SPIE AR VR MR 2020, San Francisco, February 2020

# Physical-optics analysis of lightguides for augmented and mixed reality glasses (11310-38)

S. Steiner[1], S. Zhang[1], C. Hellmann[2], and F. Wyrowski[3]
[1]LightTrans International, [2]Wyrowski Photonics, [3]University Jena (Germany)

# Teams


**LightTrans** (since 1999)

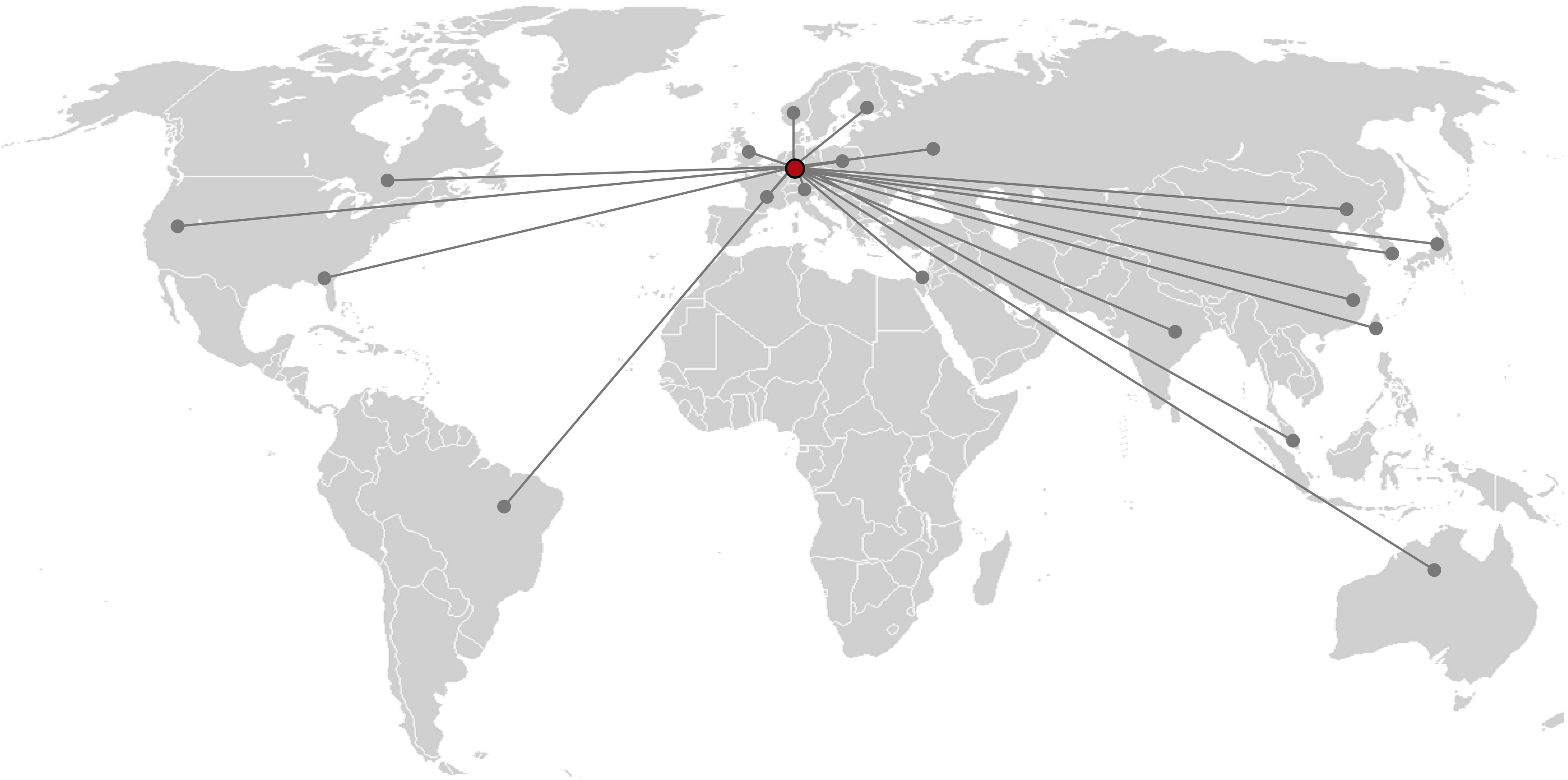
- Optical technologies development
- Technical support, seminars, and trainings
- Engineering projects
- Distribution of VirtualLab Fusion, together with distributors worldwide

WYROWSKI PHOTONICS

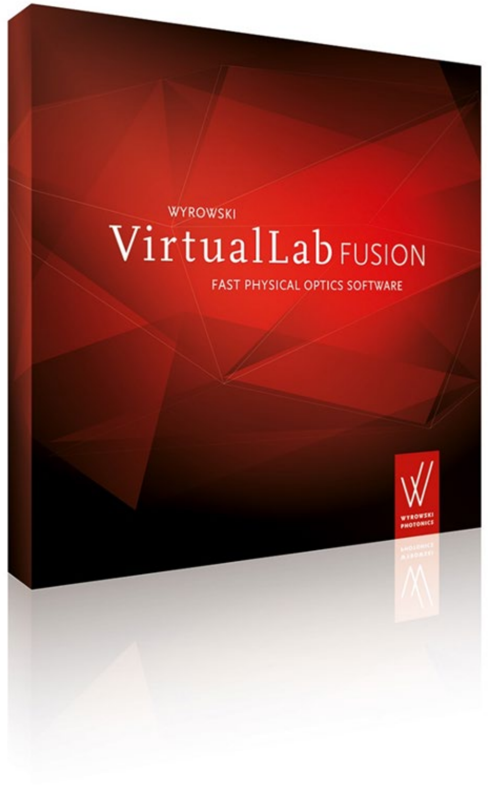
(since 2014)

*photo from wikitravel*

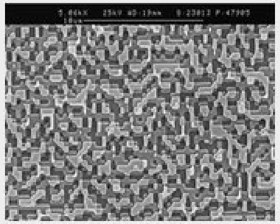
# Optical Design Software and Services

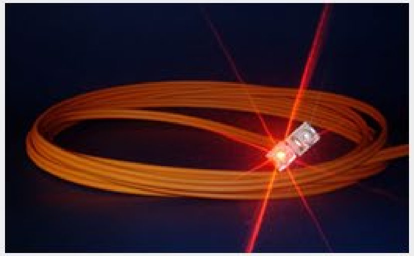


**Booth #4545 (German pavilion)**



# Physical-Optics System Modeling



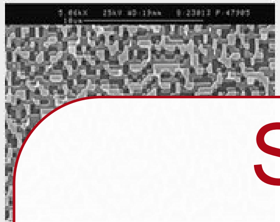


| Name | Integral equations | Differential equations |
|---|---|---|
| Gauss's law | $\oiint_{\partial\Omega} \mathbf{E}\cdot d\mathbf{S} = \frac{1}{\varepsilon_0}\iiint_\Omega \rho\, dV$ | $\nabla\cdot\mathbf{E} = \frac{\rho}{\varepsilon_0}$ |
| Gauss's law for magnetism | $\oiint_{\partial\Omega} \mathbf{B}\cdot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

Homogeneous

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

# Physical-Optics System Modeling



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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!

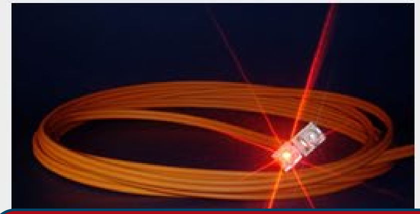
# Connecting Optical Technologies / Maxwell Solvers

Field Solver Lenses, …

Field Solver Prisms, …

Field Solver Gratings, …

Field Solver micro- and nano-structures



Field Solver fibers, …

Homogeneous medium, like air or vacuum

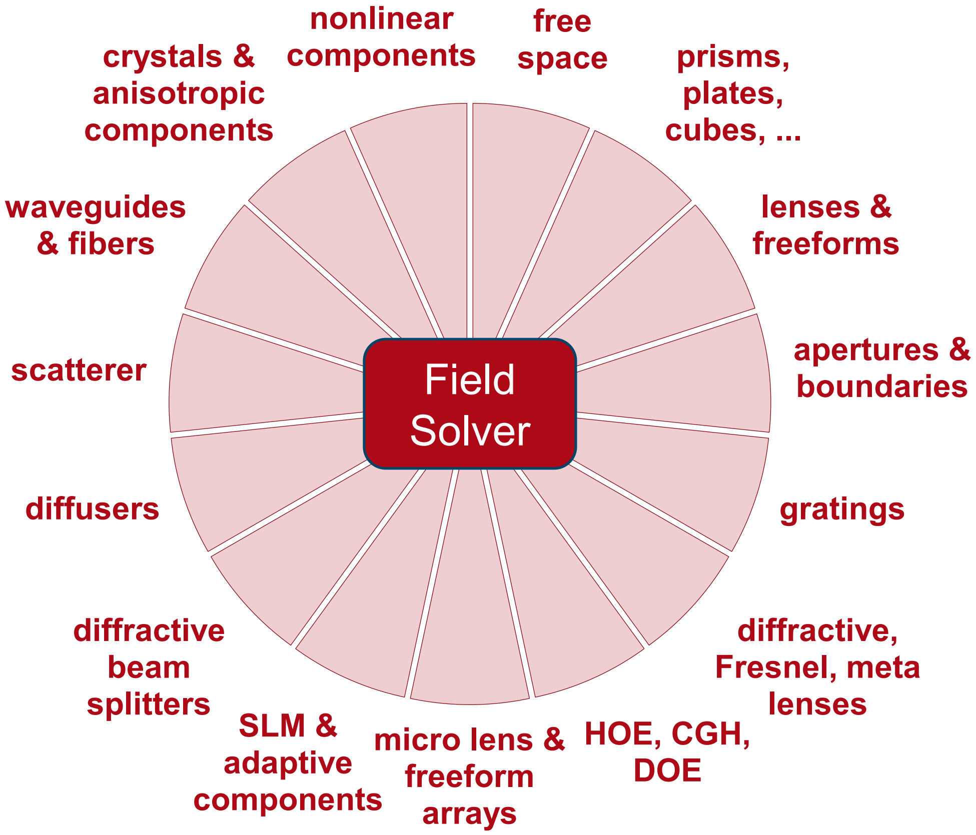
# Connecting Optical Technologies / Maxwell Solvers

## 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 a single field solver, e.g.
FEM or FDT
**Unrealistic**

## Solution:

- Decompo
  applicatio
- Interconne
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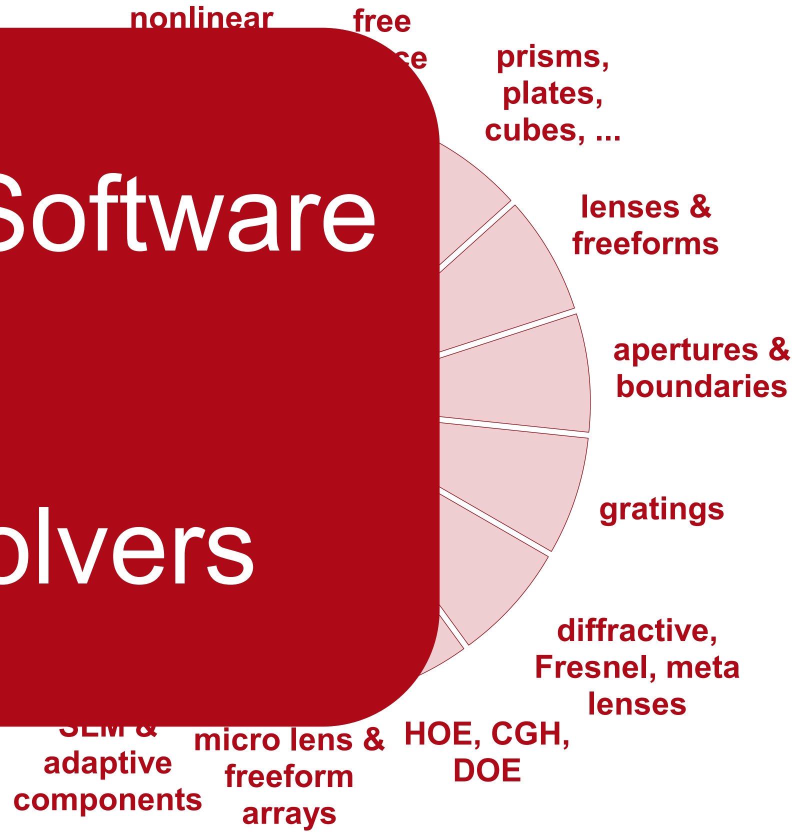
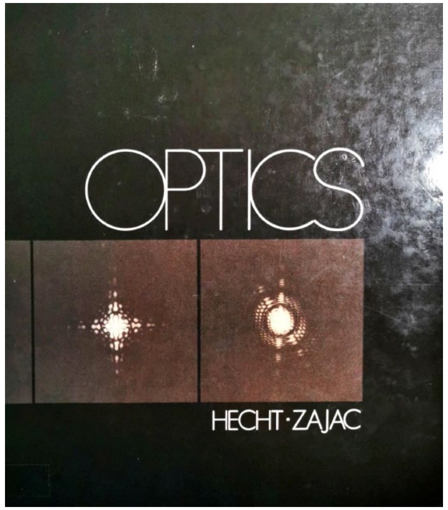



**Fast** Physical Optics Software
by
Connecting Field Solvers

# Example of Plate/Etalon



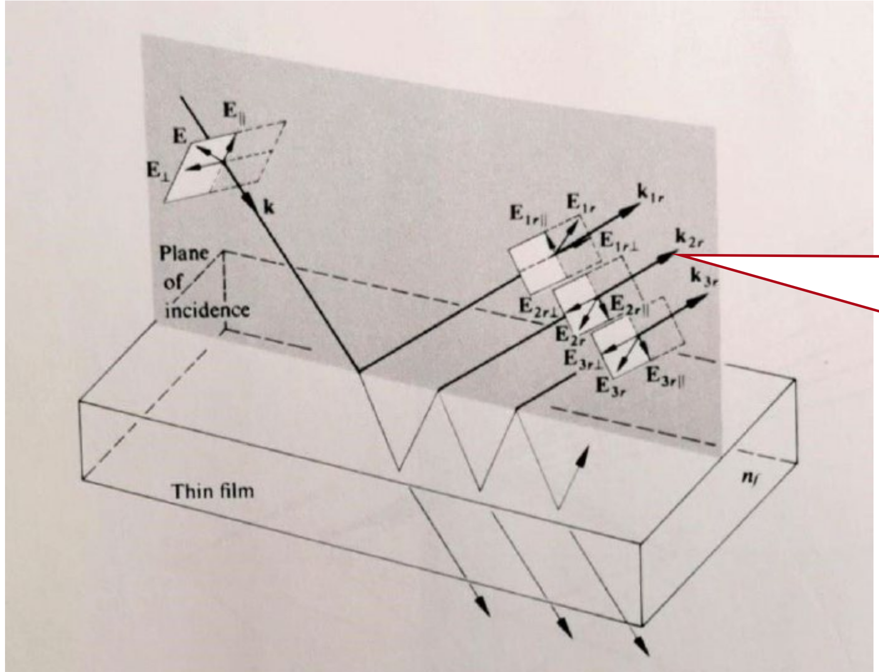




**Fig. 9.41** Phase shifts arising purely from the reflections (internal $\theta_i < \theta_p'$).

at point $P$, is then

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

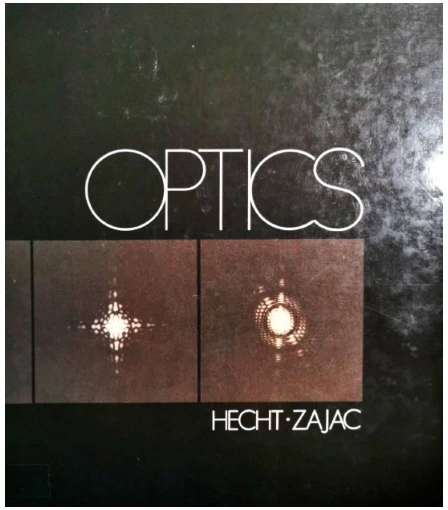
or

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

Different lightpaths because of non-sequential model

Sum of mutually coherent fields per lightpath

# Example of Plate/Etalon



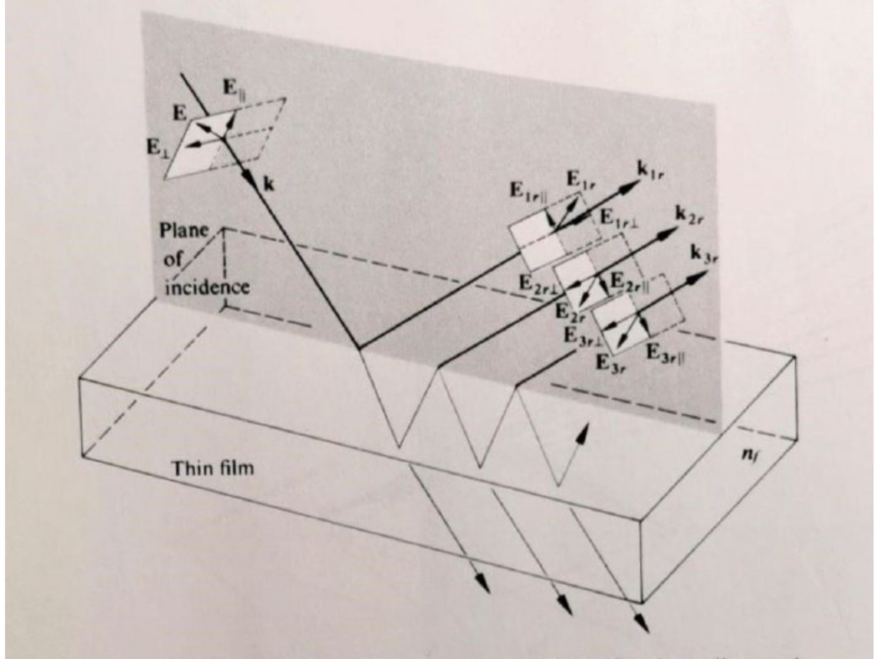




**Fig. 9.41** Phase shifts arising purely from the reflections (internal $\theta_i < \theta_p'$).

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or

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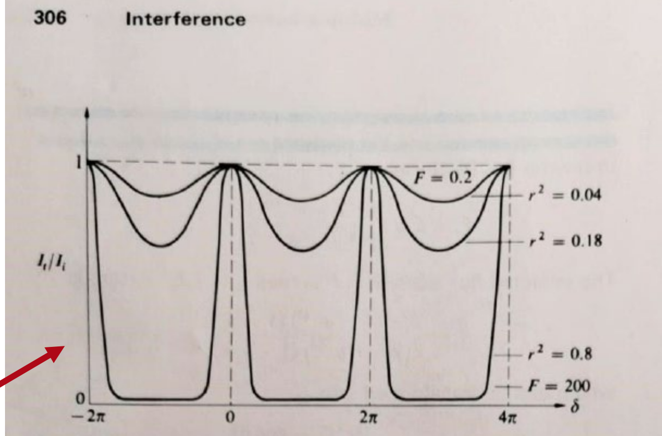
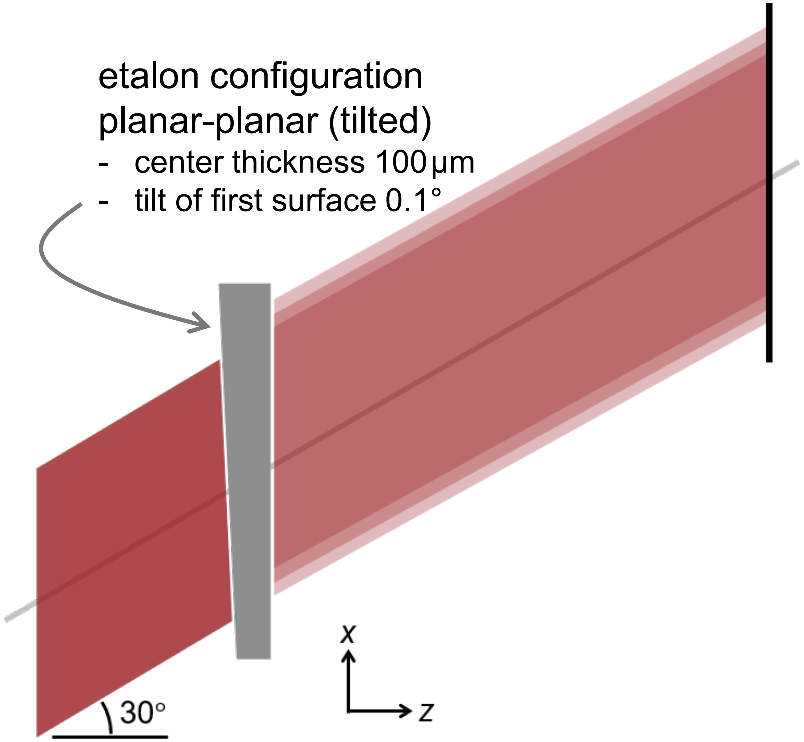


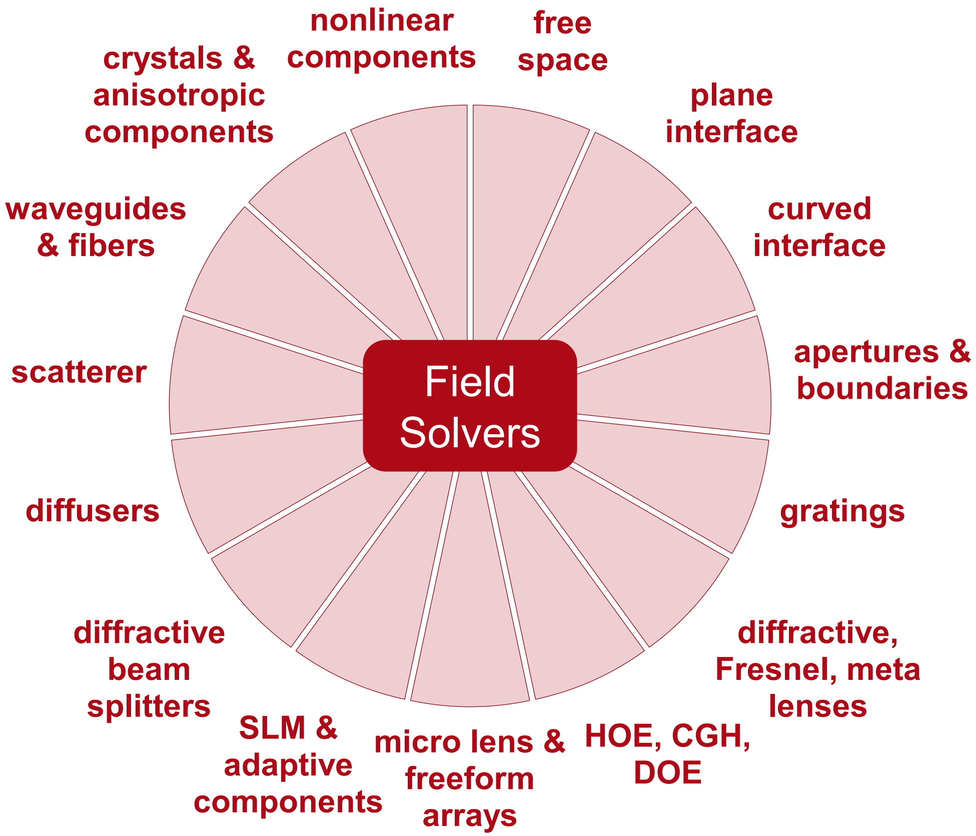

**Fig. 9.45** Airy function.

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

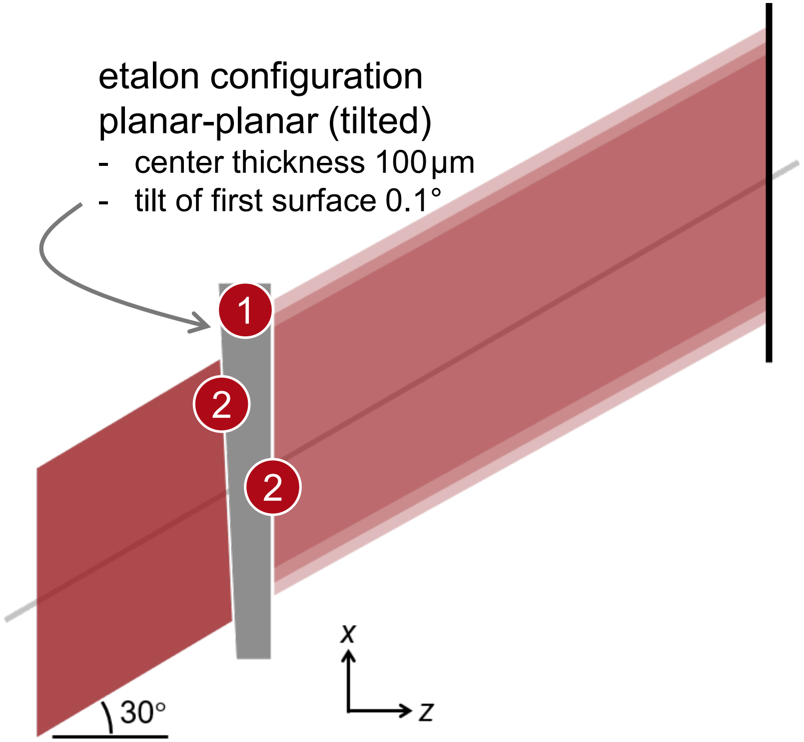
$$I_i = I_r + I_t. \qquad (9.35)$$

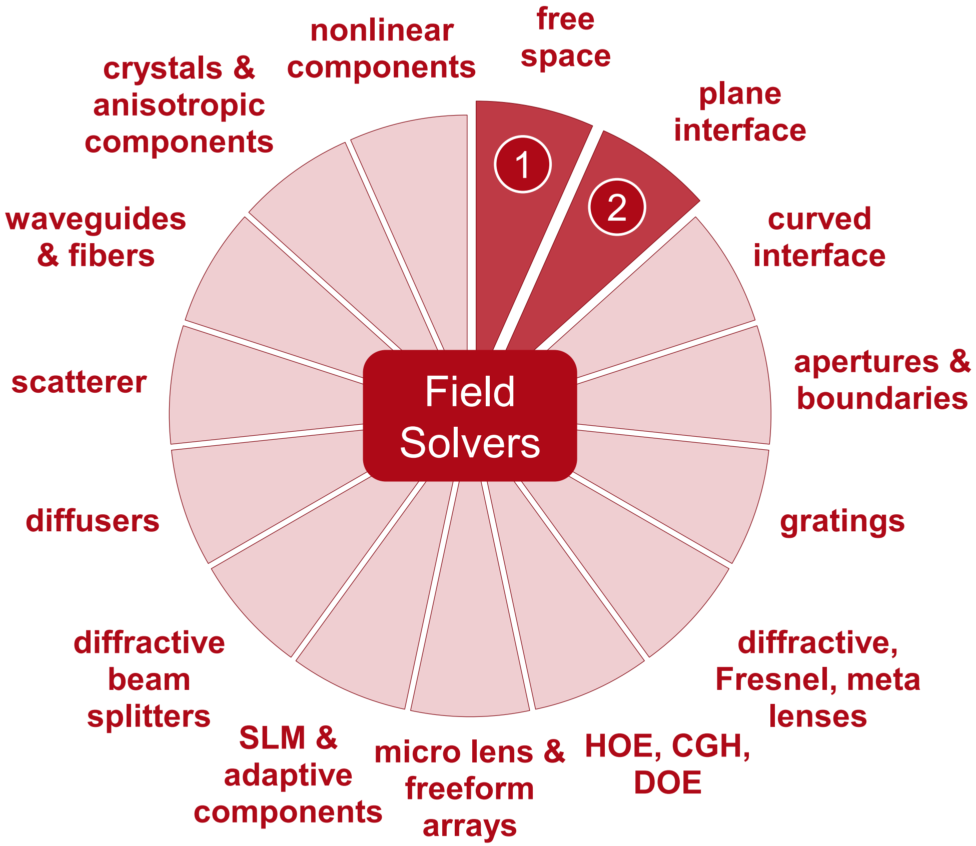
# Connecting Field Solvers: Tilted Planar-Planar Surfaces



