Santa Clara, CA, USA

Introduction to VirtualLab Fusion

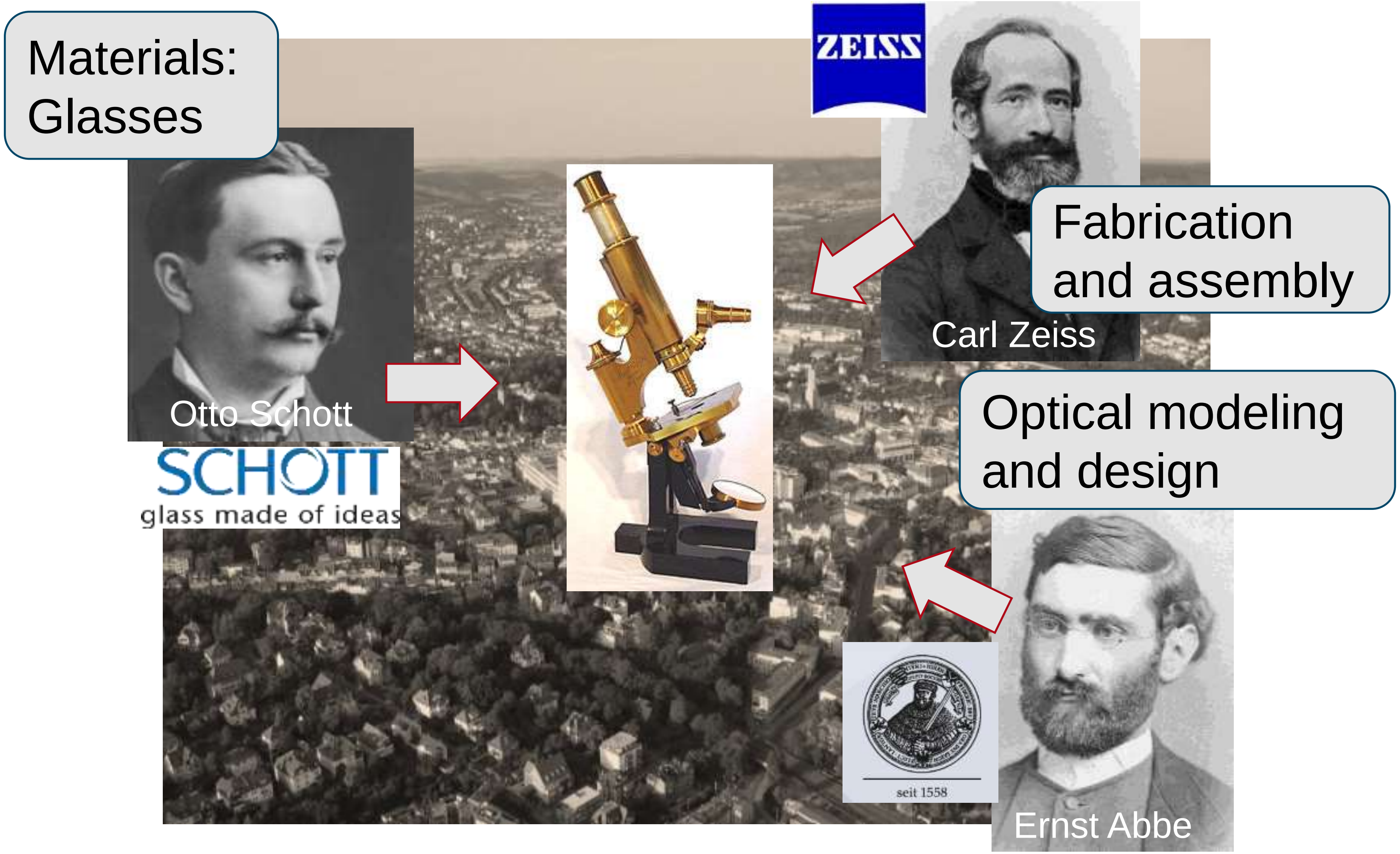
Speaker: Huiying Zhong
LightTrans International UG

Jena, Germany

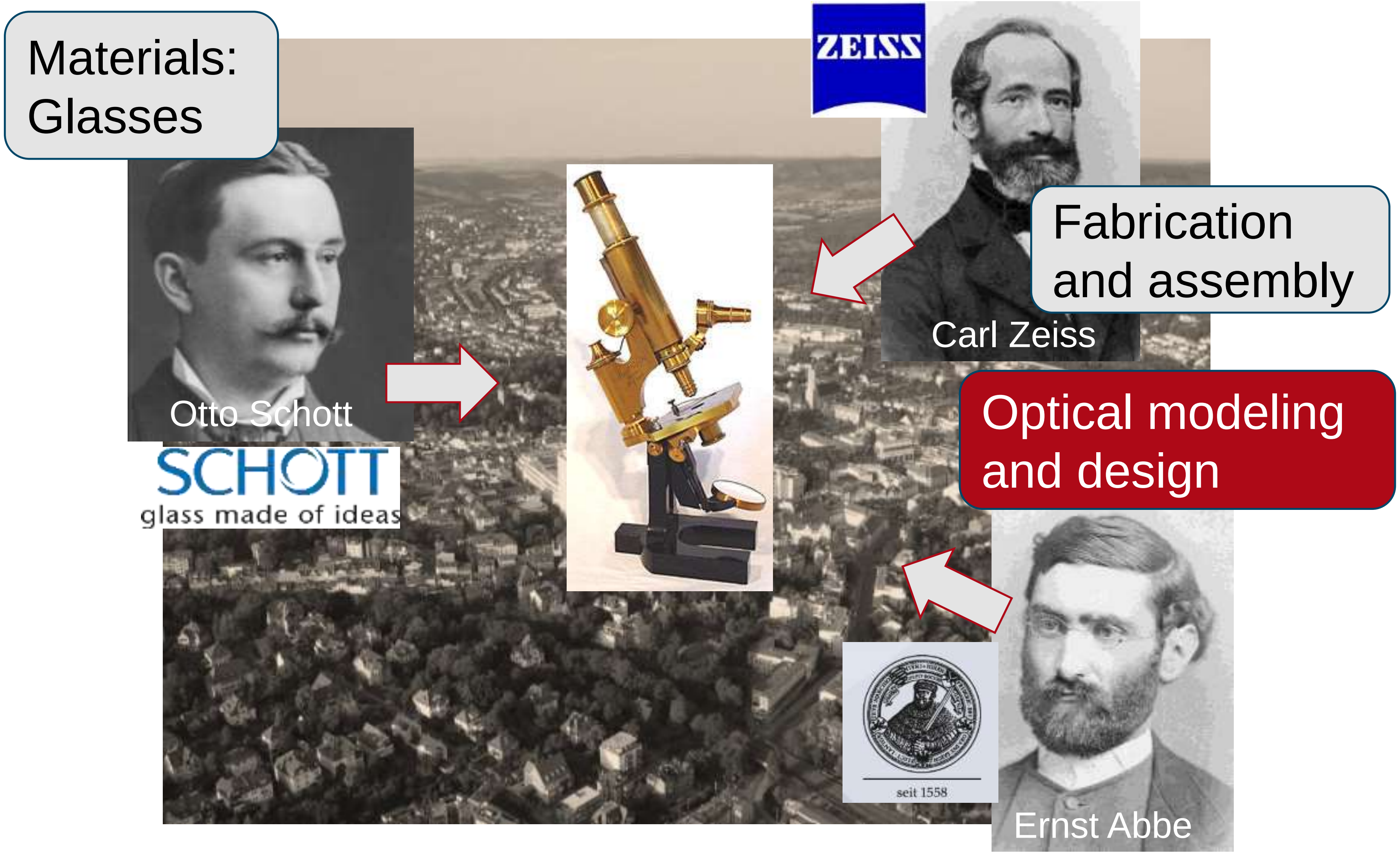
Jena, Germany

Prof. Frank Wyrowski

Jena, Germany – The Beginning (1866-)



Jena, Germany – The Beginning (1866-)



In the Tradition of Ernst Abbe: Next Generation Optical Design

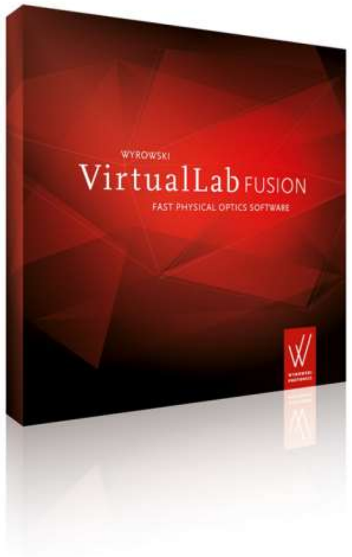
Next generation optical modeling and design by paradigm shift to **physical optics for real-world applications**.

University of Jena

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

Wyrowski Photonics

Wyrowski Photonics
Development of fast physical optics software VirtualLab Fusion

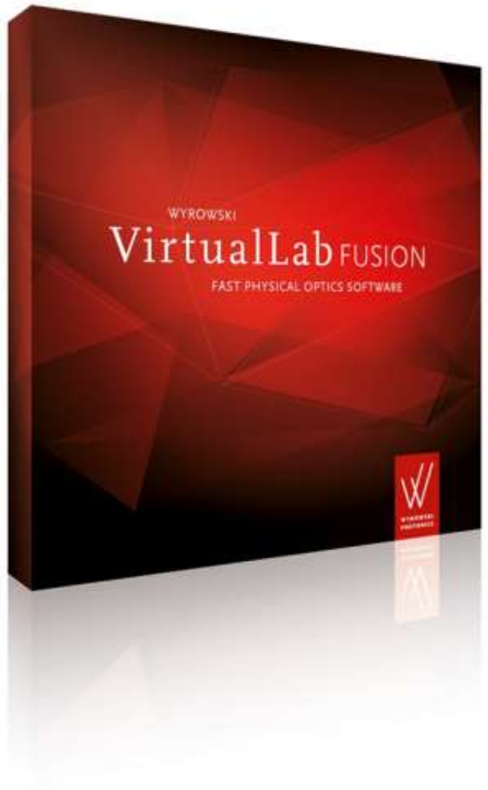


LightTrans International

LightTrans

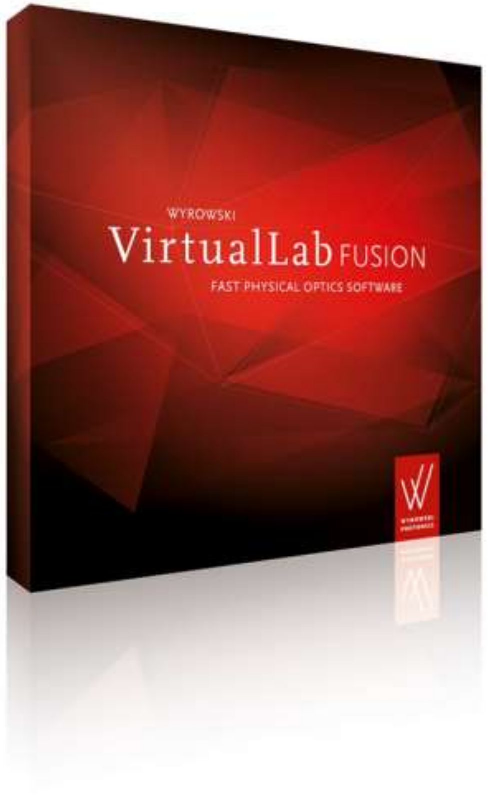
- Distribution of VirtualLab Fusion, together with distributors worldwide
- Technical support, seminars, and trainings
- Engineering projects

Optical Design Software and Services



VirtualLab Fusion

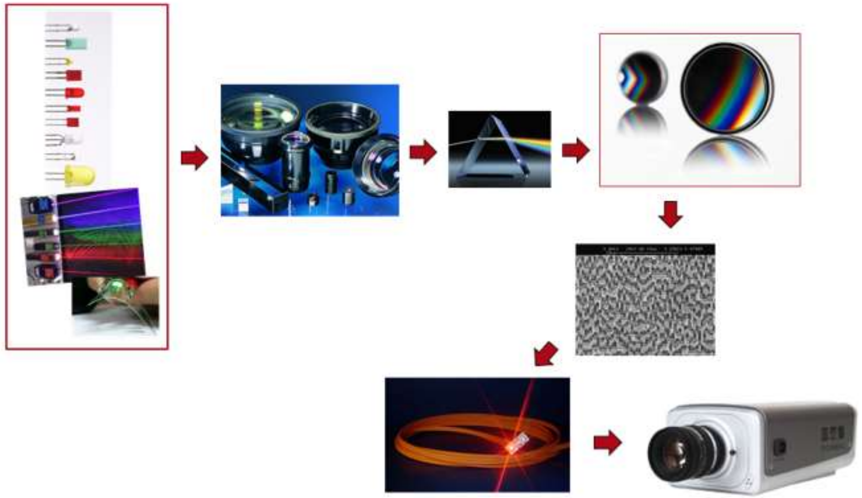
The idea behind it



VirtualLab Fusion

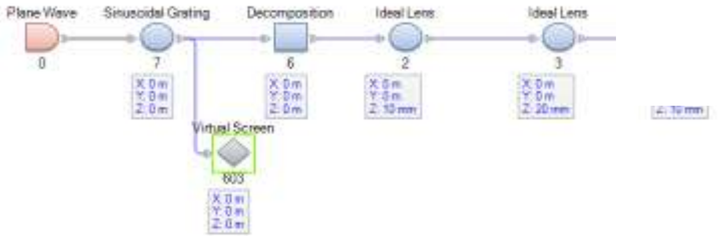
The idea behind it

VirtualLab Fusion (VLF)



Pictures from http://de.wikipedia.org/

From
real lab
to
virtual lab
(VirtualLab)



VirtualLab Fusion (VLF)

- Why Fusion? (Reason #1)
  - Ray tracing
  - Physical optics modeling: Field tracing

Pierre de Fermat

Light representation: **Rays**
Equations: **Fermat's principle**

Light representation by rays provides ray positions, directions, and **optical path/wavefront phase.**

James Clerk Maxwell

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Equations: **Maxwell's equations**

Light representation by fields enables access to any information about light, including ray information.

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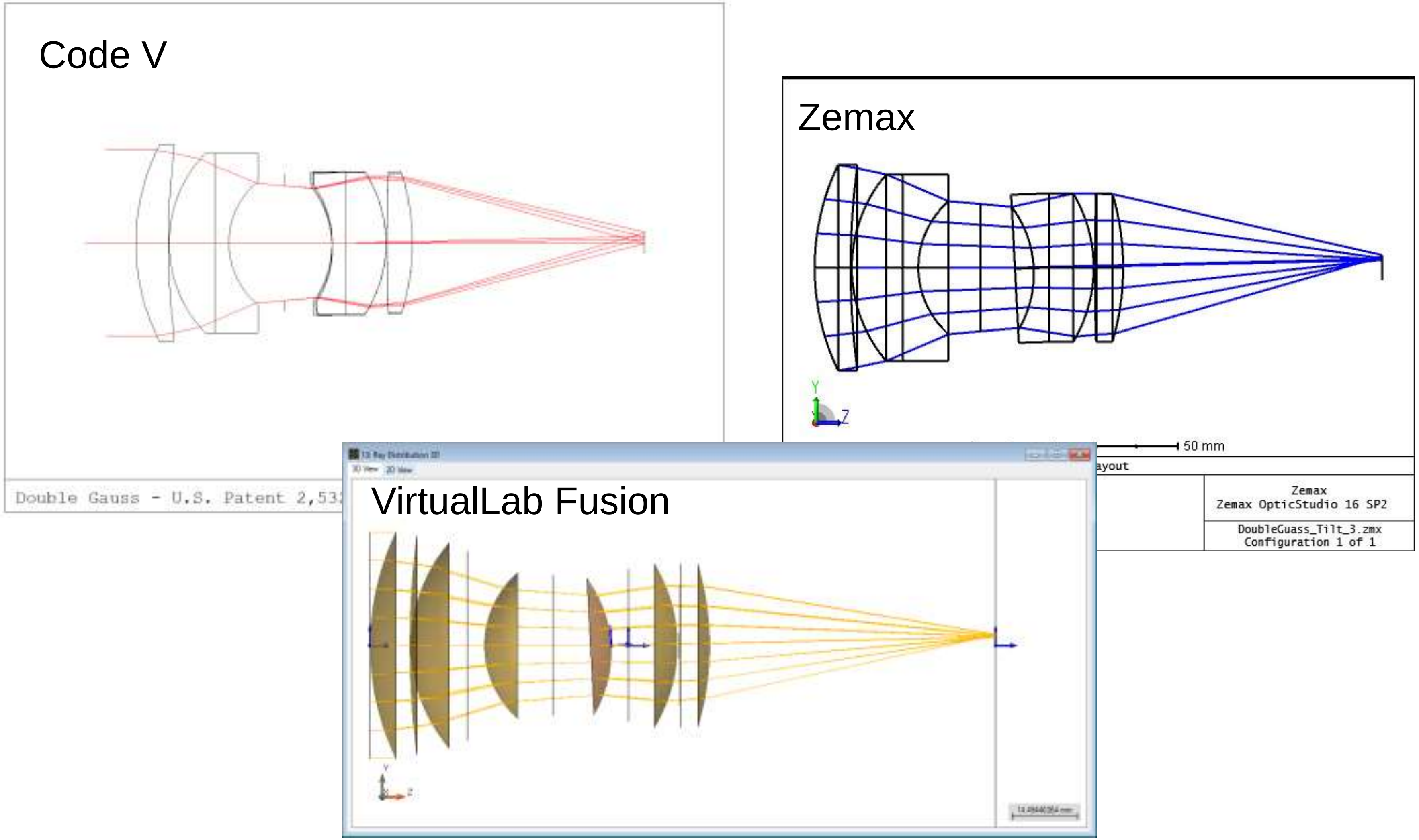
Study

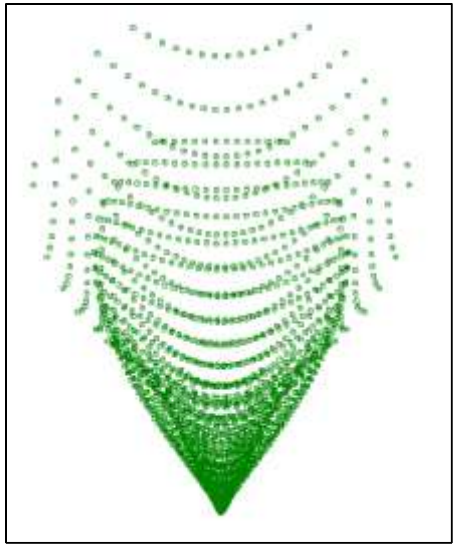
Ray Tracing Engine Comparison: VLF vs. Code V vs. Zemax

Zongzhao Wang, Tingcheng Zhang and Irfan Badar
Date: 2017, Dec, 31th
Applied Computational Optics Group, Jena
China Aerospace Science and Technology (CAST) Corporation

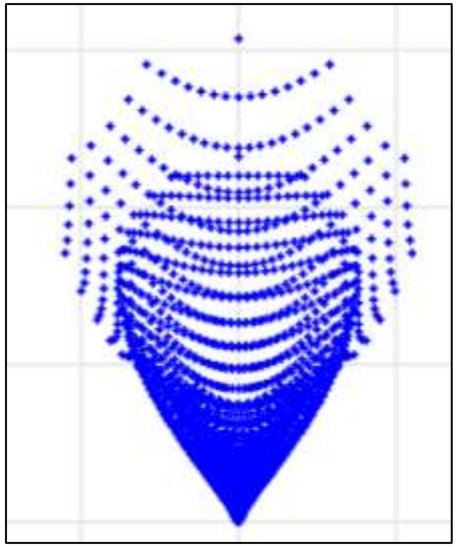
System Illustration



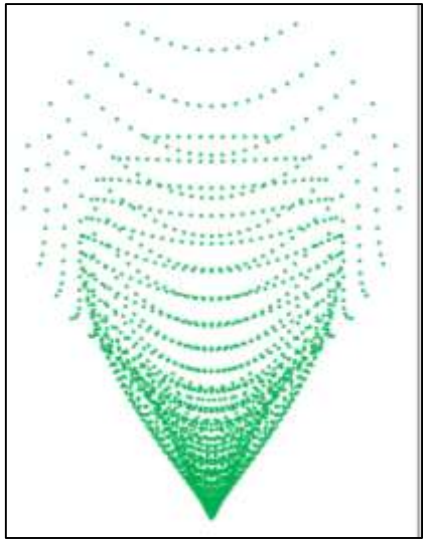
Dot Diagram Comparison: Target Plane



Code V



Zemax



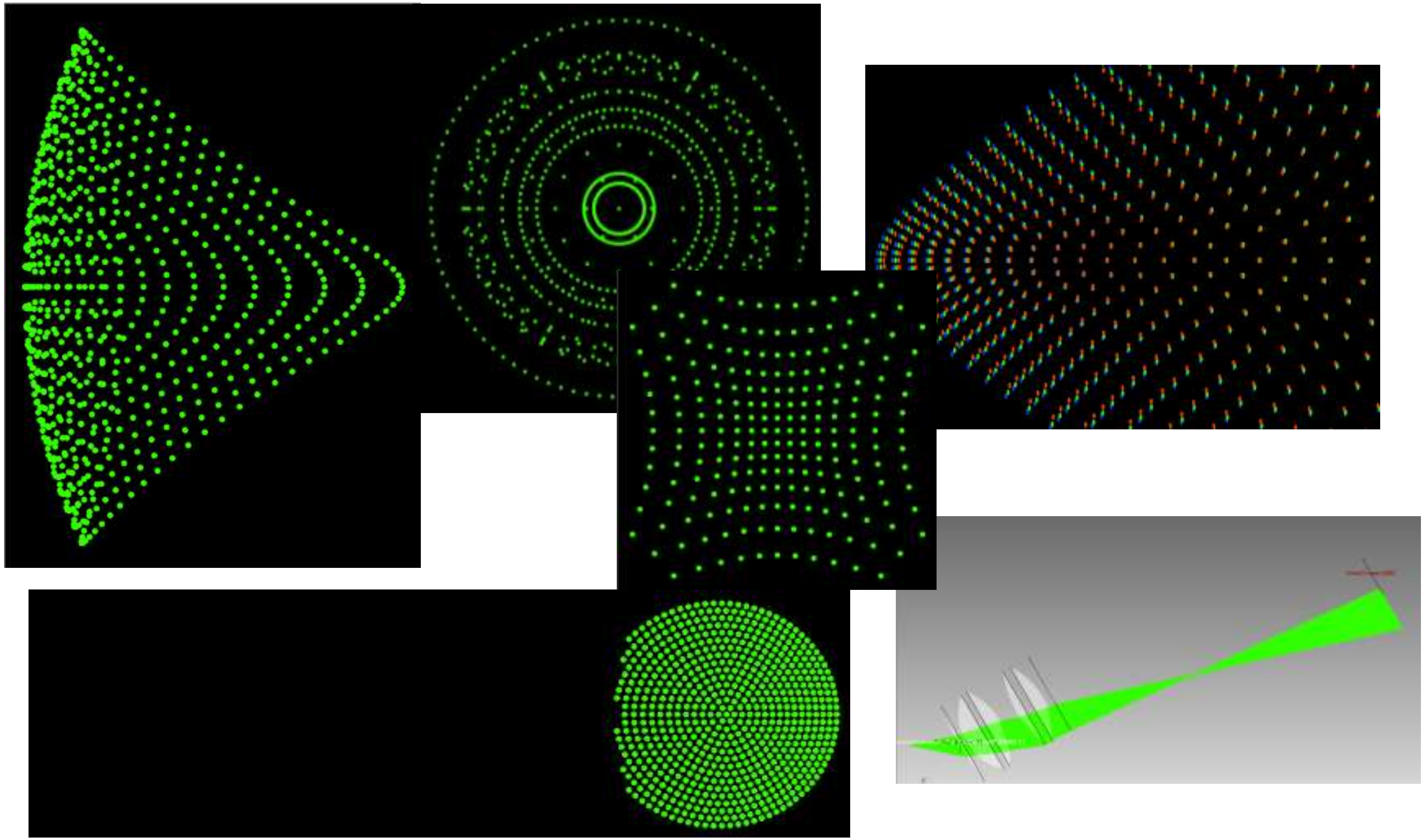
VirtualLab

Precise Comparison: Position

Ray position at initial plane			
No.	Lateral coordinates	No.	Lateral coordinates
1	(0, 15 mm)	4	(0, 7.5 mm)
2	(0, -15 mm)	5	(0, -7.5 mm)
3	(7.5 mm, 7.5 mm)	6	(7.5 mm, -7.5 mm)

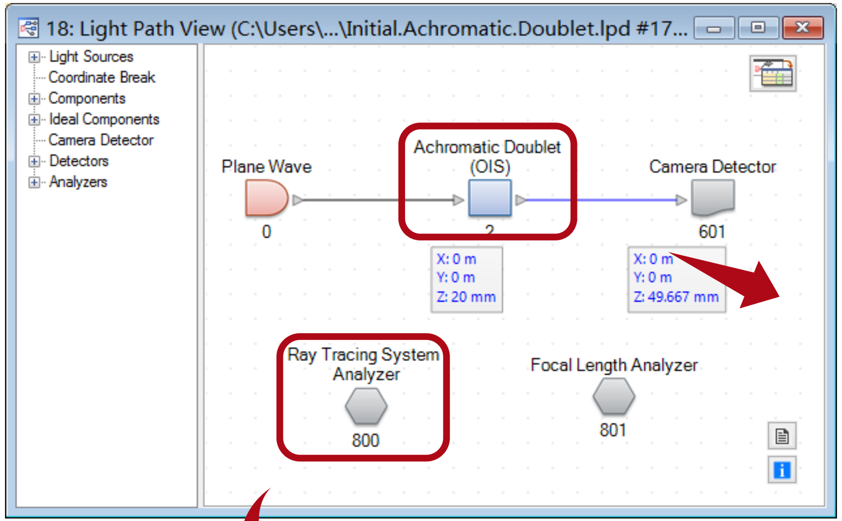
Ray position at imaging plane			
No.	VLF	Code V	Zemax
1	(0, 2.1524 mm)	(0, 2.1524 mm)	(0, 2.1524 mm)
2	(0, 2.1536 mm)	(0, 2.1536 mm)	(0, 2.1536 mm)
3	(52.07 µm, 1.927 mm)	(52.07 µm, 1.927 mm)	(52.07 µm, 1.927 mm)
4	(0, 1.905 mm)	(0, 1.905 mm)	(0, 1.905 mm)
5	(0, 1.8825 mm)	(0, 1.8825 mm)	(0, 1.8825 mm)
6	(-56.77 µm, 1.9162 mm)	(56.77 µm, 1.9162 mm)	(56.77 µm, 1.9162 mm)

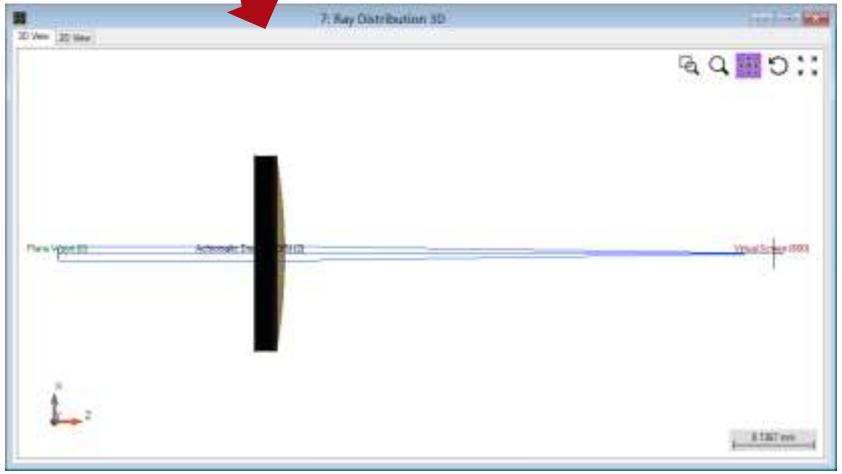
Aberration Theory

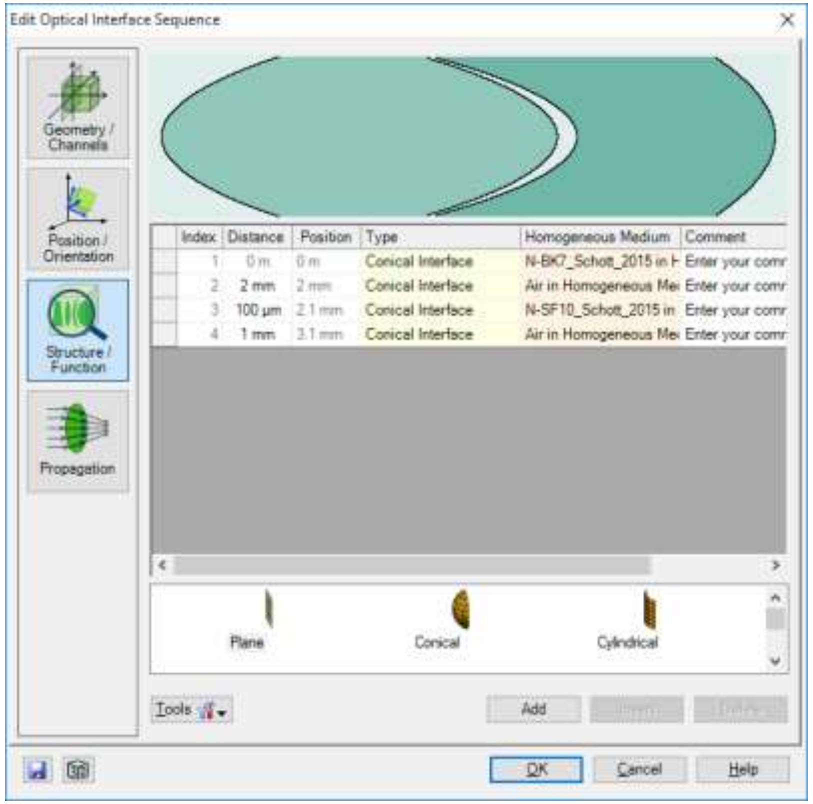


Example: Parametric optimization of an achromatic doublet

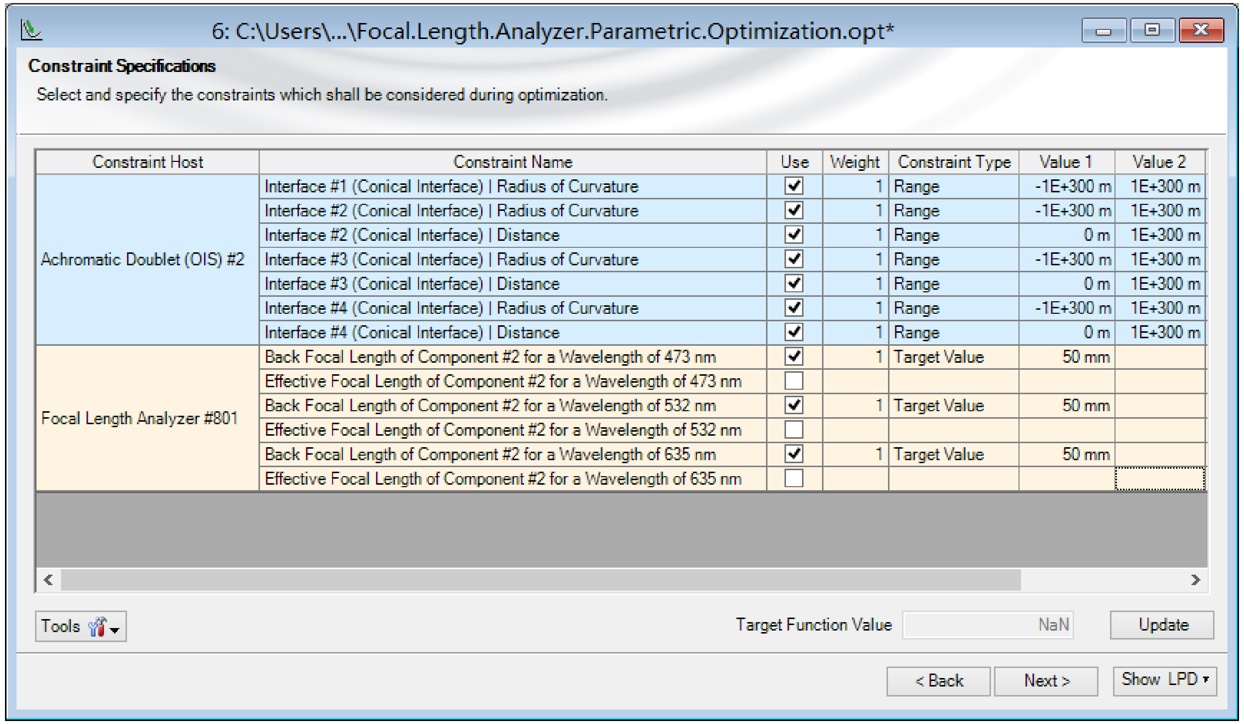
Schematic and Optical Setup





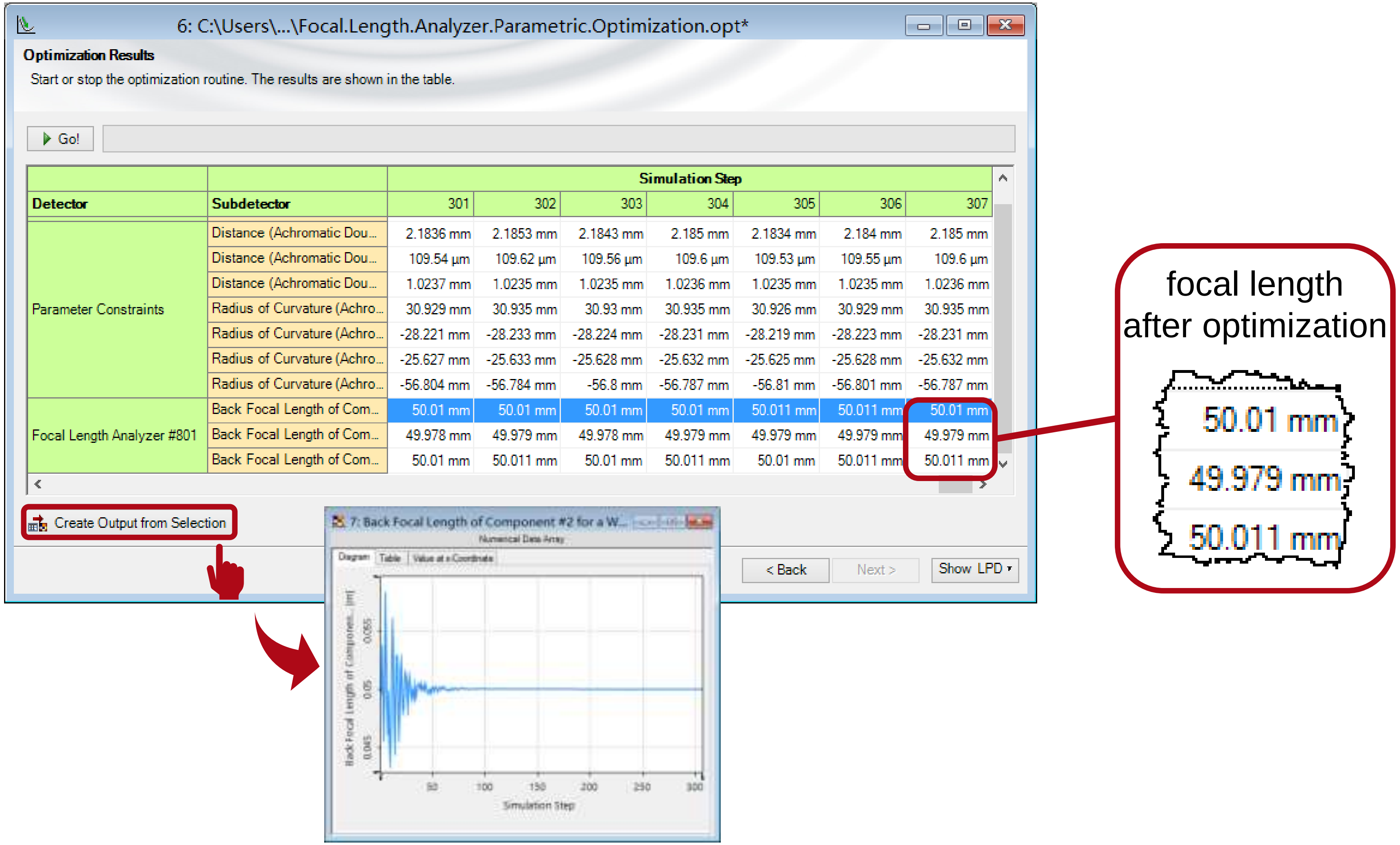


Set Optimization Target



- Focal Length Analyzer
  - Effective Focal Length is set to 50 mm: for all chosen wavelengths

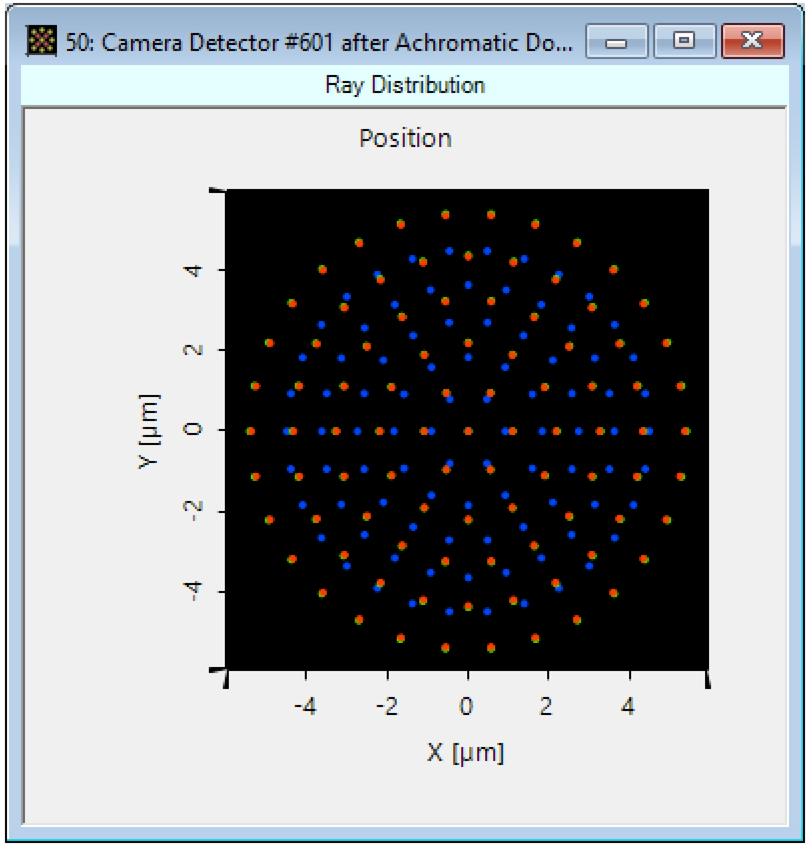
Optimization Result



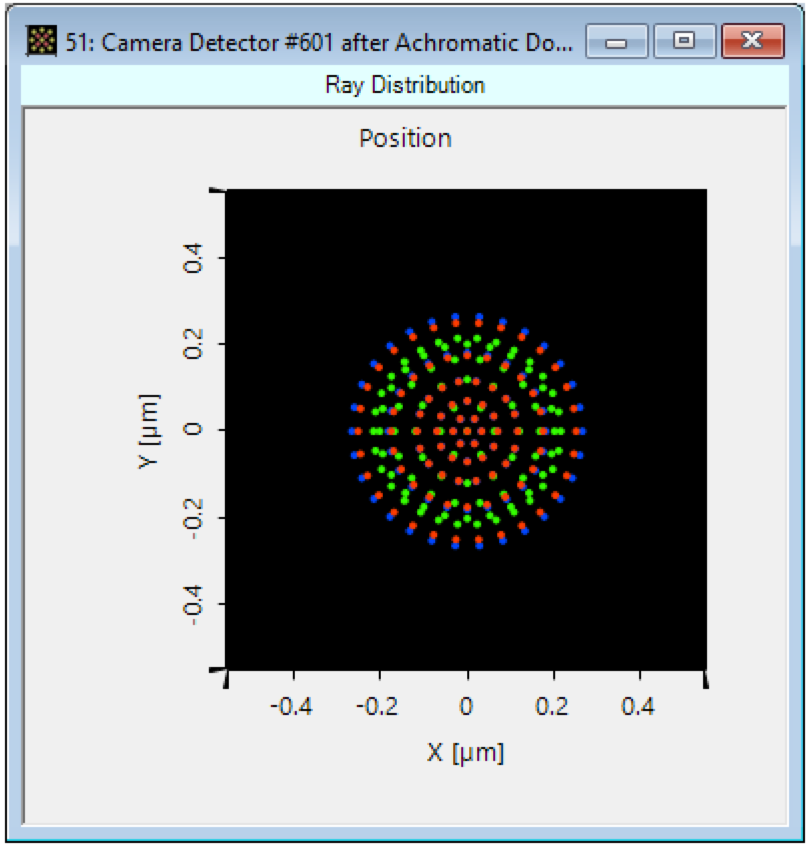
Detector	Subdetector	Simulation Step 301	302	303	304	305	306	307
Parameter Constraints	Distance (Achromatic Dou...	2.1836 mm	2.1853 mm	2.1843 mm	2.185 mm	2.1834 mm	2.184 mm	2.185 mm
	Distance (Achromatic Dou...	109.54 µm	109.62 µm	109.56 µm	109.6 µm	109.53 µm	109.55 µm	109.6 µm
	Distance (Achromatic Dou...	1.0237 mm	1.0235 mm	1.0235 mm	1.0236 mm	1.0235 mm	1.0235 mm	1.0236 mm
	Radius of Curvature (Achro...	30.929 mm	30.935 mm	30.93 mm	30.935 mm	30.926 mm	30.929 mm	30.935 mm
	Radius of Curvature (Achro...	-28.221 mm	-28.233 mm	-28.224 mm	-28.231 mm	-28.219 mm	-28.223 mm	-28.231 mm
	Radius of Curvature (Achro...	-25.627 mm	-25.633 mm	-25.628 mm	-25.632 mm	-25.625 mm	-25.628 mm	-25.632 mm
	Radius of Curvature (Achro...	-56.804 mm	-56.784 mm	-56.8 mm	-56.787 mm	-56.81 mm	-56.801 mm	-56.787 mm
Focal Length Analyzer #801	Back Focal Length of Com...	50.01 mm	50.01 mm	50.01 mm	50.01 mm	50.011 mm	50.011 mm	50.01 mm
	Back Focal Length of Com...	49.978 mm	49.979 mm	49.978 mm	49.979 mm	49.979 mm	49.979 mm	49.979 mm
	Back Focal Length of Com...	50.01 mm	50.011 mm	50.01 mm	50.011 mm	50.01 mm	50.011 mm	50.011 mm

Comparison of Results

Dot Diagram (initial setup)



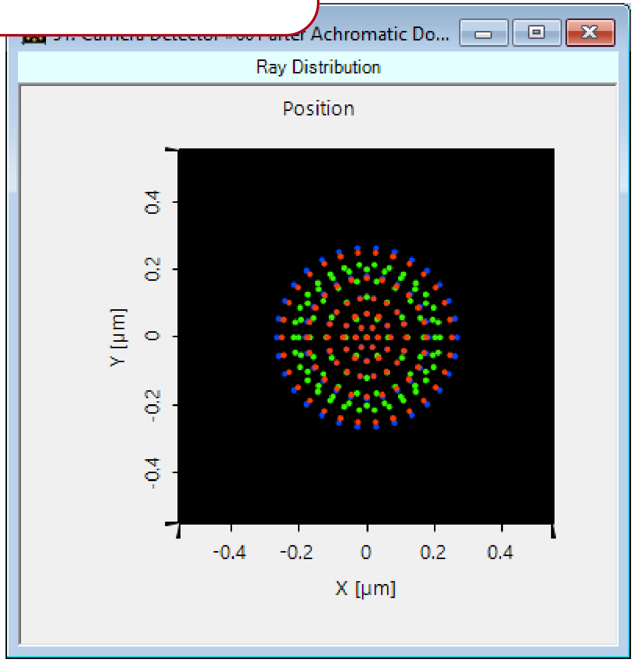
Dot Diagram (optimized)



Ray Tracing in VirtualLab Fusion

- Ray tracing engine is included
- Sequential and non-sequential in the same
- Comment: No CAD system description yet
- More to come within next 12 months to support typical lens designer workflows

We will come to this point later!!!



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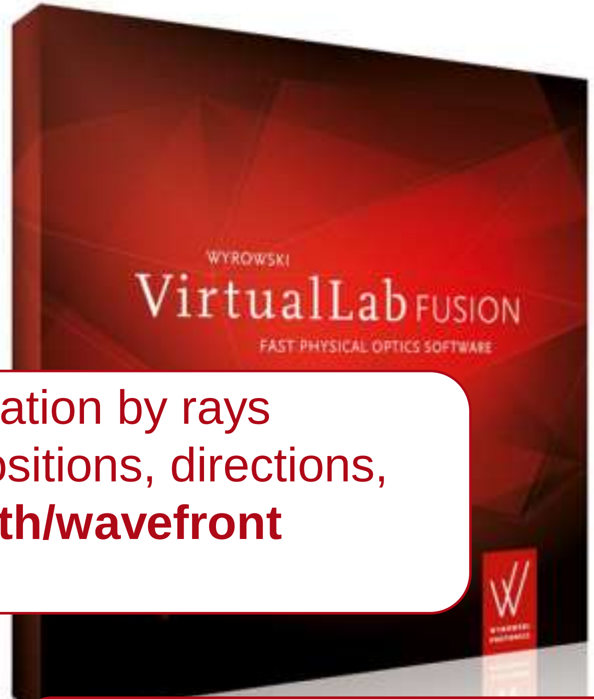

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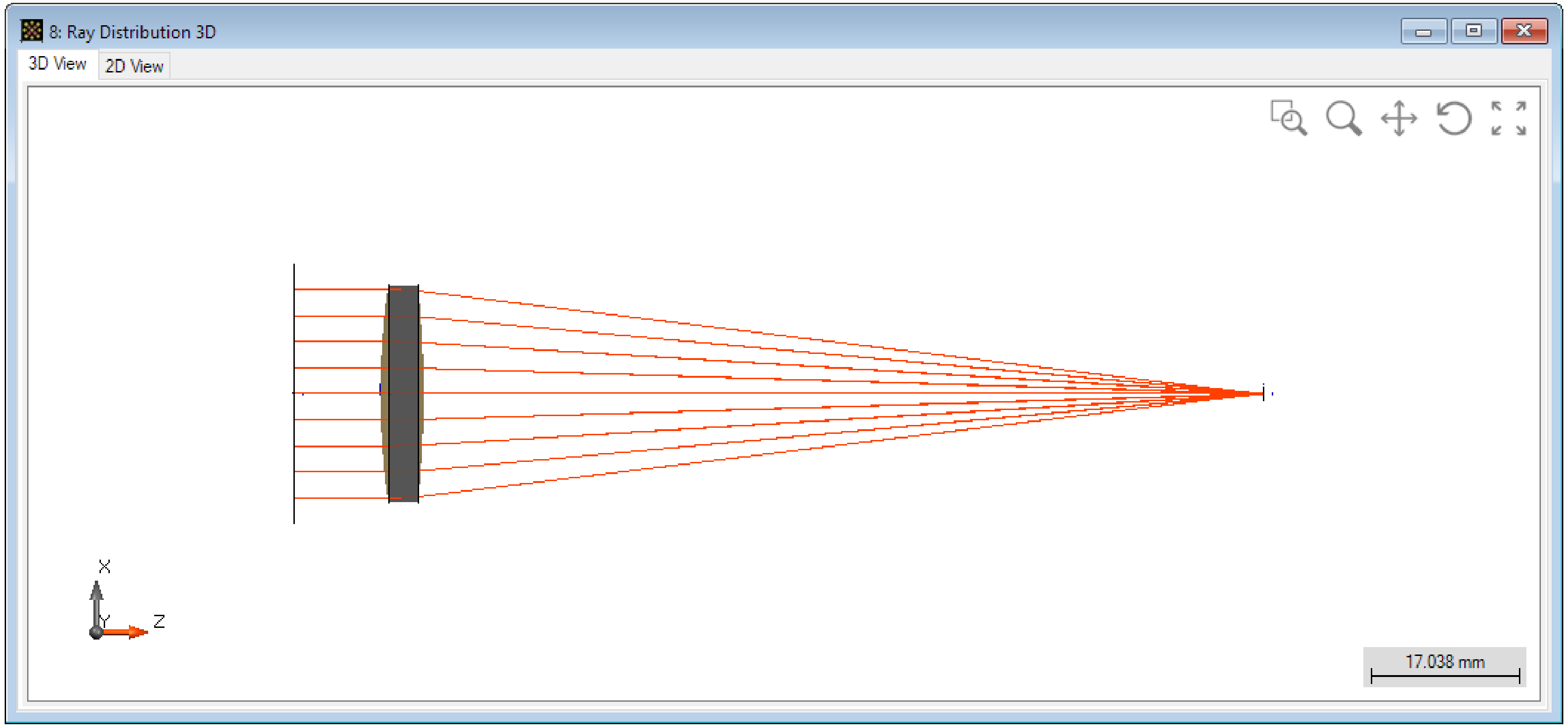
Example: Singlet

Task 5

- Design of singlet with 100 mm back focal length by ray tracing in VirtualLab.



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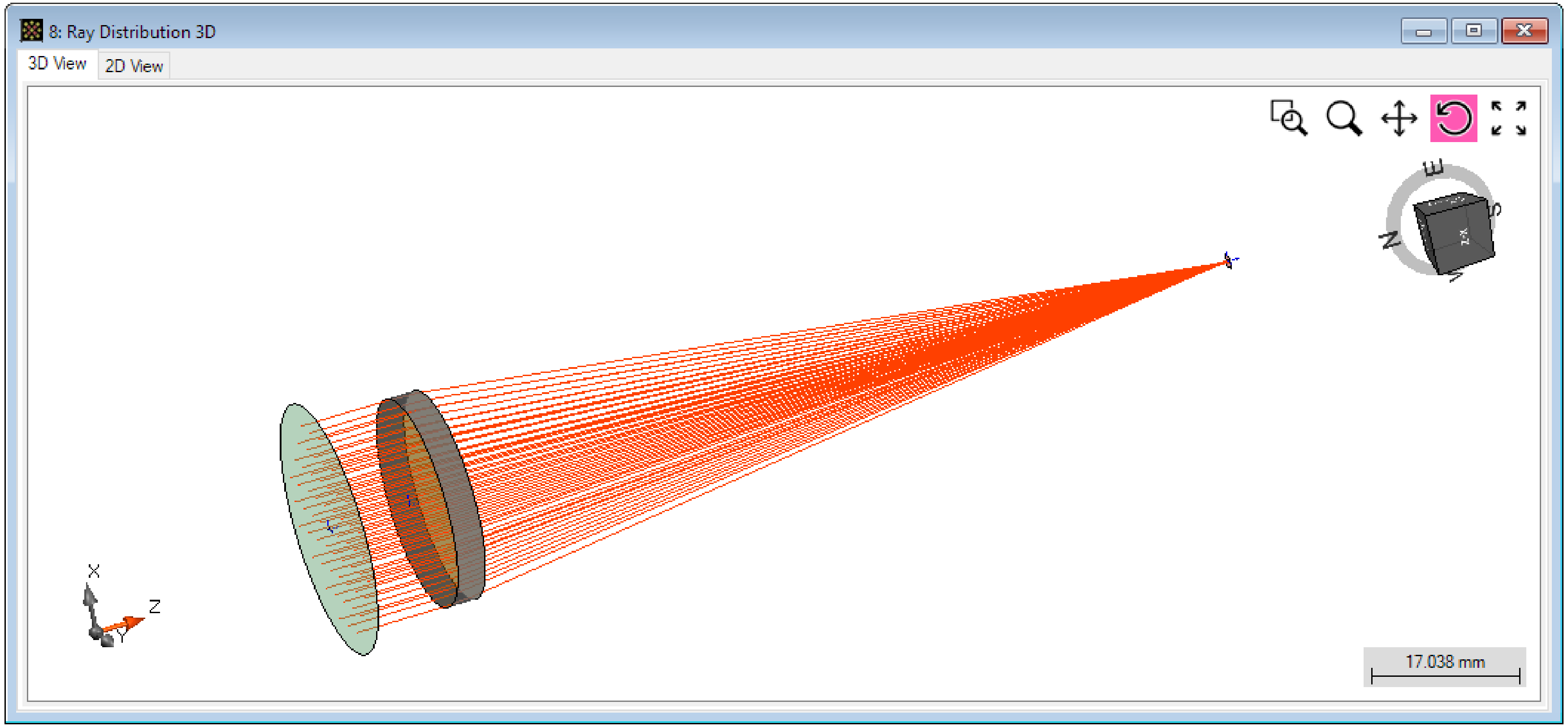
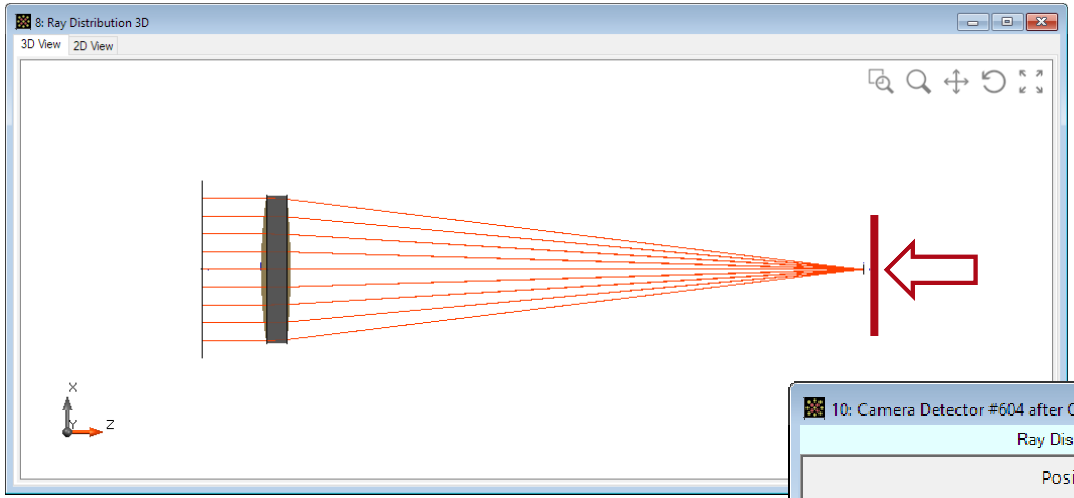
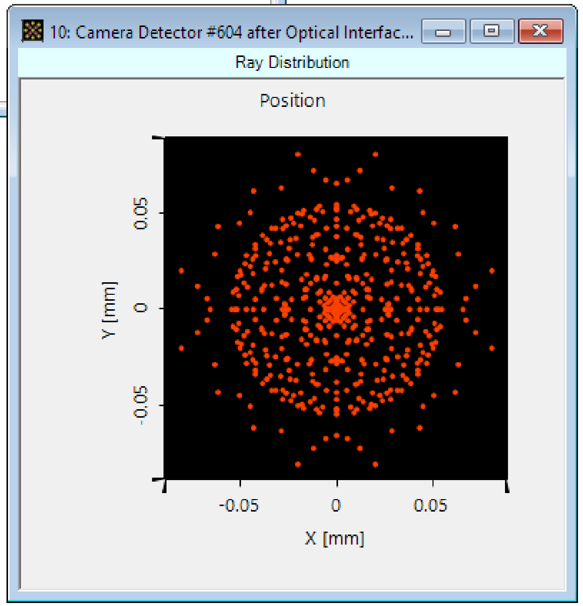
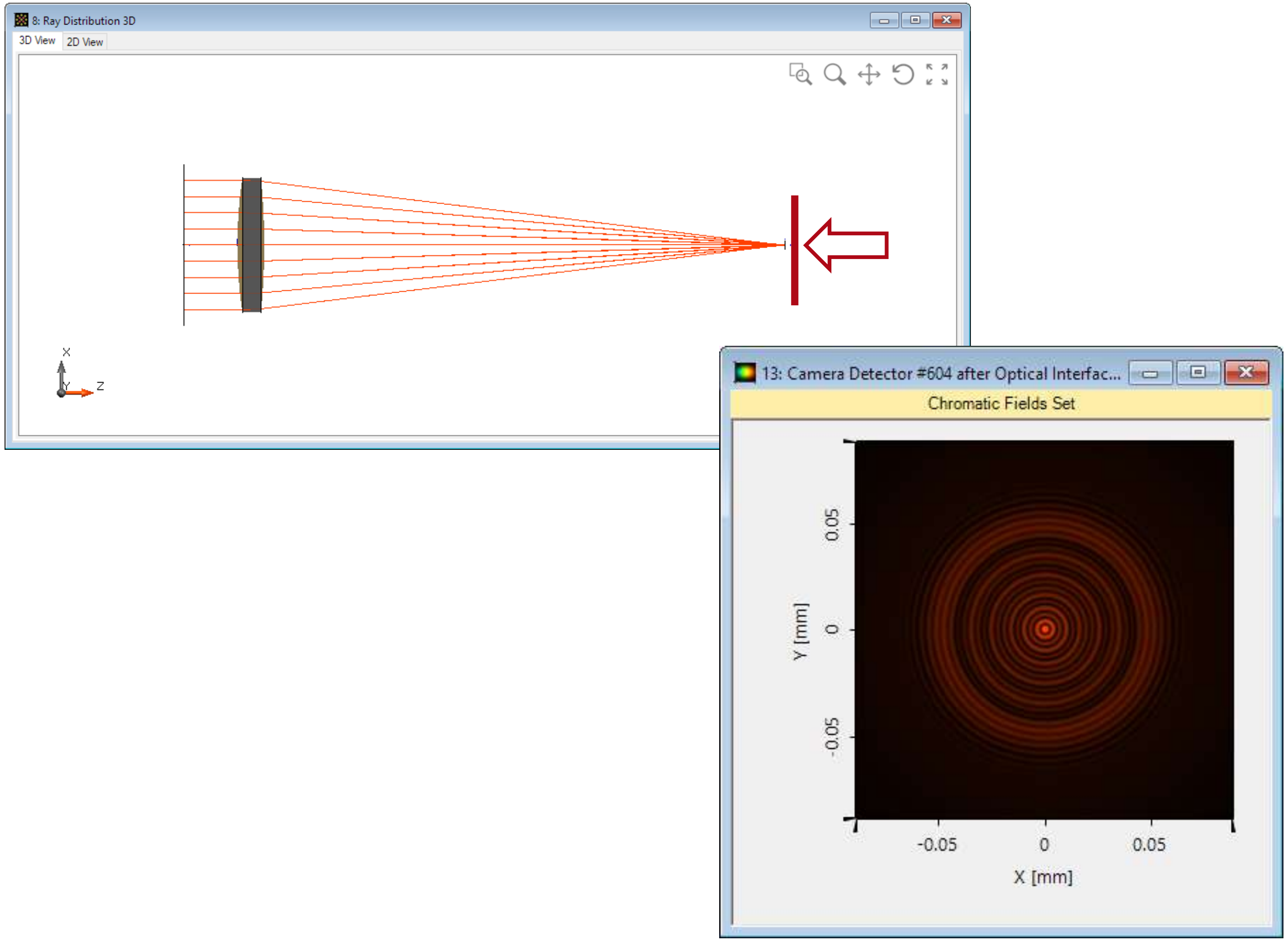


Ray Tracing: Dot Diagram





Physical Optics: Intensity



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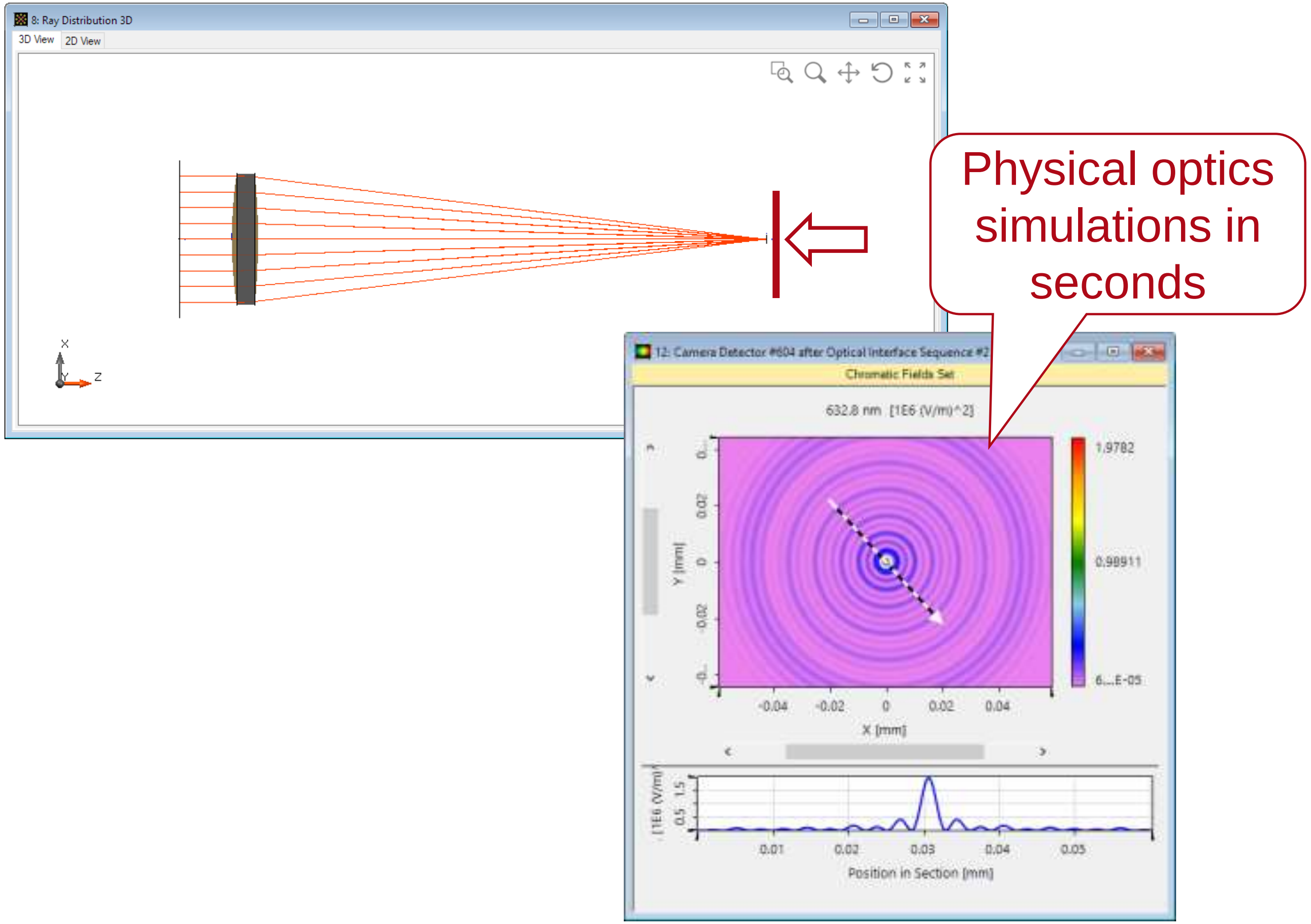
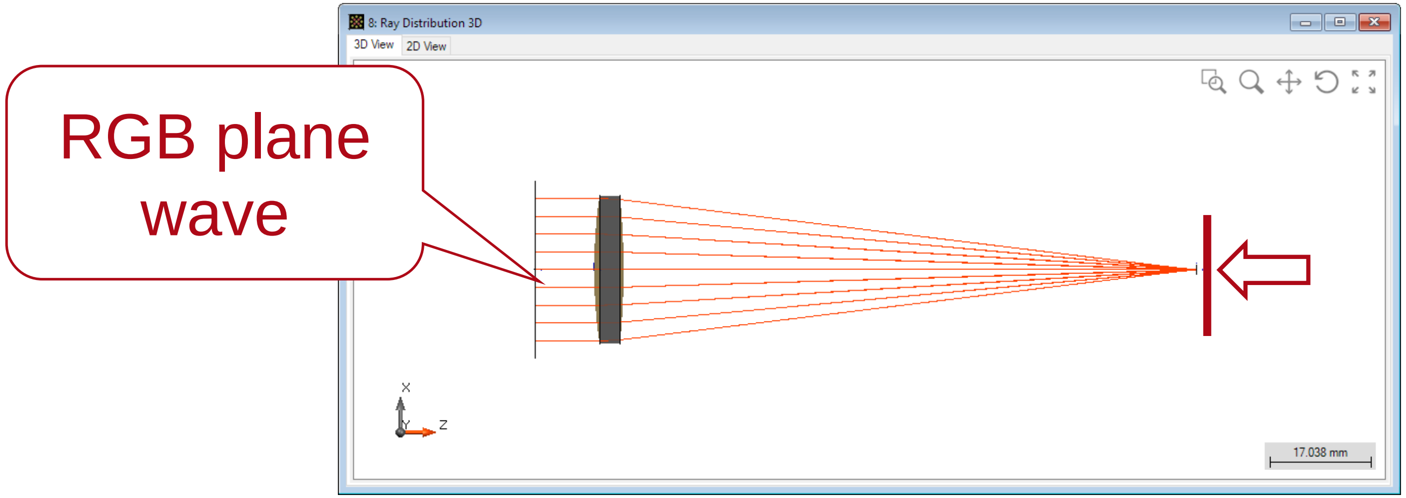


Ray Tracing: Dot Diagram



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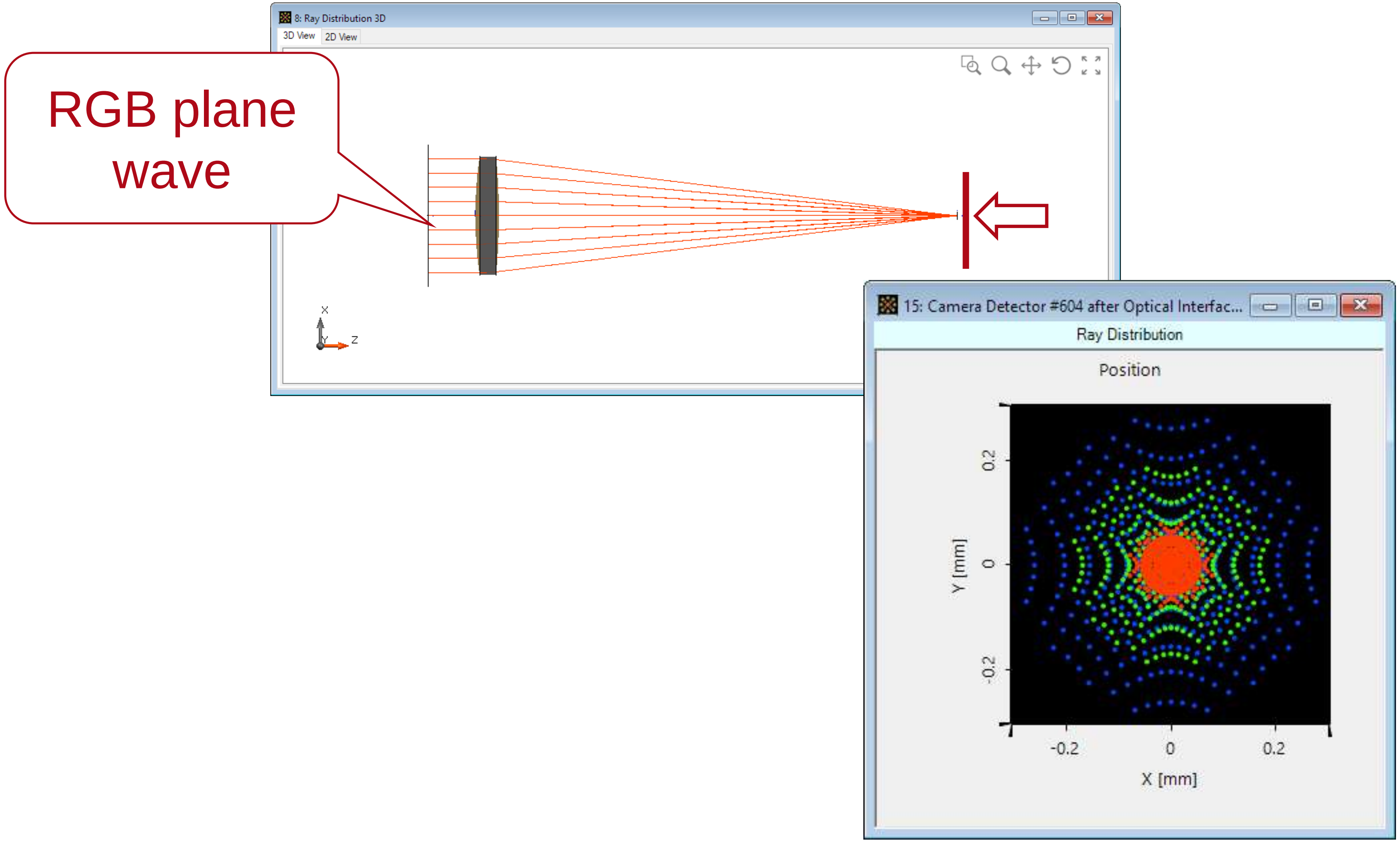

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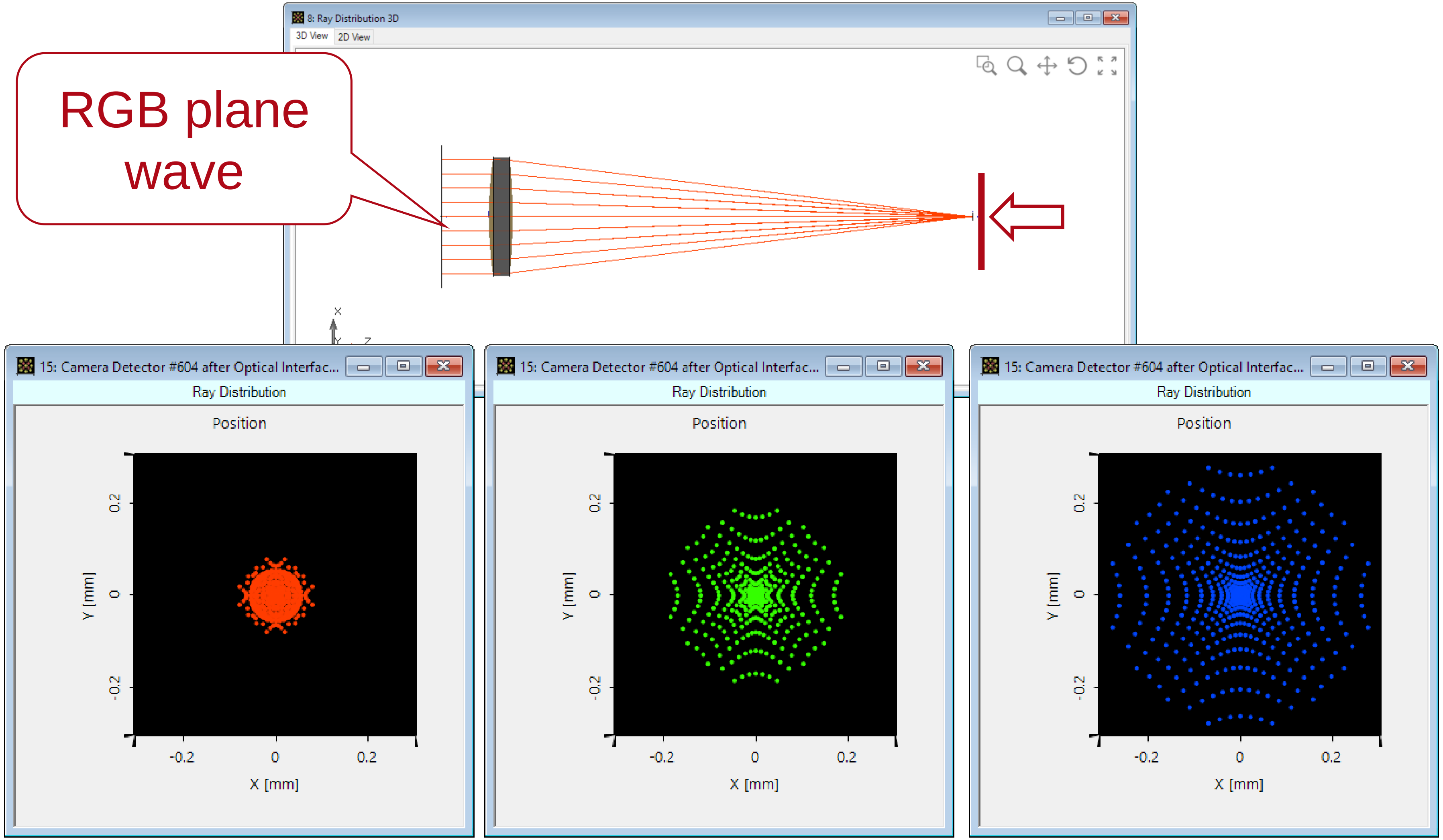

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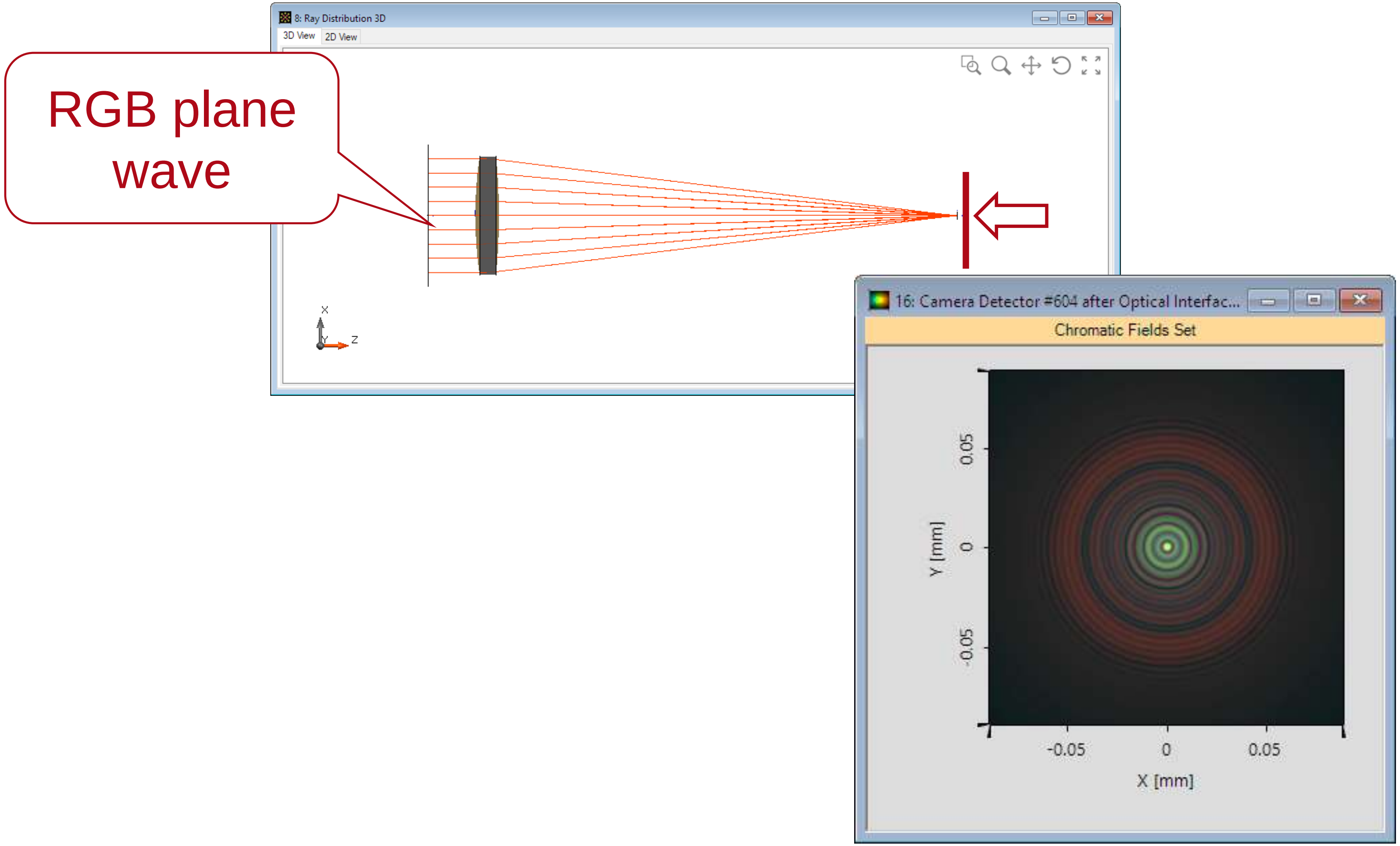
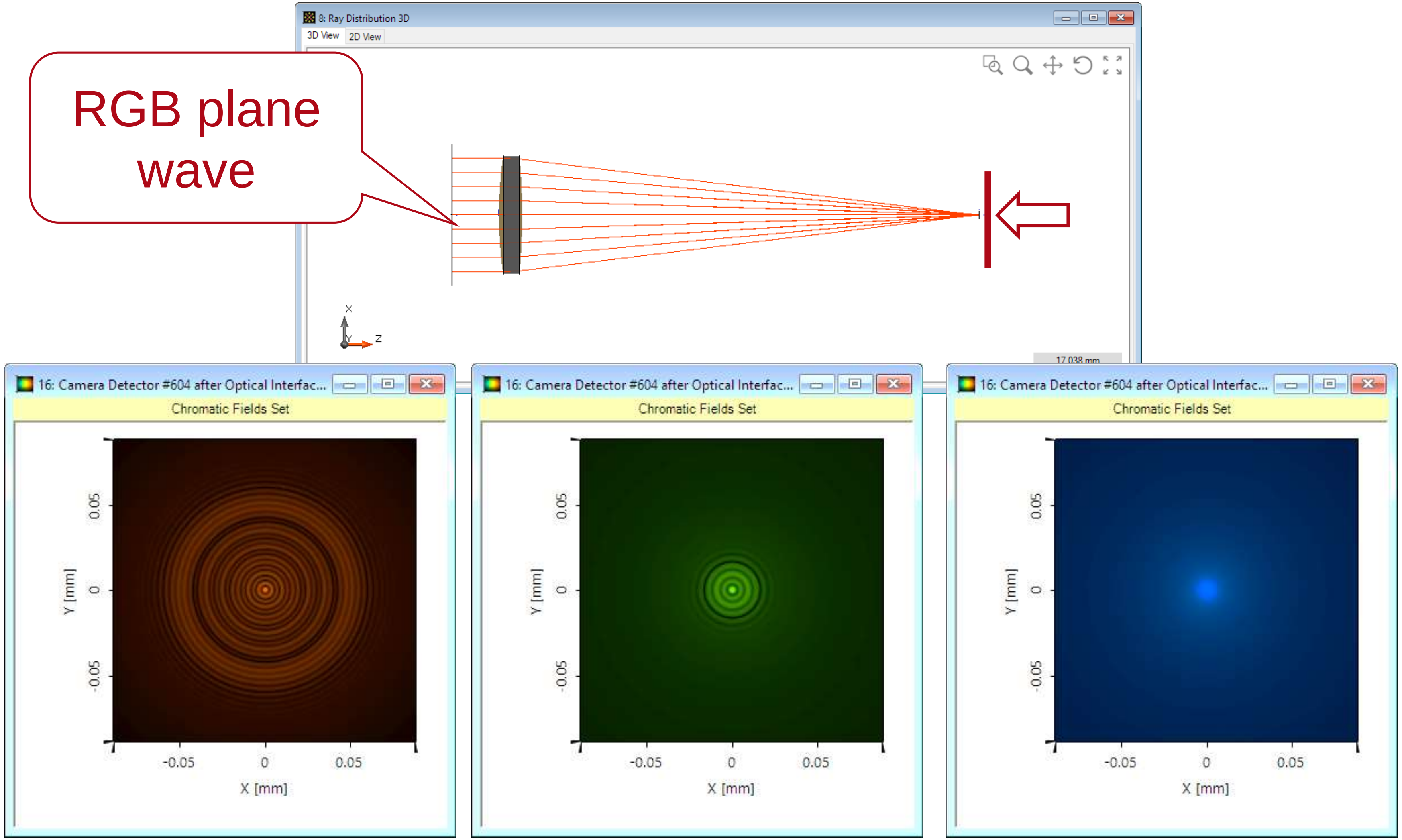
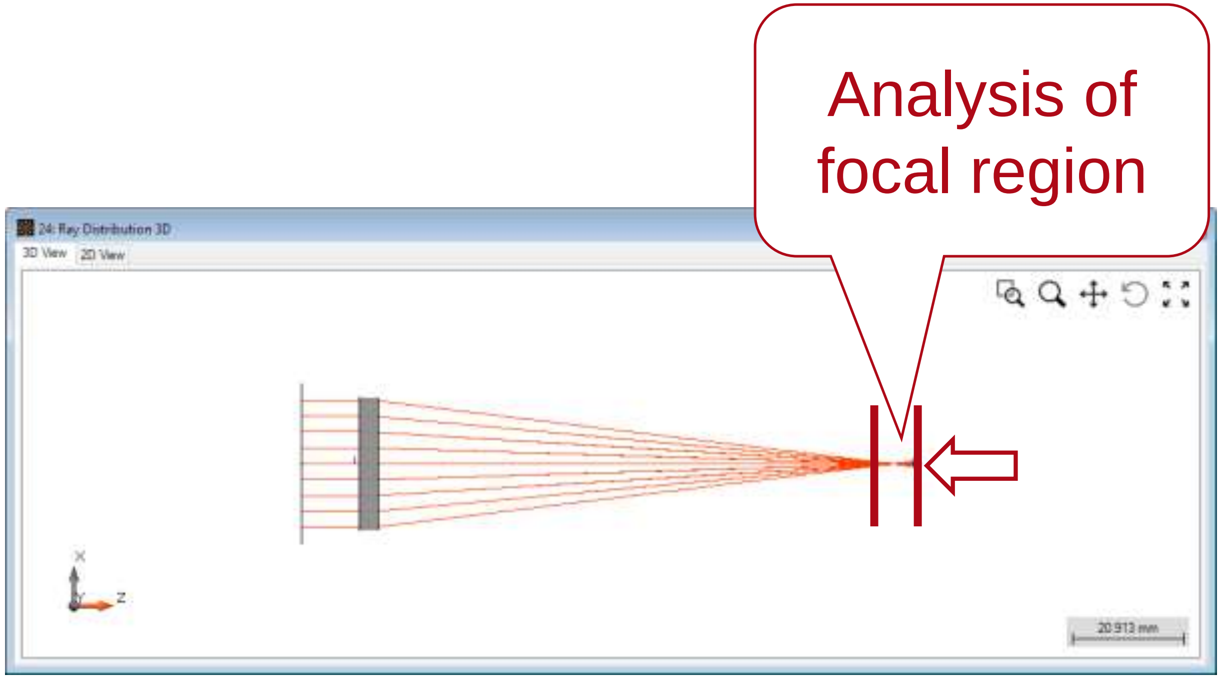


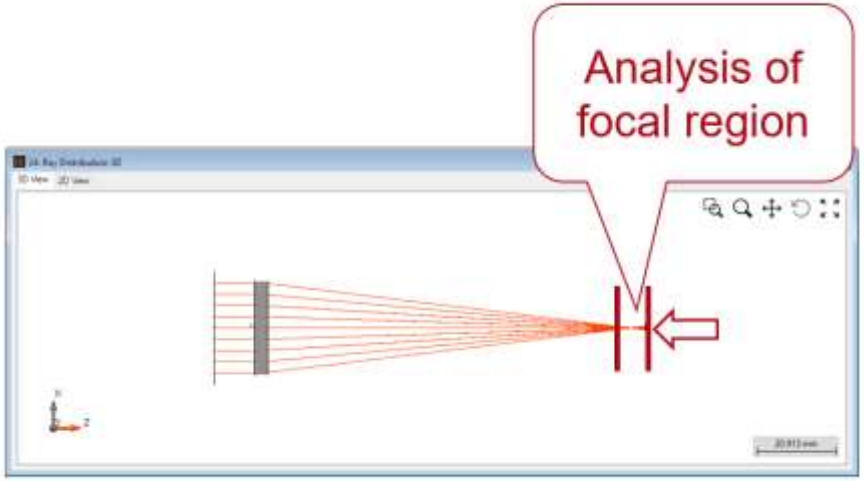
Physical Optics: Intensity

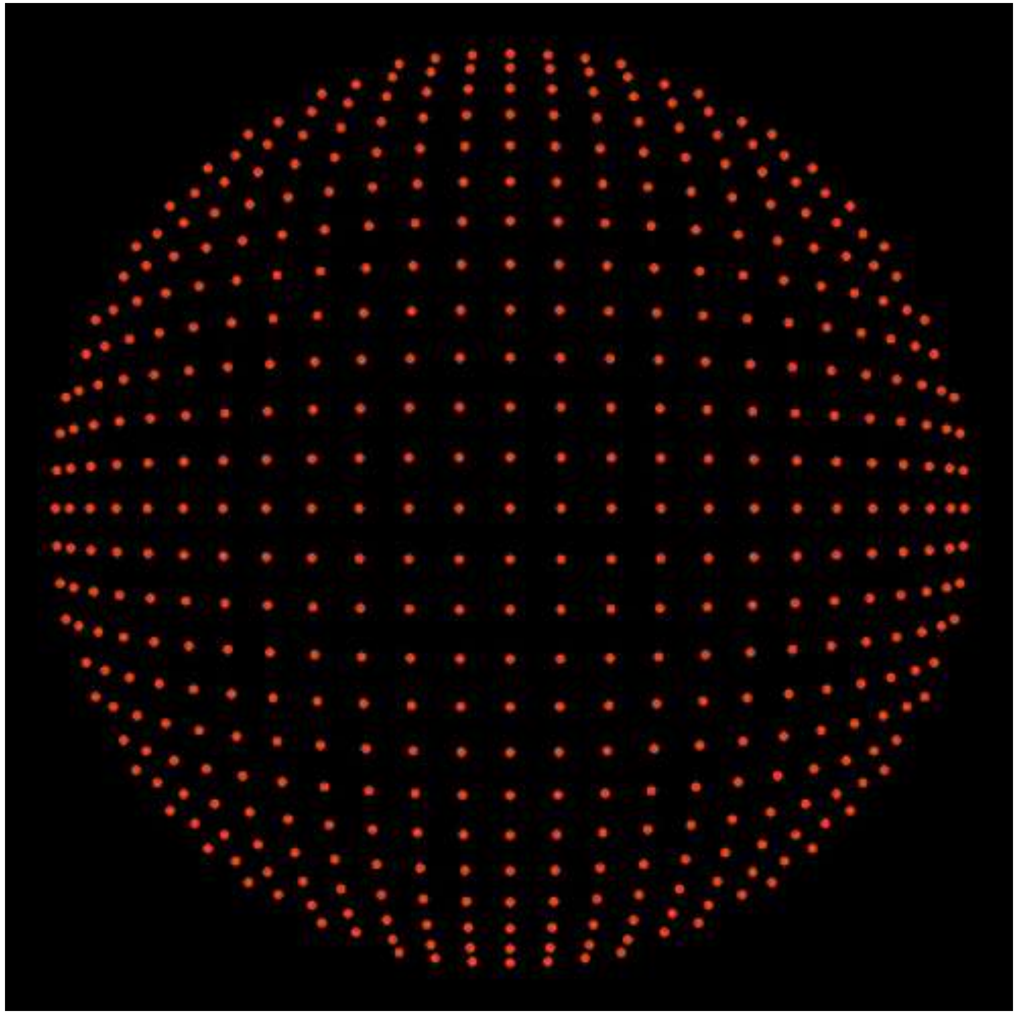


Analysis of Focal Region



Ray Tracing: 91 - 100 mm





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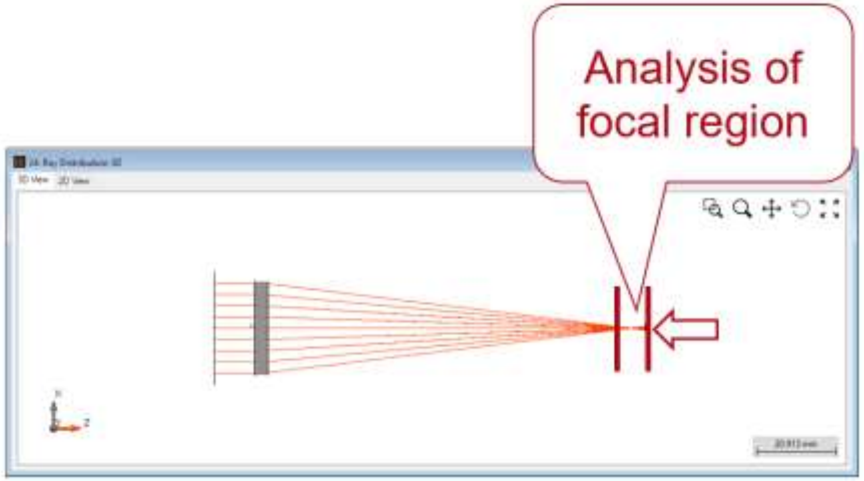
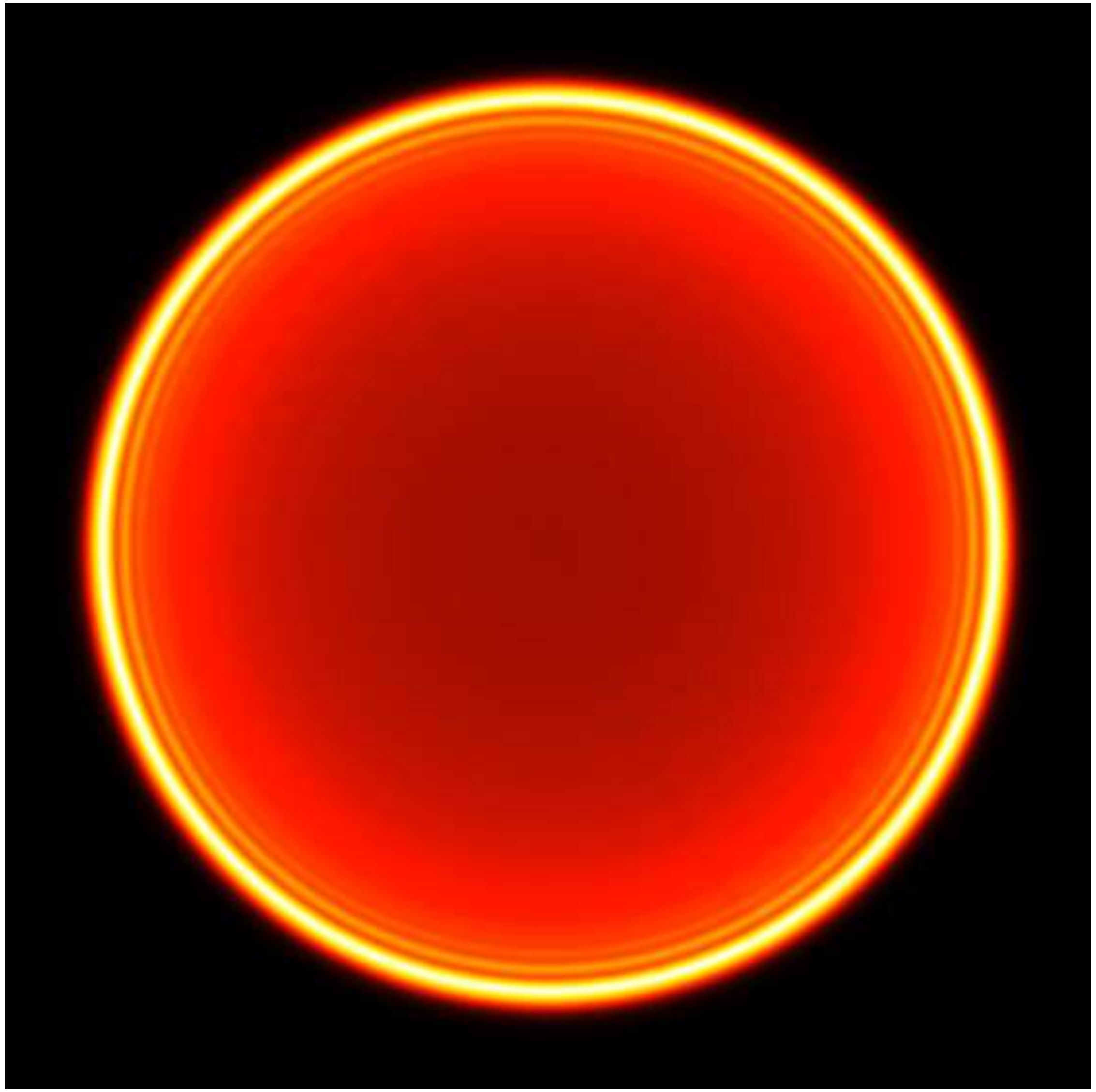
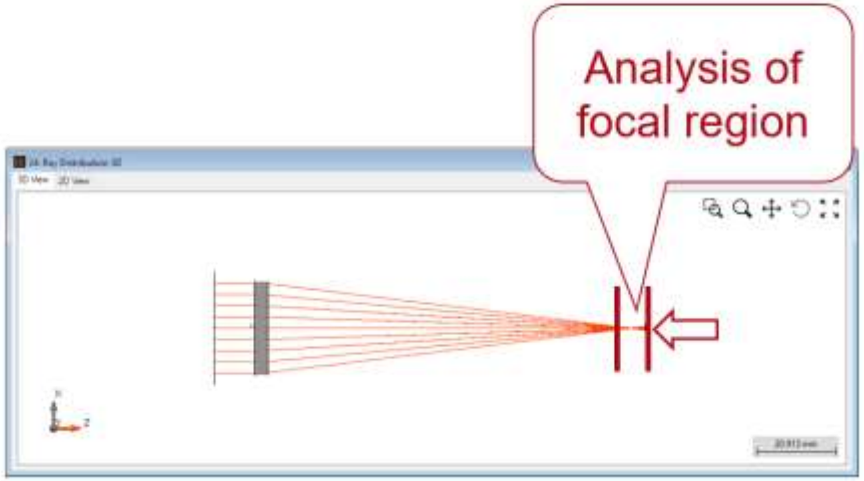
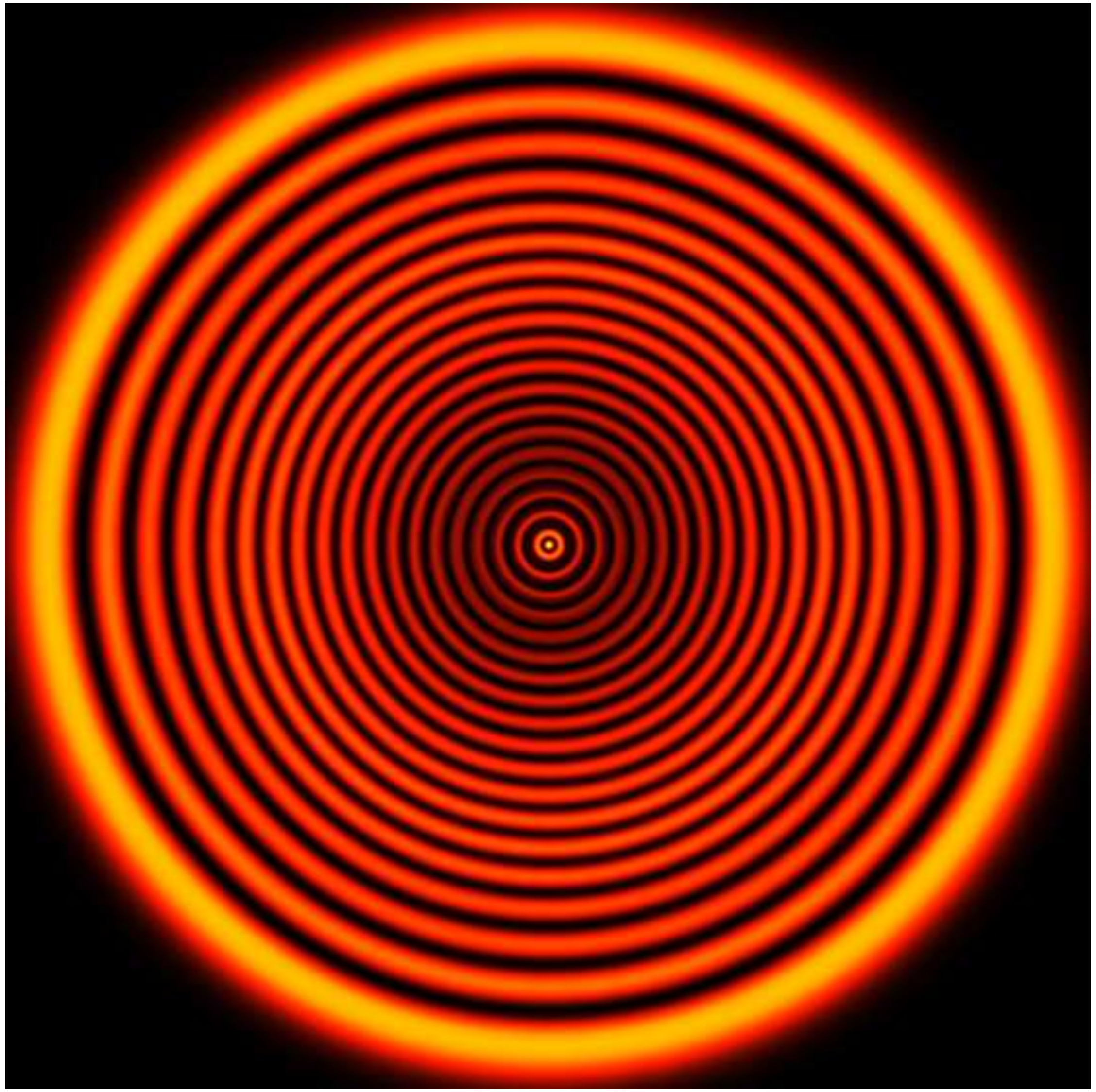




Physical Optics: 95.5 – 98.5 mm





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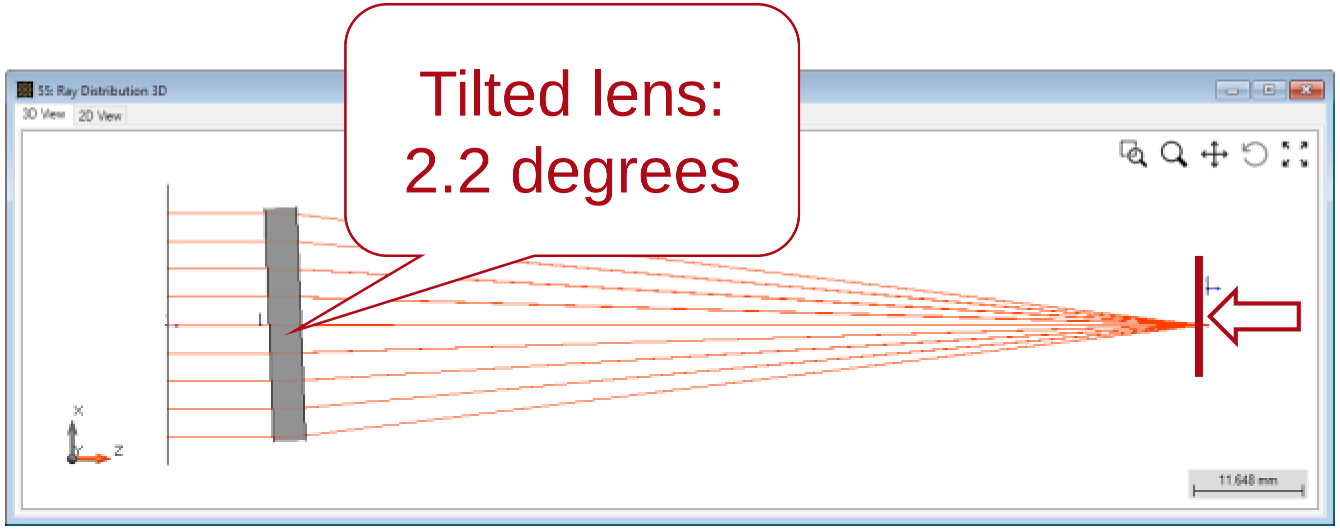

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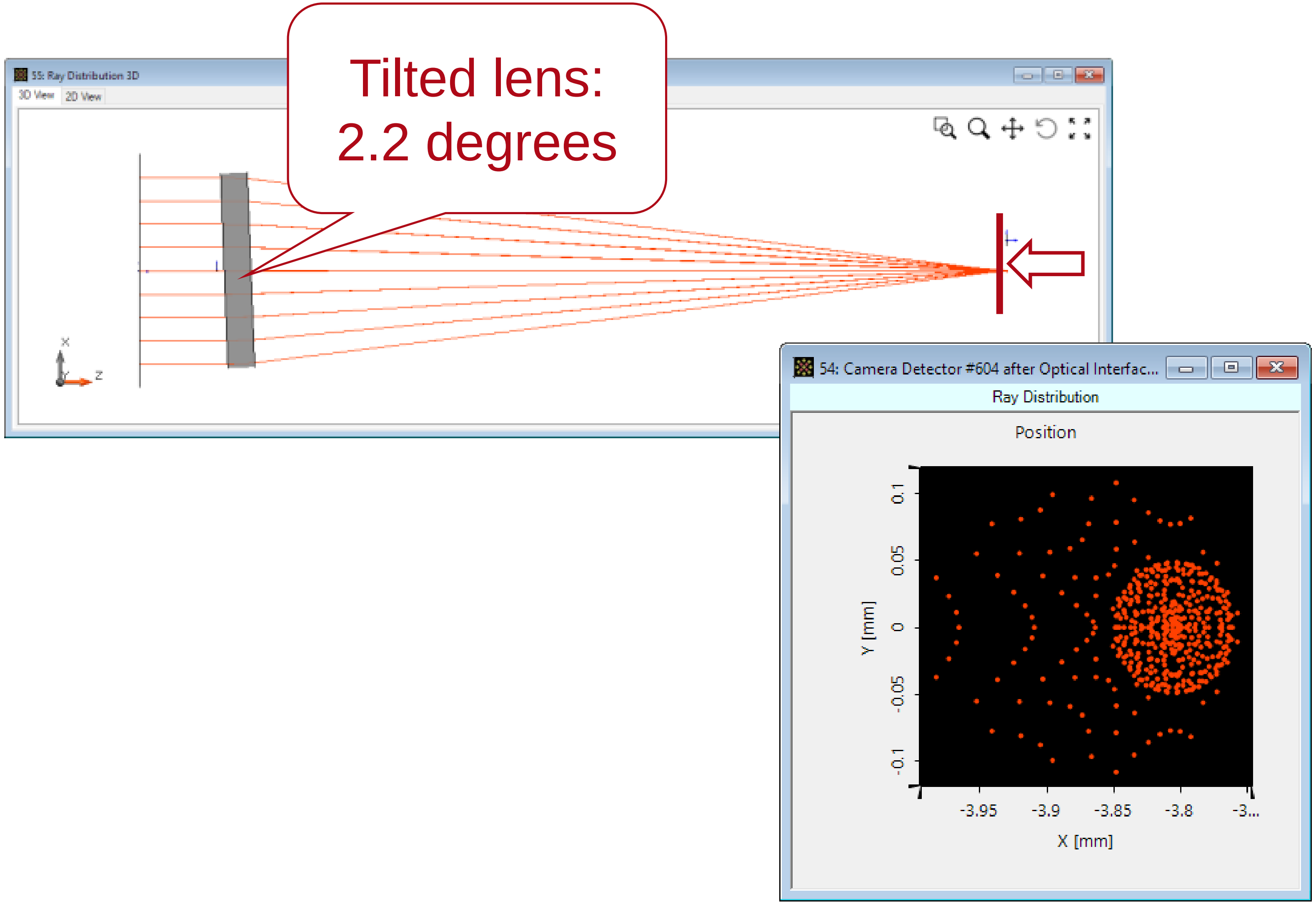
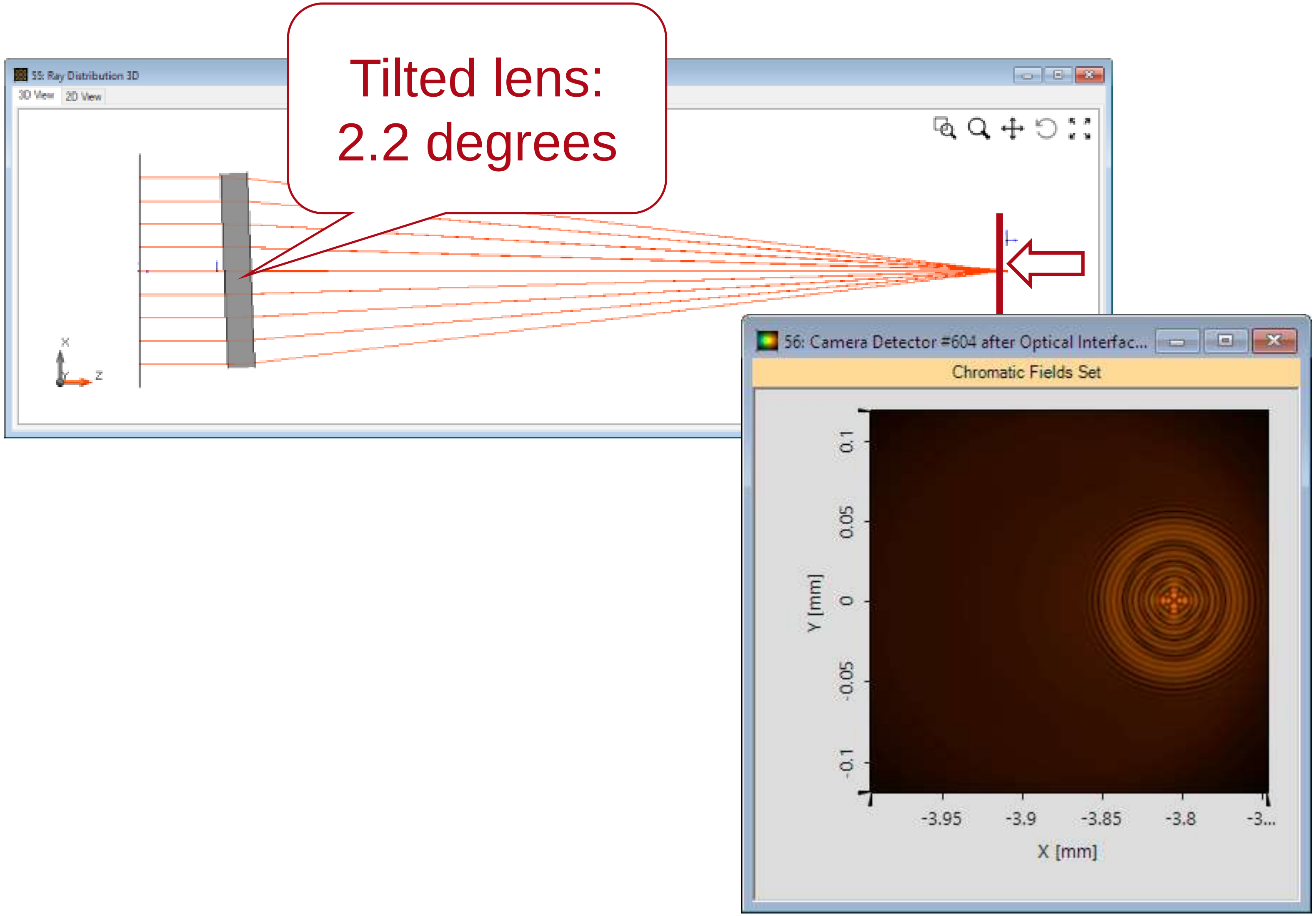
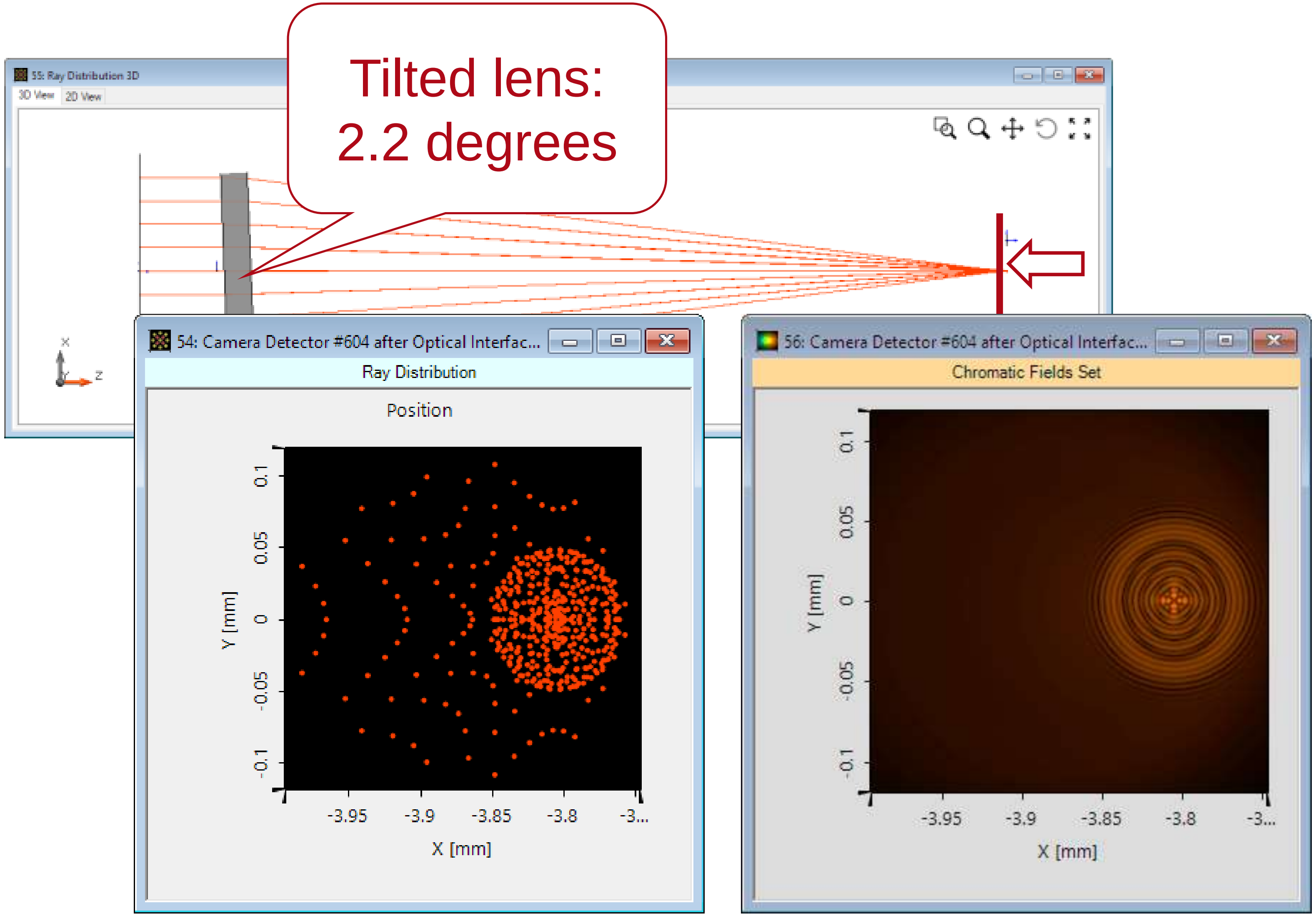


55: Ray Distribution 3D
3D View
2D View
Tilted lens:
2.2 degrees
x
z
54: Camera Detector #604 after Optical Interfac...
Ray Distribution
Position
Y [mm]
0.1
0.05
0
-0.05
-0.1
-3.95
-3.9
-3.85
-3.8
-3...
X [mm]

Physical Optics



Ray vs. Physical Optics



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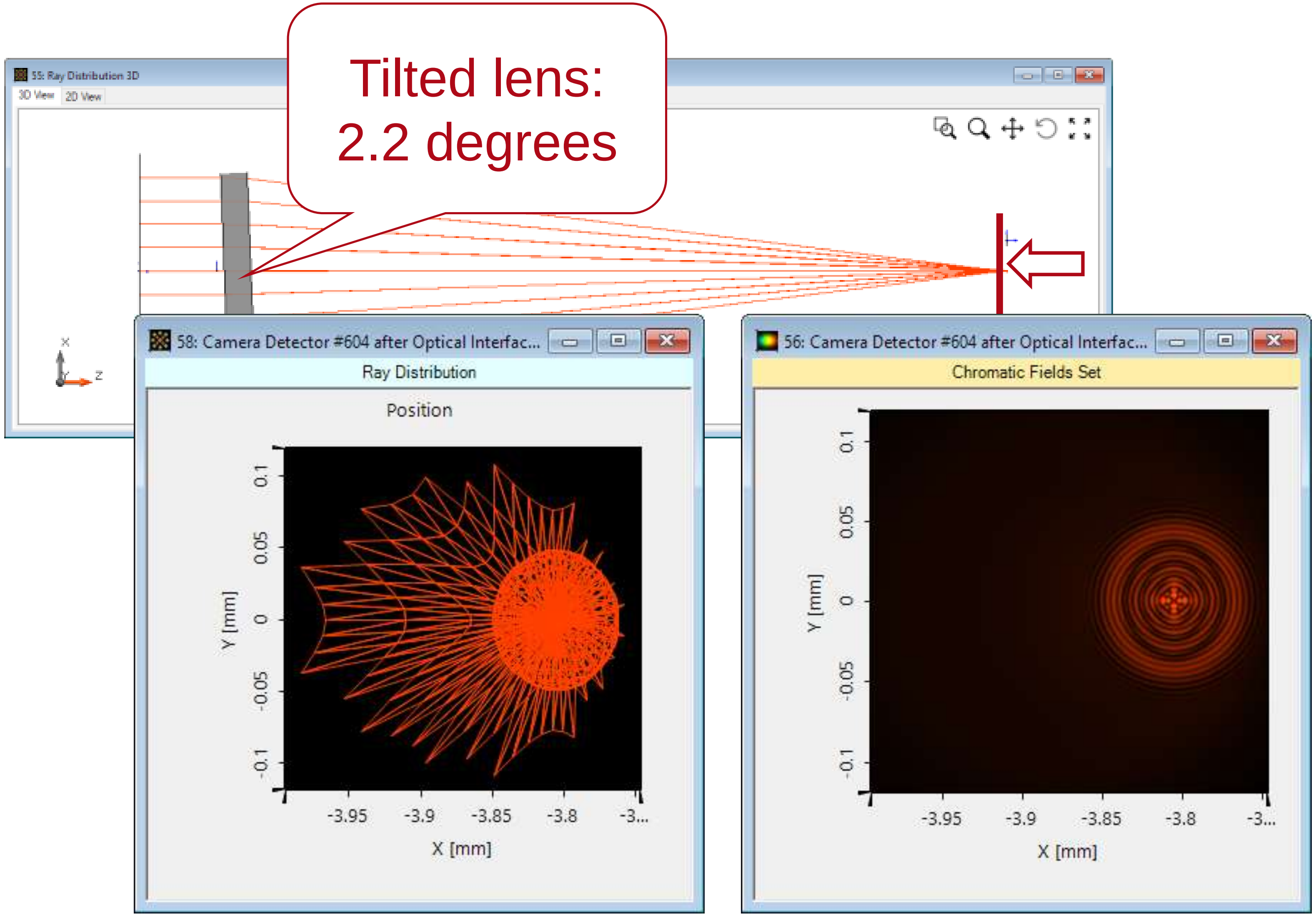

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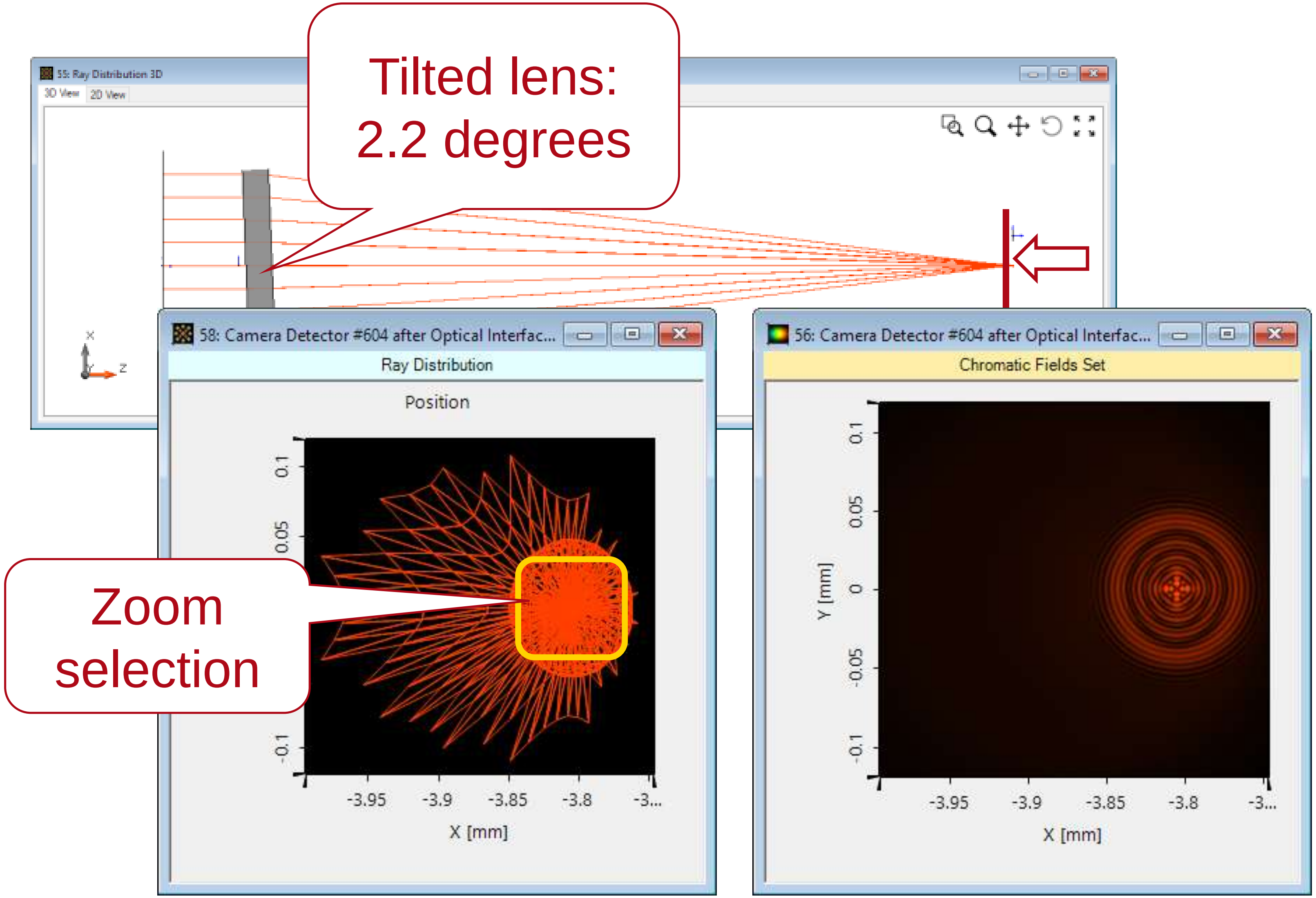

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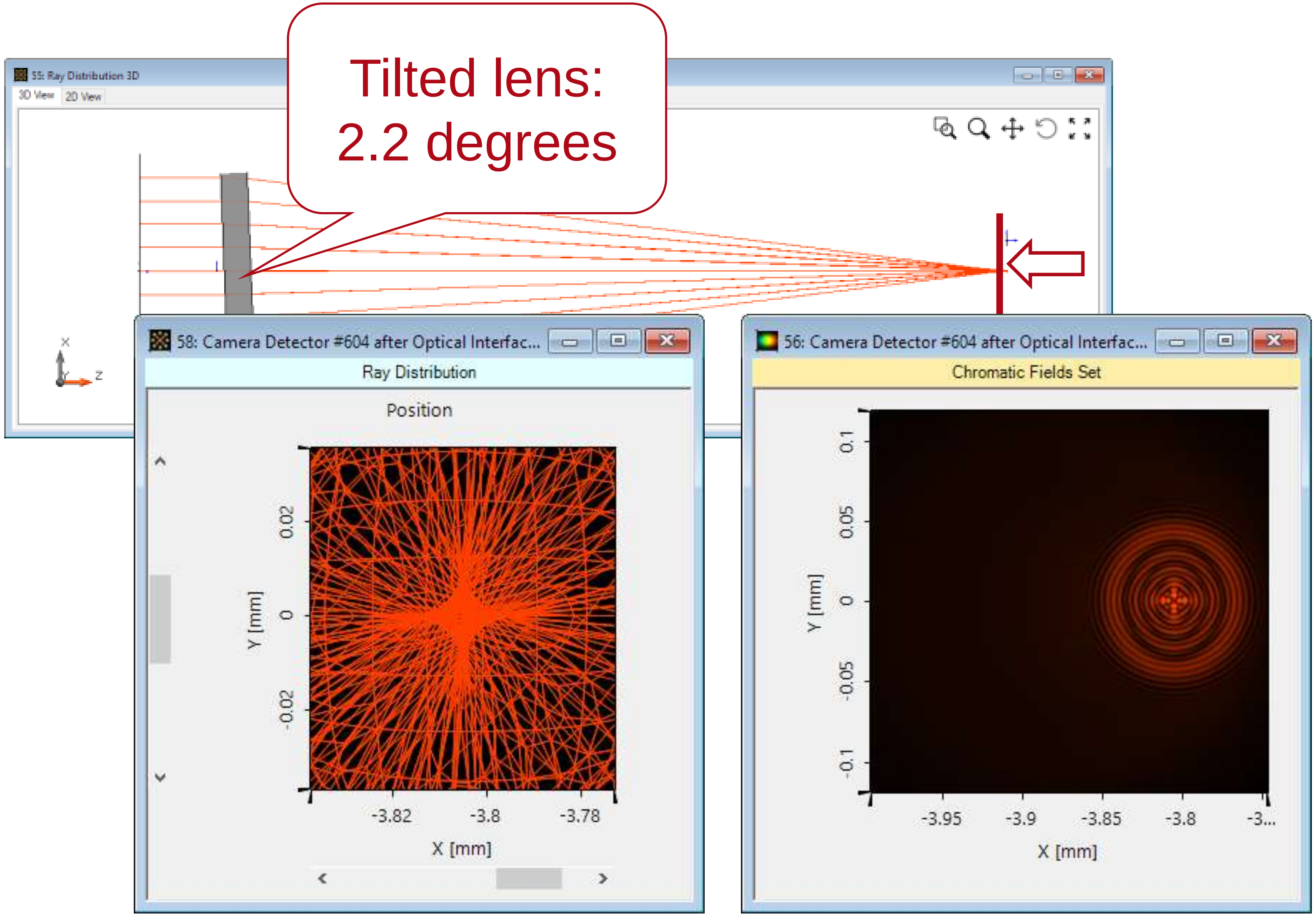

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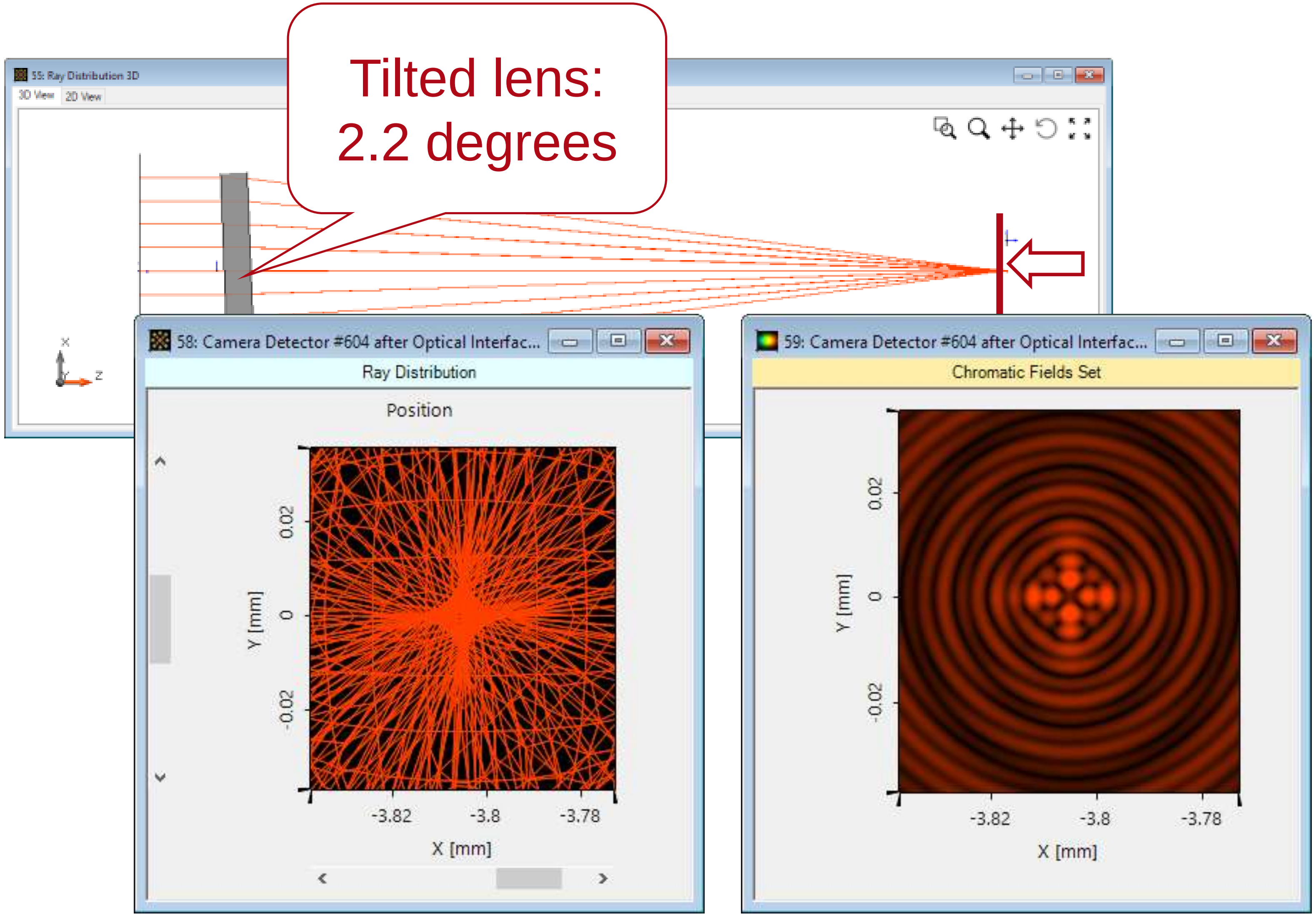
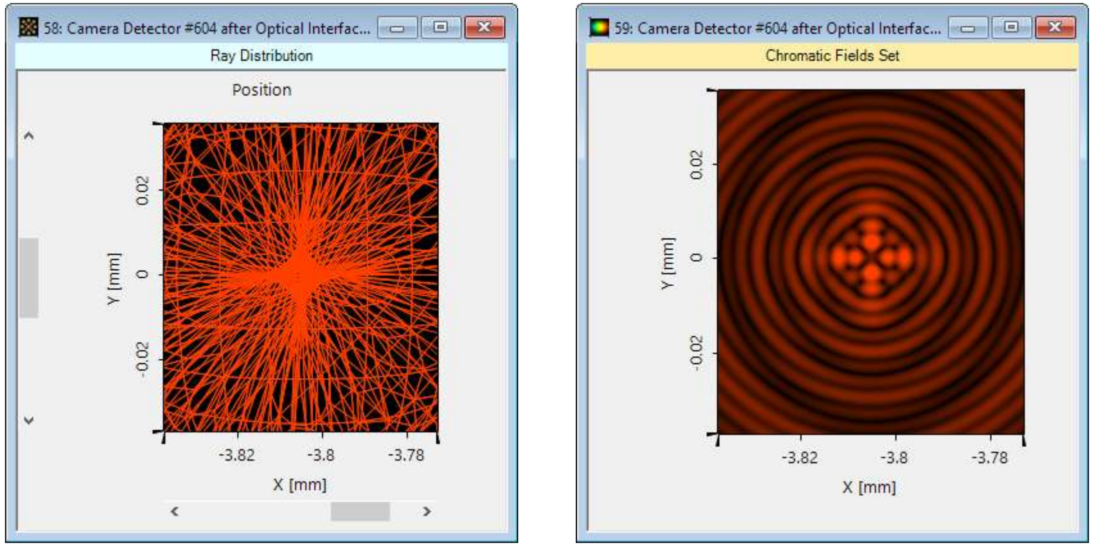
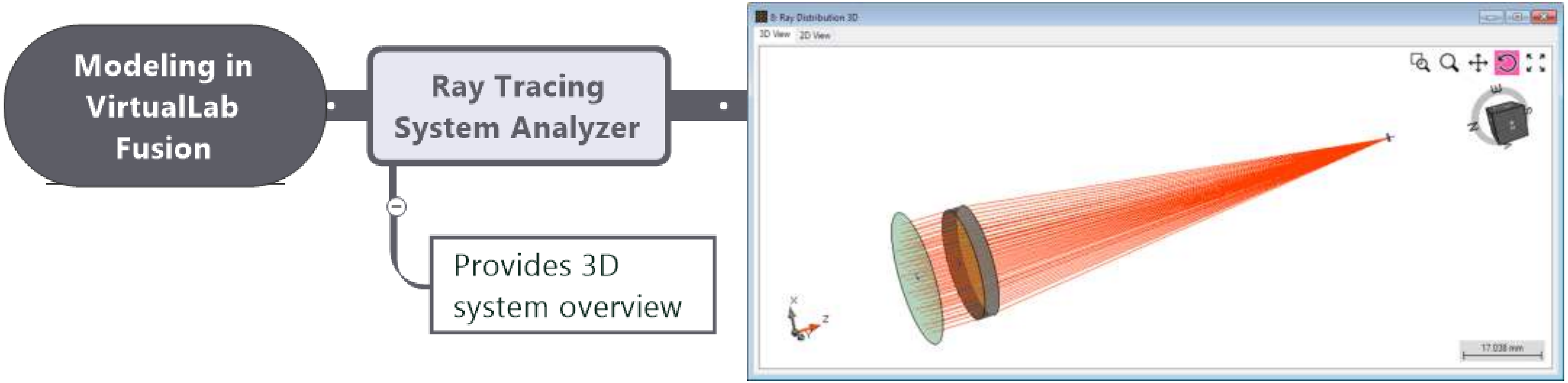


Ray and Physical Optics for Lens Systems



- Modeling of focal regions of lens systems just one example of the need for physical optics modeling and design.

Basic Workflow in VirtualLab Fusion: Modeling



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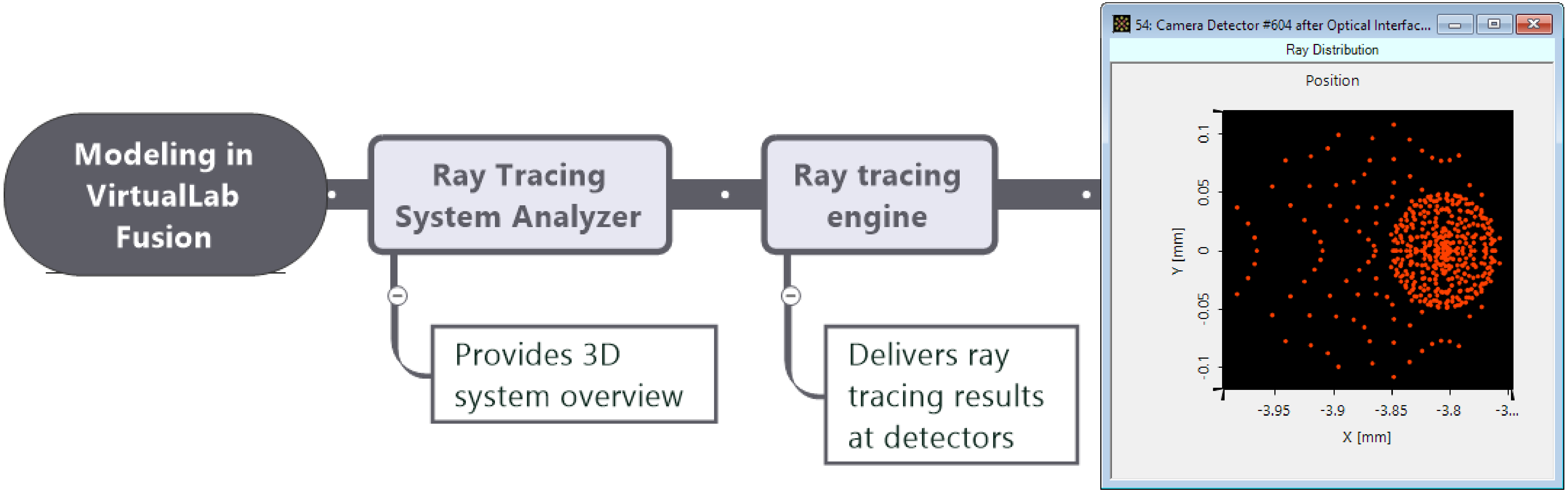

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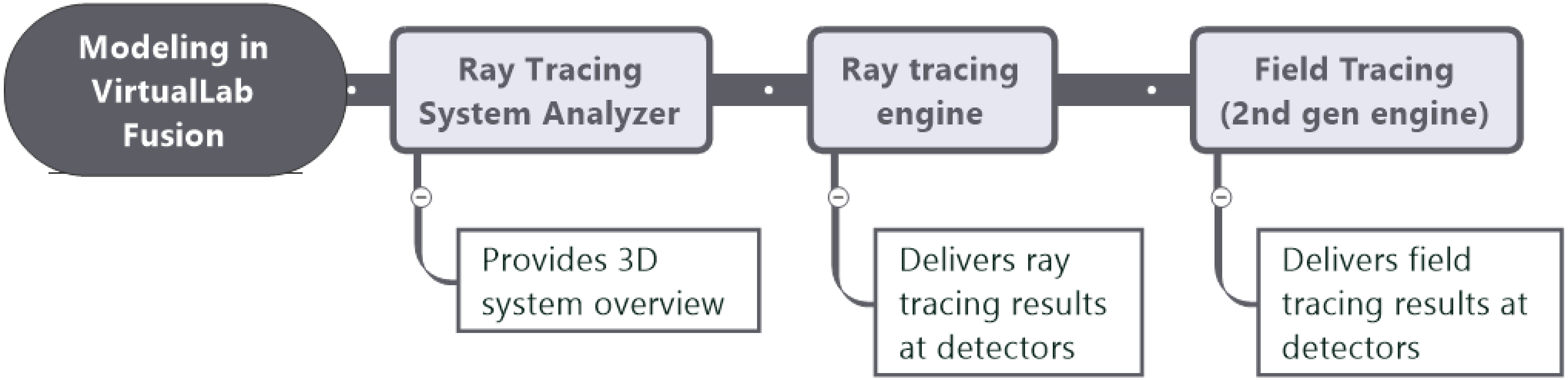

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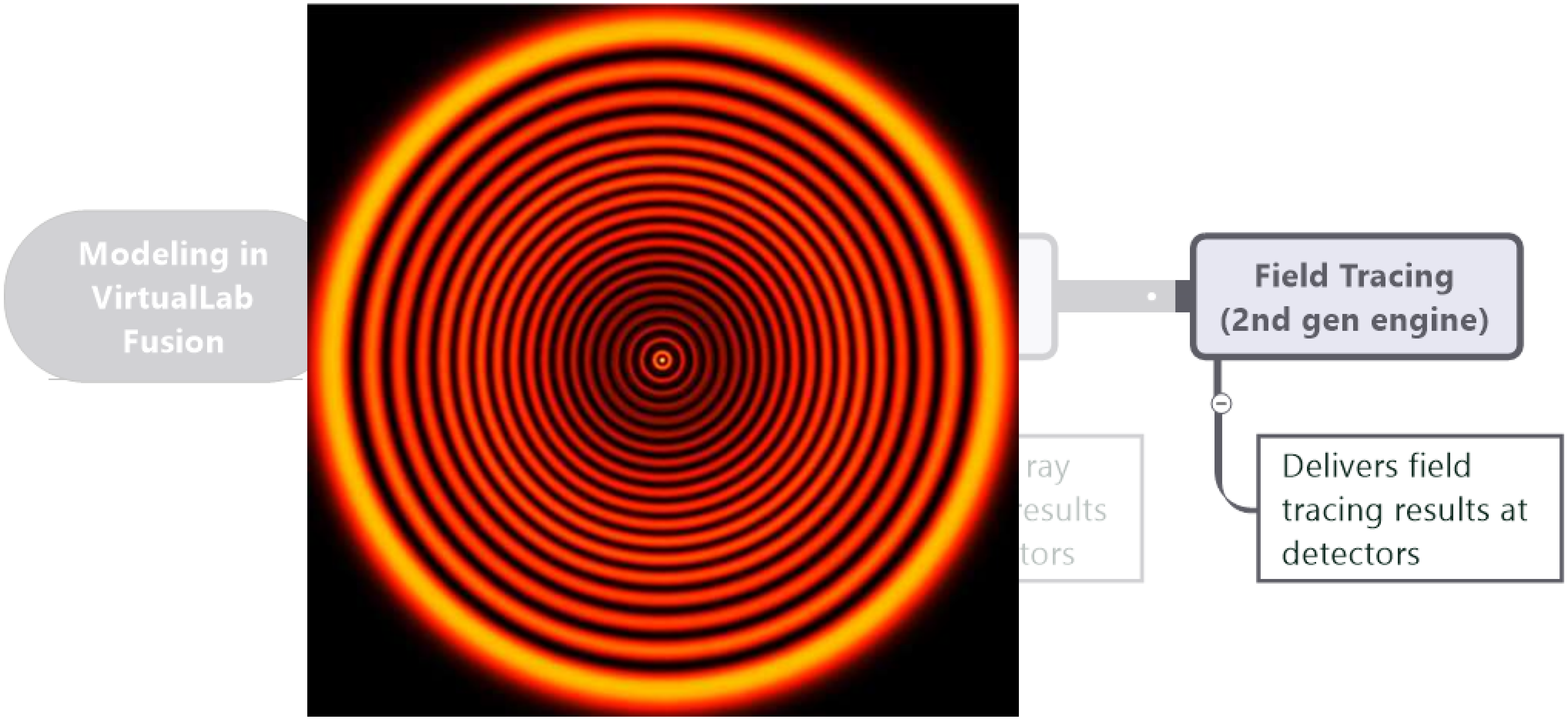

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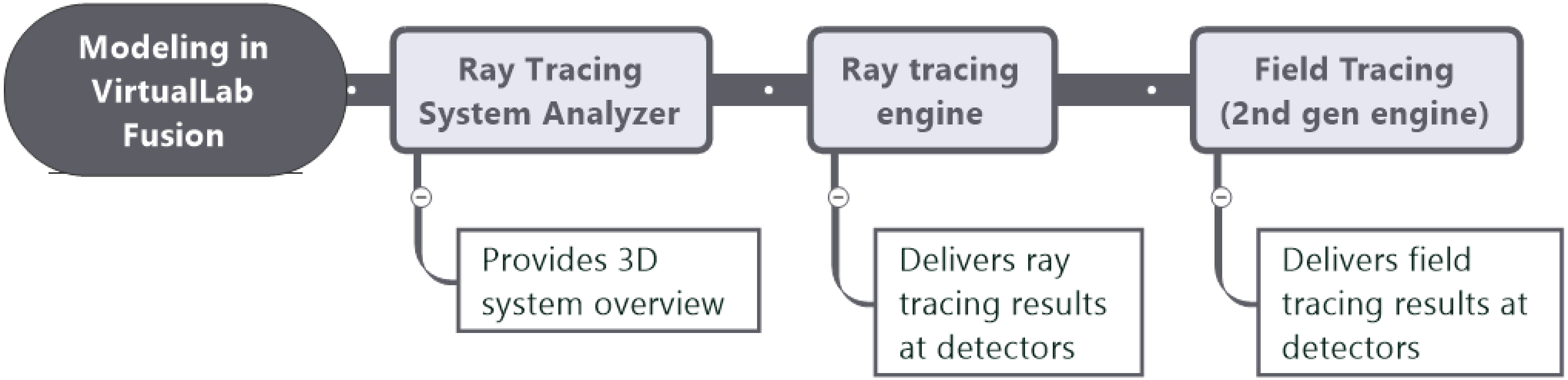

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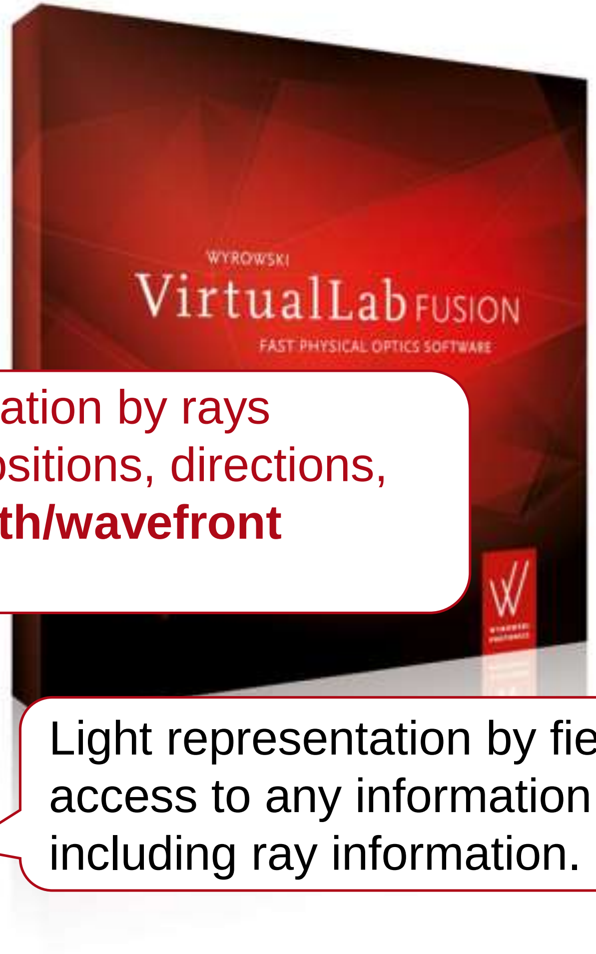

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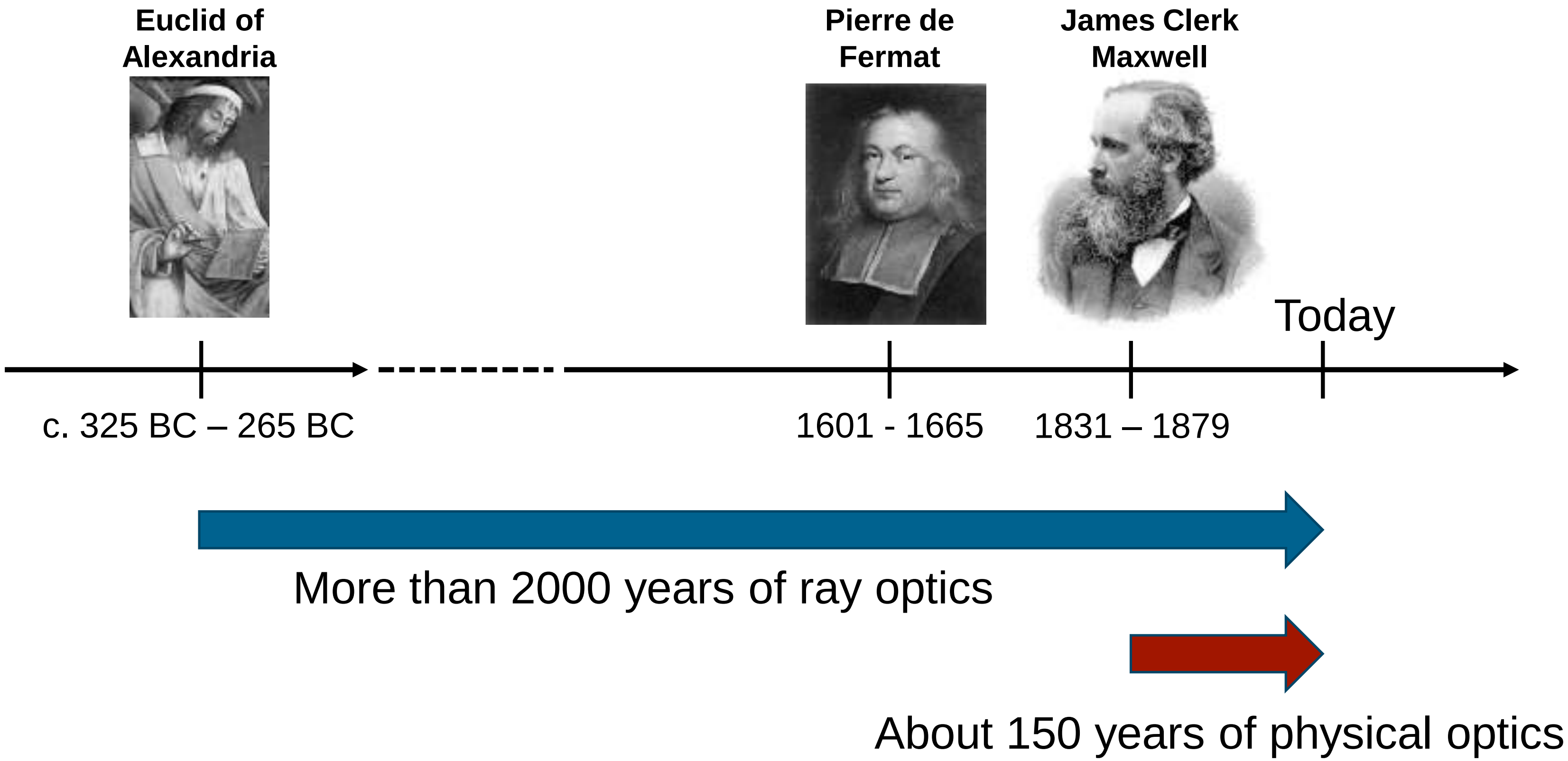
Ray and Physical Optics



Ray and Physical Optics

Euclid of Alexandria

Pierre de Fermat

James Clerk Maxwell

Today

c. 325 BC – 265 BC

1601 - 1665

1831 – 1879

More than 2000 years of ray optics

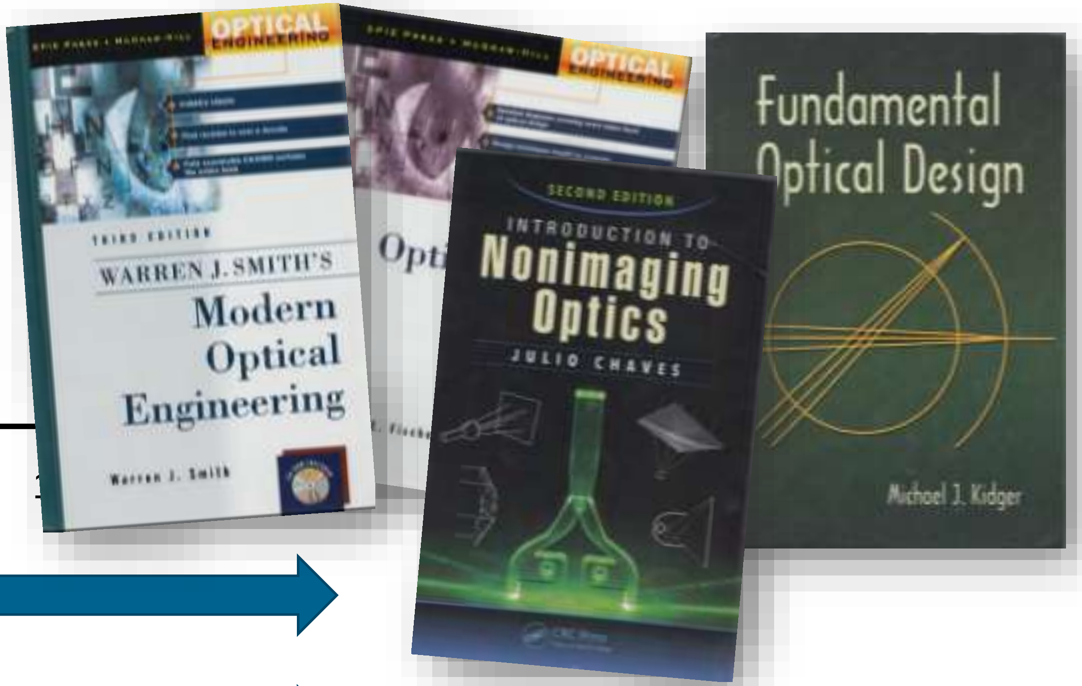
About 150 years of physical optics

Optical design mainly based on ray optics

Ray and Physical Optics

Euclid of Alexandria

Pierre de Fermat



c. 325 BC – 265 BC

1601 - 1665

More than 2000 years of ray optics

About 150 years of physical optics

Optical design mainly based on ray optics

Ray and Physical Optics

Euclid of Alexandria

c. 325 BC – 265 BC

Pierre de Fermat

1601 - 1665

Ray tracing forever?

No and Yes!

More than 2000 years of ray optics

Optical design mainly based on ray optics

Trend in Optical Design: Physical Optics

Euclid of Alexandria

c. 325 BC – 265 BC

Pierre de Fermat

1601 - 1665

James Clerk Maxwell

1831 – 1879

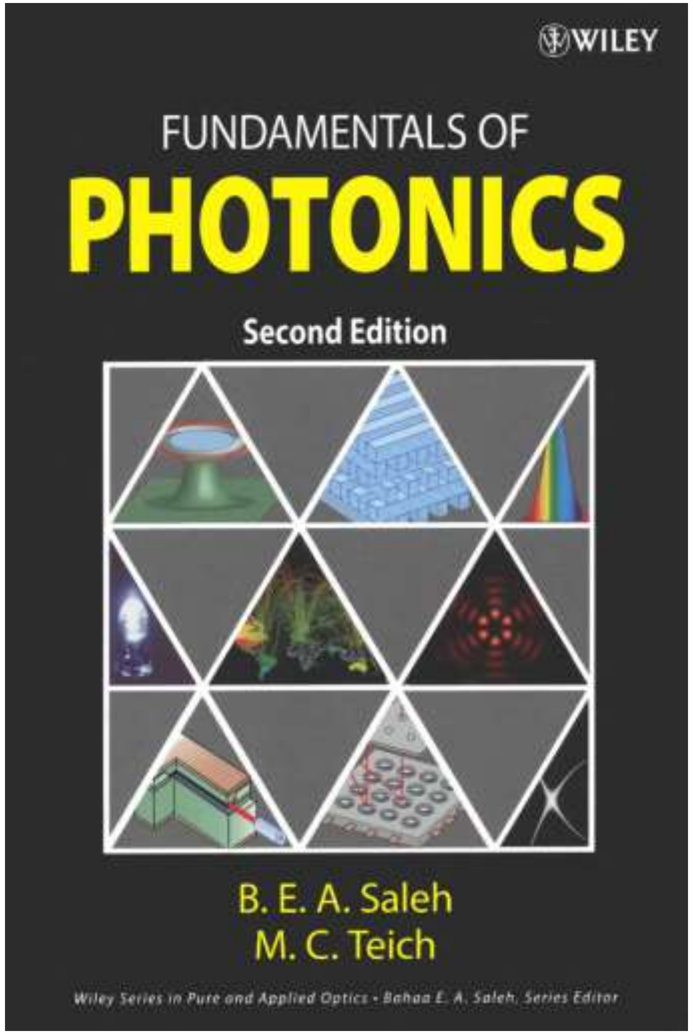
Today

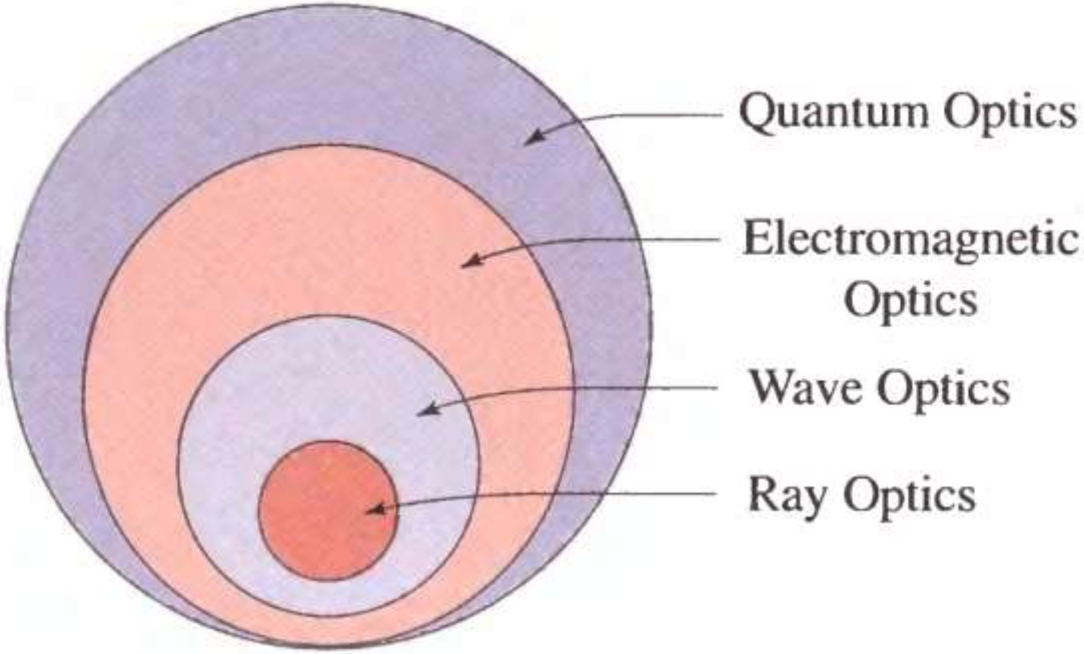
Generalization to physical optics concepts in design

Is it time for a paradigm shift?

Ray tracing remains an extremely useful technique **embedded in a more general approach**!

Physical and Ray Optics: Academical Understanding



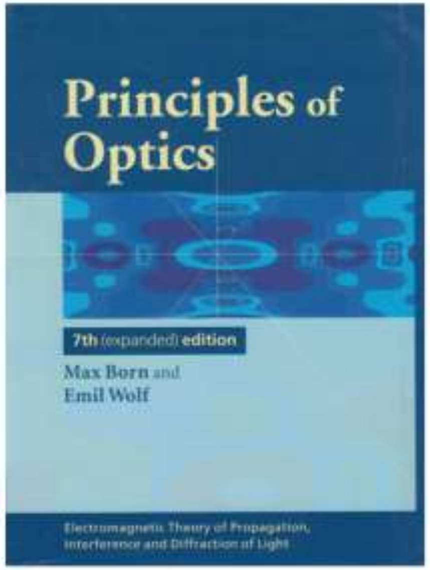


Physical and Ray Optics: Academical Understanding

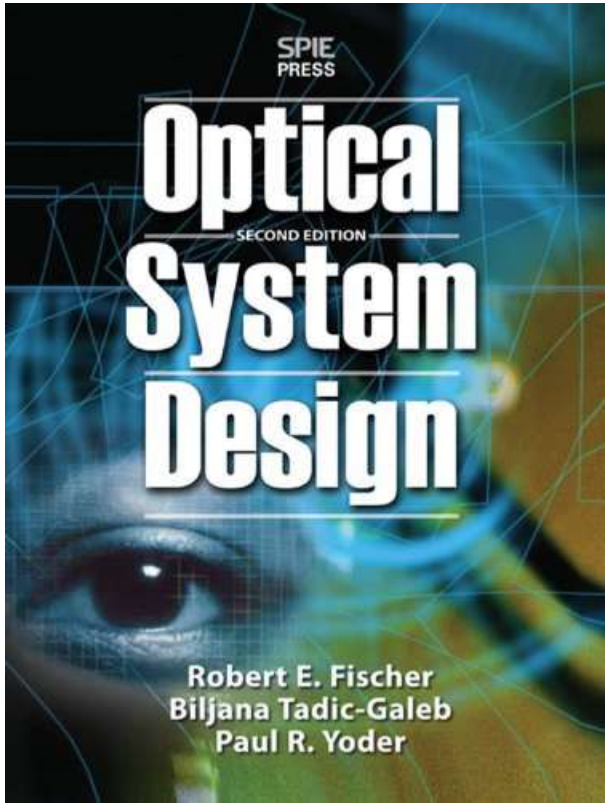
$$\nabla \times \boldsymbol{E}(\boldsymbol{r}) = \mathrm{i}\omega\mu_0 \boldsymbol{H}(\boldsymbol{r})$$
$$\nabla \times \boldsymbol{H}(\boldsymbol{r}) = -\mathrm{i}\omega\epsilon_0\check{\epsilon}_r(\omega)\boldsymbol{E}(\boldsymbol{r}),$$
$$\nabla \cdot \boldsymbol{E}(\boldsymbol{r}) = 0,$$
$$\nabla \cdot \boldsymbol{H}(\boldsymbol{r}) = 0.$$

$$\nabla\check{\psi}(\boldsymbol{r}) \times \tilde{\boldsymbol{E}}(\boldsymbol{r}) = \omega\mu_0\tilde{\boldsymbol{H}}(\boldsymbol{r})$$
$$\nabla\check{\psi}(\boldsymbol{r}) \times \tilde{\boldsymbol{H}}(\boldsymbol{r}) = -\omega\epsilon_0\check{\epsilon}_r(\omega)\tilde{\boldsymbol{E}}(\boldsymbol{r})$$
$$\nabla\check{\psi}(\boldsymbol{r}) \cdot \tilde{\boldsymbol{E}}(\boldsymbol{r}) = 0$$
$$\nabla\check{\psi}(\boldsymbol{r}) \cdot \tilde{\boldsymbol{H}}(\boldsymbol{r}) = 0$$

$$(\nabla\psi(\boldsymbol{r}))^2 = k_0^2 n^2(\boldsymbol{r}).$$



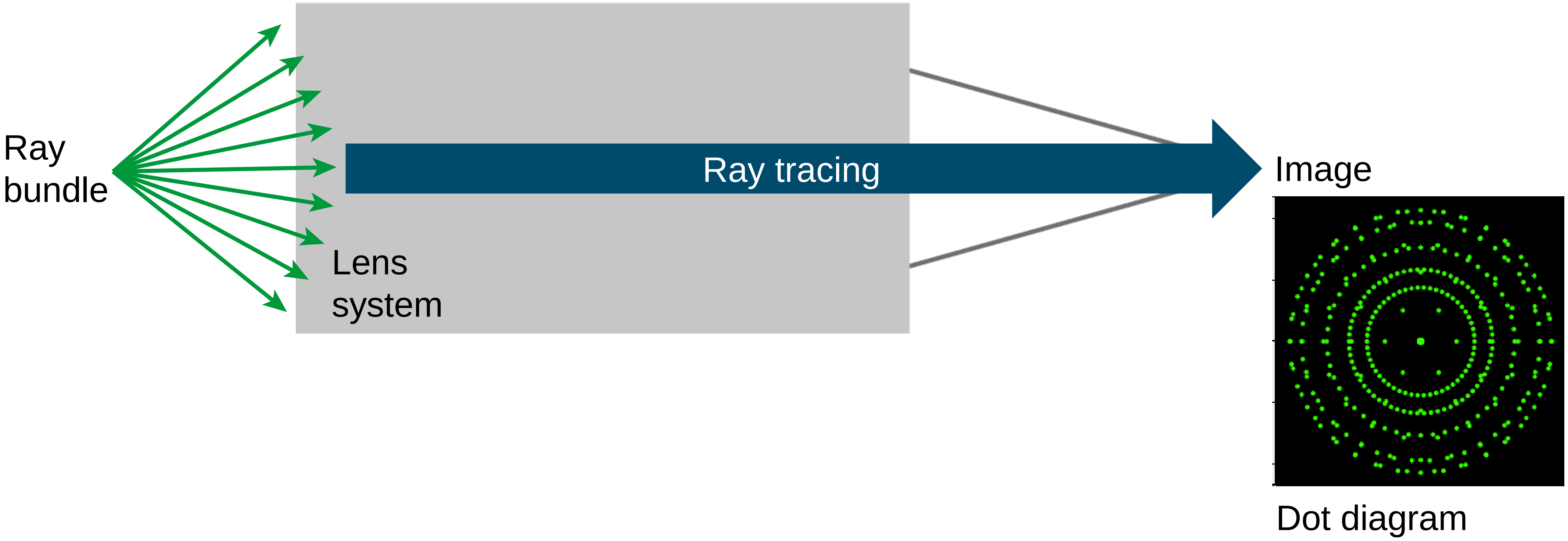
Ray and Physical Optics: Applications



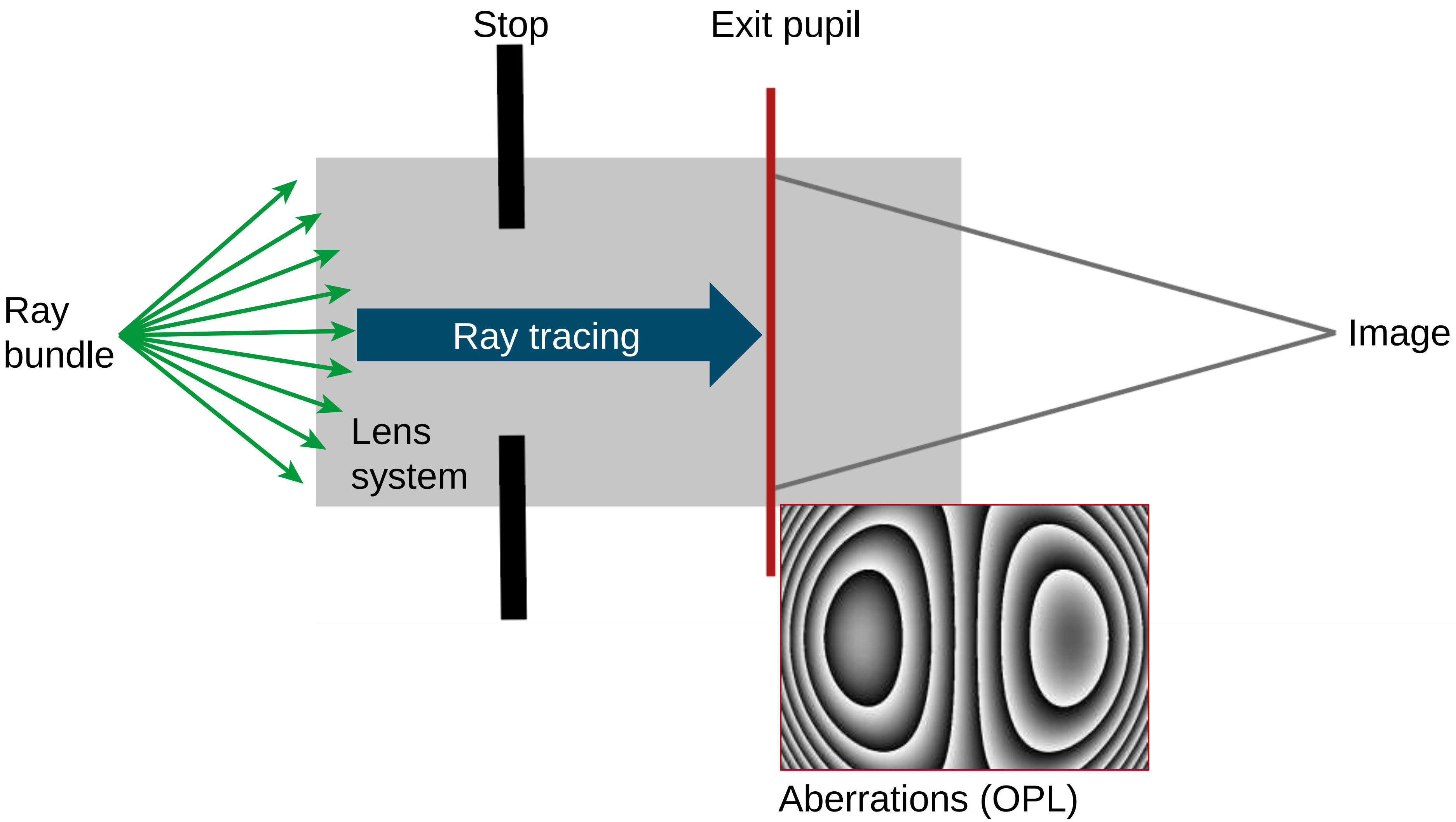
Modeling Lens Systems

Modeling Lens Systems

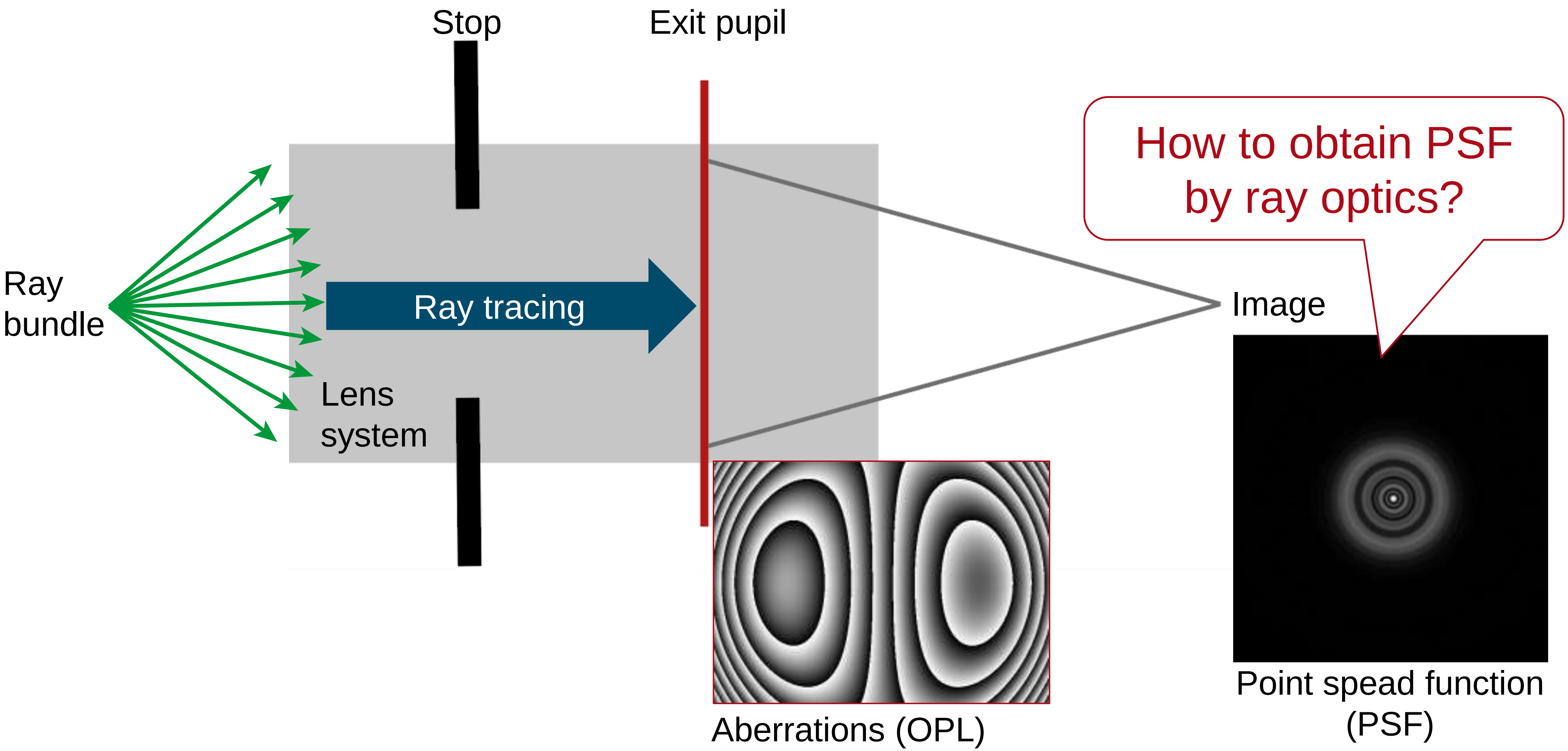
Modeling Lens Systems: Ray Tracing



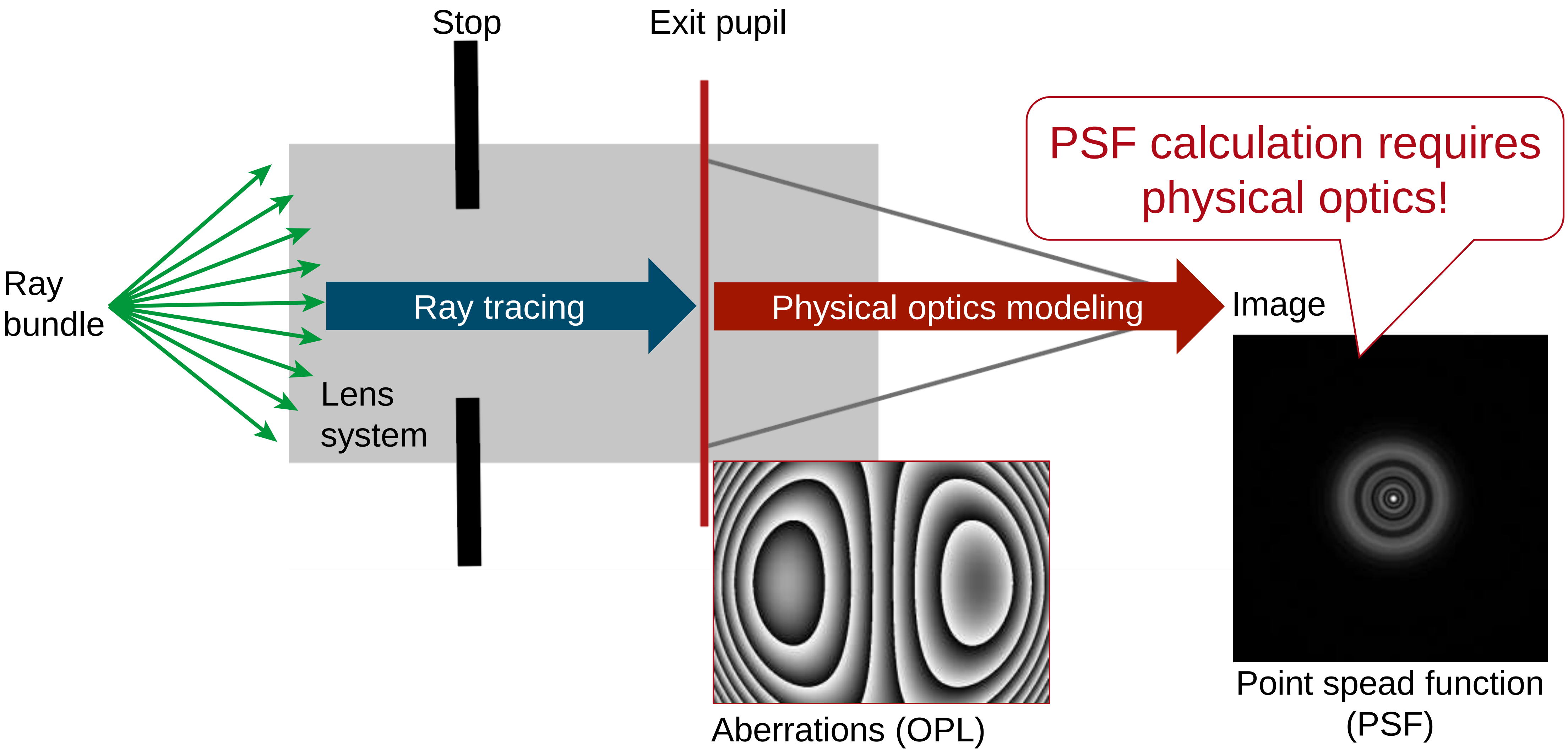
Modeling Lens Systems: Ray Tracing



Modeling Lens Systems: Ray Tracing



Modeling Lens Systems



Imaging Optics: Ray Optics + PSF/MTF

Euclid of Alexandria

c. 325 BC - 265 BC

Pierre de Fermat

1601-1665

James Clerk Maxwell

1831-1879

Imaging Optics: Ray Optics + PSF/MTF

Euclid of Alexandria

Pierre de Fermat

James Clerk Maxwell

Ernst Abbe

c. 325 BC - 265 BC

1601-1665

1831-1879

1840-1905

Diffraction limited resolution

Imaging Optics: Ray Optics + PSF/MTF

Euclid of Alexandria

Pierre de Fermat

James Clerk Maxwell

Ernst Abbe

c. 325 BC - 265 BC

1601-1665

1831-1879

1840-1905

Diffraction limited resolution

paradigm shift starts slightly from 200 years ago

Imaging Optics: Ray Optics + PSF/MTF

Euclid of Alexandria

c. 325 BC - 265 BC

Pierre de Fermat

1601-1665

James Clerk Maxwell

1831-1879

Ernst Abbe

1840-1905

Peter Debye

1884-1966

Light in focal regions

Imaging Optics: Ray Optics + PSF/MTF

Euclid of Alexandria

c. 325 BC - 265 BC

Pierre de Fermat

1601-1665

James Clerk Maxwell

1831-1879

Ernst Abbe

1840-1905

Peter Debye

1884-1966

Harold Hopkins

1918-1994

Wave theory of aberrations

Imaging Optics: Ray Optics + PSF/MTF

Euclid of Alexandria

Pierre de Fermat

James Clerk Maxwell

Ernst Abbe

Peter Debye

Harold Hopkins

Emil Wolf

c. 325 BC - 265 BC

1601-1665

1831-1879

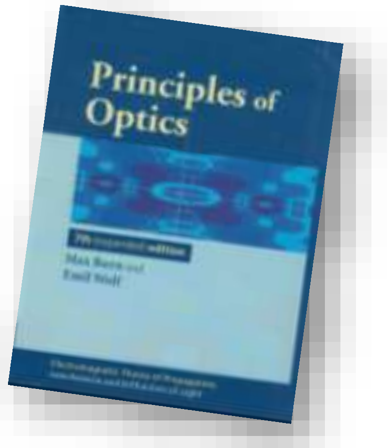
1840-1905

1884-1966

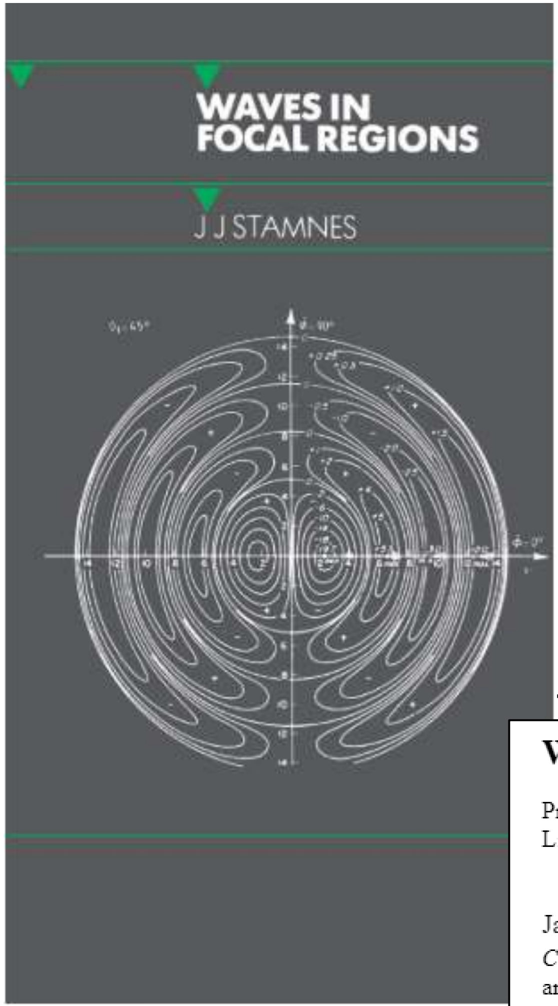
1918-1994

1922-2018

Polarization and coherence



Modeling Lens Systems: Diffraction Theory of Lens Systems



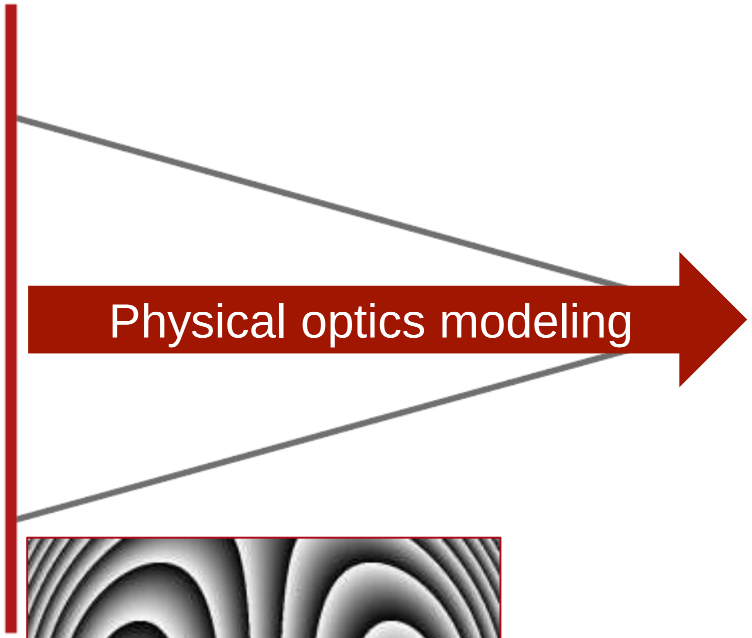
1986; 603 pages

Waves in Focal Regions

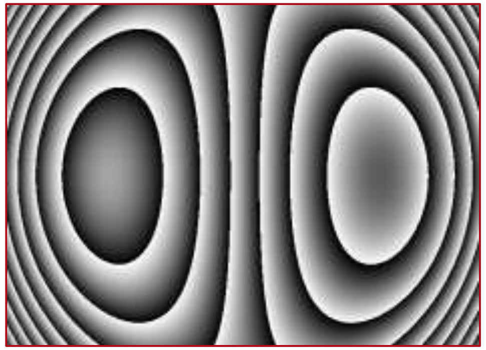
Propagation, Diffraction and Focusing of Light, Sound and Water Waves

Jakob J Stamnes
Center for Industrial Research, Oslo
and
Norwave AS

Exit pupil



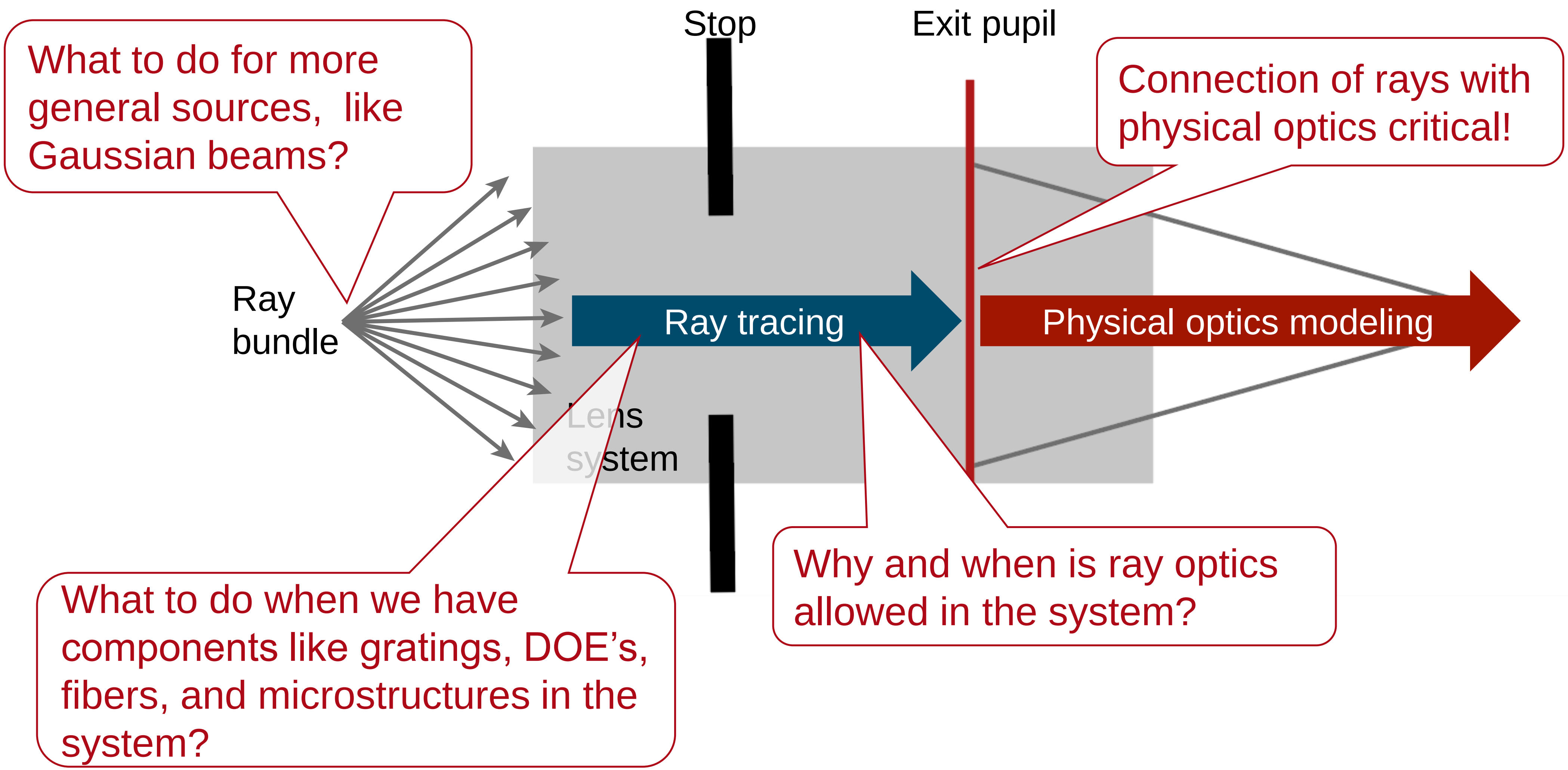
Image



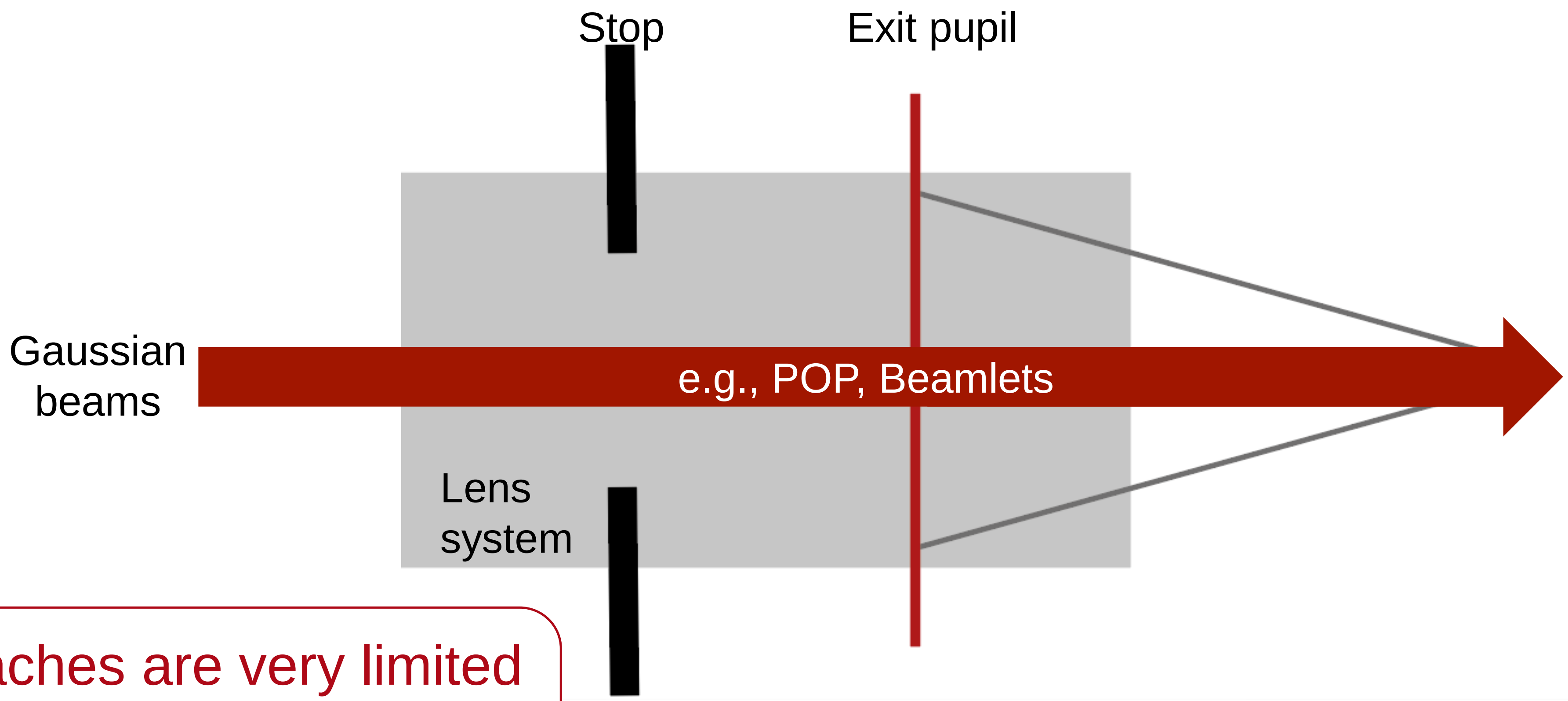
Aberrations (OPL)

Point spead function (PSF)

Modeling Lens Systems: Ray and Physical Optics



Ray Tracer: Physical-Optics Add-Ons



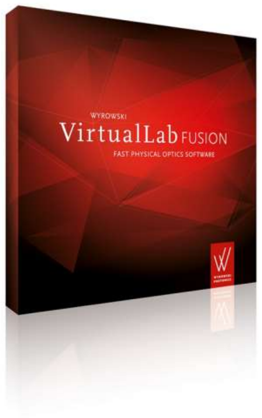
Approaches are very limited and do not provide the full benefit of physical optics!

