LASYS 2018, 2018-06-05

Optical design of beam delivery systems for cw and pulsed lasers

R. Knoth[2], C. Hellmann[1], S. Zhang[2], D. Kühn[3], F. Wyrowski[3]

- [1]Wyrowski Photonics UG
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- [3]University of Jena, Applied Computational Optics

Who, Where, What?

Applied Computational Optics Group R&D in optical modeling and design with emphasis on physical optics

Who, Where, What?

Wyrowski Photonics
Development of fast
physical optics software
VirtualLab Fusion

Who, Where, What?

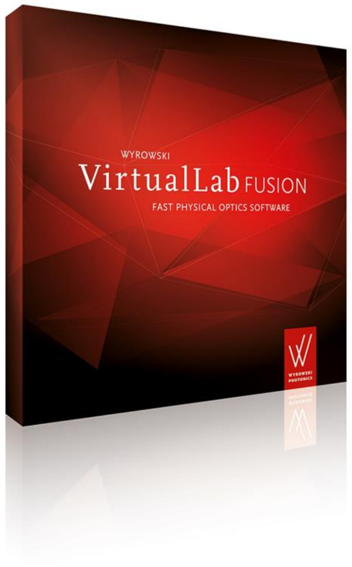
LightTrans

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

Who, Where, What?

All techniques shown in this talk are available in **VirtualLab Fusion Software** or/and as **Consulting & Engineering Services!**

Hall 4, Booth 4B71.1



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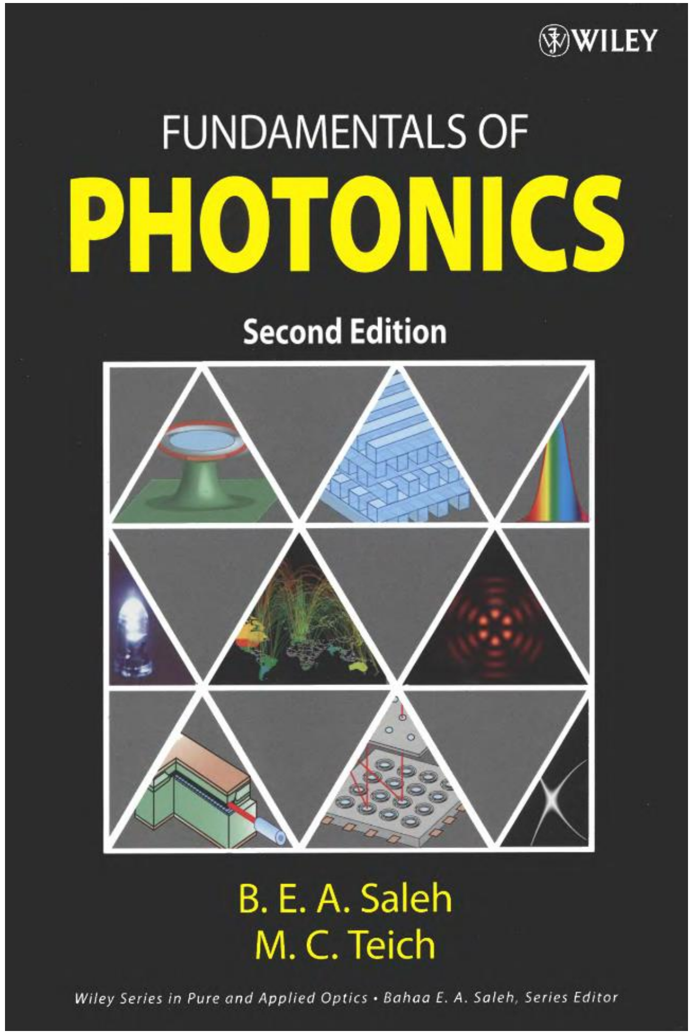
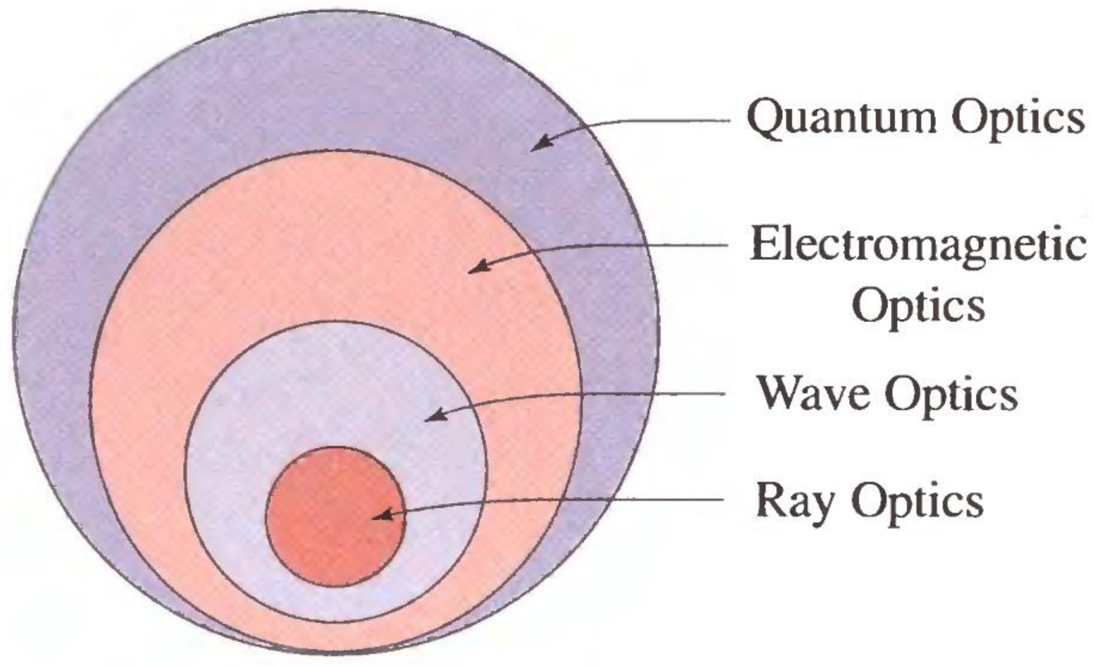
Geometric and diffractive branch of physical optics

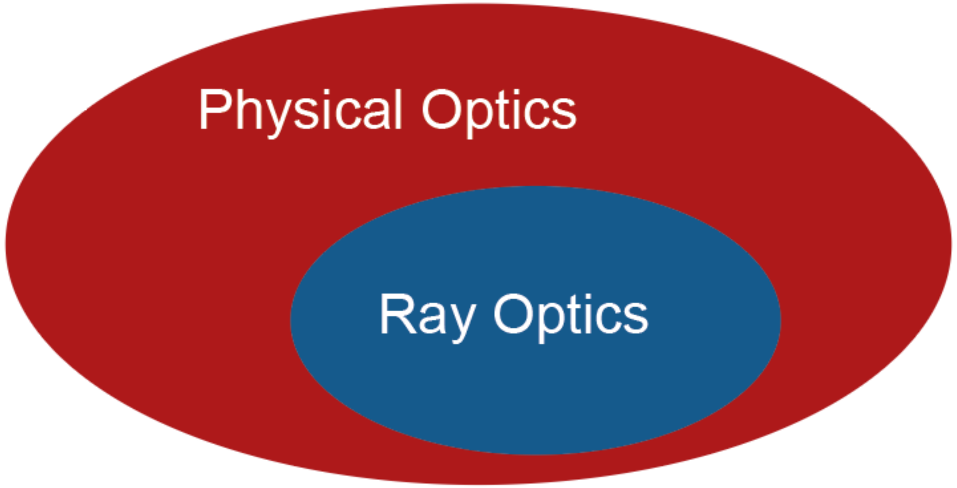
The geometric Fourier transform

Physical and Geometrical Optics: Traditional Understanding





Physical and Geometrical Optics: Traditional Understanding



- Physical optics:
  - Light represented by electromagnetic fields which
  - are governed by Maxwell's equations.

- Geometrical/ray optics:
  - Light is represented by mathematical rays (with energy flux) which
  - are governed by Fremat's principle which is mathematically expressed by ray equation.

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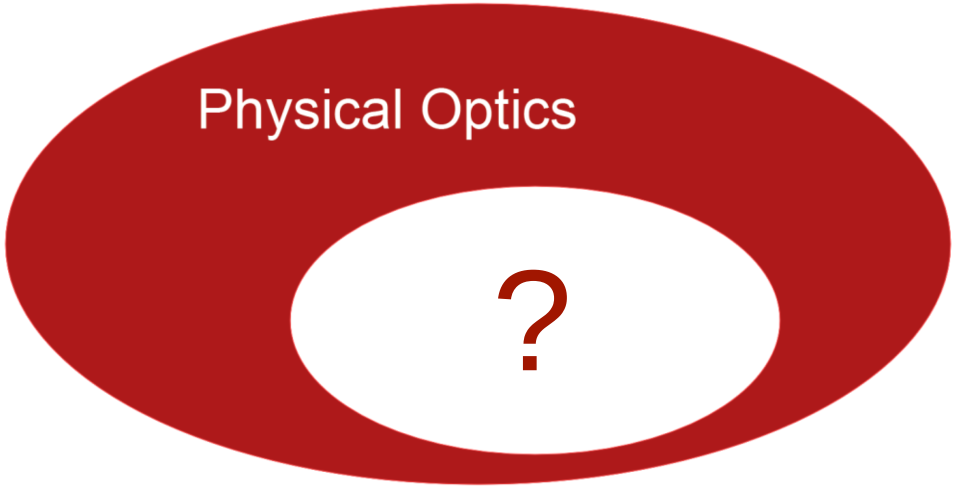

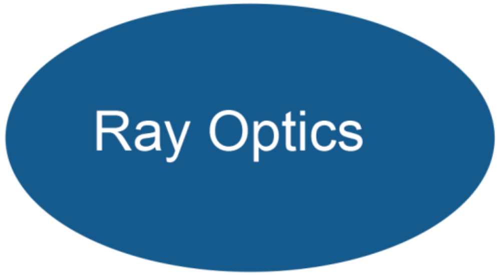

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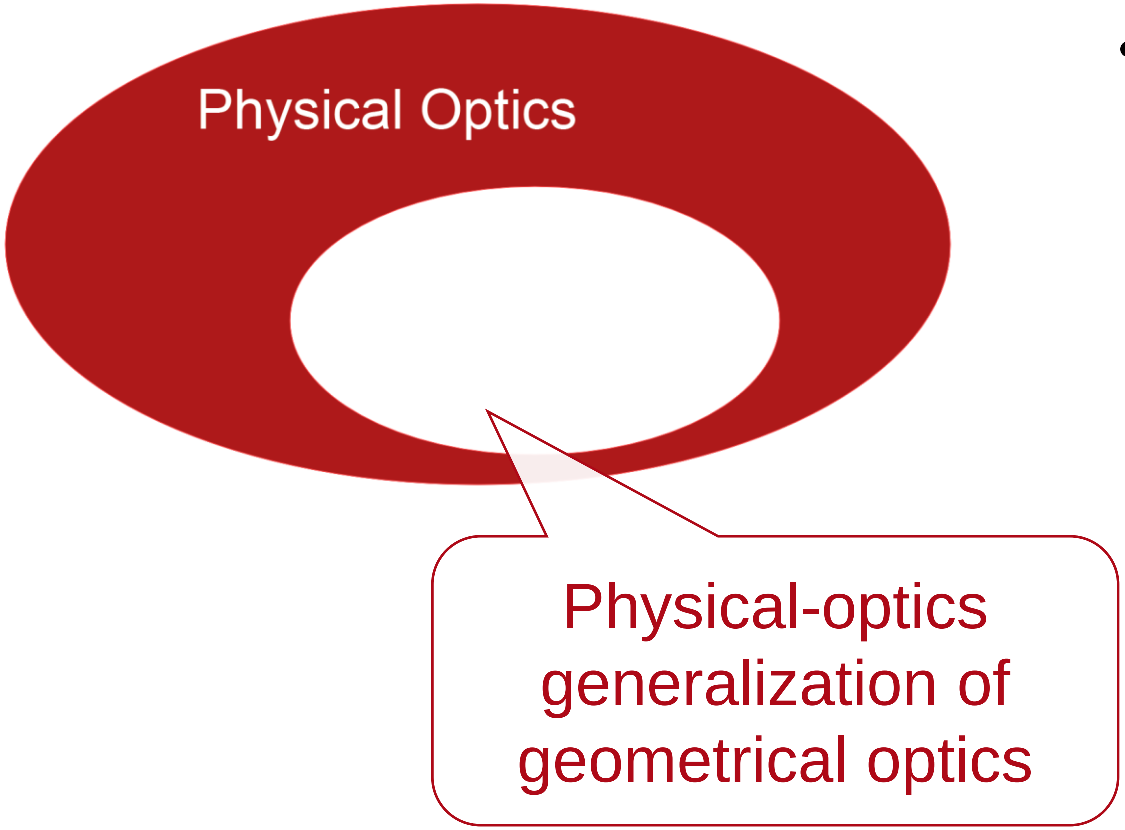
Physical and Geometrical Optics: Unified Theory



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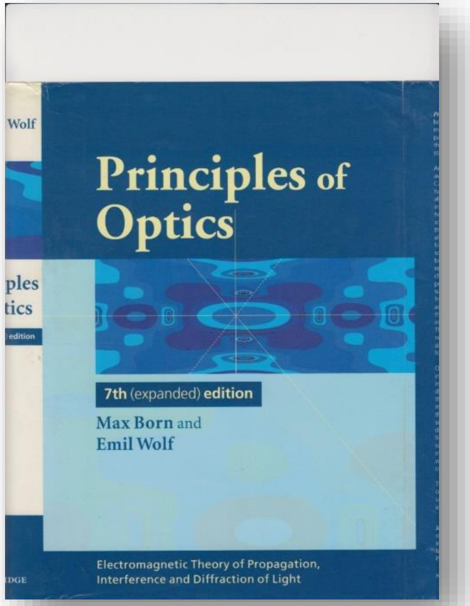
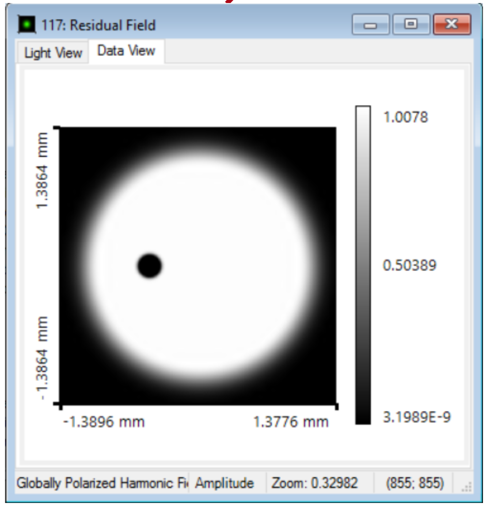
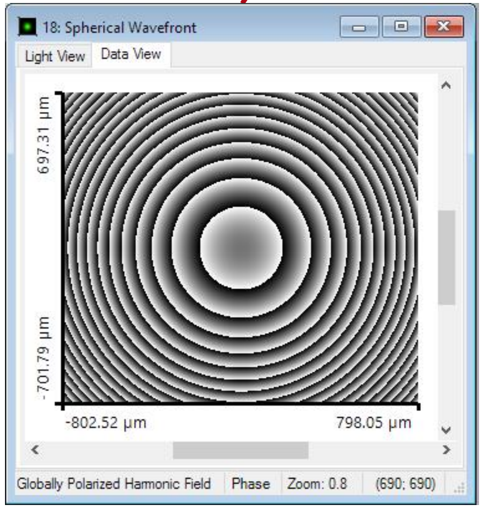


Example Spherical Field with Stop

$$V_\ell(\boldsymbol{\rho}, z, \omega) = |V_\ell(\boldsymbol{\rho}, z, \omega)| \exp(\mathrm{i}\varphi_\ell(\boldsymbol{\rho}, z, \omega)) \exp(\mathrm{i}\psi(\boldsymbol{\rho}, z, \omega))$$

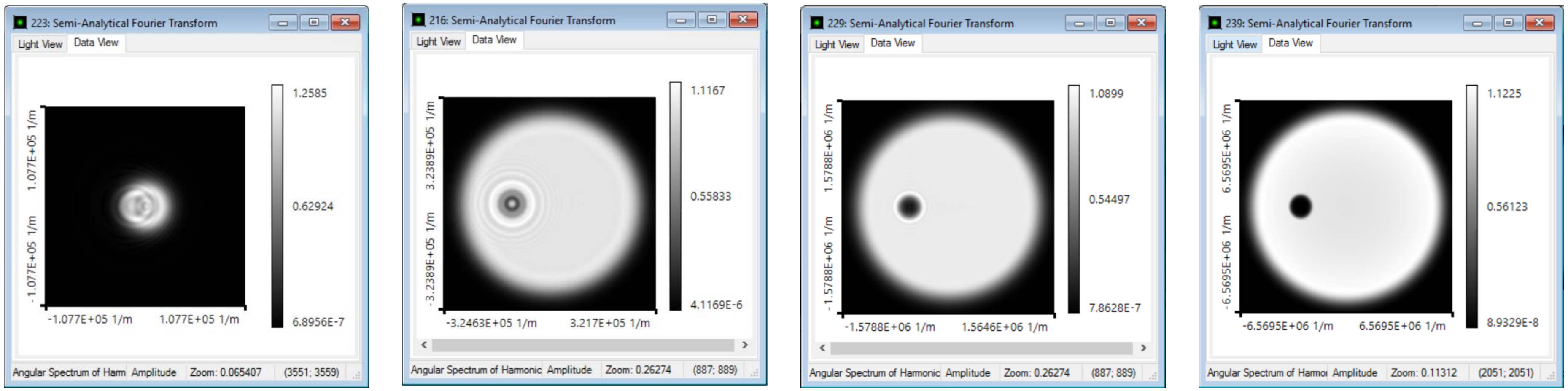




Results of Fourier Transform

$$V_\ell(\boldsymbol{\rho}, z, \omega) = |V_\ell(\boldsymbol{\rho}, z, \omega)| \exp\big(i\varphi_\ell(\boldsymbol{\rho}, z, \omega)\big) \boxed{\exp\big(i\psi(\boldsymbol{\rho}, z, \omega)\big)}$$