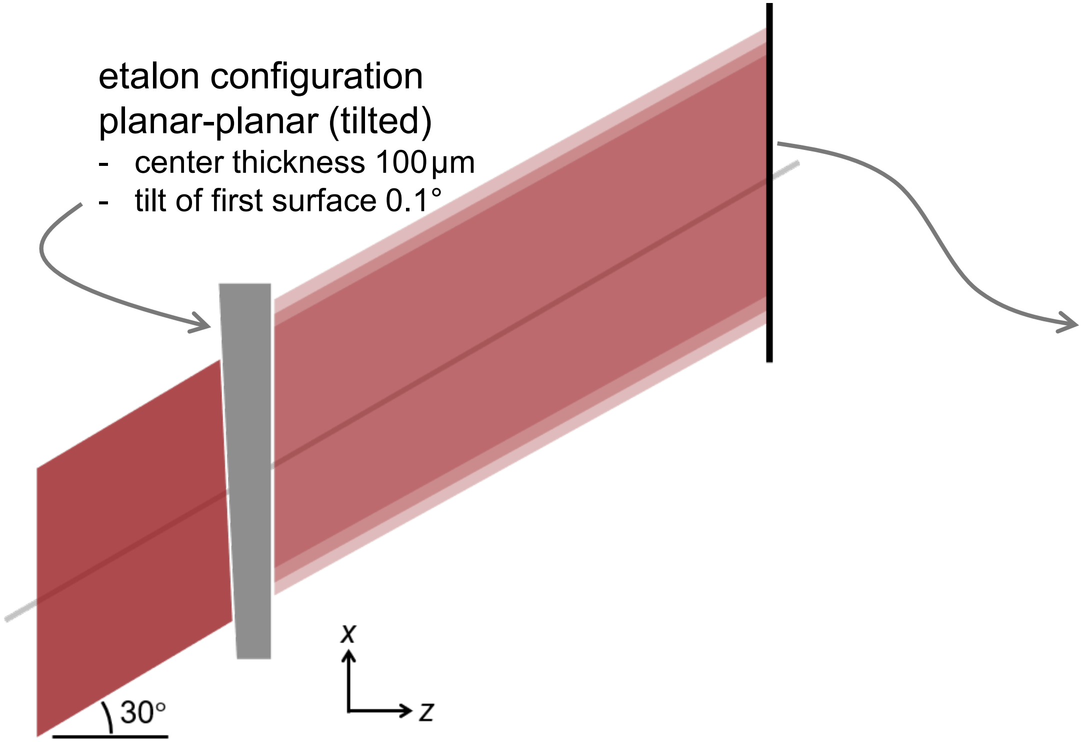



# Connecting Field Solvers: Tilted Planar-Planar Surfaces



# Connecting Field Solvers: Tilted Planar-Planar Surfaces



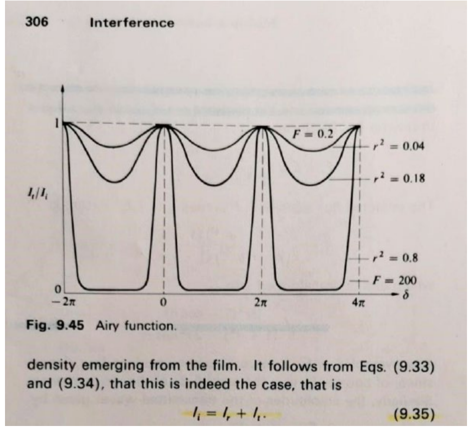


306 Interference



**Fig. 9.45** Airy function.

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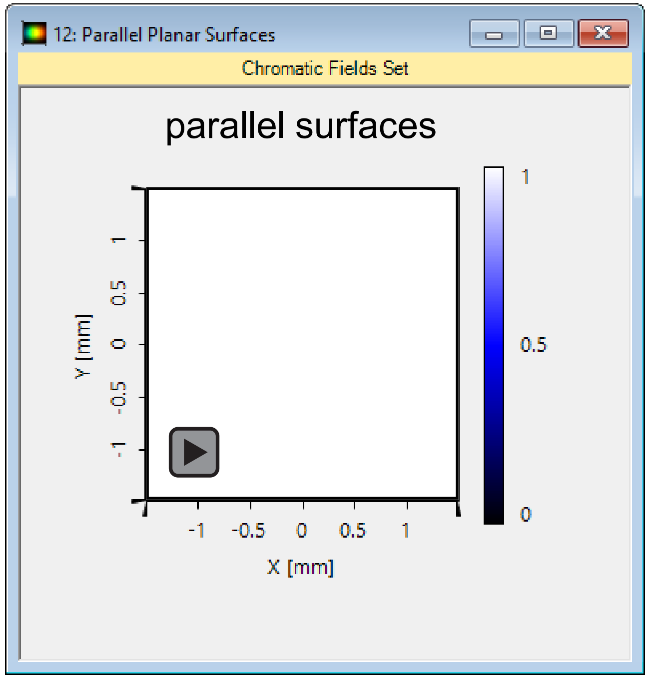
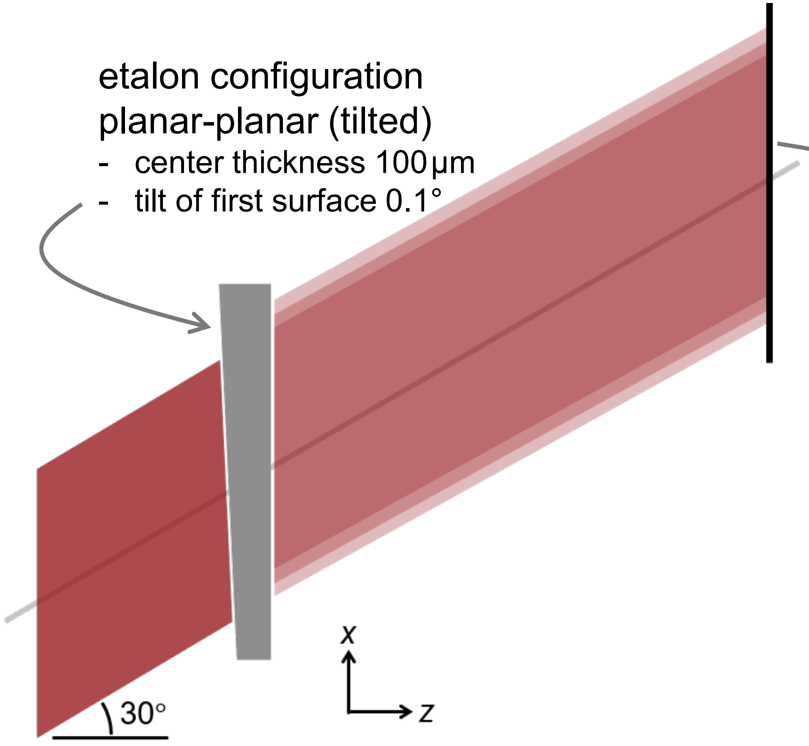
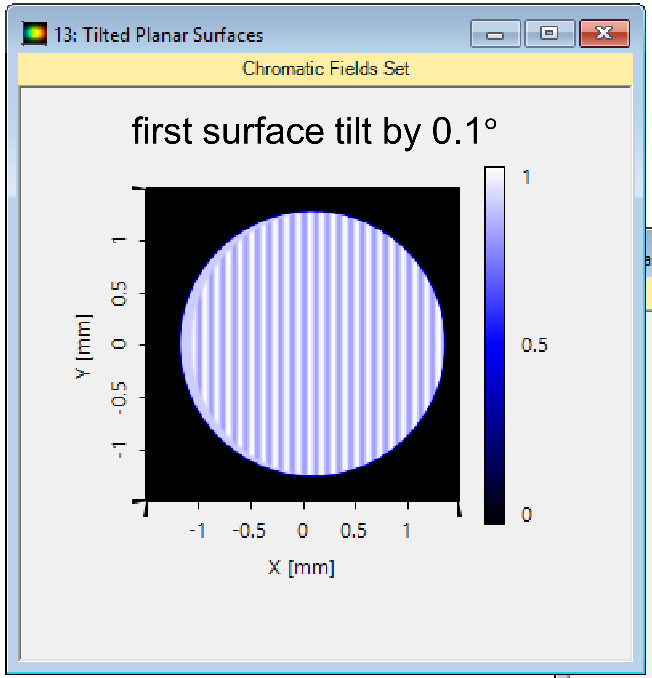
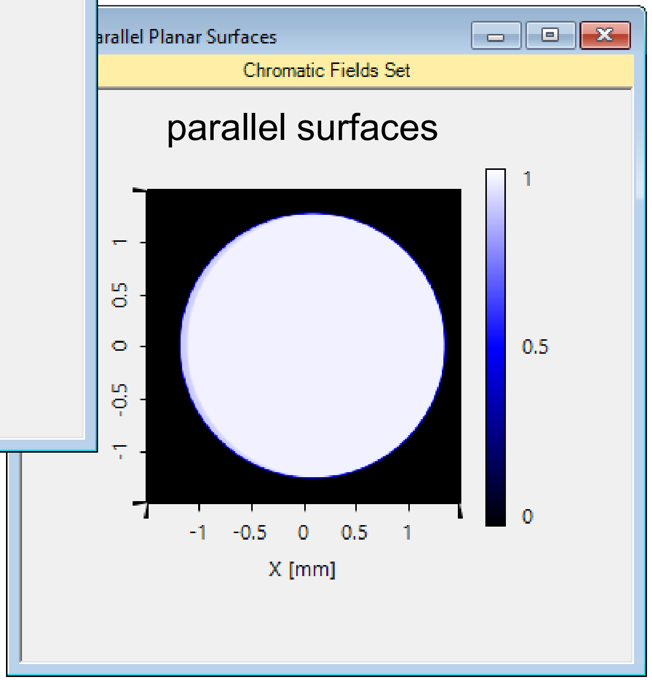


# Connecting Field Solvers: Tilted Planar-Planar Surfaces

etalon configuration
planar-planar (tilted)
- center thickness 100 µm
- tilt of first surface 0.1°

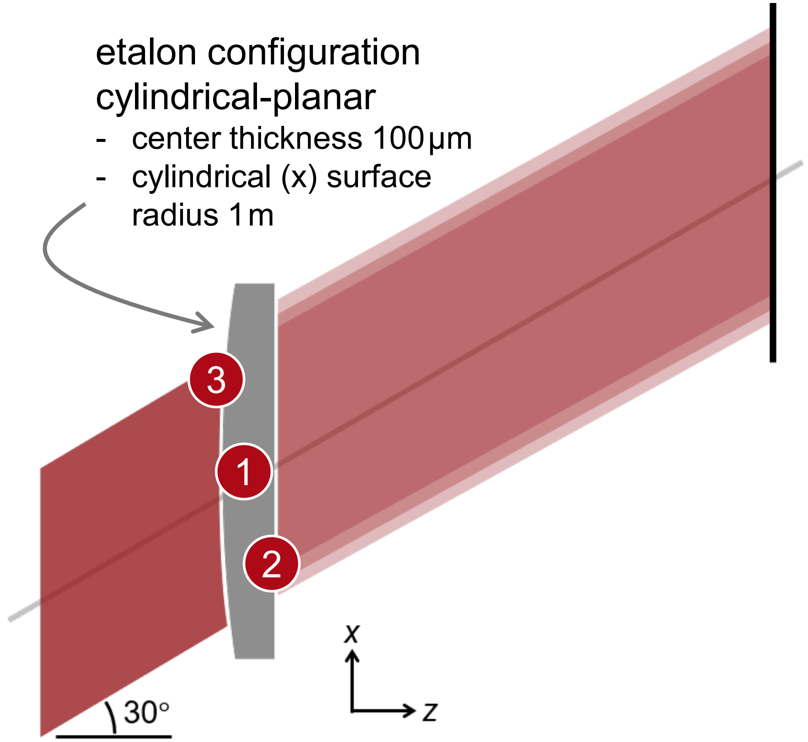


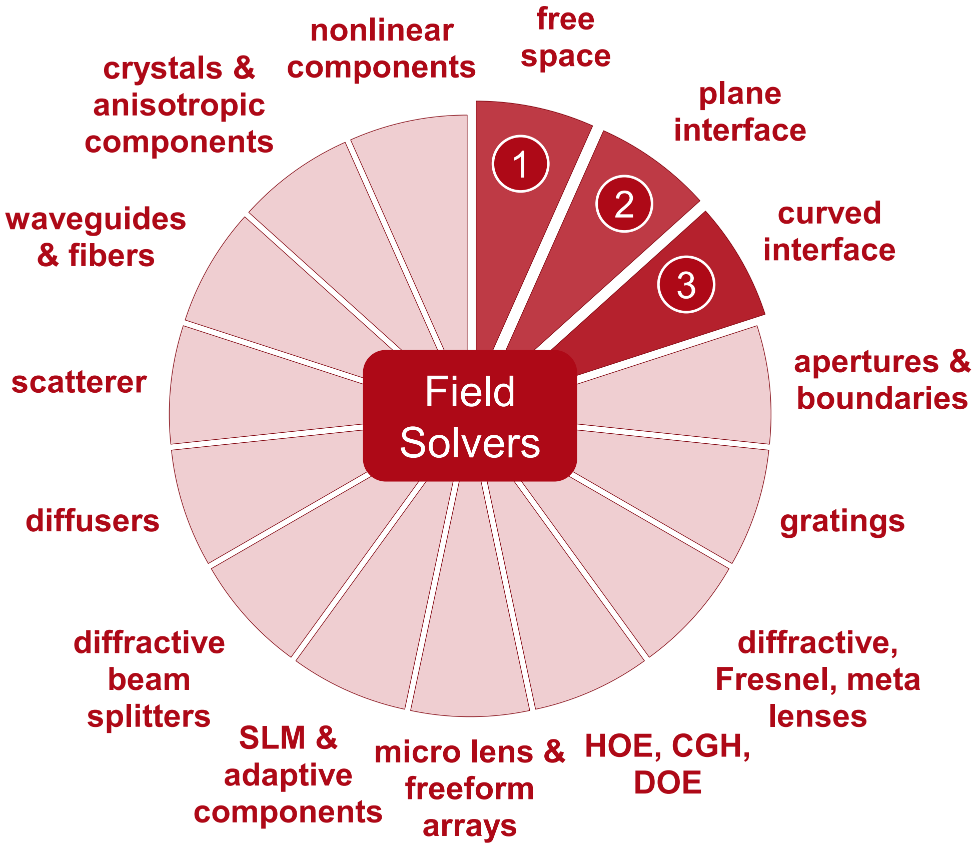



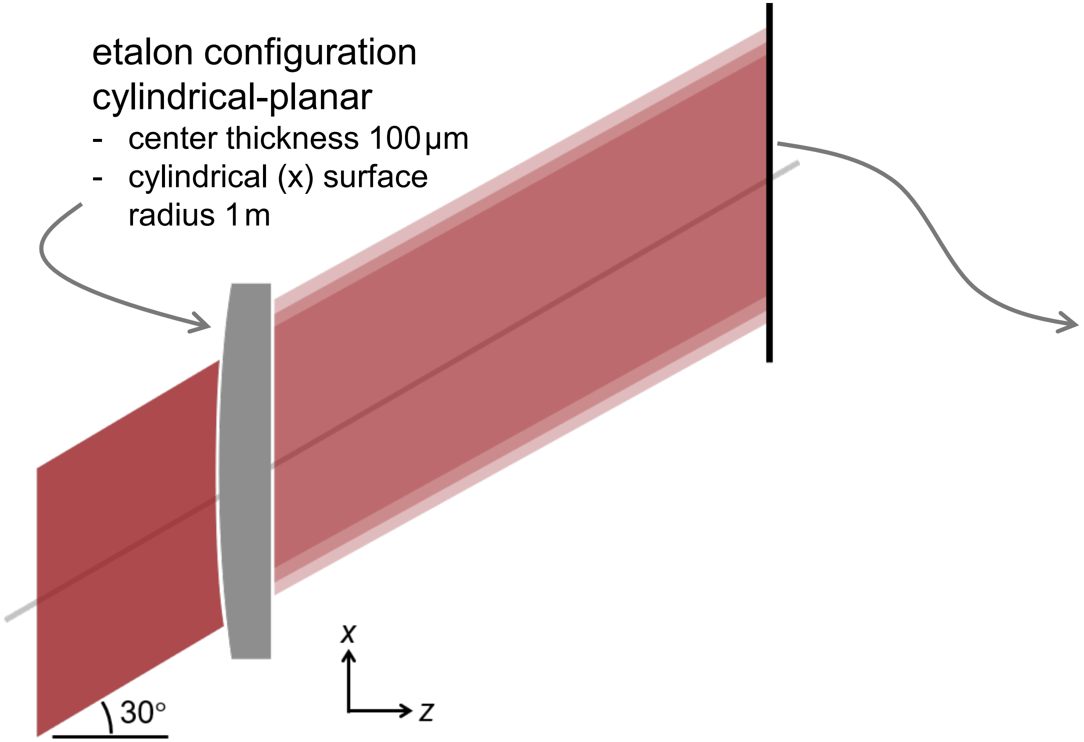

Linear interference fringes appear due to linear change of etalon thickness.

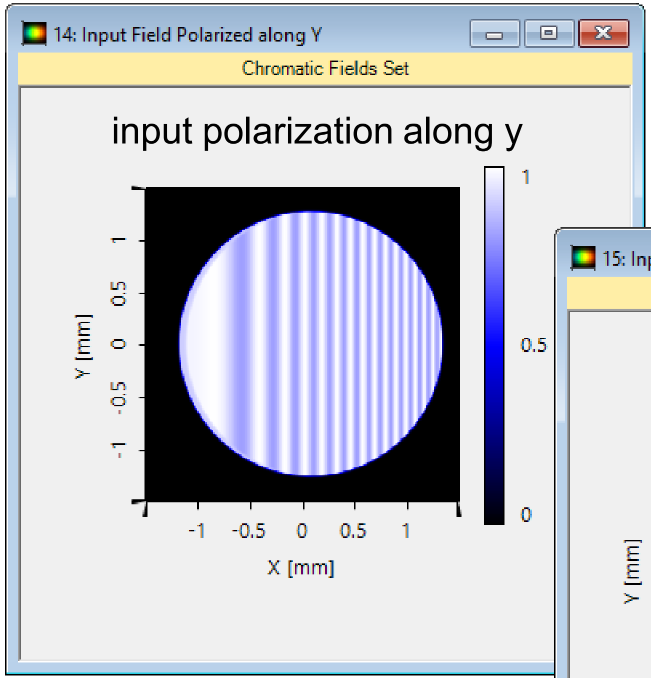
# Connecting Field Solvers



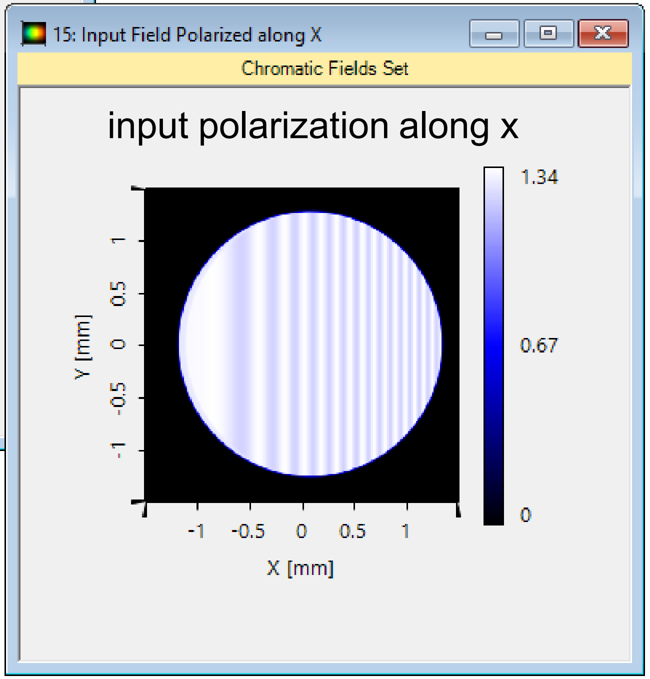



# Connecting Field Solvers: Cylindrical-Planar Surfaces

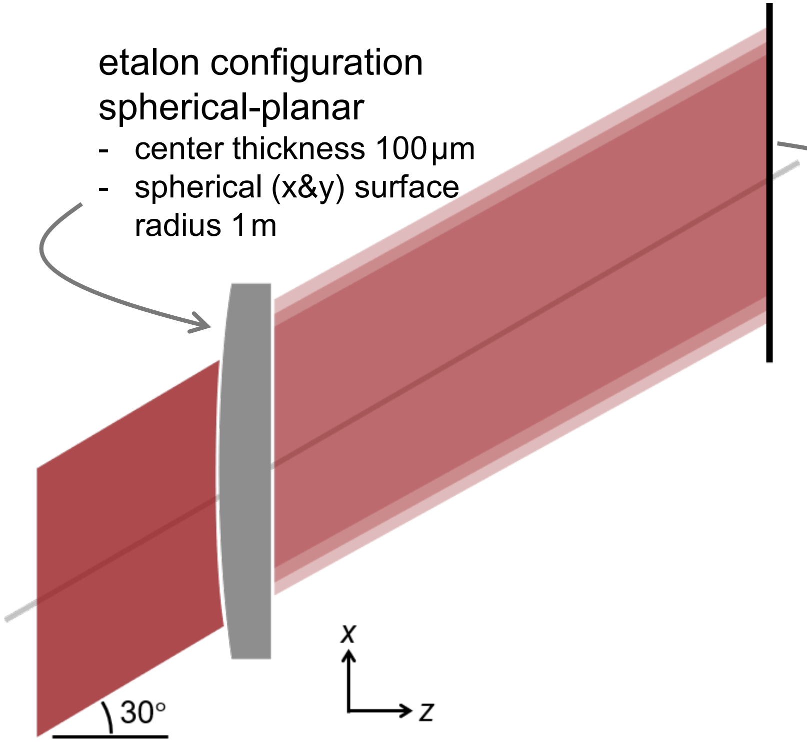


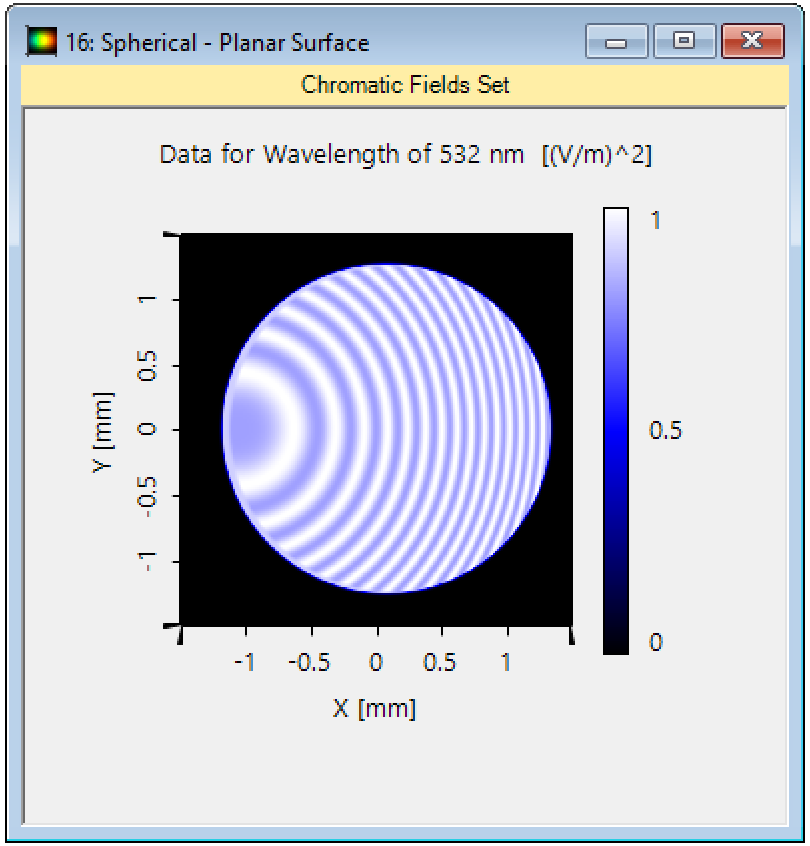




Polarization-dependent effect on the interference is considered in the simulation.



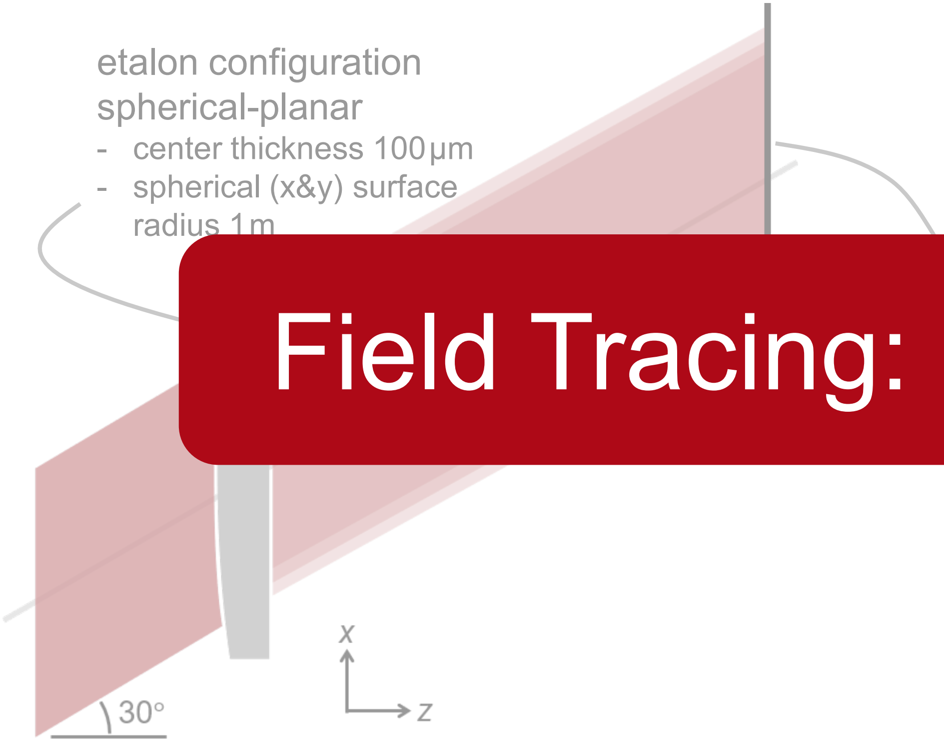
# Connecting Field Solvers: Spherical-Planar Surfaces

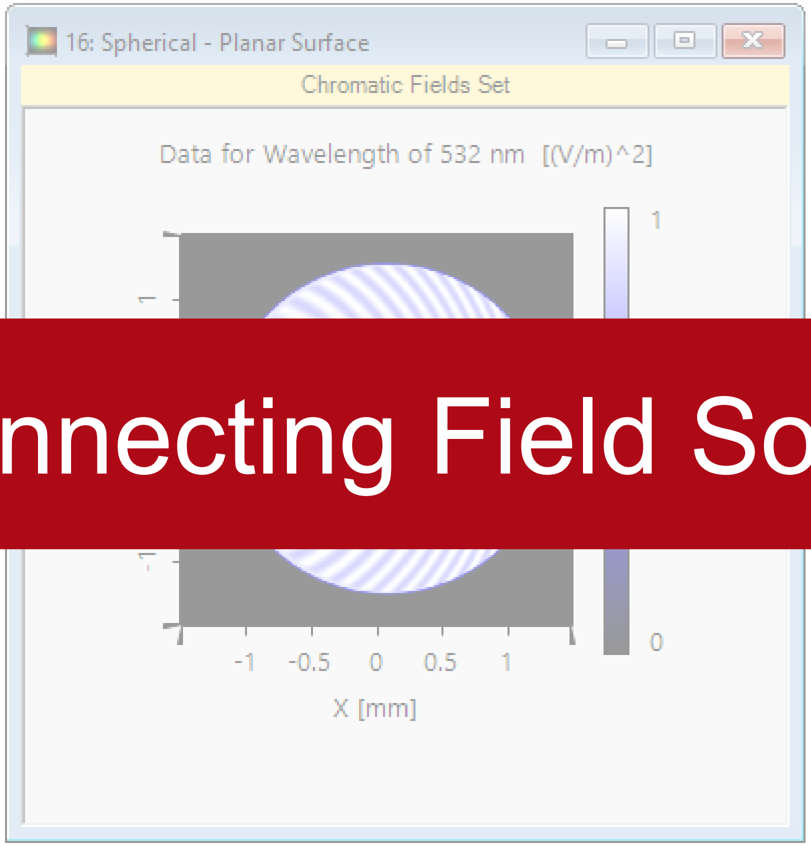



Non-sequential field tracing simulation of etalons allows the consideration of arbitrary surface types.