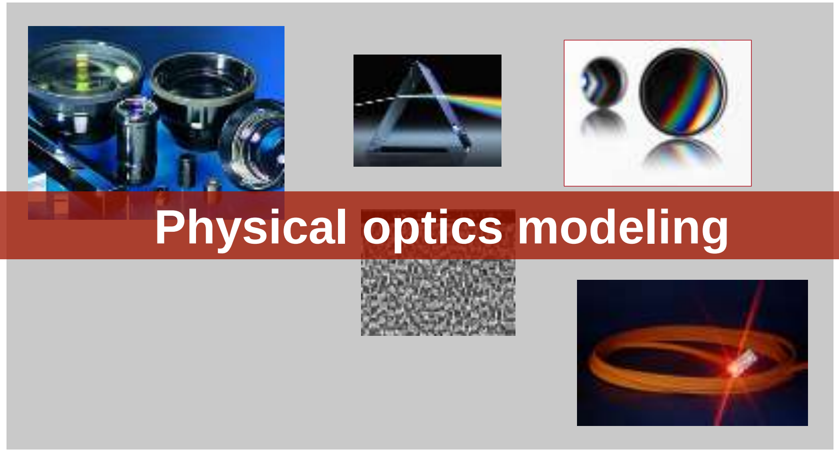
General Physical-Optics System Modeling

Sources

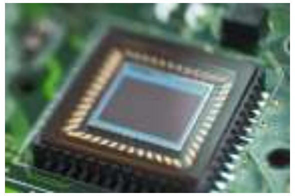
Components

Detectors





Physical optics modeling



https://c2.staticflickr.com

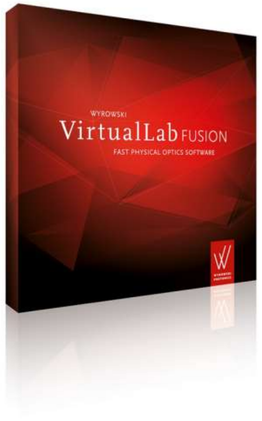
We demand full flexibility in physical optics modeling.

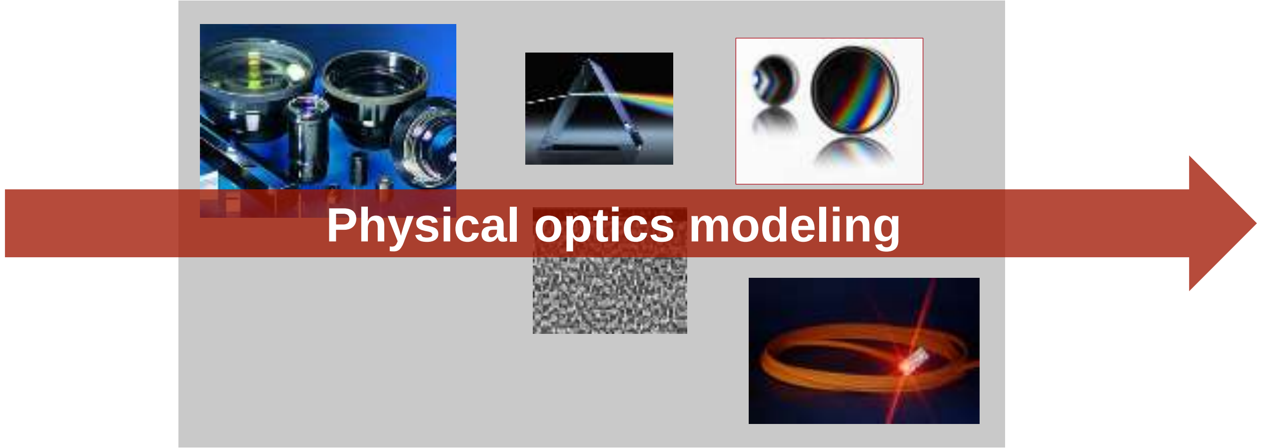
General Physical-Optics System Modeling

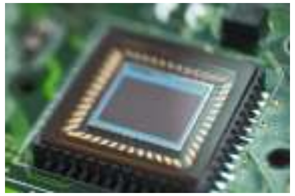
Sources

Components

Detectors



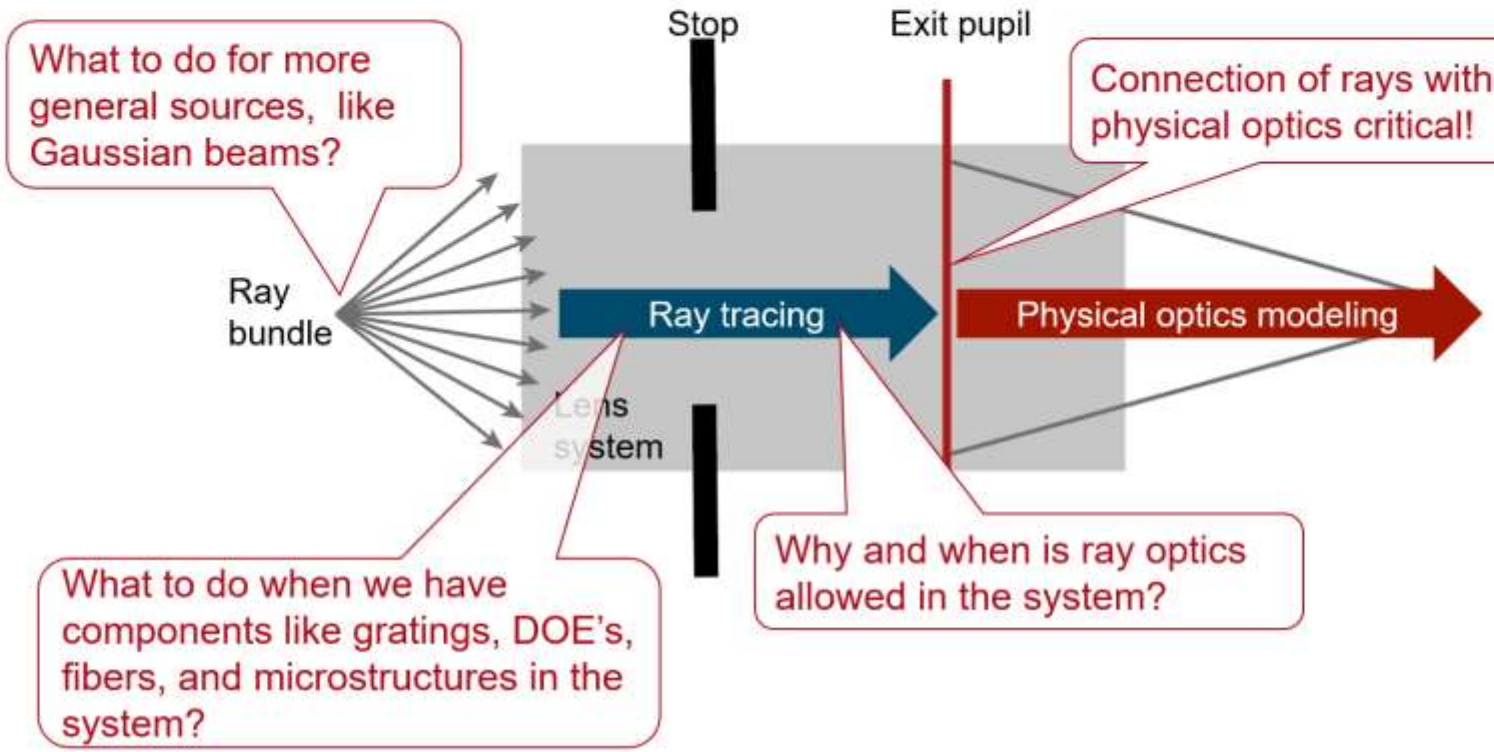




https://c2.staticflickr.com

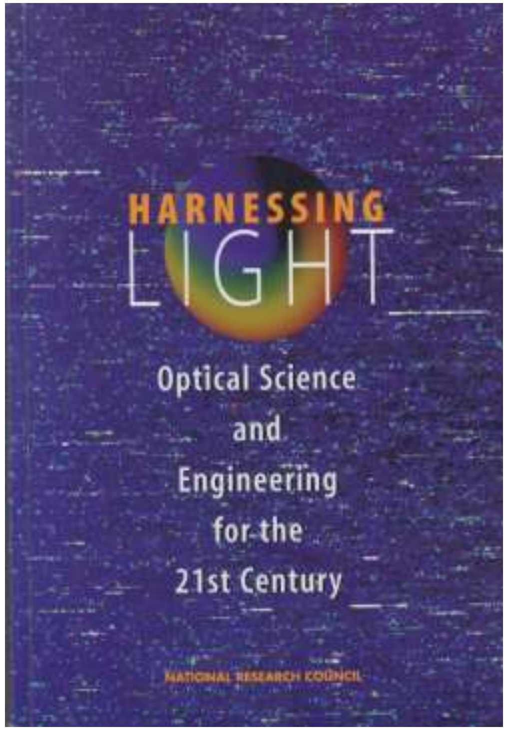
Physical optics modeling should be as fast as ray tracing wherever possible!

Why physical optics?



Why physical optics?

1998

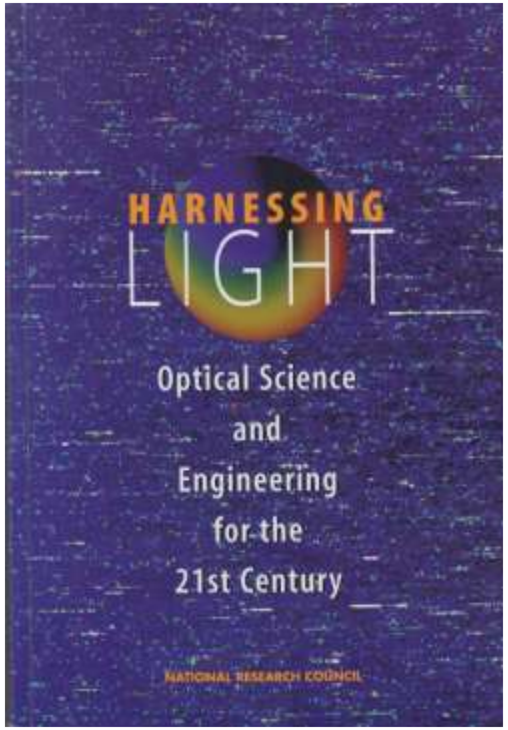


2000

Optical technologies are developing fast and in a wide variety of applications!

Why physical optics?

1998



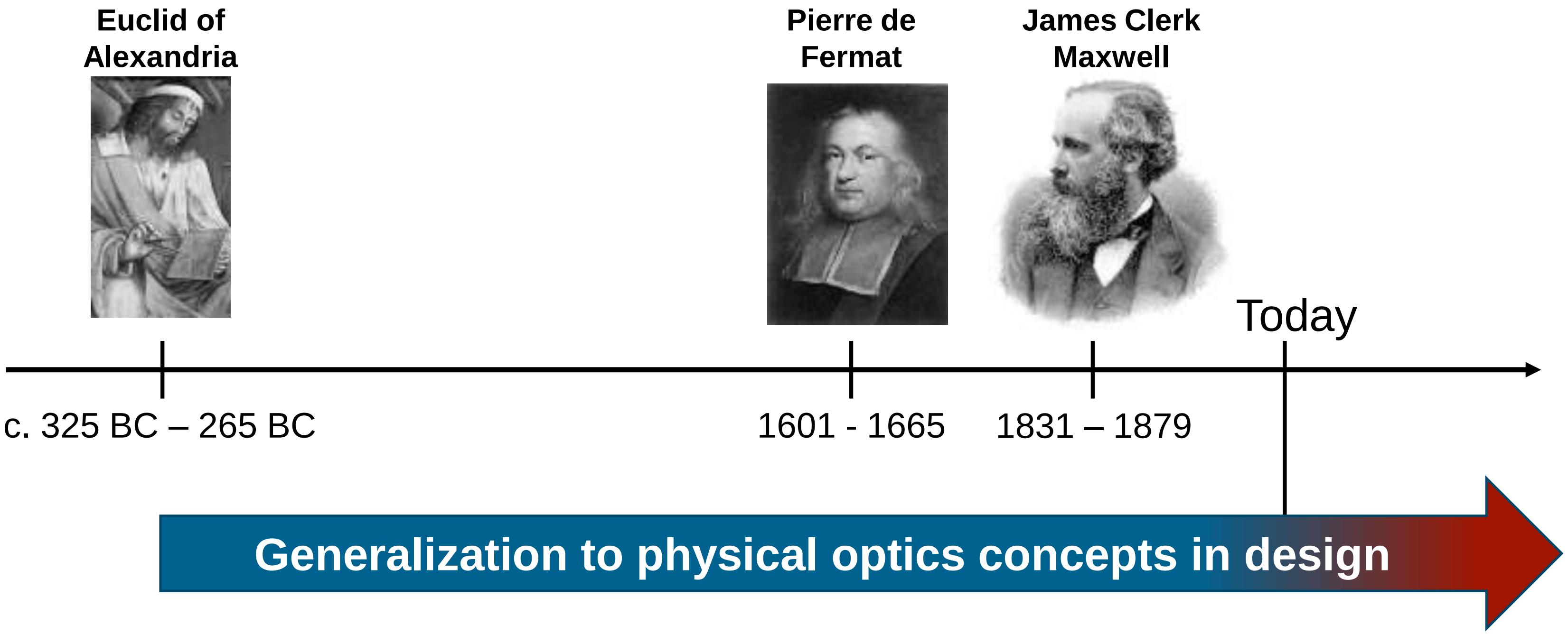
2000

Physical optics provides the fundament of innovative concepts for harnessing light!

Physical Optics to Overcome Limitations of Ray Optics?

- Theoretically solid inclusion of
  - Diffraction at apertures and of light beams
  - Vectorial effects and polarization; no paraxial assumption
  - Coherence phenomena and source models
  - Ultrashort pulse modeling
  - Interference and speckles
  - Diffraction at gratings and diffractive optical elements
  - Scattering effects
  - Crystal and metamaterial modeling
  - Nano- and microoptics
  - Special effects like Gouy phase shift and Goos Hänchen shift
  - Nonlinear optics
  - … any effect in classical optics

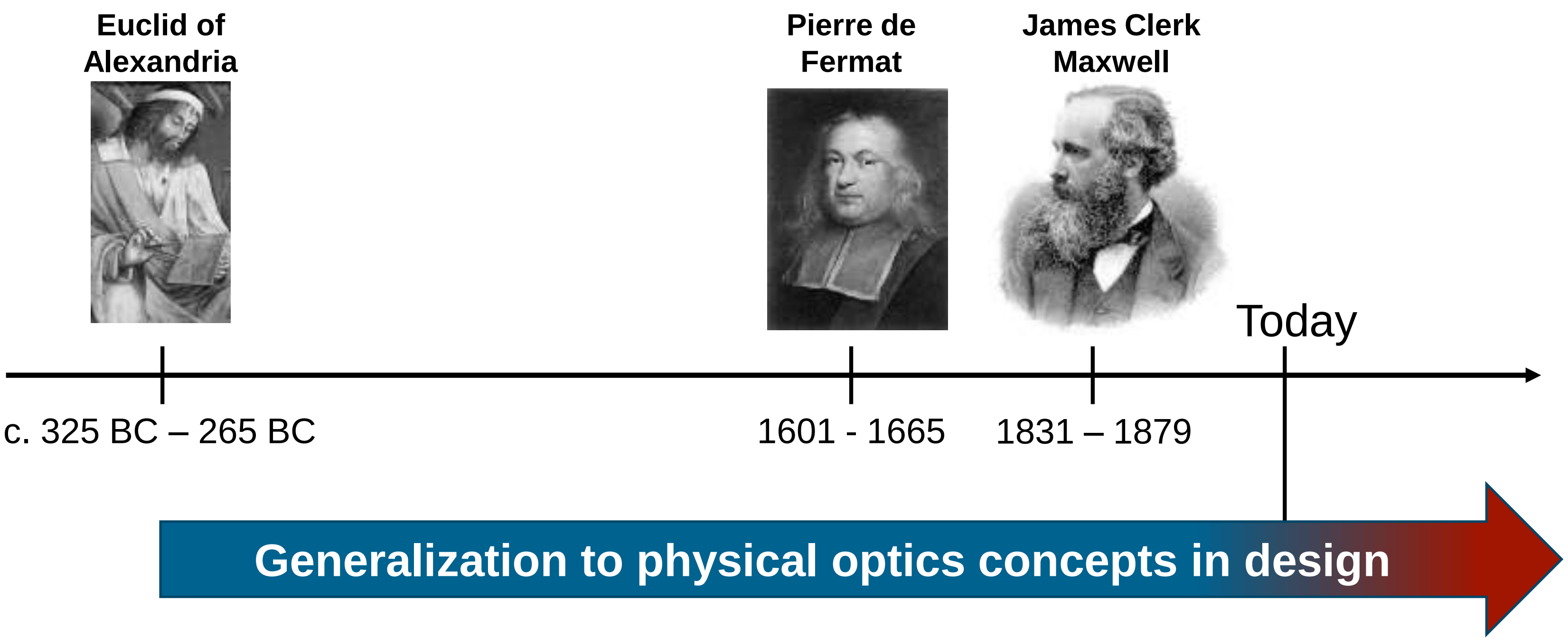
Trend in Optical Design: Physical Optics



It’s time for a paradigm shift!

Ray tracing remains an extremely useful technique **embedded in a more general approach**!

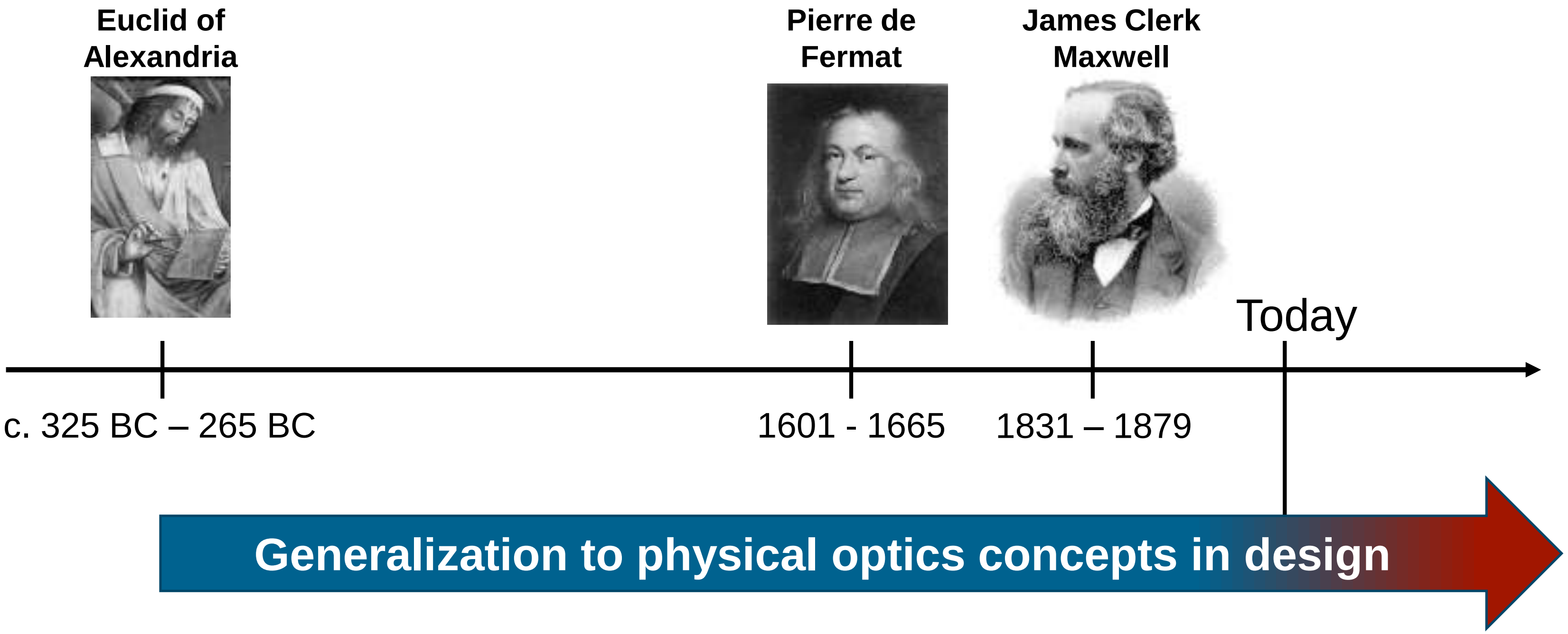
Trend in Optical Design: Physical Optics



It’s time for a paradigm shift!

Physical optics do not replace ray tracing, but enriches our way to do optical design. We can just win!

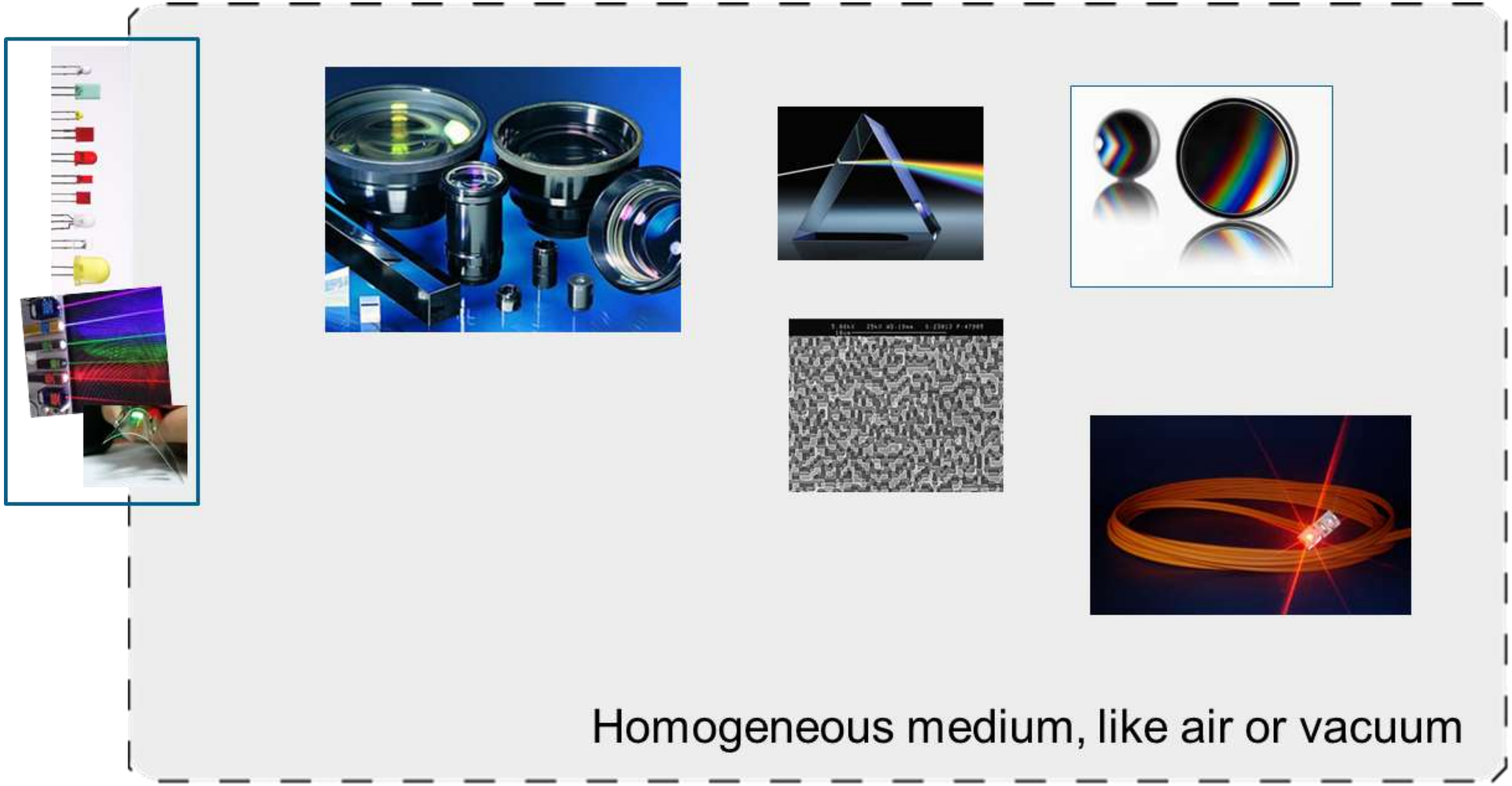
Trend in Optical Design: Physical Optics



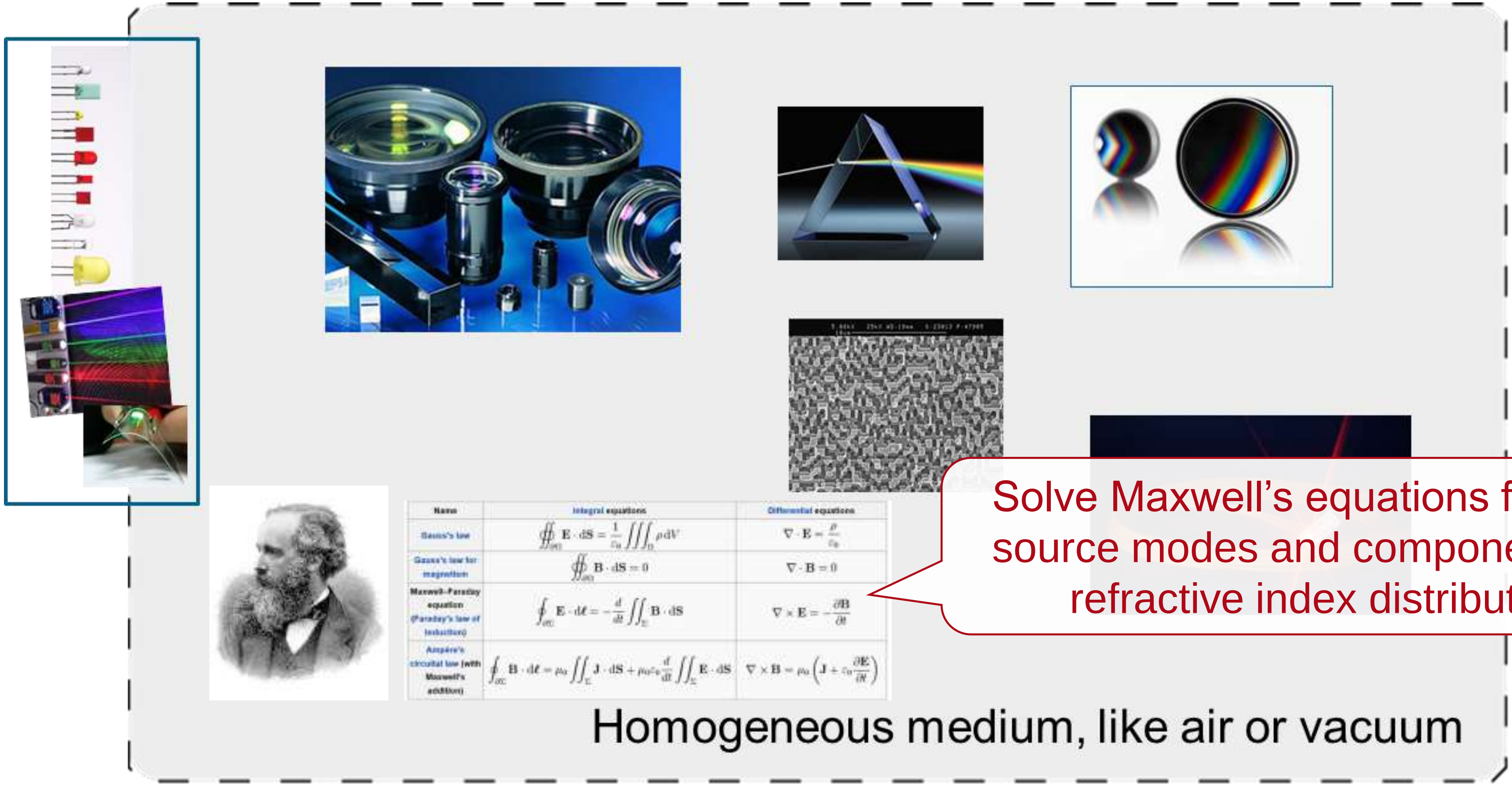
It’s time for a paradigm shift!

Physical optics do not replace ray tracing, but enriches our way to do optical design. We can just win – **if we do it smart!**

Physical-Optics System Modeling



Physical-Optics System Modeling

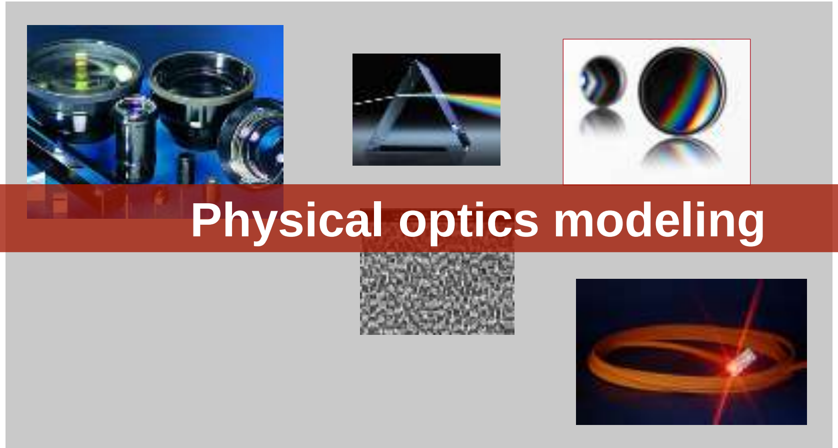


Solve Maxwell's equations for given source modes and components, i.e. refractive index distribution.

General Physical-Optics System Modeling

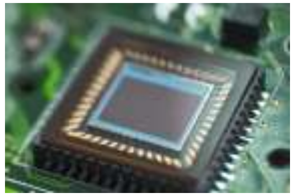
Sources

Components



Physical optics modeling

Detectors



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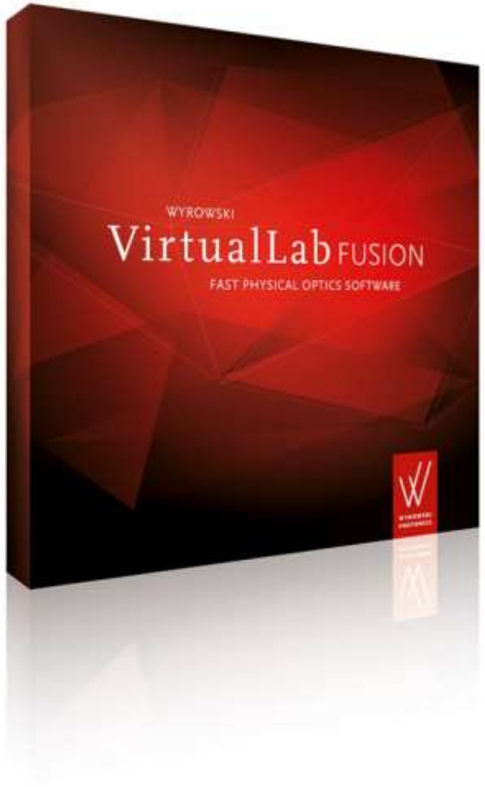
Source modeling in VirtualLab Fusion

The concept



Source Modeling

Source → Source field

- Laser
- Laser diode
- LED
- OLED
- Lamp
- Natural light

Essential starting point for all follow-up modeling and design!

Source Modeling: Mode Decomposition

Source ⇒ Source modes

- Laser
- Laser diode
- LED
- OLED
- Lamp
- Natural light

- Any source field can be decomposed into coherent and mutually uncorrelated modes

With a suitable set of source modes any degree of coherence and polarization can be represented!

Source Modeling: Mode Decomposition

Source → Source modes

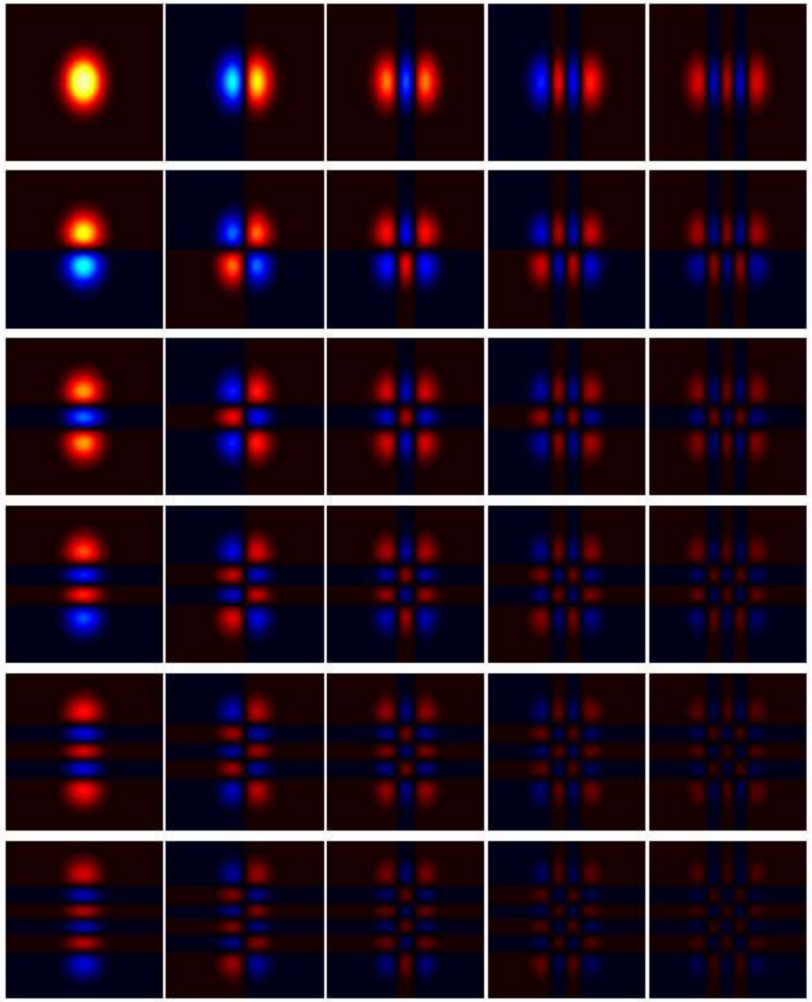
- Laser
- Laser diode
- LED
- OLED
- Lamp
- Natural light

- Any source field can be decomposed into coherent and mutually uncorrelated modes
  - Gaussian modes

Source Modeling: Gaussian Modes (Hermite)

Source → Source modes

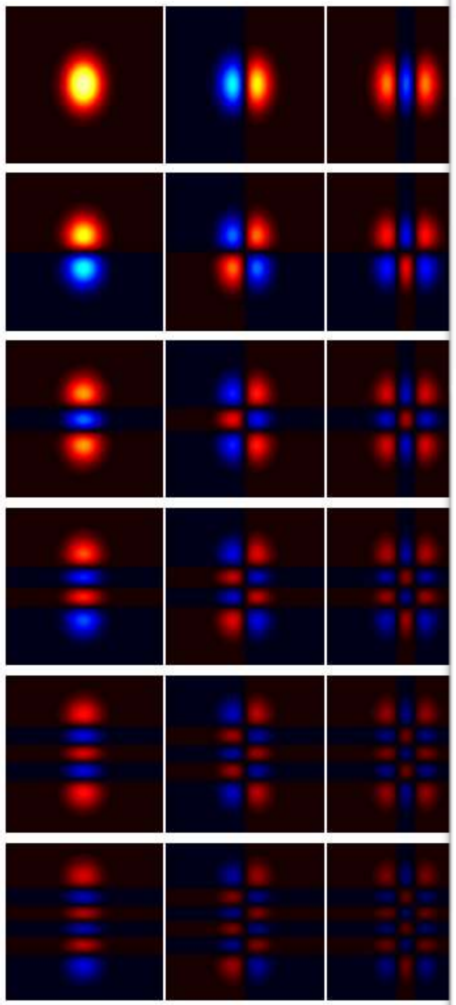
- Laser
- Laser diode
- LED
- OLED
- Lamp
- Natural light

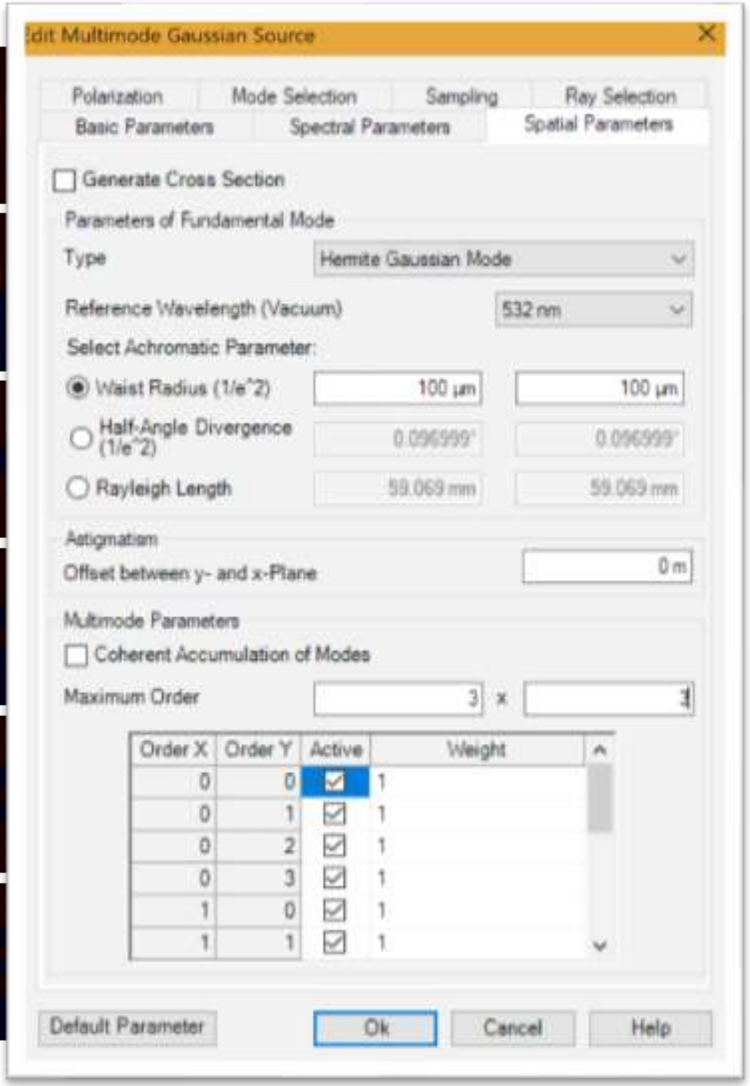


Source Modeling: Gaussian Modes (Hermite)

Source ⇨ Source modes

- Laser
- Laser diode
- LED
- OLED
- Lamp
- Natural light

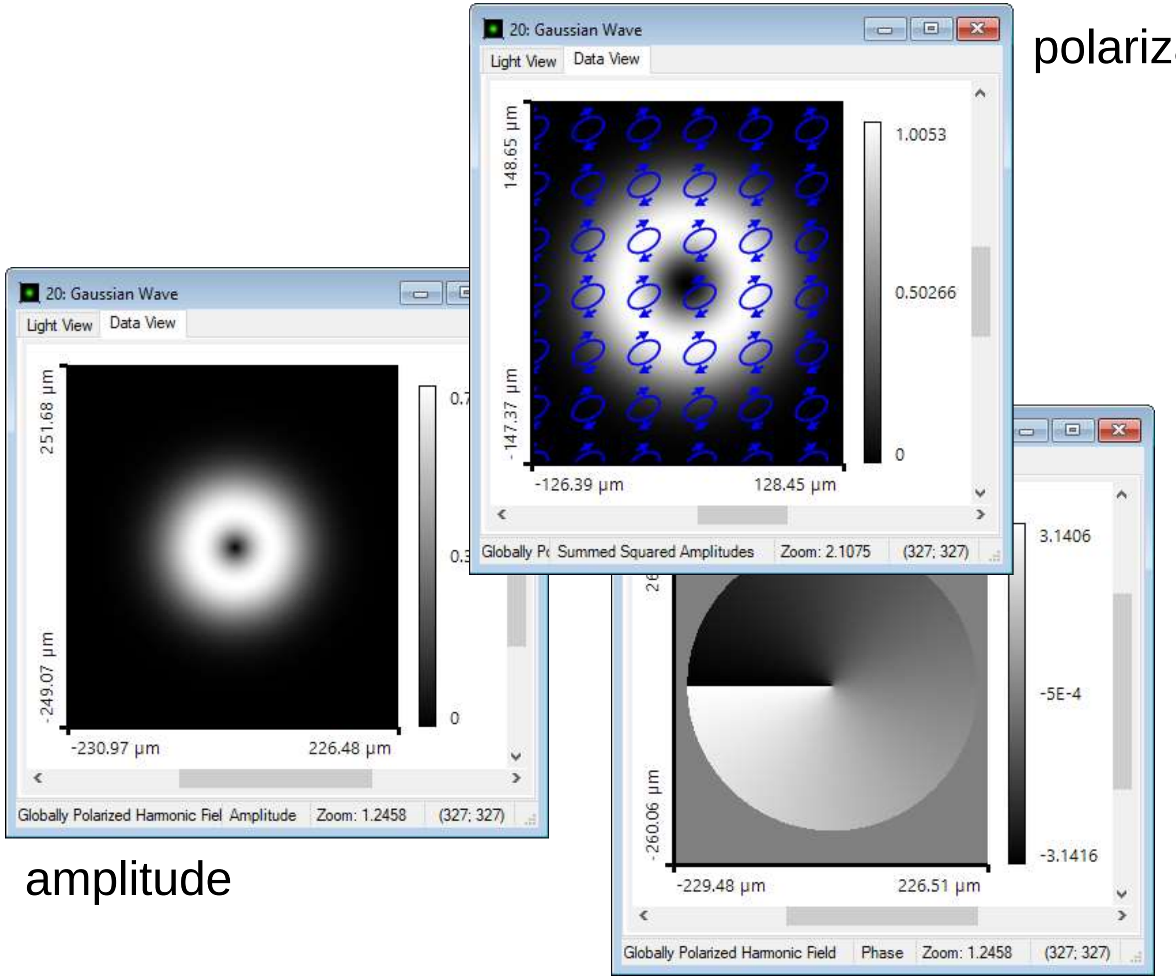




Source Modeling: Gaussian Modes (Gaussian Laguerre)

Source → Source modes

- Laser
- Laser diode
- LED
- OLED
- Lamp
- Natural light

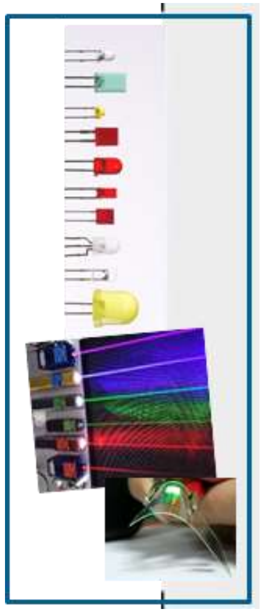


polarization

amplitude

phase

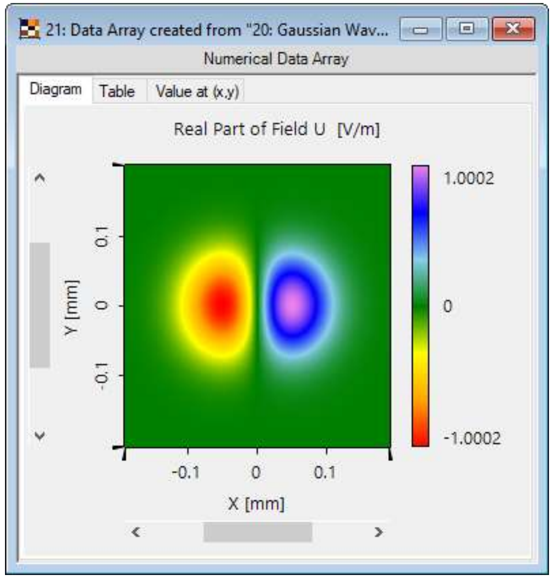
Source Modeling: Mode Decomposition (Laguerre Gaussian)



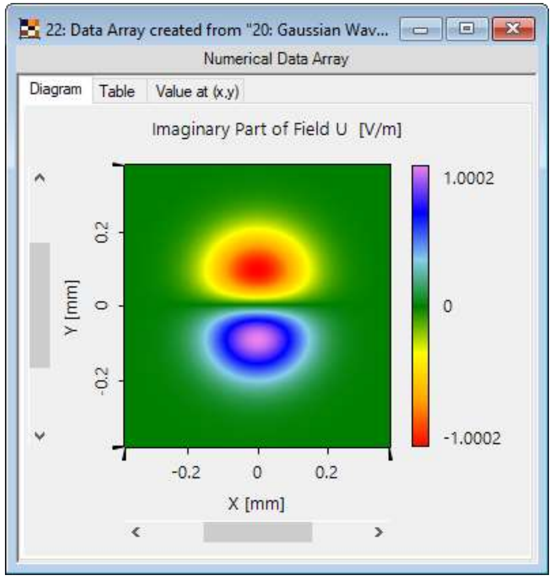
Source

Source modes

- Laser
- Laser diode
- **VCSELs**
- LED
- OLED
- Lamp
- Natural light



real part

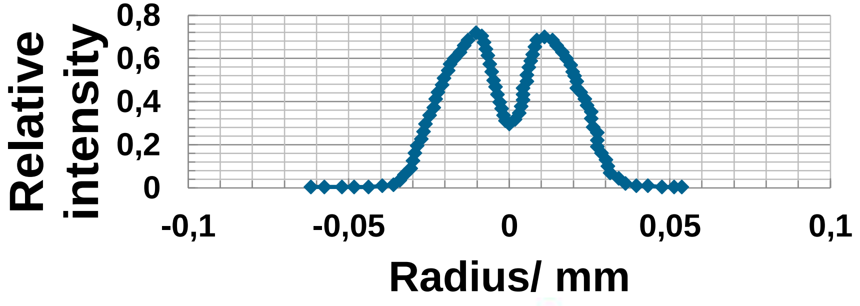


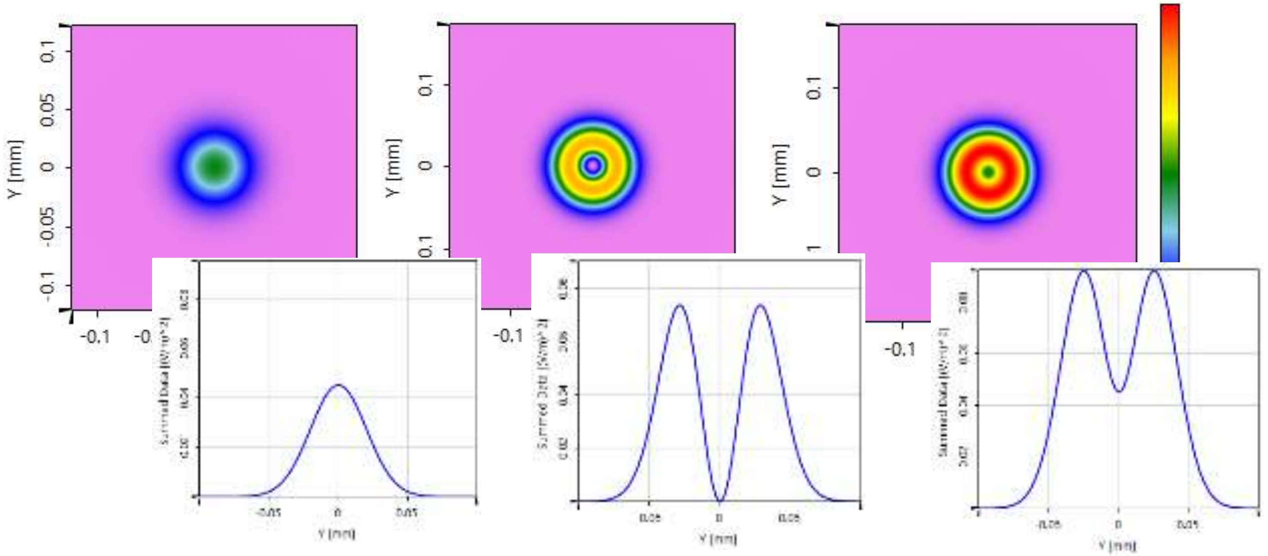
imaginary part

Source Modeling: Mode Decomposition for VCSEL

Source ⇨ Source modes

- Laser
- Laser diode
- LED
- OLED
- Lamp
- Natural light





Mode (0, 0) Mode (0, 1) Sum

Source Modeling: Mode Decompositon

Source → Source modes

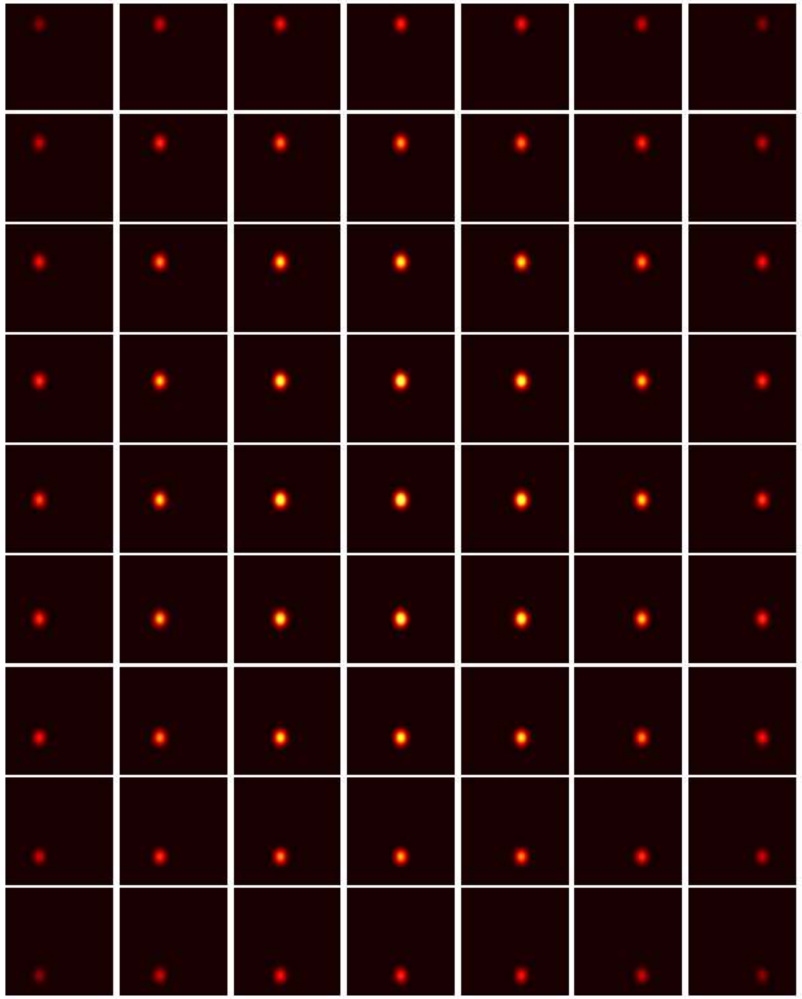
- Laser
- Laser diode
- LED
- OLED
- Lamp
- Natural light

- Any source field can be decomposed into coherent and mutually uncorrelated modes
  - Gaussian modes
  - Plane wave modes
  - Shifted modes, e.g.
    - Spherical wave
    - Lambertian mode

Source Modeling: Shifted Modes

Source ⇨ Source modes

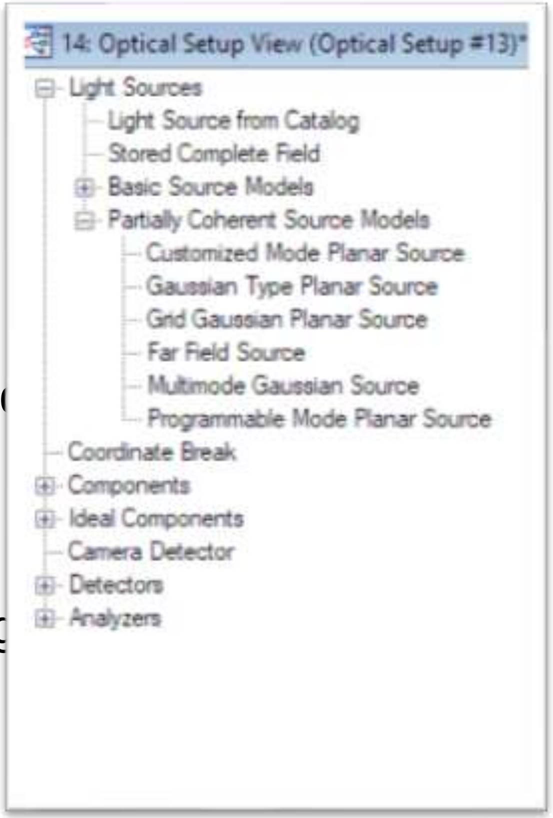
- Laser
- Laser diode
- LED
- OLED
- Lamp
- Natural light

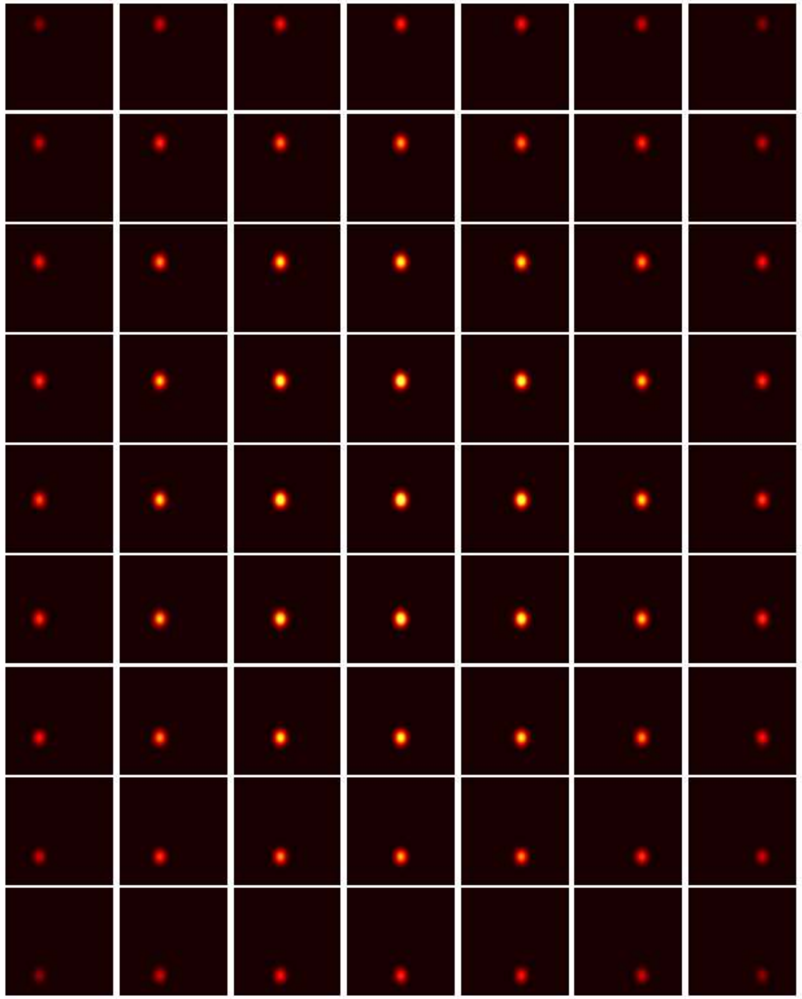


Source Modeling: Shifted Modes

Source

- Laser
- Laser dio
- LED
- OLED
- Lamp
- Natural lig



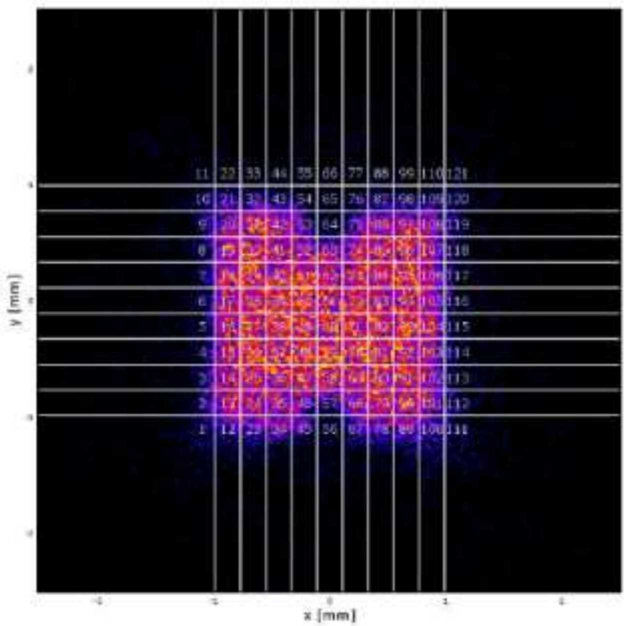


Source Modeling: Modes from Ray Data

Source → Source modes

- Laser
- Laser diode
- **LED**
- OLED
- Lamp
- Natural light

- Any source field can be decomposed into coherent and mutually uncorrelated modes
- Modes from ray data

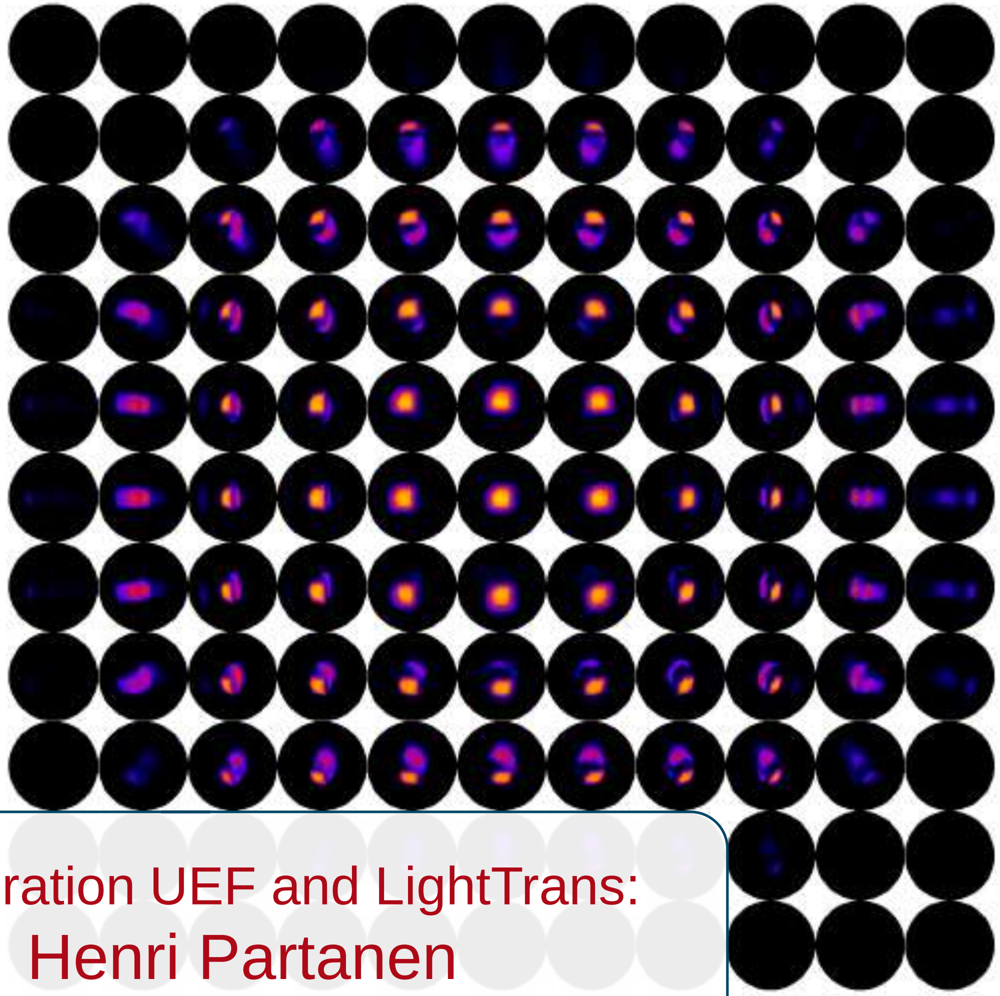


Osram GW CSSRM2pm LED (dome lens)

Source Modeling: Modes from Ray Data

Source → Source modes

- Laser
- Laser diode
- **LED**
- OLED
- Lamp
- Natural light



Cooperation UEF and LightTrans:
Henri Partanen

Illustration 1: Source Definition and Main Window Modeling

- Create two waves.
  - By using the permanent ribbons, please generate two beams:

Plane wave	Spherical wave
Diameter: 1.28 mm x 1.28 mm	Diameter: 1.28 mm x 1.28 mm
Single wavelength: 632.8 nm	Radius: 100 mm
Polarization: linearly polarized 0°	Single wavelength: 632.8 nm
	Polarization: linearly polarized 0°

  - Add both beams
  - Check the polarization state of the result field
  - Calculate the related magnetic field
  - Then create a spherical wave with polarization 90°, check the coherent addition result

Main window modeling

Illustration 1: Video in VLF

Klick the following link to watch the video:

https://youtu.be/CgigZ_5WOtU

Task 1 Donut mode creation

- Donut mode can be created by adding two Hermite Gaussian modes up.
  - By using the permanent ribbons, please generate two Gaussian beams:

Hermite Gaussian mode: (1,0)
Rayleigh length: 10 mm x 10 mm
Single wavelength: 632.8 nm
Polarization: linearly polarized 0°

Hermite Gaussian mode: (0,1)
Rayleigh length: 10 mm x 10 mm
Single wavelength: 632.8 nm
Polarization: linearly polarized 90°

  - Add both Gaussian beam
  - Check the polarization state of the result field
  - Detect the beam parameters of electric field
  - Calculate the related Poynting Vector distribution

Main window modeling

Task 1: Video

Klick the following link to watch the video:

https://youtu.be/gEpkXoRLOZ0

Source Modeling: Mode Decompositon

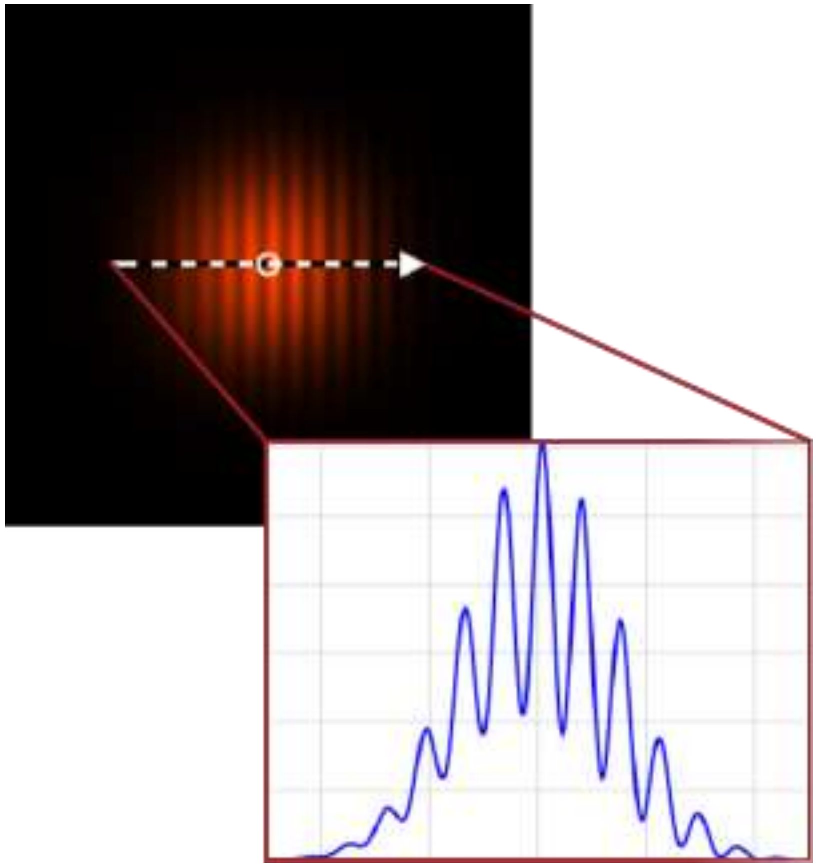
Source → Source modes

- Laser
- Laser diode
- LED
- OLED
- Lamp
- Natural light

- Any source field can be decomposed into coherent and mutually uncorrelated modes
  - VirtualLab enables the usage of any kind of source modes
- Spatial modes can be combined with any power frequency spectrum

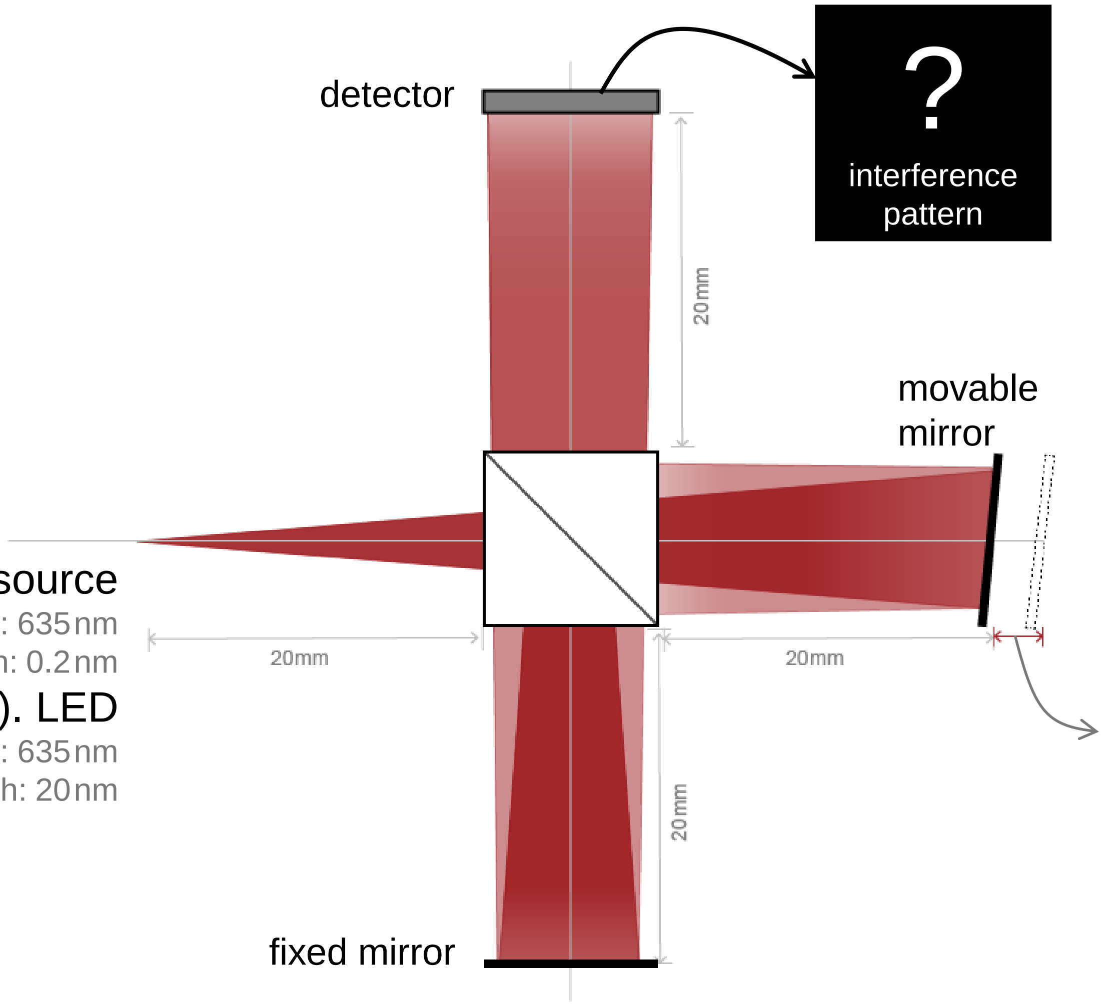
Temporal Coherence Property Measured with Michelson Interferometer

Abstract



Michelson interferometer is a typical configuration for optical interferometry. Such a basic setup is also widely used for educational purpose, e.g., to explore the temporal coherent properties of sources with different spectrum bandwidth. This use case takes one laser source and one LED as the sources to check the contrast of interference pattern, as well as the coherent lengths of both sources.

Modeling Task



a). Laser source
- wavelength: 635 nm
- spectrum bandwidth: 0.2 nm

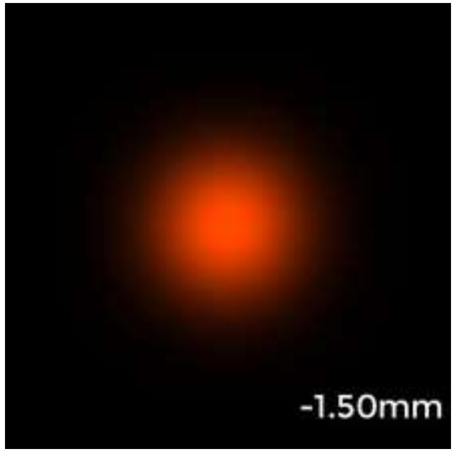
b). LED
- wavelength: 635 nm
- spectrum bandwidth: 20 nm

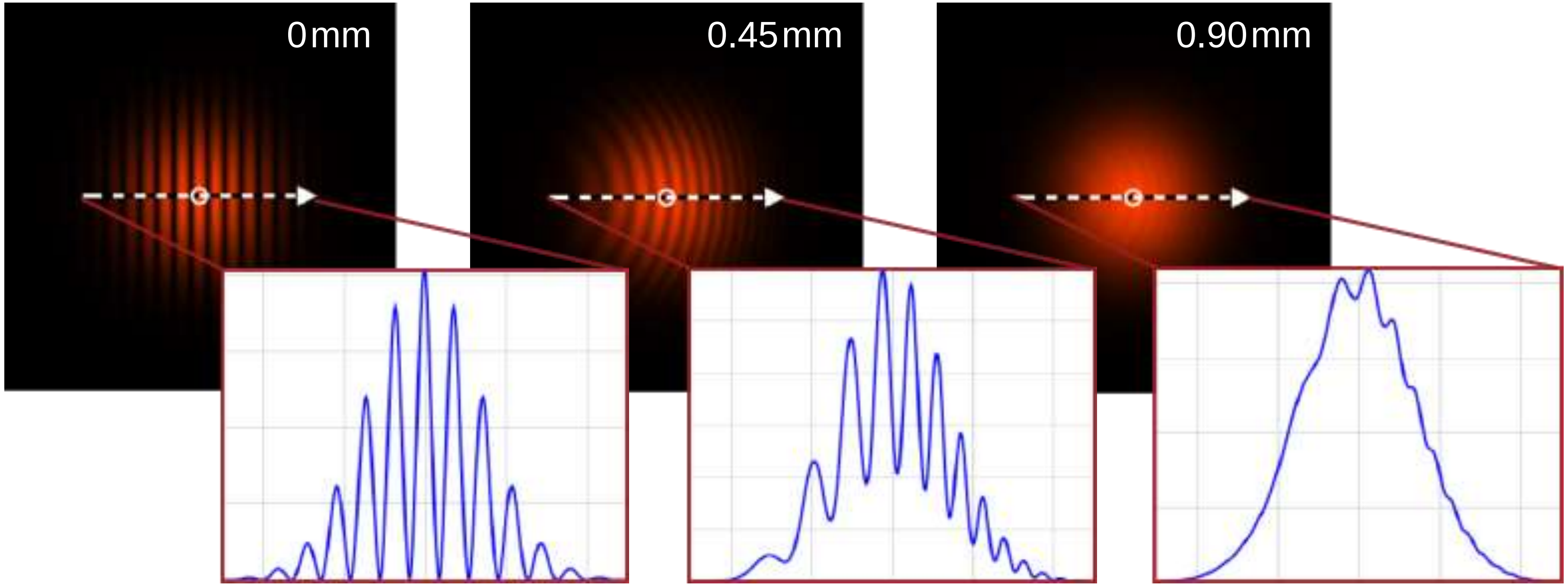
taking the source spectrum and the movement of mirror into consideration

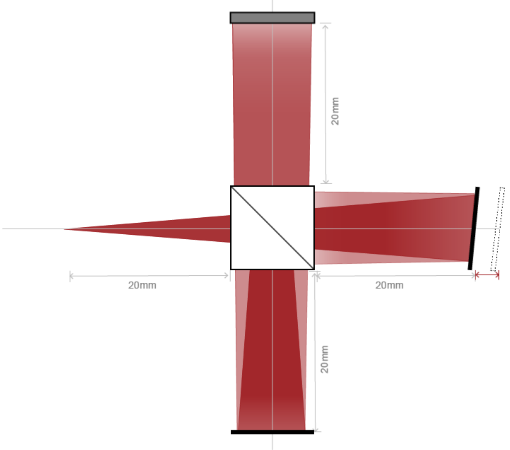
To recognize the interference pattern, we give a 0.05° rotation to the movable mirror.

a). -1.5 mm to 1.5 mm
b). -15 µm to 15 µm

Results: Laser Source



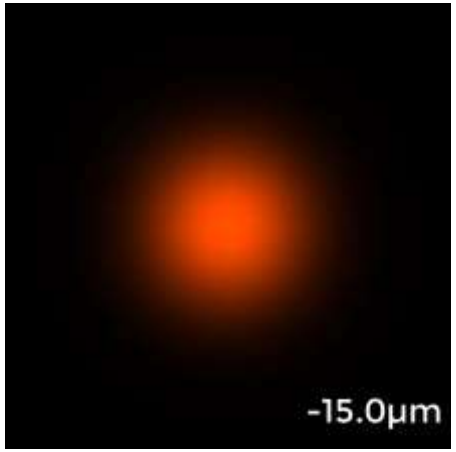


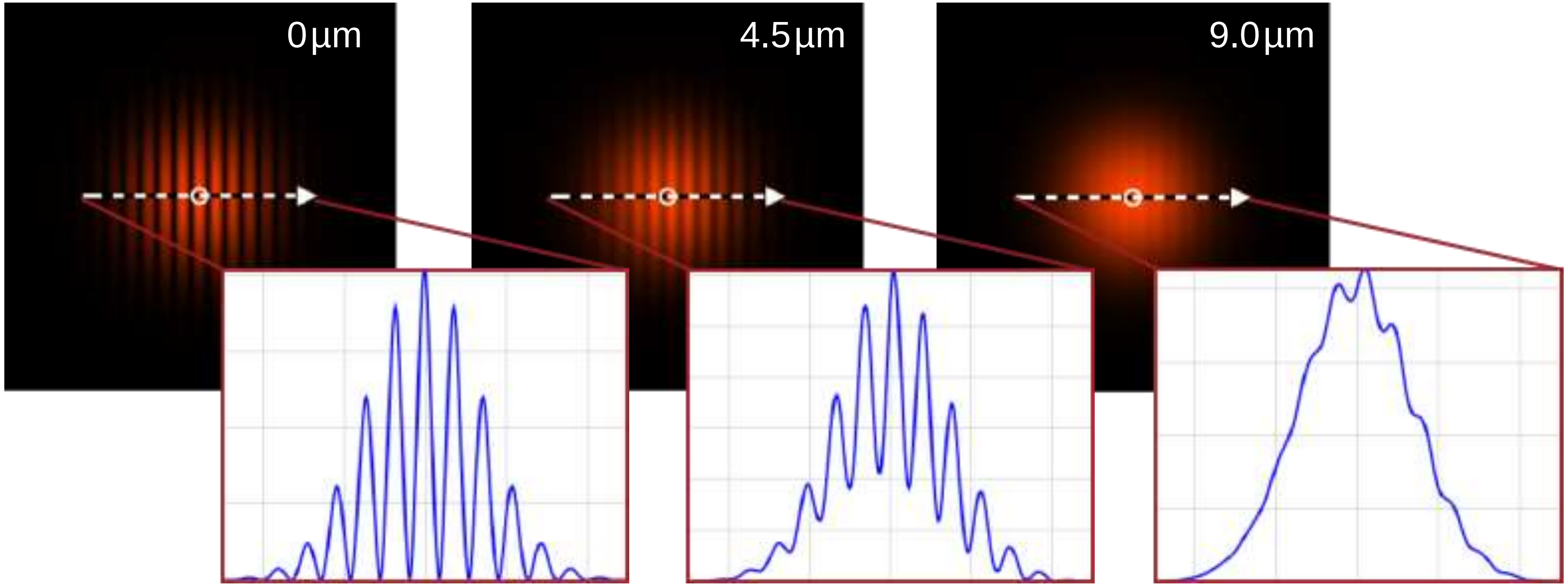


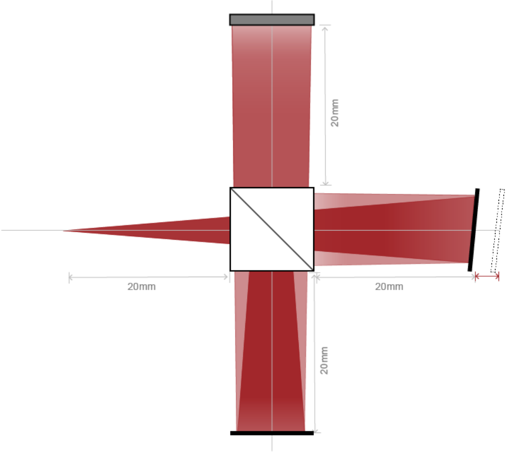
Coherent length here is around 2 mm. It matches that with literature, which is

$$L = \frac{\lambda^2}{\Delta\lambda} = \frac{635^2}{0.2}\ \text{nm} \approx 2\ \text{mm}$$

Results: Laser Source





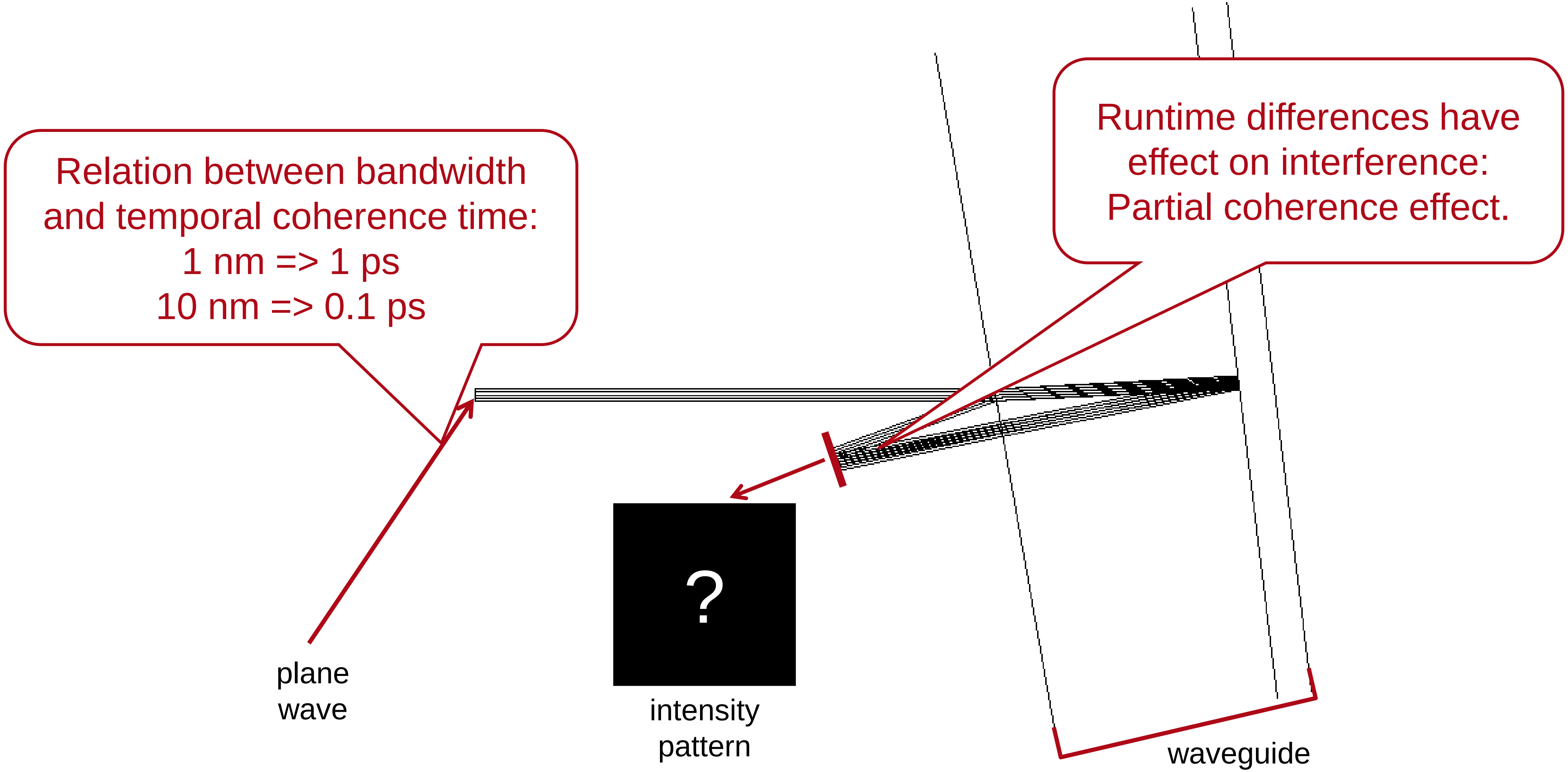


Coherent length here is around 20µm. It matches that with literature, which is

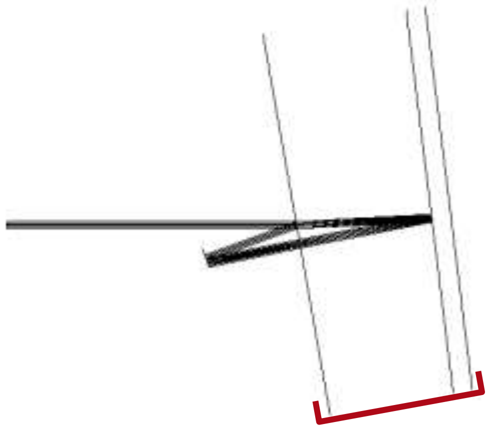
$$L = \frac{\lambda^2}{\Delta\lambda} = \frac{635^2}{20}\ \text{nm} \approx 20\ \mu\text{m}$$

Analysis of Coherence Effects in an Etalon Setup

Modeling Task

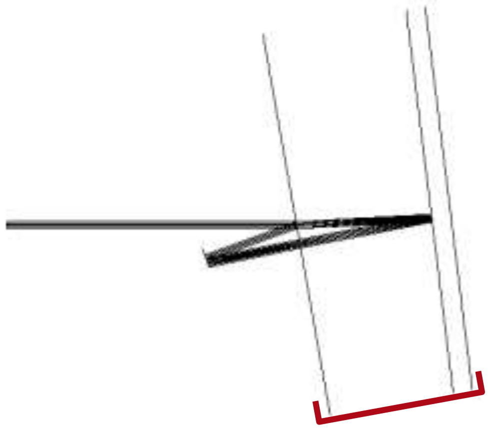


Specification: Etalon

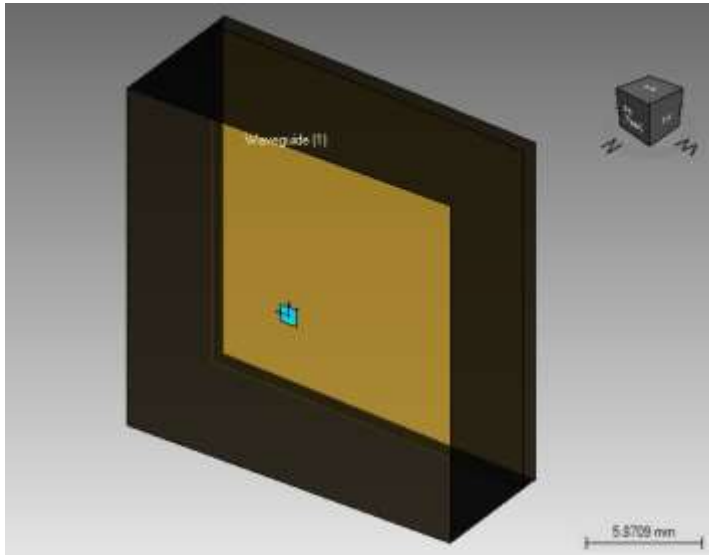


Parameter	Description / Value & Unit
component	Waveguide
number of surfaces	3
medium between surface 1 & 2	fused silica
medium between surface 1 & 2	silver
tilt of component	10°
tilt of plane surface 2 & 3	-3°

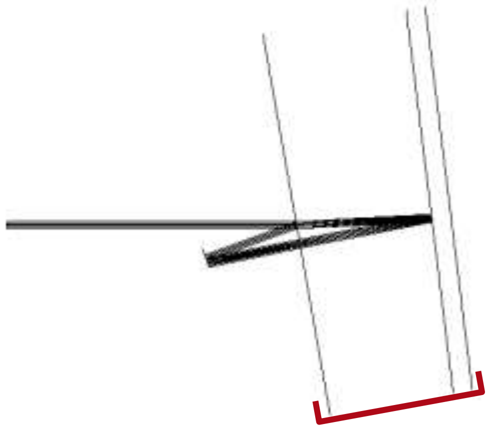
Specification: Grating of First Surface of Etalon



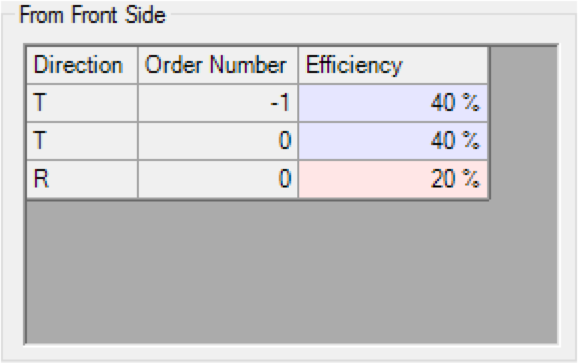
Parameter	Value & Unit
type	ideal grating
position	0 mm × 0 mm
size	0 mm × 0 mm
grating period	50 µm
efficiencies	defined manually



Specification: Grating of First Surface of Etalon

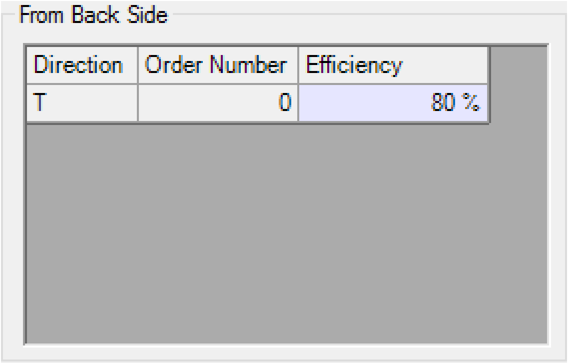


Parameter	Value & Unit
efficiency $T_{++}0$	40%
efficiency $T_{++}-1$	40%
efficiency $R_{+-}0$	20%
efficiency $T_{--}0$	80%



From Front Side

Direction	Order Number	Efficiency
T	-1	40 %
T	0	40 %
R	0	20 %

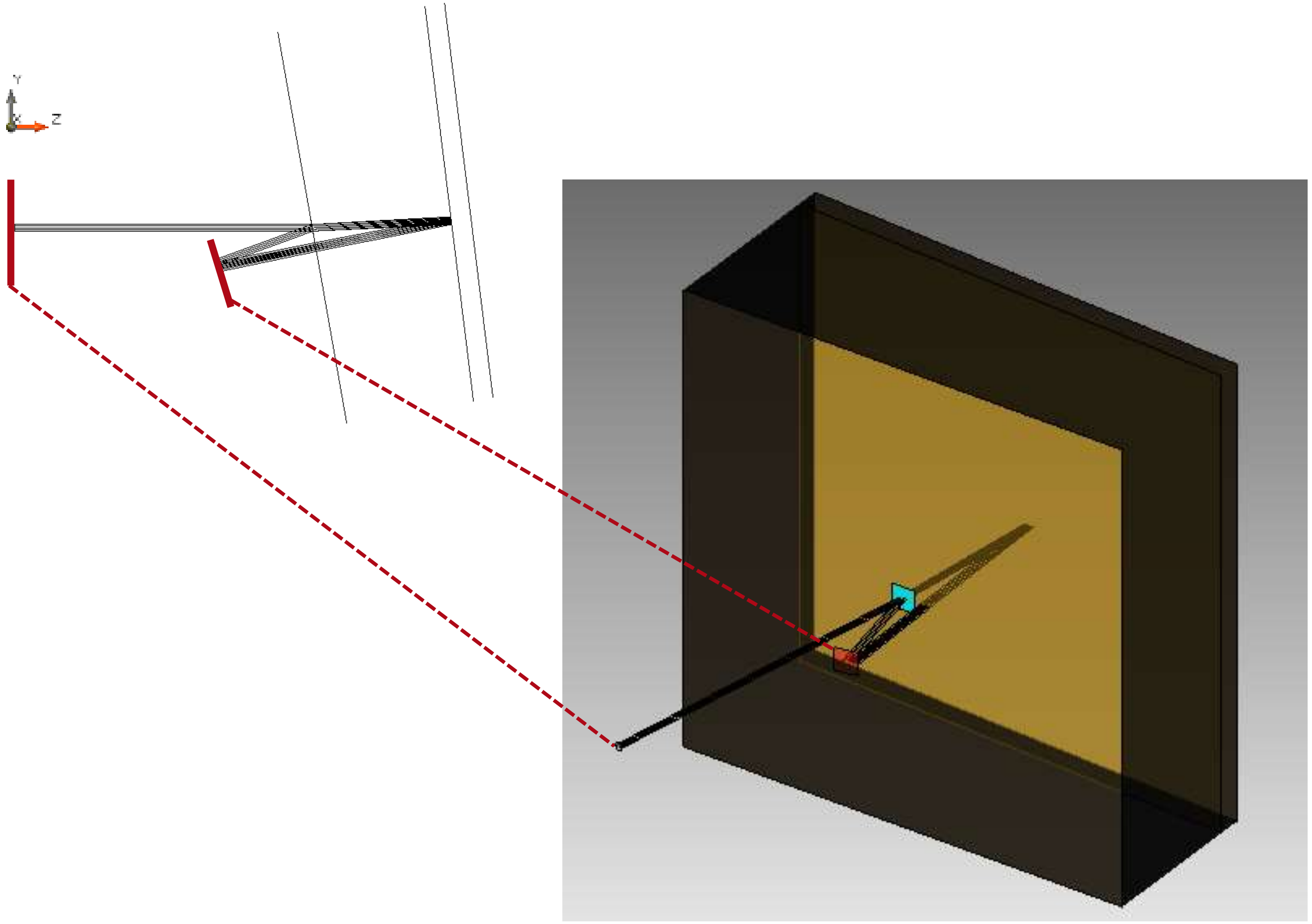


From Back Side

Direction	Order Number	Efficiency
T	0	80 %

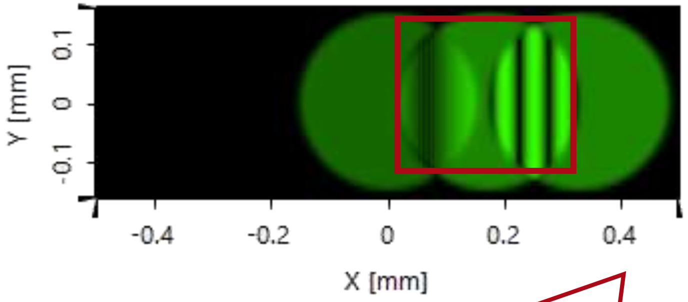
Note: The period and the efficiencies of the propagating orders are selected for demonstrational purpose.

Result: 3D Ray Tracing

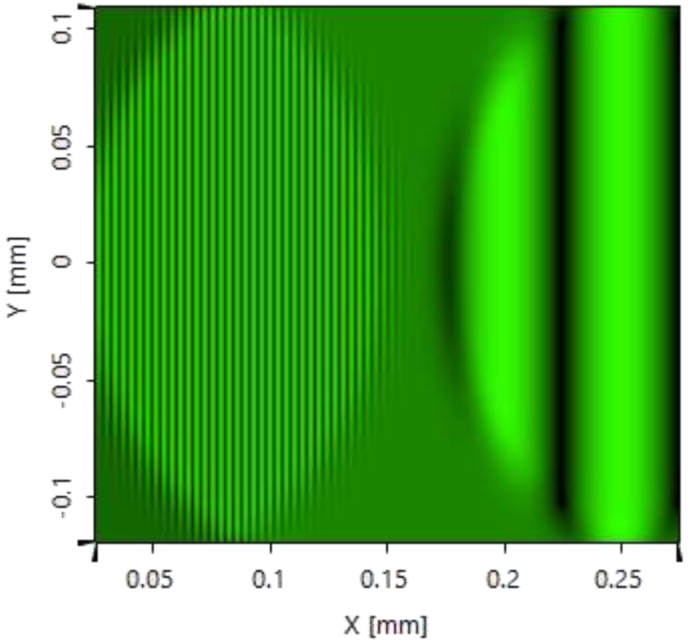


Result: Intensity Distribution (Coherently)

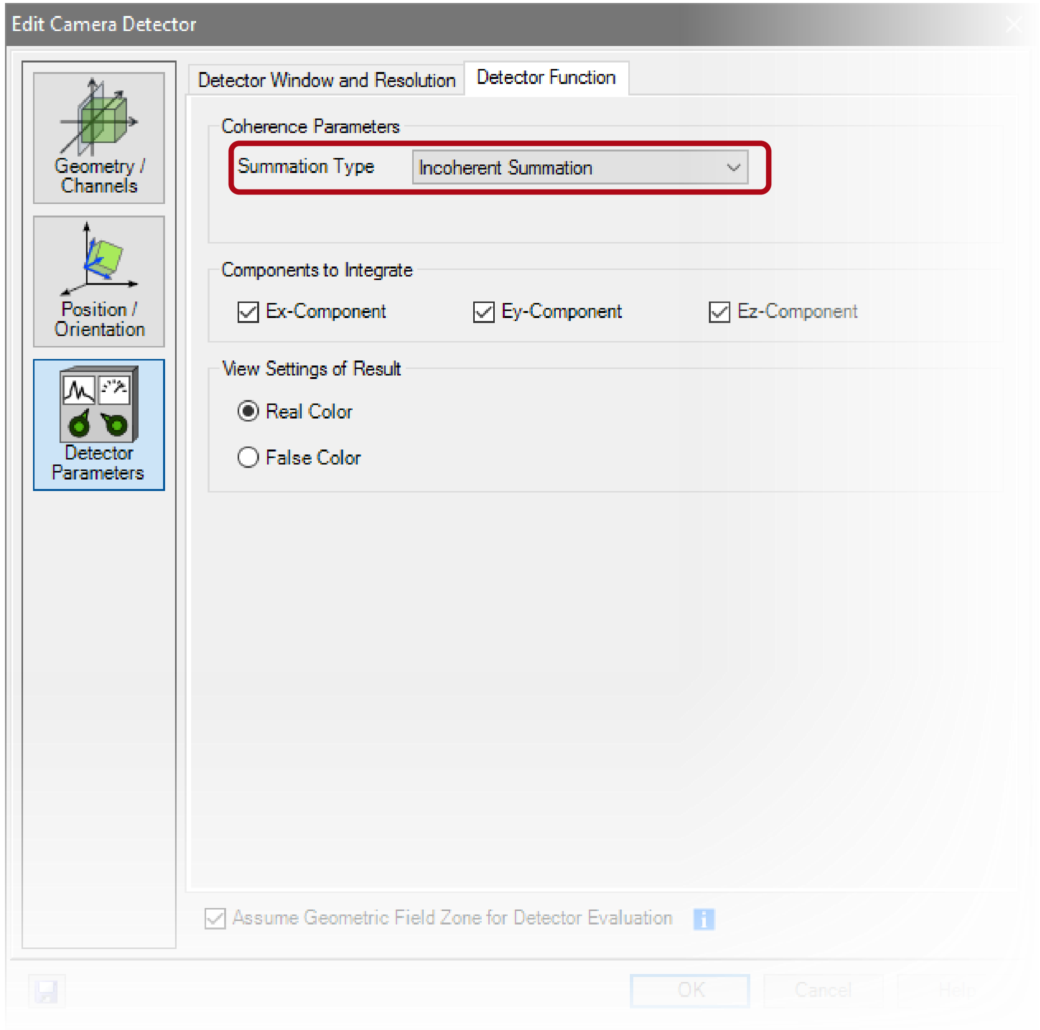
- The Camera Detector allows to define the coherence properties of the incident light.
- For a coherent incidence full interference pattern will be visible.

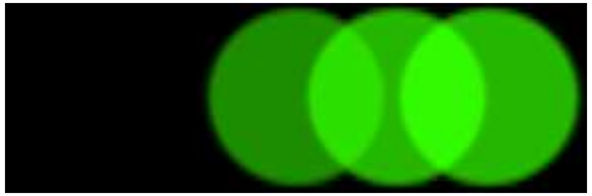


simulation time: ~2s



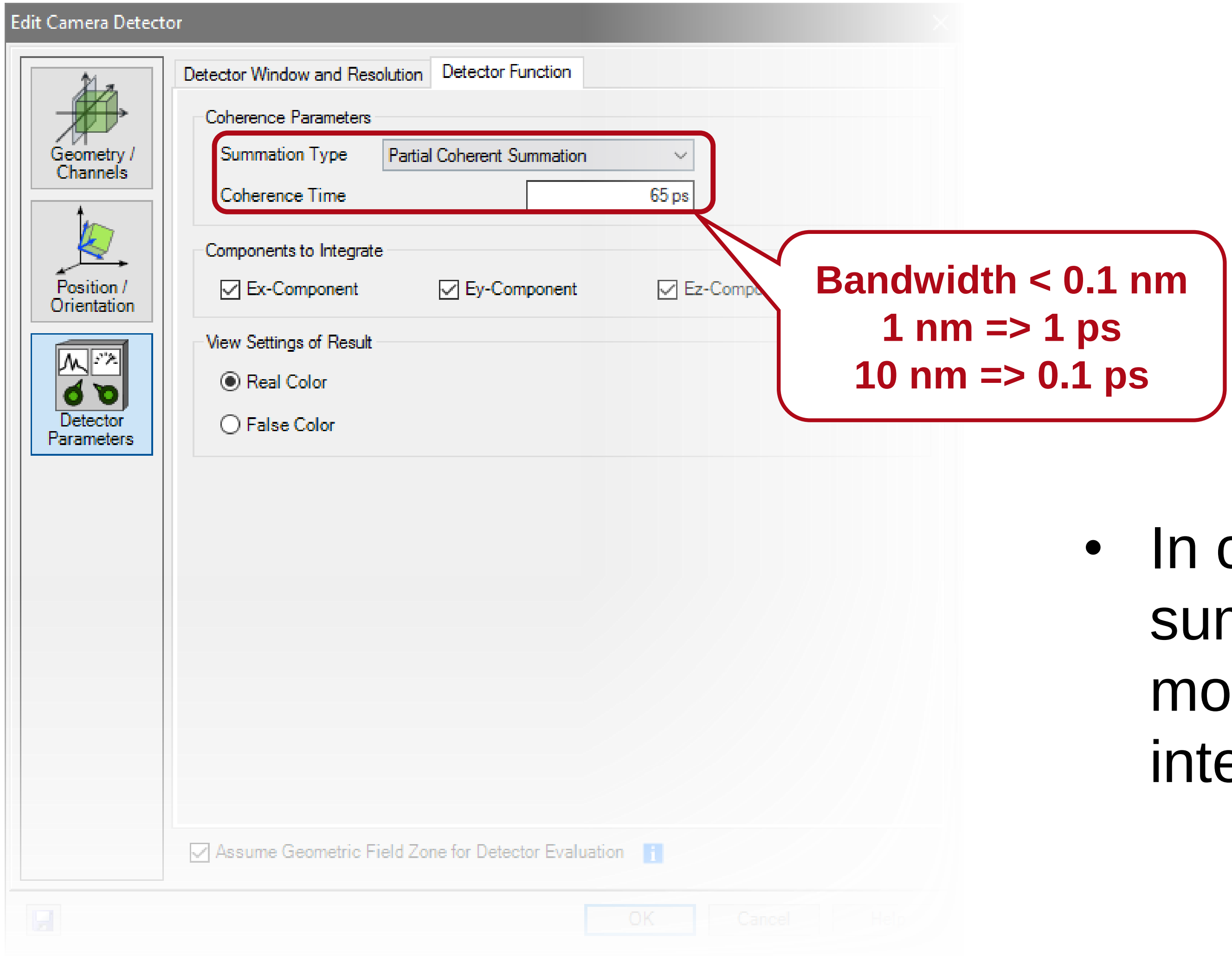
Result: Intensity Distribution (Incoherently)

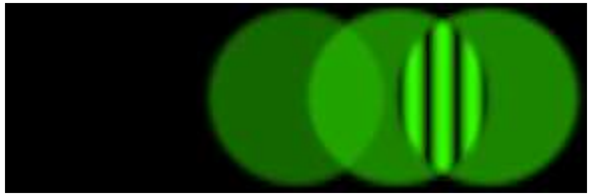




- In case of incoherent summation no interference pattern will appear.
- All modes are interpreted incoherently.

Result: Intensity Distribution (Partially Coherent)





- In case of partially coherent summation the run times of the modes will be investigated for the interference behavior.

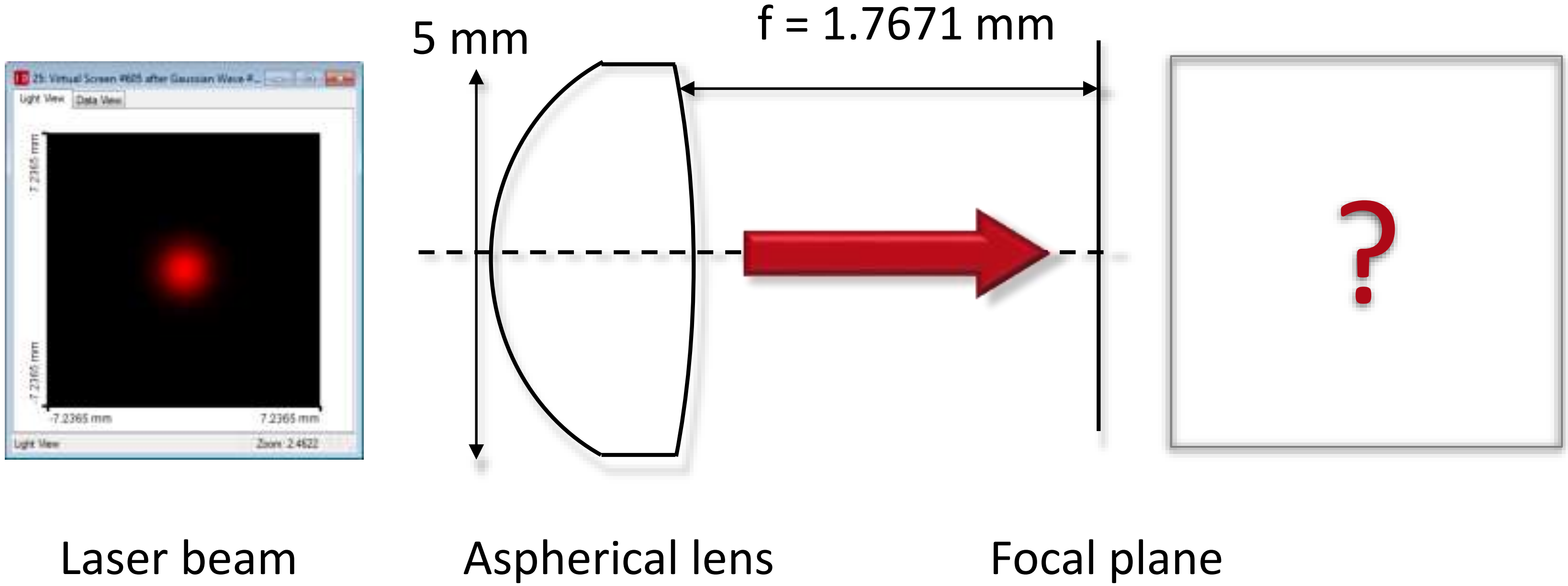
Pulsed Fields in Focal Regions

Example of strong spatiotemporal coupling

Task 15

Lens System Pulse Example

Example considers focusing of 5 fs pulse at 800 nm



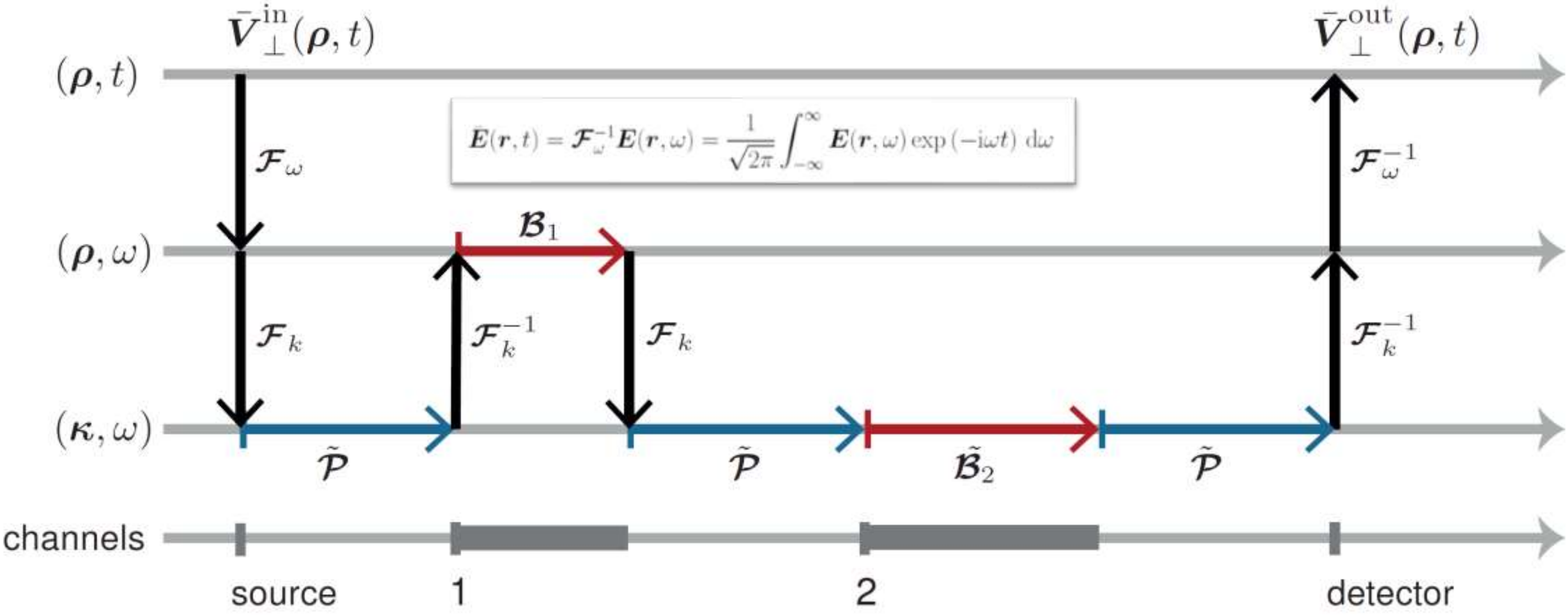
NA=0.68

$$\boldsymbol{E}(\boldsymbol{r},t) = \mathcal{F}_{\omega}^{-1}\boldsymbol{E}(\boldsymbol{r},\omega) = \frac{1}{\sqrt{2\pi}}\int_{-\infty}^{\infty} \boldsymbol{E}(\boldsymbol{r},\omega)\exp\left(-\mathrm{i}\omega t\right)\,\mathrm{d}\omega$$

Temporal pulse represented in frequency domain.

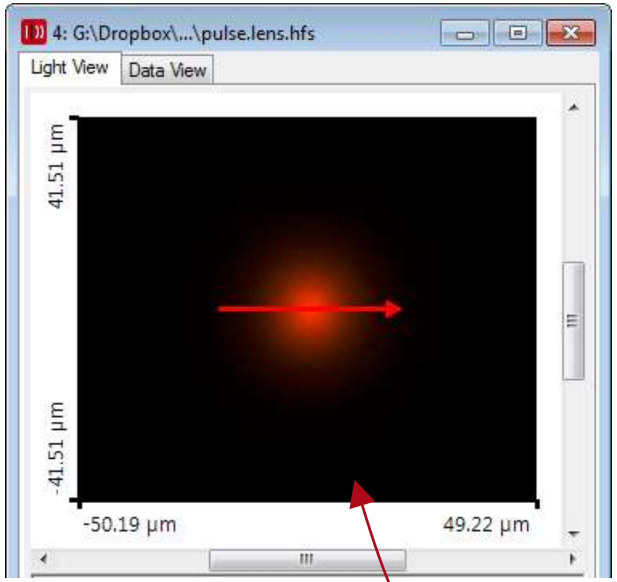
Pulse Modeling: Field Tracing Diagram Example

Sneak Peak!

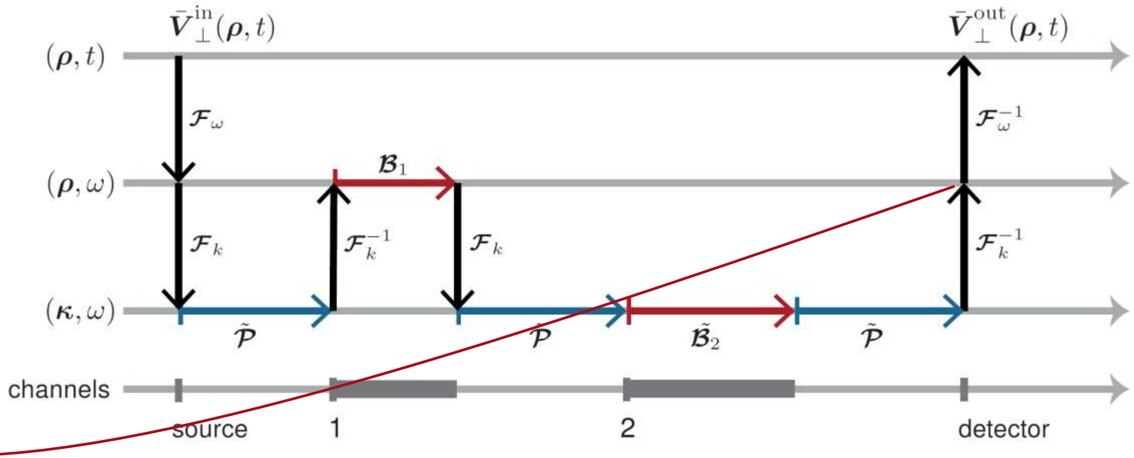


Lens System Pulse Example: Pulse in Focus

Result in frequency domain:
50 harmonic fields represent the pulse

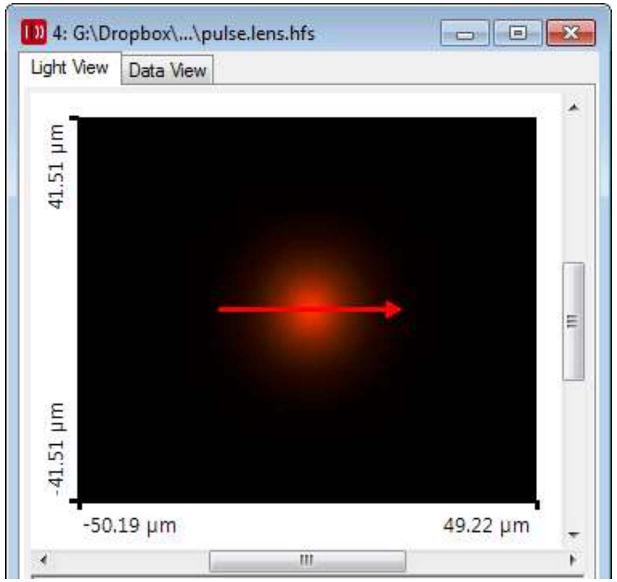


Calculation of envelope function in time domain at x-axis (40 µm)

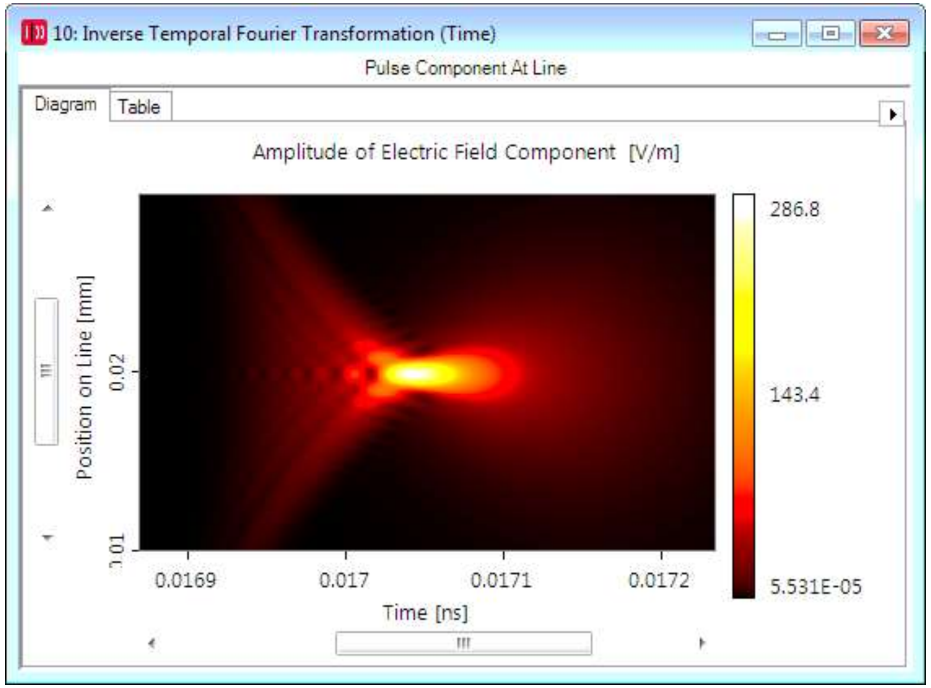


Spatiotemporal Evolution: Pulse in Focus

Result in frequency domain

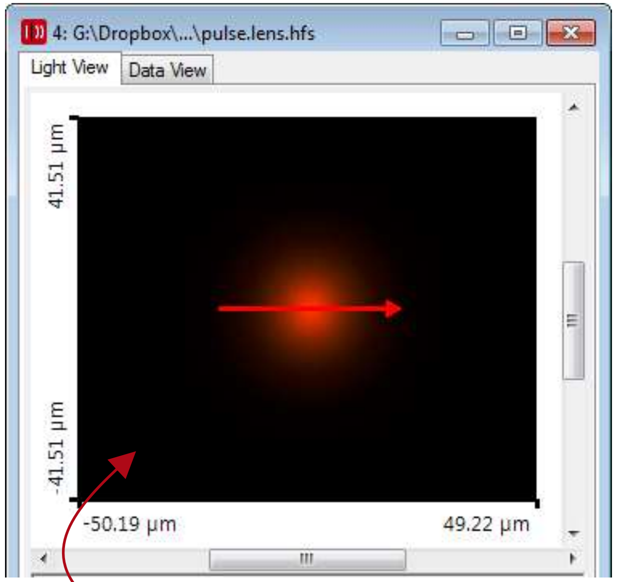


Time domain along x-axis: z-component

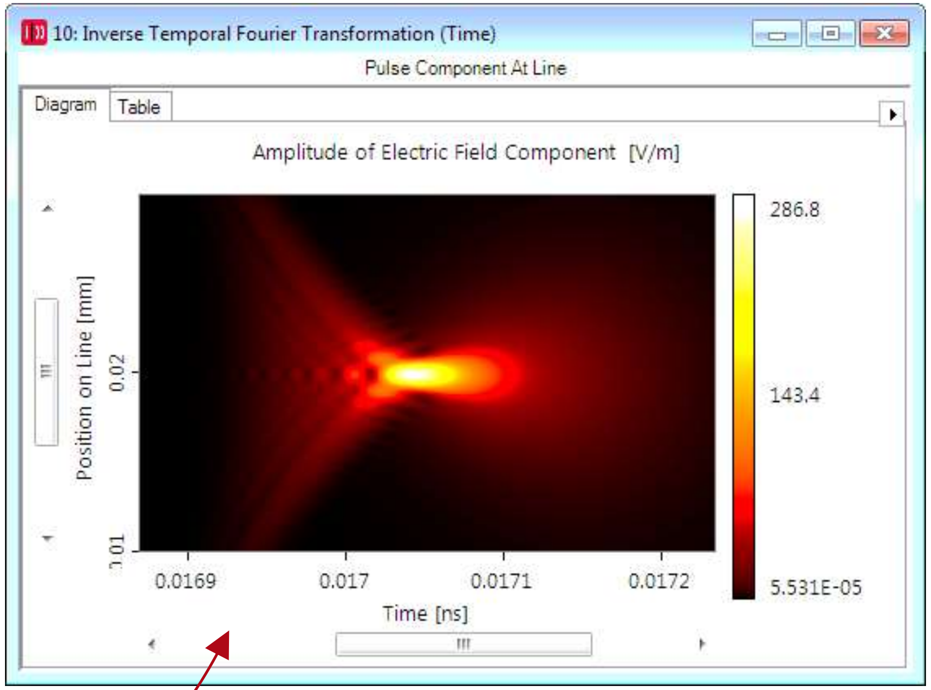


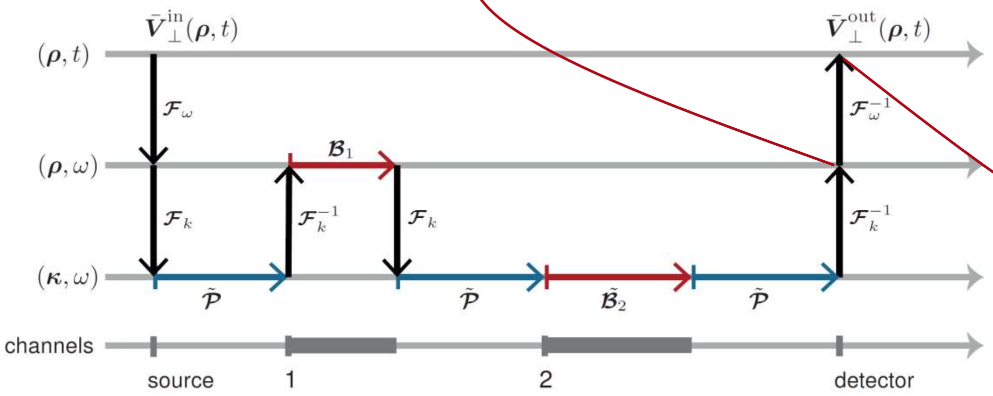
Spatiotemporal Evolution: Pulse in Focus

Result in frequency domain



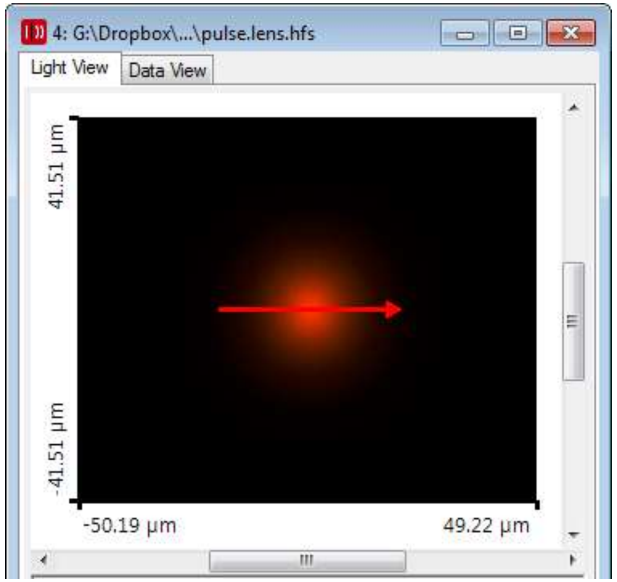
Time domain along x-axis: z-component



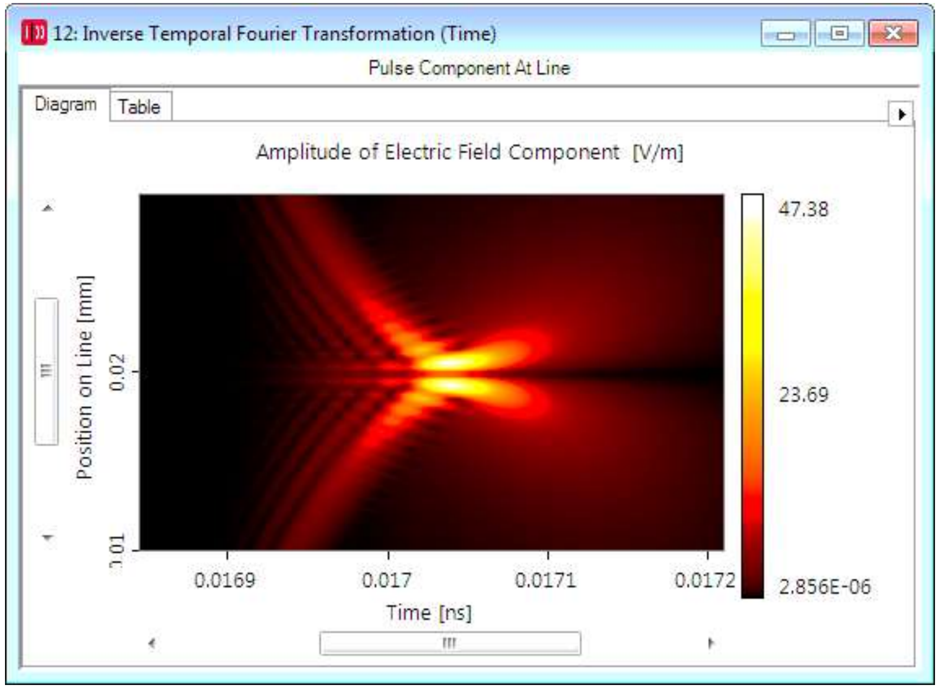


Spatiotemporal Evolution: Pulse in Focus

Result in frequency domain



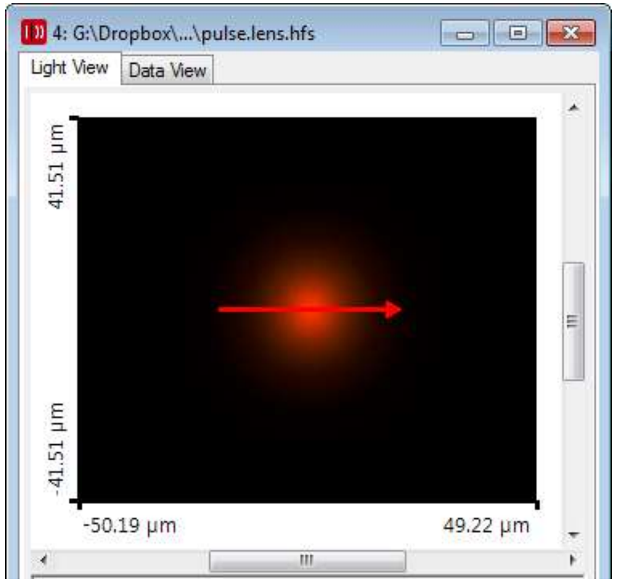
Time domain along x-axis: z-component

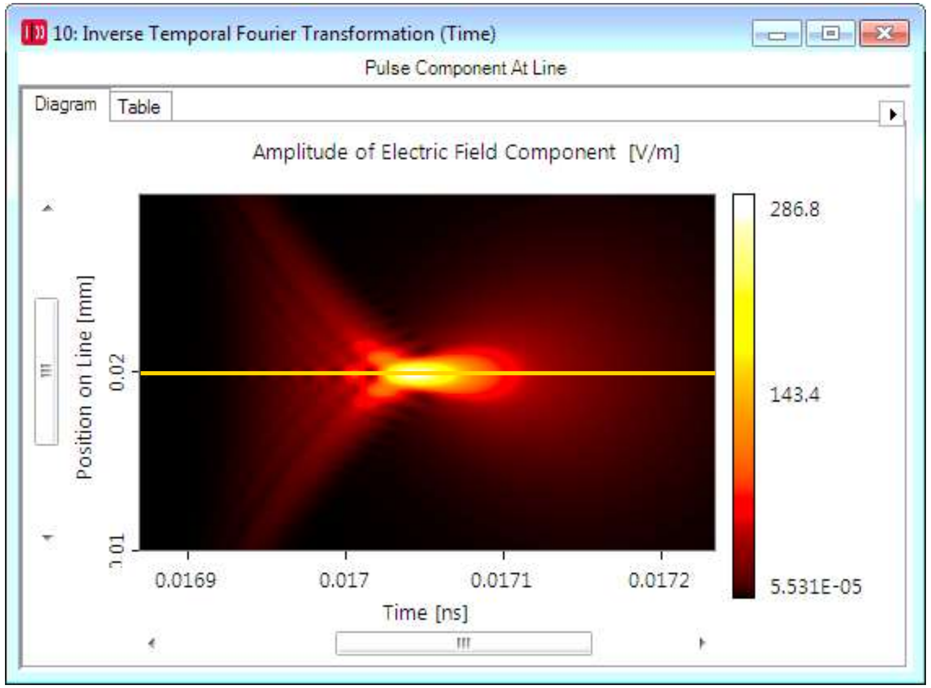


Spatiotemporal Evolution: Pulse in Focus

Time domain along x-axis: z-component

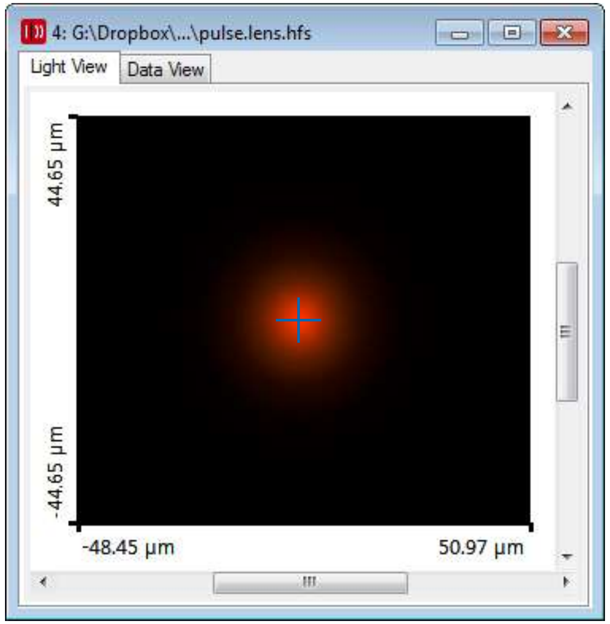
Result in frequency domain



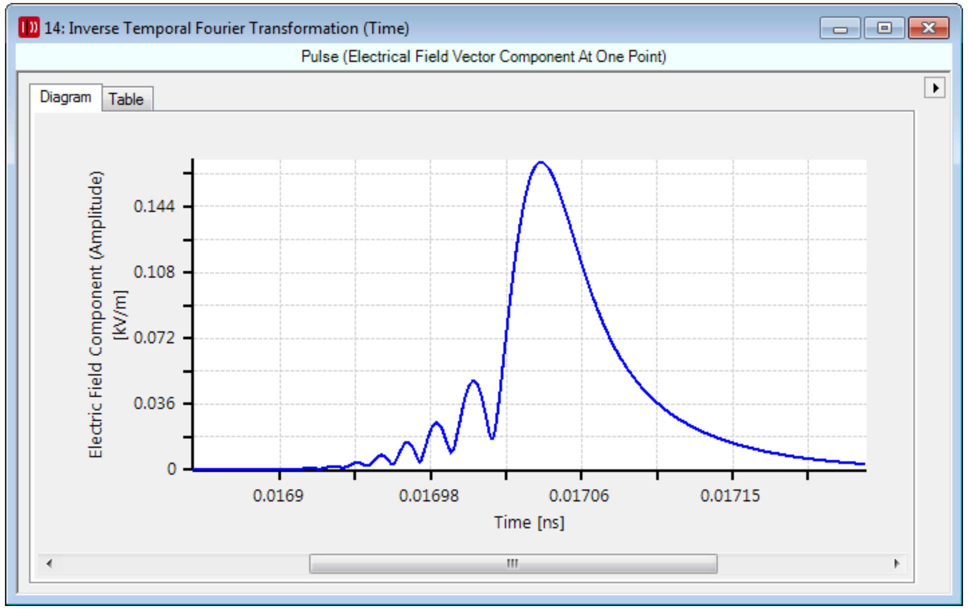


Spatiotemporal Evolution: Pulse in Focus

Result in frequency domain

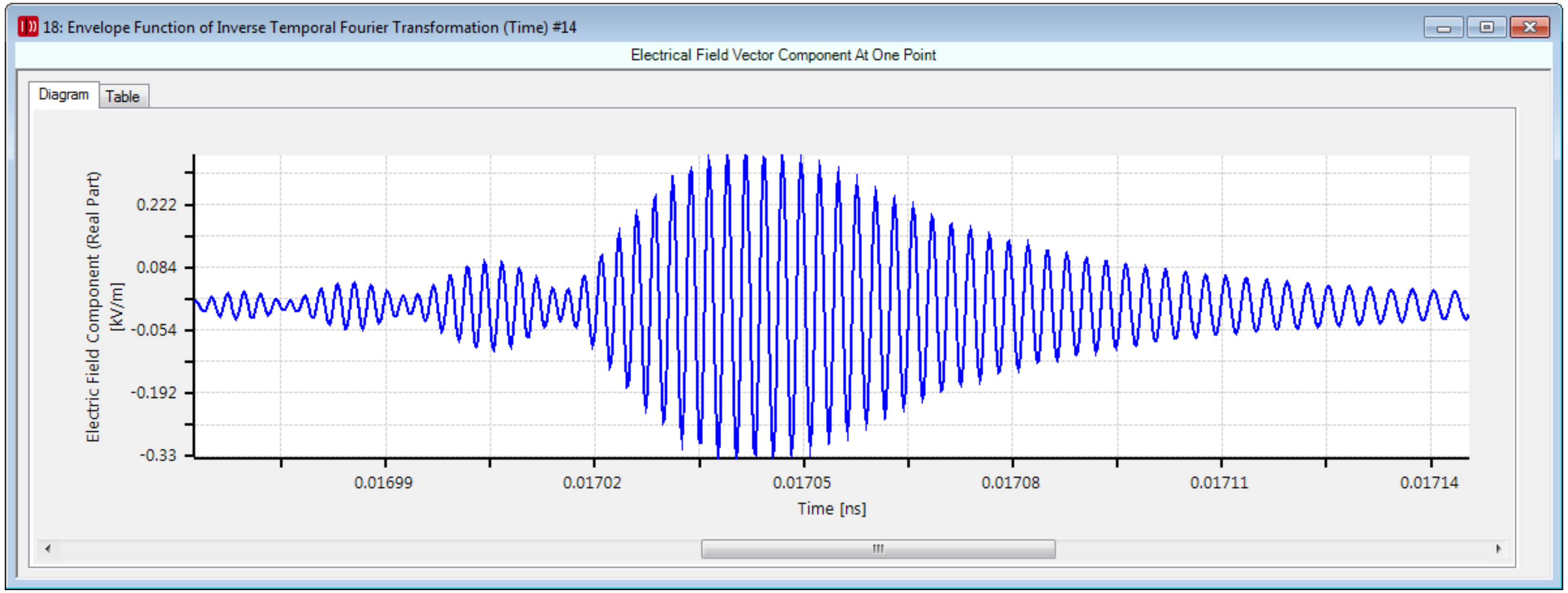


Time domain in (0,0): x-component

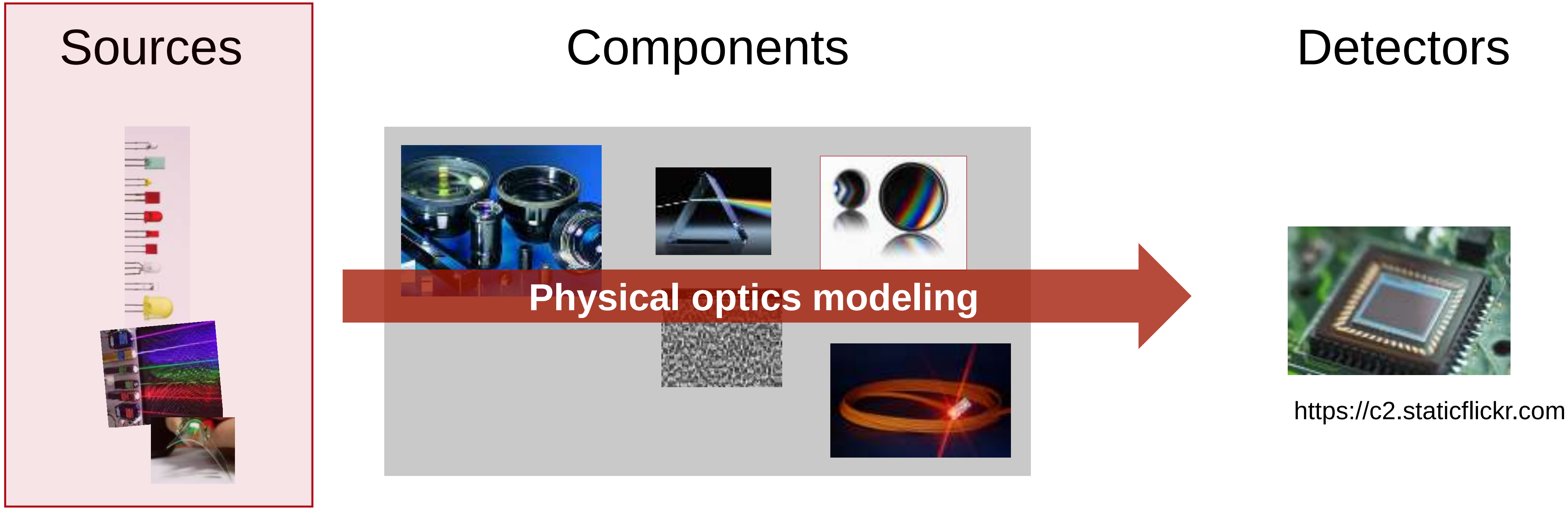


Spatiotemporal Evolution: Pulse in Focus

Time domain in (0,0): x-component with carrier frequency



General Physical-Optics System Modeling

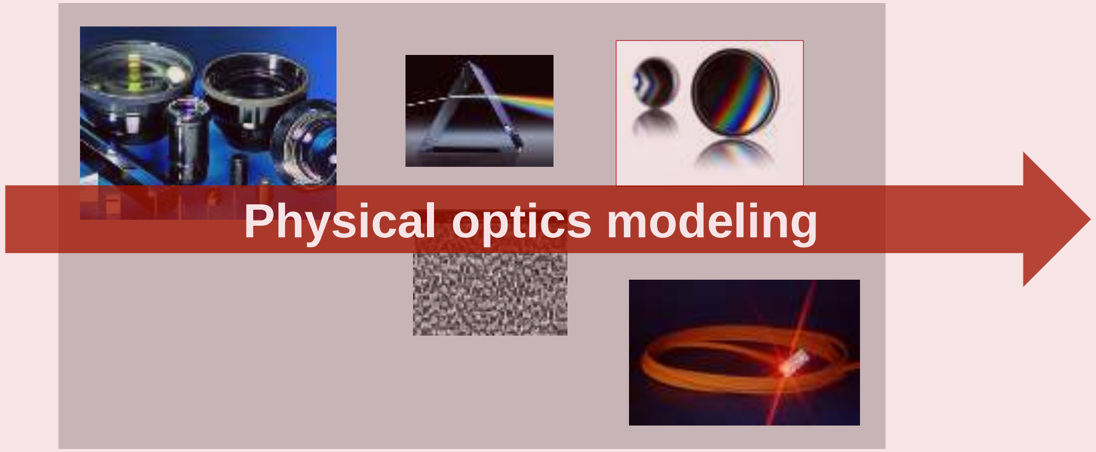


Field representation provides unsurpassed flexibility in source modeling!

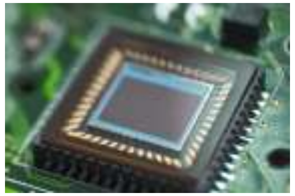
General Physical-Optics System Modeling

Sources

Components



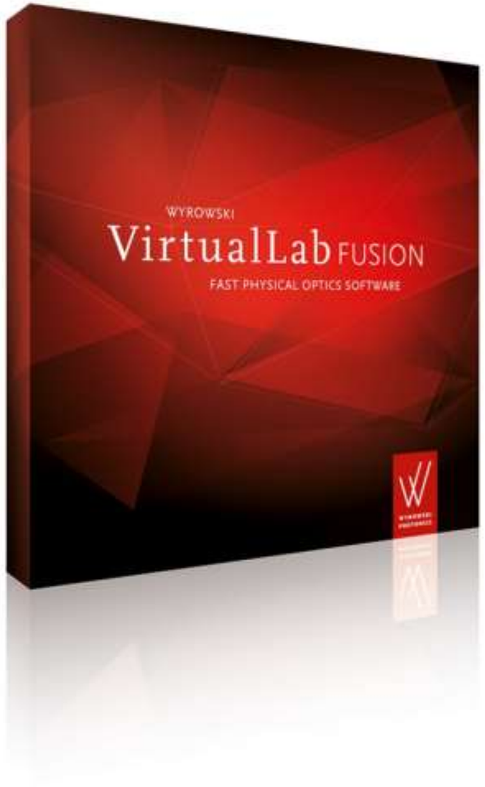
Detectors



https://c2.staticflickr.com

System and modeling configuration

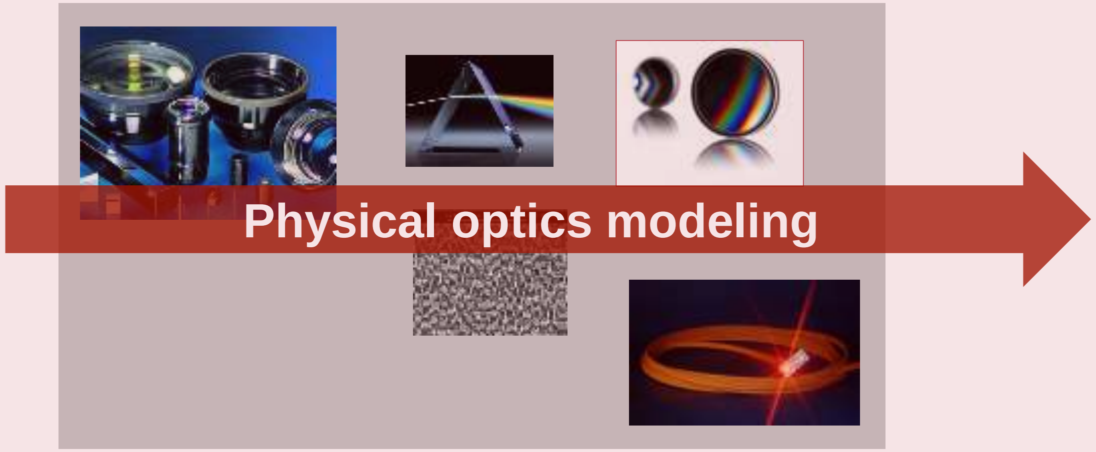
System building blocks



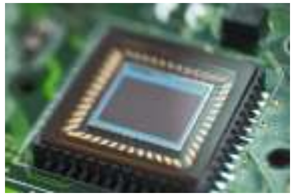
General Physical-Optics System Modeling

Sources

Components



Detectors



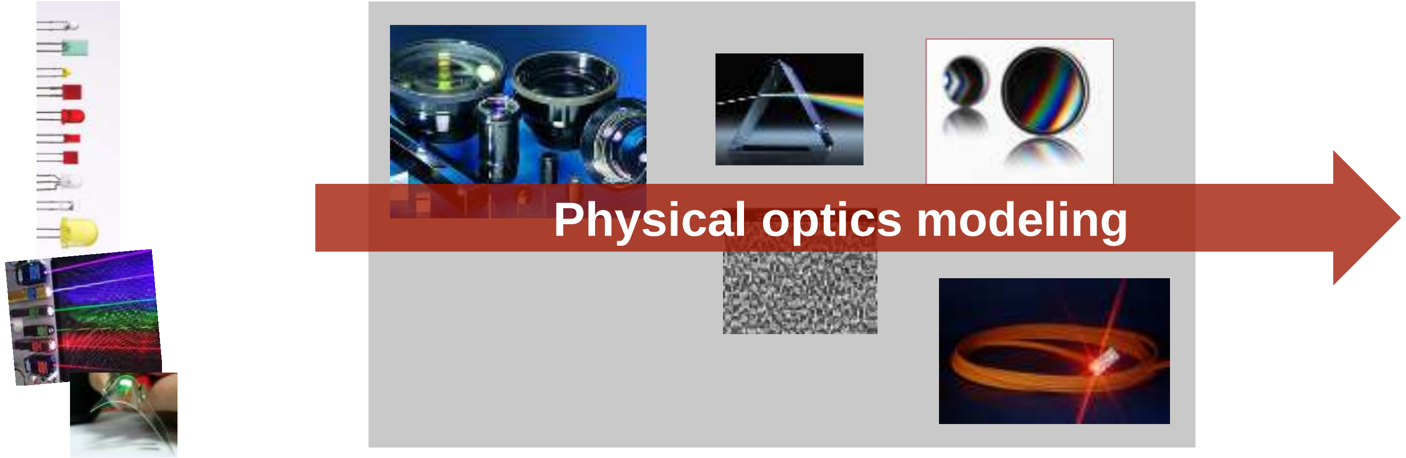
https://c2.staticflickr.com

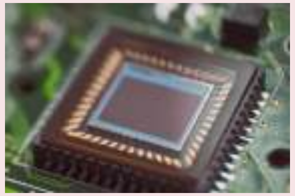
General Physical-Optics System Modeling

Sources

Components

Detectors





https://c2.staticflickr.com

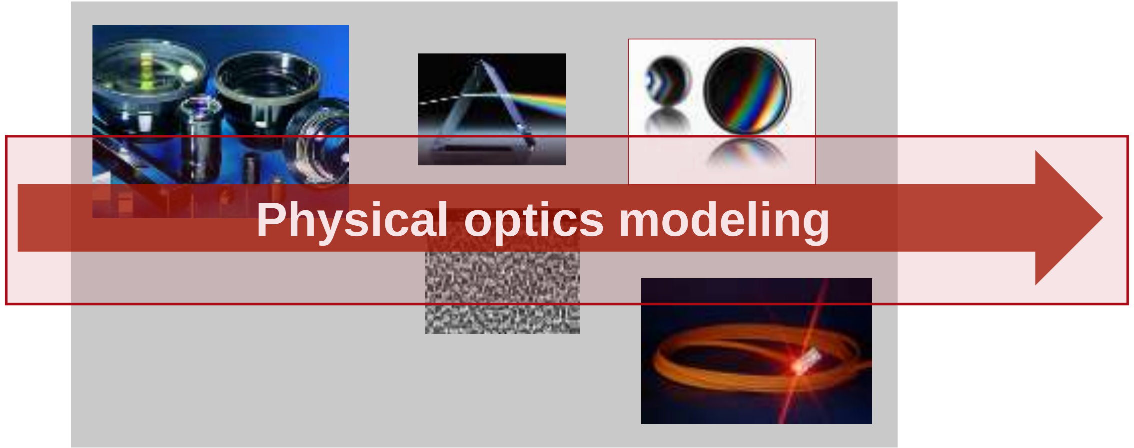
Field representation provides unsurpassed flexibility in detector modeling!

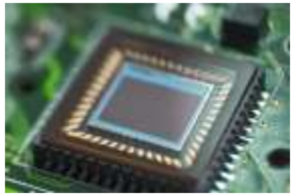
General Physical-Optics System Modeling

Sources

Components

Detectors





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How does VirtualLab realize fast physical optics modeling?

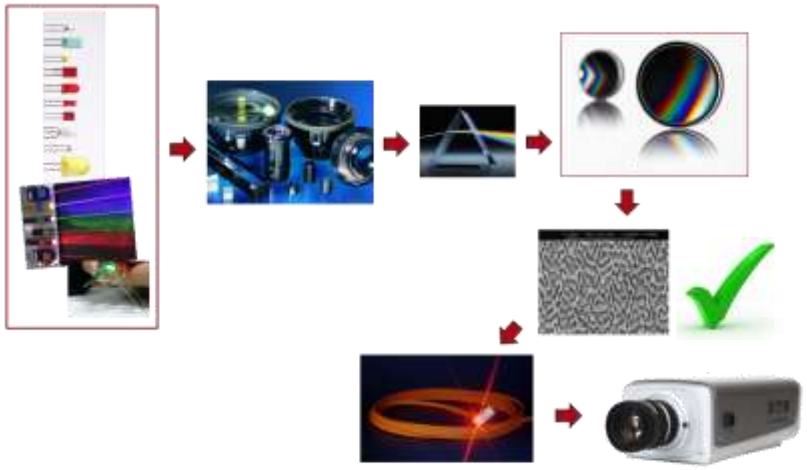
Optical Modeling: The Common Understanding

James Clerk Maxwell

Light representation: **Electromagnetic fields**
Equations: **Maxwell's equations**

Universal Maxwell solver, e.g., FMM and FEM

Universal, Rigorous Maxwell Solver

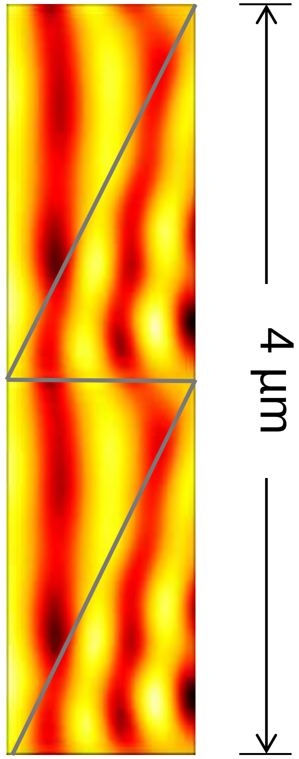


- Fourier Modal Method

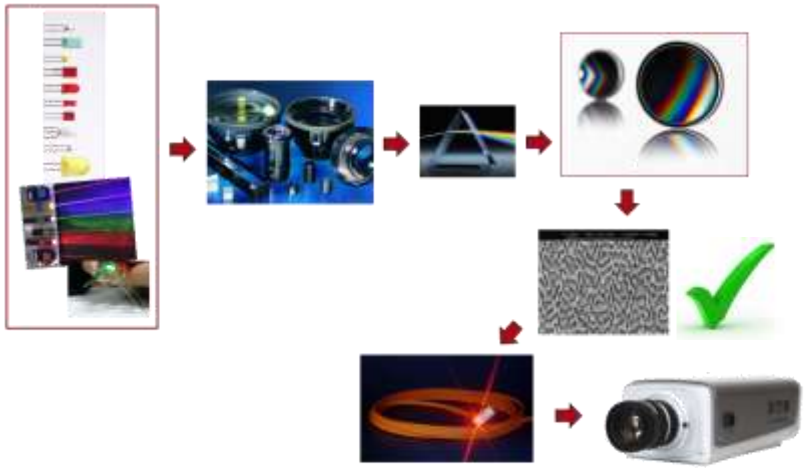
Fourier Modal Method

- Sawtooth grating
  - Diffraction angle and efficiency

Order	Angle	Efficiency
I	0°	100 %
T-3	-52.919°	0.12312 %
T-2	-32.131°	0.2671 %
T-1	-15.422°	65.654 %
T0	0°	9.2988 %
T+1	15.422°	5.6679 %
T+2	32.131°	4.1998 %
T+3	52.919°	11.072 %
R-3	52.919°	0.17409 %
R-2	32.131°	1.7735 %
R-1	15.422°	0.49041 %
R0	0°	0.19224 %
R+1	-15.422°	0.094539 %
R+2	-32.131°	0.099558 %
R+3	-52.919°	0.89336 %

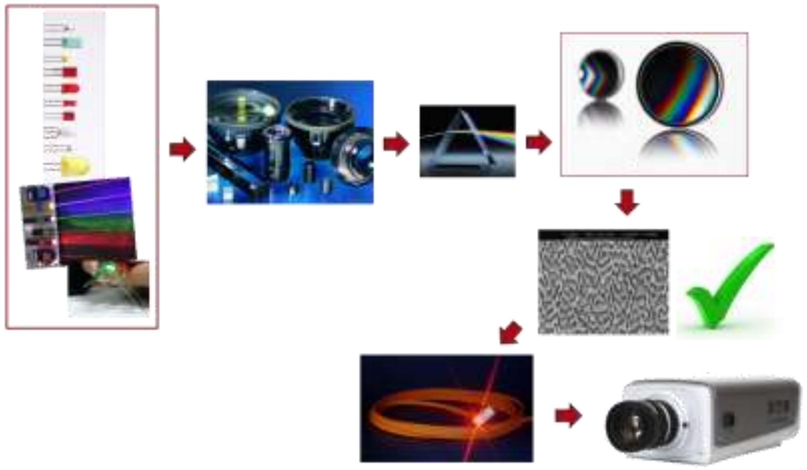


Universal, Rigorous Maxwell Solver



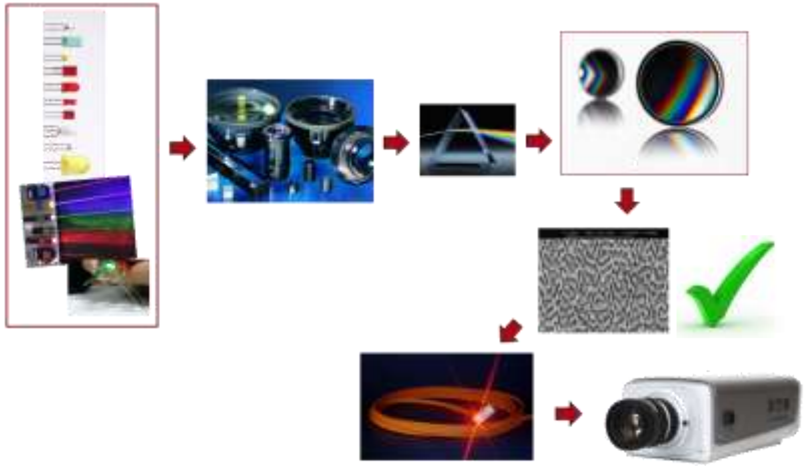
- Fourier Modal Method
- Integral Method (WIAS Berlin)

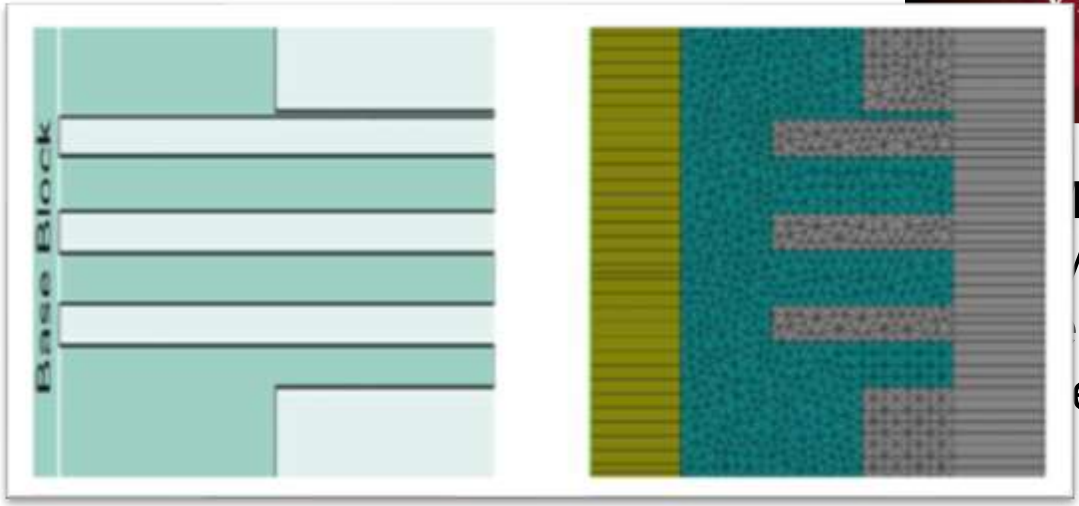
Universal, Rigorous Maxwell Solver



- Fourier Modal Method
- Integral Method (WIAS Berlin)
- Finite Element Method (Interface to JCMWave; Zuse Institut Berlin)

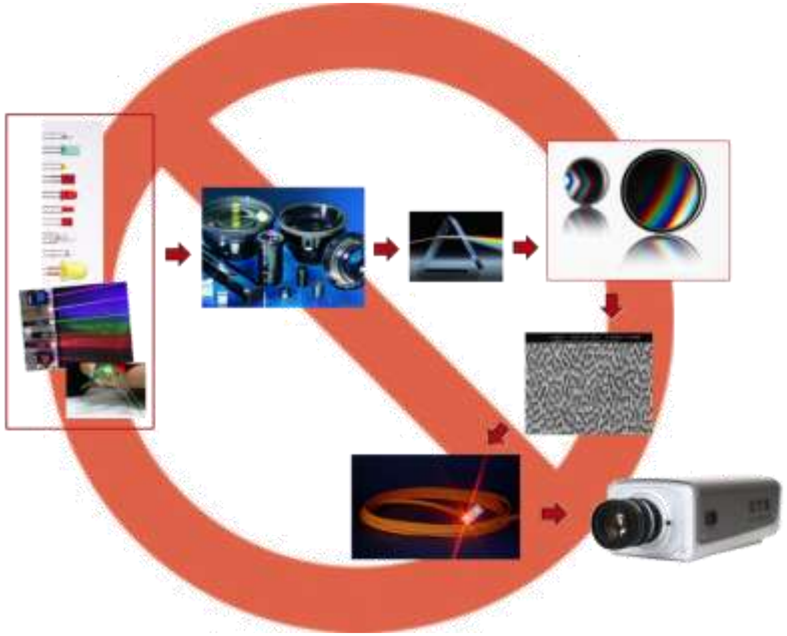
Universal, Rigorous Maxwell Solver





- lodal Method
- /lethod (WIAS Berlin)
- ment Method (Interface to
- e; Zuse Institut Berlin)

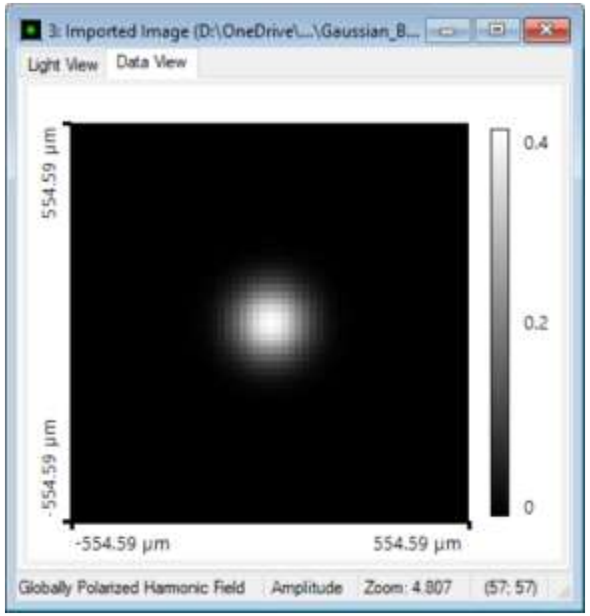
Universal, Rigorous Maxwell Solver

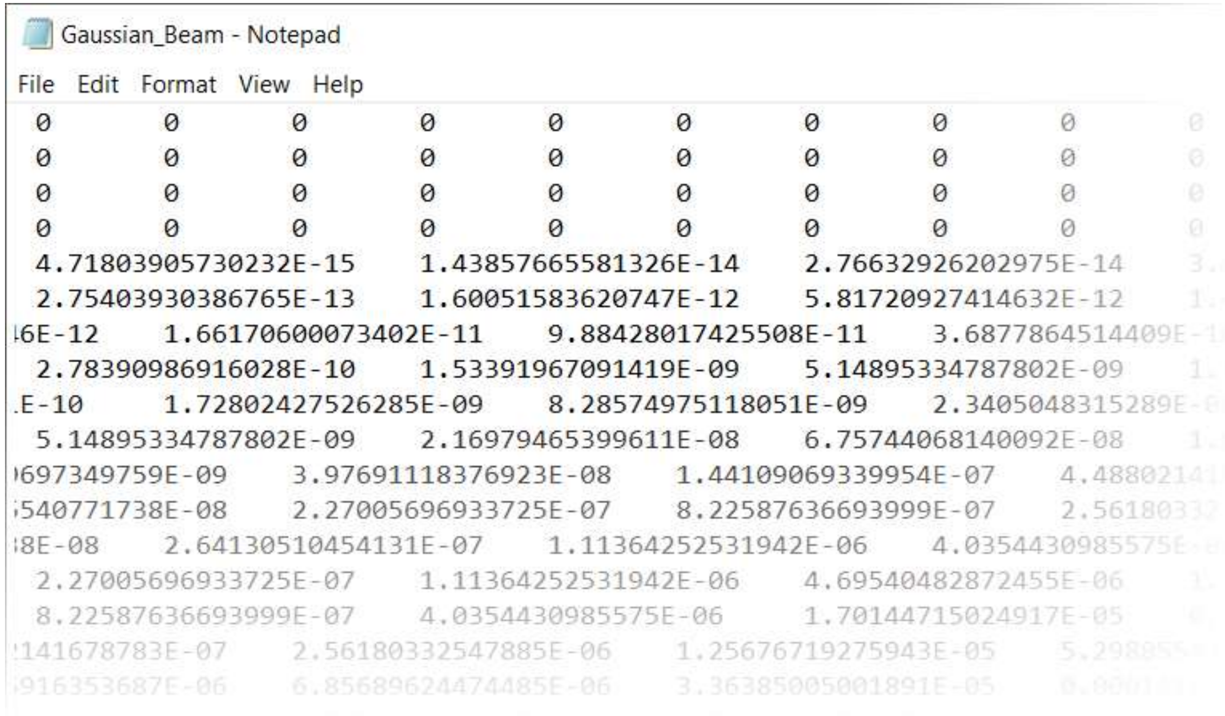


- Fourier Modal Method
- Integral Method (WIAS Berlin)
- Finite Element Method (Interface to JCMWave; Zuse Institut Berlin)

Task 2: Field Data Export and Import

- Export field data as figure/text
- Import field data into VLF and change the related numerical parameters.