Decreasing radius of cruvature;
increasing NA



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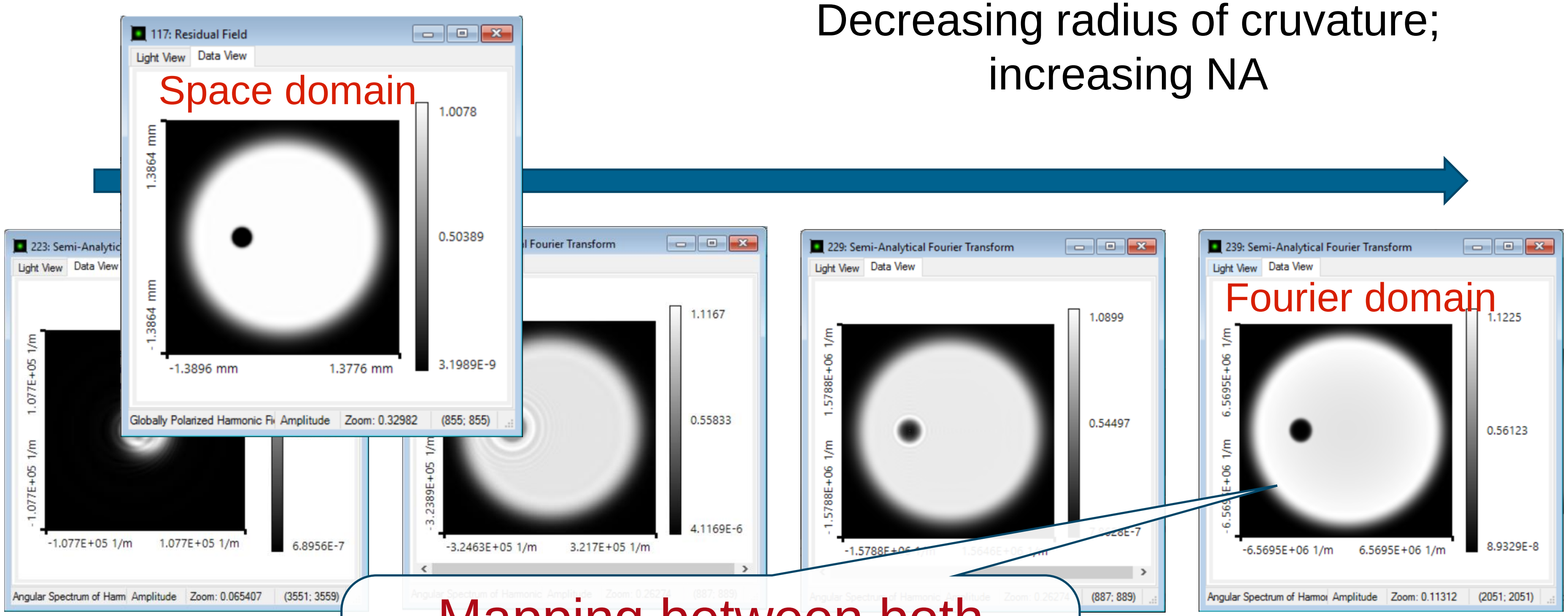


Mapping between both domains: geometric Fourier transform

Field Zones by Mathematical Definition

- Geometric Fourier transform valid in specified modeling accuracy

↓

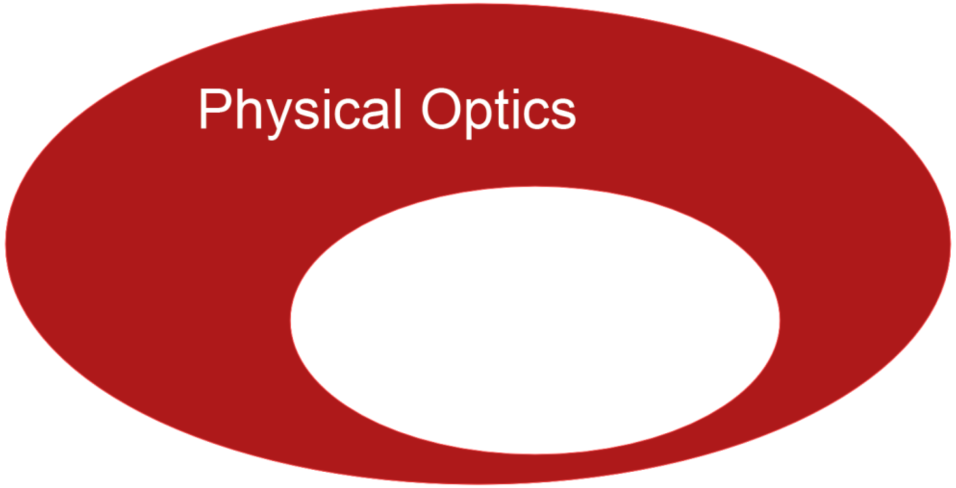
- Field on reference plane is in **geometric field zone**

- Rigorous Fourier transform required in specified modeling accuracy

↓

- Field on reference plane is in **diffractive field zone**

Physical and Geometrical Optics: Unified Theory



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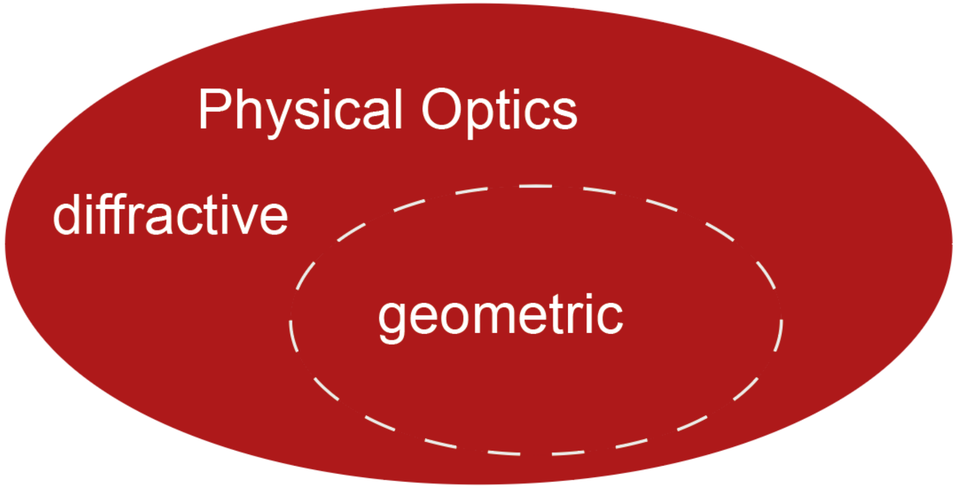

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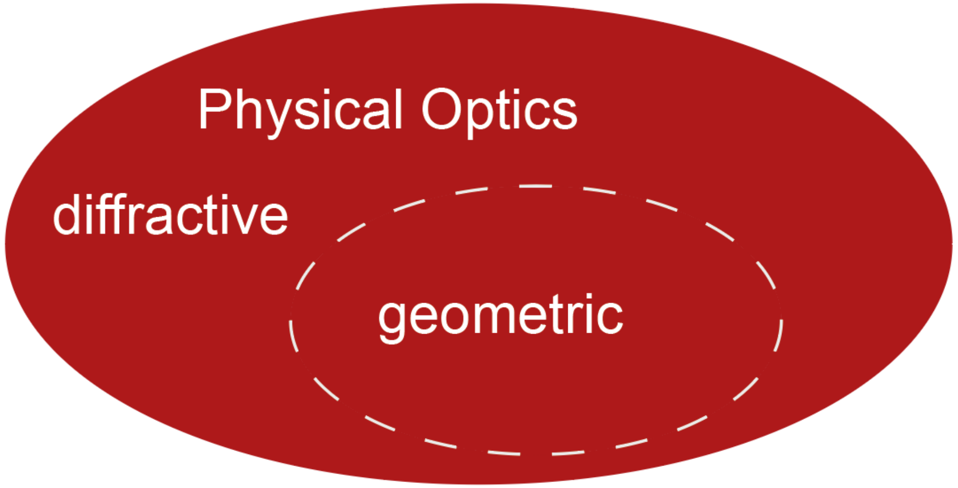

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  - Transition between diffractive/geometric branch fully specified and controlled by mathematical concept of geometric FT

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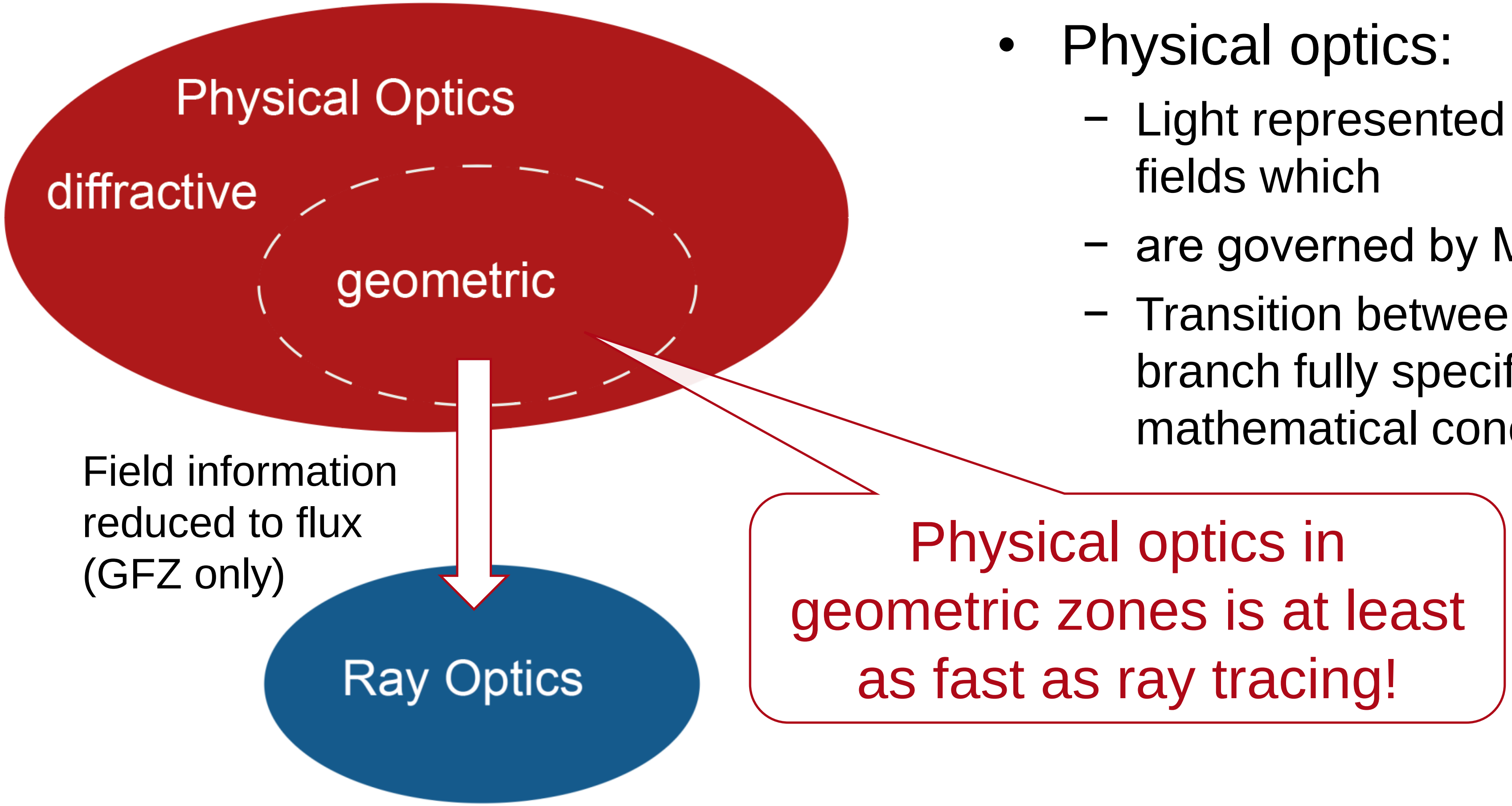

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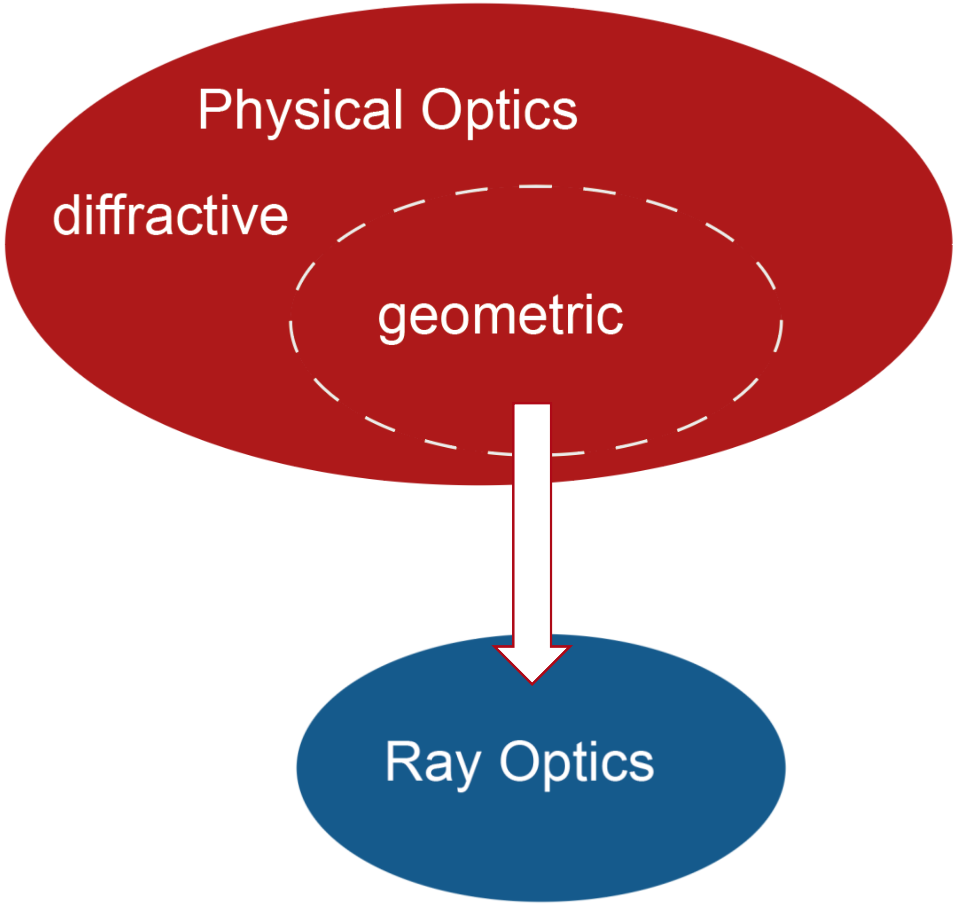
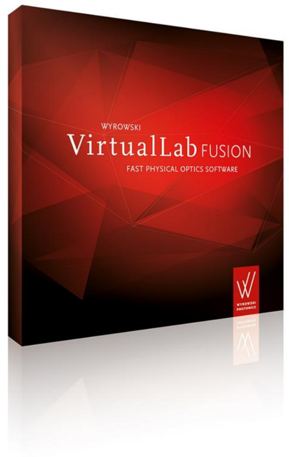


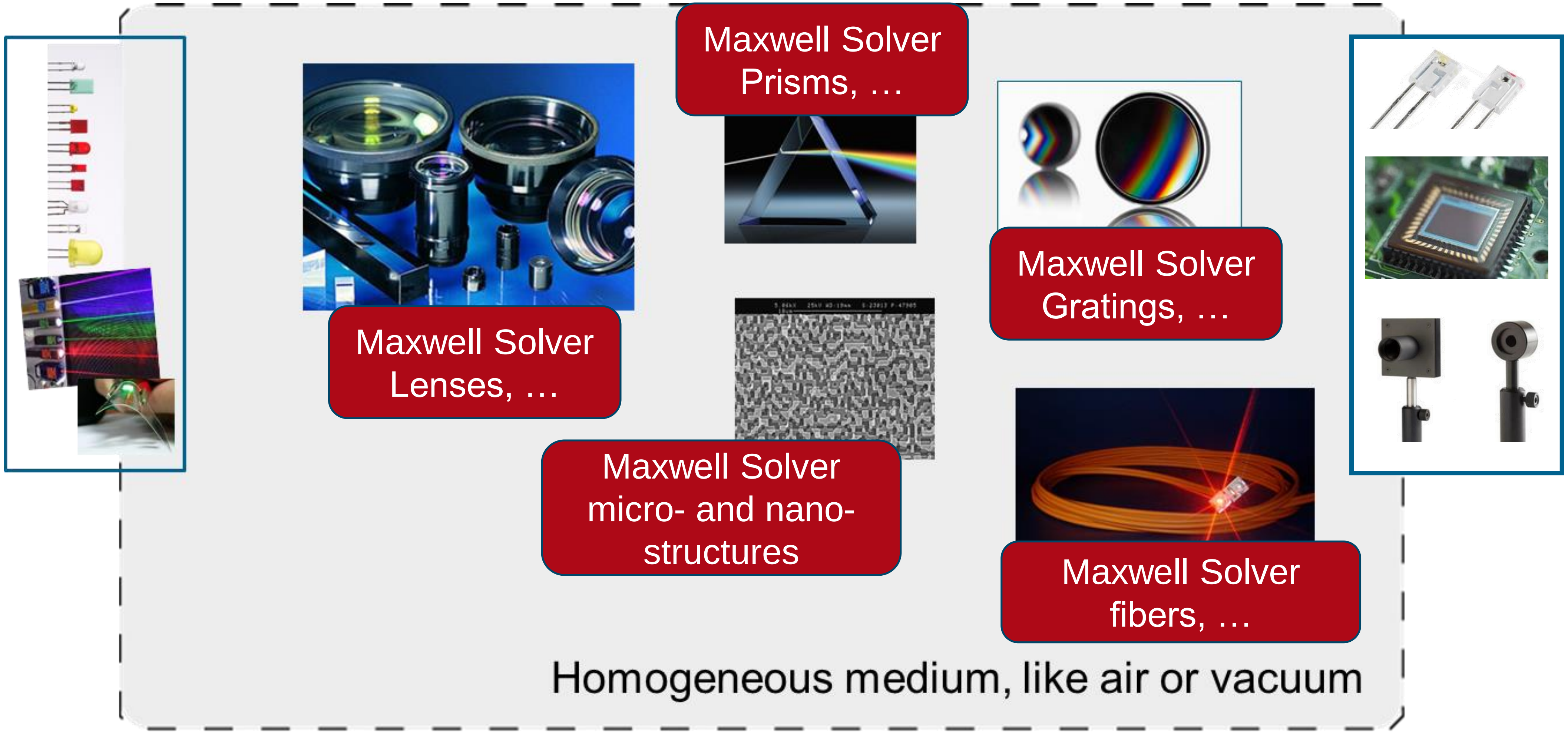


- VirtualLab Fusion manages the transition between diffractive and geometric branches of physical optics automatically (steady development).

