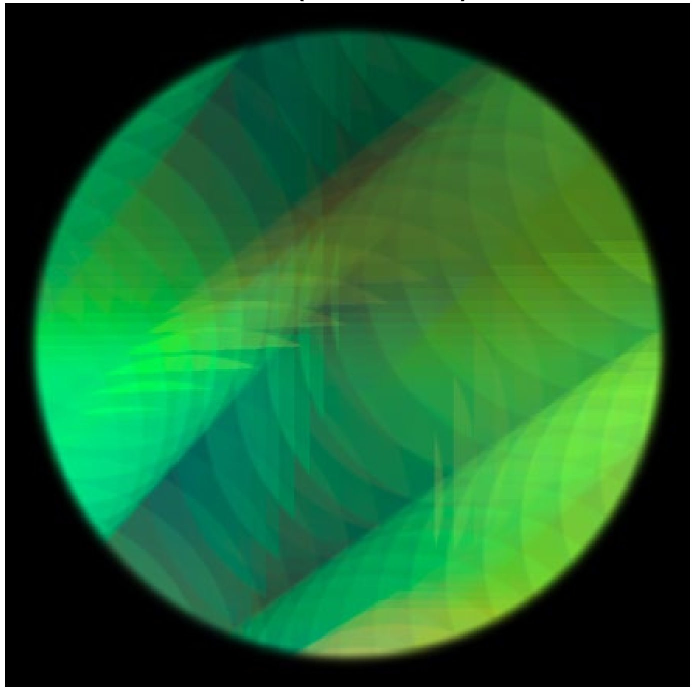
...of a
laser diode (~1 nm)



...of a
VCSEL (~20 nm)



...of an
LED (~40 nm)



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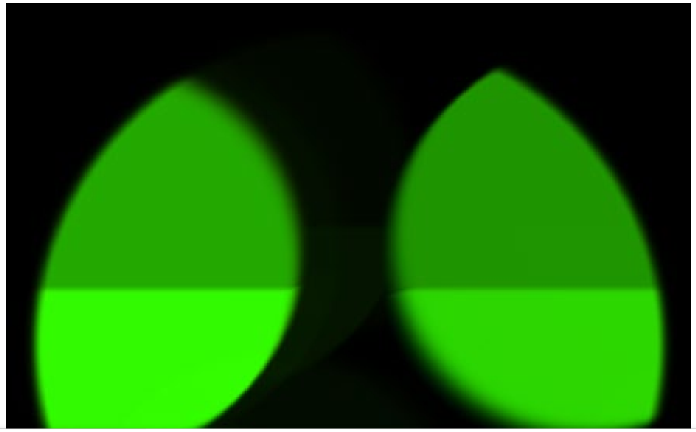
Light Modes Passing Through Eye Pupil

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



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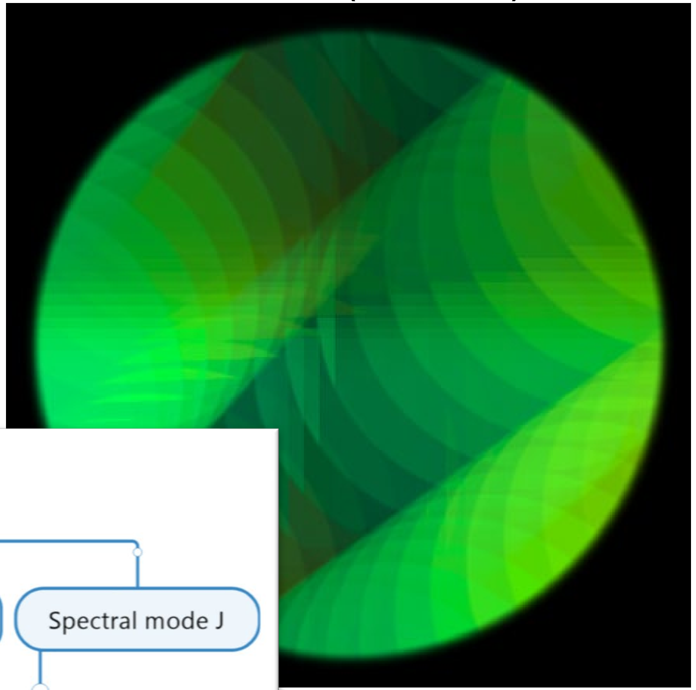

...of an
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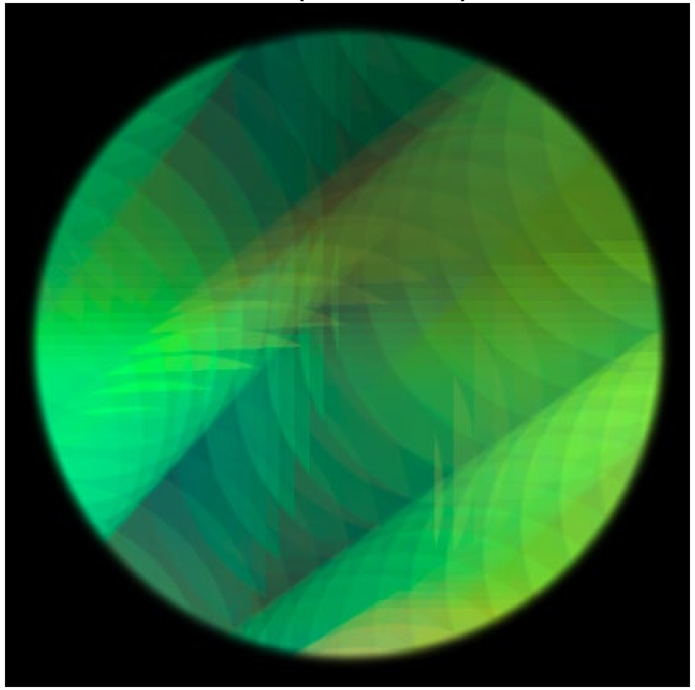
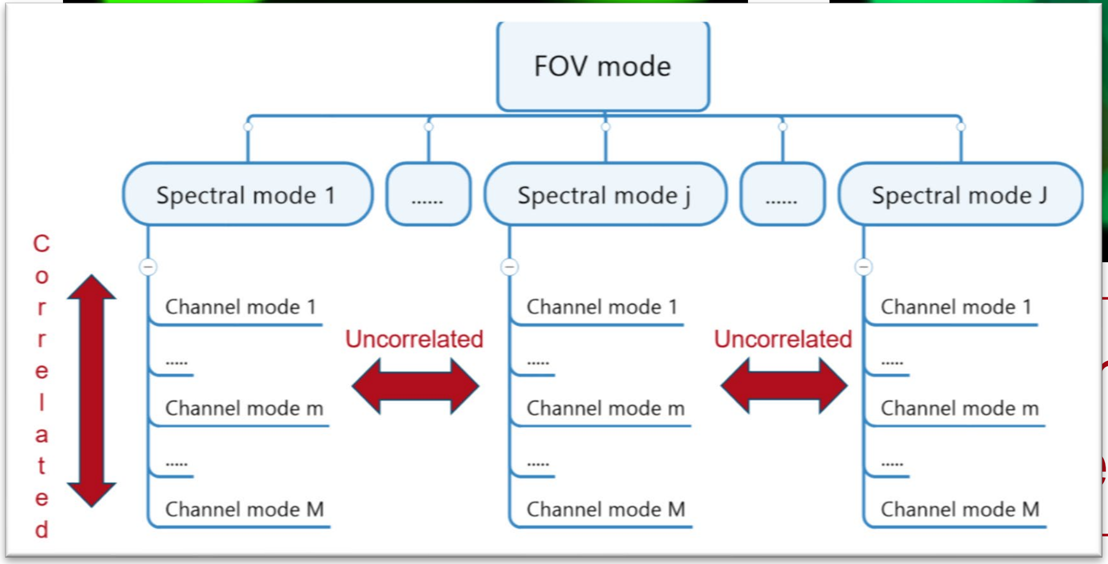


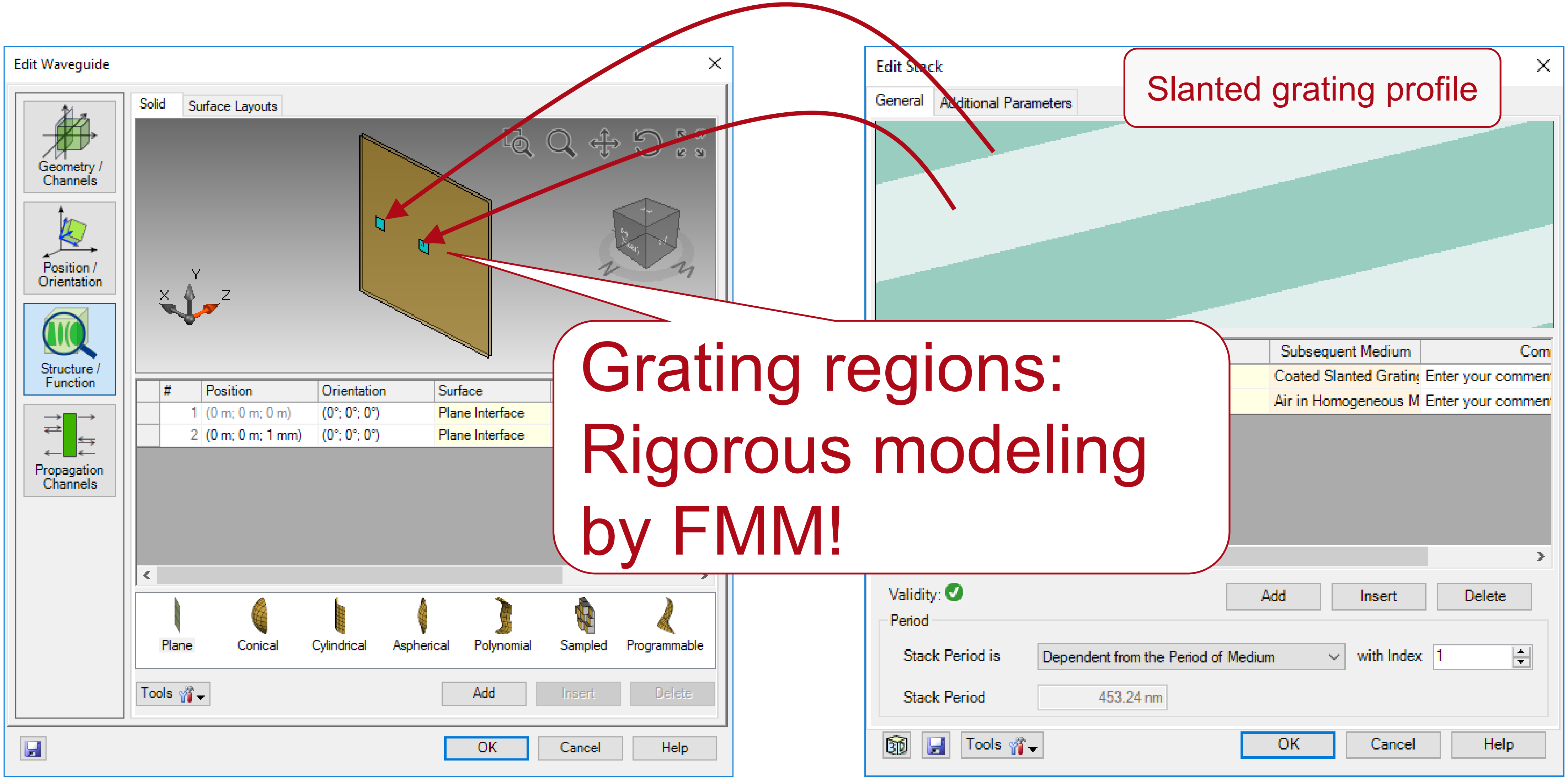


mutually correlated channel
lated spectral modes.