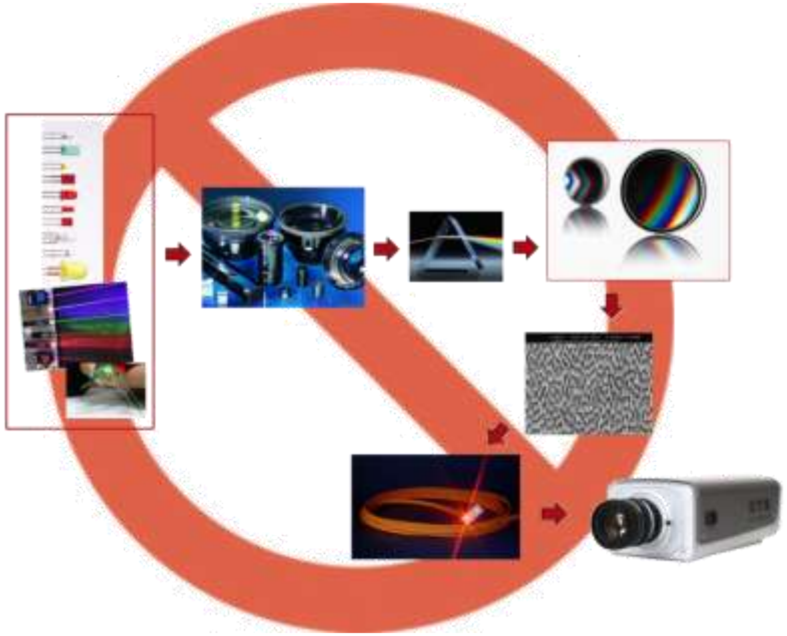


Task 2: Video

Klick the following link to watch the video:

https://youtu.be/iNTm9EgSS2Q

Universal, Rigorous Maxwell Solver

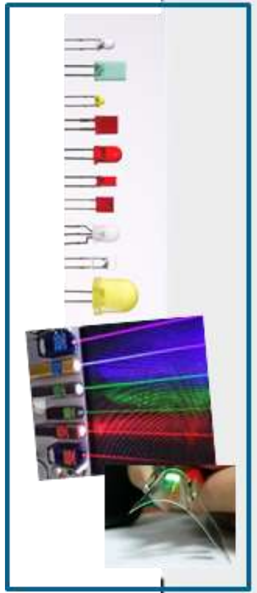


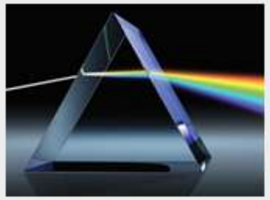
- Fourier Modal Method
- Integral Method (WIAS Berlin)
- Finite Element Method (Interface to JCMWave; Zuse Institut Berlin)

Fast physical optics modeling with VirtualLab Fusion

The concept of field tracing

Physical-Optics System Modeling



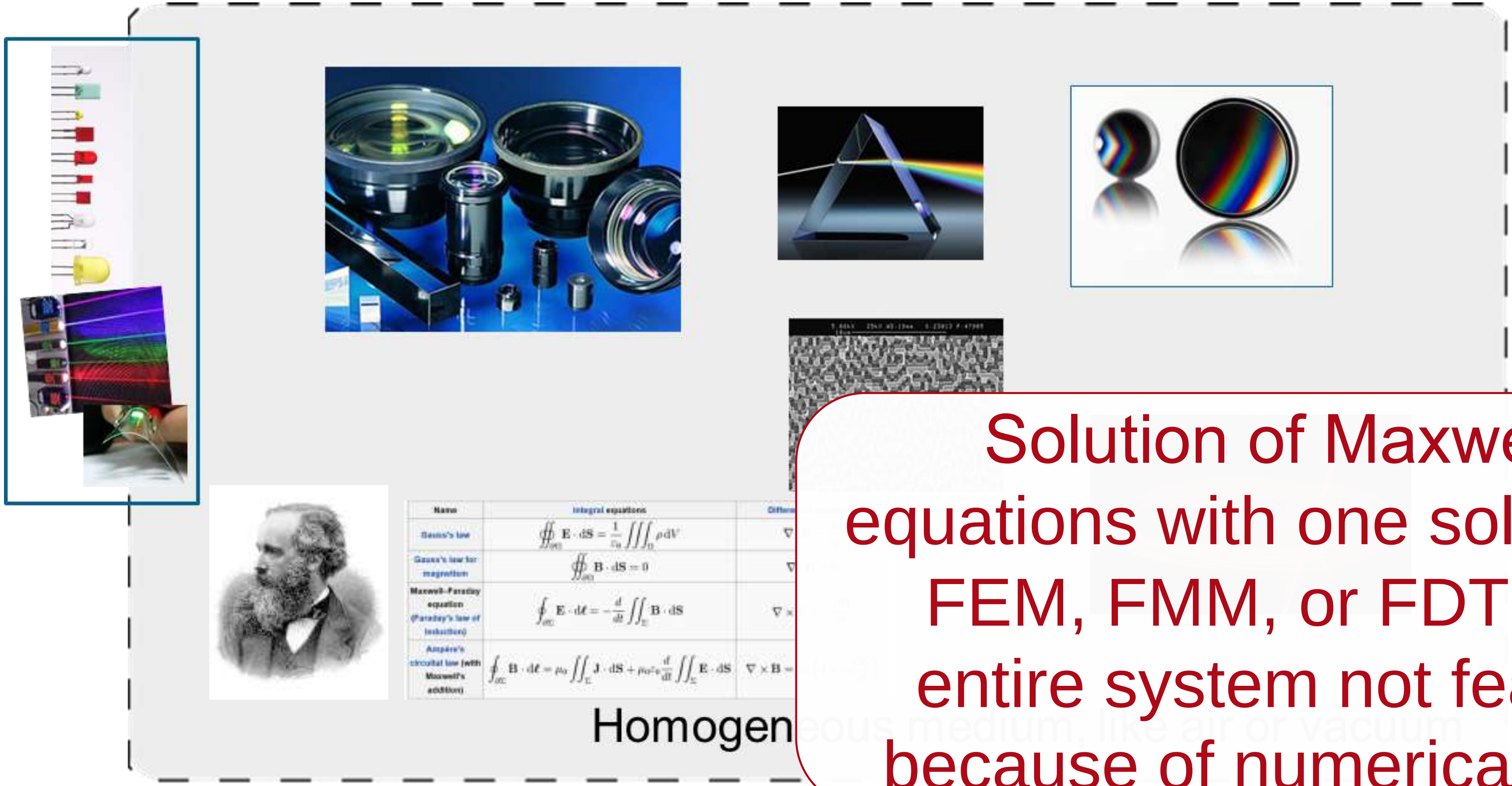


Name	Integral equations	Differential equations
Gauss's law	$\oiint_{\partial\Omega} \mathbf{E}\cdot d\mathbf{S} = \frac{1}{\varepsilon_0}\iiint_\Omega \rho\, dV$	$\nabla\cdot\mathbf{E} = \frac{\rho}{\varepsilon_0}$
Gauss's law for magnetism	$\oiint_{\partial\Omega} \mathbf{B}\cdot d\mathbf{S} = 0$	$\nabla\cdot\mathbf{B}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

Solve Maxwell's equations for given source mode and components, i.e. refractive index distribution.

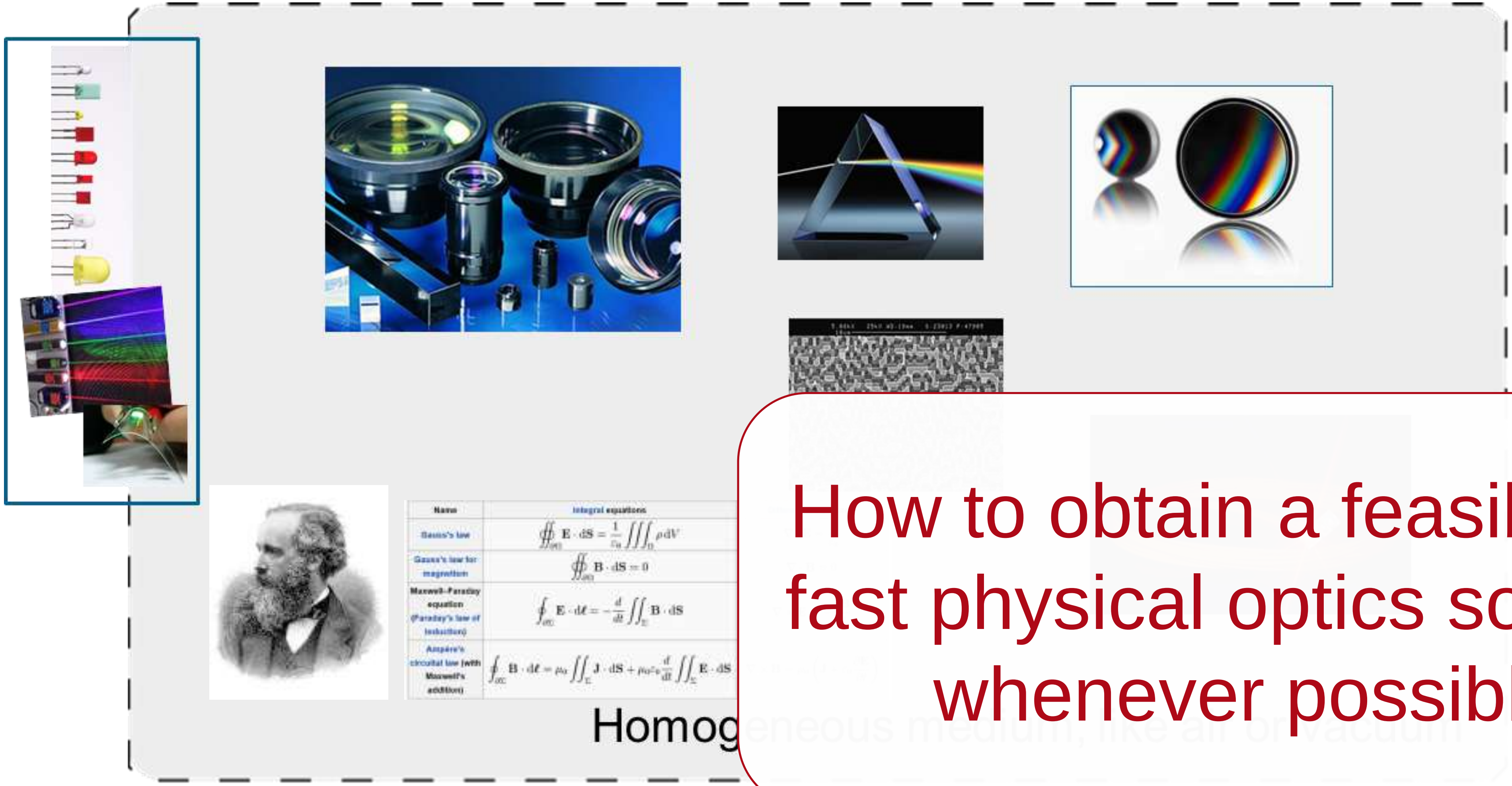
Homogeneous medium, like air or vacuum

Physical-Optics System Modeling



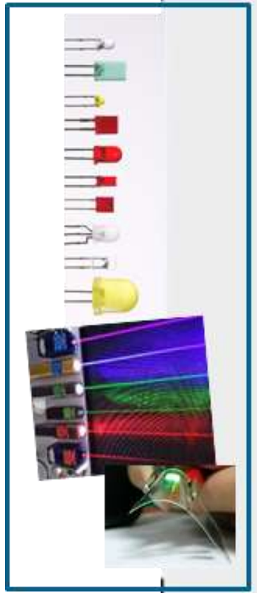
Solution of Maxwell’s equations with one solver, e.g. FEM, FMM, or FDTD, for entire system not feasible because of numerical effort!

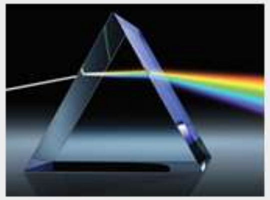
Fast Physical-Optics System Modeling

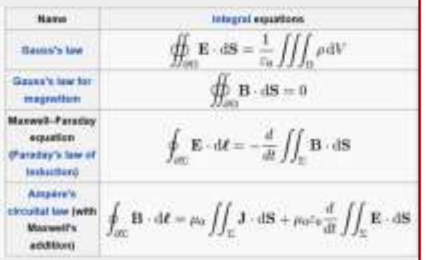


How to obtain a feasible and fast physical optics solution - whenever possible?

Fast Physical-Optics System Modeling







Homogeneous medium, like air or vacuum

How to drastically reduce the numerical effort in physical-optics modeling?

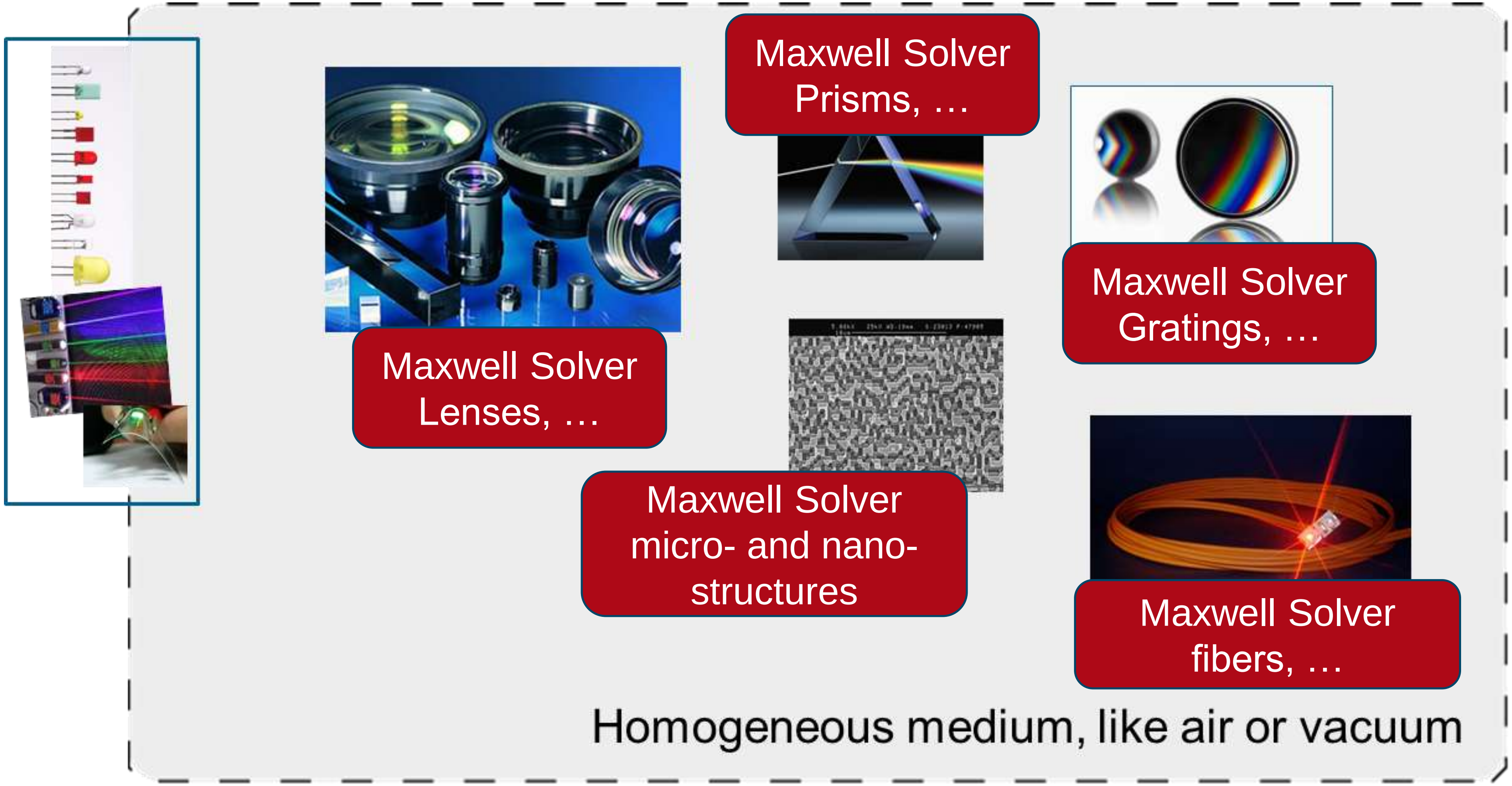
Fast physical optics strategies

Tearing and interconnection

Fast Physical Optics Strategies: Tearing and Interconnection

- **Tearing**: The optical system is decomposed into regions in which different types of Maxwell solvers can be applied:
  - Rigorous solvers
  - Solvers using mathematical approximations which exploit specific characteristics of field and modulation of refractive index
  - Always fully vectorial treatment

Physical-Optics System Modeling: Regional Maxwell Solver



Physical-Optics System Modeling: Regional Maxwell Solver

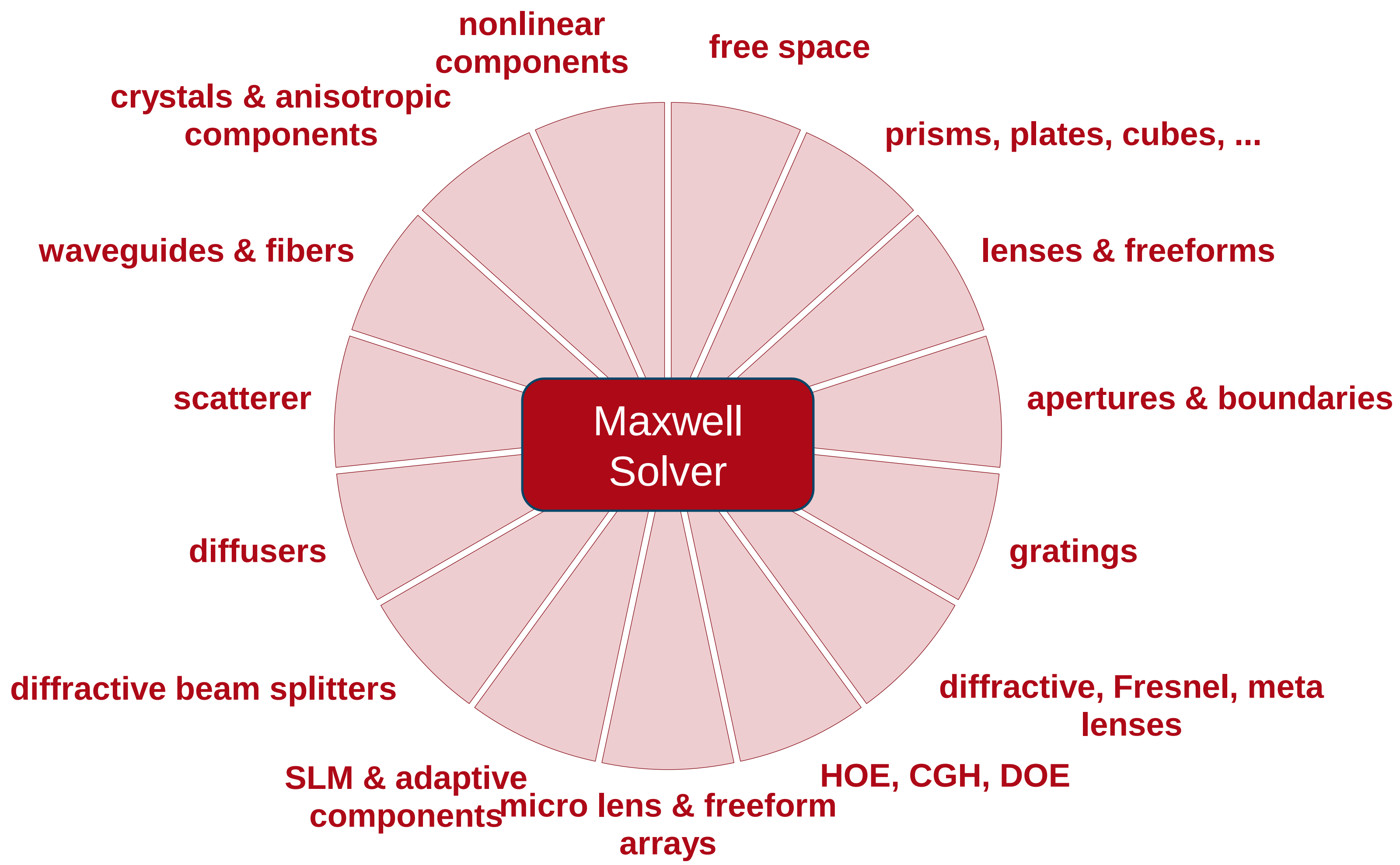
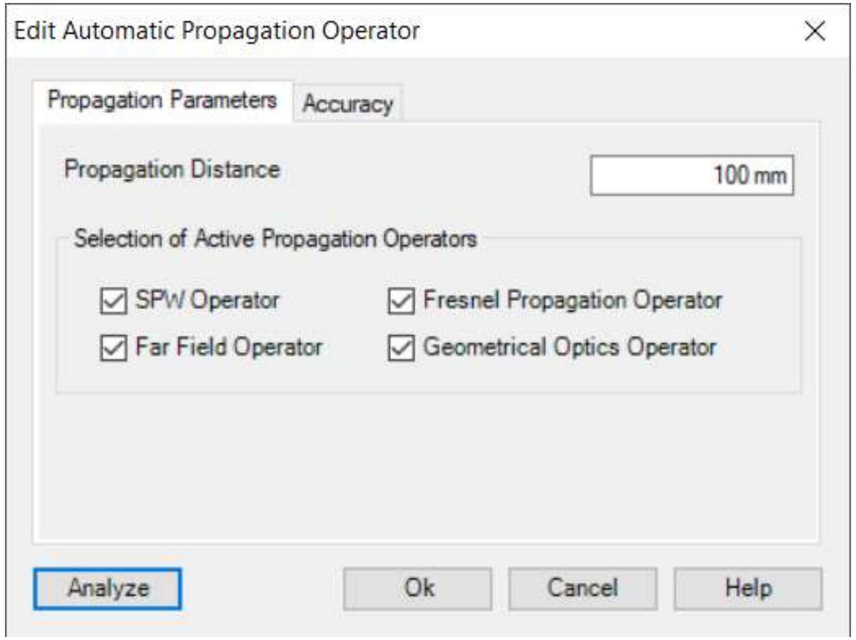
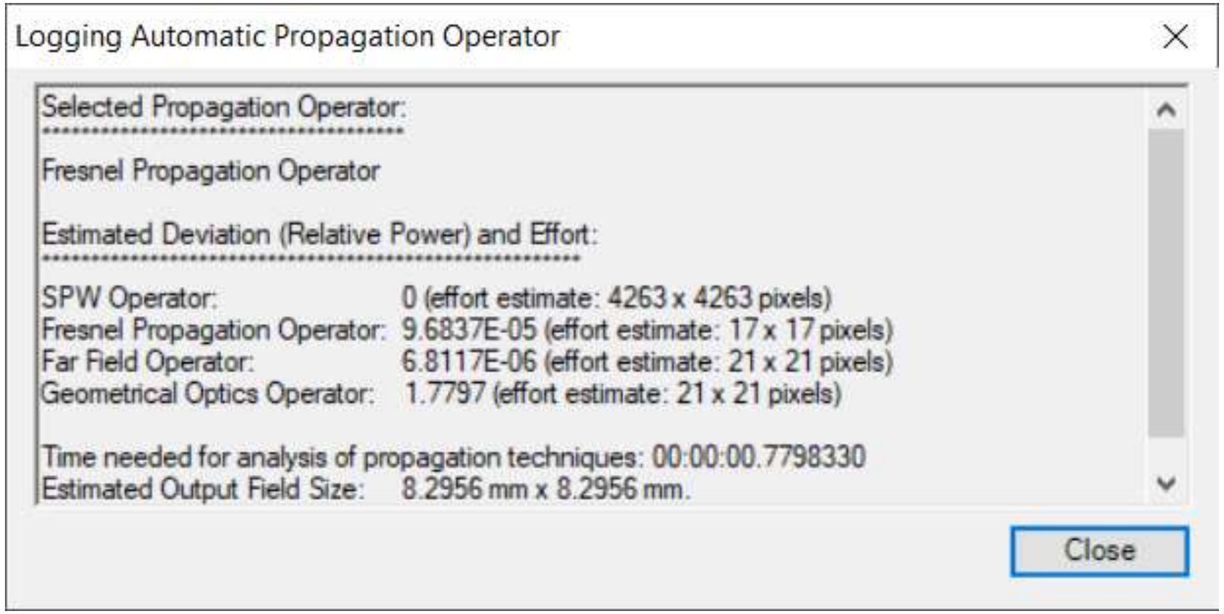


Illustration 2: Propagation Operator

- Propagating a Gaussian beam with 10 um beam waist by 1 mm, 10 mm and 100 mm





Maxwell solvers can be approximated ones. Balance between accuracy and numerical effort is always be search!

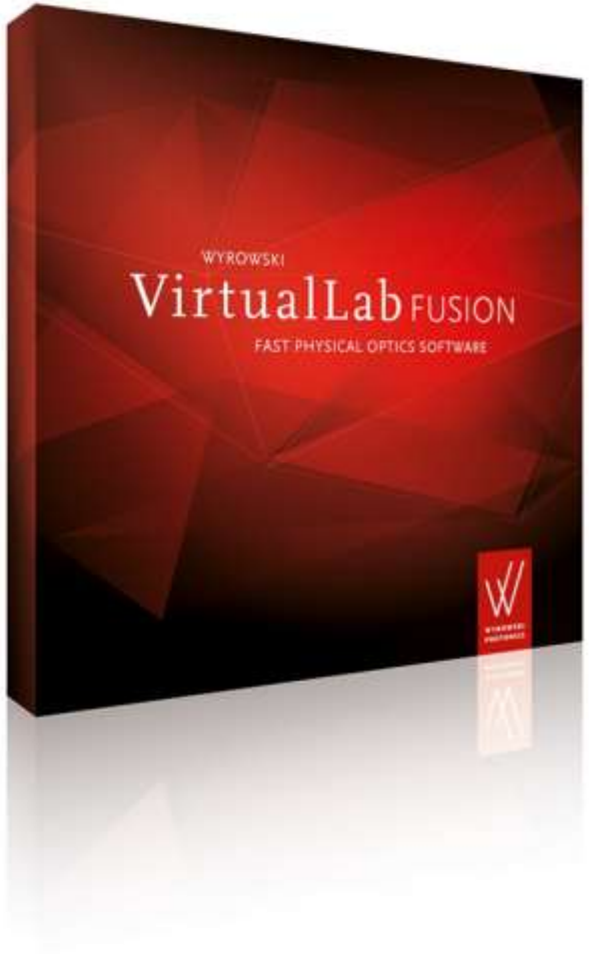
Illustration 2: Video

Klick the following link to watch the video:

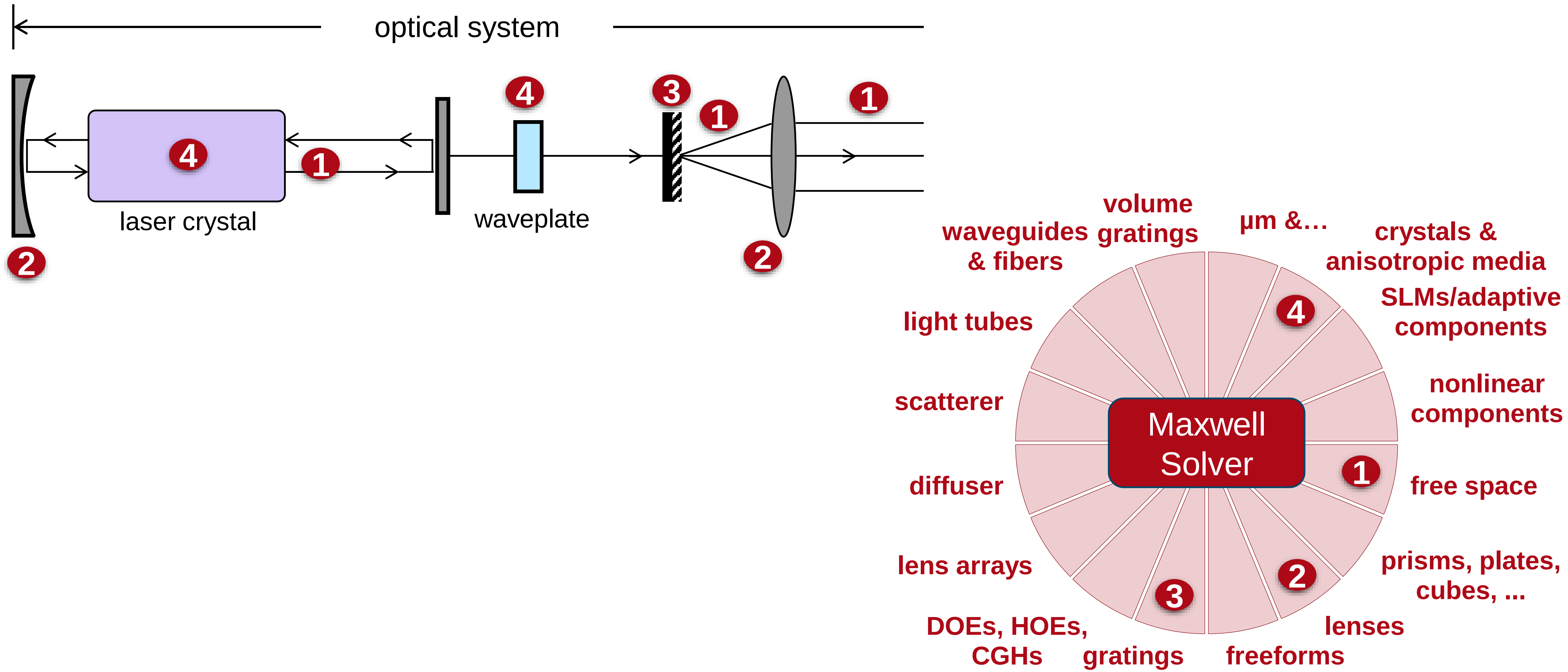
https://youtu.be/FzWZ4lHlsQ8

VirtualLab Fusion (VLF)

- Why Fusion? (Reason #1)
  - Ray tracing
  - Physical optics modeling: Field tracing
- Why Fusion? (Reason #2)
  - Combining Maxwell solvers
  - VirtualLab Fusion can be understood as a platform to connect Maxwell solvers:
    - Rigorous
    - Approximate

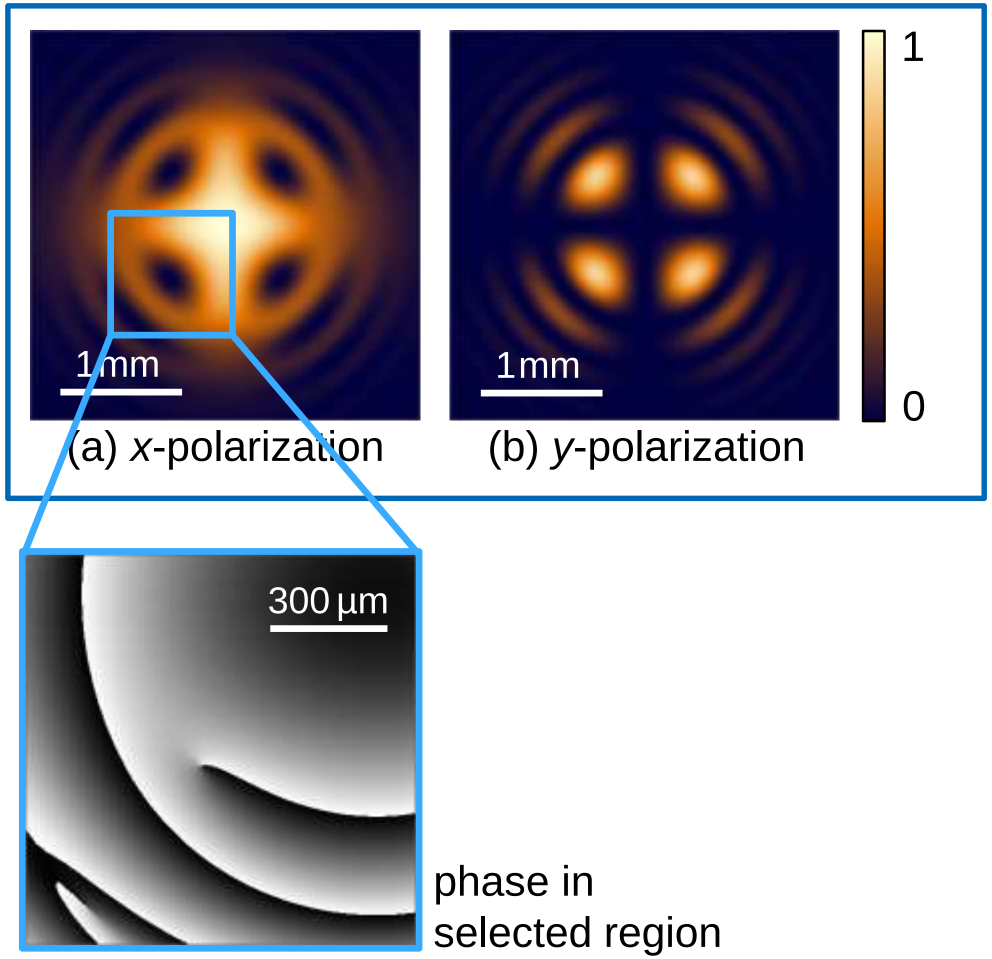


Physical-Optics System Modeling: Regional Maxwell Solver

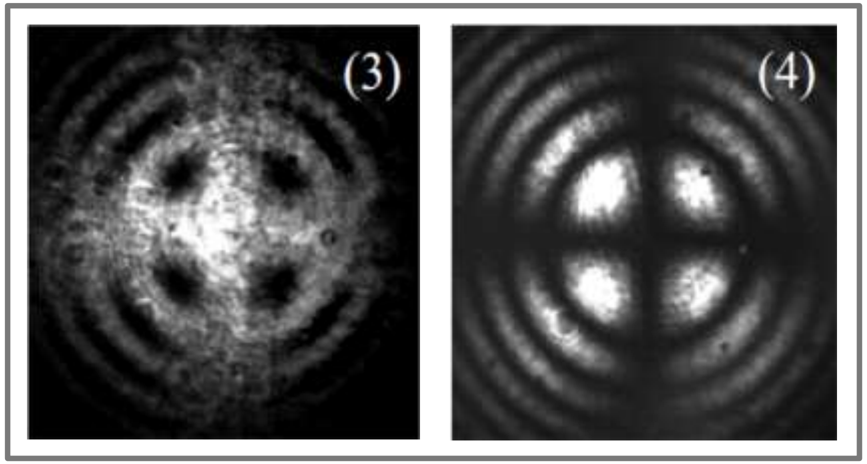


Polarization Conversion

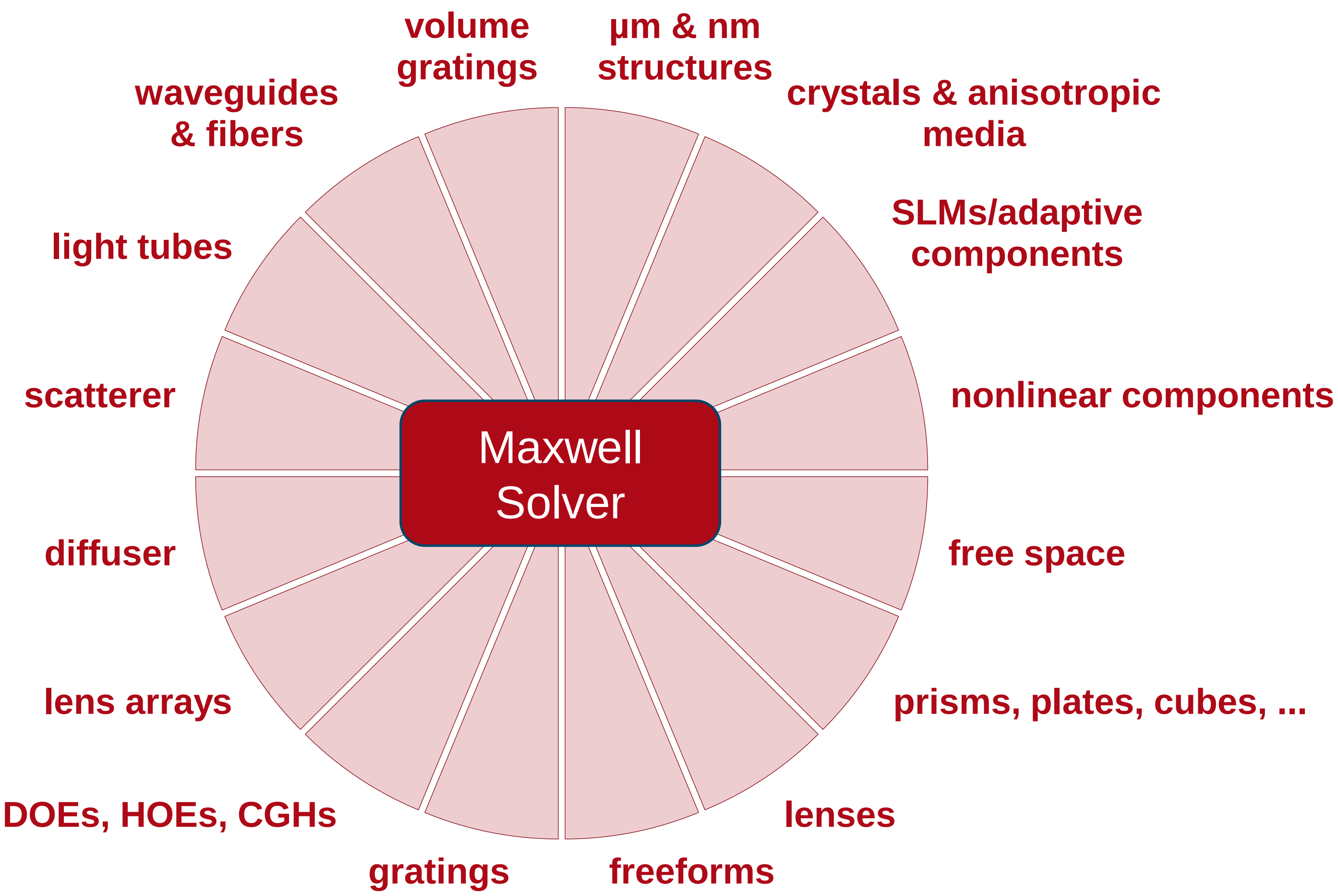
topological quadrupole [simulation]



phase in
selected region



Physical-Optics System Modeling: Regional Maxwell Solver



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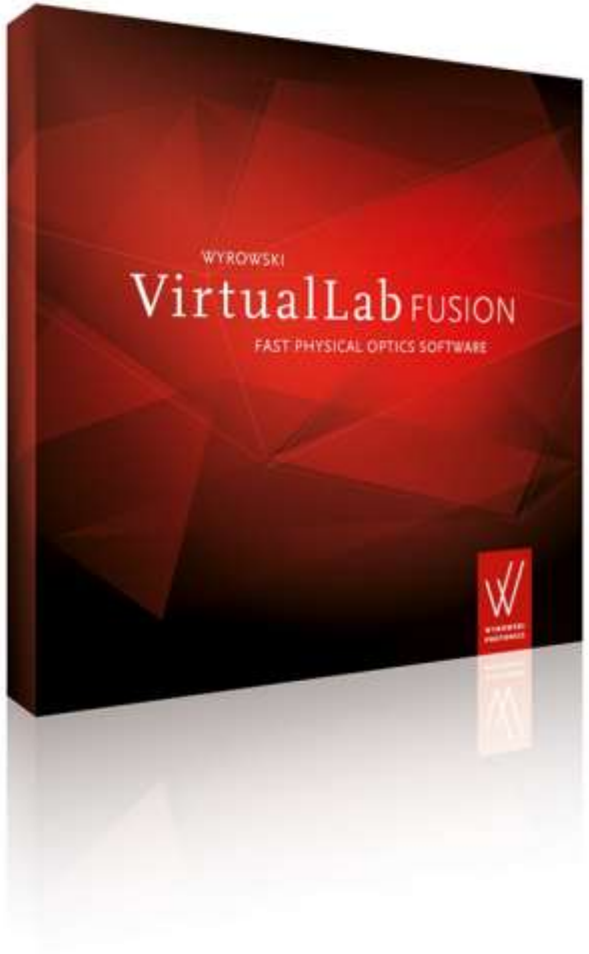

Fast Physical Optics Strategies: Tearing and Interconnection

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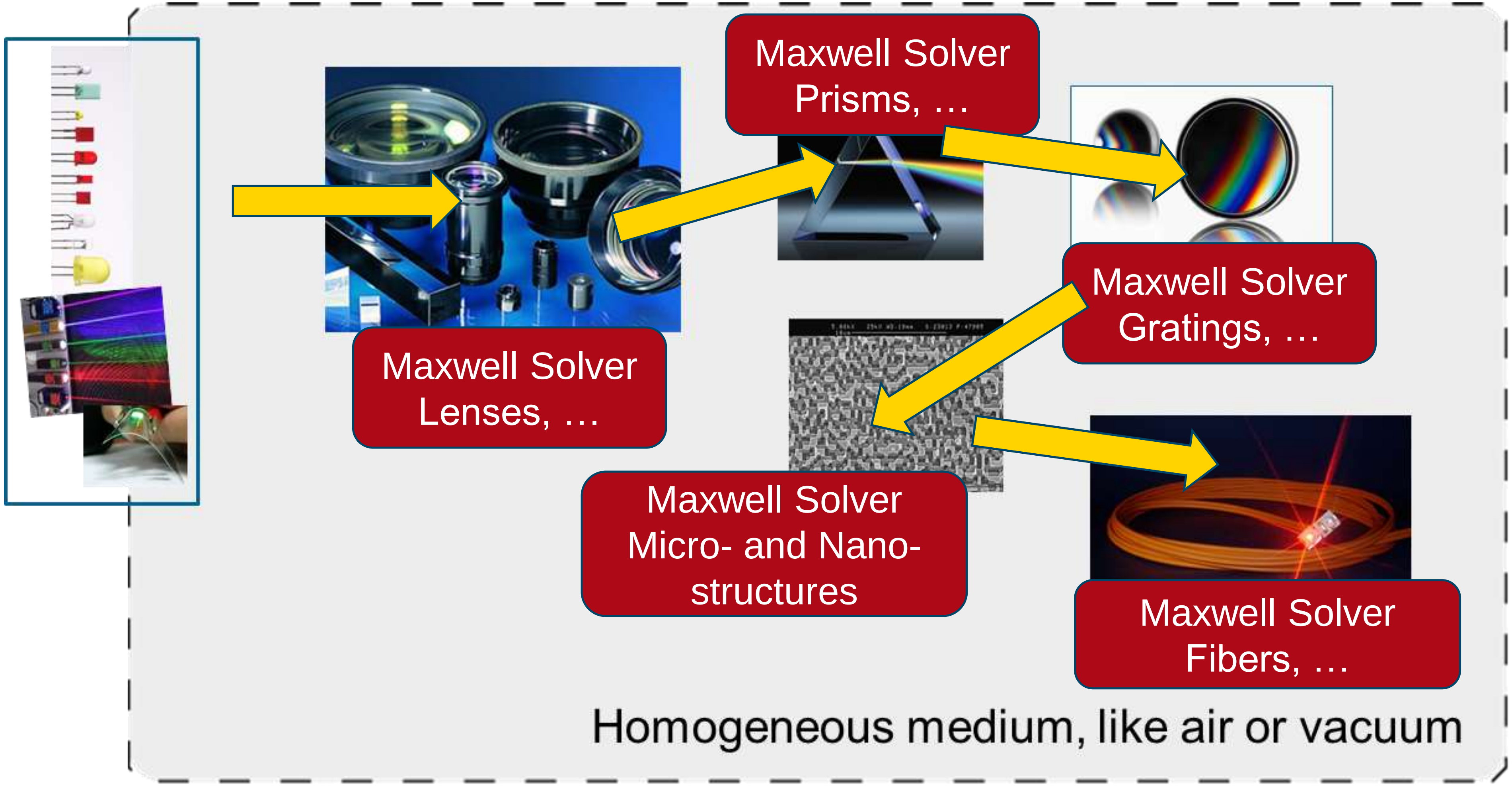
  - Solvers using mathematical approximations which exploit specific characteristics of field and modulation of refractive index
  - Always fully vectorial treatment
- **Interconnection**: The solvers per region are connected through non-sequential field tracing to solve Maxwell's equations in the entire system.

Non-Sequential Optical Field Tracing

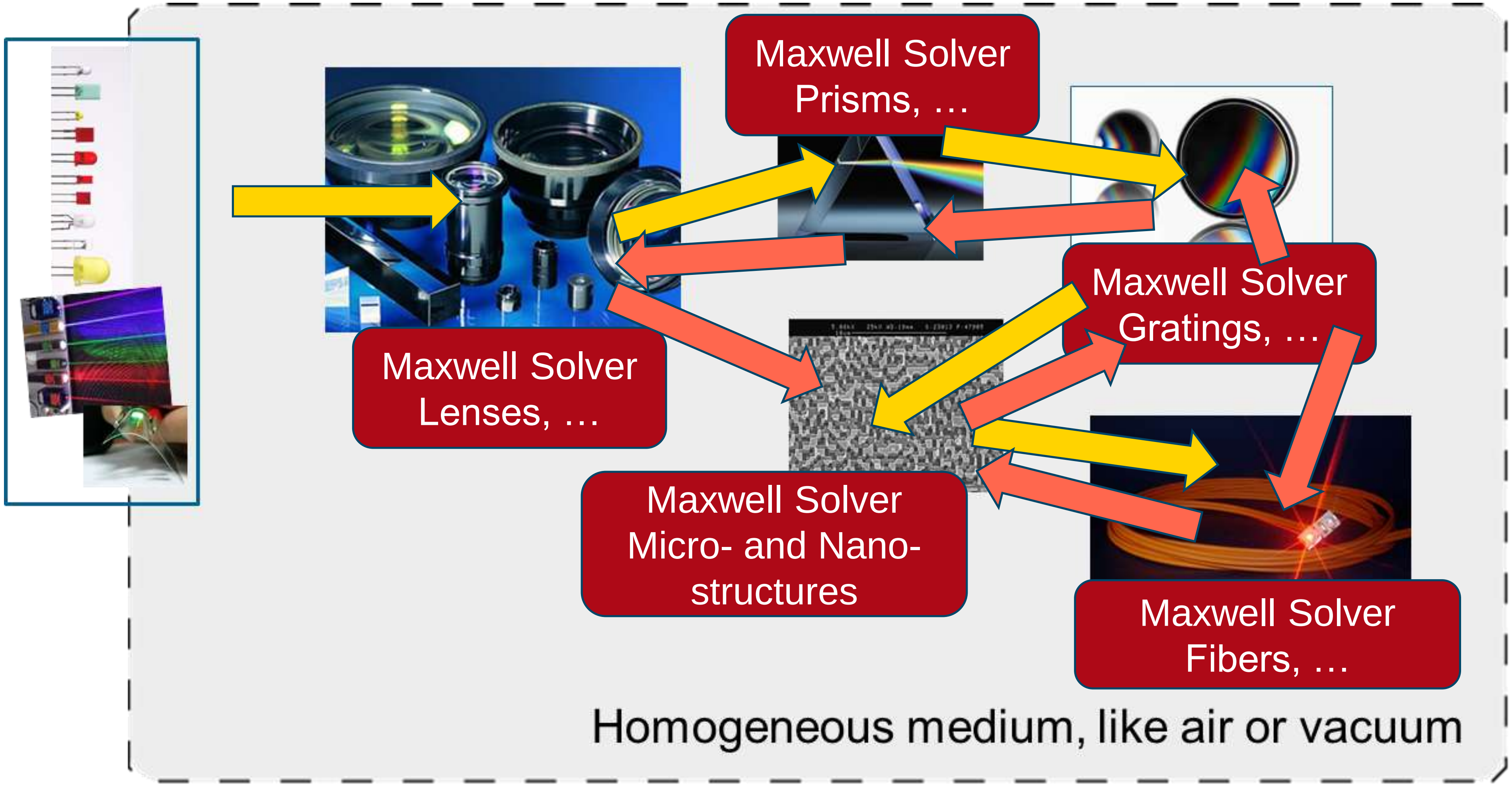
Michael Kuhn, Frank Wyrowski, and Christian Hellmann

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

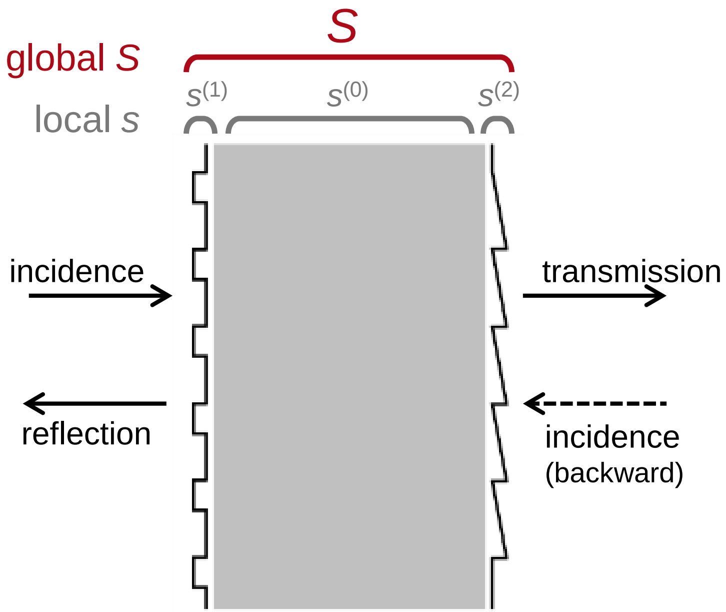


Non-sequential coupling of FMM solver

Example: Reduction of numerical effort in modeling of grating structures

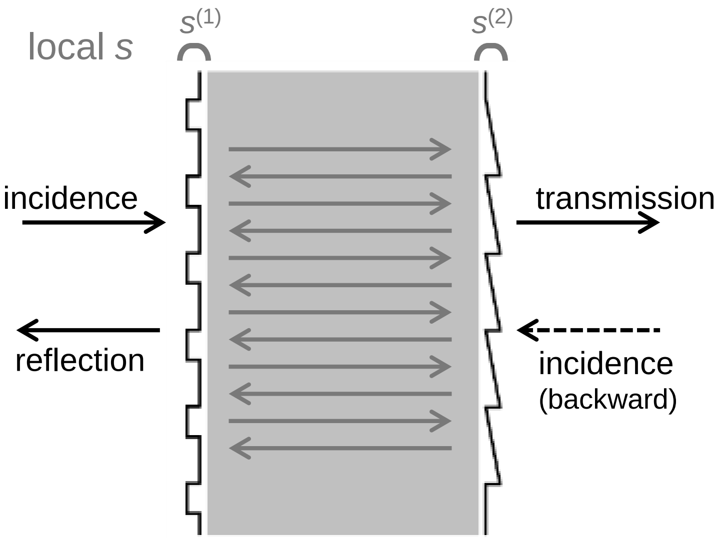
Theory Background

- Global S matrix



  - Recursion with respect to number of regions / layers

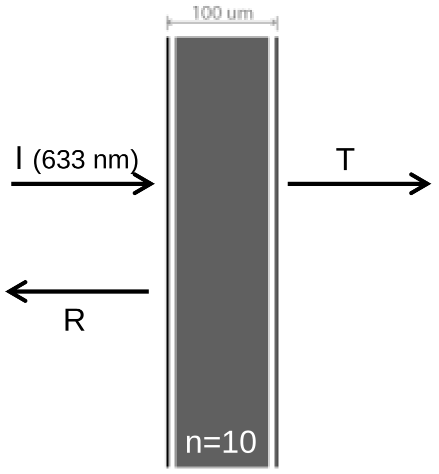
- Non-sequential field tracing



  - Recursion with respect to number of light paths

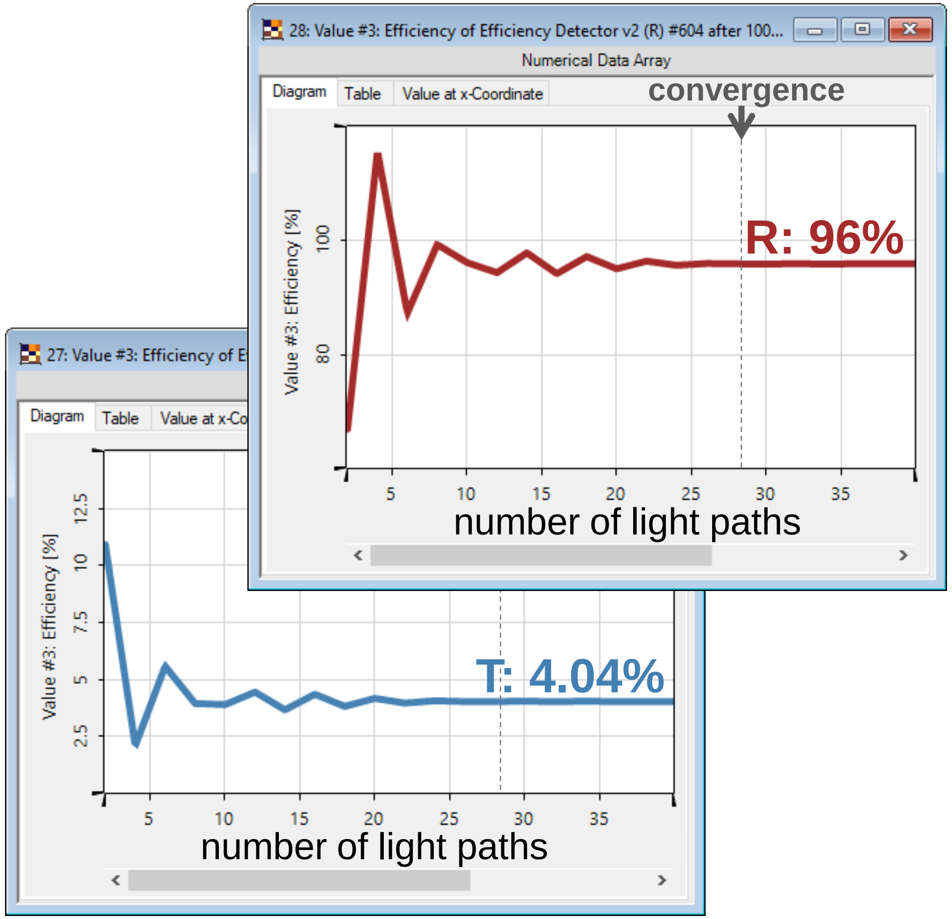
Planar Surface + Planar Surface

- Structure
- Non-sequential field tracing



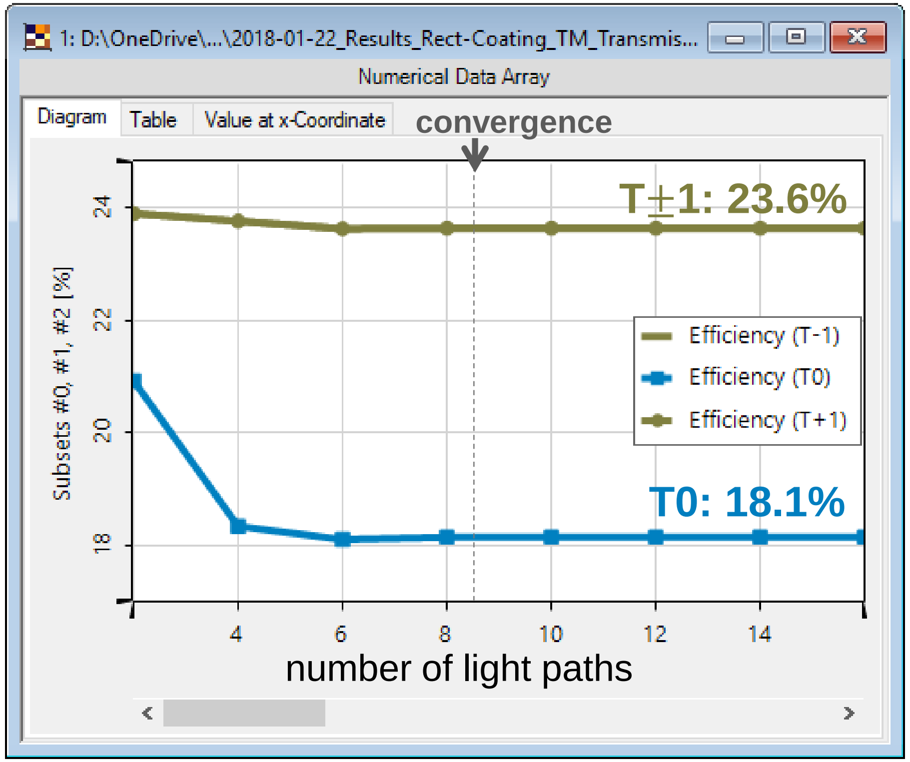
Global S matrix

Eff. (T)	Eff. (R)
4.04%	96%

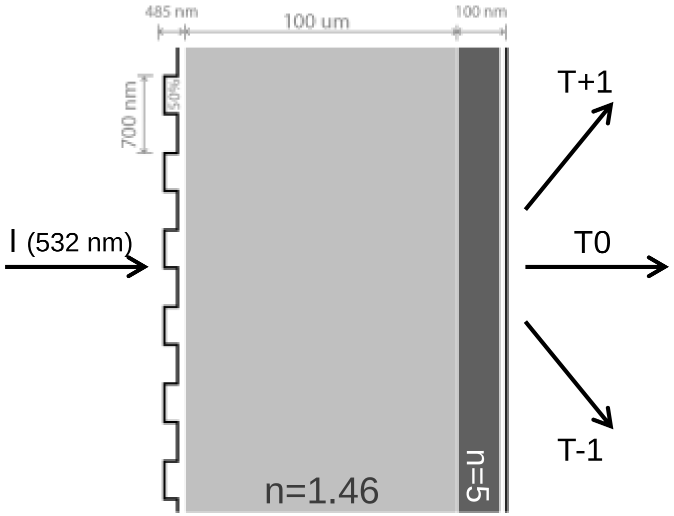


Rectangular Grating + Backside Coating

- Non-sequential field tracing



- ... with backside coating

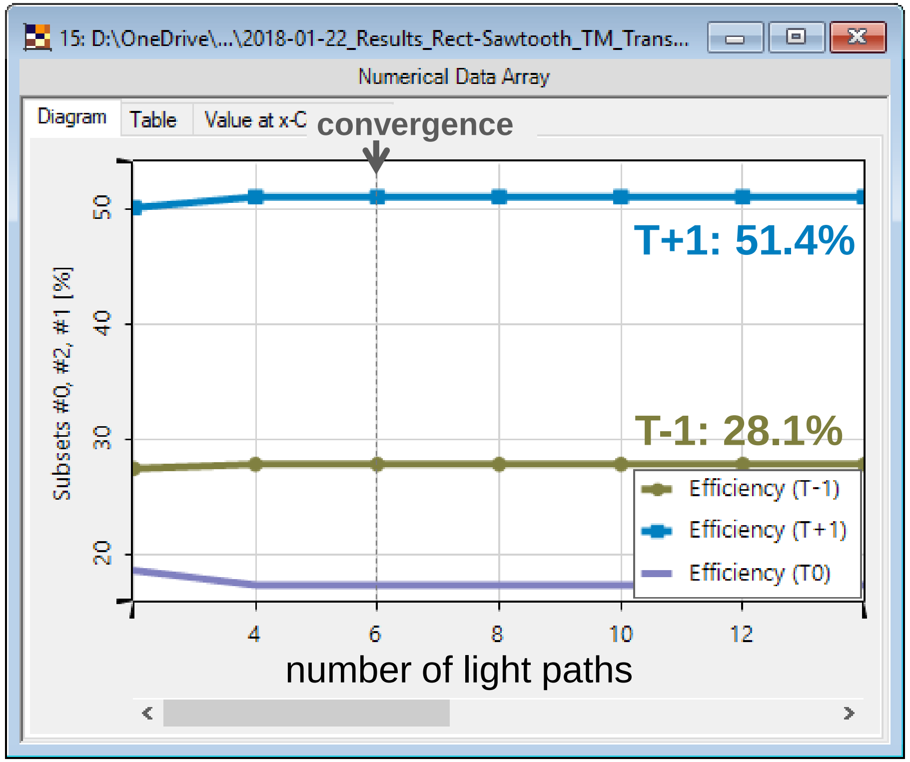


Global S matrix (TM)

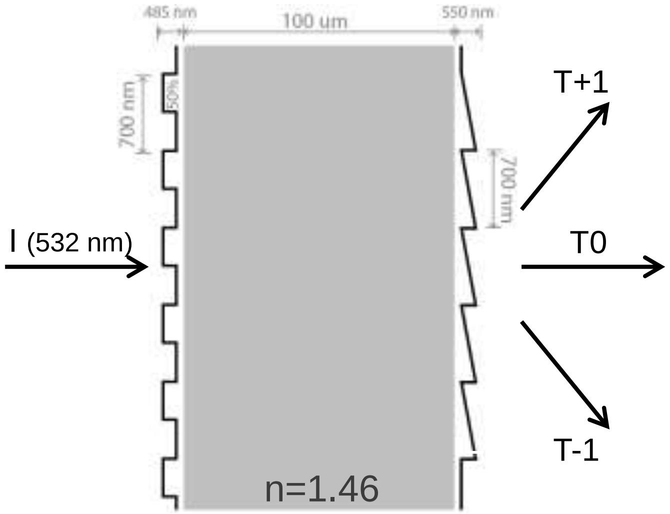
T	Eff.	R	Eff.
±1	23.6%	±1	0.762%
0	18.1%	0	33.1%

Rectangular + Sawtooth Grating (parallel)

- Non-sequential field tracing



- ... with sawtooth coating

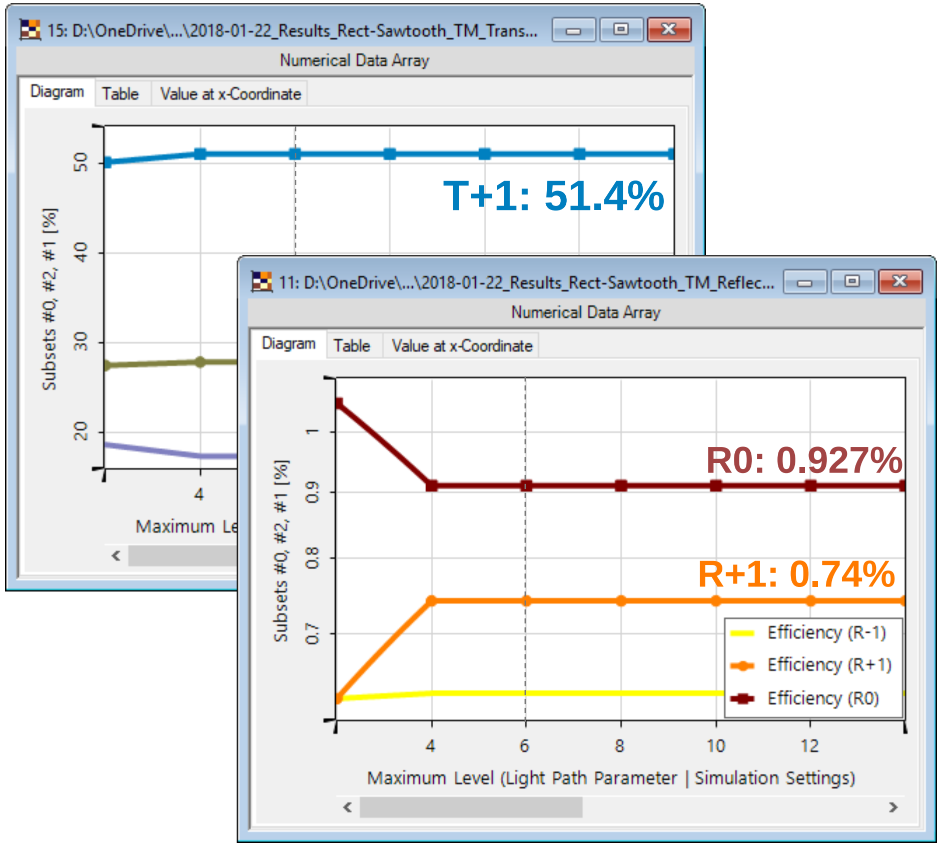


Global S matrix (TM)

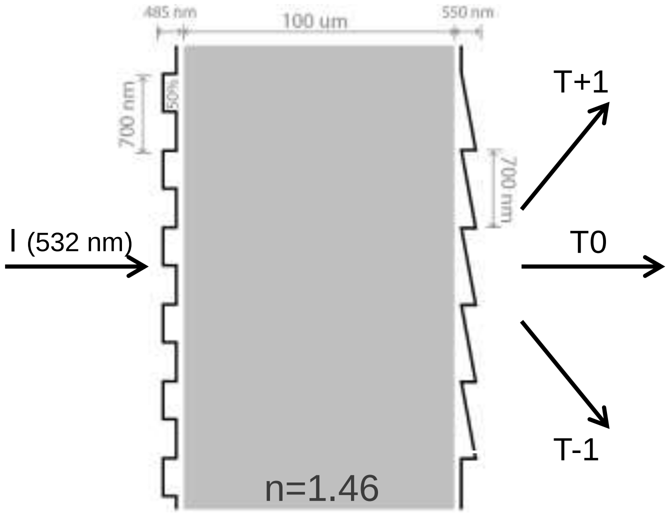
T	Eff.	R	Eff.
-1	28.1%	-1	0.65%
0	18.2%	0	0.923%
+1	51.4%	+1	0.74%

Rectangular + Sawtooth Grating (parallel)

- Non-sequential field tracing



- ... with sawtooth coating



Global S matrix (TM)

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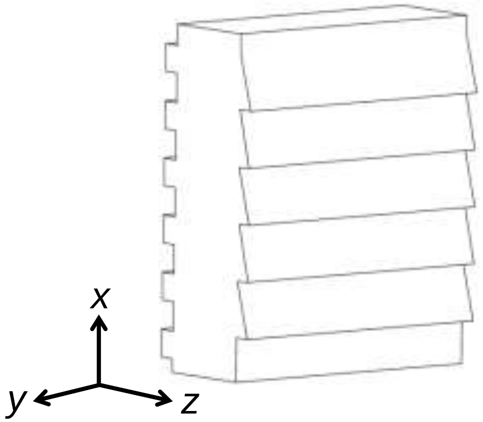
-1	28.1%	-1	0.65%
0	18.2%	**0**	**0.923%**
+1	51.4%	**+1**	**0.74%**

Computational Effort

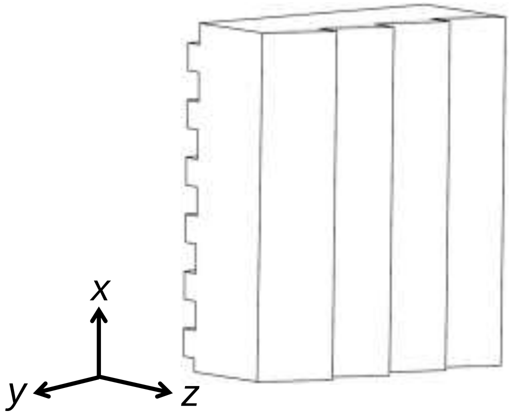
- Parallel gratings



Global S matrix	Non-sequential field tracing
$\sim M^3$ (scaling with number of layers)	$\sim M^3$ (scaling with number of light paths)

with M as the number of diffraction (evanescent included) orders used in calculation

- Crossed gratings

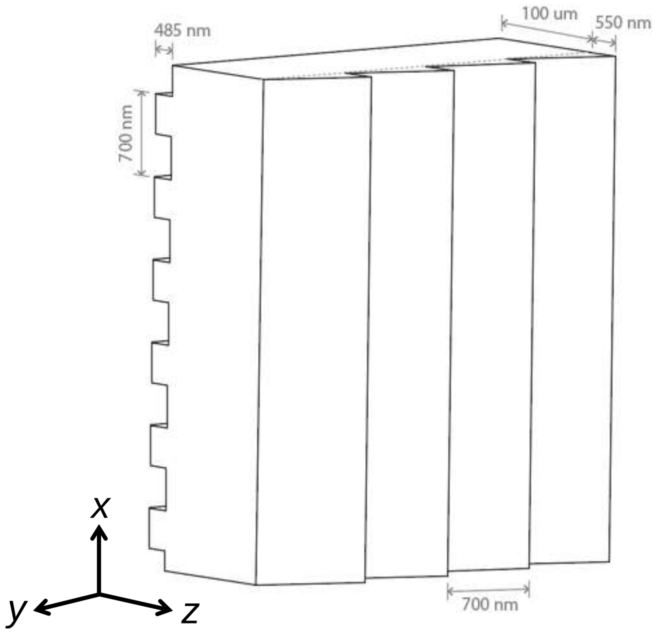


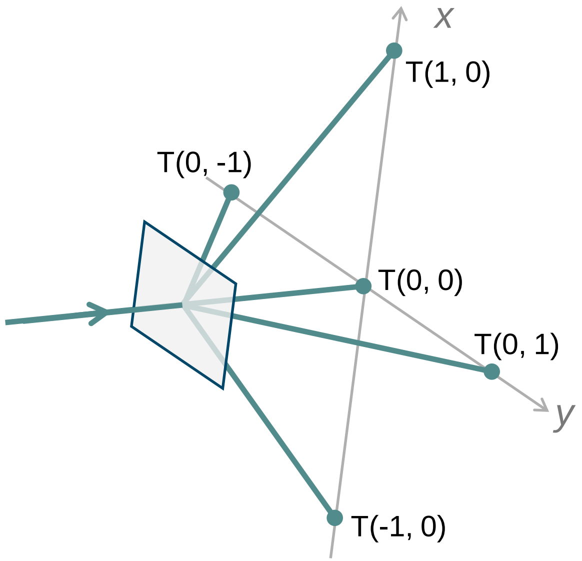
Global S matrix	Non-sequential field tracing
$\sim(M_x \times M_y)^3$ (scaling with number of layers)	$\sim(M_x^3 + M_y^3)$ (scaling with number of light paths)

with M_x and M_y as the number of diffraction (evanescent included) orders in both directions

Rectangular + Sawtooth Grating (crossed)

- Structure
  - Front: rectangular grating
    (along *x* direction)
  - Back: sawtooth grating
    (along *y* direction)



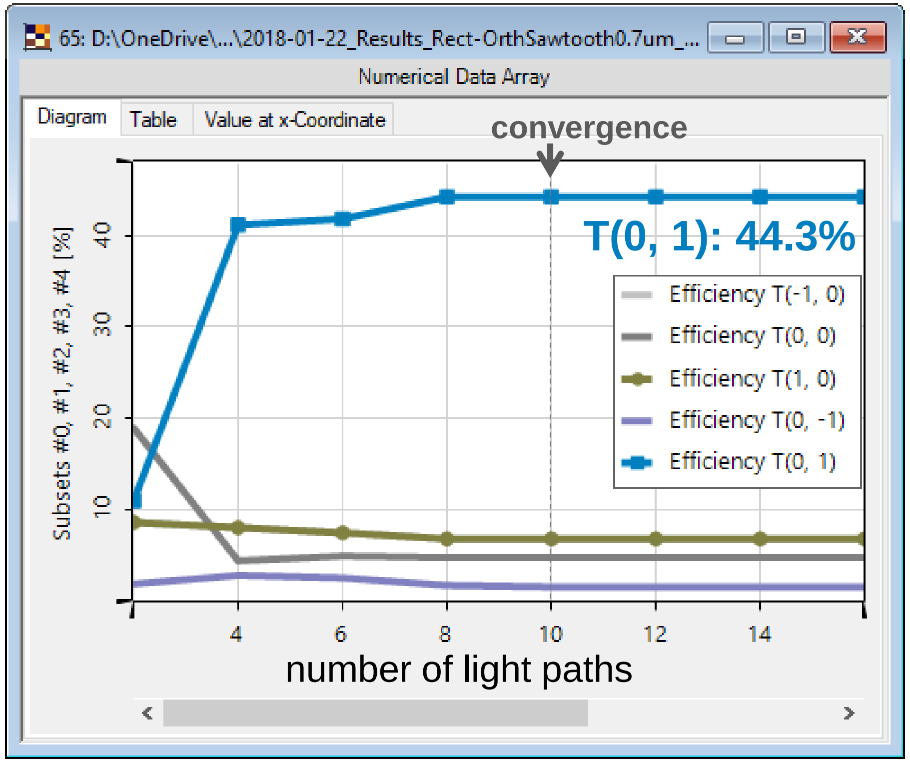


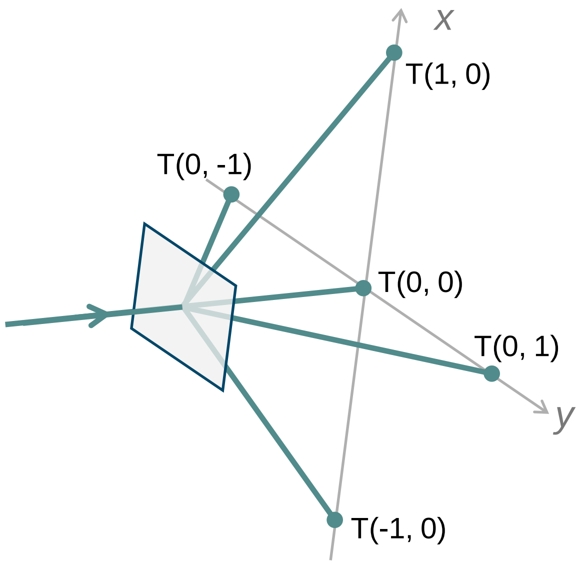
Global S matrix (TM)

T	Eff.	R	Eff.
-1, 0	5.4%	-1, 0	5.7%
0, -1	4.2%	0, -1	5.8%
0, 0	4.5%	0, 0	13.8%
0, 1	44.9%	0, 1	4.6%
1, 0	5.4%	1, 0	5.7%

Rectangular + Sawtooth Grating (crossed)

- Non-sequential field tracing (TM)



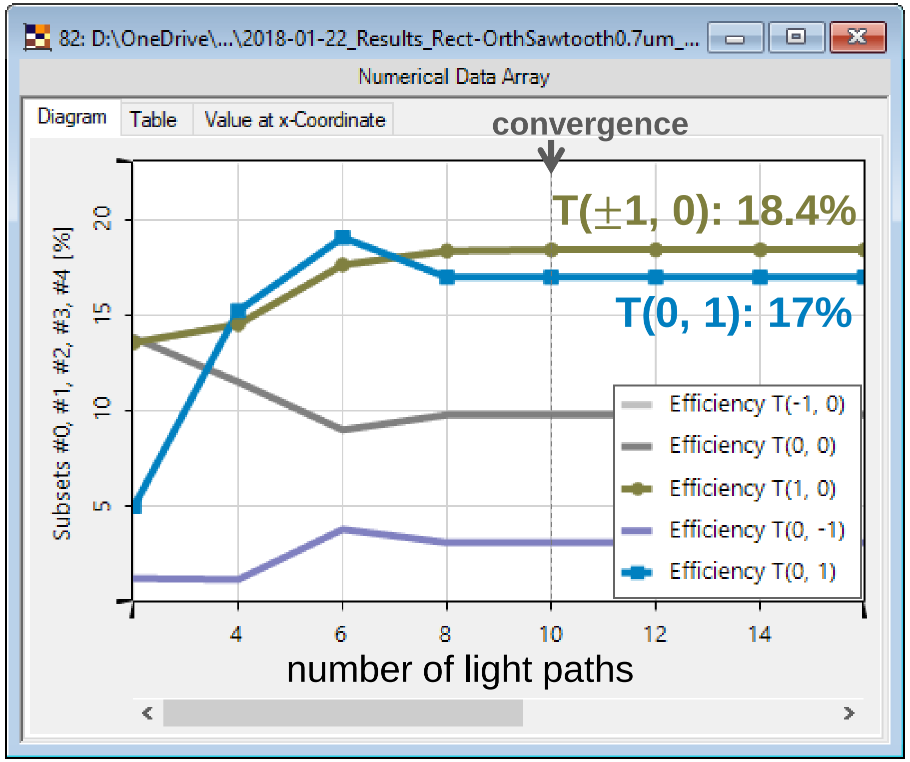


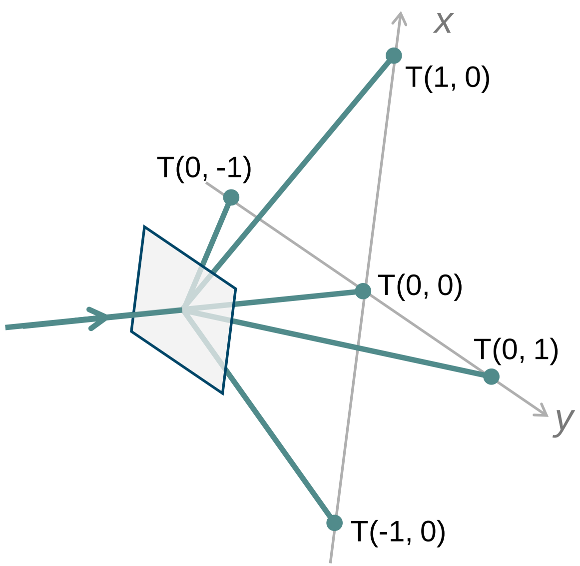
Global S matrix (TM)

T	Eff.	R	Eff.
-1, 0	5.4%	-1, 0	5.7%
0, -1	4.2%	0, -1	5.8%
0, 0	4.5%	0, 0	13.8%
0, 1	**44.9%**	0, 1	4.6%
1, 0	5.4%	1, 0	5.7%

Rectangular + Sawtooth Grating (crossed)

- Non-sequential field tracing (TE)



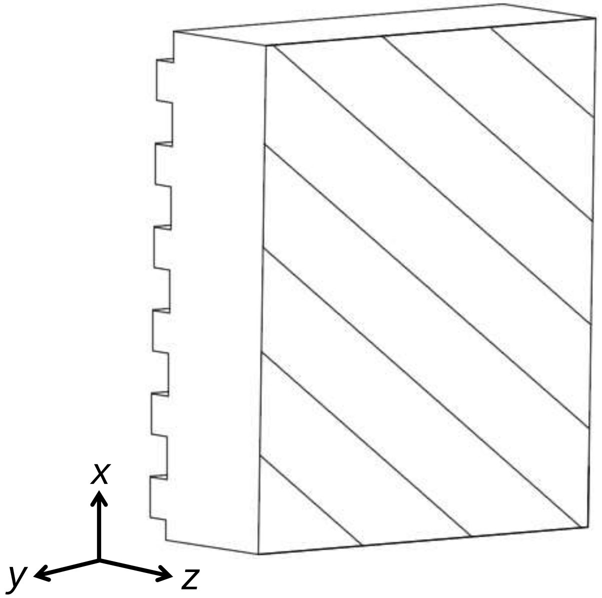


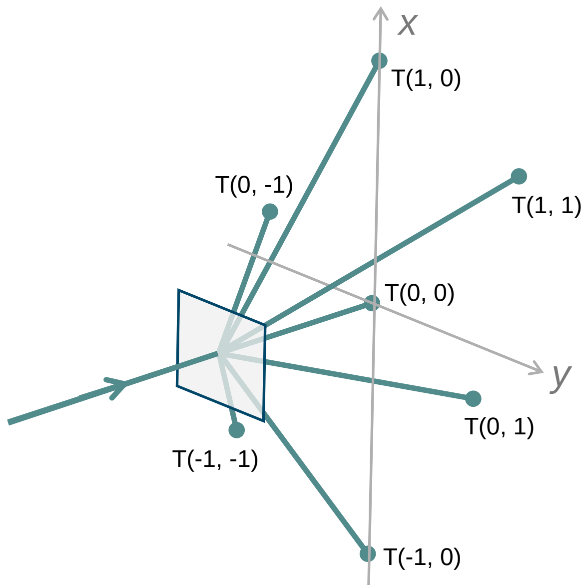
Global S matrix (TE)

T	Eff.	R	Eff.
-1, 0	**18%**	-1, 0	1.1%
0, -1	2.8%	0, -1	0.46%
0, 0	11.9%	0, 0	22.6%
0, 1	**17.1%**	0, 1	6.89%
1, 0	**18%**	1, 0	1.1%

Rectangular + Sawtooth Grating (45° rotated)

- Structure
  - Front: rectangular grating
    (along *x* direction)
  - Back: sawtooth grating
    (along *x*-*y* diagonal direction)

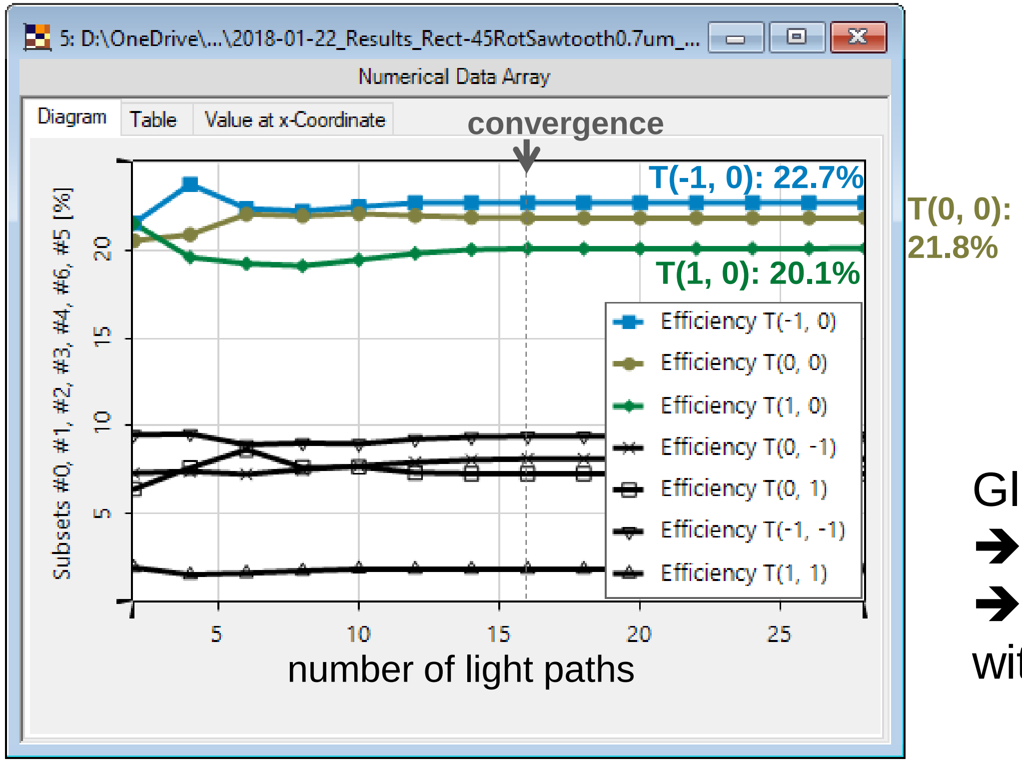


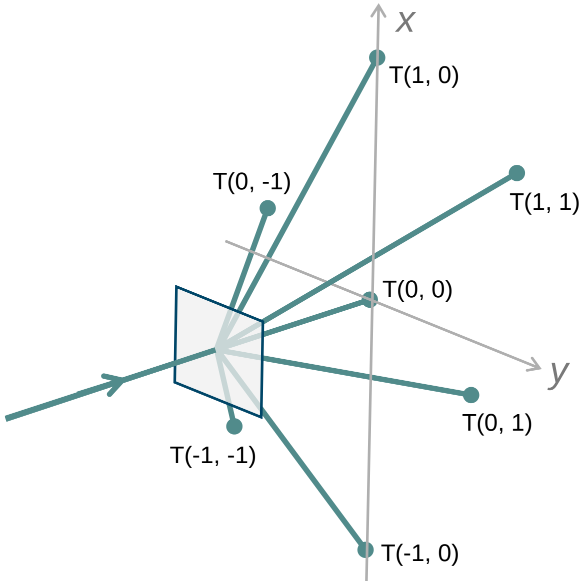


Global S matrix (TM)
➔ No common period!
➔ Huge computational effort even with approximated common period

Rectangular + Sawtooth Grating (45° rotated)

- Non-sequential field tracing (TM)





Global S matrix ***NOT*** possible!
➔ No common period
➔ Huge computational effort even with approximated common period

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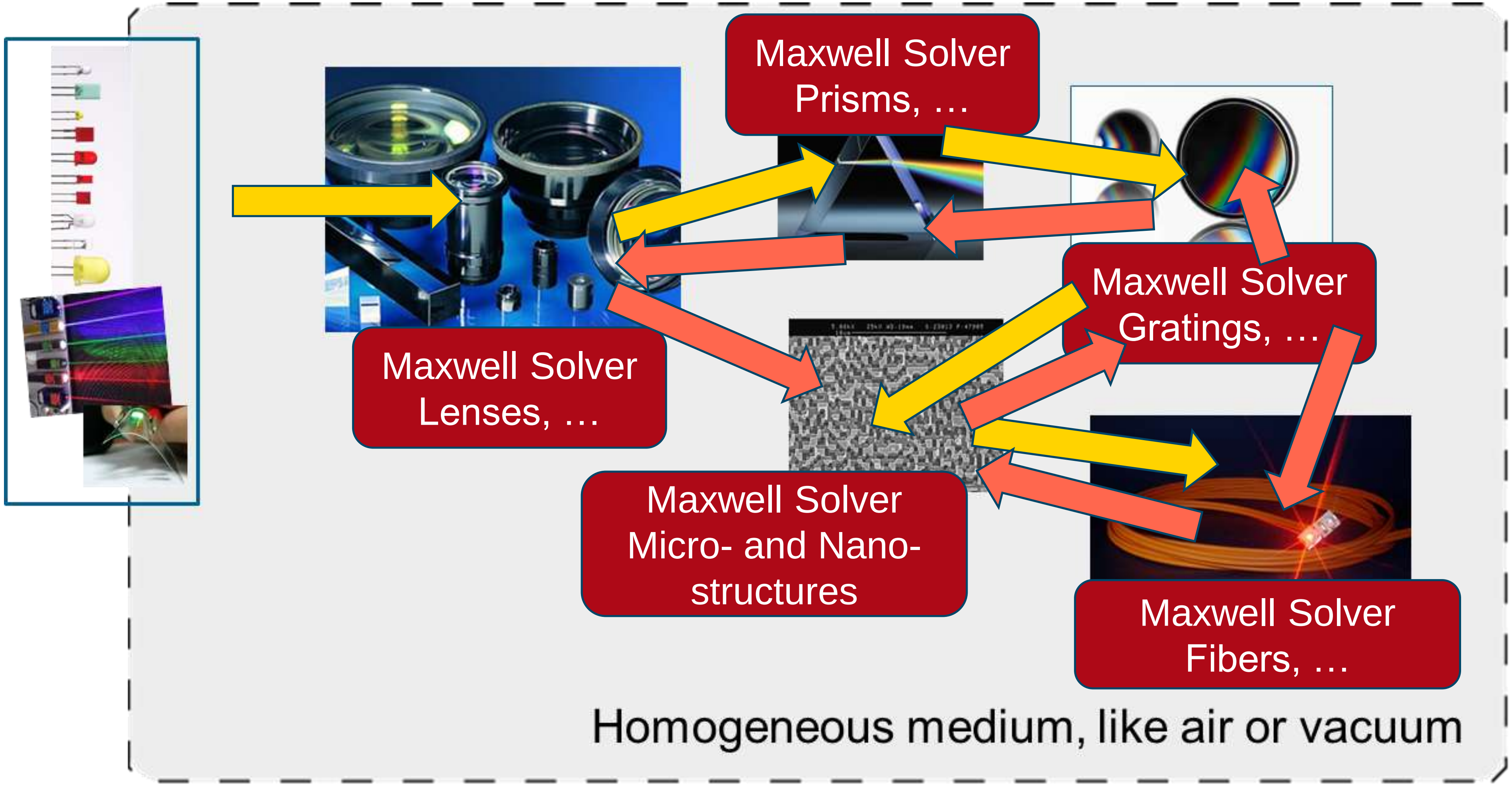
  - Rigorous solvers
  - Solvers using mathematical approximations which exploit specific characteristics of field and modulation of refractive index
  - Always fully vectorial treatment
- **Interconnection**: The solvers per region are connected through non-sequential field tracing to solve Maxwell’s equations in the entire system.

Let’s have a closer look into how field tracing connects Maxwell solvers.

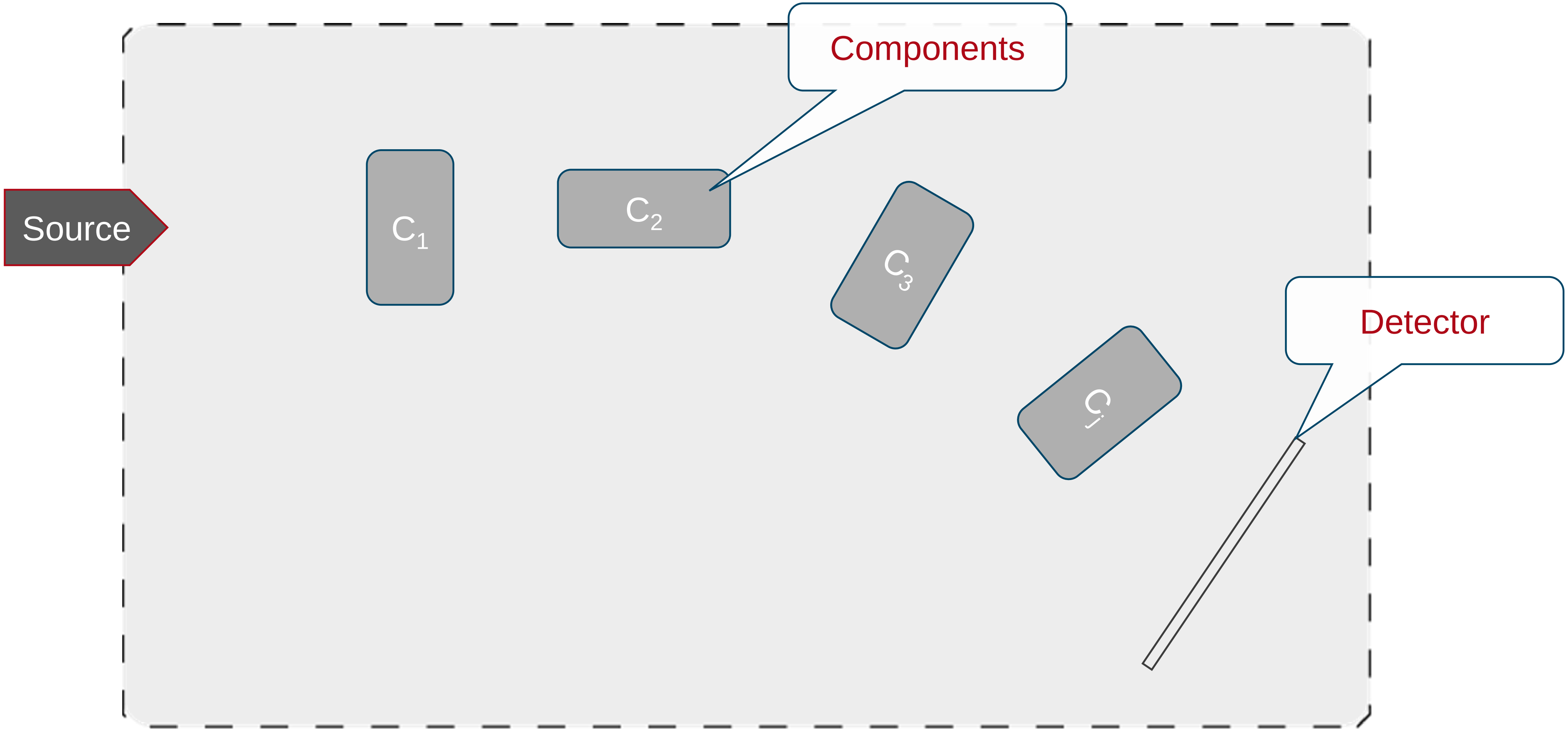
Non-sequential modeling: Lightpaths

Decomposition of modeling into lightpath operator sequences

Non-Sequential Connection of Regional Maxwell Solver



Lightpaths for Field Tracing Through System



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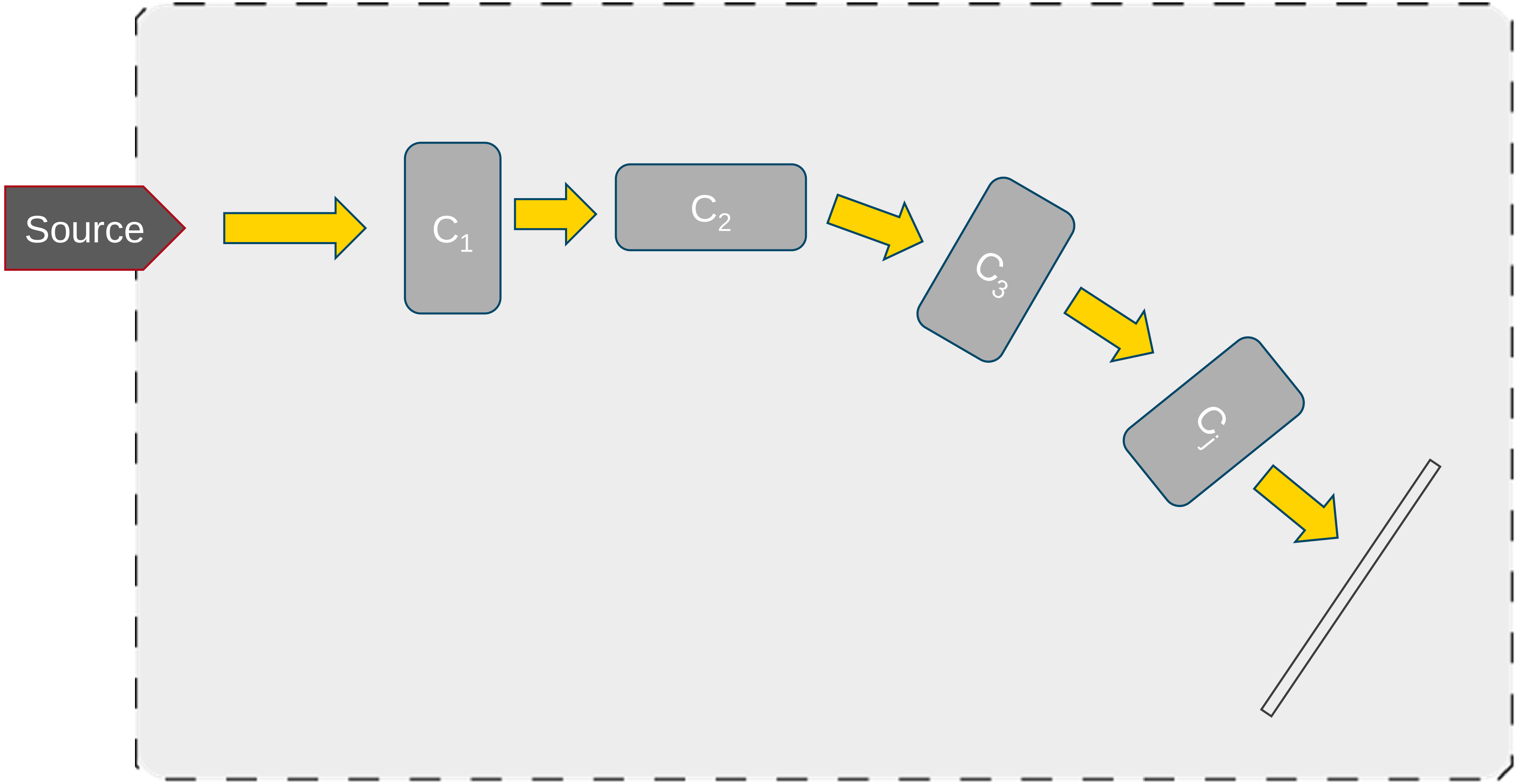
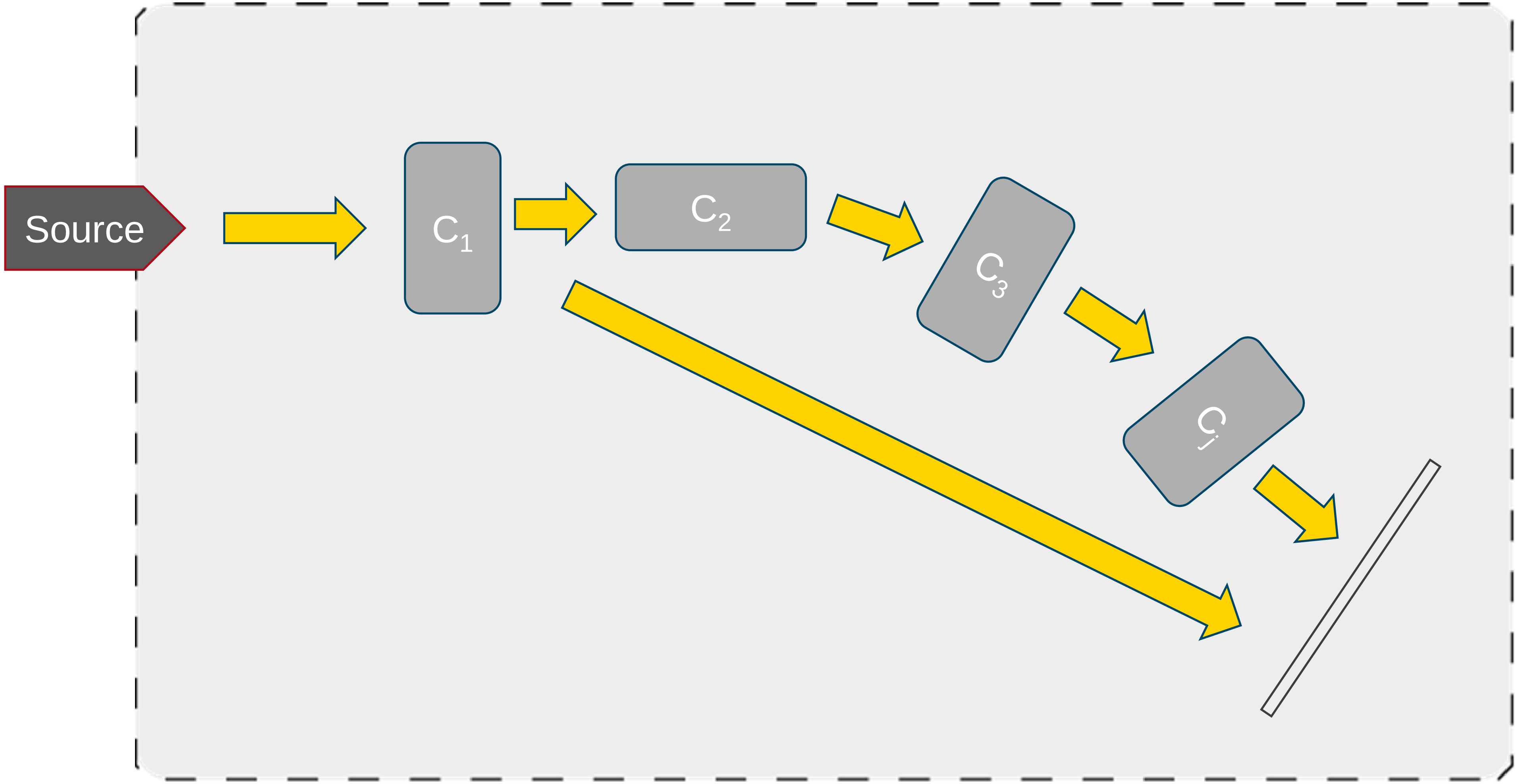
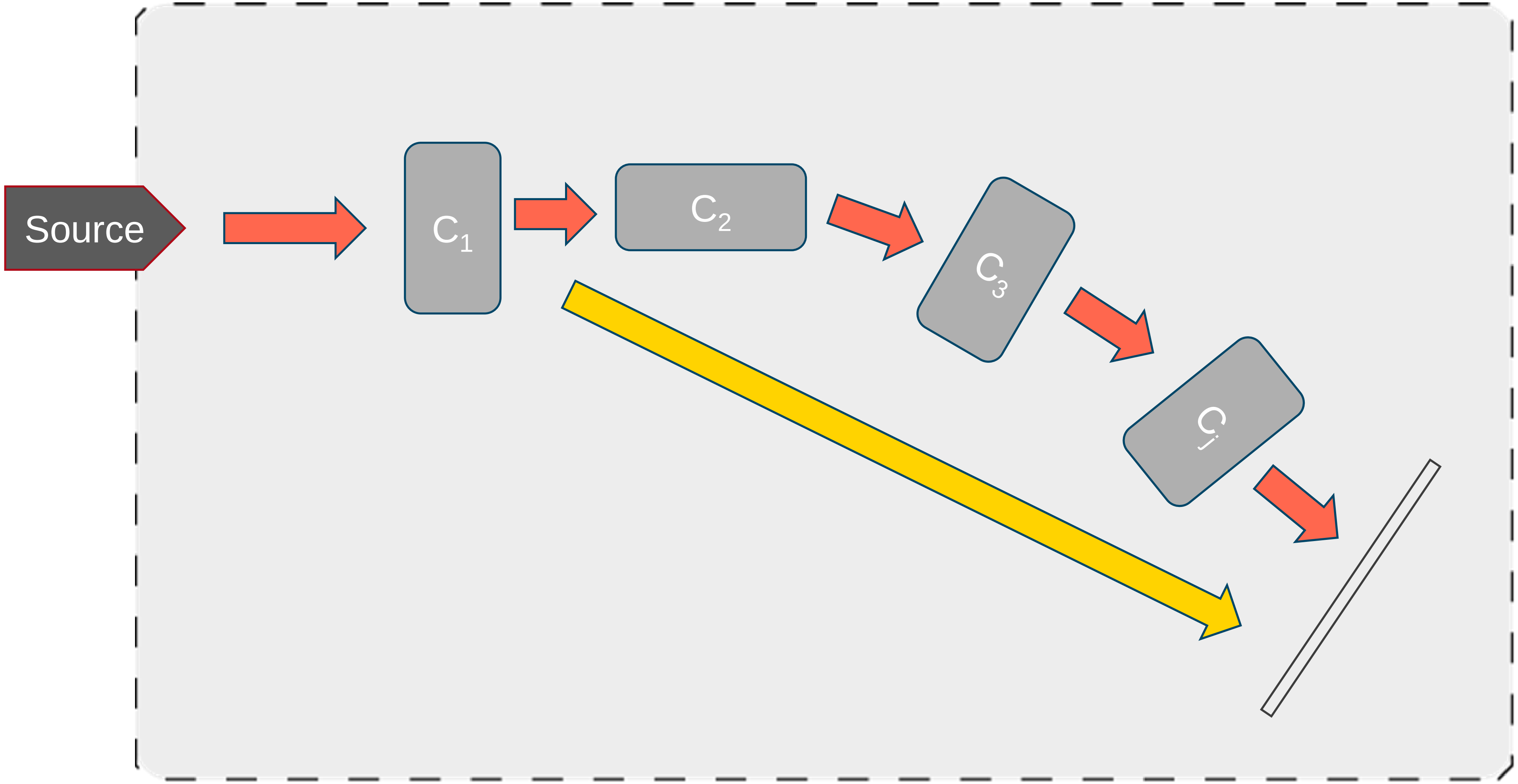


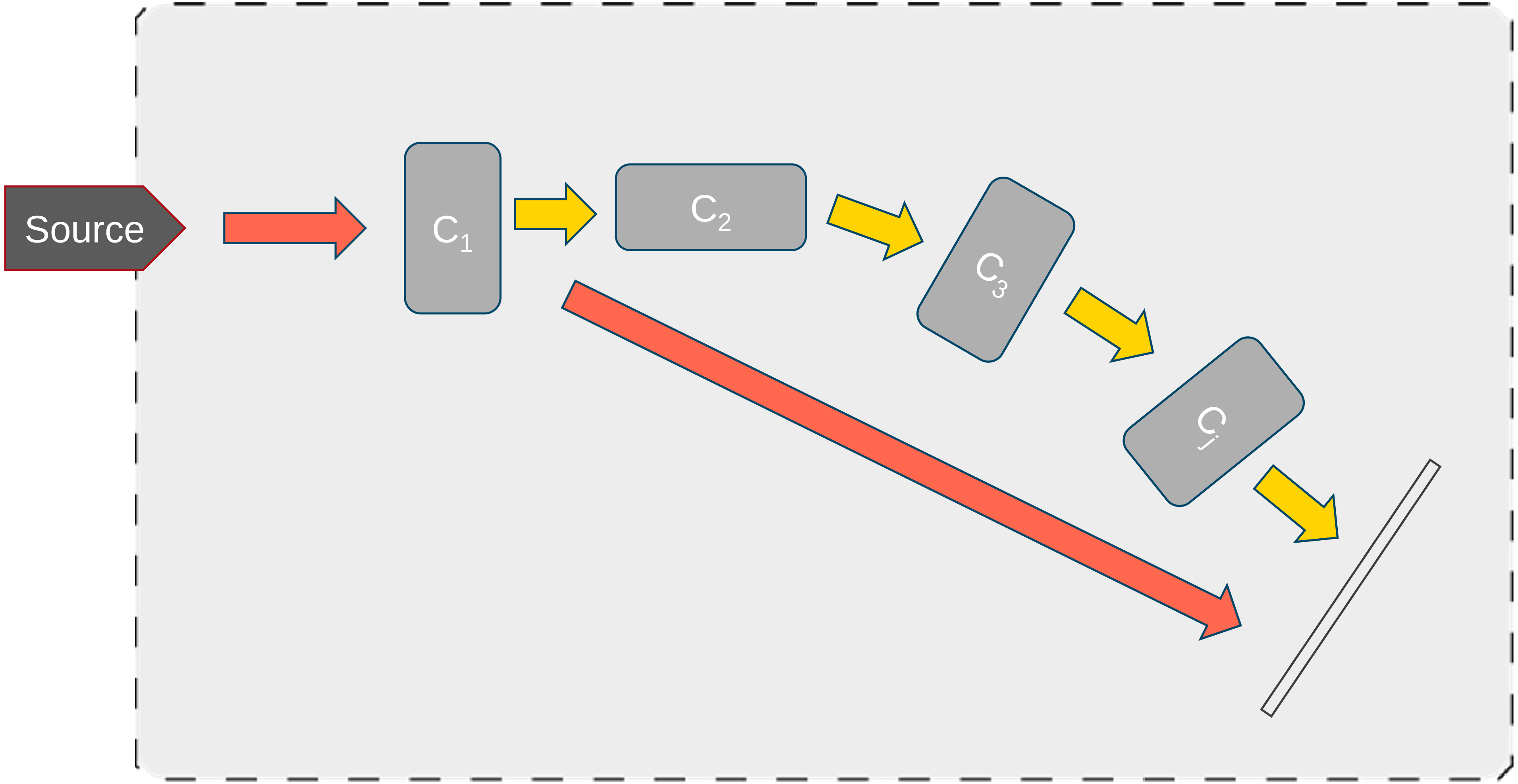
Lightpaths in Non-Sequential Modeling



Lightpaths in Non-Sequential Modeling



Lightpaths in Non-Sequential Modeling



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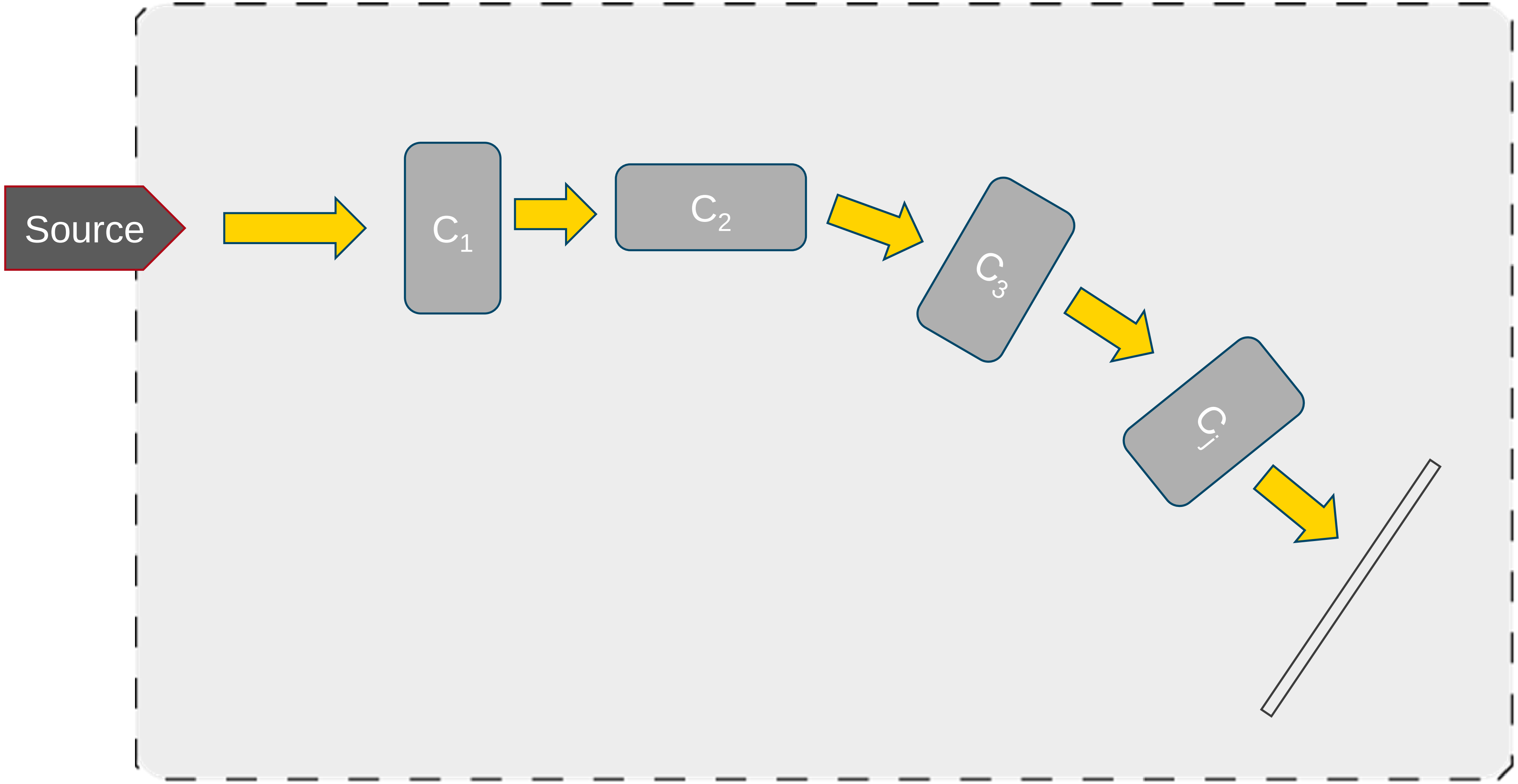
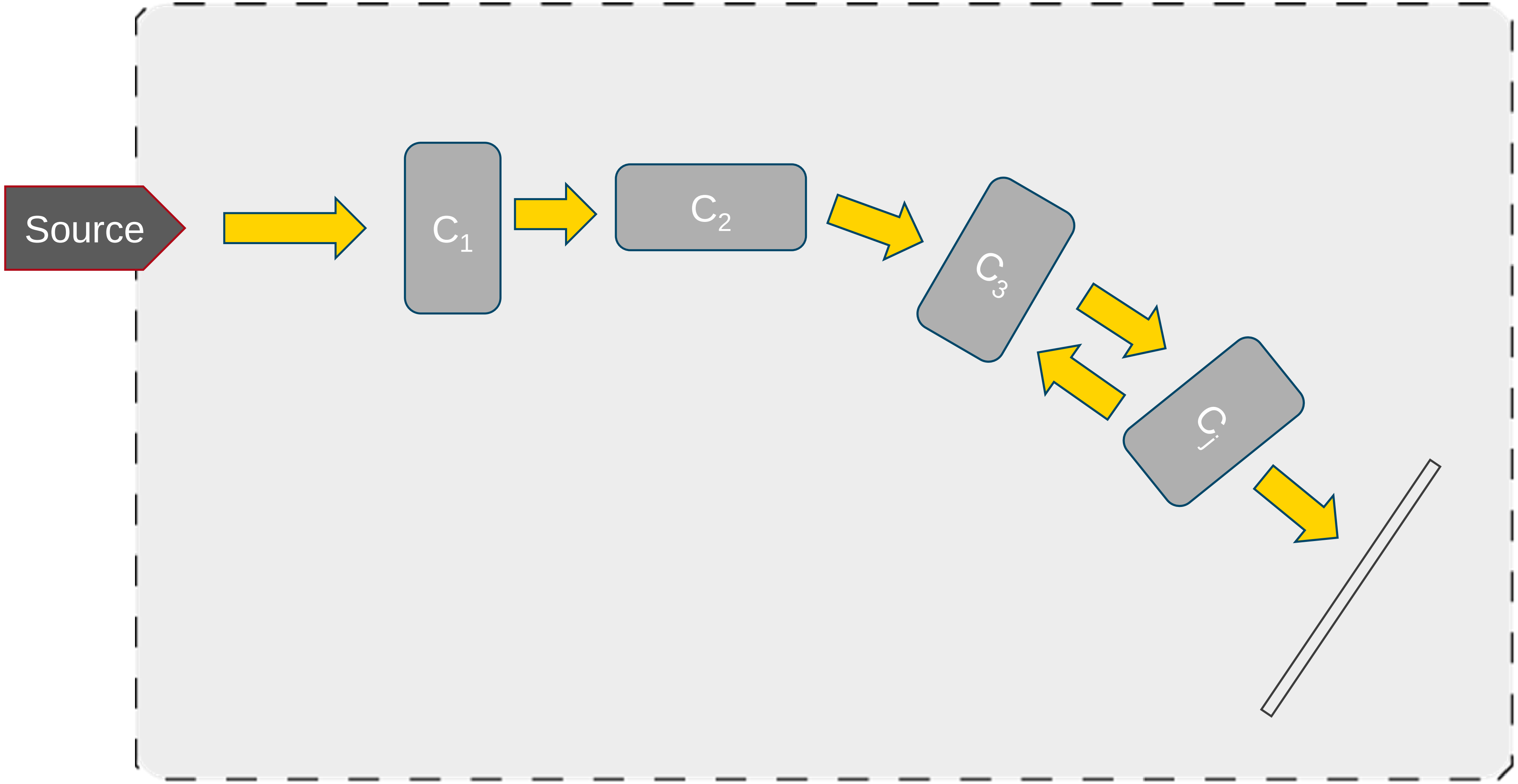
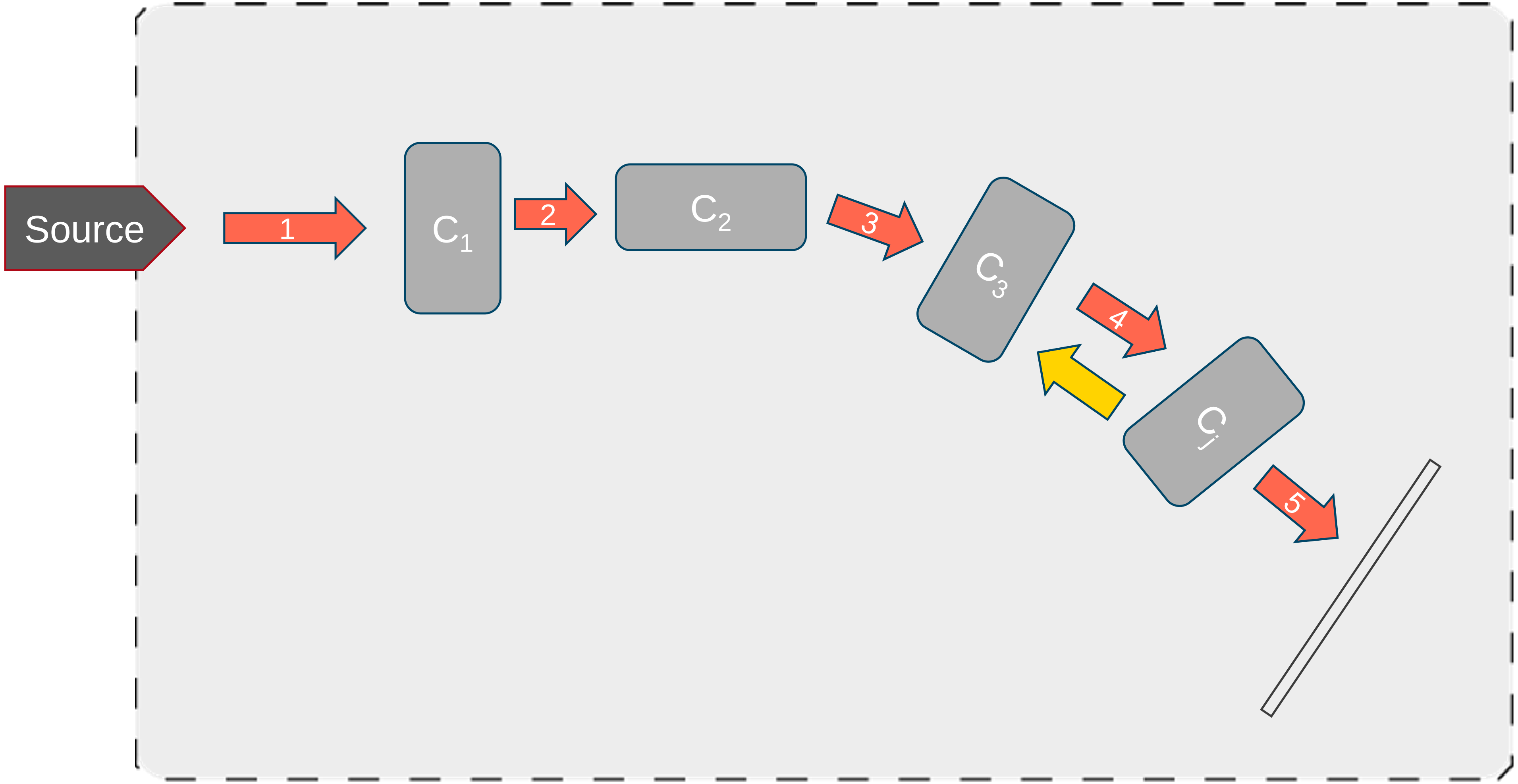


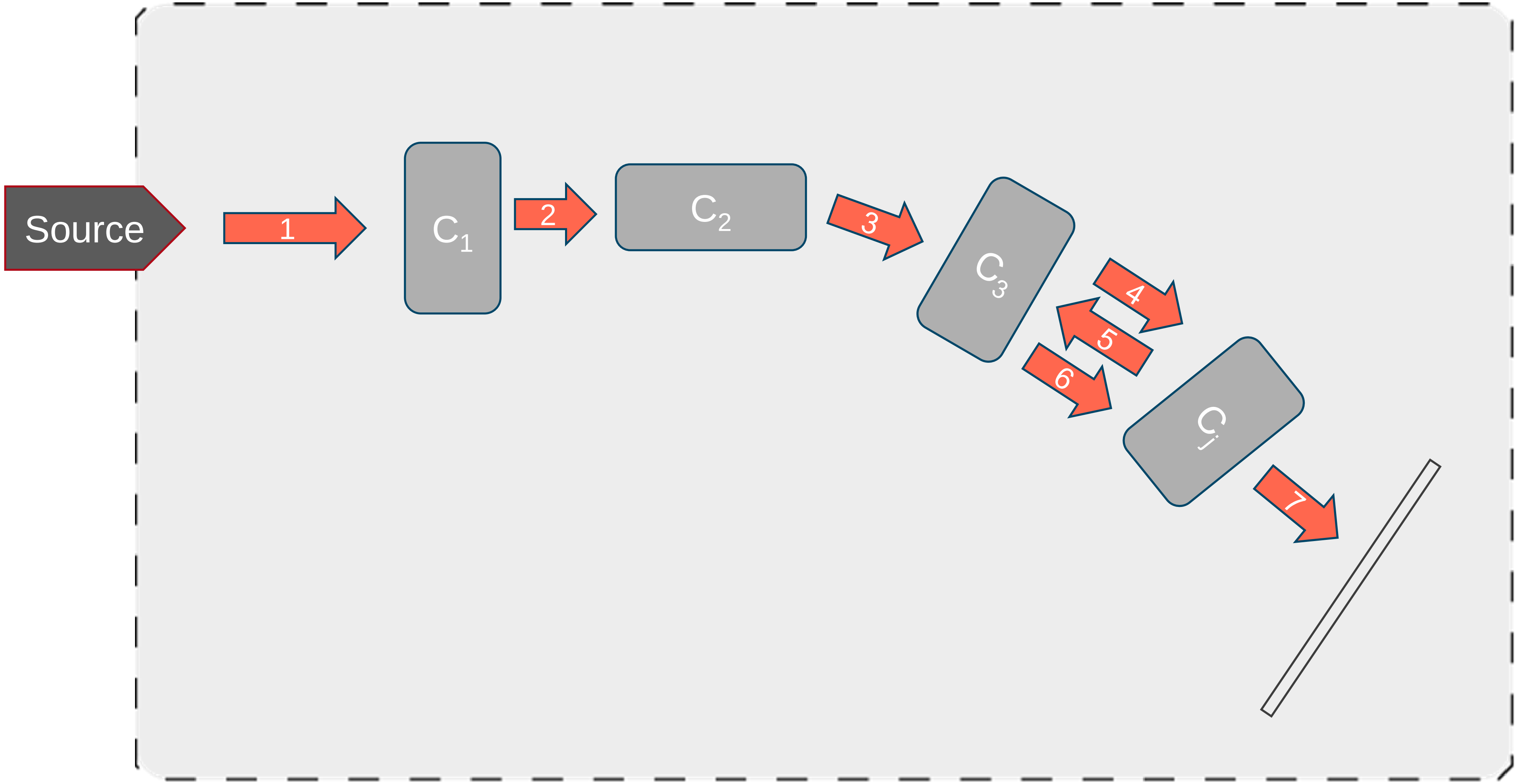
Lightpaths in Non-Sequential Modeling



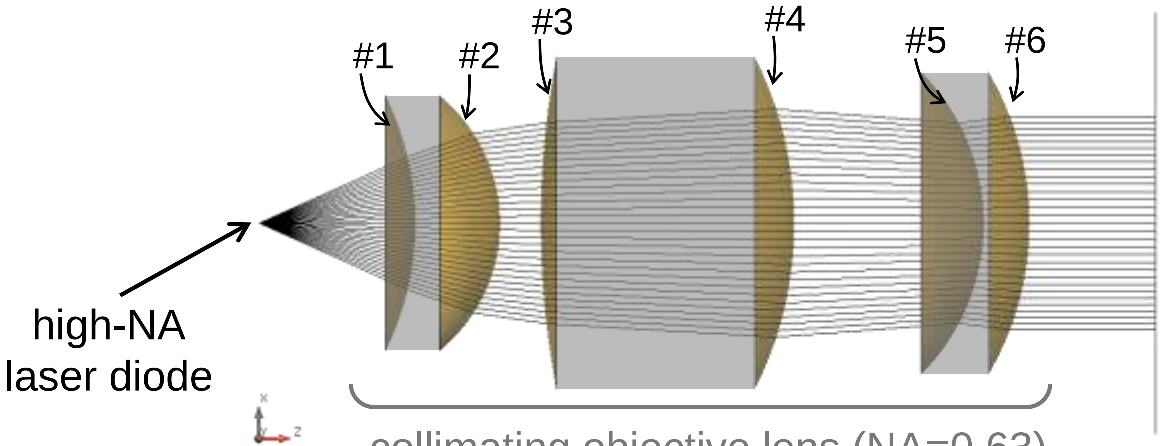
Lightpaths in Non-Sequential Modeling

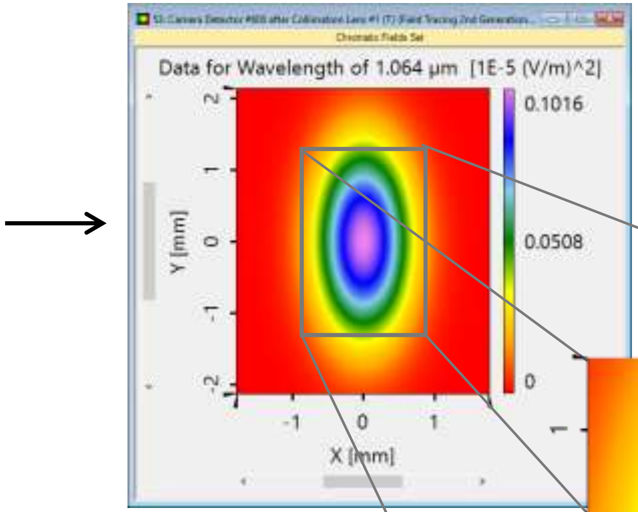


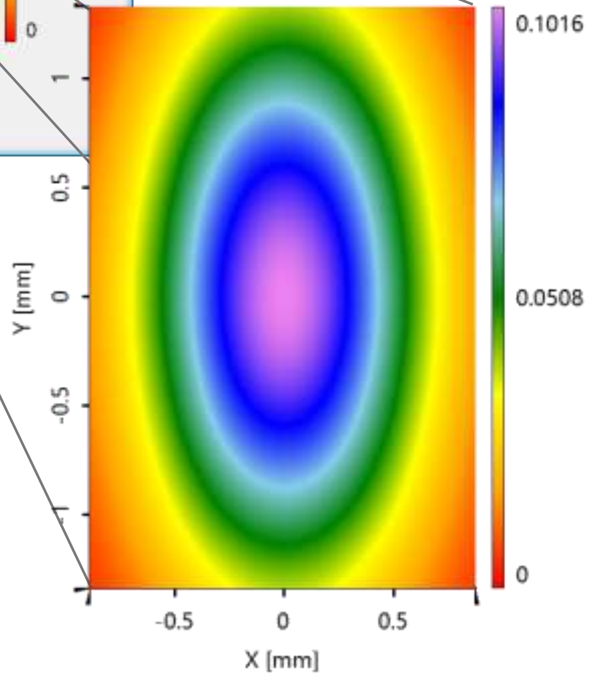
Lightpaths in Non-Sequential Modeling



Collimation System: Sequential Simulation





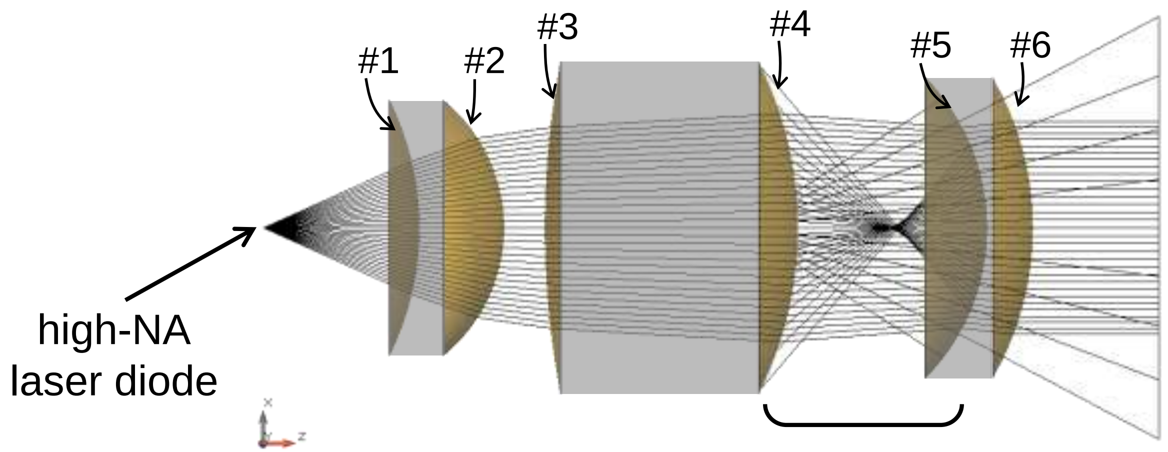


Laser Components WSLD-1064-050m-1-PD

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

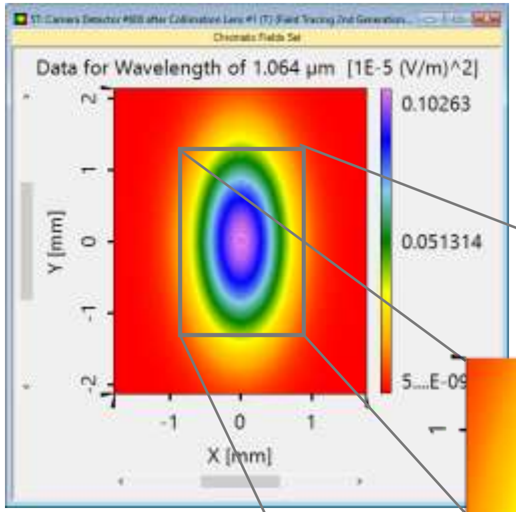
Perfect AR coating is assumed, so sequential modeling is used.

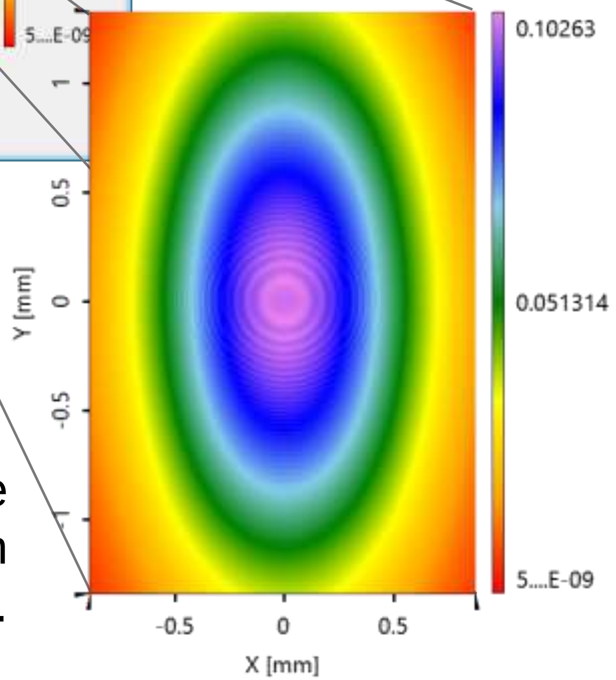
Collimation System: Non-Sequential Simulation



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

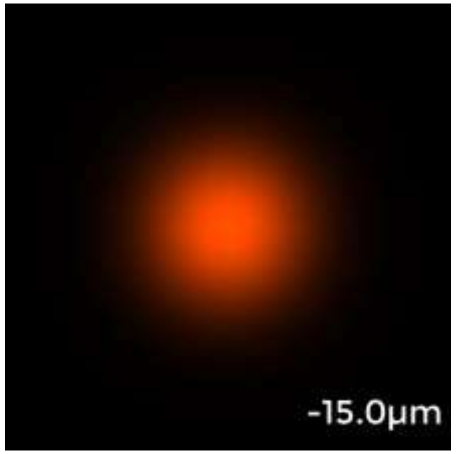
multiple reflections between uncoated surfaces #4 and #5, other surfaces are well coated.

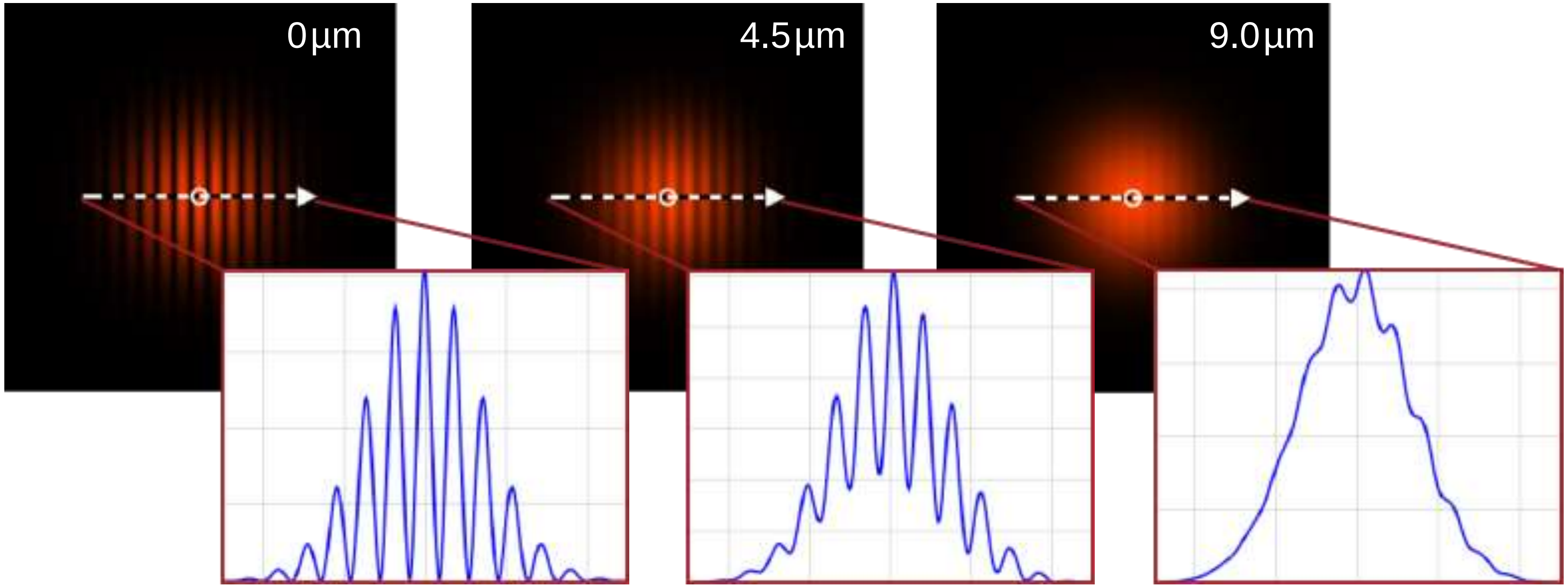


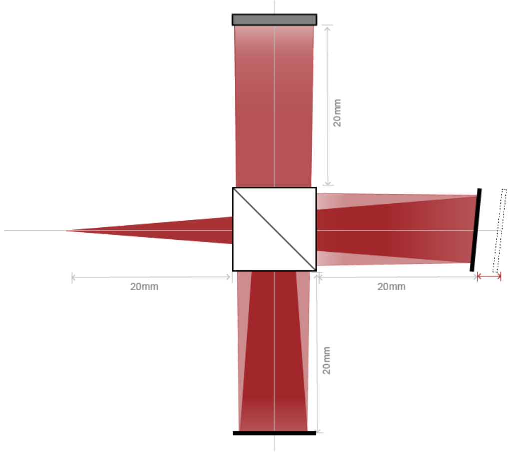


Simulation including interference caused by multiple reflections between uncoated surfaces takes 15 seconds.

Another Non-Sequential Example



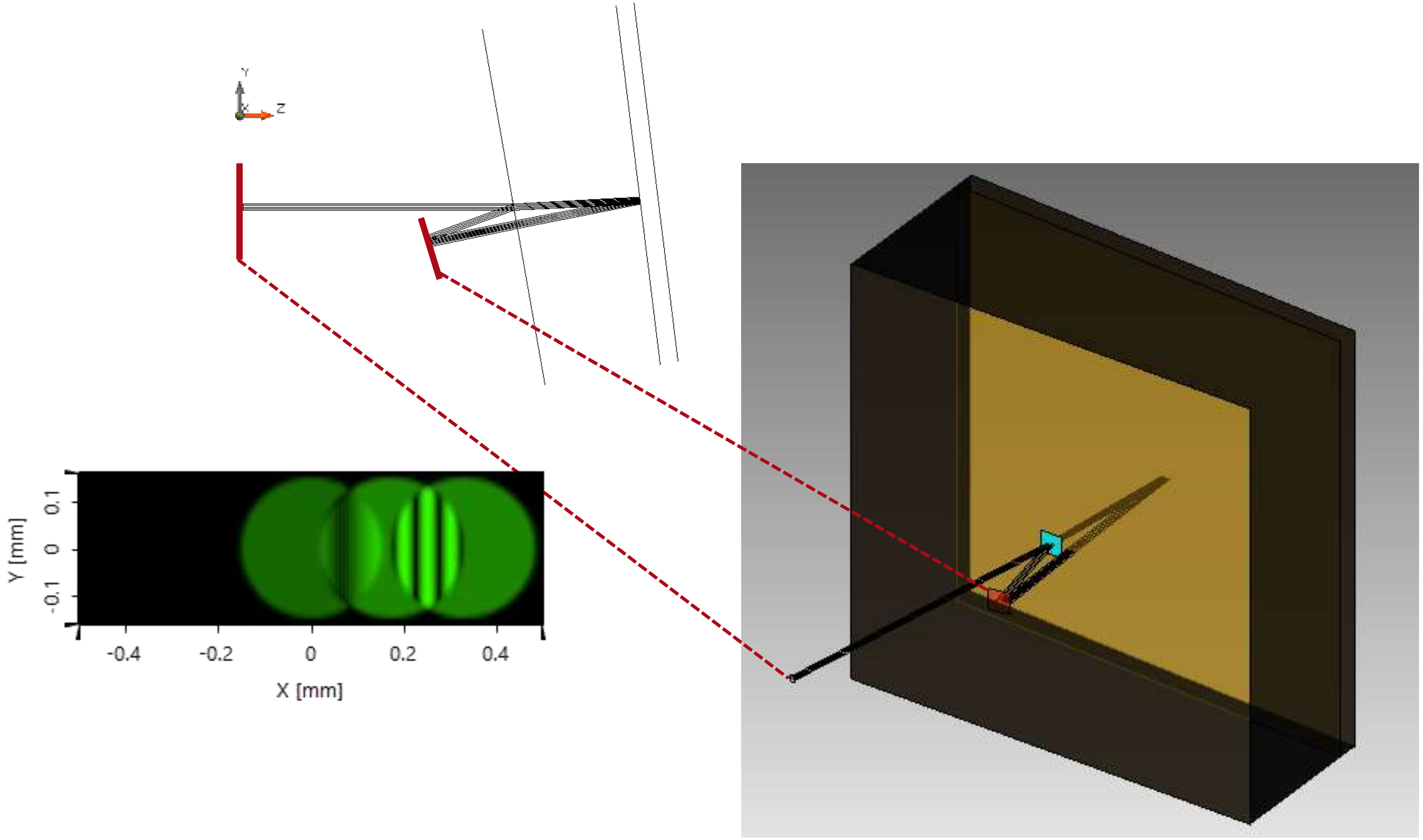




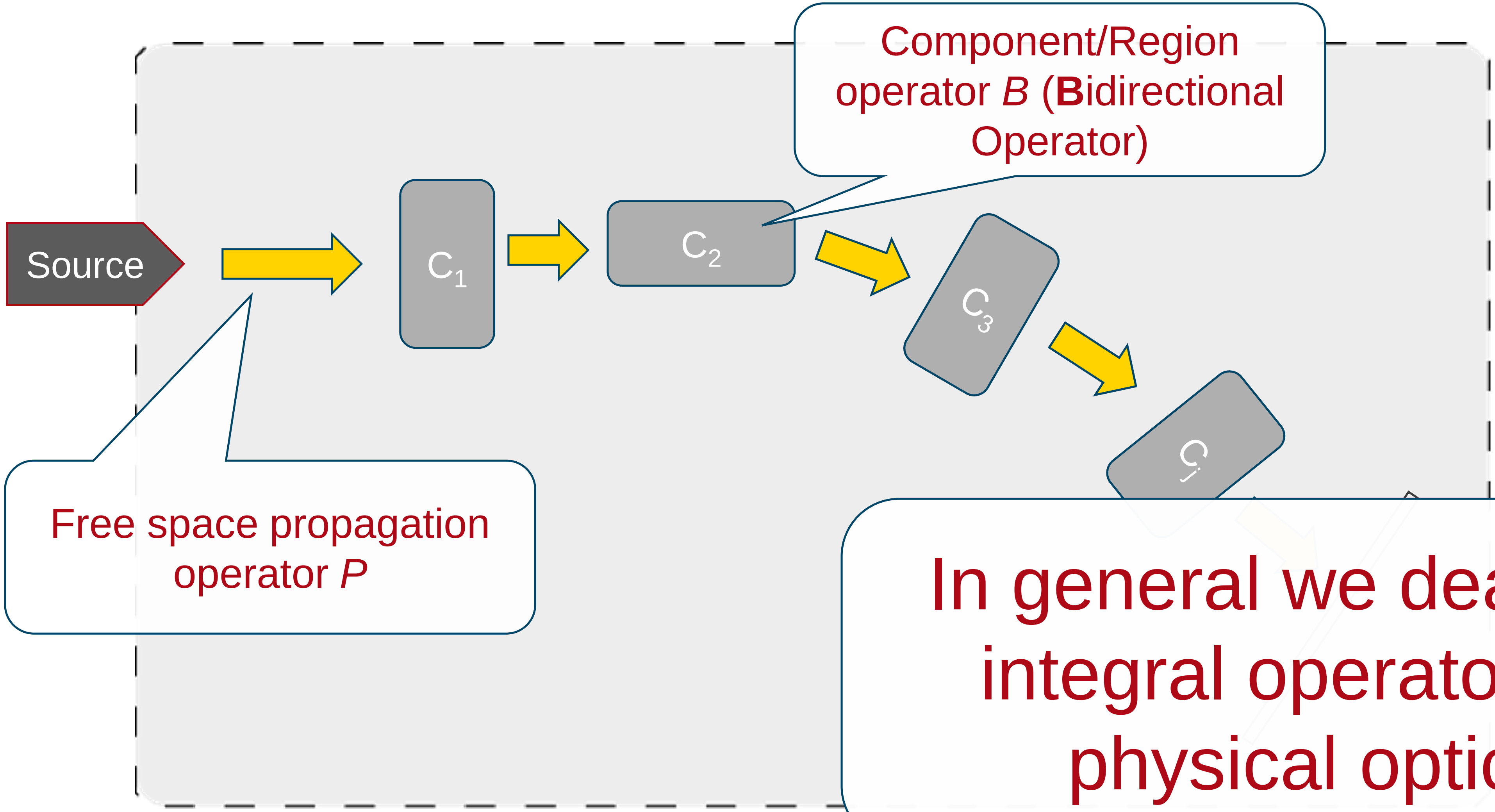
Coherent length here is around 20µm. It matches that with literature, which is

$$L = \frac{\lambda^2}{\Delta\lambda} = \frac{635^2}{20}\ \text{nm} \approx 20\ \mu\text{m}$$

Another Non-Sequential Example

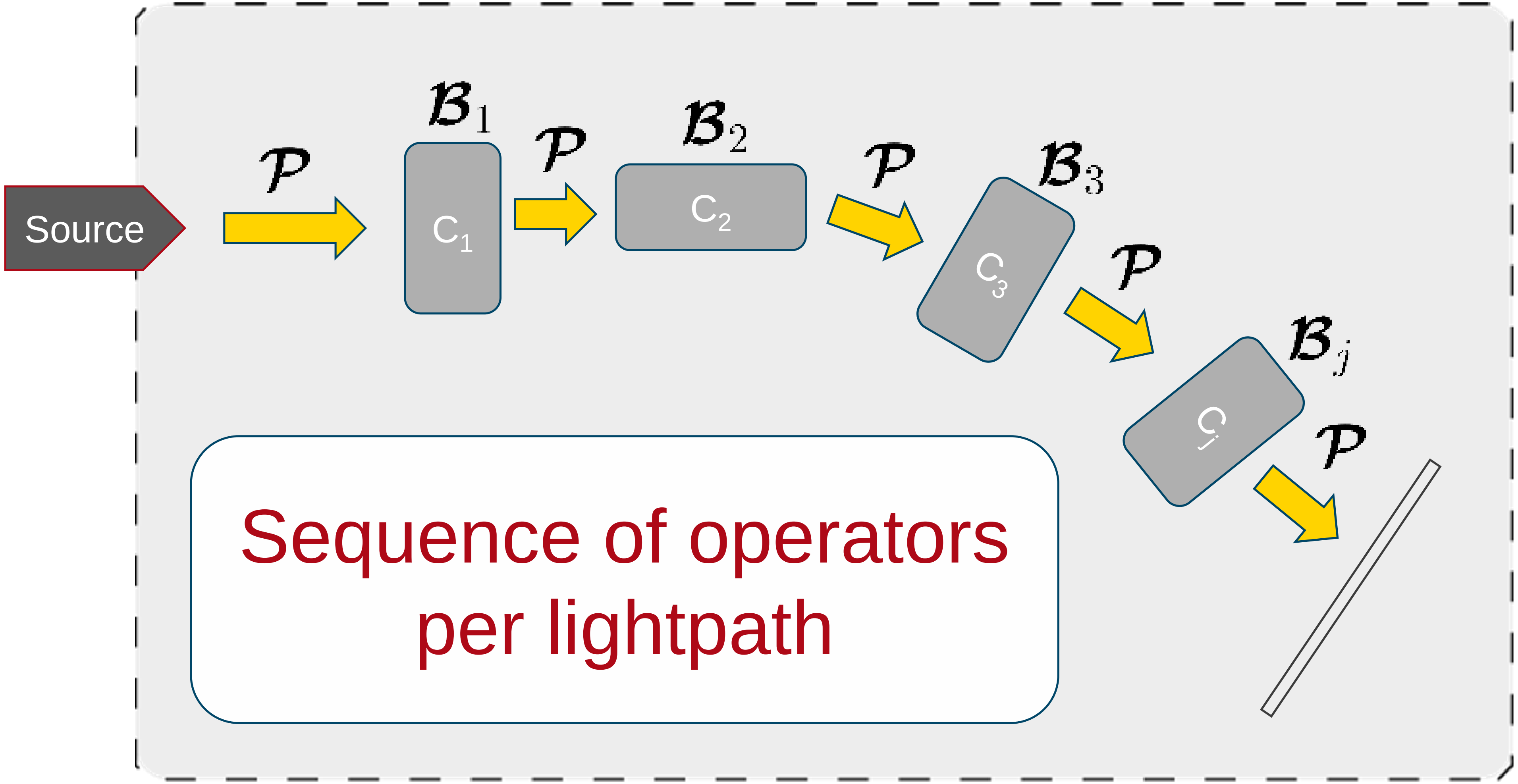


Field Tracing Sequence per Lightpath

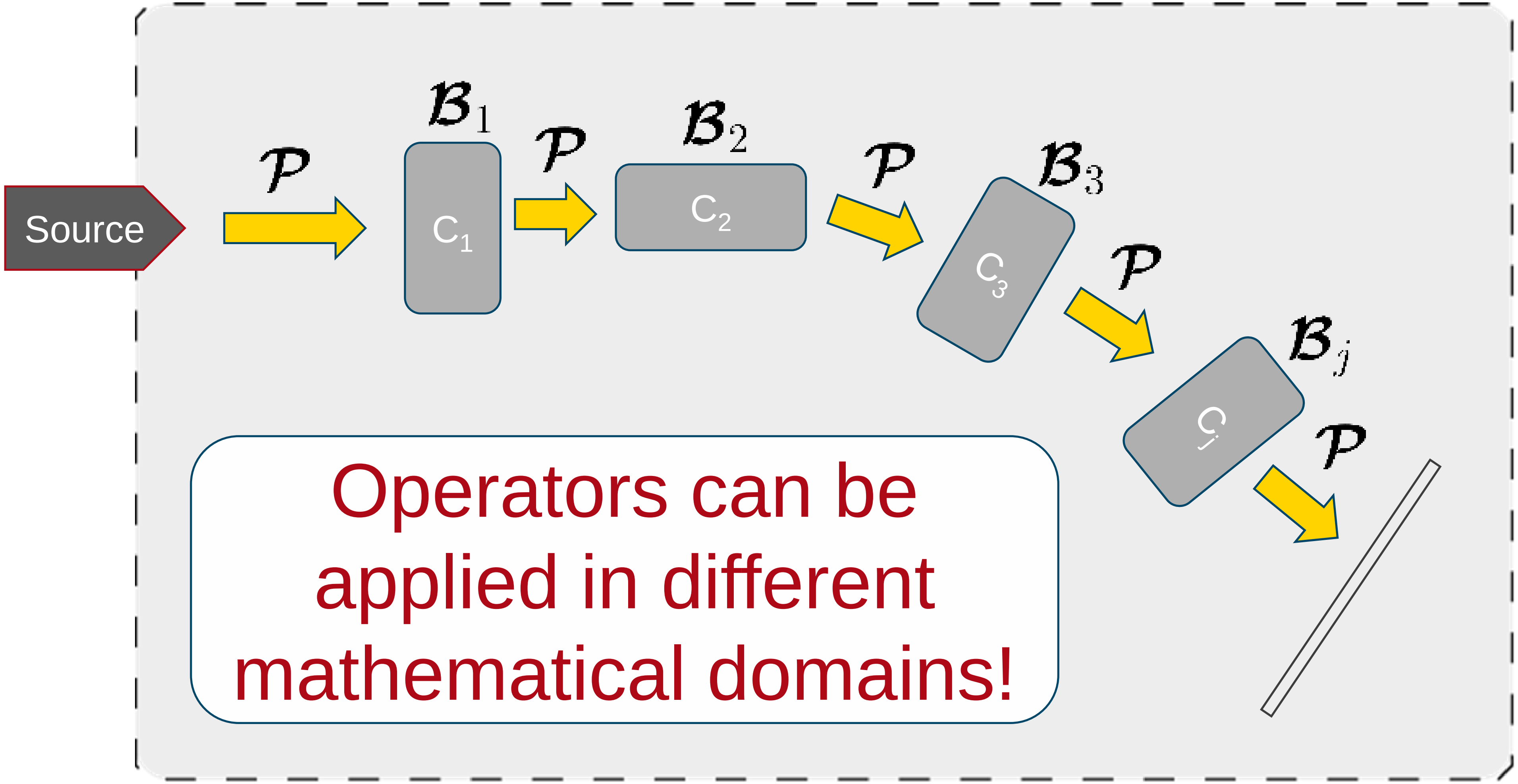


In general we deal with integral operators in physical optics

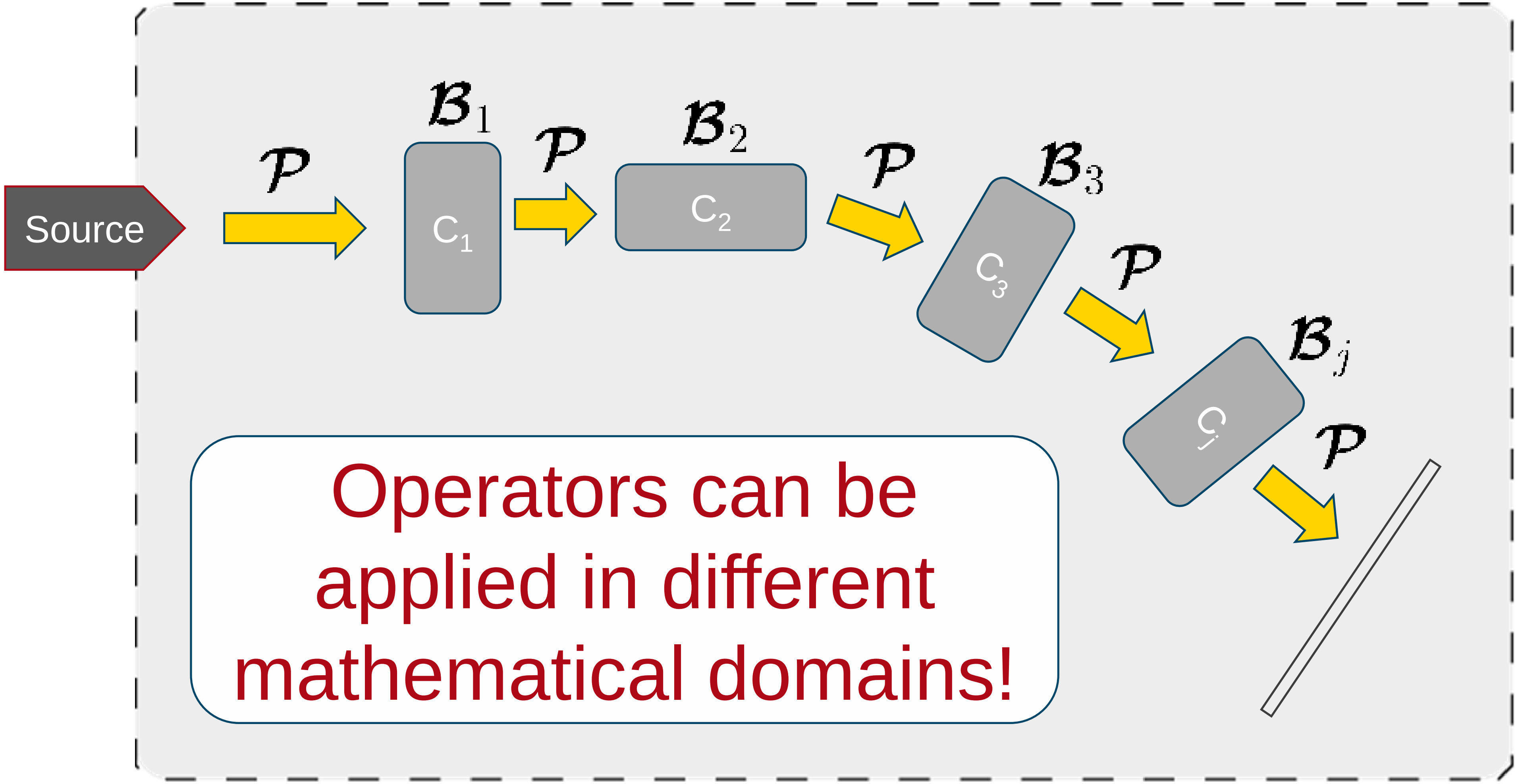
Field Tracing Sequence per Lightpath



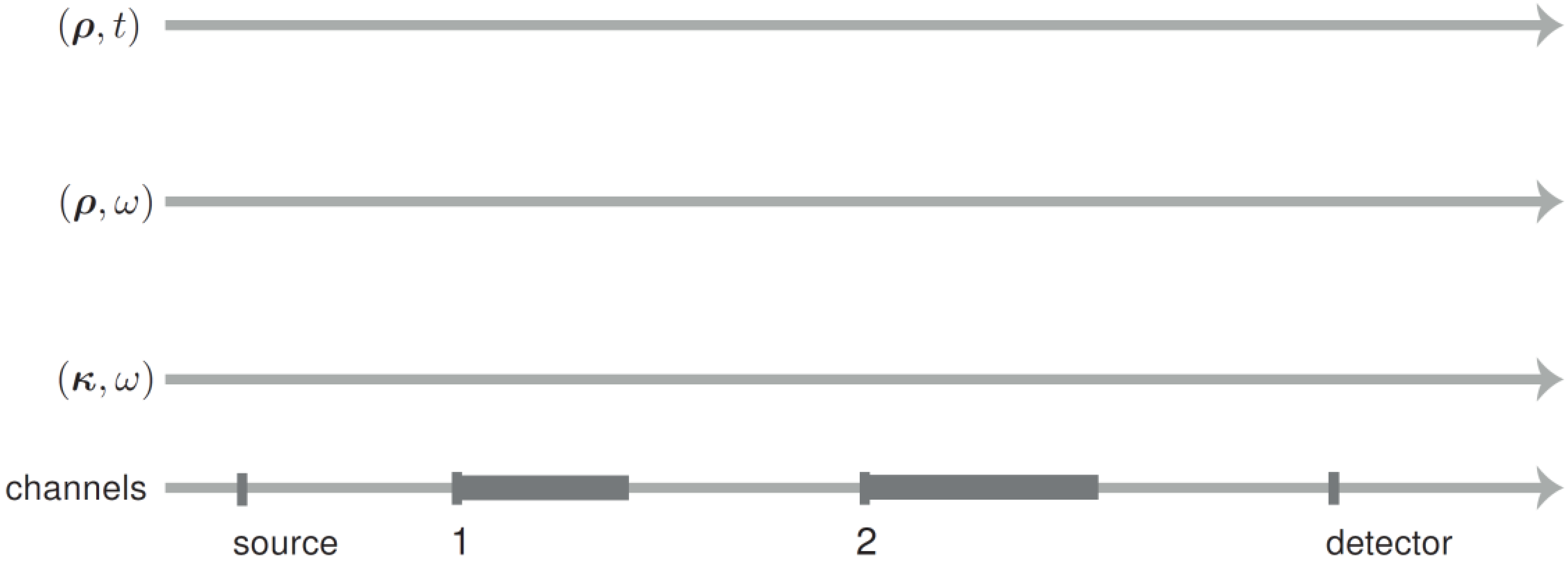
Field Tracing Sequence per Lightpath



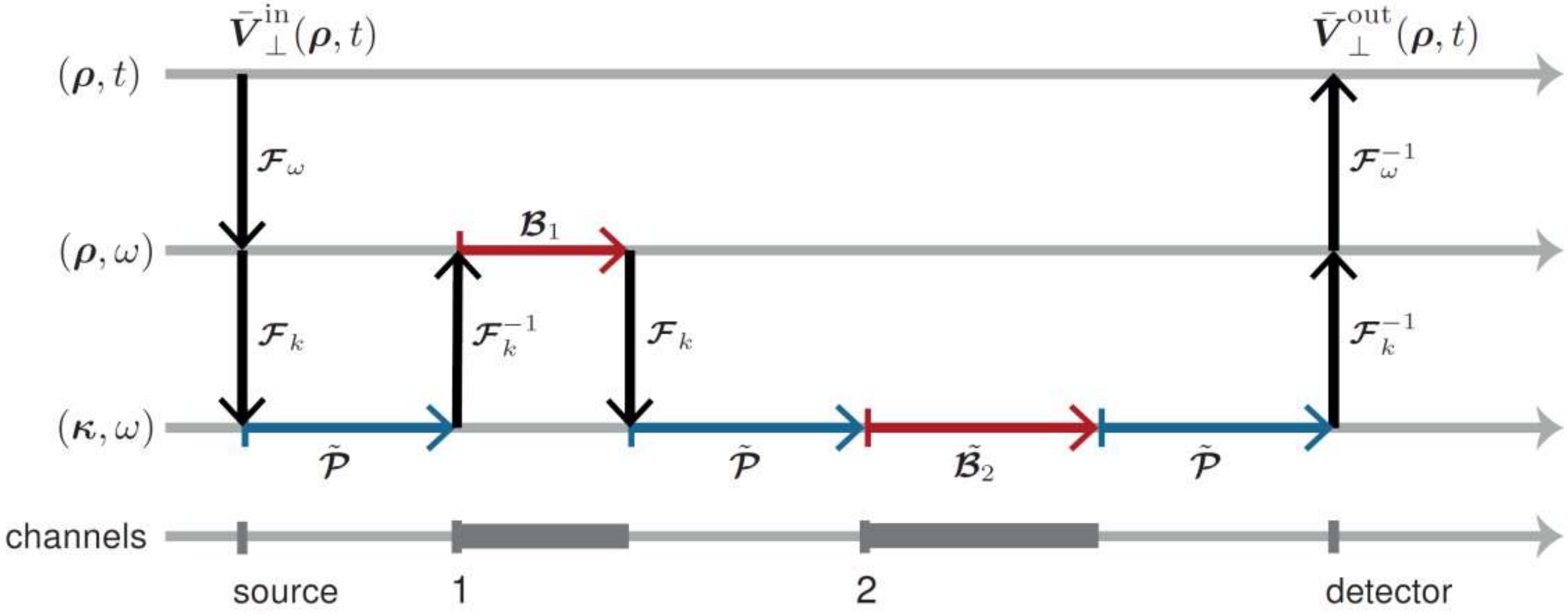
Field Tracing Sequence per Lightpath



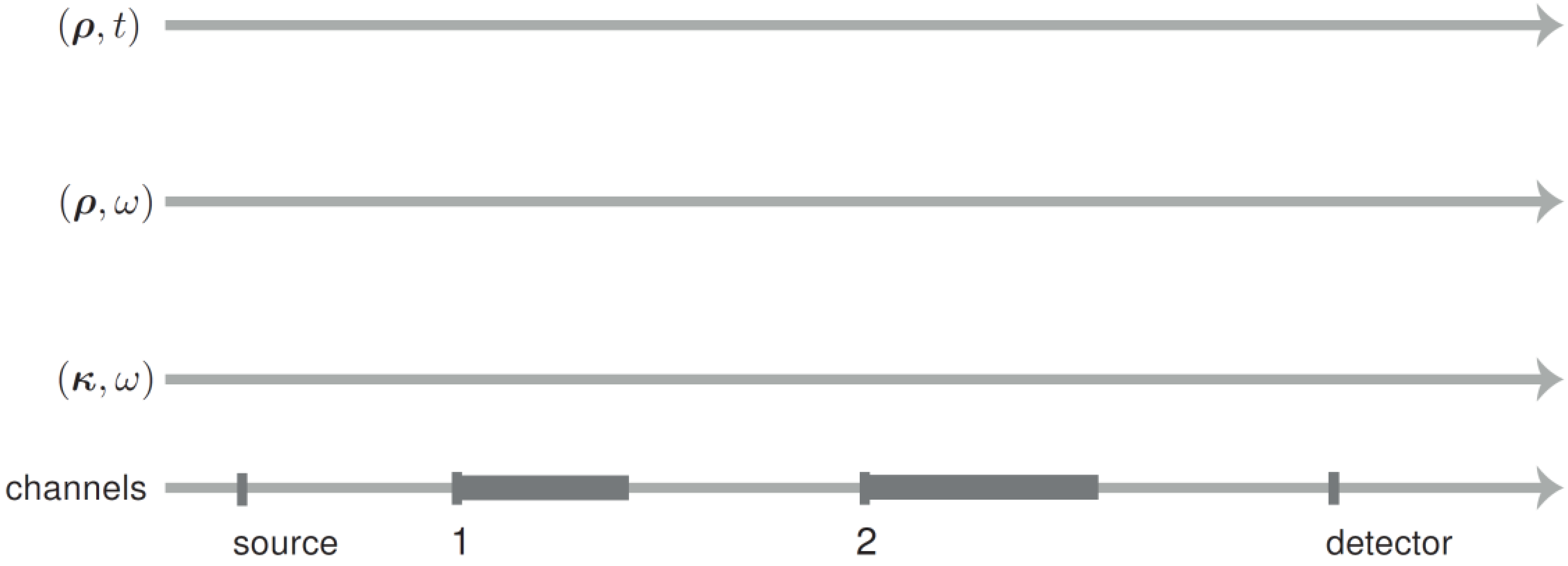
Field Tracing Diagrams



Field Tracing Diagrams: Ultrashort-Pulse Modeling

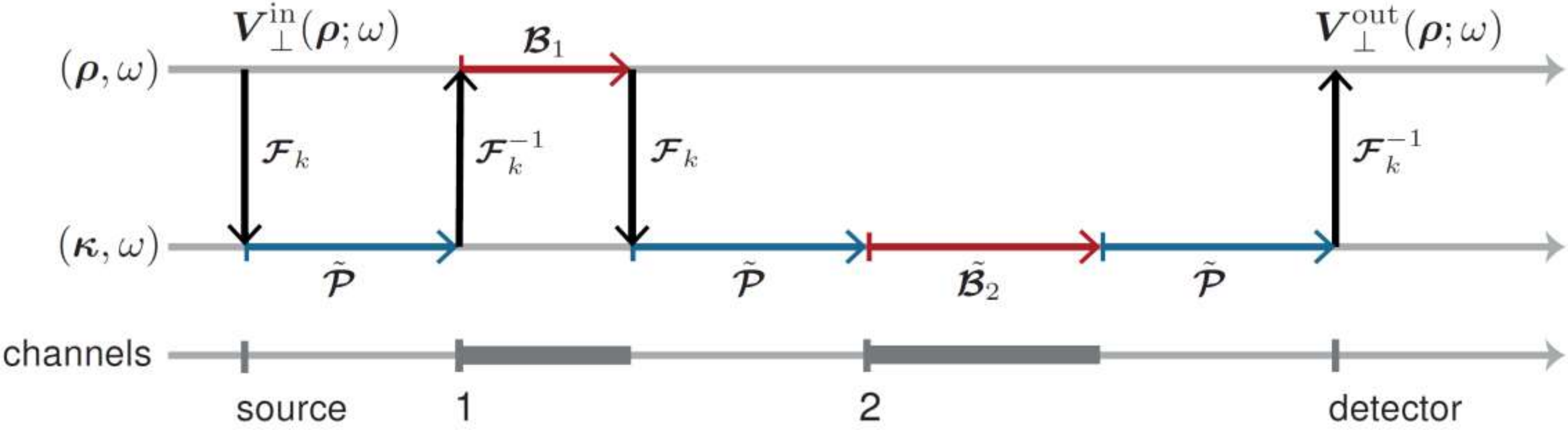


Field Tracing Diagrams

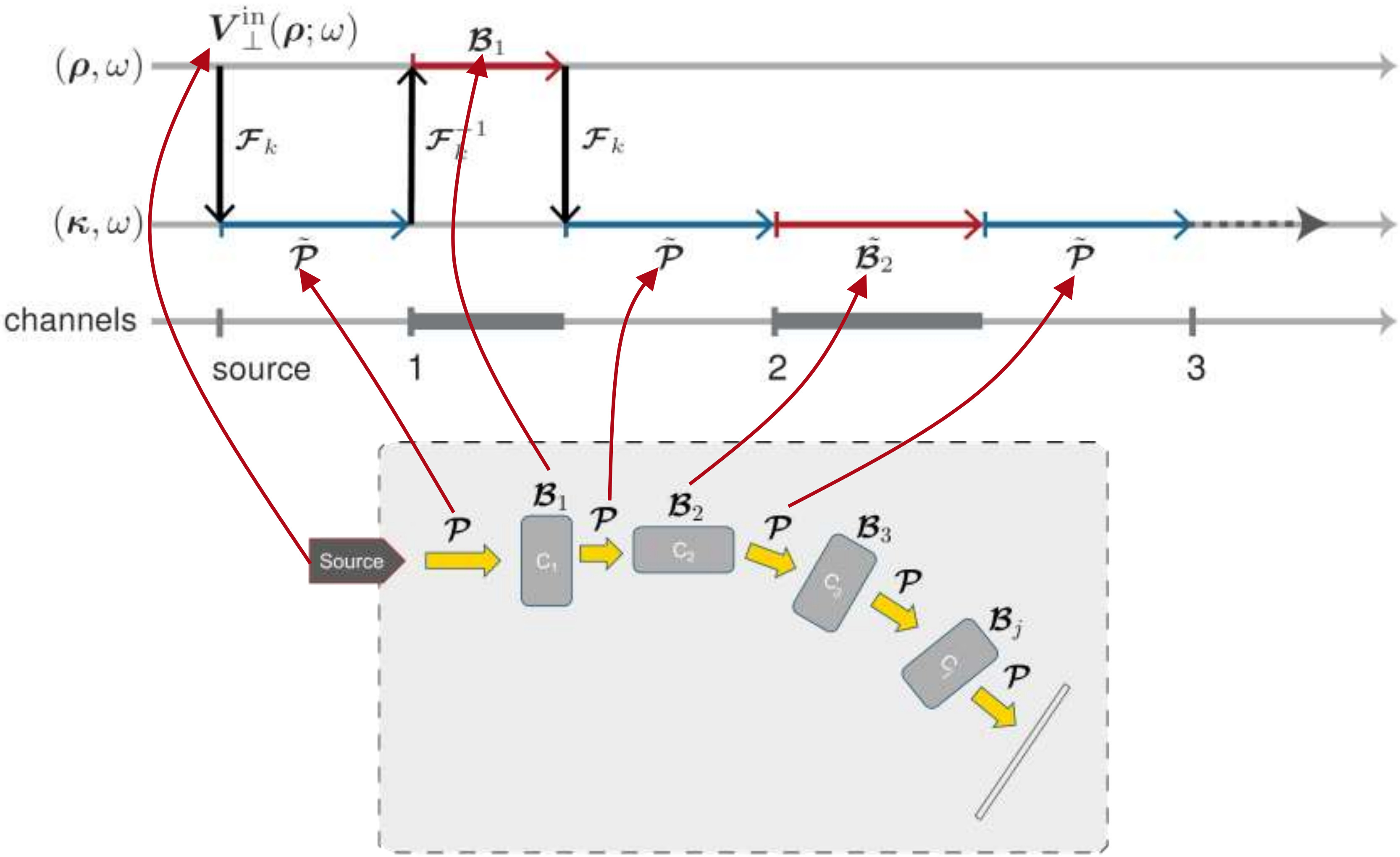


Field Tracing Diagrams

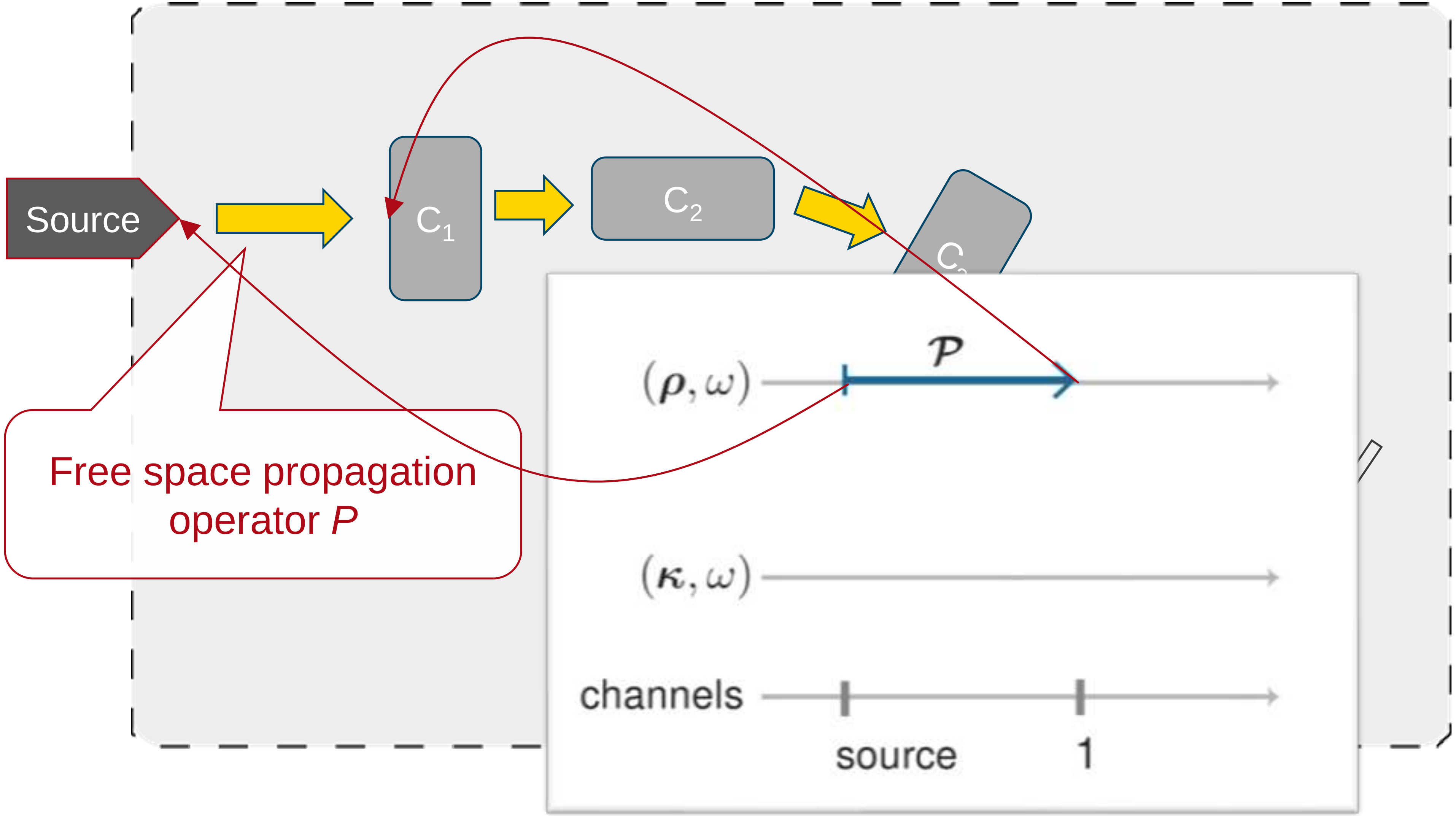
Field Tracing Diagrams



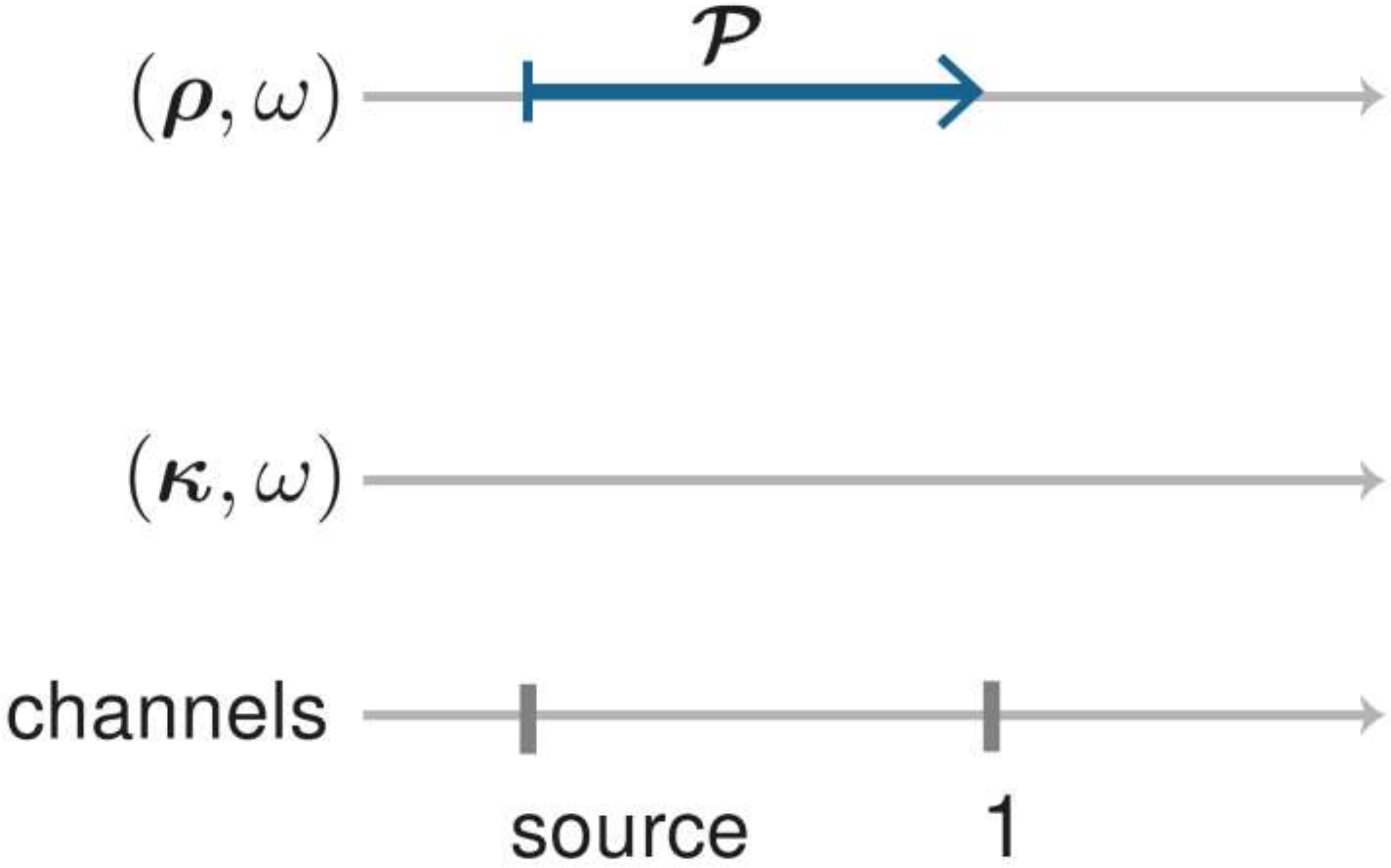
Field Tracing Diagrams



Field Tracing Diagrams



Free-Space Propagation Operator: x-Domain



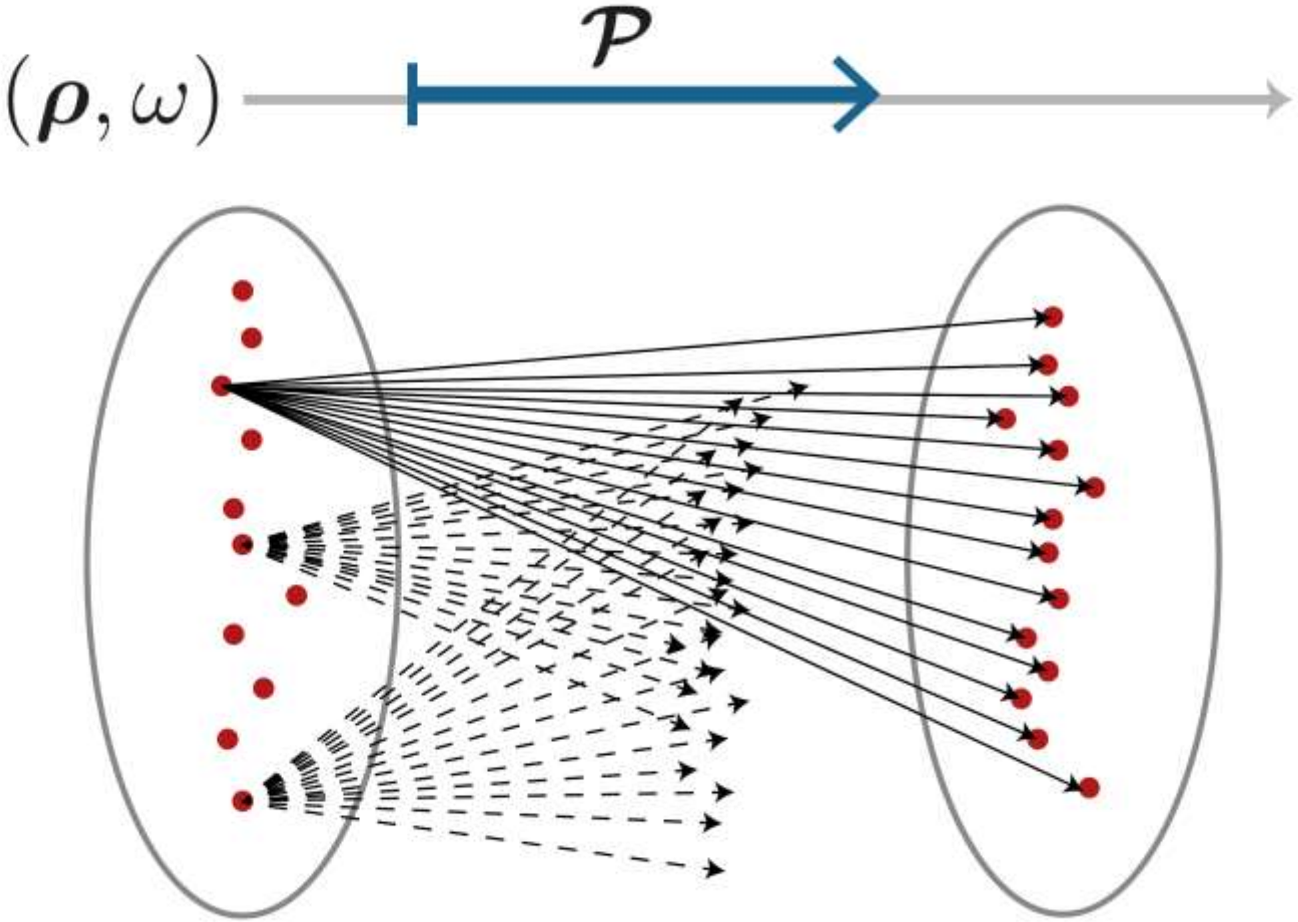
Free-Space Propagation Operator: x-Domain

Rigorous propagation in x-domain (Rayleigh-Sommerfeld integral):

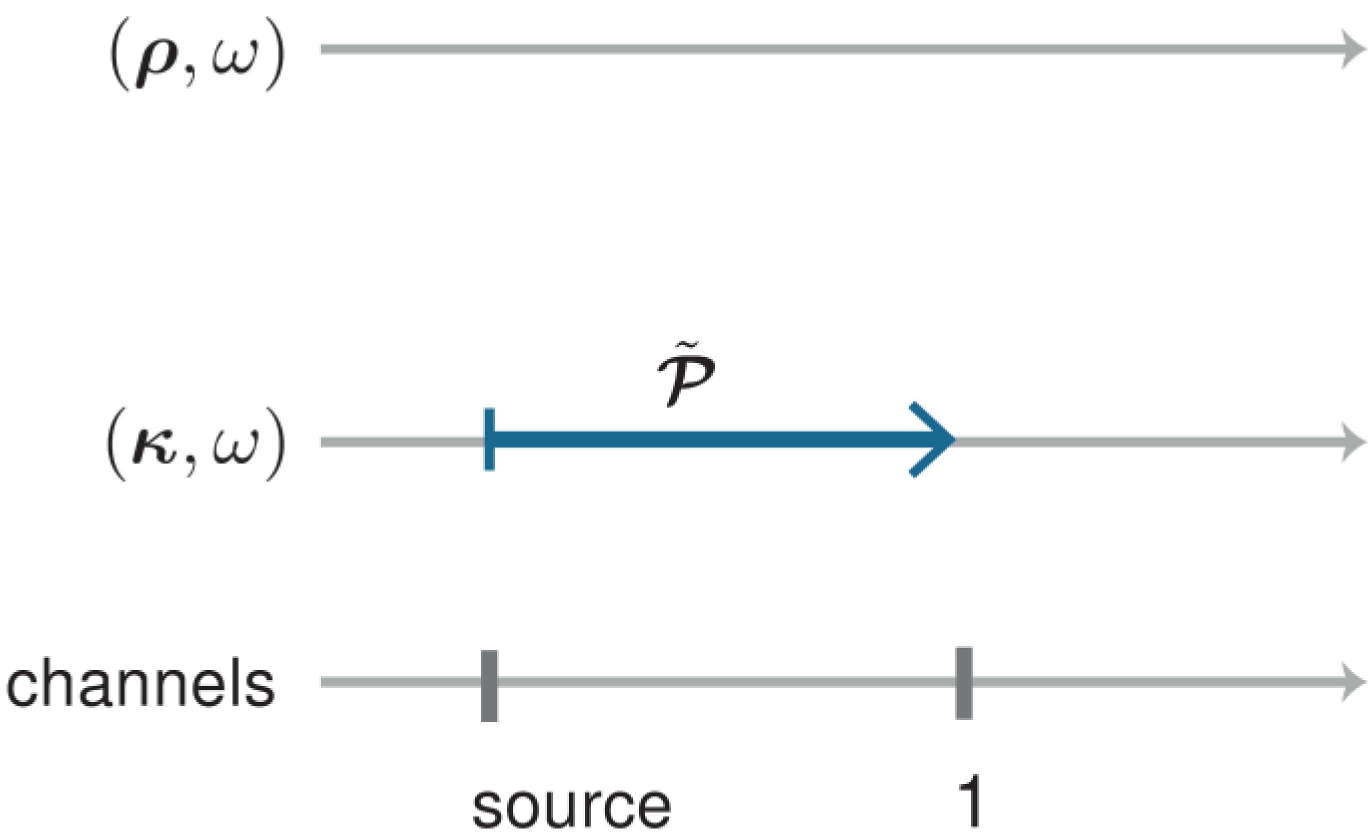
$$V^{\mathrm{out}}(\boldsymbol{\rho}, z) \propto \int\int_{-\infty}^{\infty} V^{\mathrm{in}}(\boldsymbol{\rho}', z_0) \frac{\exp(\mathrm{i}k_0\check{n}R)}{R} \left(\mathrm{i}k_0\check{n} - \frac{1}{R}\right) \frac{\Delta z}{R} \, \mathrm{d}^2\rho'$$

with $R = \sqrt{(x - x')^2 + (y - y')^2 + (\Delta z)^2}$.