# Connecting Field Solvers: Spherical-Planar Surfaces

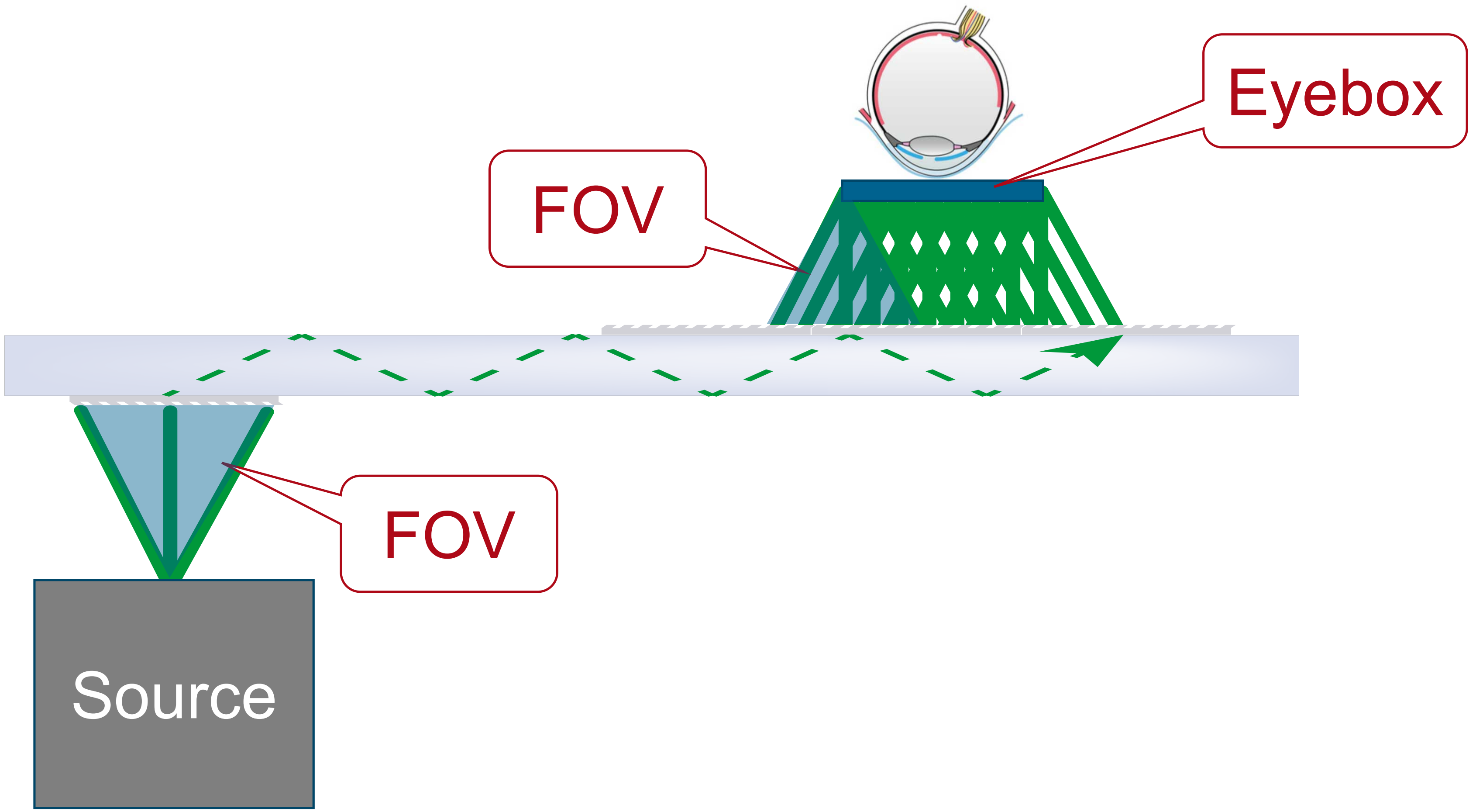


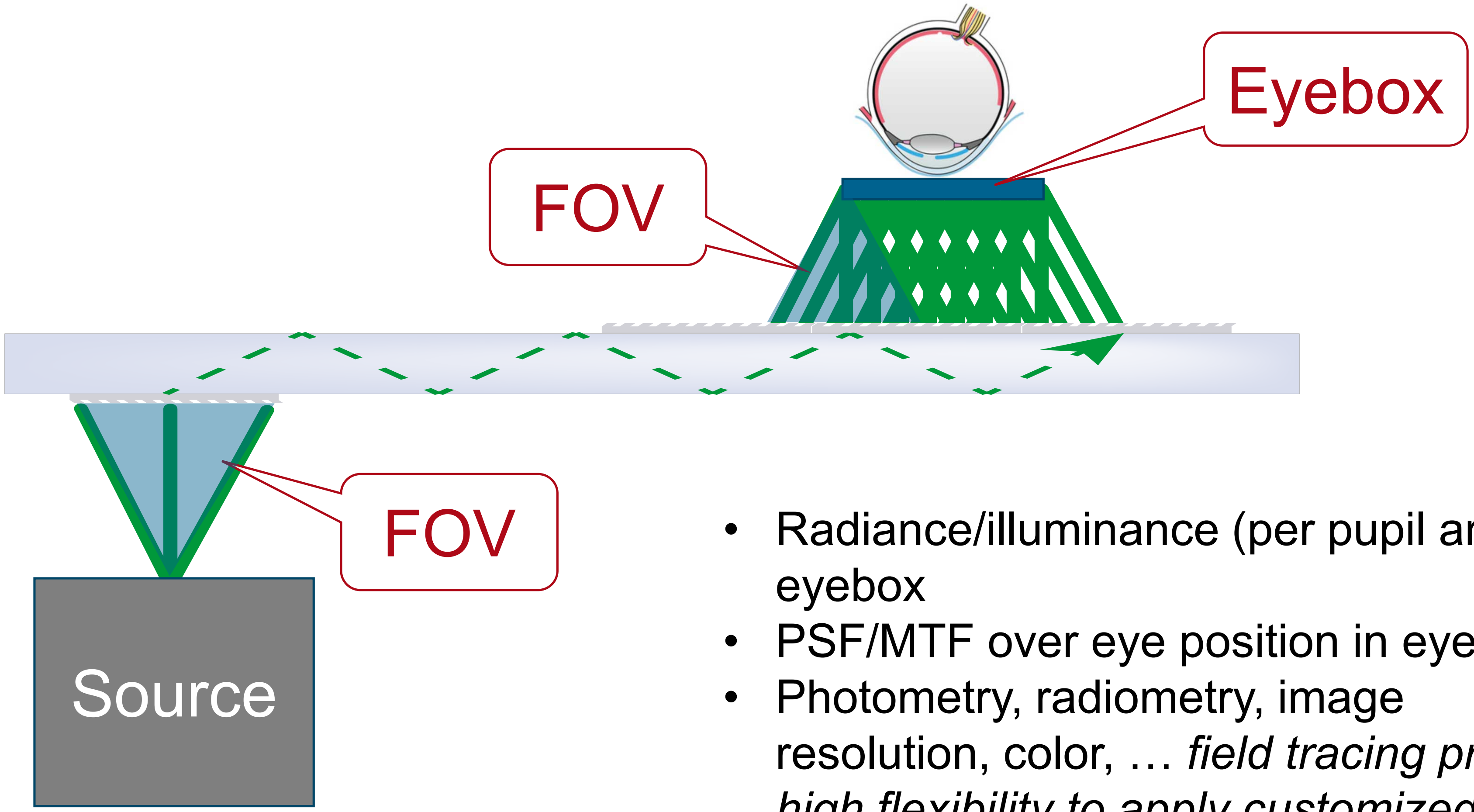

Field Tracing: Connecting Field Solvers

Non-sequential field tracing simulation of etalons allows the consideration of arbitrary surface types.

# Lightguide Concept

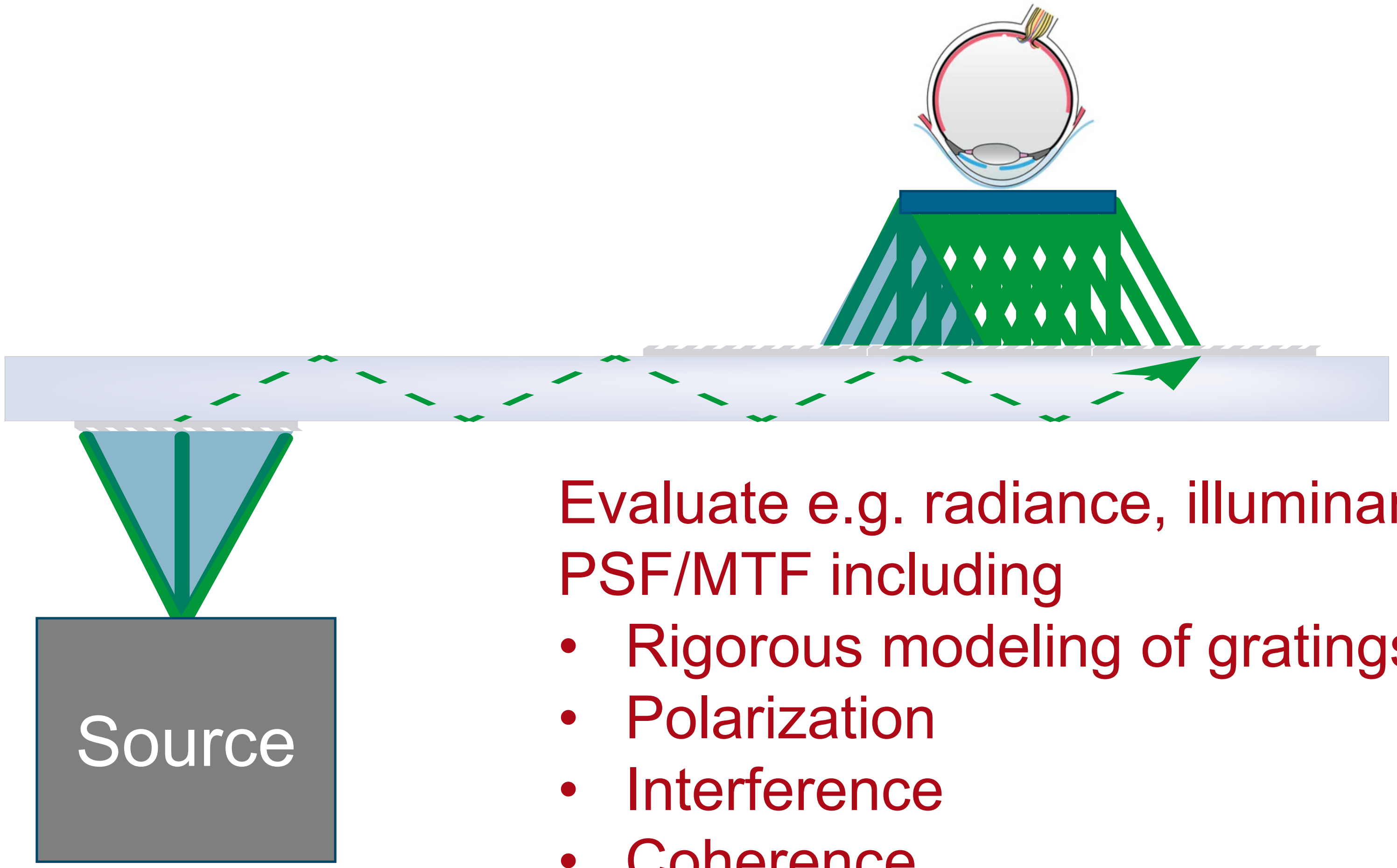


# Lightguide Concept: Fundamental Detectors




- 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*

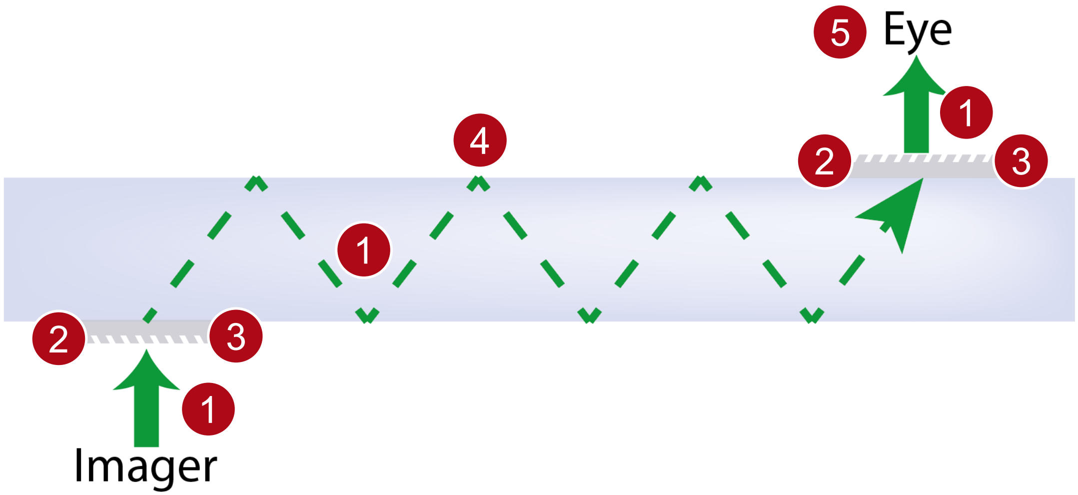
# Lightguide Concept: Modeling Task

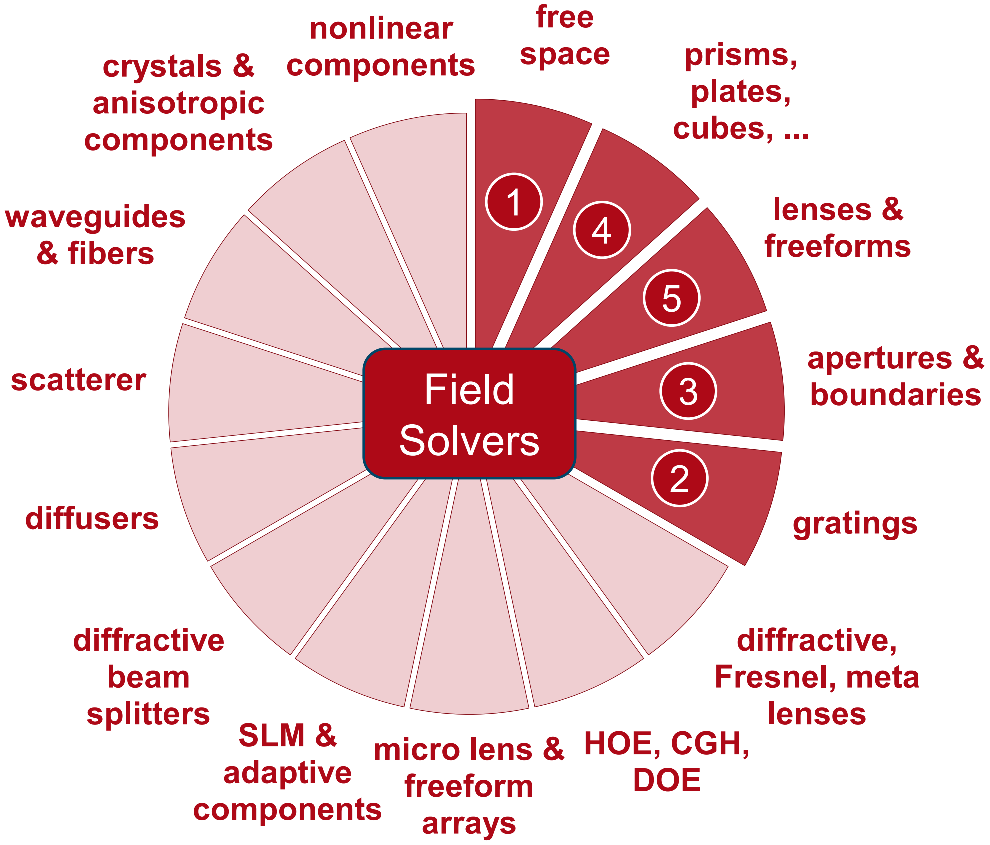



Evaluate e.g. radiance, illuminance, PSF/MTF including

- Rigorous modeling of gratings
- Polarization
- Interference
- Coherence

# Typical Modeling Situation for AR&MR Lightguide

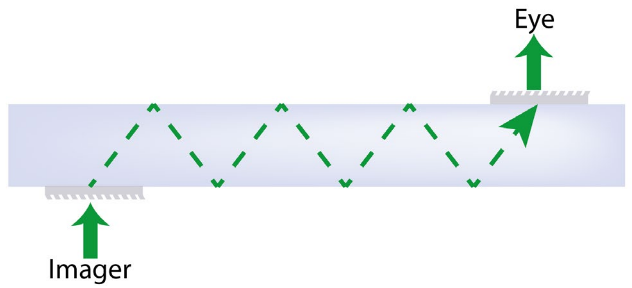


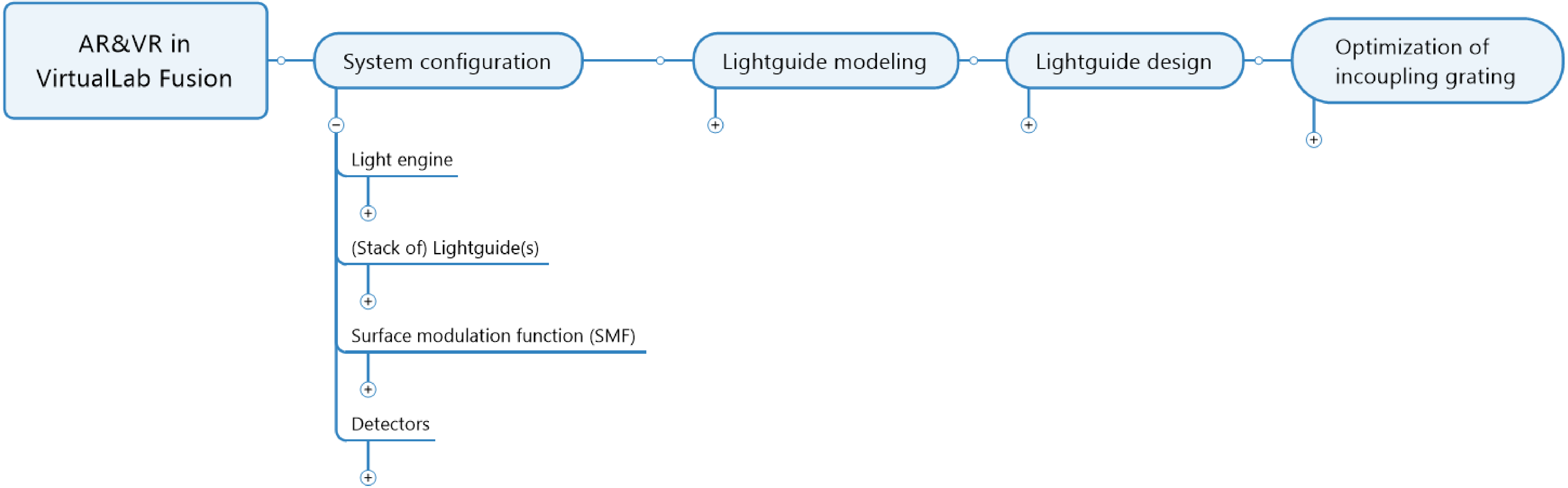
# Interference and coherence effects

# 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

AR&VR in VirtualLab Fusion

- System configuration
  - Light engine
    - Any source model can be applied in lightguide modeling
      - Any degree of coherence
      - Any degree of polarization
    - Configuration and modeling of light engine
  - (Stack of) Lightguide(s)
  - Surface modulation function (SMF)
  - Detectors
- Lightguide modeling
- Lightguide design
- Optimization of incoupling grating

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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jani.tervo@joensuu.fi
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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

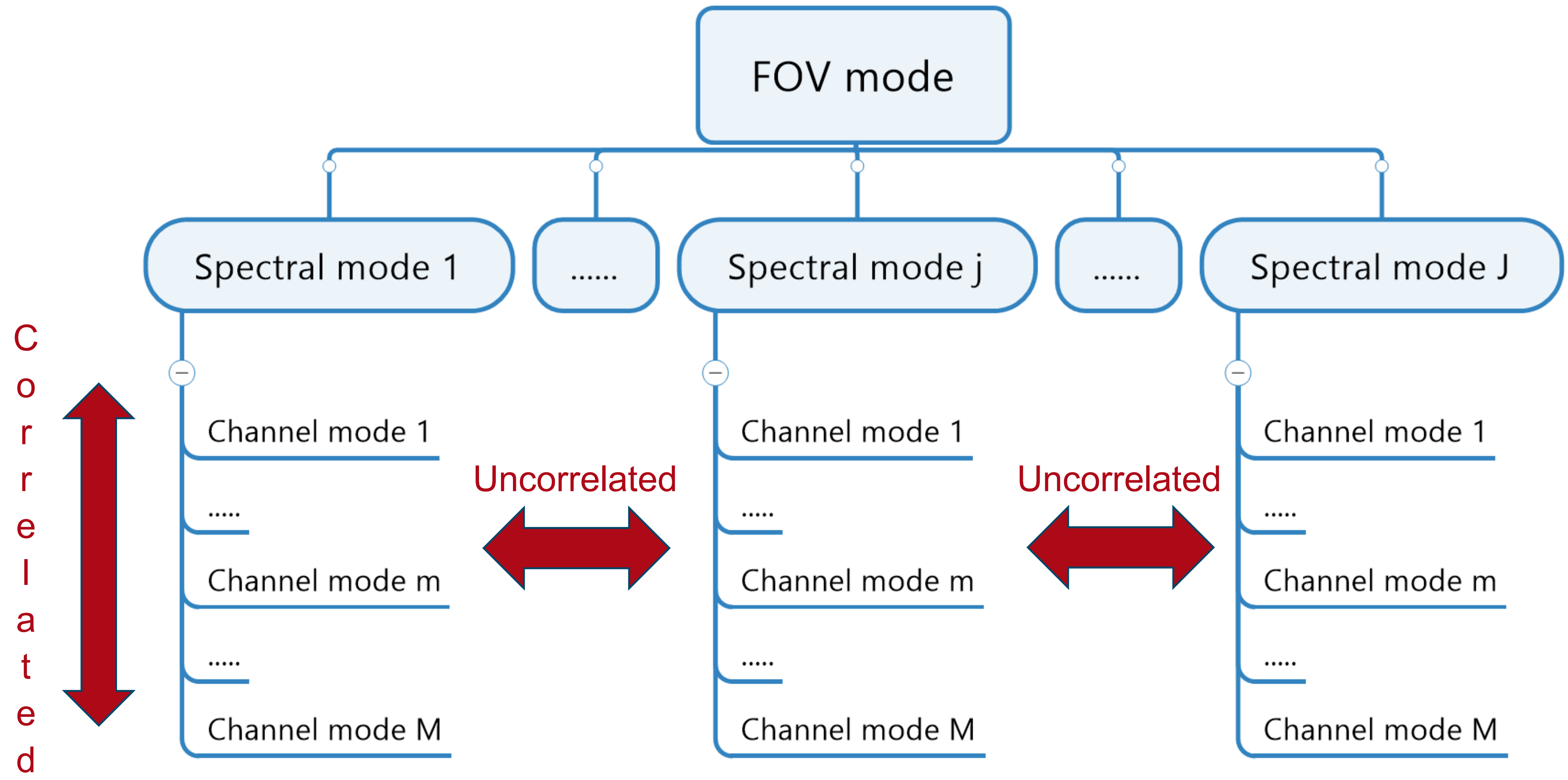
2004 J. Opt. Soc. Am. A/Vol. 27, No. 9/September 2010 Tervo *et al.*

**Shifted-elementary-mode representation for partially coherent vectorial fields**

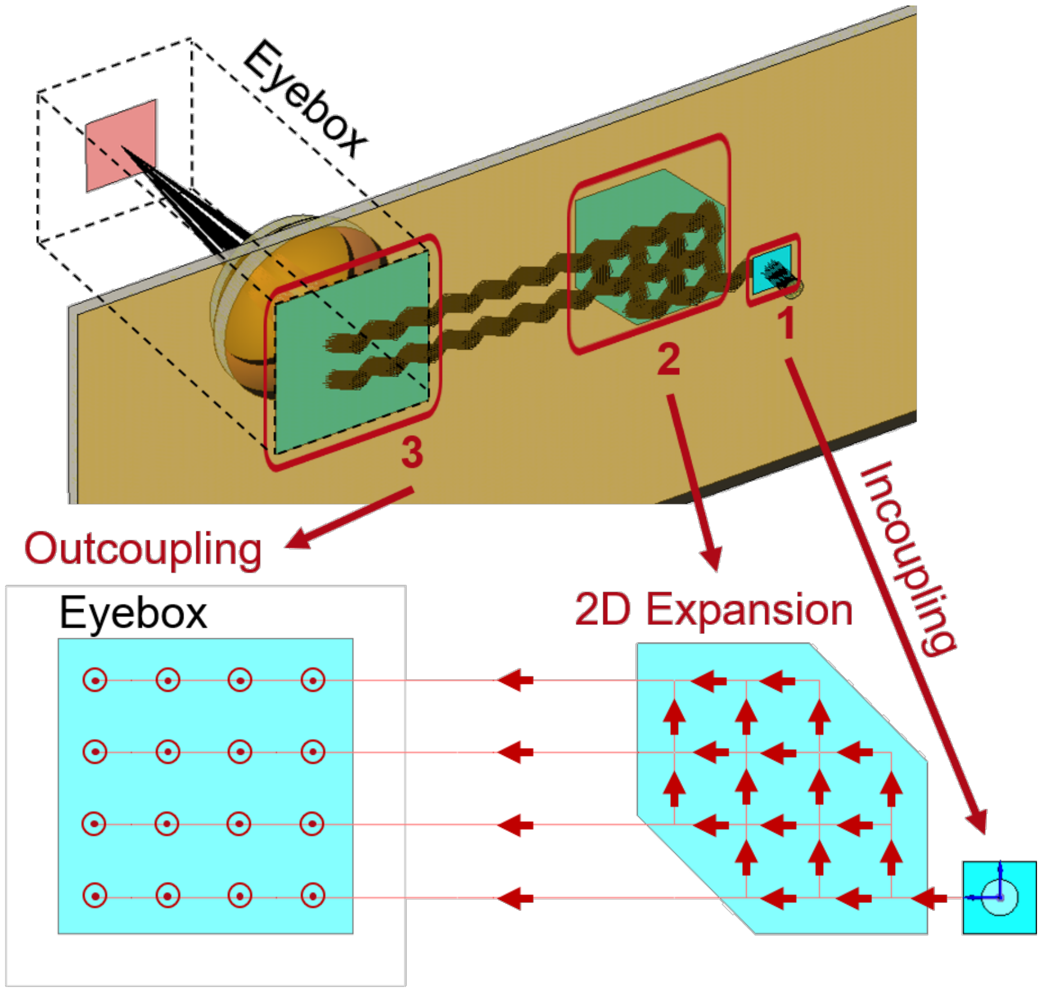
Jani Tervo,[1,*] Jari Turunen,[1] Pasi Vahimaa,[1] and Frank Wyrowski[2]

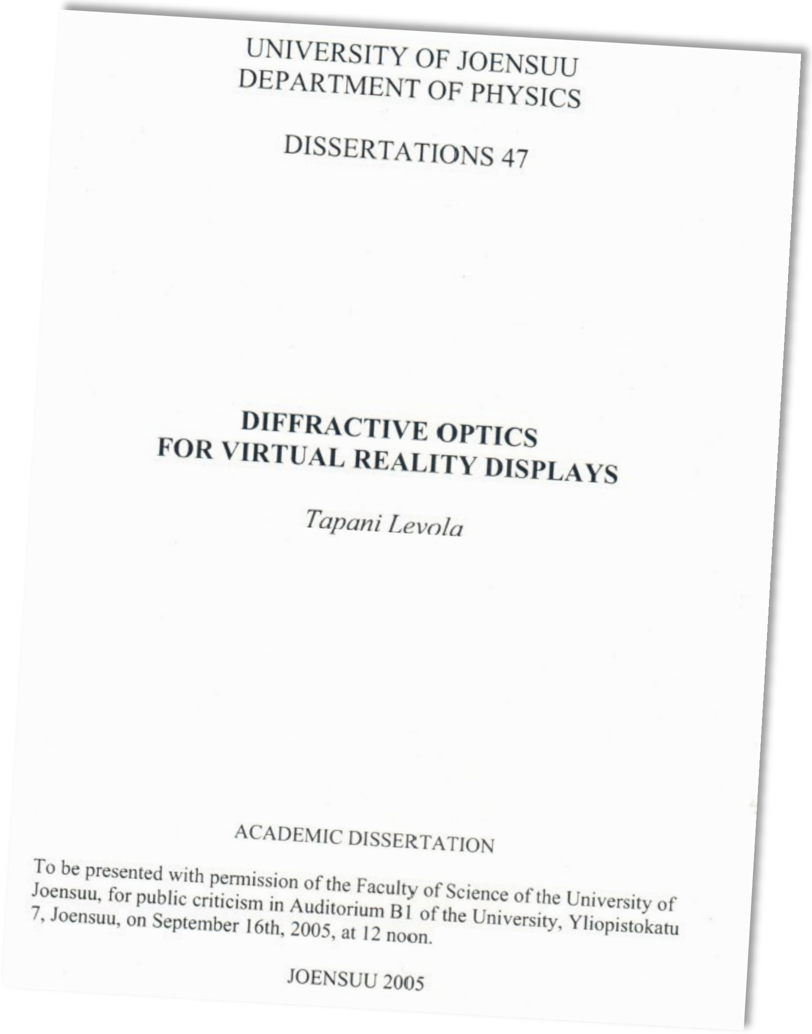
[1]*University of Eastern Finland, Department of Physics and Mathematics, P.O. Box 111, FI-80101 Joensuu, Finland*
[2]*Friedrich Schiller University of Jena, Department of Applied Physics, D-07745 Jena, Germany*
**Corresponding author: jani.tervo@joensuu.fi*

# 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**

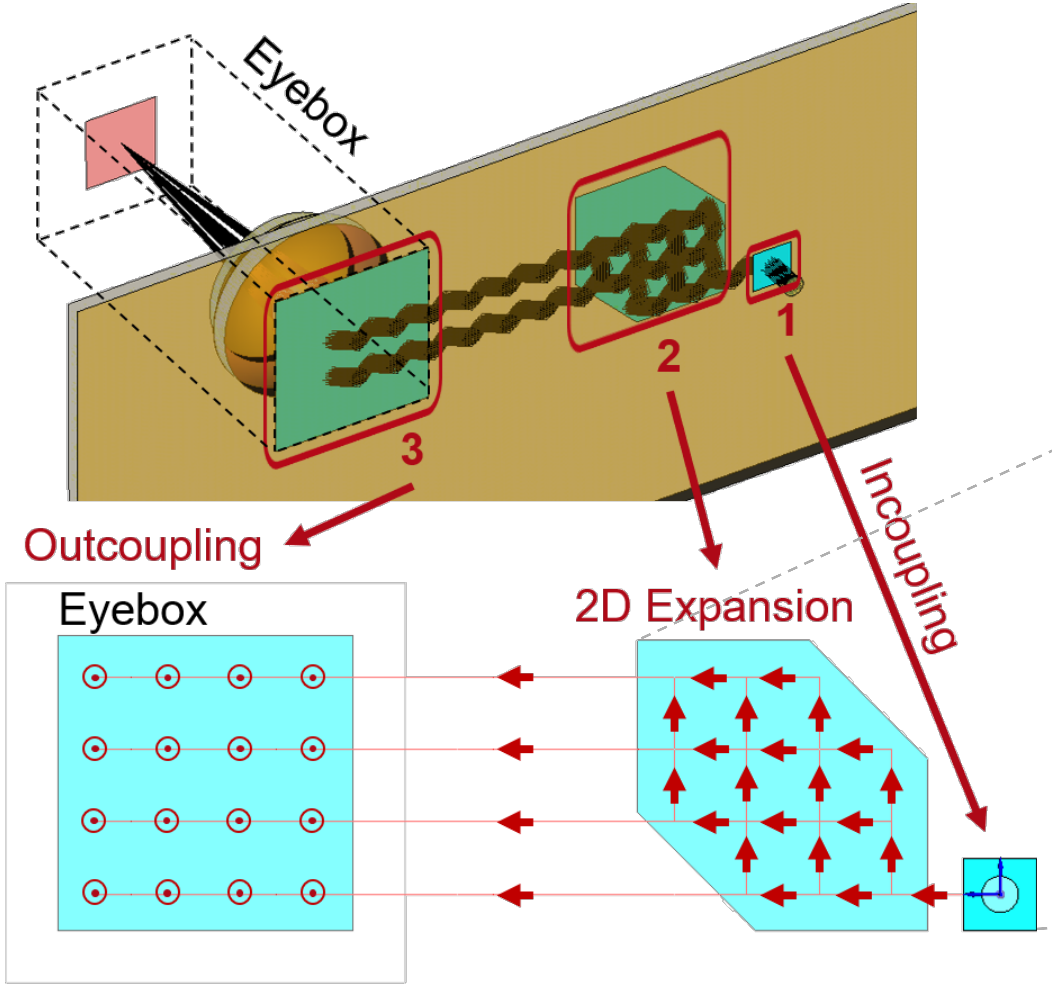
*Tapani Levola*

ACADEMIC DISSERTATION

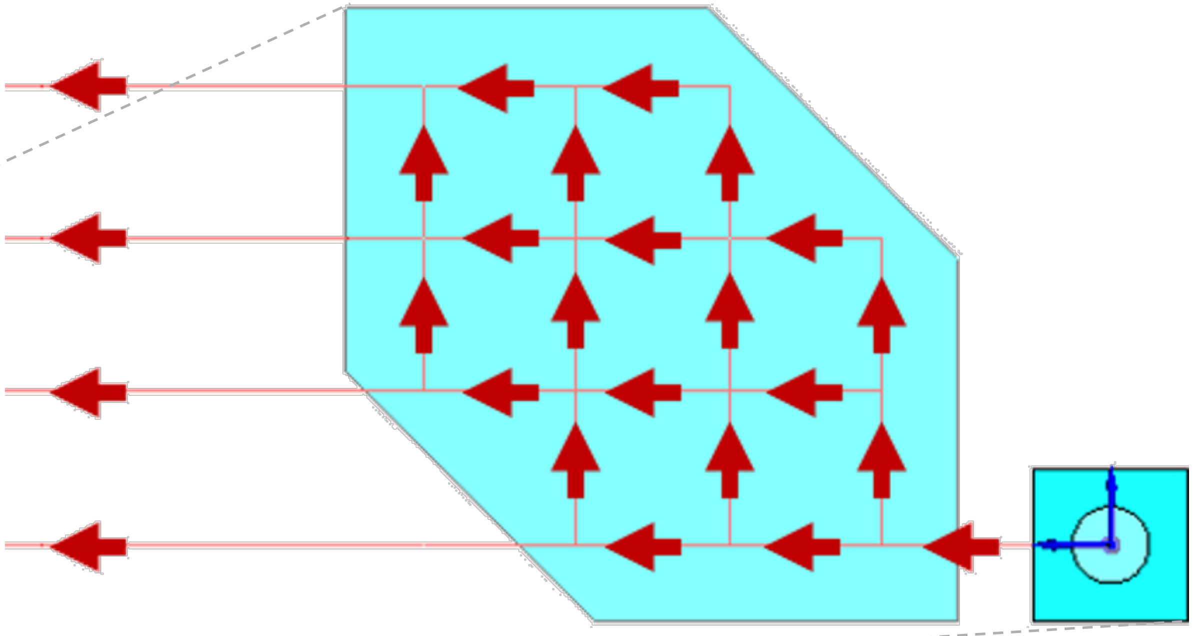
To be presented with permission of the Faculty of Science of the University of Joensuu, for public criticism in Auditorium B1 of the University, Yliopistokatu 7, Joensuu, on September 16th, 2005, at 12 noon.