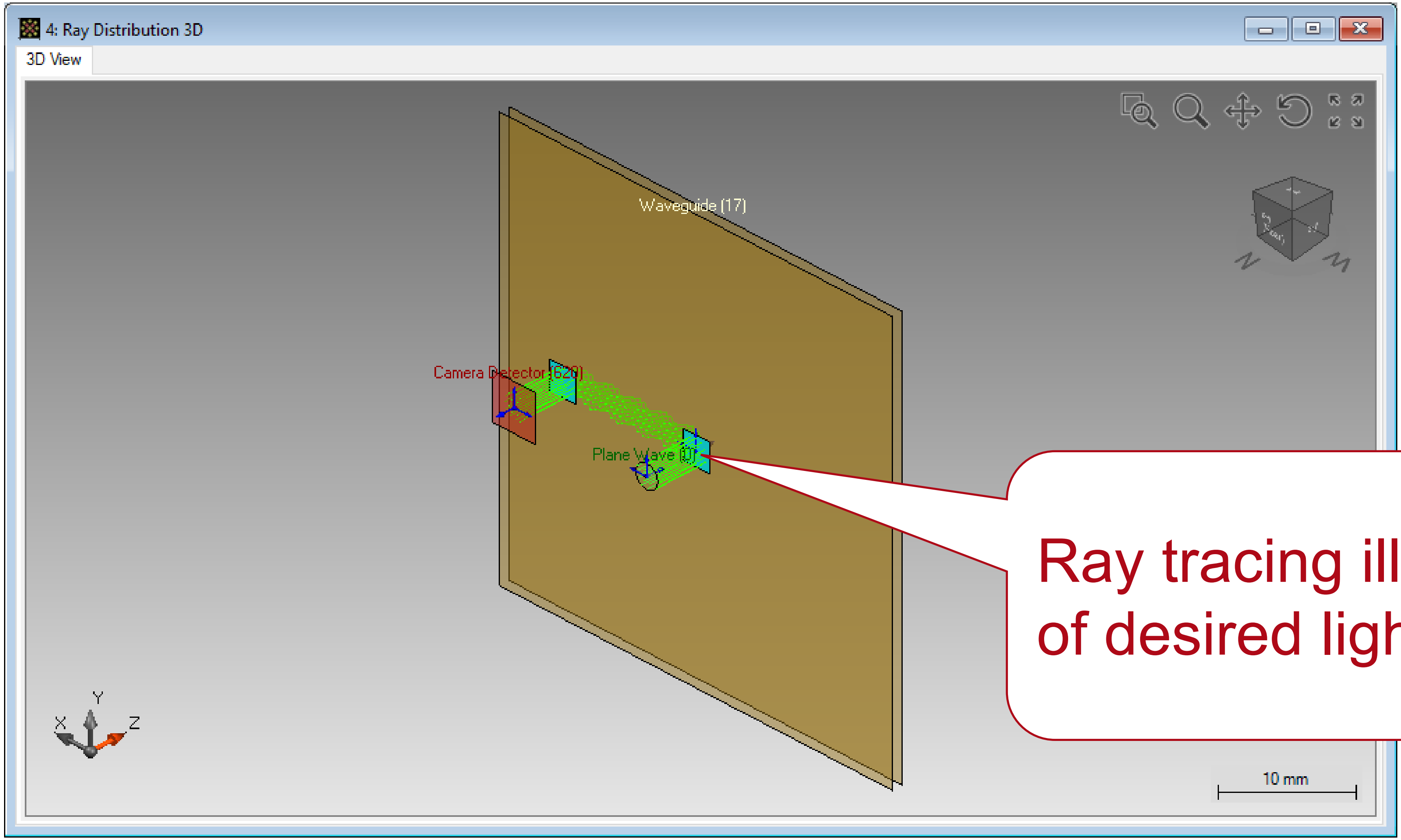
Energy conservation per spectral mode

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

Modeling Task: In- and Outcoupling

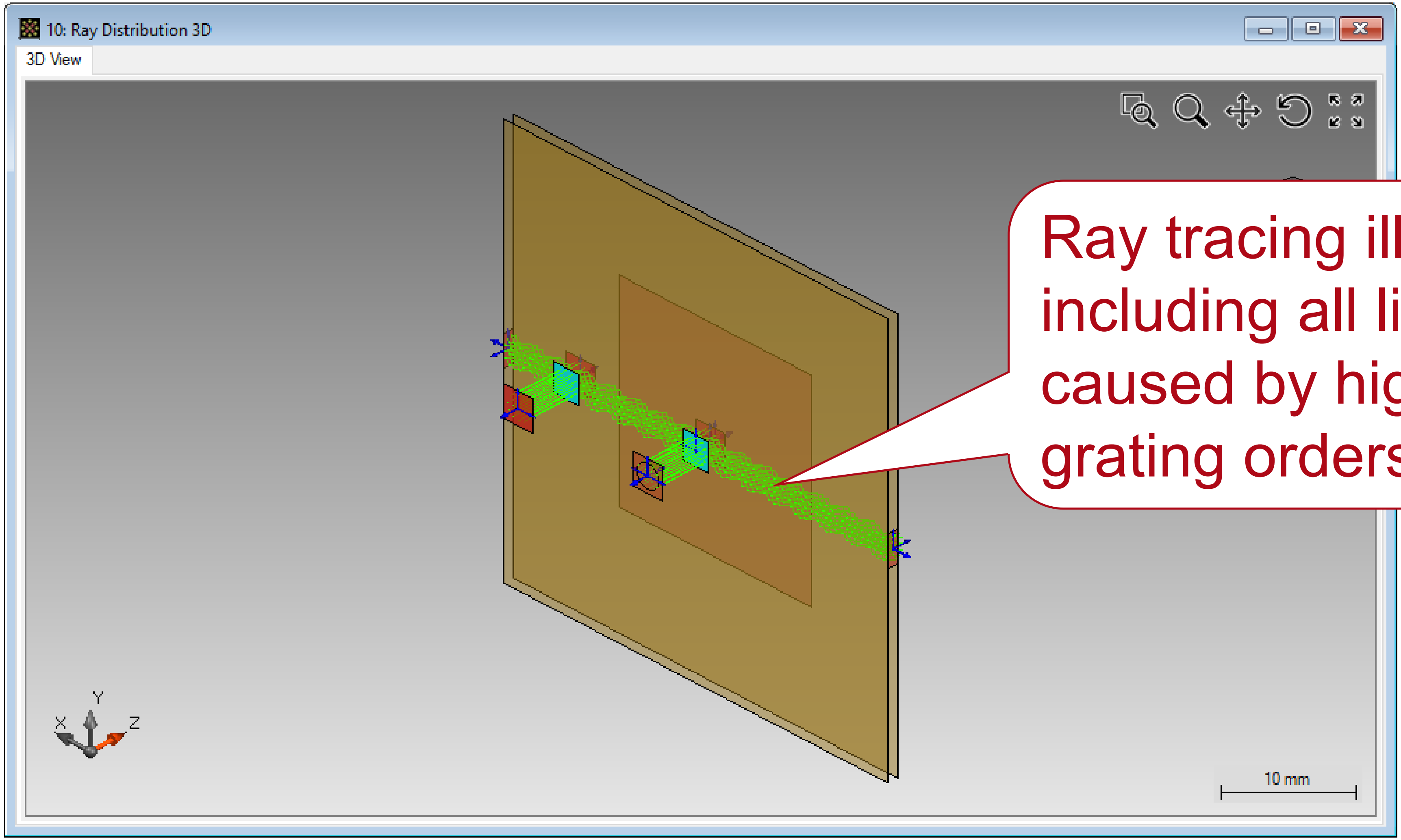


Result by 3D Ray Tracing (Working Orders)



Ray tracing illustration of desired lightpath.

Result by 3D Ray Tracing (All Orders)

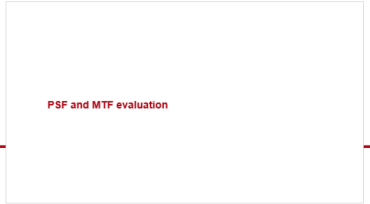


Ray tracing illustration including all lightpaths caused by higher grating orders.

Rigorous Overall Efficiency Evaluation

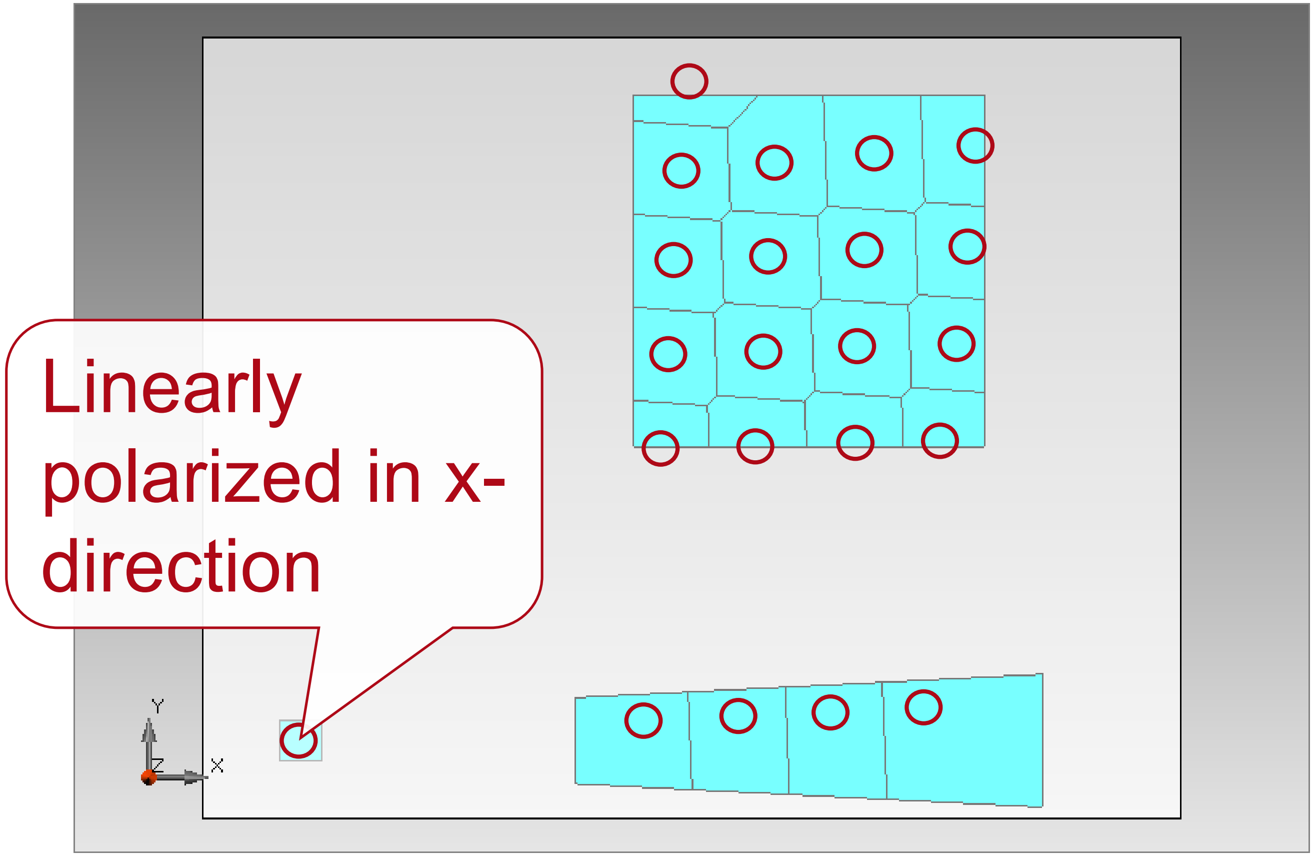
- Physical-optics analysis of all lightpaths.
- Combination including polarization and coherence!