Free-Space Propagation Operator: x-Domain



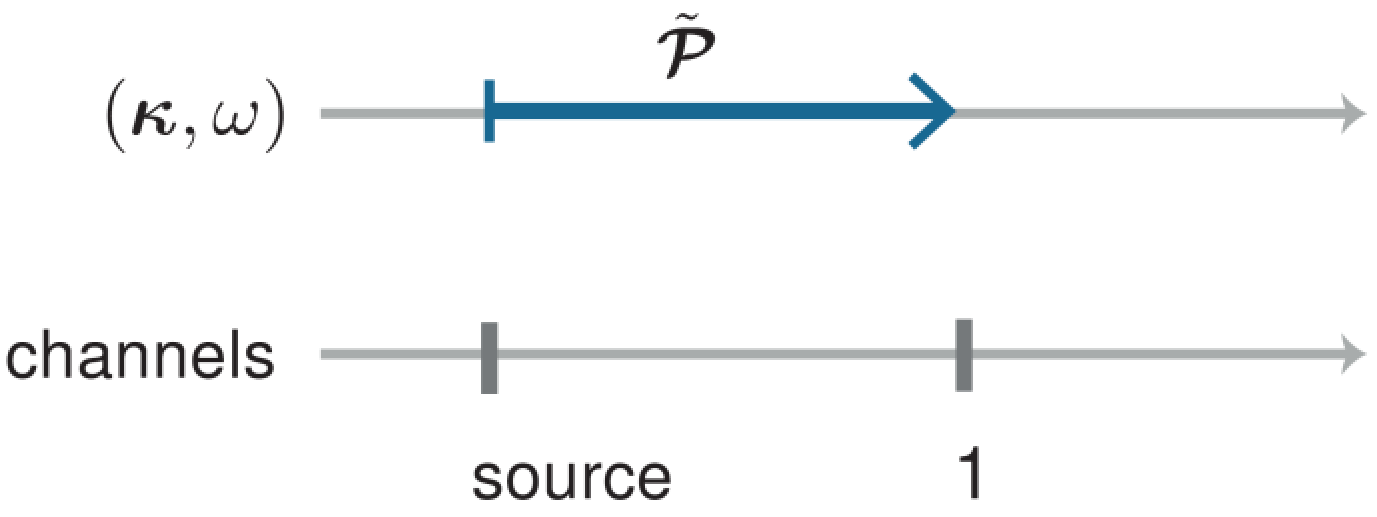
Free-Space Propagation Operator: k-Domain



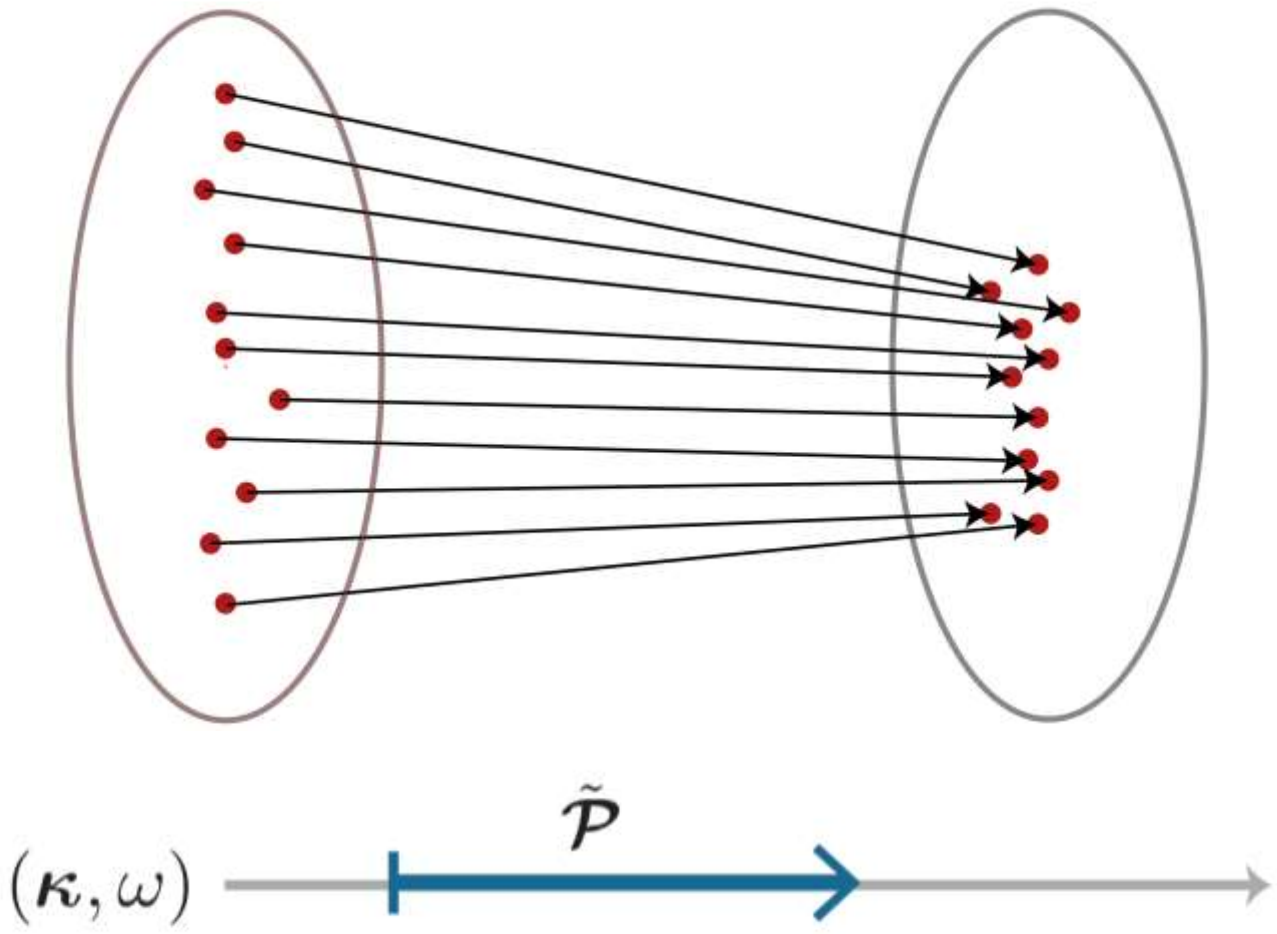
Free-Space Propagation Operator: k-Domain

Rigorous propagation in k-domain:

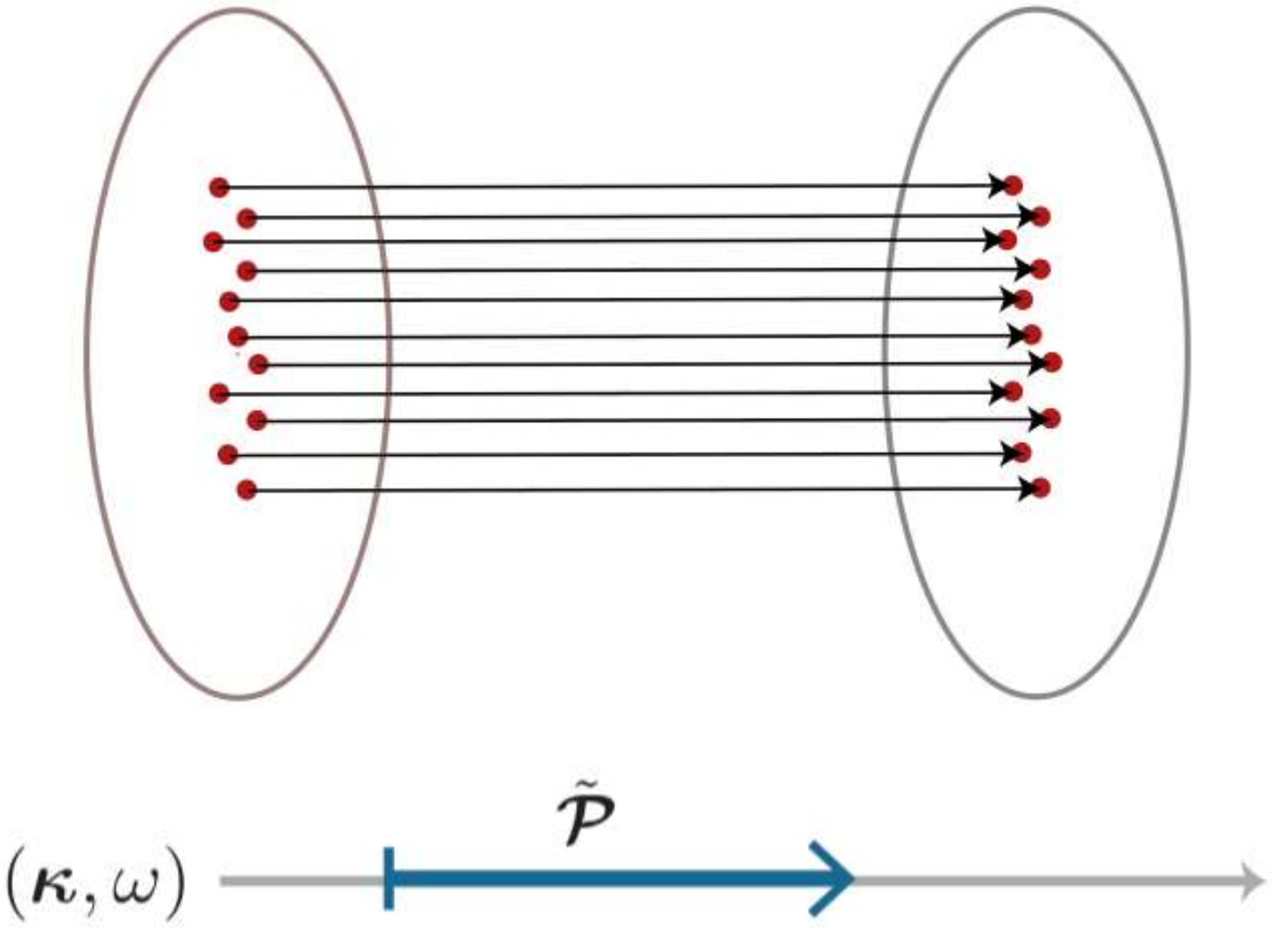
$$\tilde{V}^{\mathrm{out}}(\boldsymbol{\kappa}, z) = \tilde{V}^{\mathrm{in}}(\boldsymbol{\kappa}, z_0) \times \exp\left(\mathrm{i}\check{k}_z(\kappa)\Delta z\right)$$



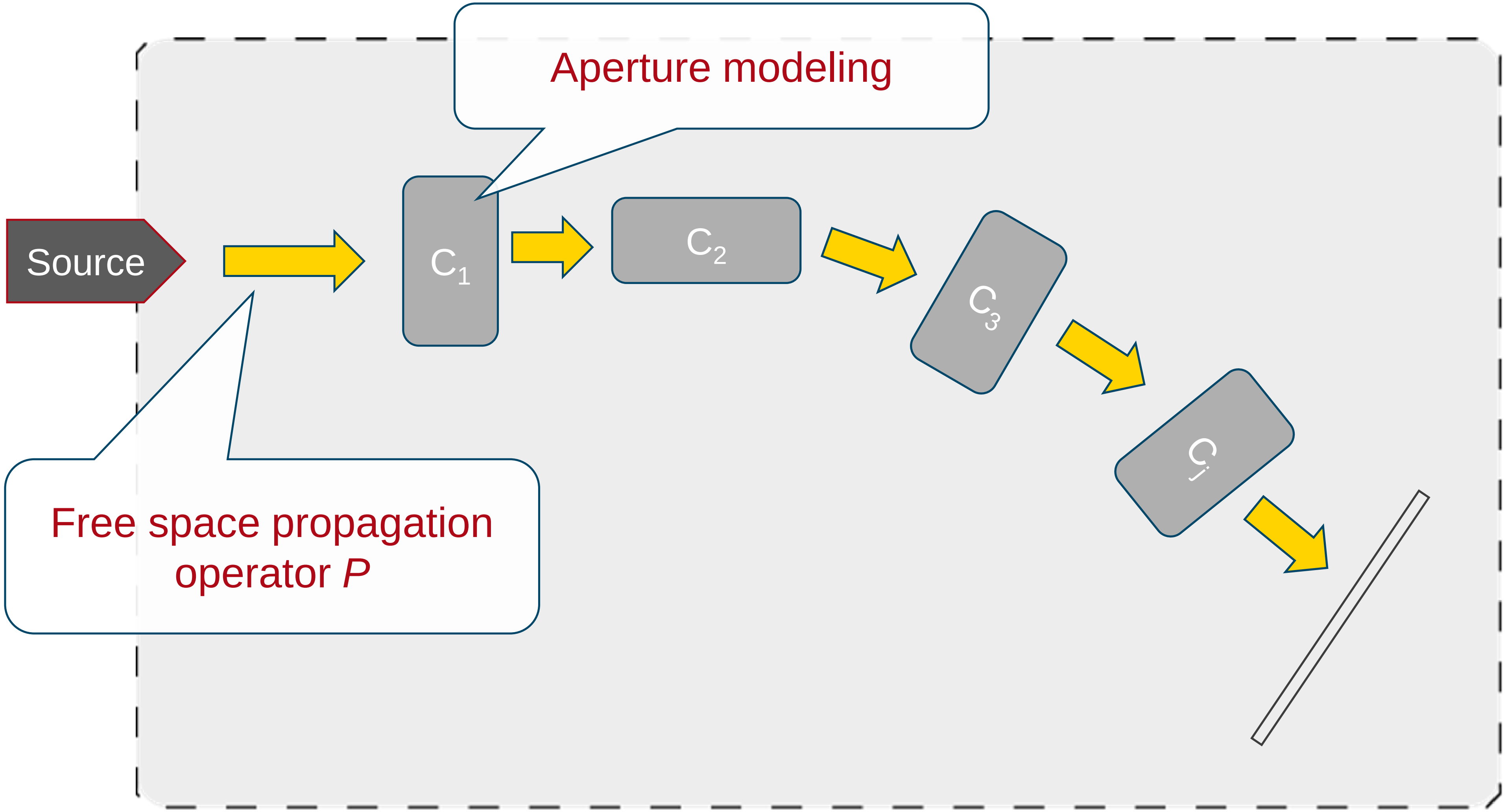
Free-Space Propagation Operator: k-Domain



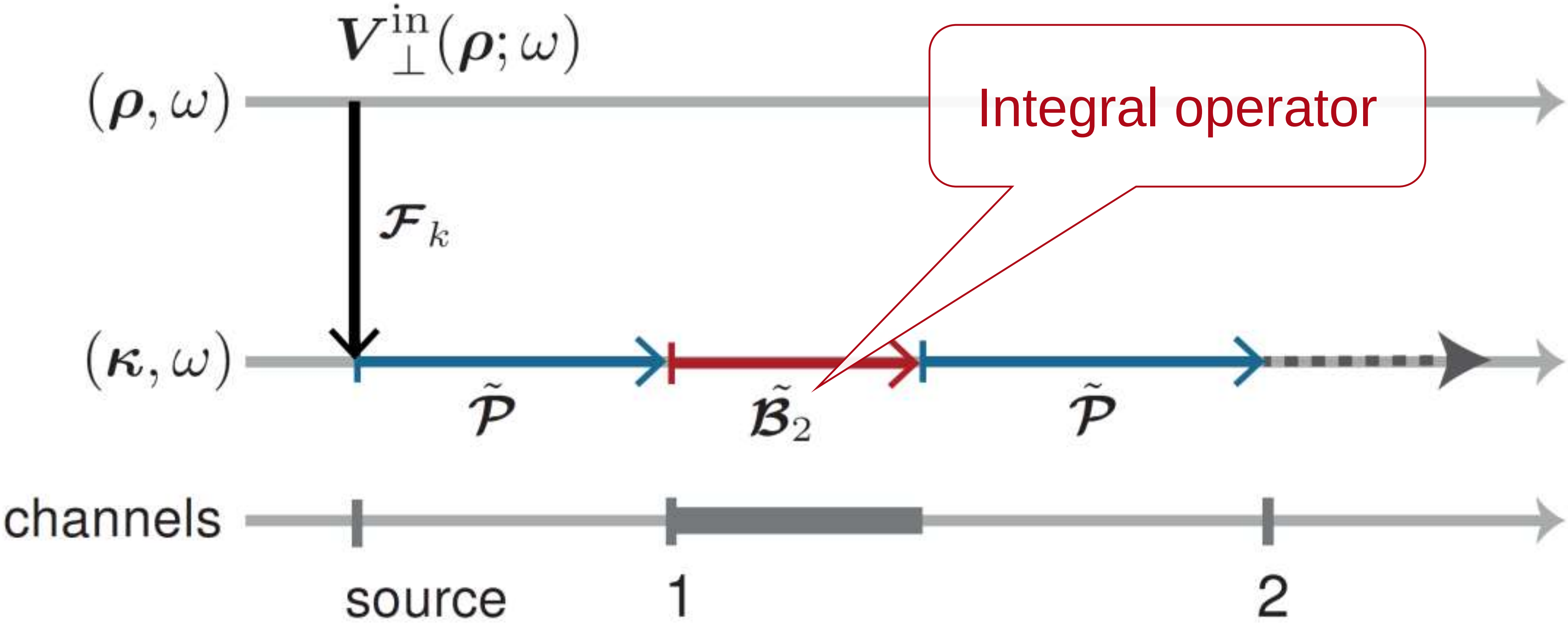
Free-Space Propagation Operator: k-Domain



Field Tracing Sequence per Lightpath

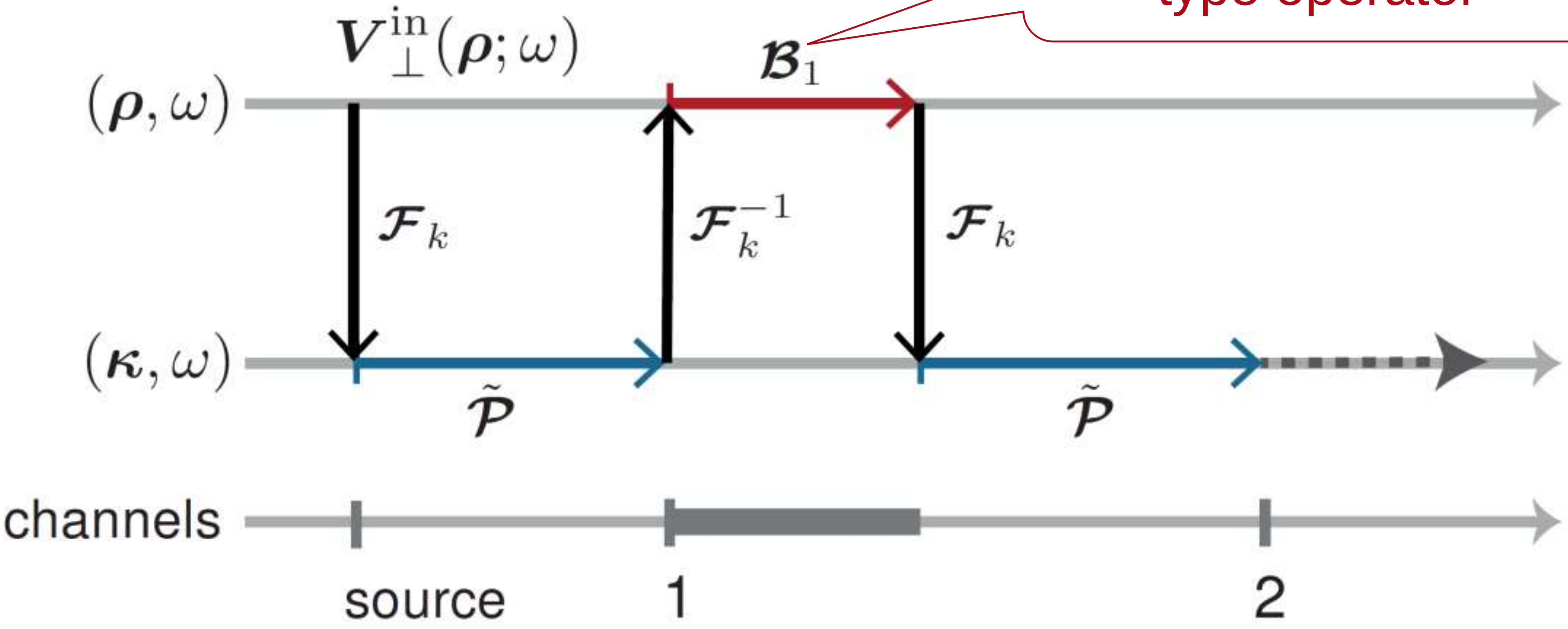


Propagation Through Aperture: k-Domain



Propagation Through Aperture: x-Domain

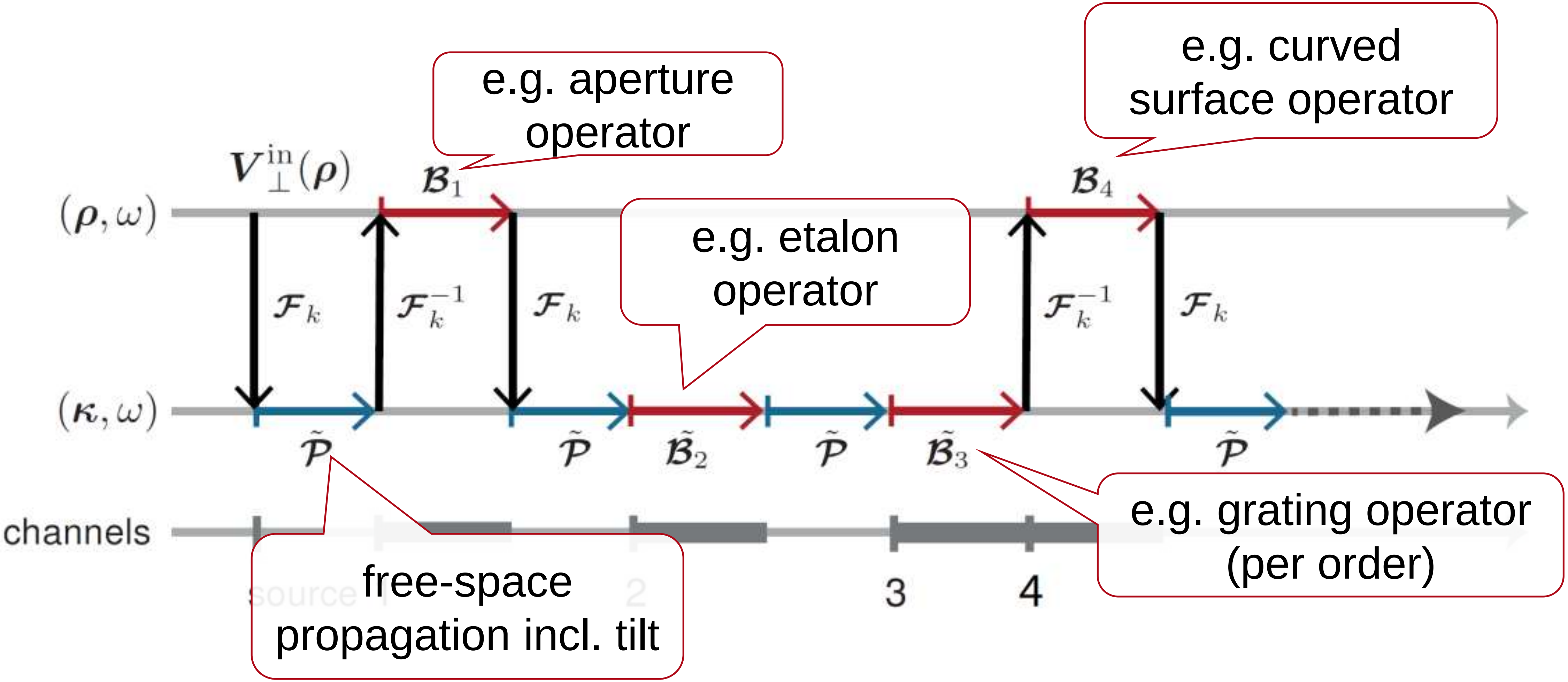
Truncation: Mapping-type operator



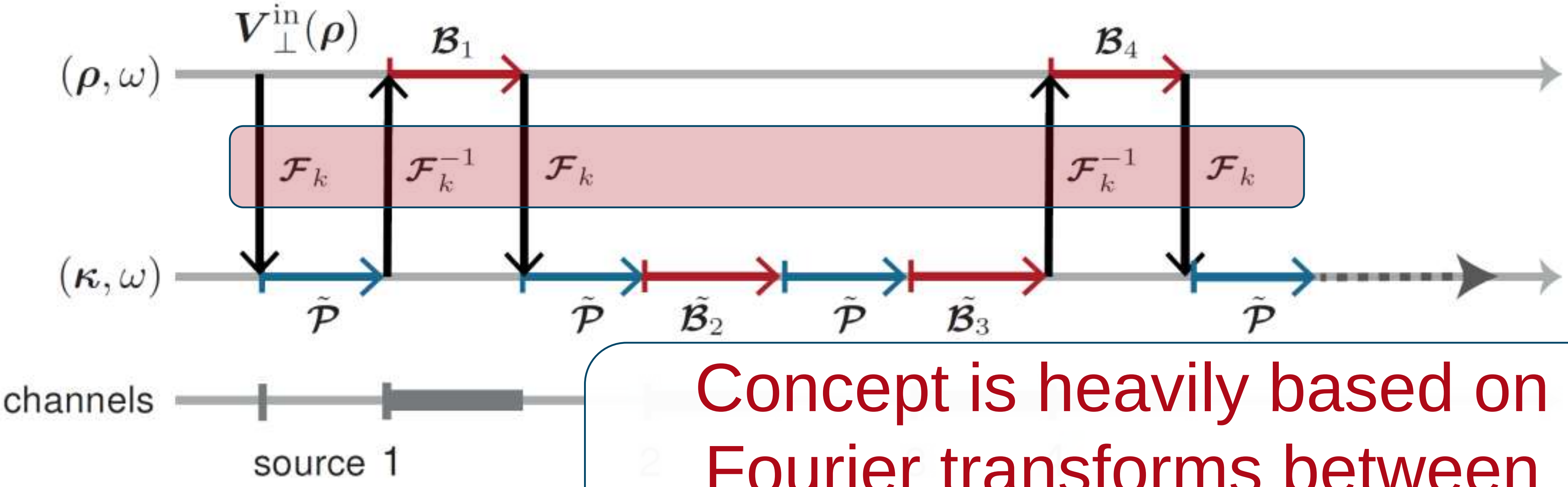
Fast physical optics strategies

Switching the modeling domains to apply mapping-type operators wherever possible

Fast Physical Optics Strategies: Switching Domains

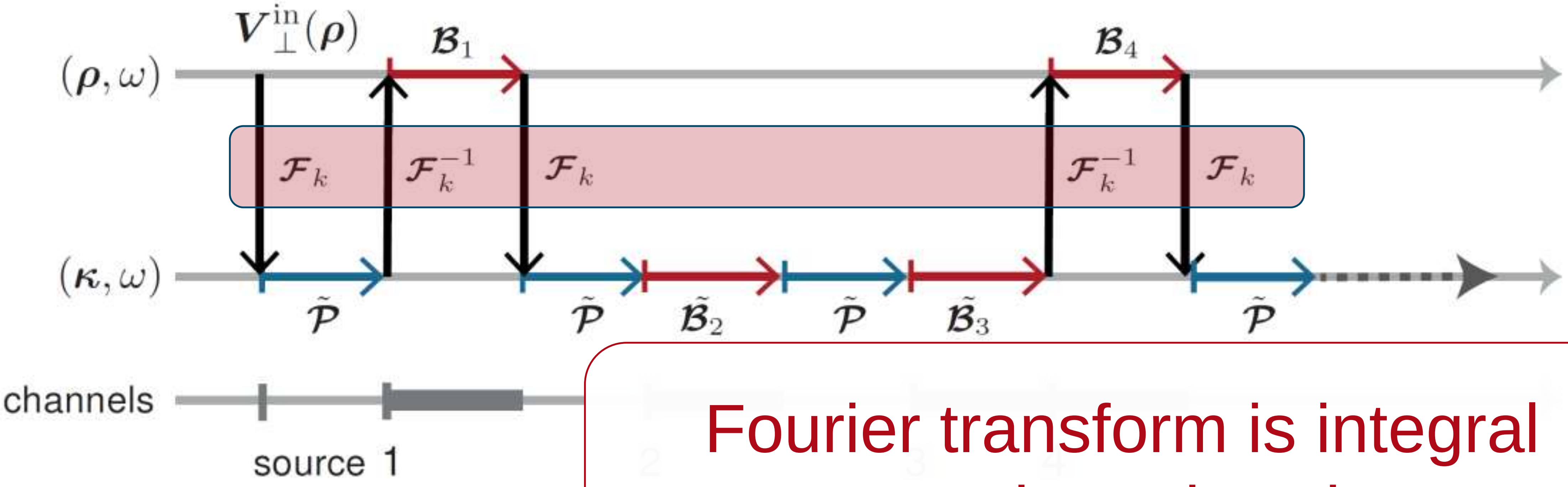


Fourier Transform Integral Operator



Concept is heavily based on Fourier transforms between domains.

Fourier Transform Integral Operator



Fourier transform is integral operator: Linear in N by FFT!

Fast physical optics strategies

Reducing sampling effort of Fourier transform integral

Wavefront Phase of Electromagnetic Fields

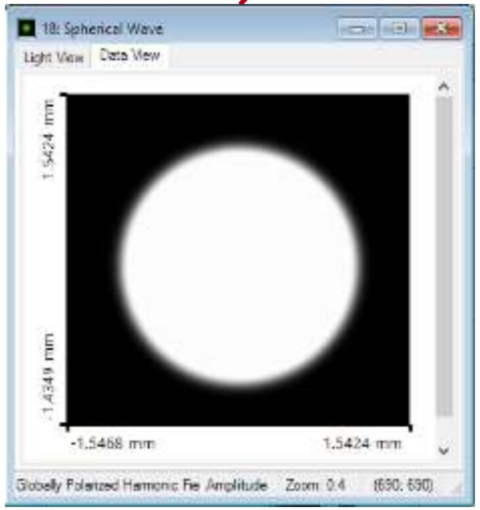
We identify in both domains the common smooth part of the phase and separate them from the field components and obtain:

$$\begin{aligned} V_\ell(\boldsymbol{\rho}, z, \omega) &= U_\ell(\boldsymbol{\rho}, z, \omega) \exp(\mathrm{i}\psi(\boldsymbol{\rho}, z, \omega)) \\ &= |V_\ell(\boldsymbol{\rho}, z, \omega)| \exp(\mathrm{i}\varphi_\ell(\boldsymbol{\rho}, z, \omega)) \boxed{\exp(\mathrm{i}\psi(\boldsymbol{\rho}, z, \omega))} \end{aligned}$$

$$\begin{aligned} \tilde{V}_\ell(\boldsymbol{\kappa}, z, \omega) &= \tilde{A}_\ell(\boldsymbol{\kappa}, z, \omega) \exp(\mathrm{i}\tilde{\phi}(\boldsymbol{\kappa}, z, \omega)) \\ &= |\tilde{V}_\ell(\boldsymbol{\kappa}, z, \omega)| \exp(\mathrm{i}\tilde{\alpha}_\ell(\boldsymbol{\kappa}, z, \omega)) \boxed{\exp(\mathrm{i}\tilde{\phi}(\boldsymbol{\kappa}, z, \omega))} \end{aligned}$$

Example Spherical Field

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



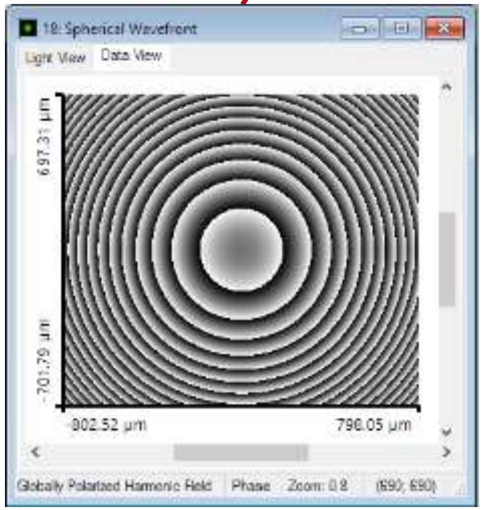
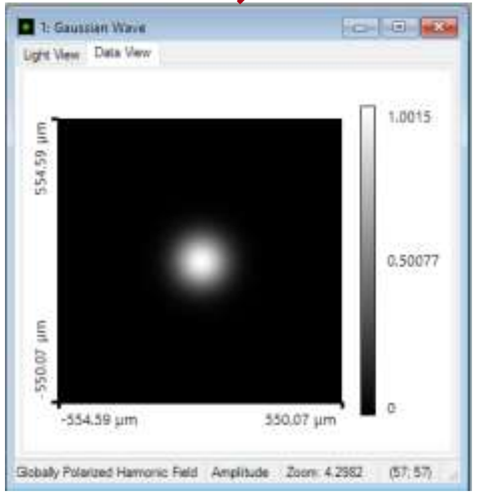


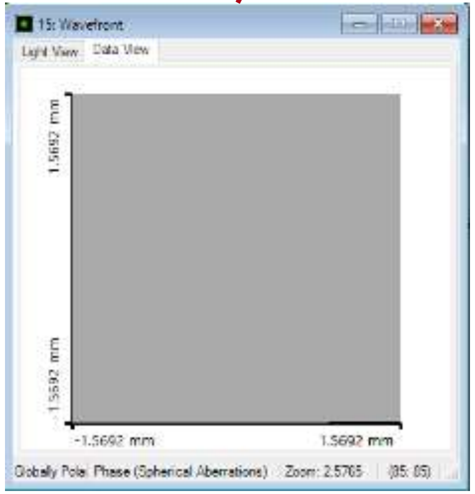
Illustration 3 in VLF

Gaussian waist radius 10 µm
Prop 1 mm by SPW

Example Gaussian Beam in Its Waist

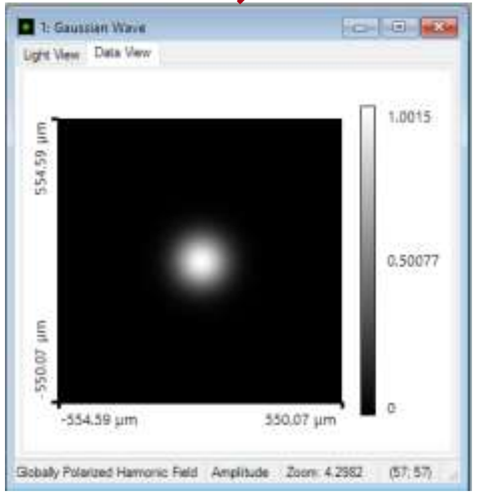
$$V_\ell(\boldsymbol{\rho}, z, \omega) = |V_\ell(\boldsymbol{\rho}, z, \omega)| \exp(i\varphi_\ell(\boldsymbol{\rho}, z, \omega)) \exp(i\psi(\boldsymbol{\rho}, z, \omega))$$

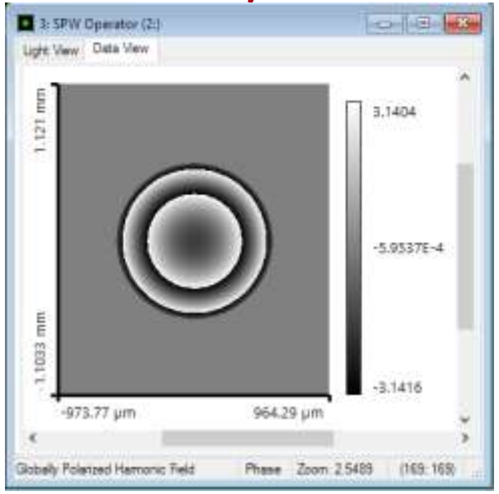




Example Propagated Gaussian Beam

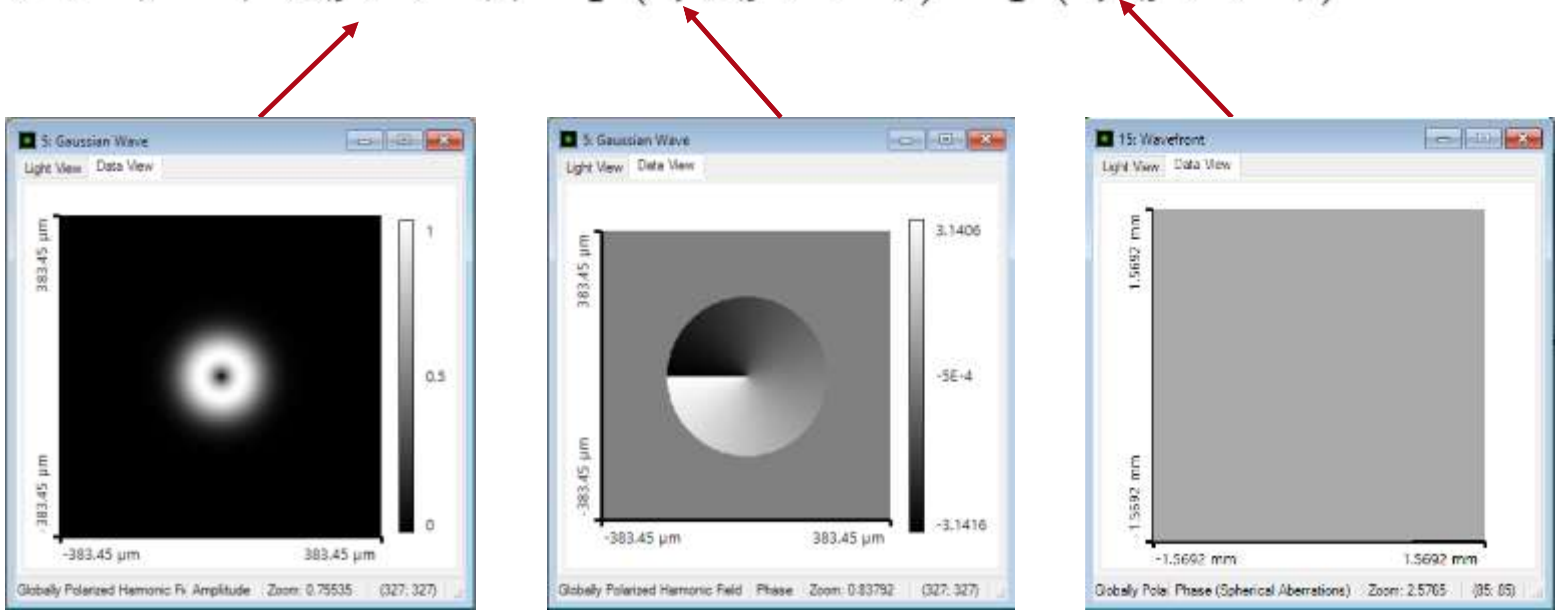
$$V_\ell(\rho, z, \omega) = |V_\ell(\rho, z, \omega)| \exp\left(i\varphi_\ell(\rho, z, \omega)\right) \exp\left(i\psi(\rho, z, \omega)\right)$$





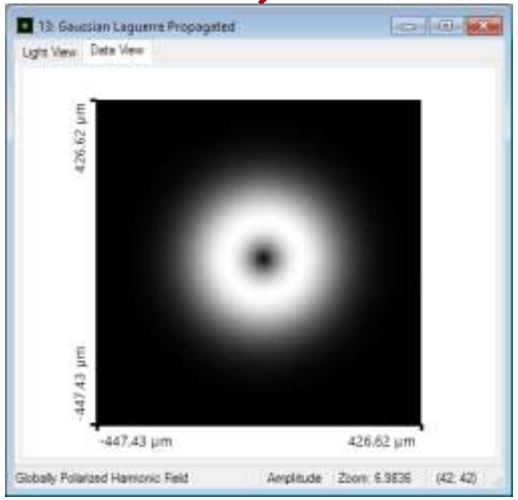
Example Gaussian Laguerre Beam in Waist

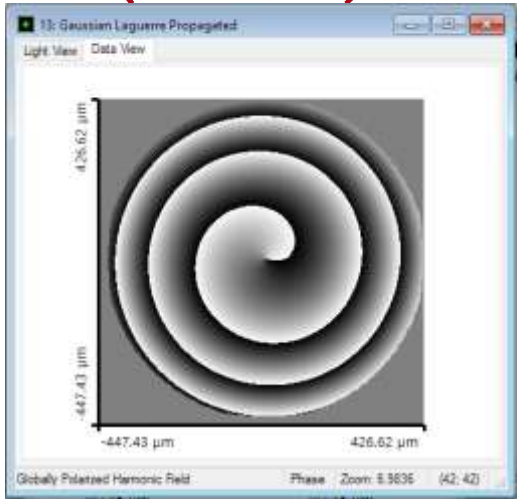
$$V_\ell(\rho,z,\omega) = |V_\ell(\rho,z,\omega)| \exp(i\varphi_\ell(\rho,z,\omega)) \exp(i\psi(\rho,z,\omega))$$



Example Propagated Gaussian Laguerre Beam

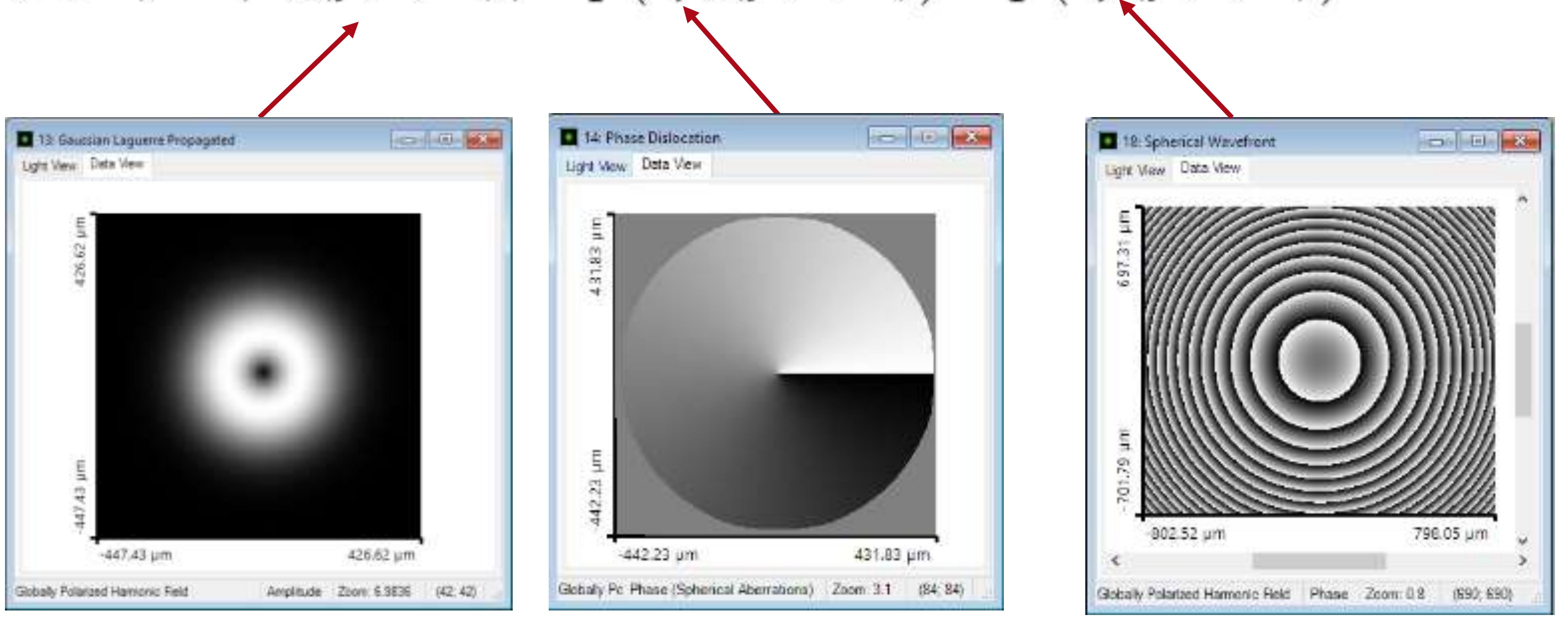
$$V_\ell(\boldsymbol{\rho},z,\omega) = |V_\ell(\boldsymbol{\rho},z,\omega)| \exp(i\varphi_\ell(\boldsymbol{\rho},z,\omega)) \exp(i\psi(\boldsymbol{\rho},z,\omega))$$





Example Propagated Gaussian Laguerre Beam

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



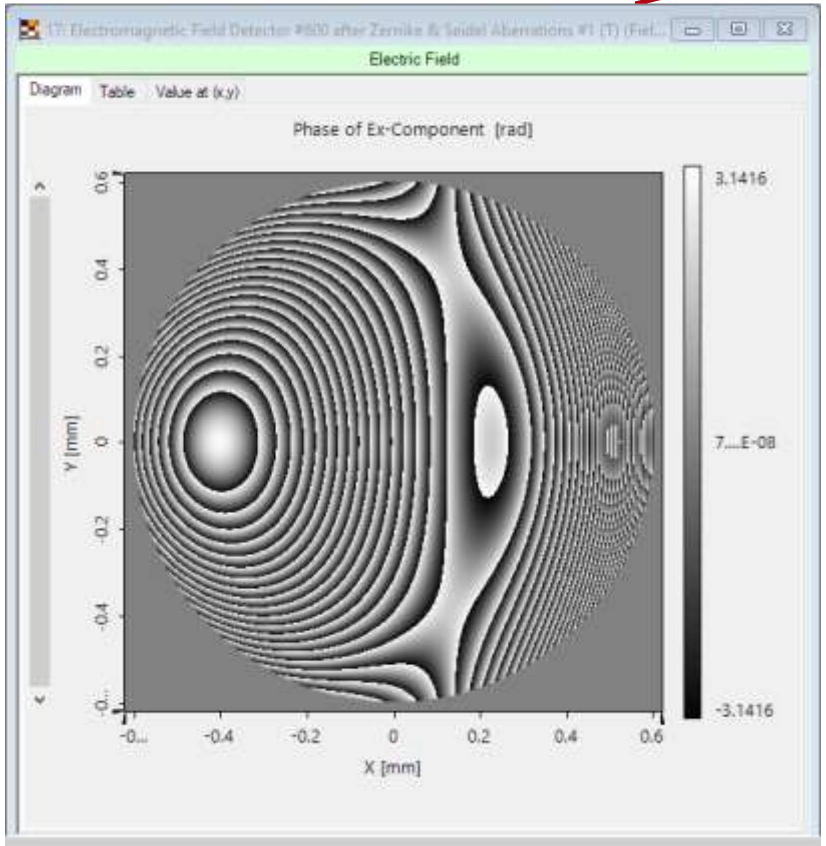
General Example with Aberrations

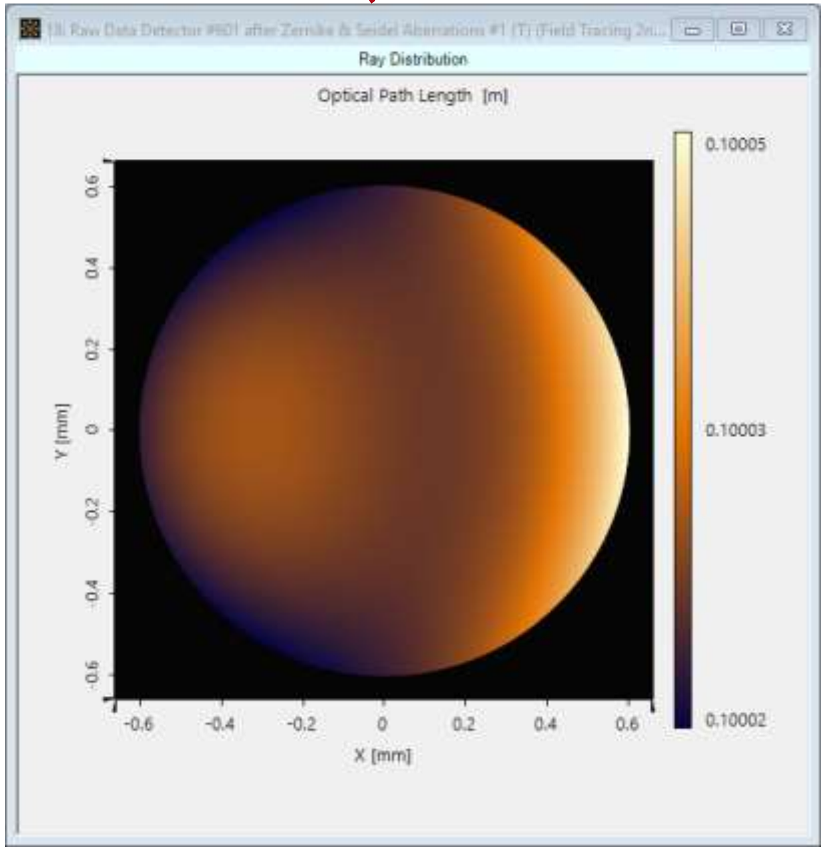
$$V_\ell(\boldsymbol{\rho}, z, \omega) = |V_\ell(\boldsymbol{\rho}, z, \omega)| \exp\left(\mathrm{i}\varphi_\ell(\boldsymbol{\rho}, z, \omega)\right) \exp\left(\mathrm{i}\psi(\boldsymbol{\rho}, z, \omega)\right)$$

Arbitrary amplitude and phase of diffractive factor.

General Example with Aberrations

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





Wavefront Phase of Electromagnetic Fields

We identify in both domains the common smooth part of the phase and separate them from the field components and obtain:

$$\begin{aligned} V_\ell(\boldsymbol{\rho},z,\omega) &= U_\ell(\boldsymbol{\rho},z,\omega)\exp\big(\mathrm{i}\psi(\boldsymbol{\rho},z,\omega)\big) \\ &= |V_\ell(\boldsymbol{\rho},z,\omega)|\exp\big(\mathrm{i}\varphi_\ell(\boldsymbol{\rho},z,\omega)\big)\exp\big(\mathrm{i}\psi(\boldsymbol{\rho},z,\omega)\big) \end{aligned}$$

$$\begin{aligned} \tilde{V}_\ell(\boldsymbol{\kappa},z,\omega) &= \tilde{A}_\ell(\boldsymbol{\kappa},z,\omega)\exp\big(\mathrm{i}\tilde{\phi}(\boldsymbol{\kappa},z,\omega)\big) \\ &= |\tilde{V}_\ell(\boldsymbol{\kappa},z,\omega)|\exp\big(\mathrm{i}\tilde{\alpha}_\ell(\boldsymbol{\kappa},z,\omega)\big)\exp\big(\mathrm{i}\tilde{\phi}(\boldsymbol{\kappa},z,\omega)\big) \end{aligned}$$

FFT requires sampling of complex amplitude V

Wavefront Phase of Electromagnetic Fields

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$$\begin{aligned} V_\ell(\boldsymbol{\rho},z,\omega) &= U_\ell(\boldsymbol{\rho},z,\omega)\exp\big(\mathrm{i}\psi(\boldsymbol{\rho},z,\omega)\big) \\ &= |V_\ell(\boldsymbol{\rho},z,\omega)|\exp\big(\mathrm{i}\varphi_\ell(\boldsymbol{\rho},z,\omega)\big)\exp\big(\mathrm{i}\psi(\boldsymbol{\rho},z,\omega)\big) \end{aligned}$$

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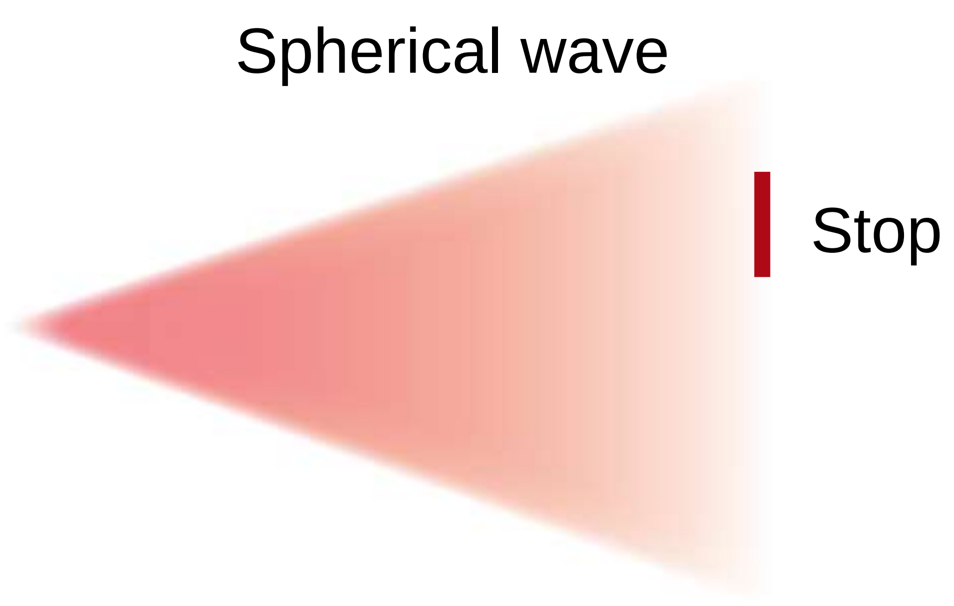
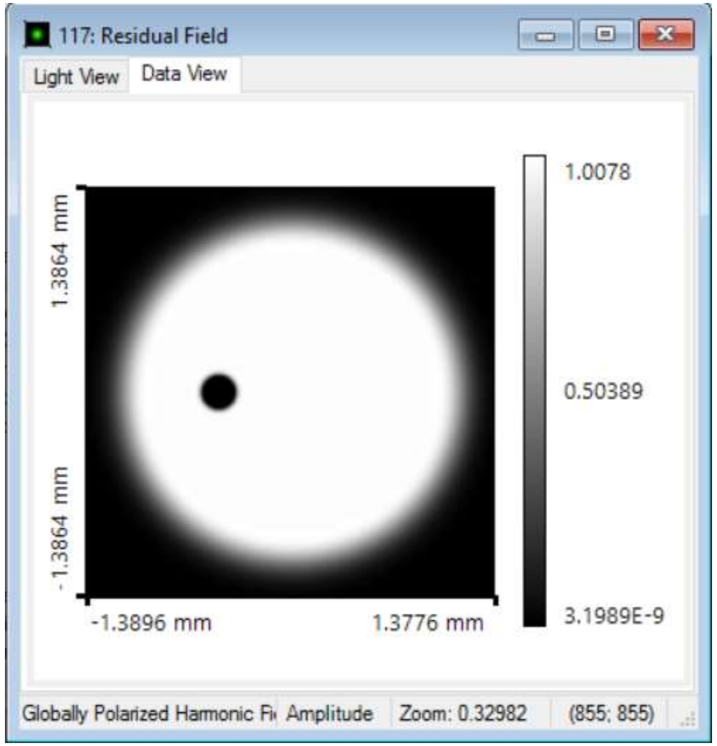
To enable fast physical optics modeling we must avoid sampling of strong wavefront phase factors for Fourier transform.

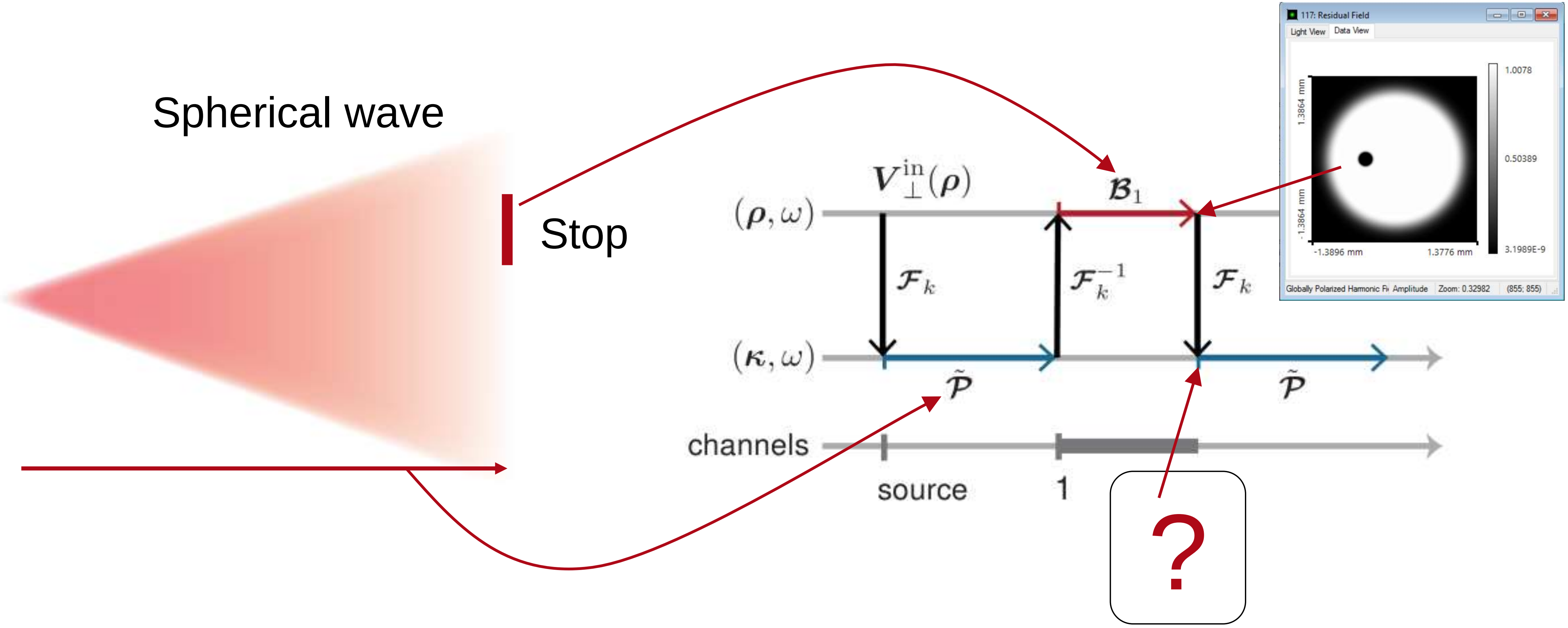
Modeling the Propagation Through a Stop



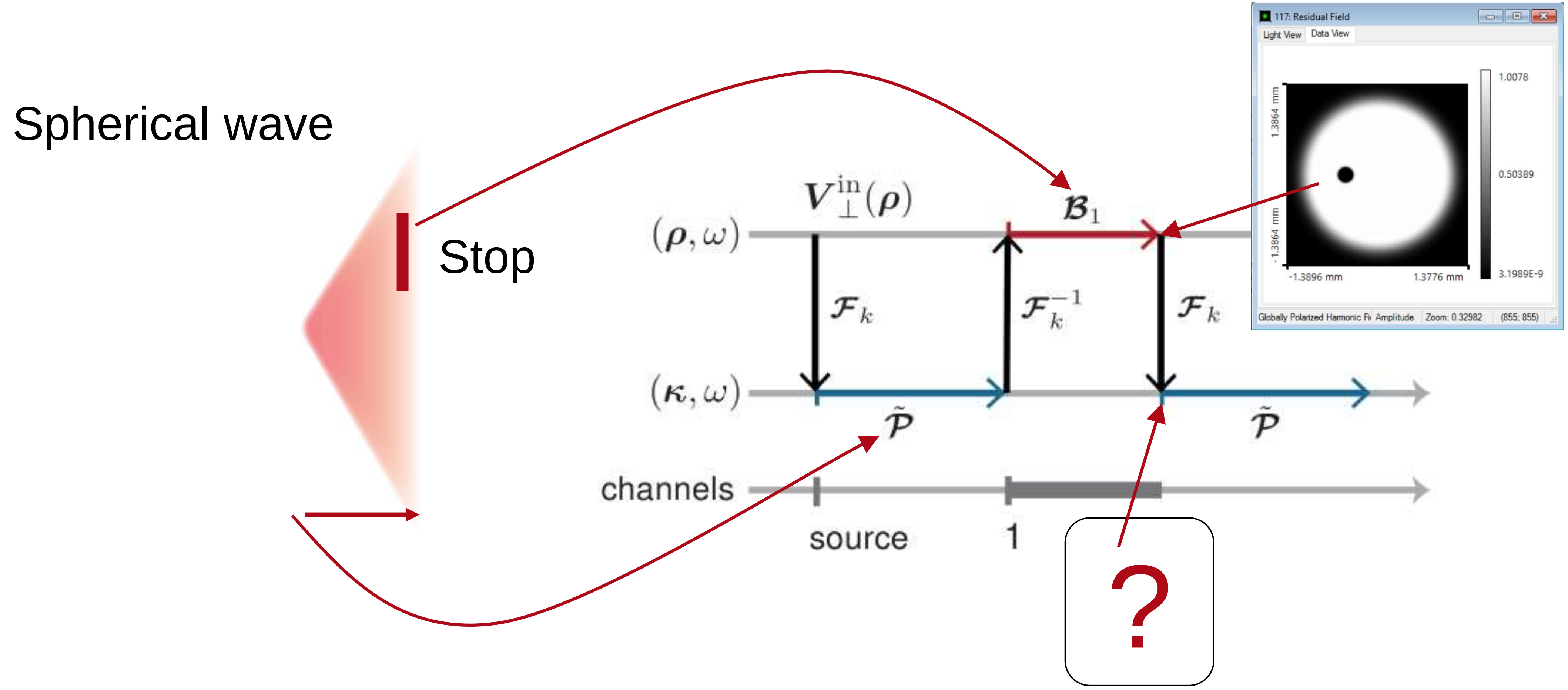
Field after stop (Amplitude)



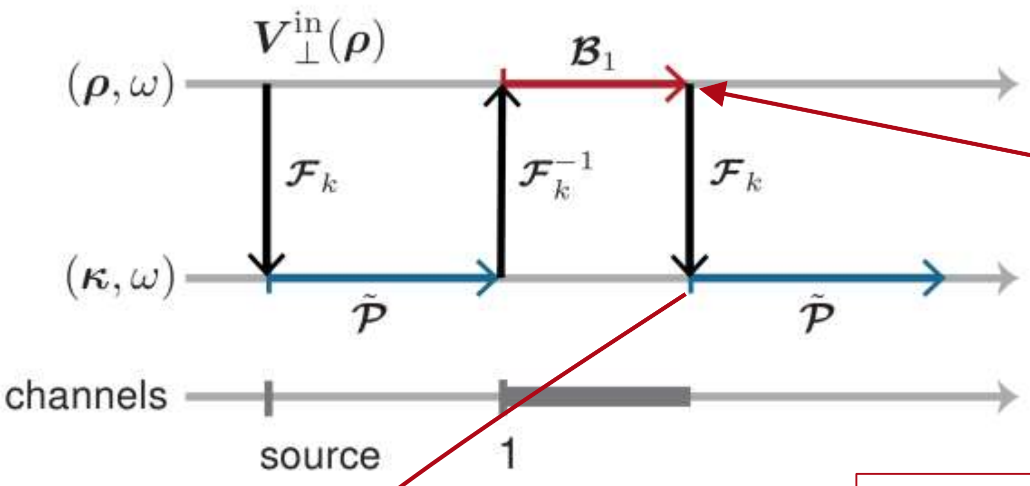
Modeling the Propagation Through a Stop

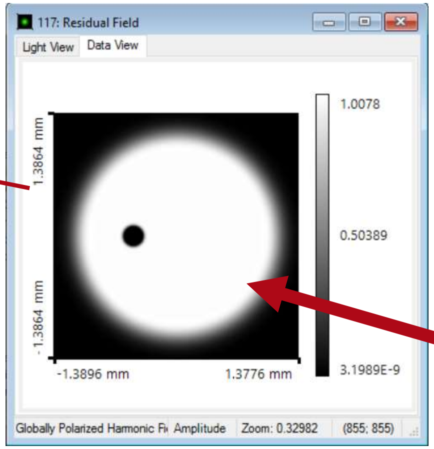


Modeling the Propagation Through a Stop

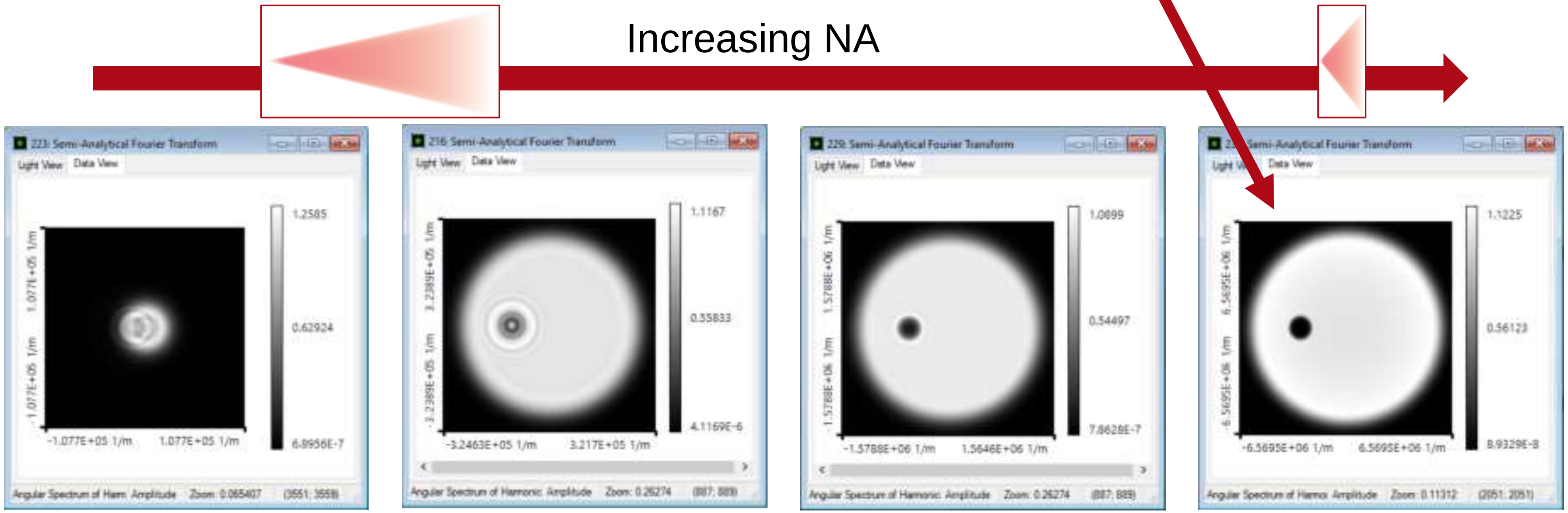


Results of Fourier Transform





For strong wavefront phase Fourier transform performs mapping!



Mapping-Type Fourier Transform

- The mapping characteristic can be mathematically derived by application of the stationary phase approximation to the Fourier integral.
- That results in a formula for a mapping-type Fourier transform
- It requires significantly less (gridless) sampling points than the FFT and reduces the computation time drastically.
- Planes in which fields allow the mapping-type Fourier transform are situated in the **geometric field zone** (GFZ). The far-field zone constitutes a special case.
- The determination of the geometric zone can be done by mathematical criteria only.
- **In VirtualLab we replace the FFT by the mapping-type Fourier transform automatically when a user-defined accuracy level is reached.**

Mapping-Type Fourier Transform

- The mapping characteristic can be mathematically derived by application of

Mathematics of mapping-type Fourier transform quite straightforward.

Implementation challenging because of hybrid sampling together with suitable interpolation techniques!

- In VirtualLab we replace the FFT by the geometric Fourier transform automatically when a user-defined accuracy level is reached.

Mapping-Type Fourier Transform

- If we detect fields in its geometric zone we perform the mapping-type Fourier transform. Accuracy of zone detection can be adjusted.
- Enables control of how accurate diffraction effects are taken into account in modeling.

Types of Fourier Transform Algorithms

- Fast Fourier Transform FFT
  - Fast for weak wavefront phase
- Semi-analytical FFT
  - Fast for wavefront phase with medium local gradient

Linear and Quadratic Wavefront Phases

- We assume to have field components of the form

$$\begin{aligned} V_\ell(\boldsymbol{\rho}) &= U_\ell(\boldsymbol{\rho}) \exp\left(\mathrm{i}\psi(\boldsymbol{\rho})\right) \\ &= U_\ell(\boldsymbol{\rho}) \exp\left(\mathrm{i}\psi^{\mathsf{res}}(\boldsymbol{\rho})\right) \exp\left(\mathrm{i}\psi_{\mathsf{q}}(\boldsymbol{\rho})\right) \\ &= U_\ell^{\mathsf{res}}(\boldsymbol{\rho}) \exp\left(\mathrm{i}\psi_{\mathsf{q}}(\boldsymbol{\rho})\right) \end{aligned}$$

with the polynomial phase of 2nd degree

$$\psi_{\mathsf{q}}(\boldsymbol{\rho}) = A + \boldsymbol{B} \cdot \boldsymbol{\rho} + Cxy + \boldsymbol{D} \cdot (x^2, y^2)$$

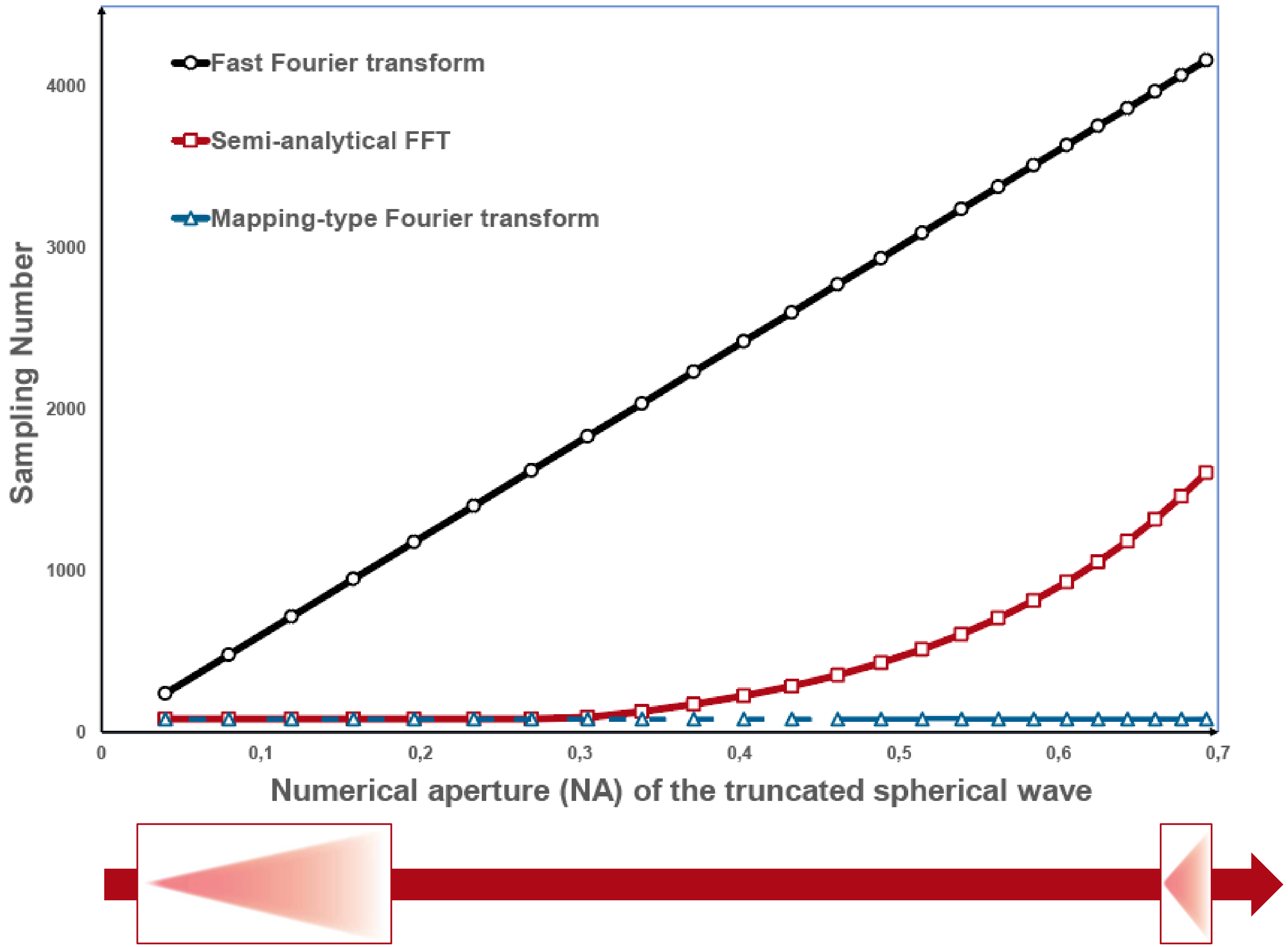
- We assume that $\exp\left(\mathrm{i}\psi_{\mathsf{q}}(\boldsymbol{\rho})\right)$ is given by its real-valued coefficients $A, \boldsymbol{B}, C$ and $\boldsymbol{D}$.

Types of Fourier Transform Algorithms

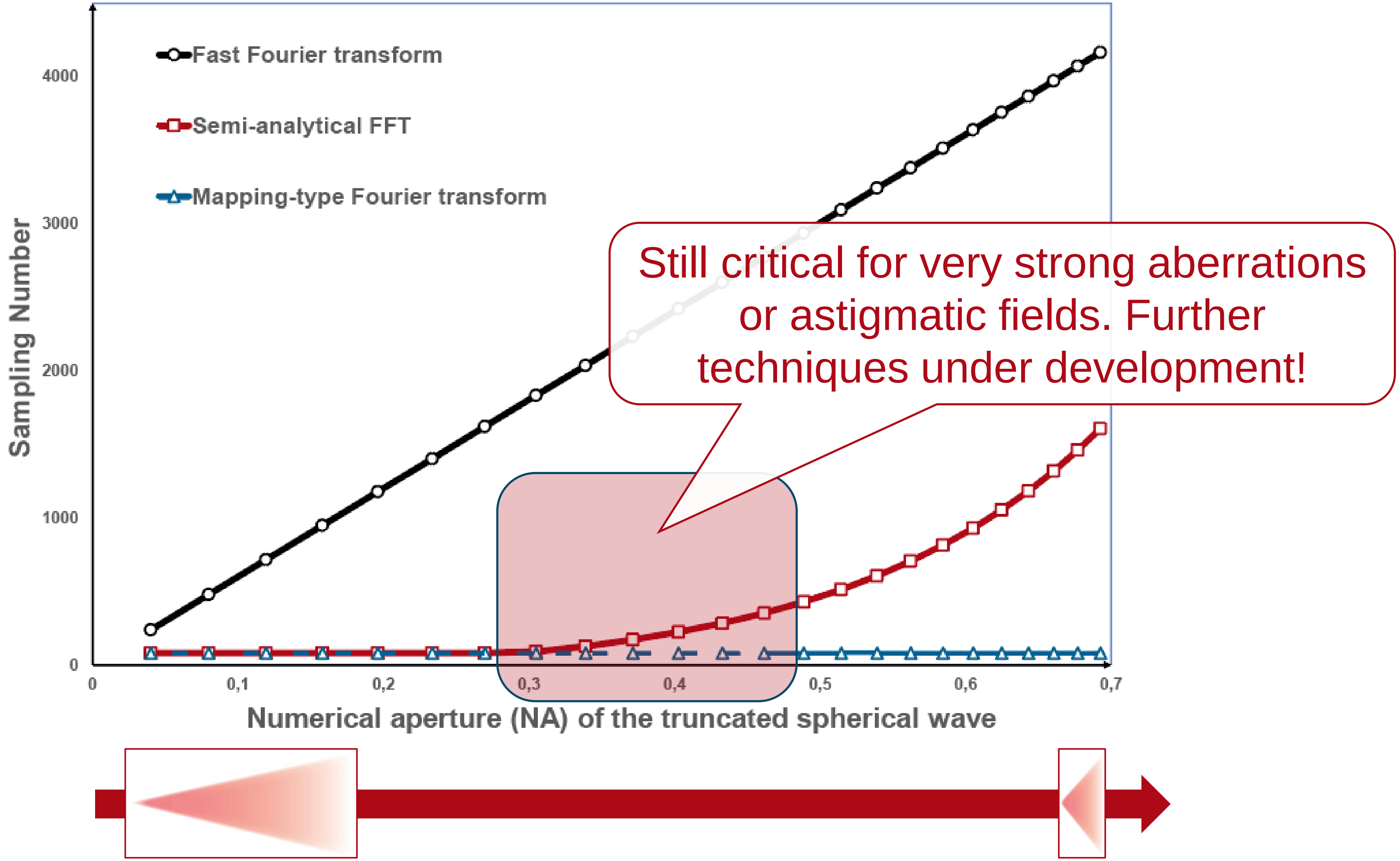
- Fast Fourier Transform FFT
  - Fast for weak wavefront phase
- Semi-analytical FFT
  - Fast for wavefront phase with medium local gradient
- Mapping-type Fourier transform
  - Accurate for strong wavefront phase

➡ Combination of Fourier transform algorithms enables fast physical optics!

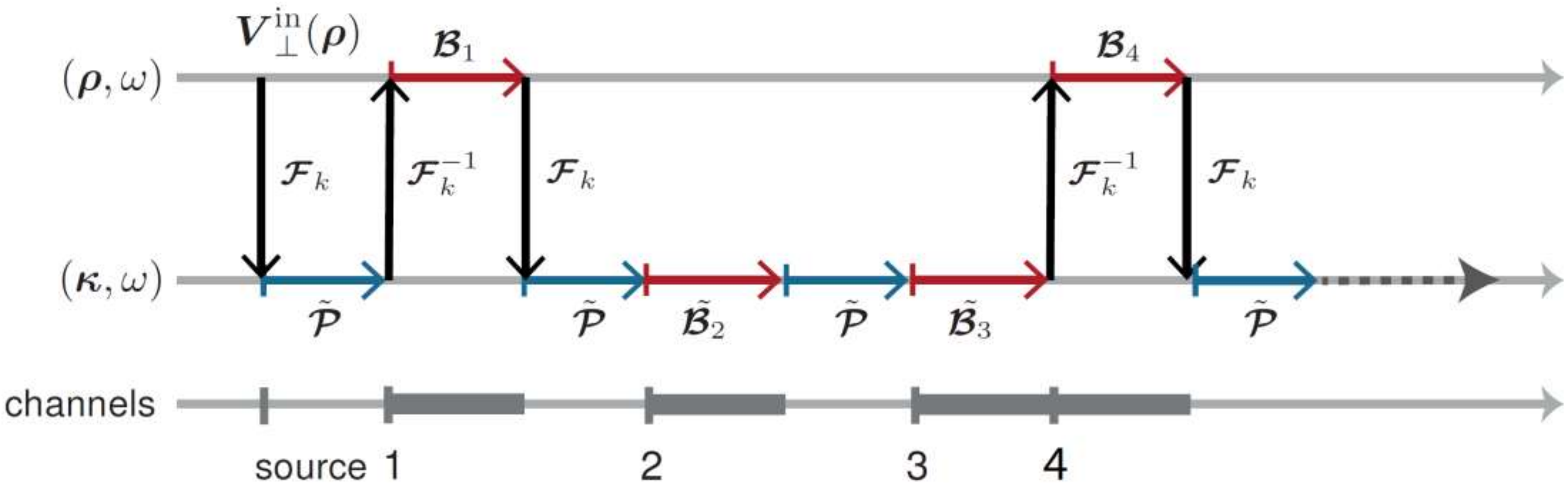
Triad of Fourier Transform Techniques



Triad of Fourier Transform Techniques



Very Fast Physical Optics Modeling: Mapping Sequence

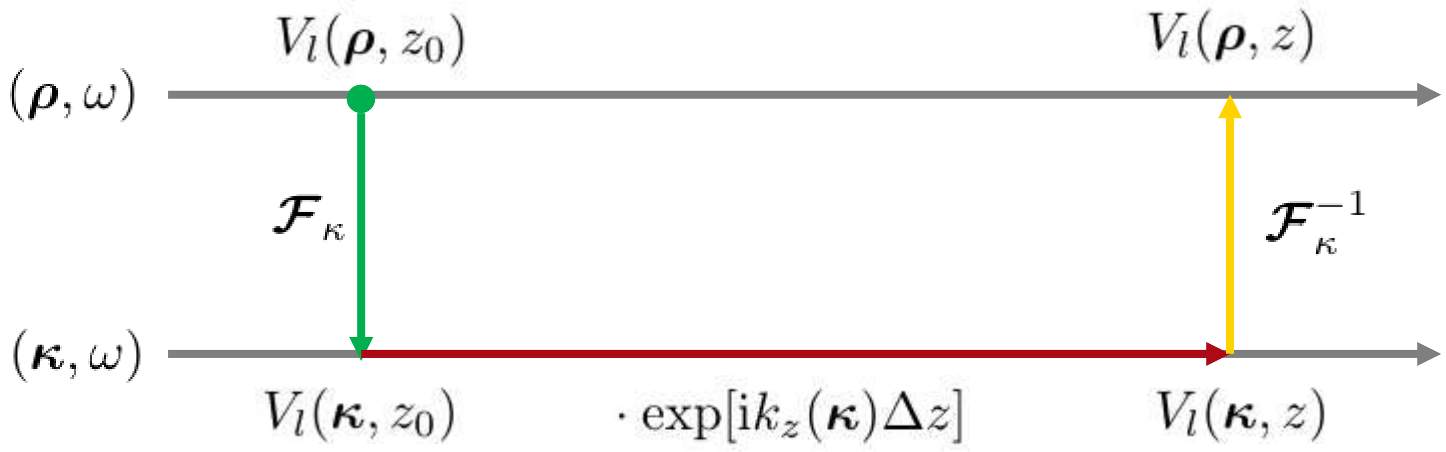


- Consider a modeling sequence (full system or part of it) for which all field tracing operators and the Fourier transforms are of mapping type.
  - That requires necessarily, that Fourier transforms are only performed in planes in which the fields are in its geometric zones.
- Mapping-type field tracing sequences can be evaluated as fast as ray tracing of the same lightpath!

Task 3 Free Space Propagation

Field Tracing Diagram

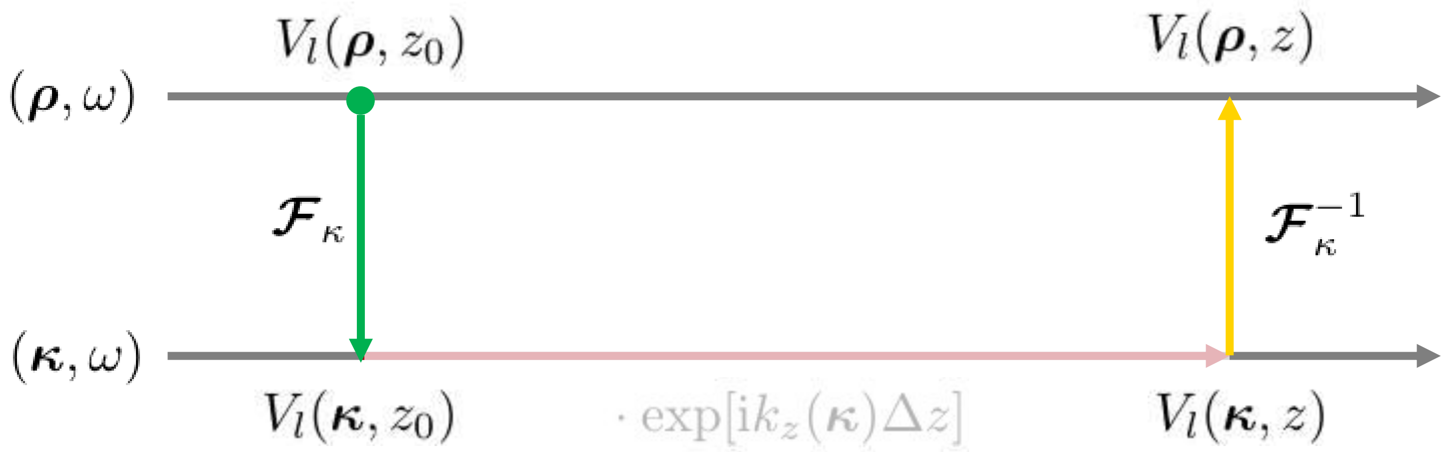
- Free space propagation
  - Input field $V_l(\boldsymbol{\rho}, z_0)$ with $\{V_l\} = \{E_x, E_y, E_z, H_x, H_y, H_z\}$ and $l = 1, 2, 3, 4, 5, 6$ in plane z_0
  - propagate from plane z_0 to z , $\Delta z = z - z_0$



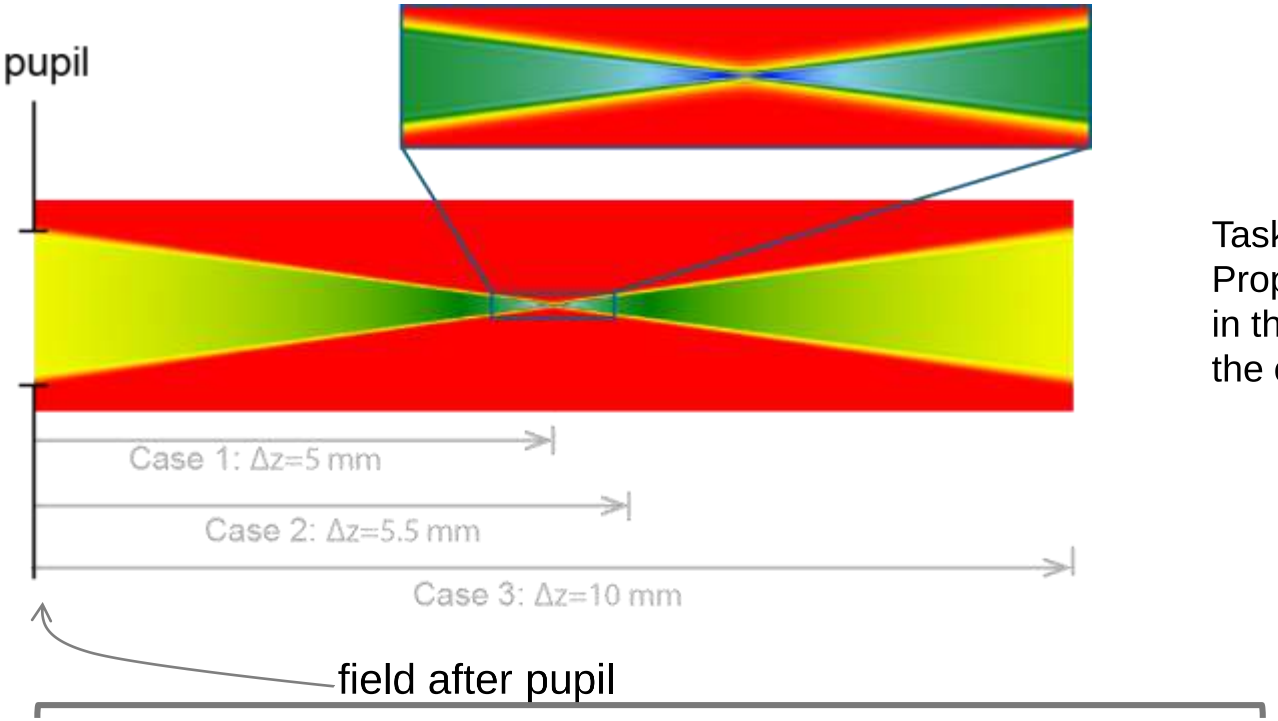
  - Output field $V_l(\boldsymbol{\rho}, z)$

Fourier Transform

- Different types of (inverse) Fourier transform (FT) can be selected, depend on the field
  - (inverse) fast/regular FT
  - (inverse) semi-analytical FT
  - (inverse) geometric FT



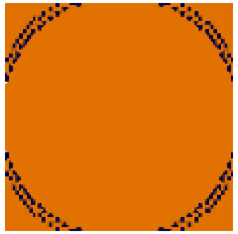
Modeling Task



Task:
Propagate the field after pupil in three cases, and observe the choices of (inverse) FTs

Truncated spherical field	
polarization	linearly polarized (0°)
sph. radius	5 mm

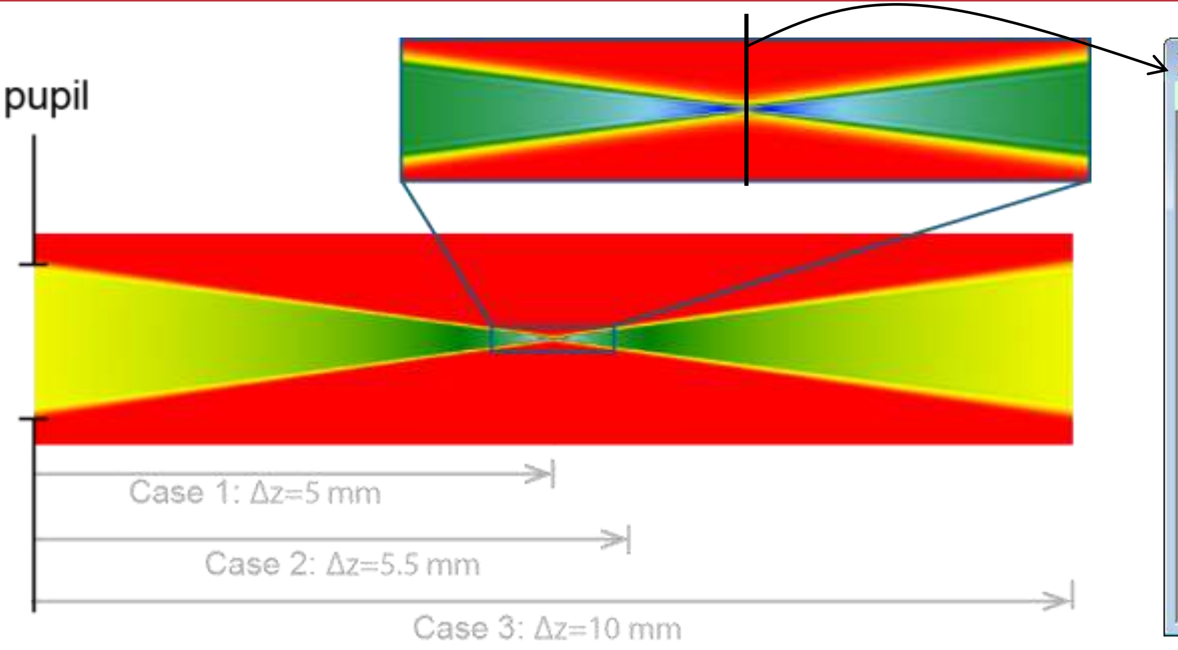
amplitude

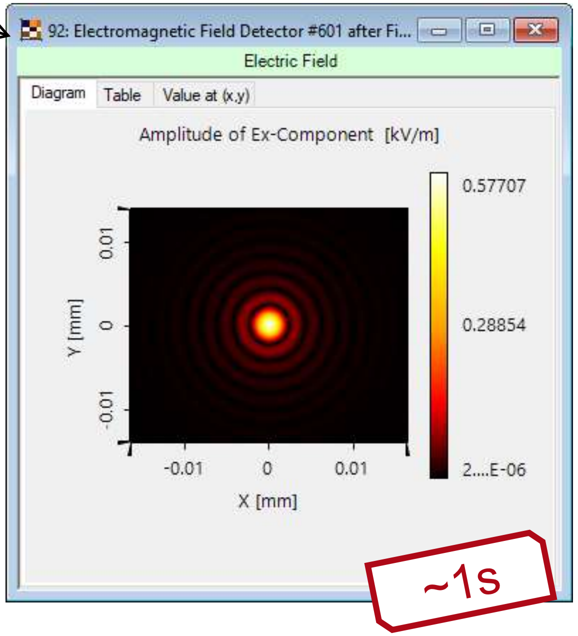


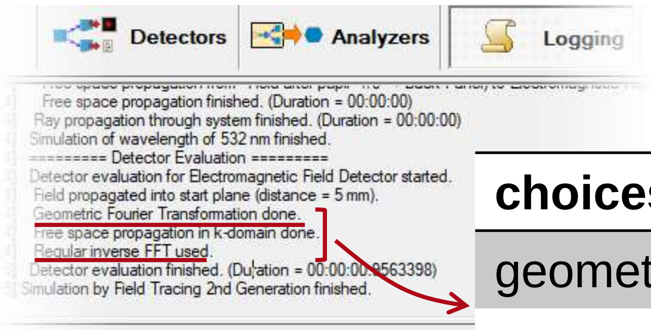
residual phase

Note:
Spherical phase is analytically recorded and tackled, so the residure phase of the field after pupil is a constant

Results of Case 1





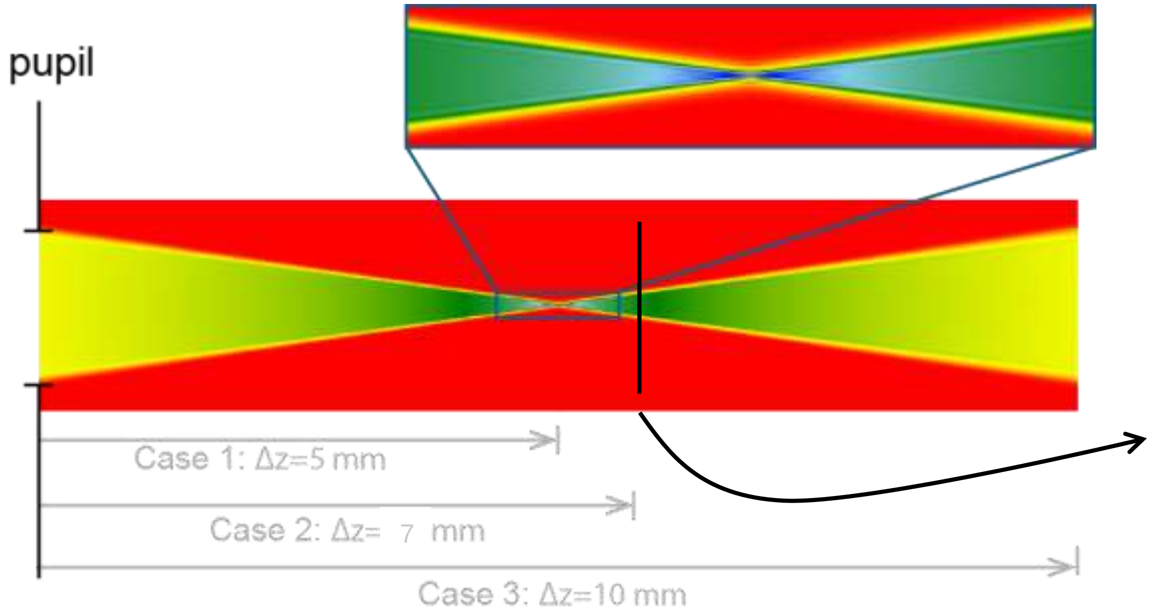


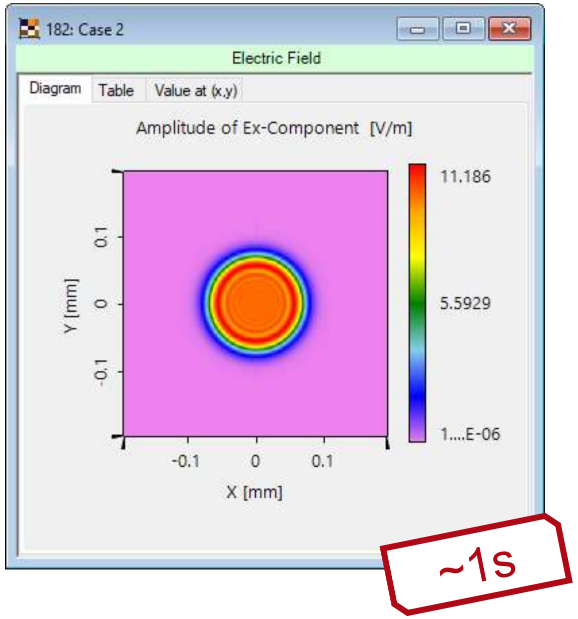
choices FTs
geometric FT
regular inverse FFT

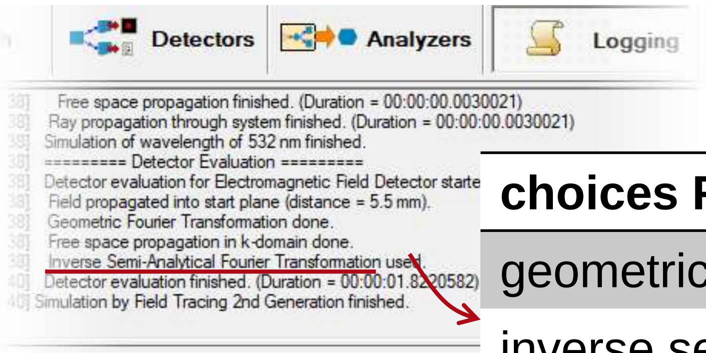
Note:
Selection of FTs is automatically done by VirtualLab Fusion.

- Field after pupil is geometric field, so geometric FT is selected
- Detected field is a diffractive field in focal plane, common smooth phase is constant, so regular inverse FFT is selected

Results of Case 2





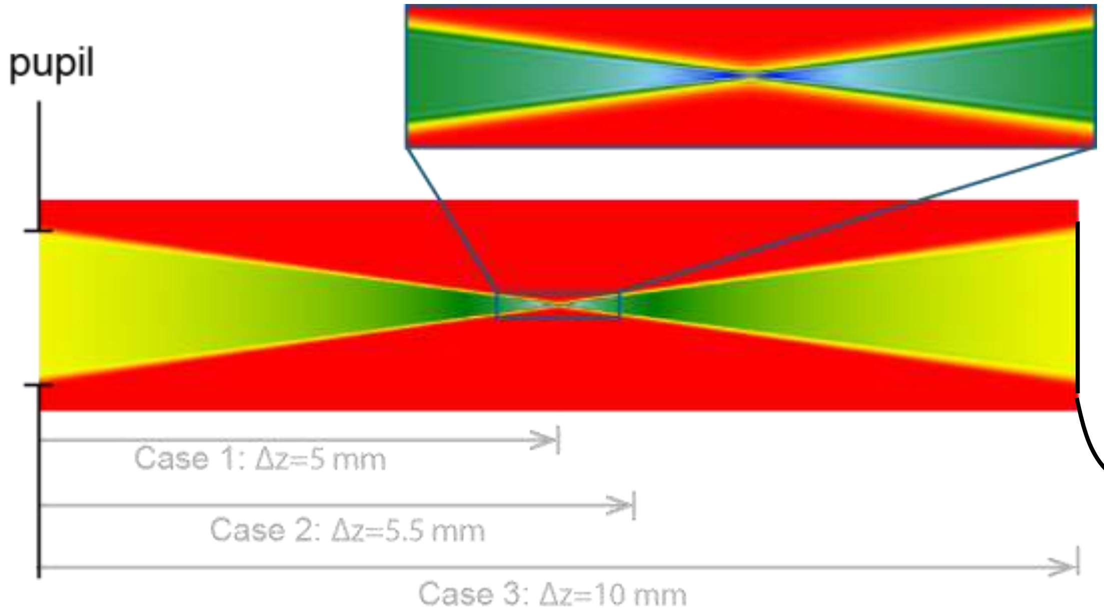


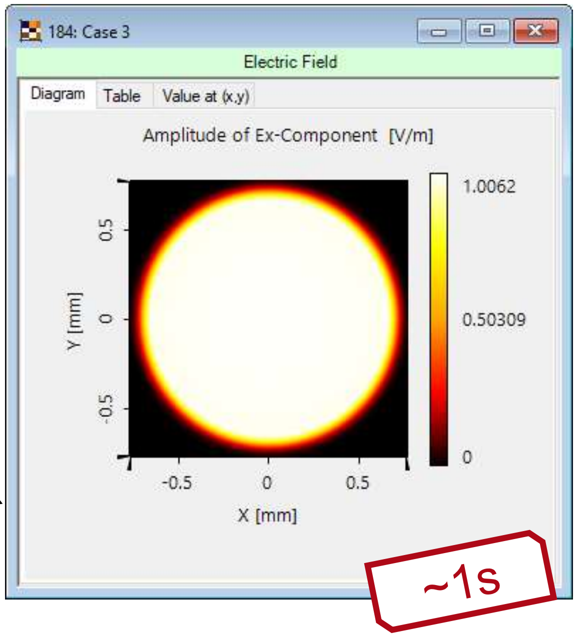
choices FTs
geometric FT
inverse semi-analytical FT

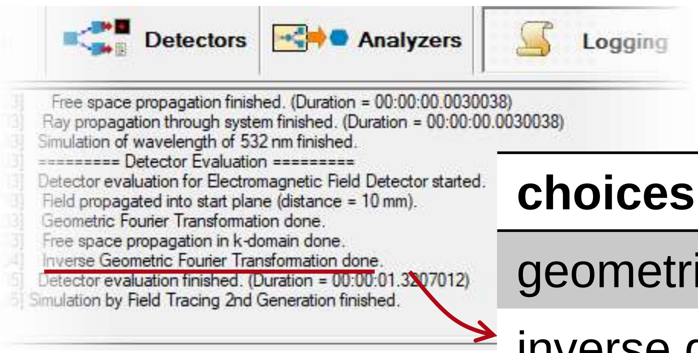
Note:
Selection of FTs is automatically done by VirtualLab Fusion.

– Detected field is a diffractive field, a quadratic common smooth phase can be analytically tackled, so inverse semi-FT is selected

Results of Case 3







choices FTs
geometric FT
inverse geometric FT

Note:
Selection of FTs is automatically done by VirtualLab Fusion.

– Detected field is a geometric, so inverse geometric FT is selected.

Task 3: Video

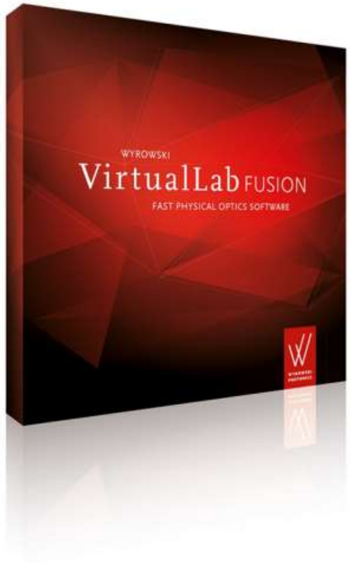
Klick the following link to watch the video:

https://youtu.be/a21sd5CBjdk

Summary Field Tracing Concept

- **Fast physical optics strategy #1**: Non-sequential coupling of different Maxwell solvers.
- **Fast physical optics strategy #2**: Maxwell solvers implemented in domains in which associated B-operator is of mapping type – wherever possible.
- **Fast physical optics strategy #3**: Drastical reduction of sampling effort of Fourier integral by mapping-type Fourier transform in geometric field zones.

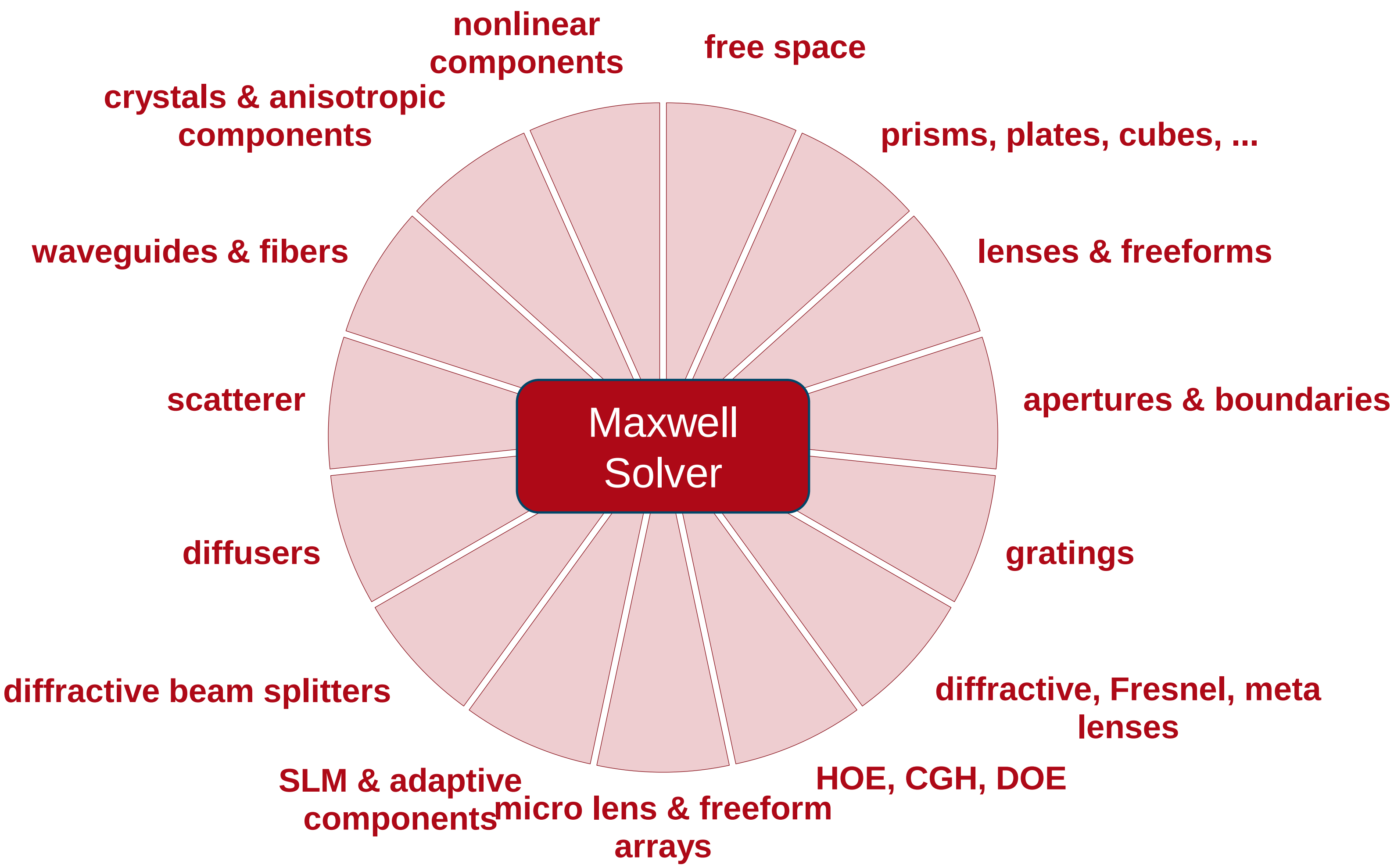
- Strategies implemented in VirtulLab Fusion software.
- Steady development!



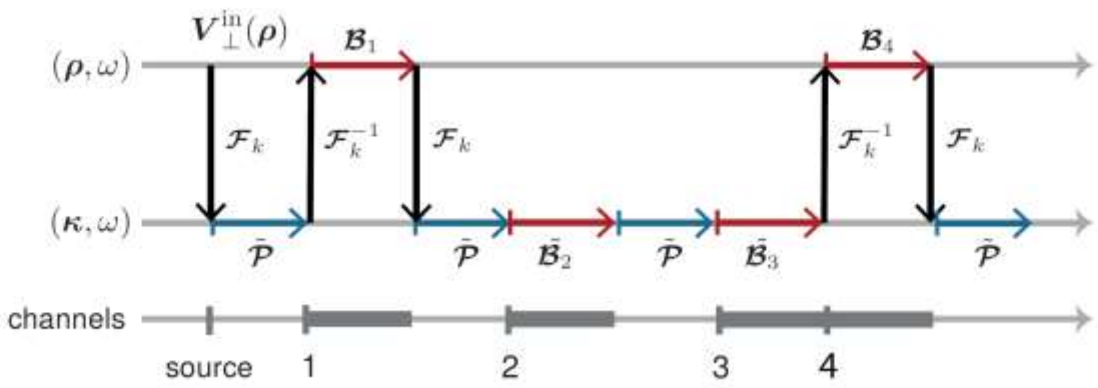
Fast physical optics modeling techniques

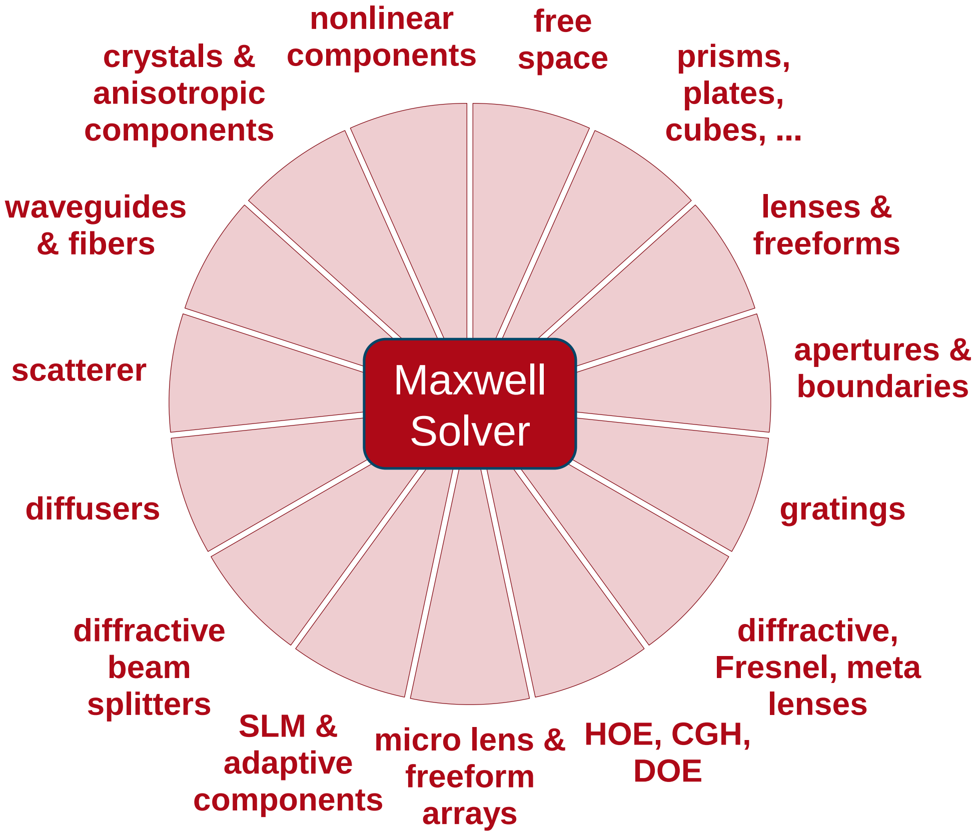
Bidirectional operators for field tracing

Physical-Optics System Modeling: Regional Maxwell Solver

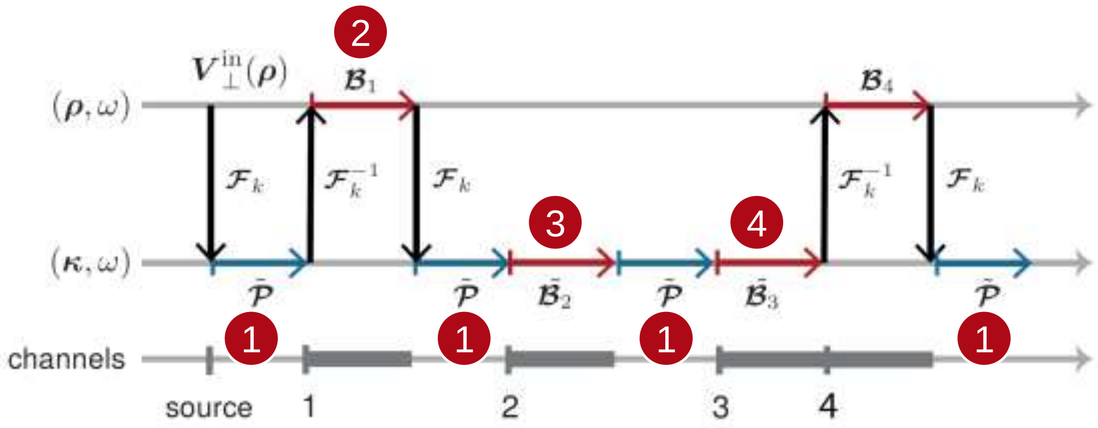


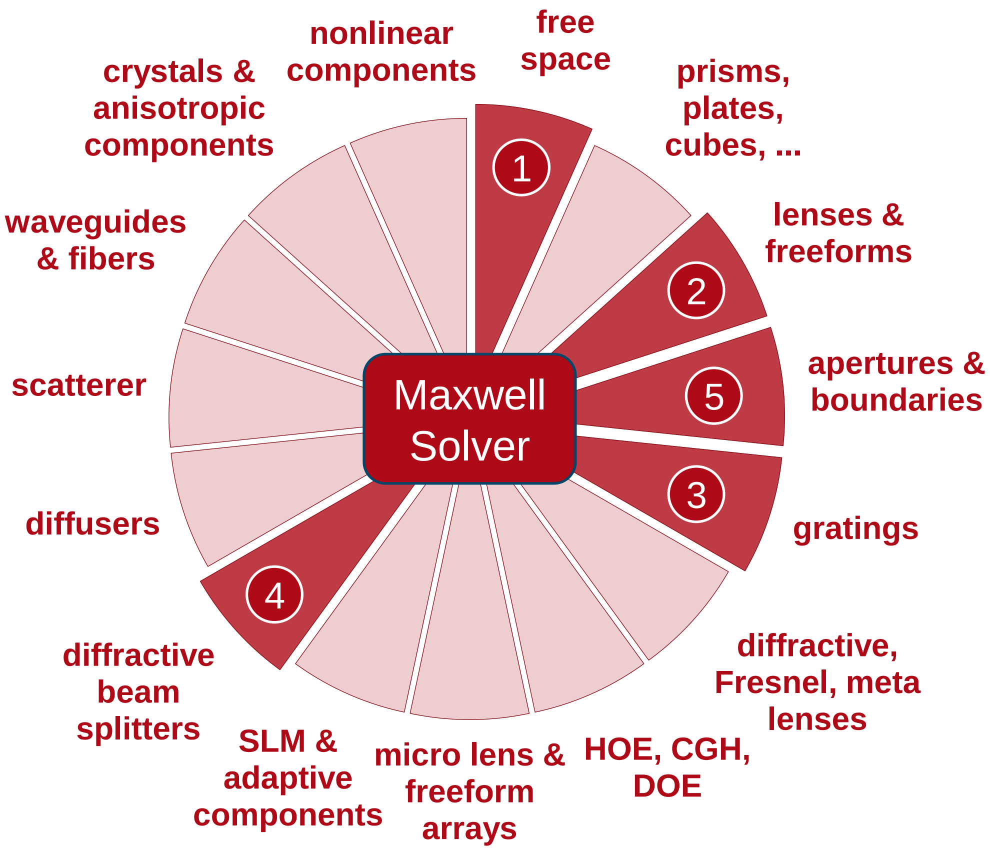
Modeling Techniques





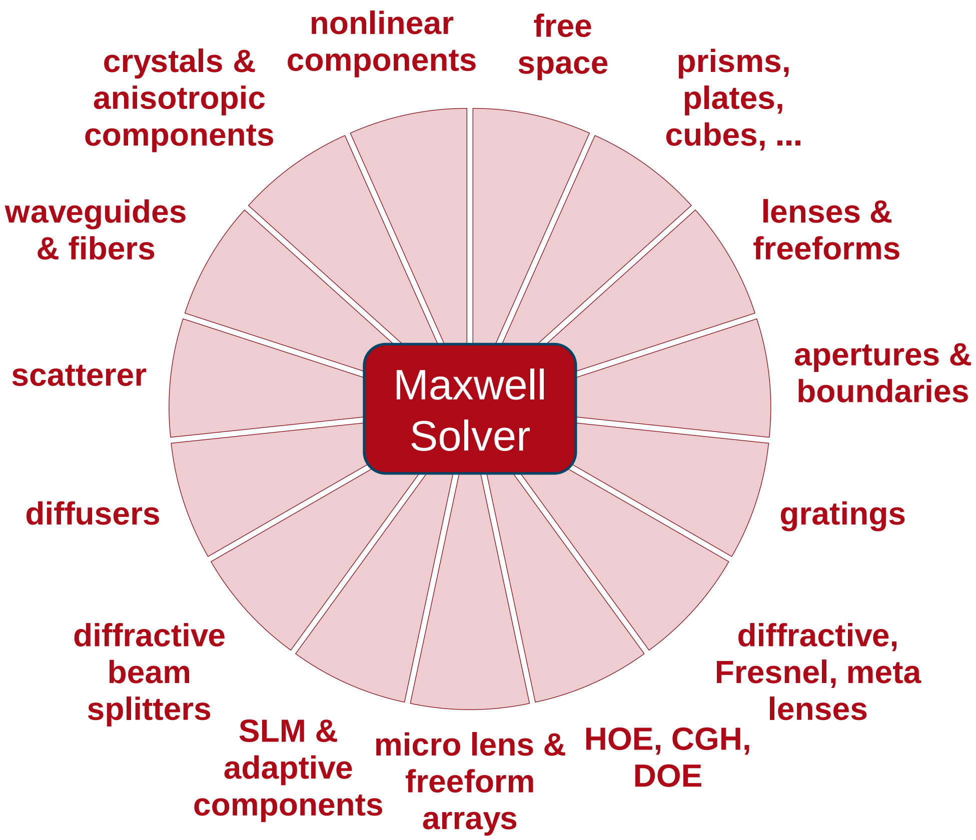
Modeling Techniques





Modeling Techniques

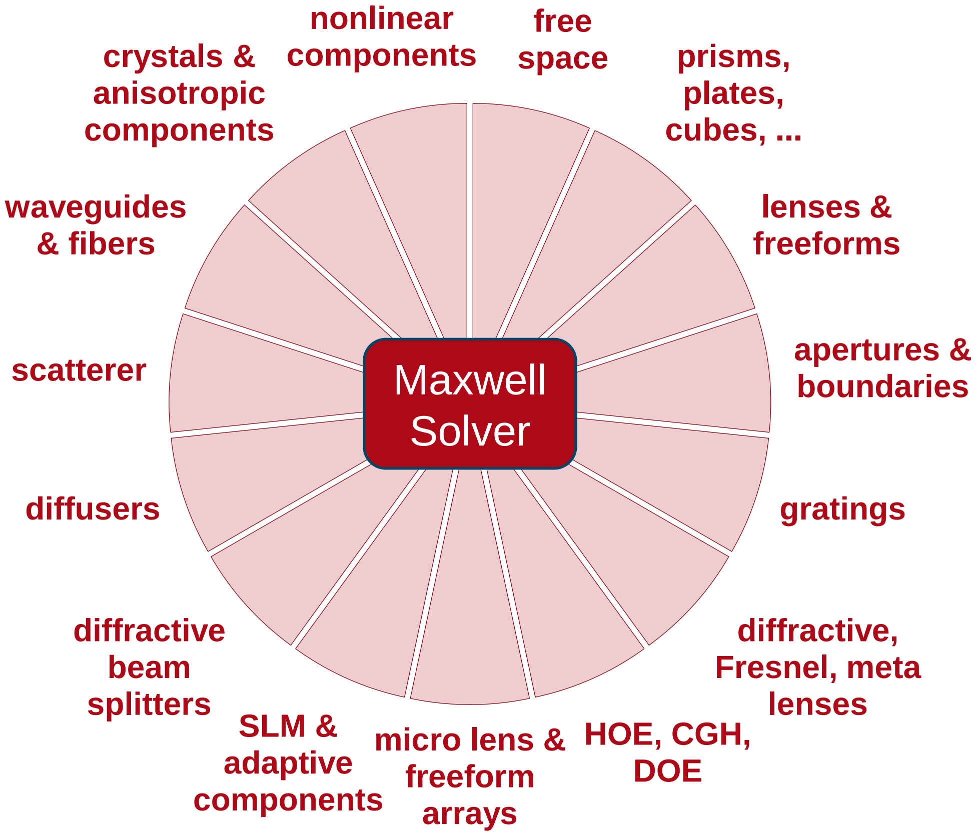
- VirtualLab provides an ever increasing number of rigorous and approximated Maxwell solvers for optical components and structures of practical concern!
- Steady and strong R&D on Maxwell solvers for fast physical optics.
- Under development: Interfaces to other software, e.g. FEM JCMSuite, Optiwave, …



Modeling Techniques

- VirtualLab provides an ever increasing number of rigorous and approximated Maxwell solvers for optical components and structures of practical concern!

Next: Overview of techniques!

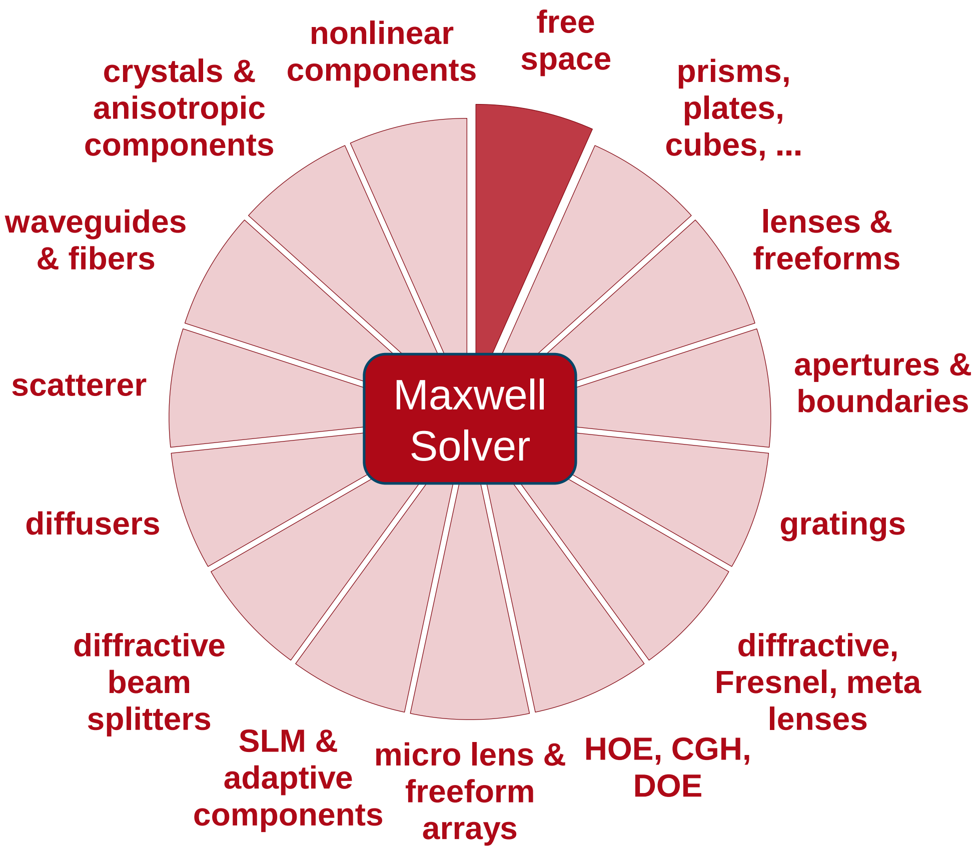


Free-Space Propagation

- Rigorous free-space propagation operator $\tilde{\mathcal{P}}$ in k-domain.
- Propagation between parallel planes with distance Δz is given by

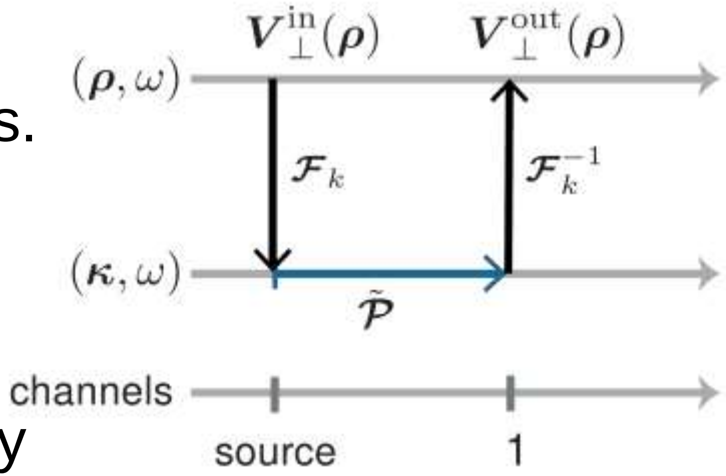
$$\tilde{\boldsymbol{V}}^{\text{out}}(\boldsymbol{\kappa}) = \exp\left(\mathrm{i}\breve{k}_z \Delta z\right) \times \tilde{\boldsymbol{V}}^{\text{in}}(\boldsymbol{\kappa})\,.$$

- This operator can be generalized for the propagation between tilted planes.
- Propagation operator in k-domain is of mapping-type.



Free-Space Propagation: Diffraction Integrals

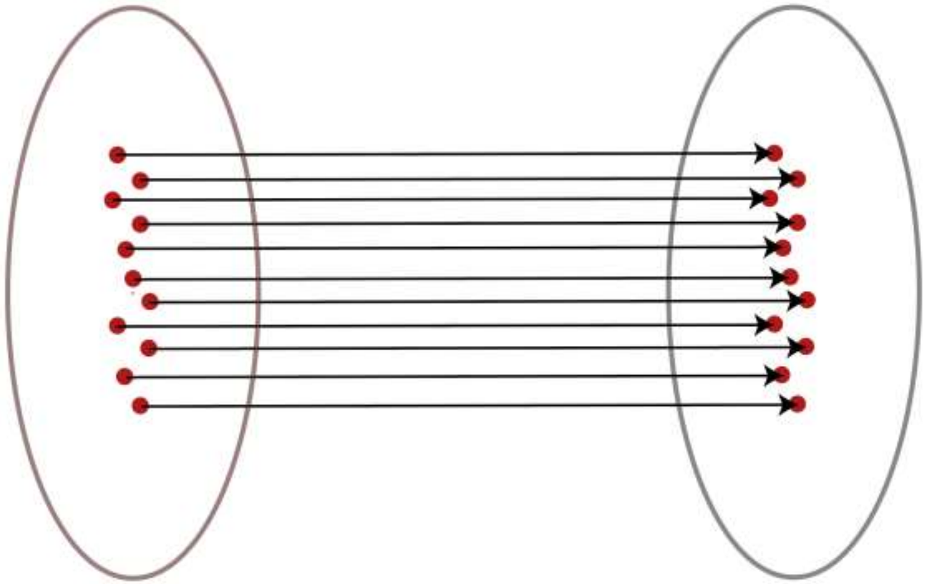
- Together with the Fourier transforms mathematically the propagation operator in space domain follows.
- For the propagation between parallel planes we obtain the so-called diffraction integrals (convolution inegrals).
- If the rigorous Fourier transform is used for both transformations, the Rayleigh-Sommerfeld integral follows.
- With one mapping-type Fourier transform we obtain the Debye integral, the far-field integral, and its generalizations.
- Use of mapping-type Fourier transform only results in very fast mapping-type propagation, which may be understood as the physical-optics generalization of ray tracing.

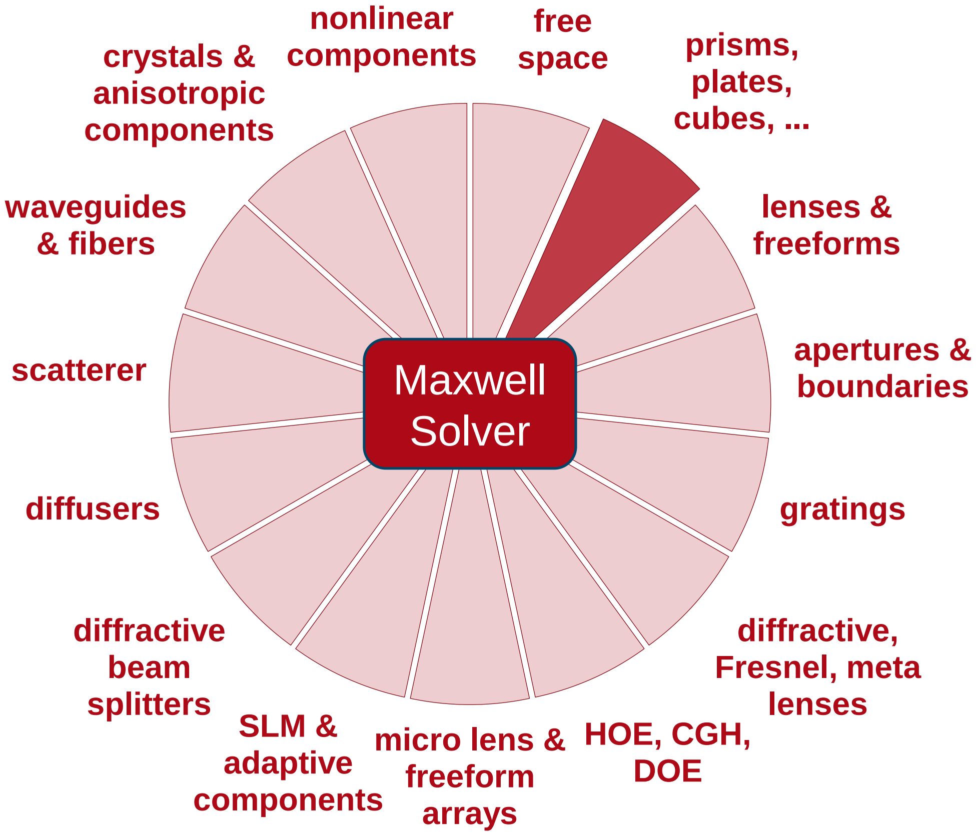


Stratified Media and Components with Planar Surfaces

- Rigorous operator in k-domain.
- Fast mapping-type operator with:

$$\boldsymbol{\kappa}^{\text{out}} = \boldsymbol{\kappa}^{\text{in}}$$

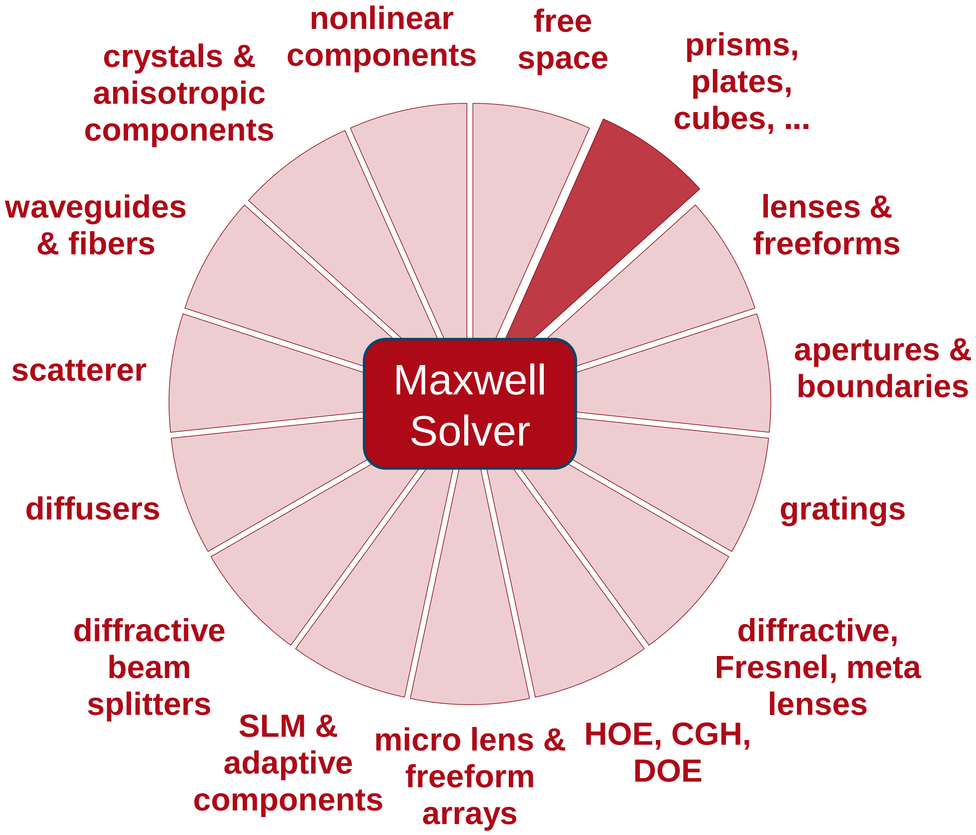




Stratified Media and Components with Planar Surfaces

- Rigorous operator in k-domain.
- Fast mapping-type operator with:

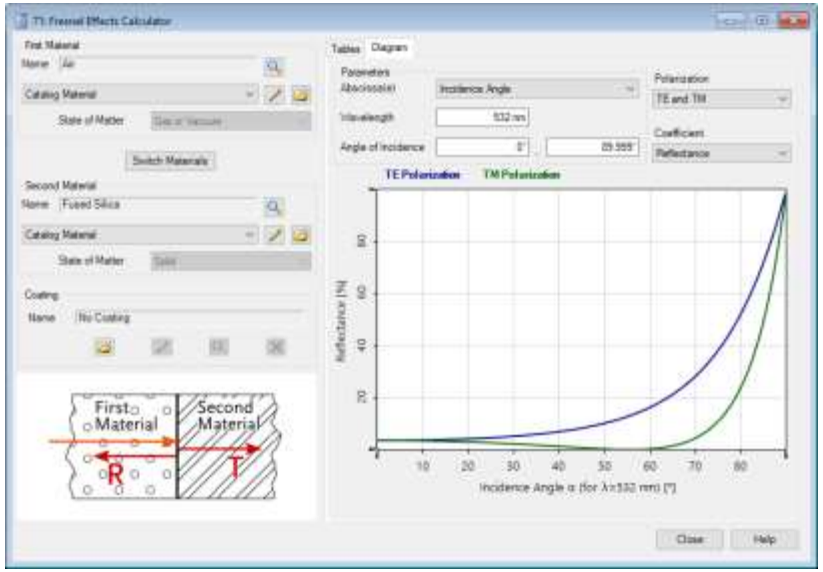
  $\boldsymbol{\kappa}^{\text{out}} = \boldsymbol{\kappa}^{\text{in}}$
- Per plane interface B-operator is layer/coating matrix metod.
- The combination of the layer matrix with free-space propagation allows the rigorous modeling of plates, cubes, prisms and any component which comprises of planar surfaces.

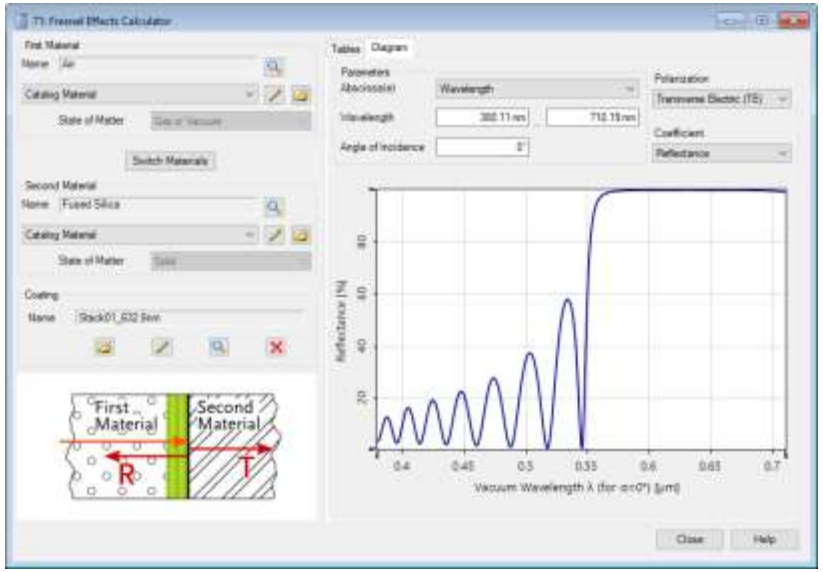


Fresnel Effects

- Fresnel effects calculator with different diagram, and possibilities to include coatings

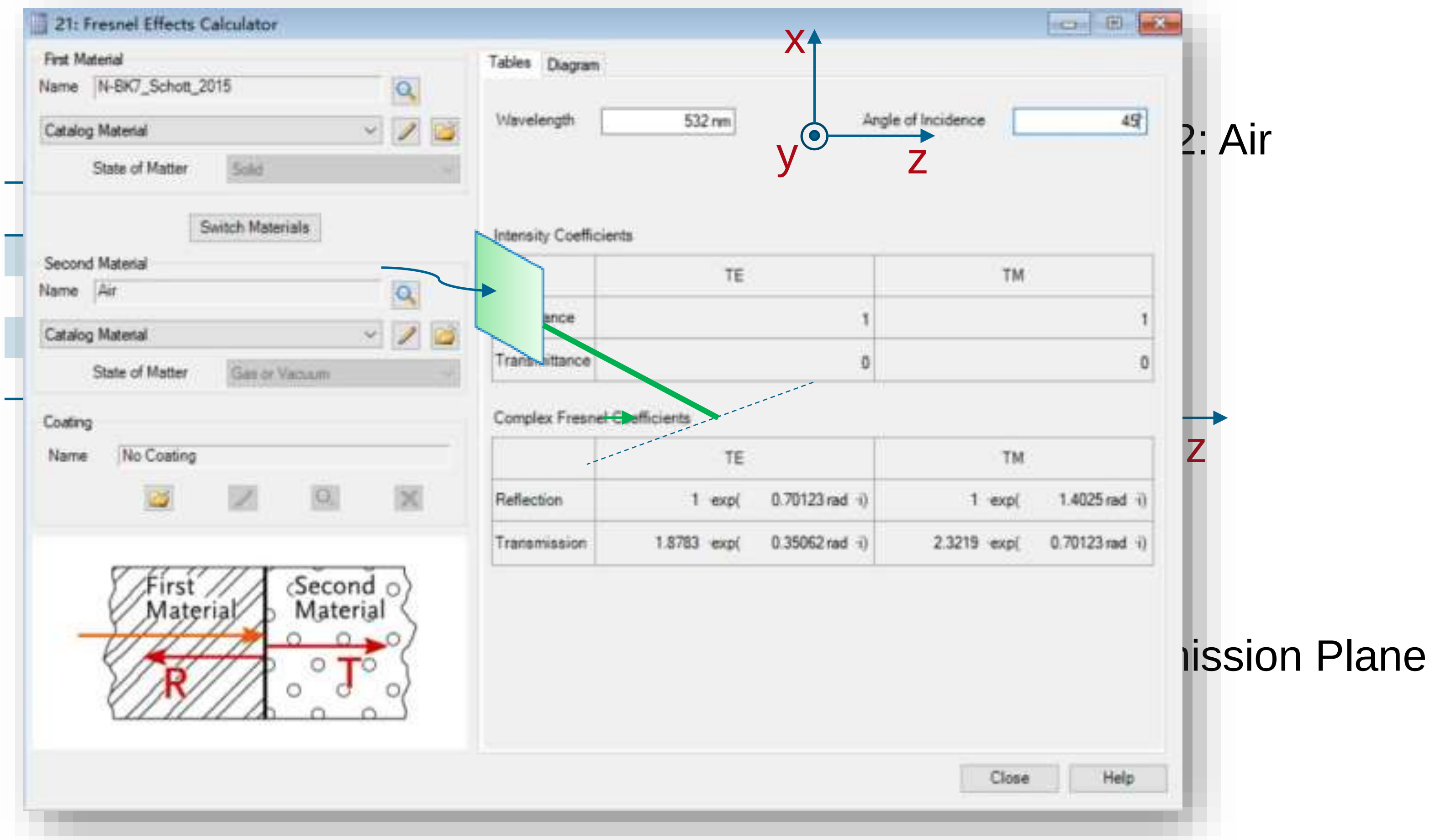
Illustration 4 in VLF





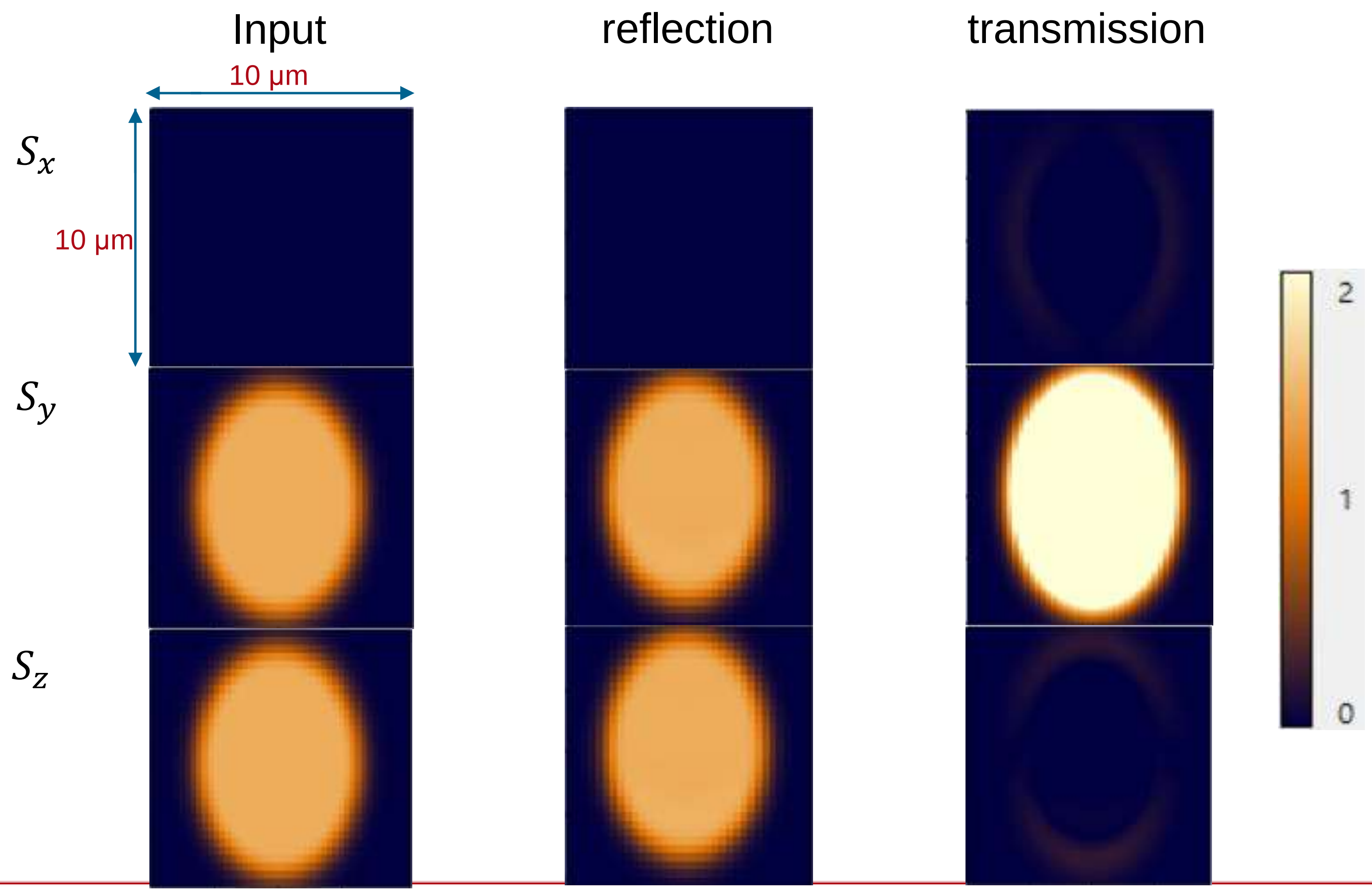
Total Reflection

- Set up



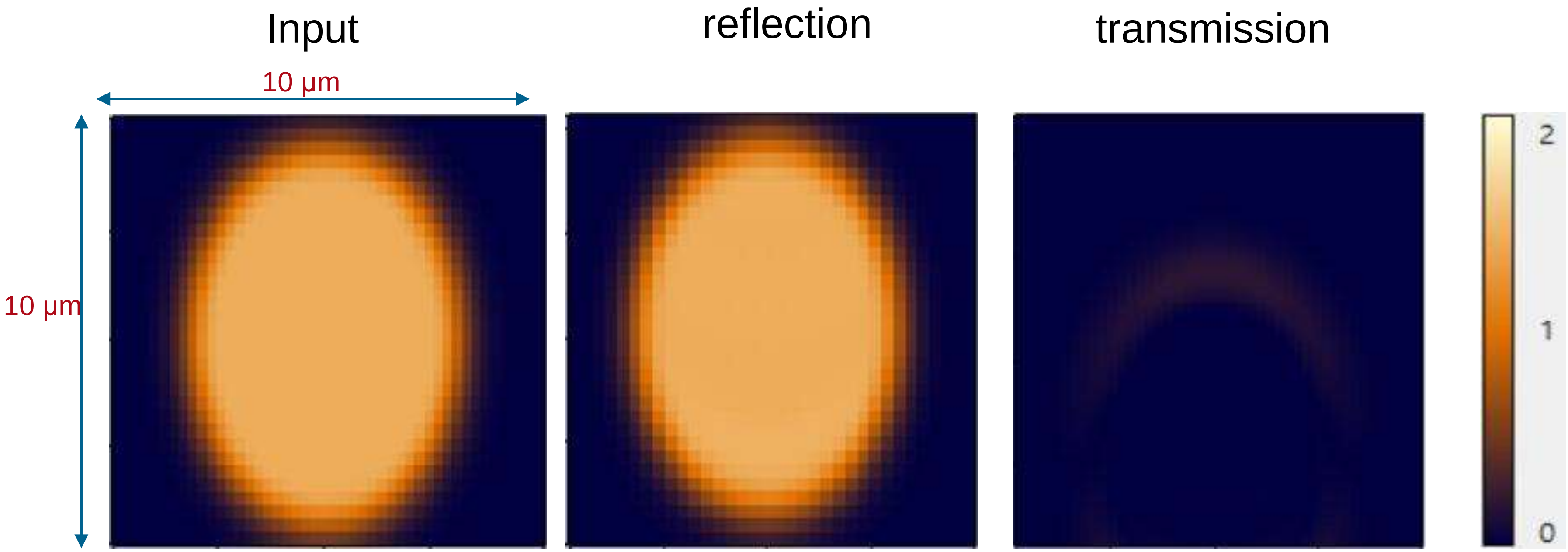
Experiment 1: Total Reflection

- Results: Time averaged Poynting Vector



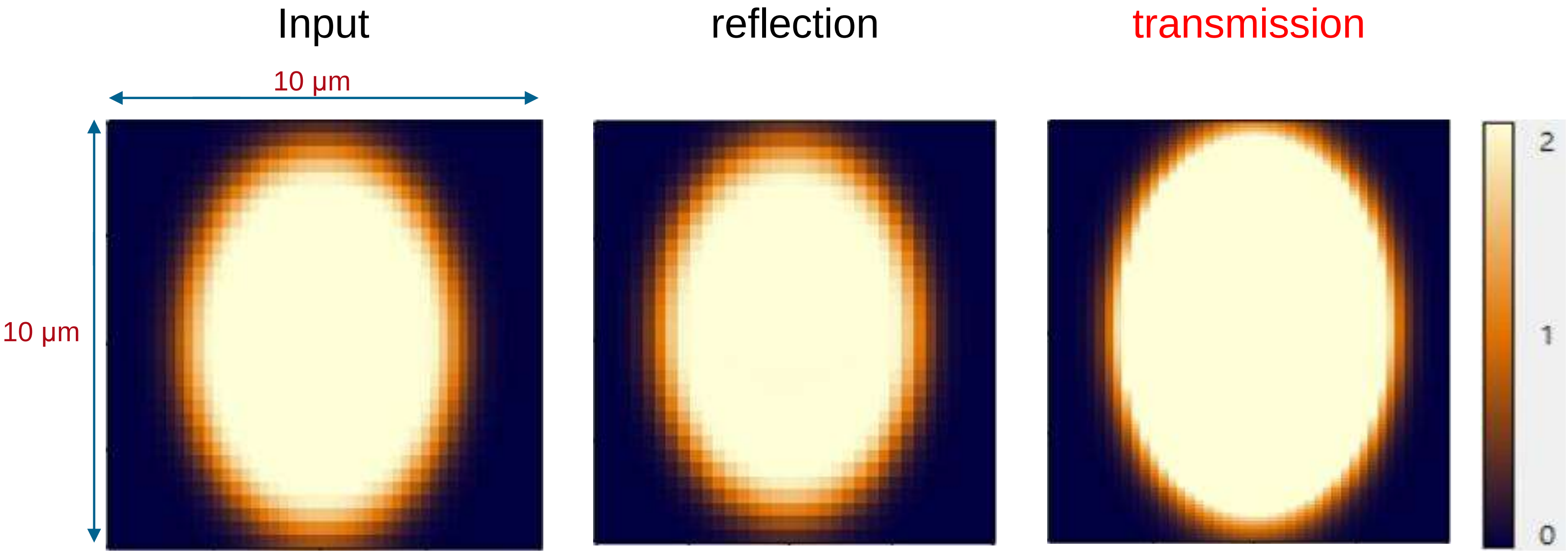
Experiment 1: Total Reflection

- Results: Irradiance

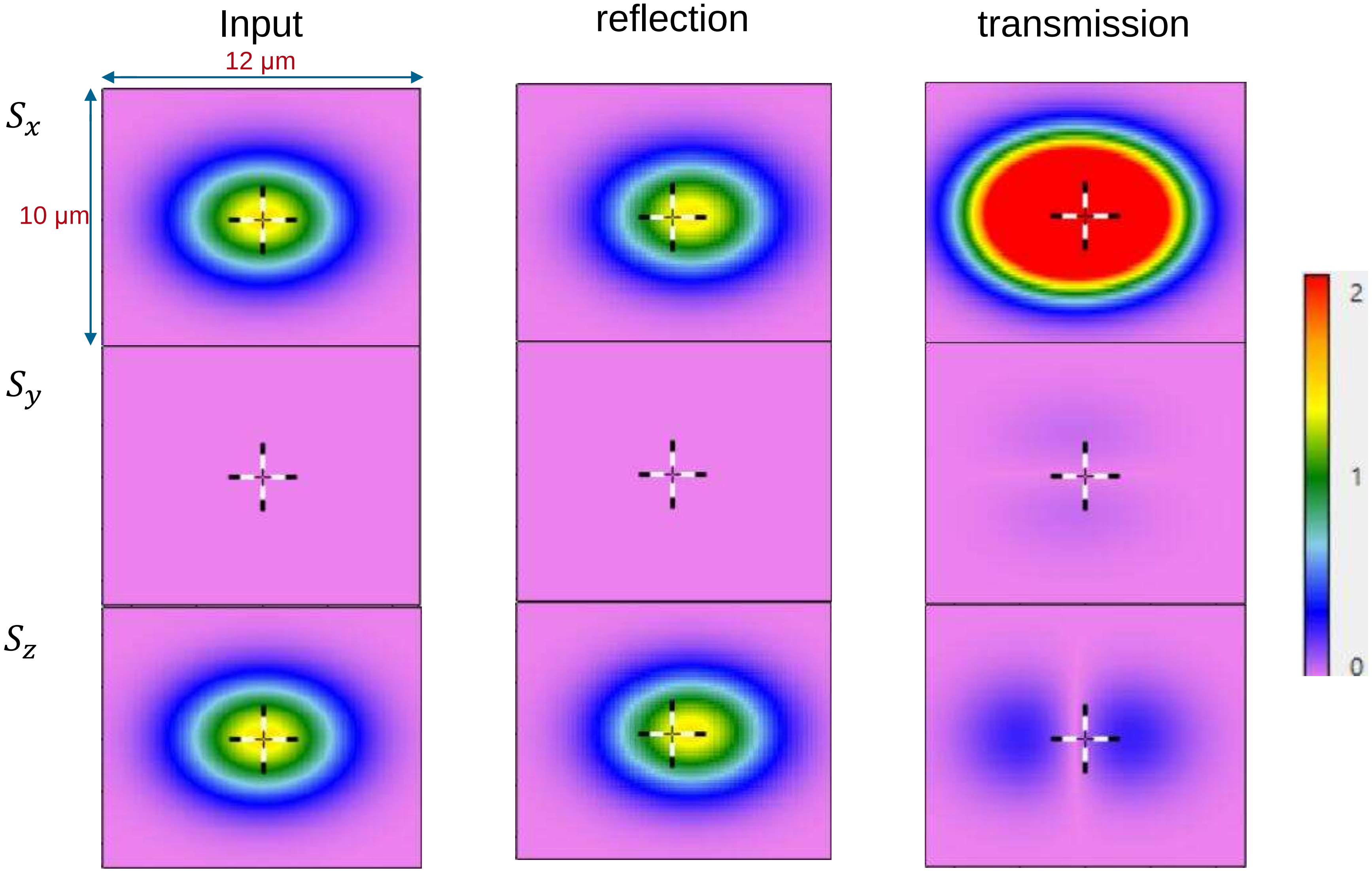


Experiment 1: Total Reflection

- Results: Intensity

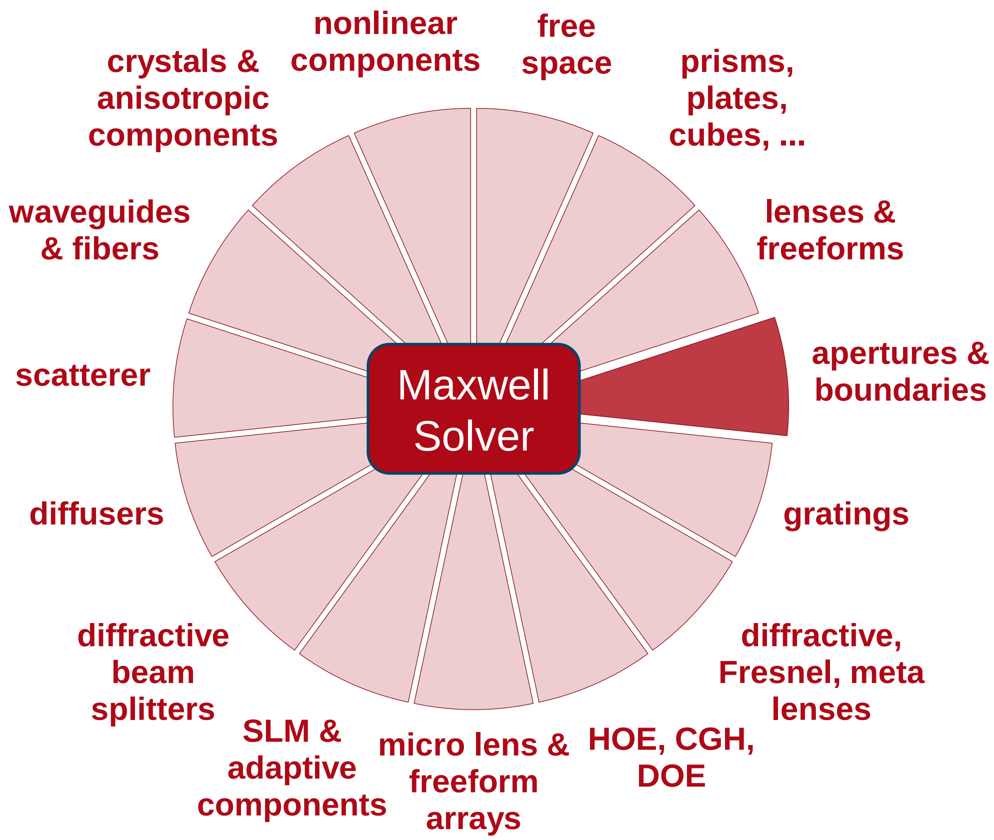


Experiment 2: Goos–Hänchen Shift

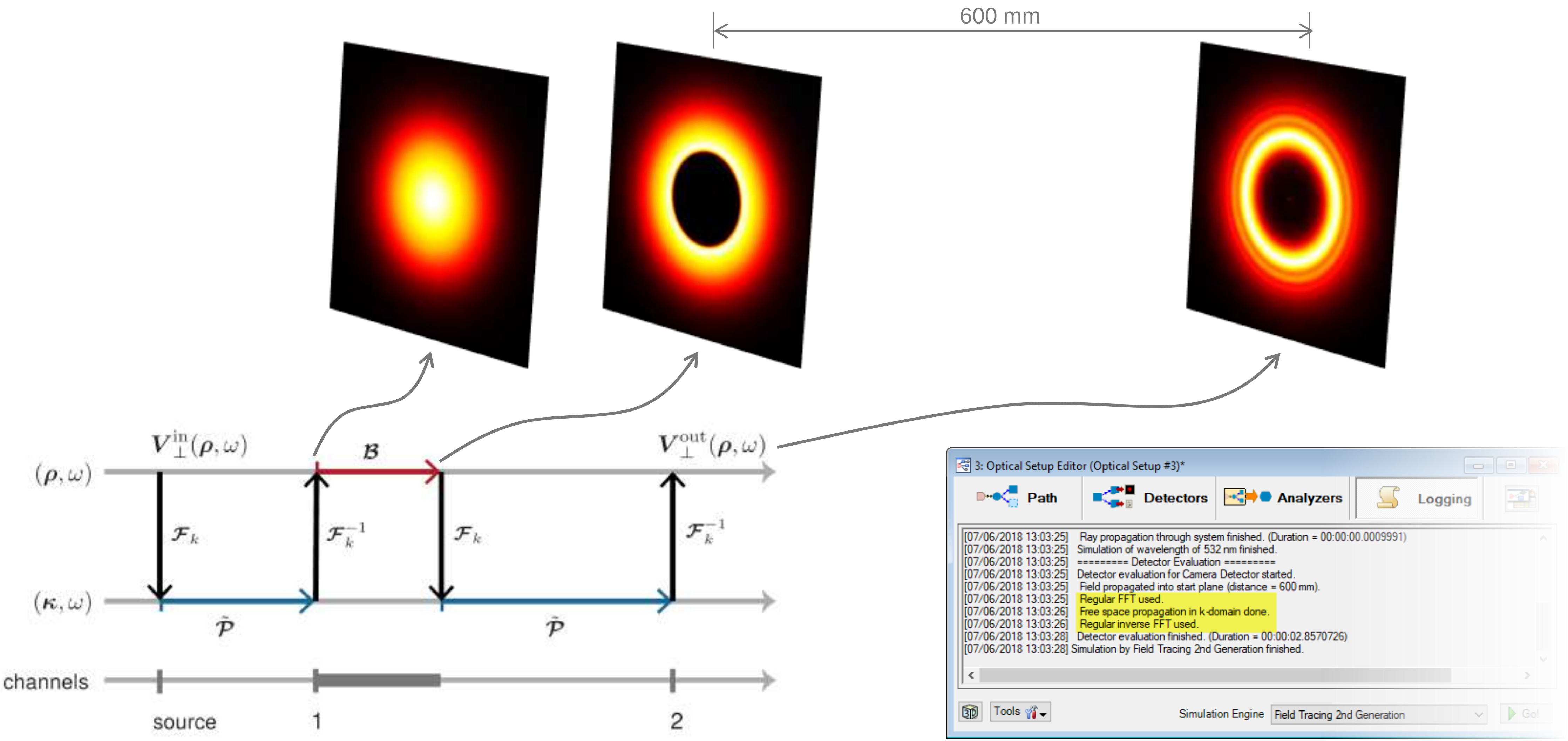


Apertures and Boundaries at Regions

- Aperture: Kirchhoff's boundary condition of diffraction theory, that is truncation of field along aperture boundary.
- General boundaries of regions: Cut field along boundary.
- Sampling control of field at boundary via soft profile.
- For very small pinhole apertures Fourier Modal Method.