JOENSUU 2005

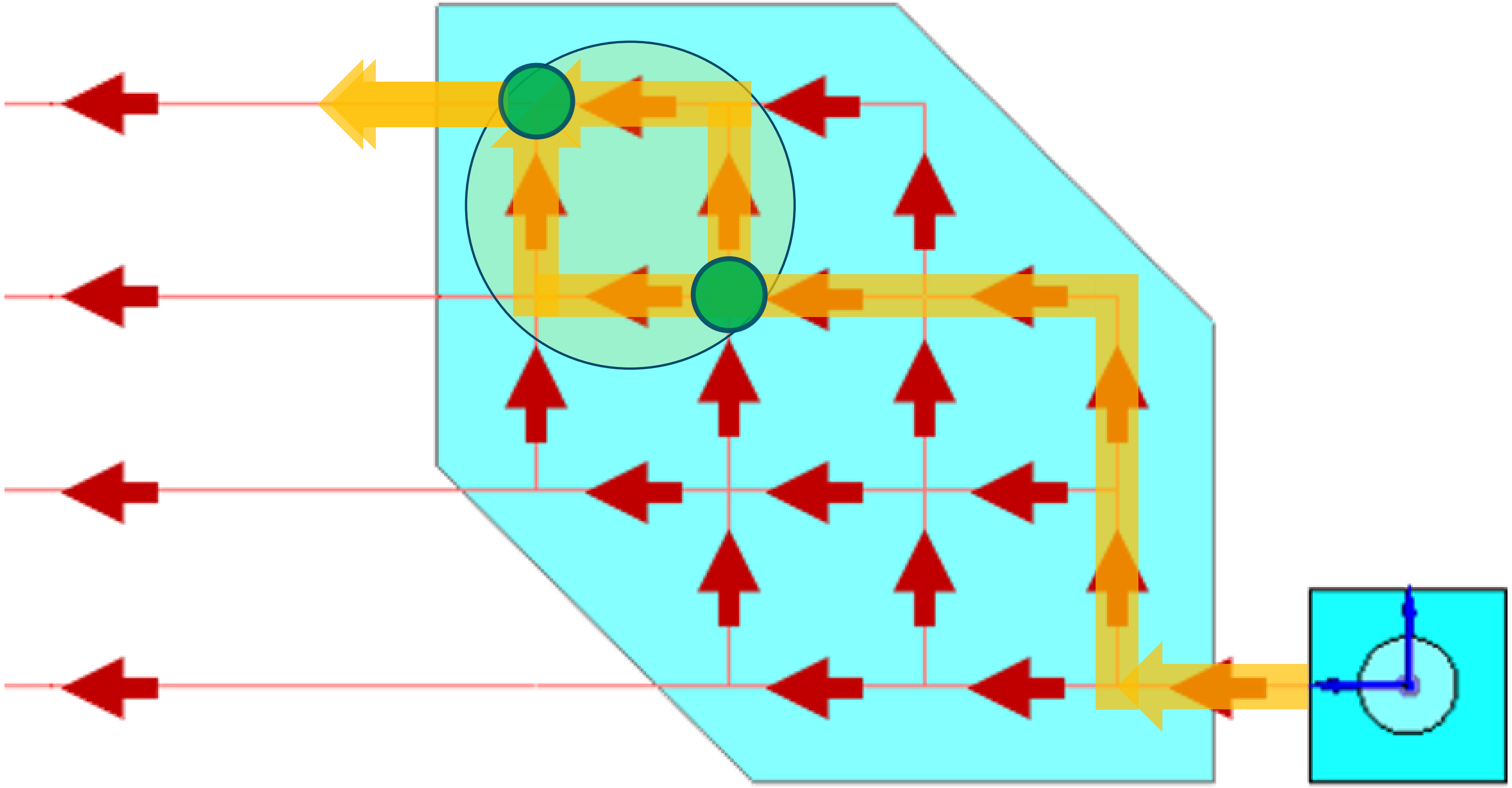
# Levola Type Geometry of Eye Pupil Expansion (EPE)



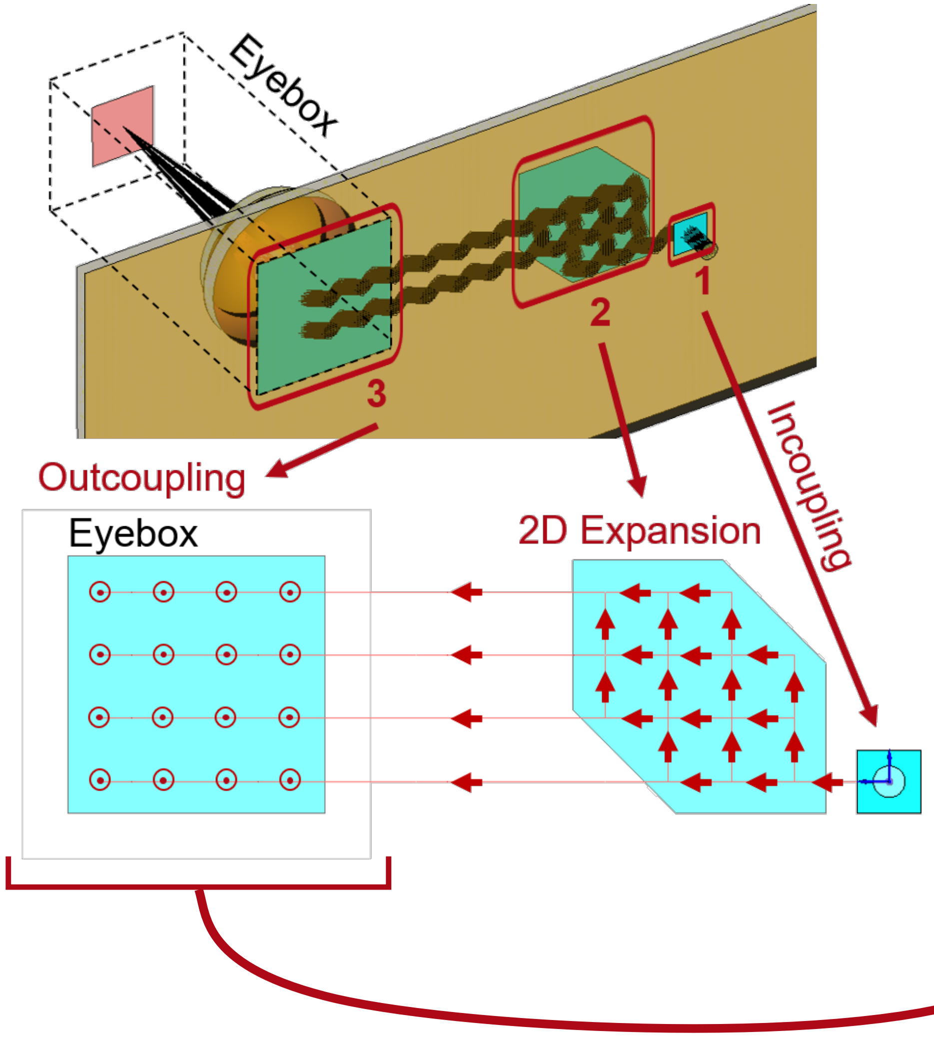

Multiple **Mini-Mach-Zehnder** Systems

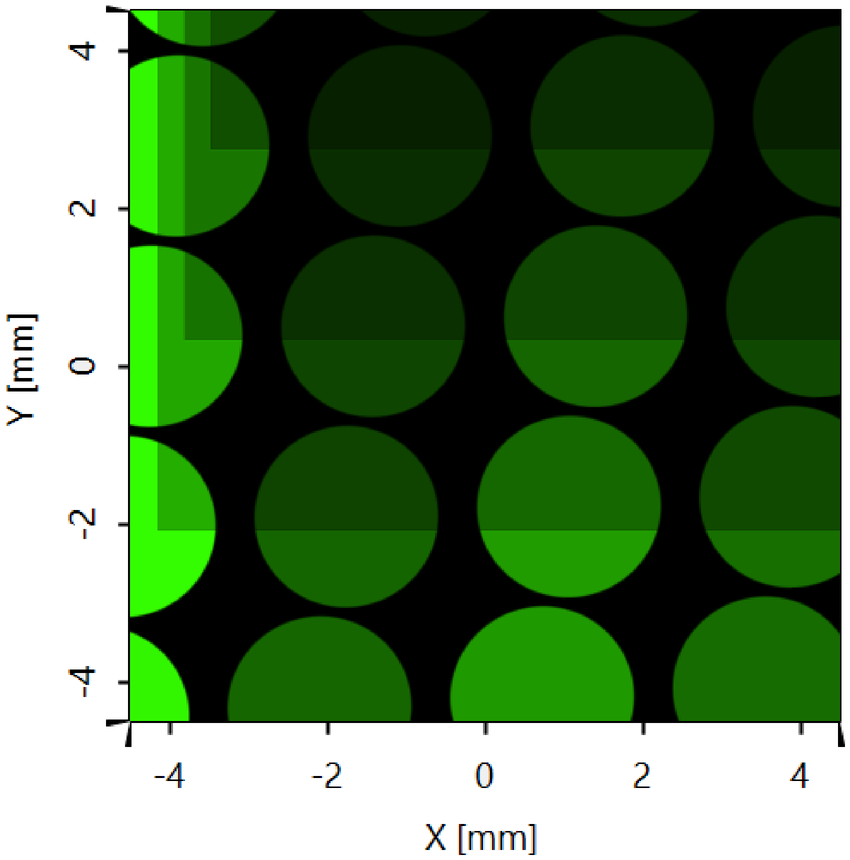


# Mini Mach-Zehnder Inferferometer Lightpaths: Channel Modes



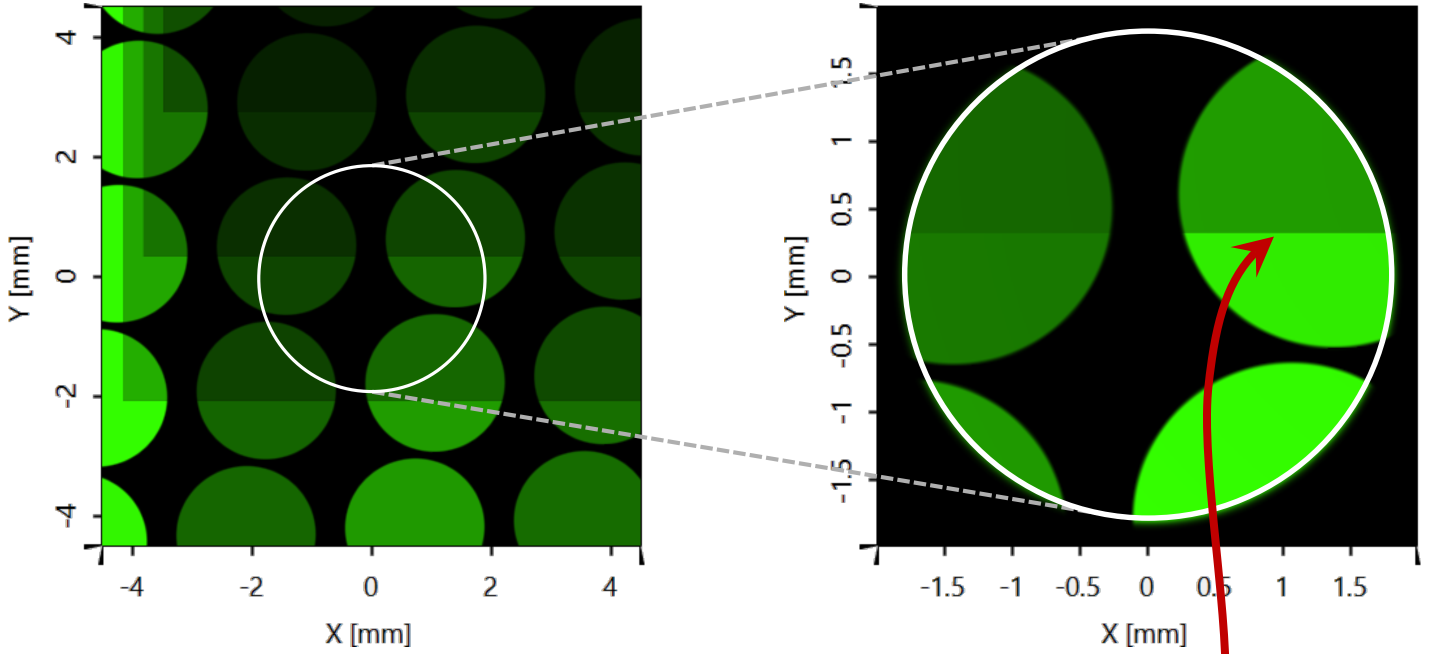
# Lightguide Setup & Evaluation of Outcoupled Light




Exemplary
Outcoupled Light

# Outcoupled Light Modes Passing Through Eye Pupil



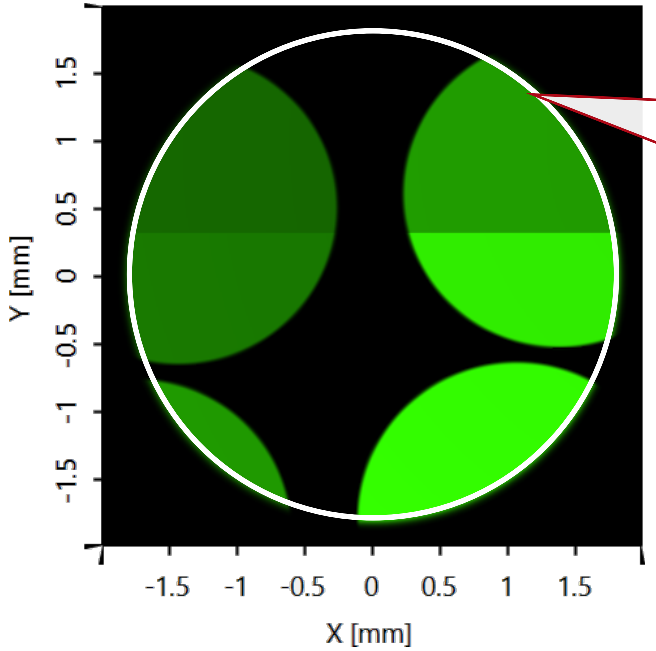

marginal area
of outcouling grating region

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

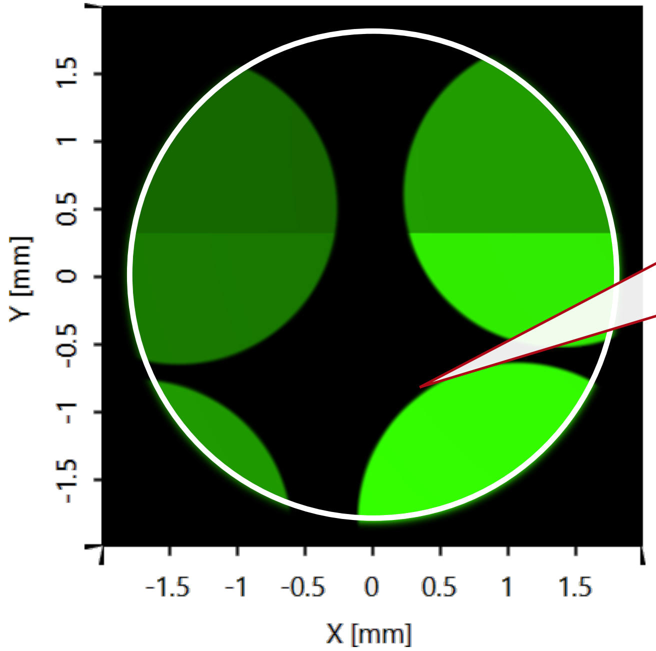
# Outcoupled Light Modes Passing Through Eye Pupil




light passing the eye pupil

Boundary effects should be included in high resolution

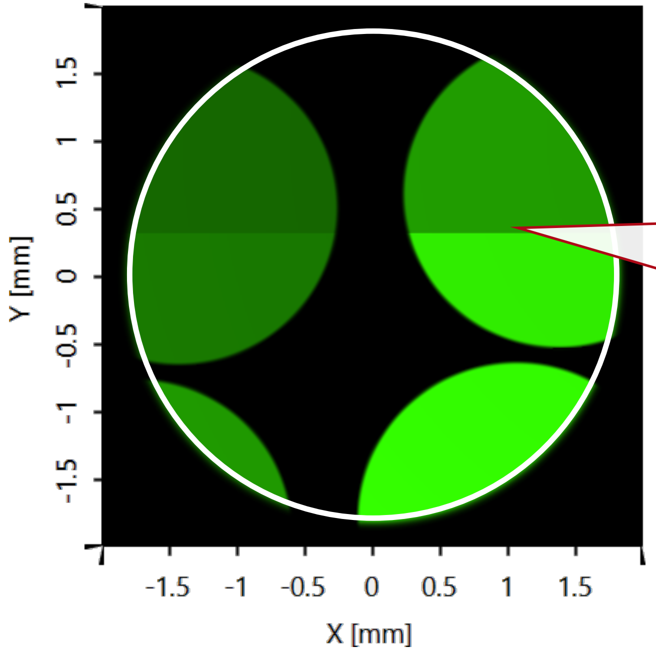
# Outcoupled Light Modes Passing Through Eye Pupil




light passing the eye pupil

Boundary effects should be included in high resolution

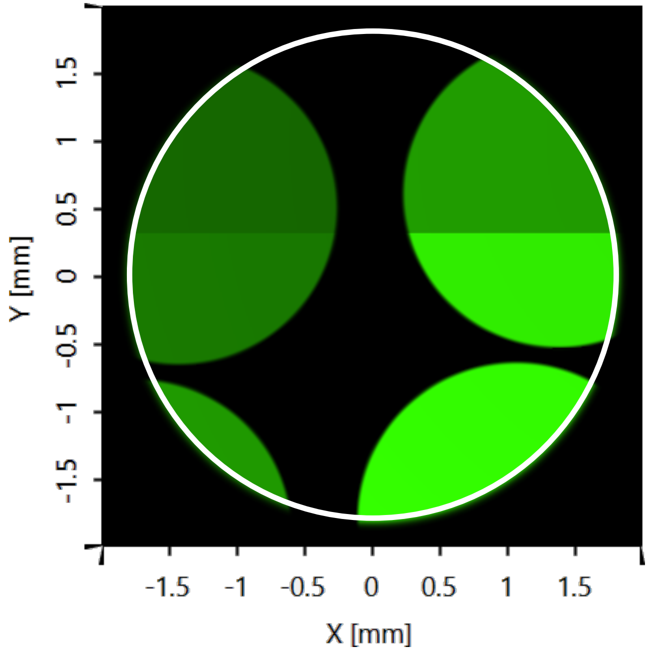
# Outcoupled Light Modes Passing Through Eye Pupil




light passing the eye pupil

Boundary effects should be included in high resolution

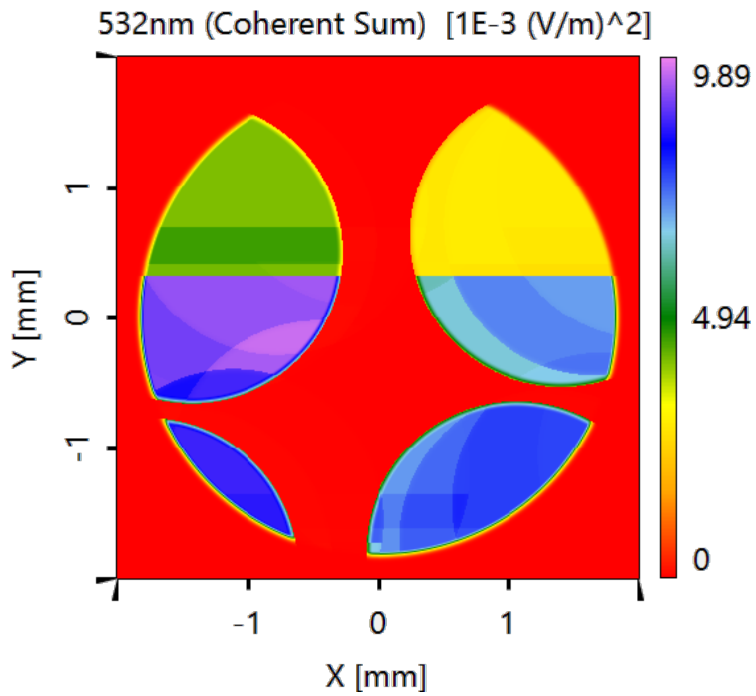
# Outcoupled Light Modes Passing Through Eye Pupil




light passing the eye pupil

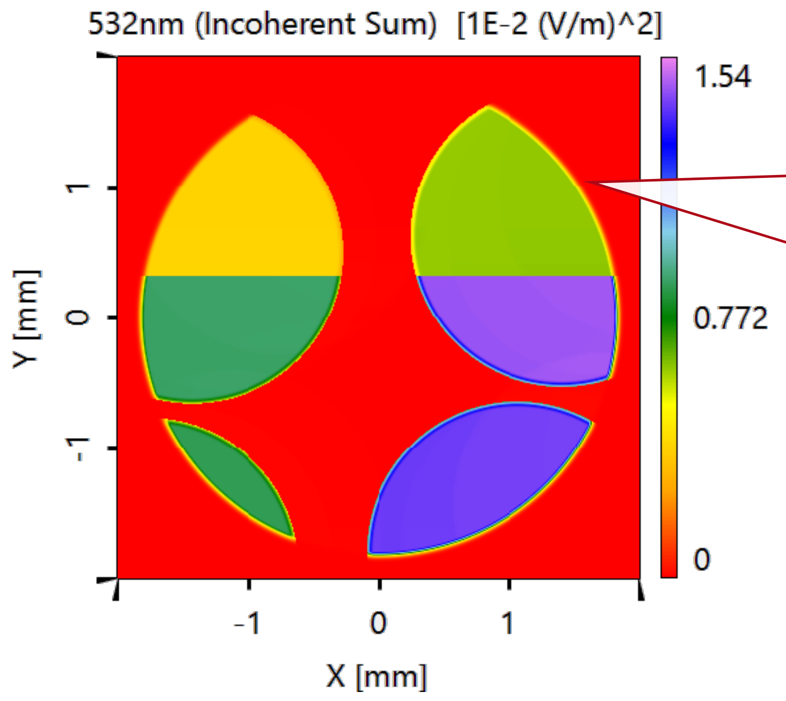
For one wavelength and one FOV the pupil is partly filled with mutually correlated channel modes.

# Outcoupled Light Modes Passing Through Eye Pupil




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

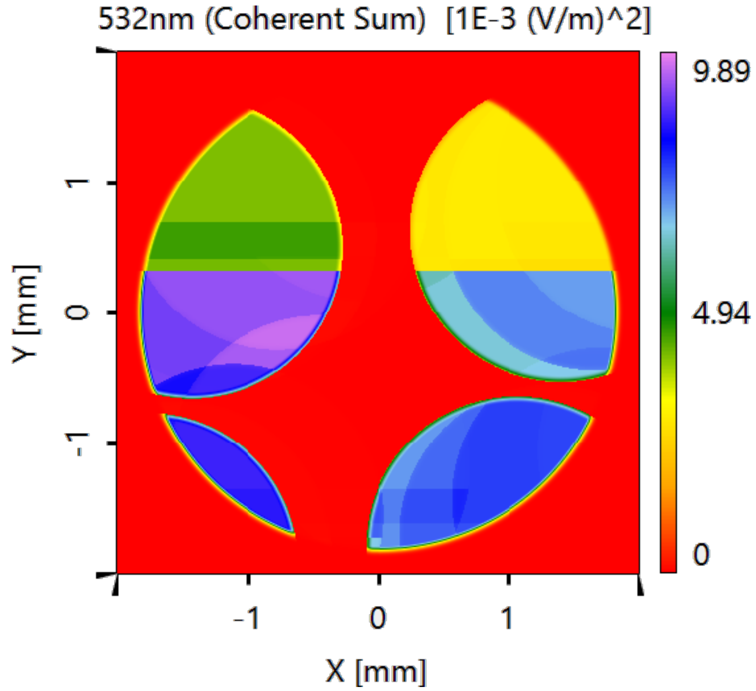
# Outcoupled Light Modes Passing Through Eye Pupil




Assumption of uncorrelated modes leads to wrong result!

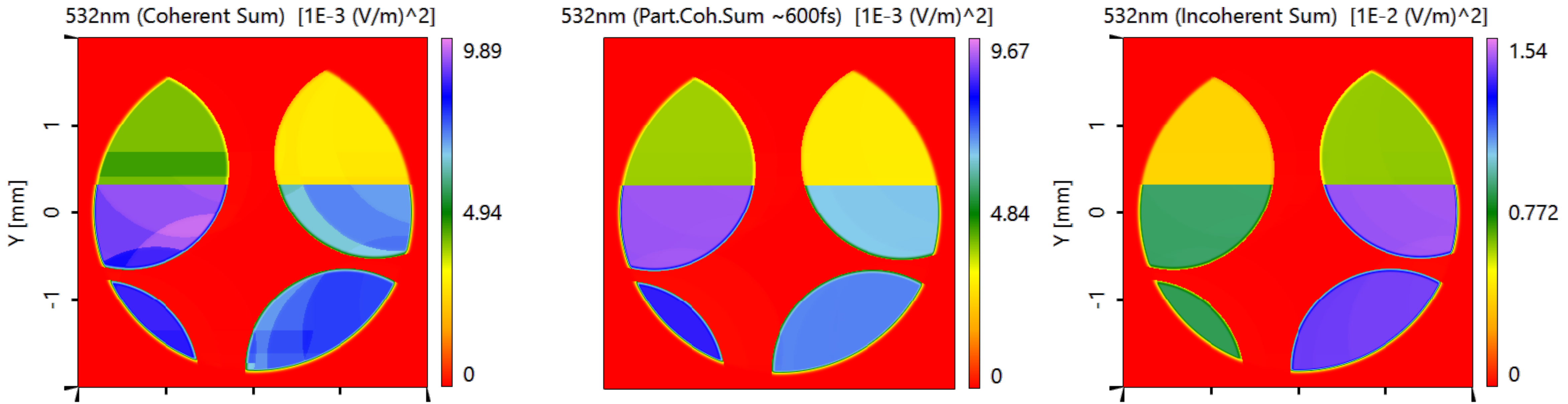
For one wavelength and one FOV the pupil is partly filled with mutually correlated channel modes.