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%**

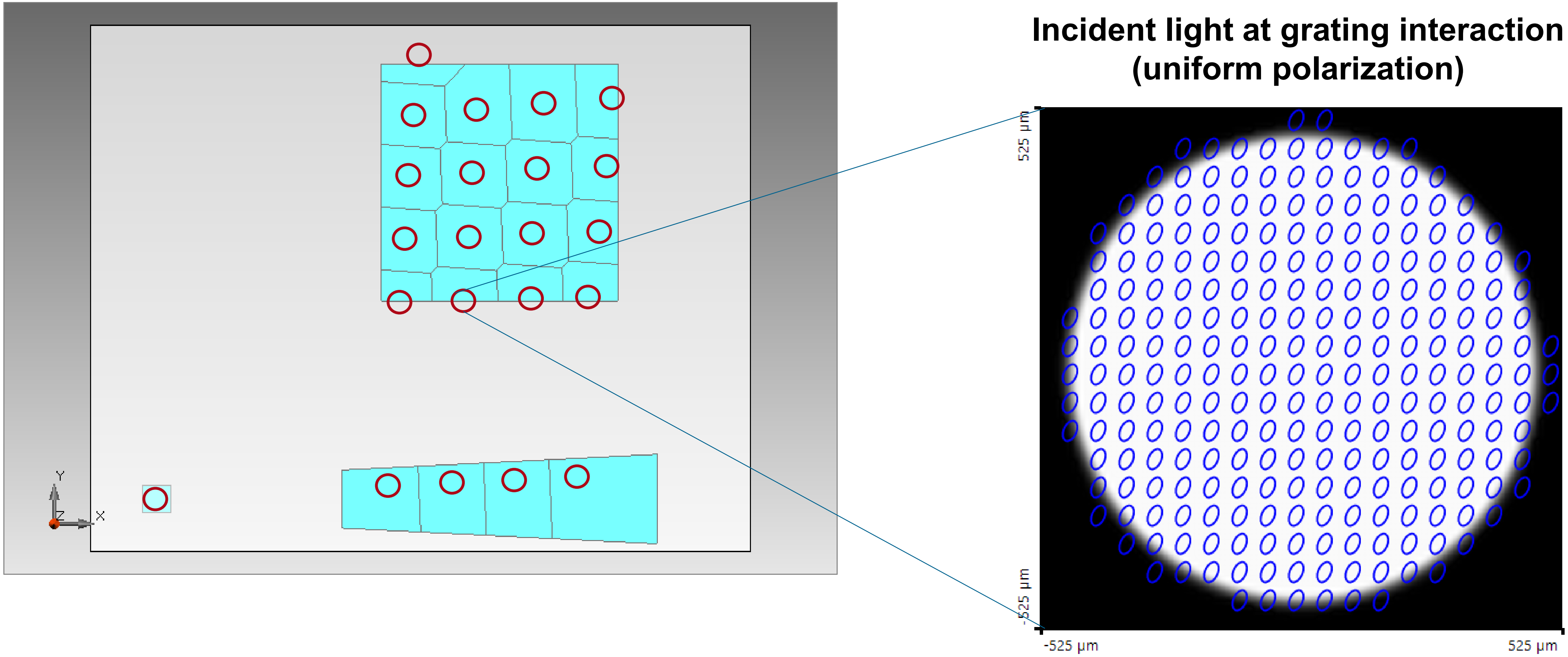


Polarization effects

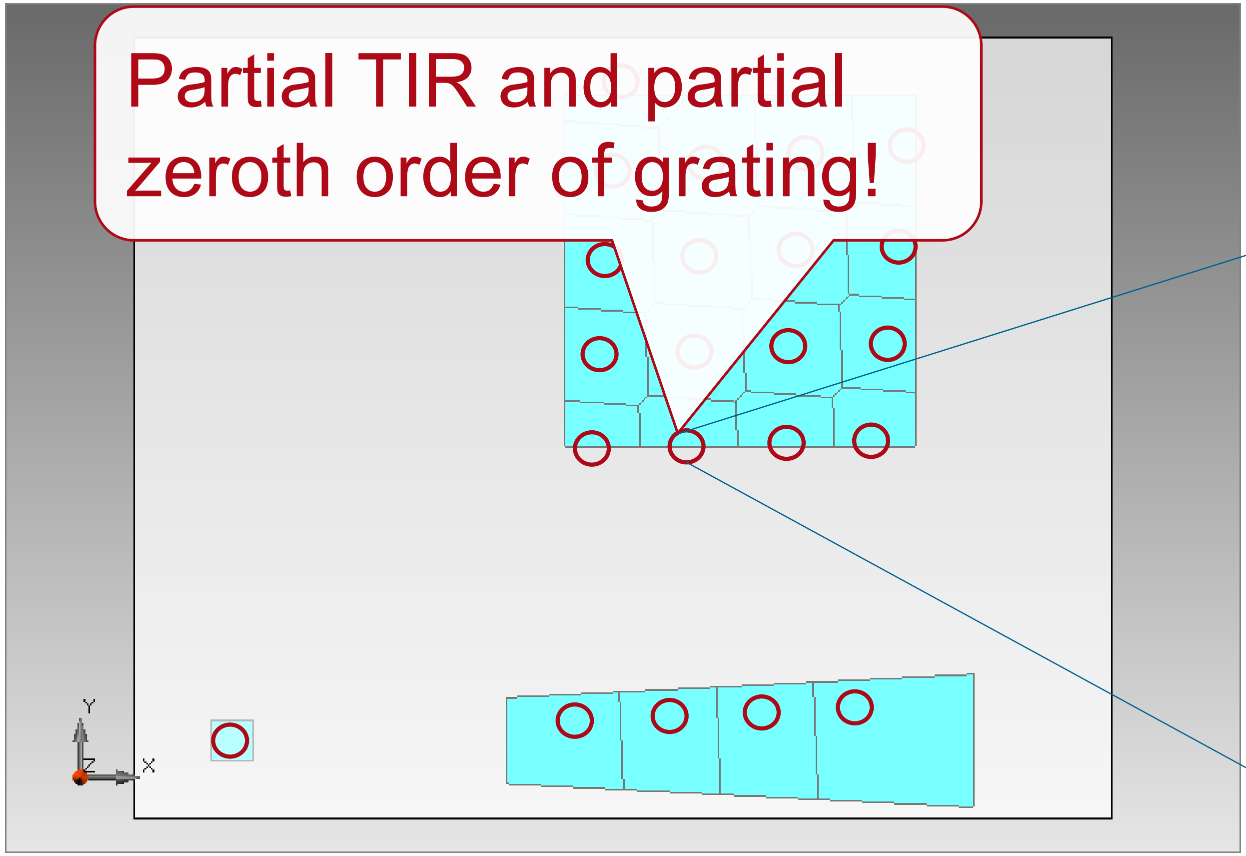
Grating Design for FOV Angle (5°, 3°) – Polarization Evaluation



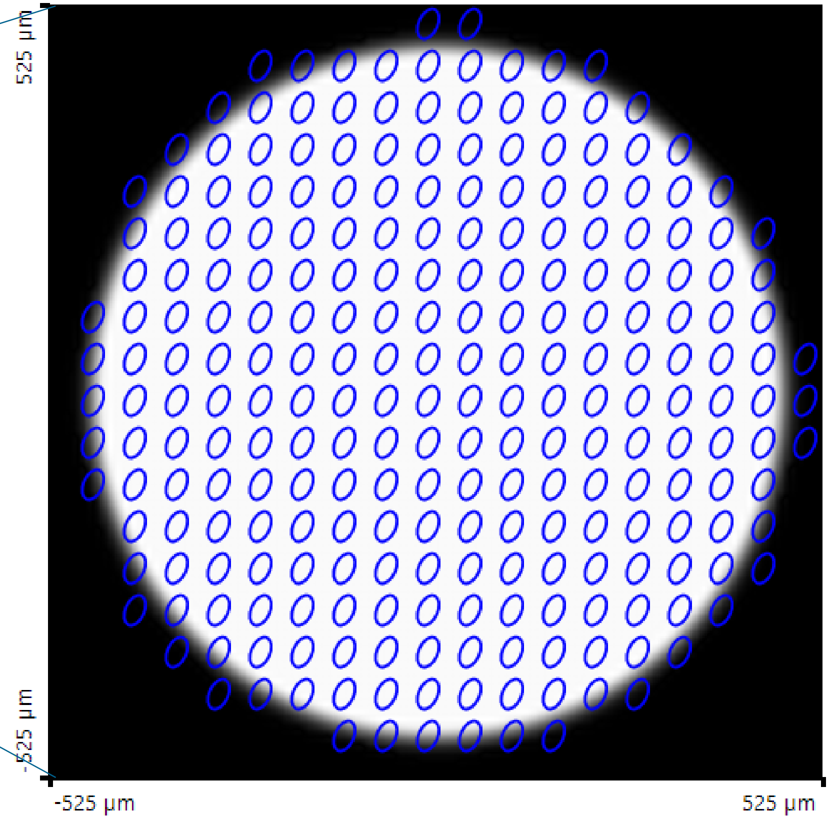
Grating Design for FOV Angle (5°, 3°) – Polarization Evaluation



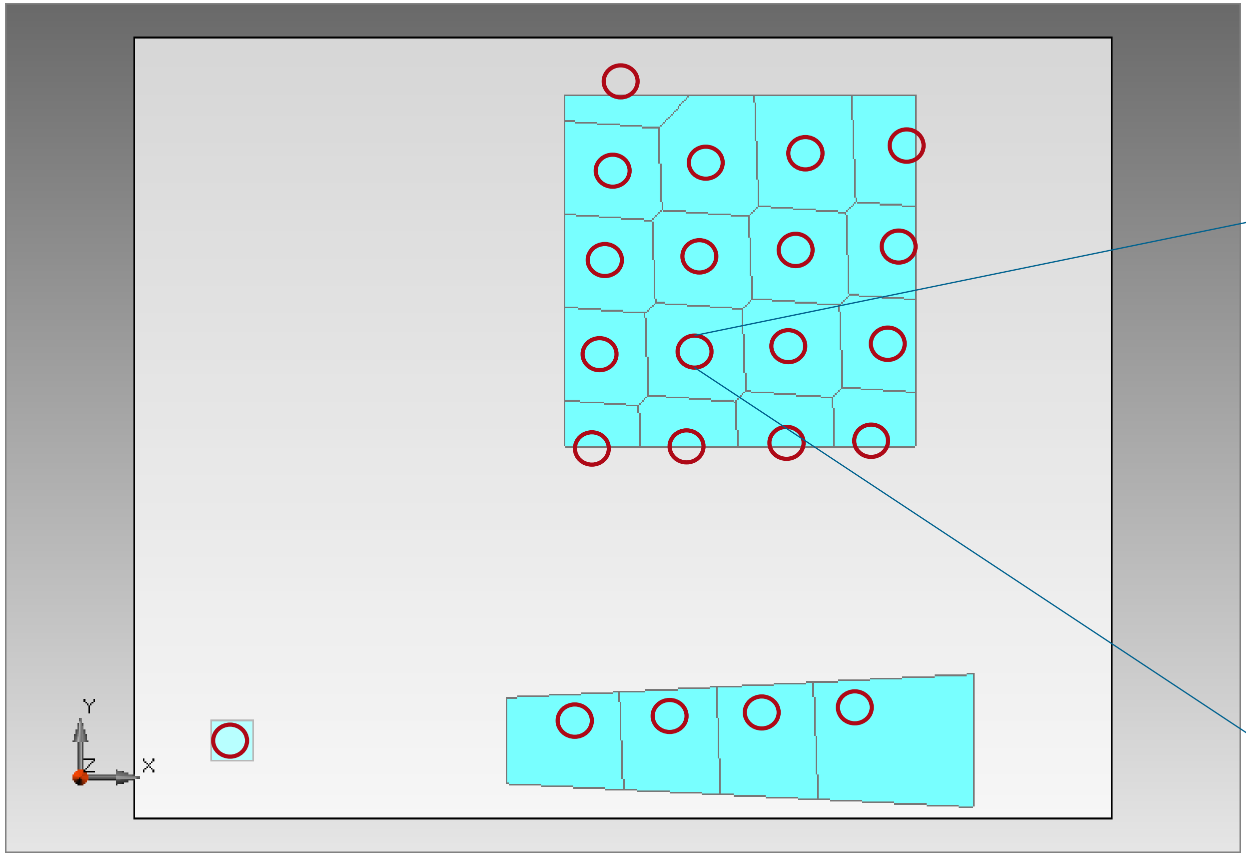
Grating Design for FOV Angle (5°, 3°) – Polarization Evaluation



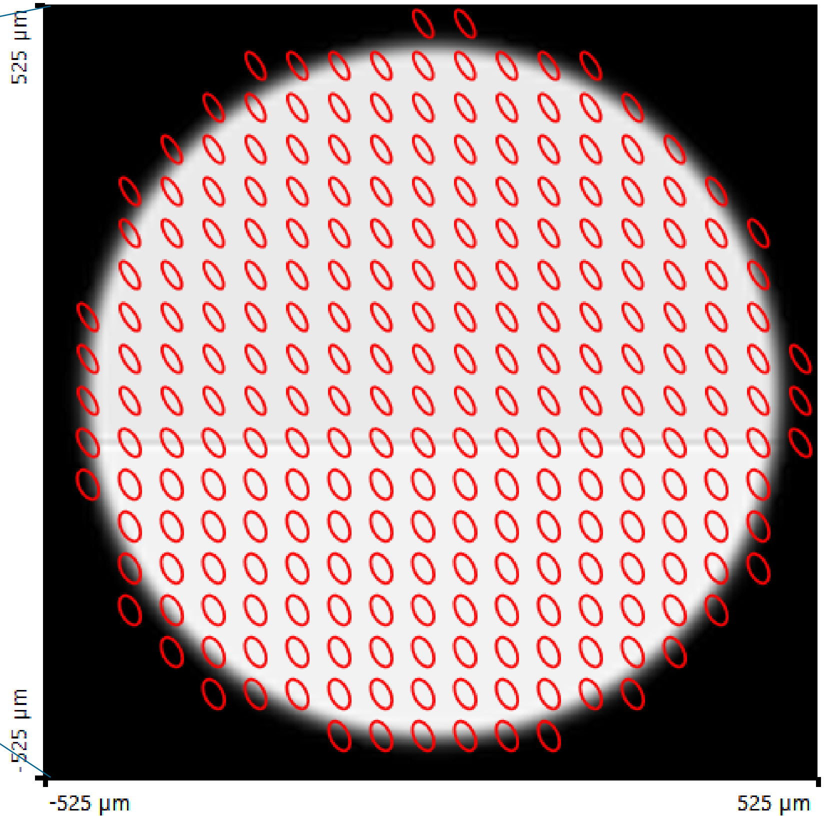
Incident light at grating interaction (uniform polarization)