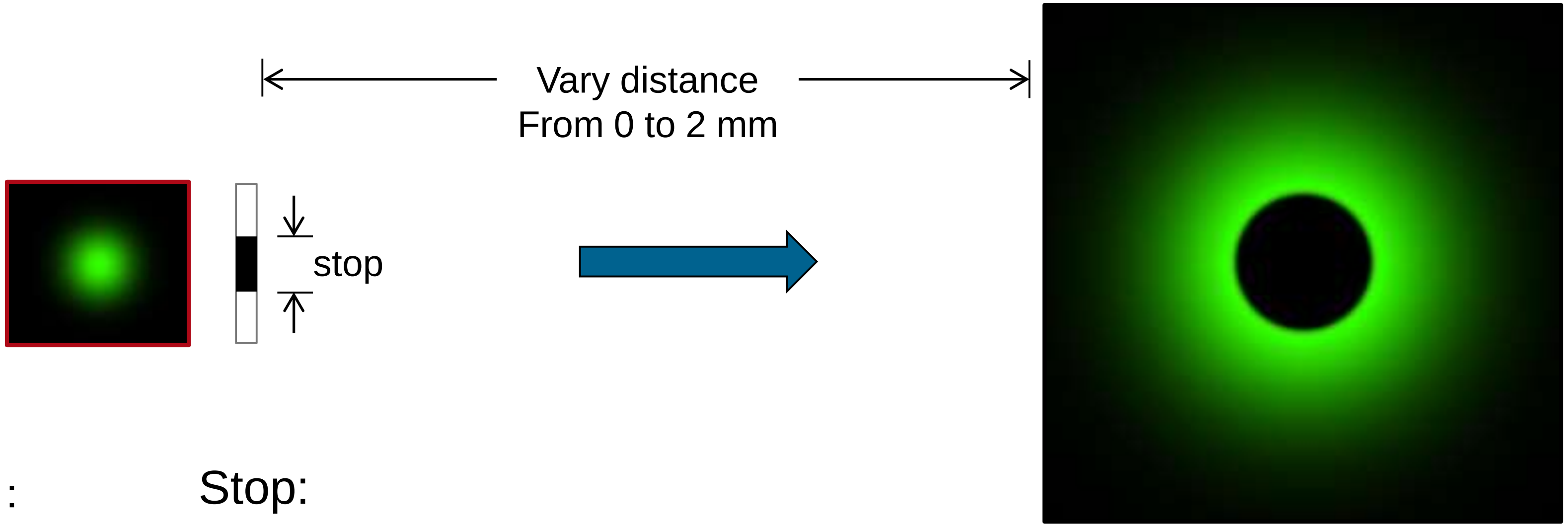


Basic Diffraction Experiment



Task 4 Poisson Spot

- Diffraction



Gaussian :
Default
parameters

Stop:
100 µm x 100 µm

Parameter Run

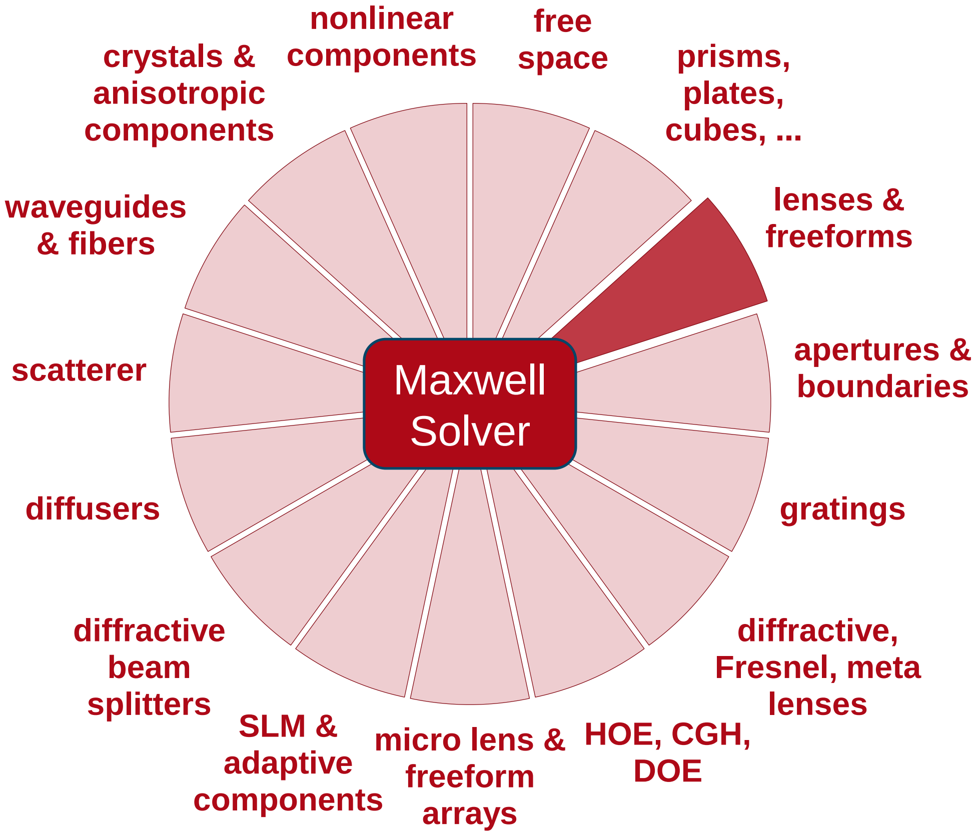
Task 4: Video

Klick the following link to watch the video:

https://youtu.be/GrDjaSt7U3Q

Lenses, Freeforms and Any Components with Curved Surfaces

- FMM+Perfectly Matched Layers
- Rigorous operator for spherical surfaces (Mie theorie).
- Local Plane Interface Approximation (LPIA): Propagation through curved surfaces by local satisfaction of boundary condition between different media.

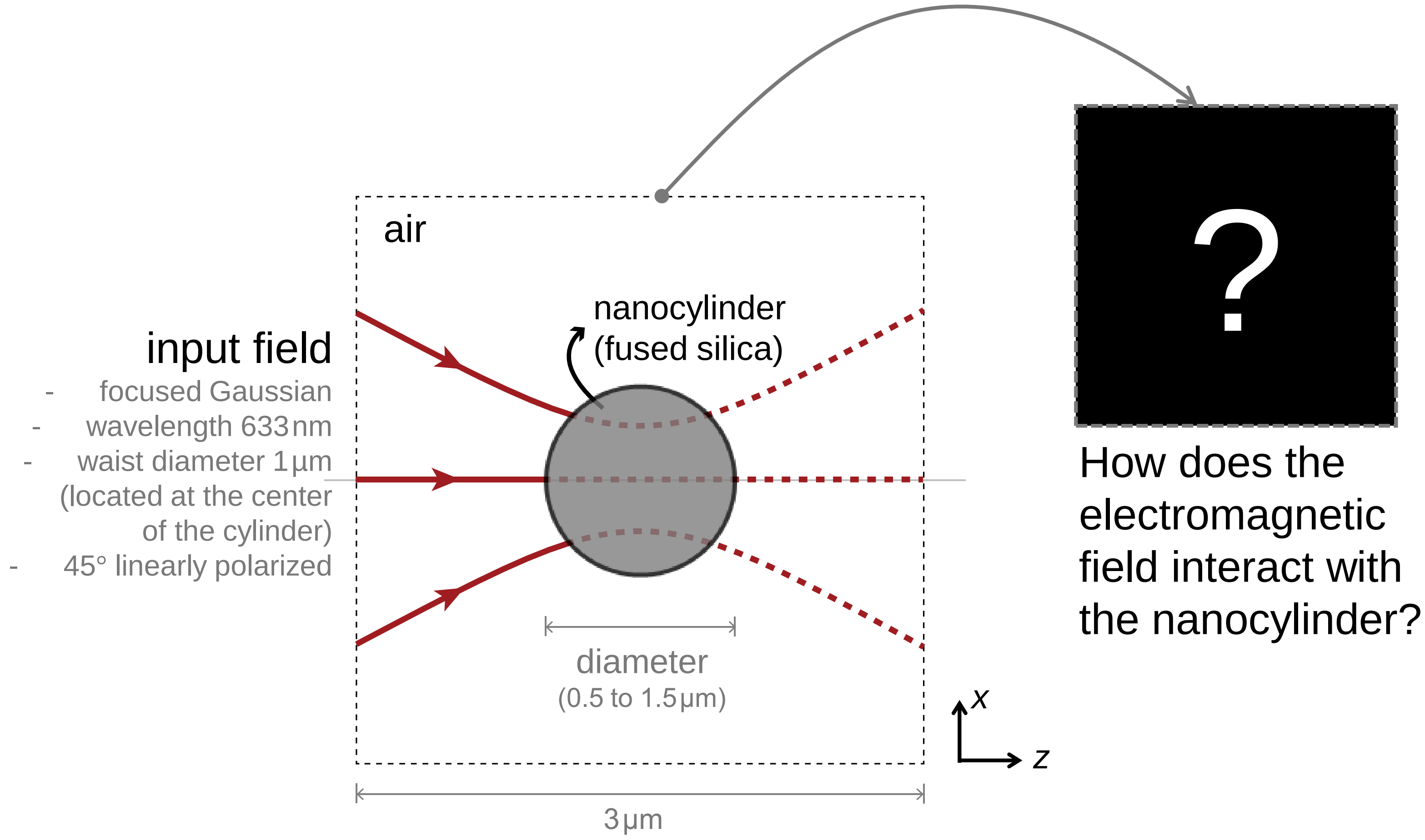


Analysis of optical elements with the local plane-interface approximation

Albrecht v. Pfeil, Frank Wyrowski, Andreas Drauschke, and Harald Aagedal

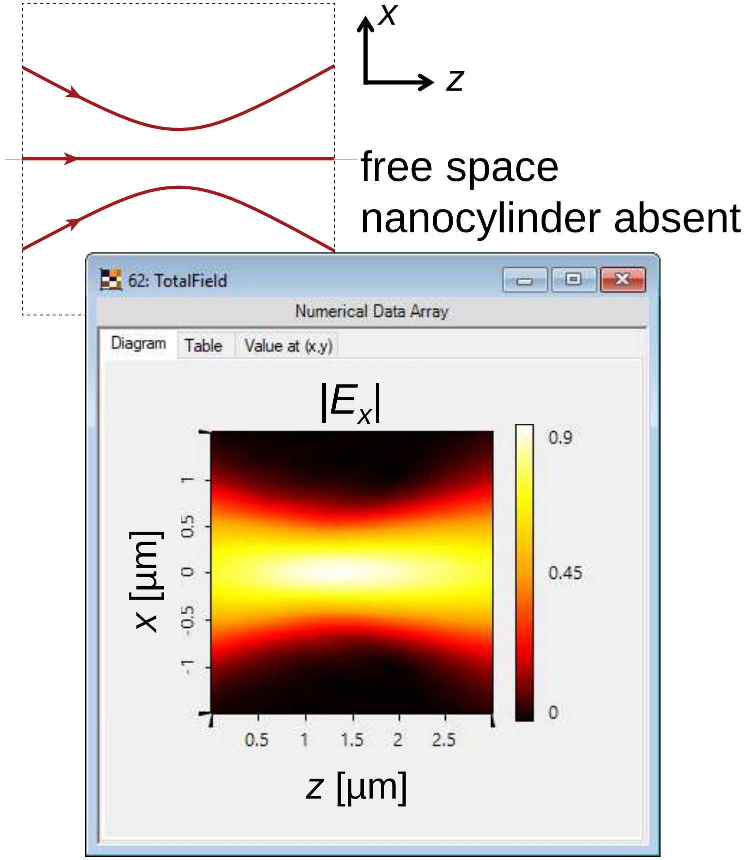
3304 APPLIED OPTICS / Vol. 39, No. 19 / 1 July 2000

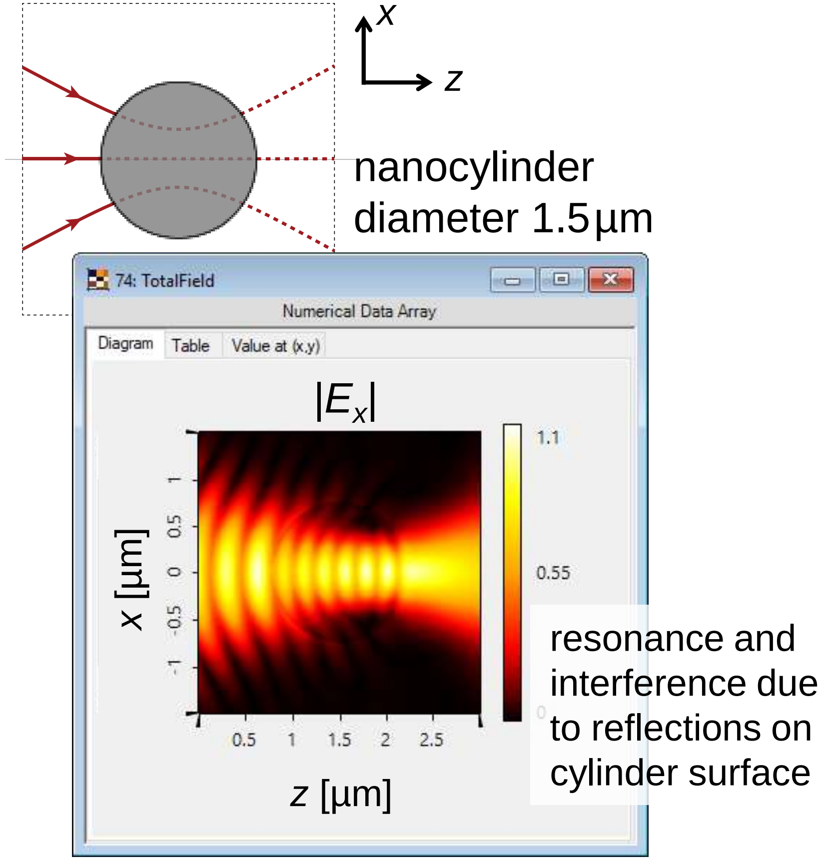
Modeling Task



How does the electromagnetic field interact with the nanocylinder?

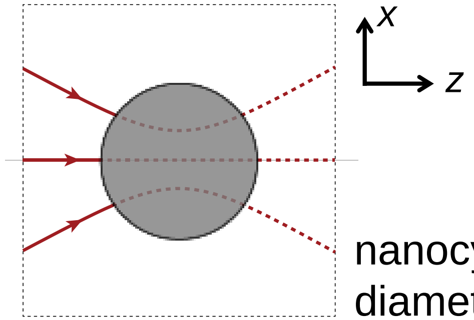
Results



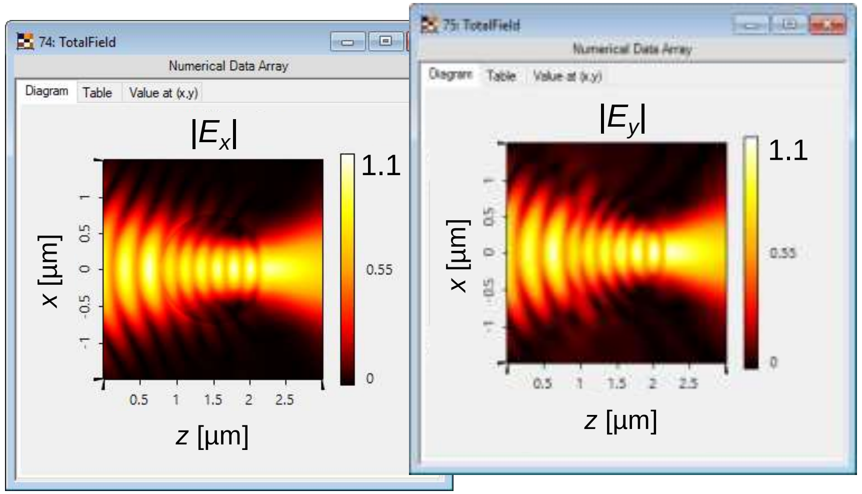


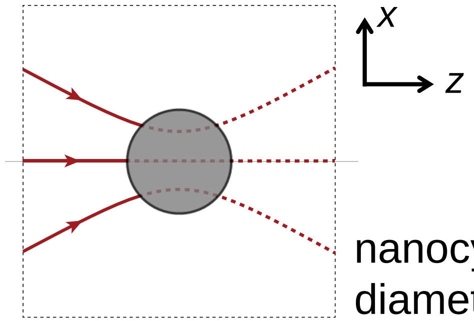
Fourier modal method (FMM) combined with perfectly matched layers (PMLs) enables the simulation of aperiodic nano structures. See reference in M. Pisarenco, *et al.*, J. Opt. Soc. Am. A 27, 2423-2431 (2010)

Results

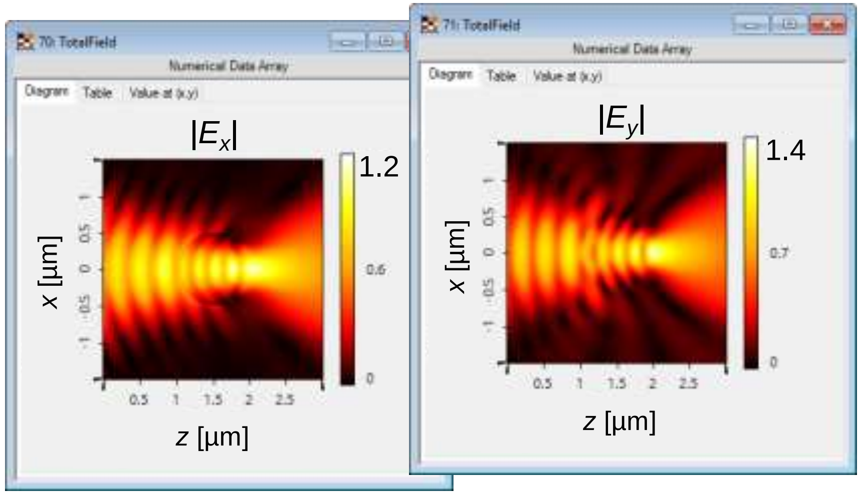


nanocylinder
diameter 1.5 µm

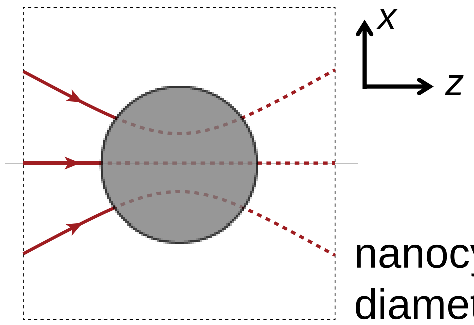




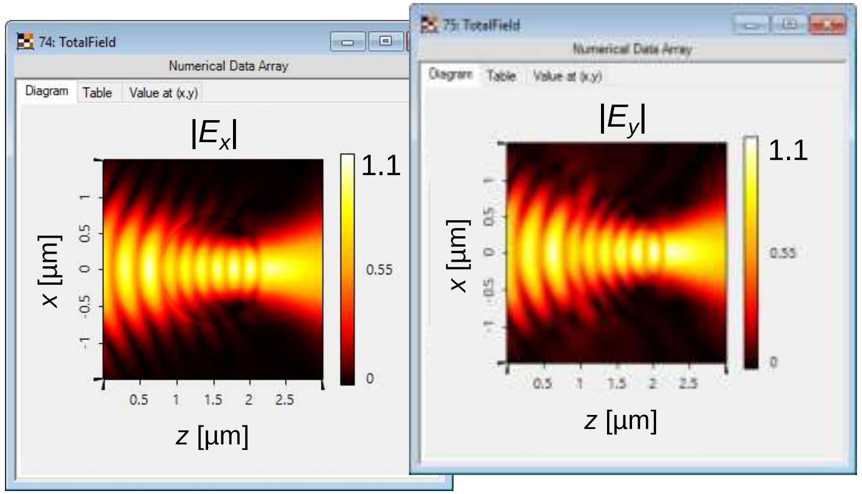
nanocylinder
diameter 1.0 µm



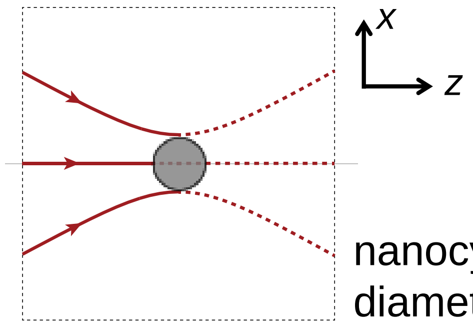
Results



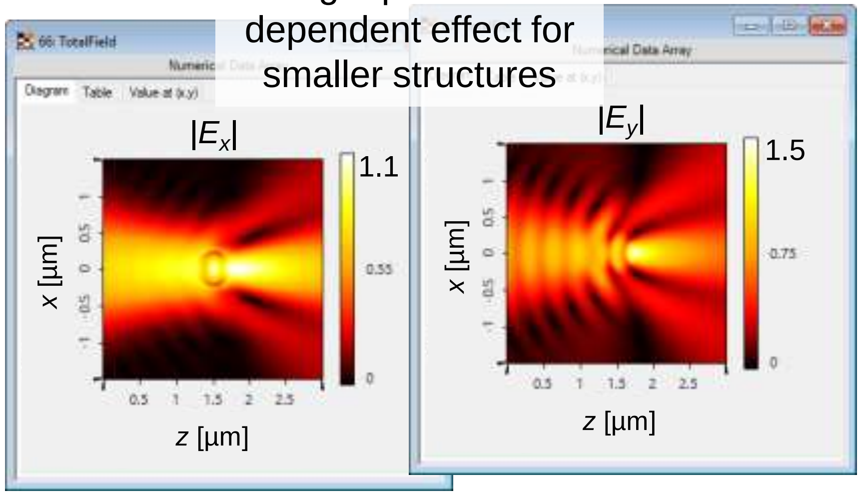
nanocylinder
diameter 1.5µm



stronger polarization-
dependent effect for
smaller structures

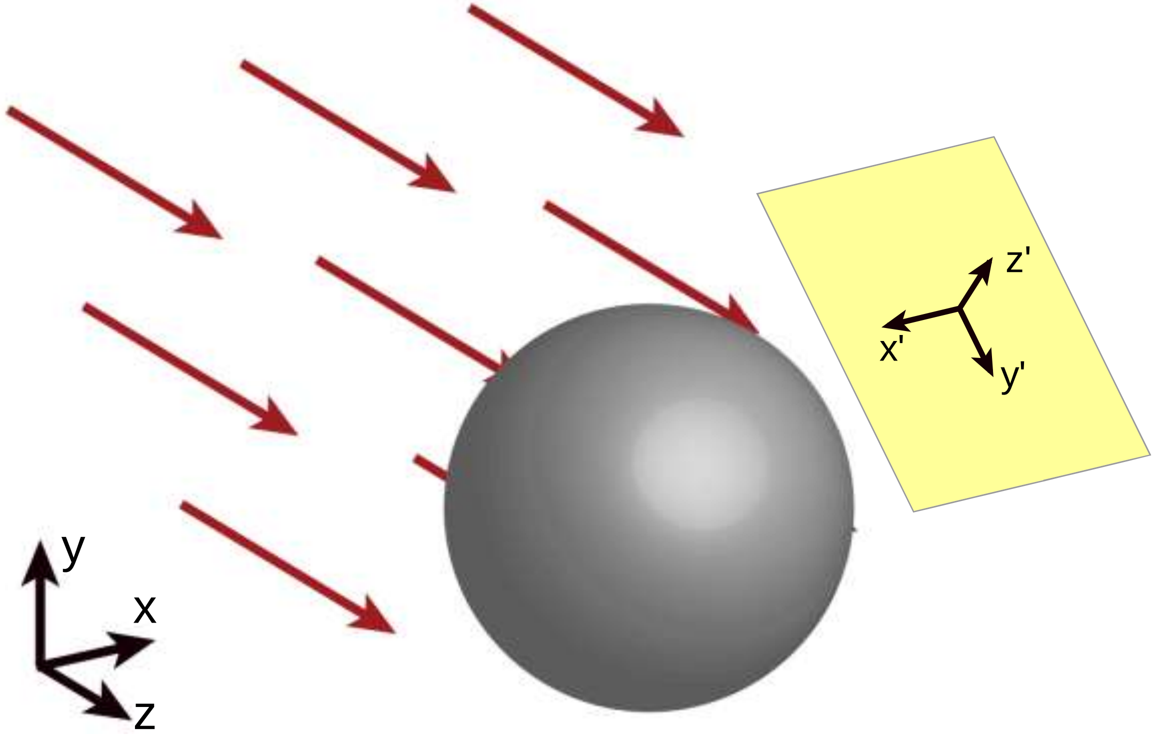


nanocylinder
diameter 0.5µm



Scattering by the Spherical Particle: Mie theory

Abstract

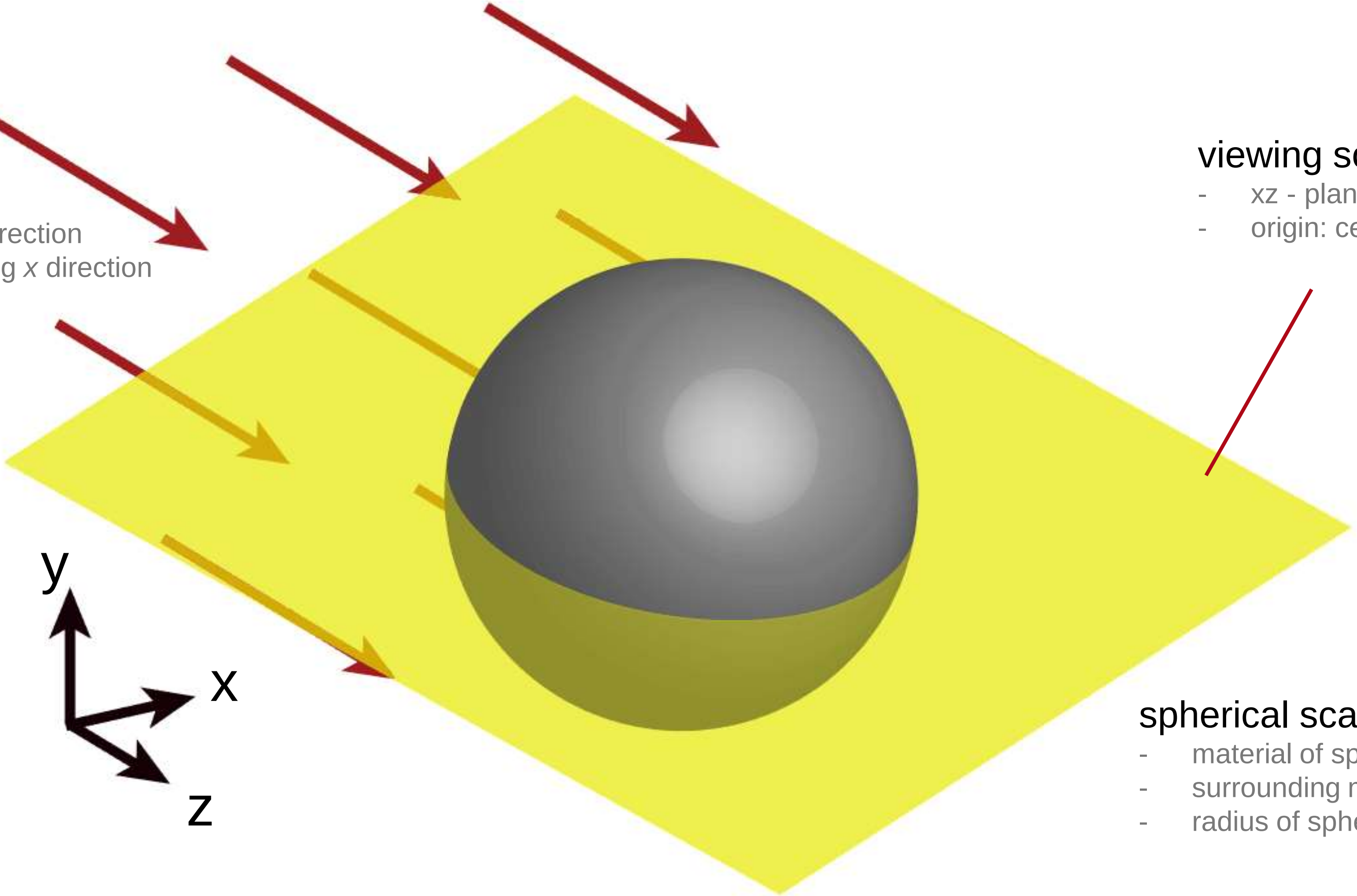


Mie theory is the rigorous Maxwell's solver for the problem of absorption and scattering of a global plane wave by a small spherical particle with an arbitrary radius and refractive index. The resulting scattering effect is highly dependent on the size of the particle. According to its characteristics, scattering can be classified into Rayleigh scattering, Mie scattering, and Geometric Optics. The full Mie theory is integrated in VirtualLab Fusion, and the scattering by spherical particle with respect to the radius of sphere is investigated.

Modeling Task

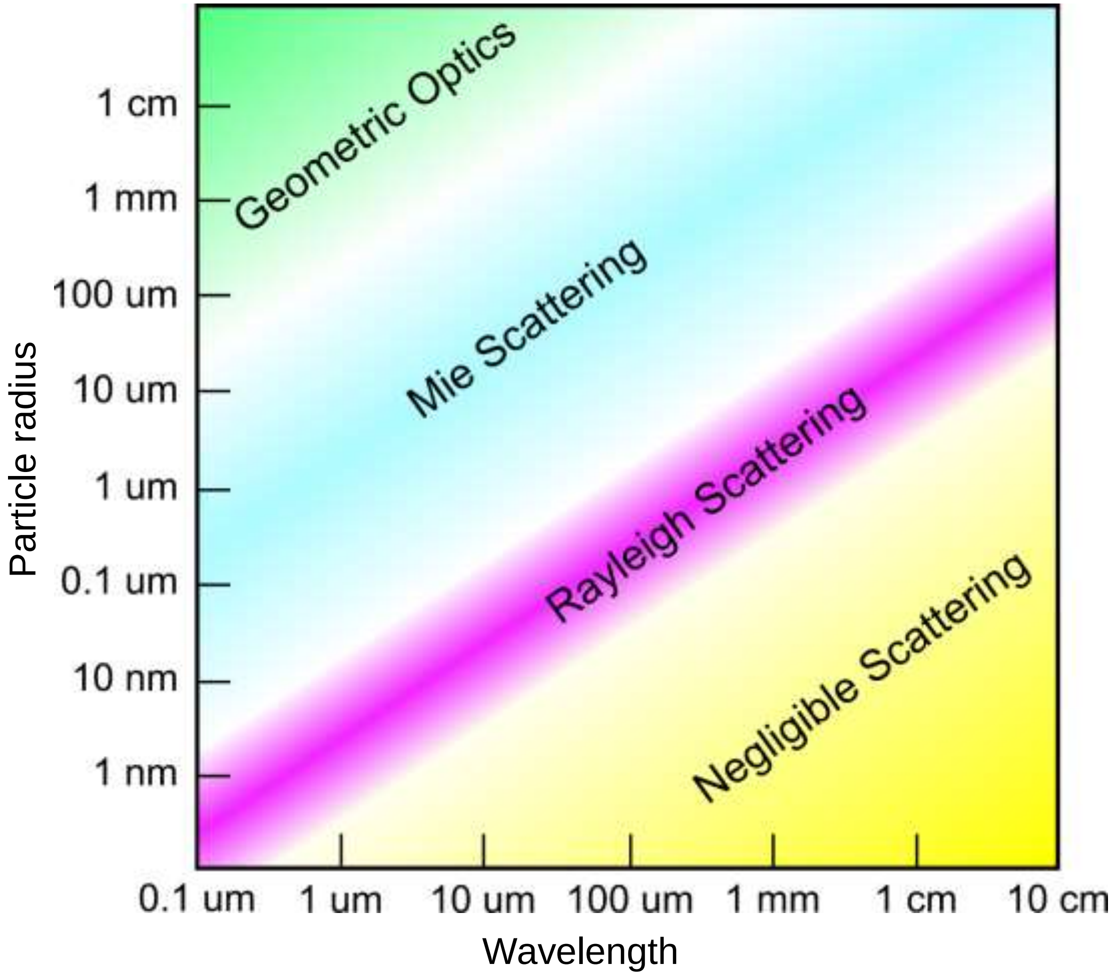
global plane wave
- wavelength: 532 nm
- propagate along *z* direction
- linearly polaried along *x* direction

viewing screen
- xz - plane
- origin: center of sphere



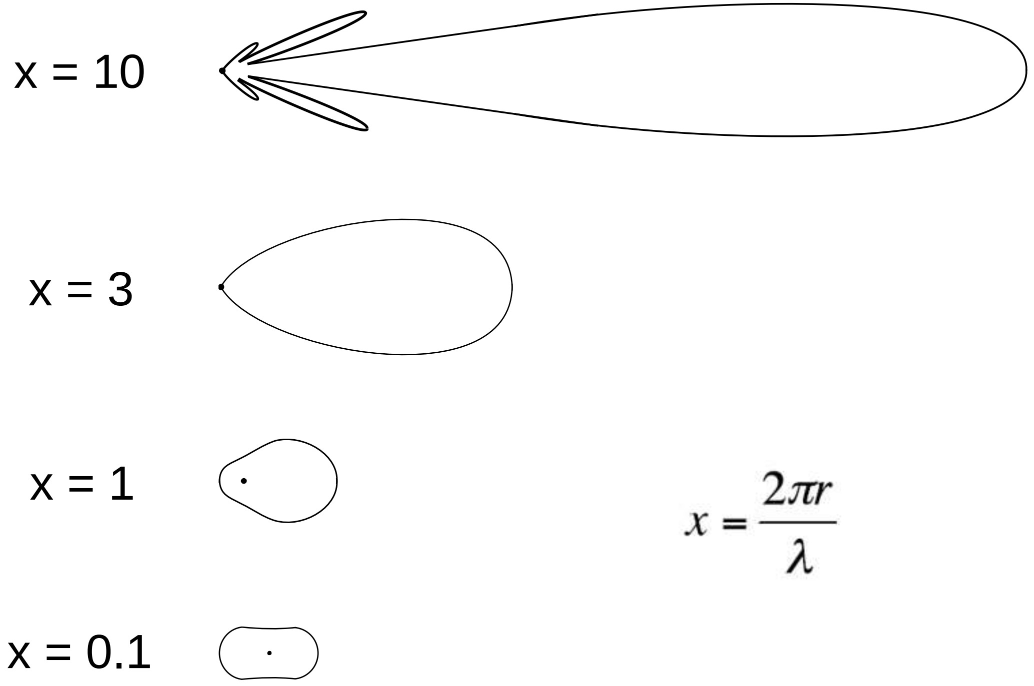
spherical scatterer
- material of sphere: fused siica
- surrounding medium: standard air
- radius of sphere: variable

Classification of Scattering



Scattering phase function

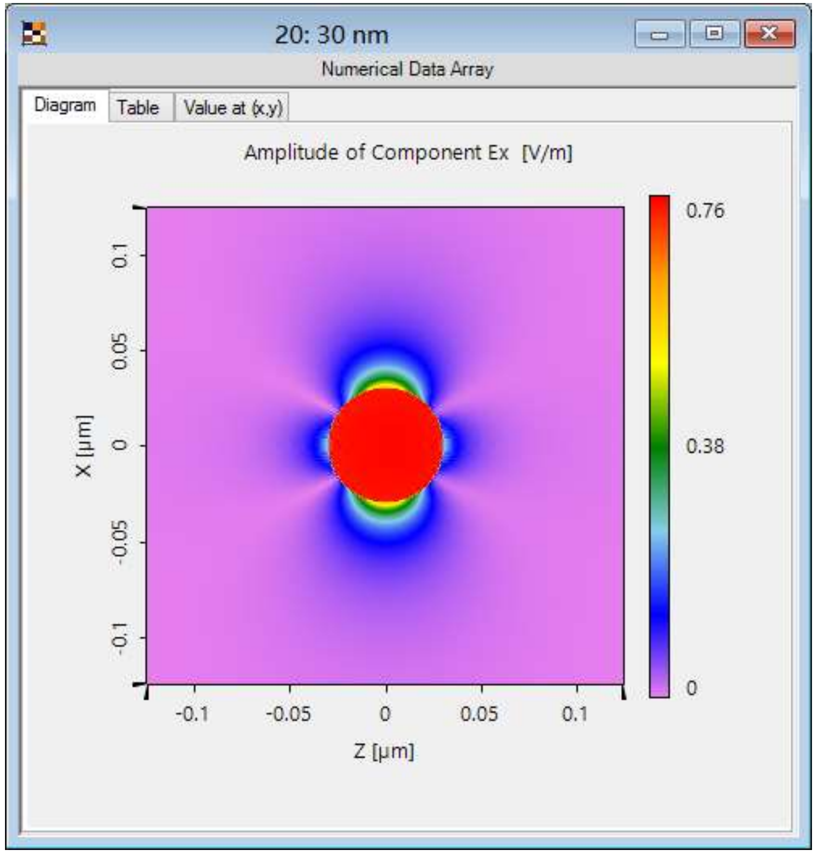
The intensity (radiance) at θ relative to the normalized integral of the scattered intensity at all angles.



$$x = \frac{2\pi r}{\lambda}$$

Rayleigh Scattering

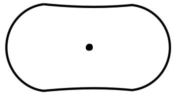
Without incident field



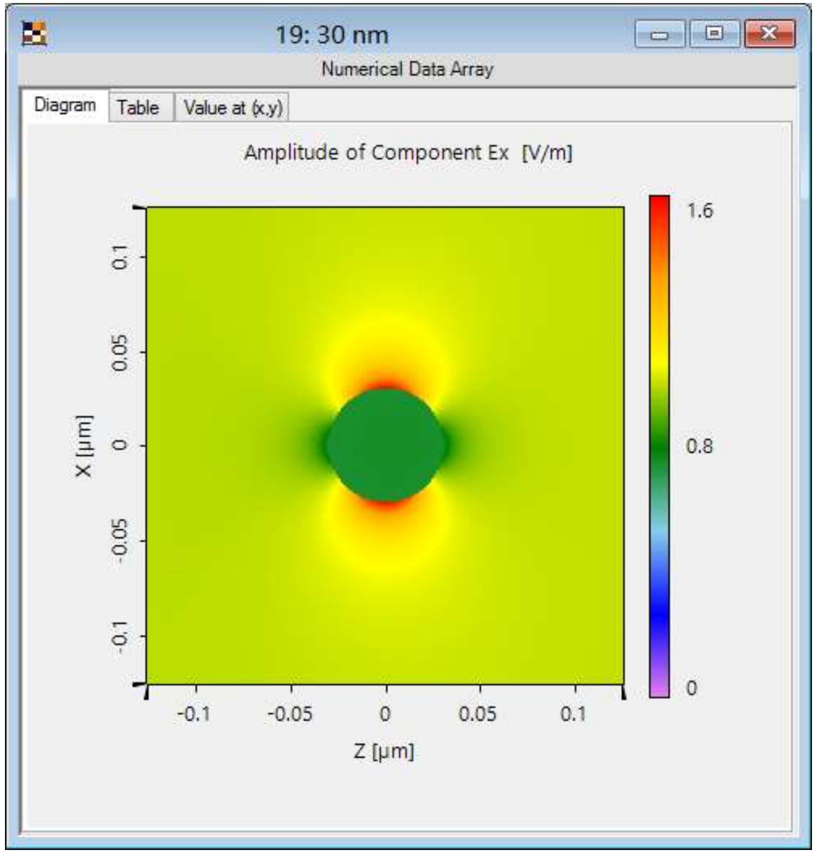
r = 30 nm

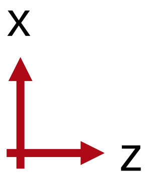
x = 0.35

scattering phase function



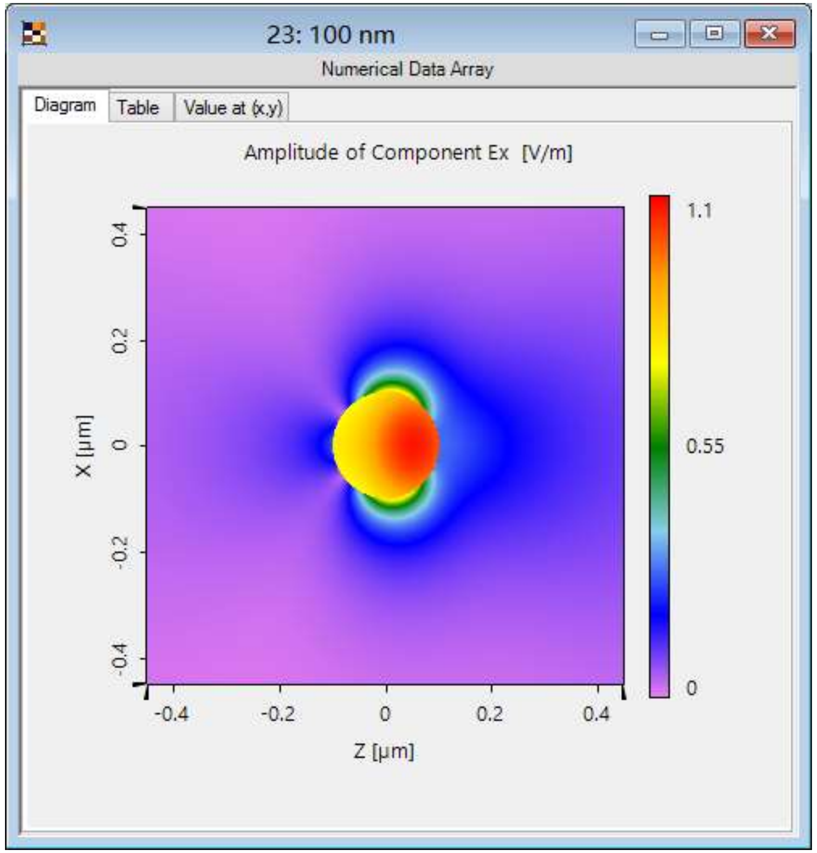
Total field





Rayleigh Scattering ~~ Mie Scattering

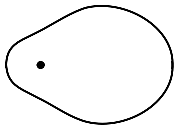
Without incident field



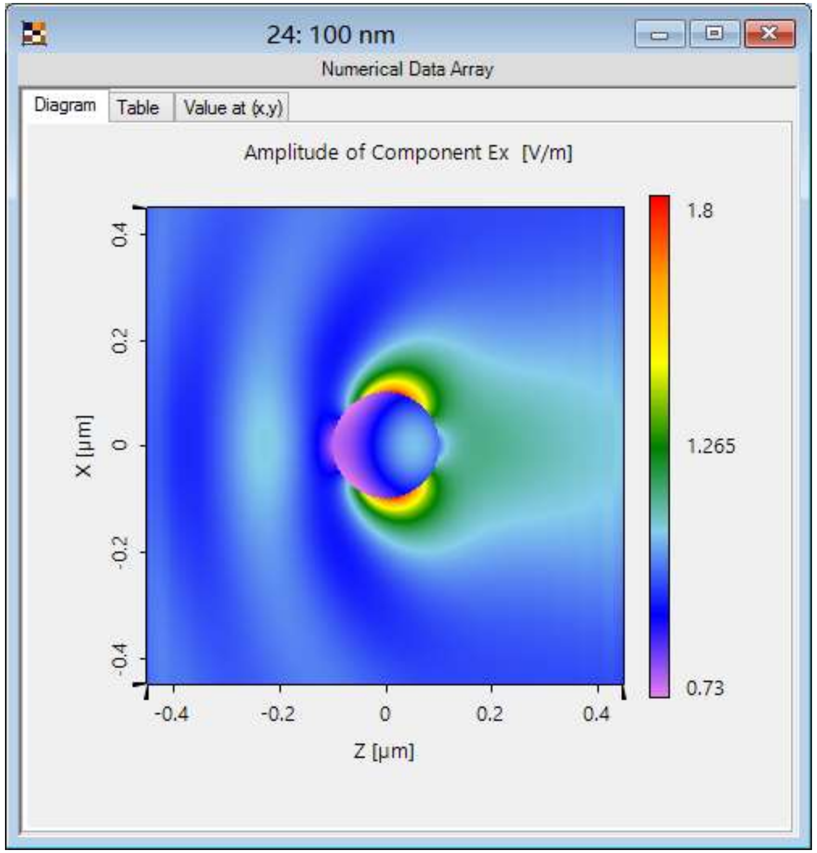
r = 100 nm

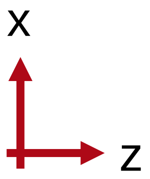
x = 1.18

scattering phase function



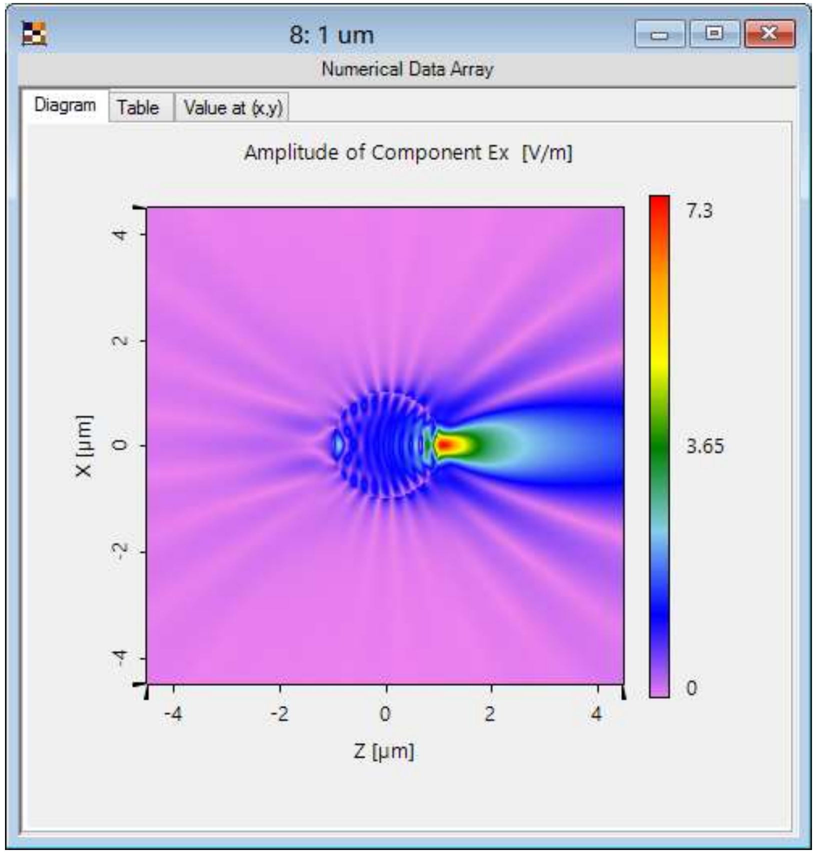
Total field



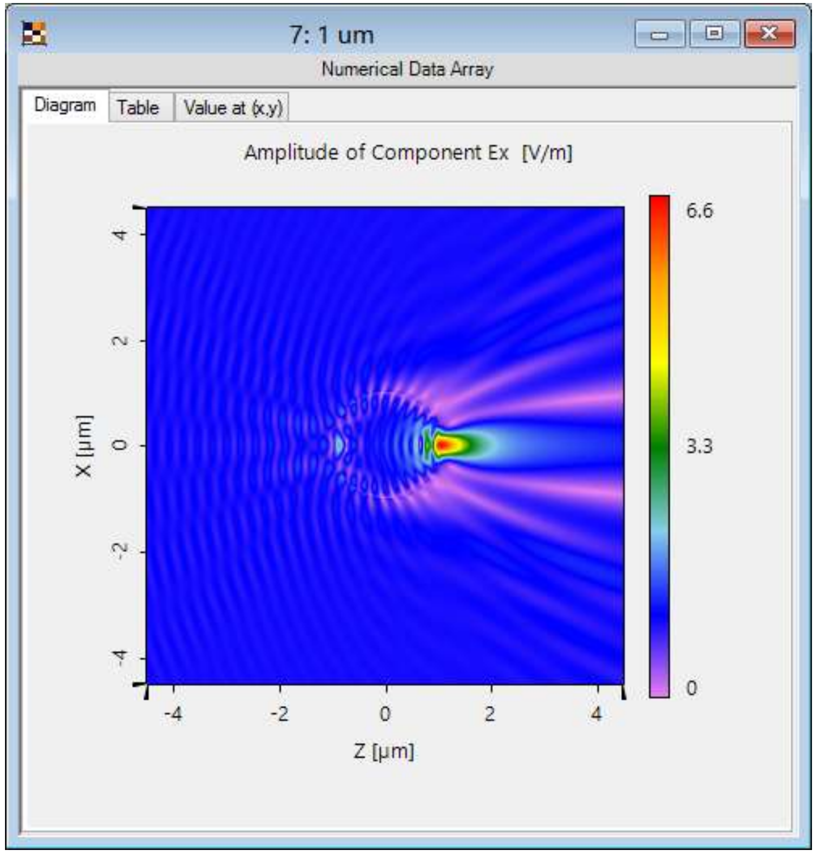


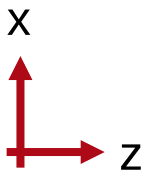
Mie Scattering

Without incident field



Total field

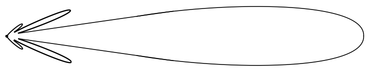




r = 1 um

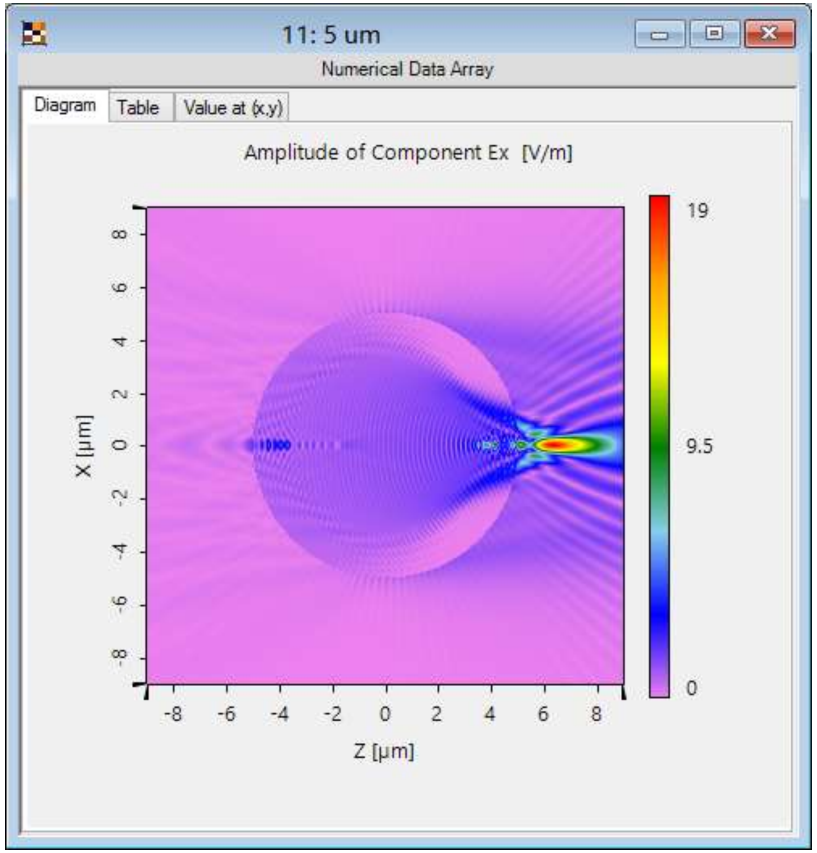
x = 11.8

scattering phase function



Mie Scattering

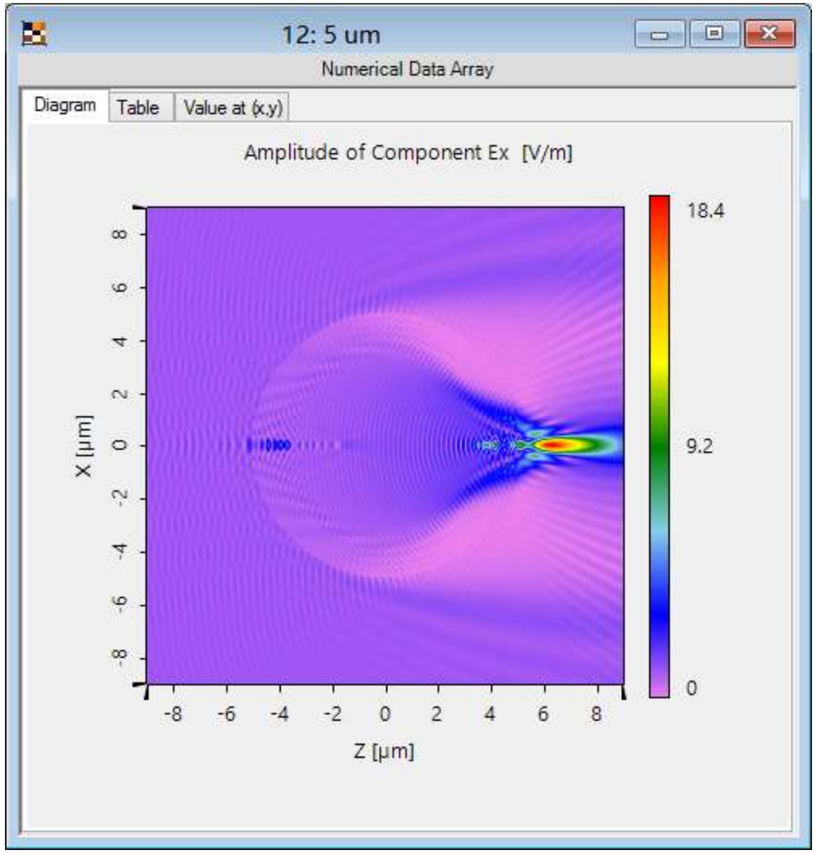
Without incident field

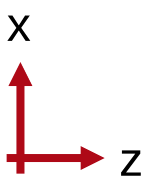


r = 5 um

x = 59

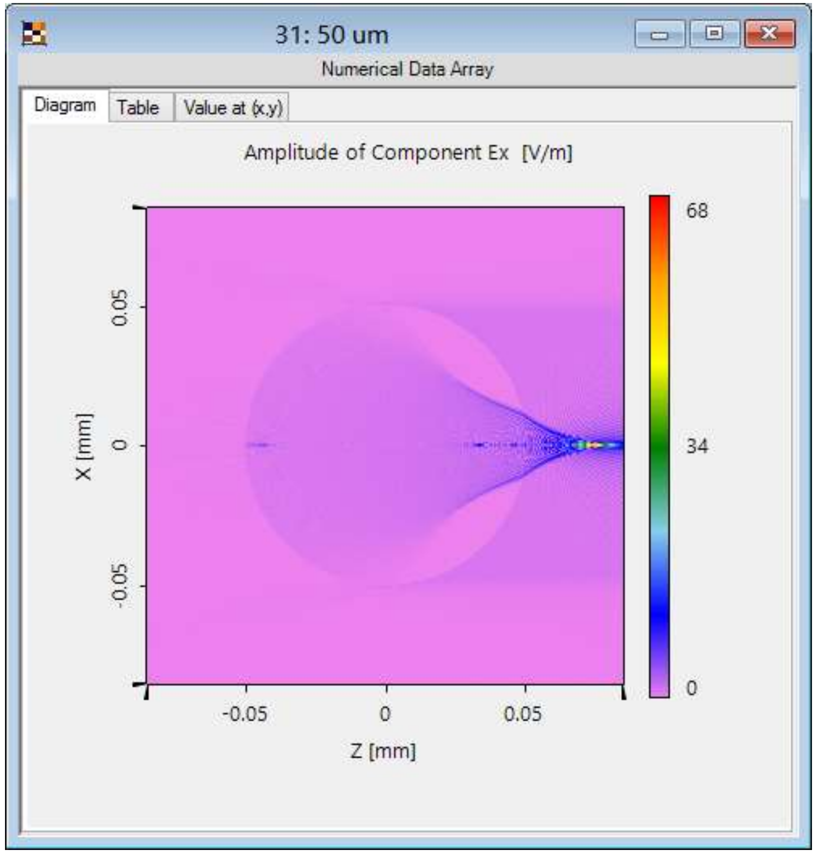
Total field





Geometric Optics

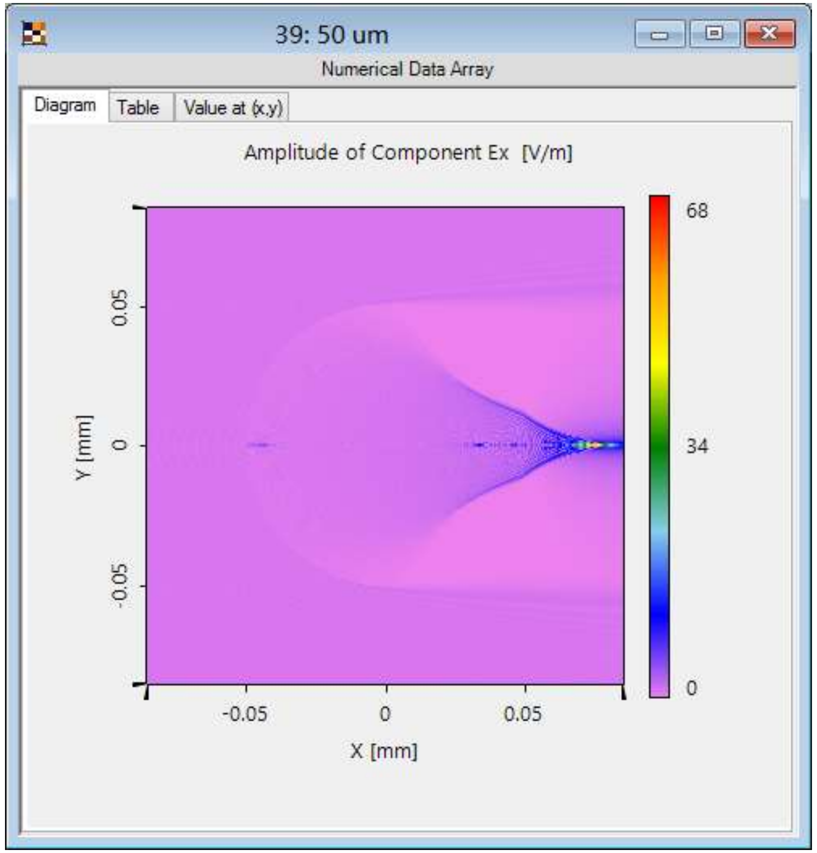
Without incident field

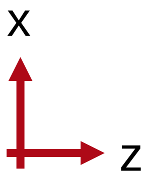


r = 50 um

x = 590

Total field





Examplary Evaluations: Computational Time

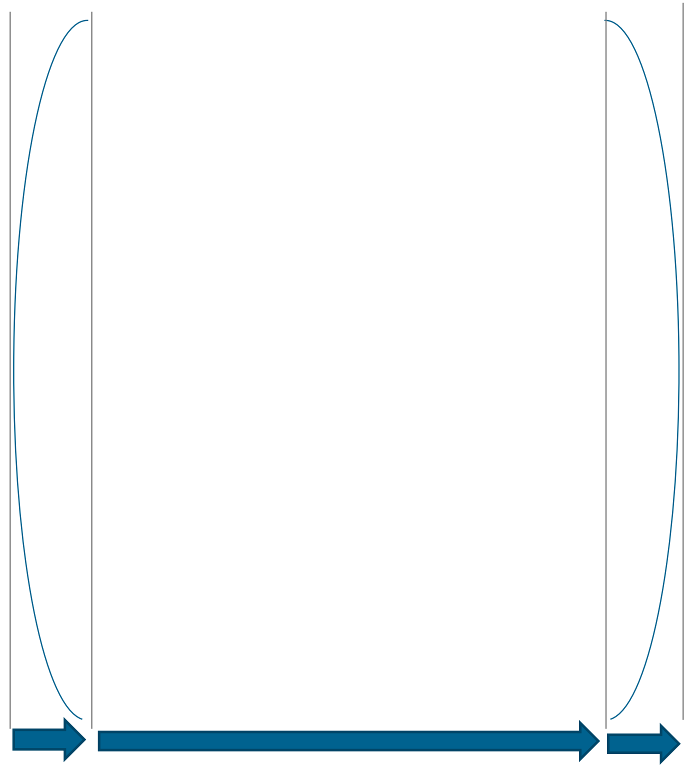
Sampling Points (SP) X × Y	Considered Number of Orders (Nt)(*)	Time
2000 × 2000	2200	?
1000 × 1000	1150	4d10h
2000 × 2000	150	1d 14h 40m
1000 × 1000	125	7h12m
1000 × 1000	80	2h 50m
1000 × 1000	30	21m
1000 × 1000	10	8m11s

(*) number of considered orders necessary for accurate computation: numerical effort is proportional to

For large spheres, Mie theory is numerically time consuming.
For lenses without high symmetry, Mie theory is not valid.

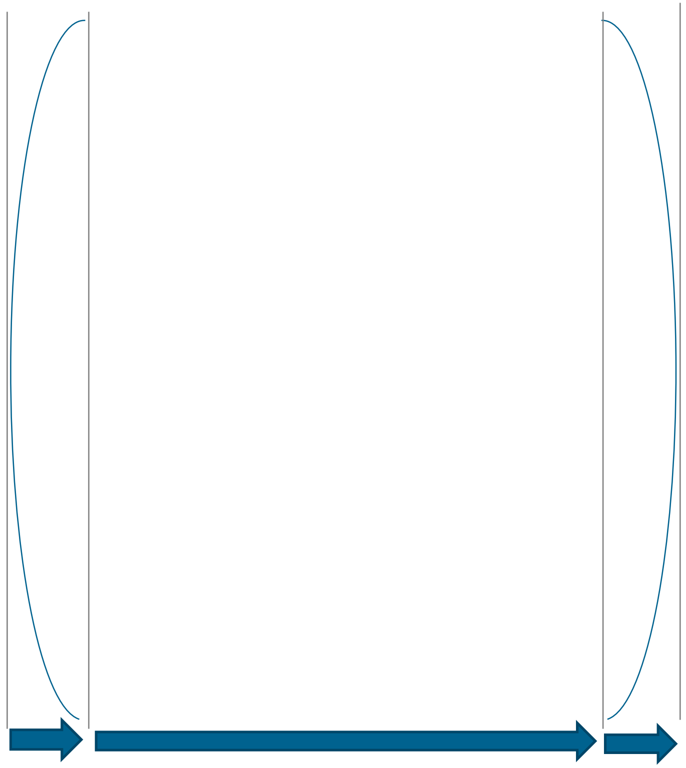
Further Tearing

1. Field propagation through a curved surface
2. Free space propagation
3. Field propagation through a curved surface
4. Further non-sequentially propagation

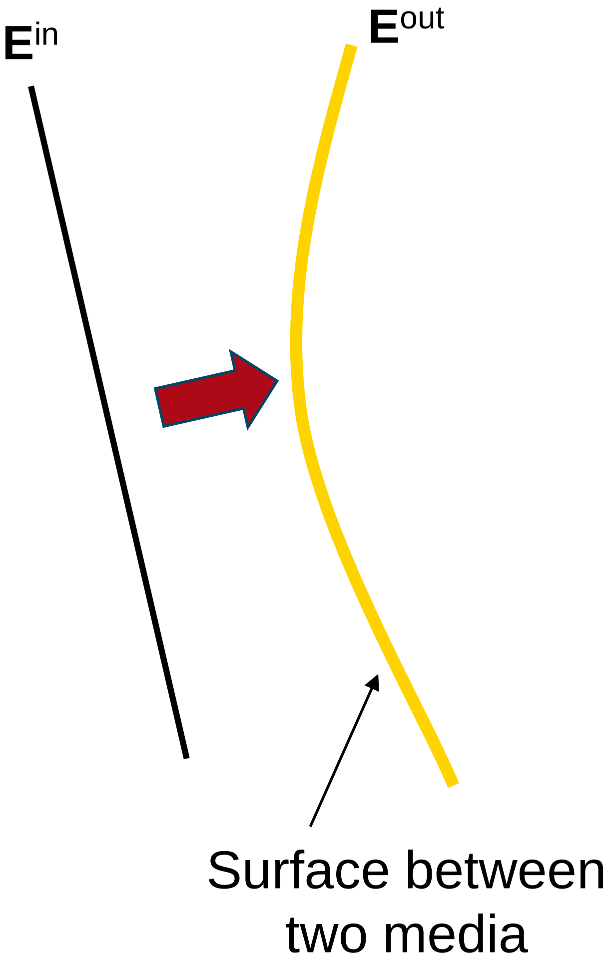


Further Tearing

1. Field propagation through a curved surface
2. Free space propagation
3. Field propagation through a curved surface
4. Further non-sequentially propagation



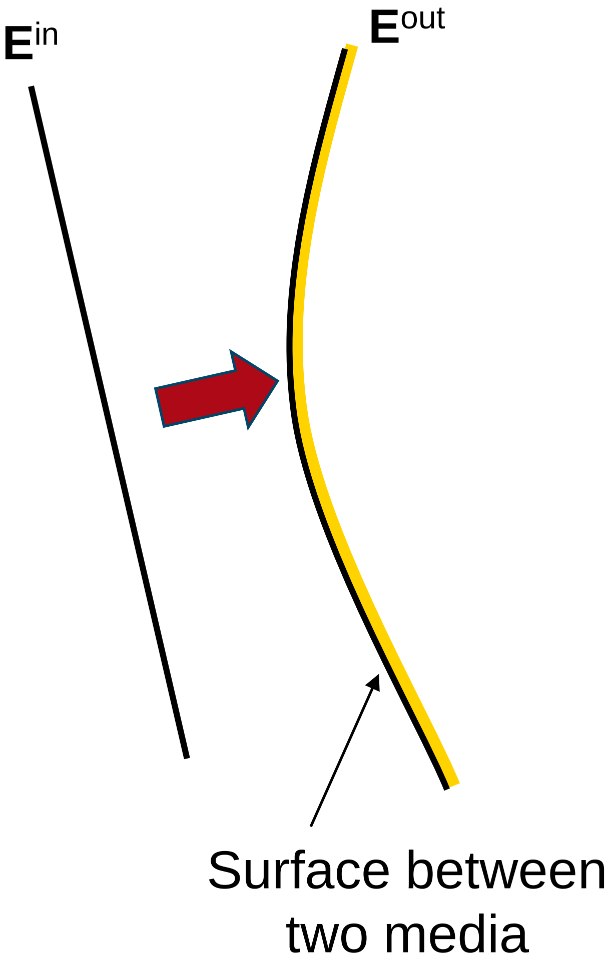
Local Plane Interface Approximation (LPIA)



- Field is propagated onto the surface.

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

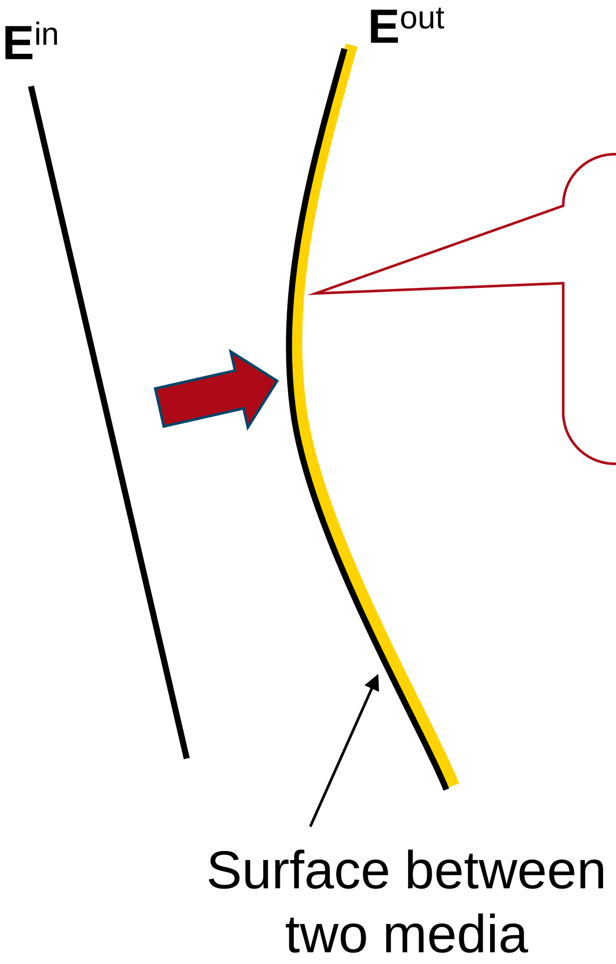
Local Plane Interface Approximation (LPIA)



- Field is propagated onto the surface.
- Response is obtained by local satisfaction of boundary condition.

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

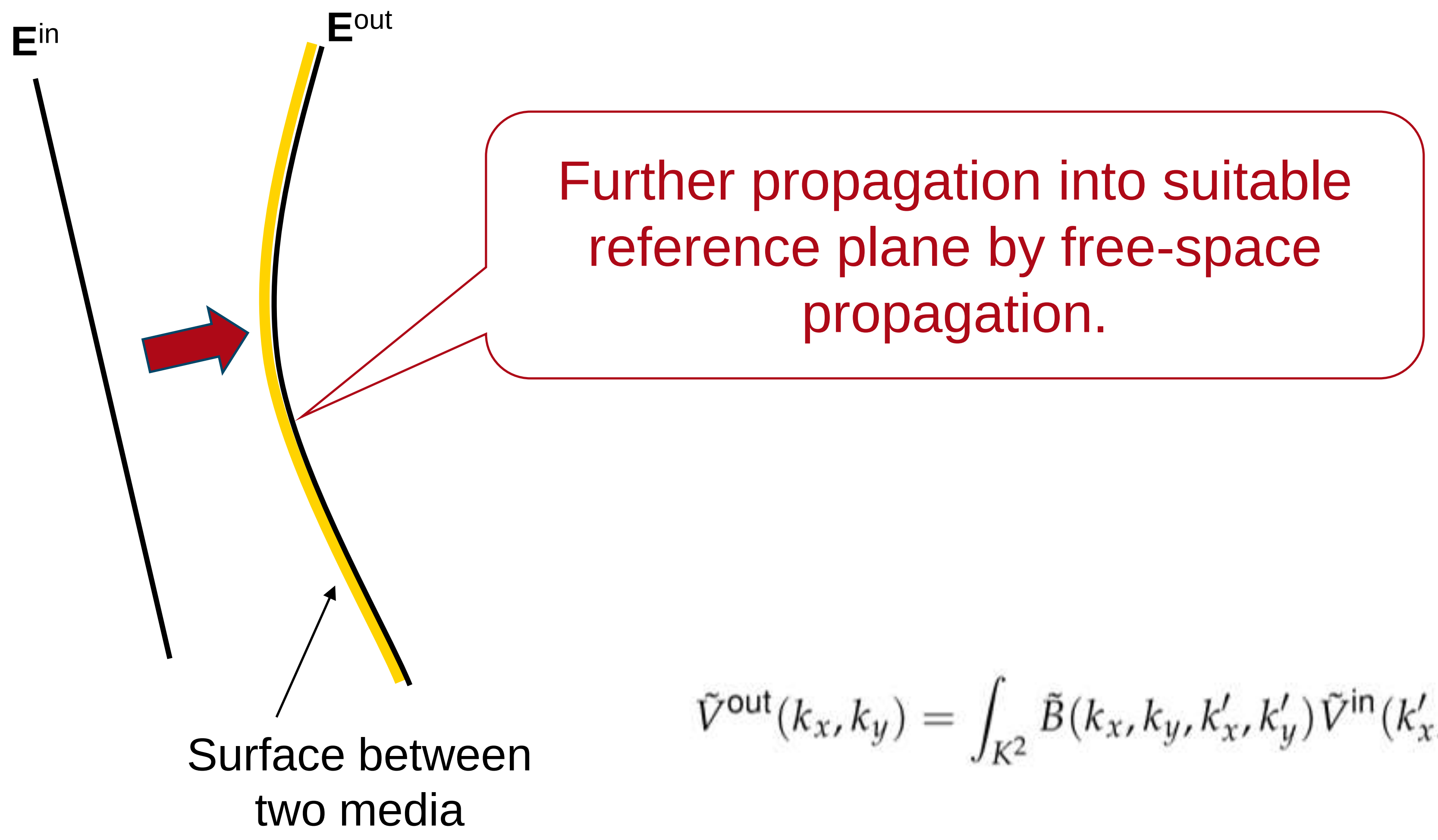
Local Plane Interface Approximation (LPIA)



LPIA: Local satisfaction of boundary condition under the assumption of local plane waves and **local plane interface.**

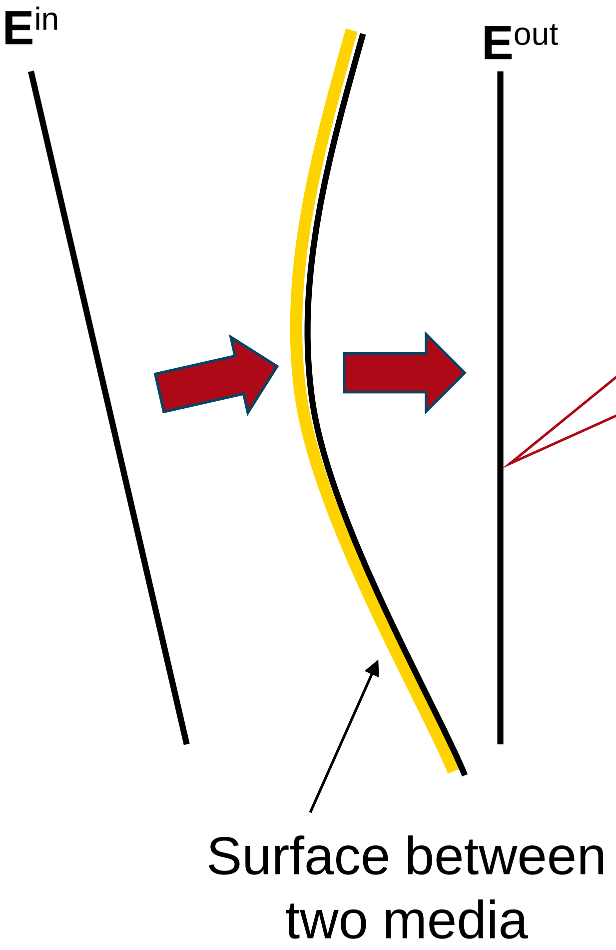
$$\tilde{V}^{\text{out}}(k_x, k_y) = \int_{K^2} \tilde{B}(k_x, k_y, k'_x, k'_y)\, \tilde{V}^{\text{in}}(k'_x, k'_y)\, \mathrm{d}k'_x\, \mathrm{d}k'_y$$

Local Plane Interface Approximation (LPIA)



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

Local Plane Interface Approximation + Propagation

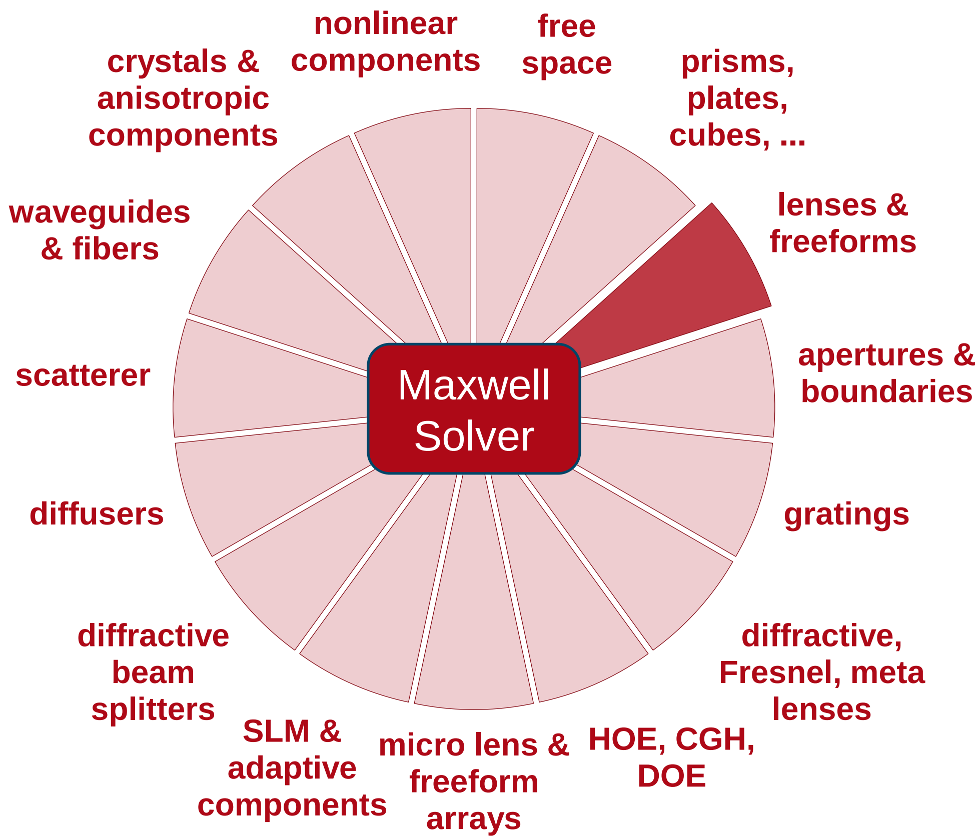


Further propagation into suitable reference plane by free-space propagation.

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

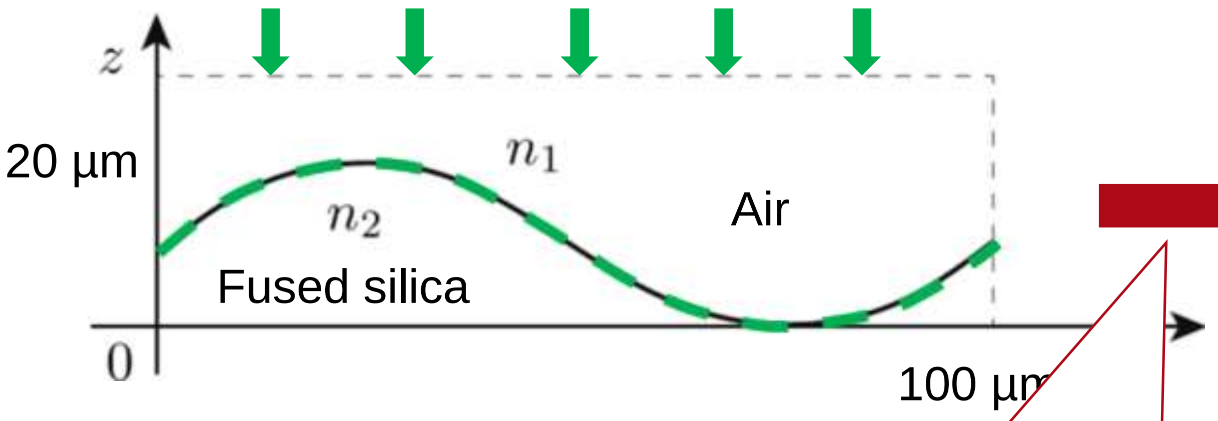
Lenses, Freeforms and Any Components with Curved Surfaces

- Rigorous operator for spherical surfaces (Mie theorie).
- Local Plane Interface Approximation: Propagation through curved surfaces by local satisfaction of boundary condition between different media.
- **Very reliable and fast technique for smooth surfaces.**

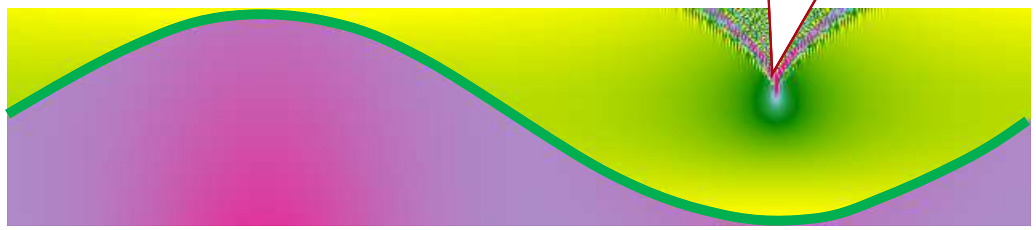


Simulations: Transmitted Field On Surface (TE polarized)

High NA focus!

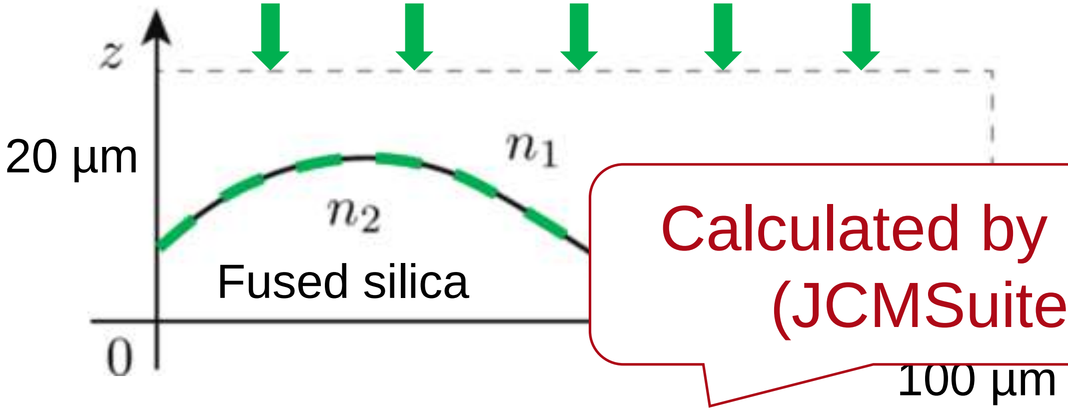


Field inside



Calculated by FEM (JCMSuite)

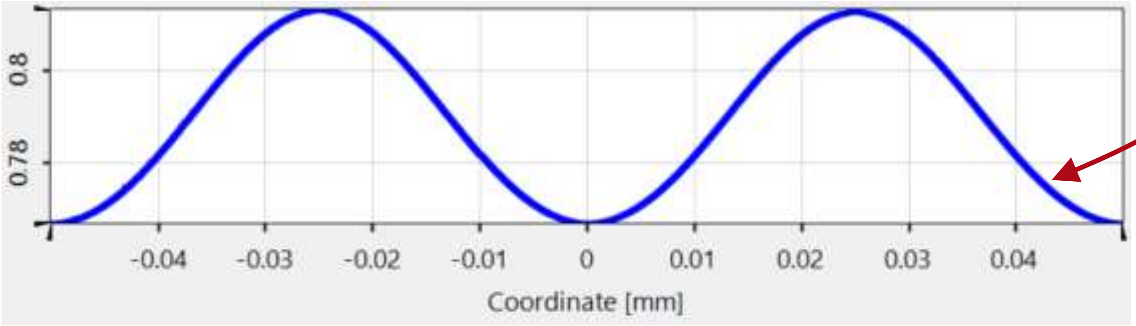
Simulations: Transmitted Field On Surface (TE polarized)



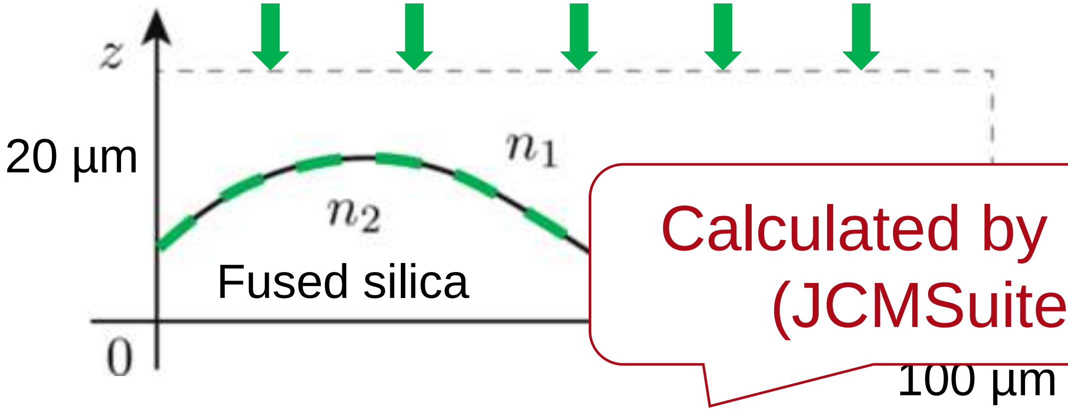
Calculated by FEM (JCMSuite)

Field on interface: Rigoros

Field inside

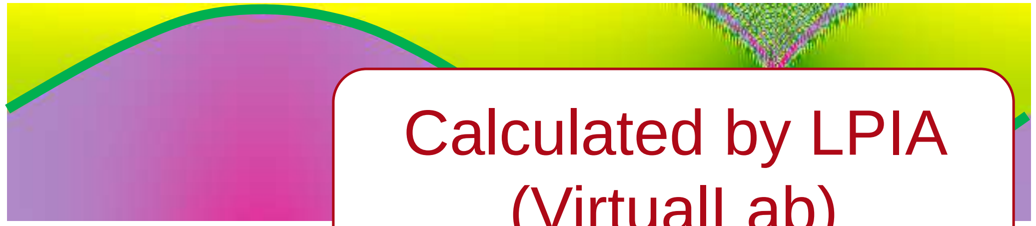


Simulations: Transmitted Field On Surface (TE polarized)



Calculated by FEM (JCMSuite)

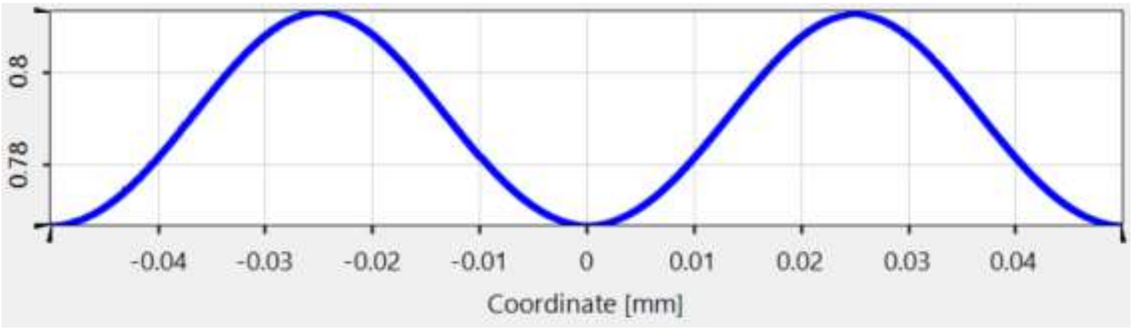
Field inside

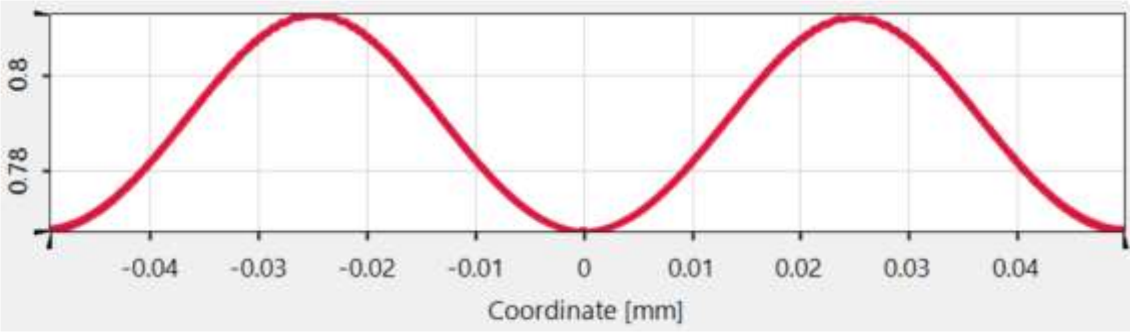


Calculated by LPIA (VirtualLab)

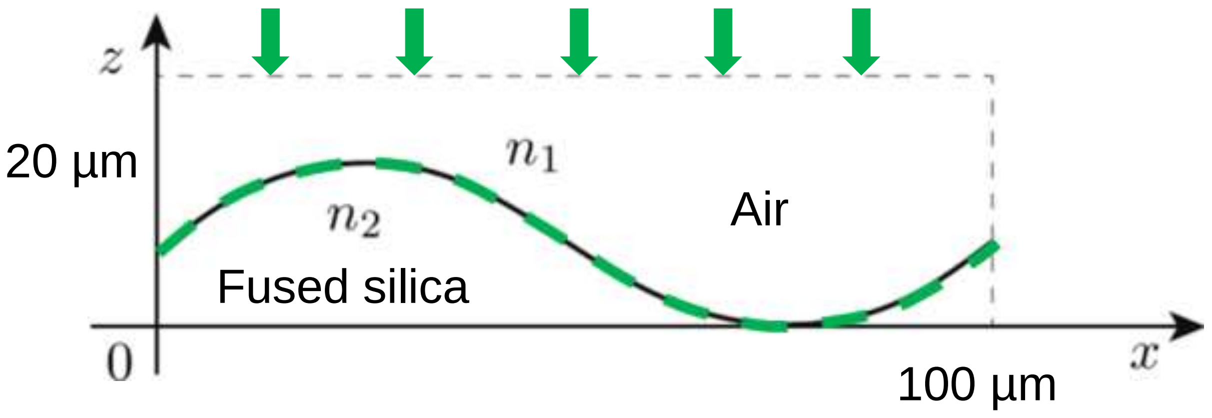
Field on interface: Rigoros

Field on interface: LPIA

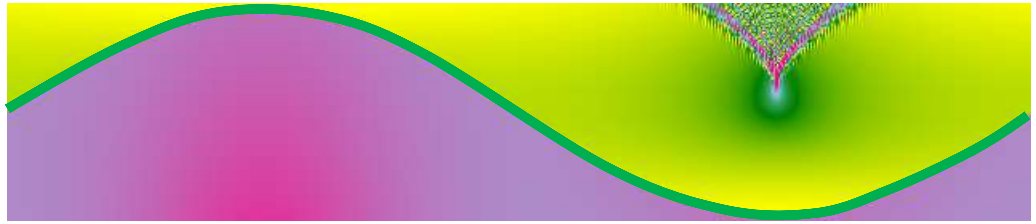




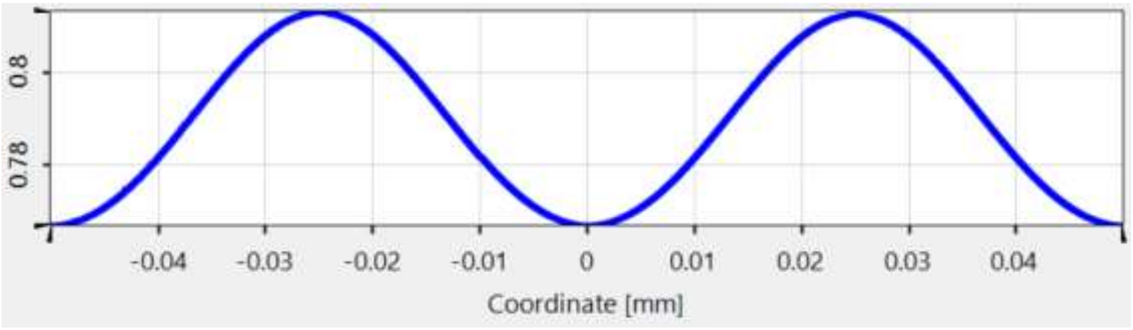
Simulations: Transmitted Field On Surface (TE polarized)



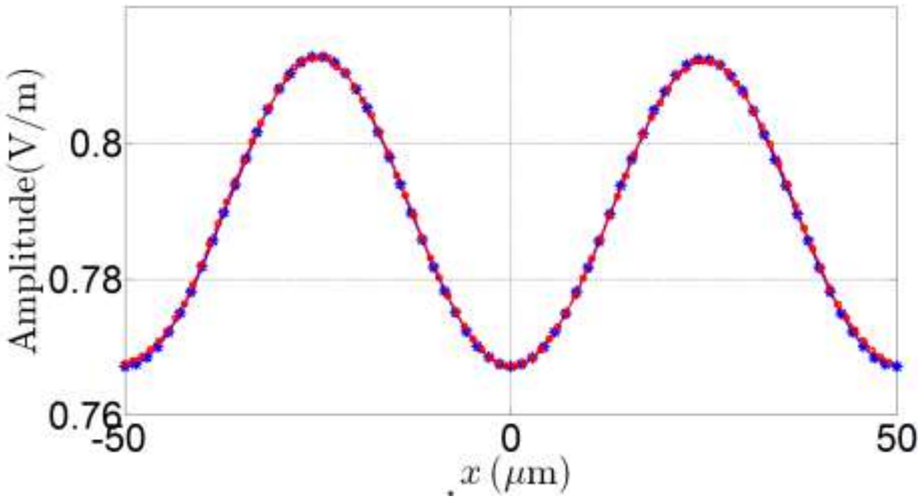
Field inside



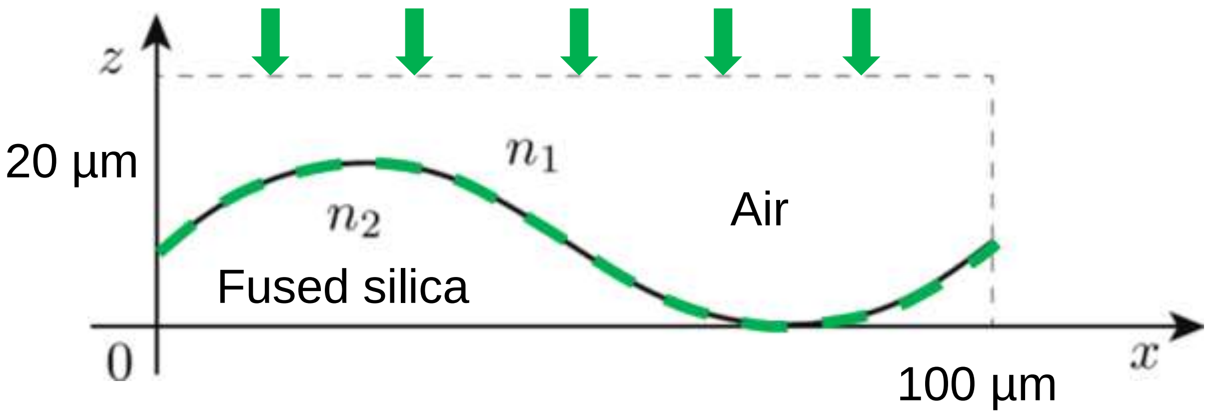
Field on interface: Rigoros



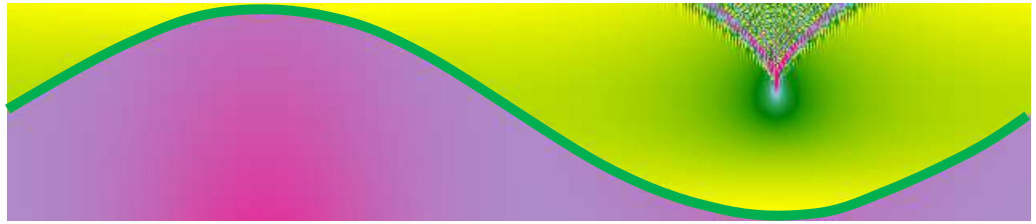
Field on interface: Comparison



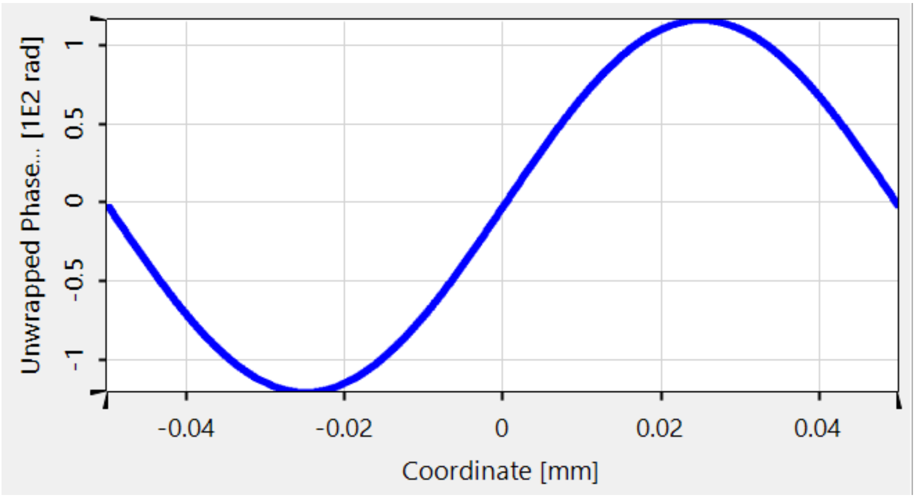
Simulations: Transmitted Phase On Surface (TE polarized)



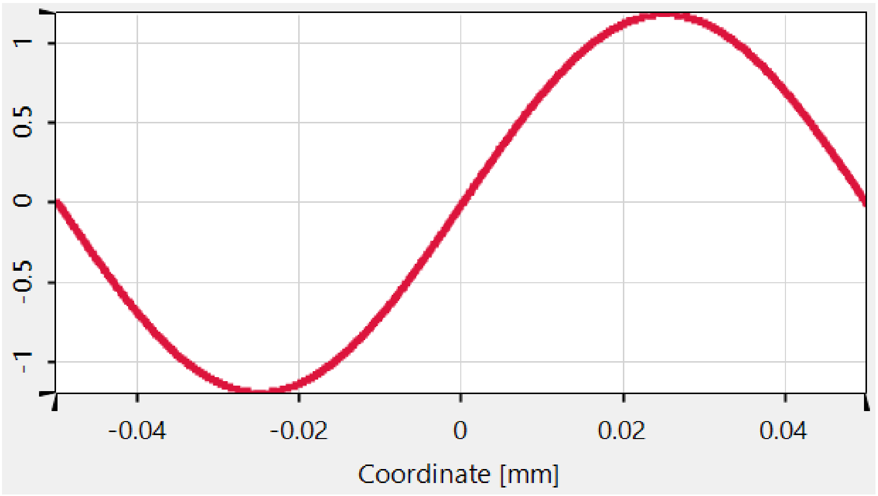
Field inside



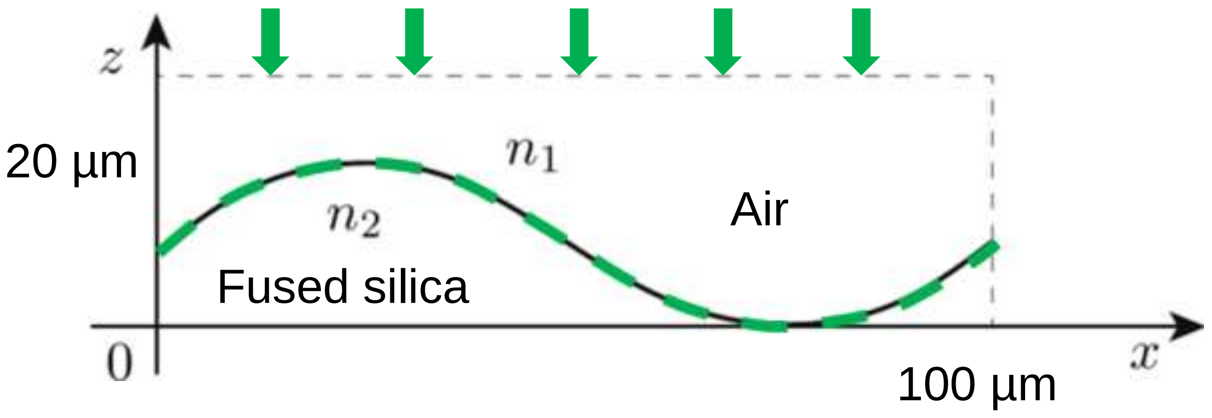
Phase on interface: Rigoros



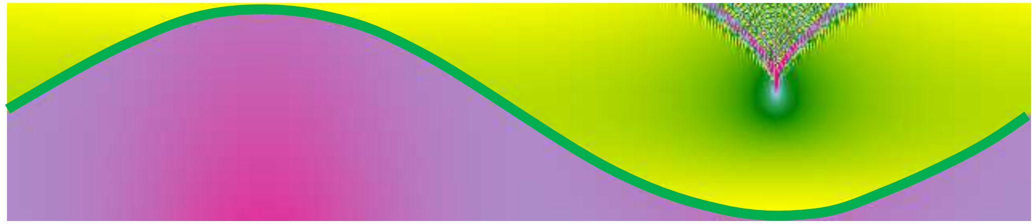
Phase on interface: LPIA



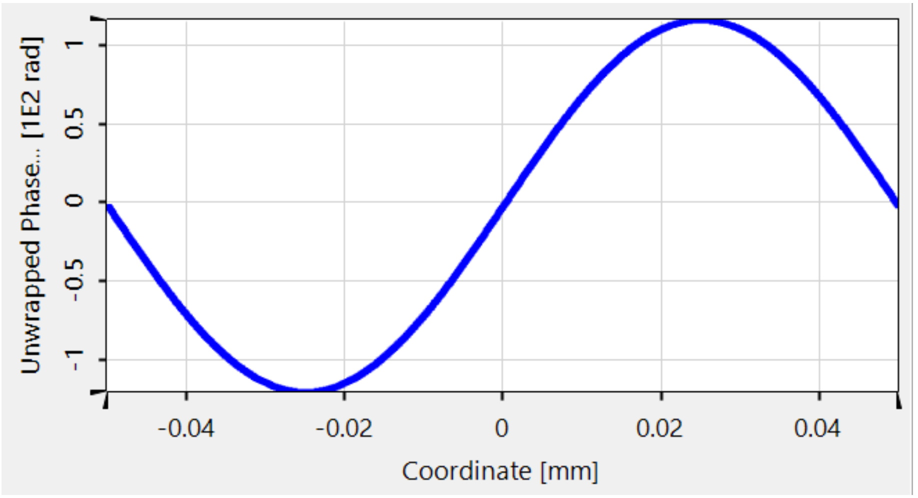
Simulations: Transmitted Phase On Surface (TE polarized)



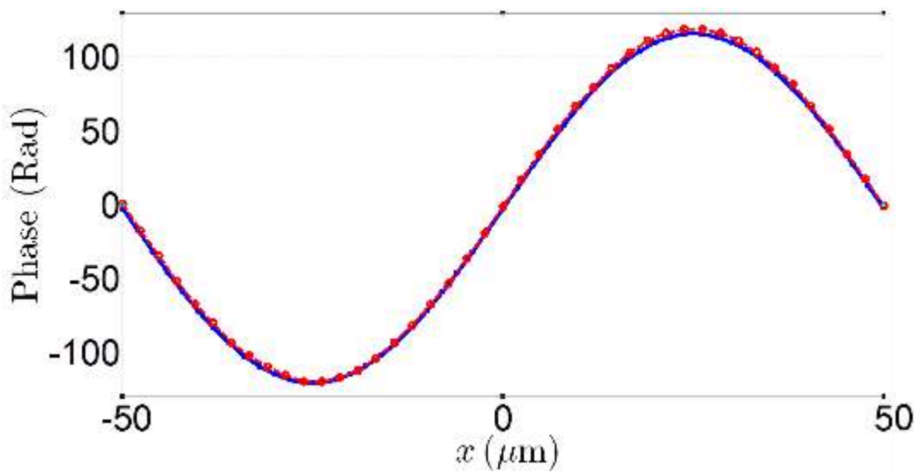
Field inside



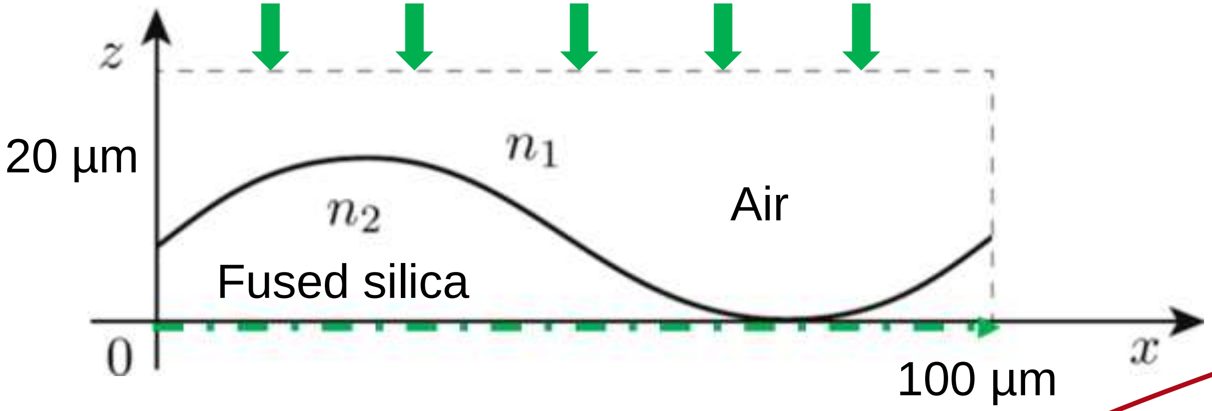
Phase on interface: Rigoros



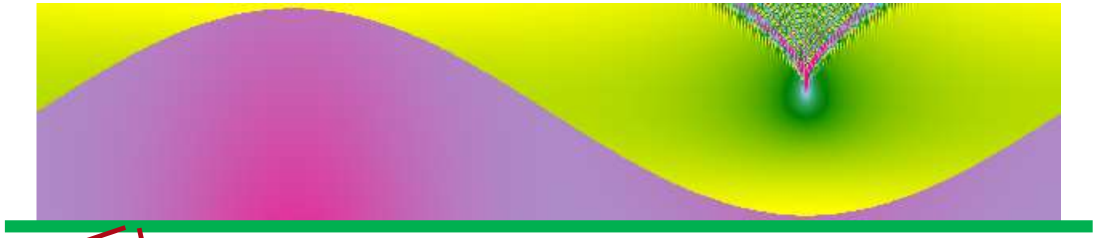
Phase on interface: Comparison



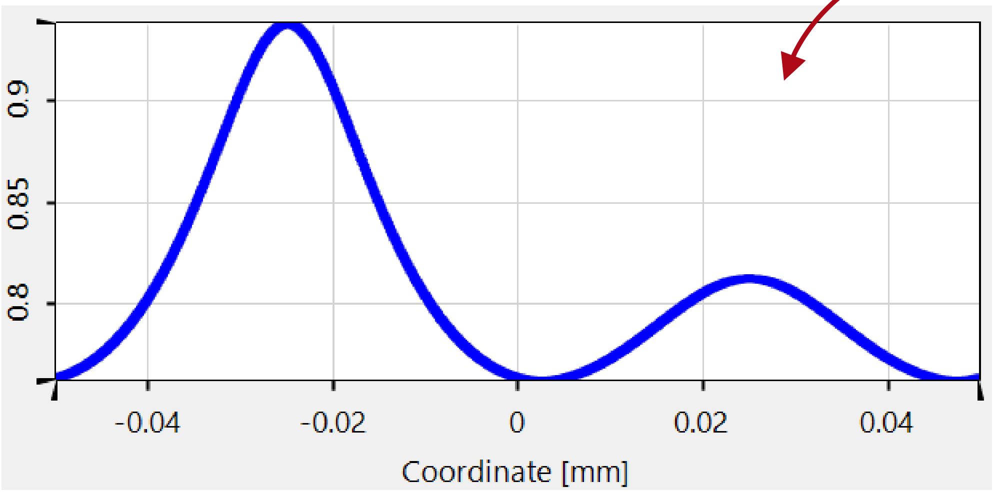
Simulations: Transmitted Field Propagated (TE polarized)



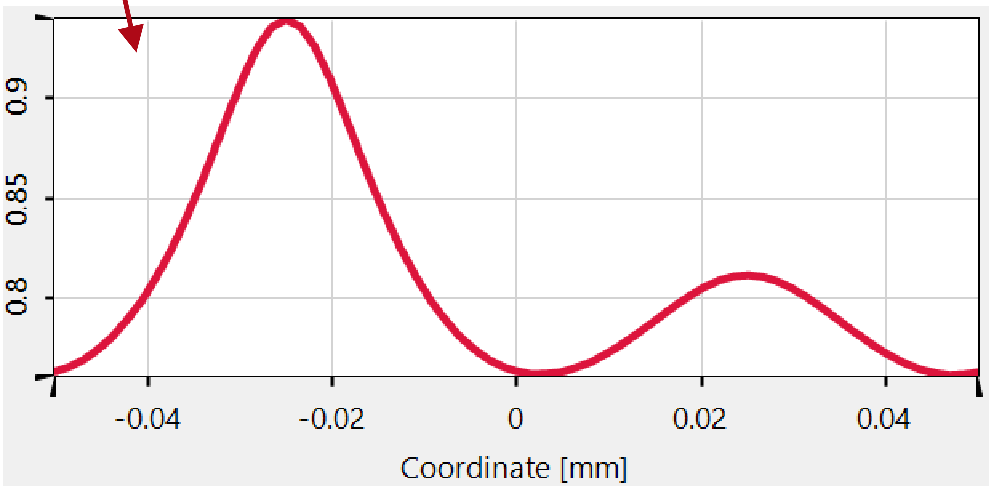
Field inside



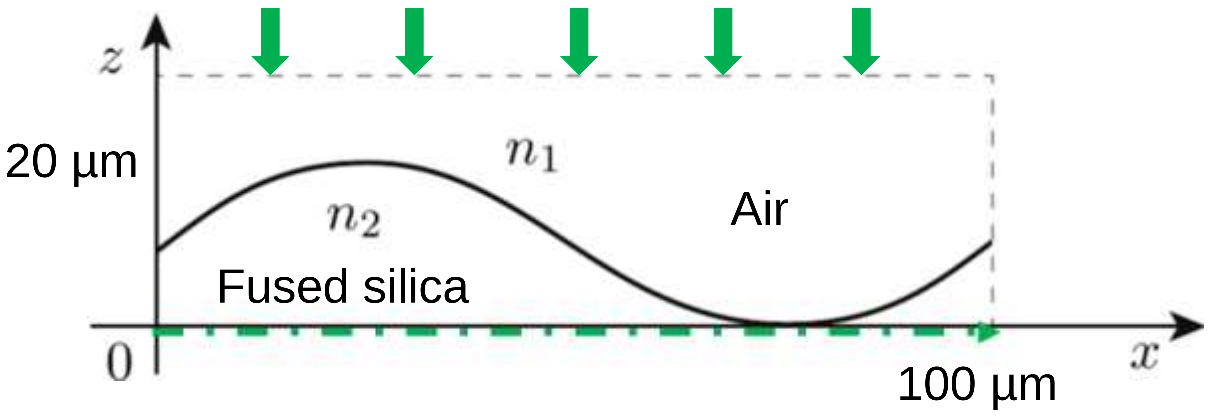
Field propagated: Rigoros



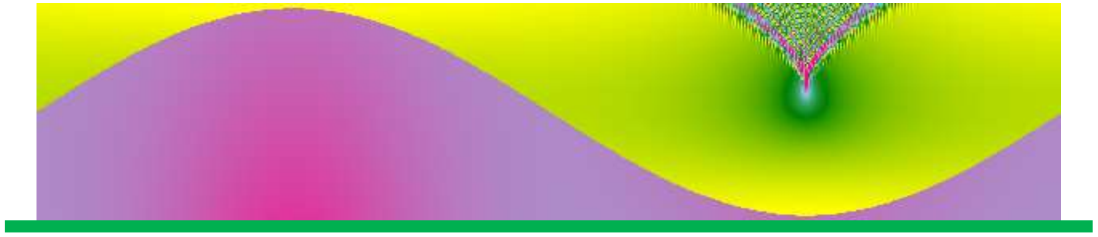
Field propagated: LPIA + Propagation



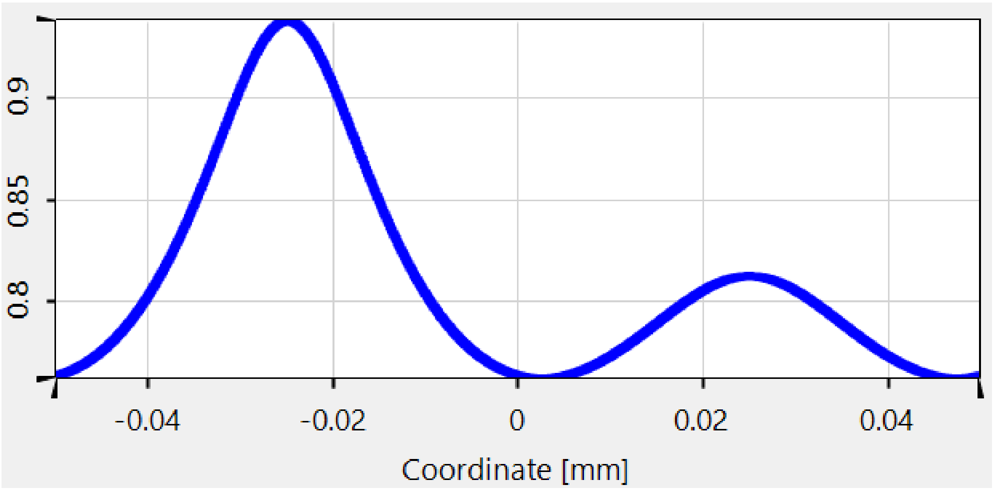
Simulations: Transmitted Field Propagated (TE polarized)



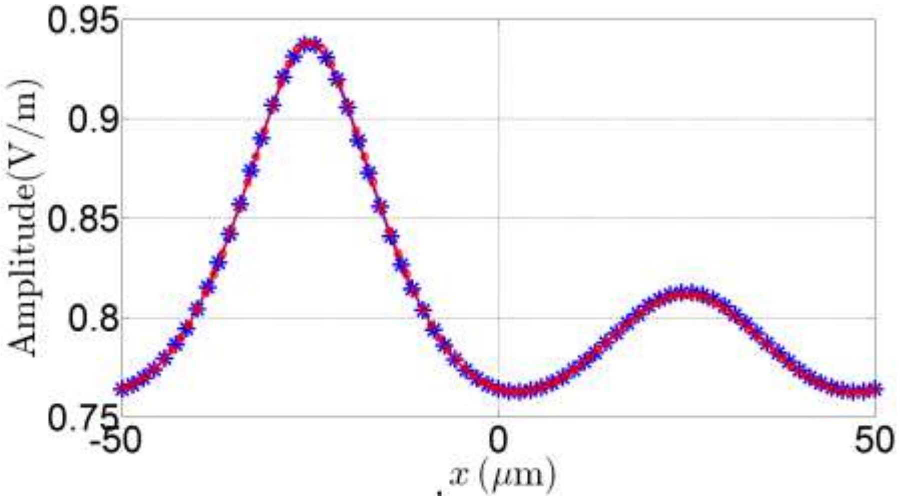
Field inside



Field propagated: Rigoros

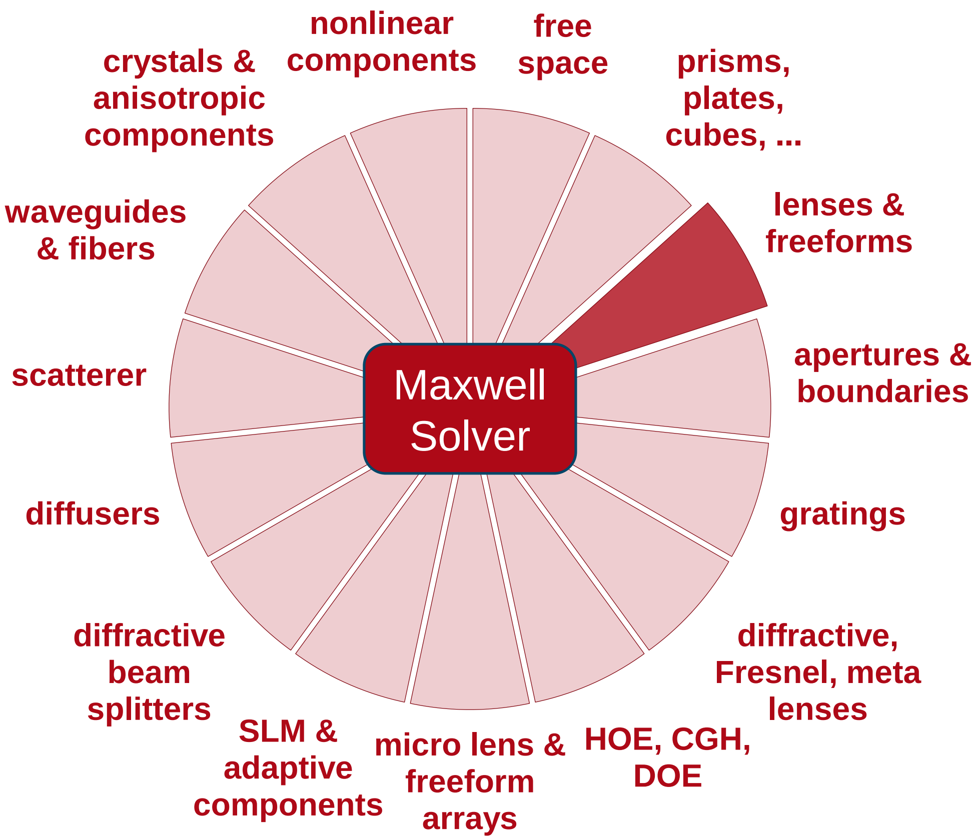


Field propagated: Comparison

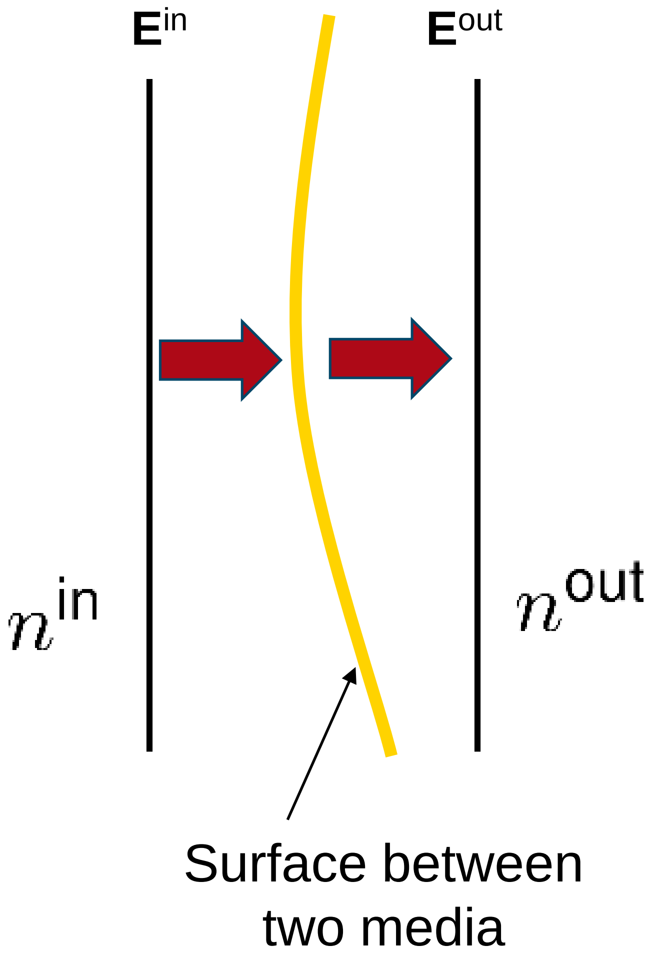


Lenses, Freeforms and Any Components with Curved Surfaces

- Rigorous operator for spherical surfaces (Mie theorie).
- Local Plane Interface Approximation: Propagation through curved surfaces by local satisfaction of boundary condition between different media.
- **Very reliable and fast technique for smooth surfaces.**
- Special case: Thin Element Approximation (TEA) (Standard in paraxial, Fourier, and laser optics).



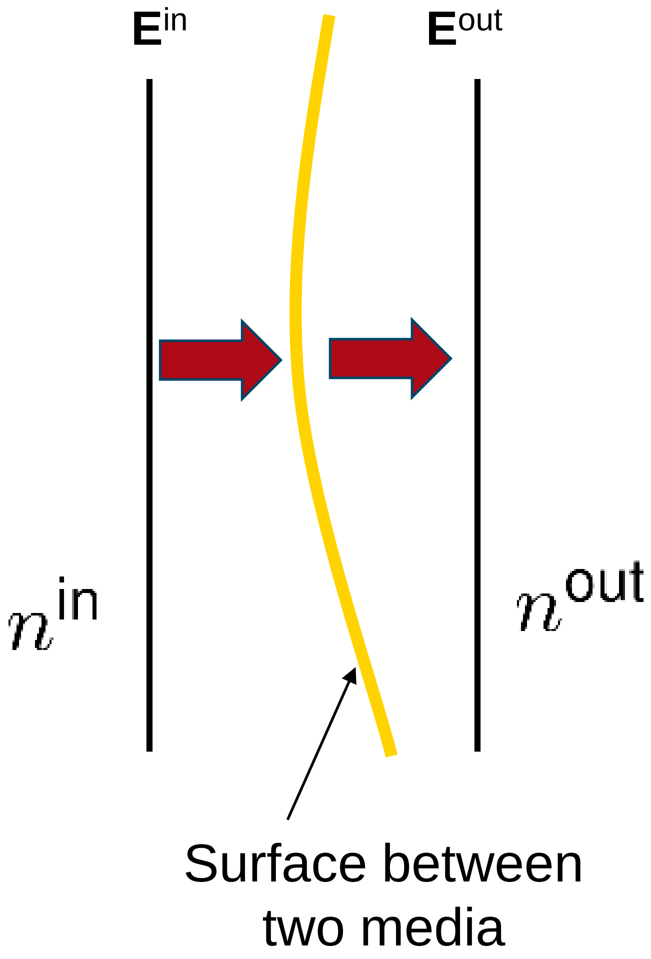
Thin Element Approximation



- In paraxial optics the local deflection at the surface by refraction is neglected.
- Then just the optical path length is considered and a phase term proportional to the height profile is obtained.

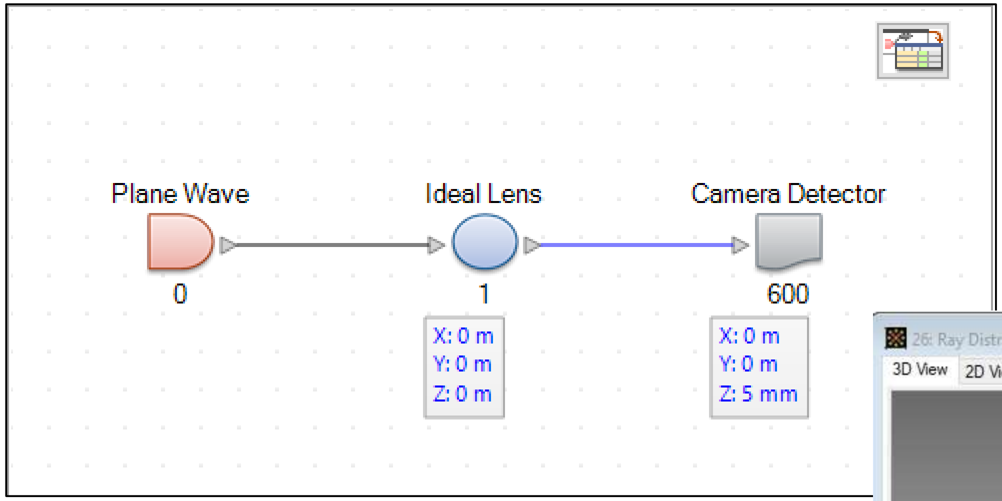
$$\Delta\phi(\boldsymbol{\rho}) = h(\boldsymbol{\rho})\frac{2\pi(n^{\text{in}} - n^{\text{out}})}{\lambda}$$

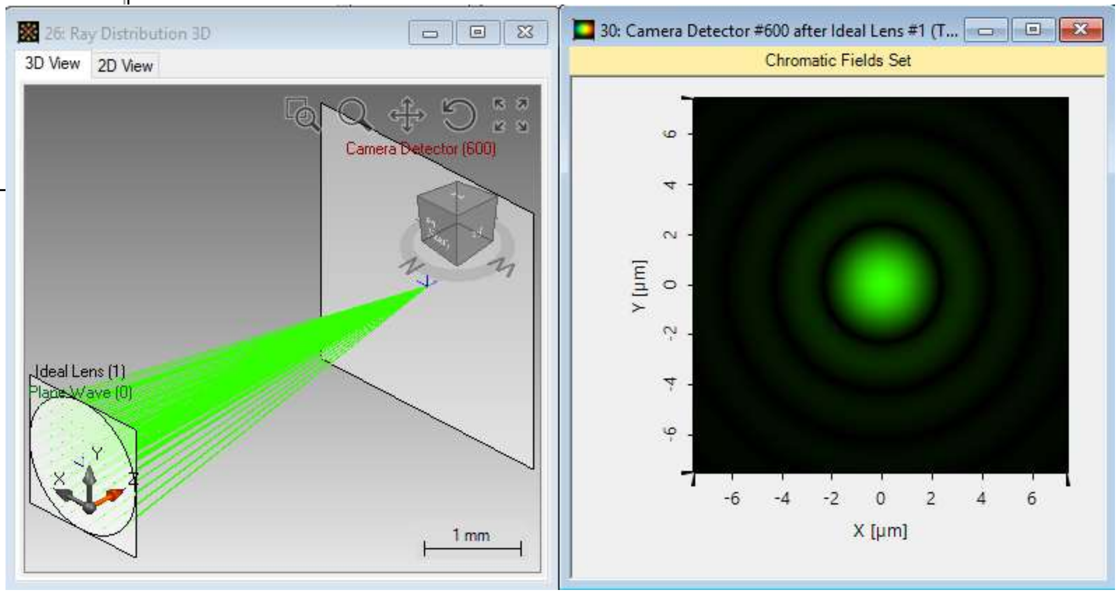
Thin Element Approximation



- In paraxial optics the local deflection at the surface by refraction is neglected.
- Then just the optical path length is considered and a phase term proportional to the height profile is obtained.
- That is the thin element approximation (TEA) frequently used in paraxial optics, e.g. Fourier and laser optics.
- Together with Fresnel integral for free-space propagation the Collins integral follows for lens systems.

Illustration 5: Airy Pattern (Optional)





Show features:

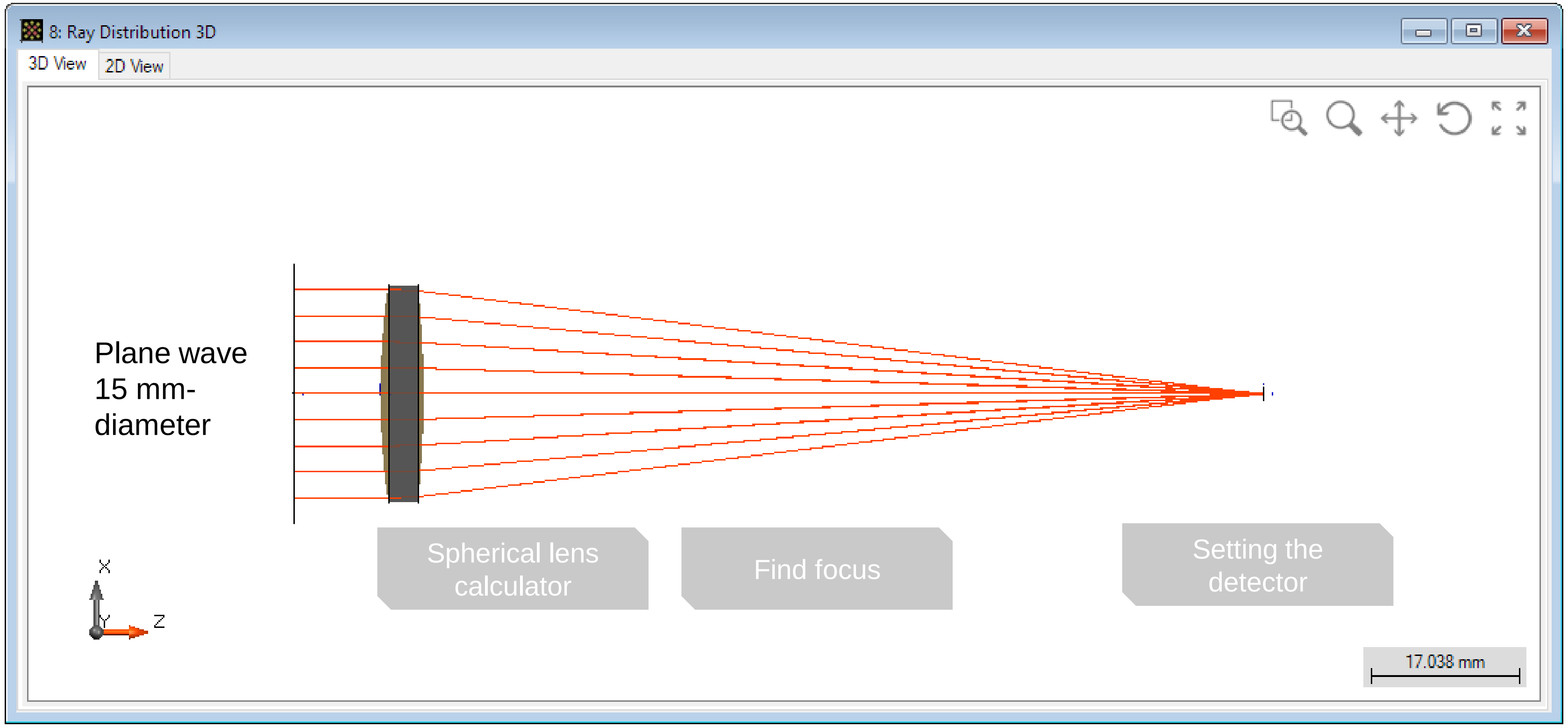
1. Parameters coupling (focal length and distance between lens and camera detector)
2. Parameter run

Physical effect:

NA increase, spot size decrease

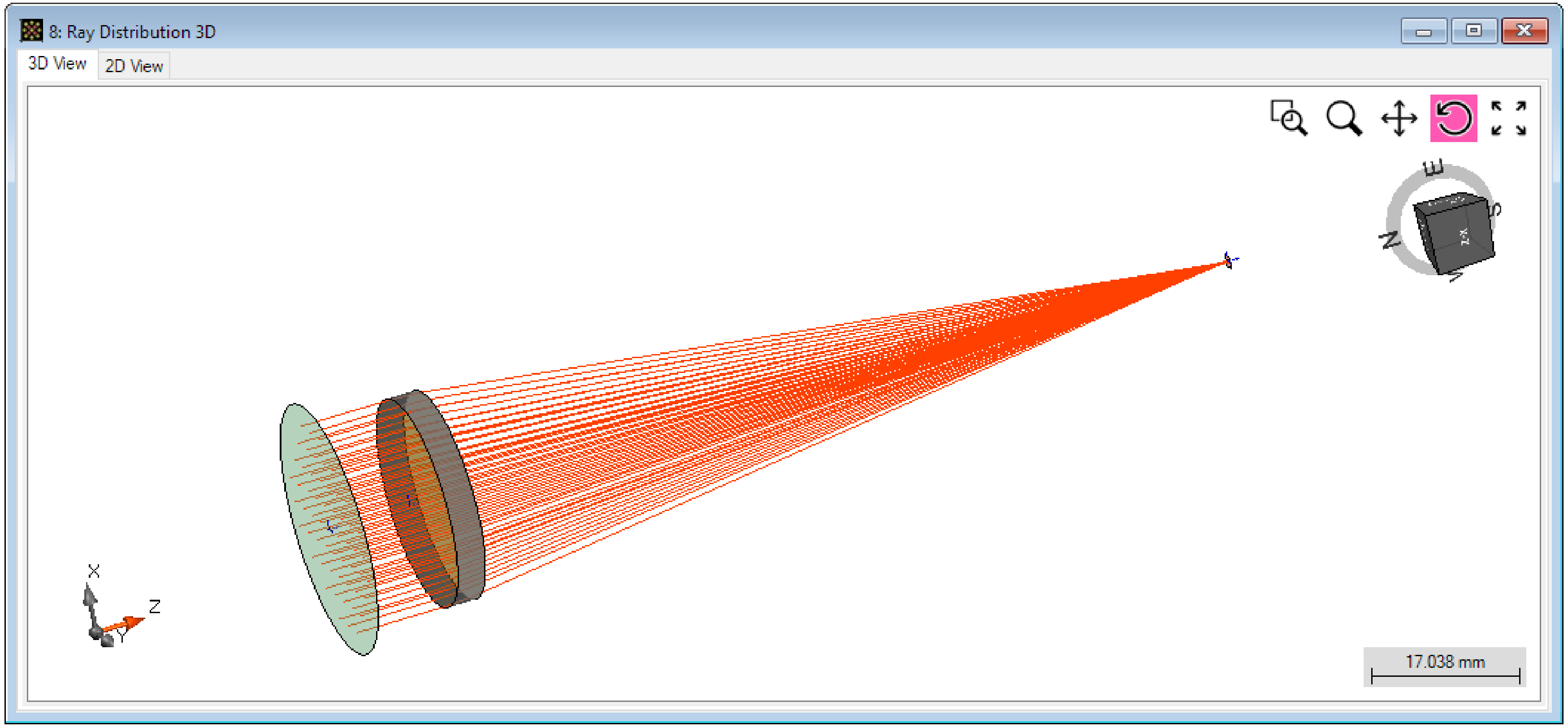
Task 5: Singlet

- Design of singlet with 100 mm effective focal length by ray tracing in VirtualLab.

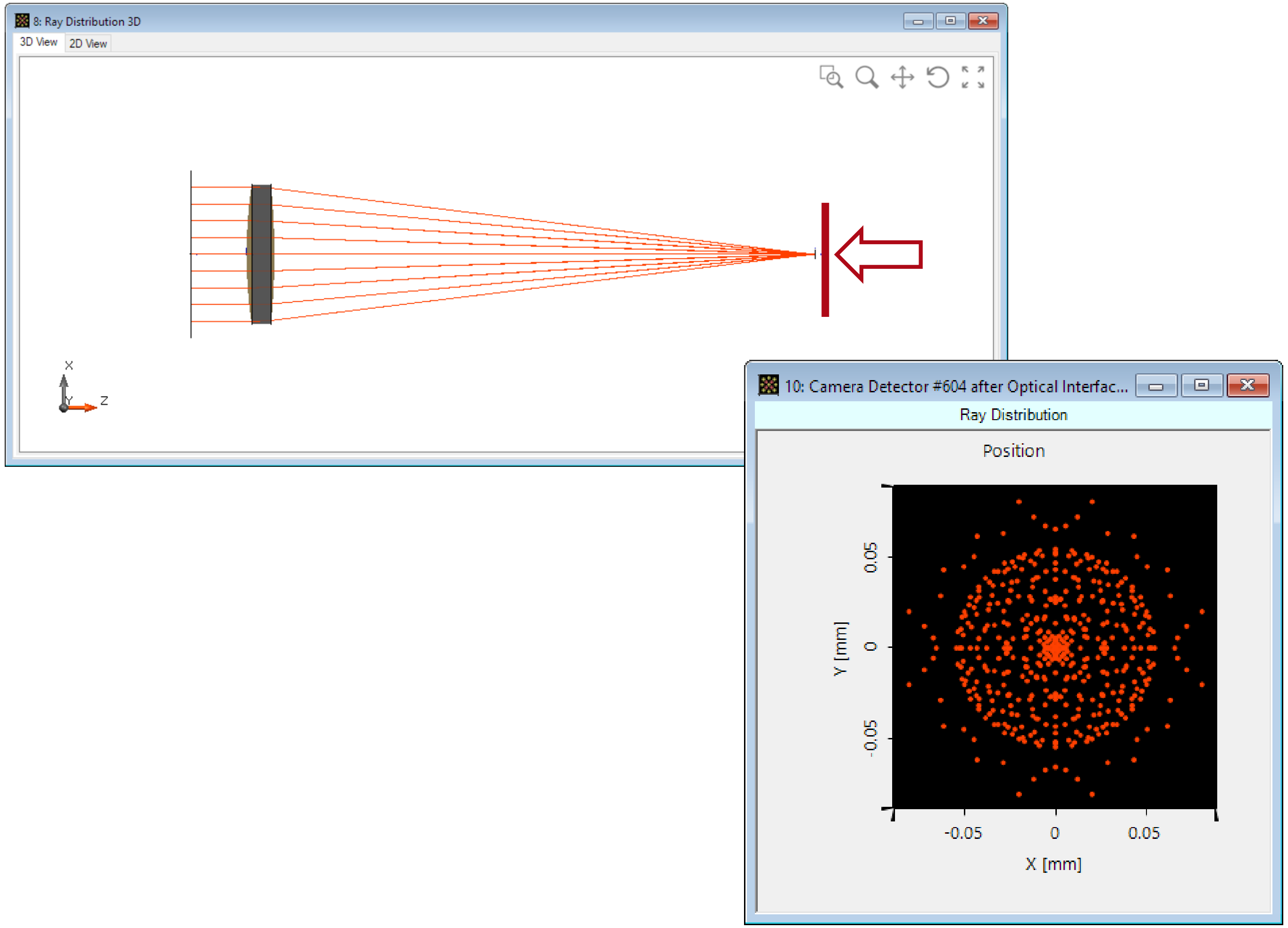


Example: Singlet

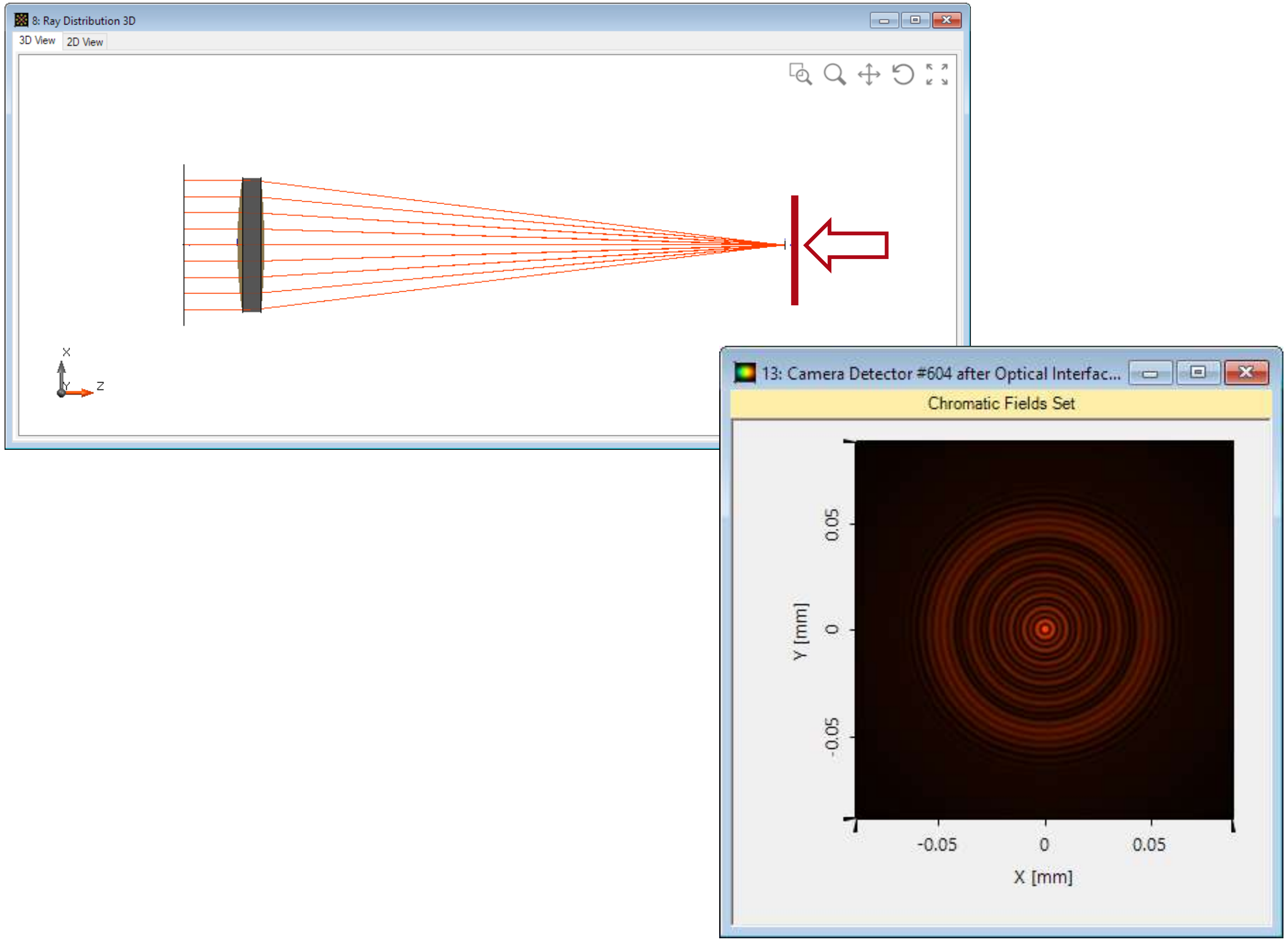
- Design of singlet with 100 mm back focal length by ray tracing in VirtualLab.



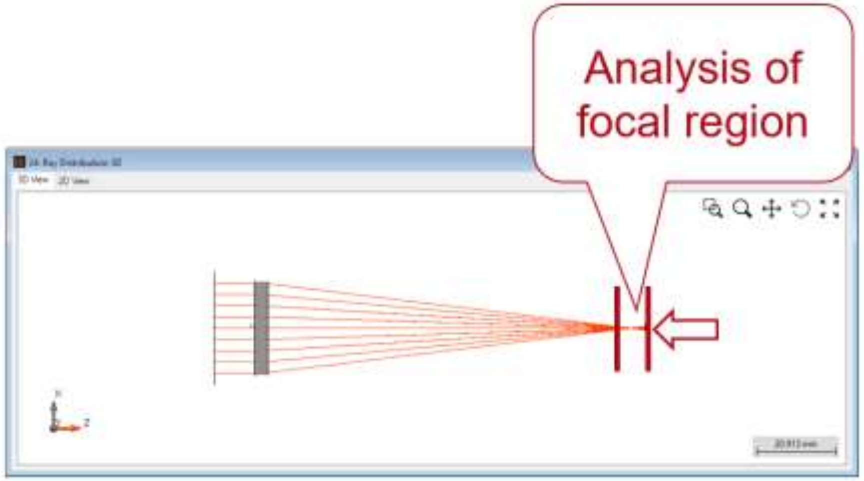
Ray Tracing: Dot Diagram

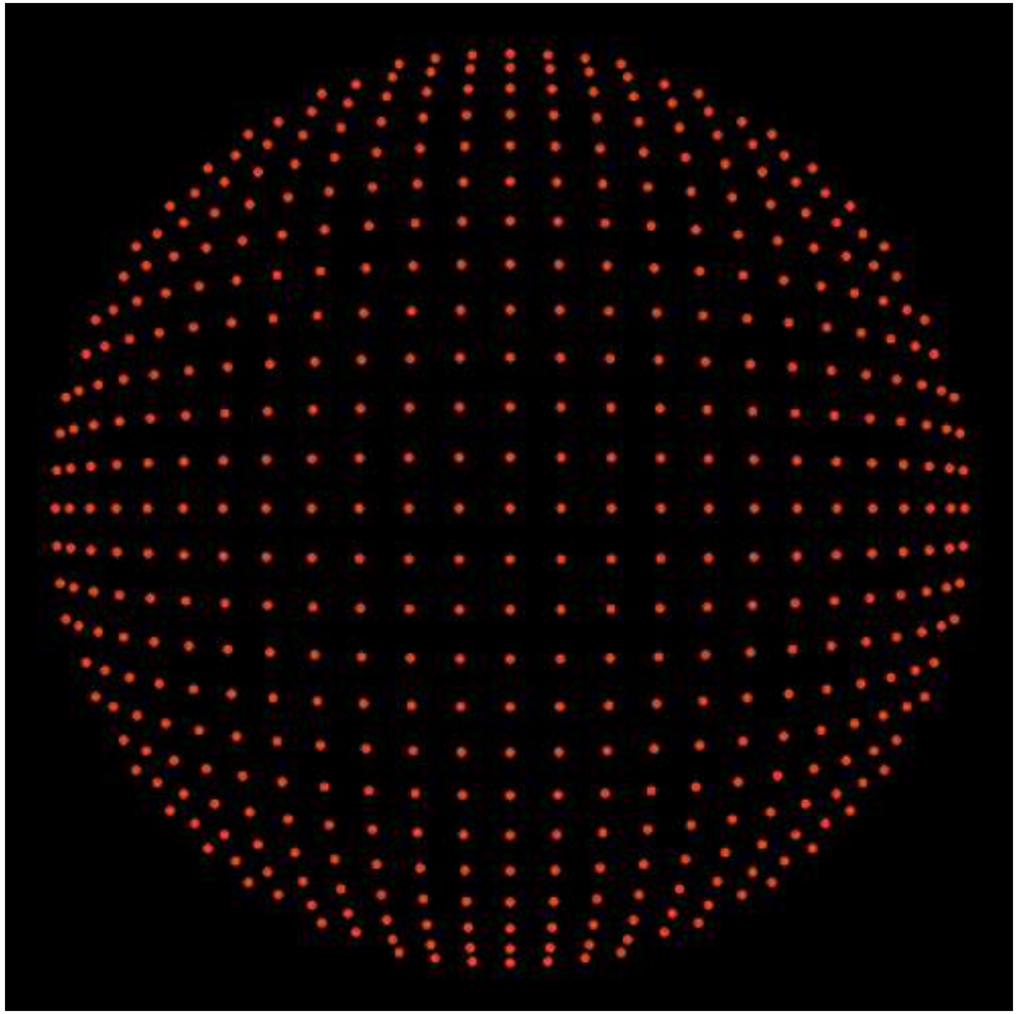


Physical Optics: Intensity

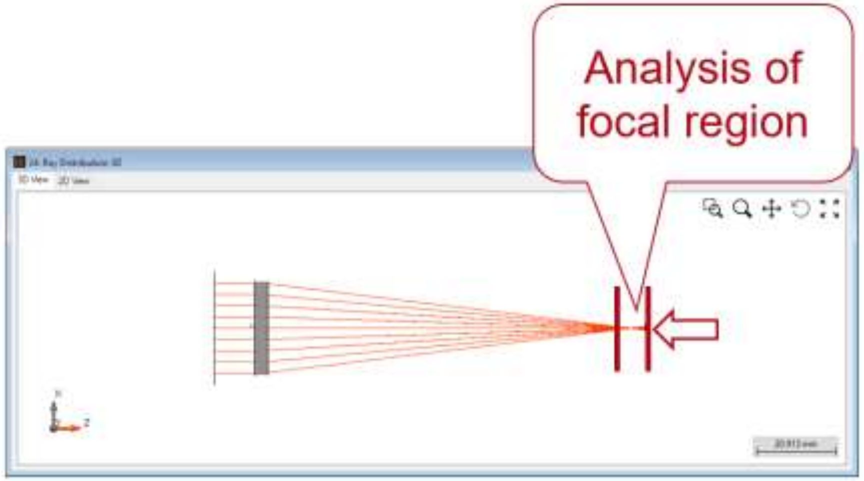


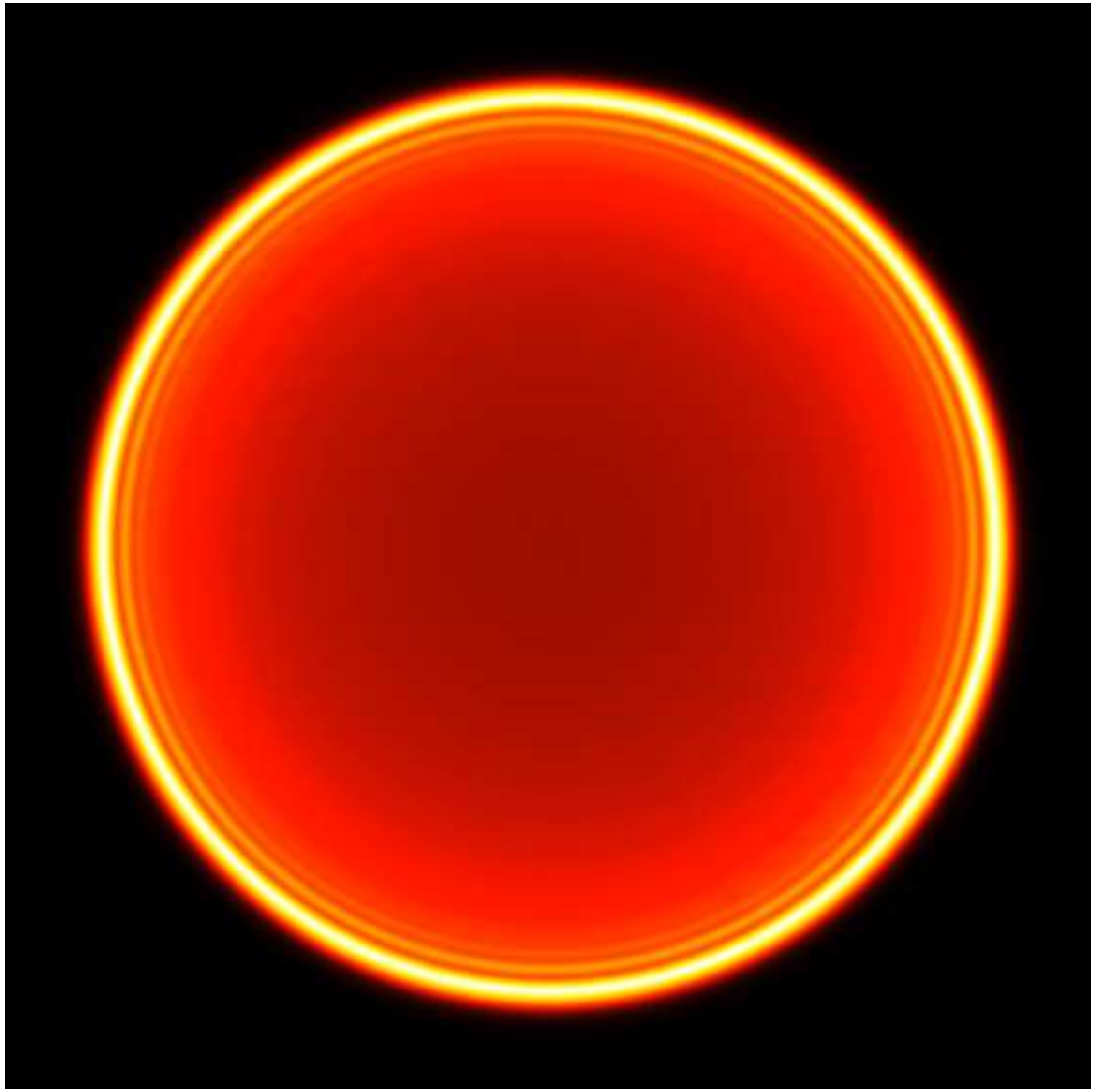
Ray Tracing: 91 - 100 mm



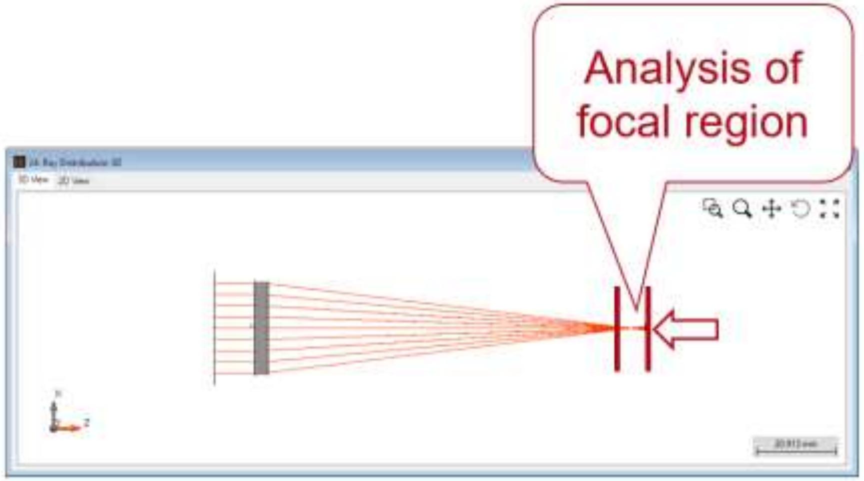


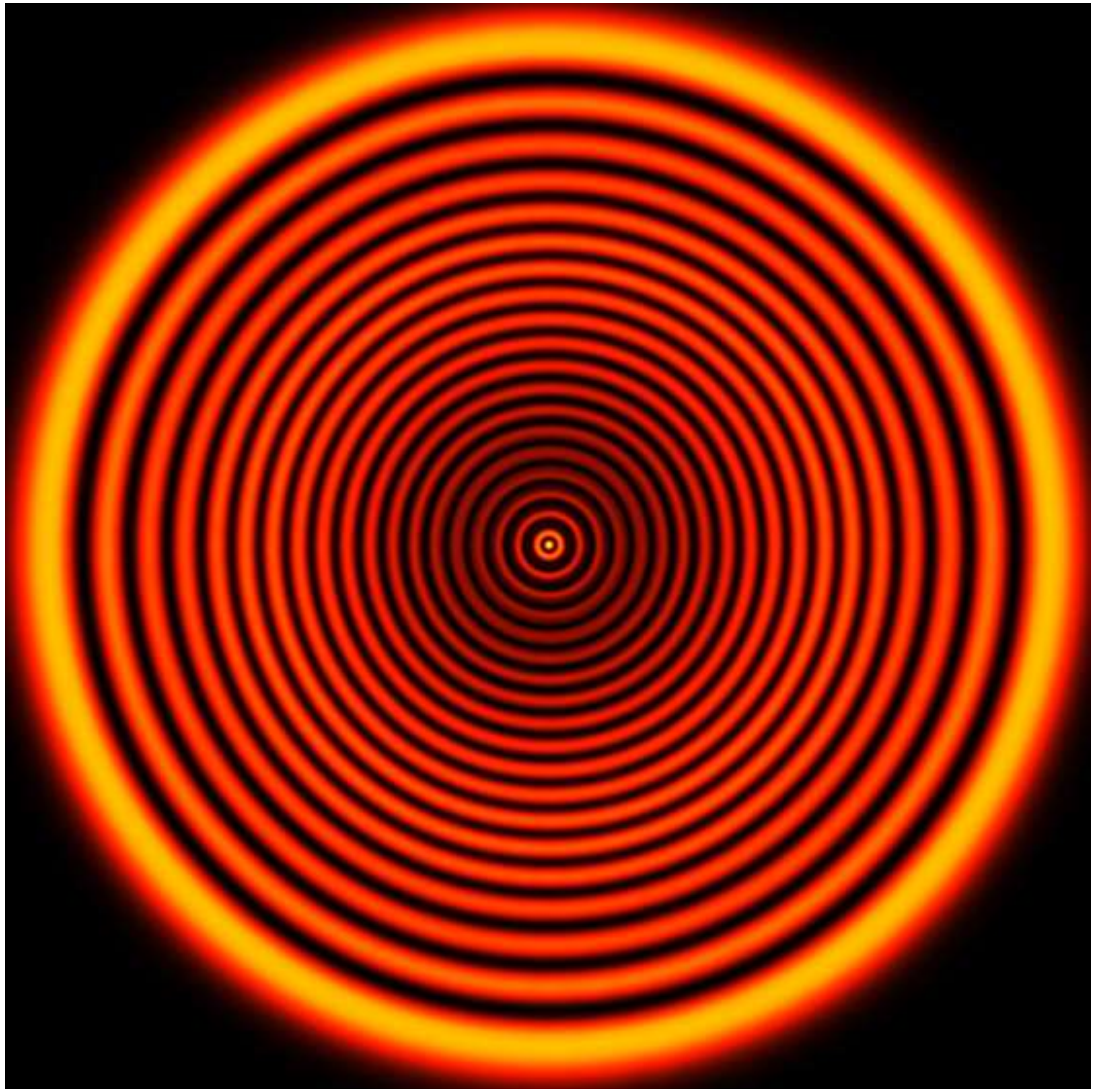
Physical Optics: 91 - 100 mm



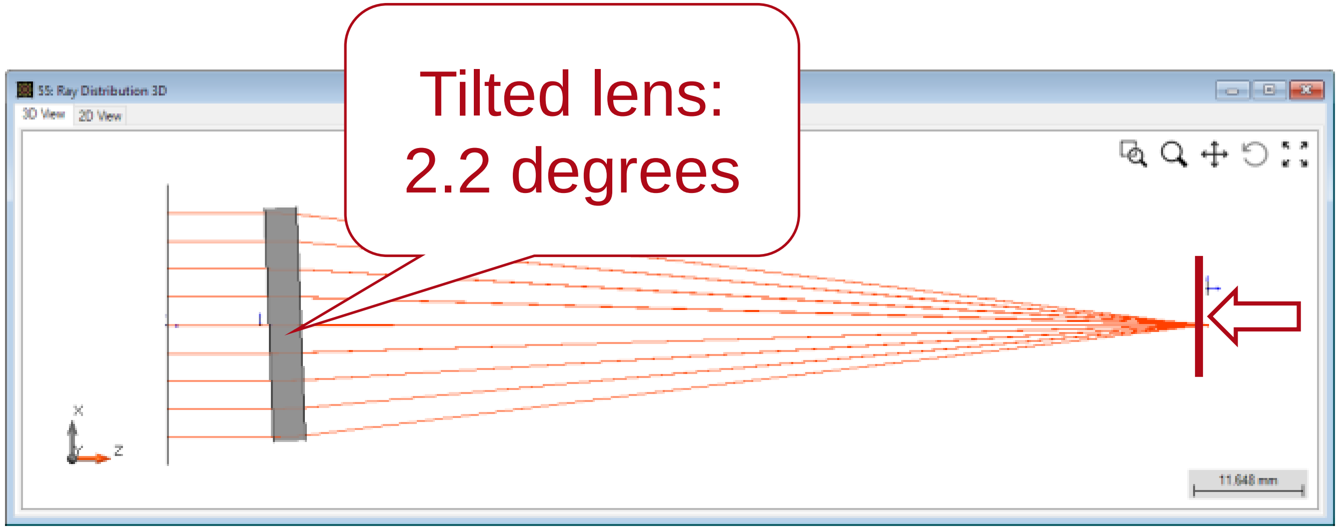


Physical Optics: 95.5 – 98.5 mm

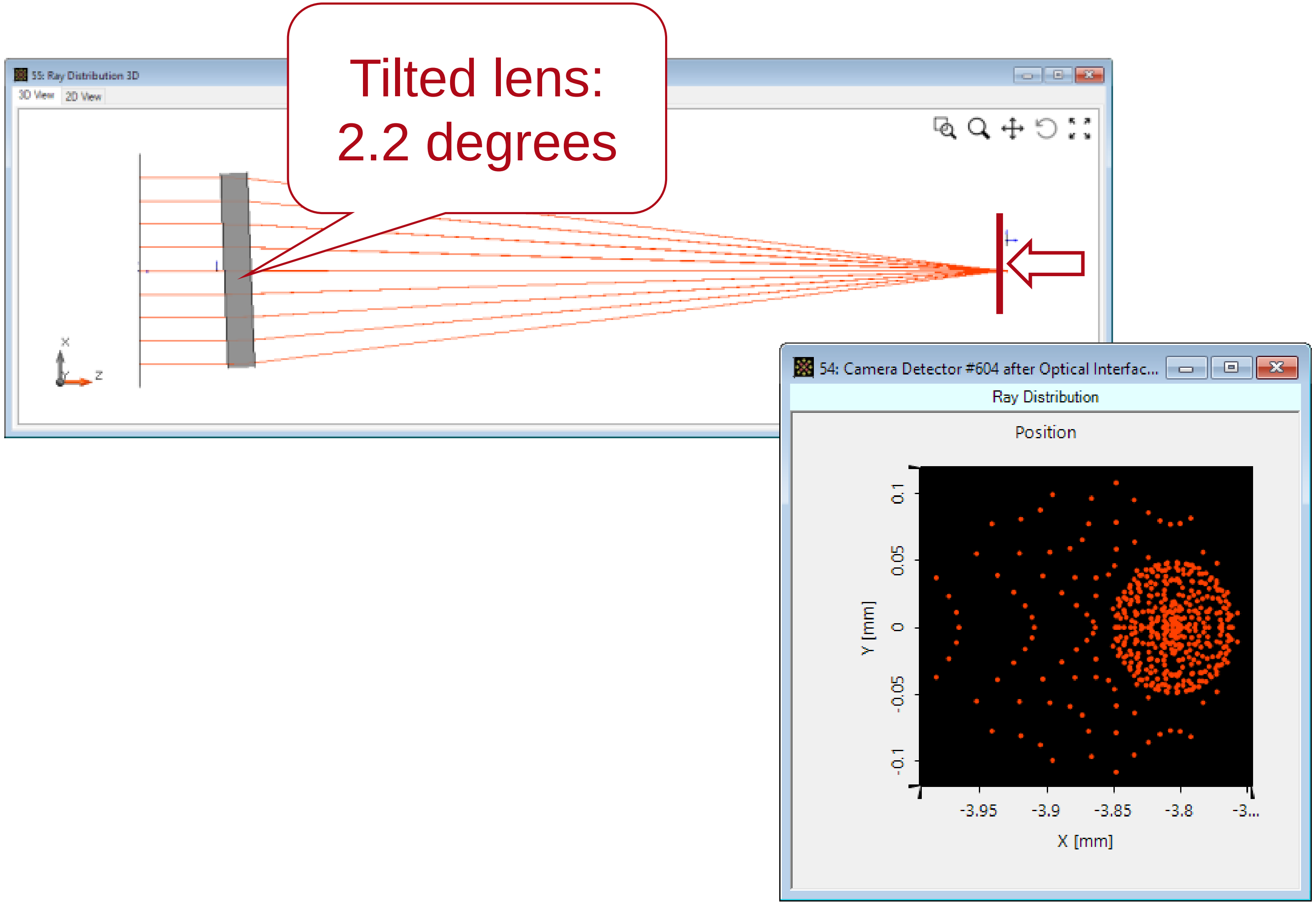




Analysis of Focal Region

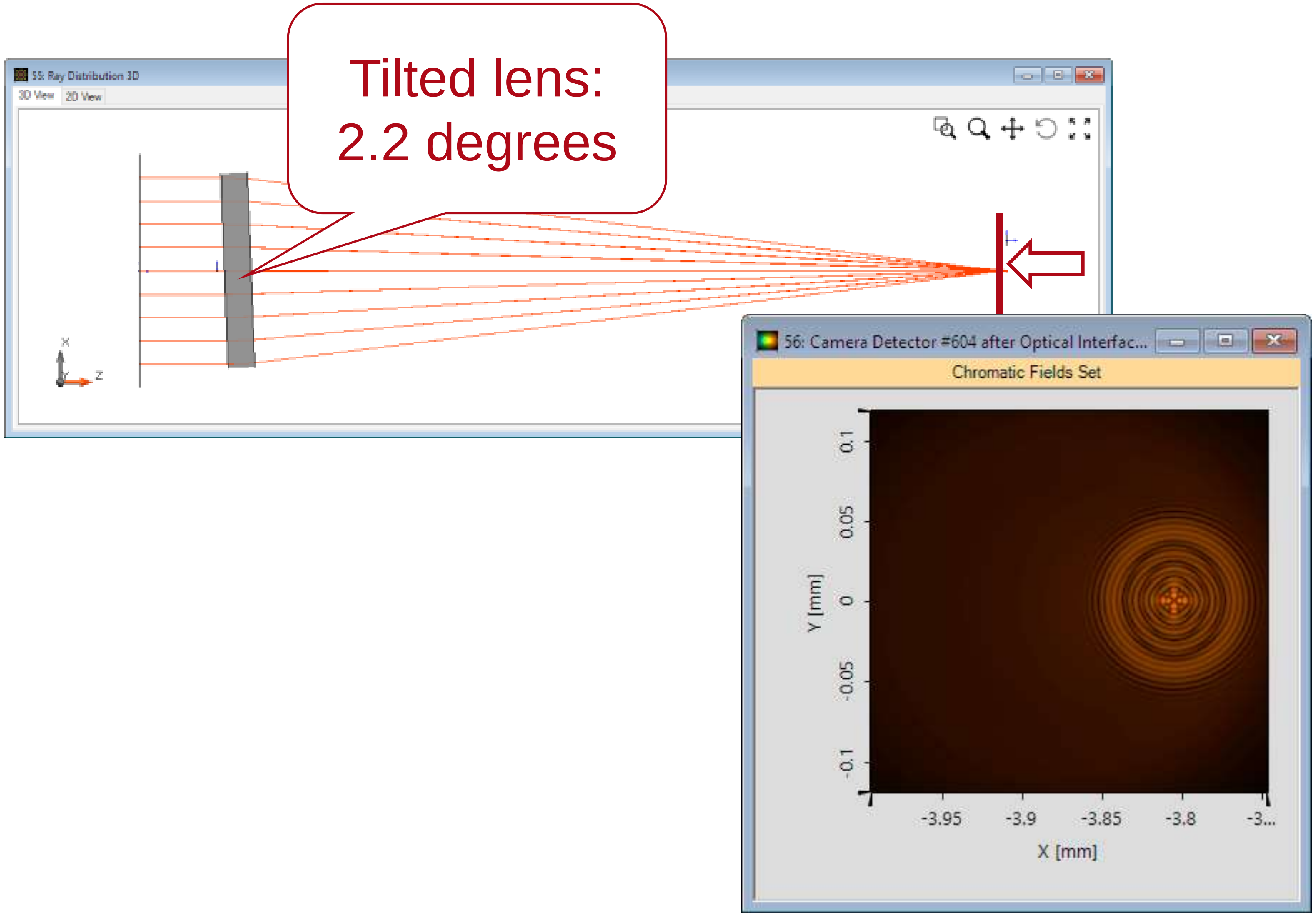


Ray Tracing

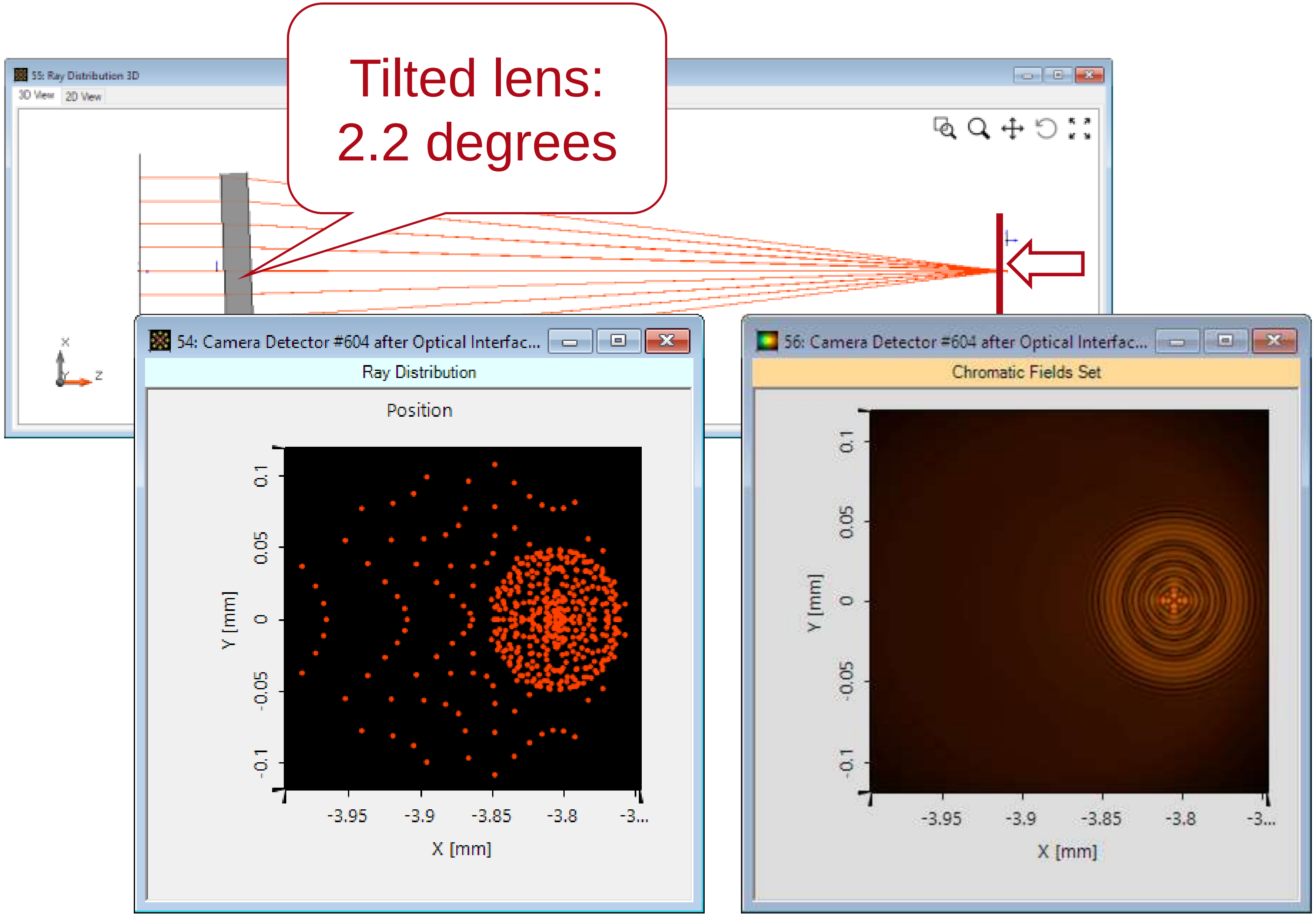


55: Ray Distribution 3D
3D View
2D View
Tilted lens:
2.2 degrees
54: Camera Detector #604 after Optical Interfac...
Ray Distribution
Position
Y [mm]
X [mm]

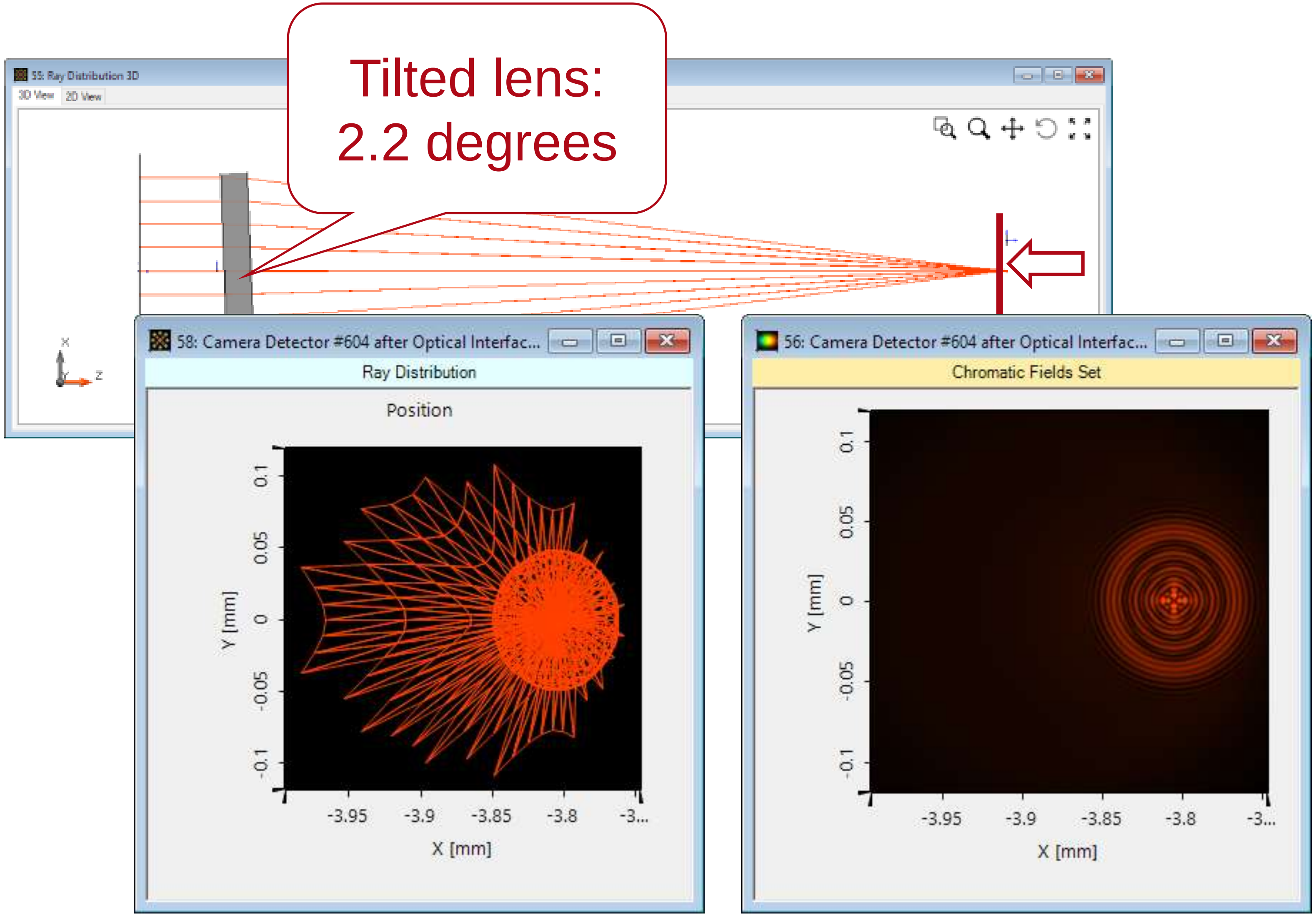
Physical Optics



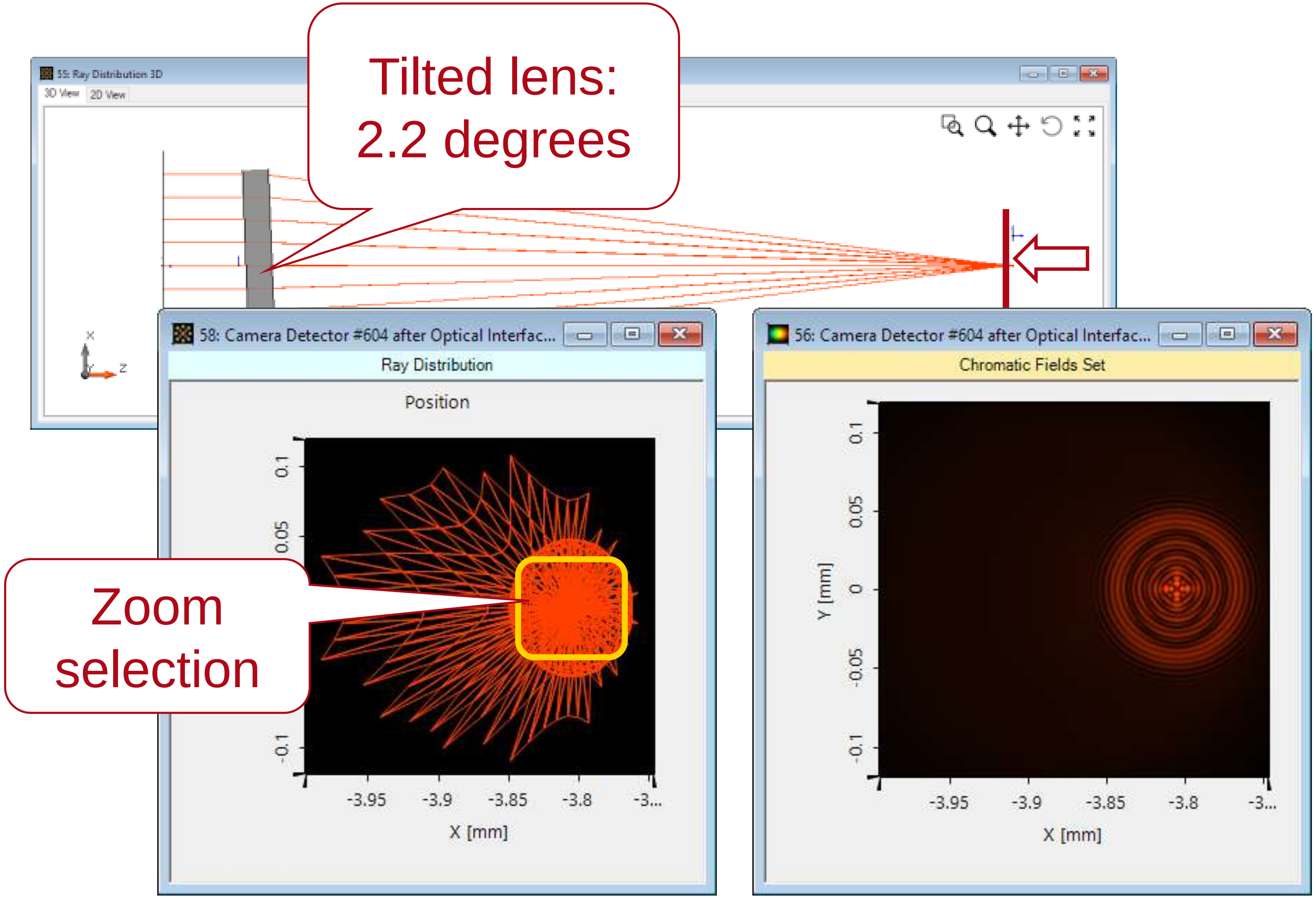
Ray vs. Physical Optics



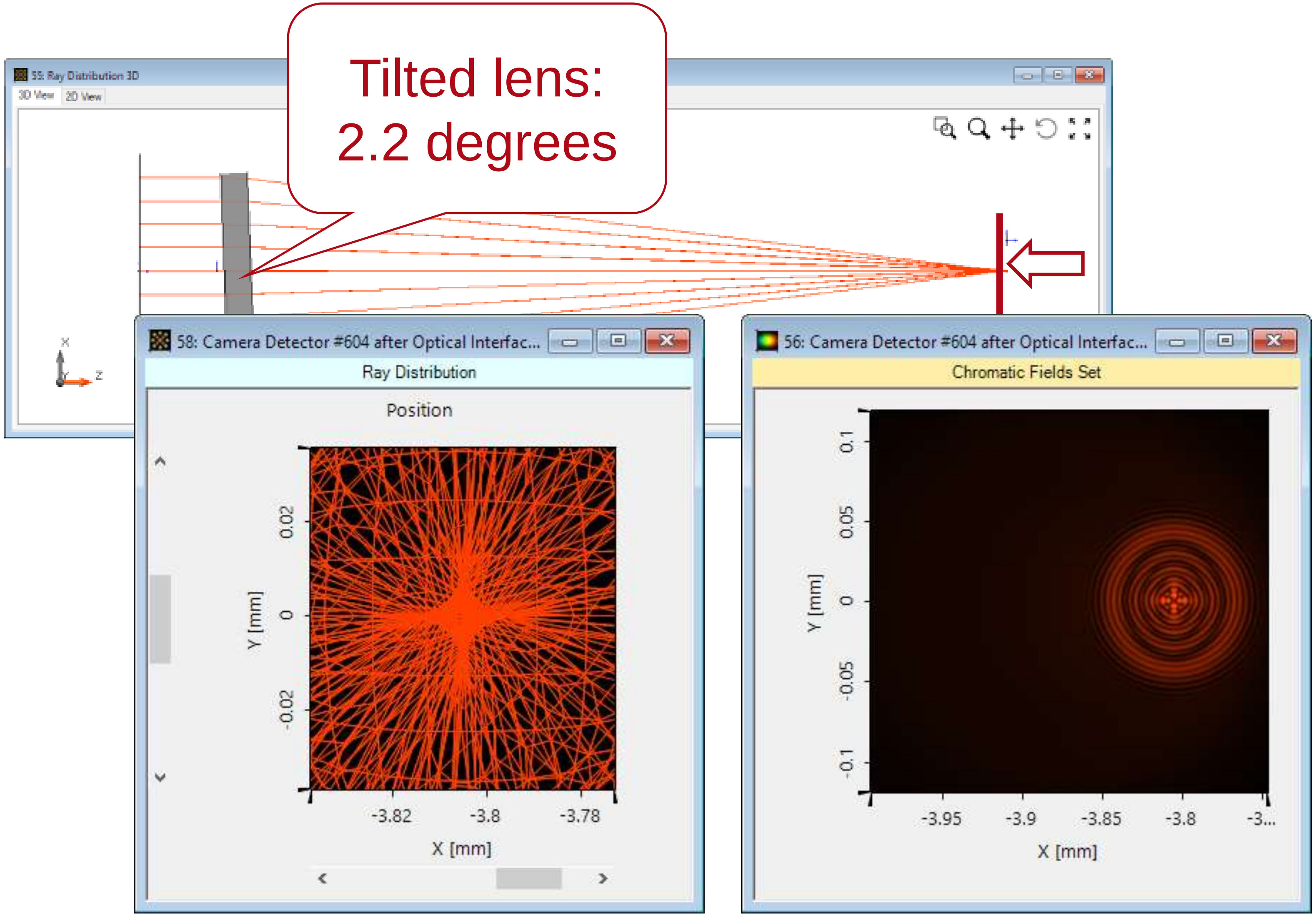
Ray vs. Physical Optics



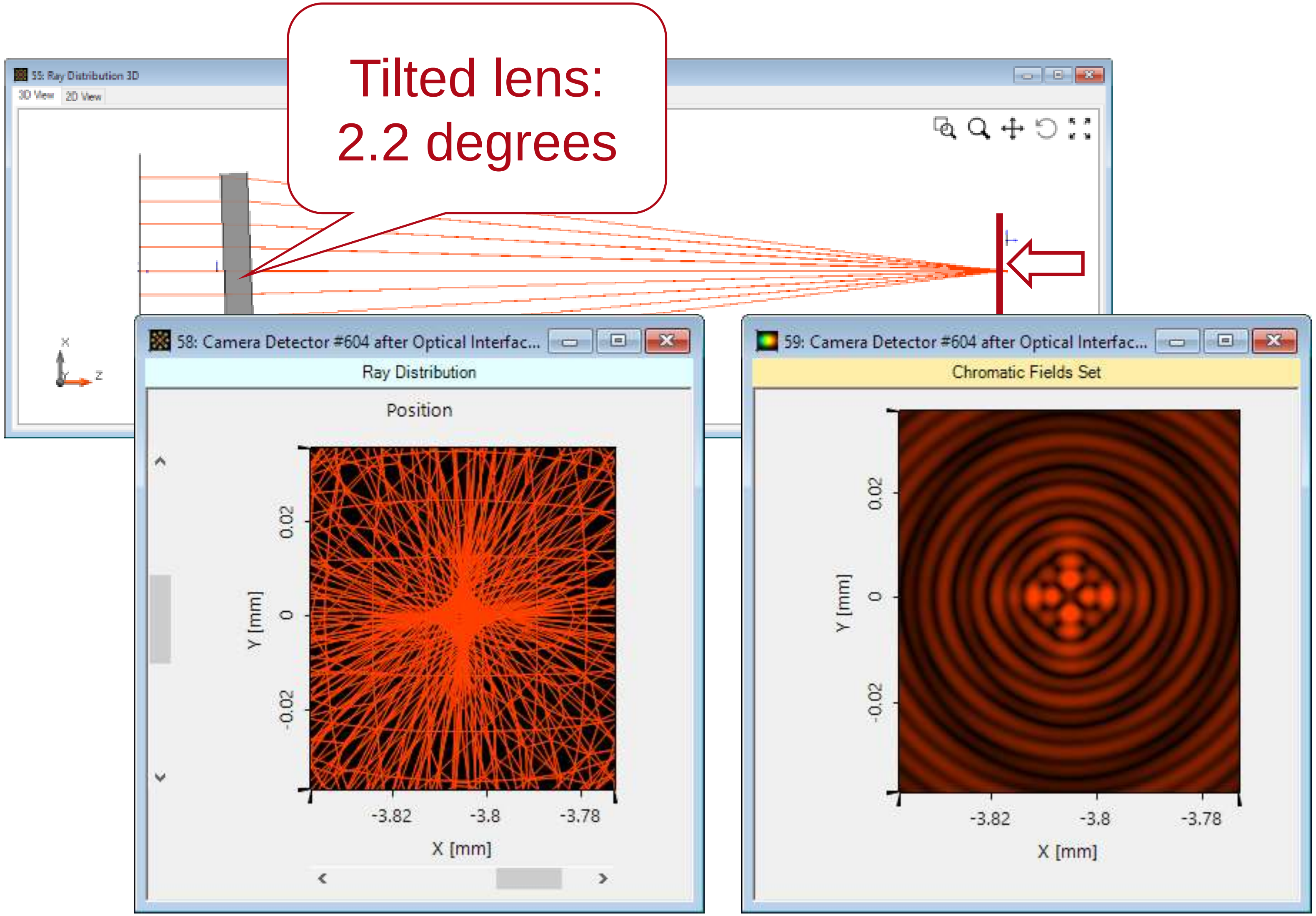
Ray vs. Physical Optics



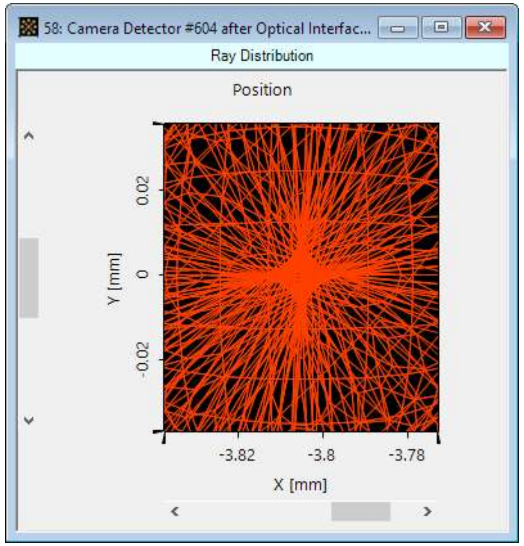
Ray vs. Physical Optics

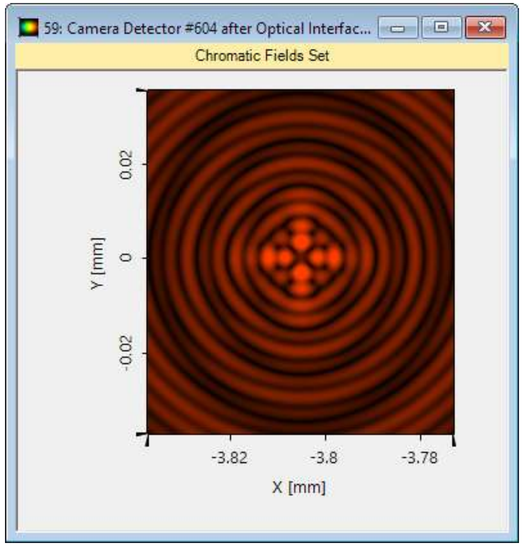


Ray vs. Physical Optics



Ray and Physical Optics for Lens Systems





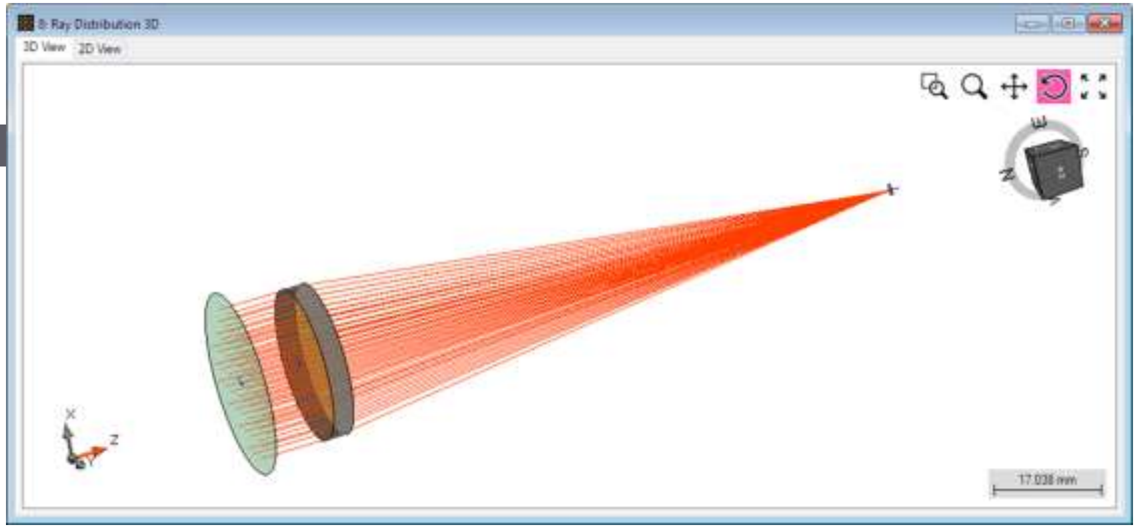
- Modeling of focal regions of lens systems just one example of the need for physical optics modeling and design.