# 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

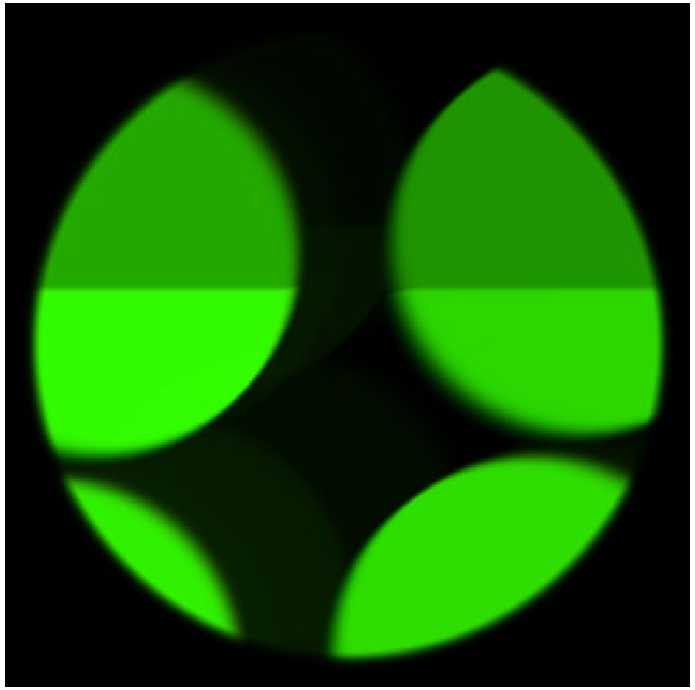
Partially Coherent

Incoherent

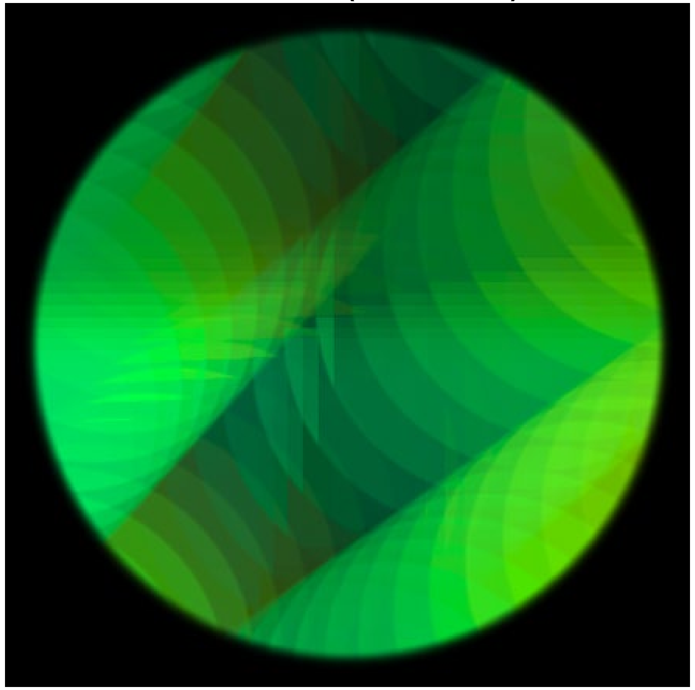
Pupil is partly filled with mutually correlated channel modes per uncorrelated spectral modes.

# Light Modes Passing Through Eye Pupil

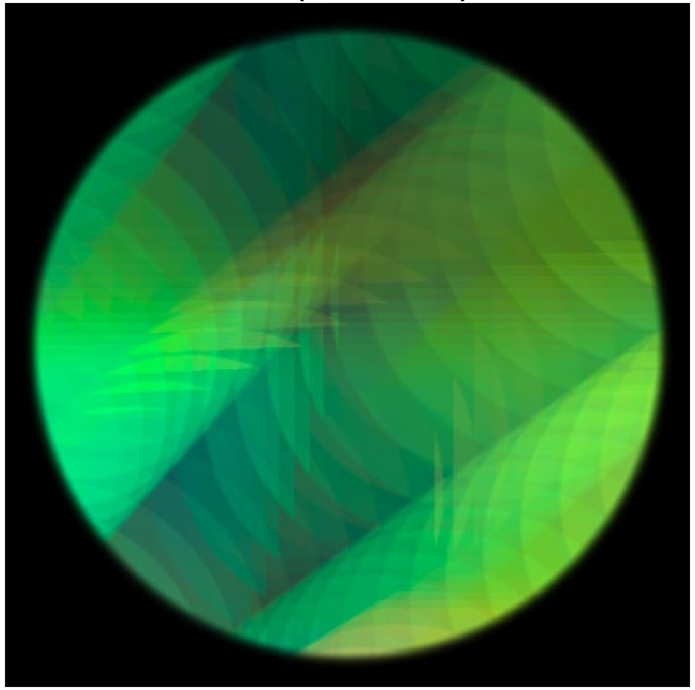
...of a
laser diode (~1 nm)



...of a
VCSEL (~20 nm)



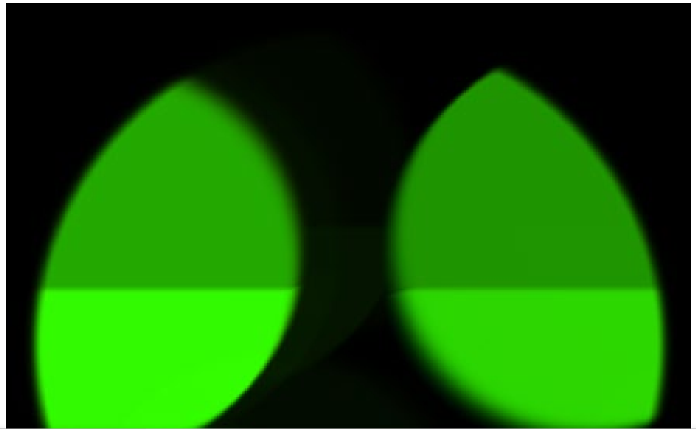
...of an
LED (~40 nm)



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)



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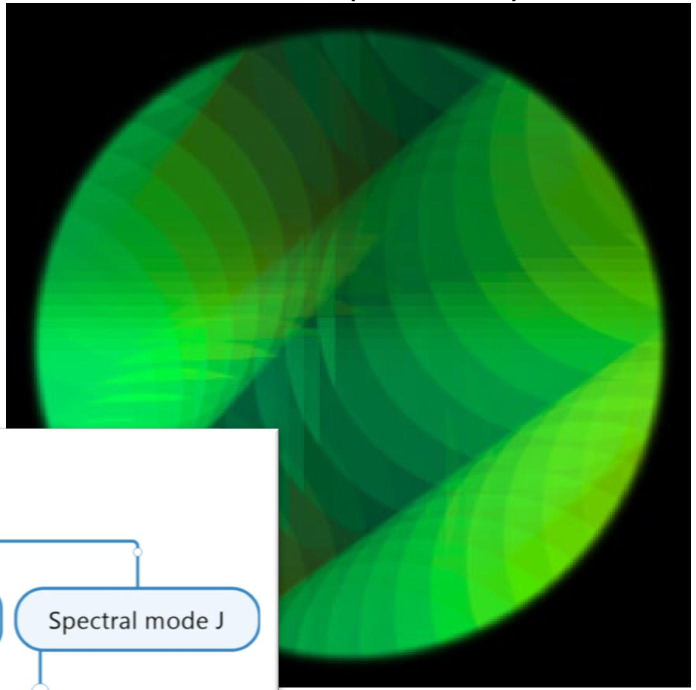

...of an
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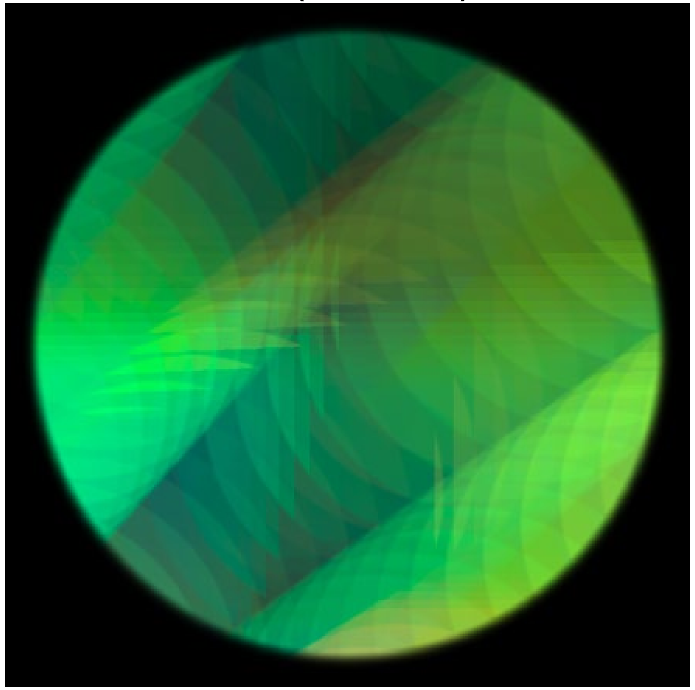
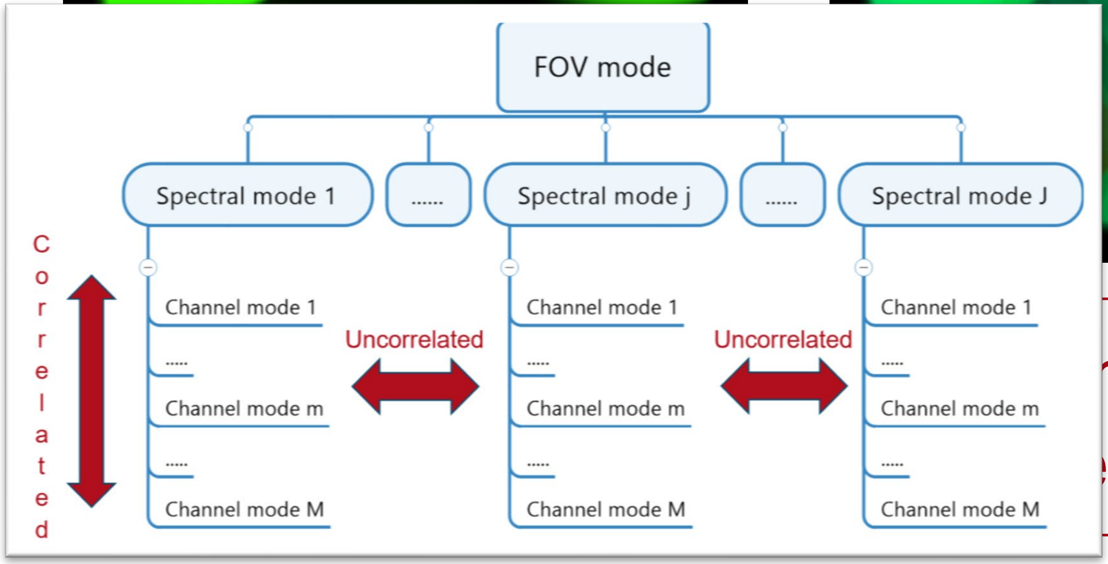
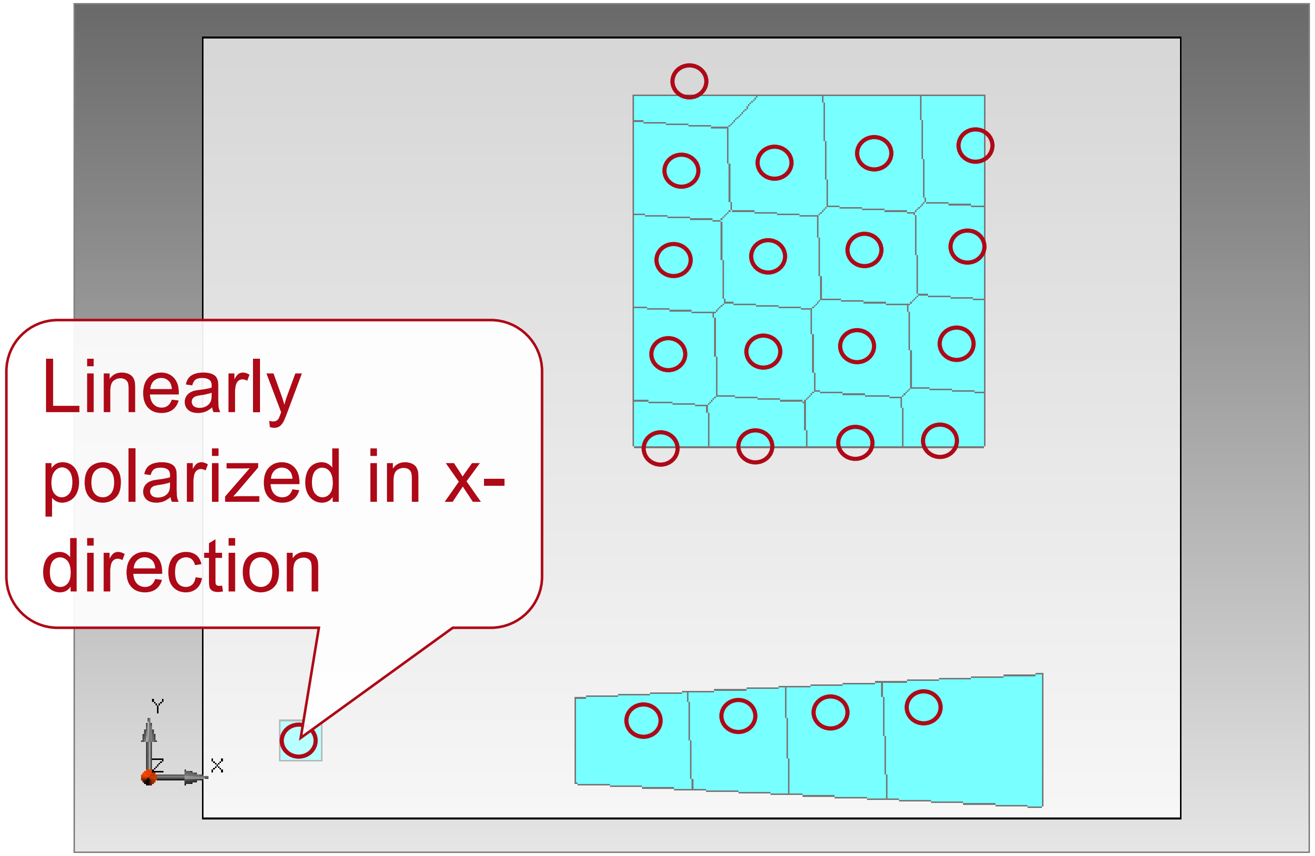





mutually correlated channel
lated spectral modes.

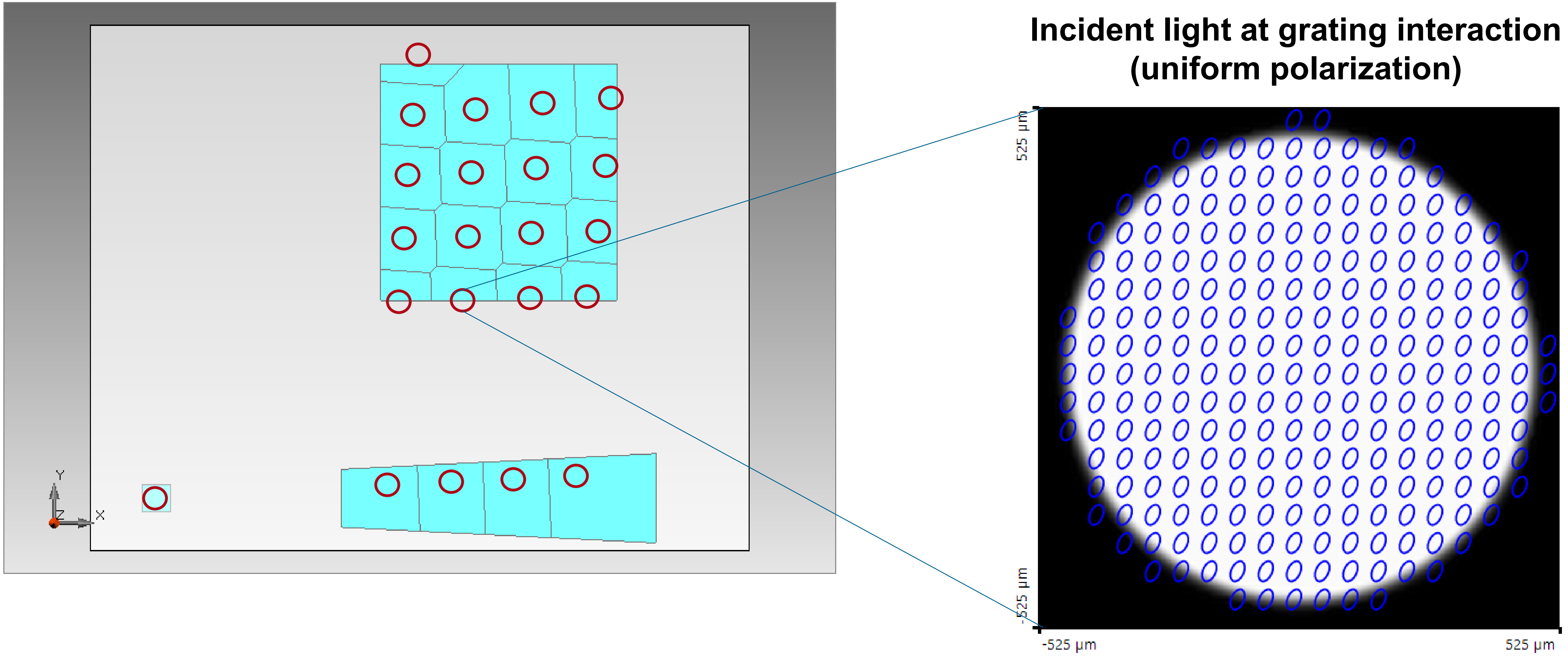
# Polarization effects

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

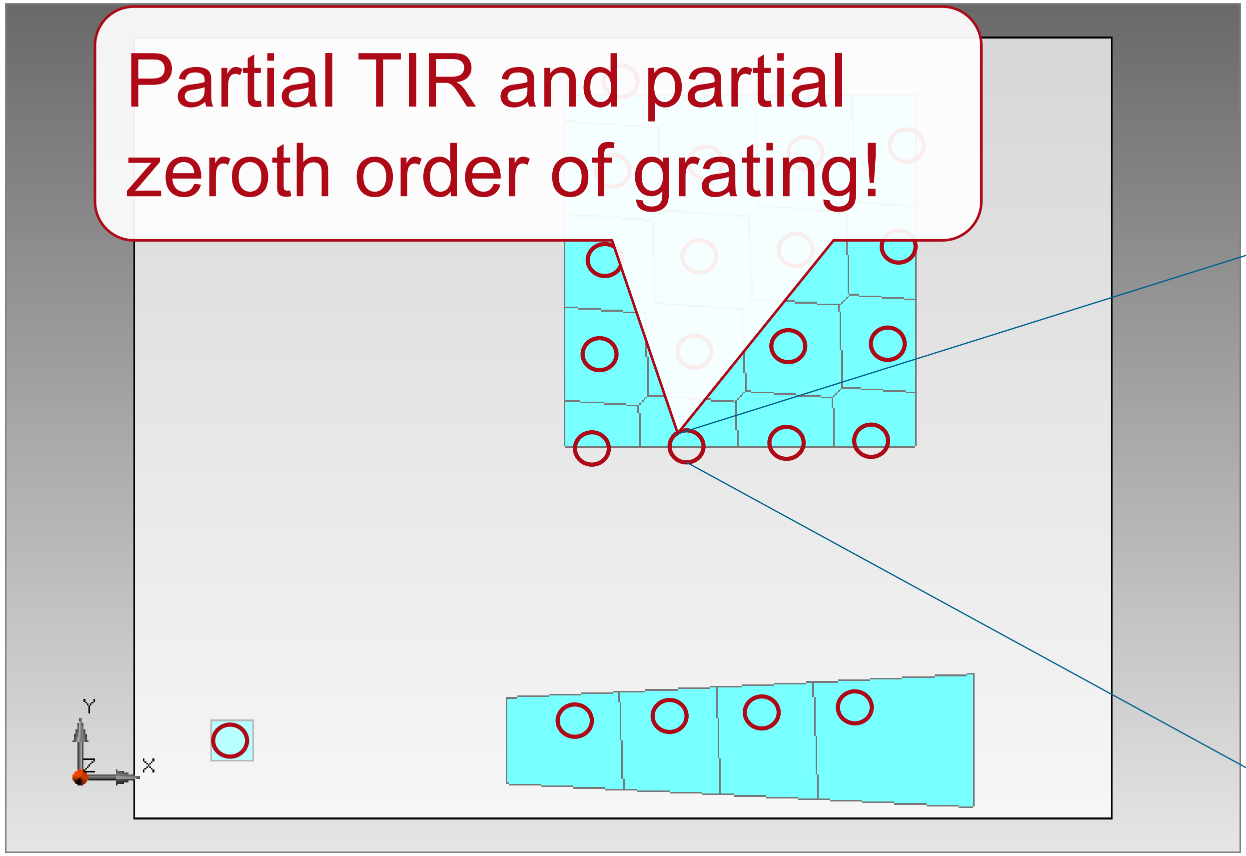


# Grating Design for FOV Angle (5°, 3°) – Polarization Evaluation

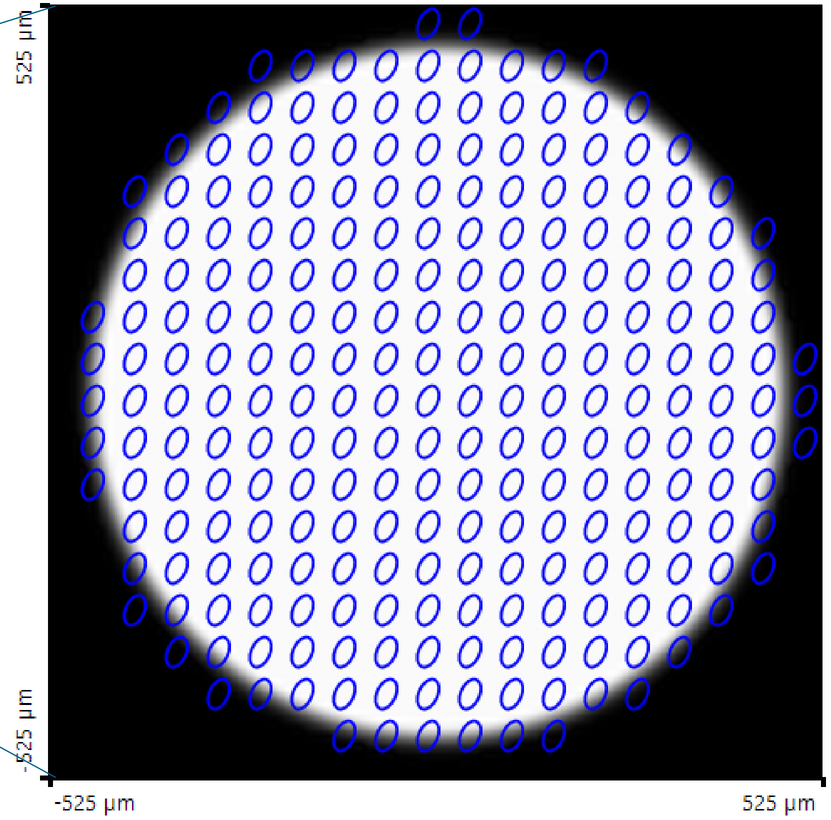
Incident light at grating interaction
(uniform polarization)



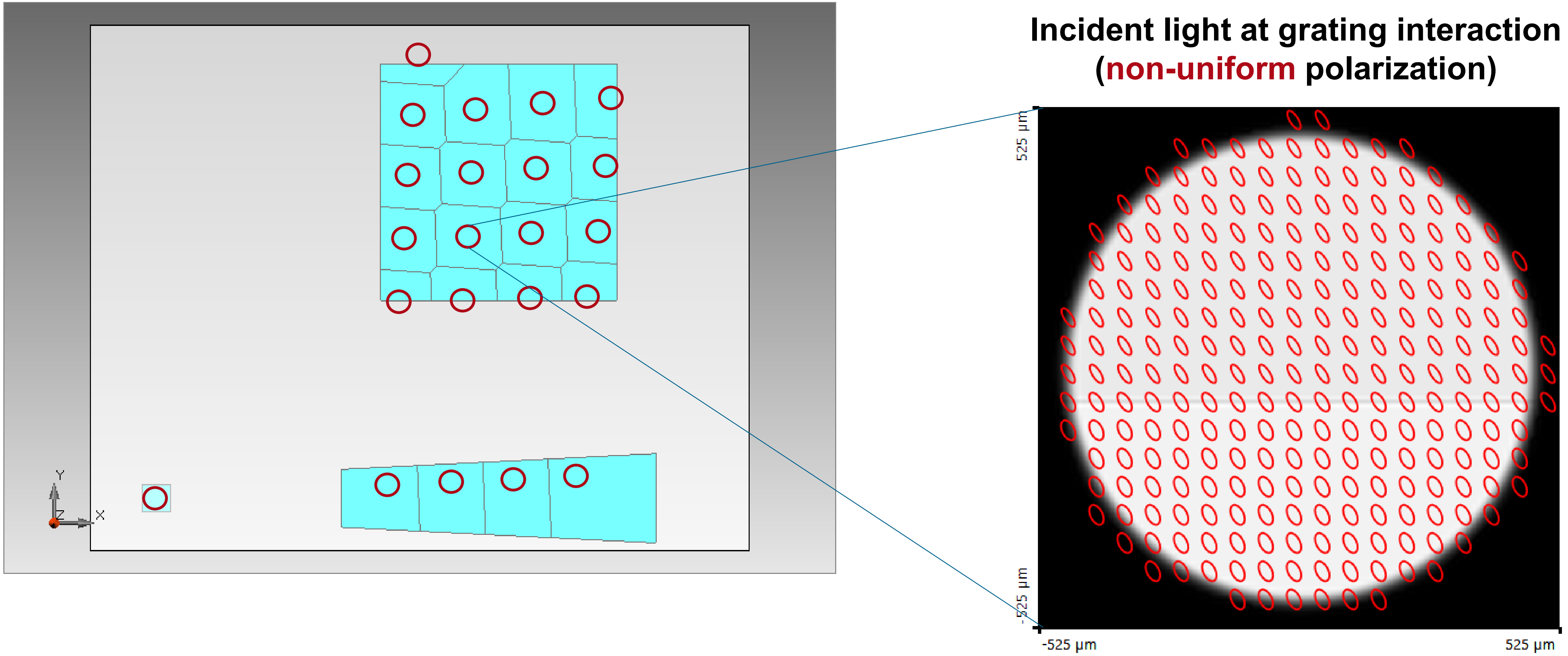
# Grating Design for FOV Angle (5°, 3°) – Polarization Evaluation



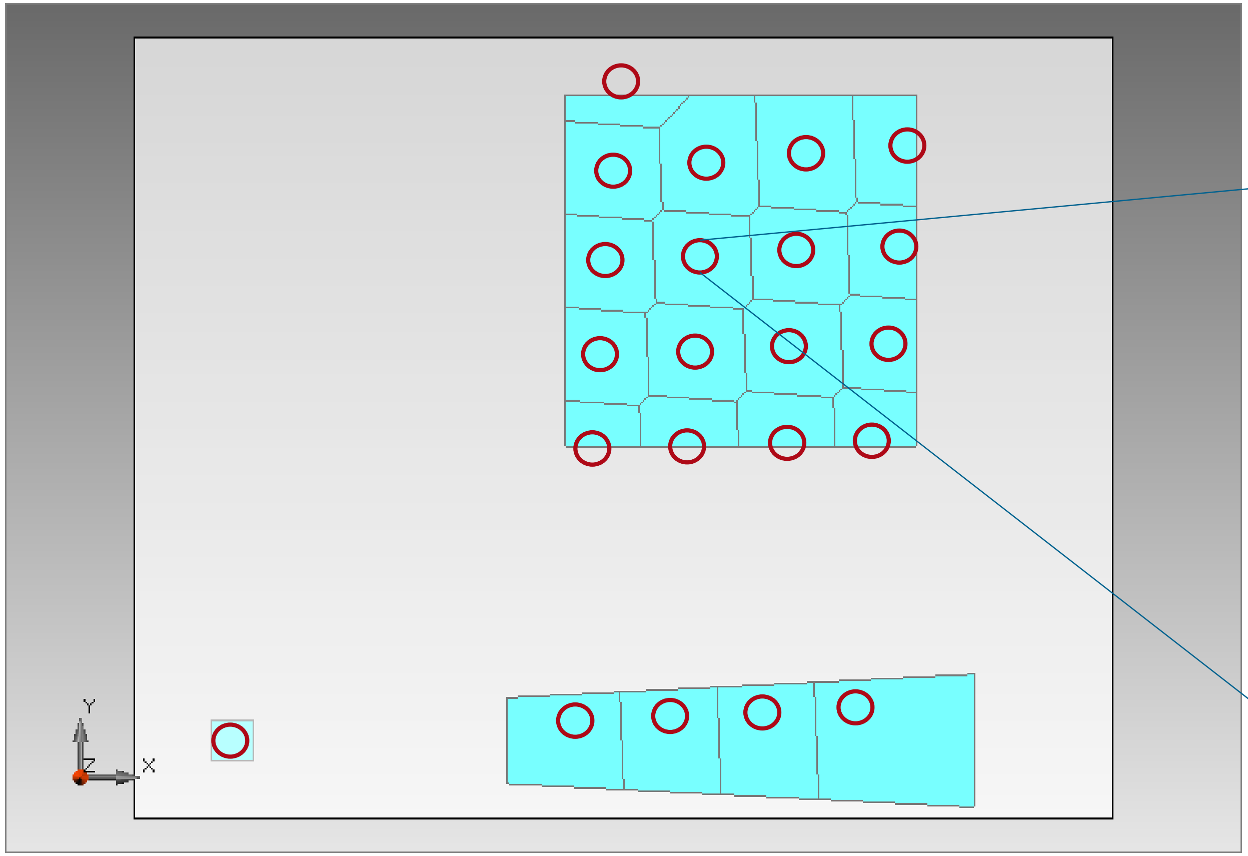

**Incident light at grating interaction (uniform polarization)**



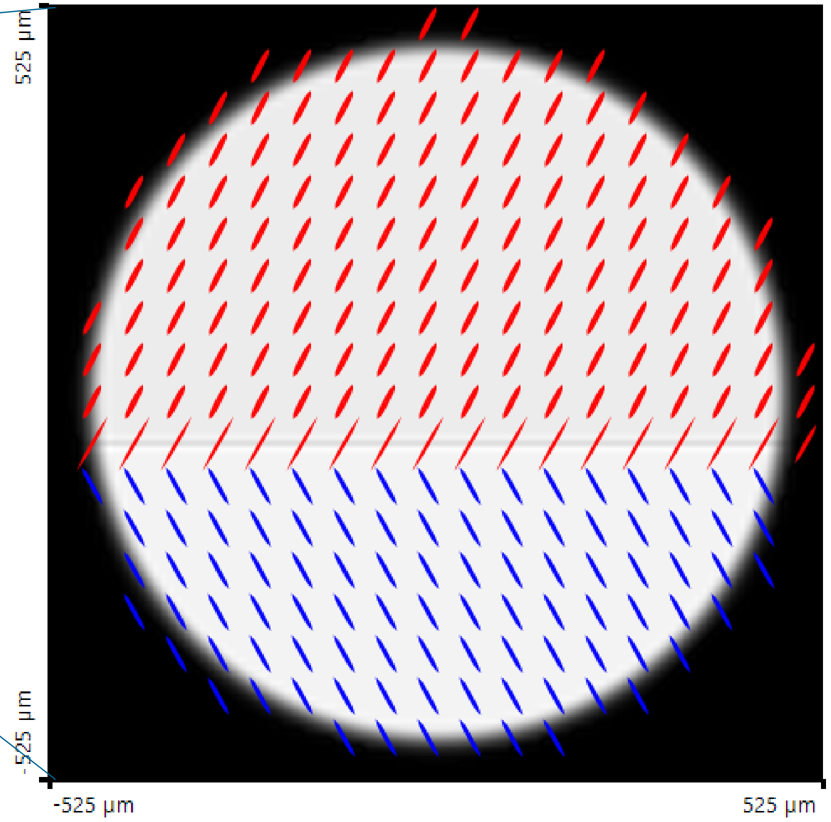
# Grating Design for FOV Angle (5°, 3°) – Polarization Evaluation