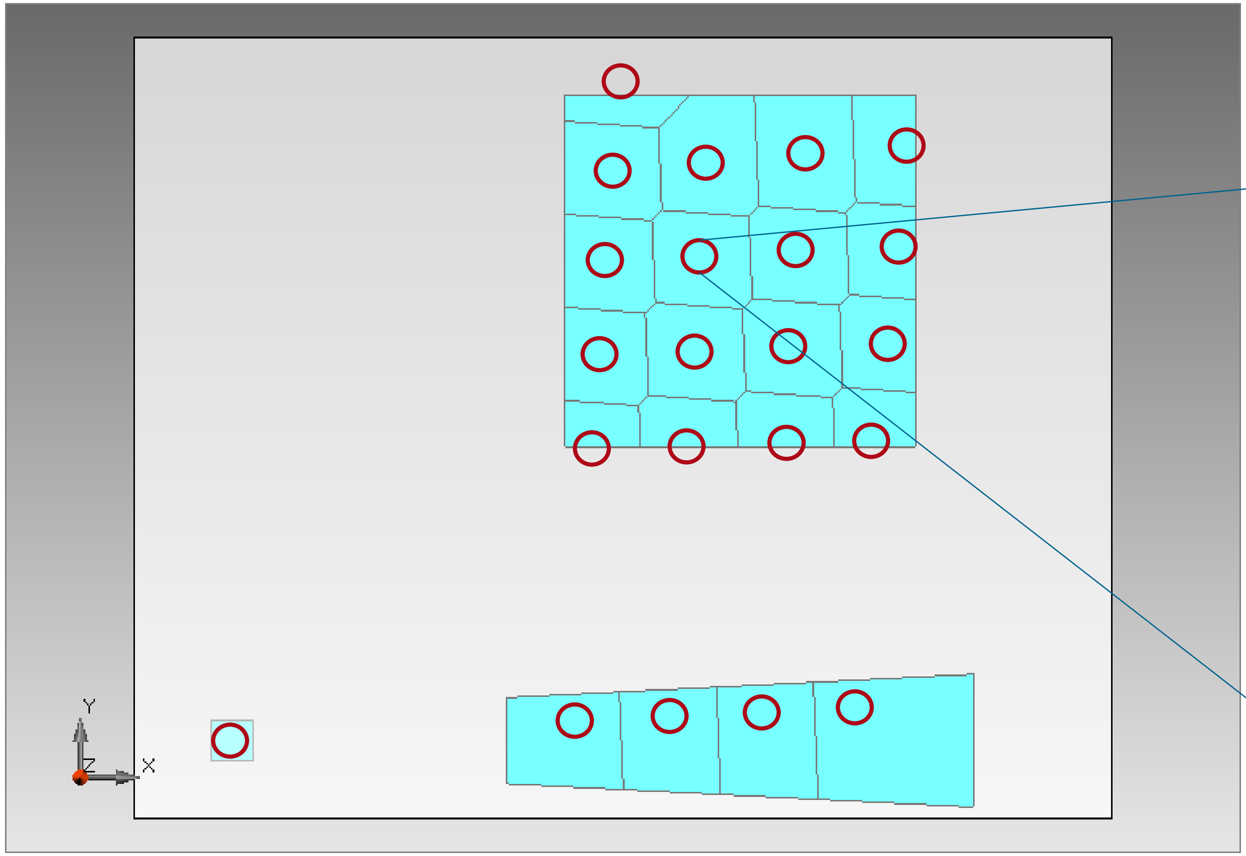
Grating Design for FOV Angle (5°, 3°) – Polarization Evaluation



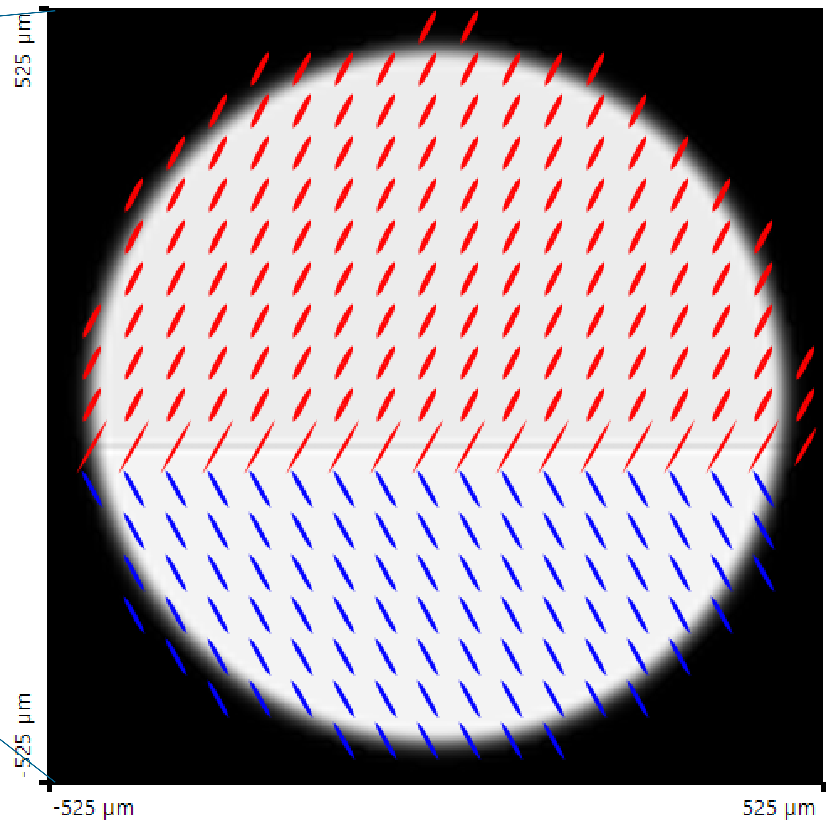
Incident light at grating interaction (non-uniform polarization)



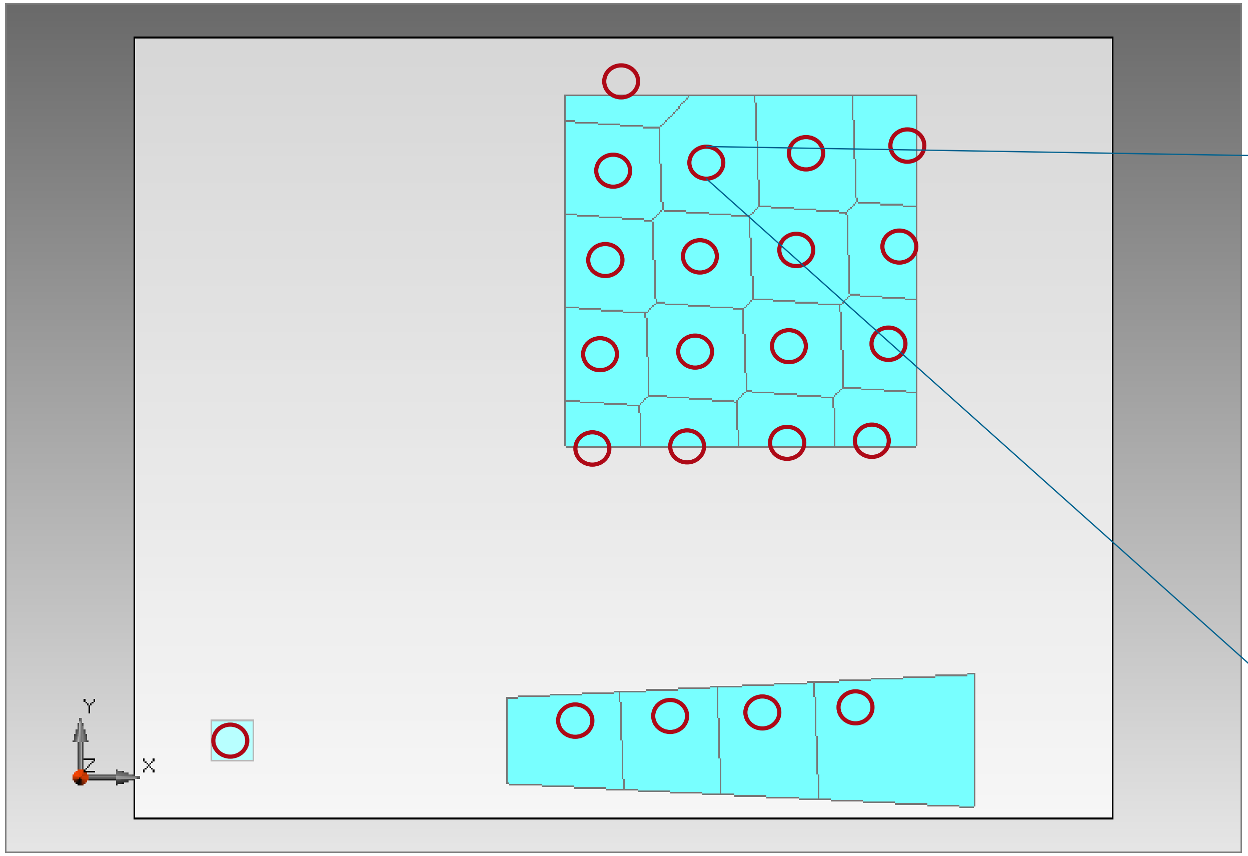
Grating Design for FOV Angle (5°, 3°) – Polarization Evaluation



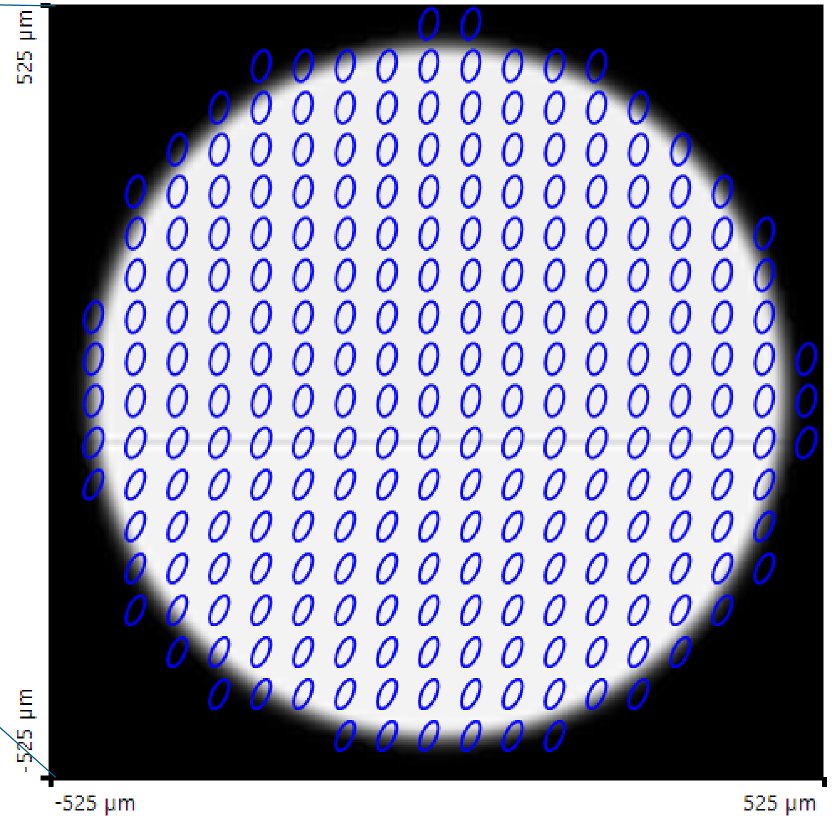
Incident light at grating interaction (non-uniform polarization)



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



Incident light at grating interaction (non-uniform polarization)



PSF and MTF evaluation

Light Modes Passing Through Eye Pupil

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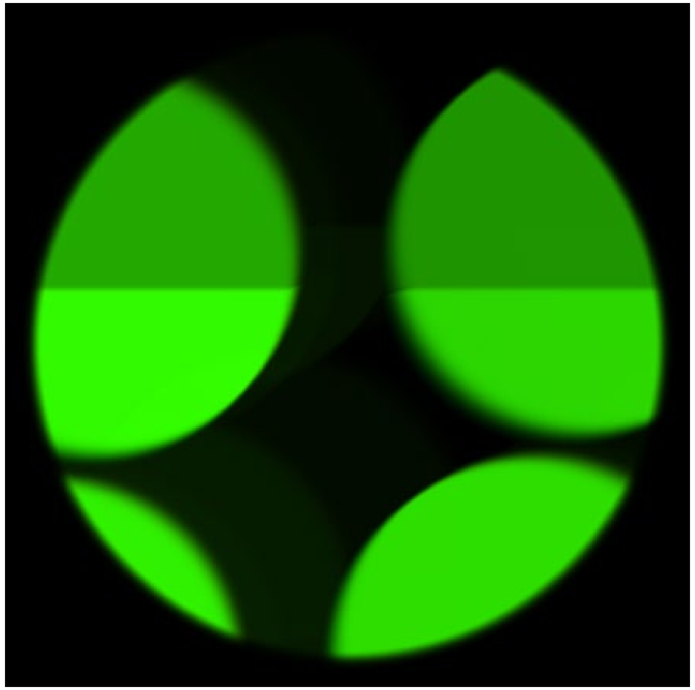
laser diode (~1 nm)