Basic Workflow in VirtualLab Fusion: Modeling

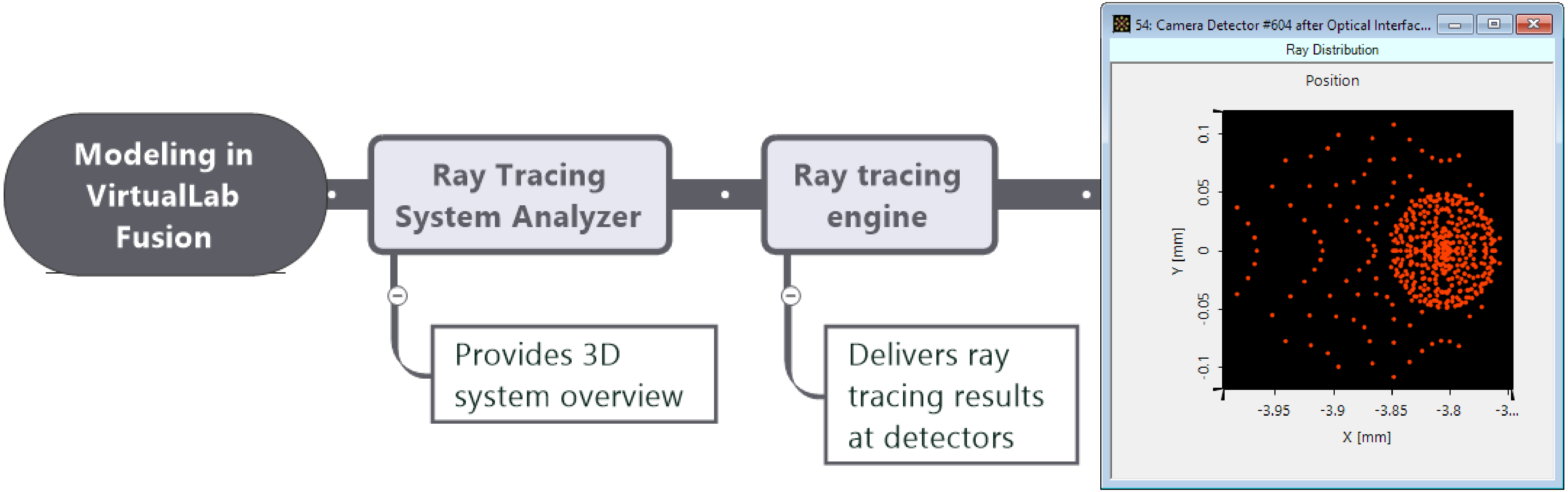
Modeling in VirtualLab Fusion

Ray Tracing System Analyzer

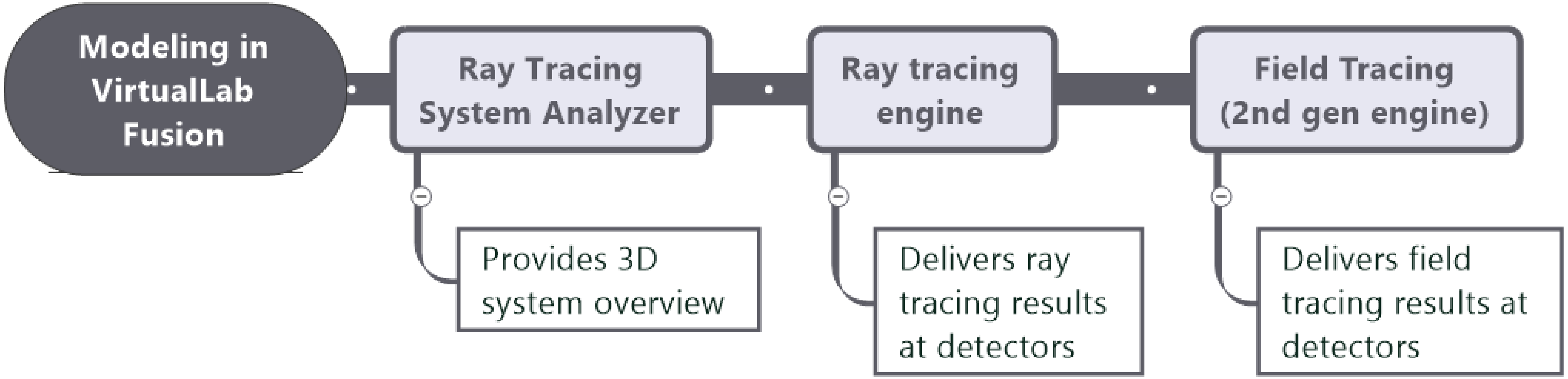
Provides 3D system overview



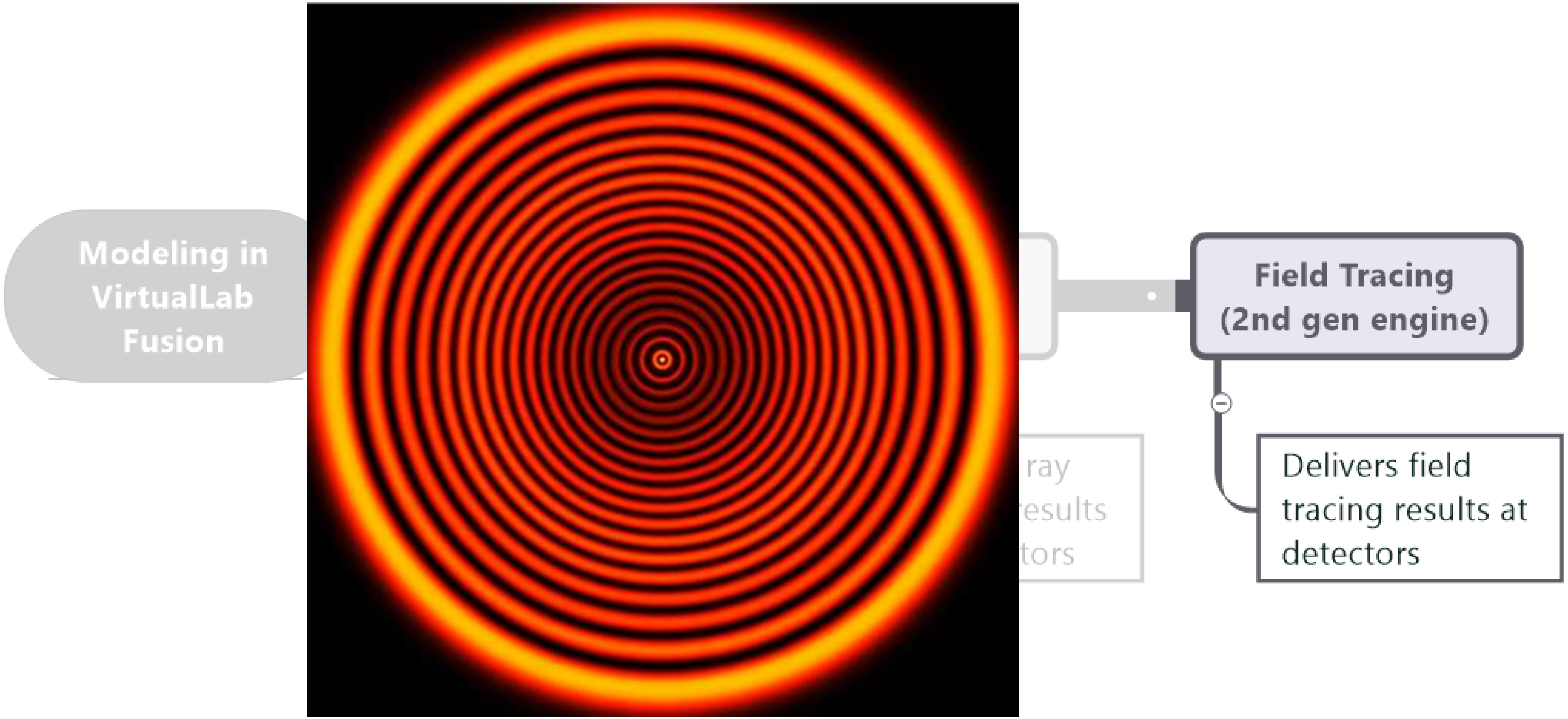
Basic Workflow in VirtualLab Fusion: Modeling



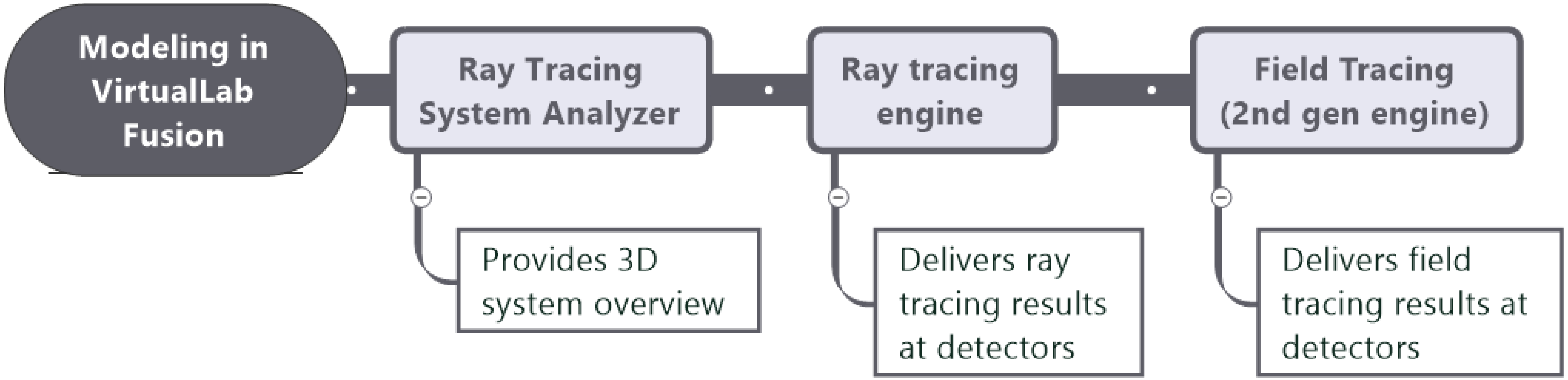
Basic Workflow in VirtualLab Fusion: Modeling



Basic Workflow in VirtualLab Fusion: Modeling



Basic Workflow in VirtualLab Fusion: Modeling



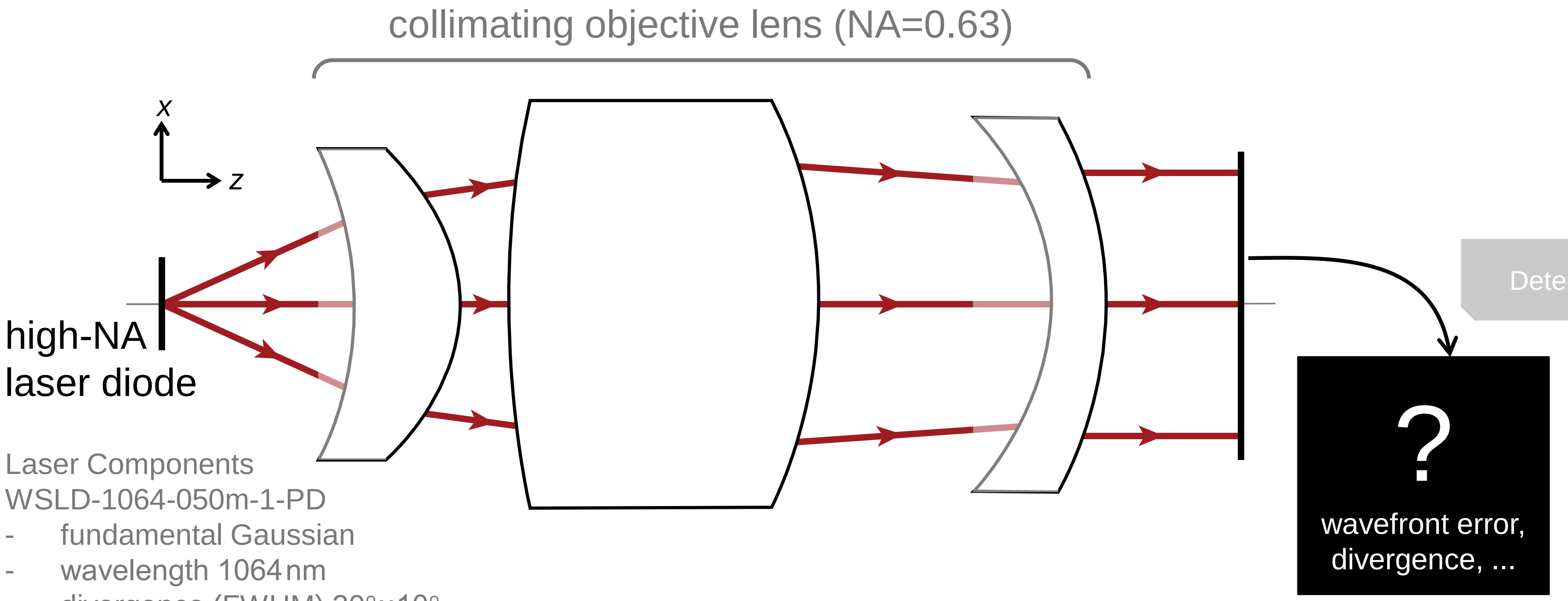
Task 5: Video

Klick the following link to watch the video:

https://youtu.be/dq0-IvXvUzQ

https://youtu.be/7eKcCognd_k

Task 6 Analysis the Collimation System of an Astigmatic Laser Diode



Detector model choice

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

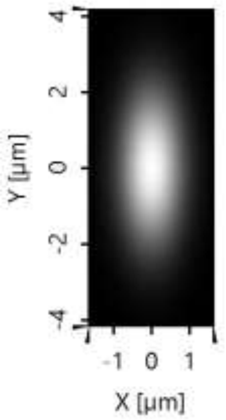
- fundamental Gaussian
- wavelength 1064 nm
- divergence (FWHM) 20° x 10°
- astigmatism 11.6 µm between *x*- and *y*-plane

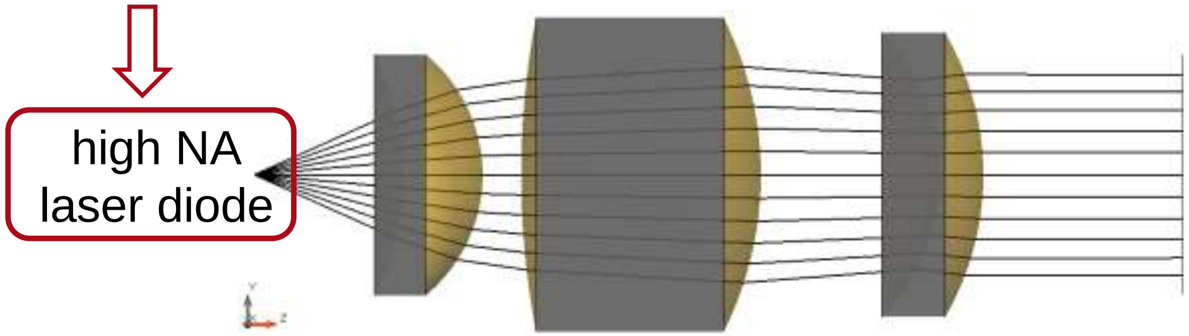
What is the wavefront error and divergence of the collimated beam, with the astigmatism taken into account?

Source setting

OIS and Parametric Overview

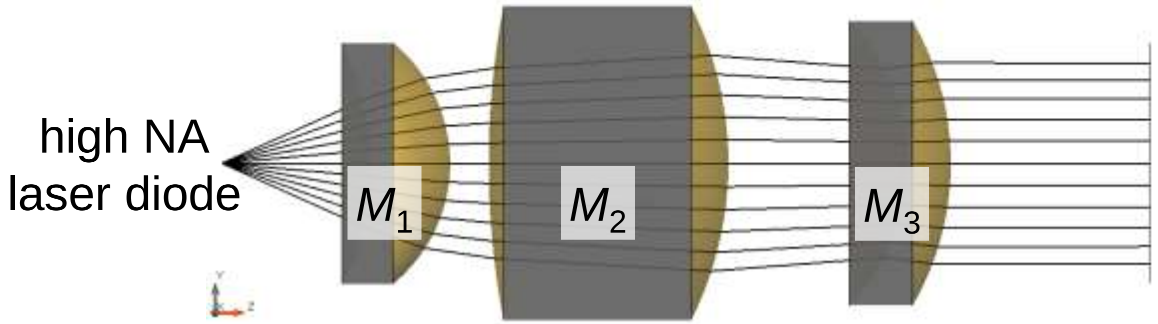
Specification: Light Source





Parameter	Description / Value & Unit
type/number	single mode IR diode laser from Laser Components: WSLD-1064-050m-1-PD
coherence/mode	single Hermite Gaussian (0,0) mode
wavelength	1064 nm
polarization	linear in y-direction (90°)
FWHM of beam divergence with astigmatism	20° × 10° (i.e. 16.97° × 8.49° referring to the 1/e^2 waist radius), astigmatic shift set to 11.6 µm
initial M^2 in x- and y-direction	1.00 × 1.00

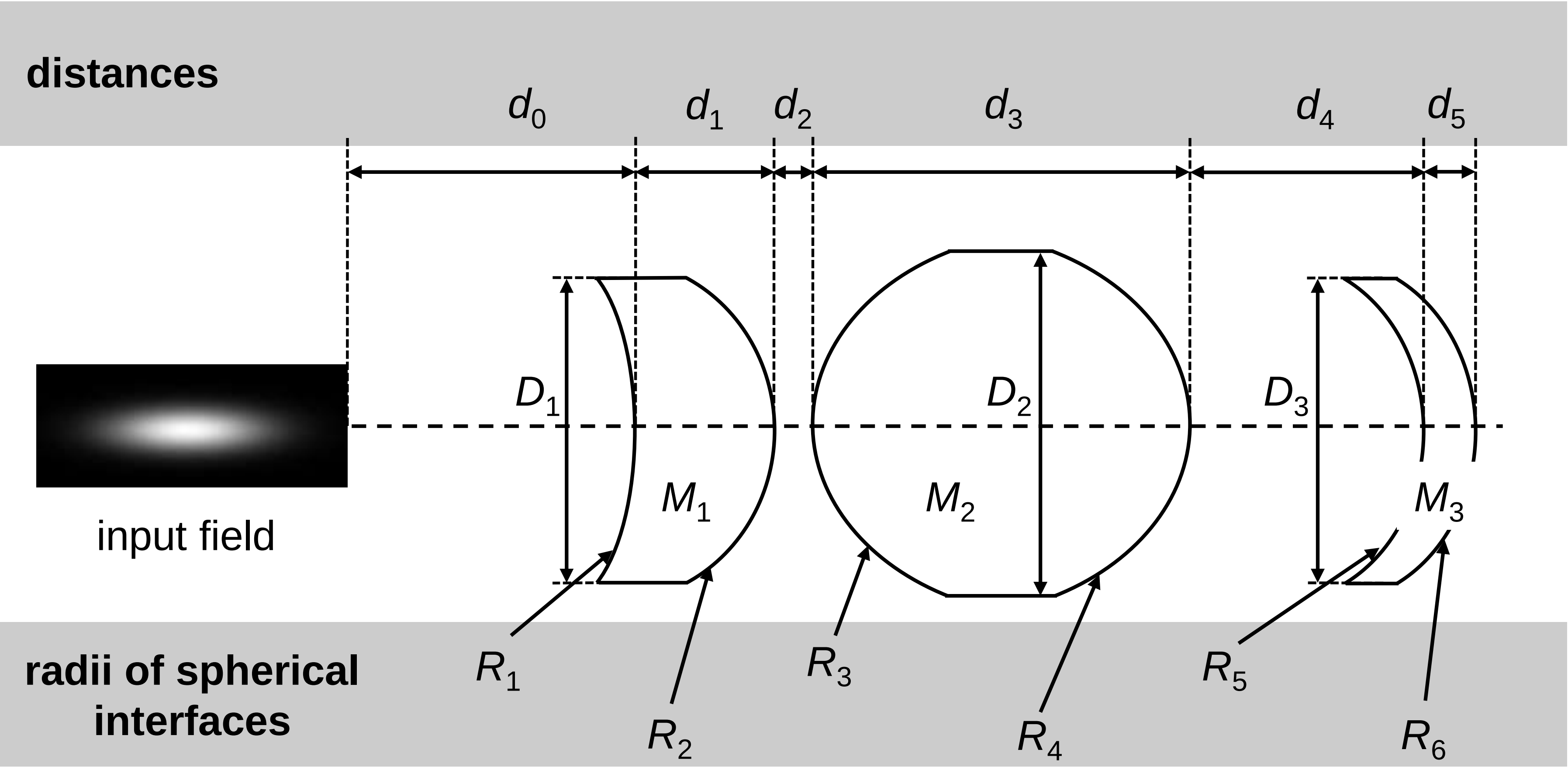
Specification: Collimating Lens



Parameter	**Value & Unit**
types of lens surfaces	3 lenses with 6 spherical surfaces
numerical aperture (NA)	0.63
materials	M_1: N-SF6* M_2,M_3: N-BK7*

** from catalog "Schott_2015"*

Specs: Collimation Objective Lens Overview



Specs: Collimation Objective Lens Parameters

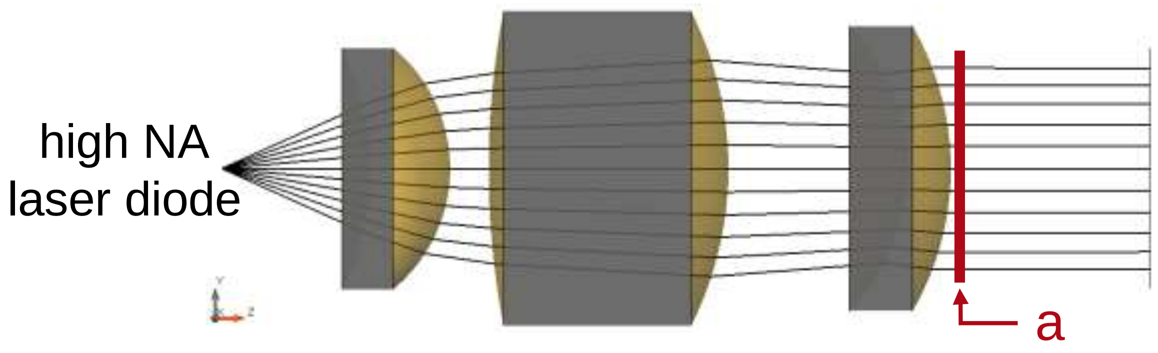
Parameter	Value & Unit
distance d_0	3.6915 mm
distance d_1	2.007 mm
distance d_2	967.46 µm
distance d_3	6.0005 mm
distance d_4	4.4892 mm
distance d_5	1.0814 mm
diameter D_1	6.04 mm
diameter D_2	7.8576 mm
diameter D_3	7.1226 mm

* from catalog Schott_2015

Parameter	Value & Unit
conical radius R_1	−6.799 mm
conical radius R_2	−3.9068 mm
conical radius R_3	21.051 mm
conical radius R_4	−8.7395 mm
conical radius R_5	−5.0489 mm
conical radius R_6	−7.0837 mm
material M_1	N-SF6*
material M_2	N-BK7*
material M_3	N-BK7*

Hint: please set diameter before conical radius

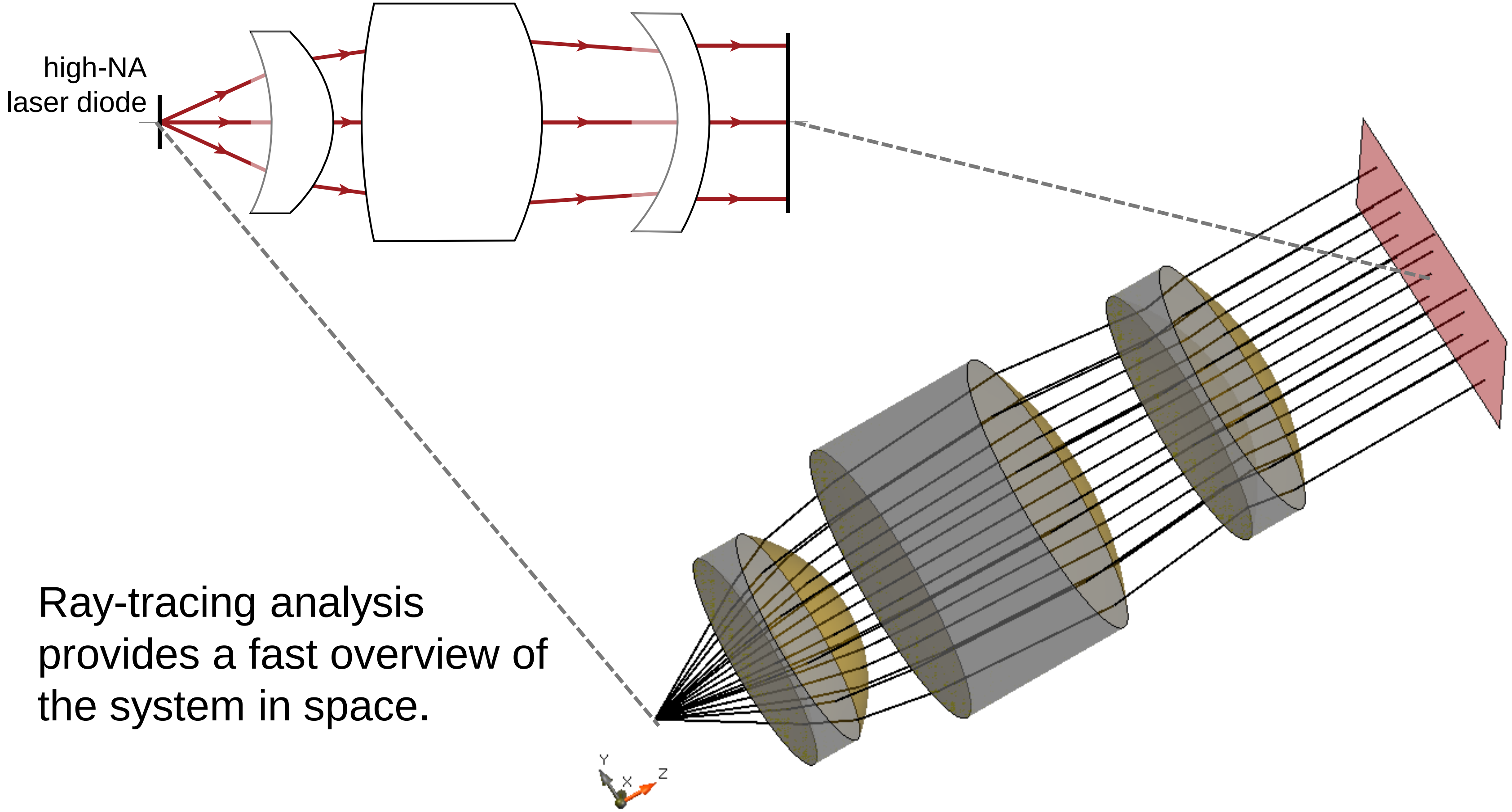
Specification: Detectors



Position	Modeling Technique	Detector/Analyzer
full system	3D system ray tracing	general overview of light behavior in system
a	ray tracing	phase aberrations (RMS of wavefront error)
a	ray tracing	ray directions from dot diagram
a	field tracing	intensity distribution
a	field tracing	beam parameters (for x × y): • full $1/e^2$ angle divergence • M^2 value

Results

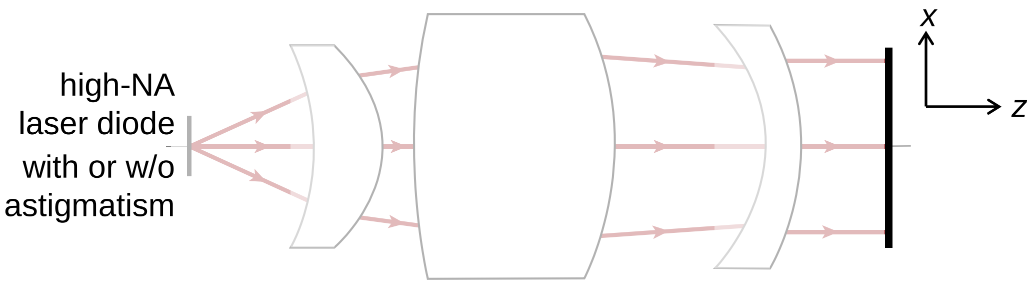
- Ray tracing – system in 3D space



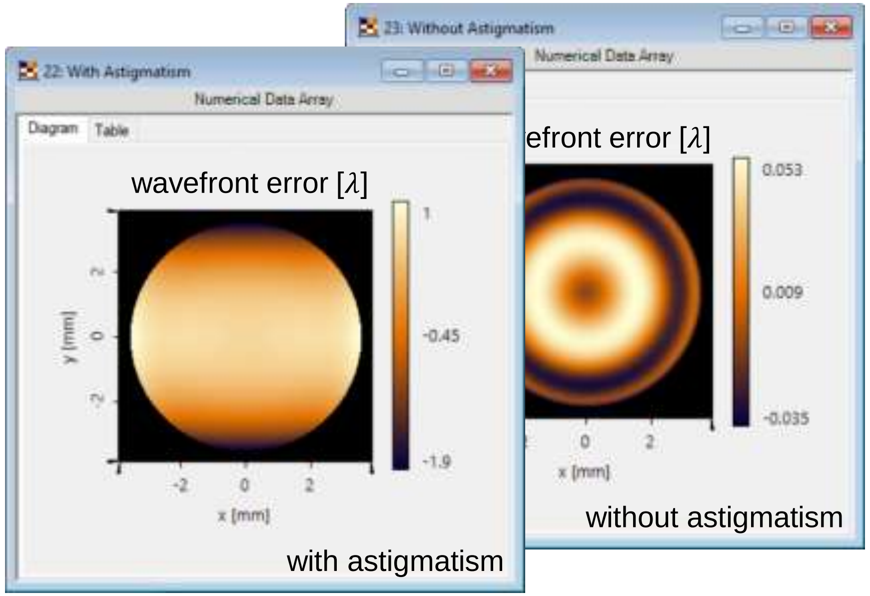
Ray-tracing analysis provides a fast overview of the system in space.

Results

- Ray tracing – wavefront analysis



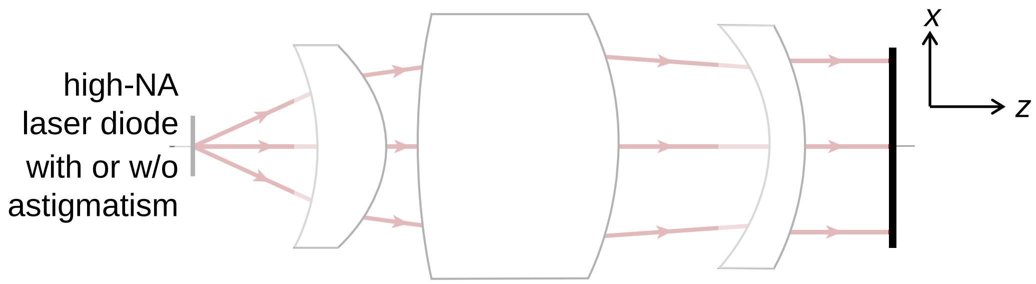
Laser diode properties, including astigmatism, are taken into account for the ray-tracing simulation.



Wavefront error	With astigmatism	Without astigmatism
P-V	2.896λ	0.089λ
RMS	0.704λ	0.026λ

Results

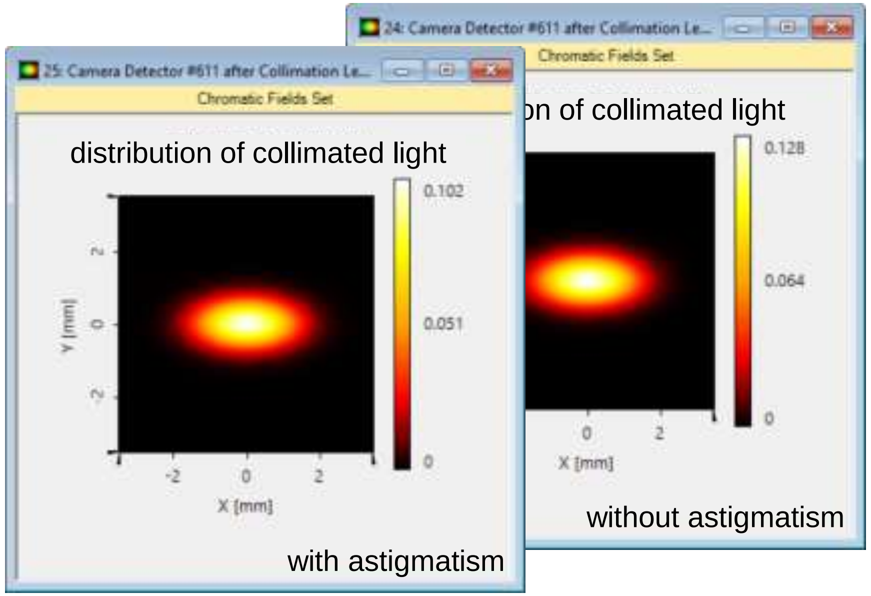
- Field tracing – divergence and beam quality



Physical-optics simulation of whole collimation system takes less than 2 seconds!

Multiple physical parameters are available for quantitative evaluations.

Parameters	With astigmatism	Without astigmatism
div. angle (*x*)	0.024°	0.024°
div. angle (*y*)	0.051°	0.043°
M^2 (*x*)	1.061	1.090
M^2 (*y*)	1.009	1.007



Task 6: Video

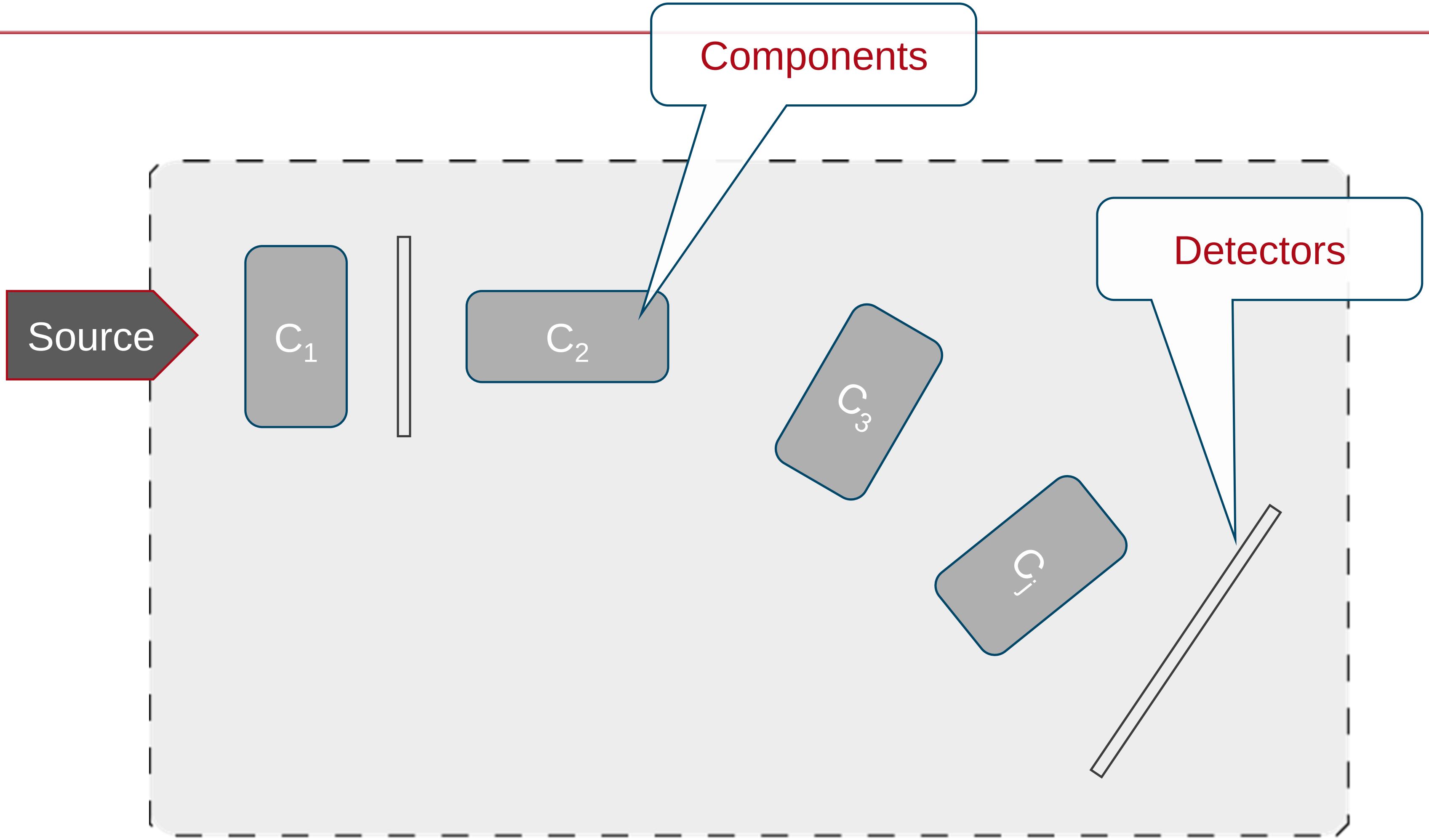
Klick the following link to watch the video:

https://youtu.be/6rdtPjBNST8

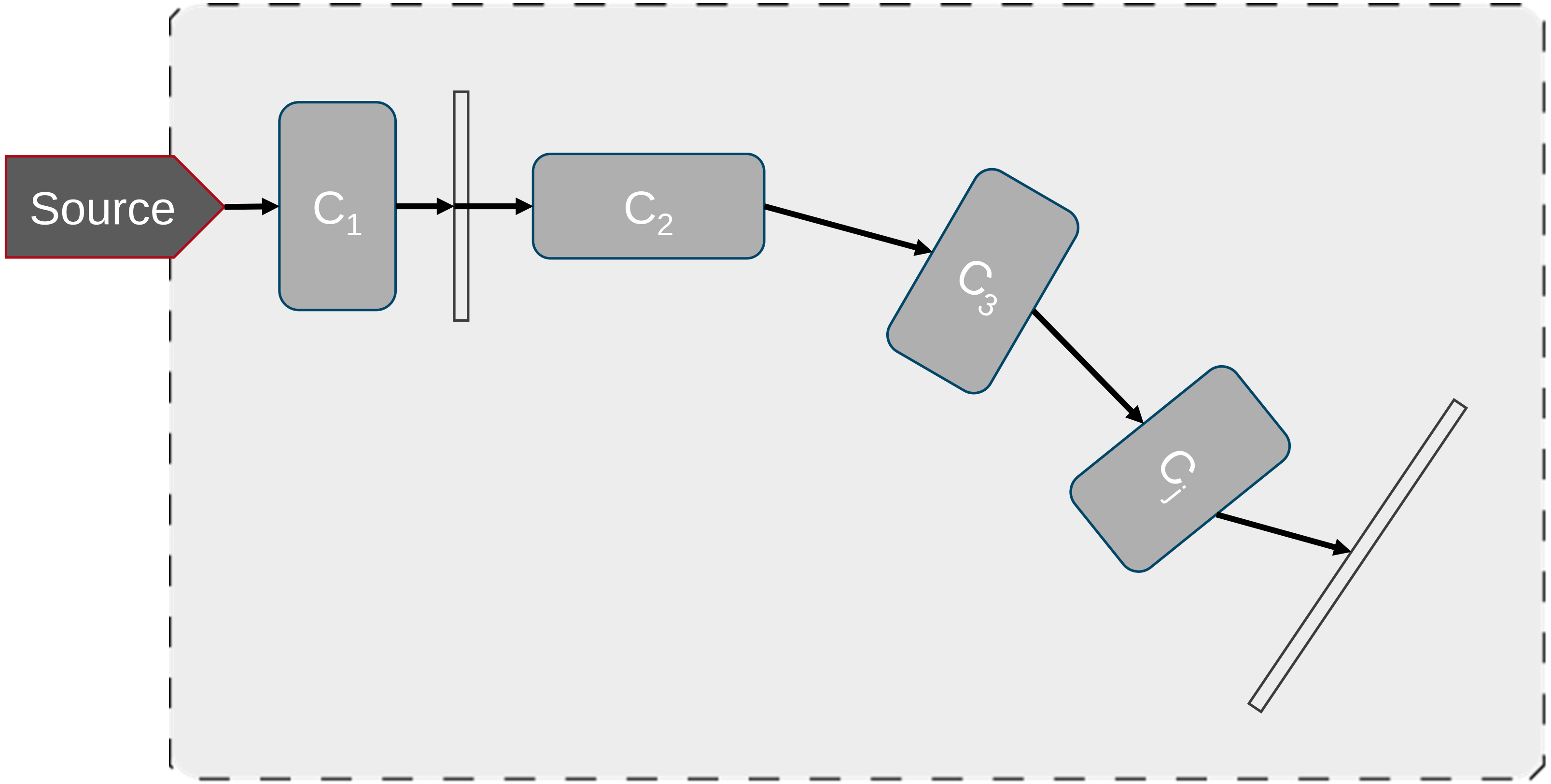
Feature: Sequential and Non-Sequential Tracing

What is Sequential and Non-Sequential Tracing?

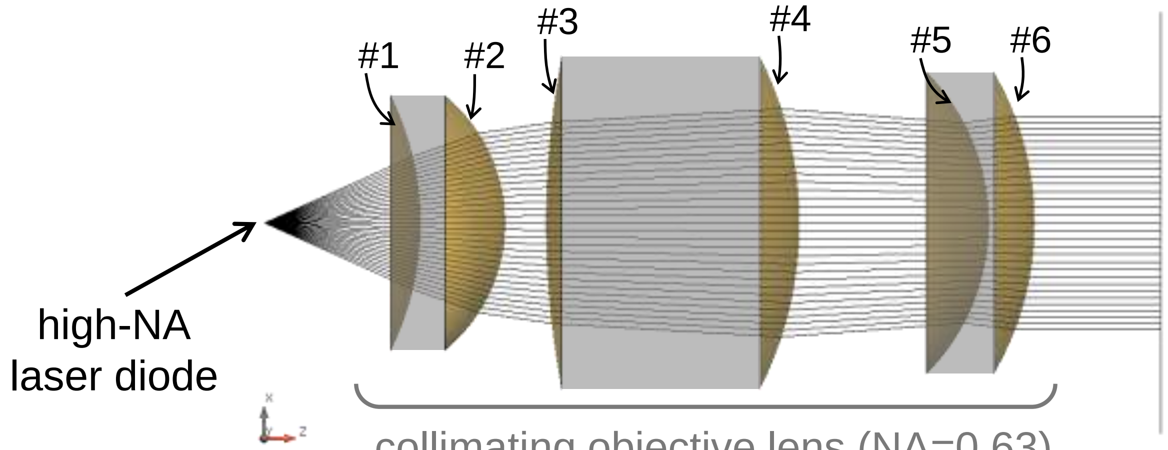
Optical Modeling Task

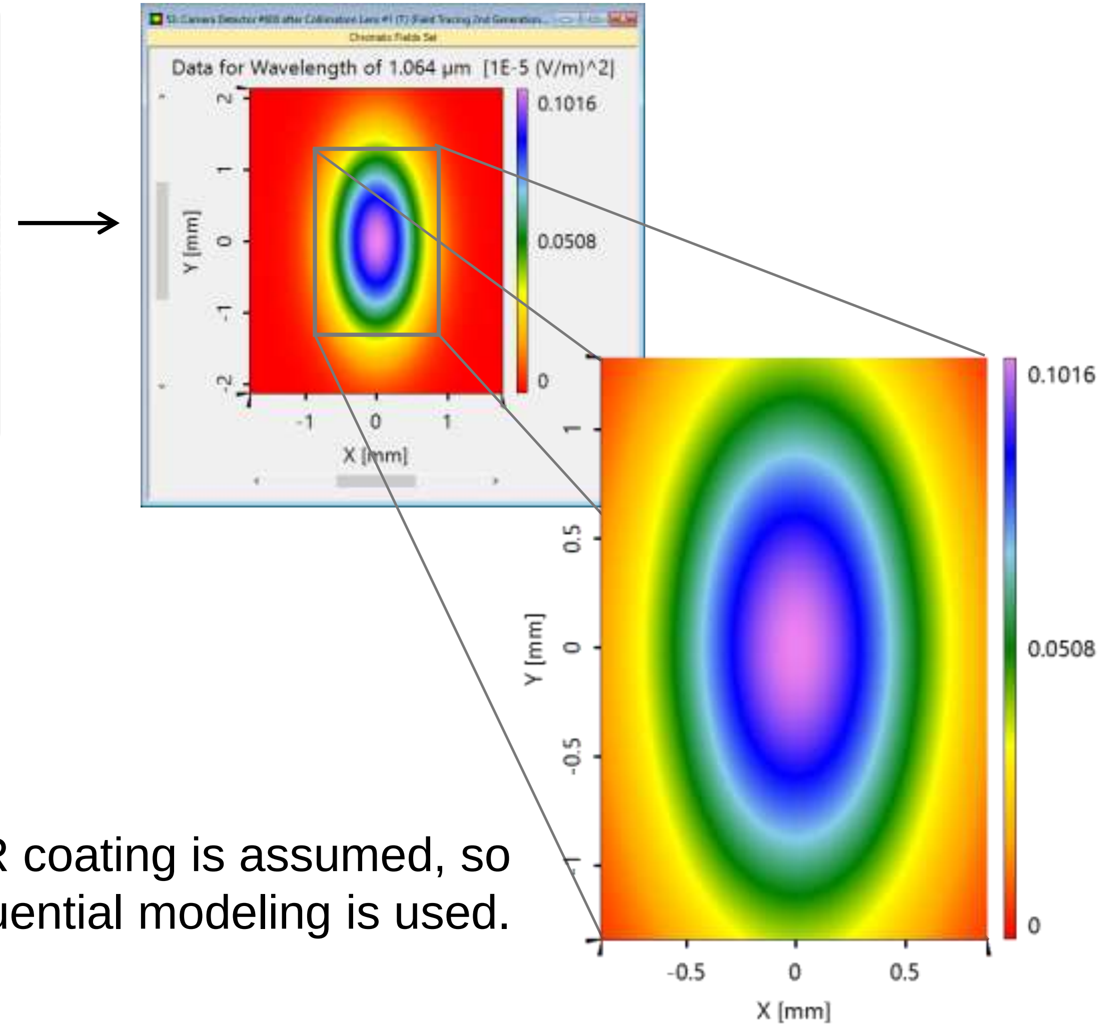


Optical Modeling: Sequential



Collimation System: Sequential Simulation

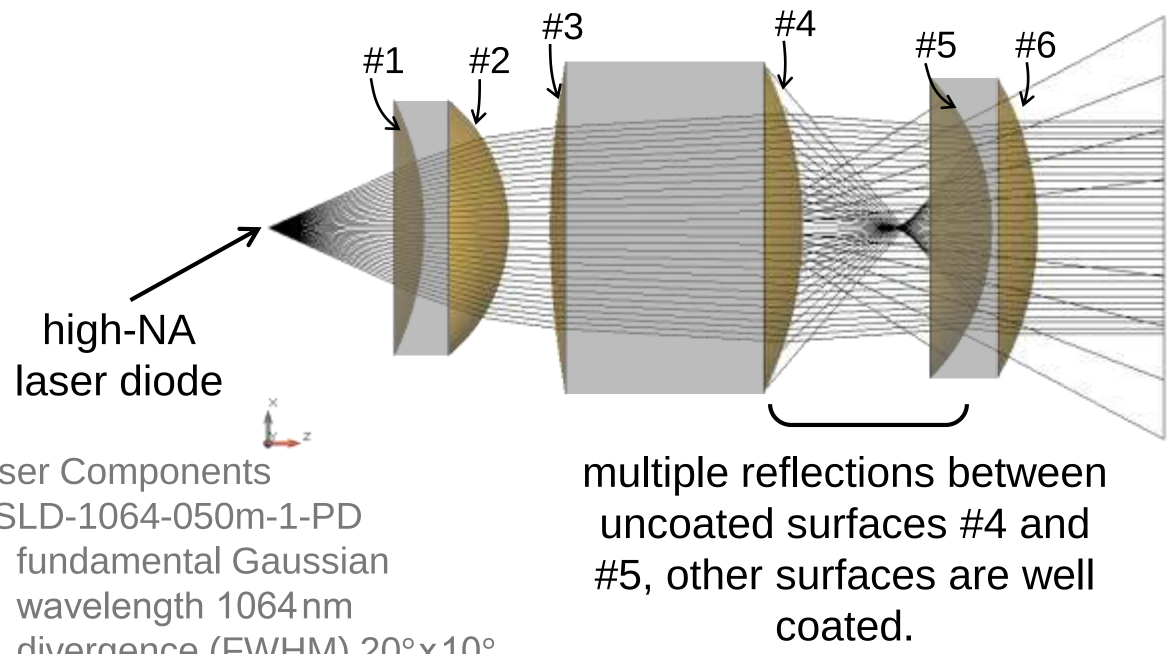




Laser Components
WSLD-1064-050m-1-PD
- fundamental Gaussian
- wavelength 1064 nm
- divergence (FWHM) 20°x10°
- astigmatism 11.6 µm between *x*- and *y*-plane

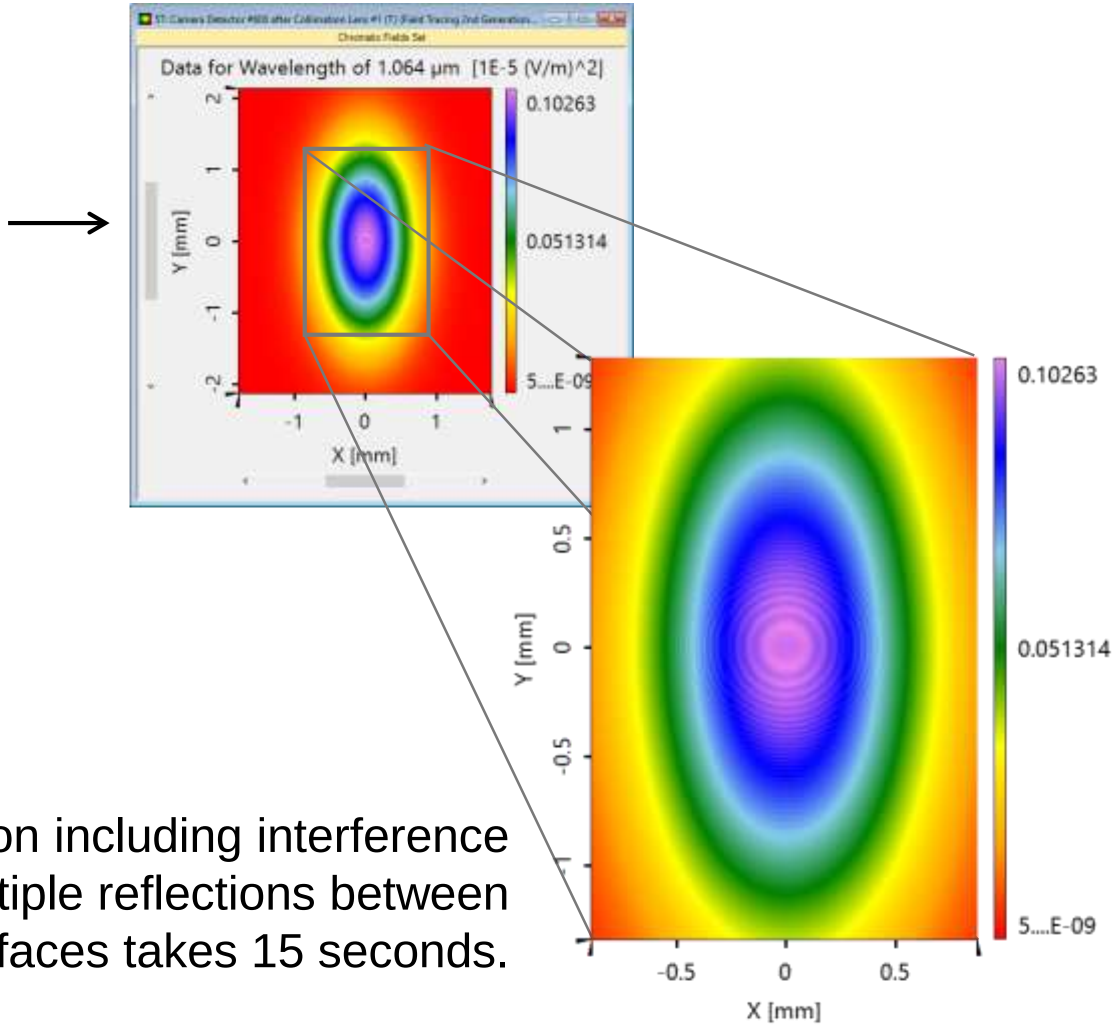
Perfect AR coating is assumed, so sequential modeling is used.

Collimation System: Non-Sequential Simulation



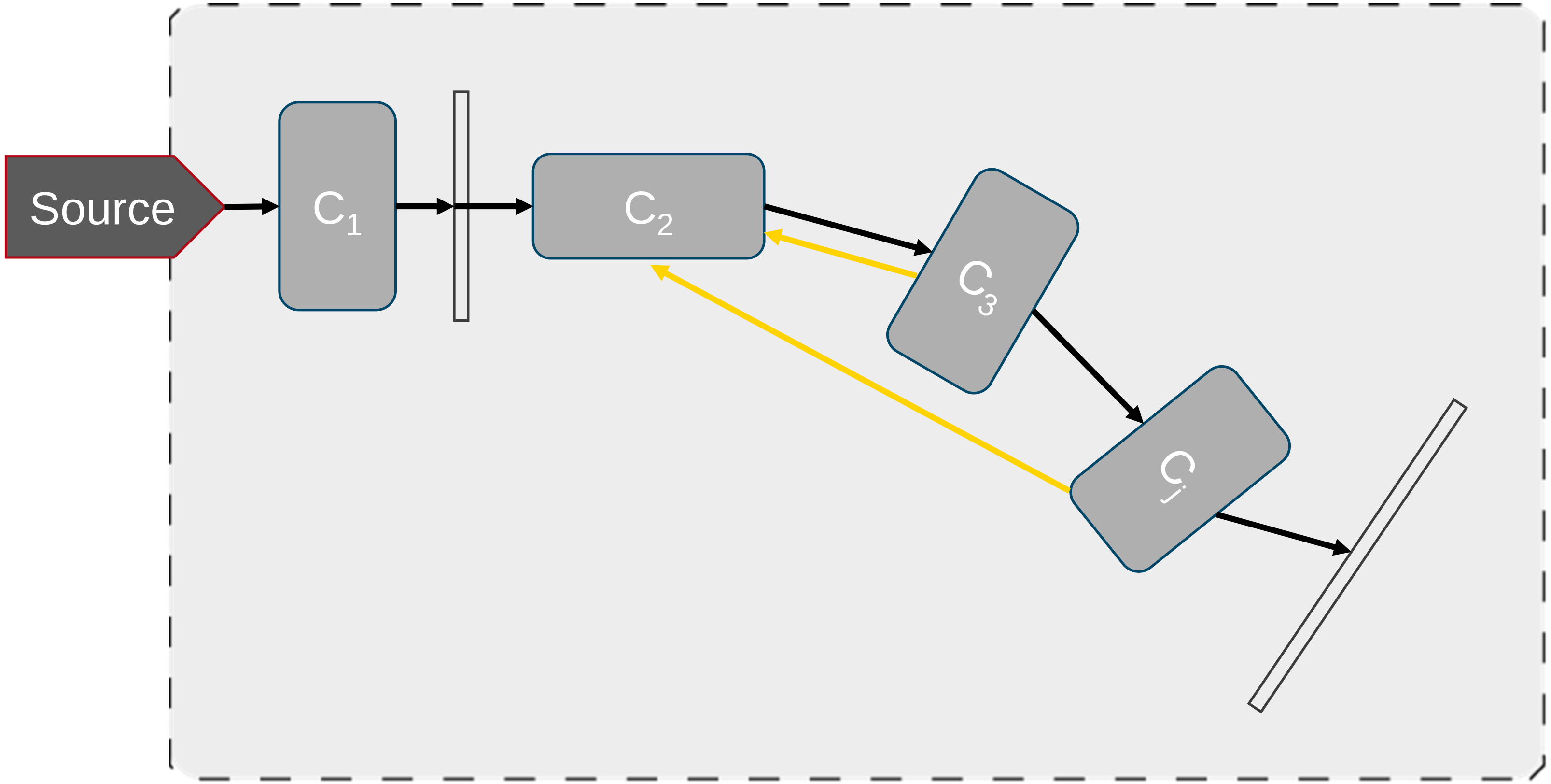
Laser Components WSLD-1064-050m-1-PD

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



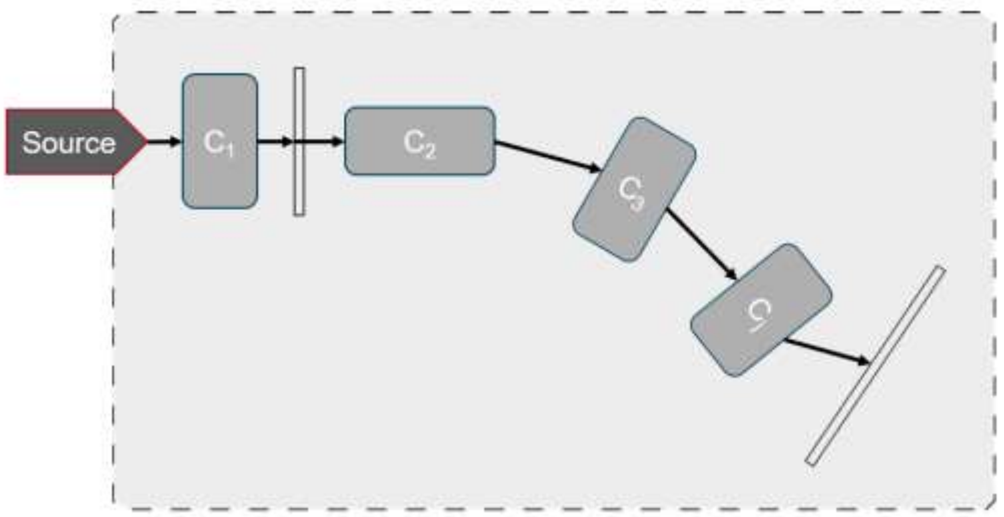
Simulation including interference caused by multiple reflections between uncoated surfaces takes 15 seconds.

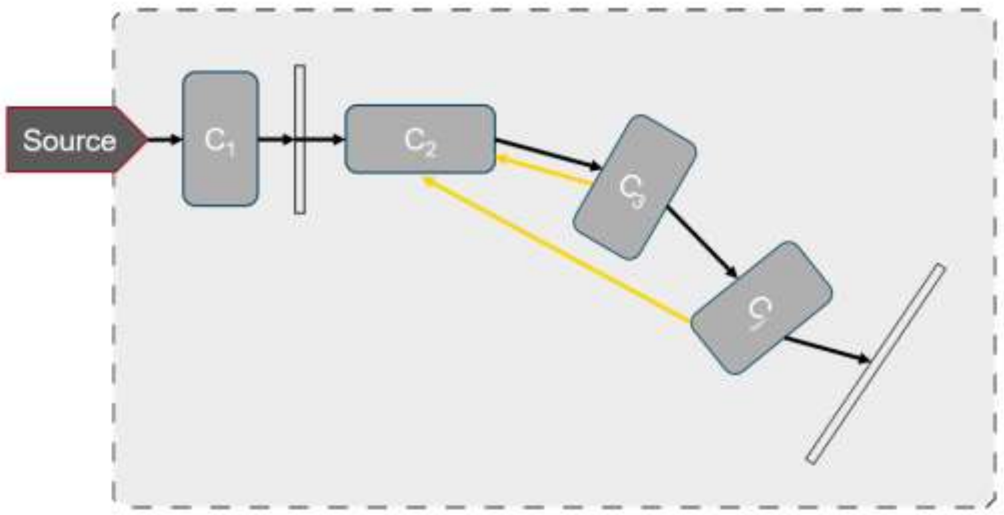
Optical Modeling: Non-Sequential



Conclusion of First Question

What is sequential and non-sequential tracing?

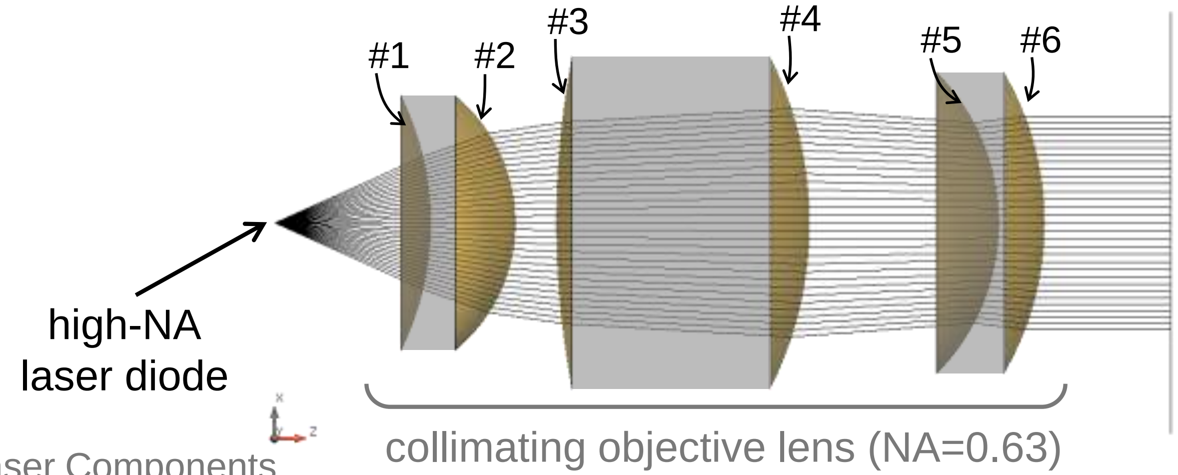




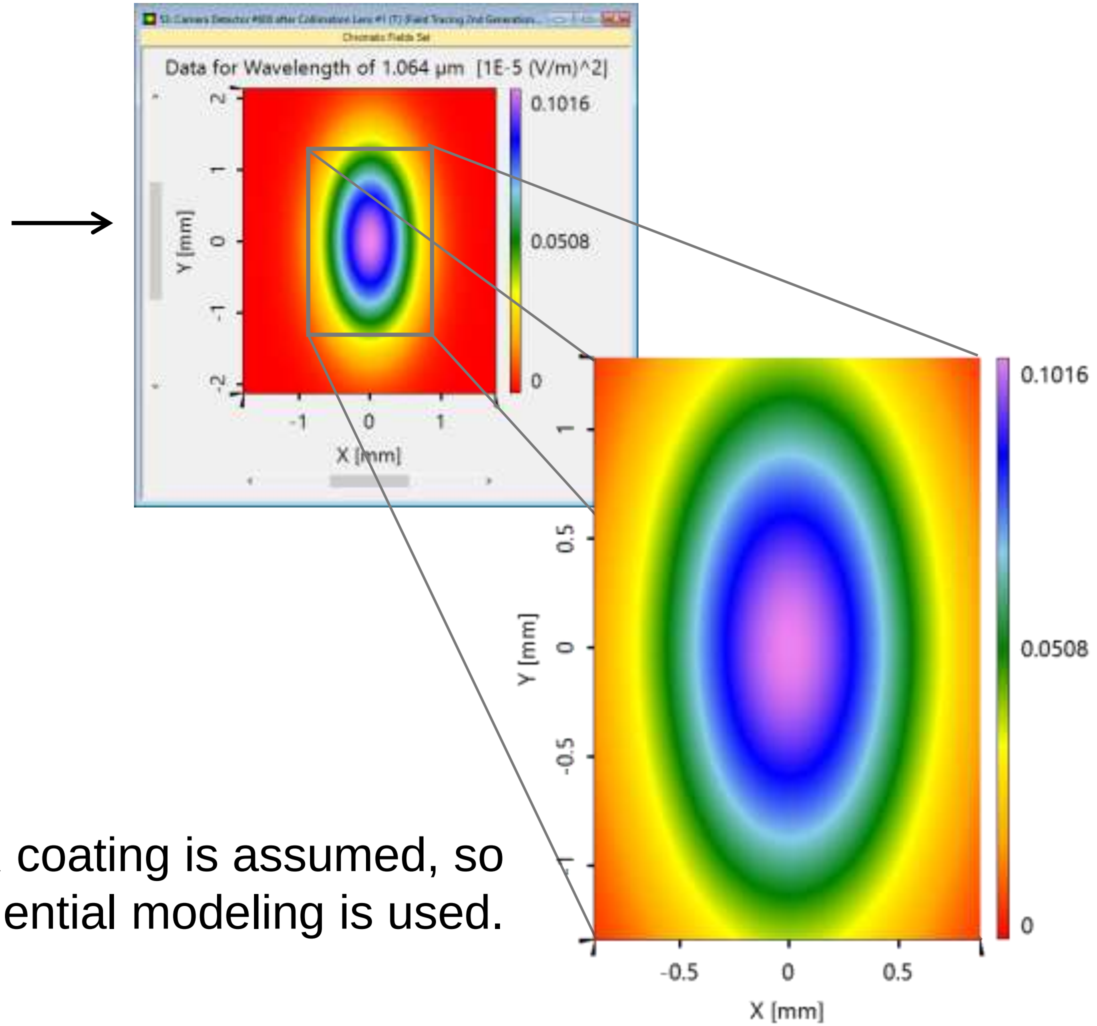
- Users predefine the sequence of the components, and light propagation through follows the sequence.
- Light propagates through/reflects from one component just once.

- Light propagation does not follow any sequence.
- Light propagates through/reflects several times from one component.
- Note: sequence of components here is only used for positioning.

Collimation System: Sequential Simulation

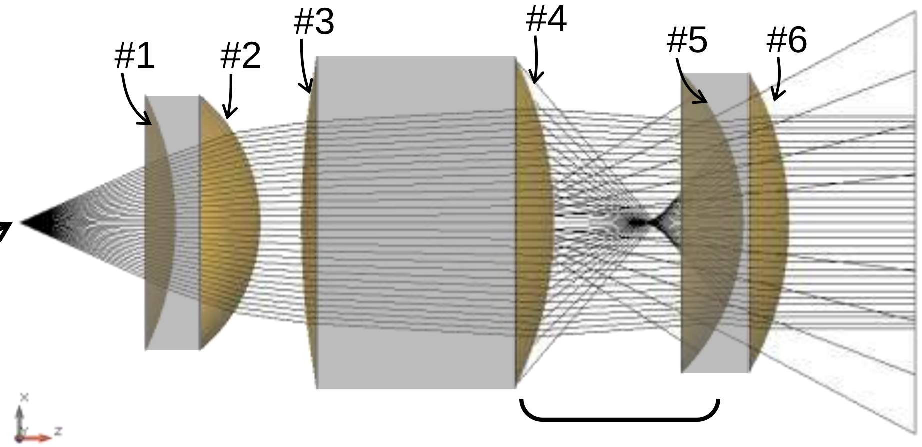


Laser Components
WSLD-1064-050m-1-PD
- fundamental Gaussian
- wavelength 1064 nm
- divergence (FWHM) 20° x 10°
- astigmatism 11.6 µm between *x*- and *y*-plane



Perfect AR coating is assumed, so sequential modeling is used.

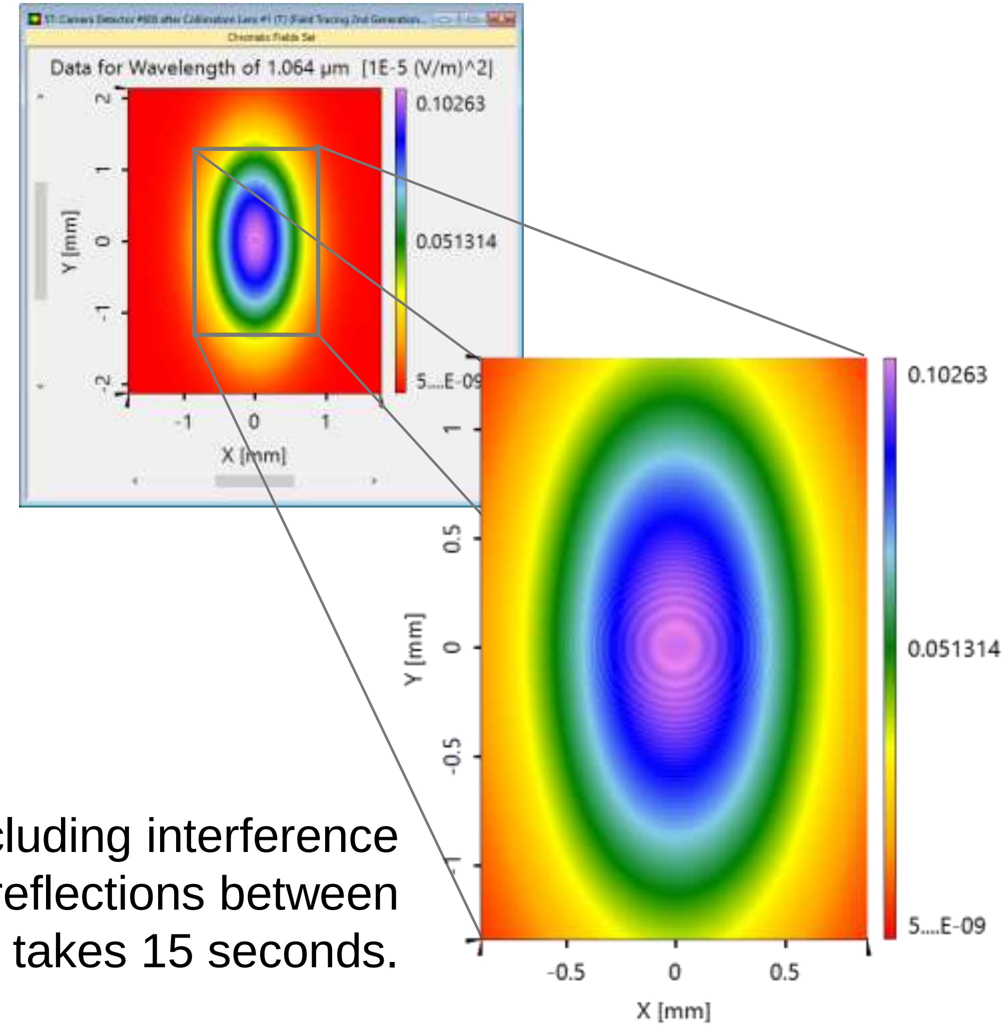
Collimation System: Non-Sequential Simulation



high-NA
laser diode

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

multiple reflections between uncoated surfaces #4 and #5, other surfaces are well coated.



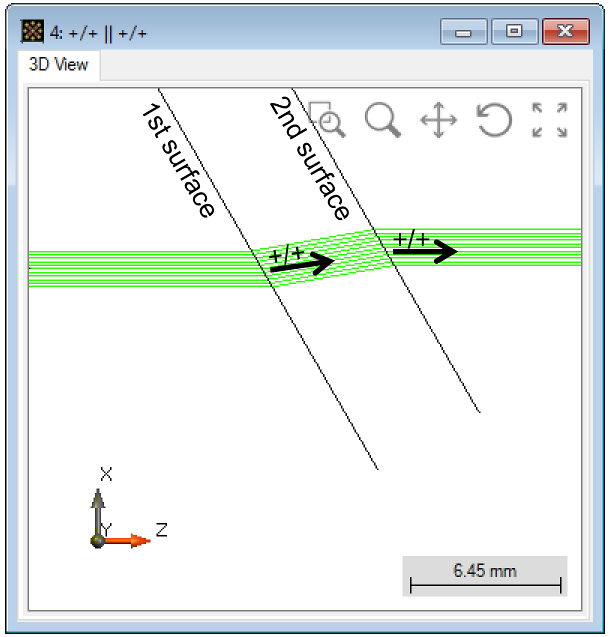
Simulation including interference caused by multiple reflections between uncoated surfaces takes 15 seconds.

How to Enable Sequential and Non-Sequential Tracing?

-- Channel Concept

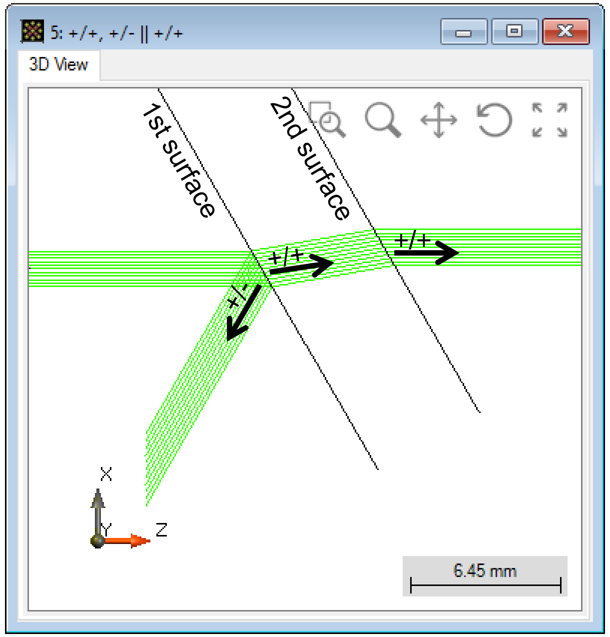
Channels

- Setting A



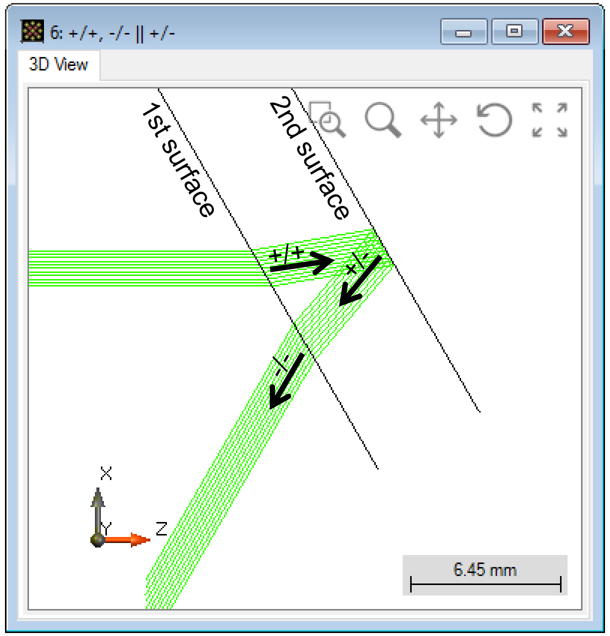
Surface	+/+	+/-	-/-	-/+
1st	×			
2nd	×			

- Setting B



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

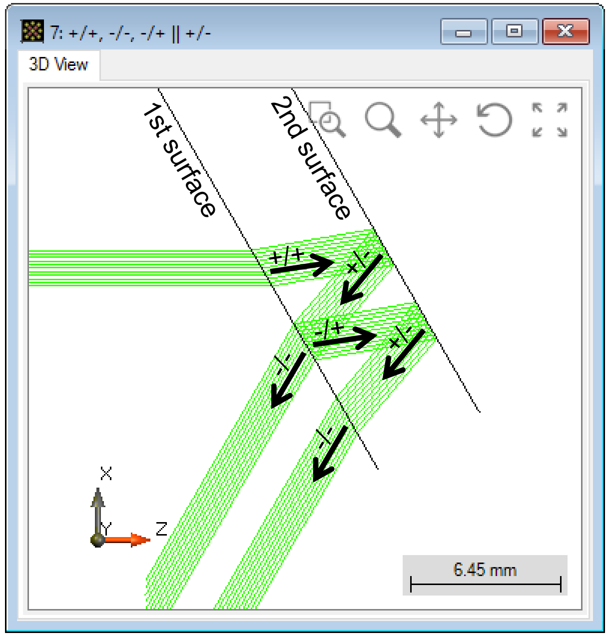
- Setting C



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

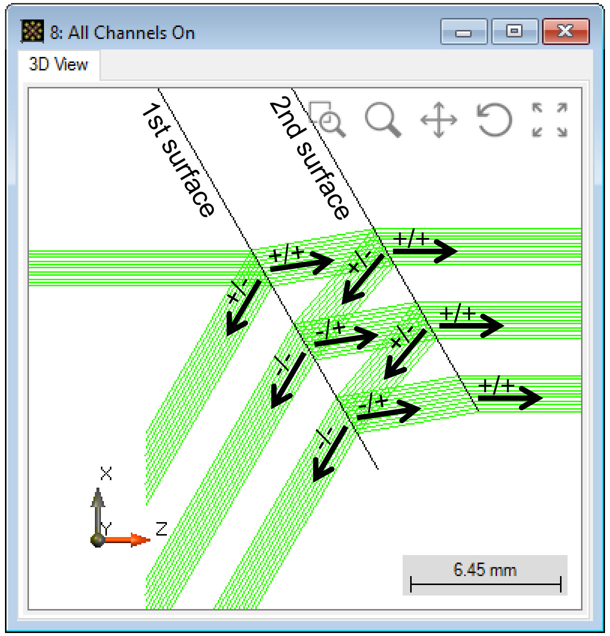
Channels

- Setting D



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

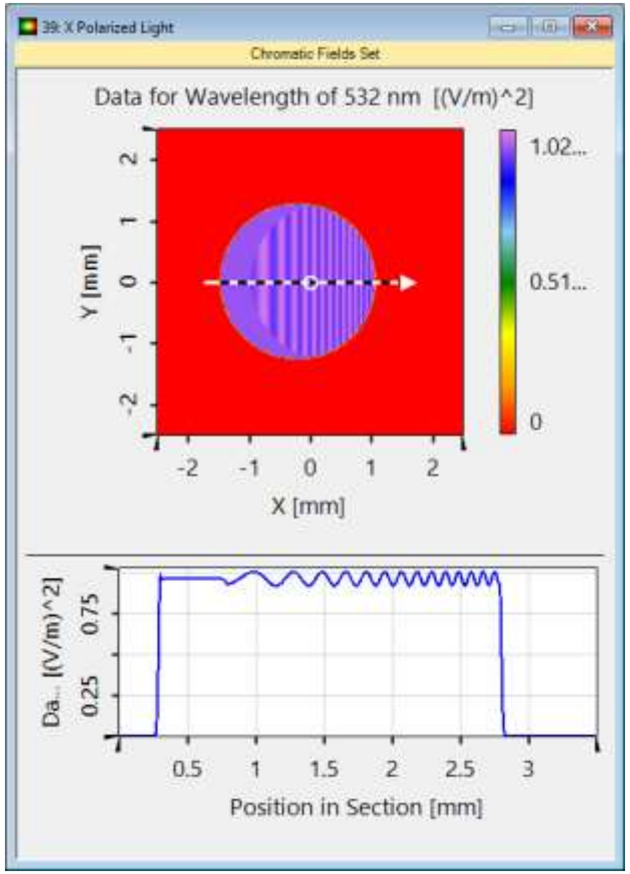
- Setting E



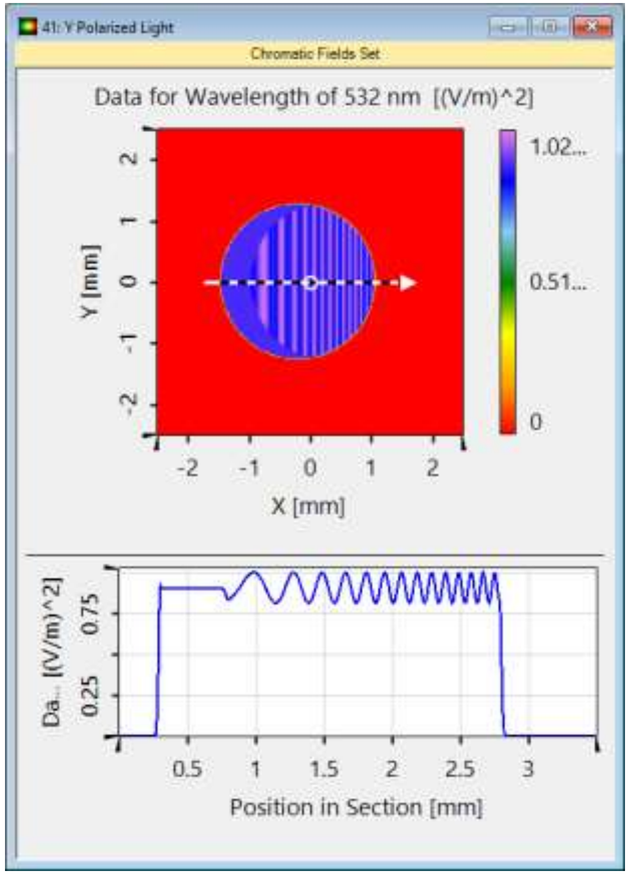
Surface	+/+	+/-	-/-	-/+
1st	×	×	×	×
2nd	×	×	×	×

Illustration 6: Optical Etalon

- Configuration of input field
  - plane wave
  - polarization (try both)
    - E_x-polarized
    - E_y-polarized
- Configuration of etalon
  - cylindrical-planar
  - center thickness 700 µm
  - cylindrical surface radius 1 m



x polarized light

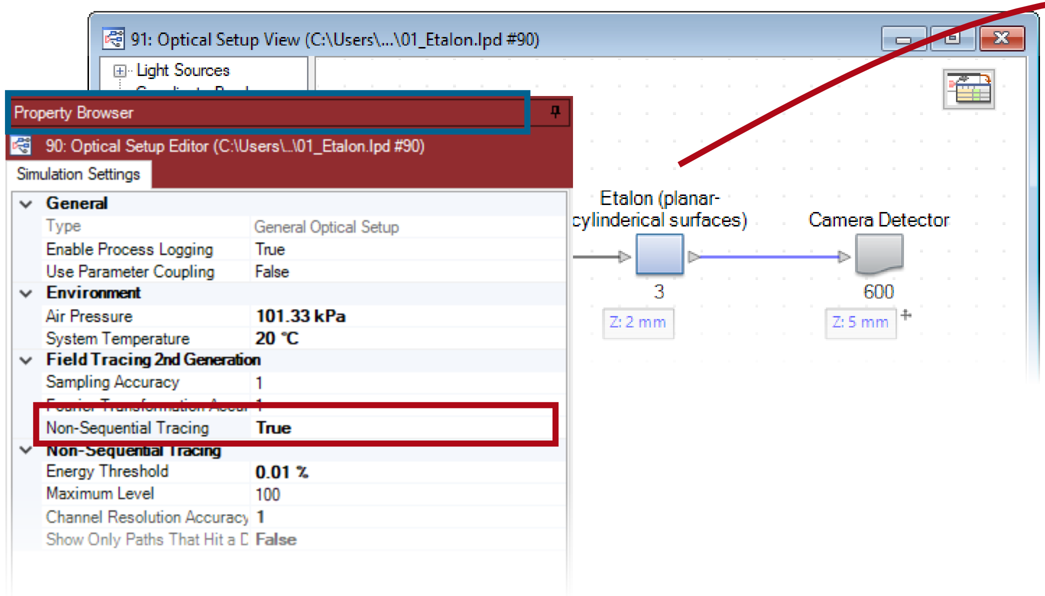


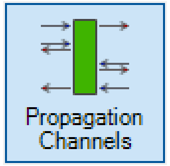
y polarized light

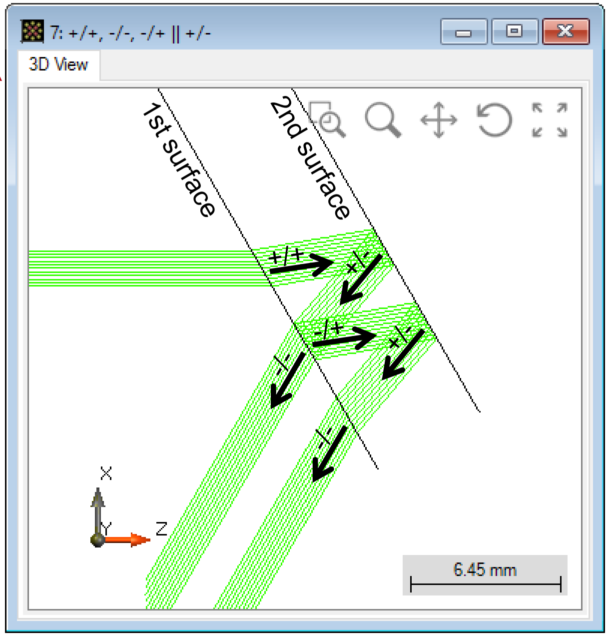
Video can be checked in https://www.youtube.com/watch?v=M5NevuRfsrg&t=1052s

Conclusion of Second Question

- How to enable sequential and non-sequential tracing?



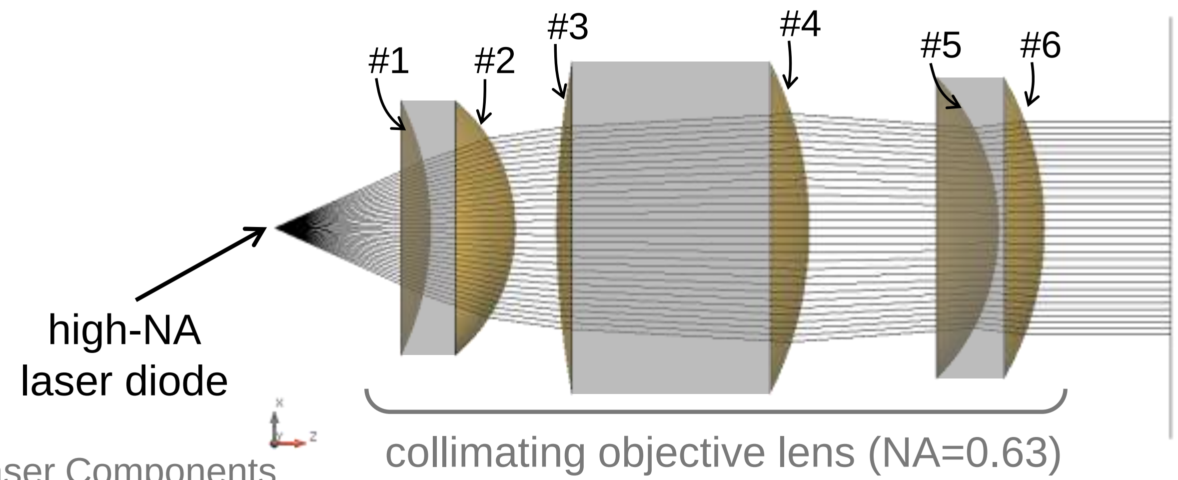


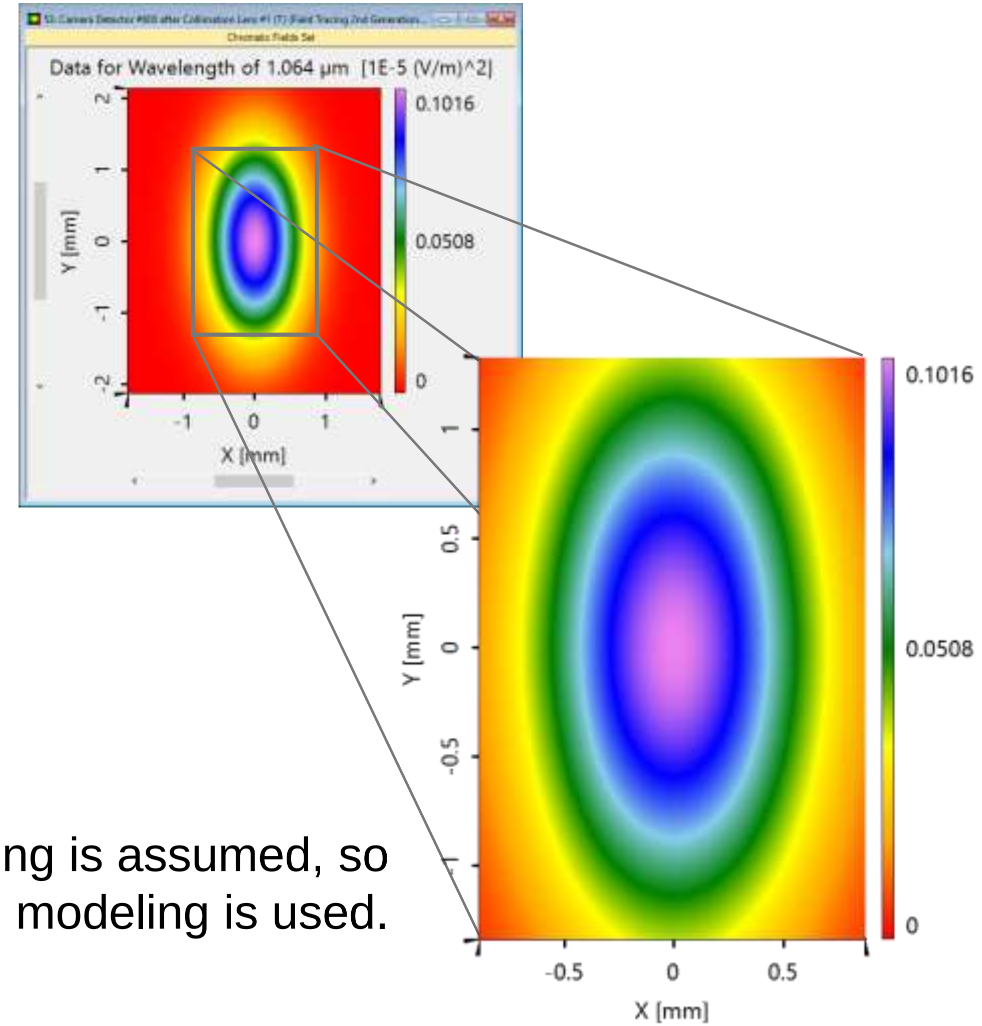


  - For each Optical Setup, enable the term *Non-Sequential Tracing*
  - Four channels can be chosen in each surface/component (+/+, +/-, -/-, -/+)

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

Task 7: Collimation System: Sequential Simulation



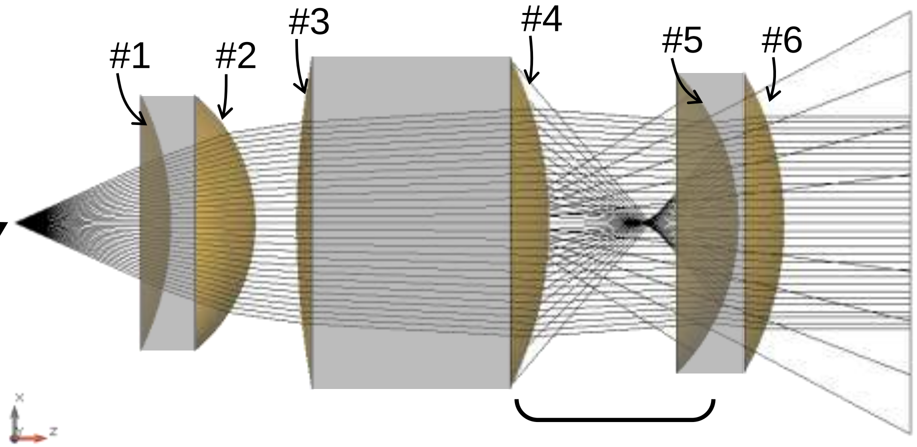


Laser Components WSLD-1064-050m-1-PD

- fundamental Gaussian
- wavelength 1064 nm
- divergence (FWHM) 10°x20°
- astigmatism 11.6 µm between *x*- and *y*-plane

Perfect AR coating is assumed, so sequential modeling is used.

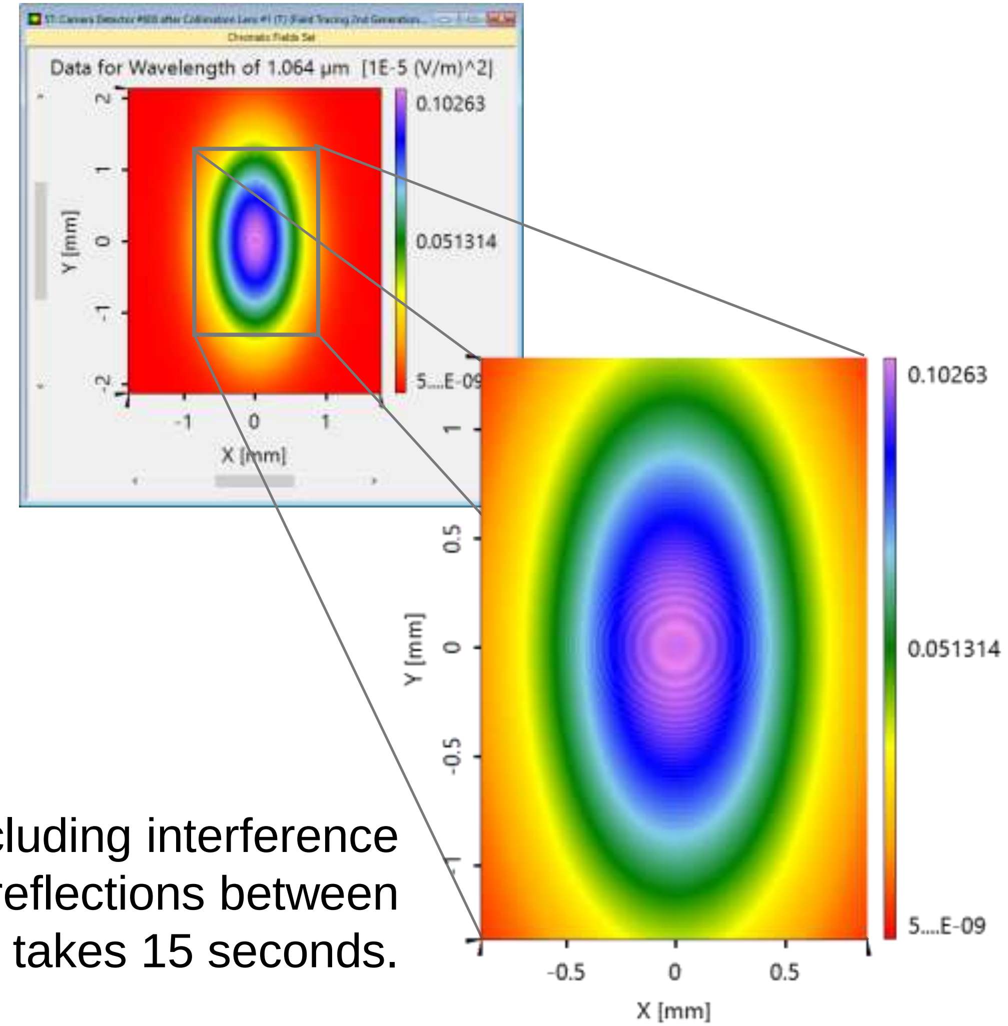
Collimation System: Non-Sequential Simulation



high-NA
laser diode

Laser Components
WSLD-1064-050m-1-PD
- fundamental Gaussian
- wavelength 1064 nm
- divergence (FWHM) 10°x20°
- astigmatism 11.6 µm between *x*- and *y*-plane

multiple reflections between uncoated surfaces #4 and #5, other surfaces are well coated.



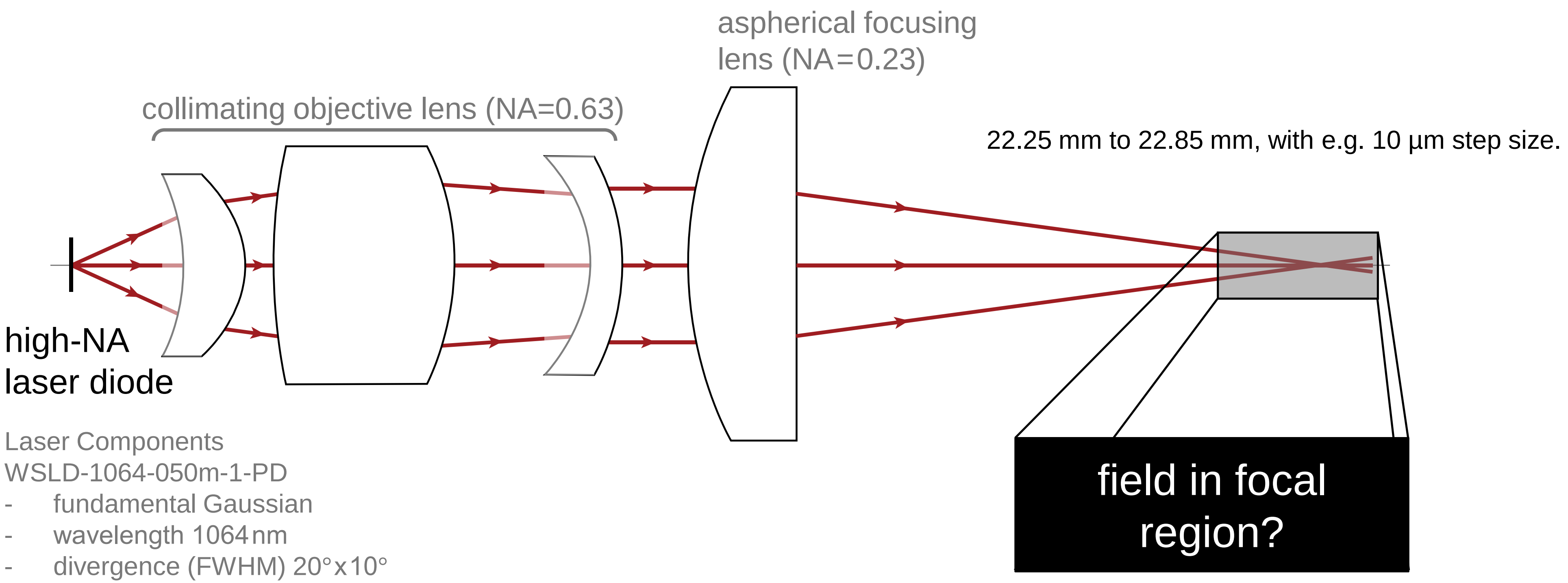
Simulation including interference caused by multiple reflections between uncoated surfaces takes 15 seconds.

Task 7: Video

Klick the following link to watch the video:

https://youtu.be/s3BBNPZ1E-c

Task 8 Focus Region Explore



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

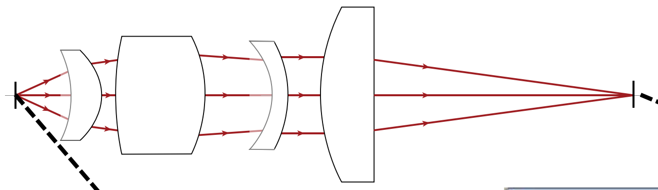
- fundamental Gaussian
- wavelength 1064 nm
- divergence (FWHM) 20° x 10°
- astigmatism 11.6 µm between *x*- and *y*-plane

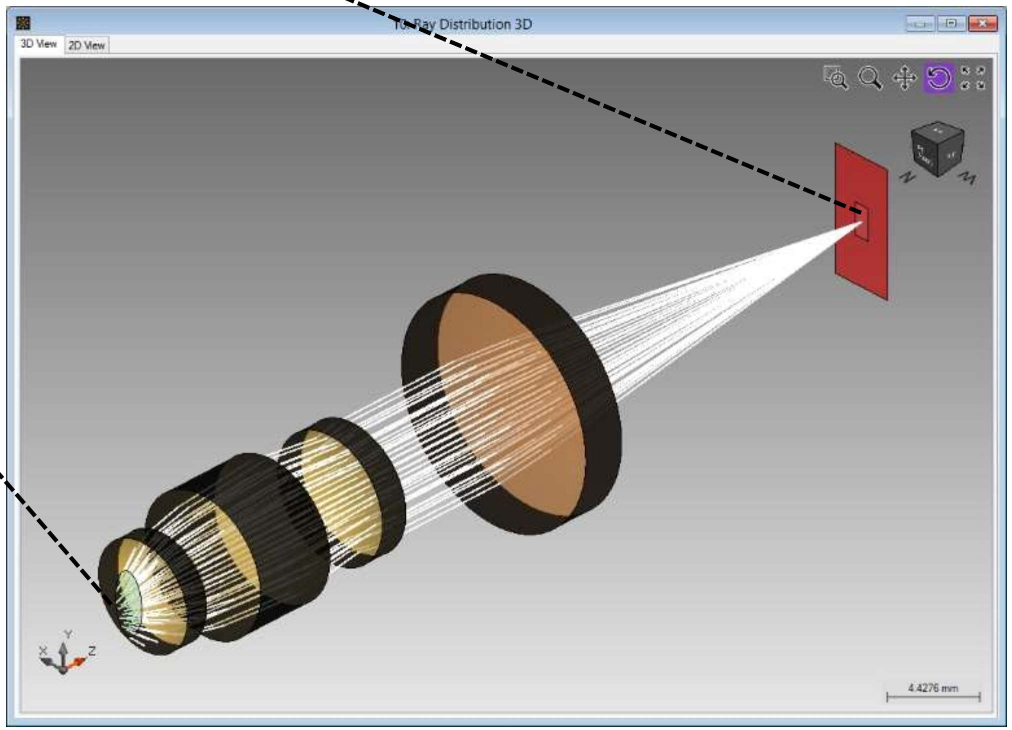
What is the field in focal region behind an aspherical lens? Especially, the astigmatism of the laser diode must be taken into account.

Detector model choice

Results

- Ray tracing – system in 3D space

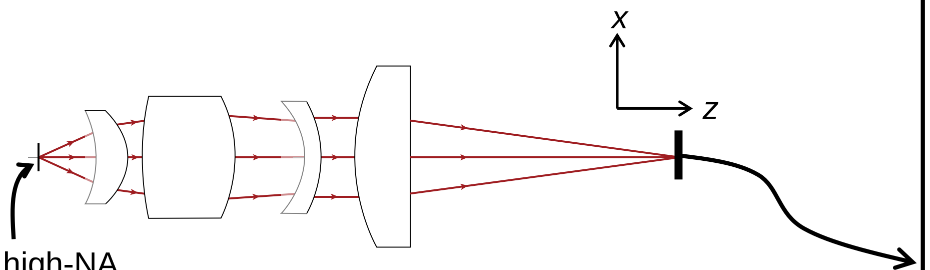




Ray-tracing analysis provides a fast overview of the system in space.

Results

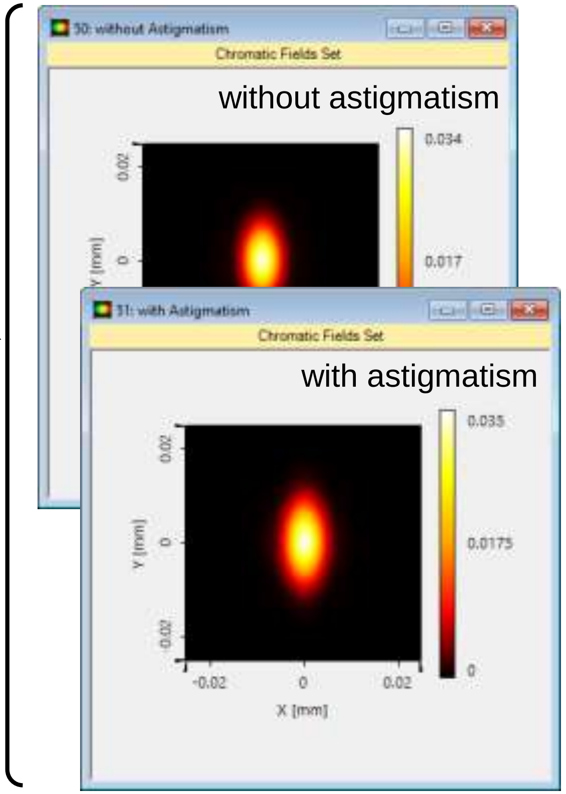
- Field tracing



high-NA
laser diode
with or w/o
astigmatism

diameter of focused beams

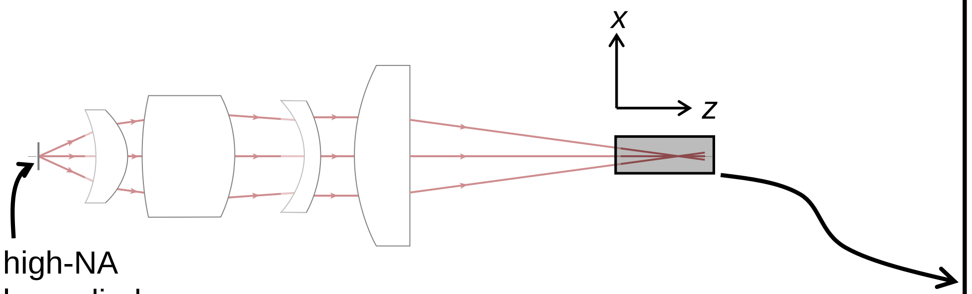
diameter	With astigmatism	Without astigmatism
x direction	11.80 µm	11.41 µm
y direction	21.48 µm	19.23 µm

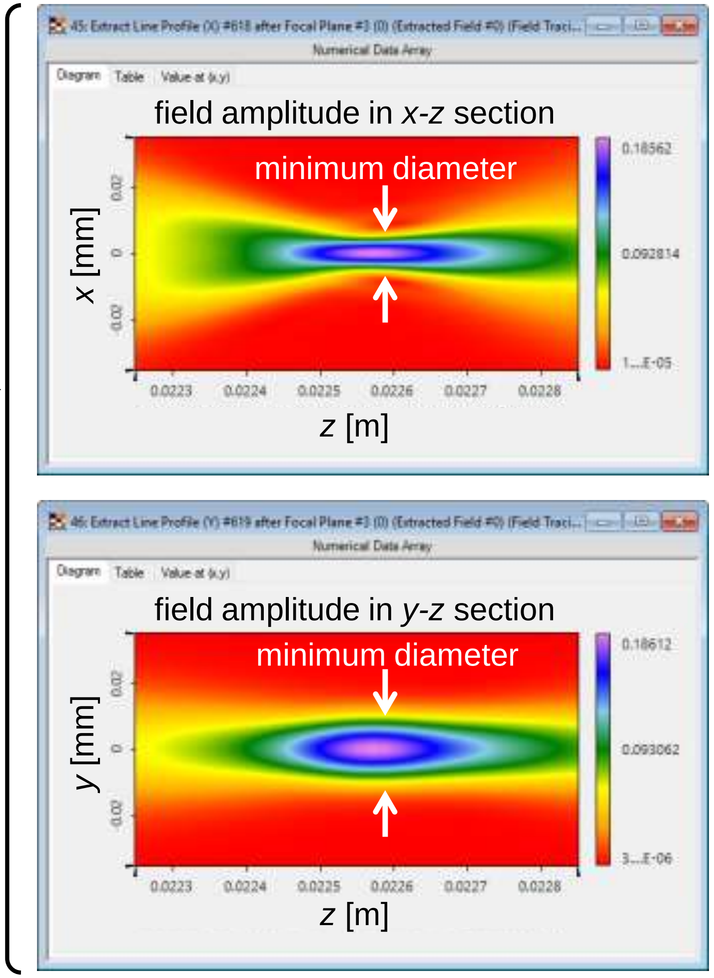


Physical-optics simulation of whole system, including collimation and focusing lenses, takes only 2 seconds!

Results

- Field tracing

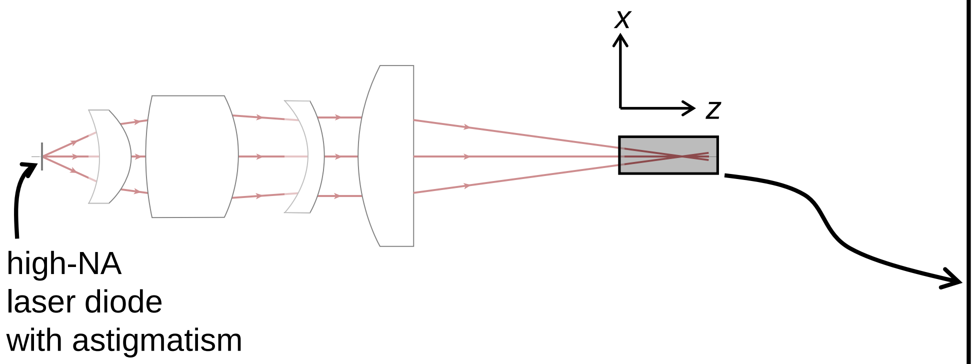


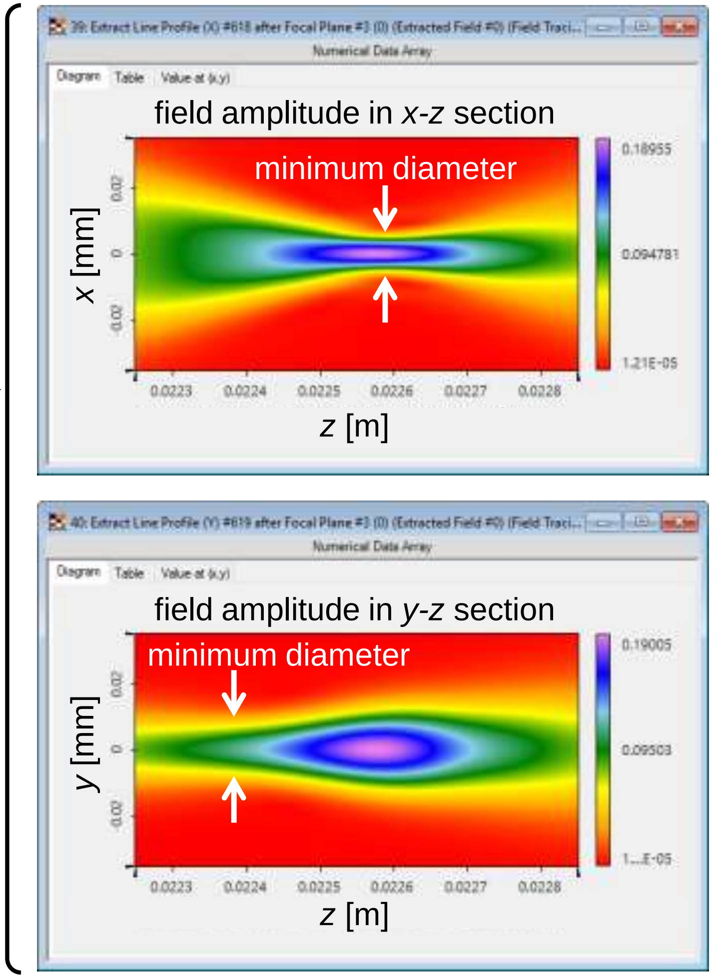


Physical-optics simulation of field evaluation within focal region, over 30 steps, takes about 90 seconds.

Results

- Field tracing

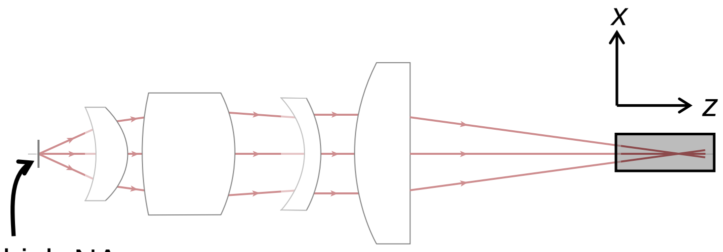




Minimum beam diameters appear at different positions along *x* and *y* directions, due to astigmatism of the laser diode.

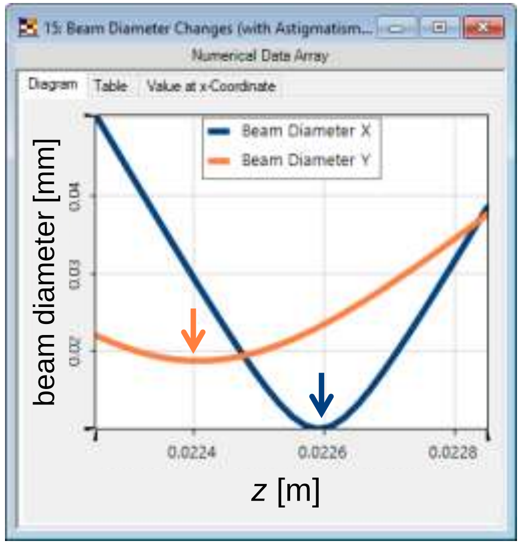
Results

- Field tracing

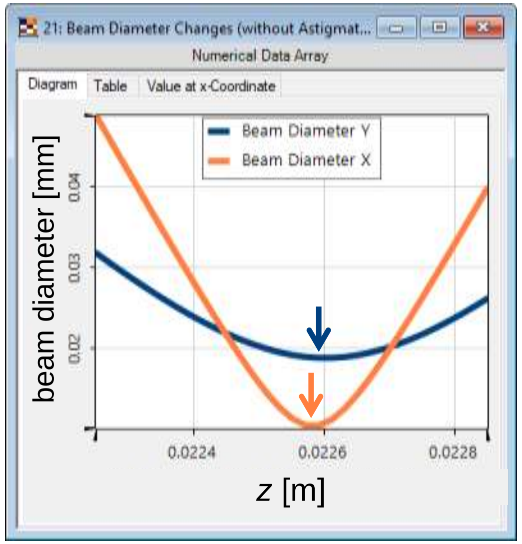


high-NA
laser diode
with or w/o
astigmatism

quantitative measurement of
the evolution of beam
diameters in both directions



with astigmatism



without astigmatism

Task 8: Video

Klick the following link to watch the video:

https://youtu.be/Og6rAoCHVkQ

Task 1 Donut mode creation

- Donut mode can be created by adding two Hermite Gaussian modes up.
  - By using the permanent ribbons, please generate two Gaussian beams:

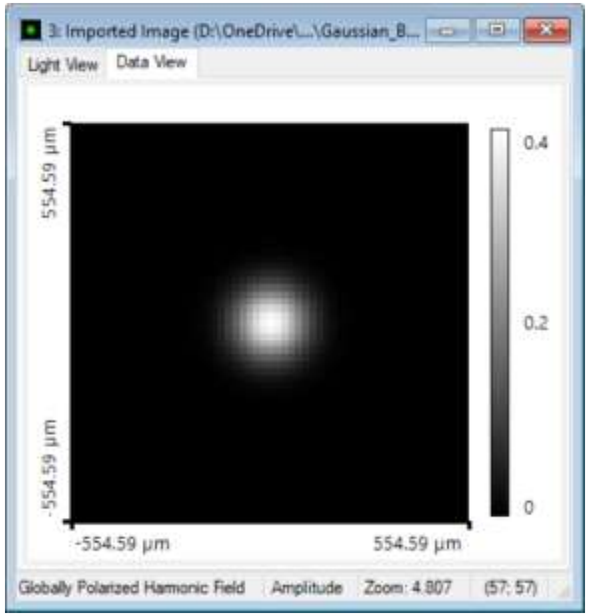
Hermite Gaussian mode: (1,0)	Hermite Gaussian mode: (0,1)
Rayleigh length: 10 mm x 10 mm	Rayleigh length: 10 mm x 10 mm
Single wavelength: 632.8 nm	Single wavelength: 632.8 nm
Polarization: linearly polarized 0°	Polarization: linearly polarized 90°

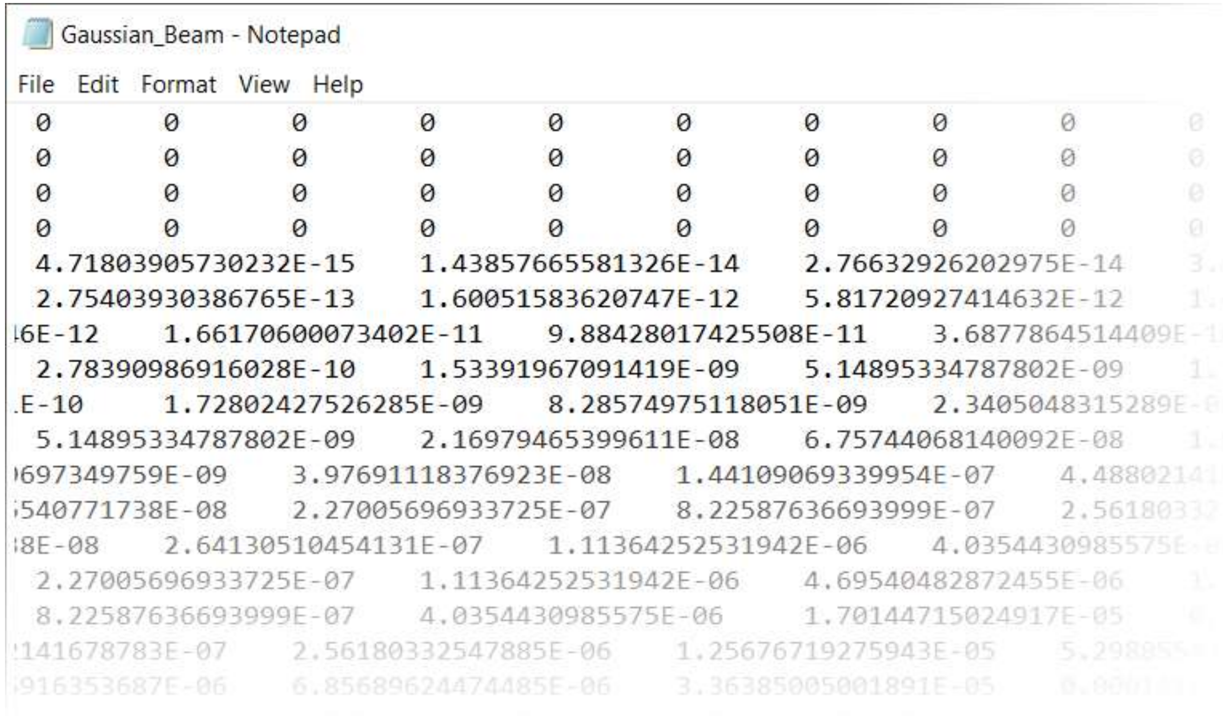
  - Add both Gaussian beam
  - Check the polarization state of the result field
  - Detect the beam parameters of electric field
  - Calculate the related Poynting Vector distribution

Main window modeling

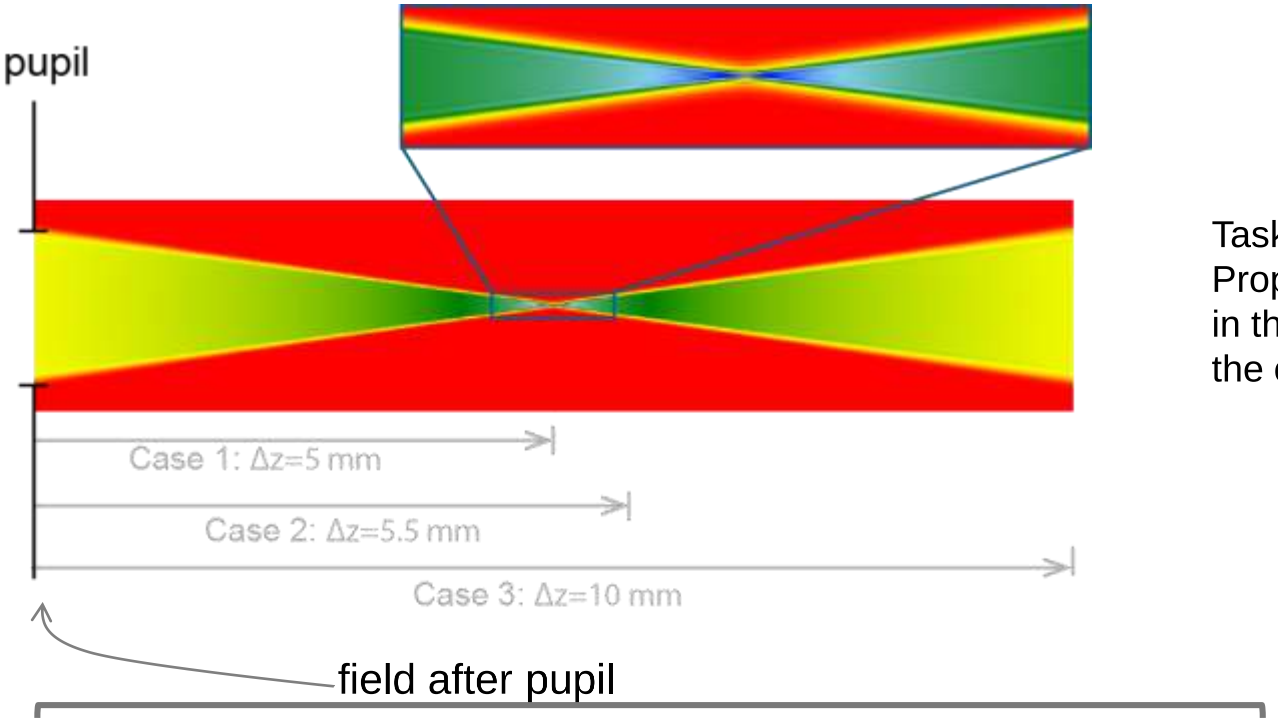
Task 2: Field Data Export and Import

- Export field data as figure/text
- Import field data into VLF and change the related numerical parameters.





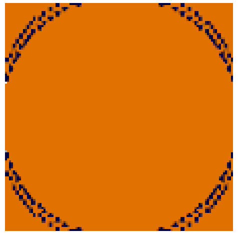
Task 3



Task:
Propagate the field after pupil in three cases, and observe the choices of (inverse) FTs

Truncated spherical field	
polarization	linearly polarized (0°)
sph. radius	5 mm

amplitude

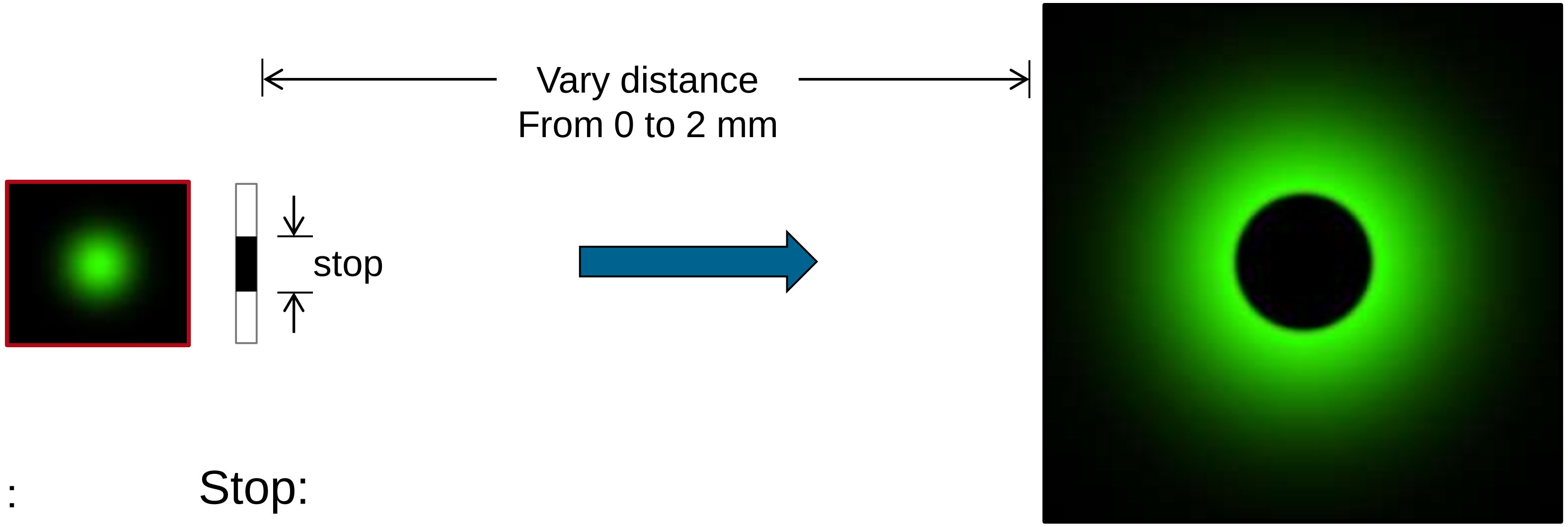


residual phase

Note:
Spherical phase is analytically recorded and tackled, so the residure phase of the field after pupil is a constant

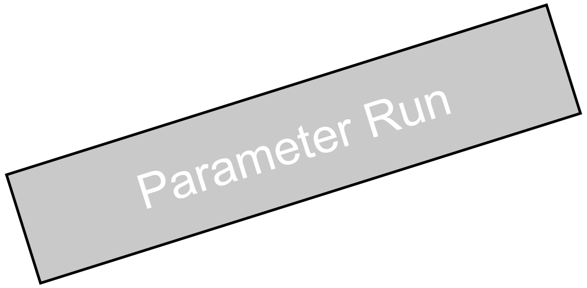
Task 4 Poisson Spot

- Diffraction



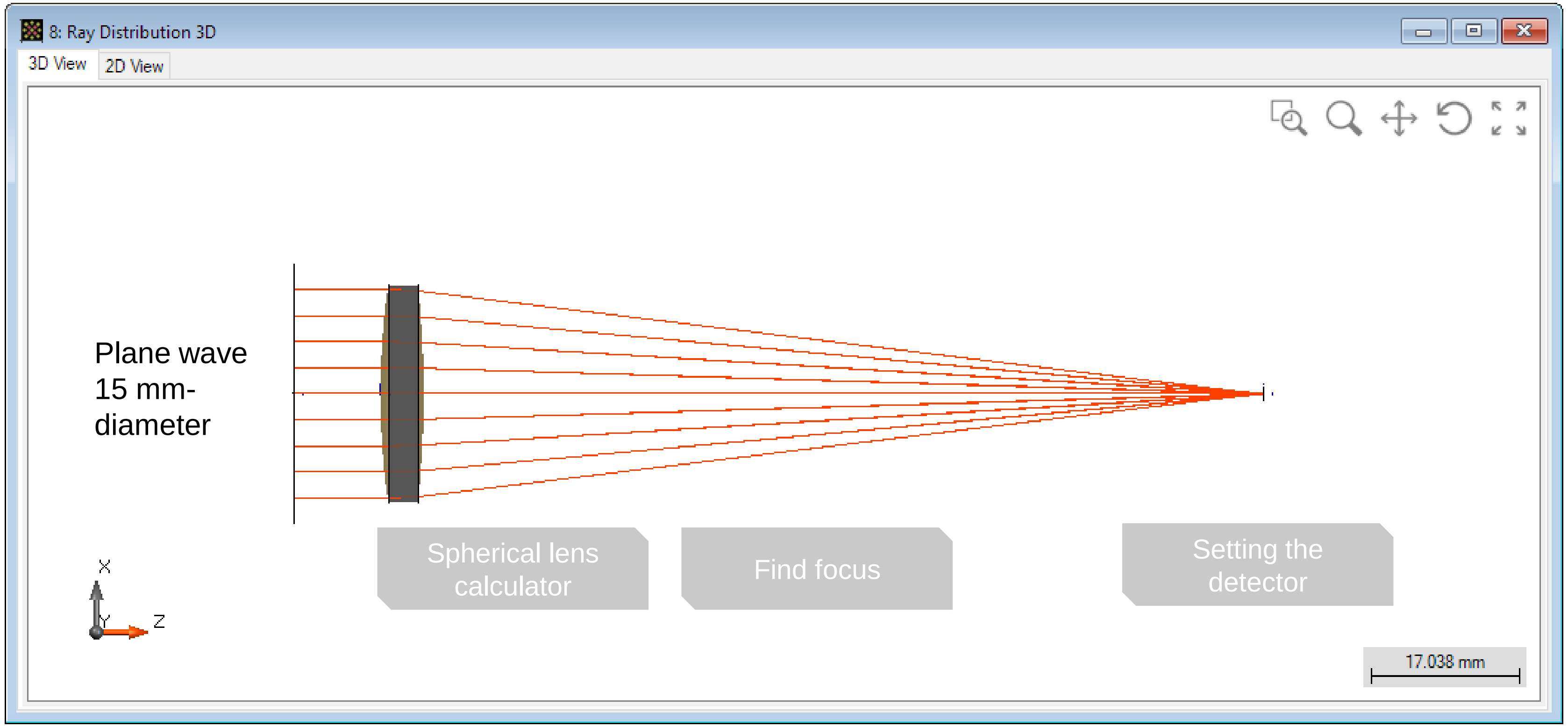
Gaussian : Default parameters

Stop:
100 µm x 100 µm

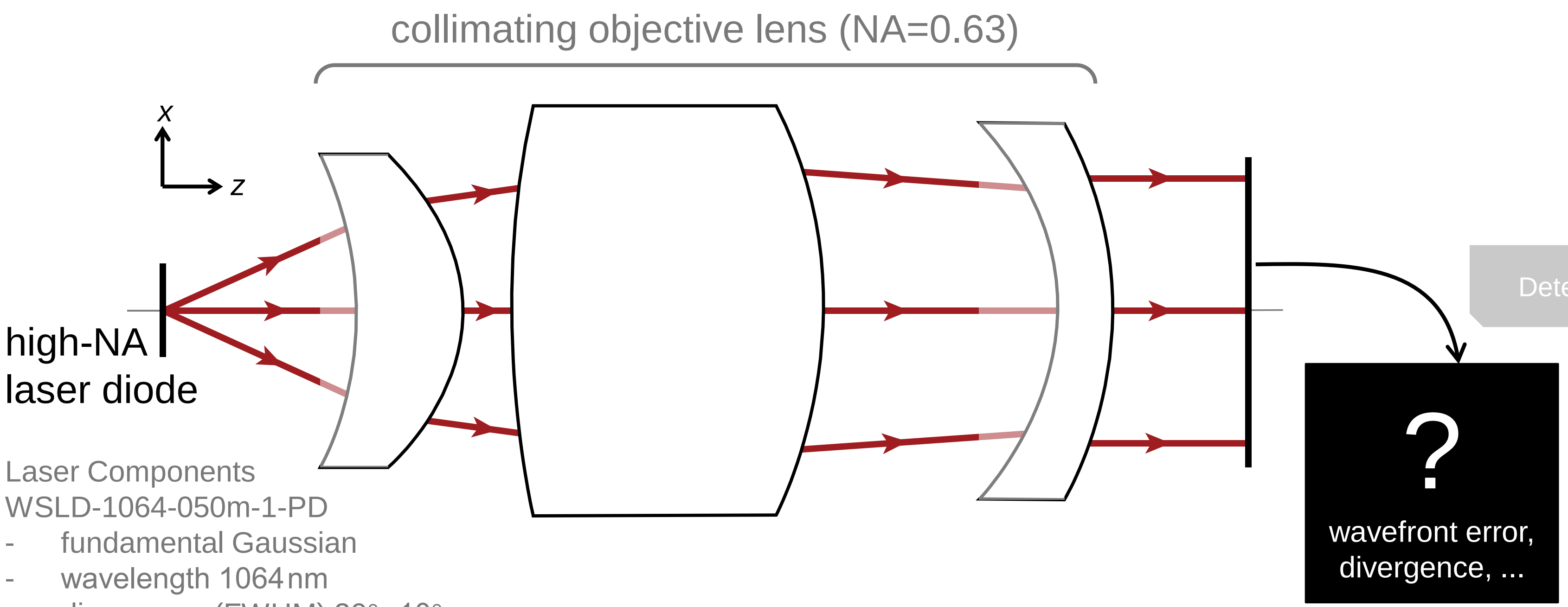


Task 5: Singlet

- Design of singlet with 100 mm effective focal length by ray tracing in VirtualLab.



Task 6 Analysis the Collimation System of an Astigmatic Laser Diode



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

- fundamental Gaussian
- wavelength 1064 nm
- divergence (FWHM) 20° x 10°
- astigmatism 11.6 μm between *x*- and *y*-plane

Detector model choice

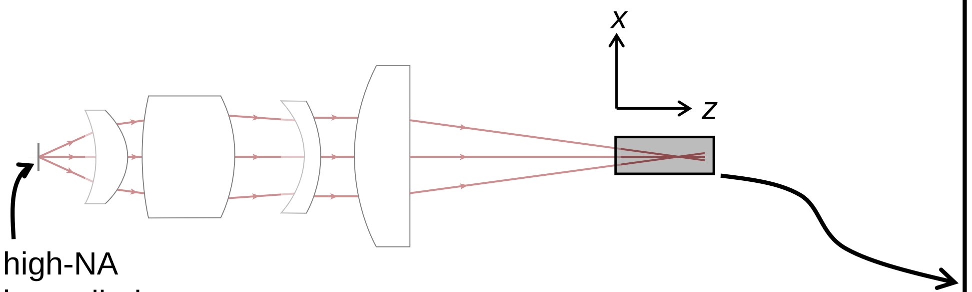
What is the wavefront error and divergence of the collimated beam, with the astigmatism taken into account?

Source setting

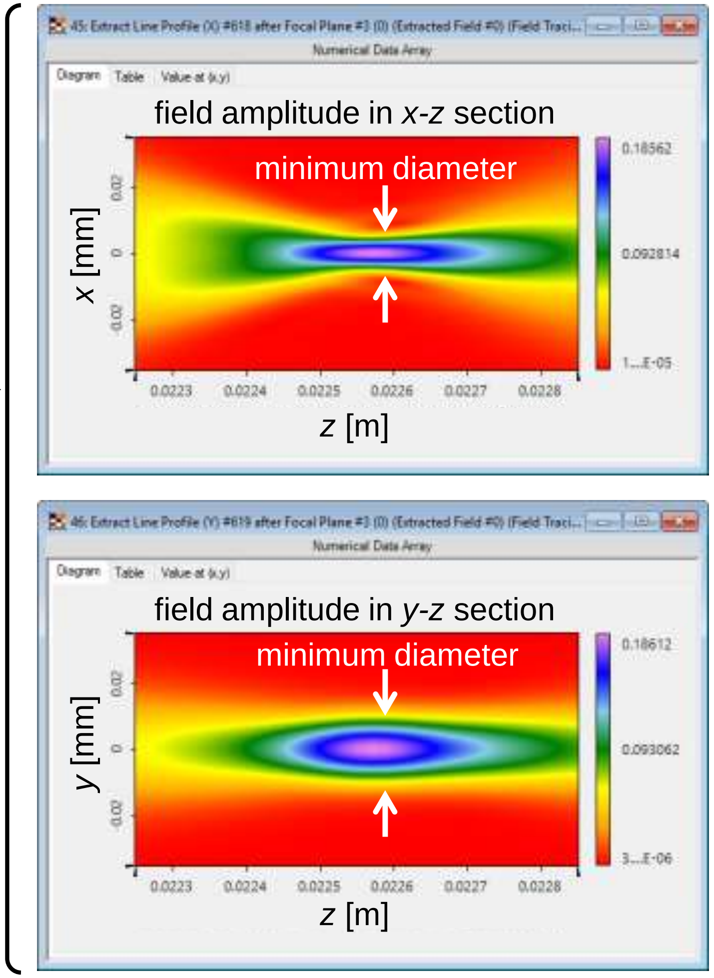
OIS and Parametric Overview

Task8

- Field tracing



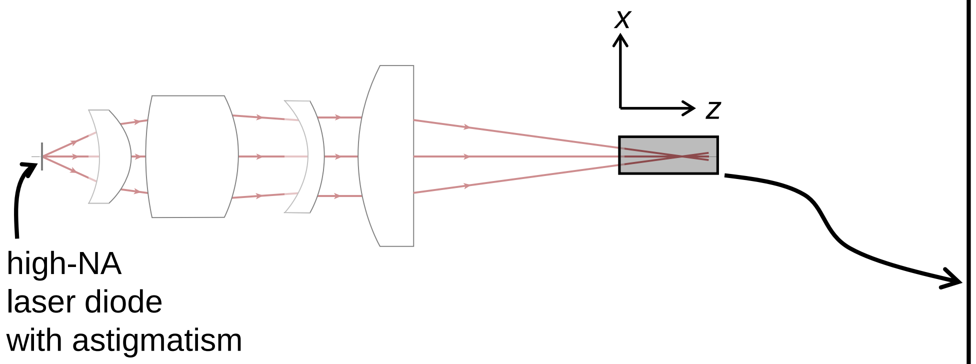
high-NA
laser diode
without astigmatism

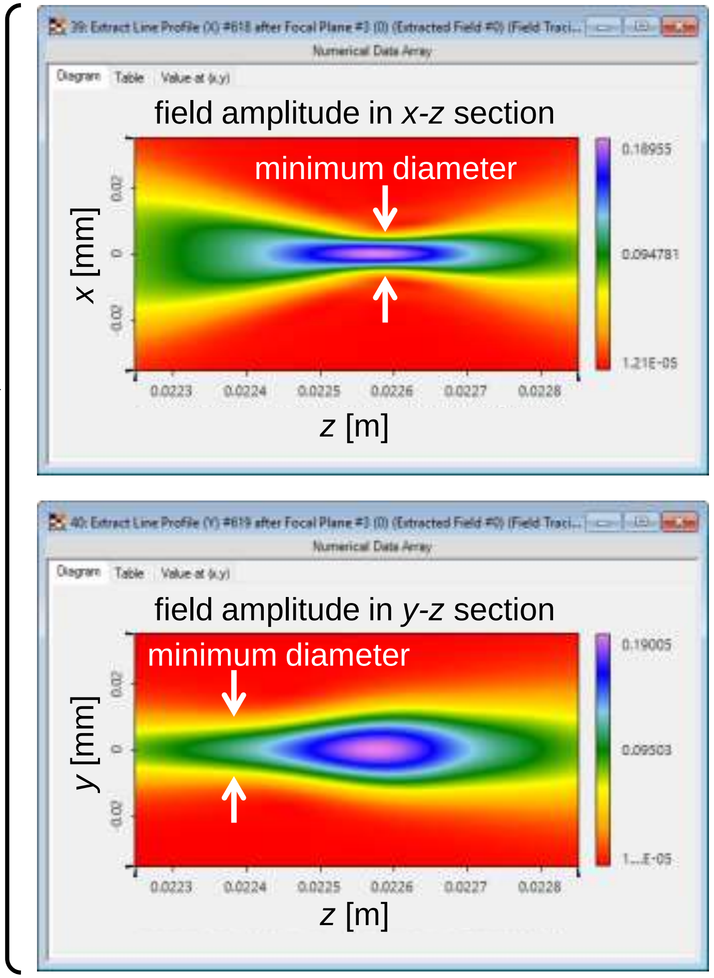


Physical-optics simulation of field evaluation within focal region, over 30 steps, takes about 90 seconds.

Results

- Field tracing

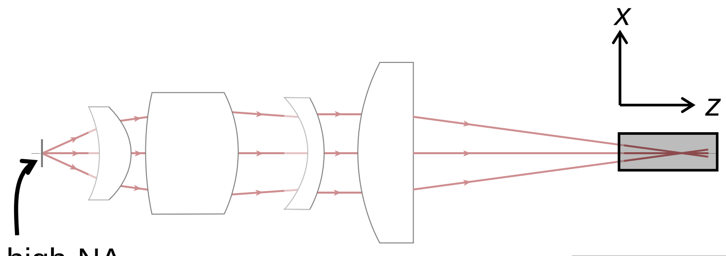




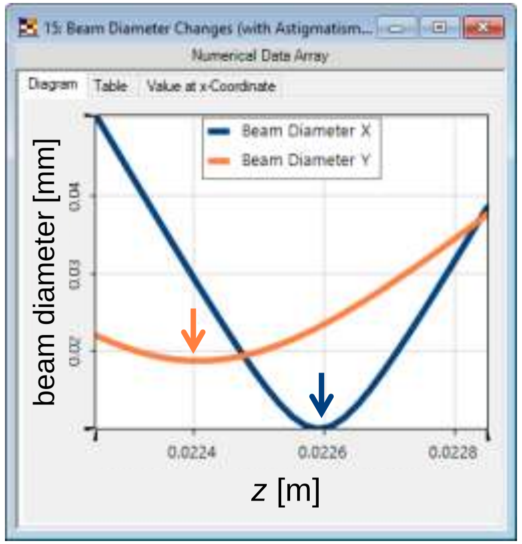
Minimum beam diameters appear at different positions along *x* and *y* directions, due to astigmatism of the laser diode.

Results

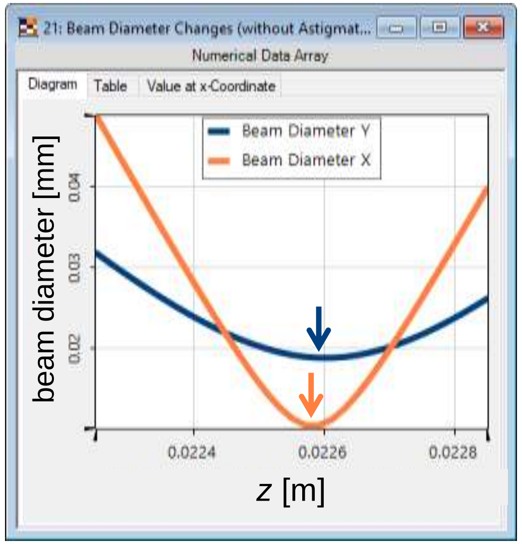
- Field tracing



quantitative measurement of the evolution of beam diameters in both directions



with astigmatism

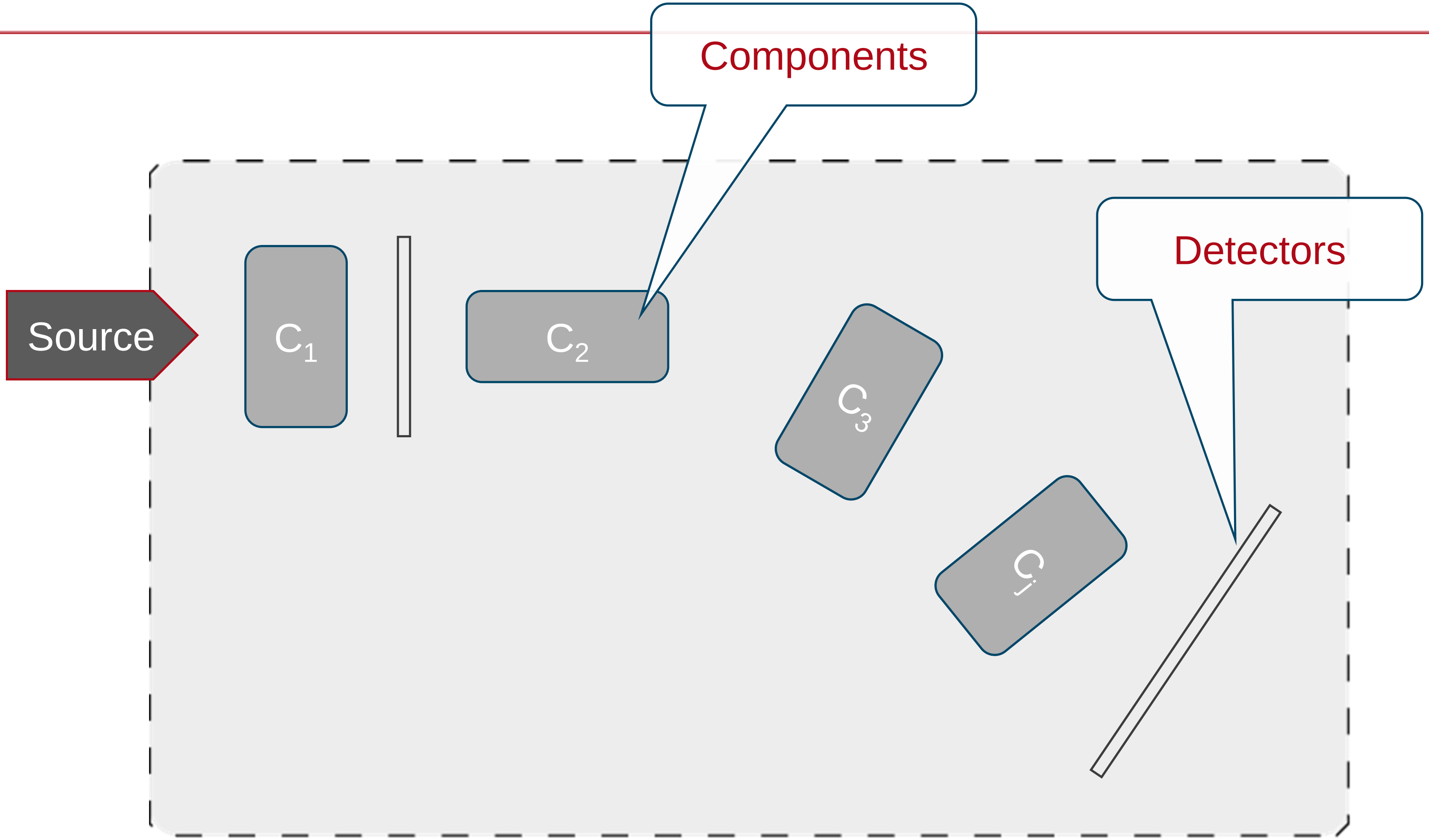


without astigmatism

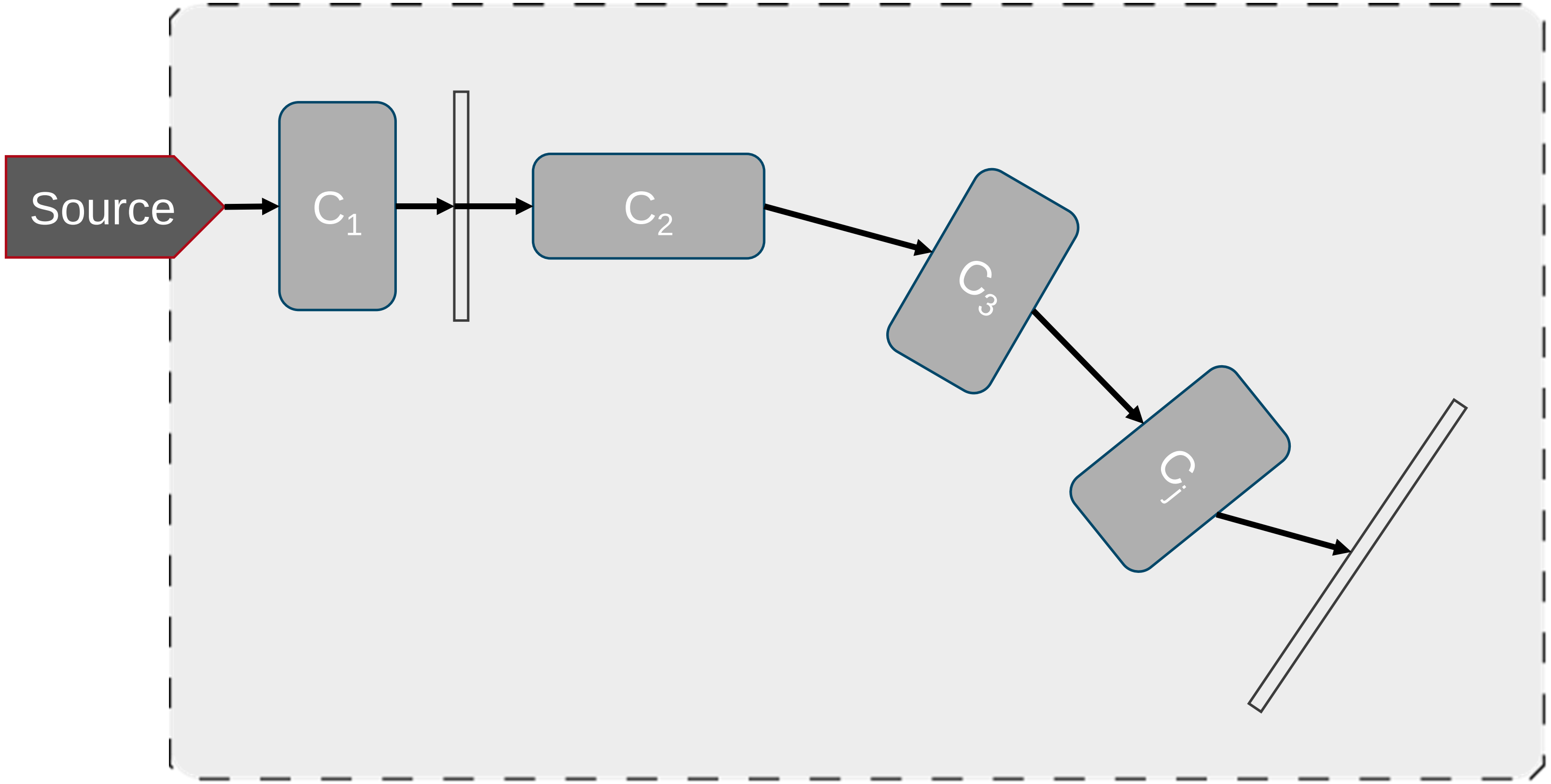
Feature: Sequential and Non-Sequential Tracing

What is Sequential and Non-Sequential Tracing?