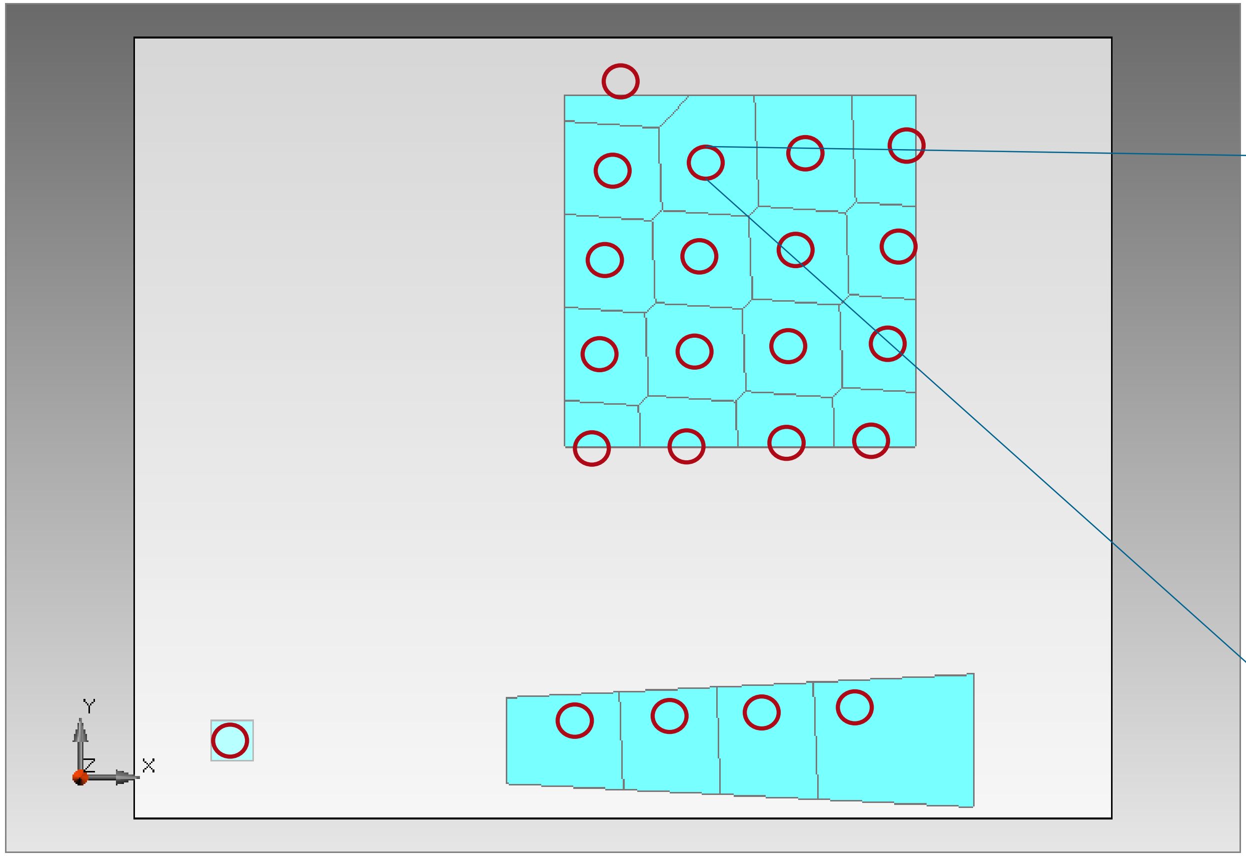
# Grating Design for FOV Angle (5°, 3°) – Polarization Evaluation



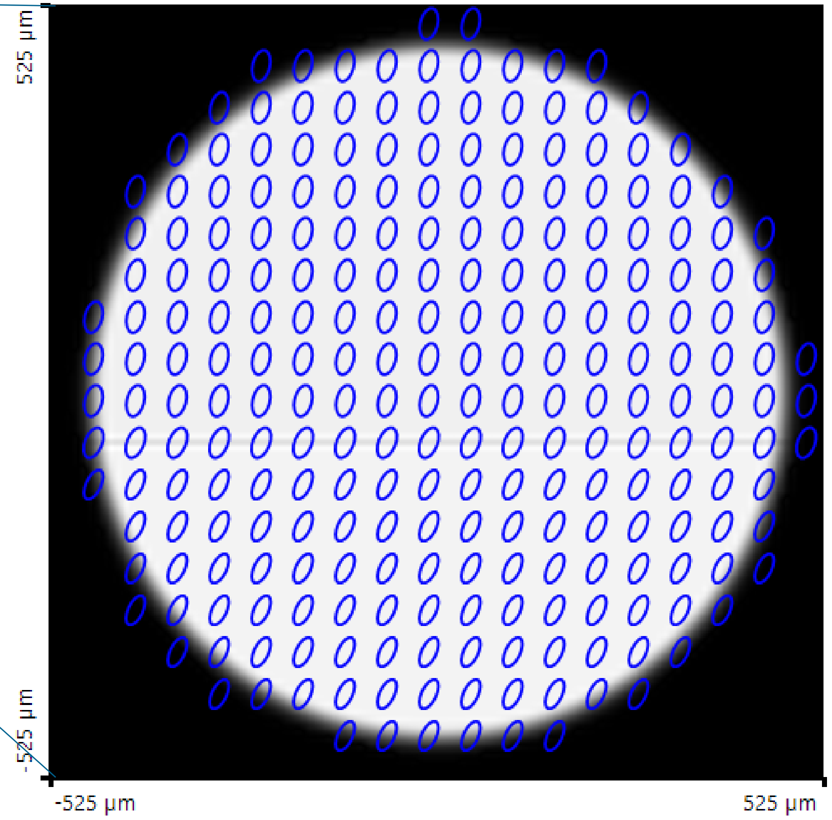

**Incident light at grating interaction (non-uniform polarization)**



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



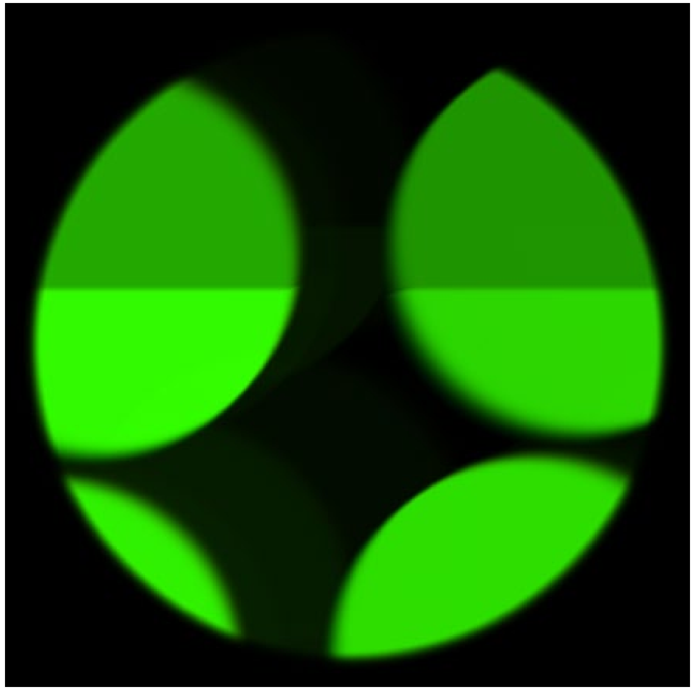

**Incident light at grating interaction (non-uniform polarization)**



# PSF and MTF evaluation

# Light Modes Passing Through Eye Pupil

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



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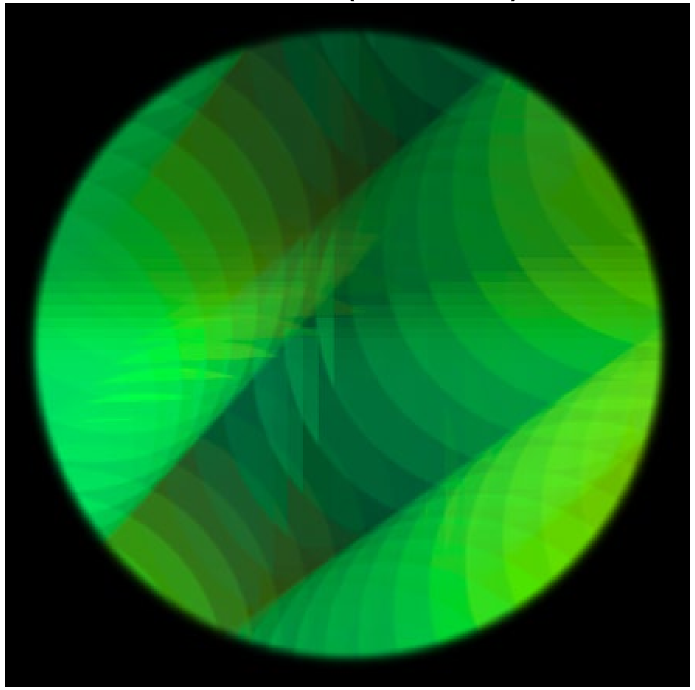
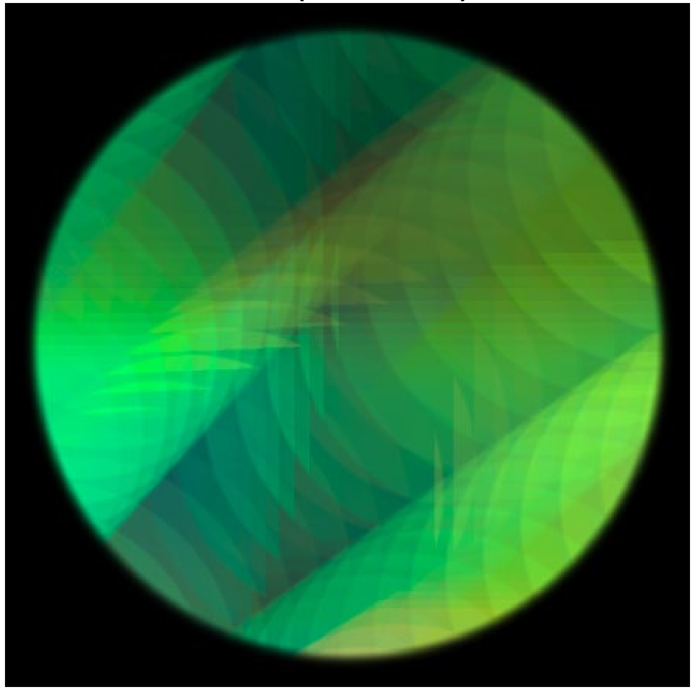
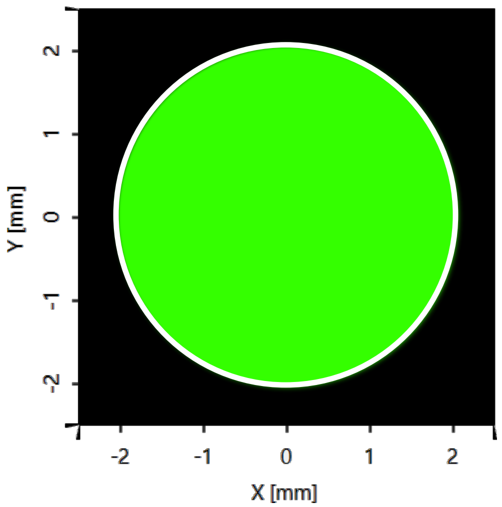


...of an
LED (~40 nm)

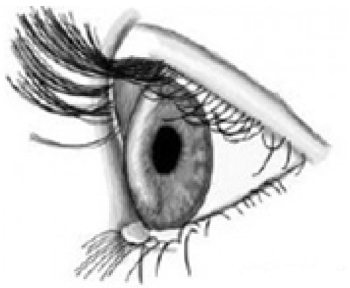


Pupil is partly filled with mutually correlated channel modes per uncorrelated spectral modes.

# Results: Full Pupil Illumination



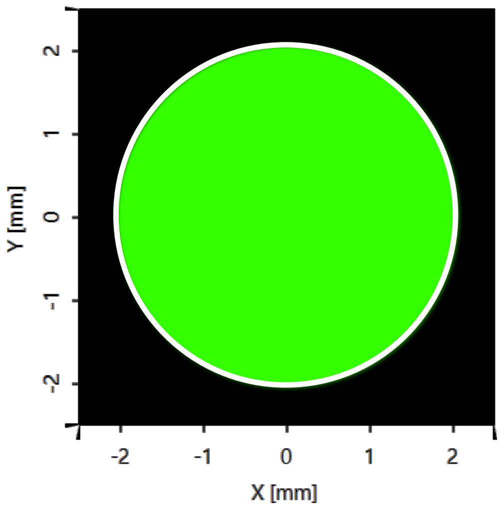
behind eye pupil



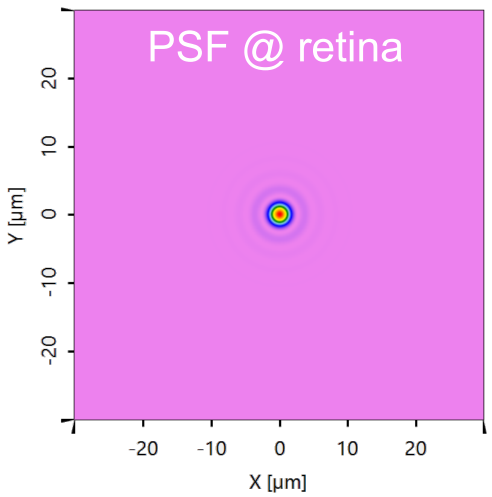
**Ideal Eye Model**

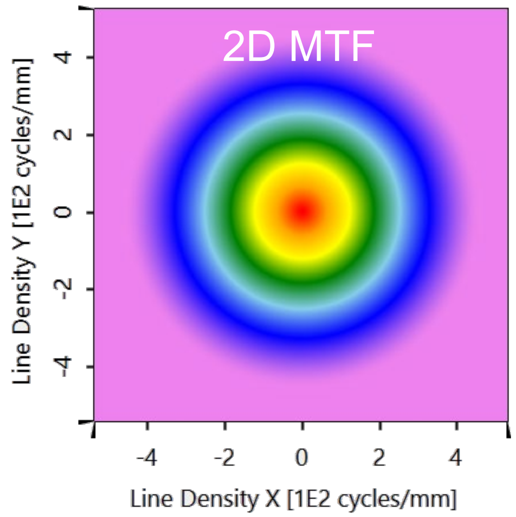
- pupil diameter = 4 mm
- ideal lens with focal length = 17 mm

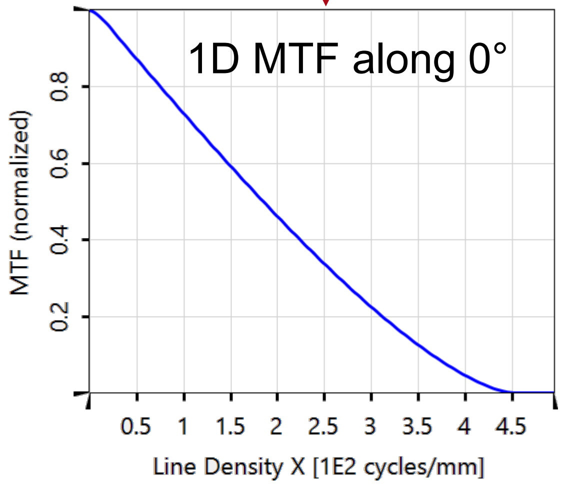
# Results: Full Pupil Illumination

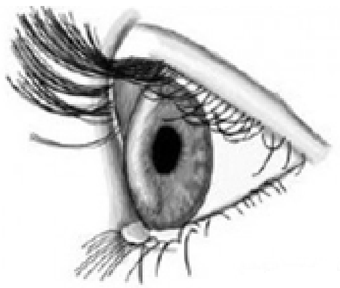



behind eye pupil



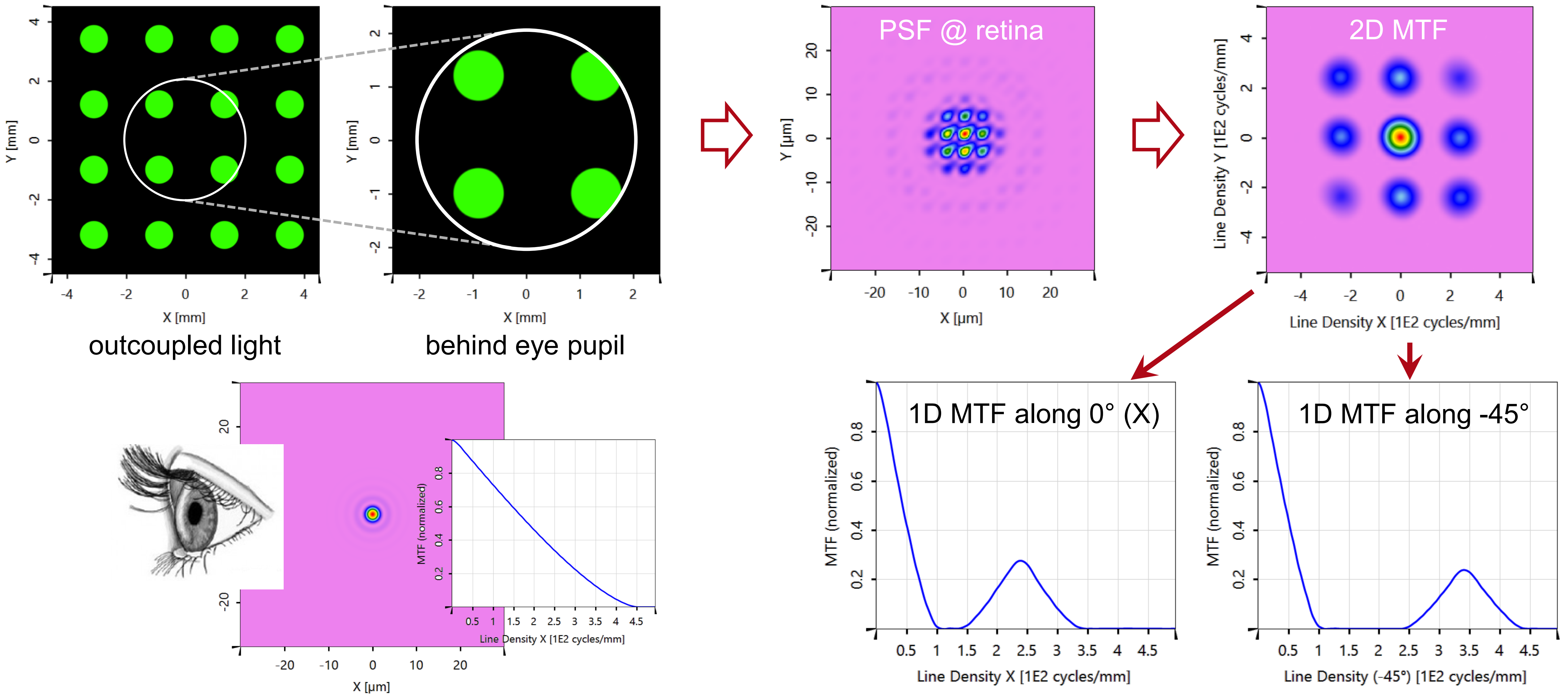



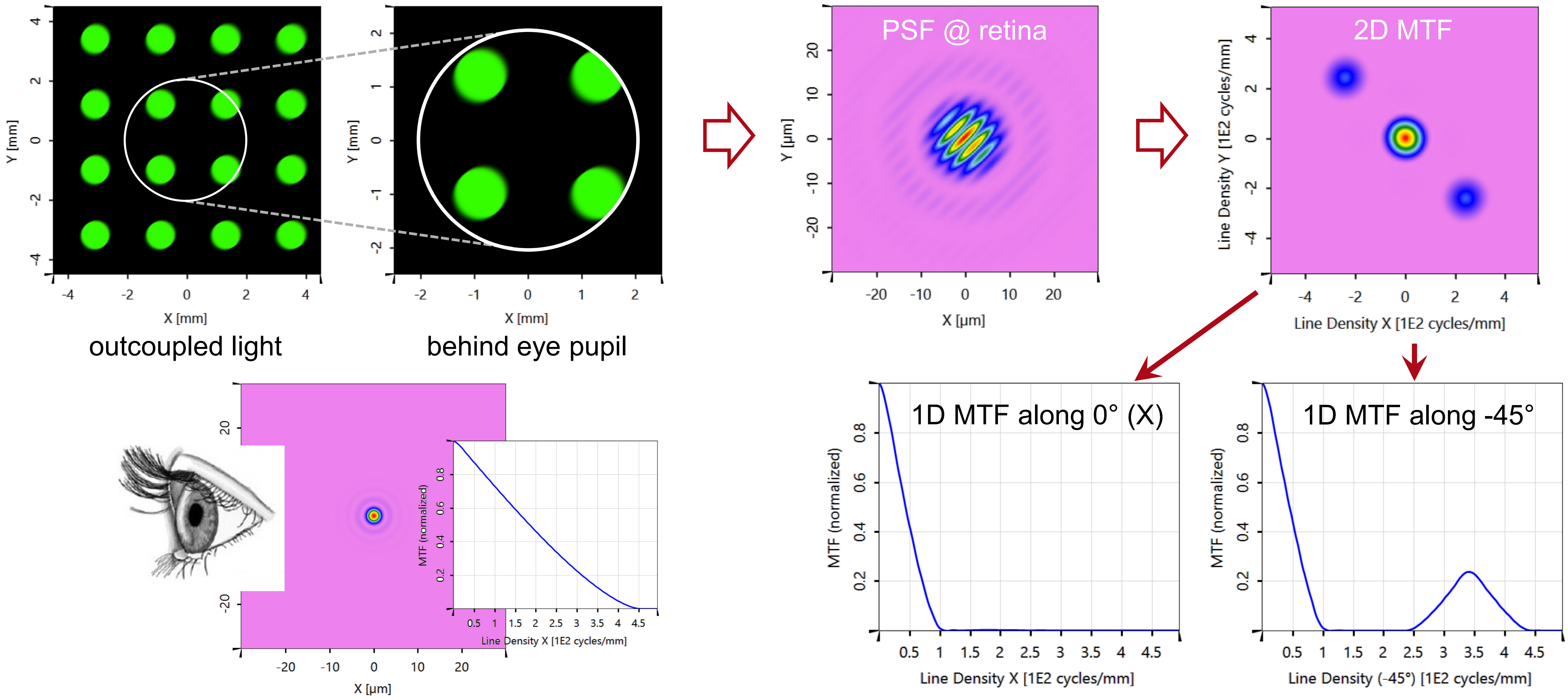
**Ideal Eye Model**

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

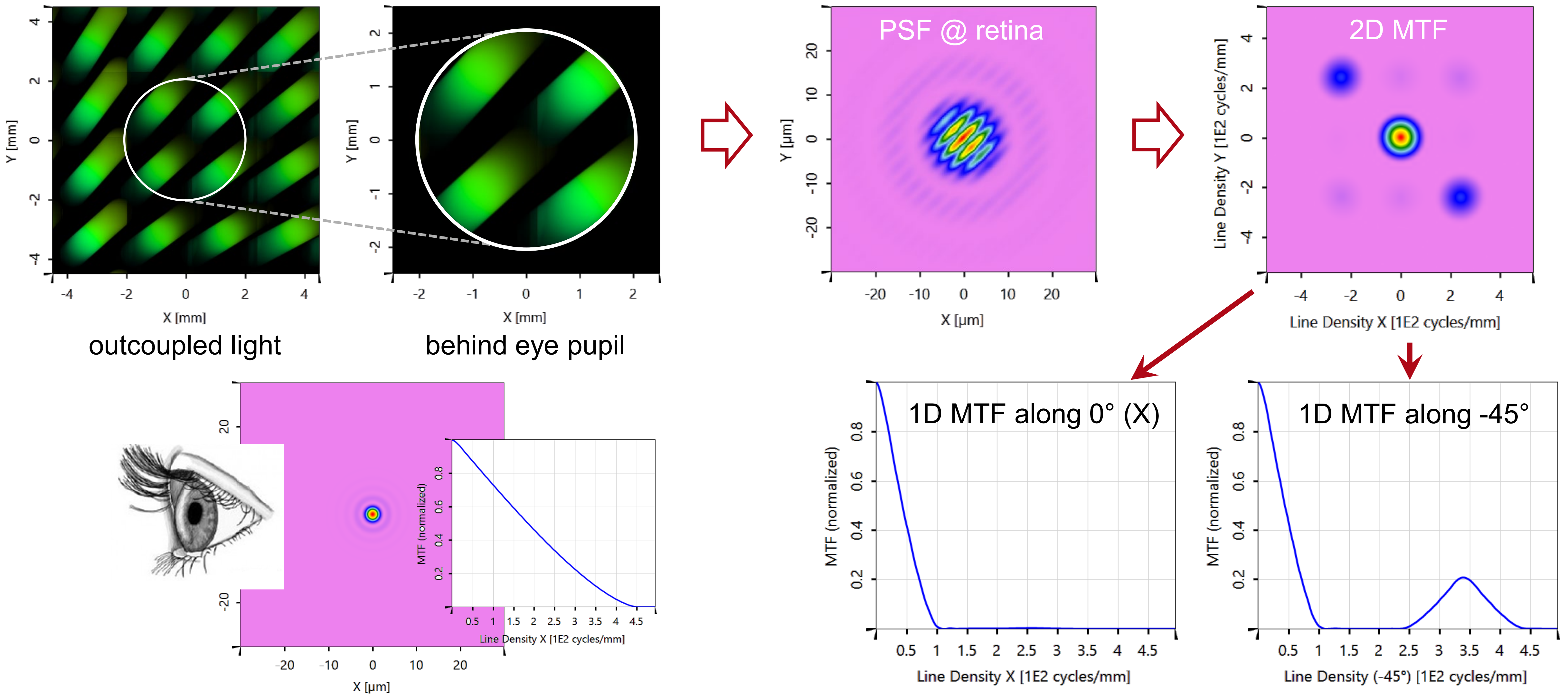
# Results: FoV = (0°; 0°), Monochromatic 532 nm



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

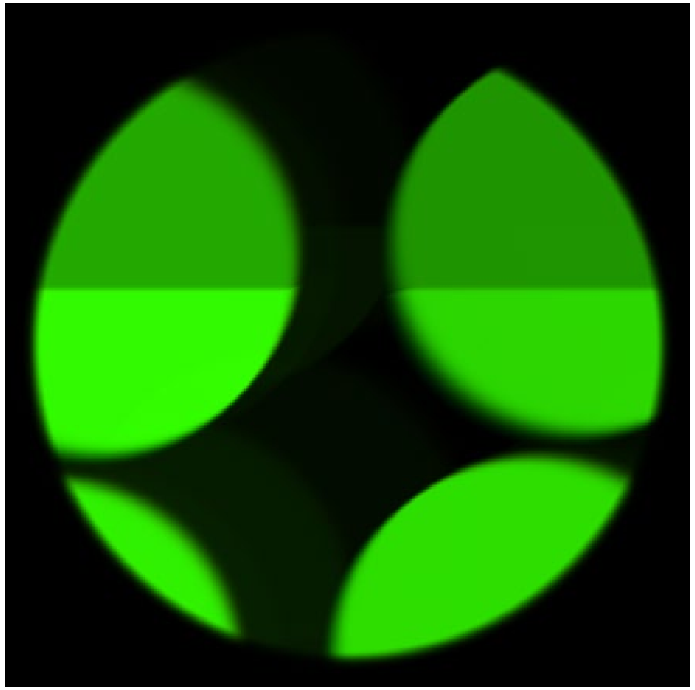


# Results: FoV = (0°; 0°), Spectrum 10 nm Bandwidth (100 samples)



# Light Modes Passing Through Eye Pupil

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



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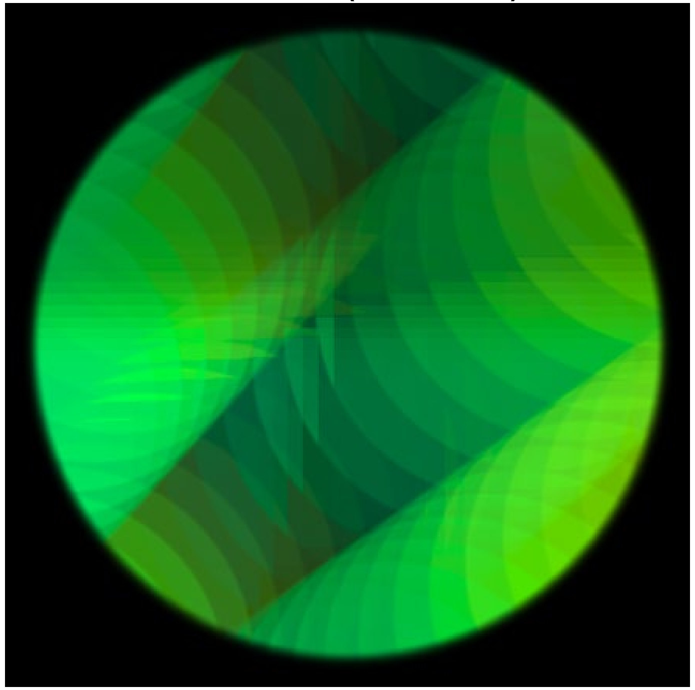