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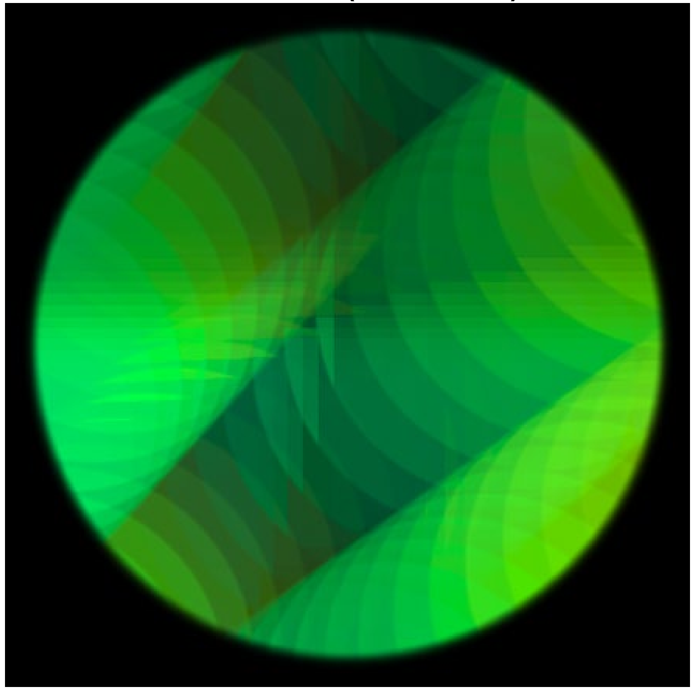

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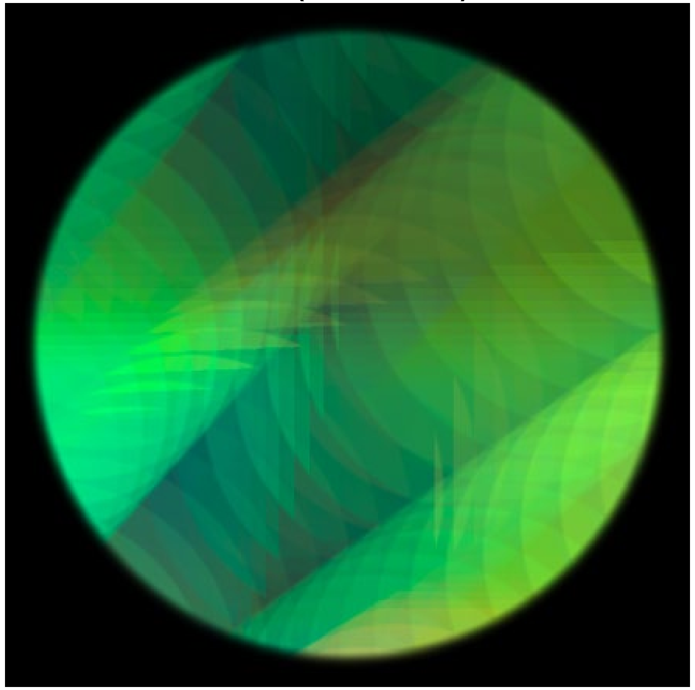
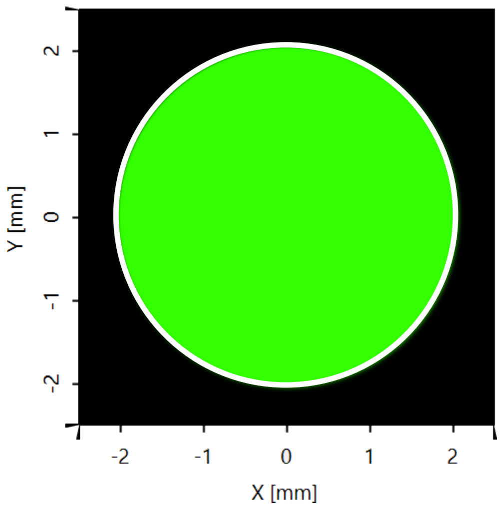
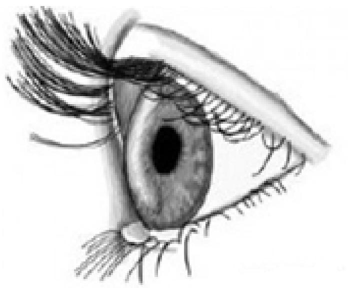


Pupil is partly filled with mutually correlated channel modes per uncorrelated spectral modes.

Results: Full Pupil Illumination



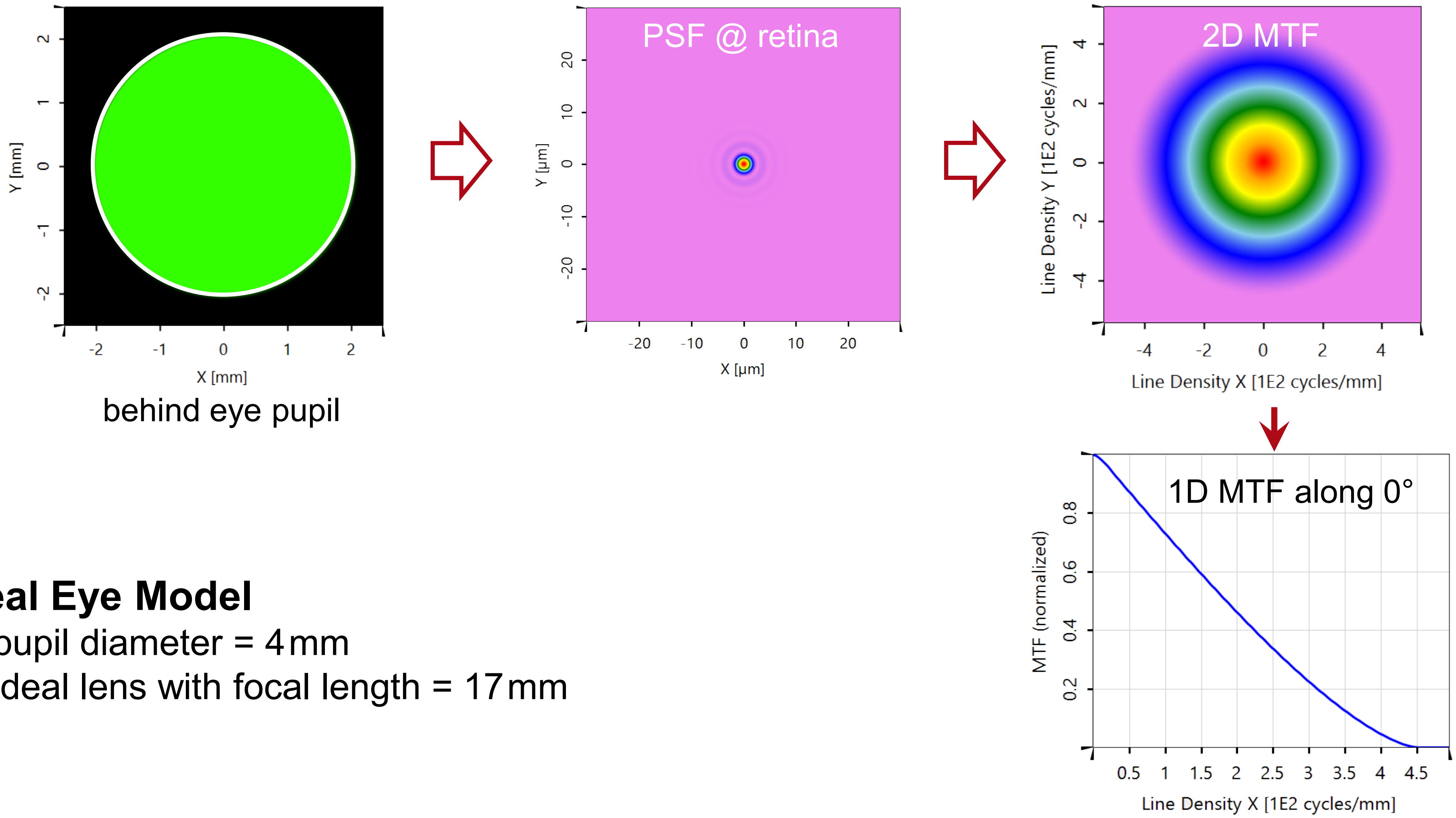
behind eye pupil

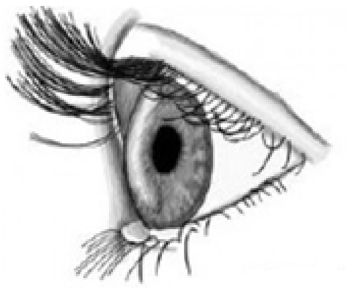


Ideal Eye Model

- pupil diameter = 4 mm
- ideal lens with focal length = 17 mm

Results: Full Pupil Illumination

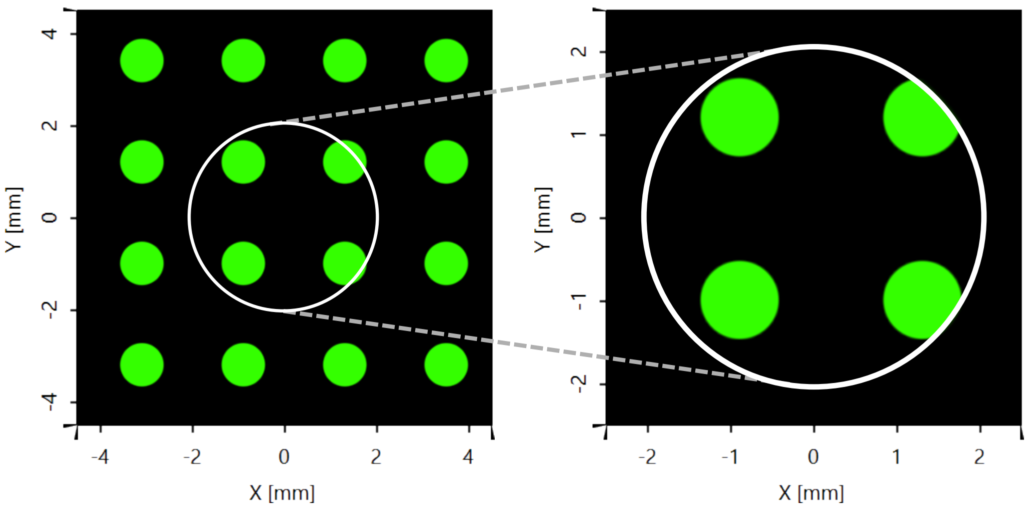




Ideal Eye Model

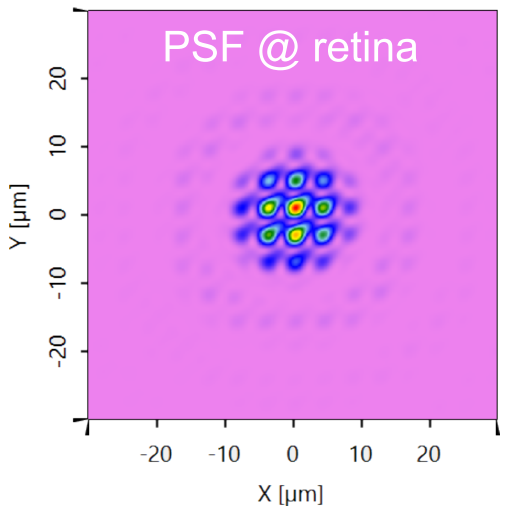
- pupil diameter = 4 mm
- ideal lens with focal length = 17 mm

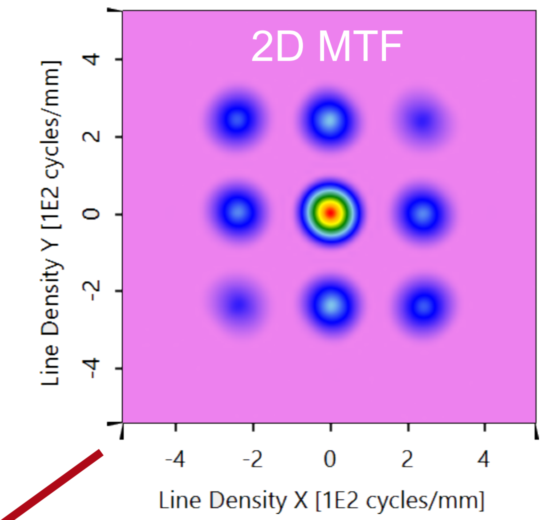
Results: FoV = (0°; 0°), Monochromatic 532nm