Modeling and design of beam delivery systems by physical optics

An introduction to non-sequential field tracing

Physical-Optics System Modeling: Regional Maxwell Solver

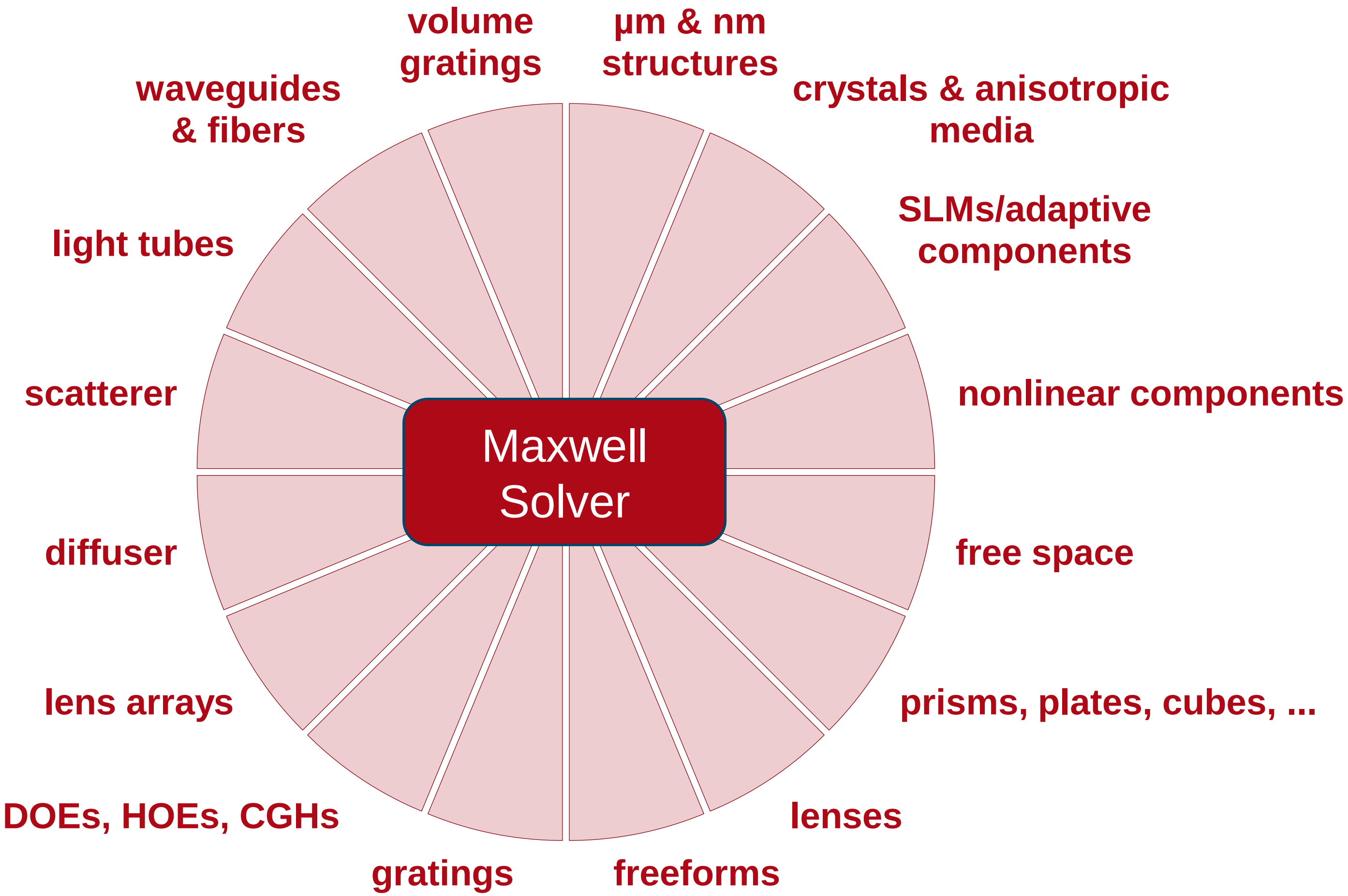


Fast Physical Optics by Field Tracing

In **Fast Physical Optics** we comply with the following strategies:

1. Tearing: The optical system is decomposed into various regions in which different types of specialized Maxwell solvers are applied.

Physical-Optics System Modeling: Regional Maxwell Solver



Fast Physical Optics by Field Tracing

In **Fast Physical Optics** we comply with the following strategies:

1. Tearing: The optical system is decomposed into various regions in which different types of specialized Maxwell solvers are applied.

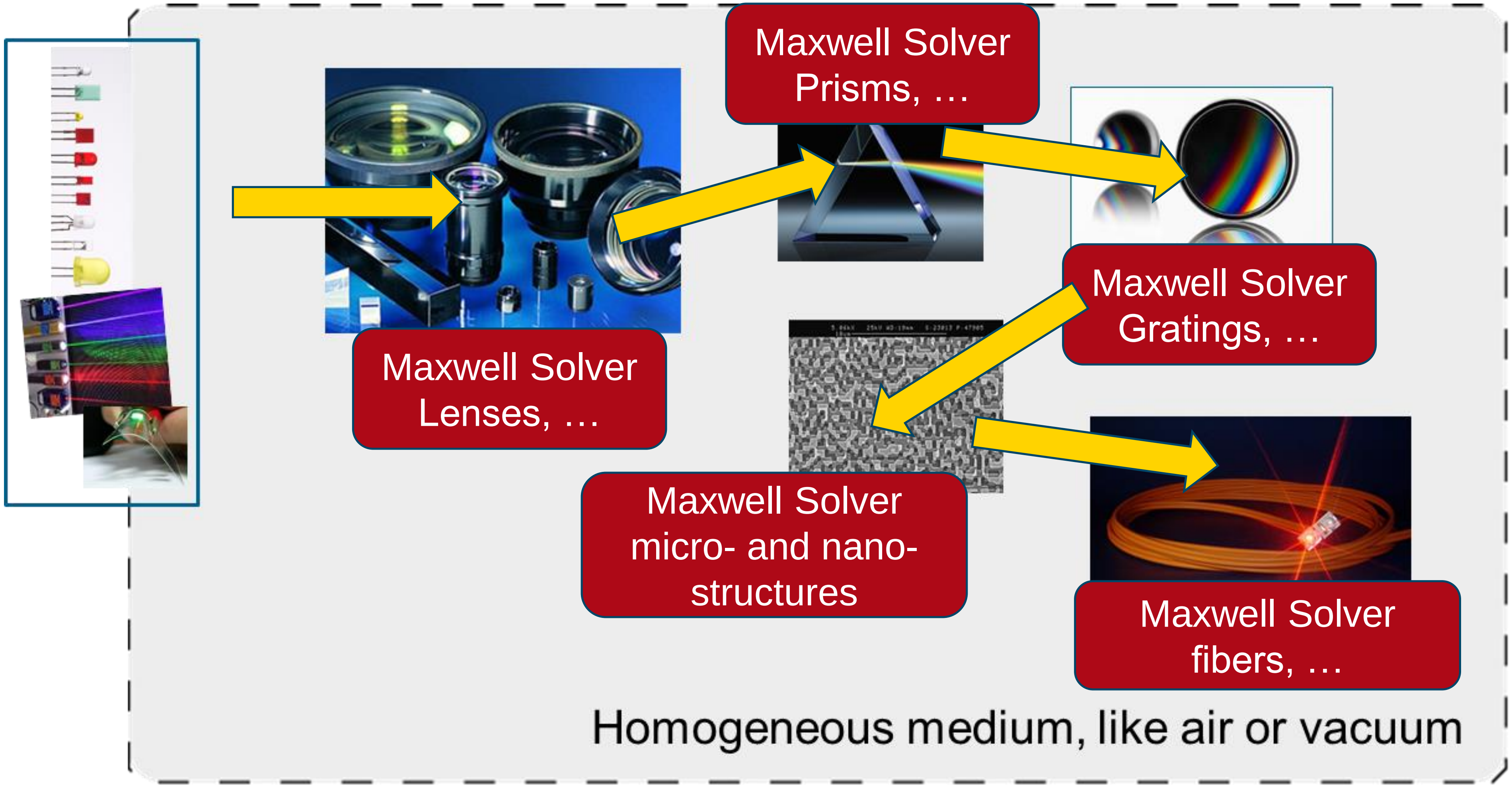
2. Interconnection: The solutions per region are connected through non-sequential field tracing to solve Maxwell's equations in the entire system.

Non-Sequential Optical Field Tracing

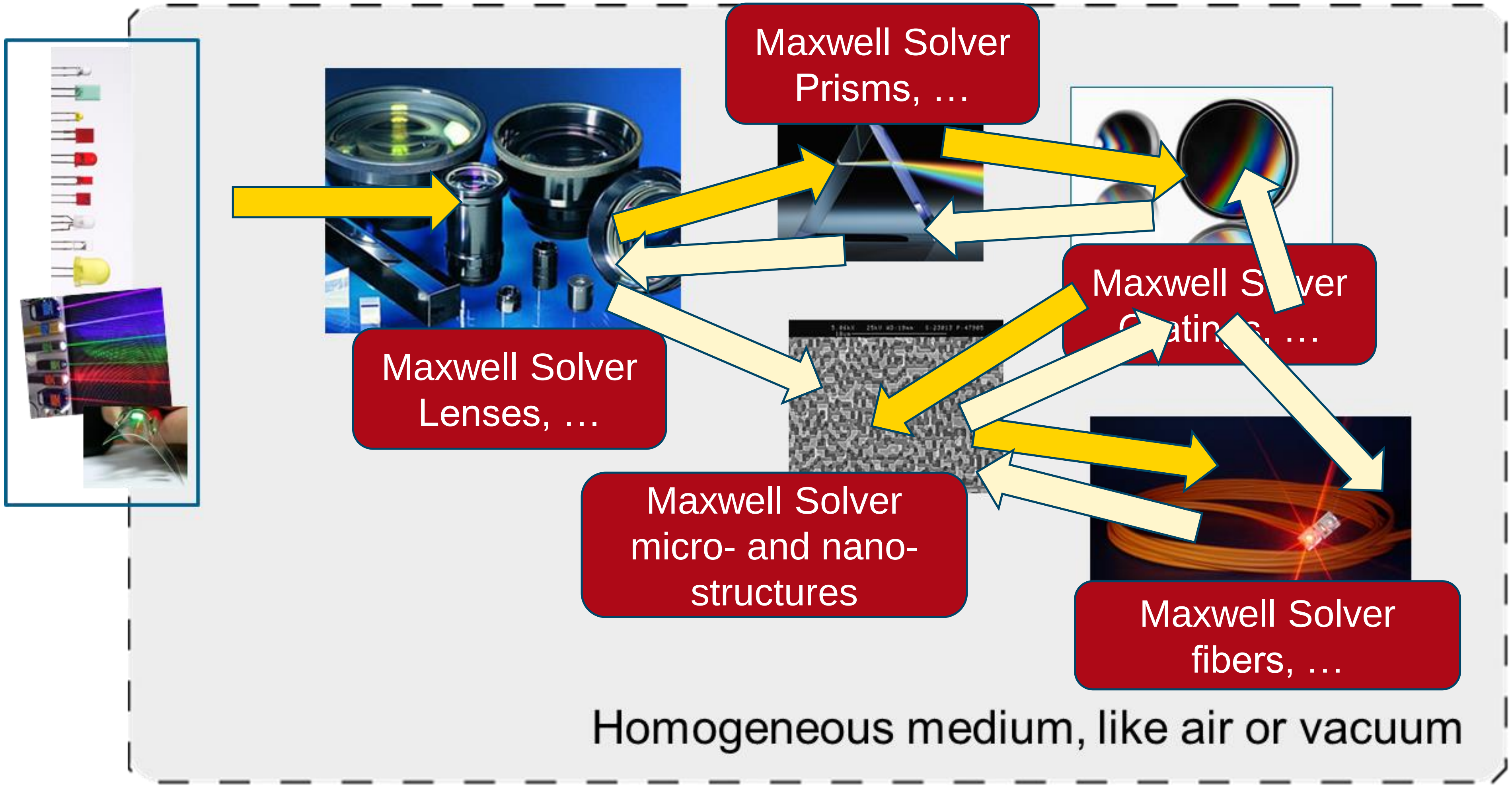
Michael Kuhn, Frank Wyrowski, and Christian Hellmann

Kuhn, M.; Wyrowski, F. & Hellmann, C. (2012), Non-sequential optical field tracing, *in* T. Apel & O. Steinbach, ed., 'Finite Element Methods and Applications', Springer-Verlag, Berlin, , pp. 257-274.

Sequential Connection of Regional Maxwell Solver



Non-Sequential Connection of Regional Maxwell Solver



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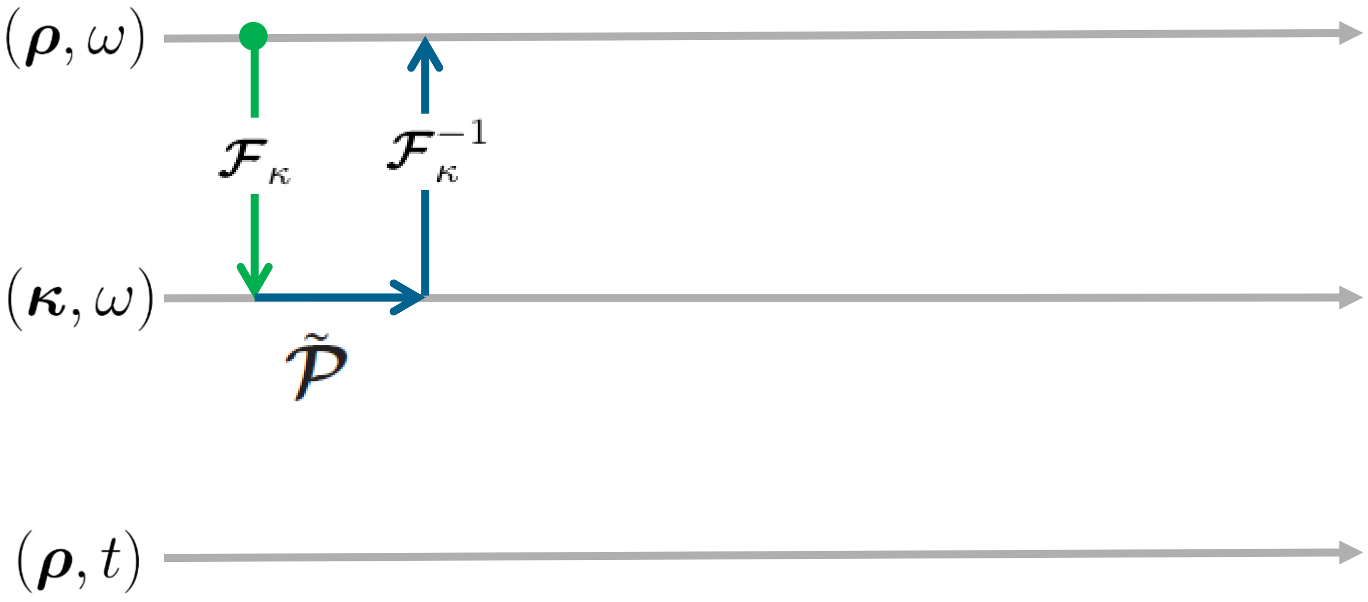