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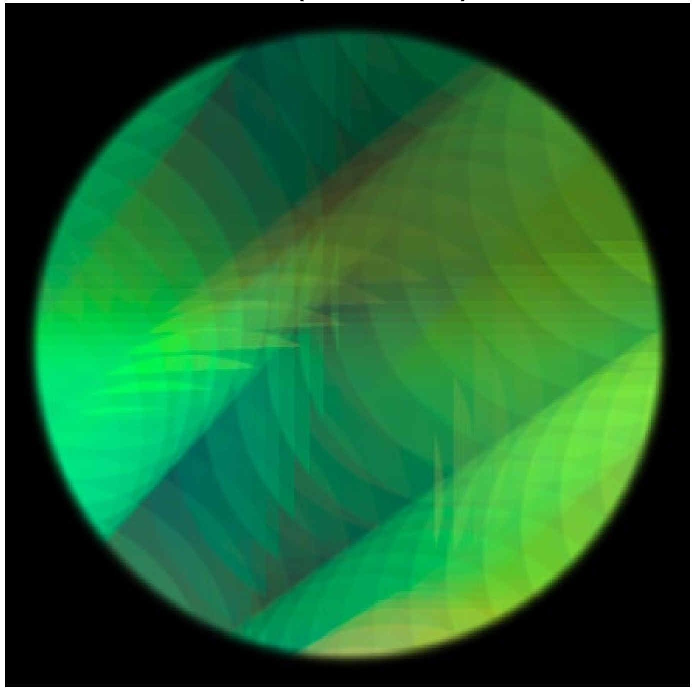
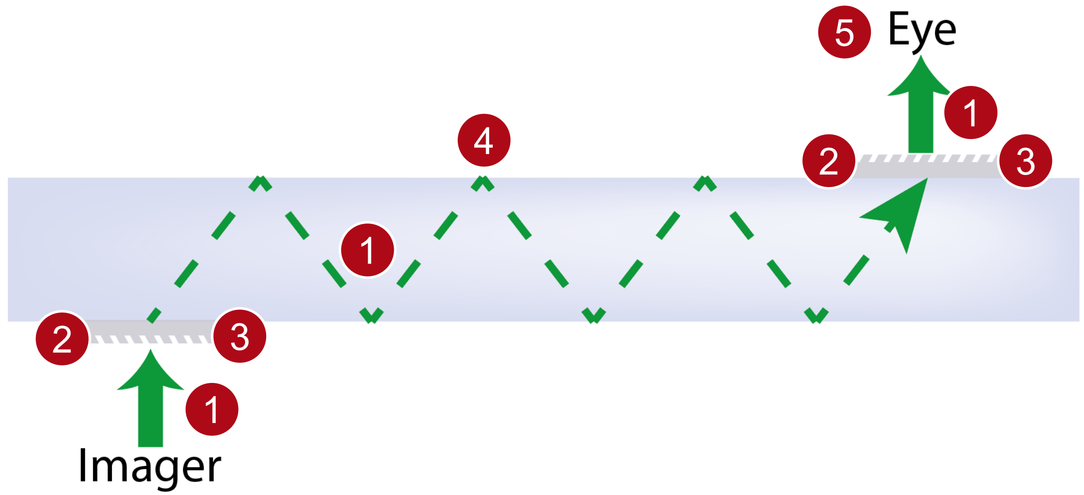
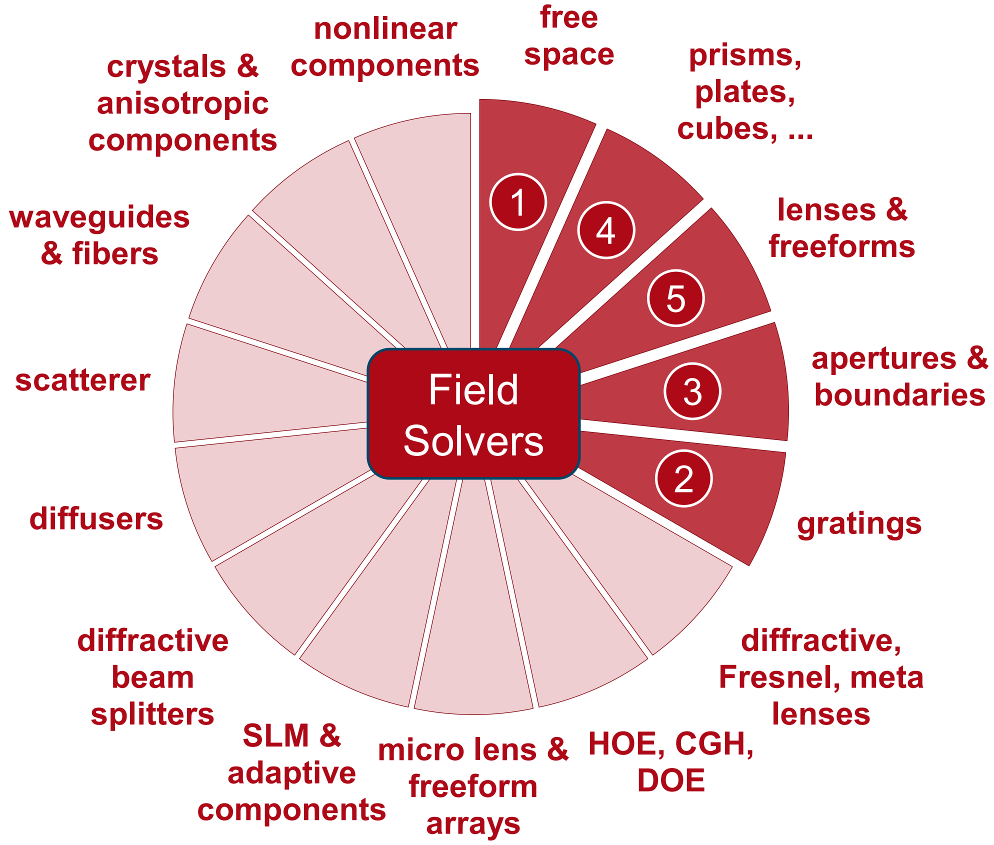


For one wavelength and one FOV the pupil is partly filled with mutually correlated channel modes.

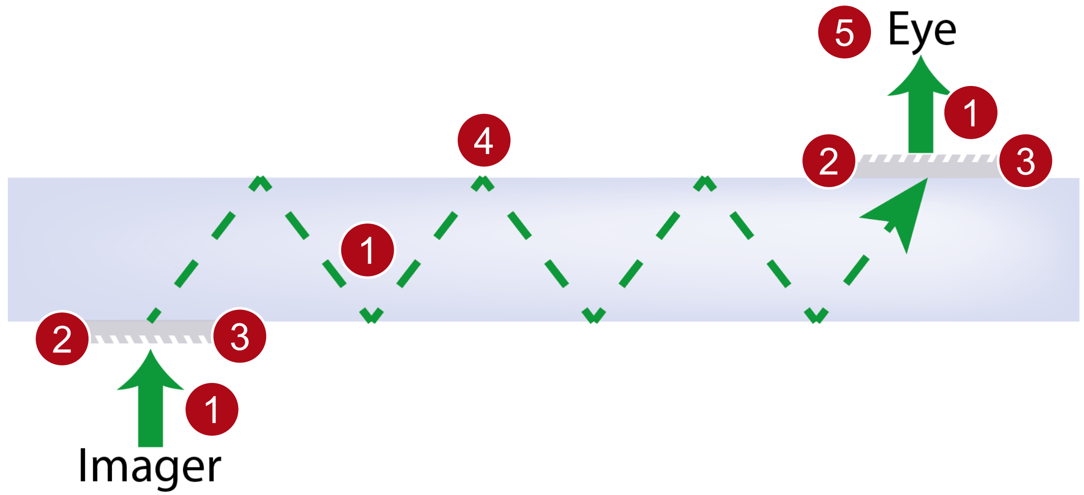
# Diffraction in Lightguide

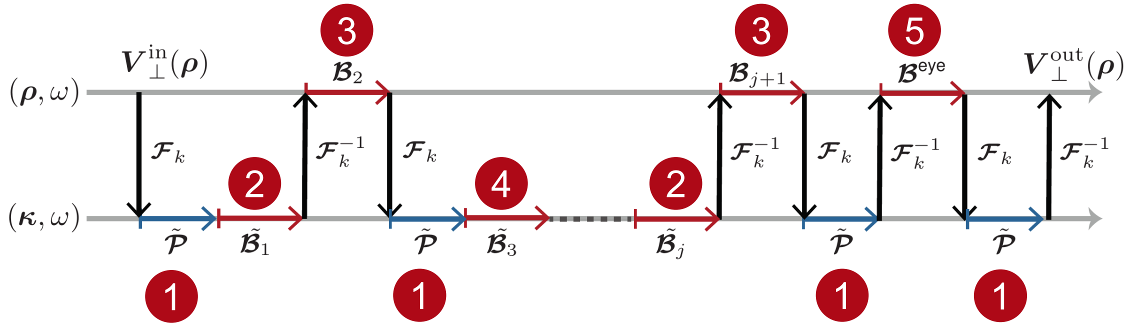
# Typical Modeling Situation for AR&MR Lightguide

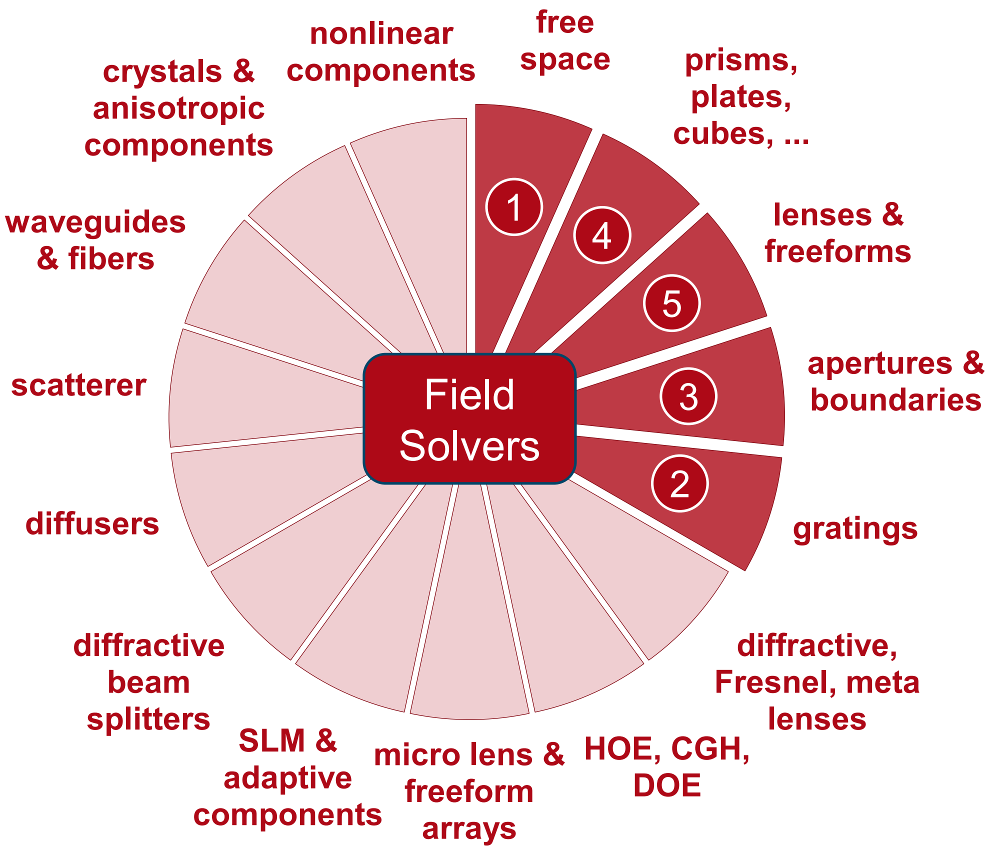


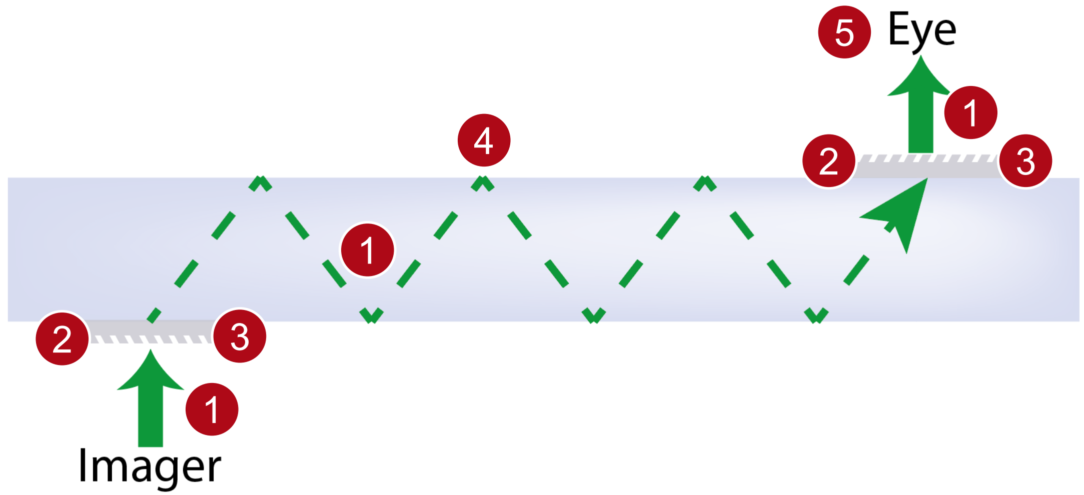
# Typical Modeling Situation for AR&MR Lightguide

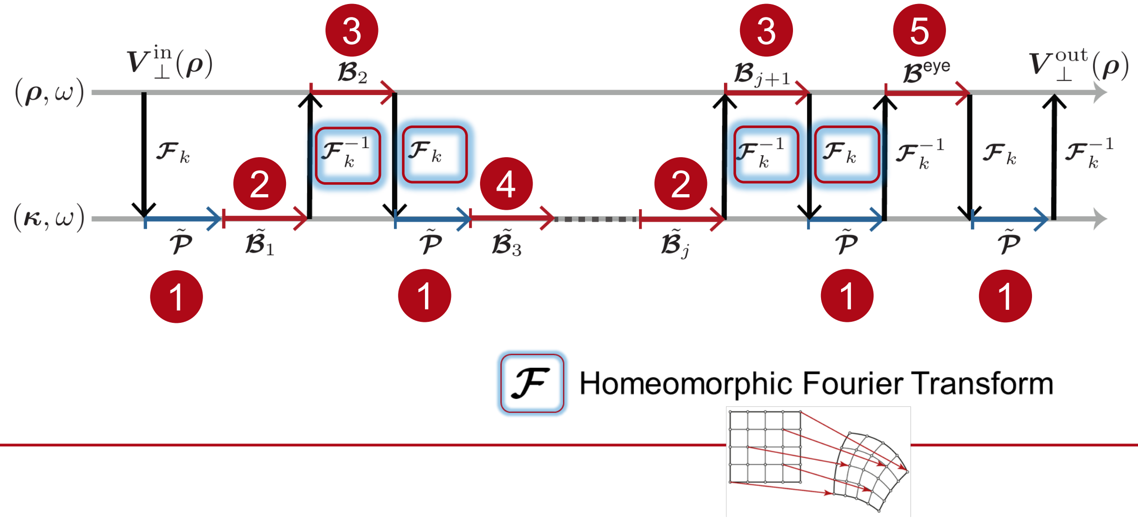


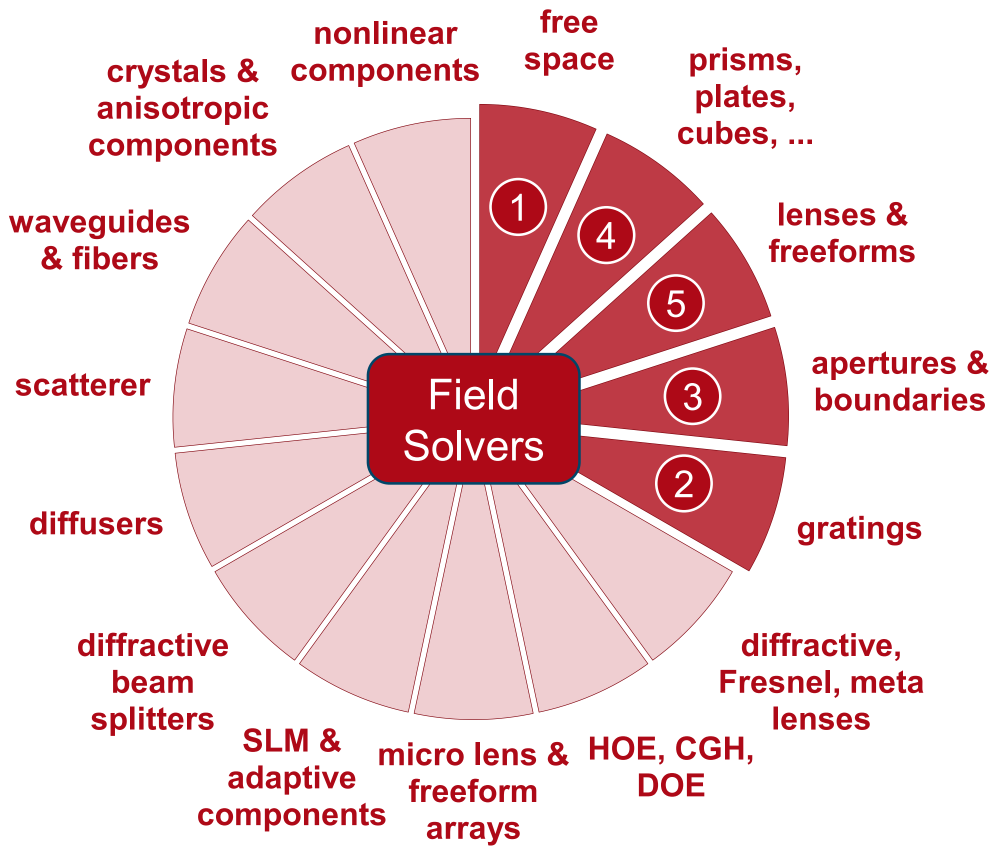



# Typical Modeling Situation for AR&MR Lightguide

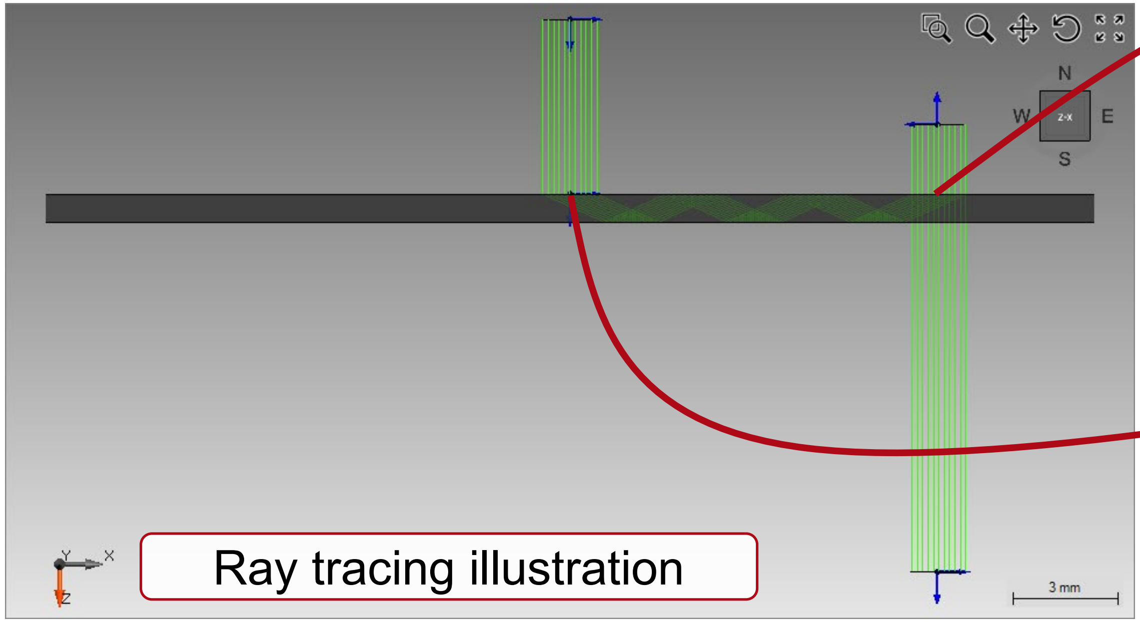


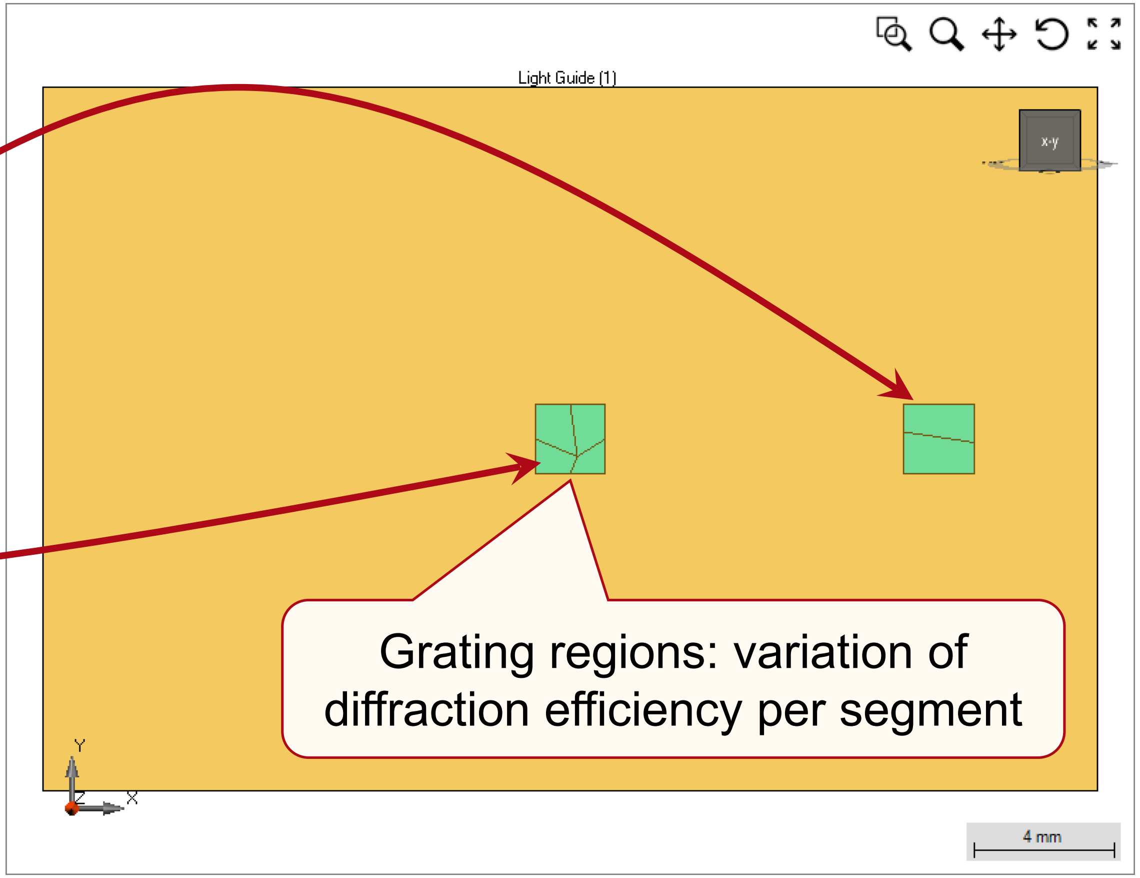



# Cascaded Diffraction in Lightguide Modeling: Layout

Lightguide: Front View



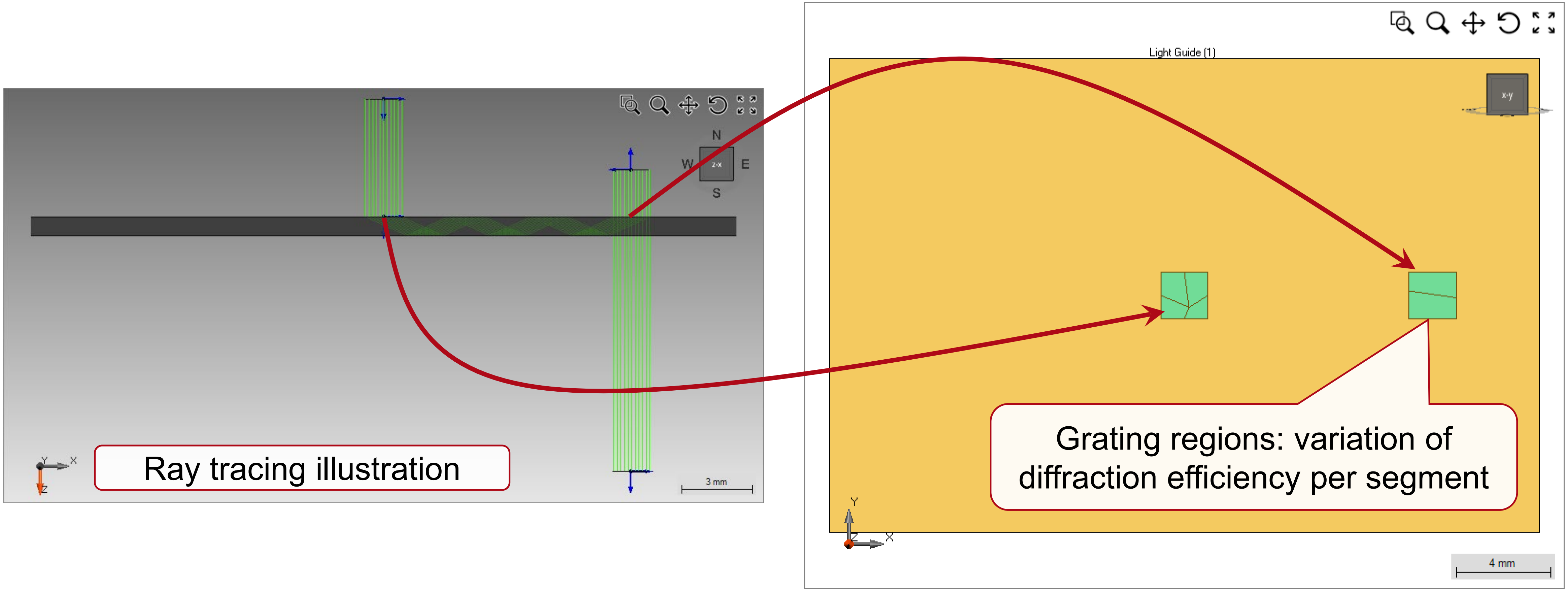

Lightguide: Top View



# Cascaded Diffraction in Lightguide Modeling: Layout

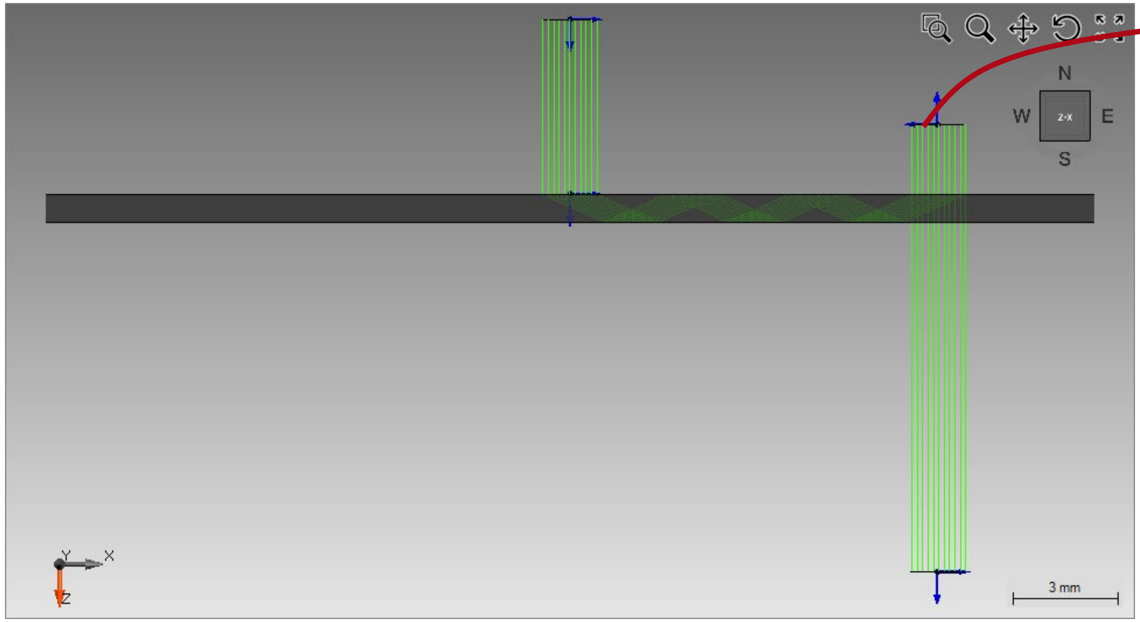
Lightguide: Front View

Lightguide: Top View

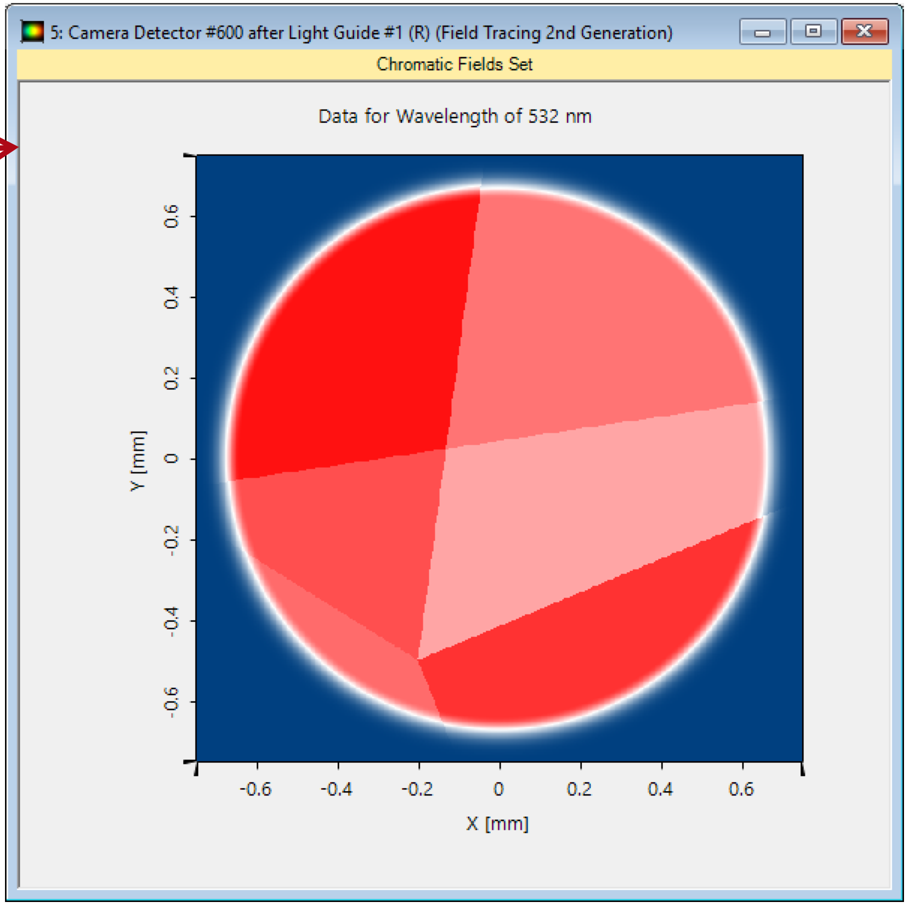


# Lightguide Modeling: Suppressed Diffraction Effects (Homeomorphic)

Lightguide: Front View



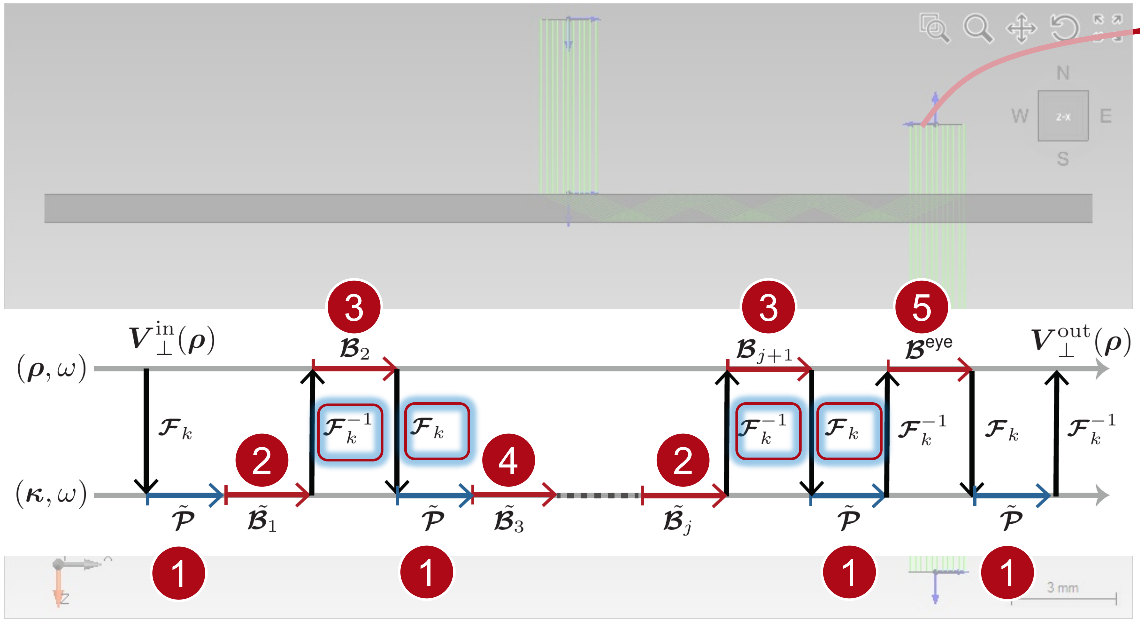

Intensity (homeomorphic model)