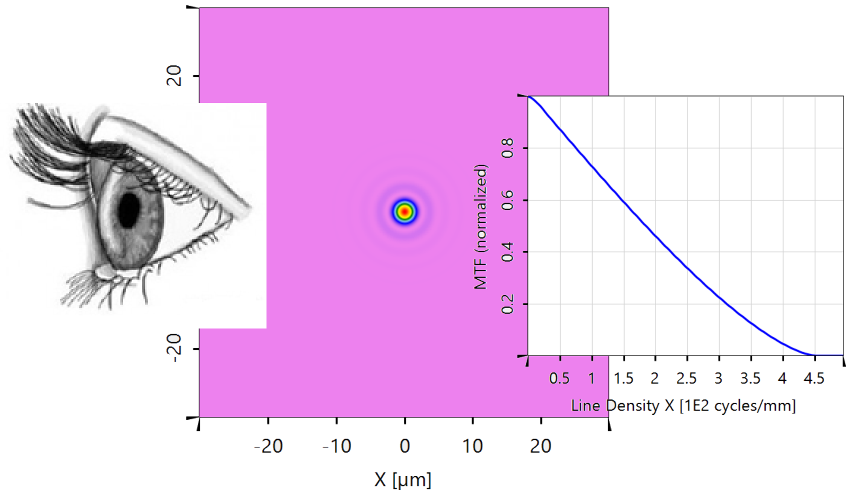


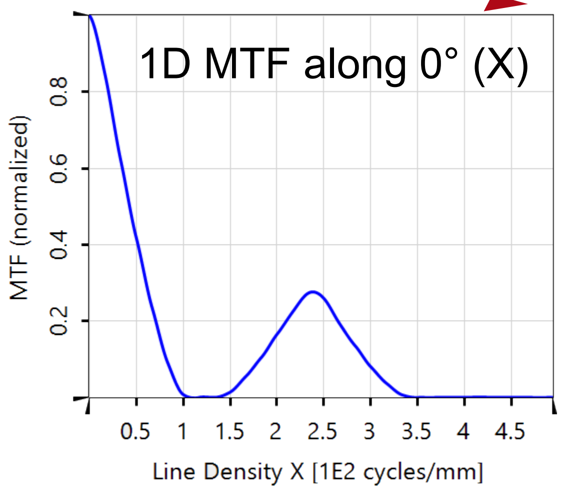
outcoupled light

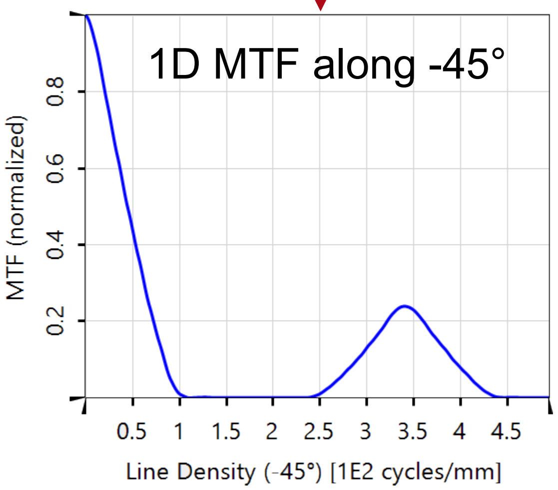
behind eye pupil











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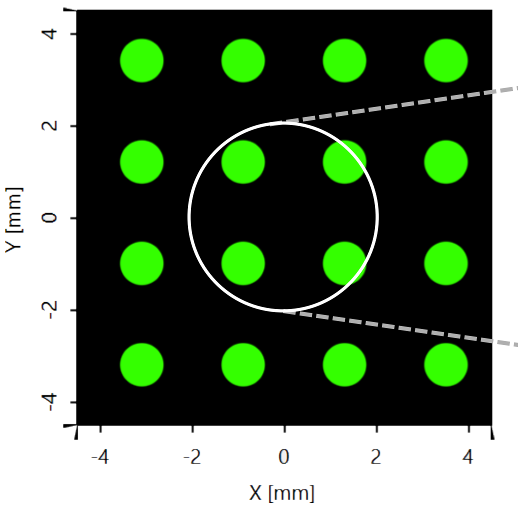
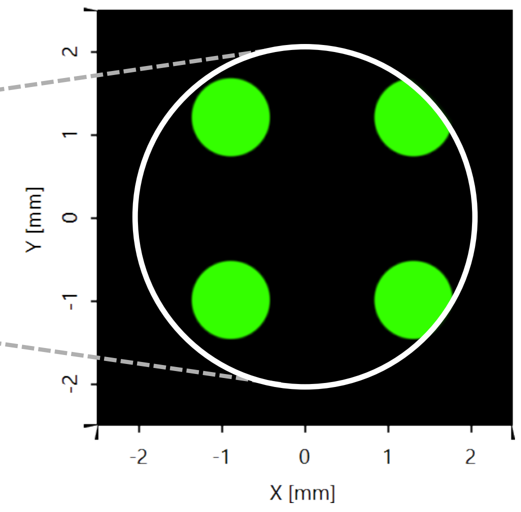


outcoupled light



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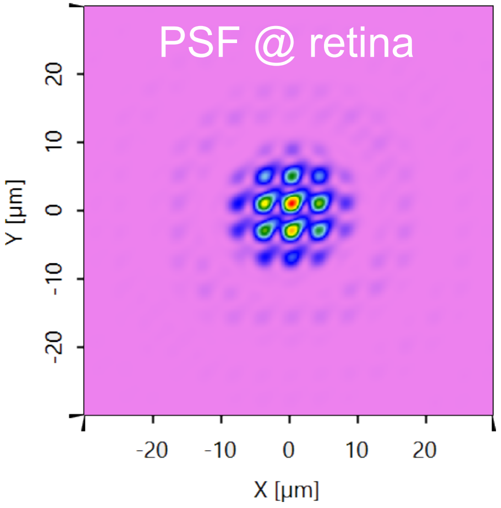
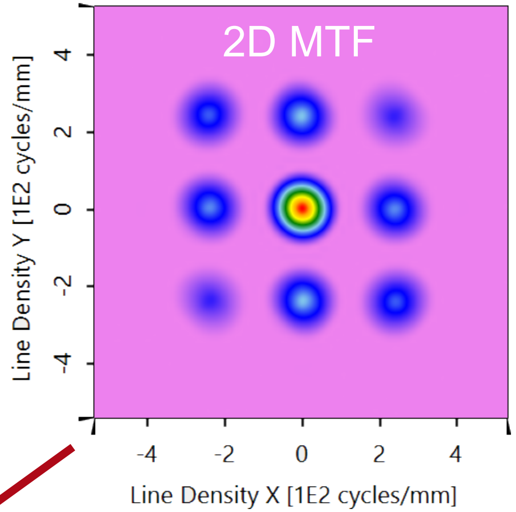
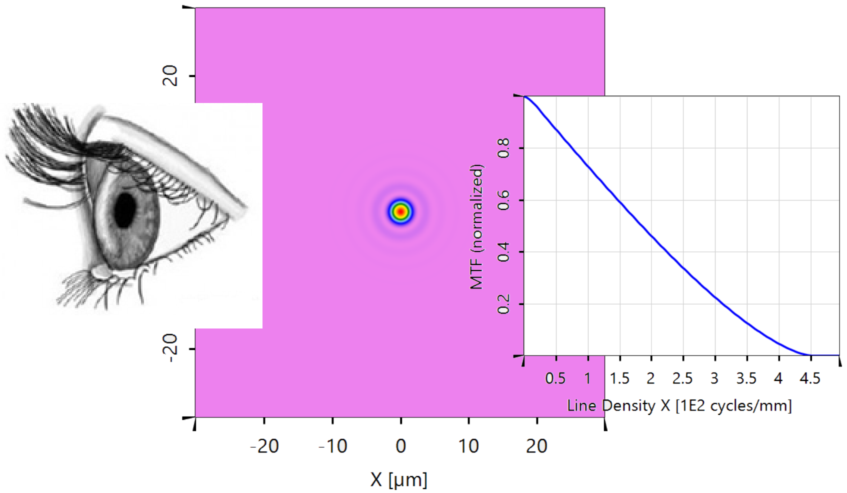
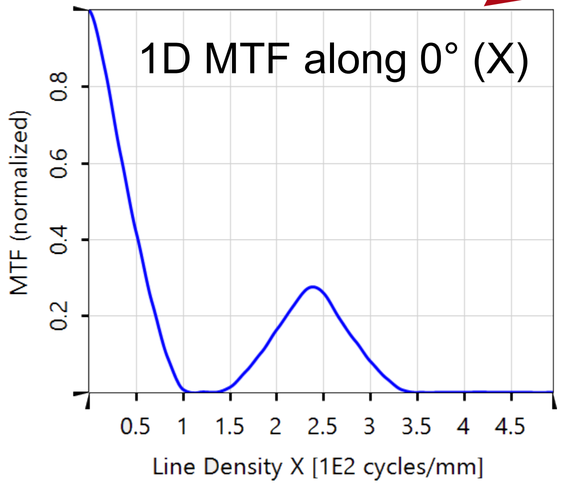
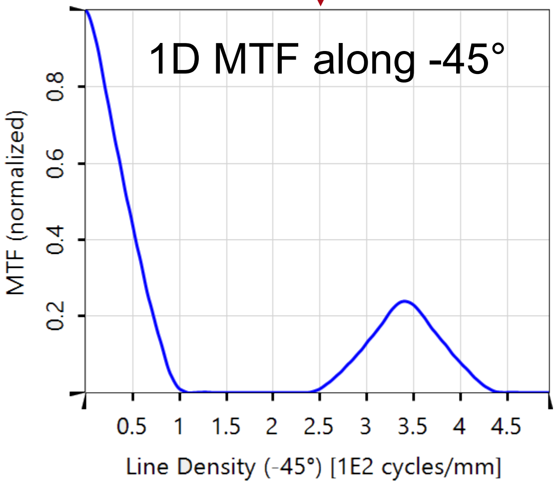