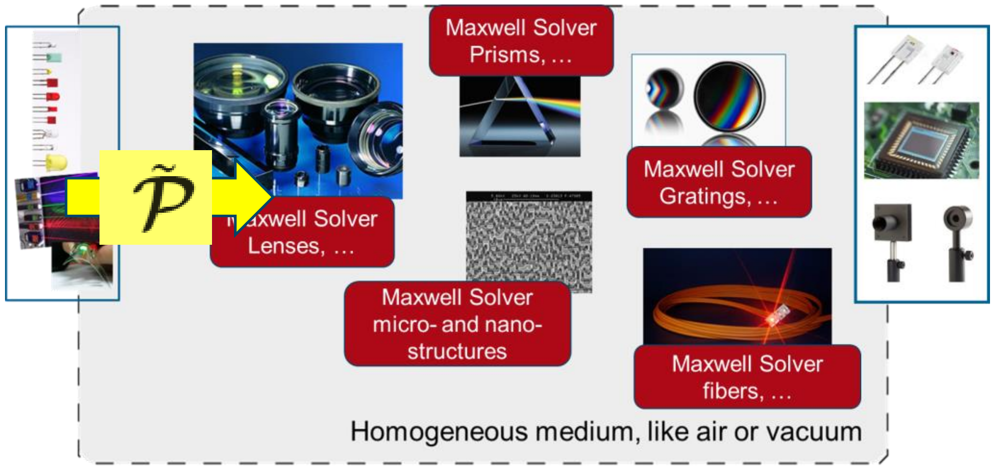

Rigorous propagation in k-domain:

$$\tilde{V}^{\mathrm{out}}(\boldsymbol{\kappa}, z) = \tilde{V}^{\mathrm{in}}(\boldsymbol{\kappa}, z_0) \underbrace{\times \exp\Big(\mathrm{i}\check{k}_z(\kappa)\Delta z\Big)}_{\tilde{\mathcal{P}}}$$

Field Tracing Operators: Space- and k-Domain

- The free-space operator equation is given by

$$\boldsymbol{E}_\perp^{\text{out}}(\boldsymbol{\rho},\omega) = \boldsymbol{\mathcal{P}}\boldsymbol{E}_\perp^{\text{in}}(\boldsymbol{\rho},\omega)$$

and in matrix form by

$$\begin{pmatrix} E_x^{\text{out}}(\boldsymbol{\rho},\omega) \\ E_y^{\text{out}}(\boldsymbol{\rho},\omega) \end{pmatrix} = \begin{pmatrix} \mathcal{P} & 0 \\ 0 & \mathcal{P} \end{pmatrix} \begin{pmatrix} E_x^{\text{in}}(\boldsymbol{\rho},\omega) \\ E_y^{\text{in}}(\boldsymbol{\rho},\omega) \end{pmatrix} .$$

- The free-space operator equation in k-domain is given by

$$\tilde{\boldsymbol{E}}_\perp^{\text{out}}(\boldsymbol{\kappa},\omega) = \tilde{\boldsymbol{\mathcal{P}}}\tilde{\boldsymbol{E}}_\perp^{\text{in}}(\boldsymbol{\kappa},\omega)$$

with $\boldsymbol{\kappa} = (k_x, k_y)$. In matrix form we have

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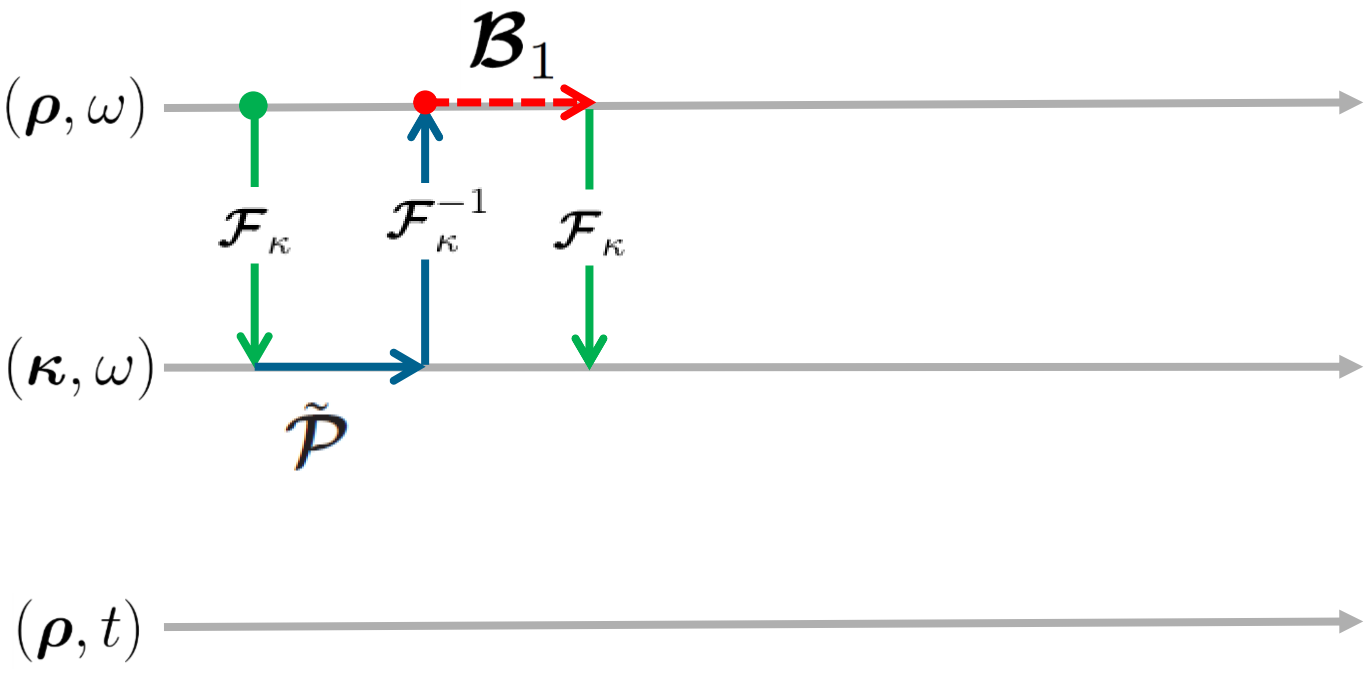

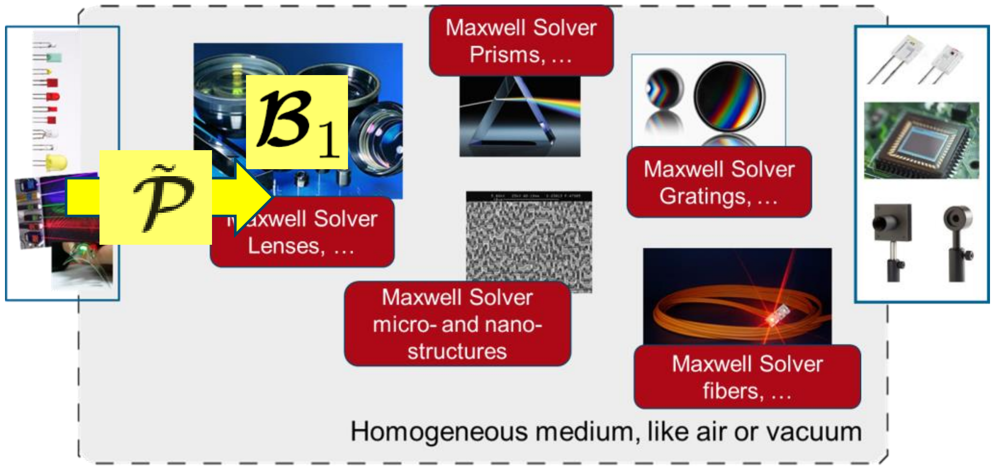

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- Analogously we have for the B-operator

$$\boldsymbol{E}_{\perp}^{\text{out}}(\boldsymbol{\rho},\omega) = \boldsymbol{\mathcal{B}}\boldsymbol{E}_{\perp}^{\text{in}}(\boldsymbol{\rho},\omega)$$

and in matrix form

$$\begin{pmatrix} E_x^{\text{out}}(\boldsymbol{\rho},\omega) \\ E_y^{\text{out}}(\boldsymbol{\rho},\omega) \end{pmatrix} = \begin{pmatrix} \mathcal{B}_{xx} & \mathcal{B}_{xy} \\ \mathcal{B}_{yx} & \mathcal{B}_{yy} \end{pmatrix} \begin{pmatrix} E_x^{\text{in}}(\boldsymbol{\rho},\omega) \\ E_y^{\text{in}}(\boldsymbol{\rho},\omega) \end{pmatrix} .$$

- The free-space operator equation in k-domain is given by

$$\tilde{\boldsymbol{E}}_{\perp}^{\text{out}}(\boldsymbol{\kappa},\omega) = \tilde{\boldsymbol{\mathcal{P}}}\tilde{\boldsymbol{E}}_{\perp}^{\text{in}}(\boldsymbol{\kappa},\omega)$$

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Bidirectional Operator: k-Domain

Bidirectional operator
Generalization of Bidirectional Scattering Distribution Function (BSDF).

- For the bidirectional operator in k-domain we
  trix element the integral of the form

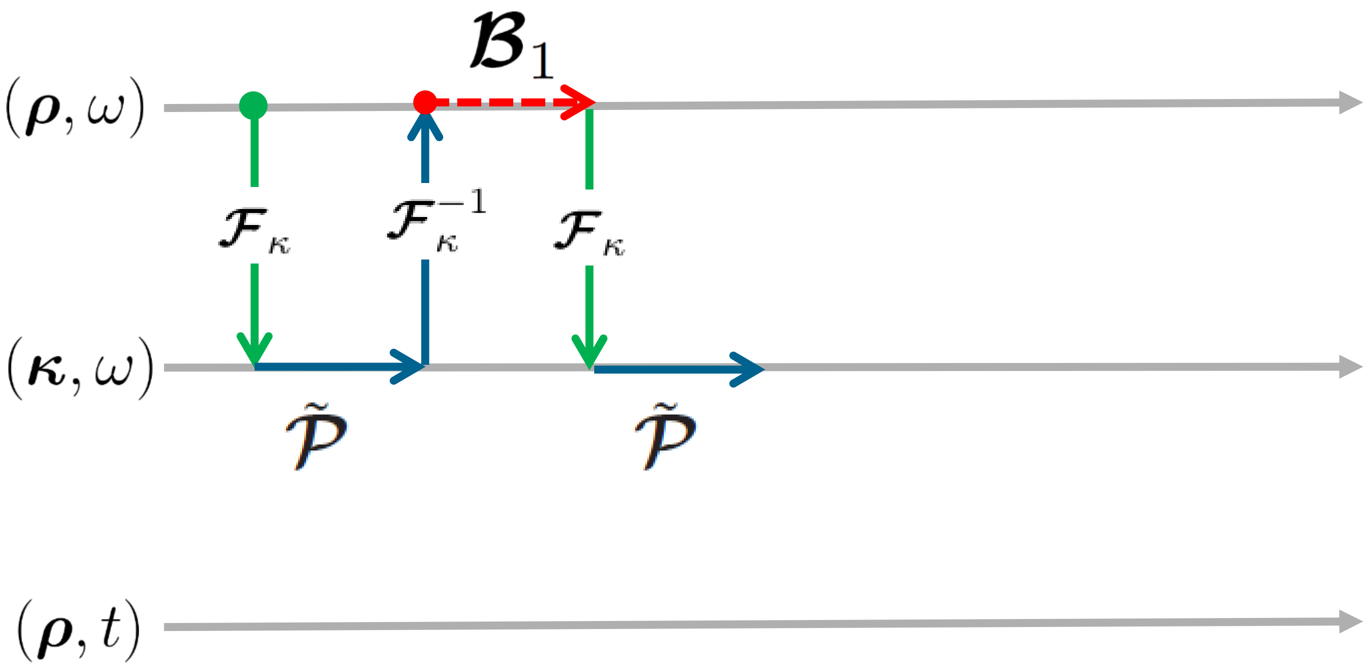
$$\tilde{V}^{\text{out}}(k_x, k_y) = \int_{K^2} \tilde{B}(k_x, k_y, k_x', k_y') \tilde{V}^{\text{in}}(k_x', k_y') \, \mathrm{d}k_x' \, \mathrm{d}k_y' \, .$$

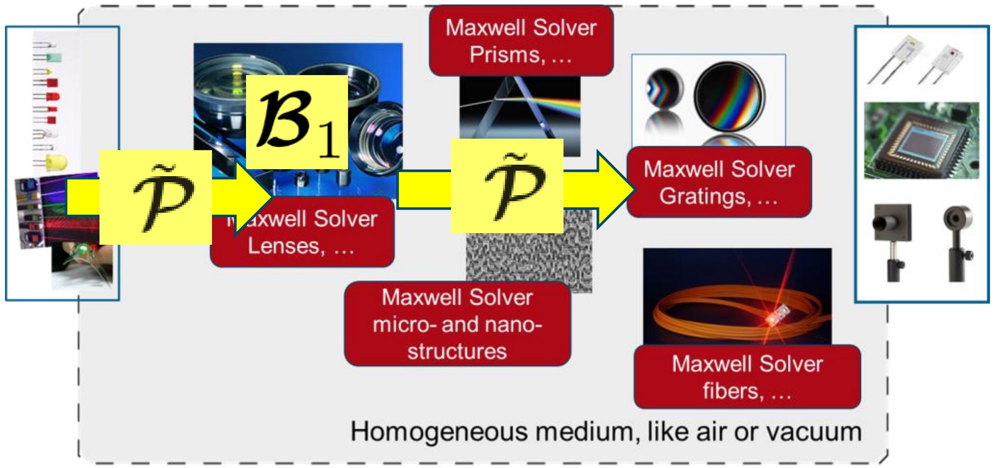
  with he integral kernel $\tilde{B}(k_x, k_y, k_x', k_y')$.

$$\begin{pmatrix} \tilde{\mathcal{B}}_{xx} & \tilde{\mathcal{B}}_{xy} \\ \tilde{\mathcal{B}}_{yx} & \tilde{\mathcal{B}}_{yy} \end{pmatrix}$$

- Since $\tilde{V}^{\text{in}}(k_x', k_y')$ can be understood as a decomposition into (inhomogeneous) plane waves, the bidirectional operator provides the plane-waves response on one incident plane wave.
- The integral operator reduces to a multiplication for stratified media and gratings per order (with k-value mapping).

Non-Sequential Connection of Regional Maxwell Solver





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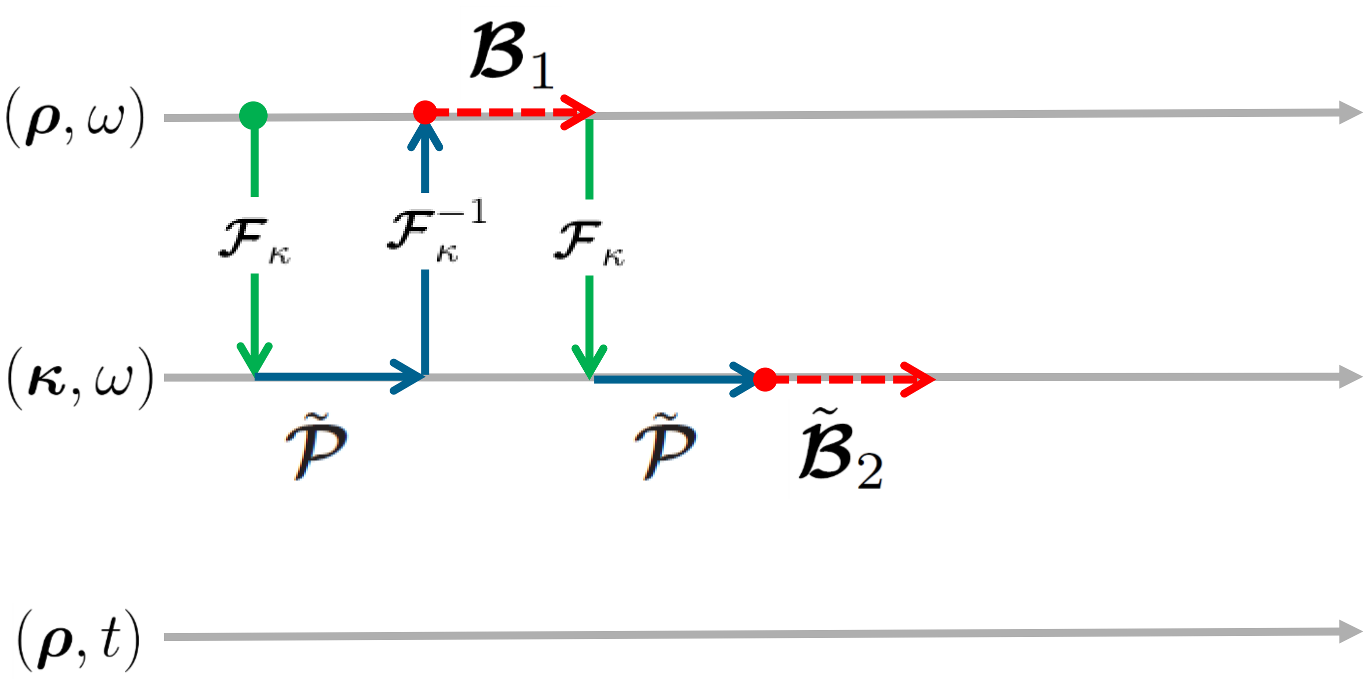