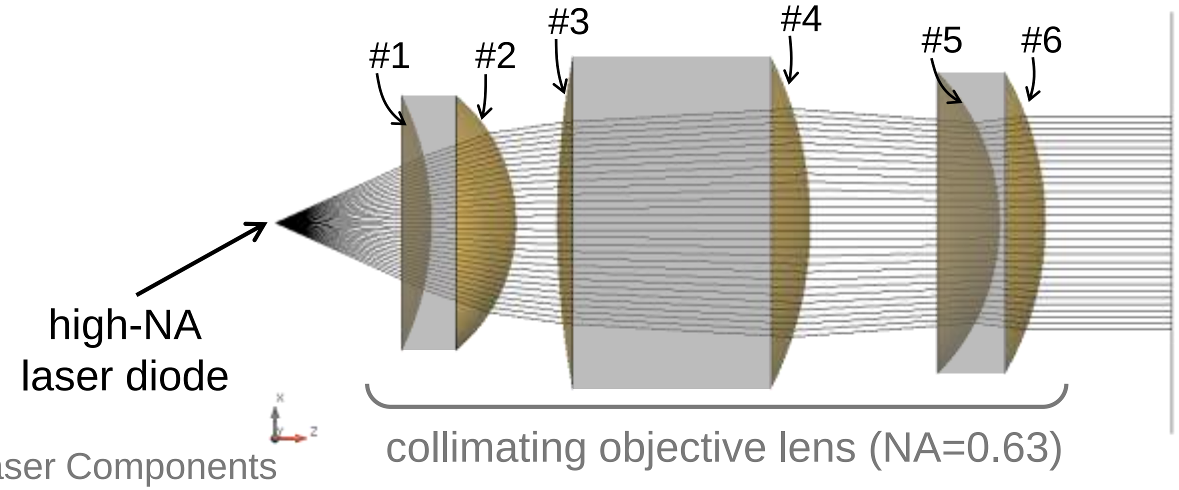
Optical Modeling Task

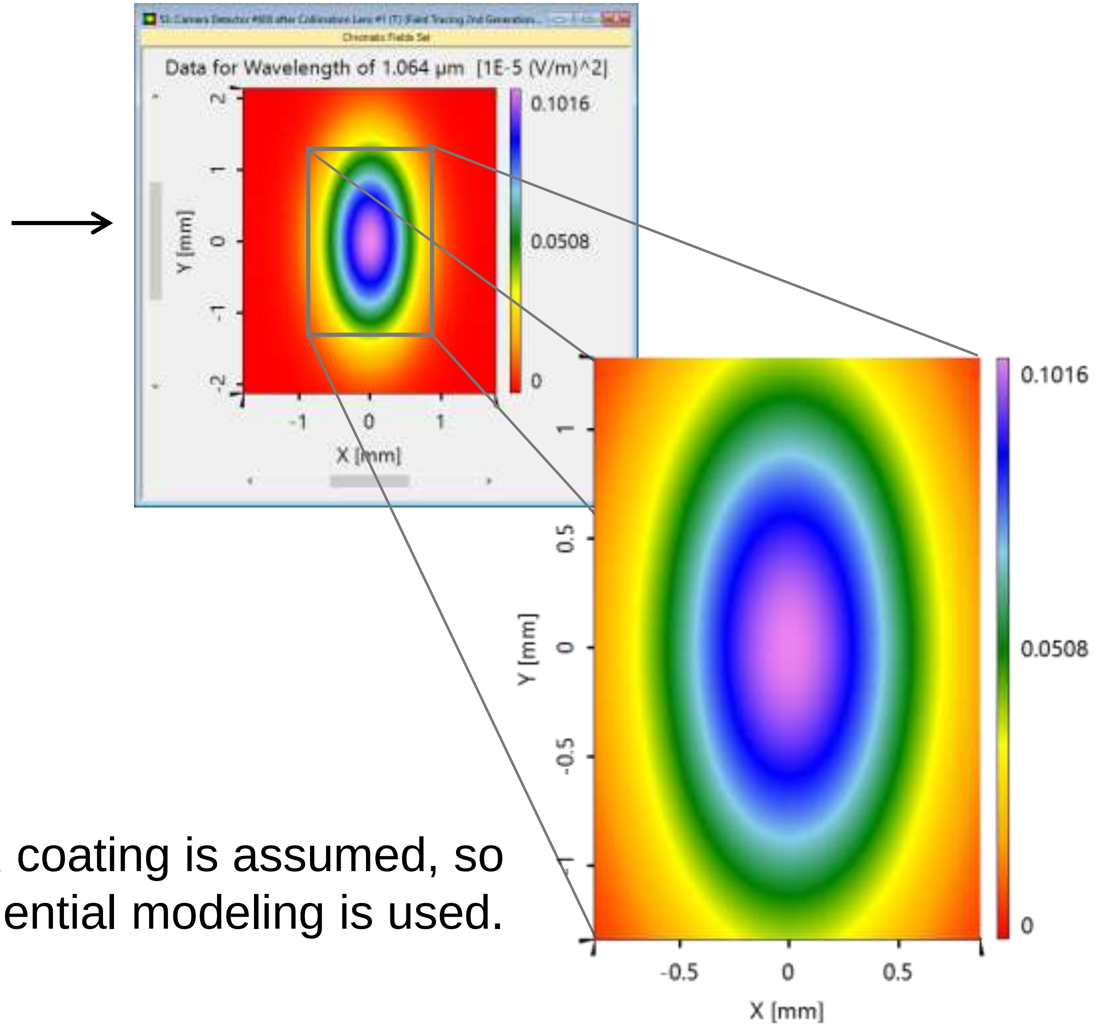


Optical Modeling: Sequential



Collimation System: Sequential Simulation



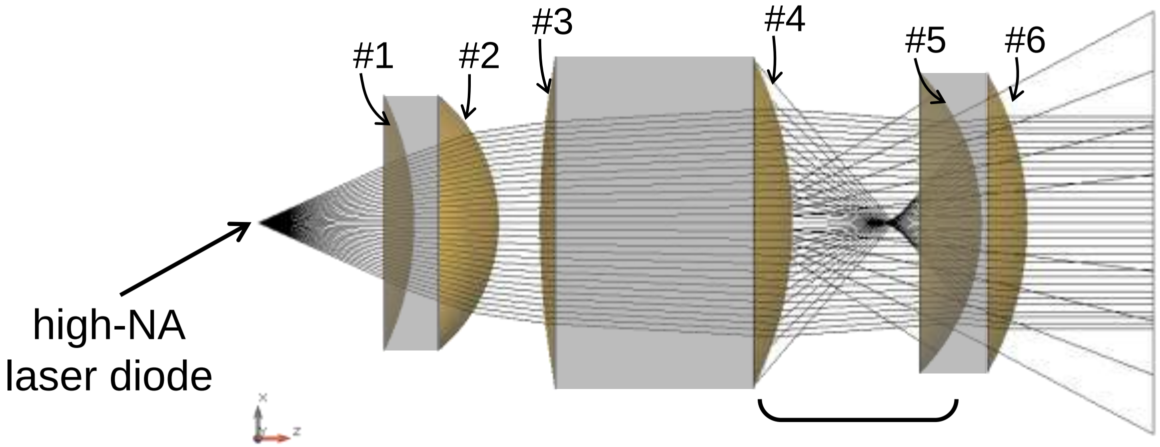


Laser Components
WSLD-1064-050m-1-PD

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

Perfect AR coating is assumed, so sequential modeling is used.

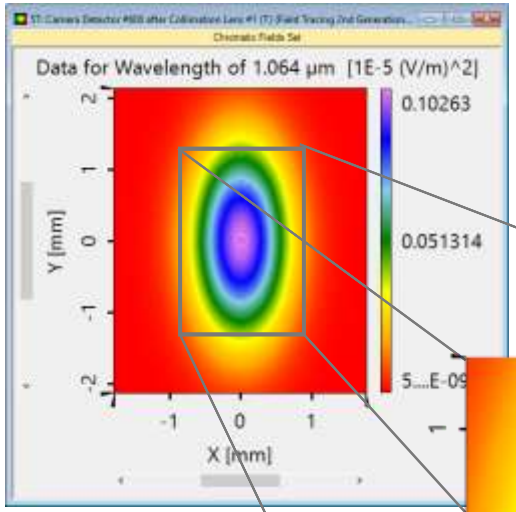
Collimation System: Non-Sequential Simulation

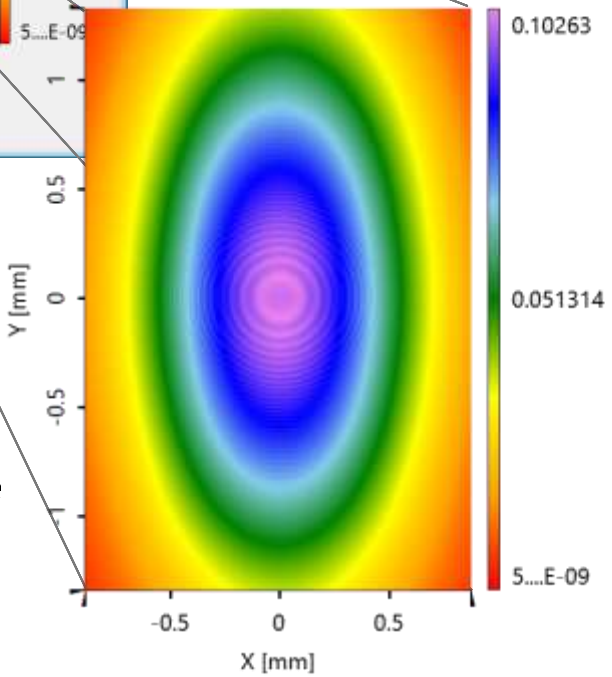


multiple reflections between uncoated surfaces #4 and #5, other surfaces are well coated.

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

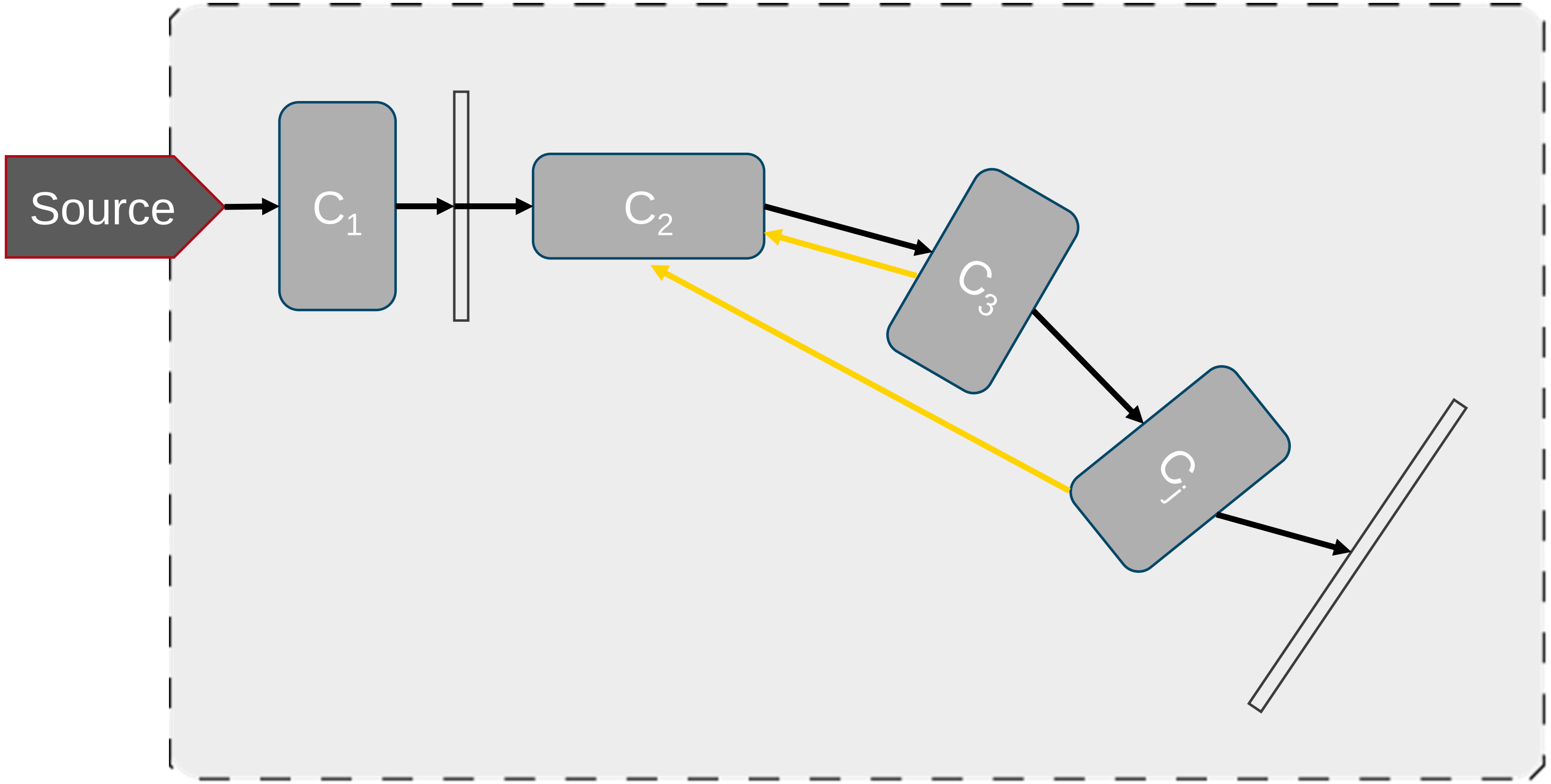
- fundamental Gaussian
- wavelength 1064 nm
- divergence (FWHM) 20°x10°
- astigmatism 11.6 µm between *x*- and *y*-plane





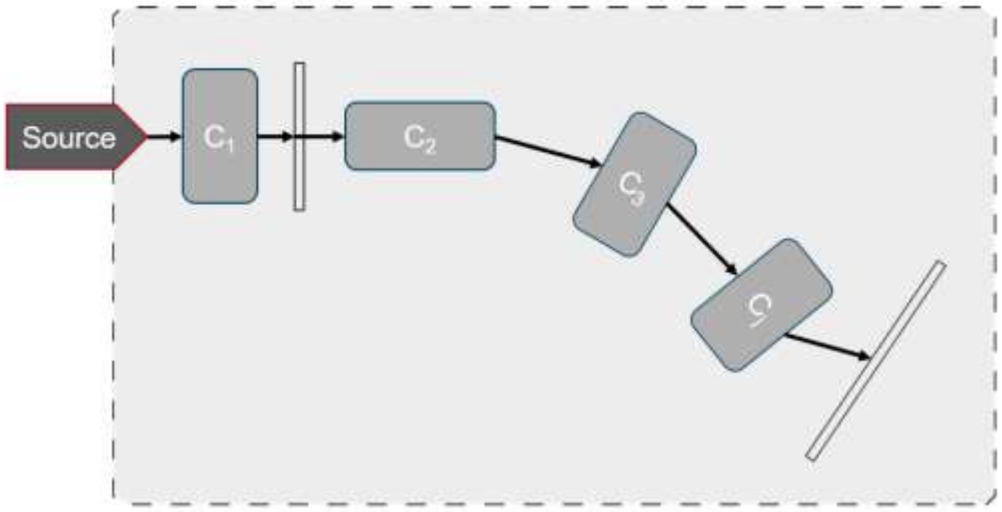
Simulation including interference caused by multiple reflections between uncoated surfaces takes 15 seconds.

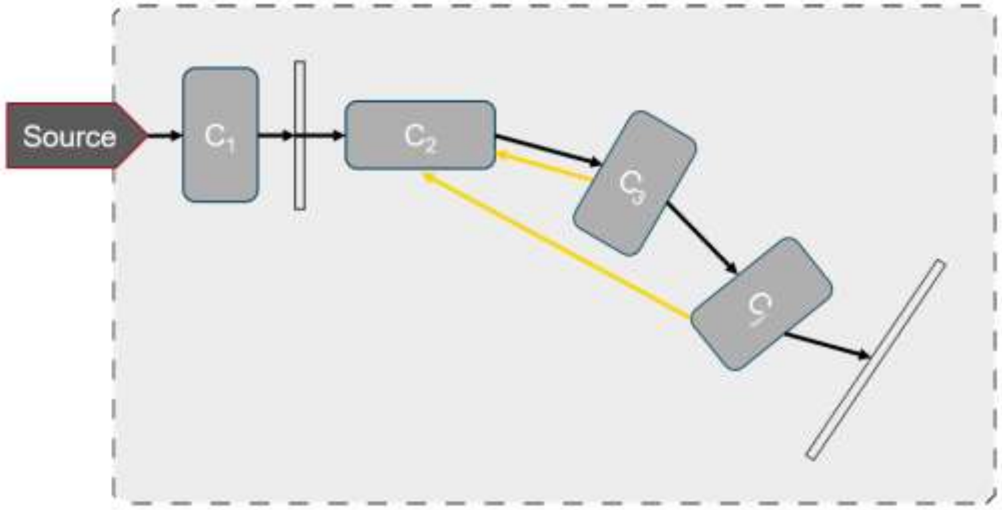
Optical Modeling: Non-Sequential



Conclusion of First Question

What is sequential and non-sequential tracing?





- Users predefine the sequence of the components, and light propagation through follows the sequence.
- Light propagates through/reflects from one component just once.

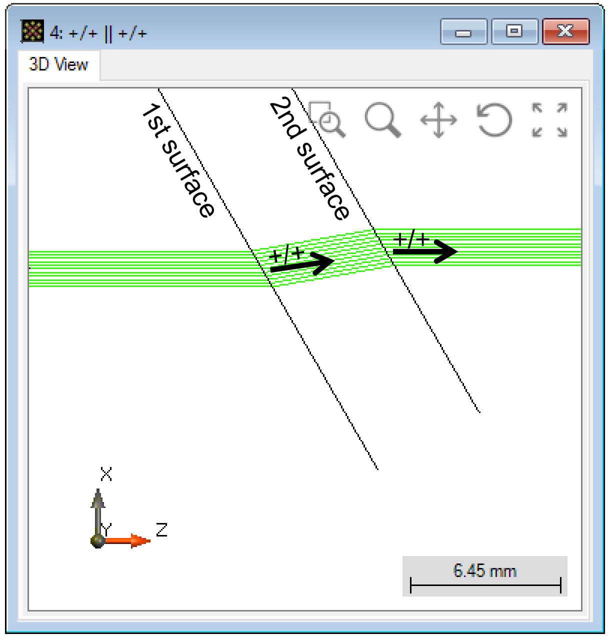
- Light propagation does not follow any sequence.
- Light propagates through/reflects several times from one component.
- Note: sequence of components here is only used for positioning.

How to Enable Sequential and Non-Sequential Tracing?

-- Channel Concept

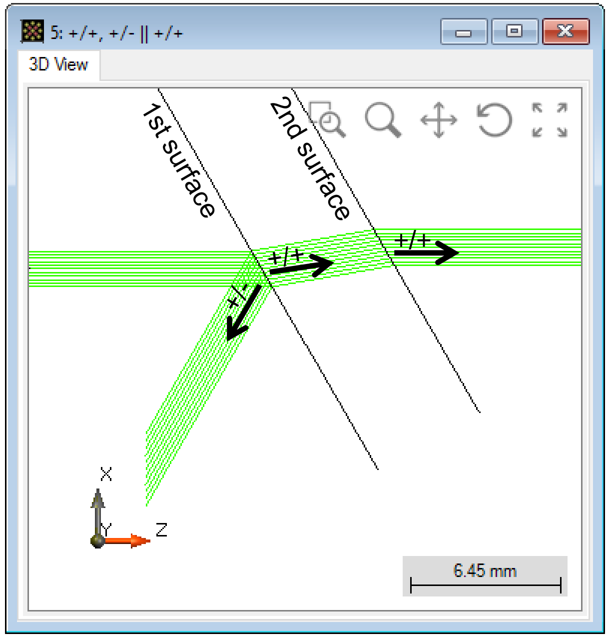
Channels

- Setting A



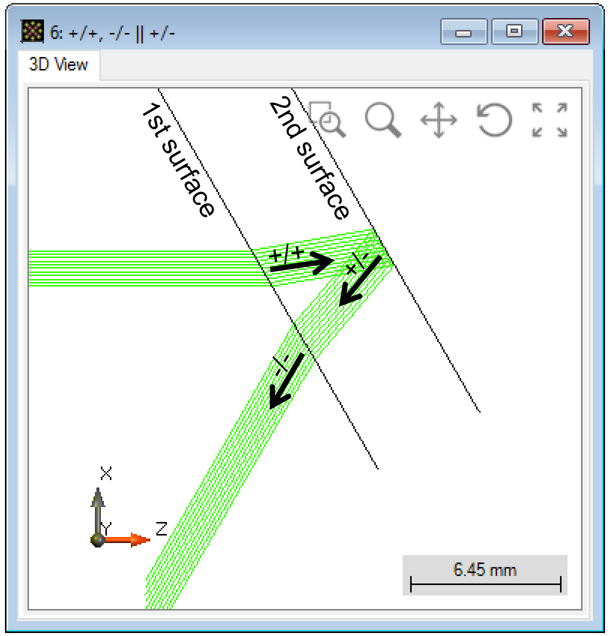
Surface	+/+	+/-	-/-	-/+
1st	×			
2nd	×			

- Setting B



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

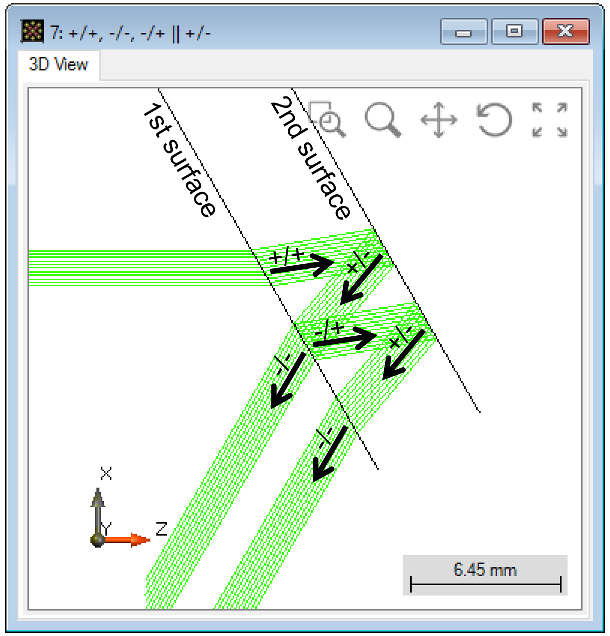
- Setting C



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

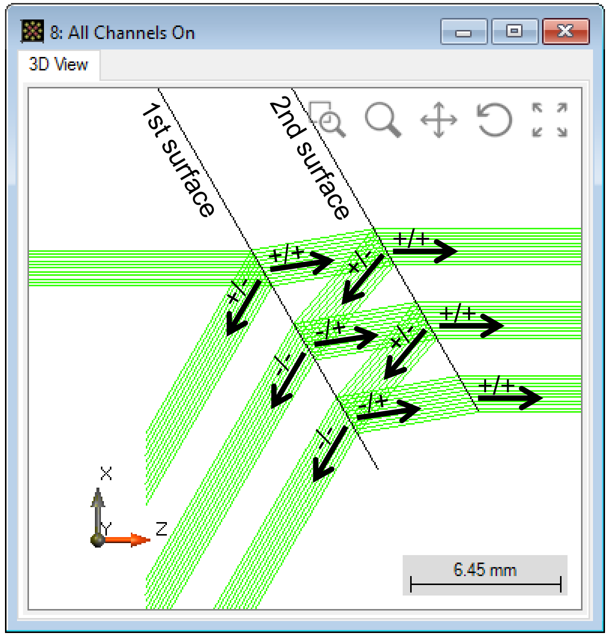
Channels

- Setting D



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

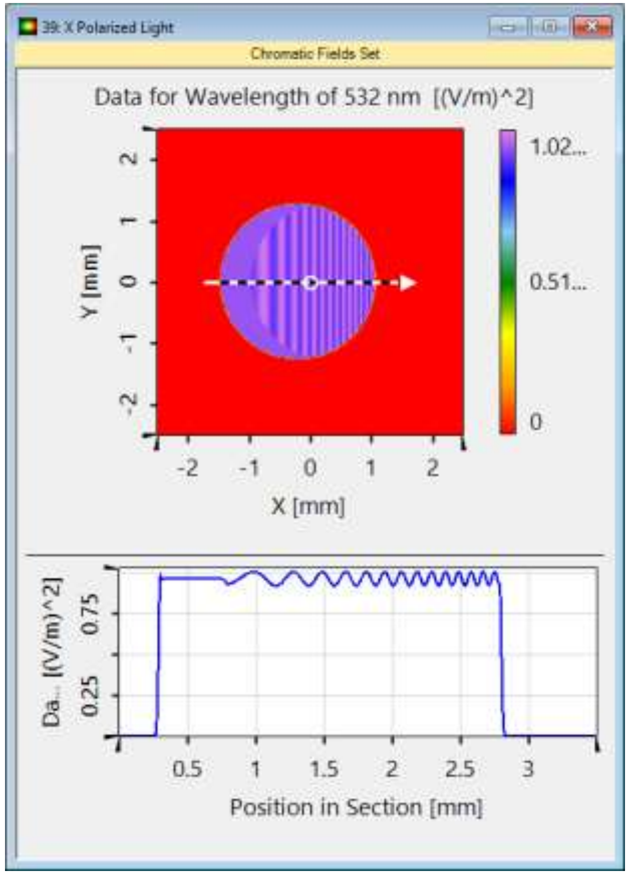
- Setting E



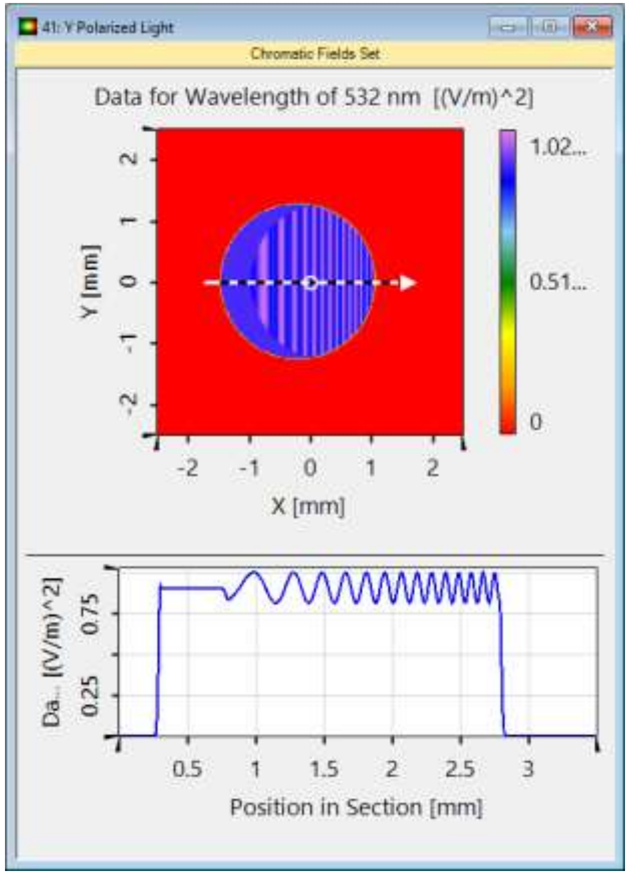
Surface	+/+	+/-	-/-	-/+
1st	×	×	×	×
2nd	×	×	×	×

Illustration 6: Optical Etalon

- Configuration of input field
  - plane wave
  - polarization (try both)
    - E_x-polarized
    - E_y-polarized
- Configuration of etalon
  - cylindrical-planar
  - center thickness 700 µm
  - cylindrical surface radius 1 m



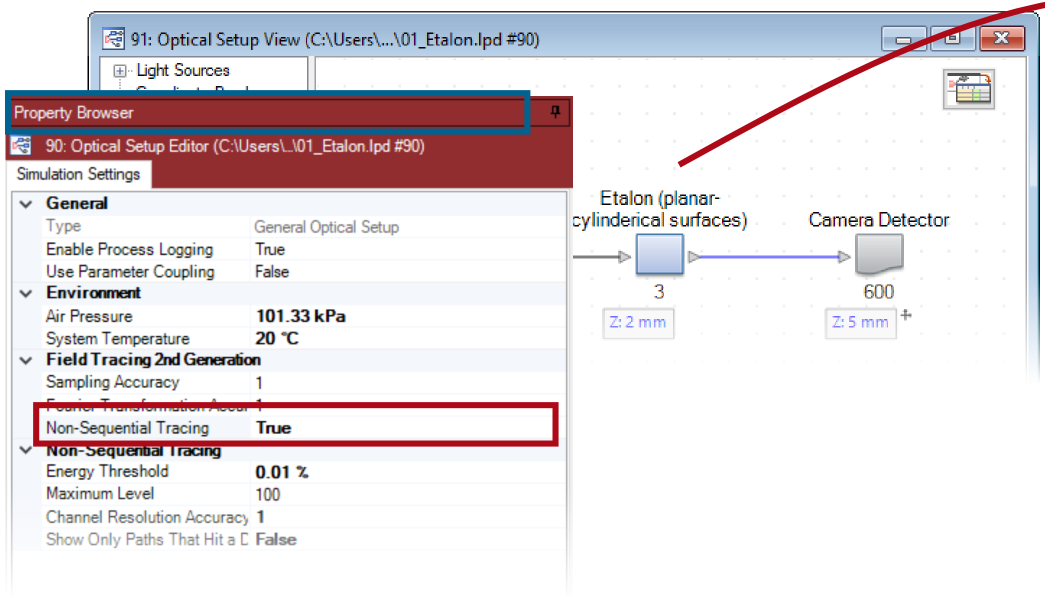
x polarized light

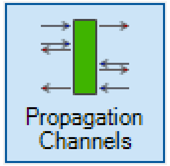


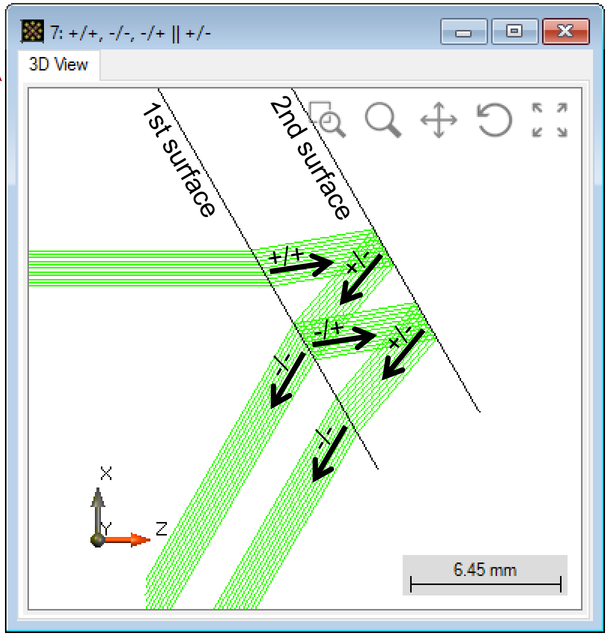
y polarized light

Conclusion of Second Question

- How to enable sequential and non-sequential tracing?





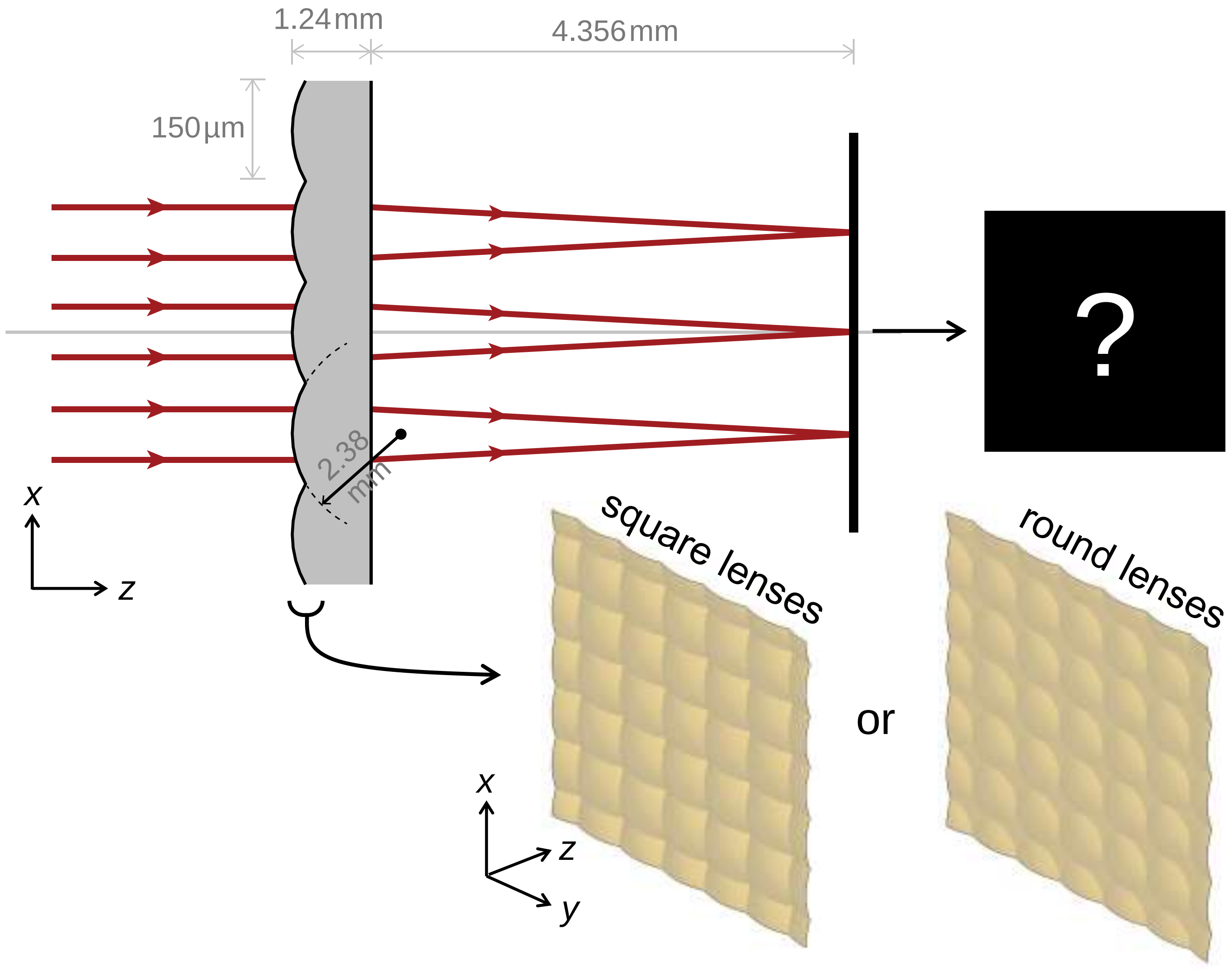


- For each Optical Setup, enable the term *Non-Sequential Tracing*
- Four channels can be chosen in each surface/component (+/+, +/-, -/-, -/+)

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

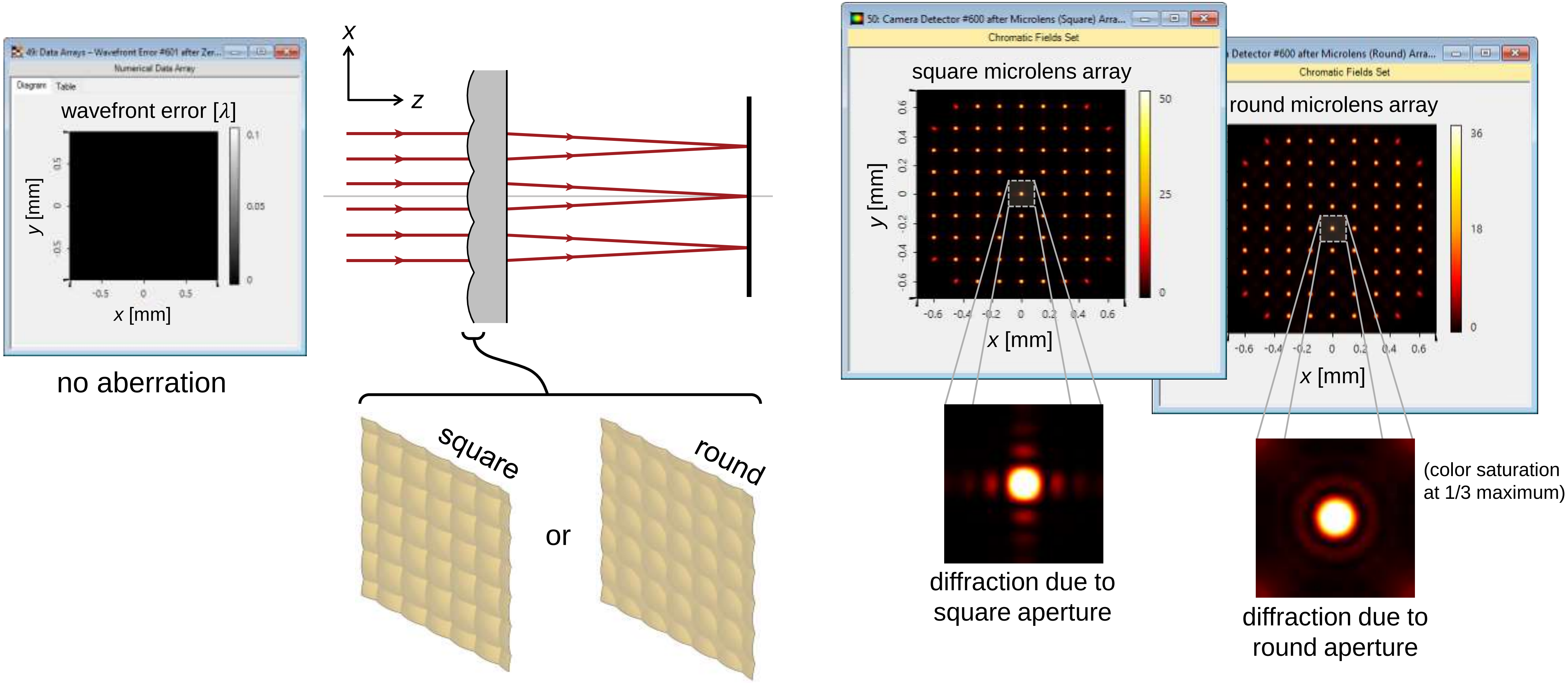
Wavefront Sensor: Modeling Task

input field
- wavelength 633 nm
- diameter 1.5 mm
- uniform amplitude
- phase distributions
  1) no aberration
  2) spherical aberration
  3) coma aberration
  4) trefoil aberration

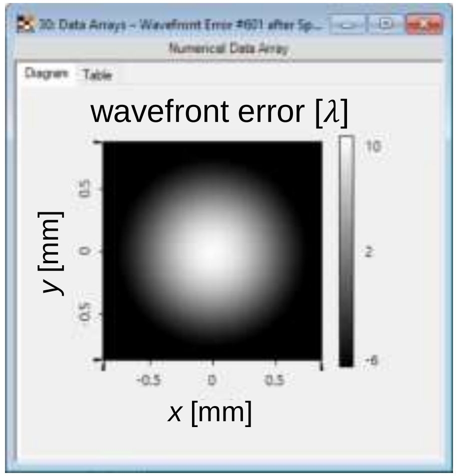


How to calculate field on focal plane behind different types of microlens arrays, and how does the spot distribution change with the input field aberration?

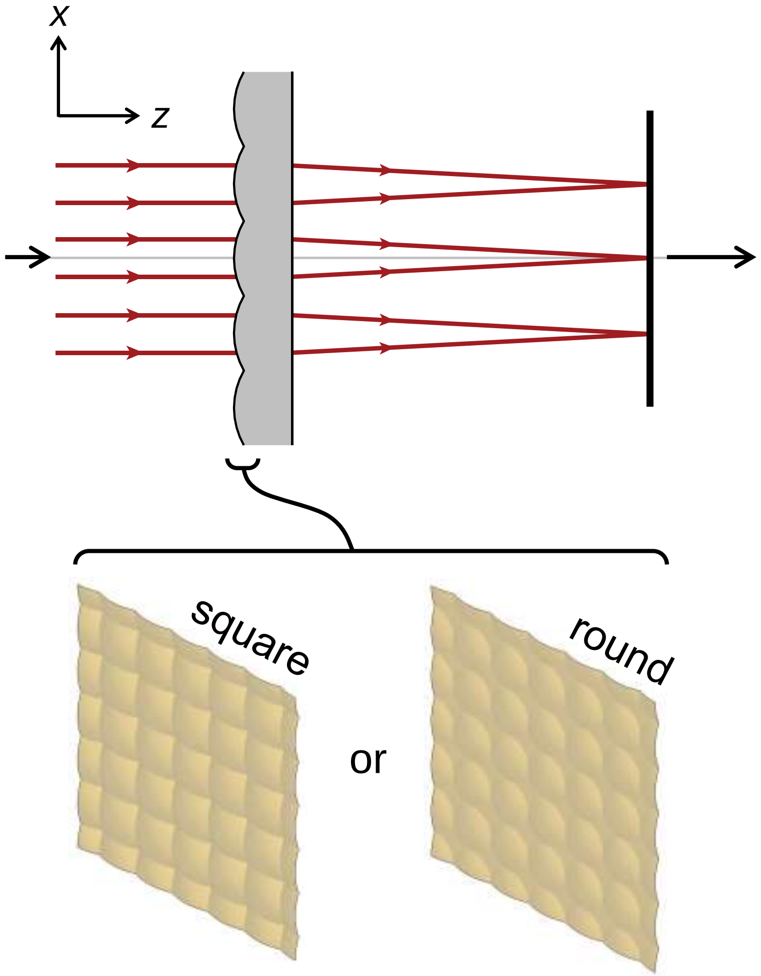
Results

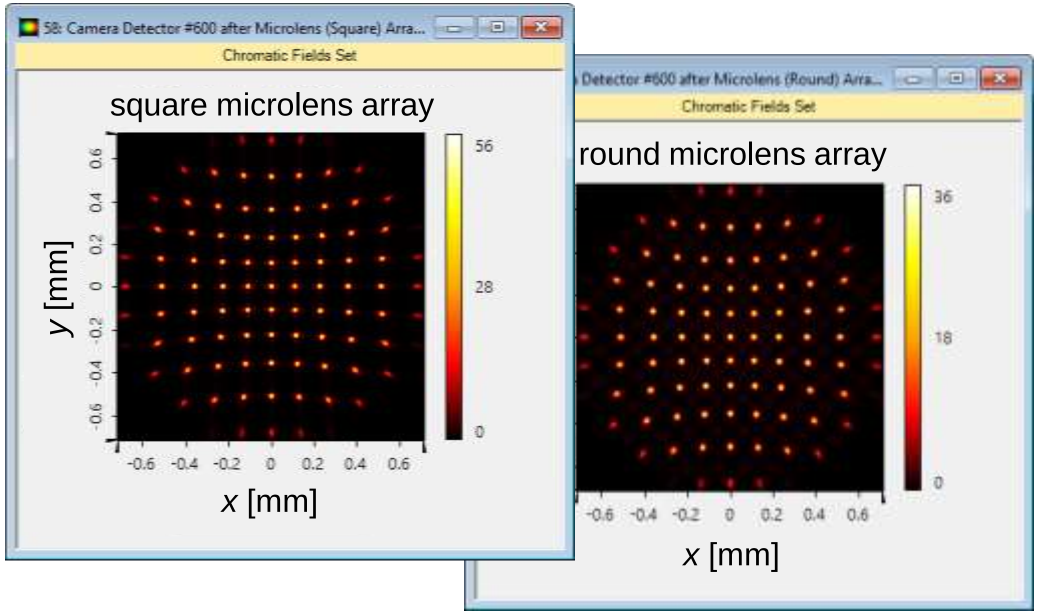

wavefront error [λ]
y [mm]
x [mm]
no aberration
x
z
square
or
round
square microlens array
y [mm]
x [mm]
round microlens array
x [mm]
diffraction due to square aperture
diffraction due to round aperture
(color saturation at 1/3 maximum)

Results



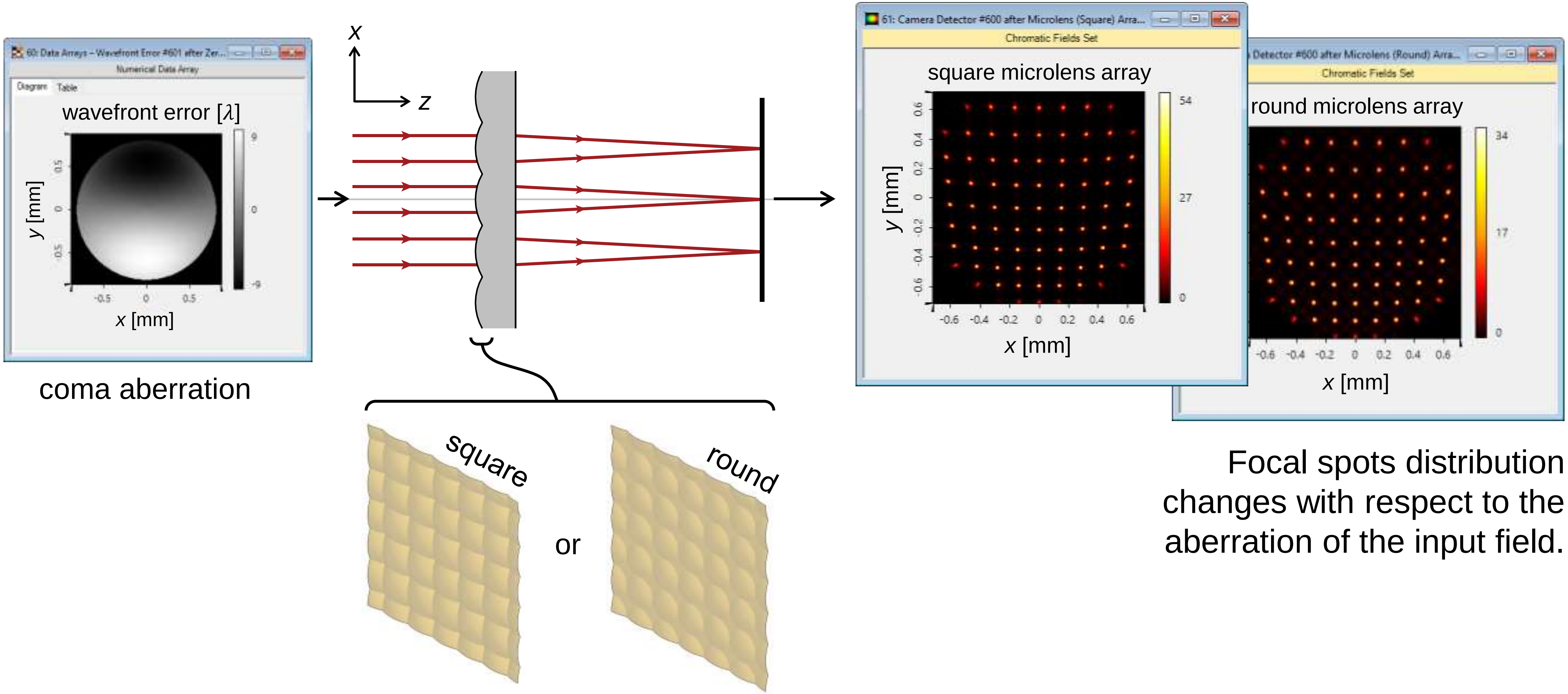
spherical aberration





Fully physical-optics simulation of system containing microlens array takes less than 10 seconds.

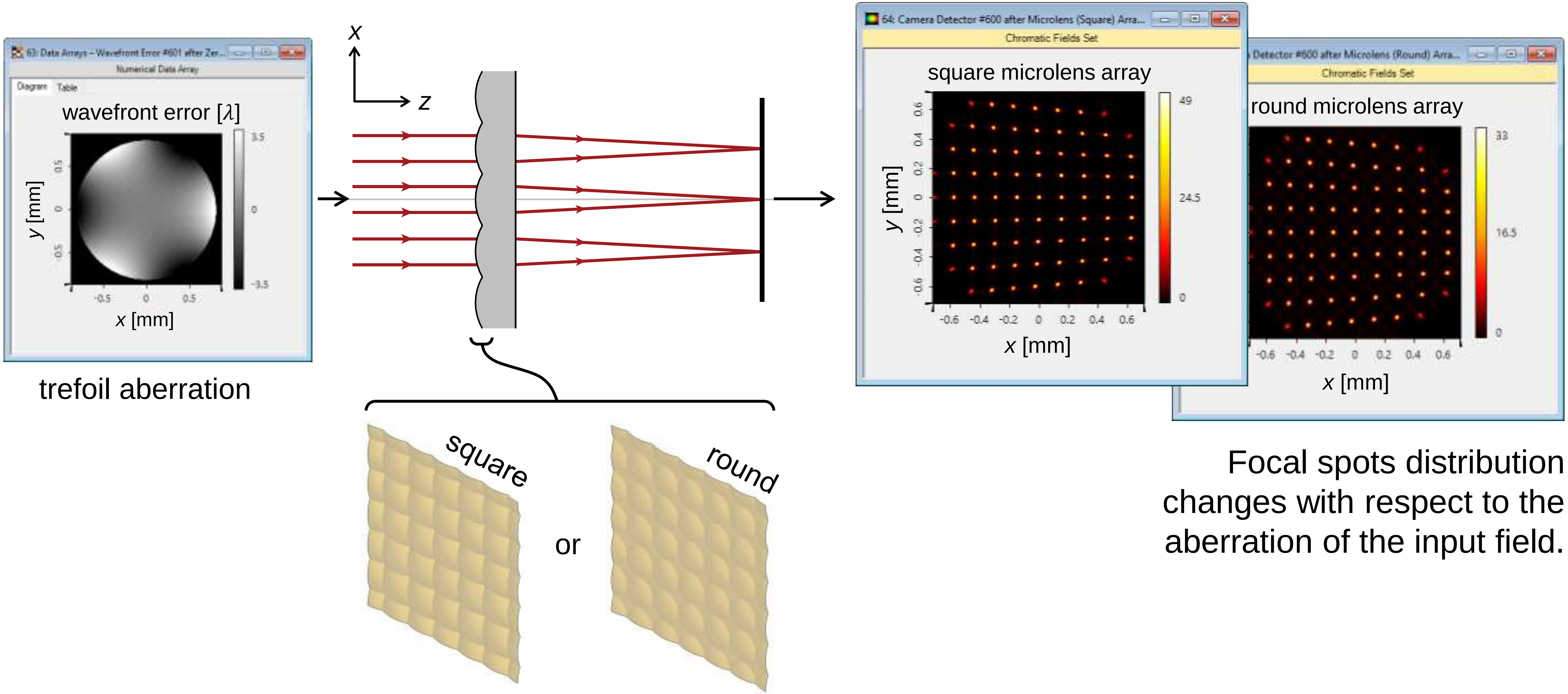
Results



coma aberration

Focal spots distribution changes with respect to the aberration of the input field.

Results

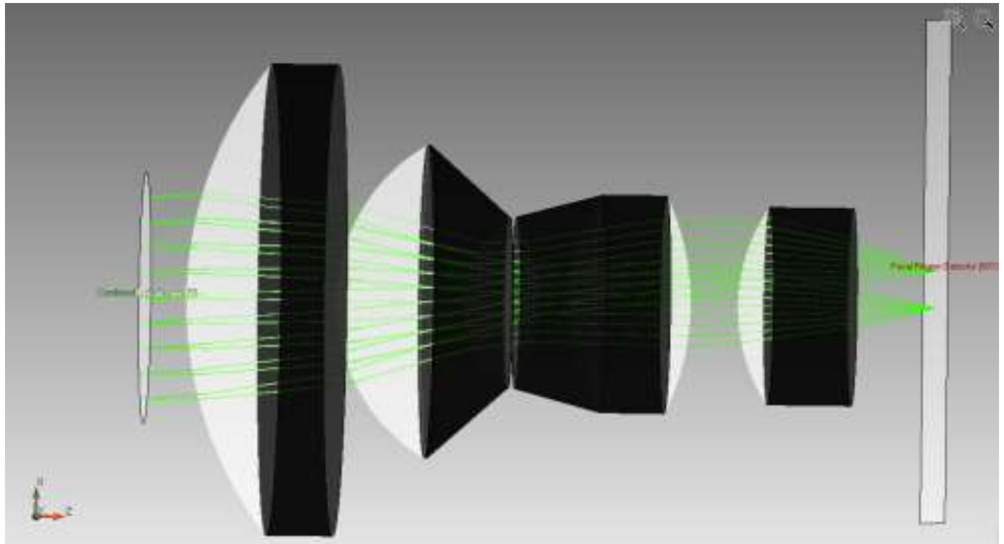


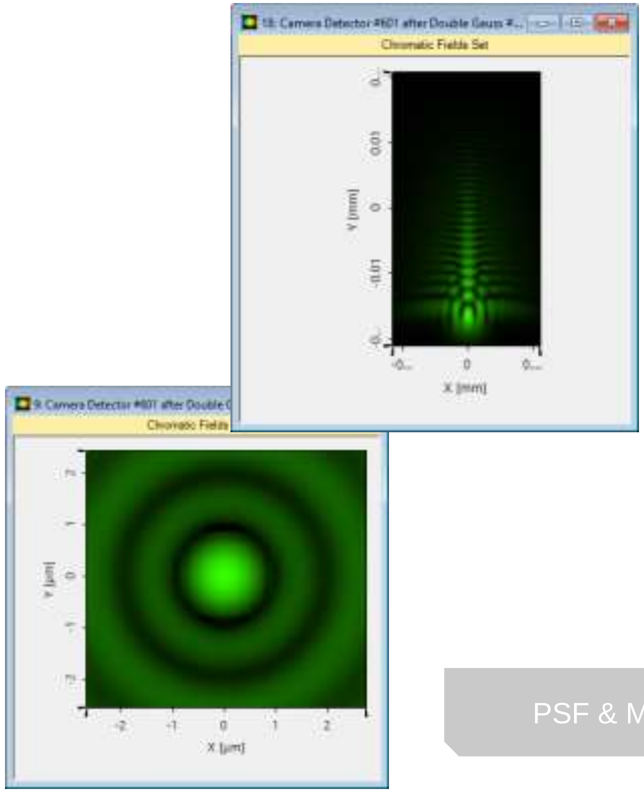
trefoil aberration

Focal spots distribution changes with respect to the aberration of the input field.

Task 9 (Final Lens Task) Import Zemax Data into VLF

- Import a Zemax file “Double Gauss 5 degree field”
- Check the rays propagation through the system
- Check the focus





PSF & MTF Calc

Task 9: Video

Klick the following link to watch the video:

https://youtu.be/RJvjxD9HITo

(v0.9.2)

Zemax Import Options

Two Zemax Import Mechanisms

- elementary import
- advanced import

In general the user has three options do start the import:

- drag‘n‘drop a ZMX file into your VirtualLab window
- go via File menu → Import → Import Zemax System
- import from the edit dialog of an optical interface sequence (OIS) component via the tools button

Which import technique is used depends only on the fact if you have Zemax installed and a valid license running or not:

- The advanced import technique needs access to the Zemax installation to extract more detailed information of the system which is to be imported.
- The elementary import technique needs only the Zemax‘ glass catalog directory in order to load the right materials during the import.

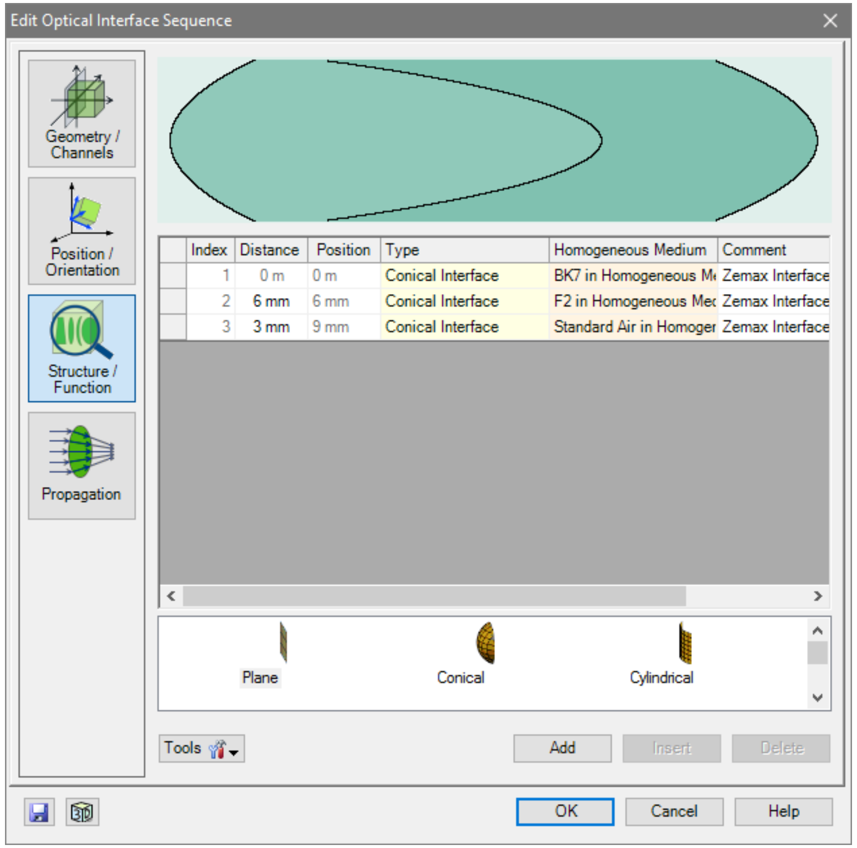
Elementary Zemax Import

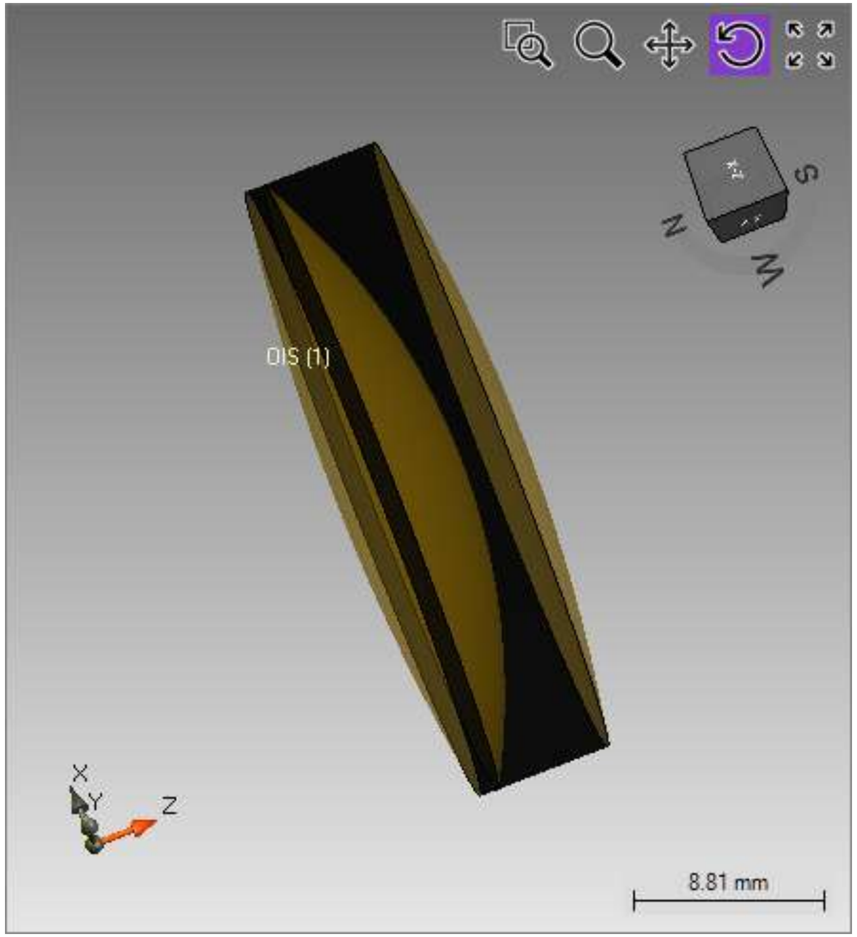
The **elementary Zemax** import is fully **sufficient** for the **import of most lens data** that is provided on manufacturers‘ websited via Zemax files.

Even though manufacturers also start to provide VirtualLab files, Zemax files are still a standard.

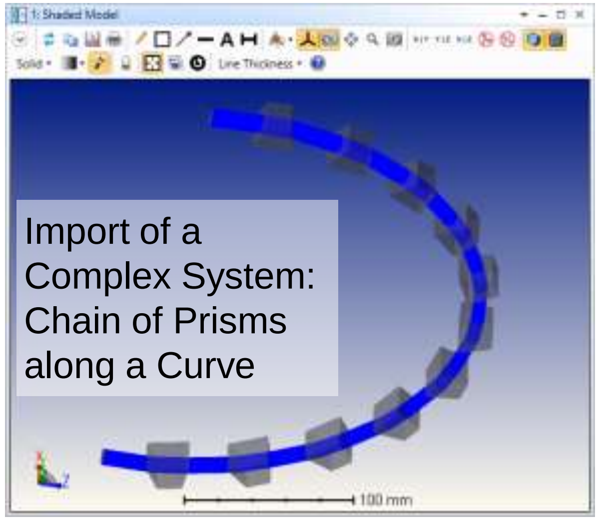
Elementary Zemax Import

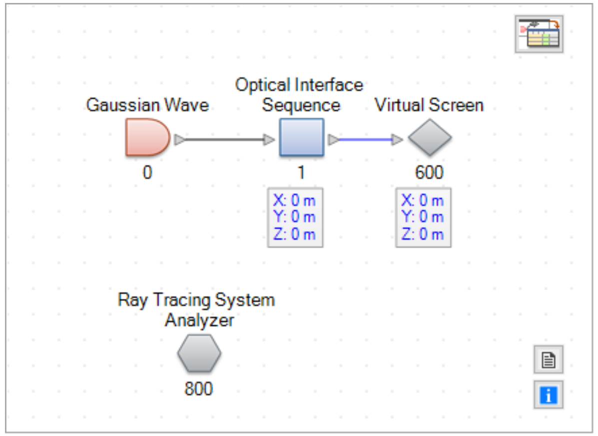
After the import some manual adaptions are needed, then the result looks like the following:

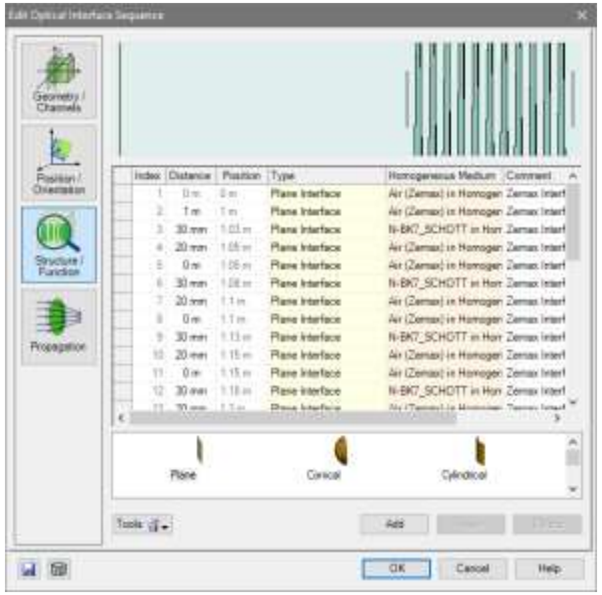


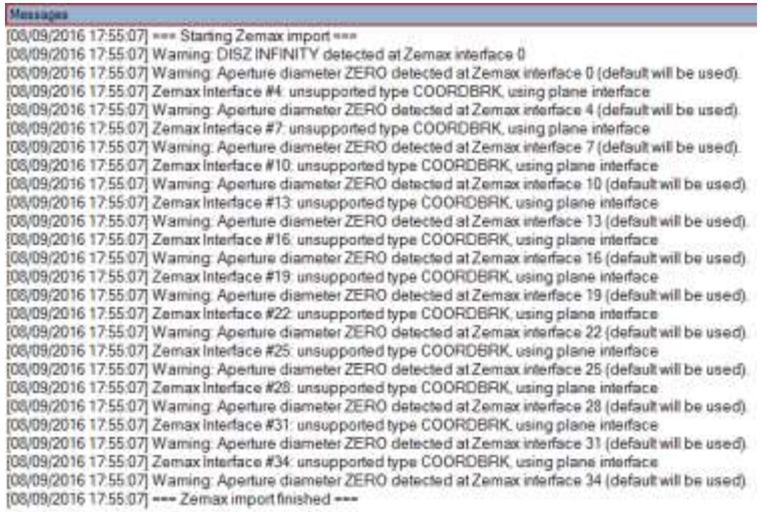


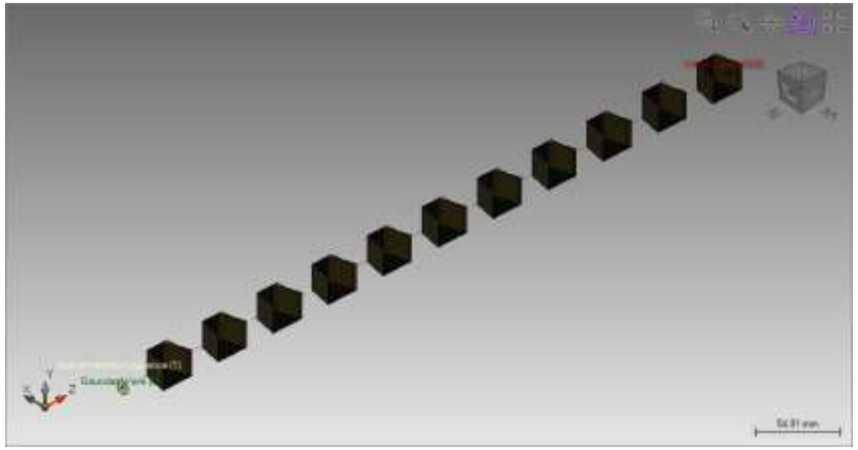
Limits of the Elementary Zemax Import



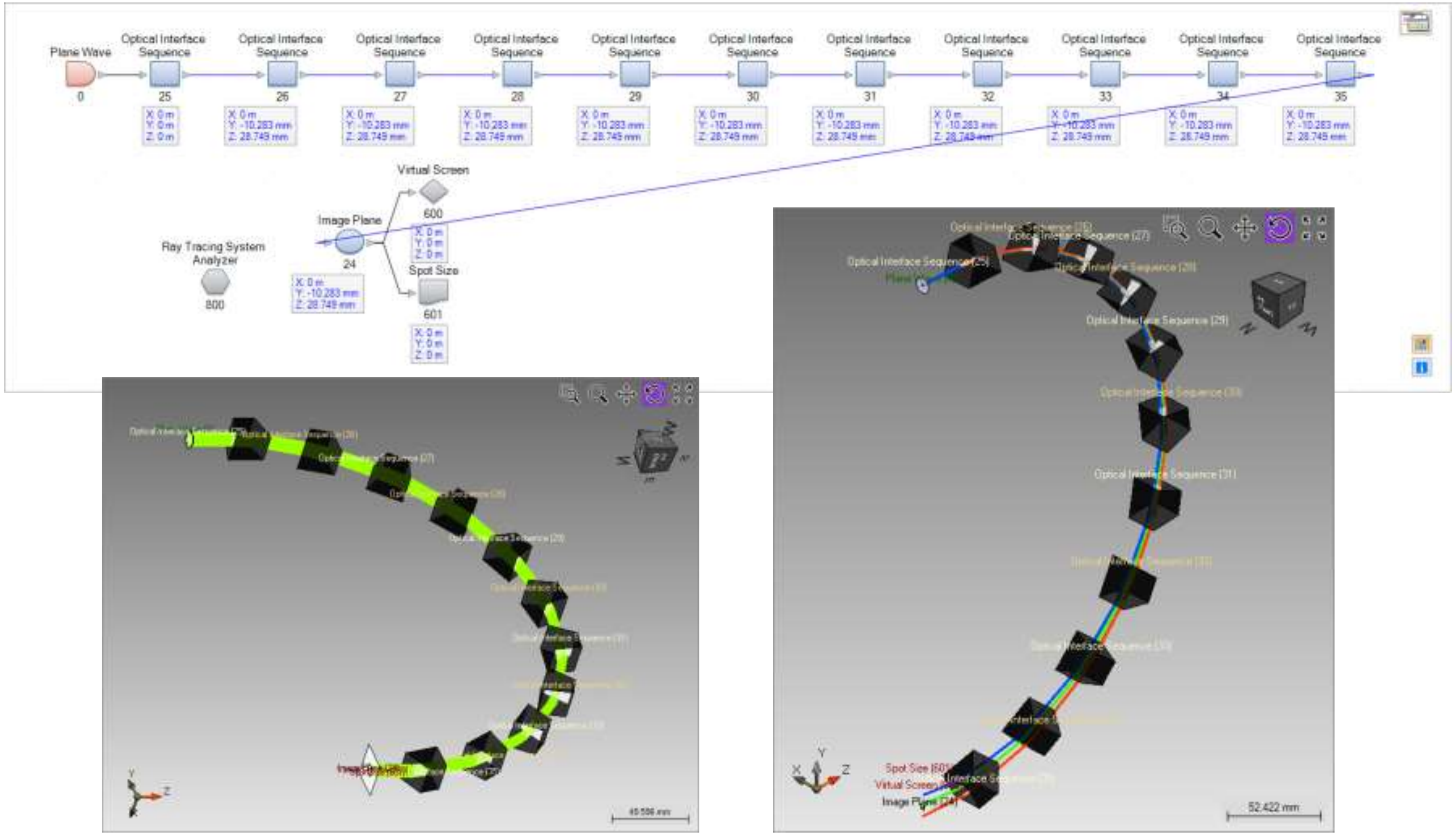





Messages
[08/09/2016 17:55:07] === Starting Zemax import ===
[08/09/2016 17:55:07] Warning: DISZ INFINITY detected at Zemax interface 0
[08/09/2016 17:55:07] Warning: Aperture diameter ZERO detected at Zemax interface 0 (default will be used).
[08/09/2016 17:55:07] Zemax Interface #4: unsupported type COORDBRK, using plane interface
[08/09/2016 17:55:07] Warning: Aperture diameter ZERO detected at Zemax interface 4 (default will be used).
[08/09/2016 17:55:07] Zemax Interface #7: unsupported type COORDBRK, using plane interface
[08/09/2016 17:55:07] Warning: Aperture diameter ZERO detected at Zemax interface 7 (default will be used).
[08/09/2016 17:55:07] Zemax Interface #10: unsupported type COORDBRK, using plane interface
[08/09/2016 17:55:07] Warning: Aperture diameter ZERO detected at Zemax interface 10 (default will be used).
[08/09/2016 17:55:07] Zemax Interface #13: unsupported type COORDBRK, using plane interface
[08/09/2016 17:55:07] Warning: Aperture diameter ZERO detected at Zemax interface 13 (default will be used).
[08/09/2016 17:55:07] Zemax Interface #16: unsupported type COORDBRK, using plane interface
[08/09/2016 17:55:07] Warning: Aperture diameter ZERO detected at Zemax interface 16 (default will be used).
[08/09/2016 17:55:07] Zemax Interface #19: unsupported type COORDBRK, using plane interface
[08/09/2016 17:55:07] Warning: Aperture diameter ZERO detected at Zemax interface 19 (default will be used).
[08/09/2016 17:55:07] Zemax Interface #22: unsupported type COORDBRK, using plane interface
[08/09/2016 17:55:07] Warning: Aperture diameter ZERO detected at Zemax interface 22 (default will be used).
[08/09/2016 17:55:07] Zemax Interface #25: unsupported type COORDBRK, using plane interface
[08/09/2016 17:55:07] Warning: Aperture diameter ZERO detected at Zemax interface 25 (default will be used).
[08/09/2016 17:55:07] Zemax Interface #28: unsupported type COORDBRK, using plane interface
[08/09/2016 17:55:07] Warning: Aperture diameter ZERO detected at Zemax interface 28 (default will be used).
[08/09/2016 17:55:07] Zemax Interface #31: unsupported type COORDBRK, using plane interface
[08/09/2016 17:55:07] Warning: Aperture diameter ZERO detected at Zemax interface 31 (default will be used).
[08/09/2016 17:55:07] Zemax Interface #34: unsupported type COORDBRK, using plane interface
[08/09/2016 17:55:07] Warning: Aperture diameter ZERO detected at Zemax interface 34 (default will be used).
[08/09/2016 17:55:07] === Zemax import finished ===



Advanced Zemax Import



Further Info about Advanced Zemax Import

- Due to the complexity and the differences of both programs (Zemax & VirtualLab) even the advanced import algorithm needs to make certain assumptions and has some limitations.
- **Example assumptions:**
  - The used wavelengths of the Zemax file are used to define the spectrum of the VirtualLab source.
  - The entrance pupil diameter of Zemax defines the input field size of the source in VirtualLab.
- **Example limitation:**
  Lateral positions and angles of the fields specified in Zemax are ignored. Such configurations need to be reset manually after the import.

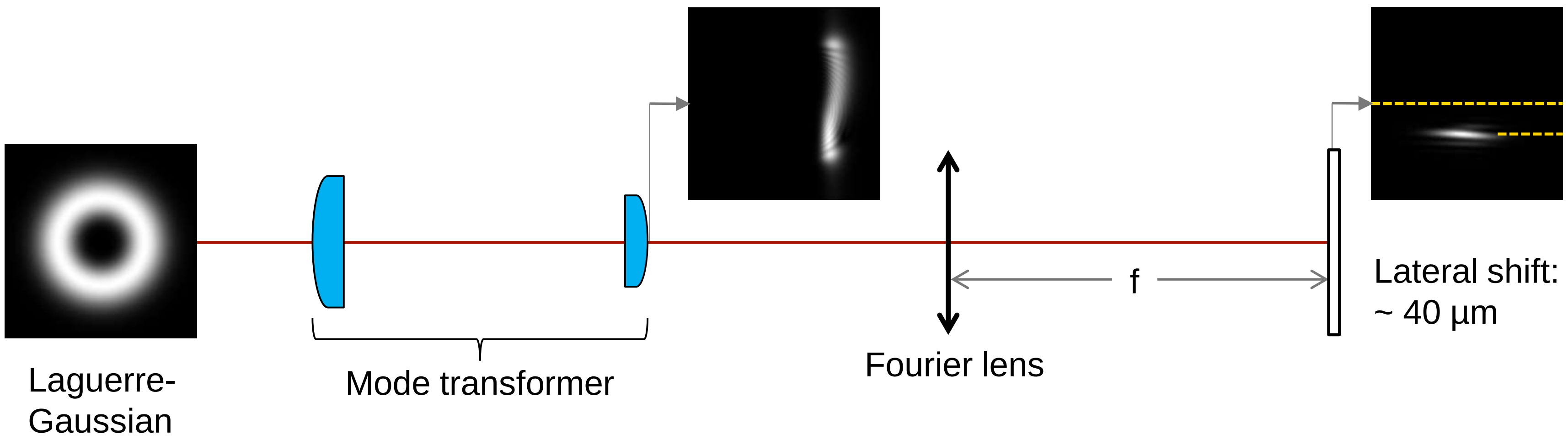
For more detailed information please consult the manual or help file.

Example: Freeform modeling

Measurement of Orbital Angular Momentum

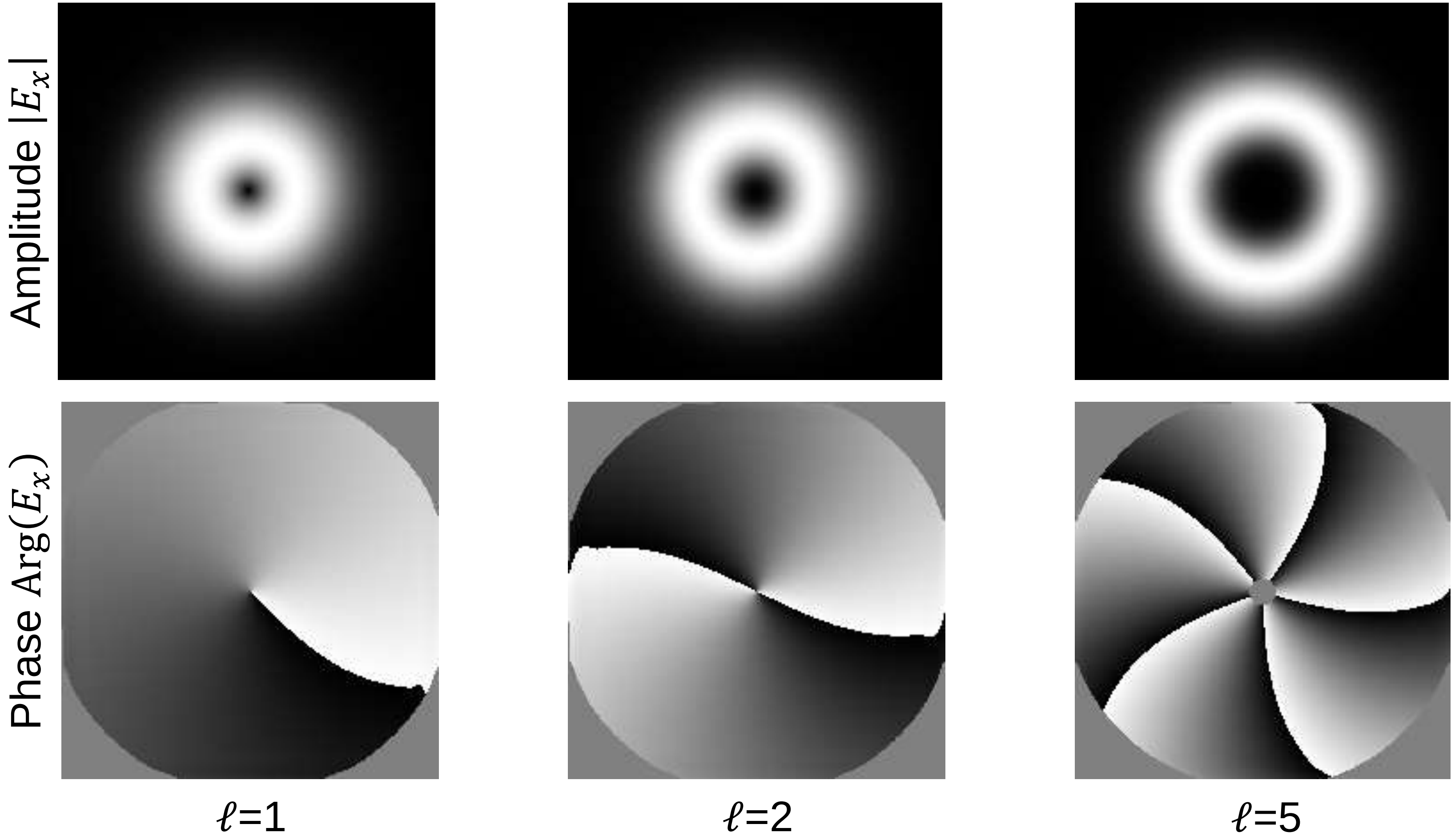
Martin P. J. Lavery, *et al*., "Refractive elements for the measurement of the orbital angular momentum of a single photon," Opt. Express 20, 2110-2115 (2012)

Simulation in VirtualLab Fusion



Laguerre-Gaussian

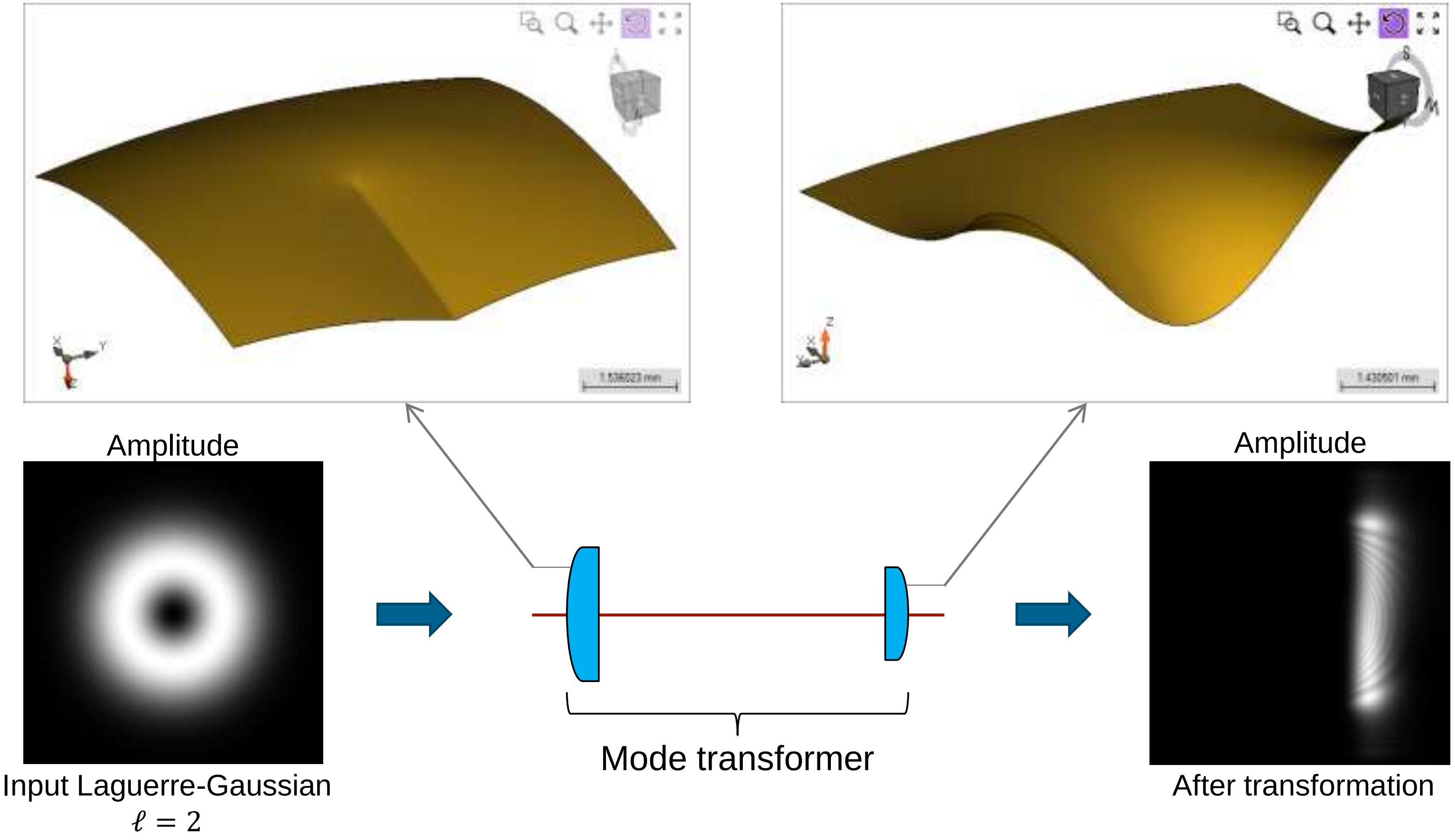
- Light source



Mode Transformer

$$Z_1(x,y) = \frac{a}{f(n-1)}\left[y\arctan\left(\frac{y}{x}\right) - x\ln\left(\frac{\sqrt{x^2+y^2}}{b}\right) + x - \underbrace{\frac{1}{a}\left(\frac{1}{2}(x^2+y^2)\right)}_{\text{lens term}}\right]$$

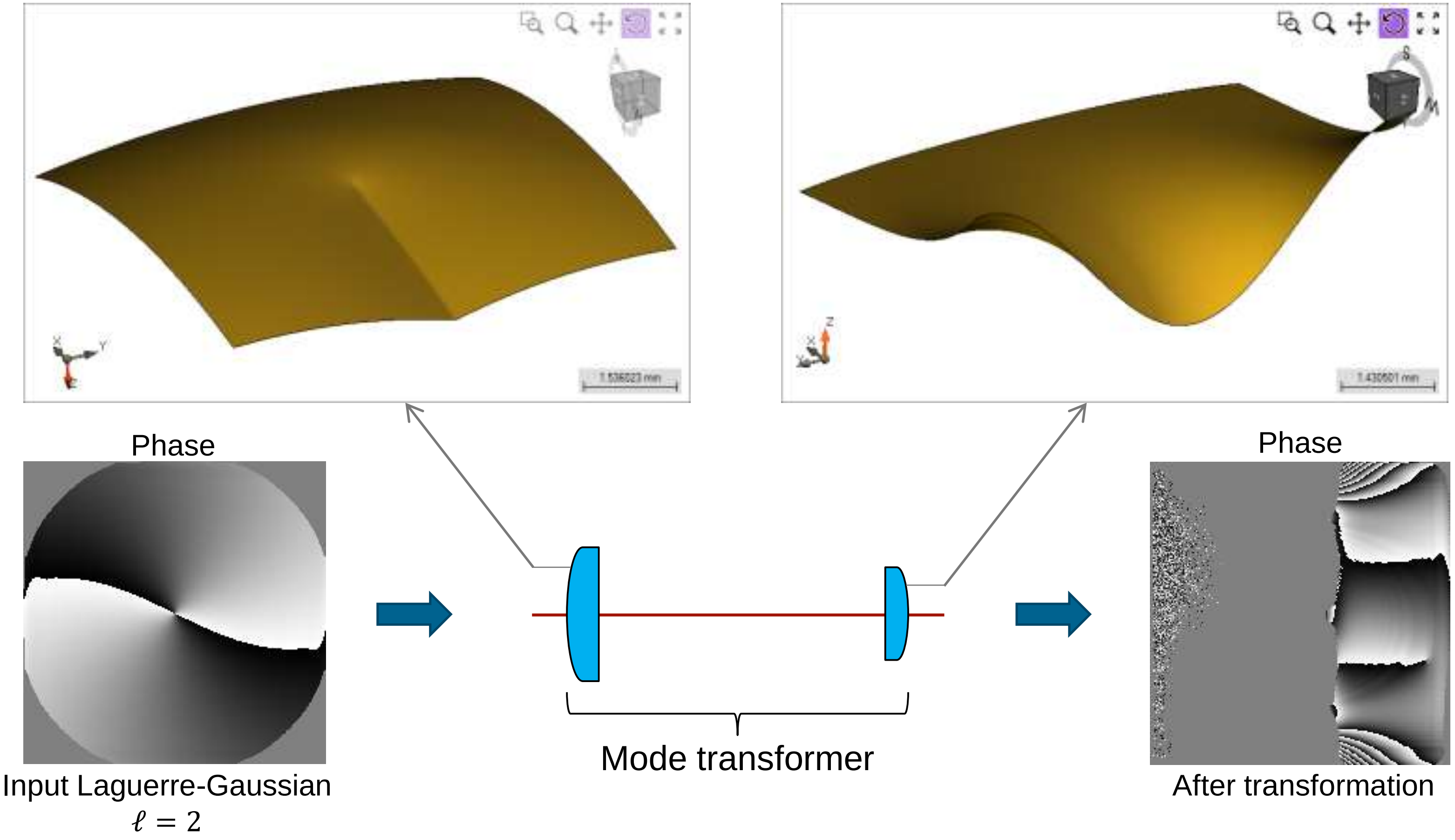
$$Z_2(x,y) = -\frac{ab}{f(n-1)}\left[\exp\left(-\frac{u}{a}\right)\cos\left(\frac{v}{a}\right) - \underbrace{\frac{1}{ab}\left(\frac{1}{2}(u^2+v^2)\right)}_{\text{lens term}}\right]$$



Mode Transformer

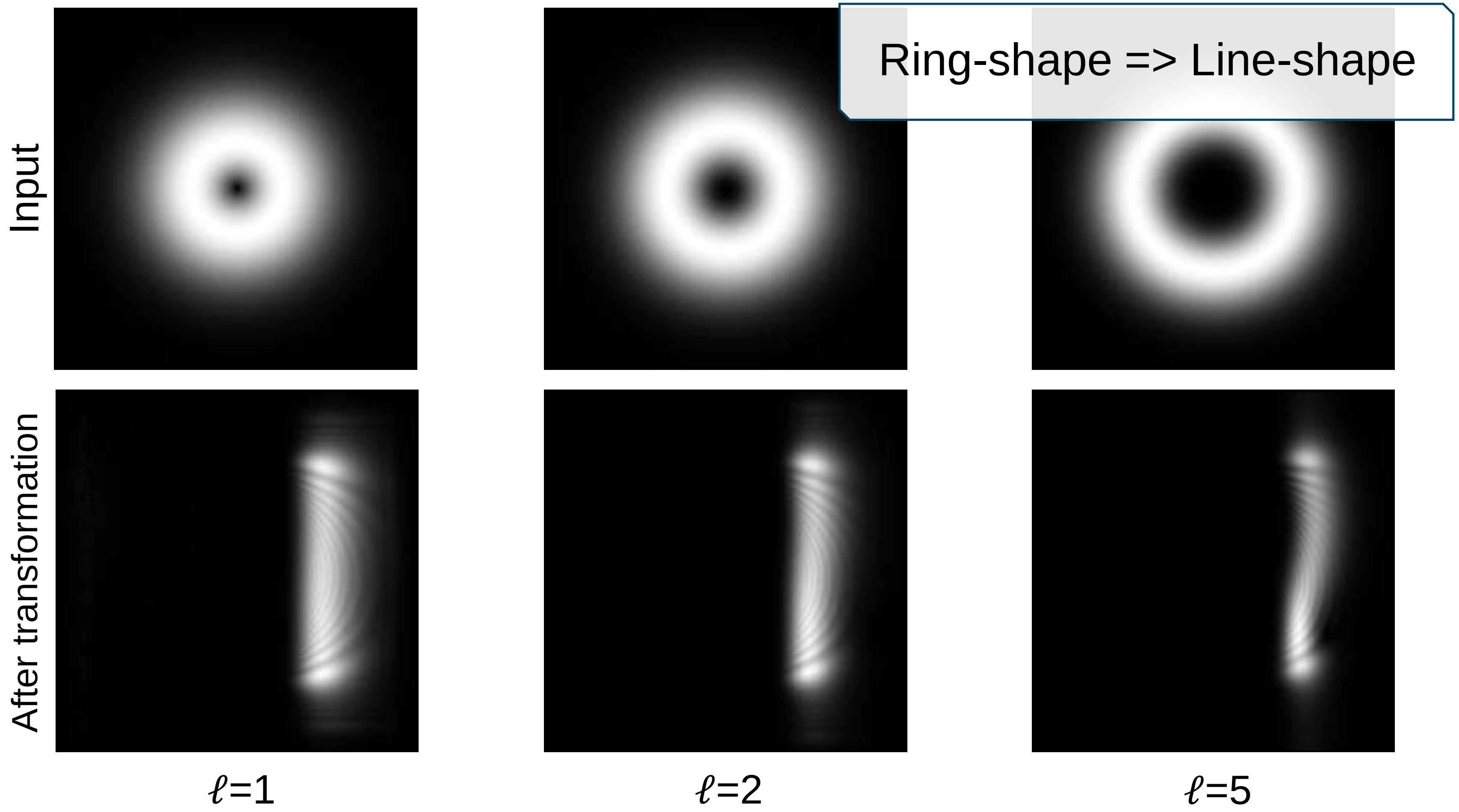
$$Z_1(x,y) = \frac{a}{f(n-1)}\left[y\arctan\left(\frac{y}{x}\right) - x\ln\left(\frac{\sqrt{x^2+y^2}}{b}\right) + x - \underbrace{\frac{1}{a}\left(\frac{1}{2}(x^2+y^2)\right)}_{\text{lens term}}\right]$$

$$Z_2(x,y) = -\frac{ab}{f(n-1)}\left[\exp\left(-\frac{u}{a}\right)\cos\left(\frac{v}{a}\right) - \underbrace{\frac{1}{ab}\left(\frac{1}{2}(u^2+v^2)\right)}_{\text{lens term}}\right]$$



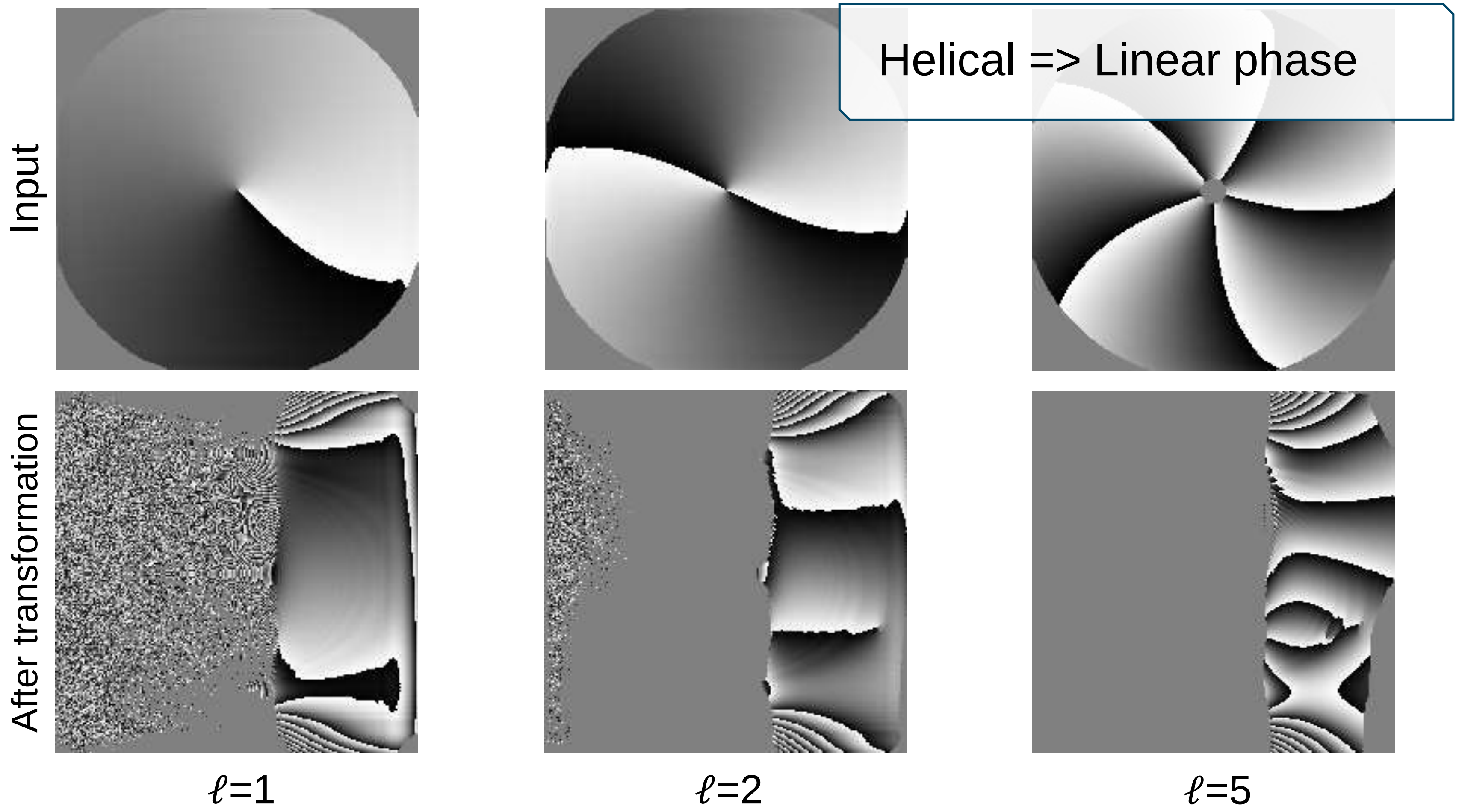
Mode Transformer

- Amplitude distributions before and after transformation



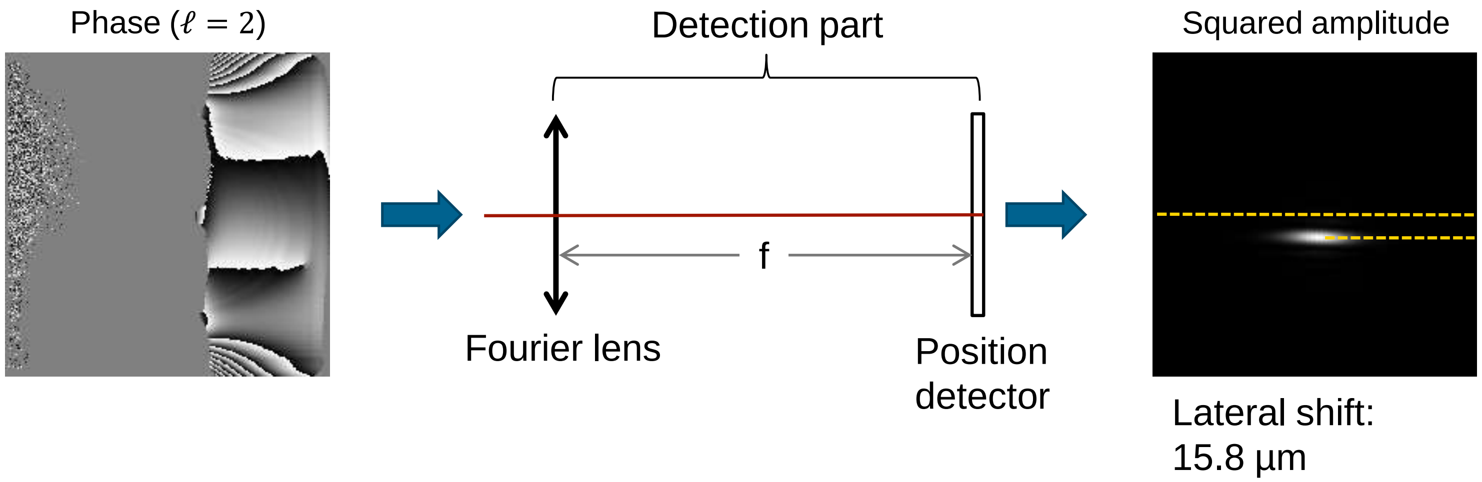
Mode Transformer

- Phase distribution before and after transformation



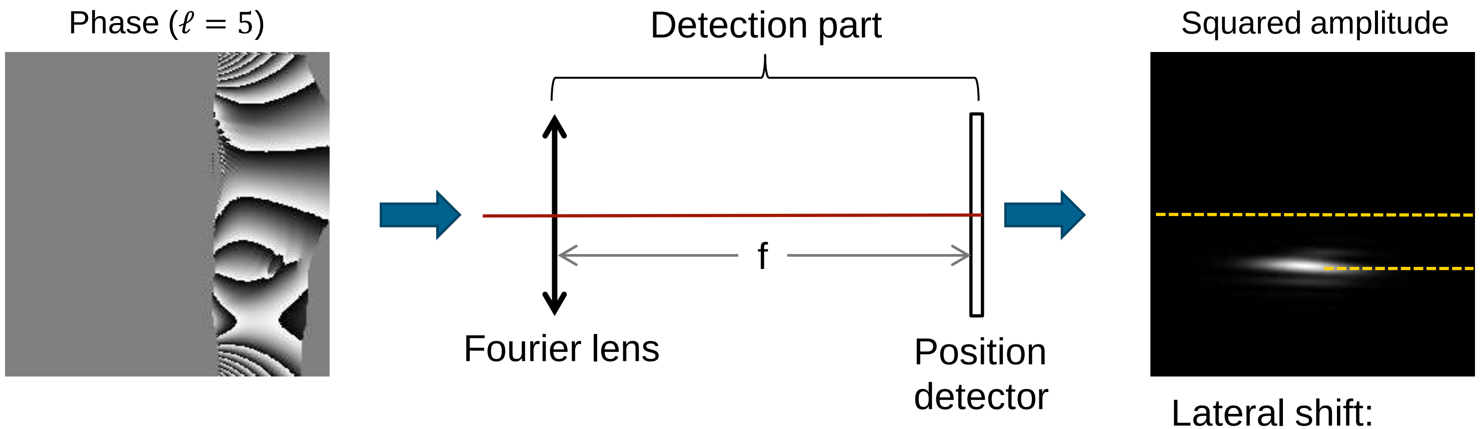
Detection Part

- Shift theorem
  - A linear phase in one domain leads to a lateral shift in the other domain according to Fourier transformation



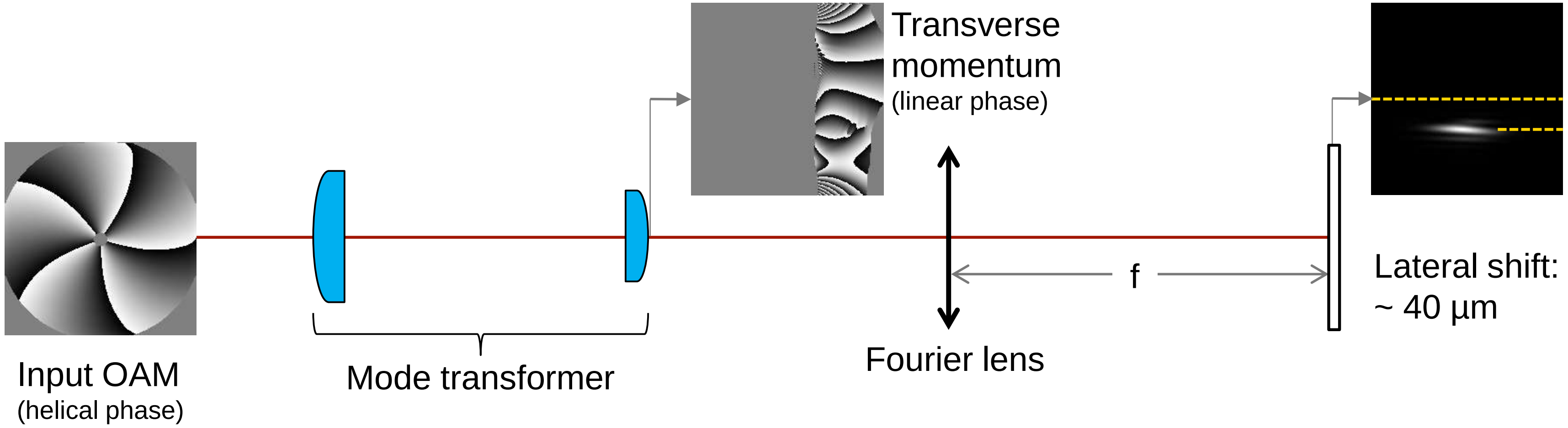
Detection Part

- Shift theorem
  - A linear phase in one domain leads to a lateral shift in the other domain according to Fourier transformation



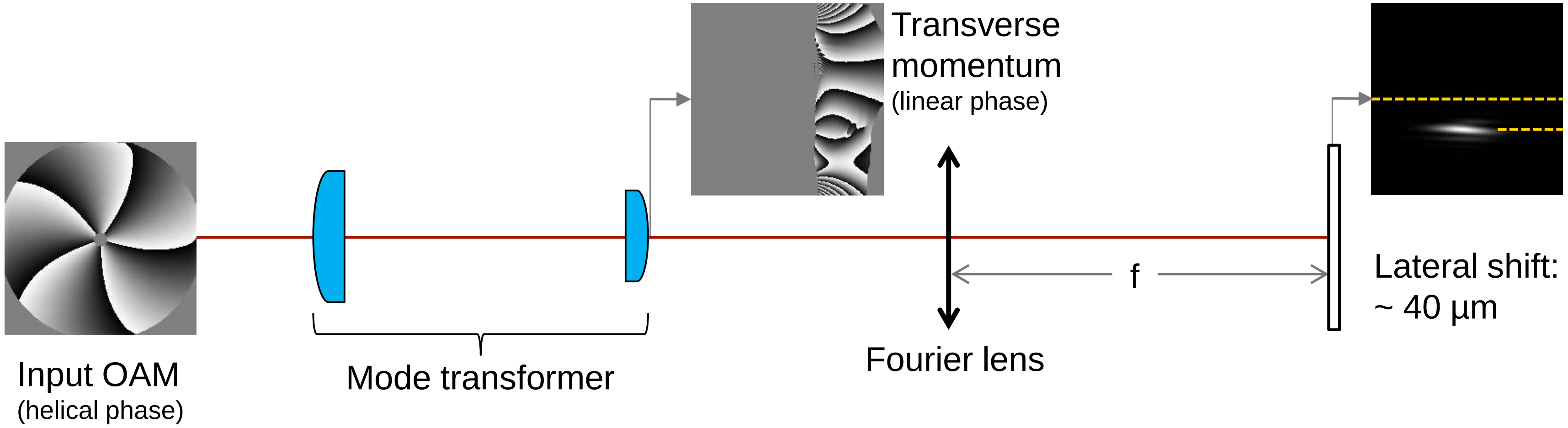
Lateral shift: 39.6 µm

System Functioning



- An input OAM is firstly transformed to transverse momentum by the mode transformer, which is composed of two freeform refractive optical elements
- The transverse momentum is then transformed into lateral position shift by a Fourier lens
- By precise measurement of the lateral shift, one reads the OAM state i.e. the encoded information

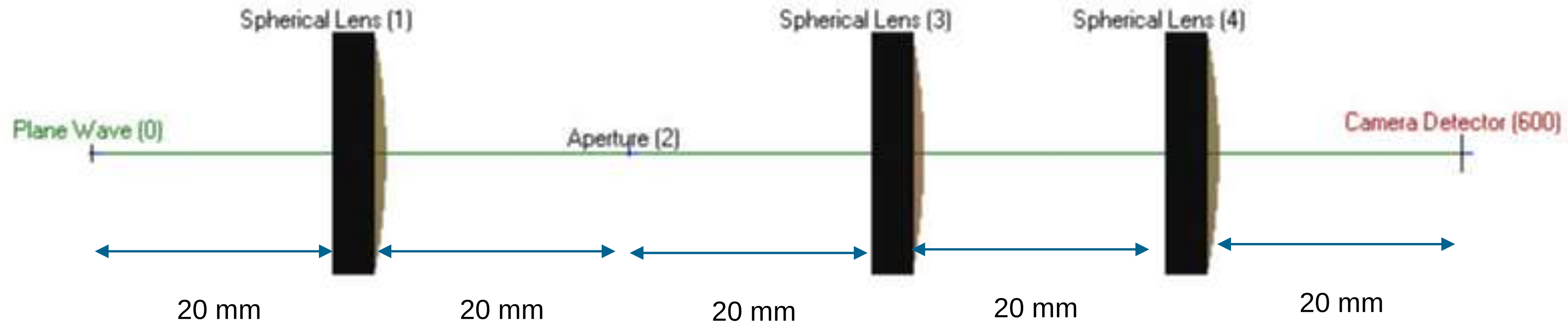
System Functioning



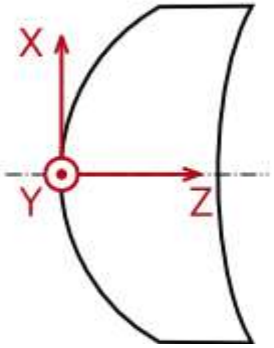
- Testing
  - Using ParameterRun and set the angular order of input OAM from 1 to 15, and measure the detected lateral position

Feature: Position and Orientation

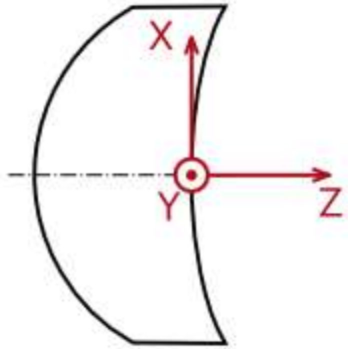
Illustration 7: Position and Orientation



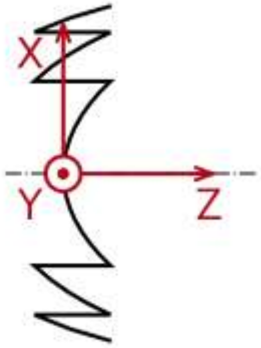
Channels

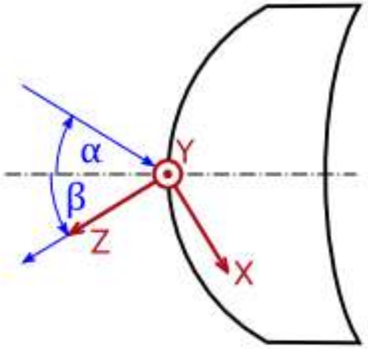


Input channel coordinate system



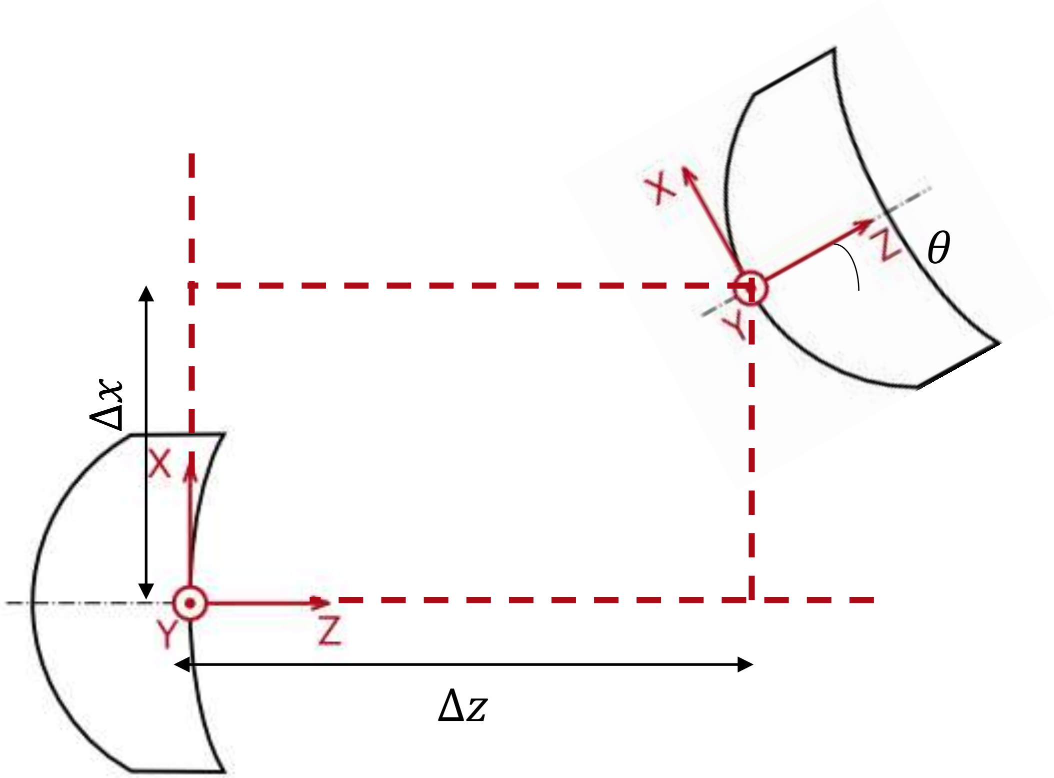
Transmission channel coordinate system



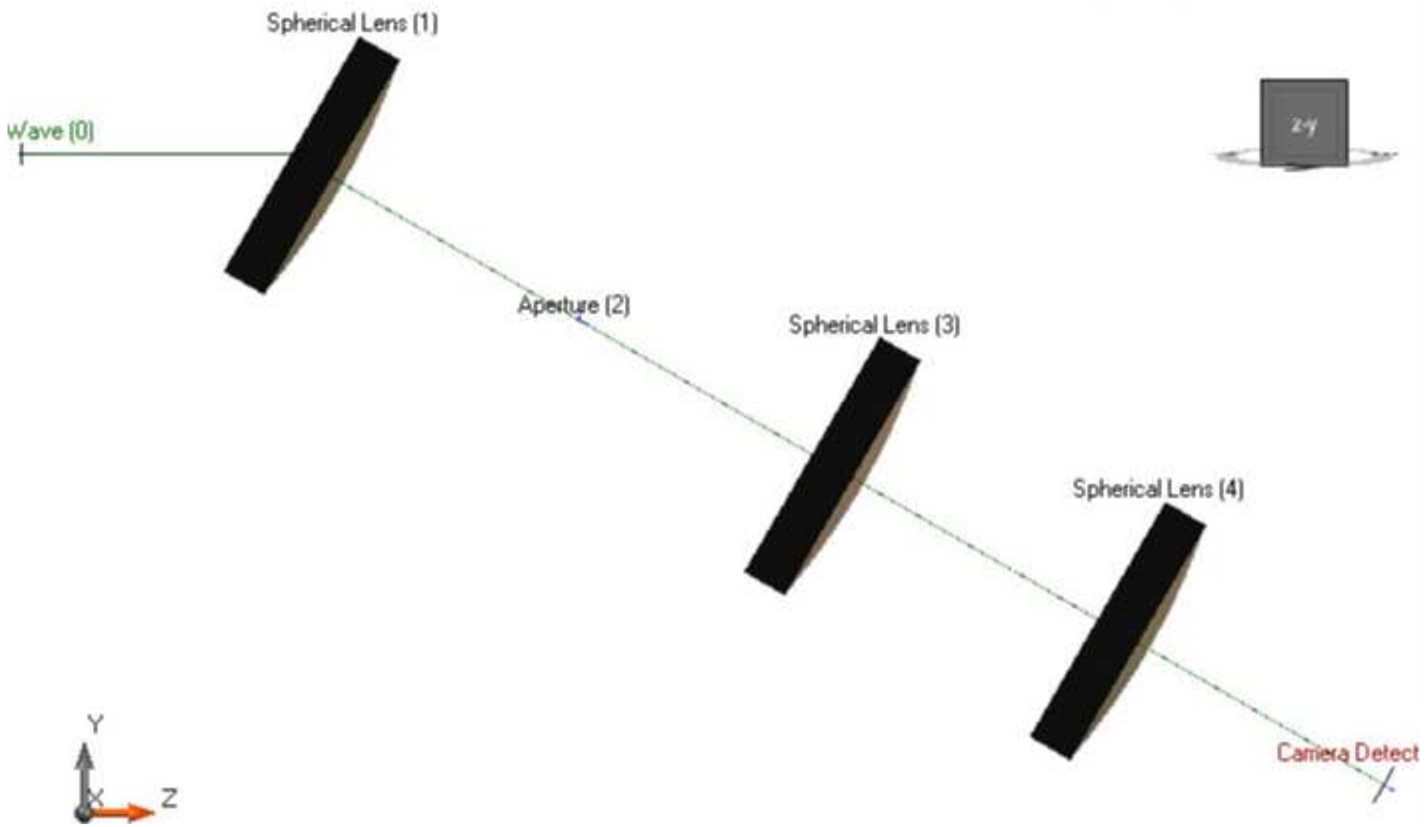


Reflection channel coordinate system

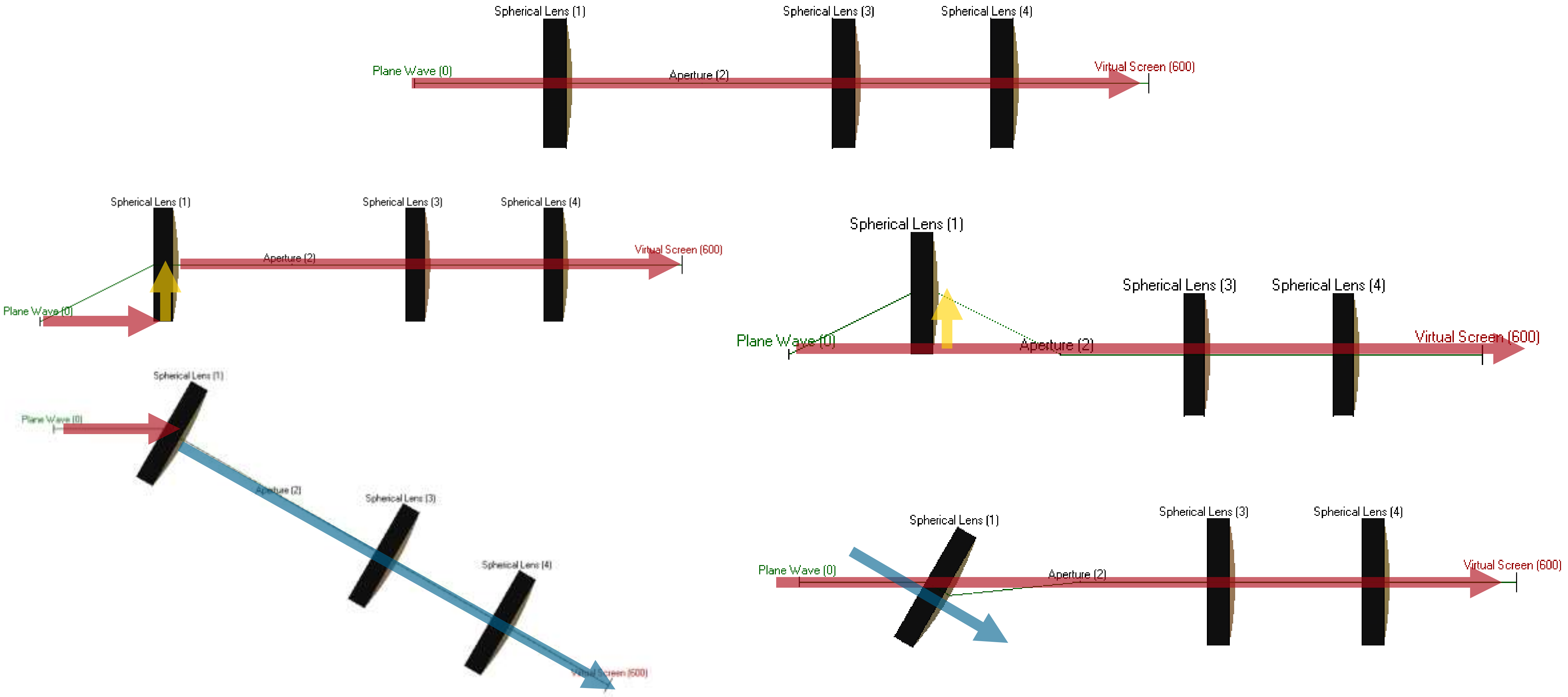
Basal Positioning



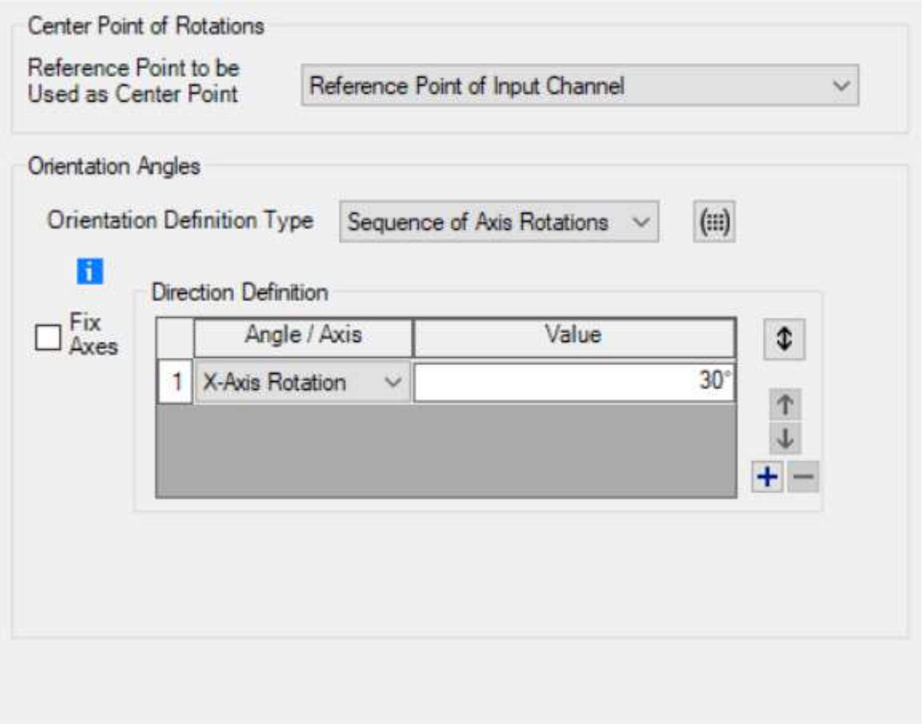
Optical Setup 2

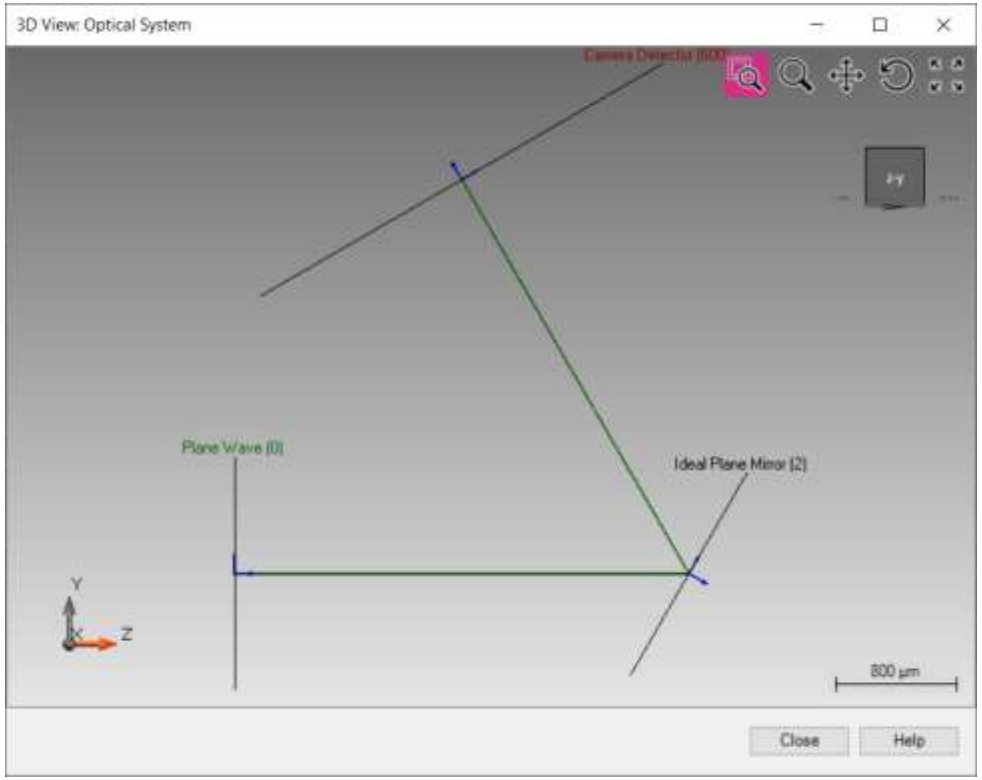


Basal Positioning and Isolated Positioning



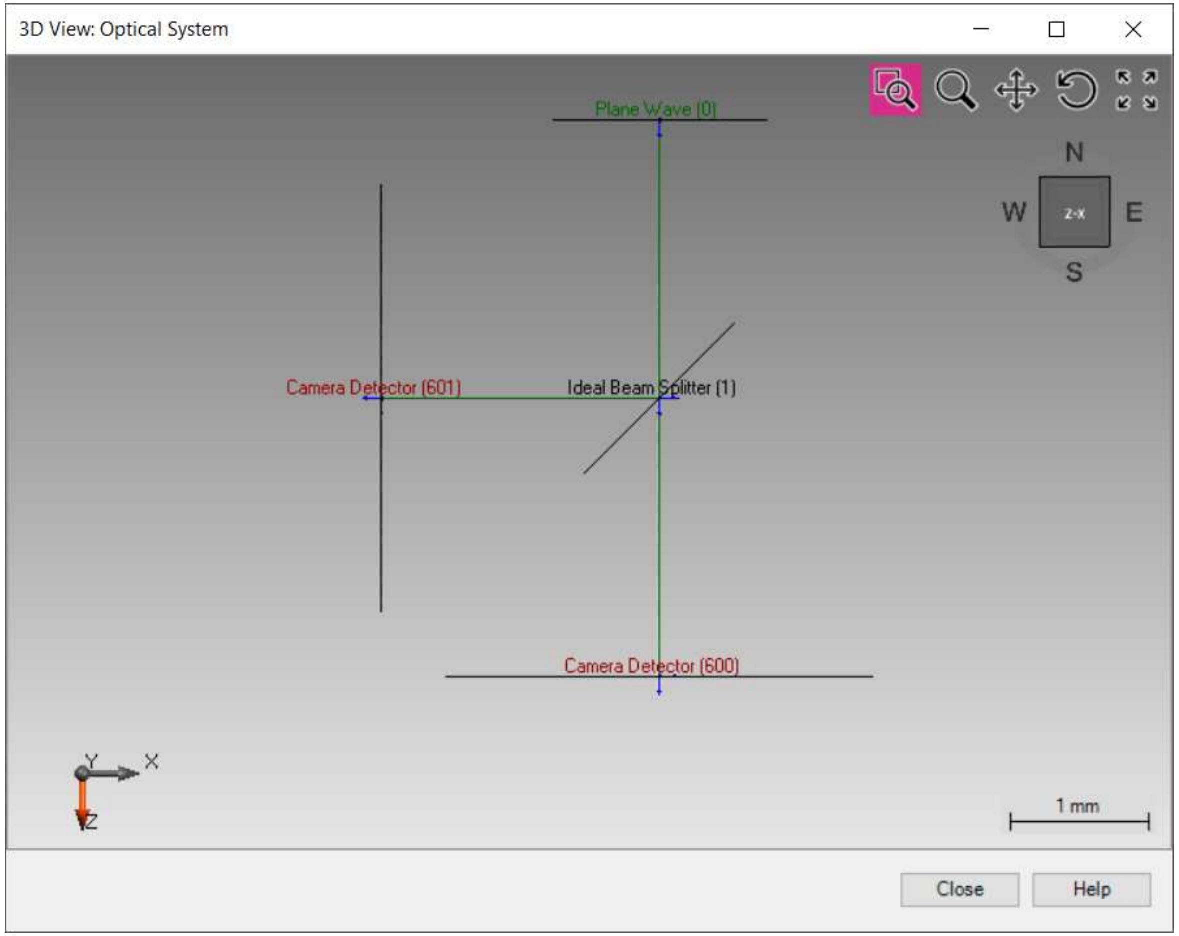
Special Components: Mirror





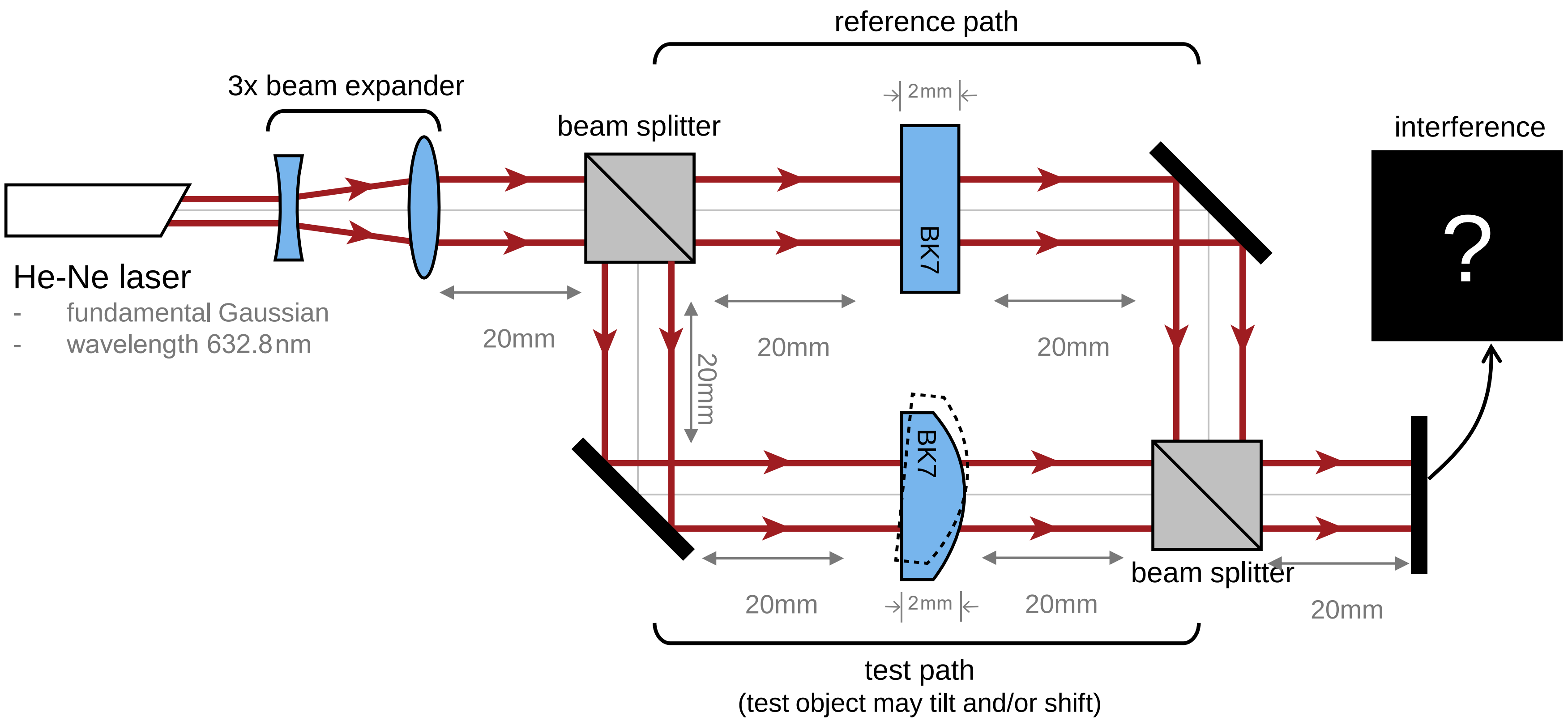
Special Components: Ideal Beam Splitter

Two perpendicular output channels are automatically defined.

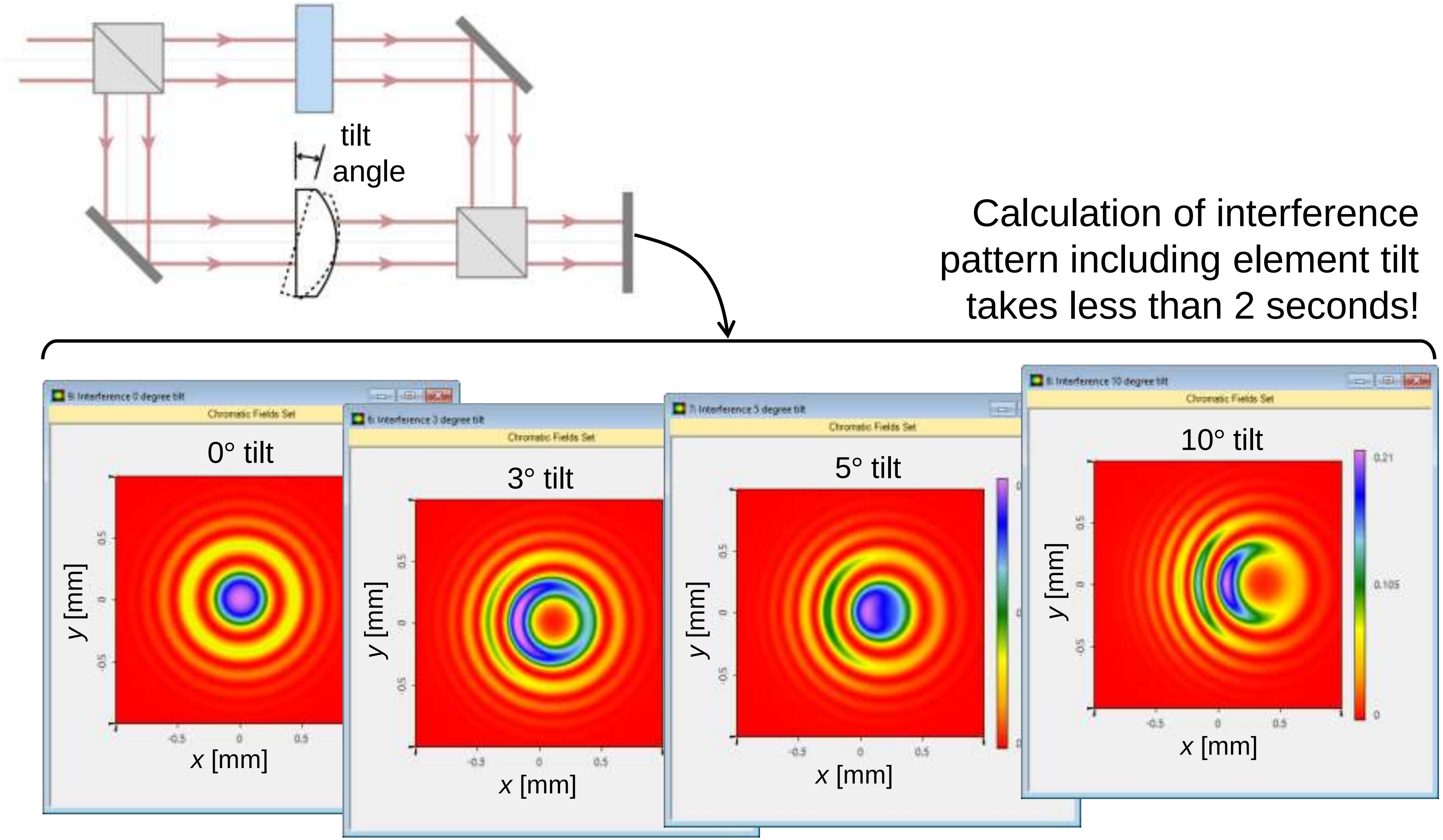


Task 10: Mach-Zehnder Interferometer

Modeling Task

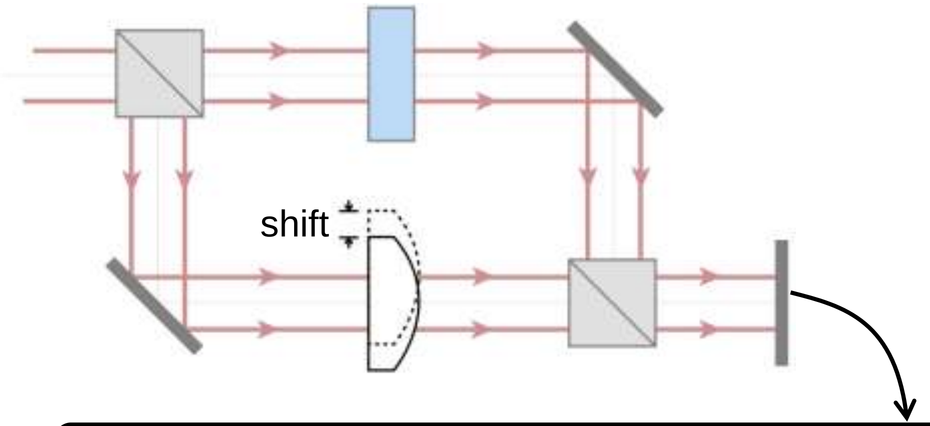


Results

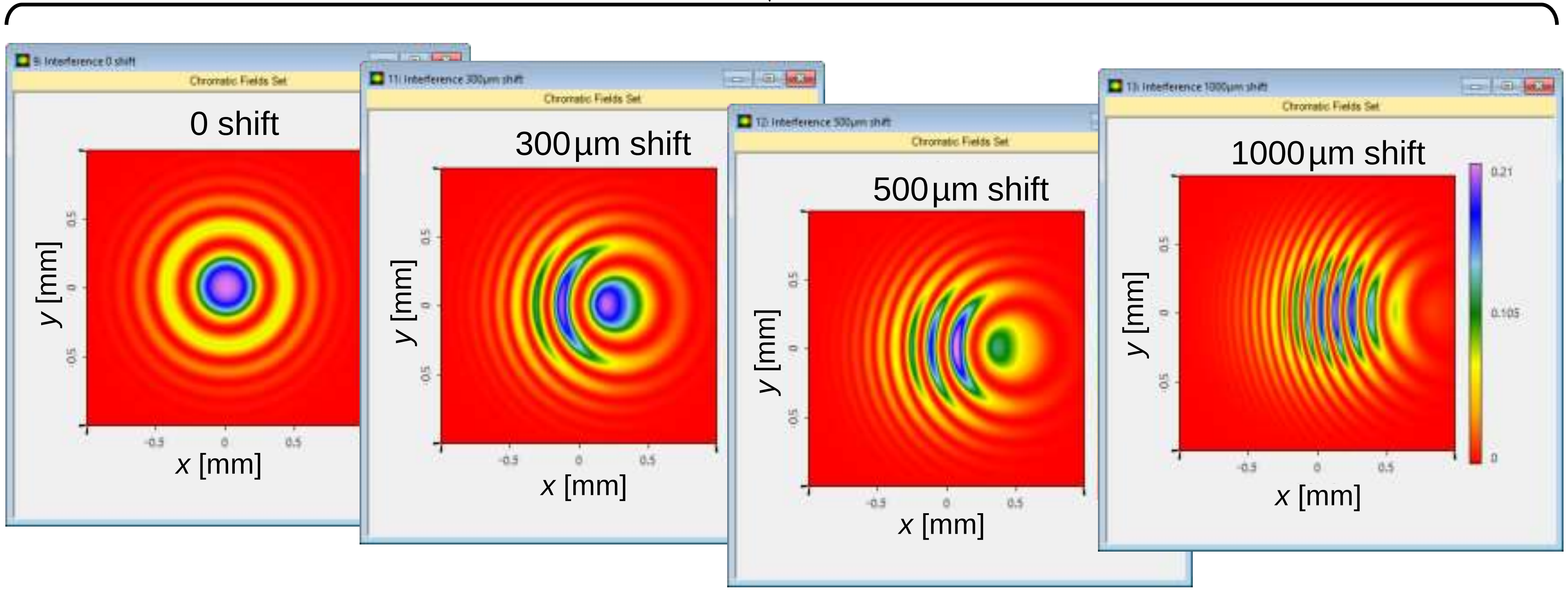


Calculation of interference pattern including element tilt takes less than 2 seconds!

Results



Calculation of interference pattern including element shift takes less than 2 seconds!

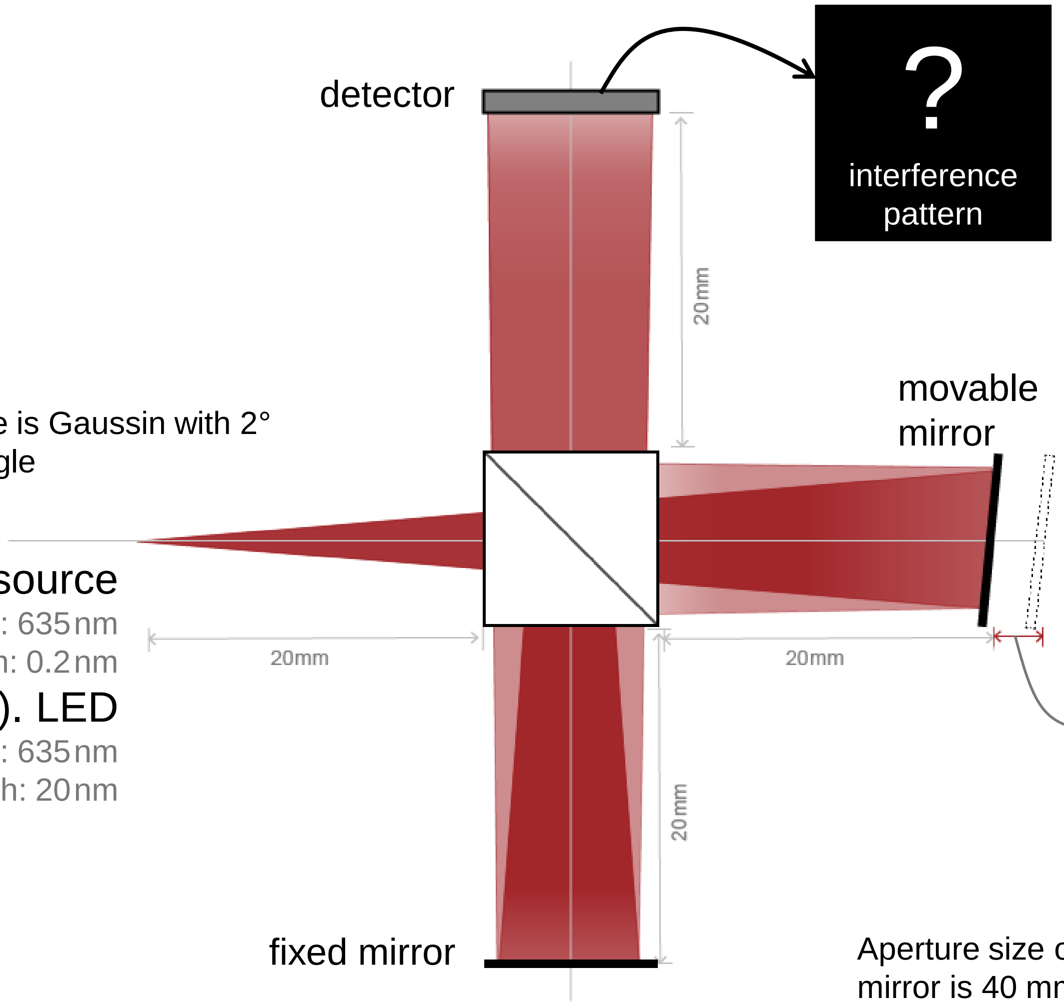


Task 10: Video

Klick the following link to watch the video:

https://youtu.be/smW3HiLscYo

Task 11: Michelson Interferometer



taking the source spectrum and the movement of mirror into consideration

Source mode is Gaussin with 2° divergent angle

a). Laser source
- wavelength: 635 nm
- spectrum bandwidth: 0.2 nm

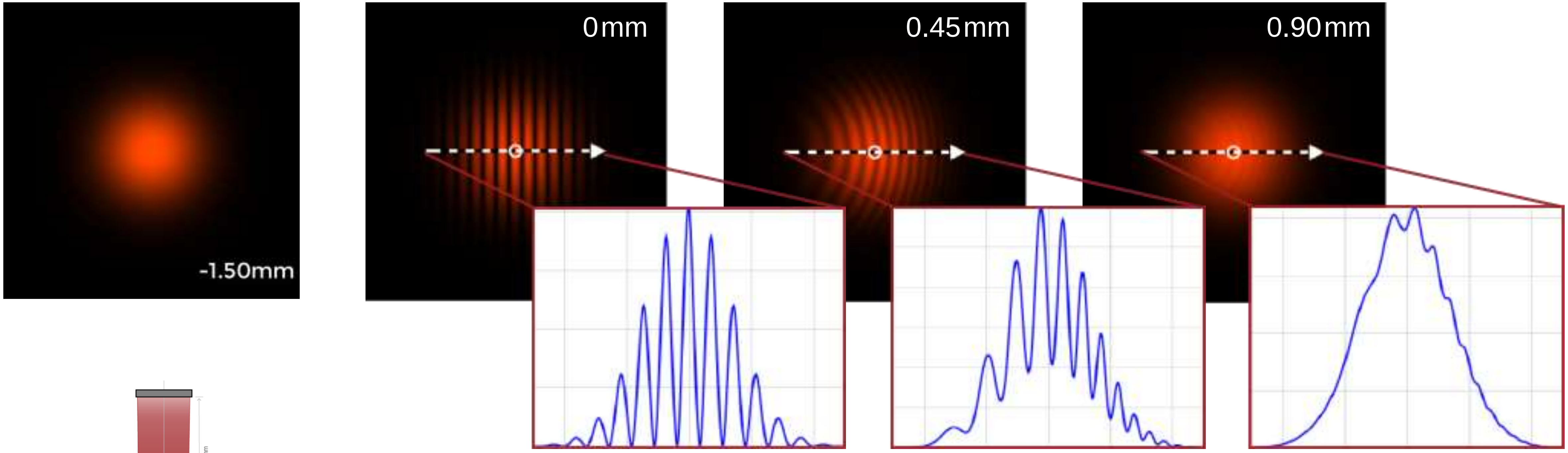
b). LED
- wavelength: 635 nm
- spectrum bandwidth: 20 nm

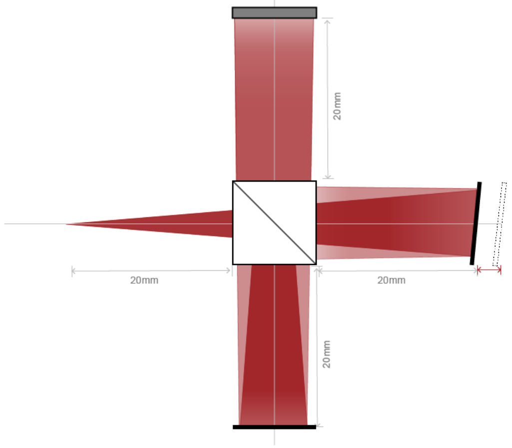
To recognize the interference pattern, we give a 0.05° rotation to the movable mirror.

a). -1.5 mm to 1.5 mm
b). -15 µm to 15 µm

Aperture size of beam splitter and mirror is 40 mm

Results: Laser Source

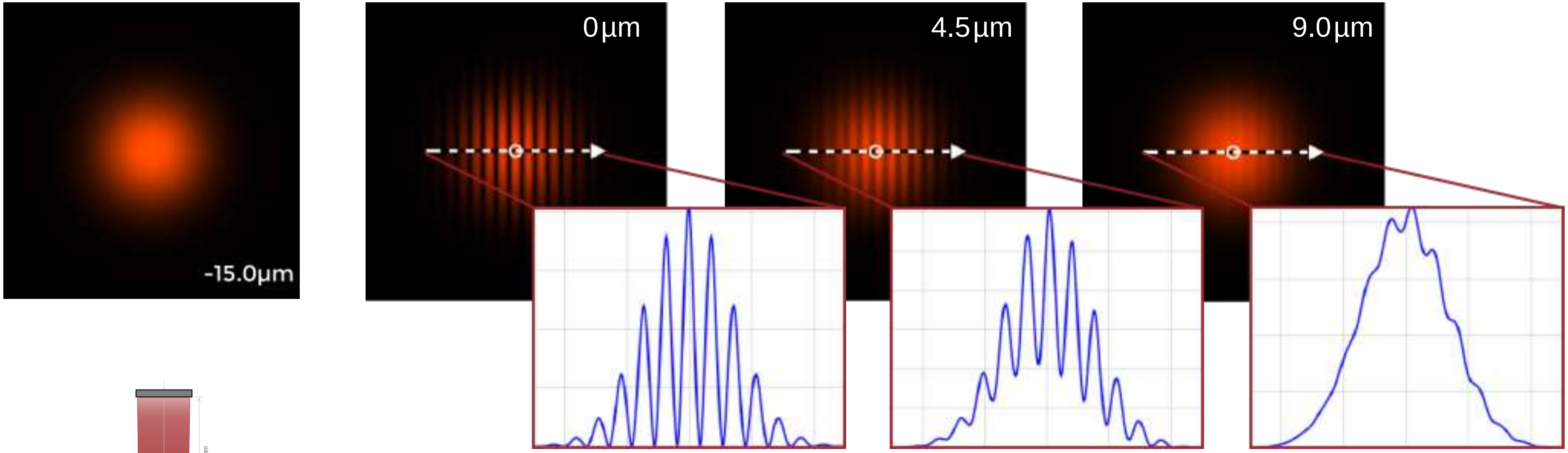


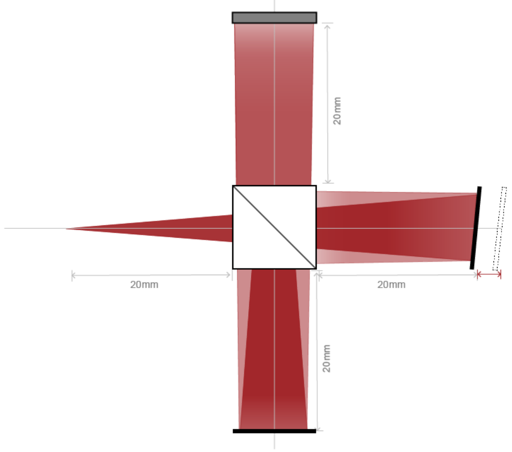


Coherent length here is around 2 mm. It matches that with literature, which is

$$L = \frac{\lambda^2}{\Delta\lambda} = \frac{635^2}{0.2}\ \text{nm} \approx 2\ \text{mm}$$

Results: Laser Source





Coherent length here is around 20μm. It matches that with literature, which is

$$L = \frac{\lambda^2}{\Delta\lambda} = \frac{635^2}{20}\ \mathrm{nm} \approx 20\ \mu\mathrm{m}$$

Task 11:Video

Klick the following link to watch the video:

https://youtu.be/rO_X4CspDeY

Summary

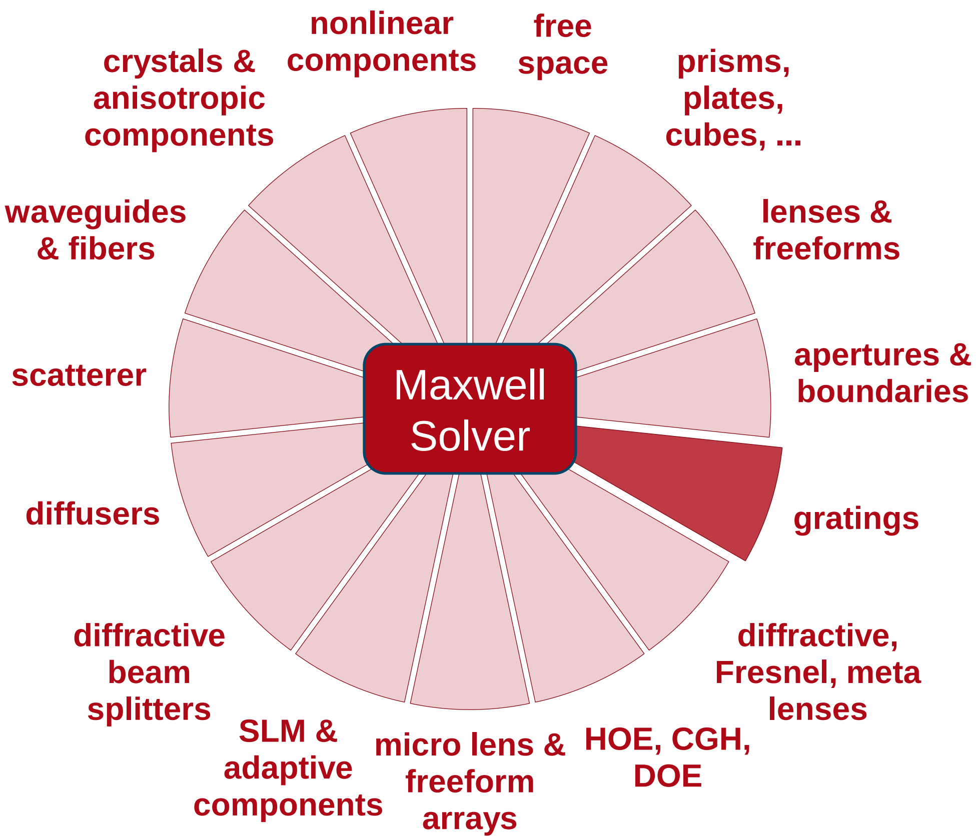
- Be familiar with the definition of position and orientation
- Analysis of alignment tolerance by using isolated positioning

Gratings

- Gratings are rigorously modeled in the k-domain by the Fourier Modal Method (FMM), which is also referred to as RCWA.
- The operator $\tilde{\boldsymbol{\mathcal{B}}}$ is of the form

$$\tilde{\boldsymbol{\mathcal{B}}}(\boldsymbol{\kappa}^{\text{out}}, \boldsymbol{\kappa}^{\text{in}}) = \begin{pmatrix} \tilde{\mathcal{B}}_{xx} & \tilde{\mathcal{B}}_{xy} \\ \tilde{\mathcal{B}}_{yx} & \tilde{\mathcal{B}}_{yy} \end{pmatrix}$$

- This is a fully vectorial operation. Modeling via diffraction efficiencies is not sufficient.



Gratings: Rayleigh Coefficients

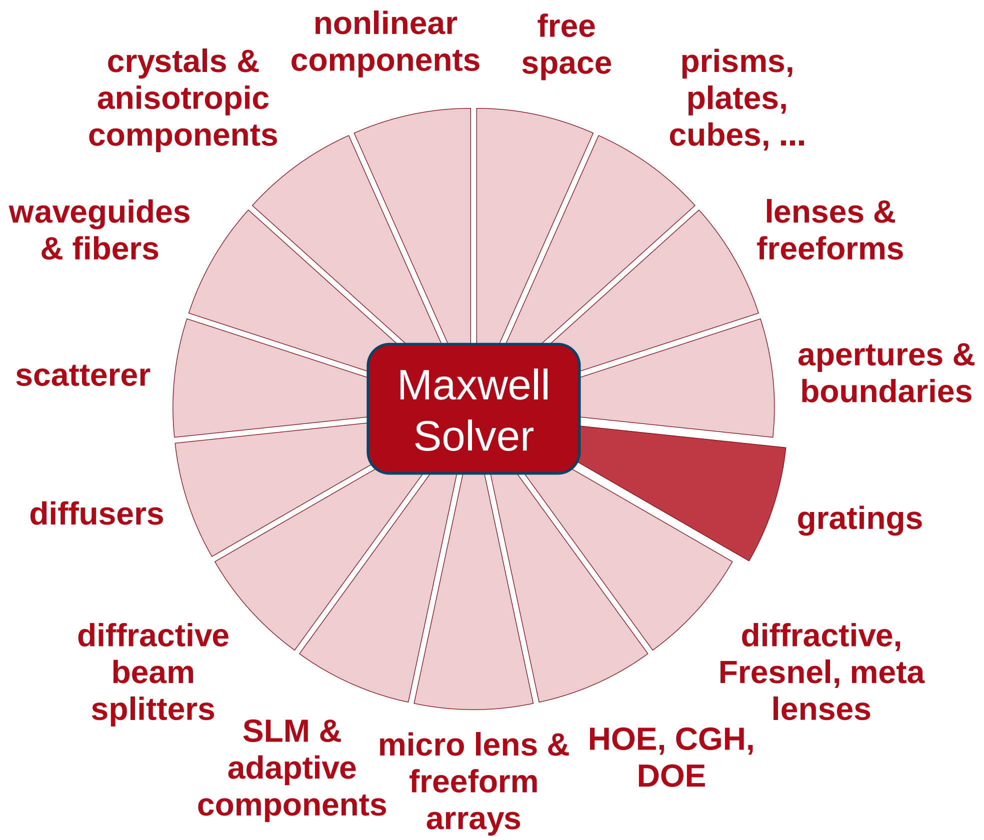
- Each incident plane wave ($\boldsymbol{\kappa}^{\text{in}}$) must be multiplied by the Rayleigh matrix $\tilde{\mathbf{B}}$ to obtain one grating-order related output plane wave ($\boldsymbol{\kappa}^{\text{out}}$):

$$\tilde{\boldsymbol{V}}_{\perp}^{\text{out}}(\boldsymbol{\kappa}^{\text{out}}) = \tilde{\mathbf{B}}(\boldsymbol{\kappa}^{\text{out}}, \boldsymbol{\kappa}^{\text{in}})\tilde{\boldsymbol{V}}_{\perp}^{\text{in}}(\boldsymbol{\kappa}^{\text{in}})$$

- The Rayleigh matrix is given by

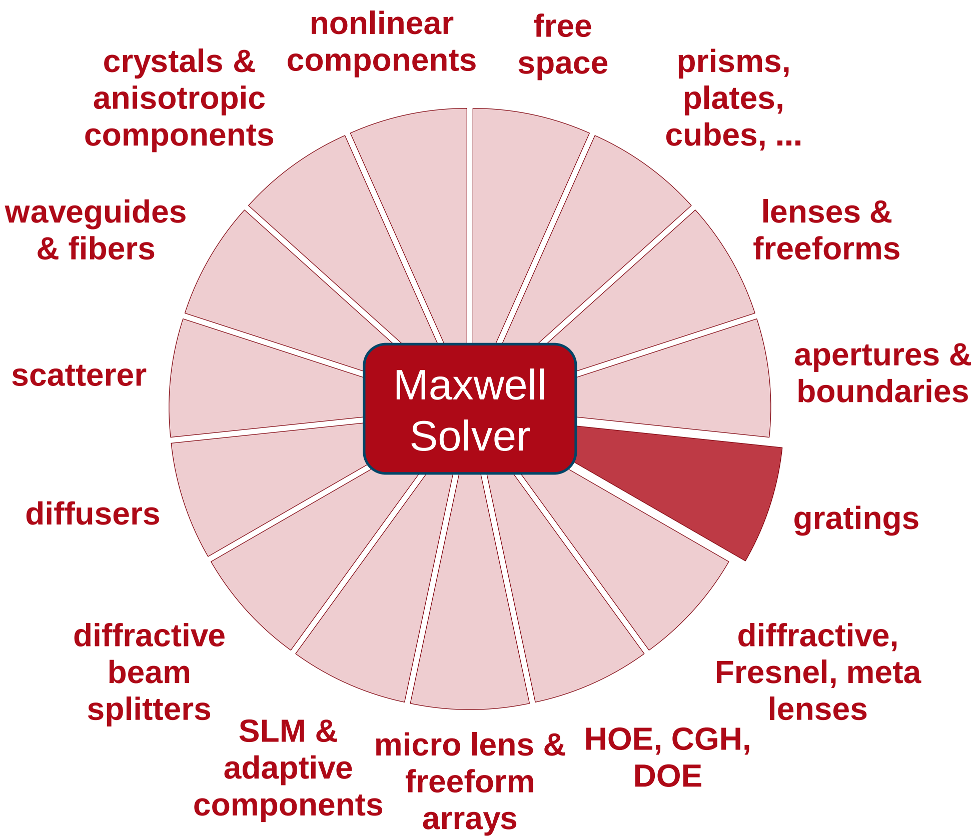
$$\tilde{\mathbf{B}} = \begin{pmatrix} R_{xx} & R_{xy} \\ R_{yx} & R_{yy} \end{pmatrix}$$

with the Rayleigh coefficients R for the order of concern.



Gratings

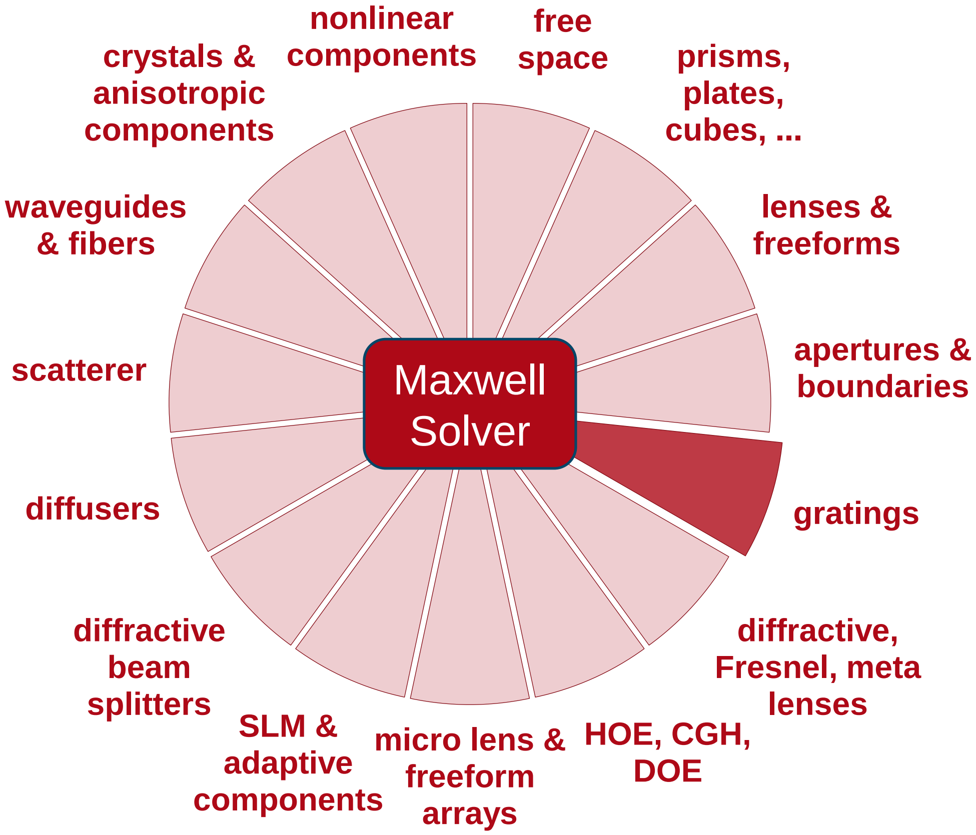
- VirtualLab Fusion treats the calculation of all matrices automatically and stores the results in lookup-tables for later usage.
- For large grating periods VirtualLab automatically switches to faster modeling techniques (LPIA, TEA).



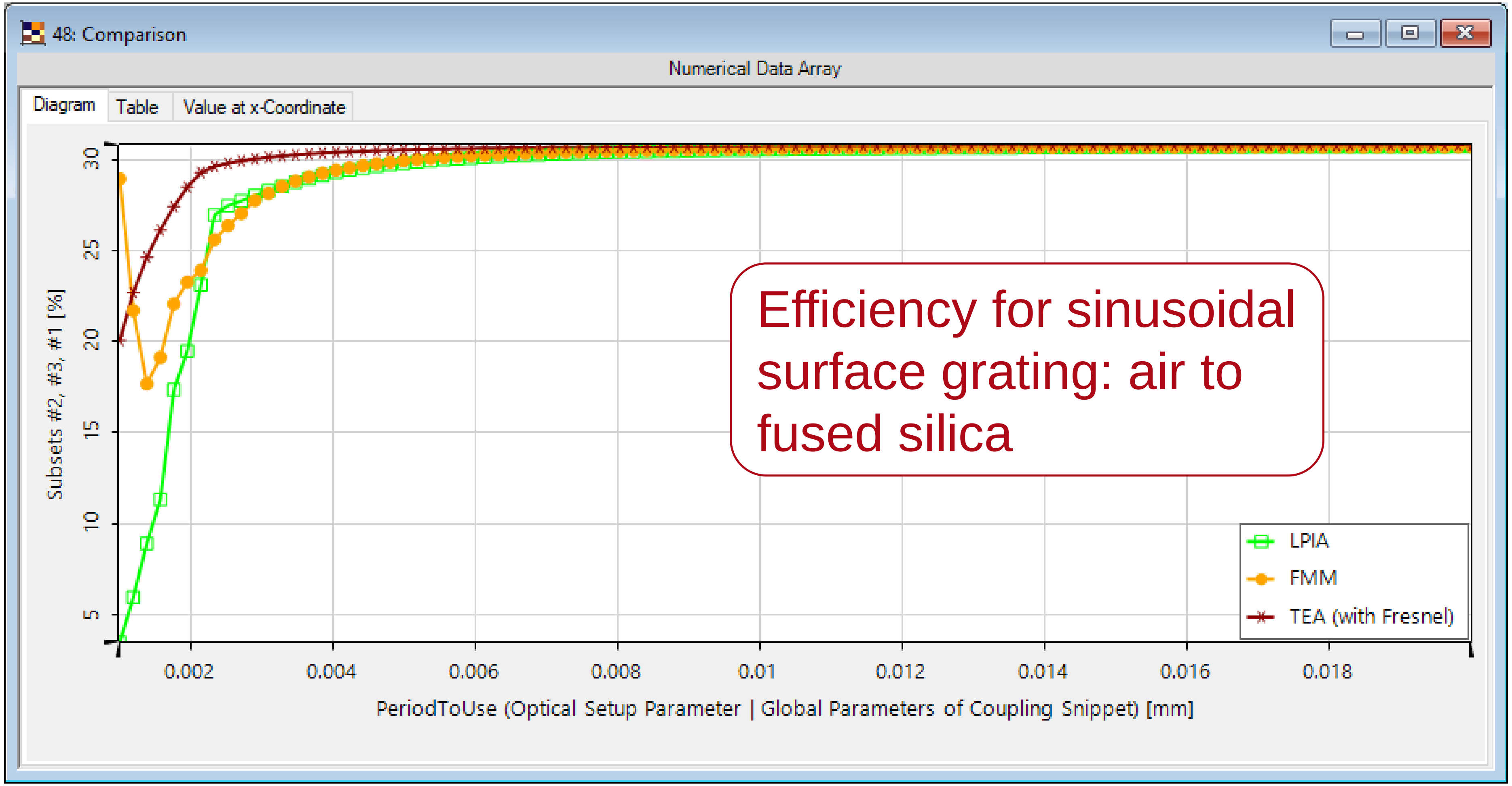
Gratings: Example Sinusoidal Grating

- VirtualLab Fusion treats the calculation of all matrices automatically and stores the results in lookup-tables for later usage.
- For large grating periods VirtualLab automatically switches to faster modeling techniques (LPIA, TEA).

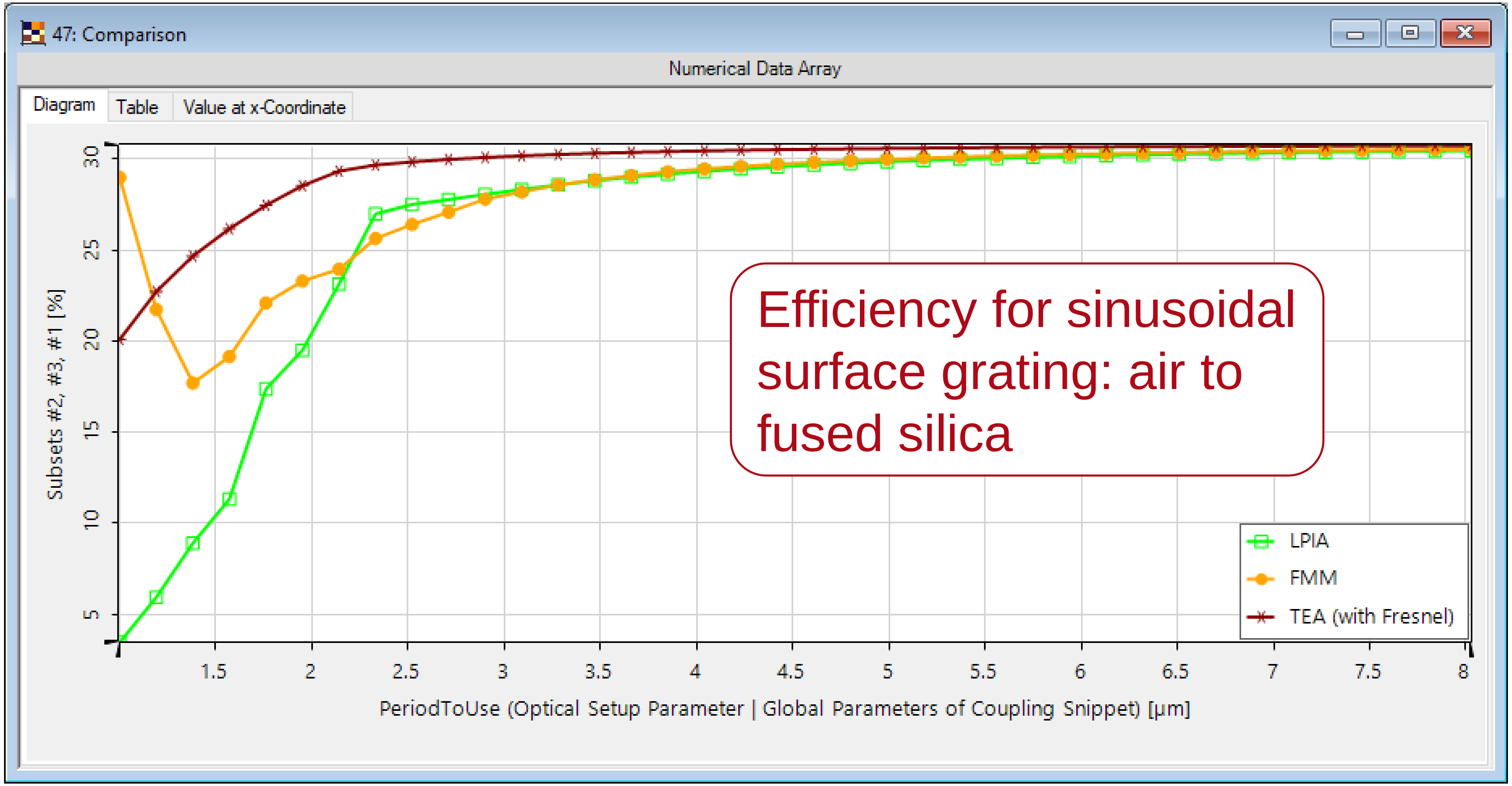
Efficiency for sinusoidal surface grating: air to fused silica: FMM, LPIA, TEA



Efficiency of +1st Order: Period 0.9 – 20 µm; Depth 630 nm

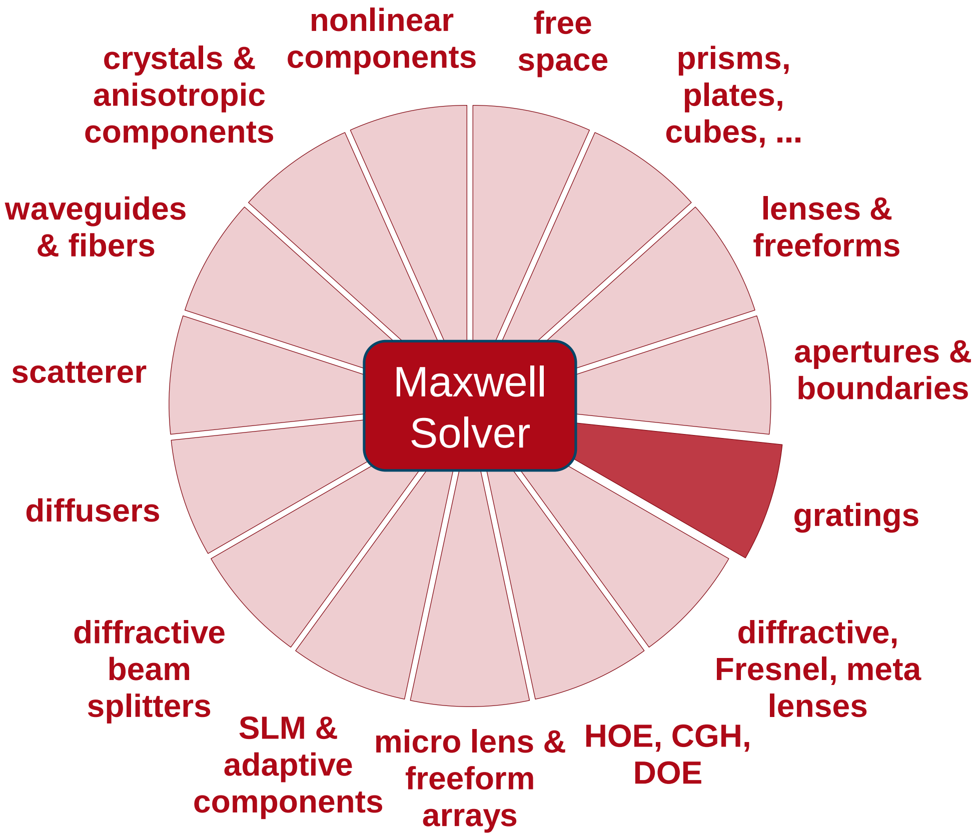


Efficiency of +1st Order: Period 0.9 – 8 µm; Depth 630 nm



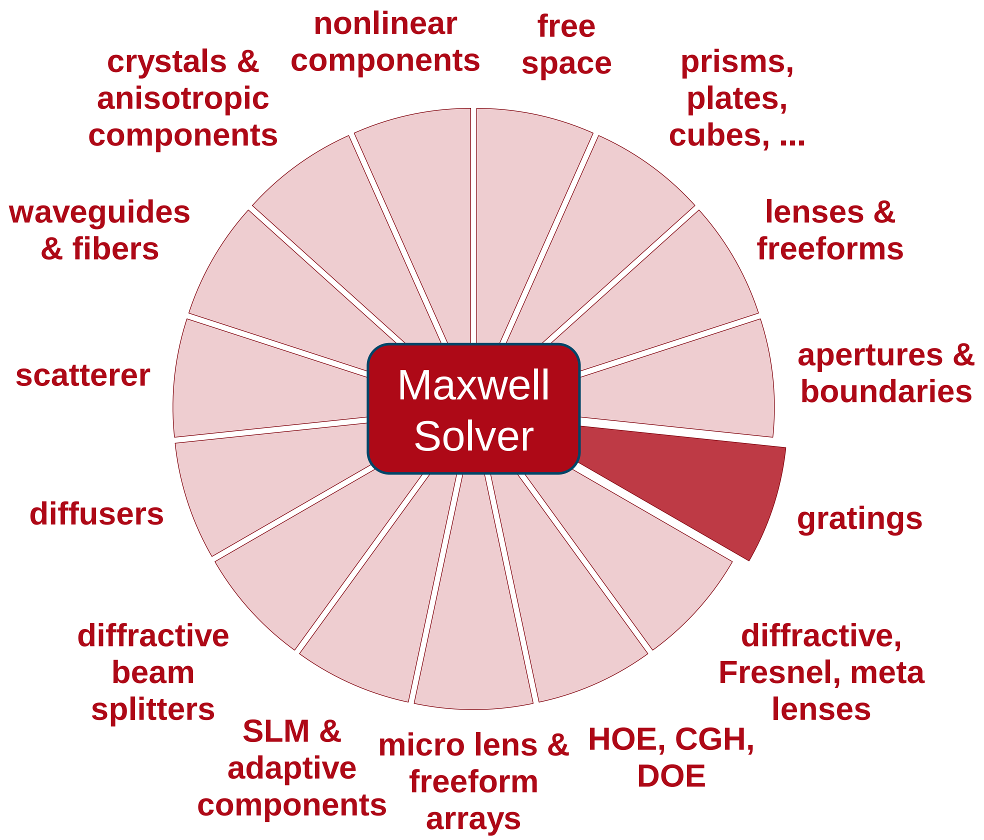
Gratings

- VirtualLab Fusion treats the calculation of all matrices automatically and stores the results in lookup-tables for later usage.
- For large grating periods VirtualLab automatically switches to faster modeling techniques (LPIA, TEA).
- Remark: Integral method for slanted gratings under development as alternative technqiue to FMM for tolerancing.