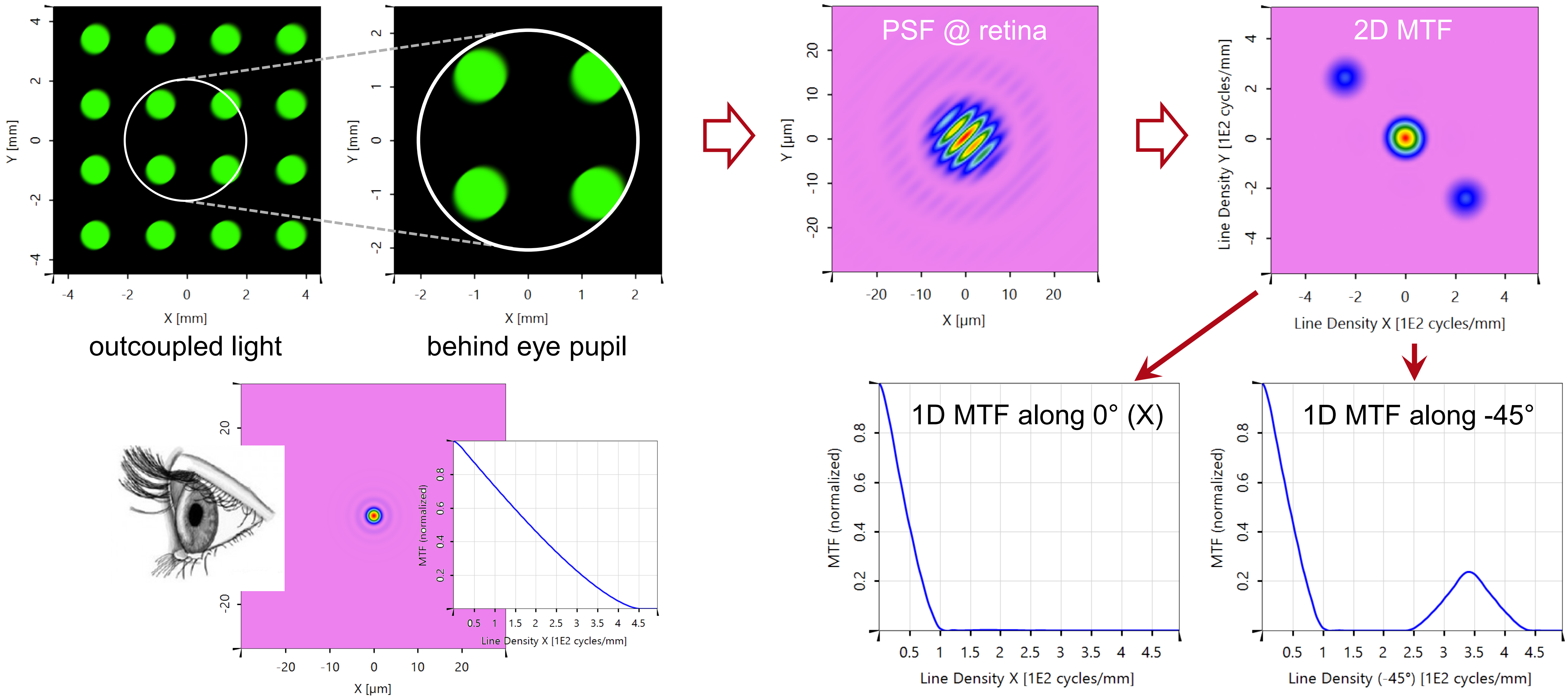




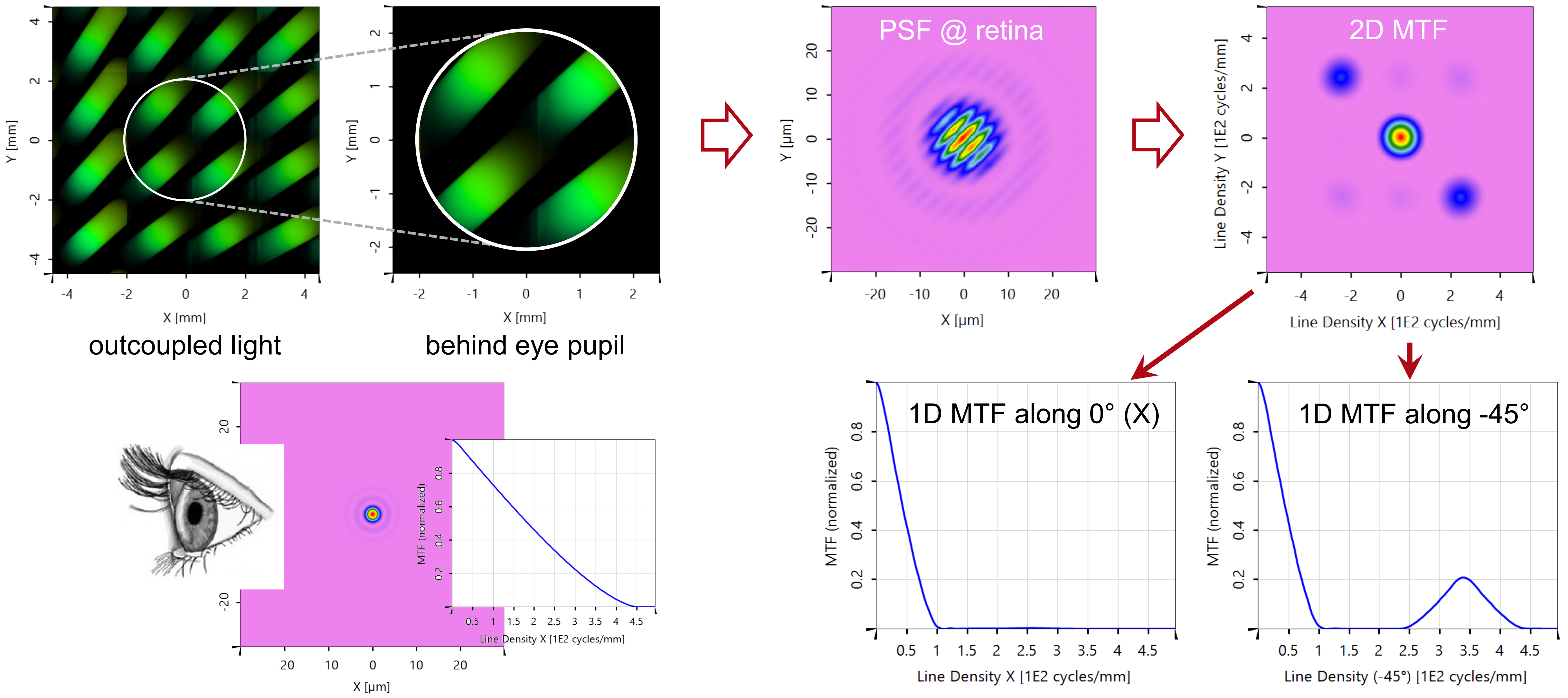




Results: FoV = (0°; 0°), Spectrum 1nm Bandwidth (24samples)



Results: FoV = (0°; 0°), Spectrum 10 nm Bandwidth (100 samples)



Light Modes Passing Through Eye Pupil

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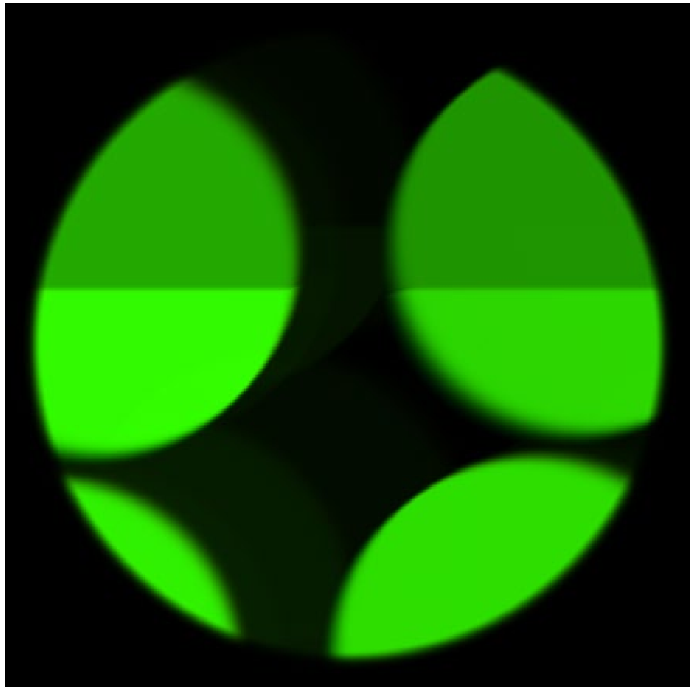

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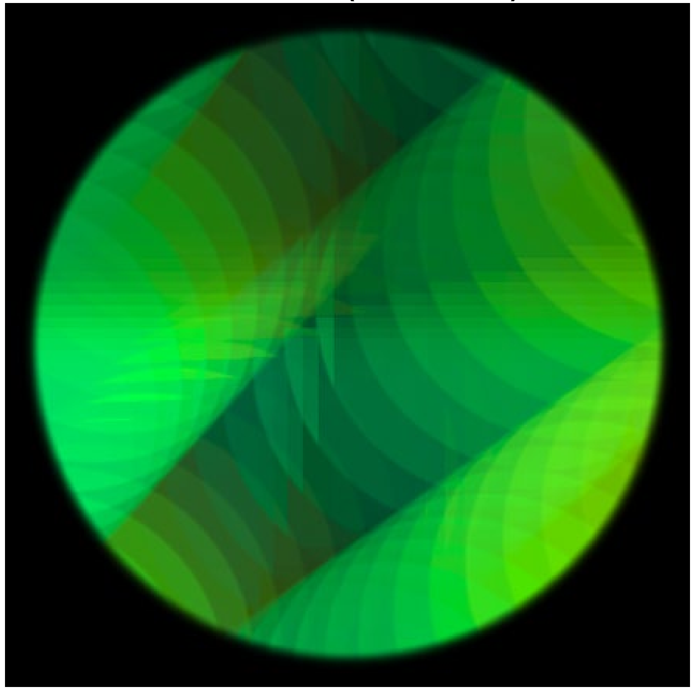

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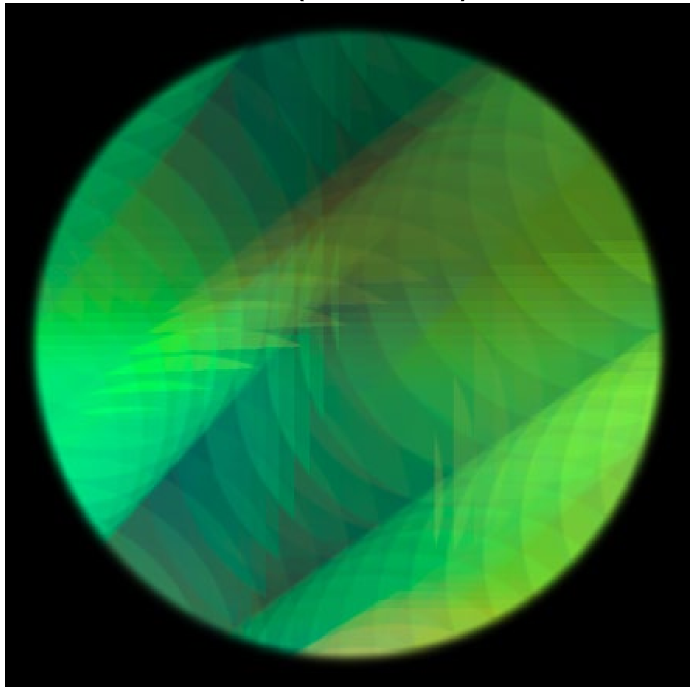

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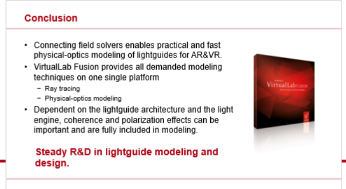


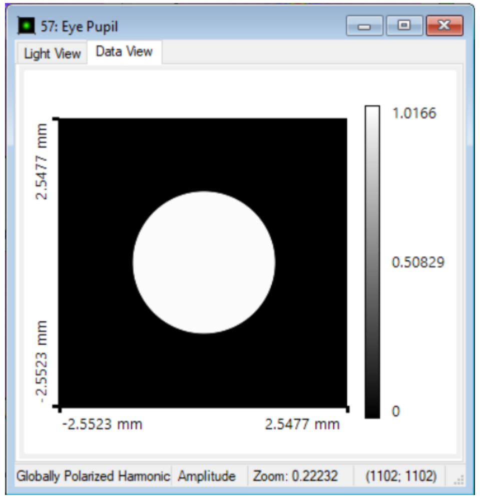
Conclusion

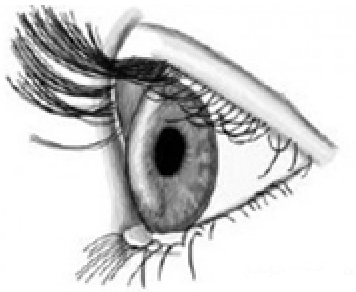
- Connecting field solvers enables practical and fast physical-optics modeling of lightguides for AR&VR.
- VirtualLab Fusion provides all demanded modeling techniques on one single platform
  - Ray tracing
  - Physical-optics modeling
- Dependent on the lightguide architecture and the light engine, coherence and polarization effects can be important and are fully included in modeling.

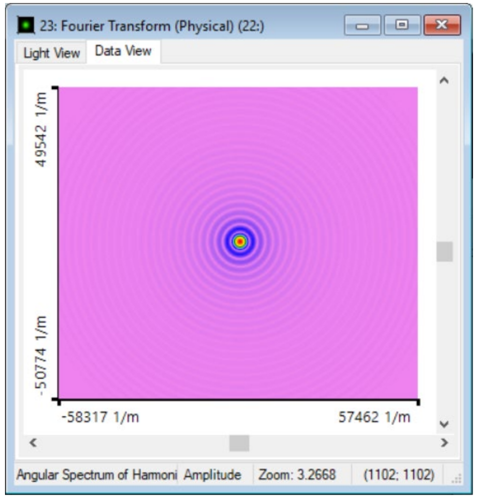
Steady R&D in lightguide modeling and design.