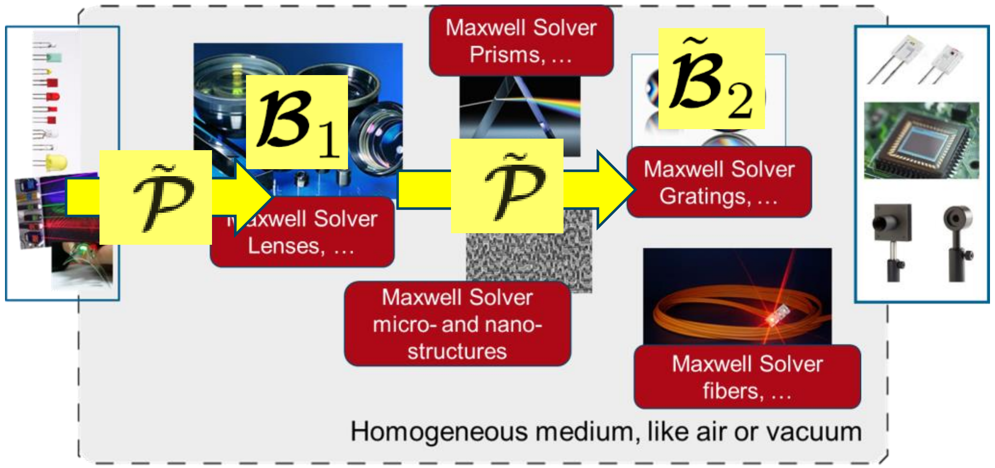

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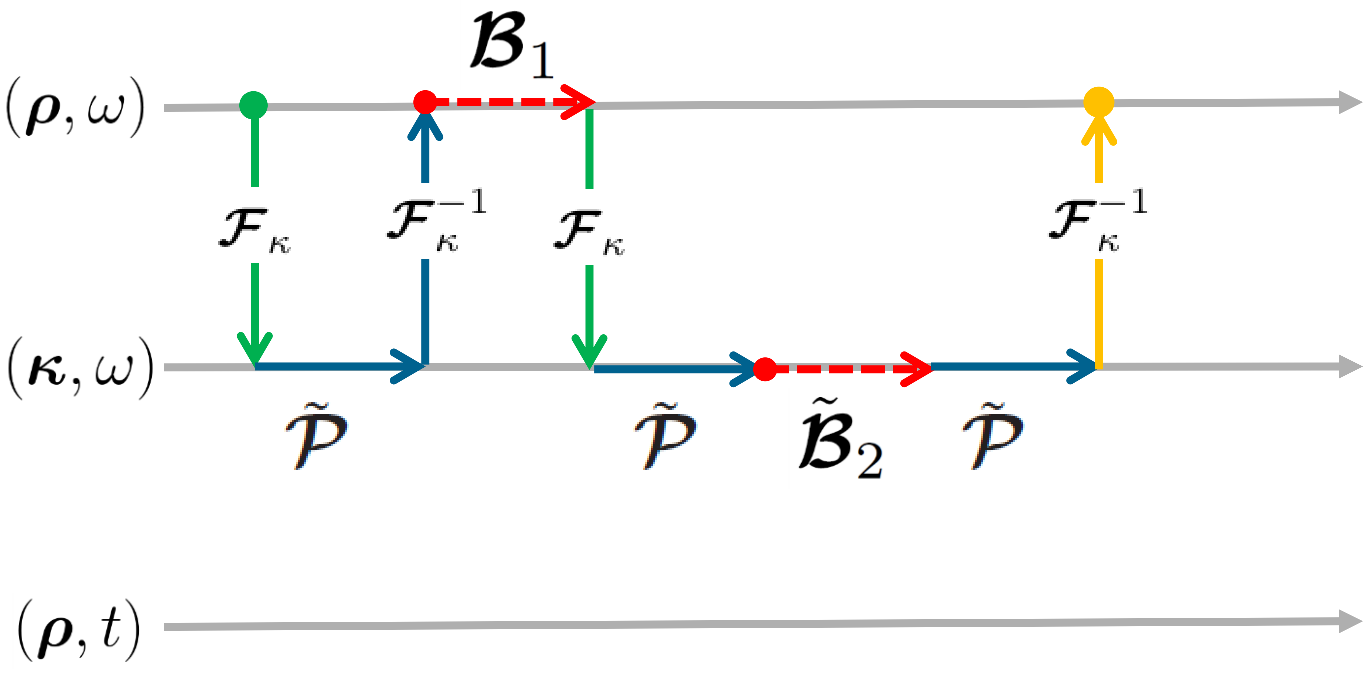

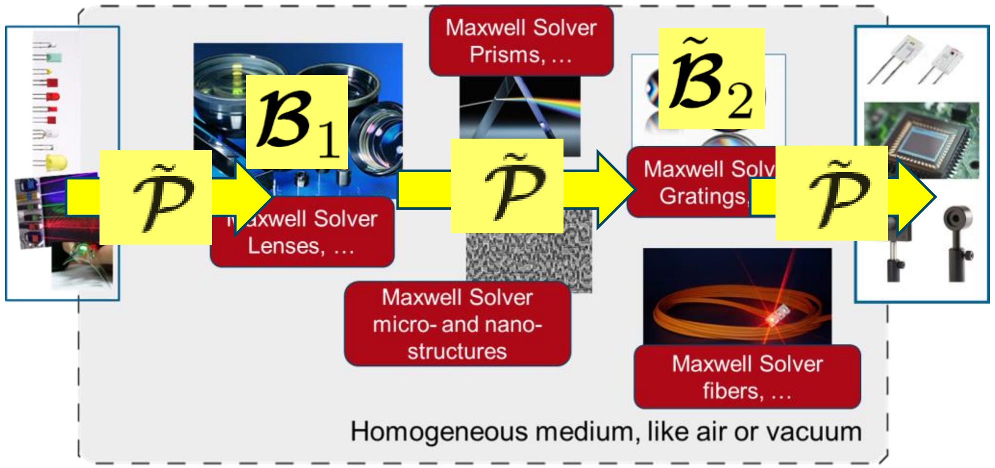

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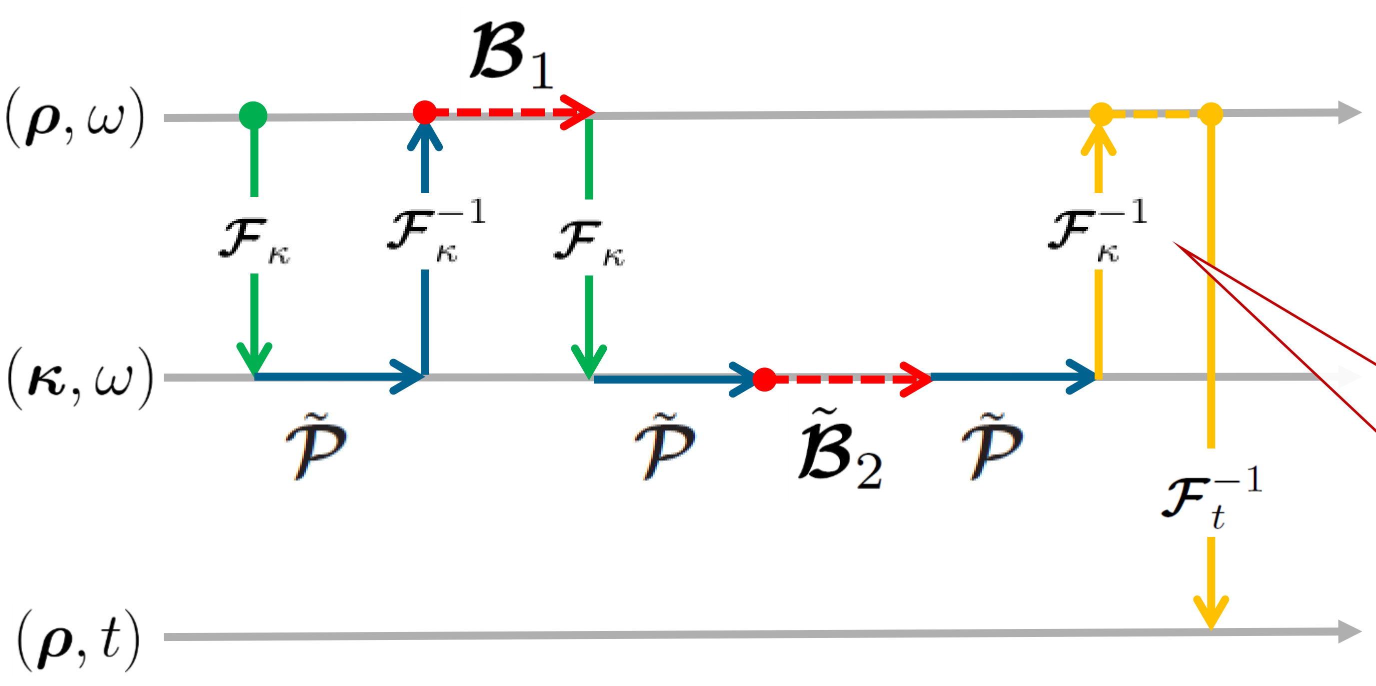
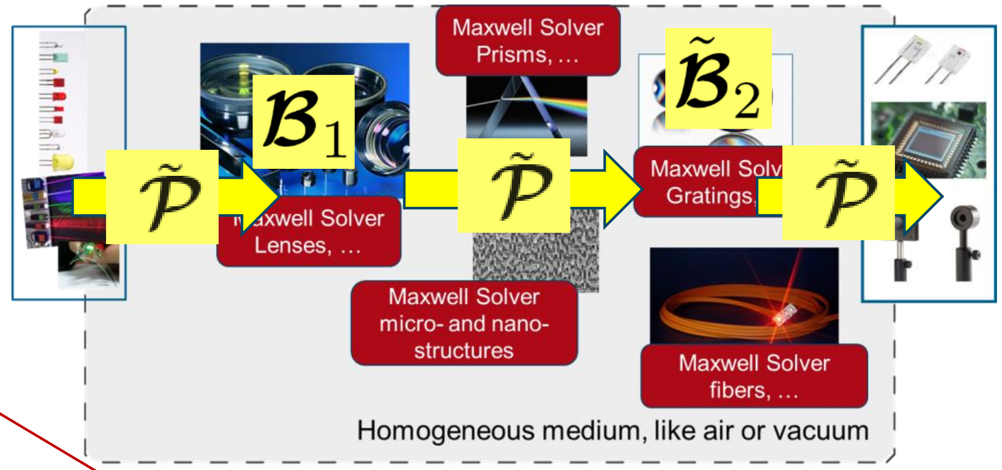
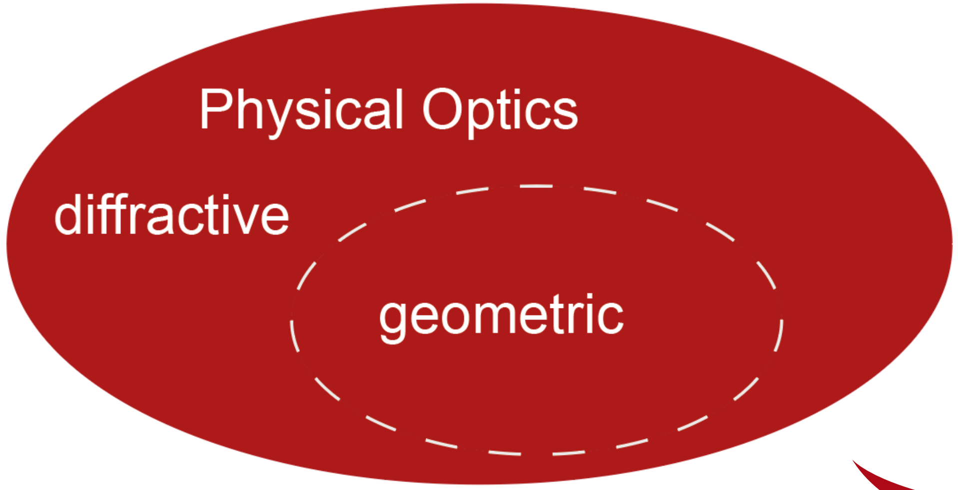
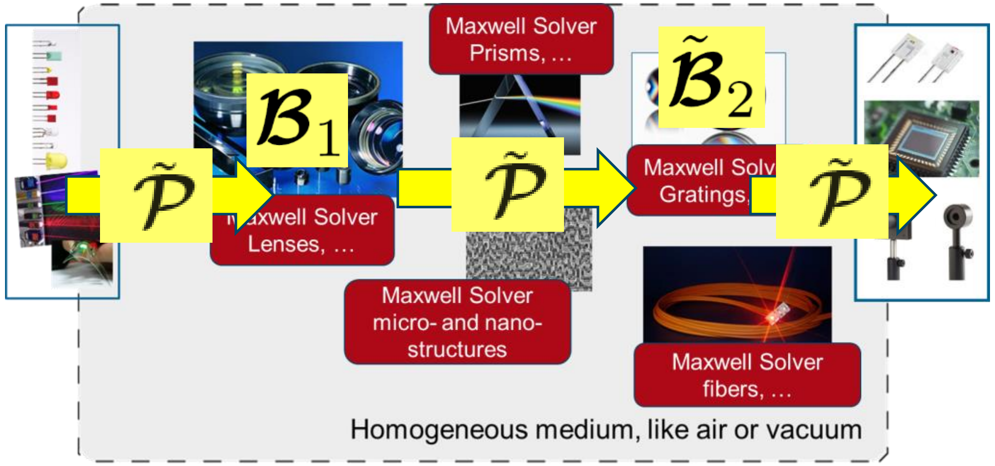


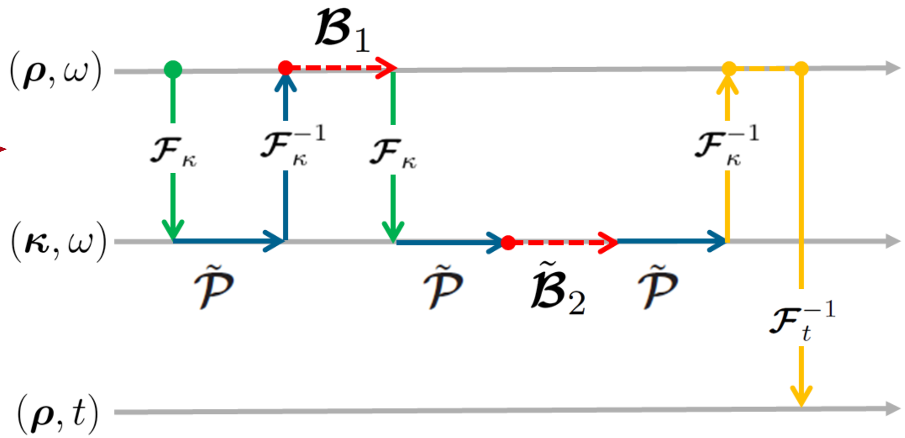


Characteristics of connection between the domains of utmost importance!

Modeling and Design of Optical Systems by Physical Optics



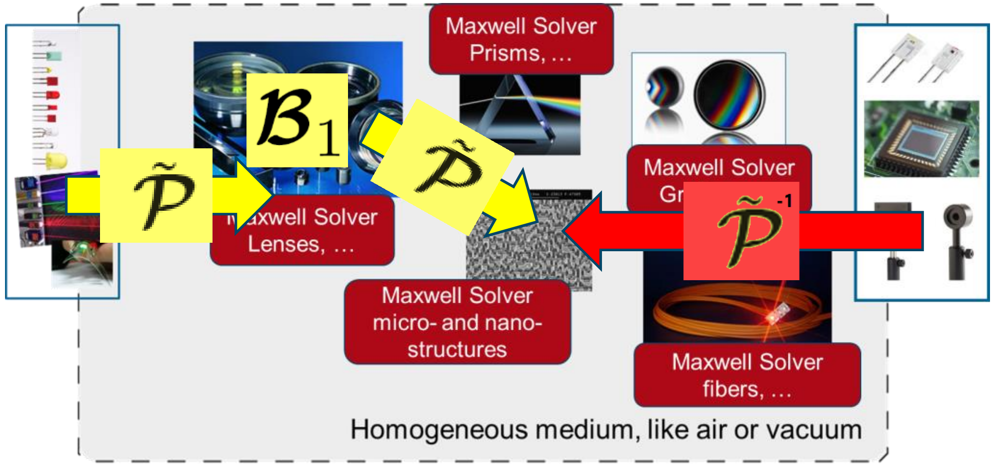


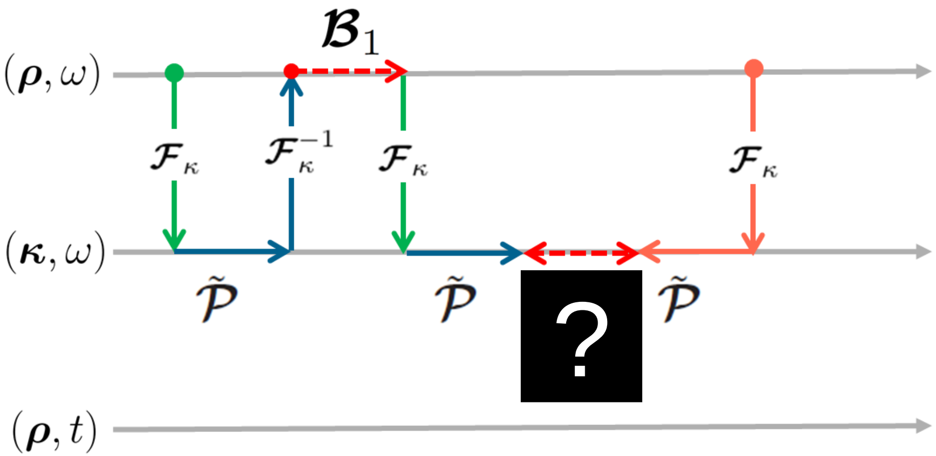


- Geometric Fourier Transform (GFT)
- Rigorous Fourier Transform (FFT)

Modeling and Design of Optical Systems by Physical Optics

- Compared to ray tracing You do not lose anything by fast physical optics
- Ray tracing is included in VirtualLab Fusion software on a solid base knowing about limitations of ray optics
- **By going beyond ray tracing**
  - You win more information about the light in your system
  - You get better insight into the performance of your system
  - You can include and investigate more effects
  - You can model with higher accuracy
  - You are ready for new optical design concepts and by that for innovative optical solutions