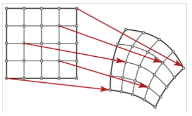

$$I(\boldsymbol{\rho}) = |E_x(\boldsymbol{\rho})|^2 + |E_y(\boldsymbol{\rho})|^2 + |E_z(\boldsymbol{\rho})|^2$$

# Lightguide Modeling: Suppressed Diffraction Effects (Homeomorphic)

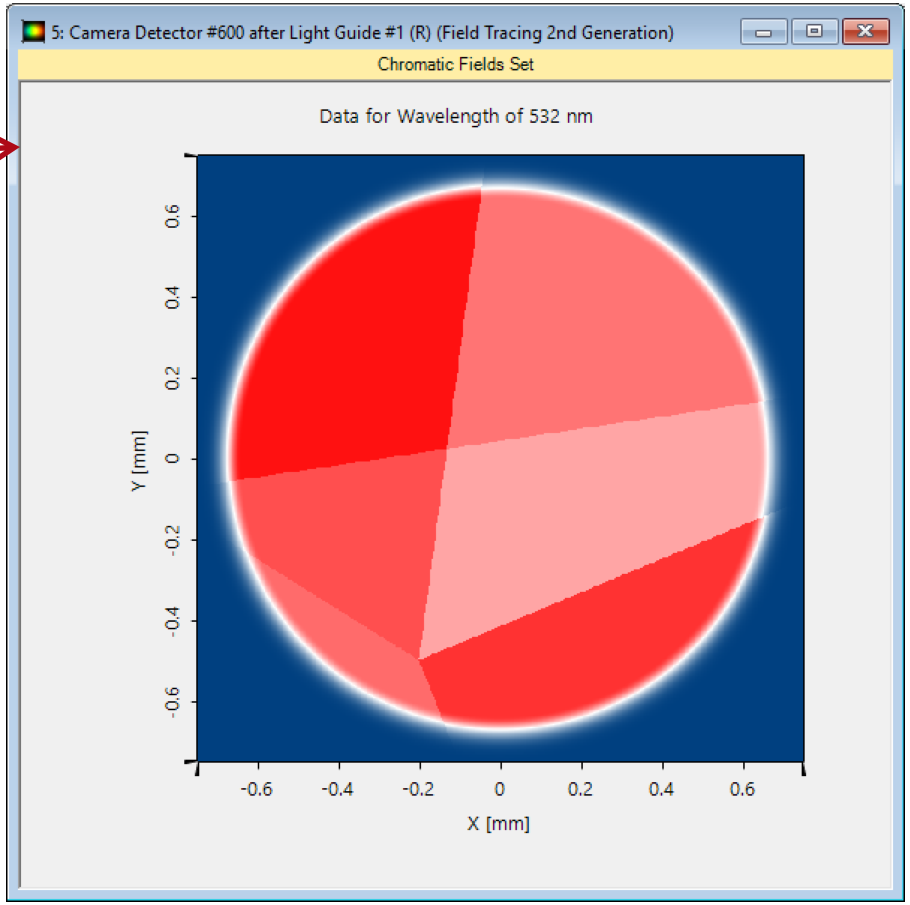
Lightguide: Front View




$\boxed{\mathcal{F}}$ Homeomorphic Fourier Transform



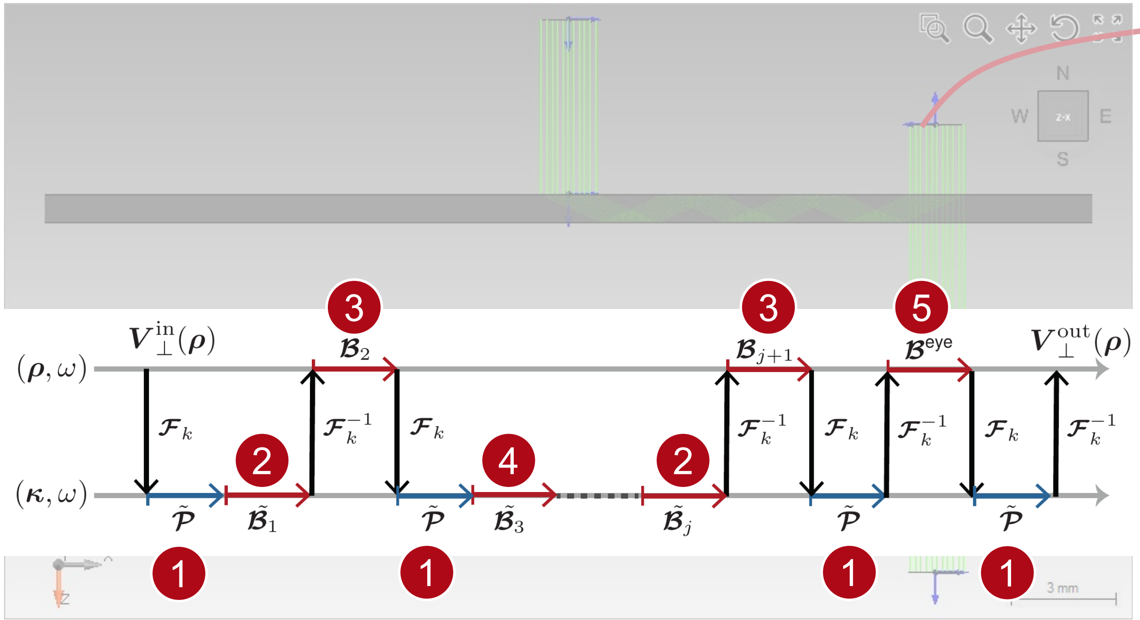
Intensity (homeomorphic model)



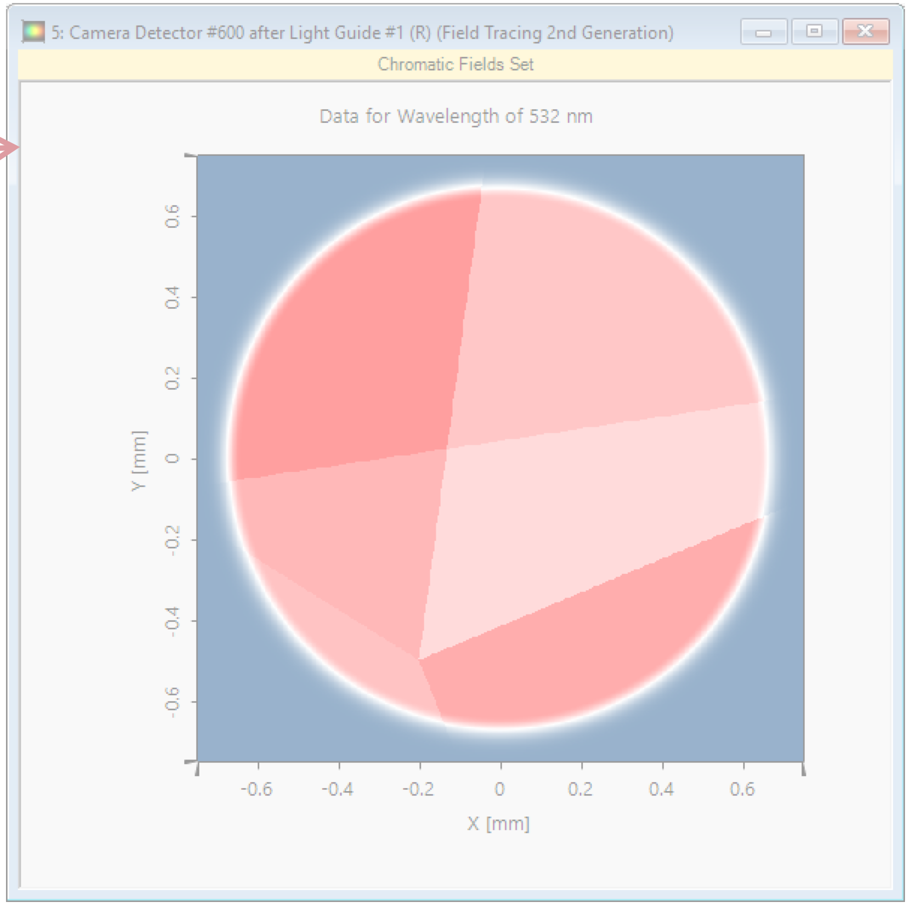

$$I(\boldsymbol{\rho}) = |E_x(\boldsymbol{\rho})|^2 + |E_y(\boldsymbol{\rho})|^2 + |E_z(\boldsymbol{\rho})|^2$$

# Lightguide Modeling: Diffraction Effects Included

Lightguide: Front View



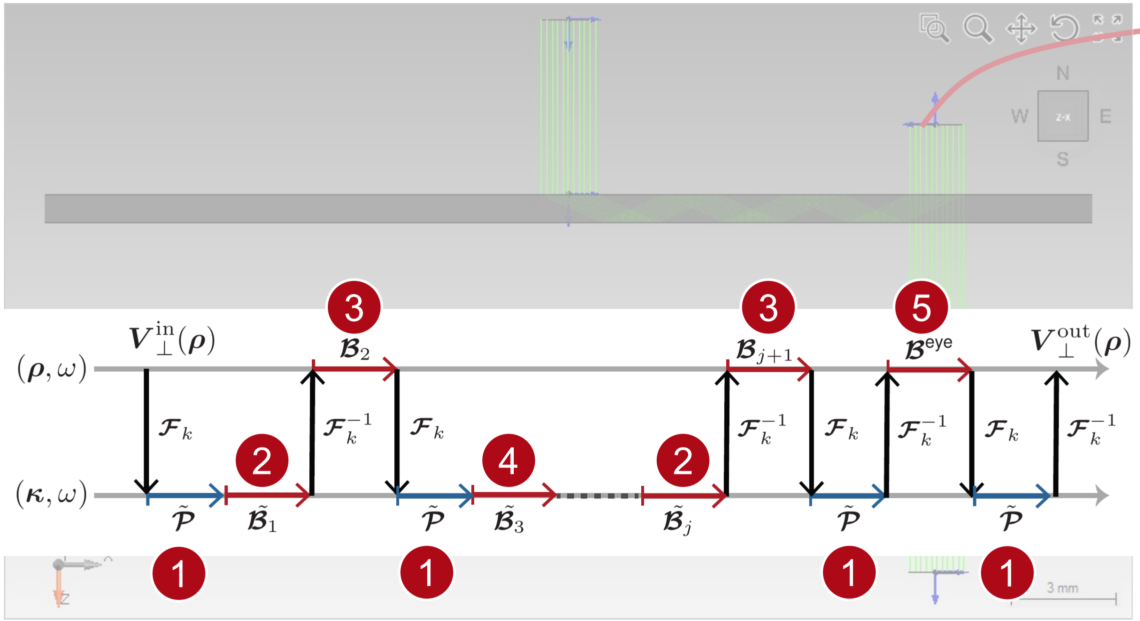

Intensity (homeomorphic model)



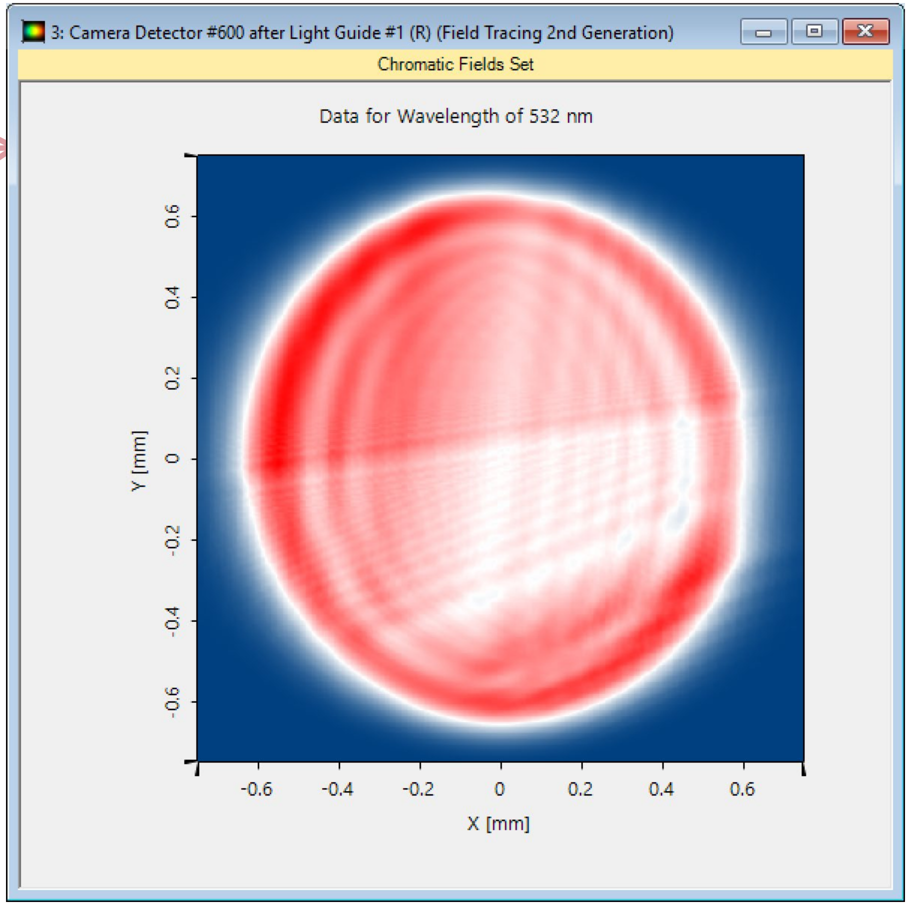

$$I(\rho) = |E_x(\rho)|^2 + |E_y(\rho)|^2 + |E_z(\rho)|^2$$

# Lightguide Modeling: Diffraction Effects Included

Lightguide: Front View




Intensity

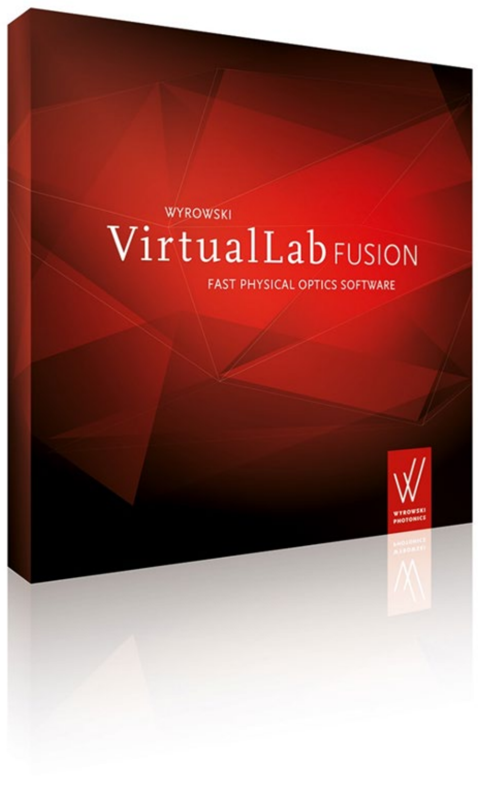



$$I(\rho) = |E_x(\rho)|^2 + |E_y(\rho)|^2 + |E_z(\rho)|^2$$

# 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, interference, coherence, polarization, and diffraction effects can be important and are fully included in modeling.

**Steady R&D in lightguide modeling and design.**

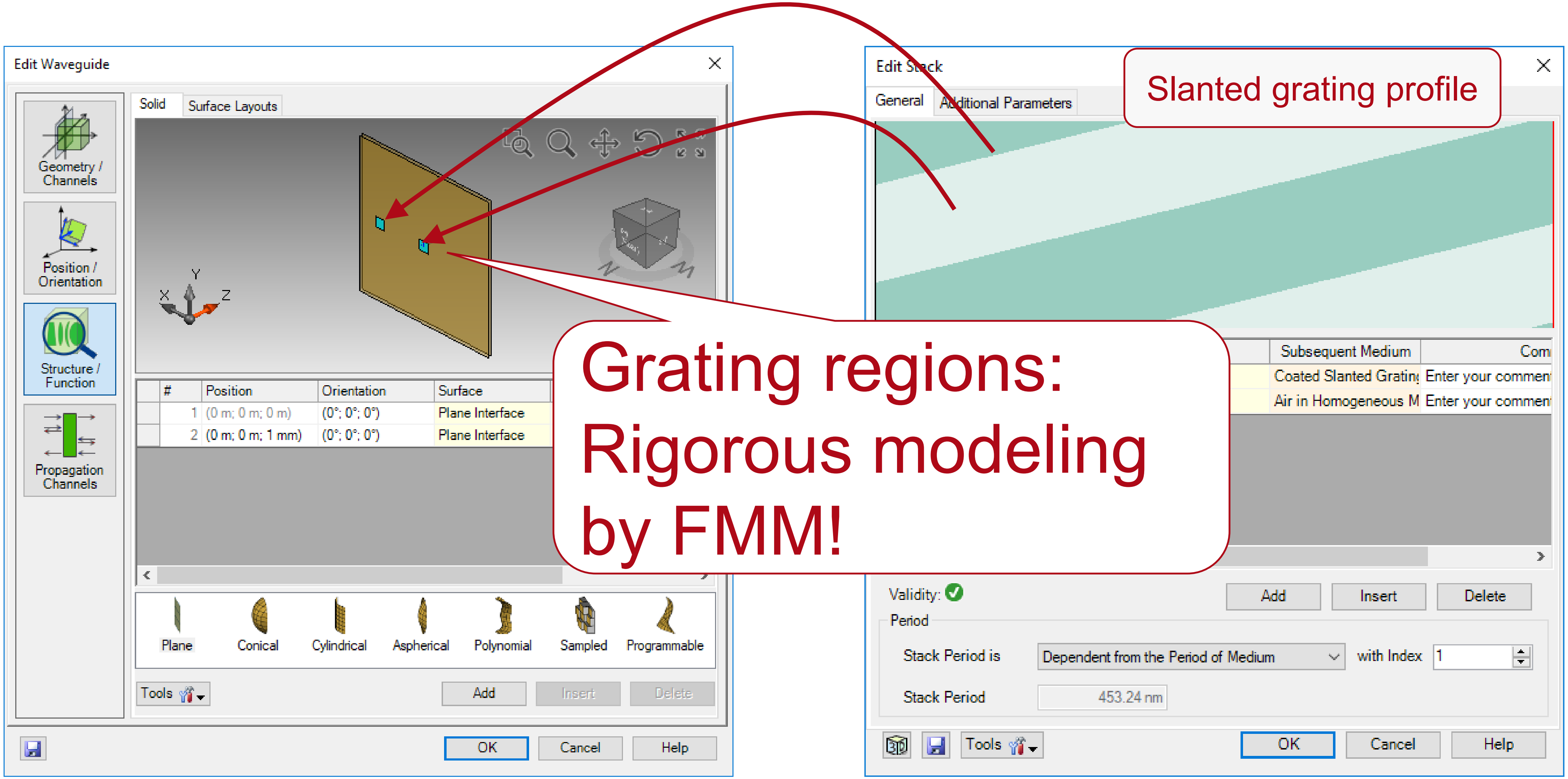


# Thank You!

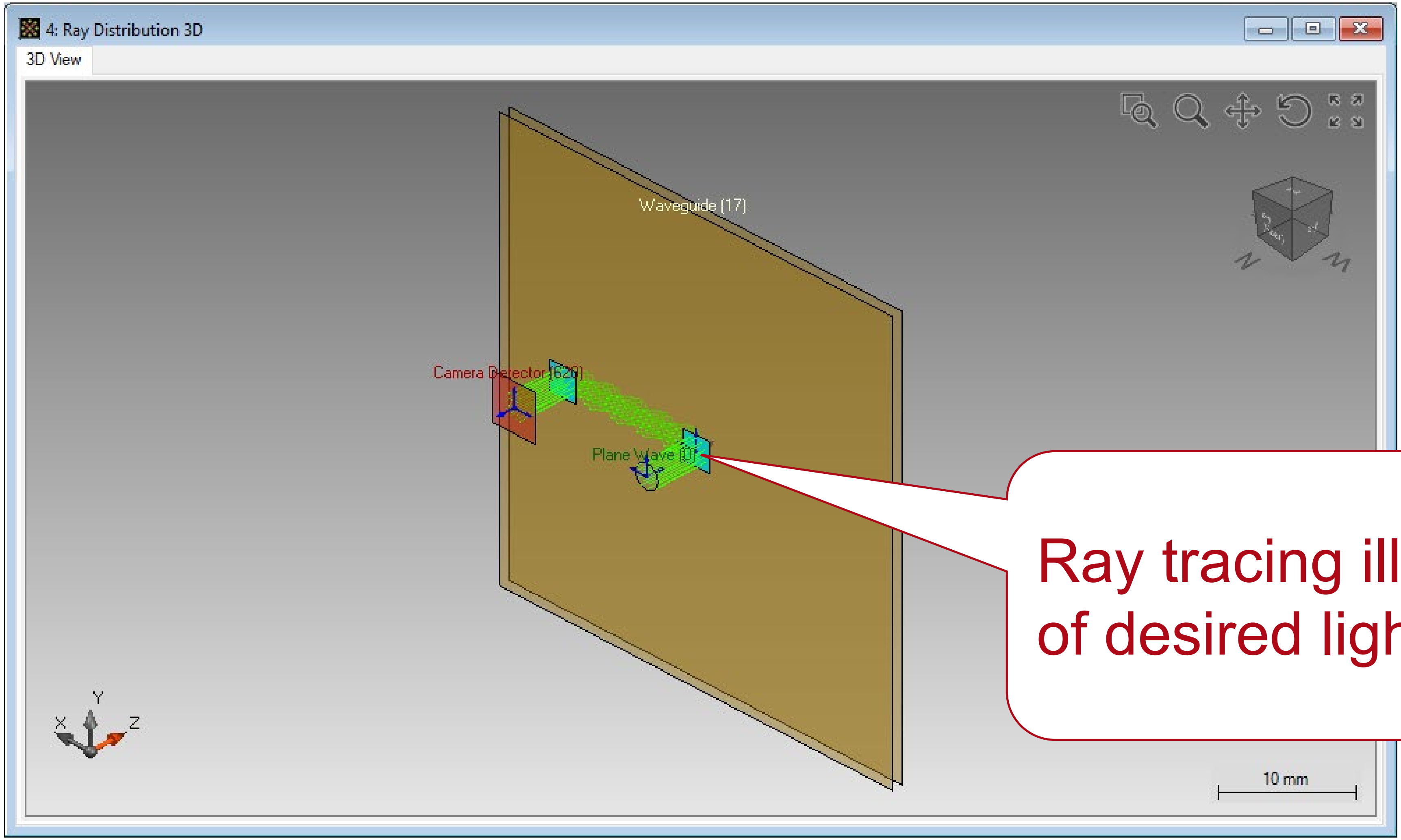
## Energy conservation per spectral mode

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

# Modeling Task: In- and Outcoupling

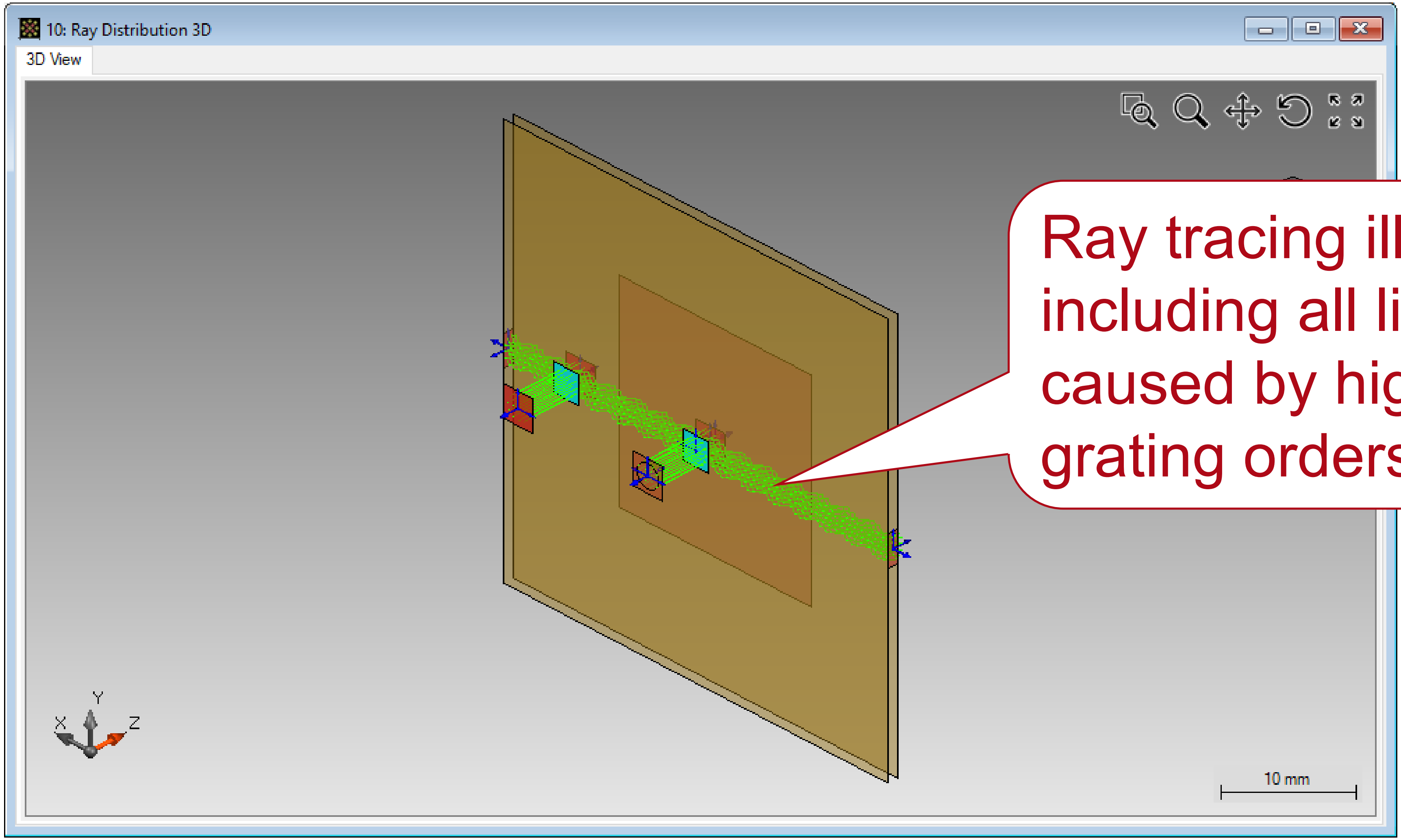


# Result by 3D Ray Tracing (Working Orders)




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%** |