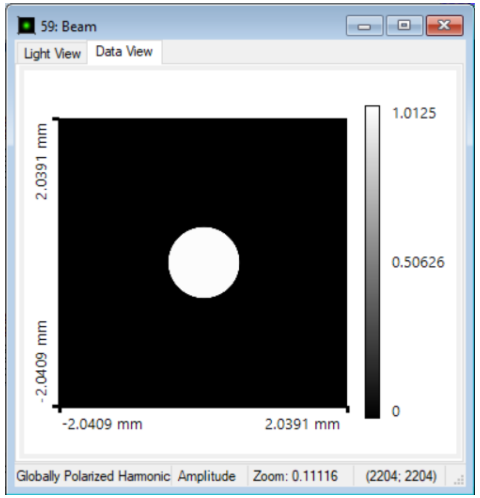
Illustration of PSF vs. Filling of Eye Pupil

Pupil vs. PSF (Fourier Transform)

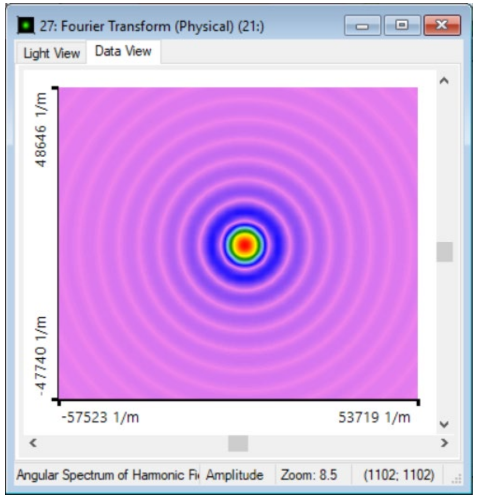




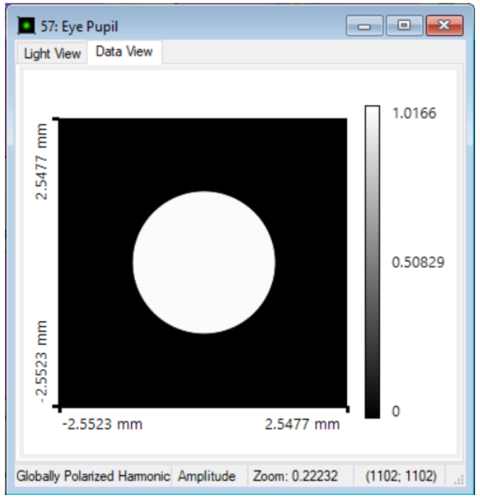


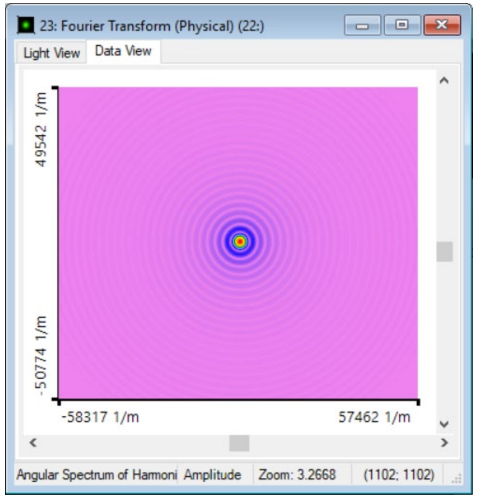


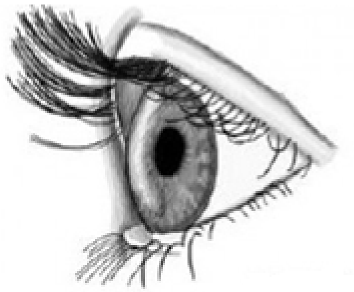
Beam

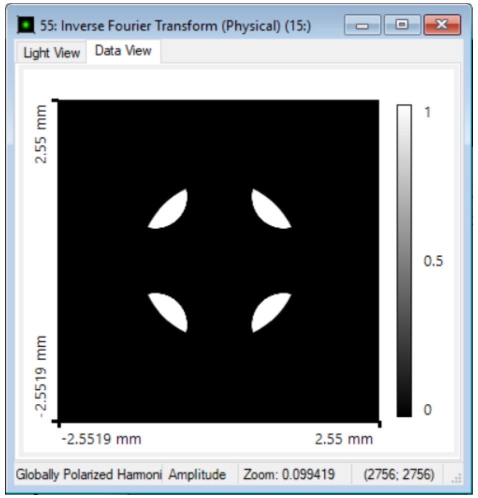


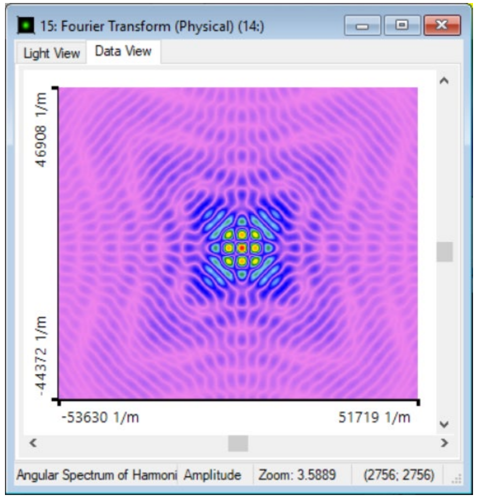
Pupil vs. PSF (Fourier Transform)



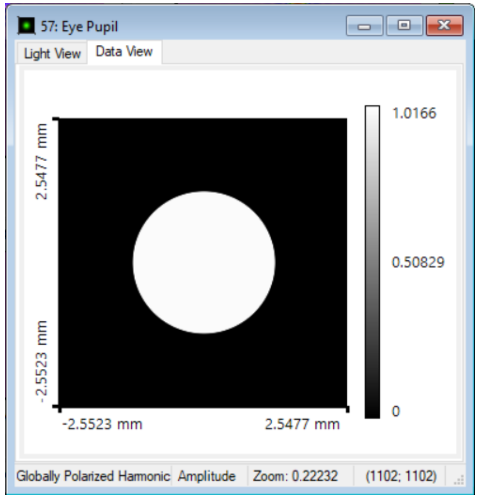


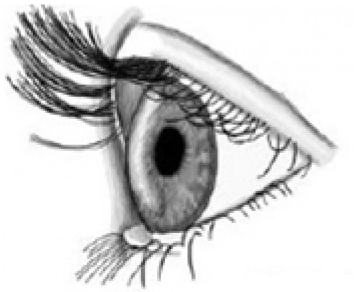


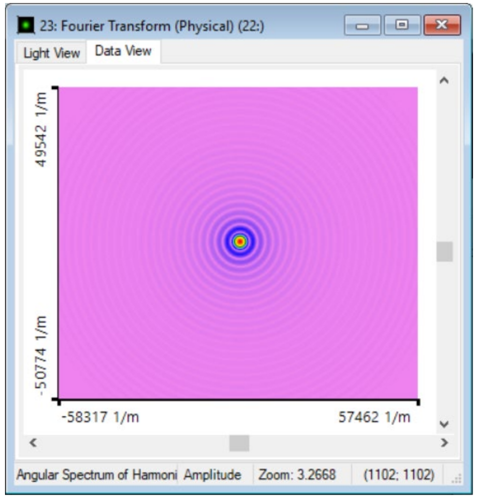


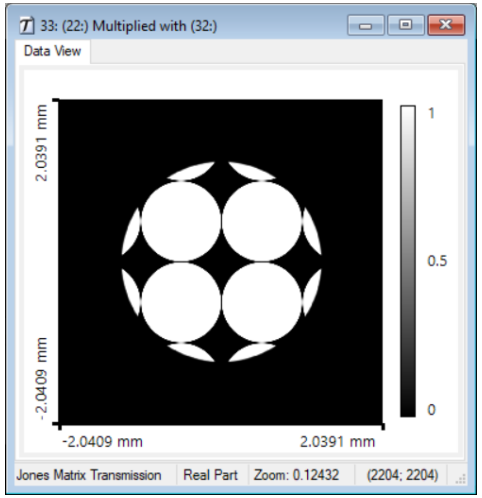


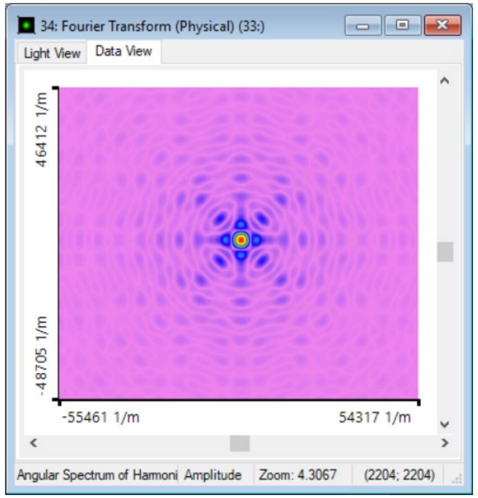
Pupil vs. PSF (Fourier Transform)



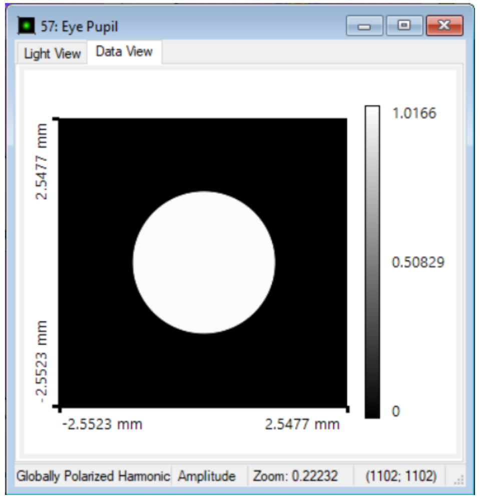


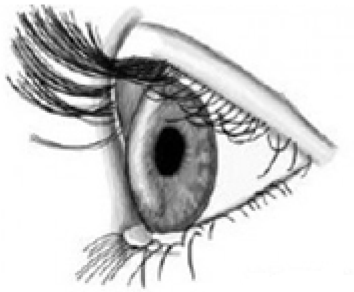


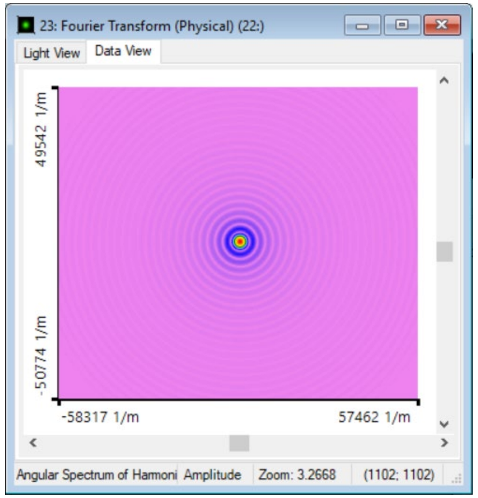


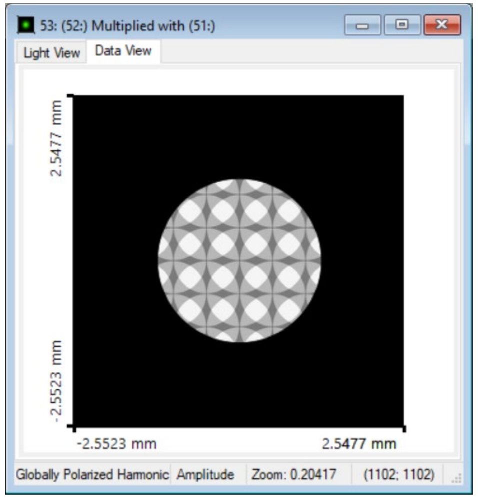


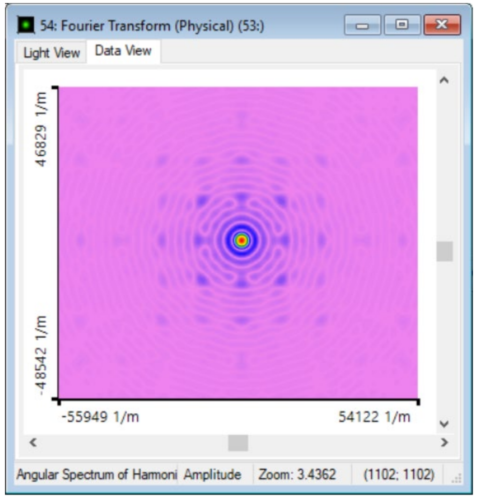
Pupil vs. PSF (Fourier Transform)





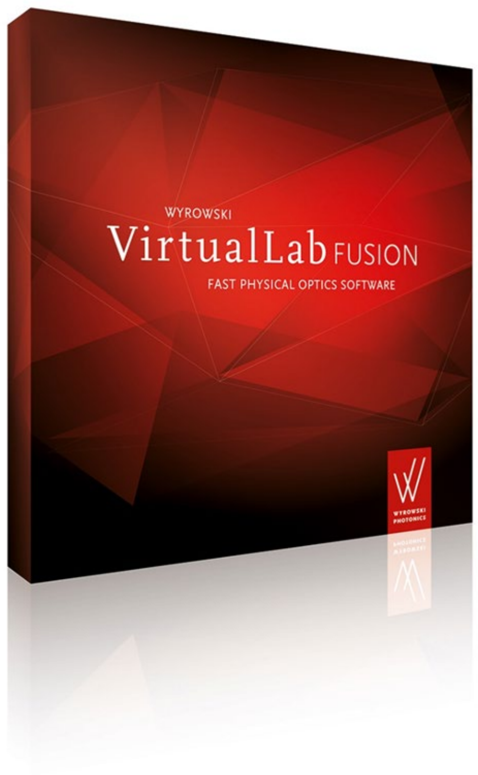






Conclusion

- Connecting field solvers enables practical and fast physical-optics modeling of lightguides for AR&VR.
- VirtualLab Fusion provides all demanded modeling techniques on one single platform
  - Ray tracing
  - Physical-optics modeling
- Dependent on the lightguide architecture and the light engine, coherence and polarization effects can be important and are fully included in modeling.



Steady R&D in lightguide modeling and design.

Thank You!