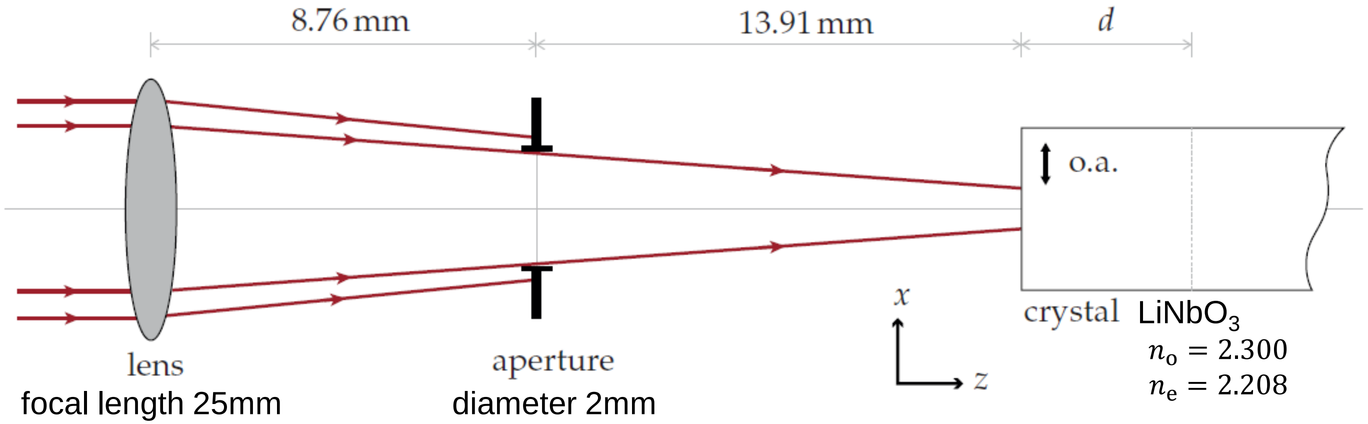
Example

Focusing Properties inside Crystal

Example – Focusing Properties inside Crystal

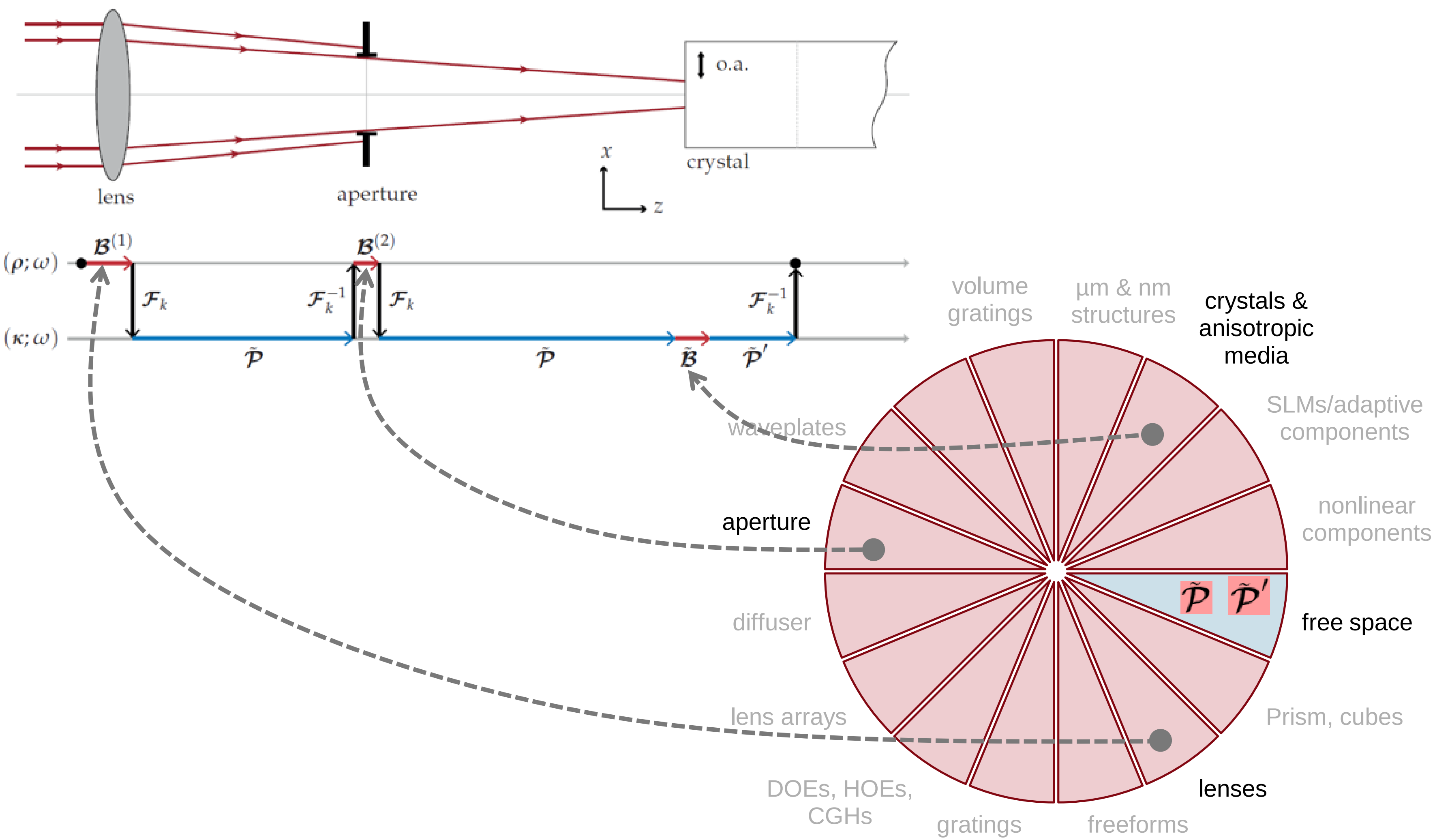
Many laser crystals are made out of birefringent materials whose optical properties depends strongly on the polarization of light and the orientation of the crystal

Input laser beam
633nm wavelength
linearly polarized
along *x* direction



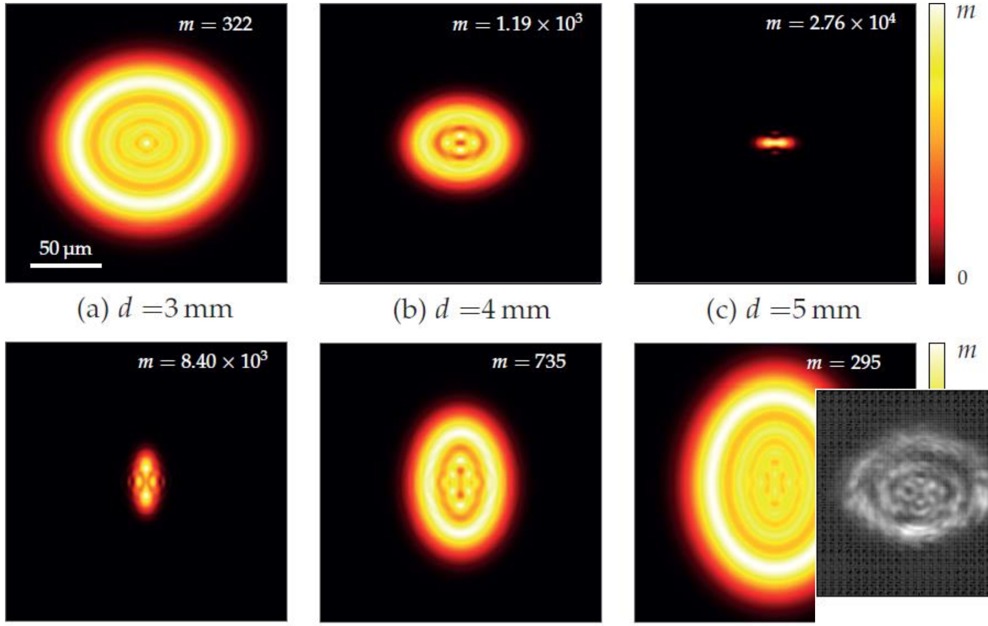
The optic axis of the crystal is first set along the *x* direction, then along the *y* direction

Field Tracing Diagram



Simulation Results

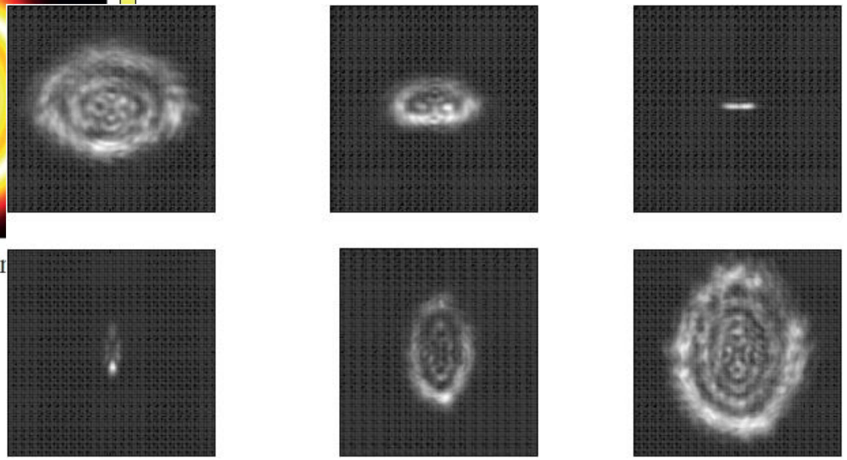
- Light distribution at different depth (o.a. along *y* direction)



(a) d =3 mm (b) d =4 mm (c) d =5 mm

(d) d =6 mm (e) d =7 mm (f) d =8

Experimental measurement



Calculation at one depth: ~ **9** s
with Intel Core i7-4910MQ

M. Jain et al., J. Opt. Soc. Am. A 26, 691-698 (2009)

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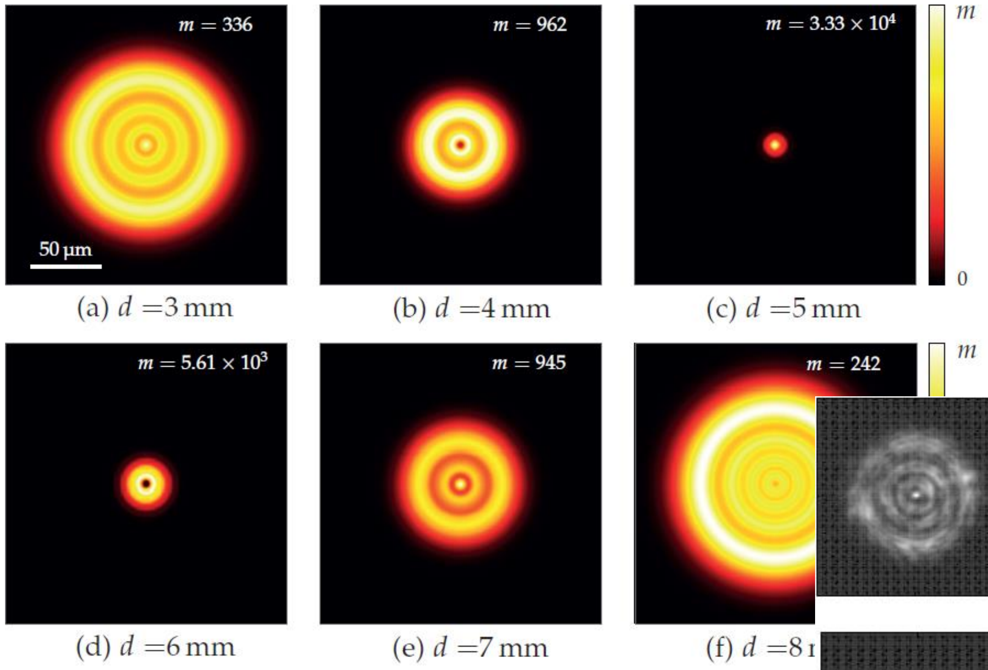
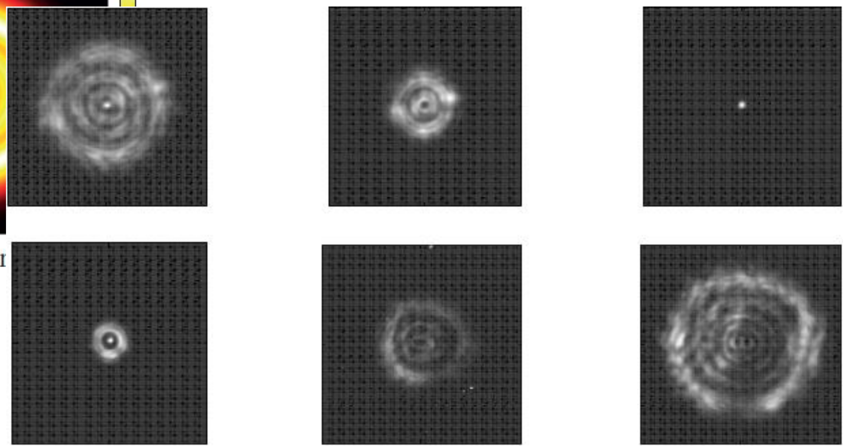


Experimental measurement

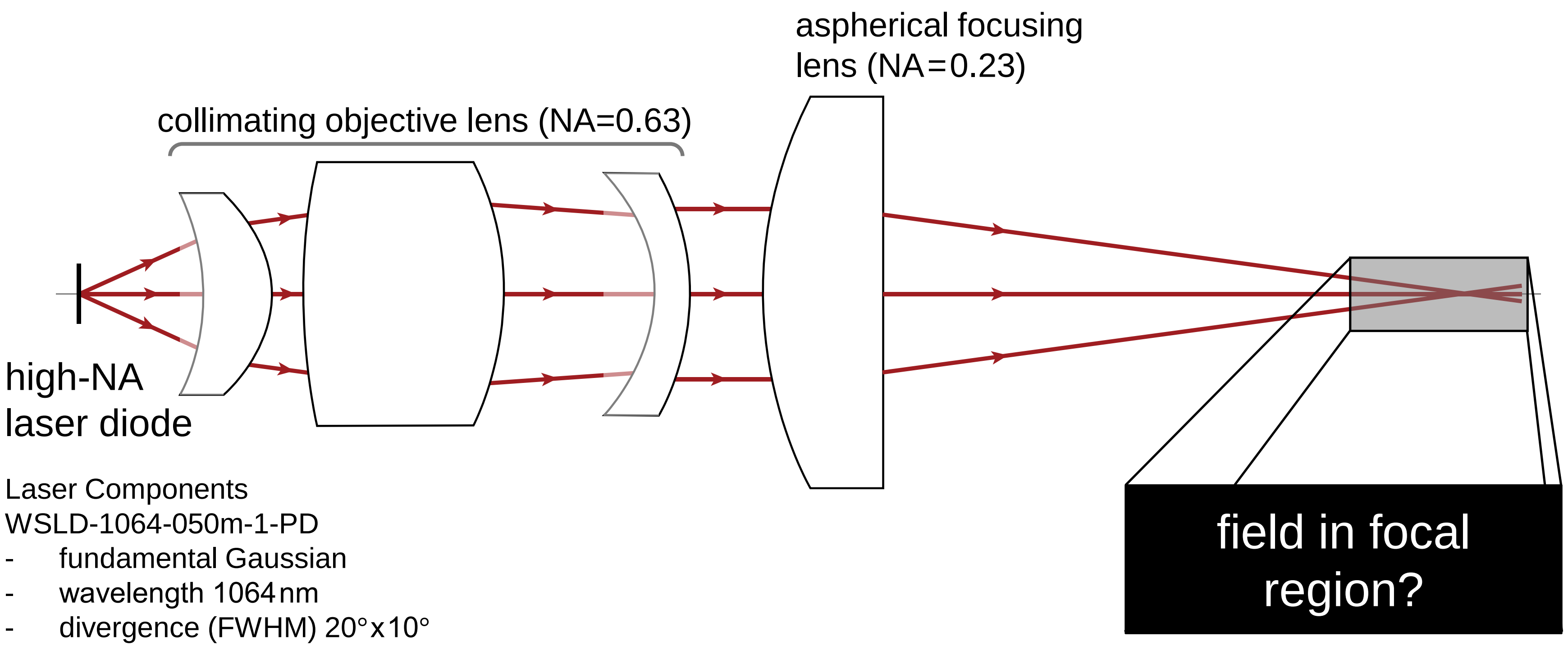


M. Jain et al., J. Opt. Soc. Am. A 26, 691-698 (2009)

Example

Focusing of an high-NA laser diode

Modeling Task



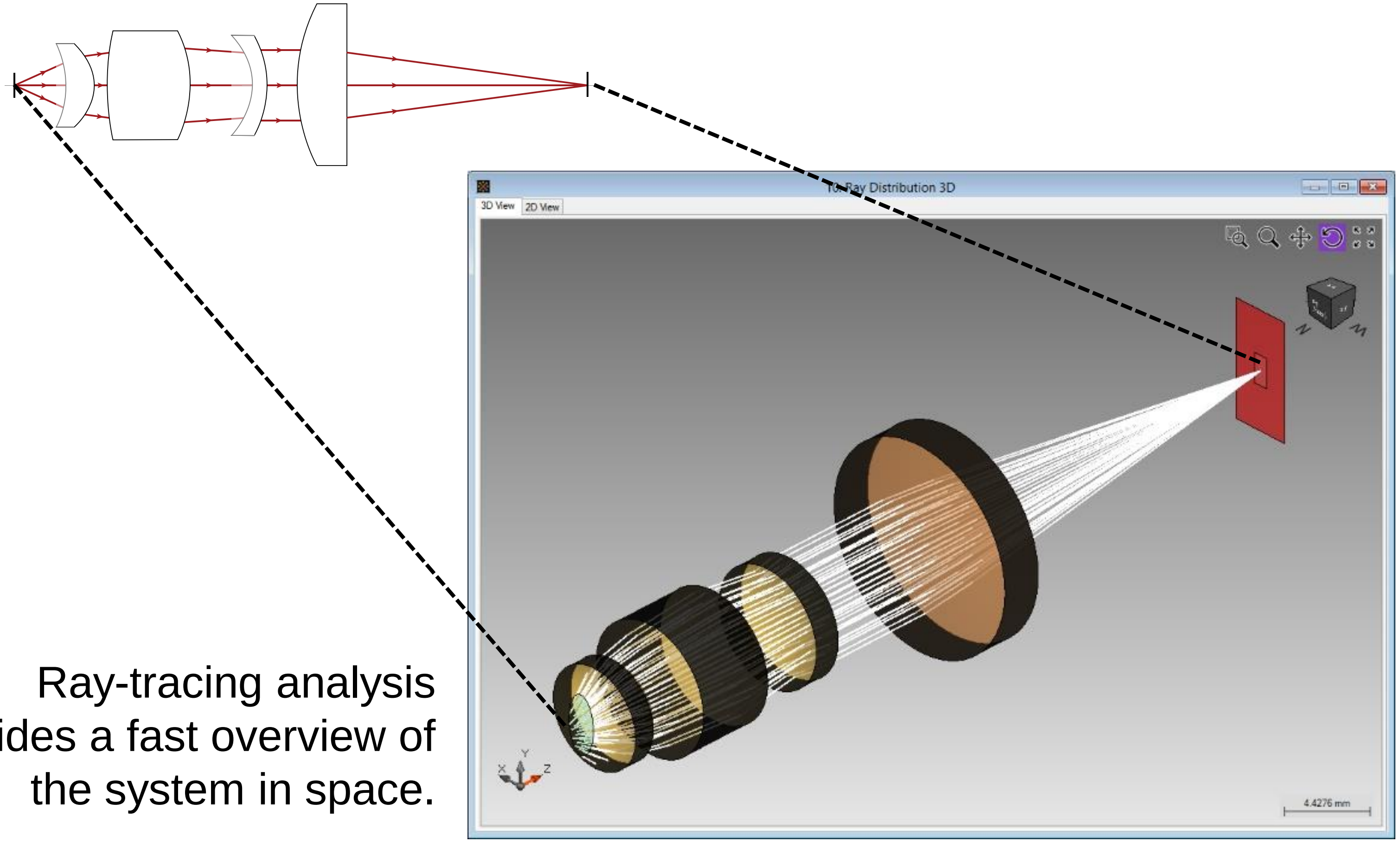
Laser Components
WSLD-1064-050m-1-PD

- fundamental Gaussian
- wavelength 1064 nm
- divergence (FWHM) 20°x10°
- astigmatism 11.6 μm between *x*- and *y*-plane

What is the field in focal region behind an aspherical lens? Especially, the astigmatism of the laser diode must be taken into account.

Results – 3D Ray Tracing

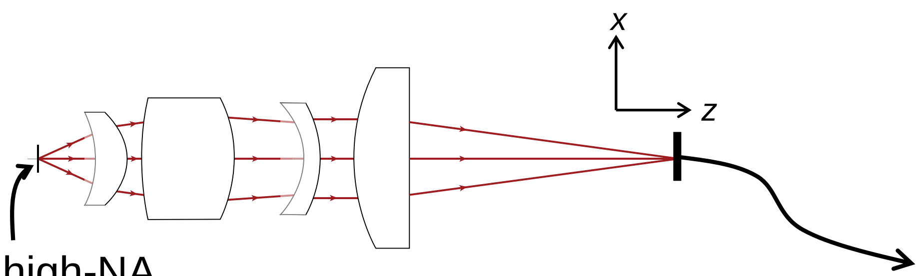
- Ray tracing – system in 3D space



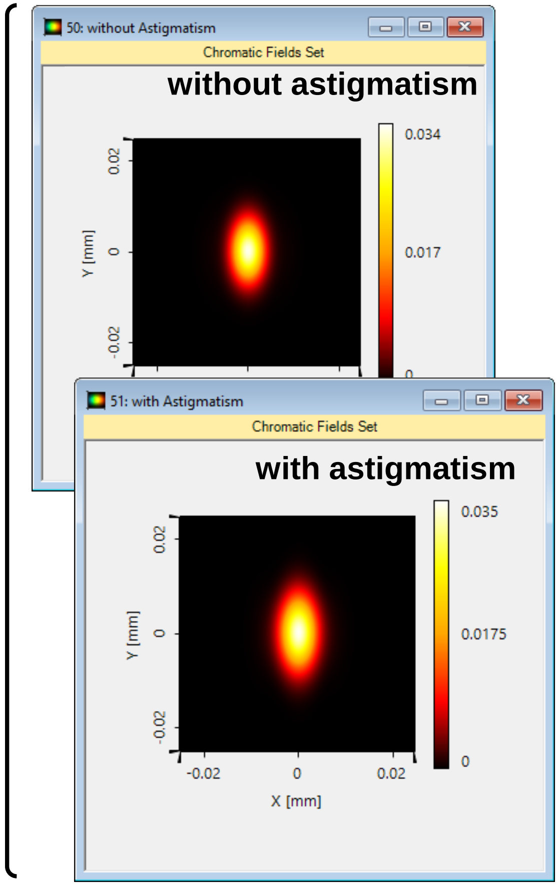
Ray-tracing analysis provides a fast overview of the system in space.

Results – Intensity at Focal Plane

- Field tracing



high-NA
laser diode
with or w/o astigmatism



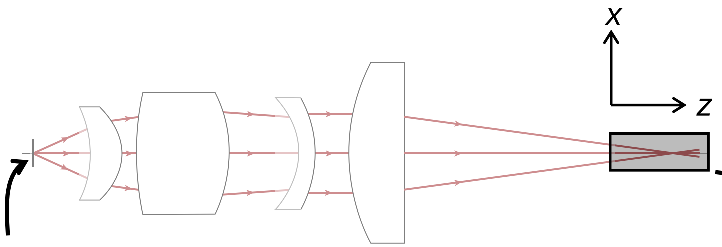
diameter of focused beams

diameter	**With astigmatism**	**Without astigmatism**
x direction	11.80 µm	11.41 µm
y direction	21.48 µm	19.23 µm

Physical-optics simulation of whole system, including collimation and focusing lenses, takes only 2 seconds!

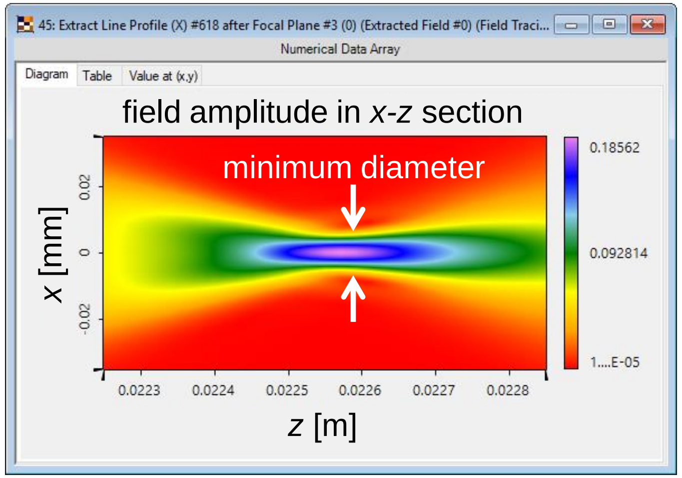
Results – Intensity in Focal Region (without Astigmatism)

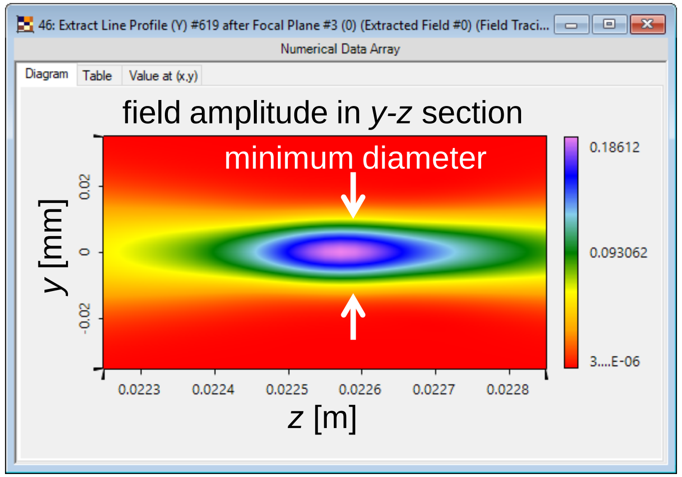
- Field tracing



high-NA
laser diode
without astigmatism

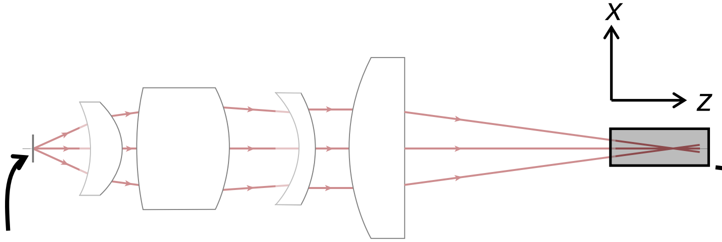
Physical-optics simulation of field evaluation within focal region, over 30 steps, takes about 90 seconds.



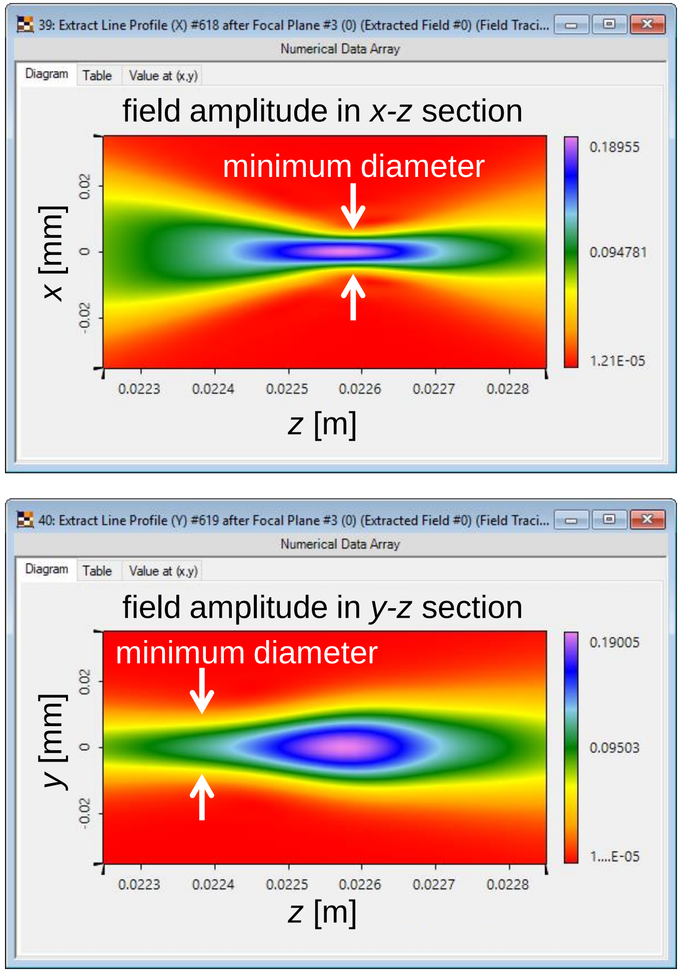


Results – Intensity in Focal Region (with Astigmatism)

- Field tracing



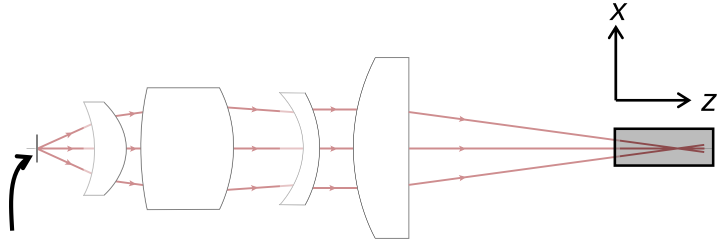
high-NA
laser diode
with astigmatism



Minimum beam diameters appear at different positions along *x* and *y* directions, due to astigmatism of the laser diode.

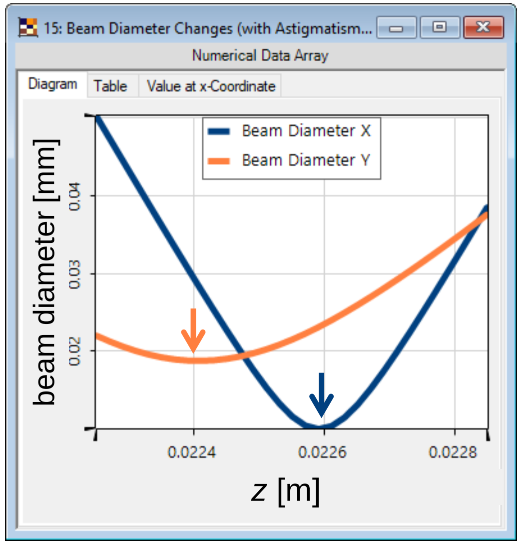
Results – Beam Diameter in Focal Region

- Field tracing

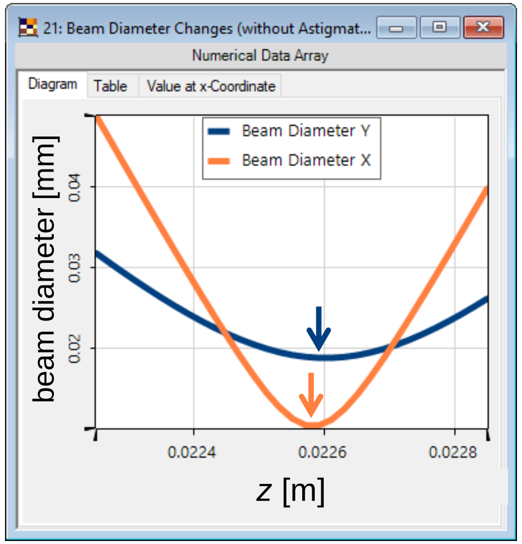


high-NA
laser diode
with or w/o
astigmatism

quantitative measurement of
the evolution of beam
diameters in both directions



with astigmatism

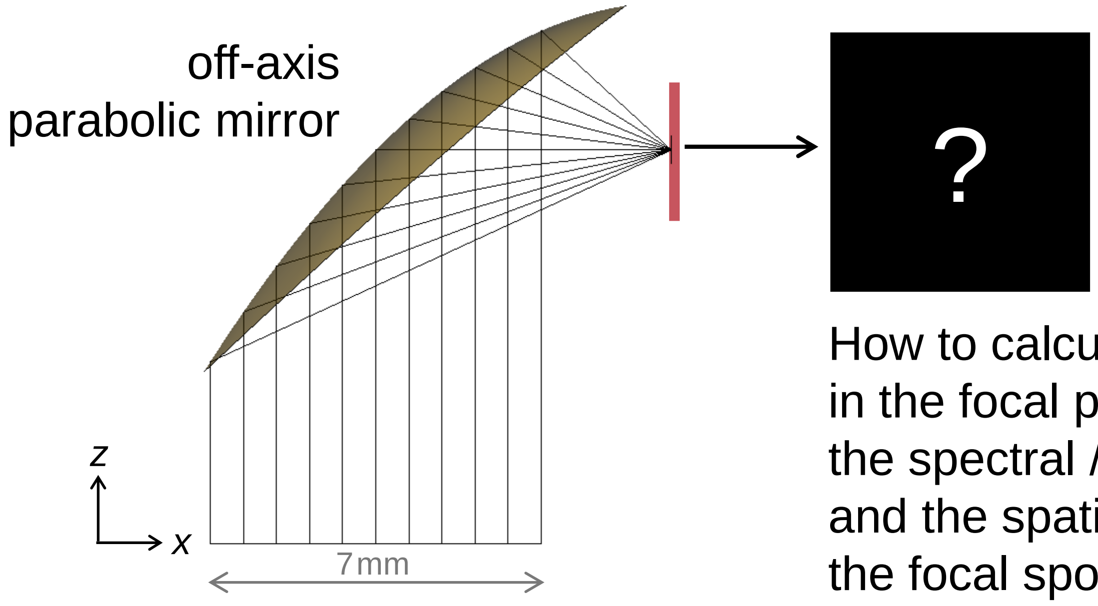


without astigmatism

Example

Focusing of a pulse by an off-axis parabolic mirror

Modeling Task

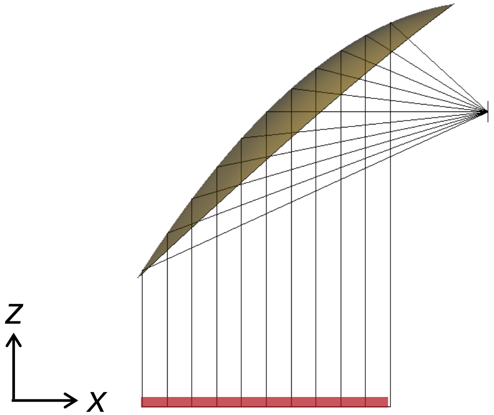


How to calculate output pulse in the focal plane, including the spectral / temporal profile and the spatial distribution of the focal spot for all vectorial field components?

input pulse

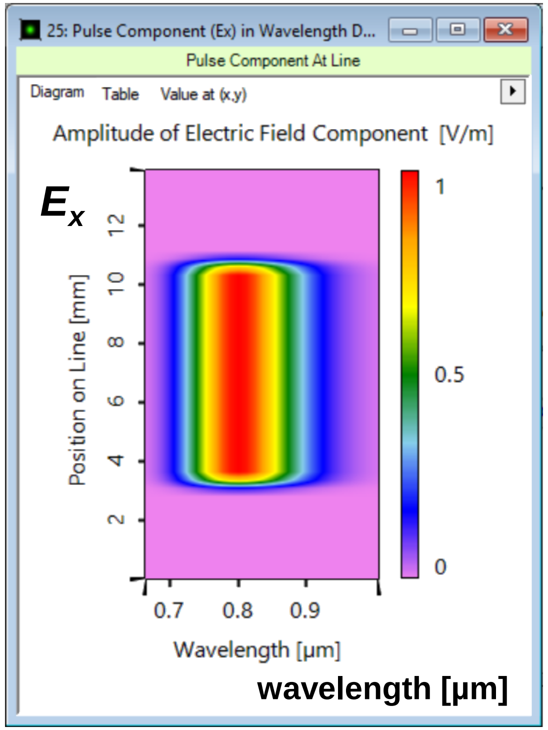
- time duration 10 fs (FWHM)
- carrier wavelength 800 nm
- beam diameter 7 mm
- linearly poalrized in *x* direction

Spectral and Temporal Amplitudes at Input Plane

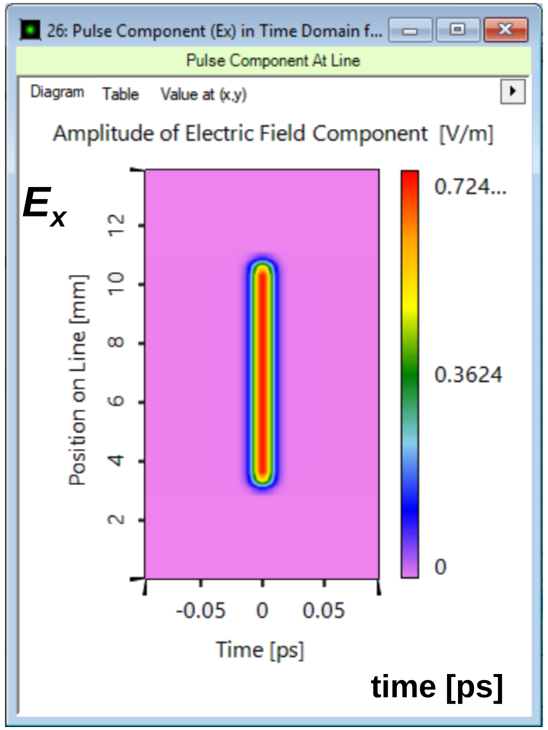


simulation time
~seconds

Spectral Amplitude

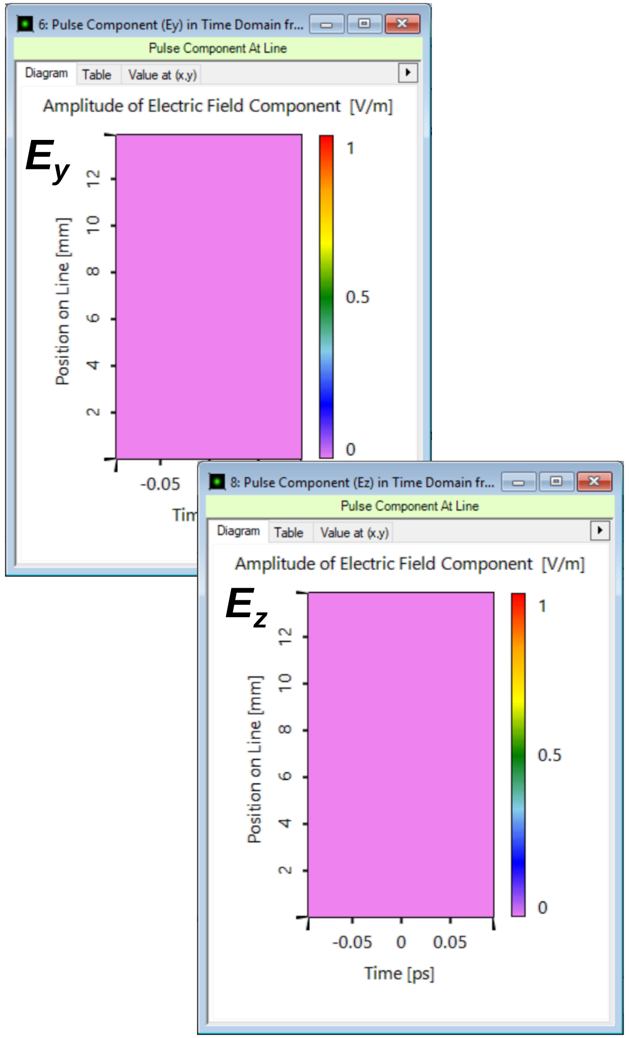


Temporal Amplitude

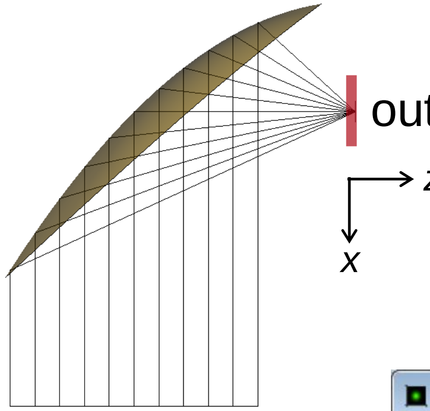


The linearly polarized input pulse has an E_y & E_z component with zero amplitude.

Temporal Amplitudes



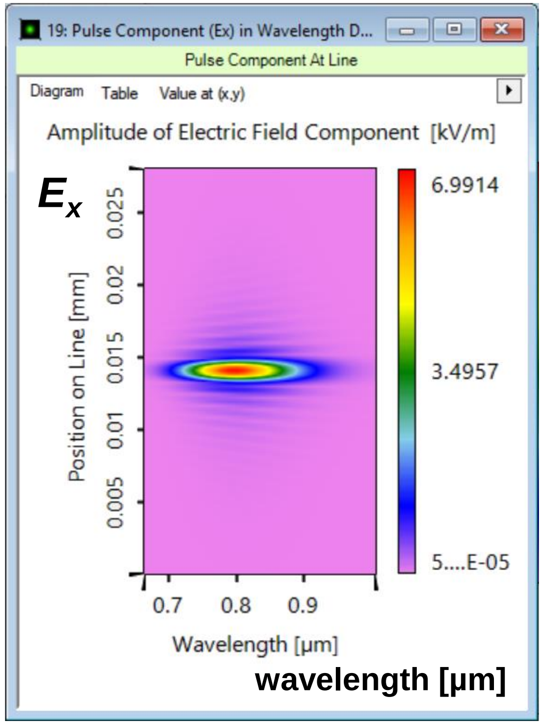
Spectral and Temporal Amplitudes at Output Plane



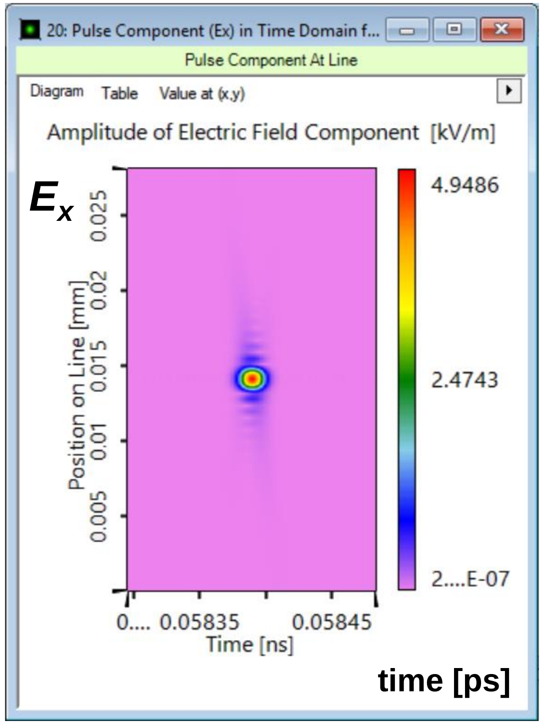
Non-zero E_y & E_z component appears due to polarization crosstalk in high-NA focusing situation.

simulation time ~seconds

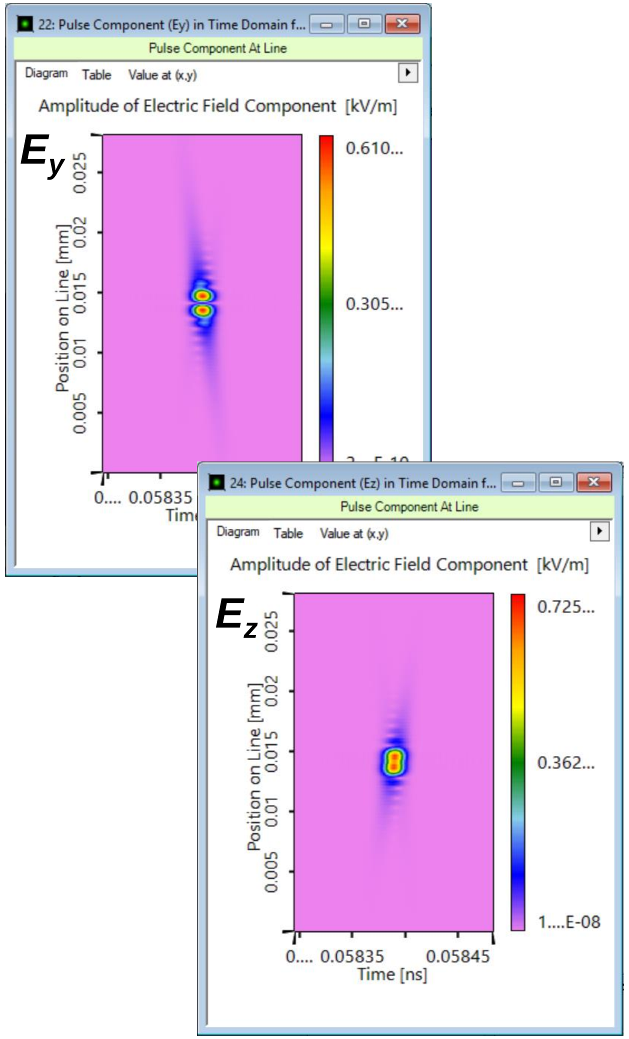
Spectral Amplitude



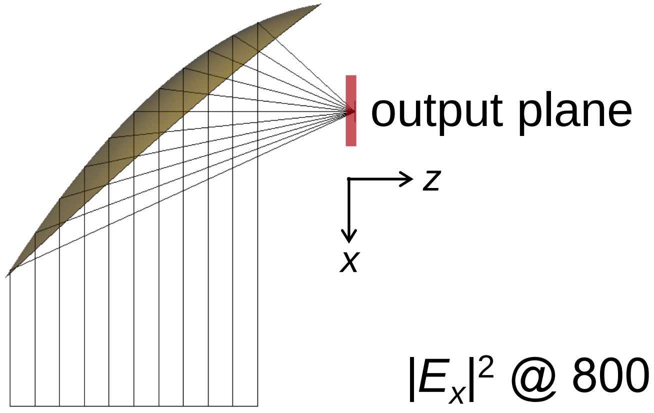
Temporal Amplitude



Temporal Amplitudes

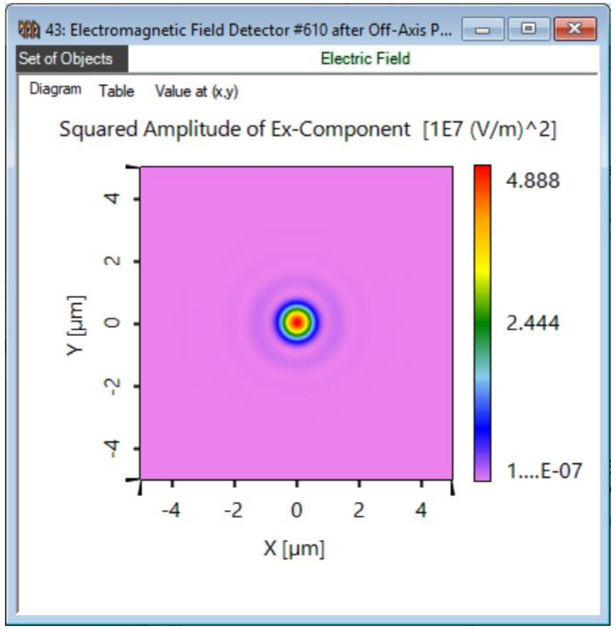


Spatial Distribution at Output Plane

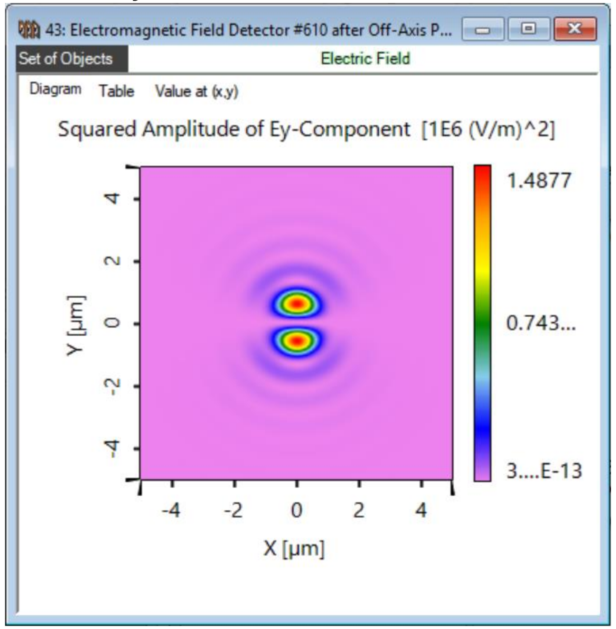


Spatial Distribution

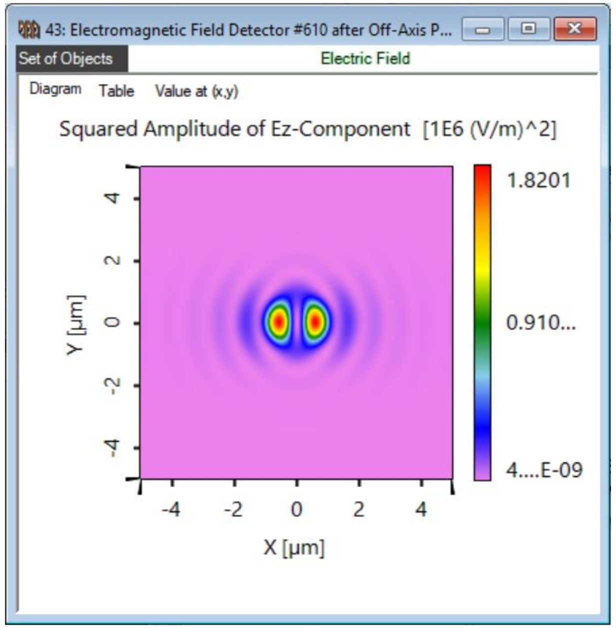
$|E_x|^2$ @ 800 nm $\stackrel{\text{def}}{=}$ 100%



$|E_y|^2$ @ 800 nm = 3%

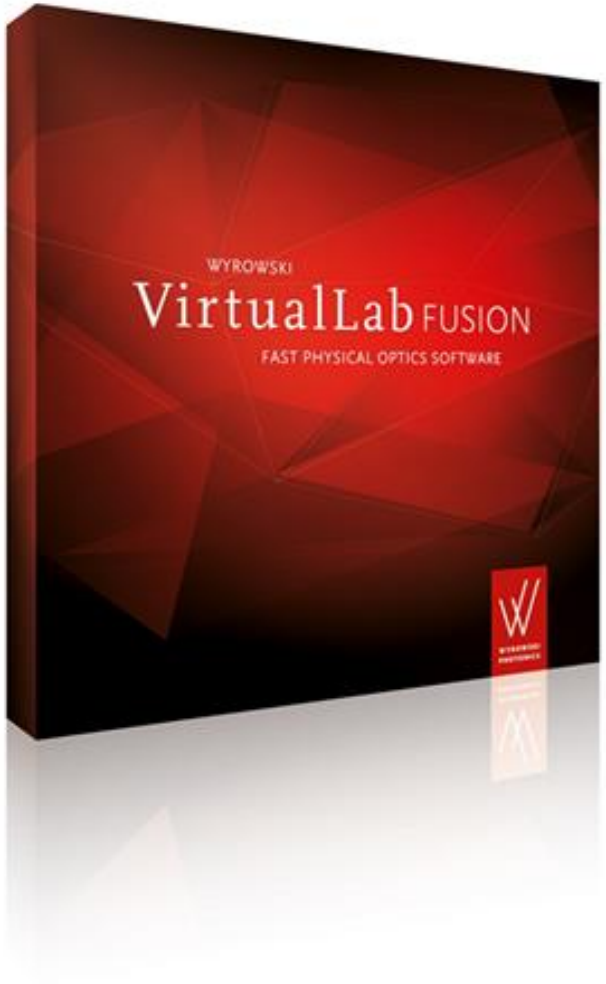


$|E_z|^2$ @ 800 nm = 4%



Summary

- Fast physical optics is as fast as ray tracing (geometric zones of a system)
- Fast physical optics enables numerous innovative solutions in light shaping.
- All examples in talk were provided by **VirtualLab Fusion software**.
- **LightTrans International:** Consulting and Engineering Services



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