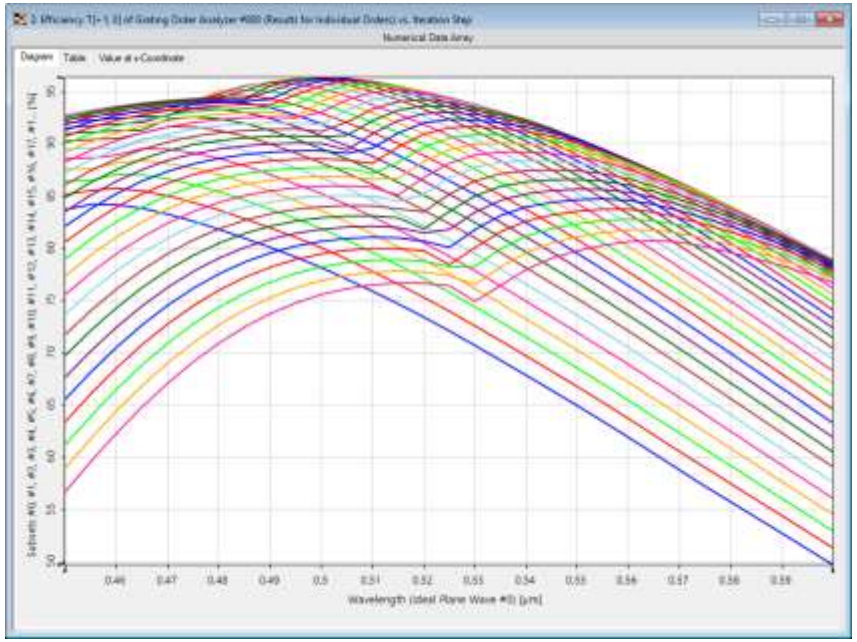
Gratings

- VirtualLab Fusion enables modeling of any kind of stacked grating structures.
- That includes surface gratings with coating.
- VirtualLab Fusion also provides the analysis of holographic volume gratings.
- Optimization and tolerancing is available.



Analysis of Blazed Grating by Fourier Modal Method

Abstract

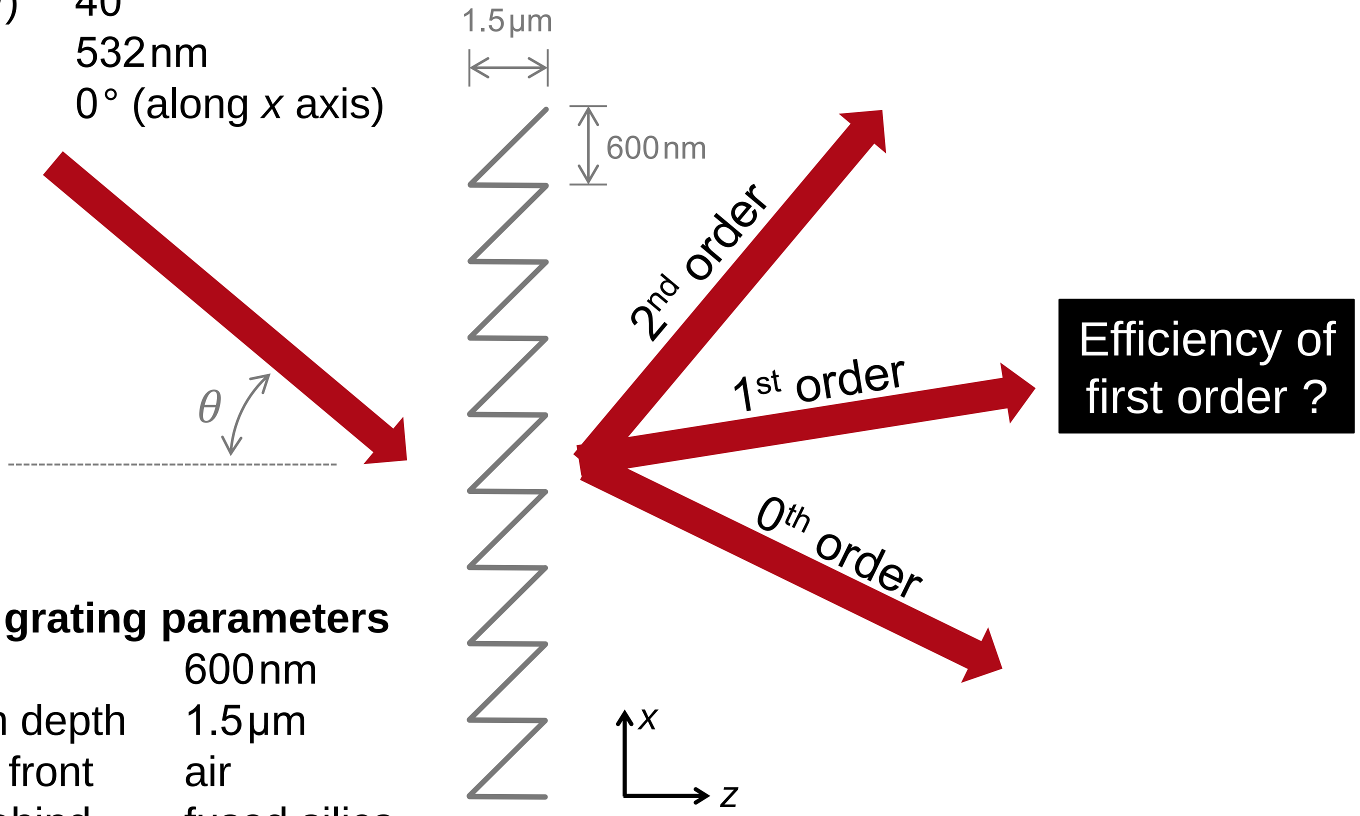


The Fourier modal method (FMM) can be used to analyze grating efficiencies rigorously. In VirtualLab you can setup your grating system, perform the rigorous analysis, and present the results in different format (e.g. grating order collection, single values, …). In combination with the parameter run you can also scan a given parameter space to investigate the performance of the specified structure for different configurations. For the evaluation of the results of the parameter run, several evaluation tools are available to give you the best insight in your optical setup.

Modeling Task

Incident plane wave

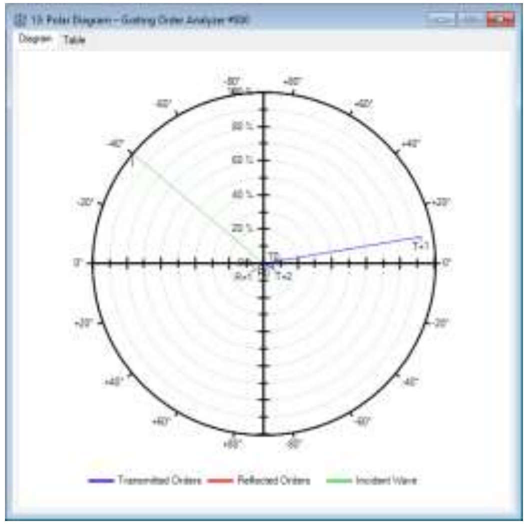
incident angle (θ)	40°
wavelength (λ)	532 nm
polarization	0° (along x axis)



Sawtooth grating parameters

period	600 nm
modulation depth	1.5 µm
material in front	air
material behind	fused silica

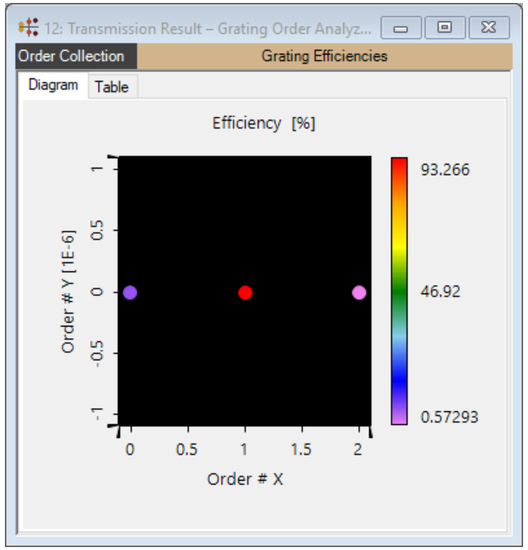
Results



Polar diagram
used for projected visualization of grating efficiencies for transmission and reflection

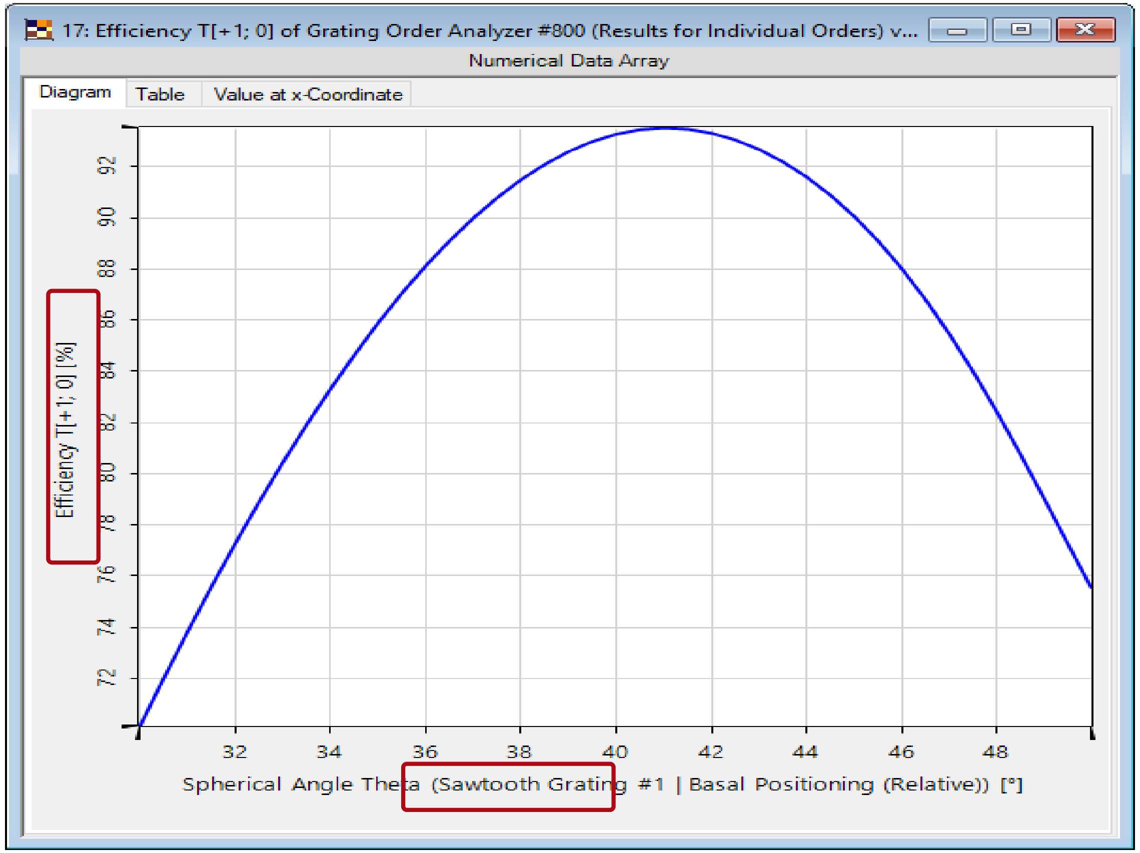
Results in transmission:

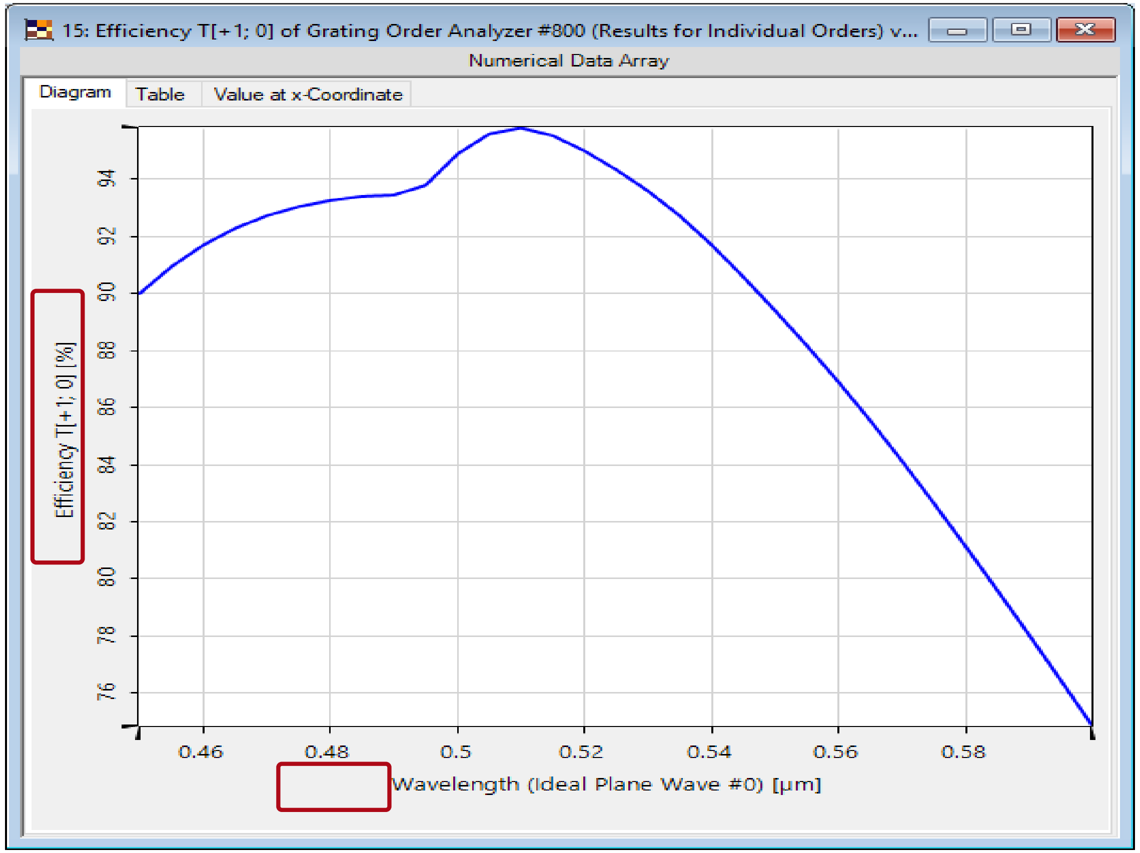
	Angle	Efficiency
0^{th} order	-26.107°	6.1579 %
1^{st} order	9.6014°	93.266 %
2^{nd} order	50.682°	0.57293 %



Order collection
display of efficiency or other quantity with respect to e.g. diffraction order, angle, etc.

Results





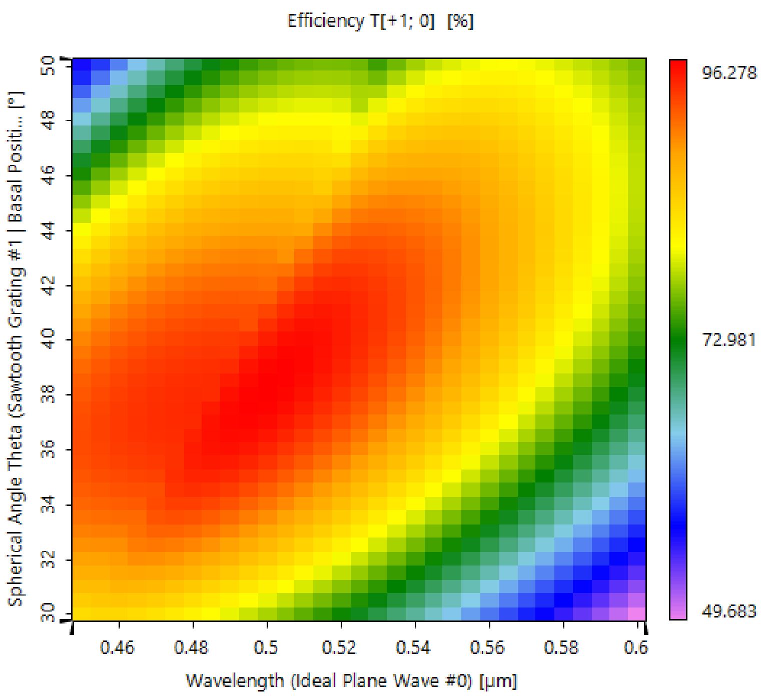
Parameter variation (fixed $\lambda = 532\,\text{nm}$)

theta 30° - 50°

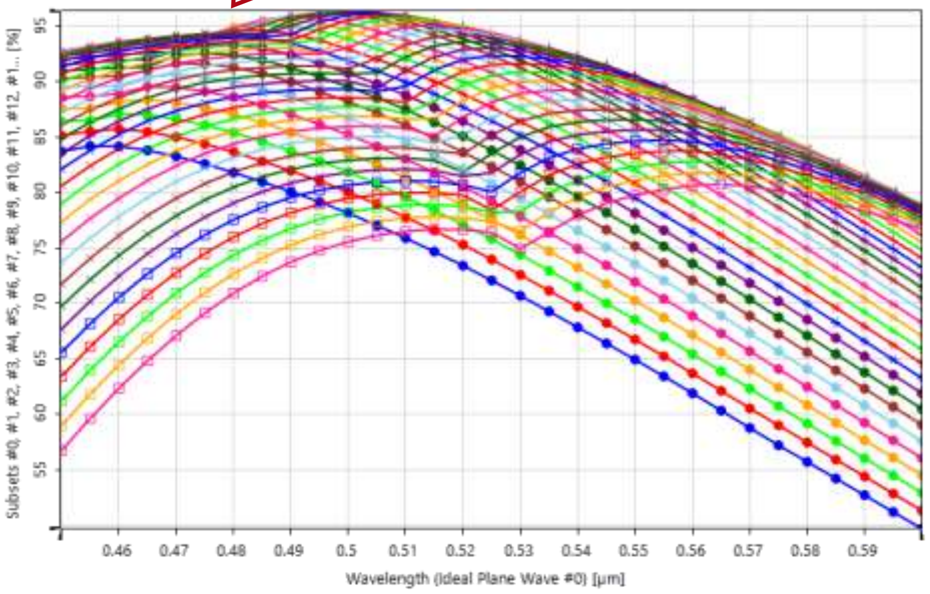
Parameter variation (fixed $\theta = 40°$)

wavelength 450 nm - 600 nm

Results



VirtualLab allows to plot the efficiencies also as 1D multigraphs. Each curve is associated with one incident angle.



Parameter Variation

theta	30° - 50°
wavelength	450 nm - 600 nm

Step 1: Configure a Grating (Video)

Klick the following link to watch the video:

https://youtu.be/p1aamDT58f4

Step 2: Check the Convergence

Klick the following link to watch the video:

https://youtu.be/EK2SlSHRQDs

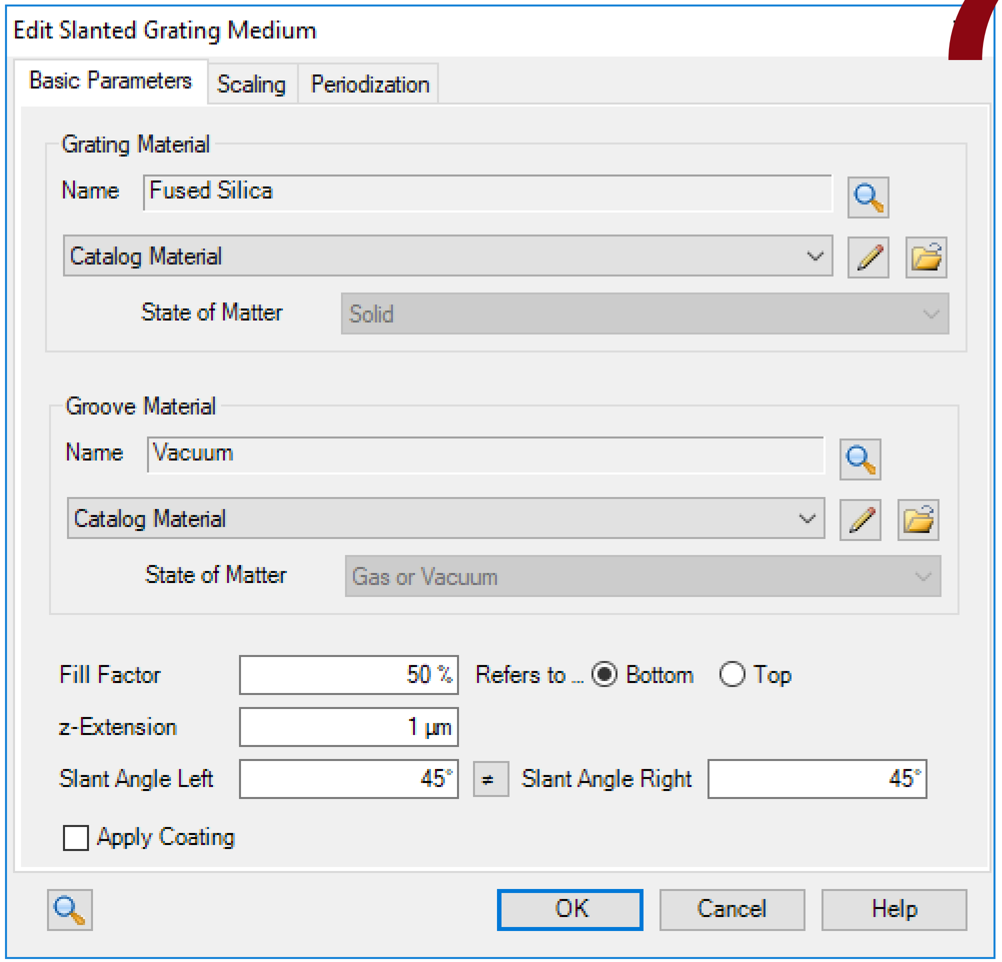
Step 3: Simulation of Grating Properties

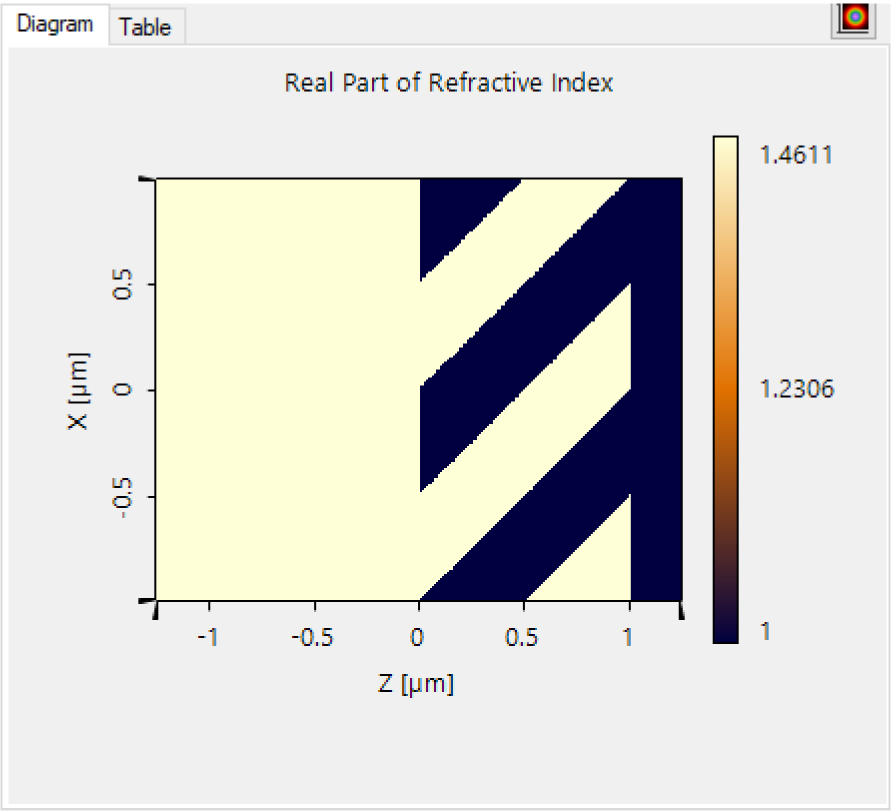
Klick the following link to watch the video:

https://youtu.be/OpSefzqUDAQ

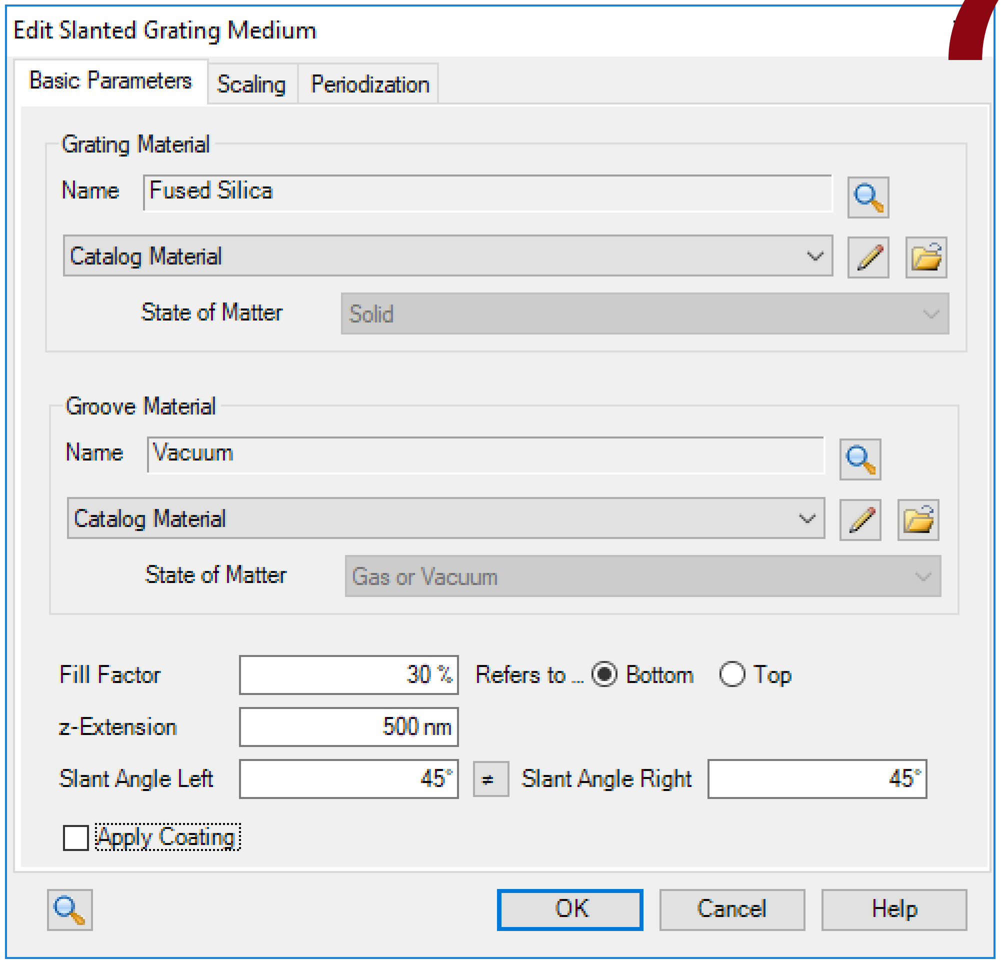
Sample Configurations of Slanted Grating Medium

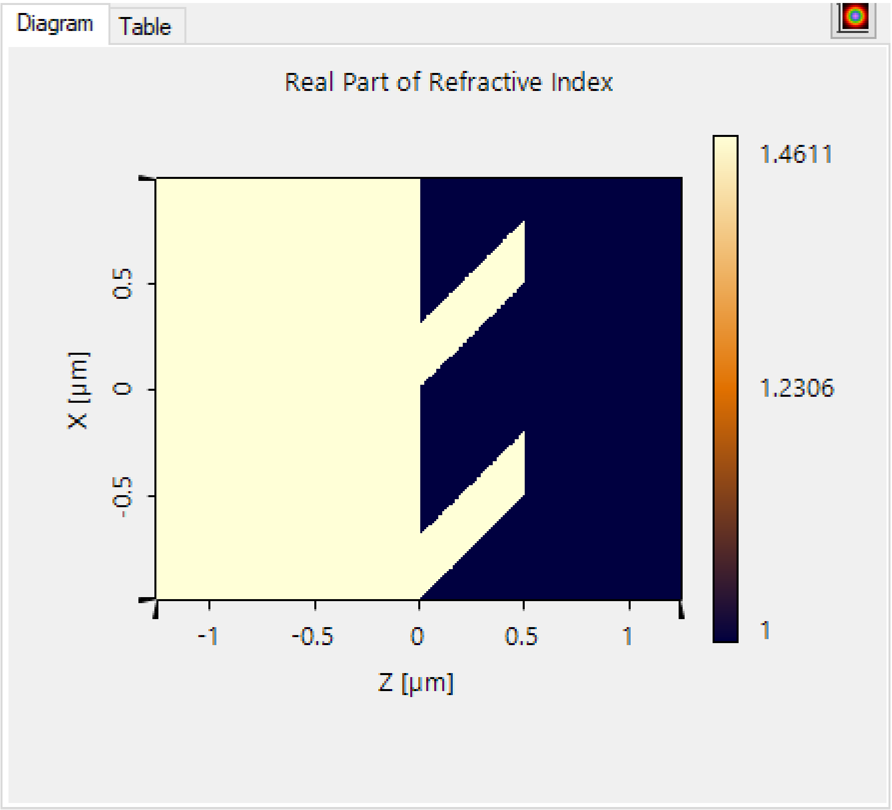
Sample Slanted Grating #1



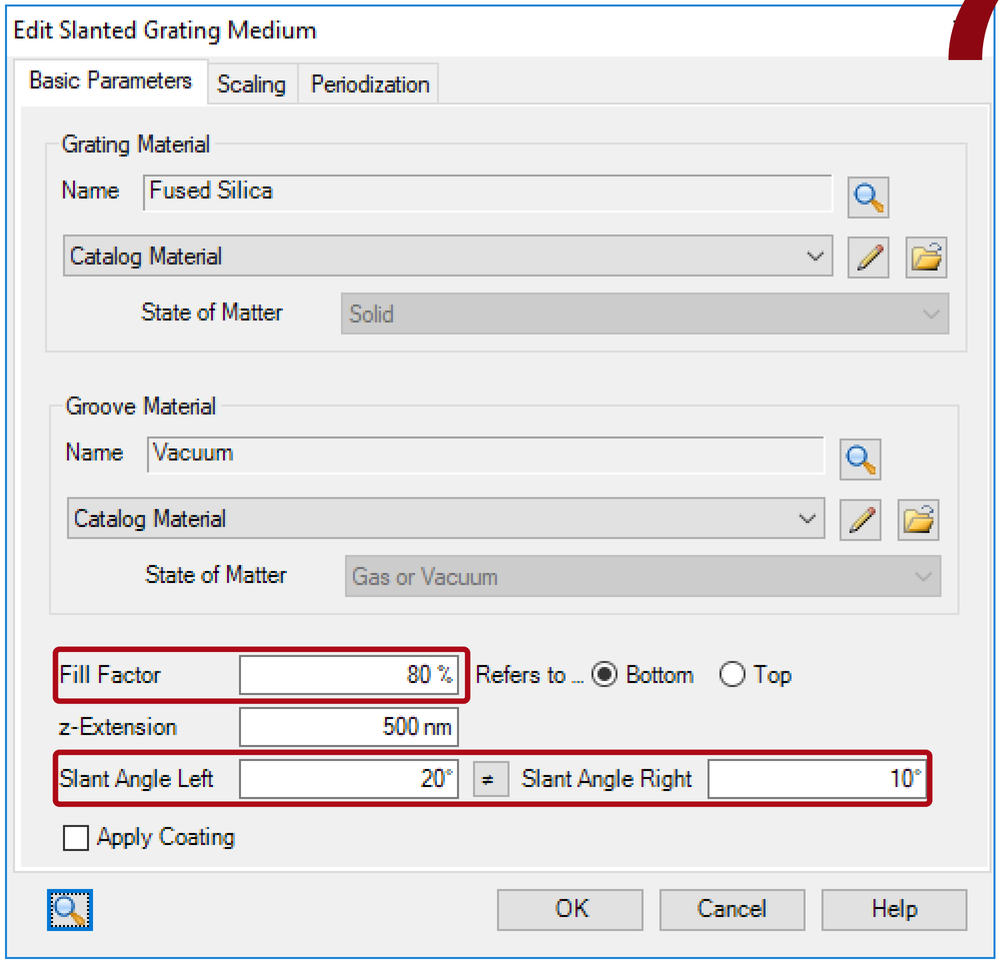


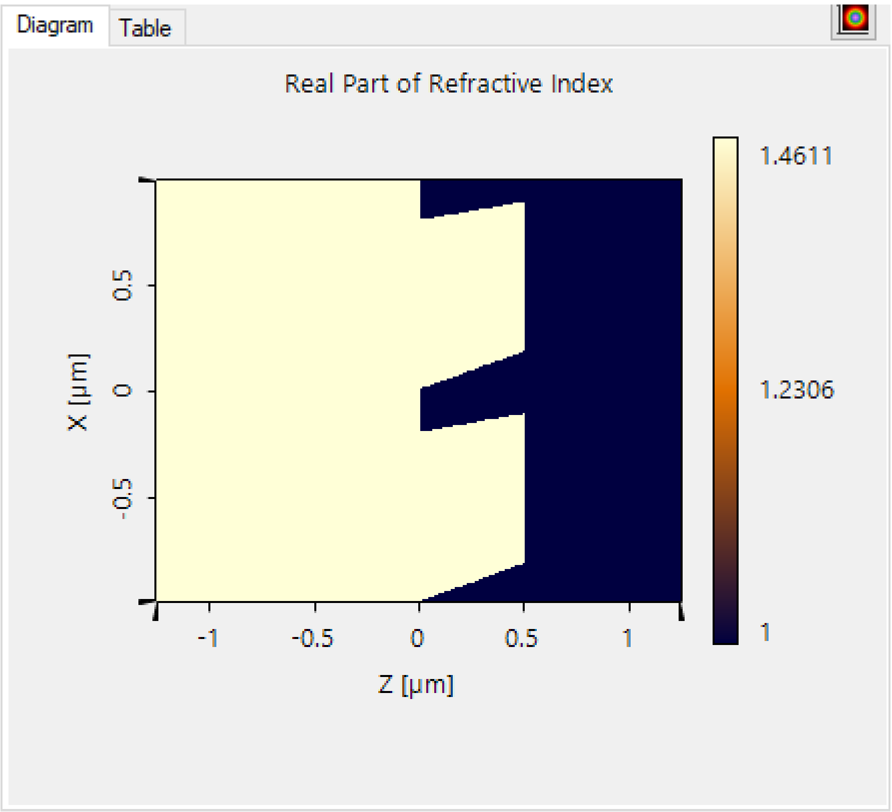
Sample Slanted Grating #2



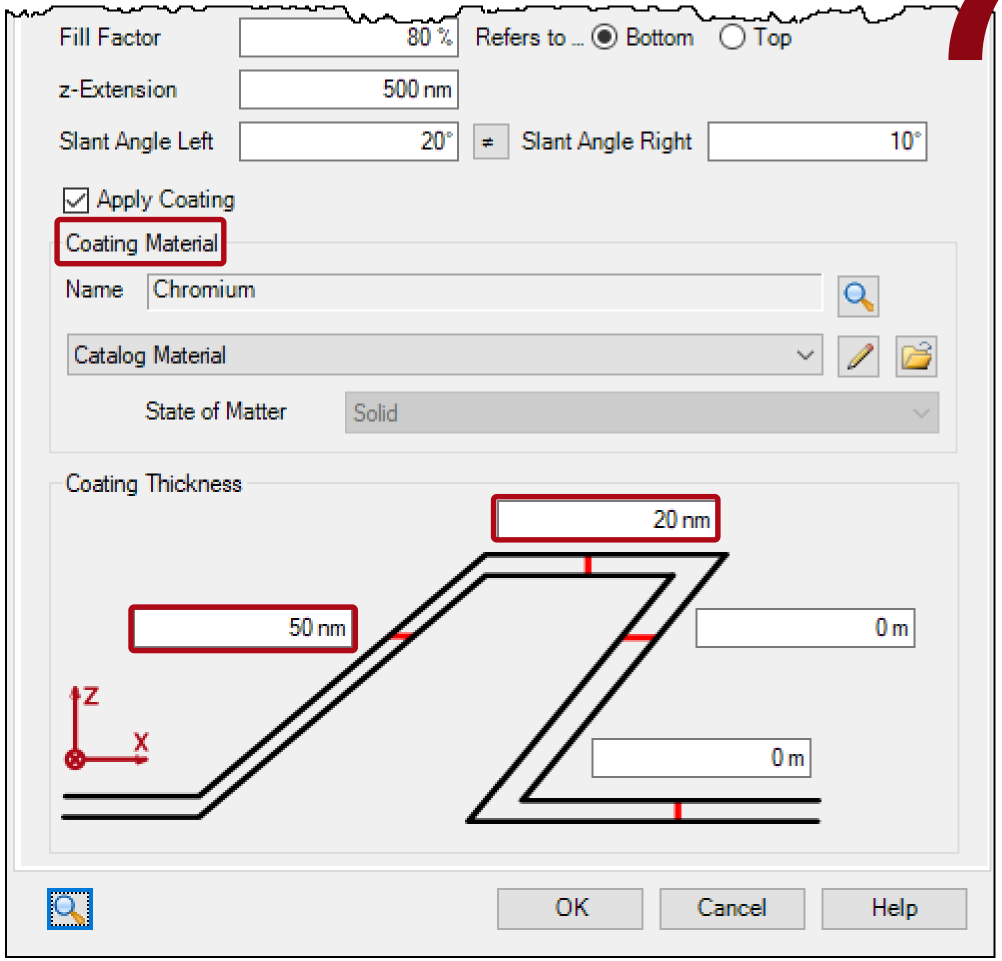


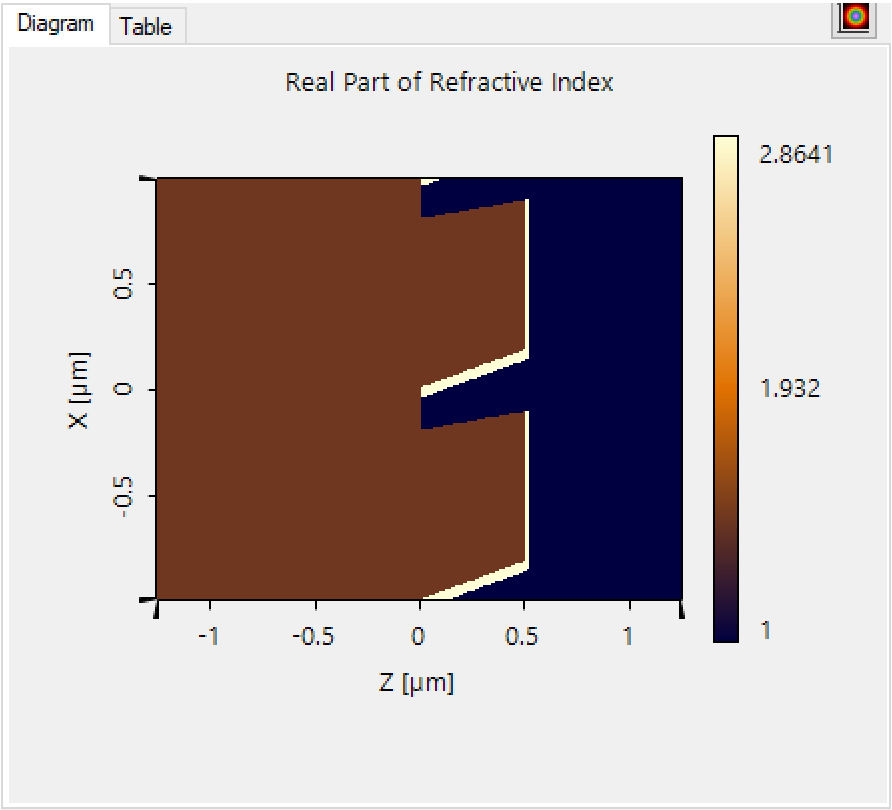
Sample Slanted Grating #3





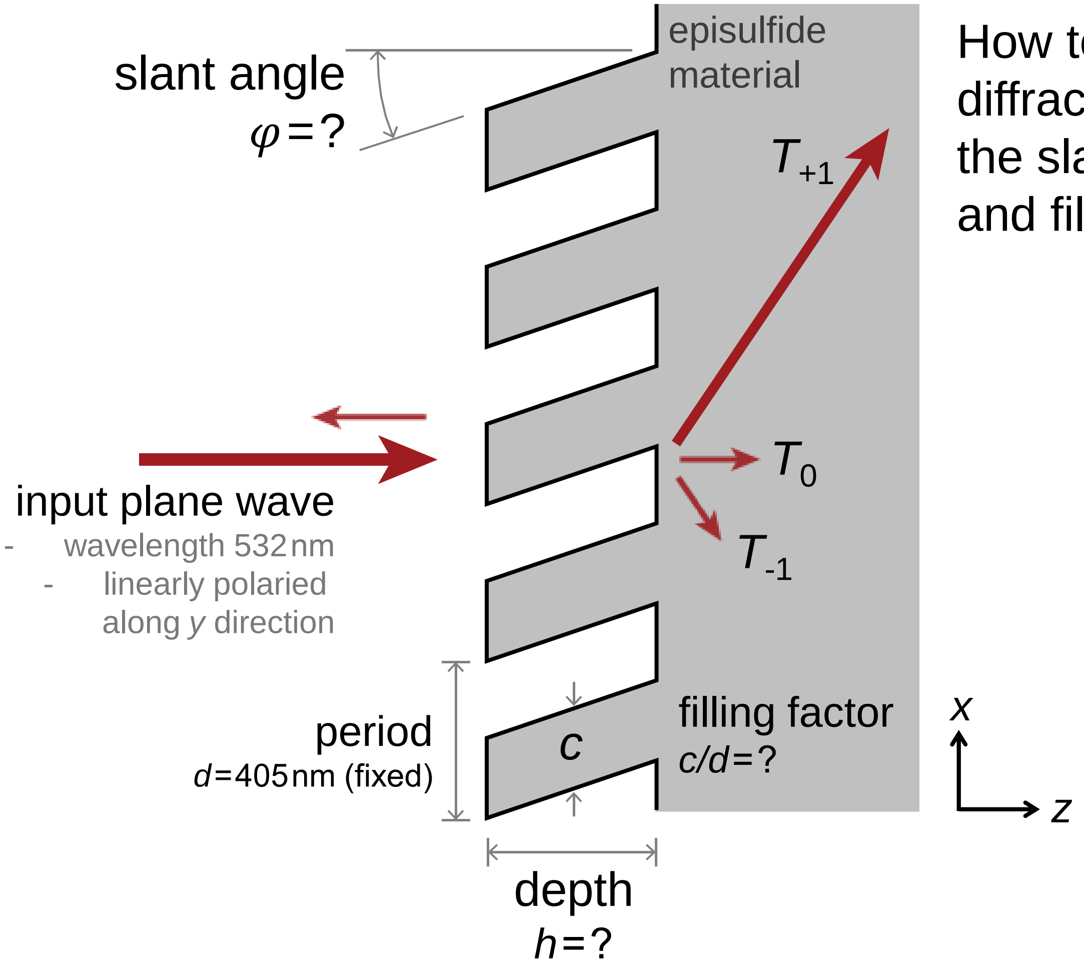
Sample Slanted Grating #4



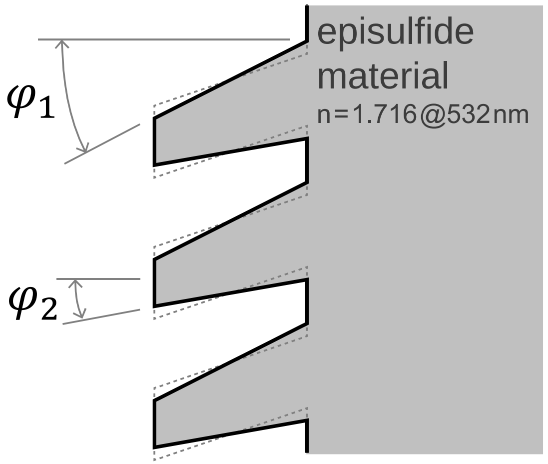


Parametric Optimization and Tolerance Analysis of Slanted Gratings

Modeling Task



How to optimize the T_{+1} order diffraction efficiency, by adjusting the slant angle φ, grating depth *h*, and filling factor *c/d*?

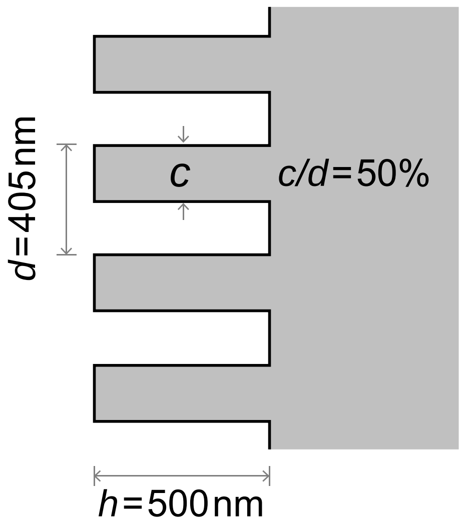


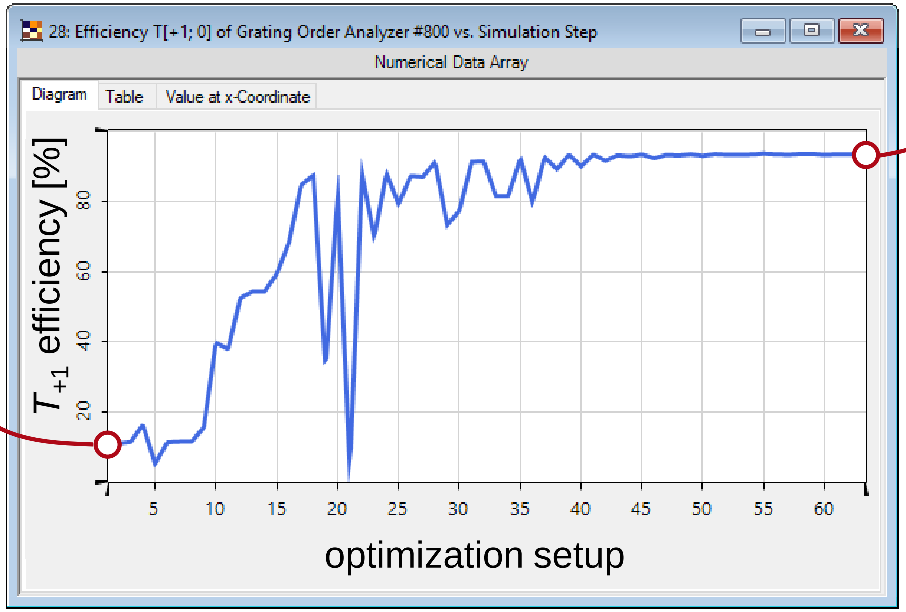
$$\varphi = (\varphi_1 + \varphi_2)/2$$

In addition, how to evaluate the grating performance with the slope deviation due to the fabrication technique taken into account?

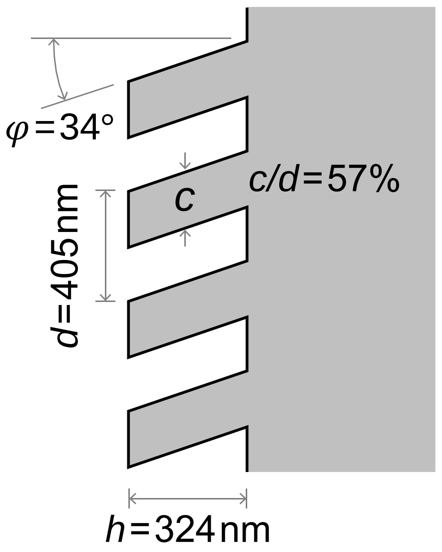
Results – Parametric Optimization

initial structure





optimized structure



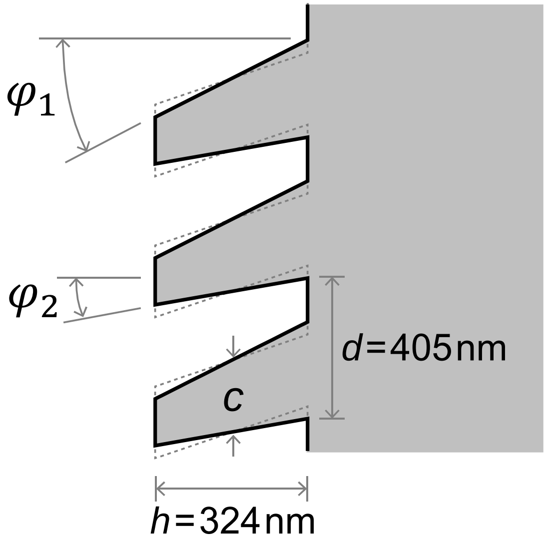
Order	Efficiency
-1	11.551%
0	72.795%
+1	11.551%

parametric optimization – downhill simplex – with rigorous Fourier modal method for grating efficiency calculation

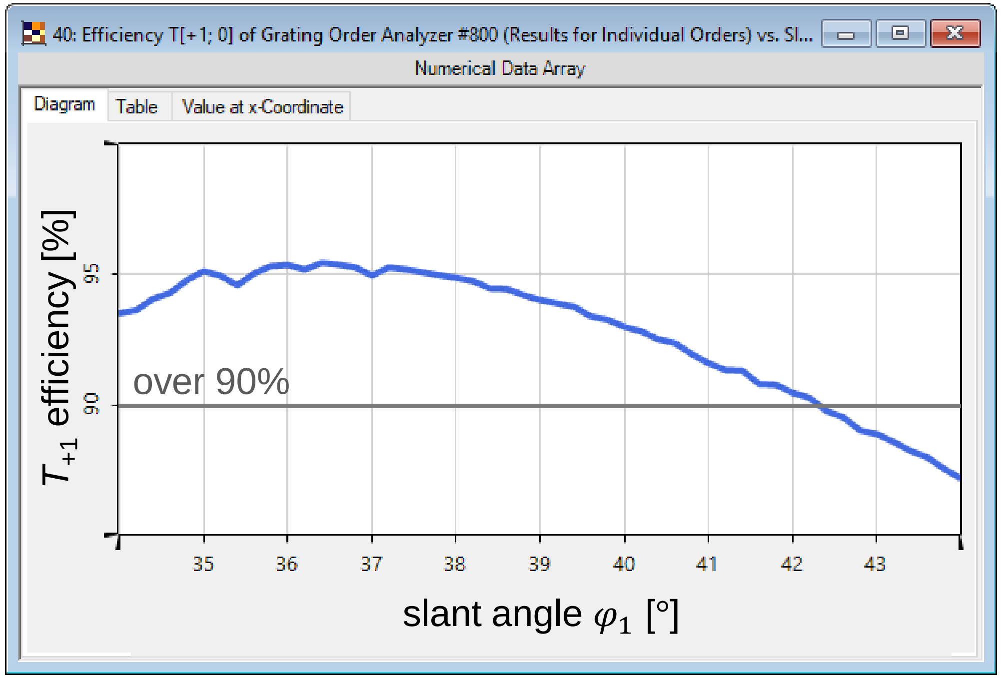
Order	Efficiency
-1	0.267%
0	6.027%
+1	**91.275%**

Results – Tolerance Analysis

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



- fixed average slant angle $\varphi = (\varphi_1 + \varphi_2)/2 = 34°$
- fixed filling factor c/d=57%
- varying φ_1 from 34 to 44°



Rigorous simulation with Fourier modal method, for tolerance analysis over 50 steps, takes 30 seconds.

Slanted Grating …

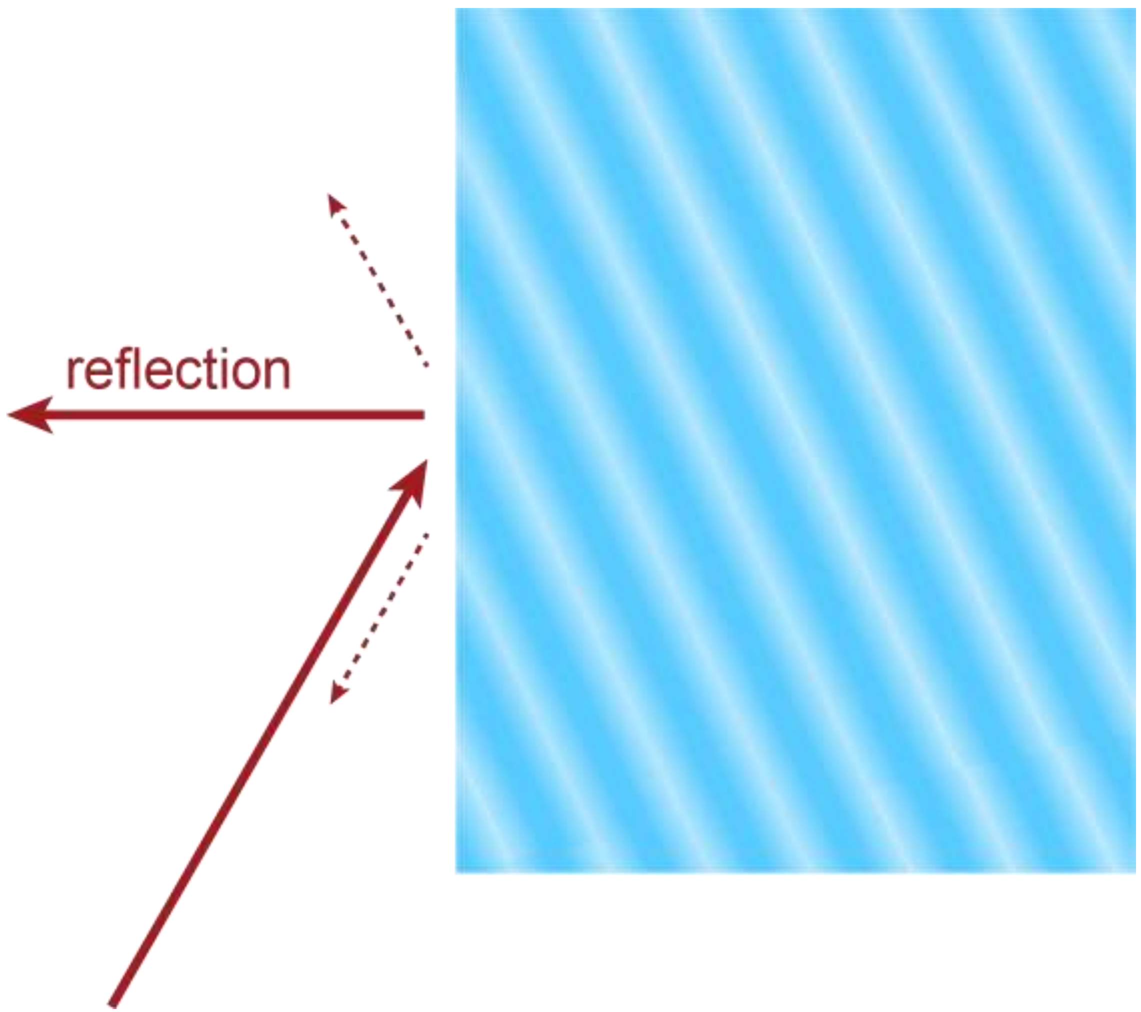
Grating Optimization: Video

Klick the following link to watch the video:

https://youtu.be/ReOLnklrgRs

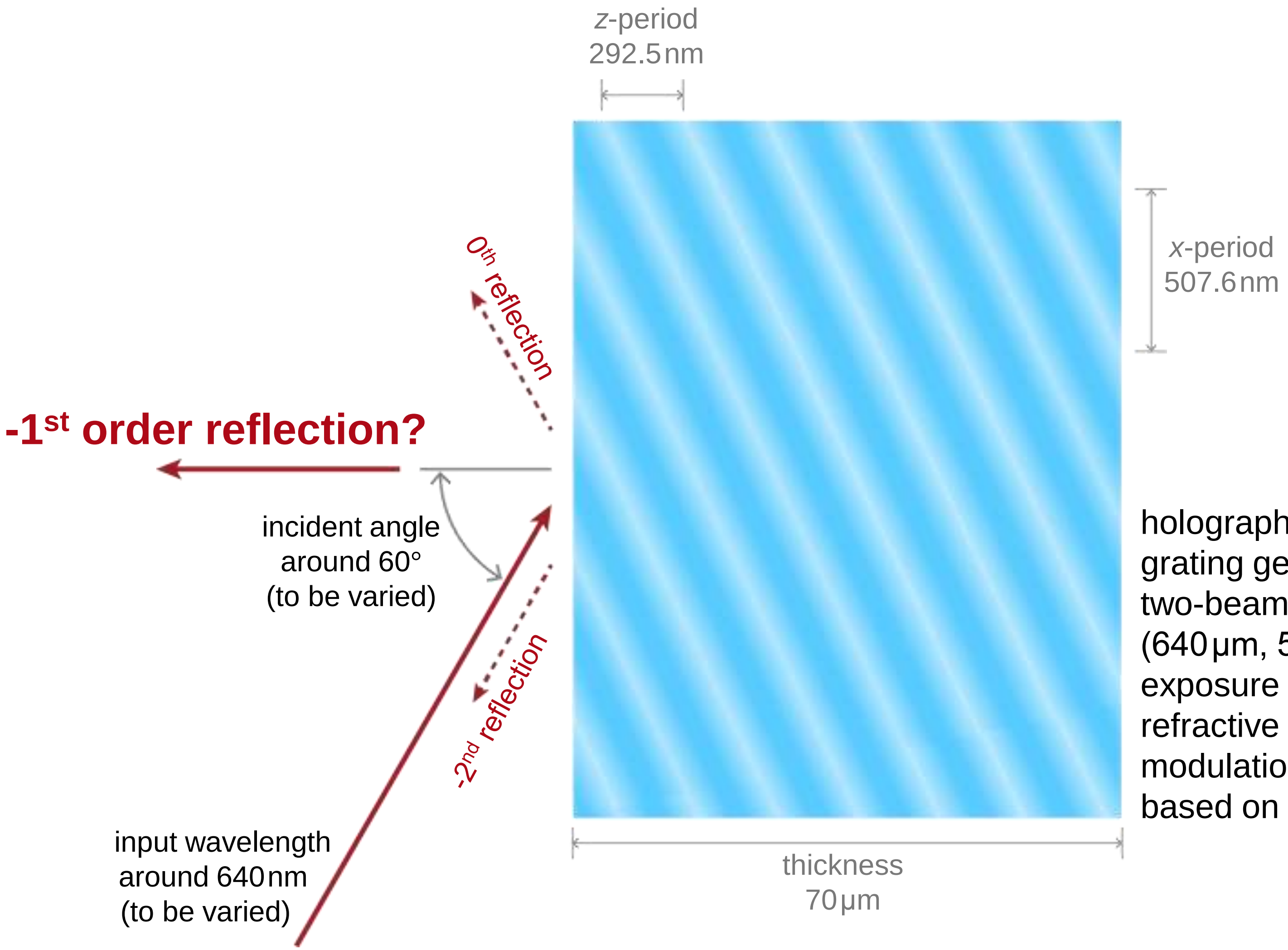
Rigorous Simulation of Holographic Generated Volume Grating

Abstract



- Holographic generated volume gratings, with a thickness much larger than the wavelength, often shows a narrow bandwidth around particular wavelength and angle. Following the two-beam interference exposure process, a volume grating inside fused silica is generated and simulated with the rigorous Fourier modal method (FMM) in VirtualLab. Both the spectral and angular dependent reflection property of the grating are analyzed.

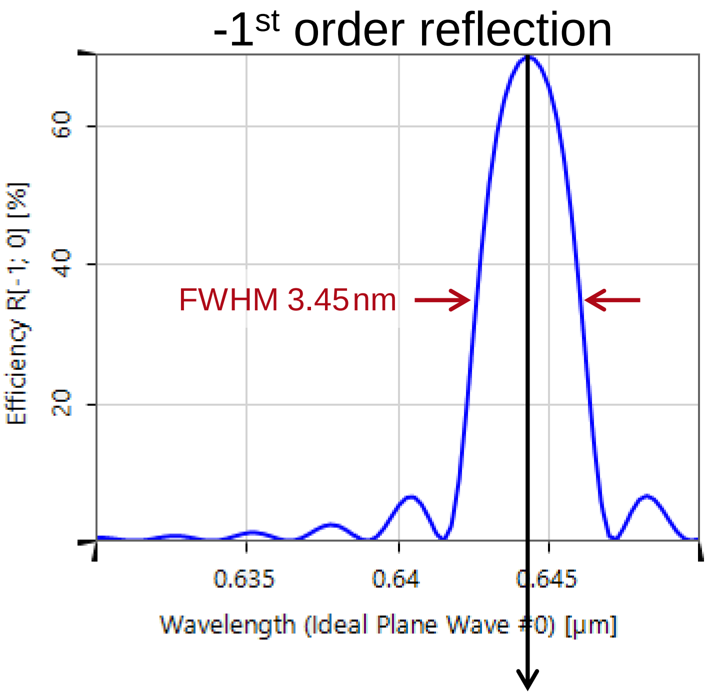
Modeling Task



holographic volume grating generated by two-beam interference (640 µm, 59.9° angle) exposure process, with refractive index modulation of 0.01 based on fused silica

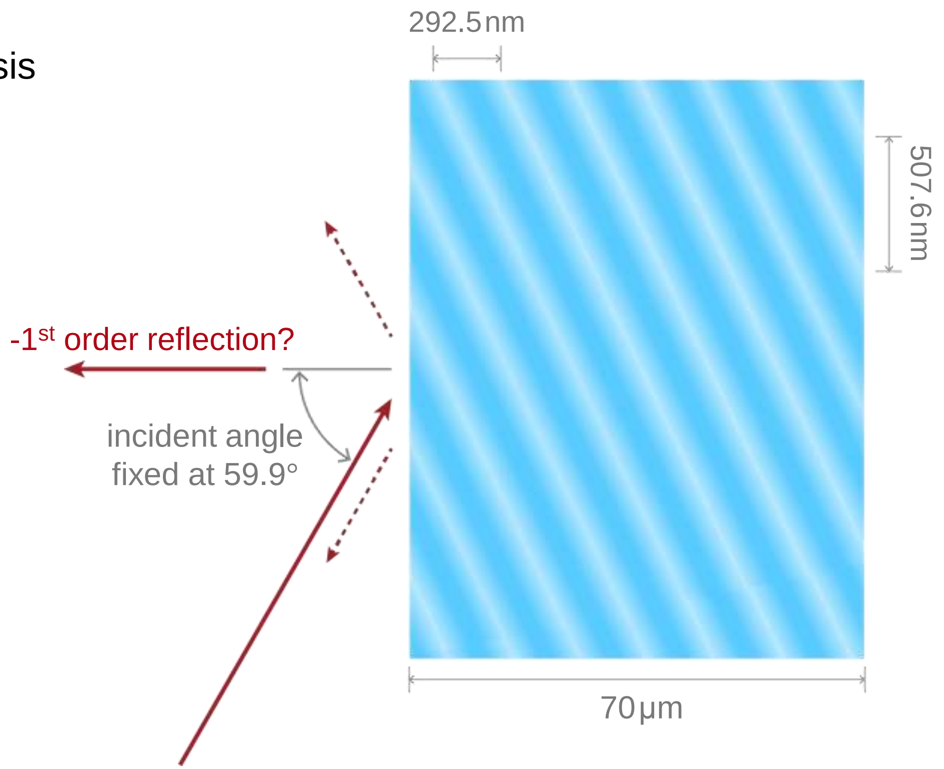
Results

- Wavelength scanning



shift of wavelength dependent reflection due to locally increased effective refraction index

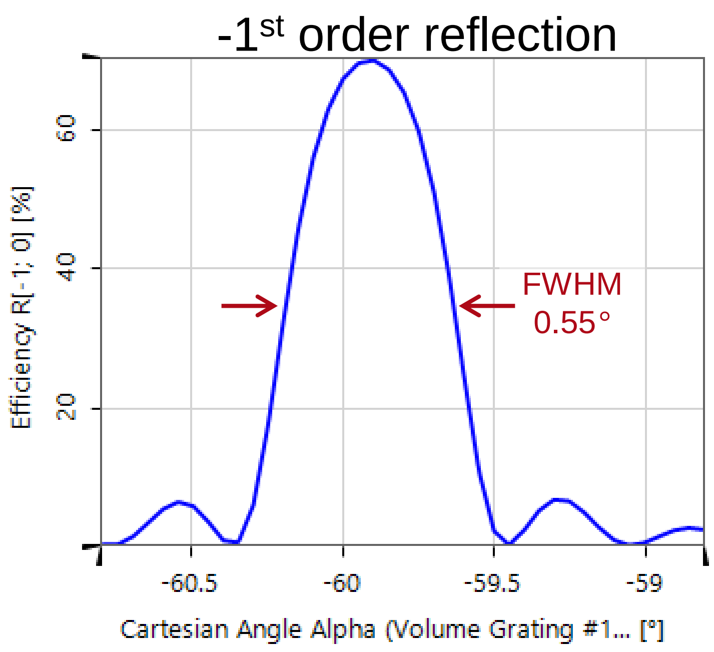
rigorous FMM analysis of single wavelength within **18 seconds**

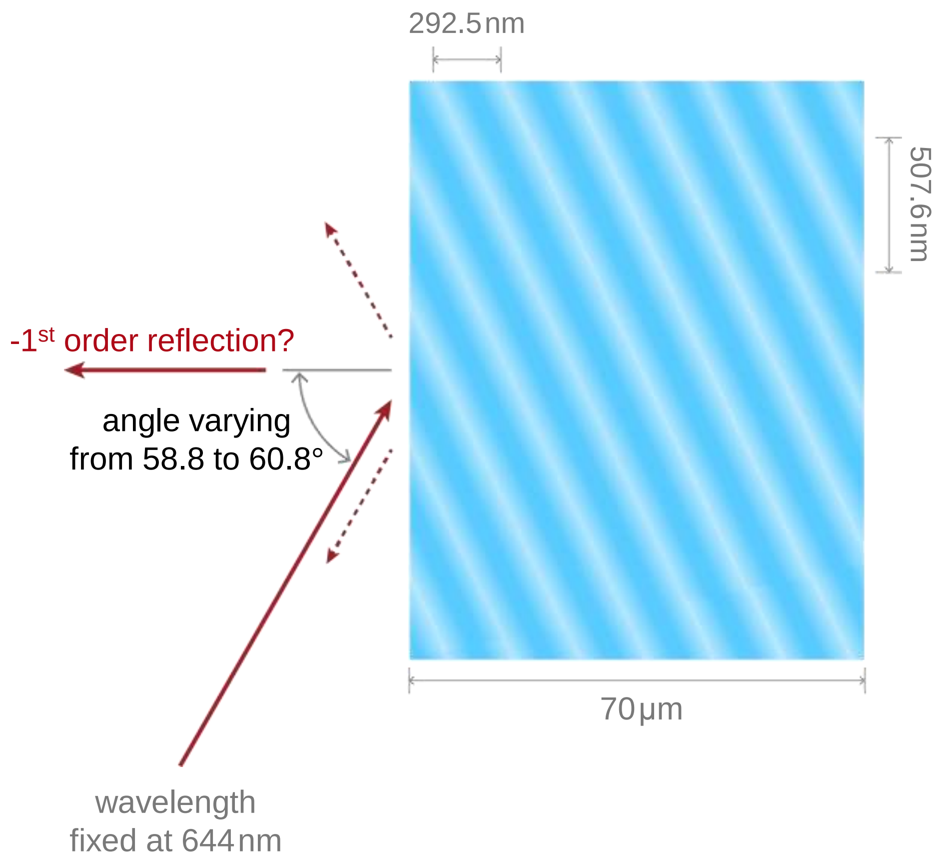


wavelength varying from 630 to 650 nm

Results

- Angle scanning

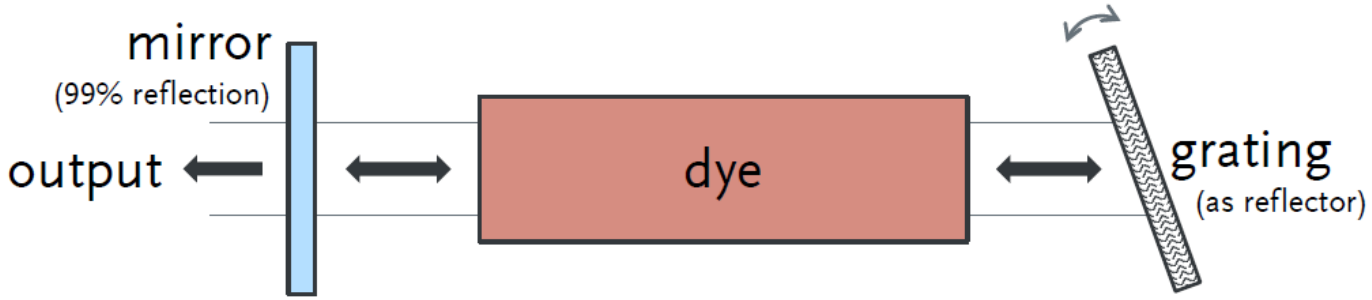




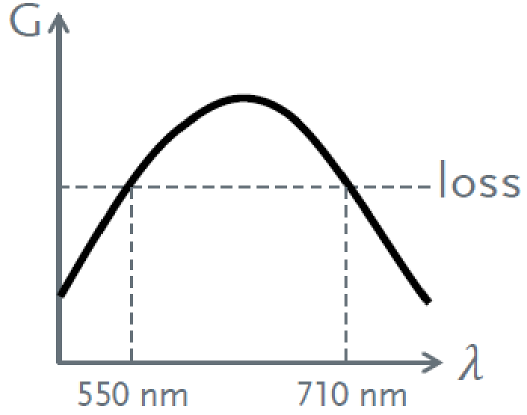
Volume Grating …

Task 12: Grating at Littrow Configuration- Tuning a Dye Laser

Tunable Dye Laser



- Gain spectrum
  - Amplification of dye is from 550 nm to 710 nm
  - We would like to take use of the full range of amplification to build up a tunable laser



Grating Equation

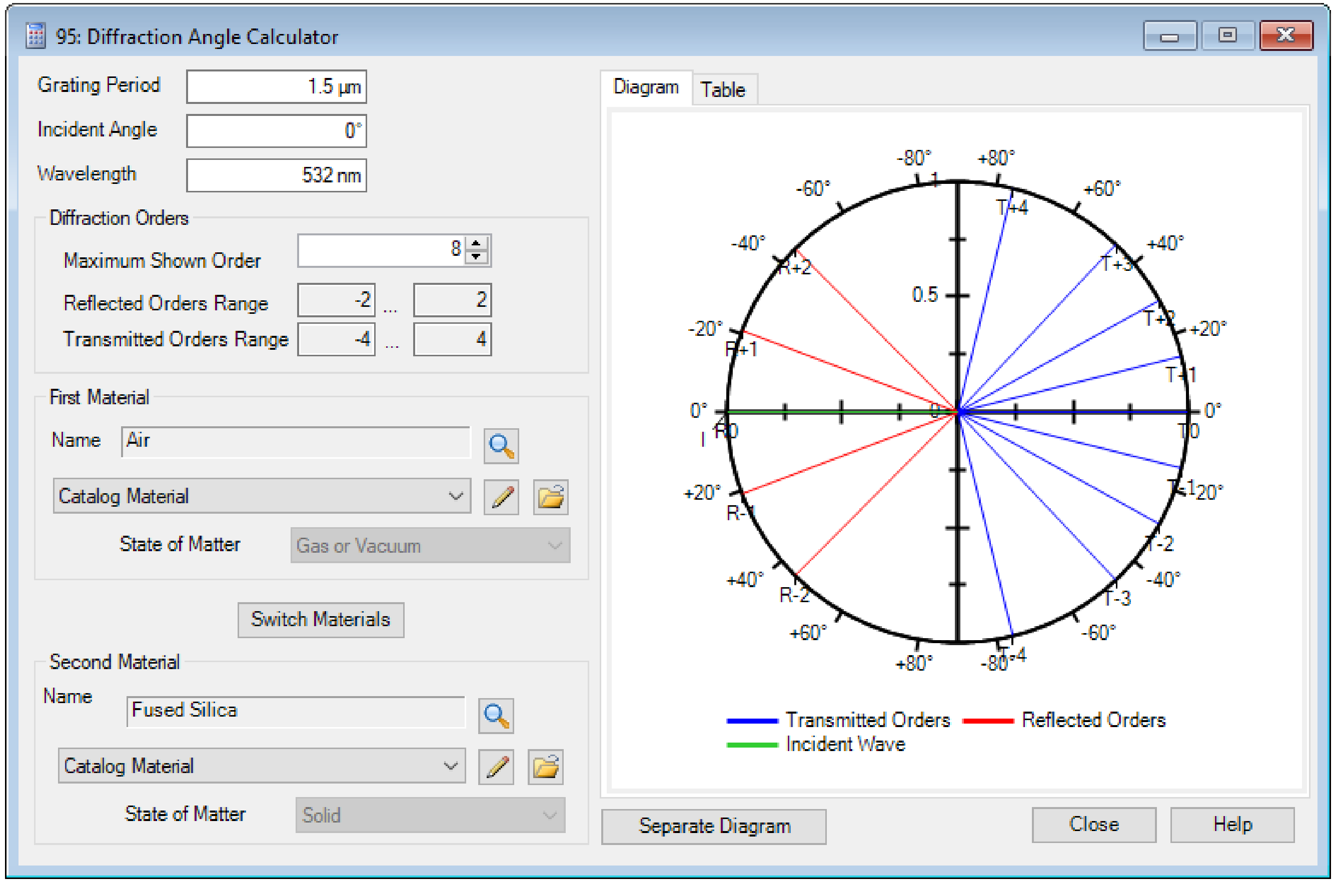
- Incident plane wave has wave vector $\boldsymbol{k}^{\text{in}} = (k_x^{\text{in}}, k_y^{\text{in}}, k_z^{\text{in}})$
- Grating period $\Lambda = (\Lambda_x, \Lambda_y)$
- The output orders are discrete, and wave vector for the order (i, j) is

$$k_x^{\text{out}} = k_x^{\text{in}} + \frac{2\pi}{\Lambda_x} i$$

$$k_y^{\text{out}} = k_y^{\text{in}} + \frac{2\pi}{\Lambda_y} j$$

$$k_z^{\text{out}} = \sqrt{\left(\frac{2\pi}{\lambda} n^{\text{out}}\right)^2 - \left({k_x^{\text{out}}}^2 + {k_y^{\text{out}}}^2\right)}$$

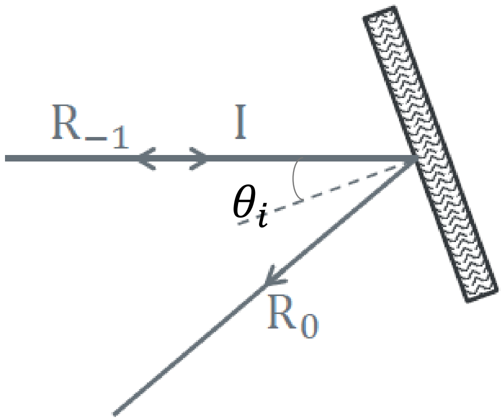
Illustration: Calculator of Grating Equation



- Order directions are calculated by using grating equation
- We may find:
  - Period decreases, order separation increases
  - Refractive index increases, more propagation orders
  - !!!!!!!! Order direction is just related to grating period and refractive index. Nothing about grating structure.

Littrow Mount

- Configuration
  - Angle of grating θ_i →-1st order of λ_i has opposite direction with the incident beam
  - In out tunable laser, we aspect
    - -1st order should have a high reflectance, so the grating works as a reflector
    - No other reflection orders are desired.
  - In the next two pages, we give detailed calculation of the period and condition. Here we directly give the parameters:



- Incident angle

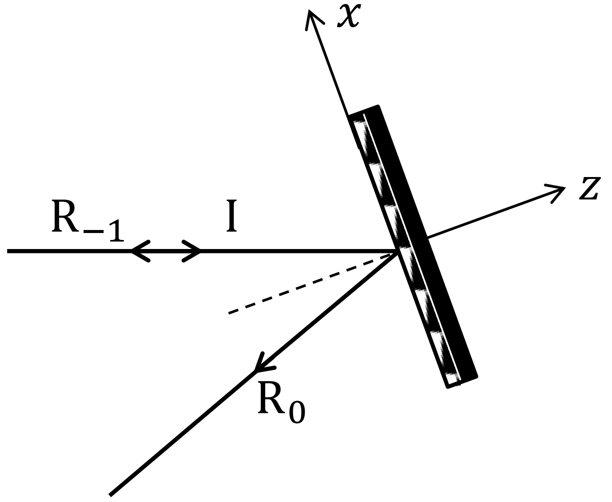
$$\vartheta^{\mathrm{I}} = 20°$$

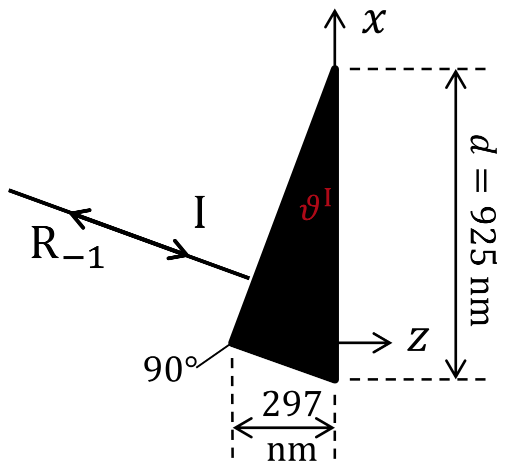
- Grating period

$$d = \frac{\lambda_0}{2n_{\mathrm{i}} \sin \vartheta^{\mathrm{I}}} = \frac{633\mathrm{nm}}{2 \times 1.0003 \times \sin 20°} = 0.925\mu\mathrm{m}$$

Grating Sturcture

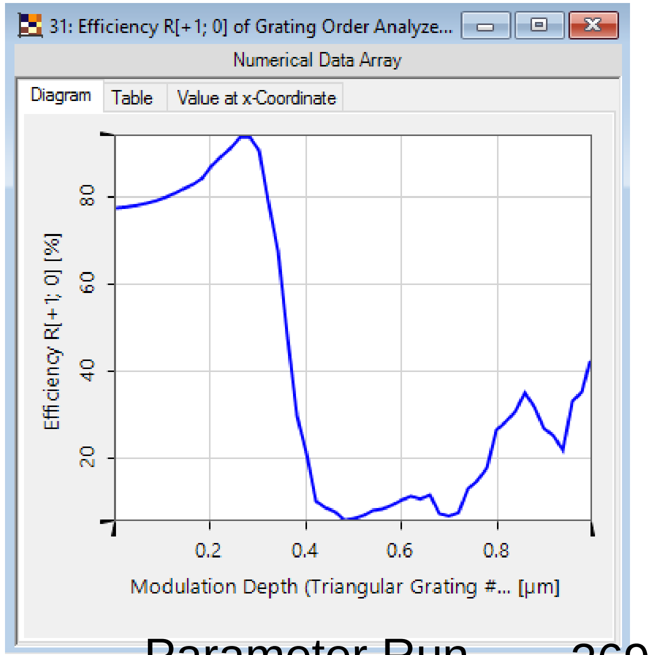
- Initial guess
  - To enhance the -1st reflection order, which is towards the incidence, we think of using orthogonal planes to the wave vector, as is shown.
  - It is a triangular grating, with one side just perpendicular to the incidence.
  - With grating period and the incident angle, the triangle is determined.





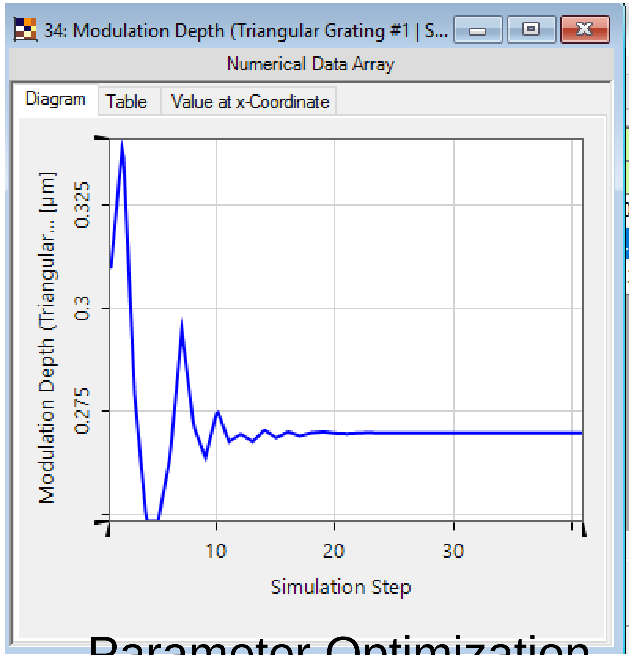
Optimization

- Check the total reflection efficiency and transmission one. Do we need HR-coating?
- Add the HR-coating and vary the modulation depth and check when we can achieve highest efficiency?



Parameter Run

269.48 nm

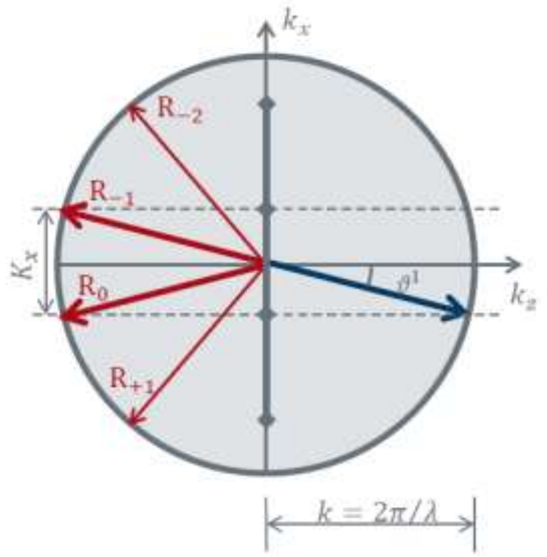


Parameter Optimization

Littrow Mount

- Littrow Condition (Ewald's sphere)
  - We need the -1st reflection order:
    $$k_{x-1} = k_{x0} - K_x$$
  - We require -1st reflection order has opposite direction with the incident:
    $$k_{x-1} = -k_{x0}$$
  - Therefore:
    $$K_x = \frac{2\pi}{d} = 2k_{x0} = 2k\sin\theta^I$$
  - The grating period:
    $$d = \frac{2\pi}{2k\sin\theta^I} = \frac{\lambda_0}{2n\sin\theta^I}$$

  with n is refractive index of air and λ_0 is central wavelength



Diffraction Angle Control

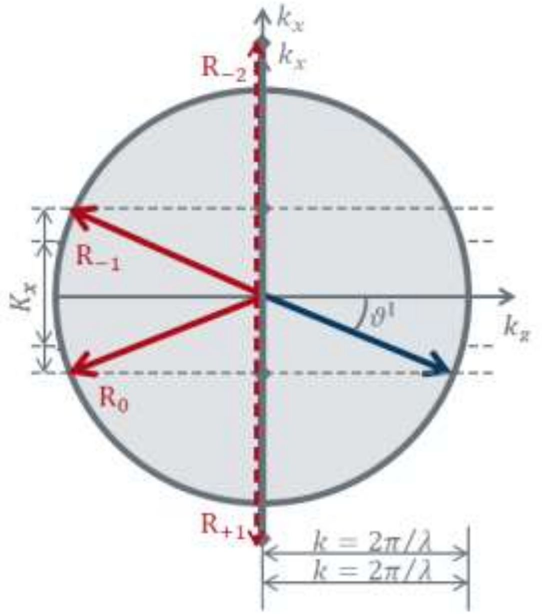
- We wish that only 0th order and -1st order exsit, while they others are evanescent:

$$3K_x > 2k$$

- Related equations to the incident angle θ^I

$$\sin\theta^I > \frac{1}{3}$$

$$\Rightarrow \theta^I > 19.48°$$



- Therefore

  - Incident angle

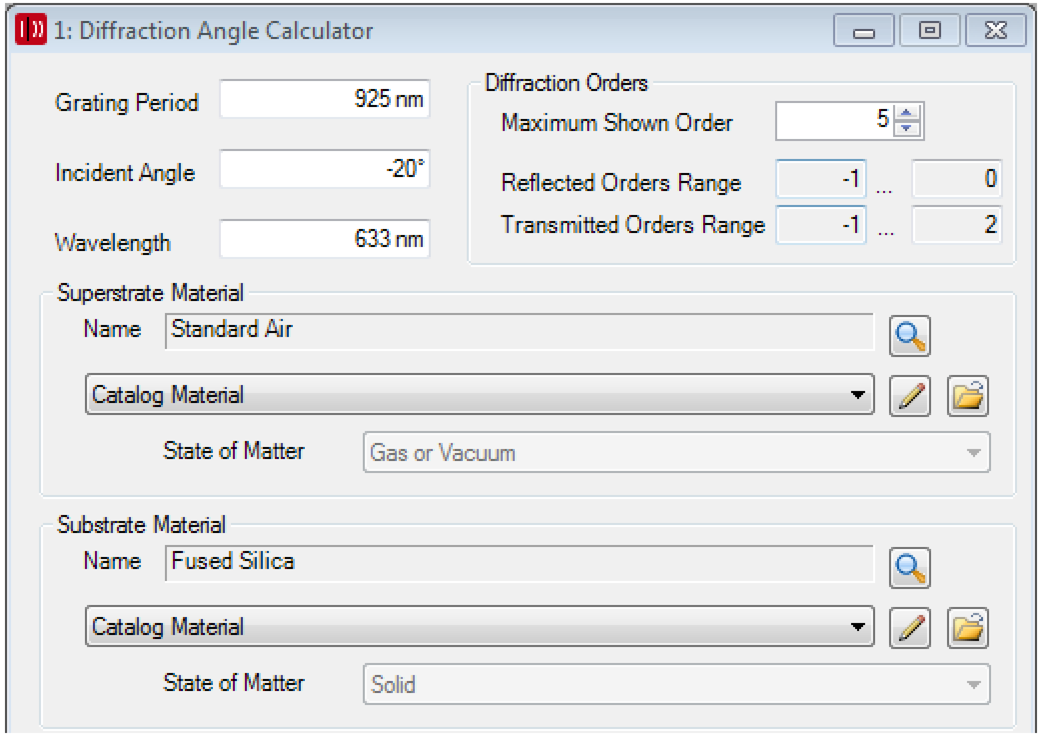
$$\vartheta^I = 20°$$

  - Grating period

$$d = \frac{\lambda_0}{2n_i \sin\vartheta^I} = \frac{633\text{nm}}{2 \times 1.0003 \times \sin 20°} = 0.925\mu\text{m}$$

Diffraction Angle Control

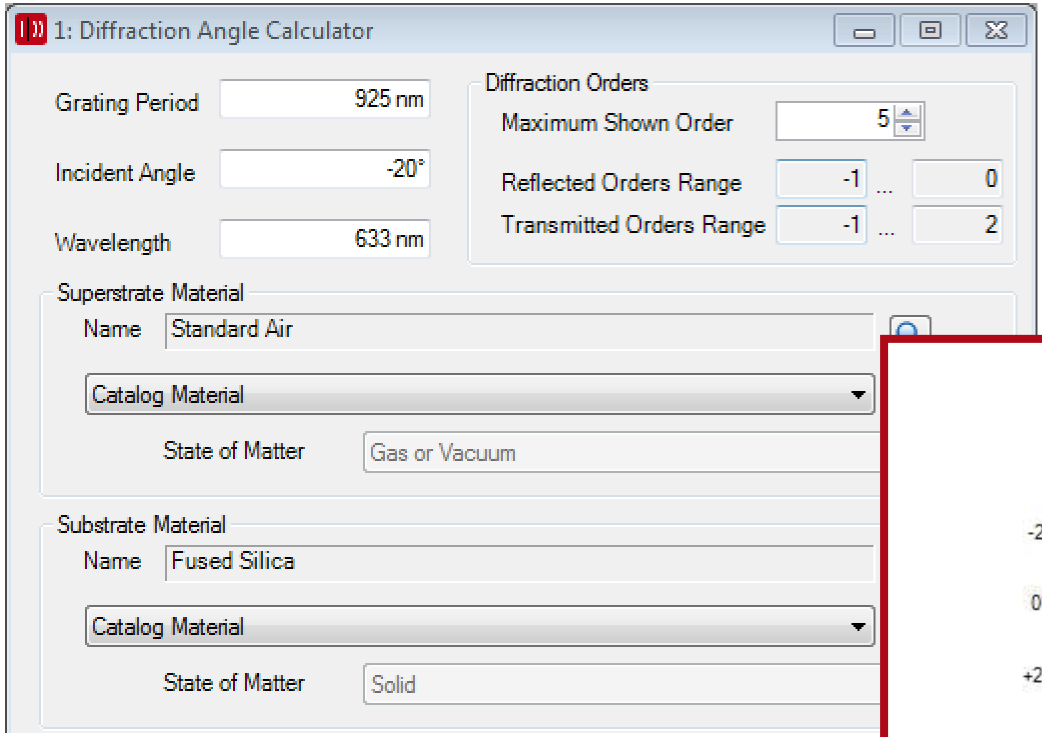
- VL - Diffraction angle calculator



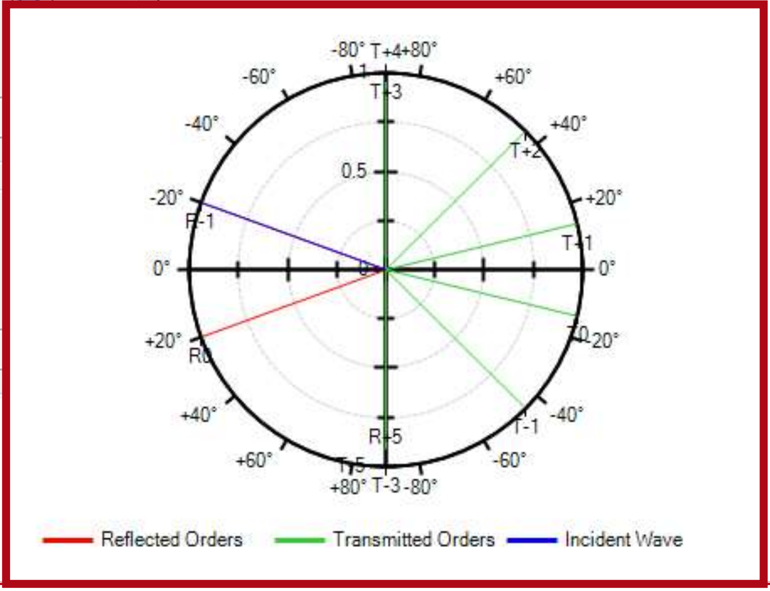
- Grating period: 925 nm
- Incident angle: -20º
- Wavelength: 633 nm

Diffraction Angle Control

- VL - Diffraction angle calculator

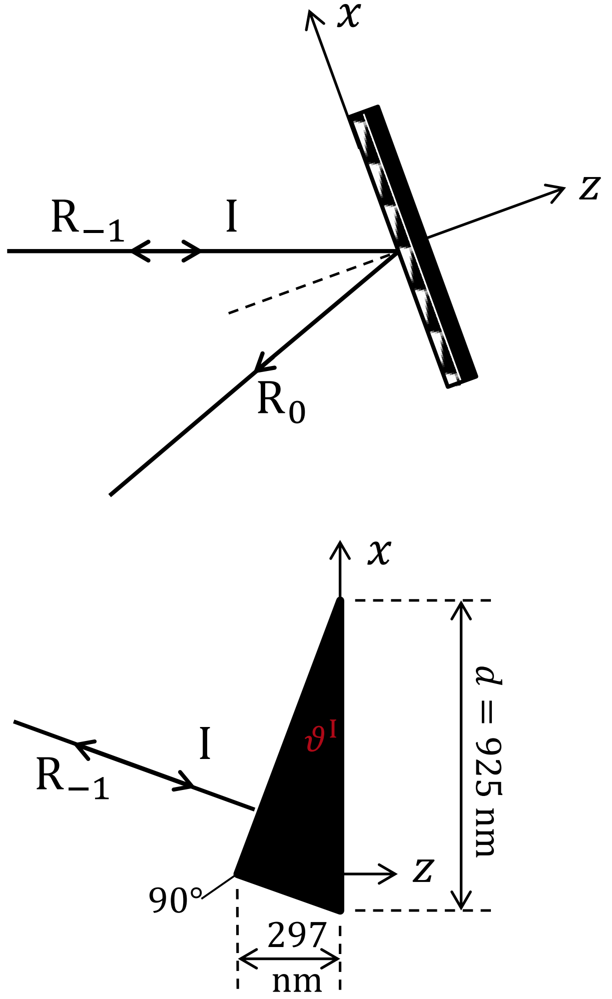


- Grating period: 925 nm
- Incident angle: -20º
- Wavelength: 633 nm



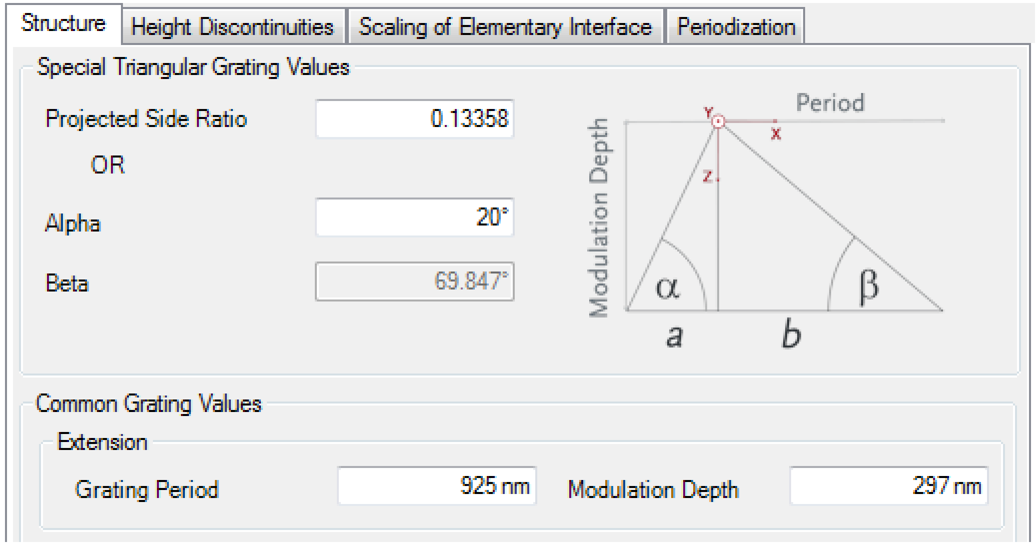
Grating Sturcture

- Initial guess
  - To enhance the -1st reflection order, which is towards the incidence, we think of using orthogonal planes to the wave vector, as is shown.
  - It is a triangular grating, with one side just perpendicular to the incidence.
  - With grating period and the incident angle, the triangle is determined.



Grating Sturcture

- VL optimization
  - Via the grating toolbox in VirtualLab, we can define such a triangular grating as

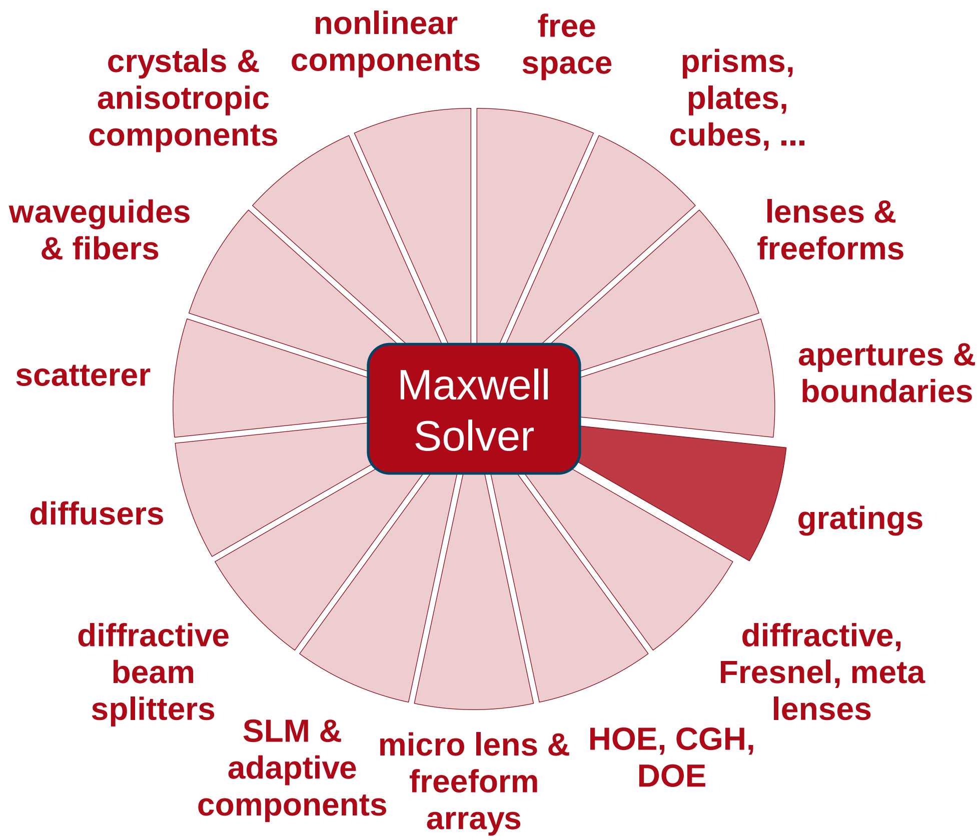


- Grating period: 925 nm
- Modulation depth: 297 nm
- Alpha: 20º

  - Then using FMM to examine the -1st order reflection coefficients, while changing the modulation depth.

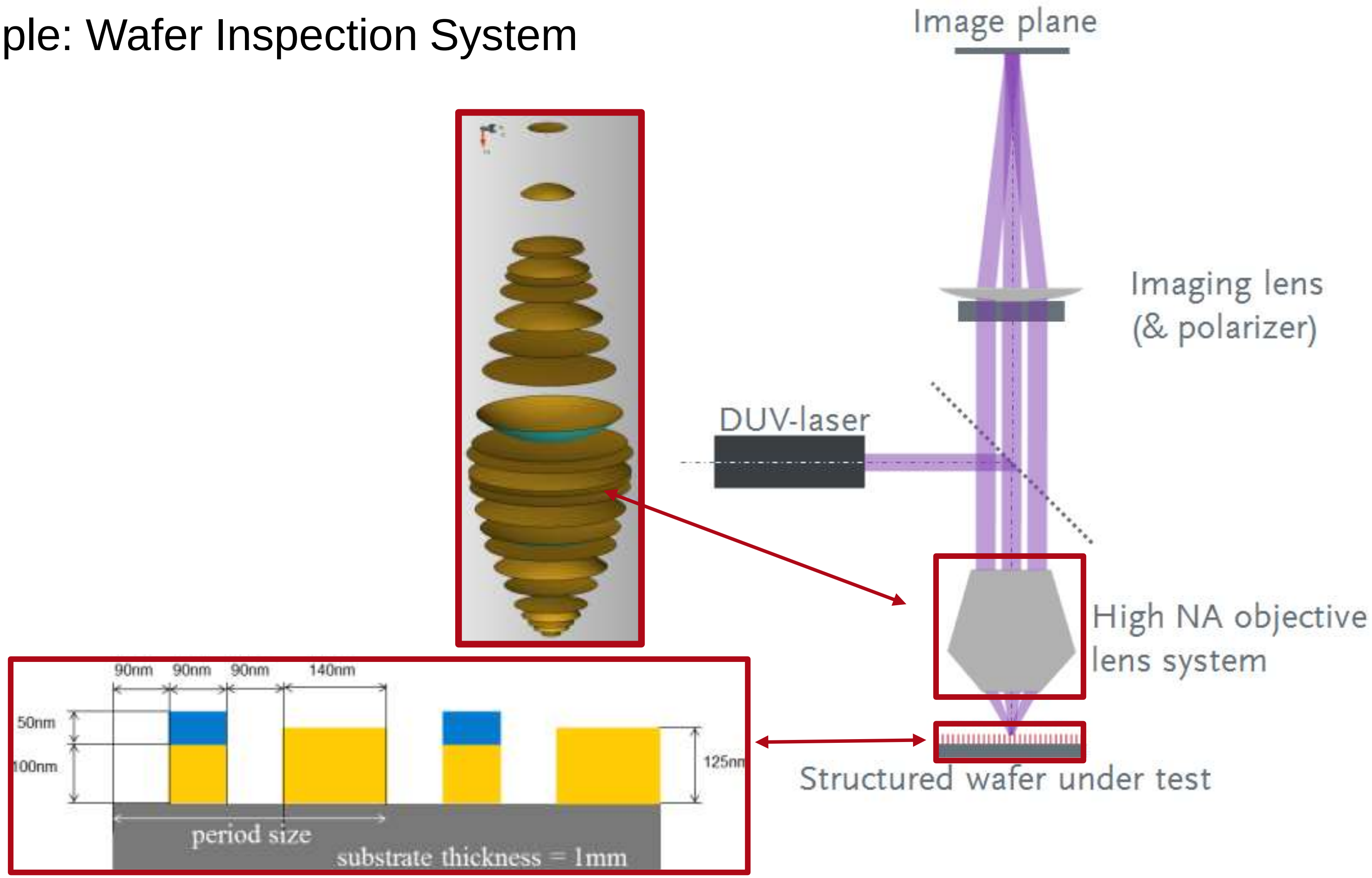
Gratings

- VirtualLab Fusion enables modeling of any kind of stacked grating structure.
- That includes surface gratings with coating.
- VirtualLab Fusion also provides the analysis of holographic volume gratings.
- Optimization and tolerancing is available.

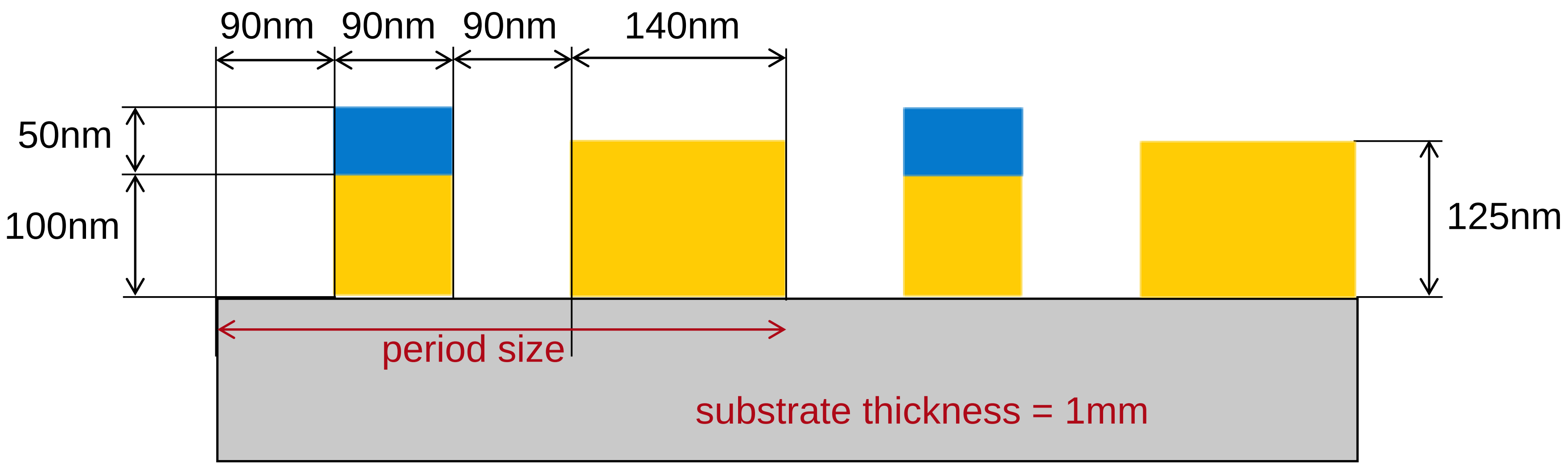


Example of Multi-Scale Optical System

Example: Wafer Inspection System

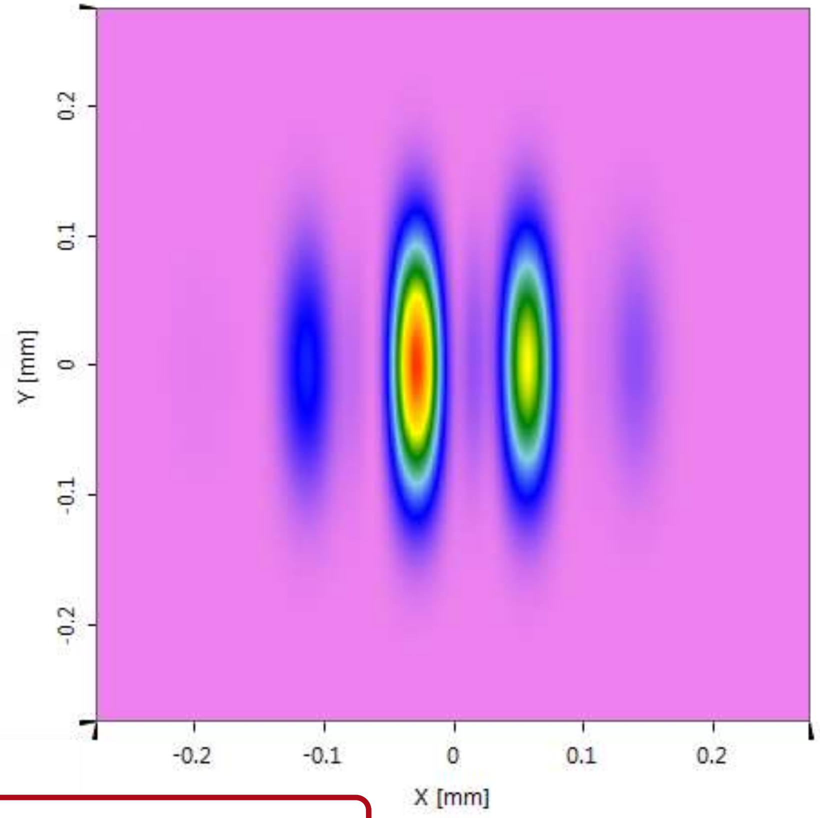


Base Grating Structure

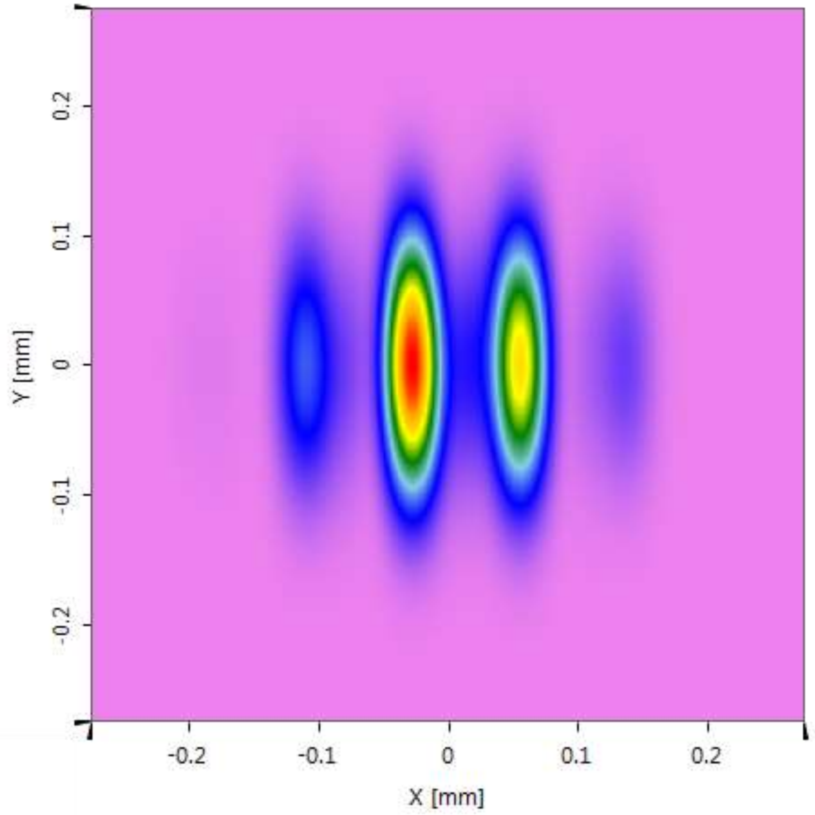


Base Structure Analysis

Intensity Image of Grating after Polarizer in X-Direction

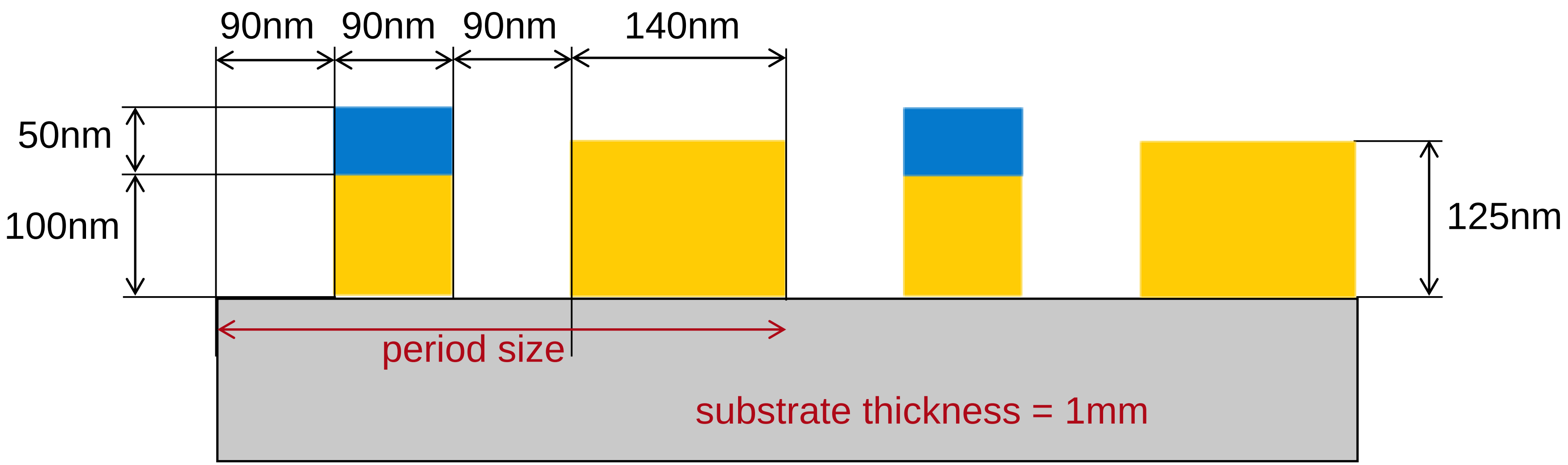


Intensity Image of Grating after Polarizer in Y-Direction

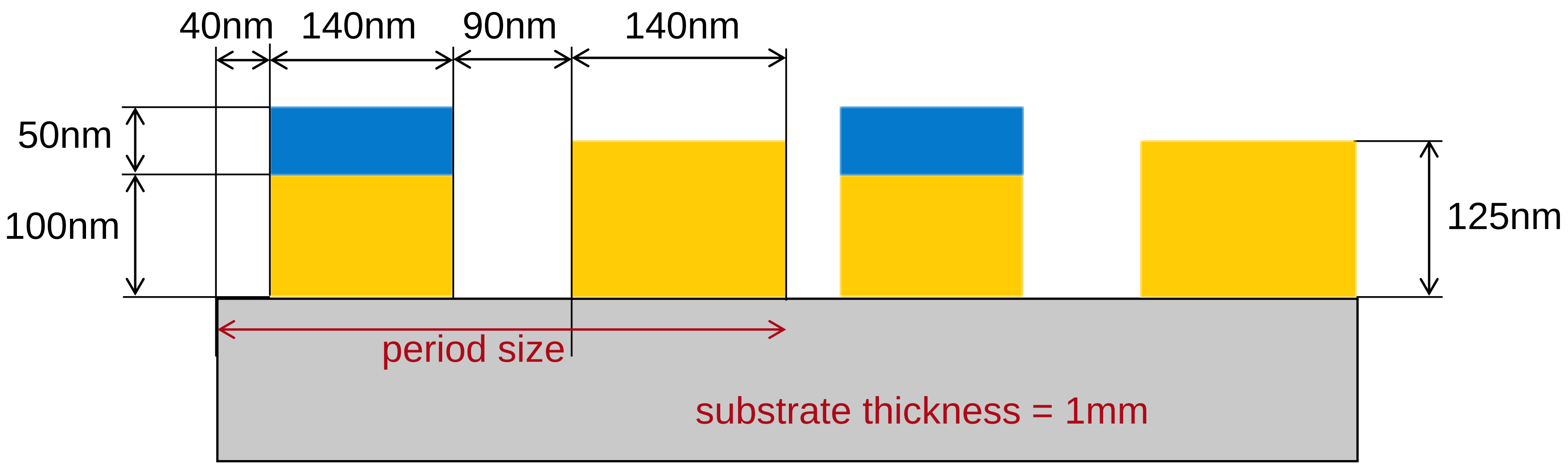


Simulation time few seconds

Base Grating Structure

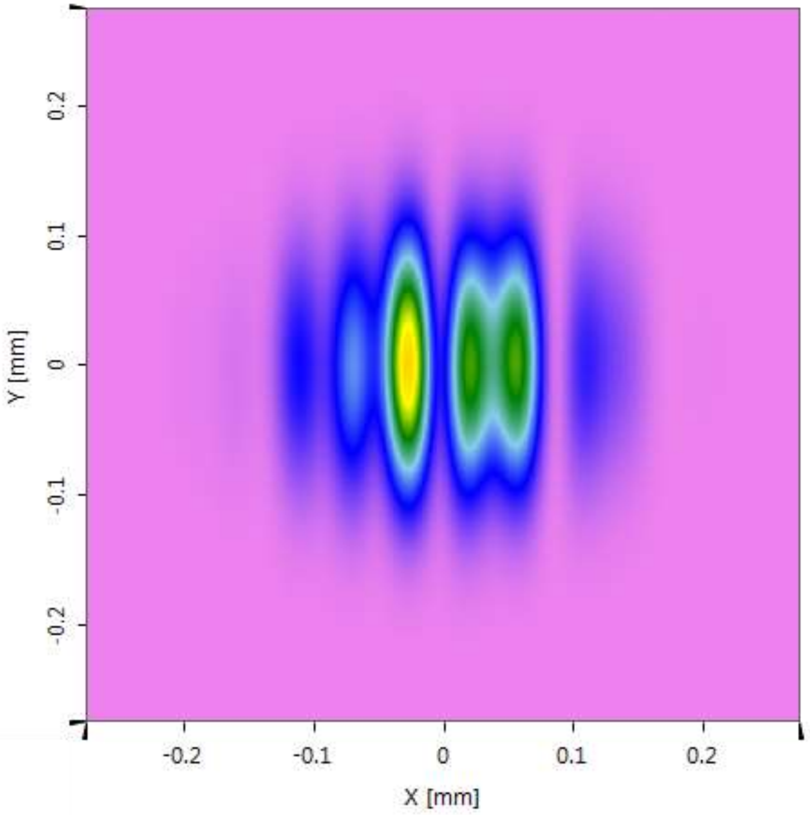


Modified Grating Structure

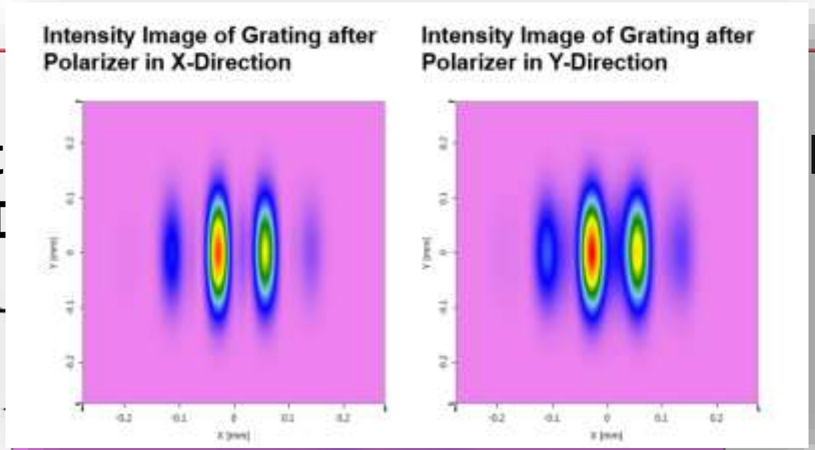


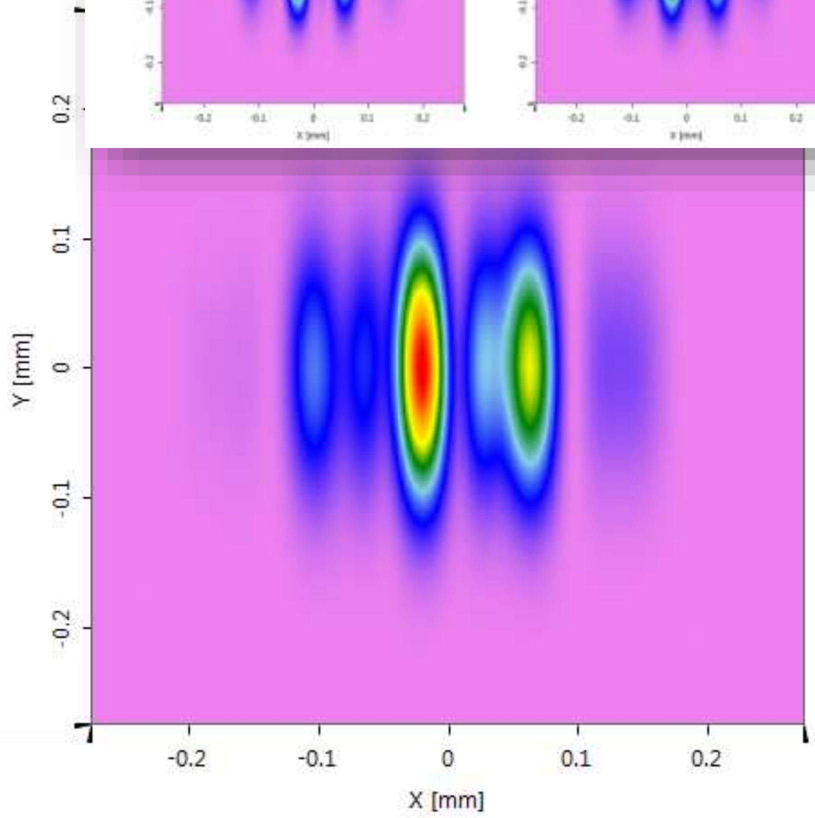
Modified Structure Analysis

Intensity Image of Grating after Polarizer in X-Direction



Int … larizer in Y-D

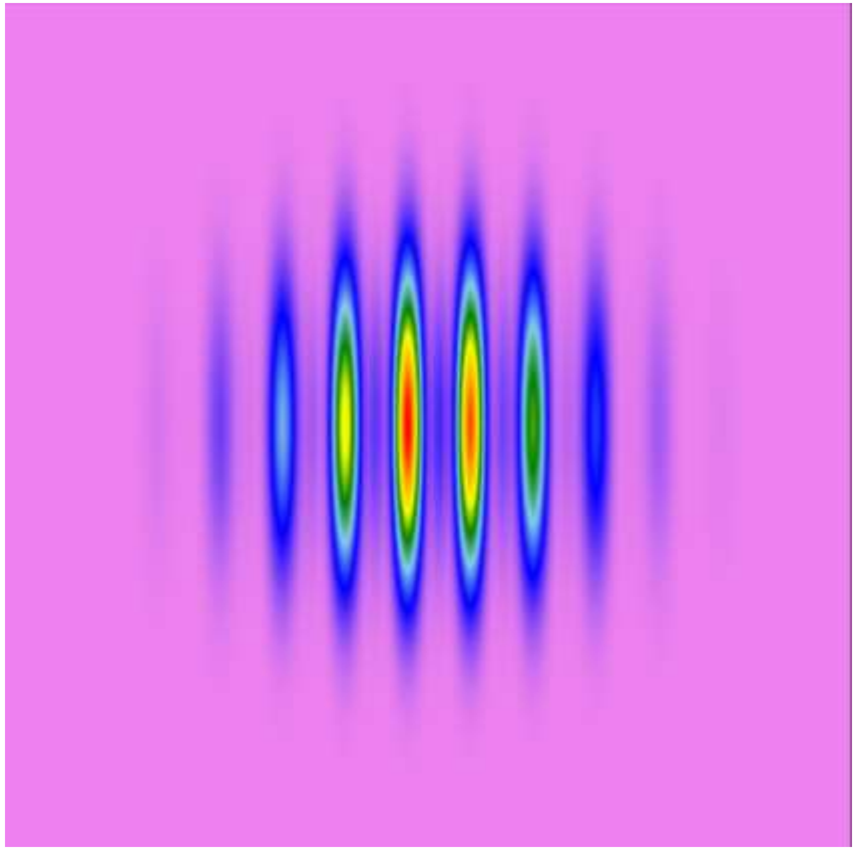




Task 13

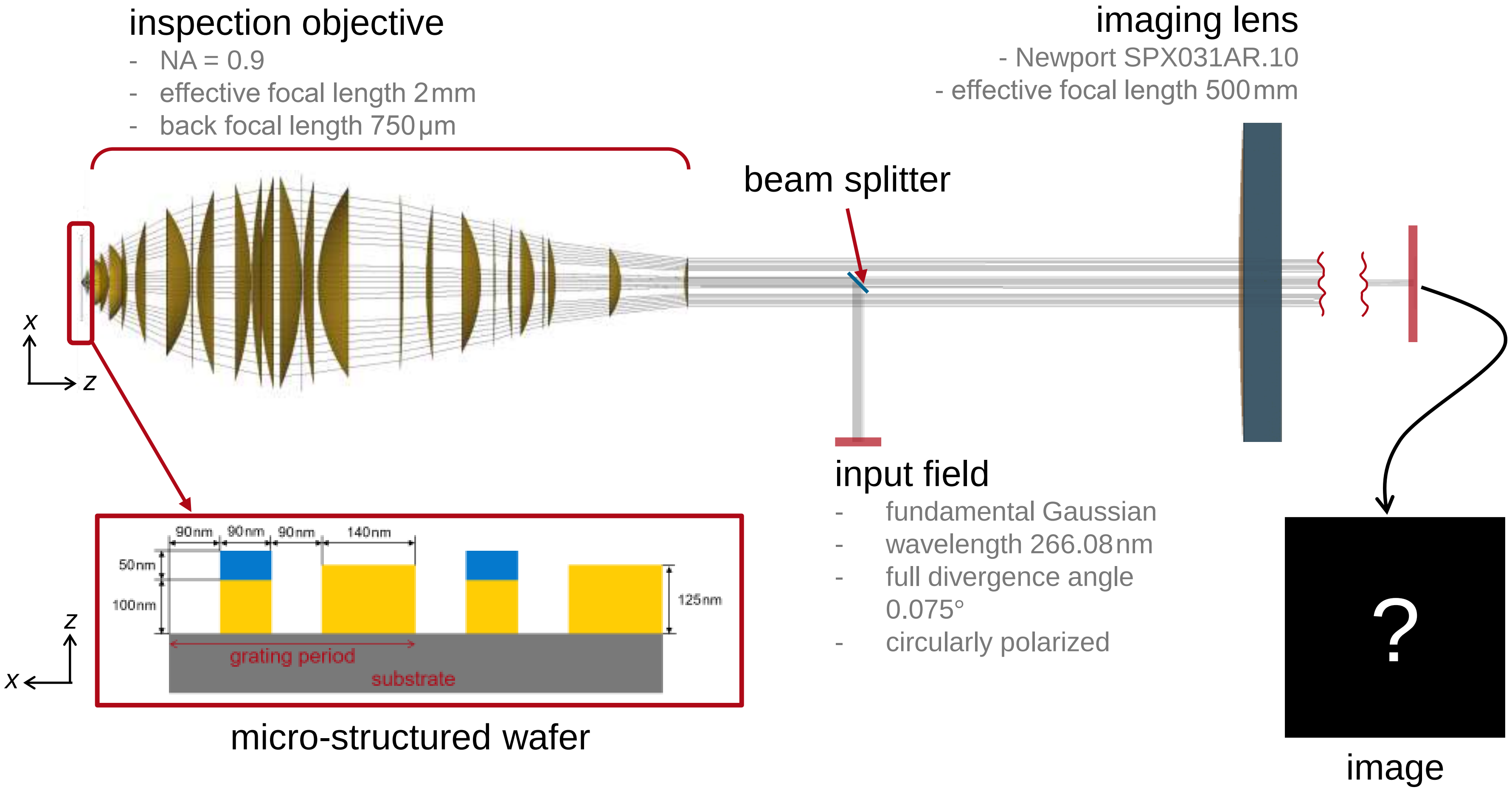
Optical System for Inspection of Micro-Structured Wafer

Abstract

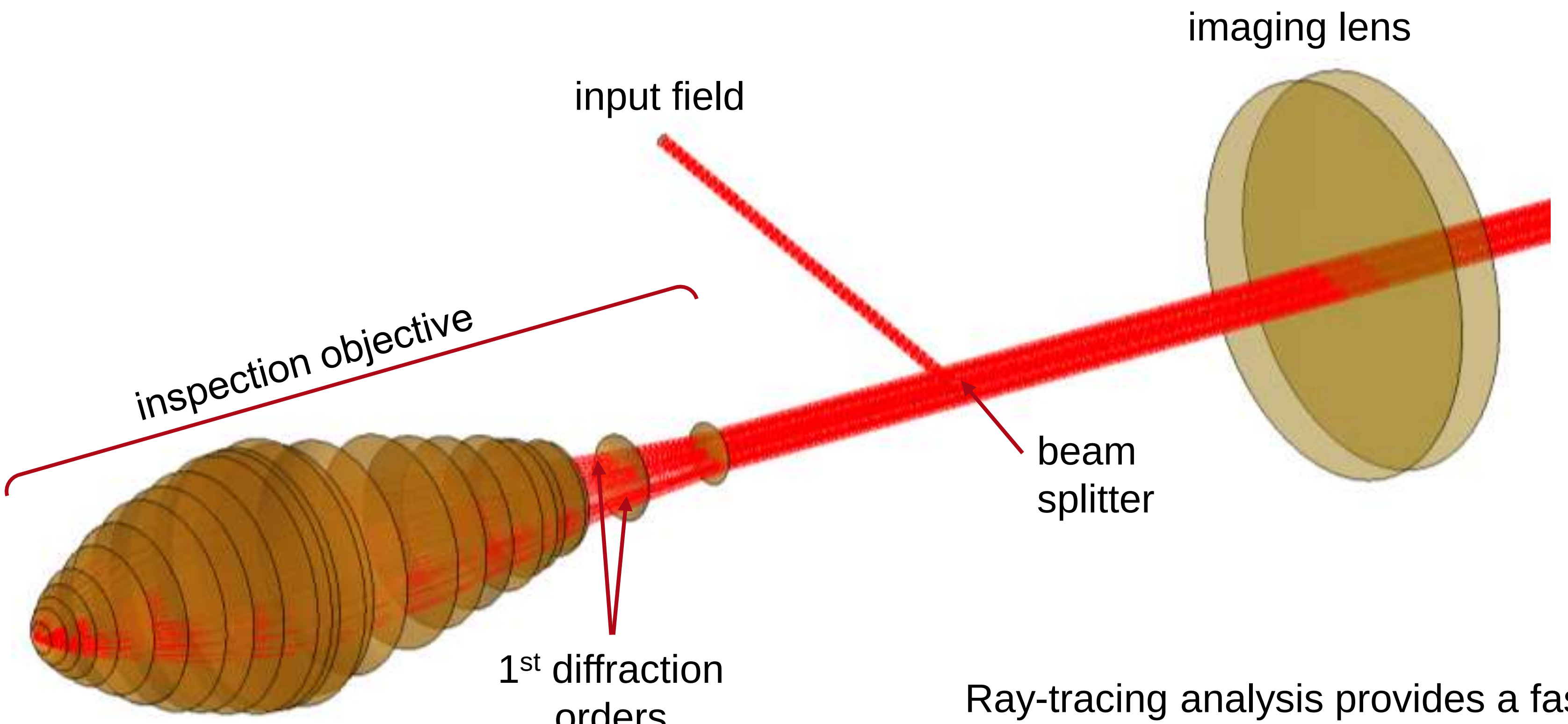


In semiconductor industry, wafer inspection systems are used to detect defects on a wafer and find their positions. To ensure the image resolution for the microstructures, the inspection system often employs a high-NA objective and works in the UV wavelength range. As an example, a complete wafer inspection system including high-NA focusing effect and light interaction with microstructures is modeled, and the formation of image is demonstrated.

Modeling Task

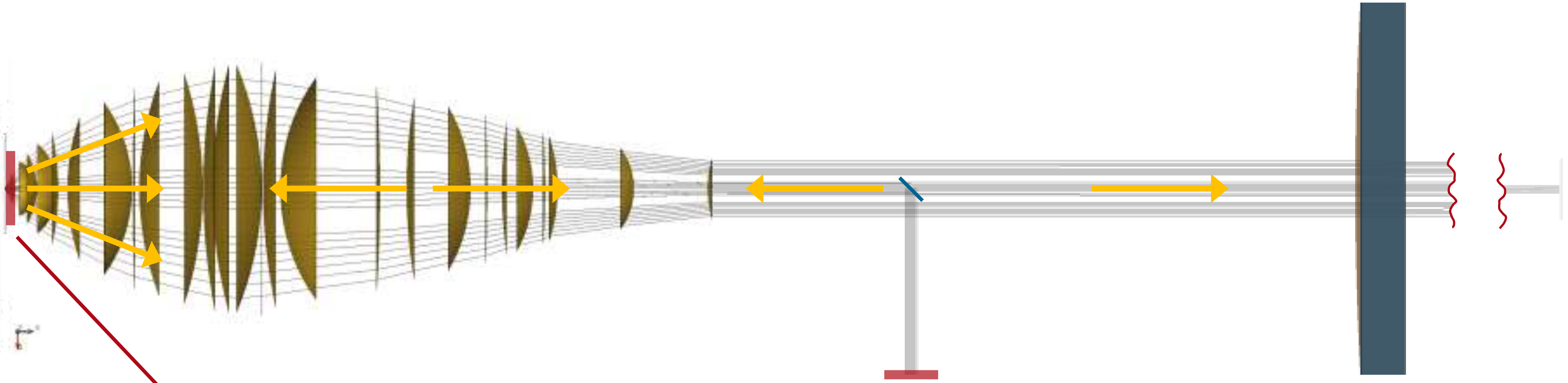


Results

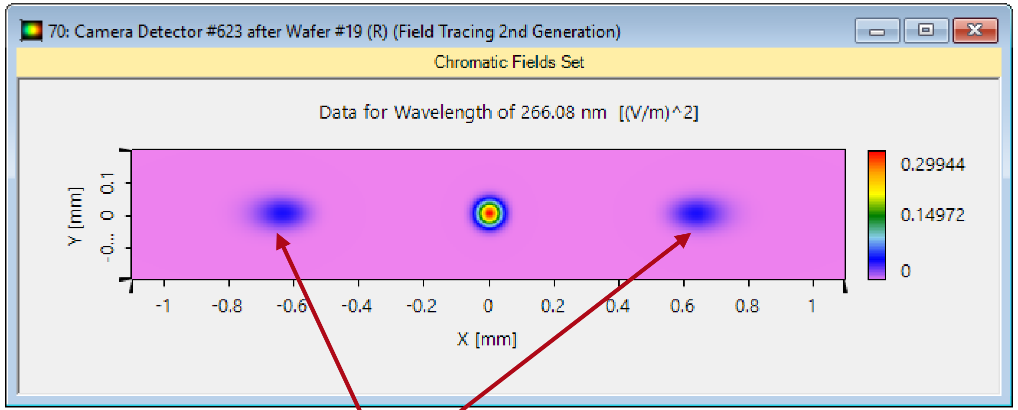


Ray-tracing analysis provides a fast overview of the complete system, including high-NA lens and grating.

Results



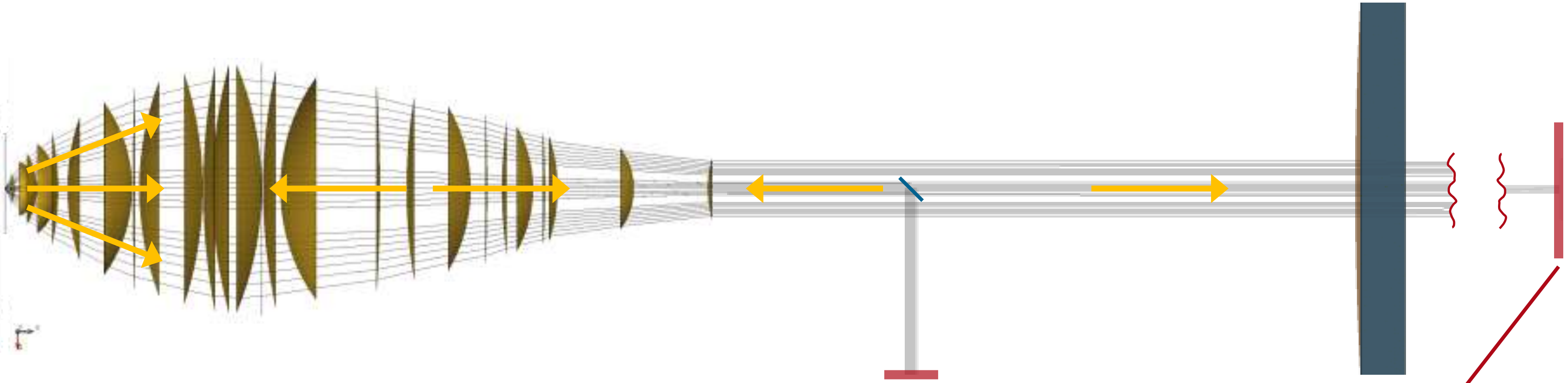
behind micro-structured wafer



Rigorous simulation of grating with Fourier modal method (FMM) is imbedded within the system simulation.

1st diffraction orders

Results



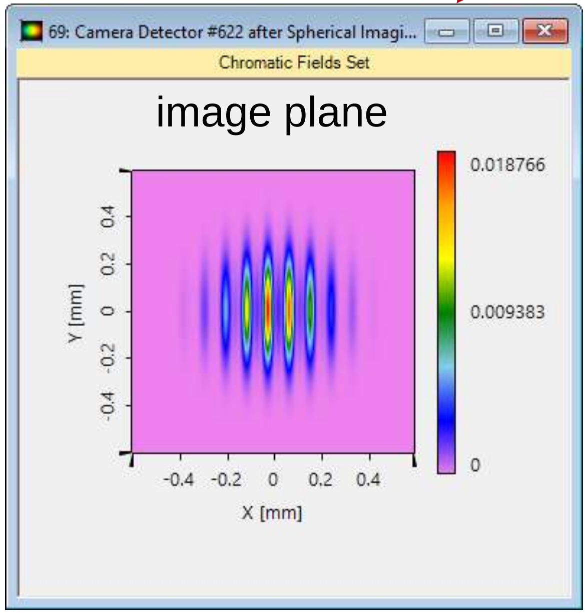
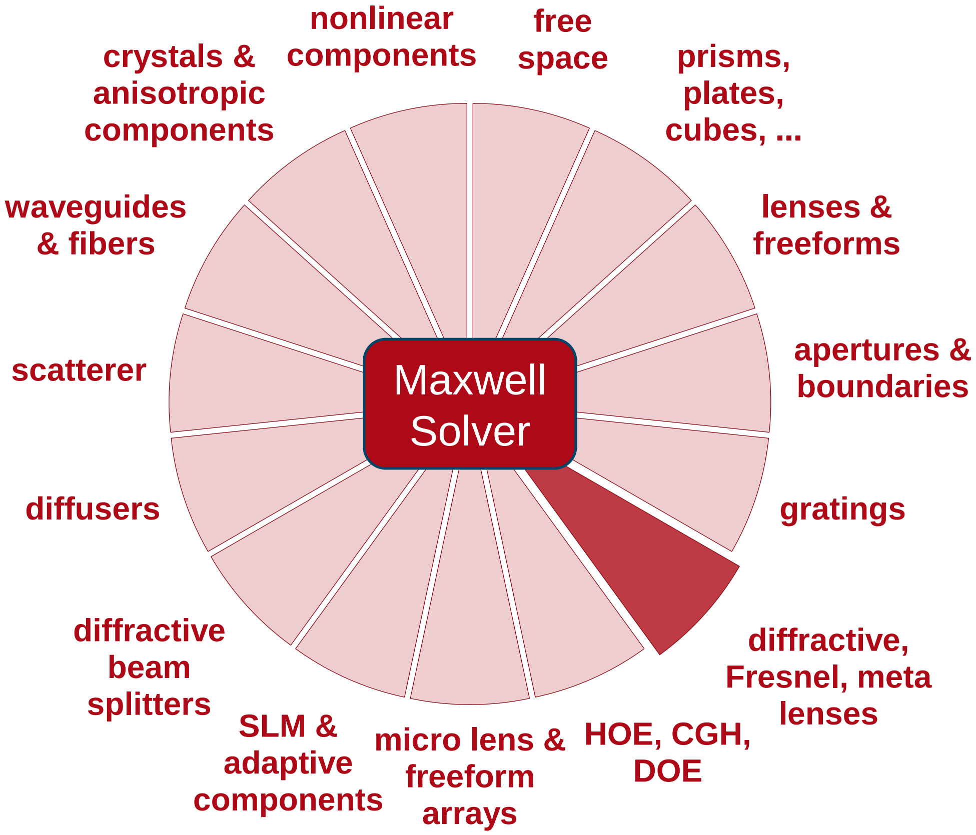


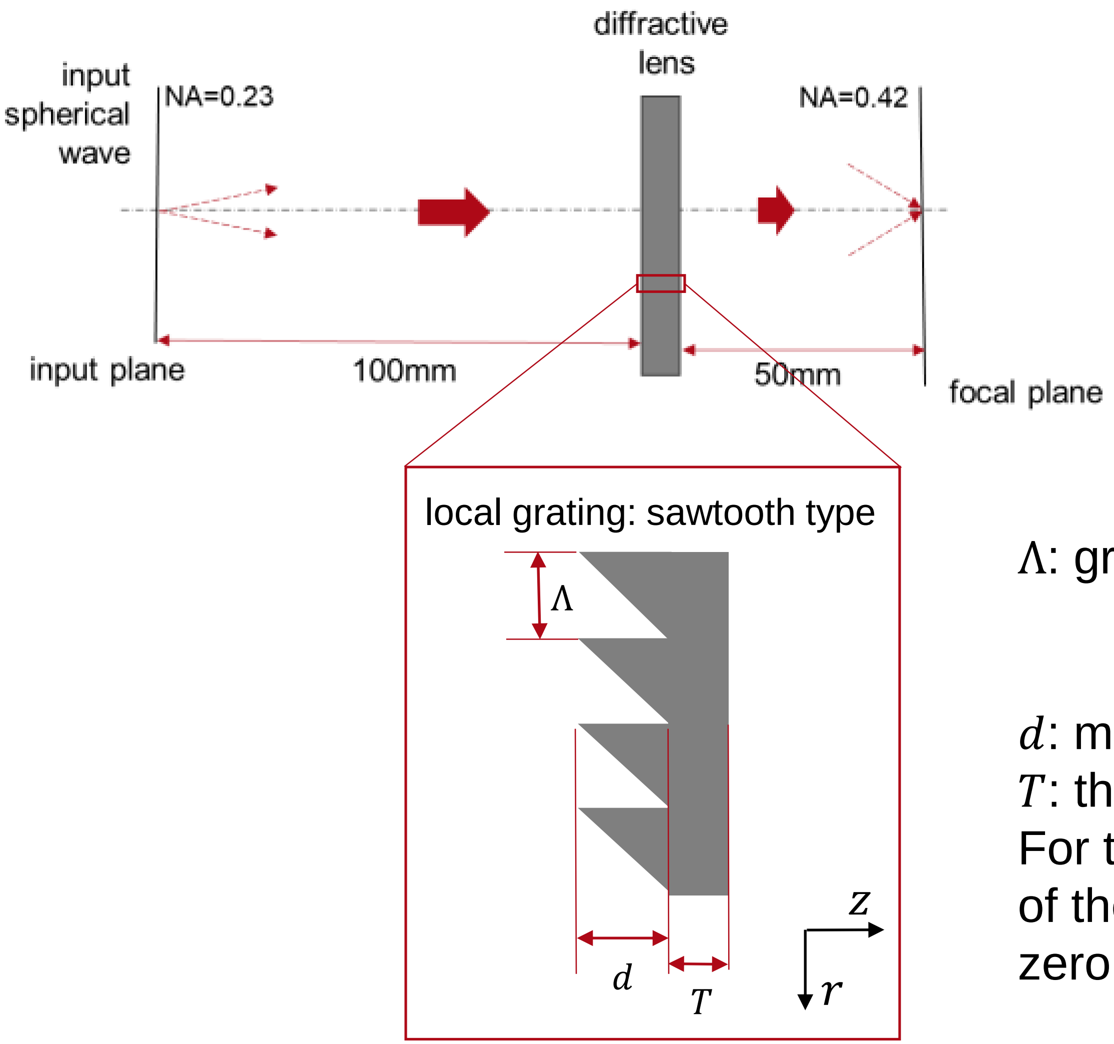
Image is formed by interference of different diffraction orders. Simulation of complete system from input field to image plane takes less than 5 seconds!

Diffractive, Fresnel, Meta Lenses

- For small apertures rigorous modeling, e.g. by FMM.
- For most practical situations local assumption of linear grating or specific nanostructures.
- In order to investigate stray light use of LPIA/TEA or split-step techniques.
- Further techniques under development.



Imaging with Diffractive Lens



Λ: grating period

$$\Lambda(x,y) = \frac{2\pi}{|\nabla\varphi(x,y)|}$$

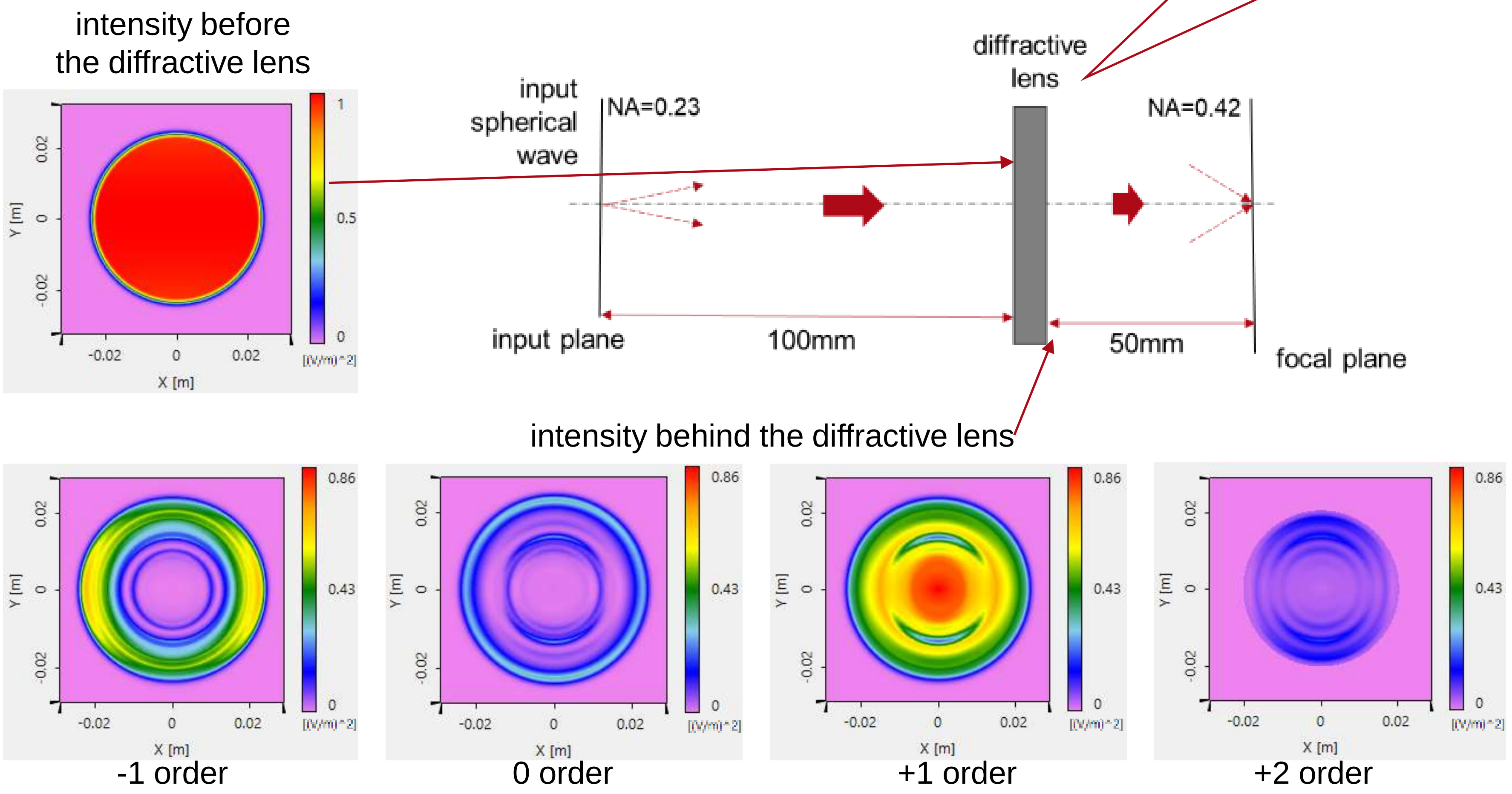
d: modulation depth

T: thickness of base block.

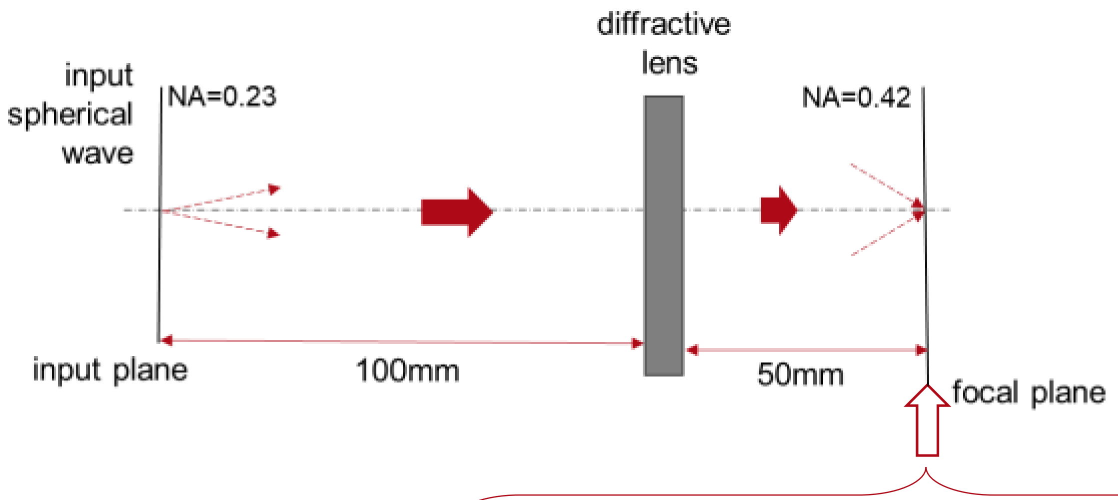
For the design, the thickness of the base block is set as zero, $T = 0$

Imaging with Diffractive Lens

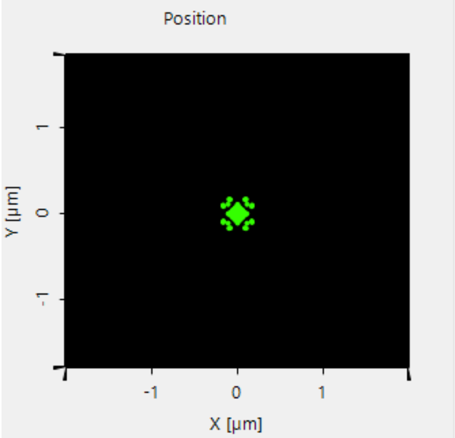
Modeling with rigorous RCWA/FMM



Imaging with Diffractive Lens

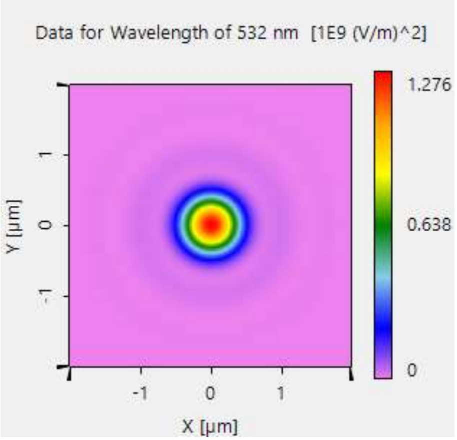


Ray tracing result



Dot pattern of the working order

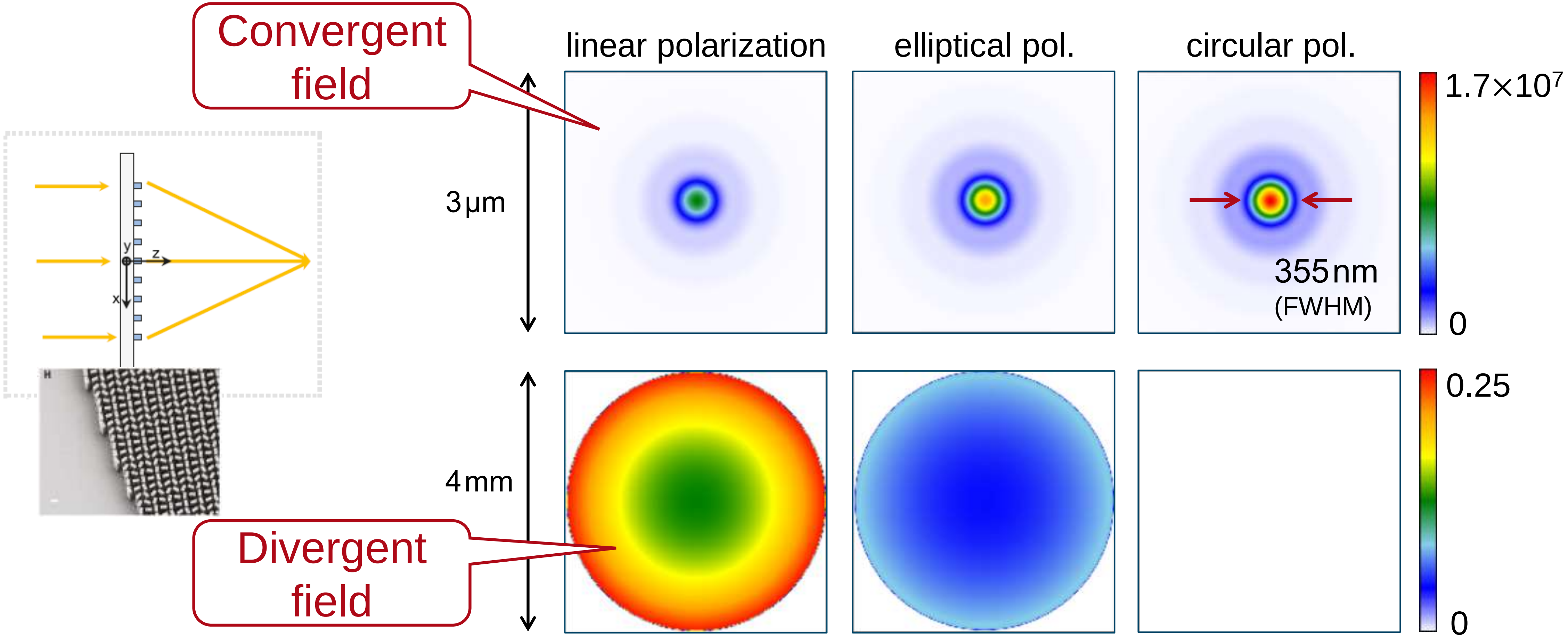
Field tracing result



PSF

Metalens based on Birefringent Nanofin Structure

- Analysis with different input polarizations



Diffractive, Fresnel, Meta Lenses

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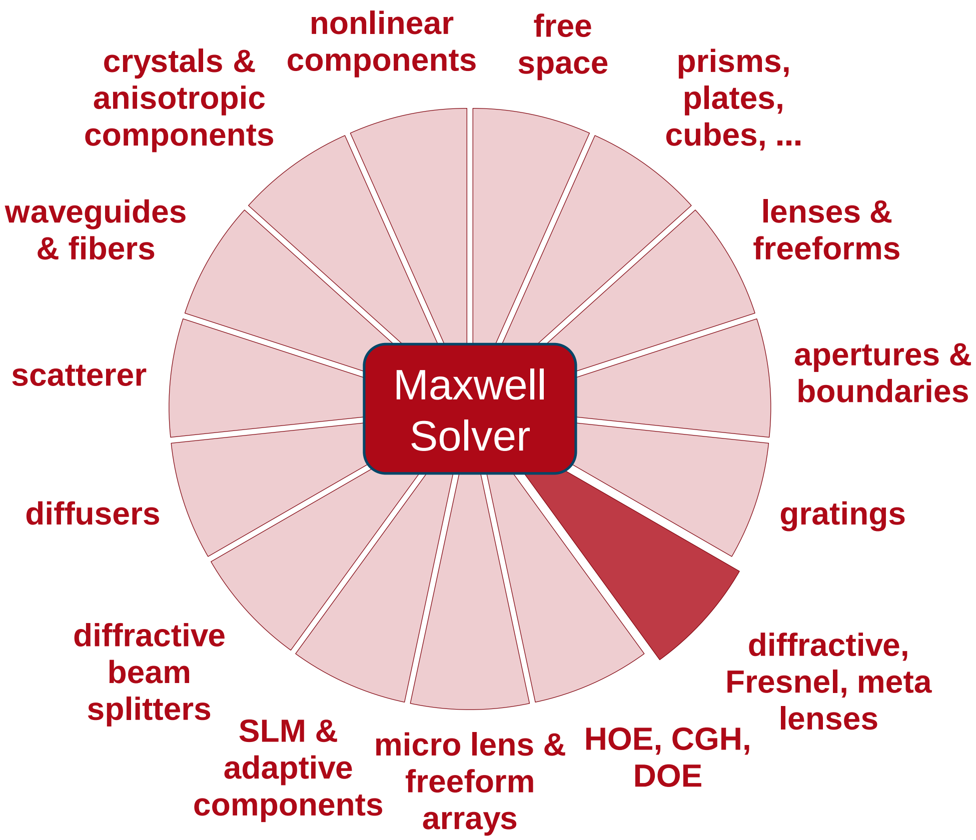
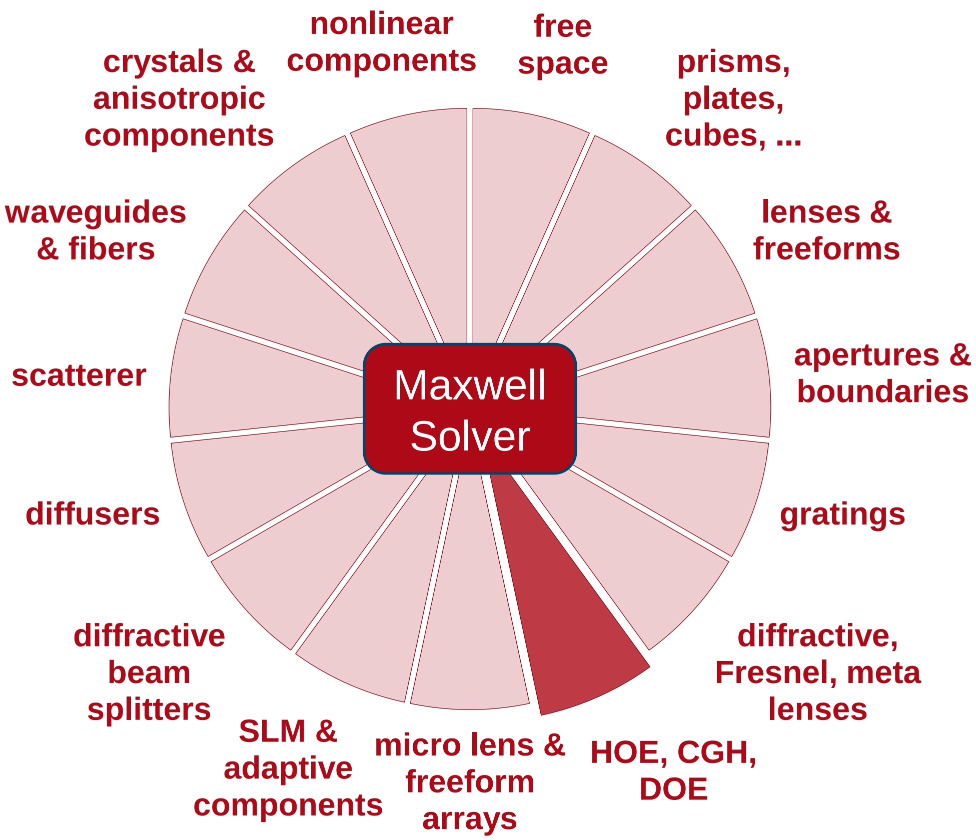
- In order to investigate stray light use of LPIA/TEA or split-step techniques.
- Further techniques under development.

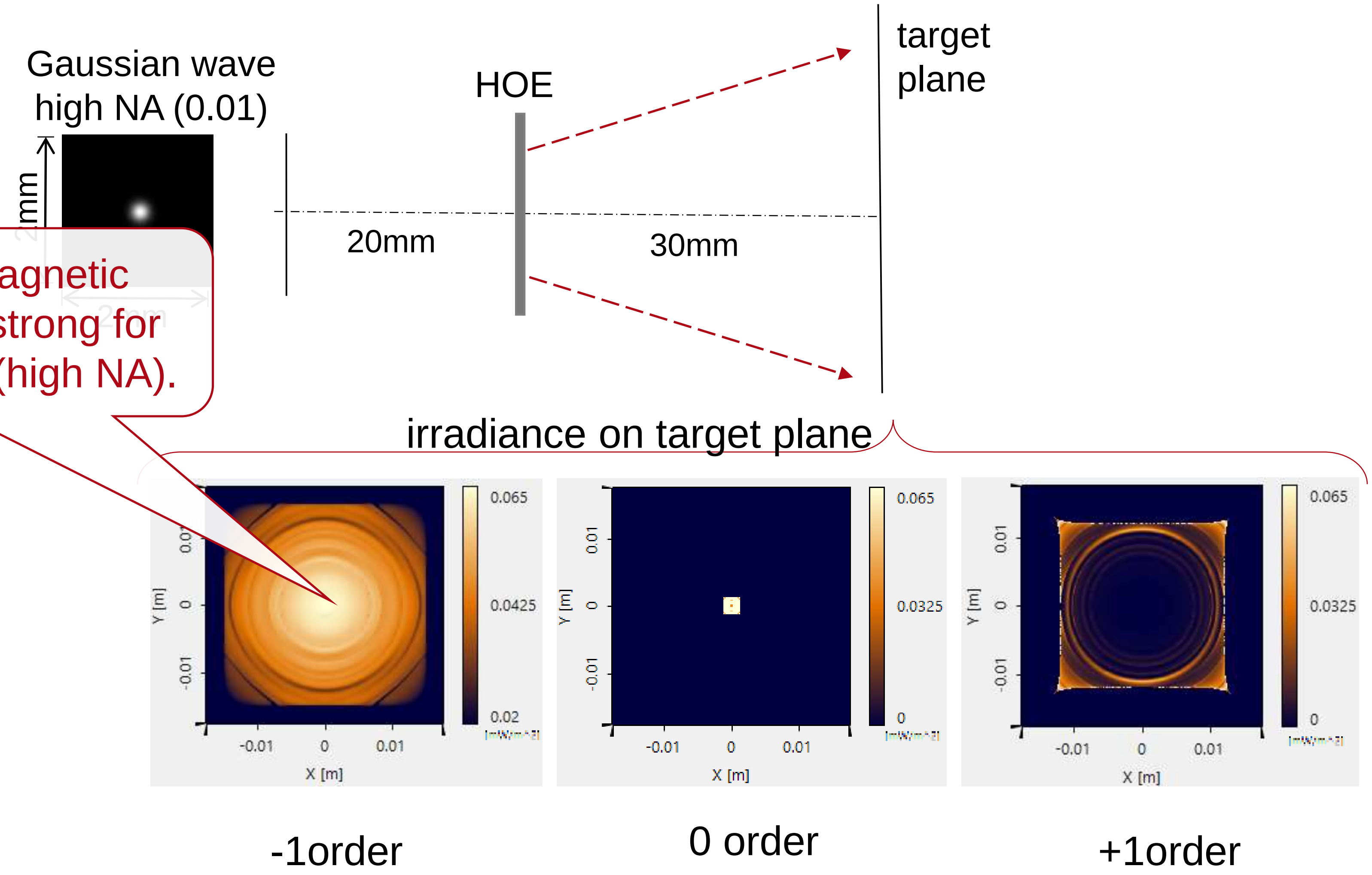


HOE, CGH, DOE

- For small apertures rigorous modeling, e.g. by FMM.
- For most practical situations local assumption of linear grating or specific nanostructures.
- In order to investigate stray light use of LPIA/TEA or split-step techniques.
- Further techniques under development.

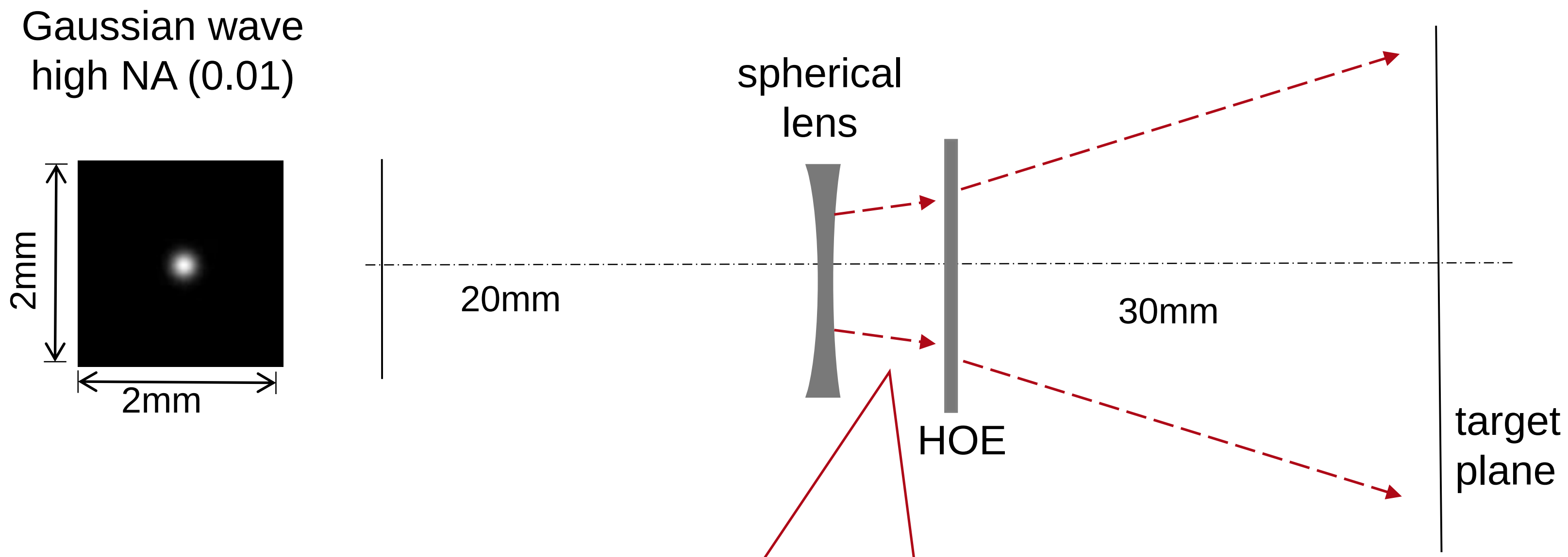


Gaussian to Top-Hat: Structural Design by HOE



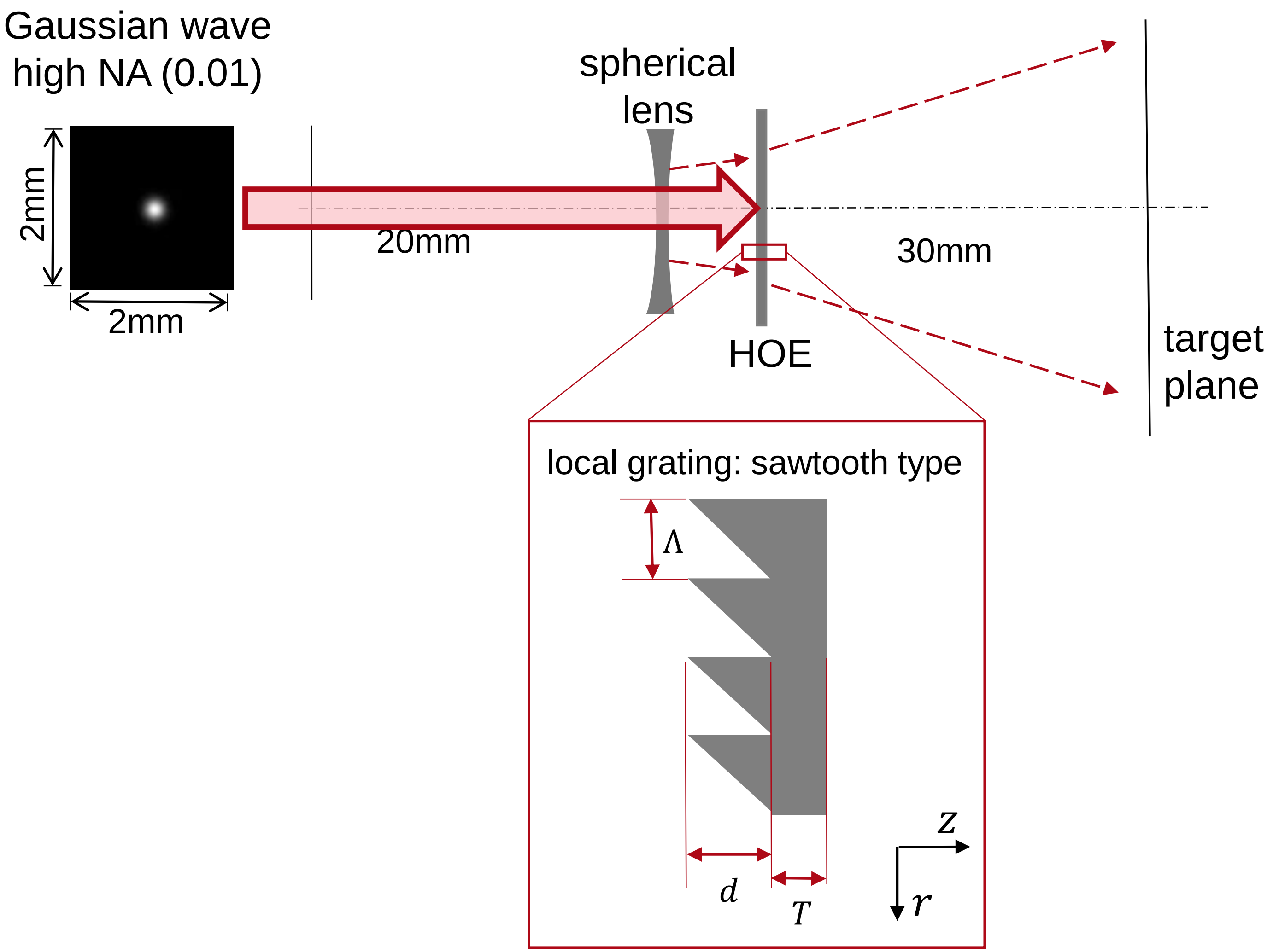
Unwanted electromagnetic effects in HOE too strong for small local periods (high NA).

Gaussian to Top-Hat: Lens + HOE

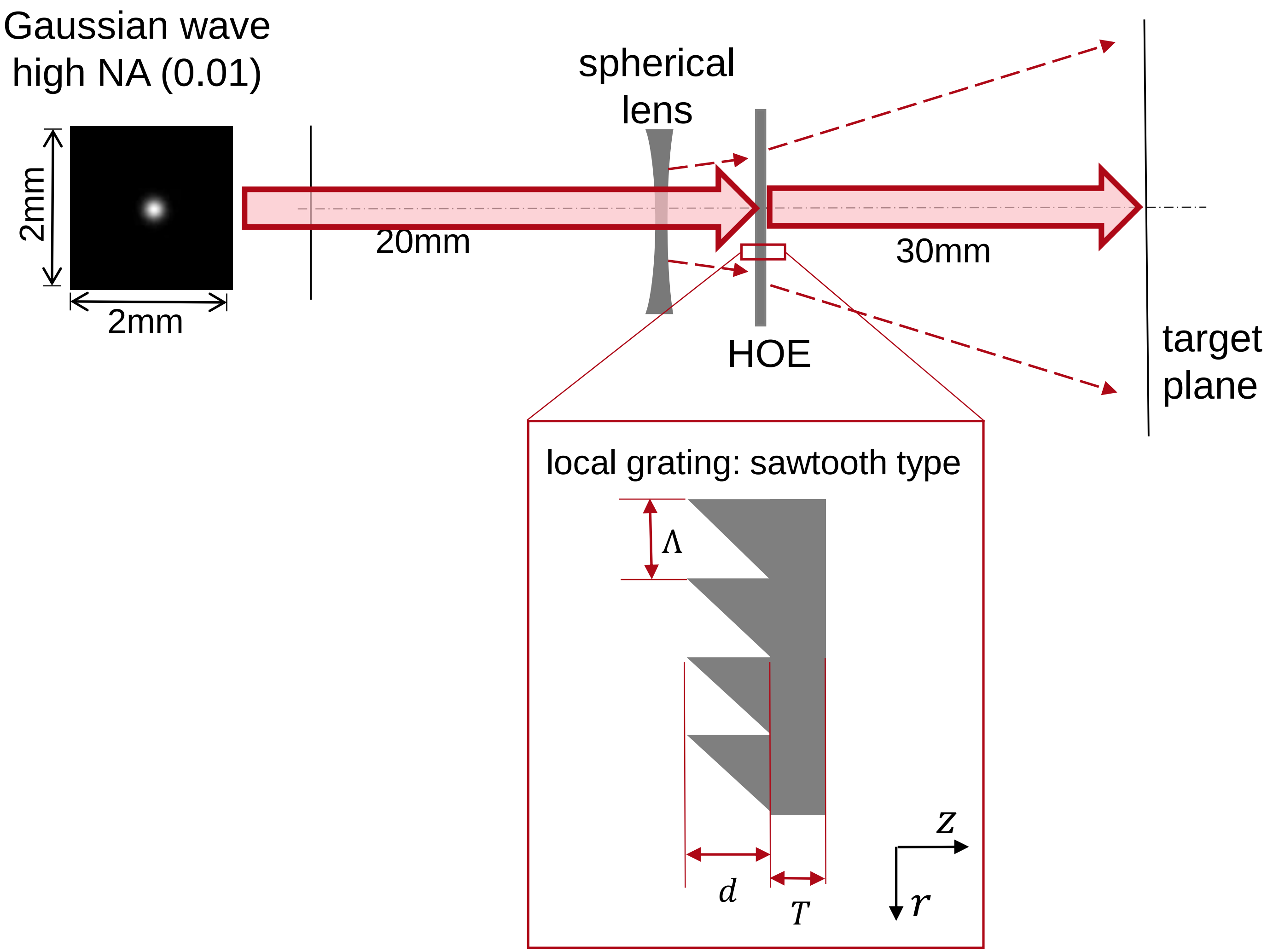


Hybrid solution:
- Spherical lens provides major divergence power
- HOE controls/introduces aberrations

Gaussian to Top-Hat: Structural Design



Gaussian to Top-Hat: Structural Design

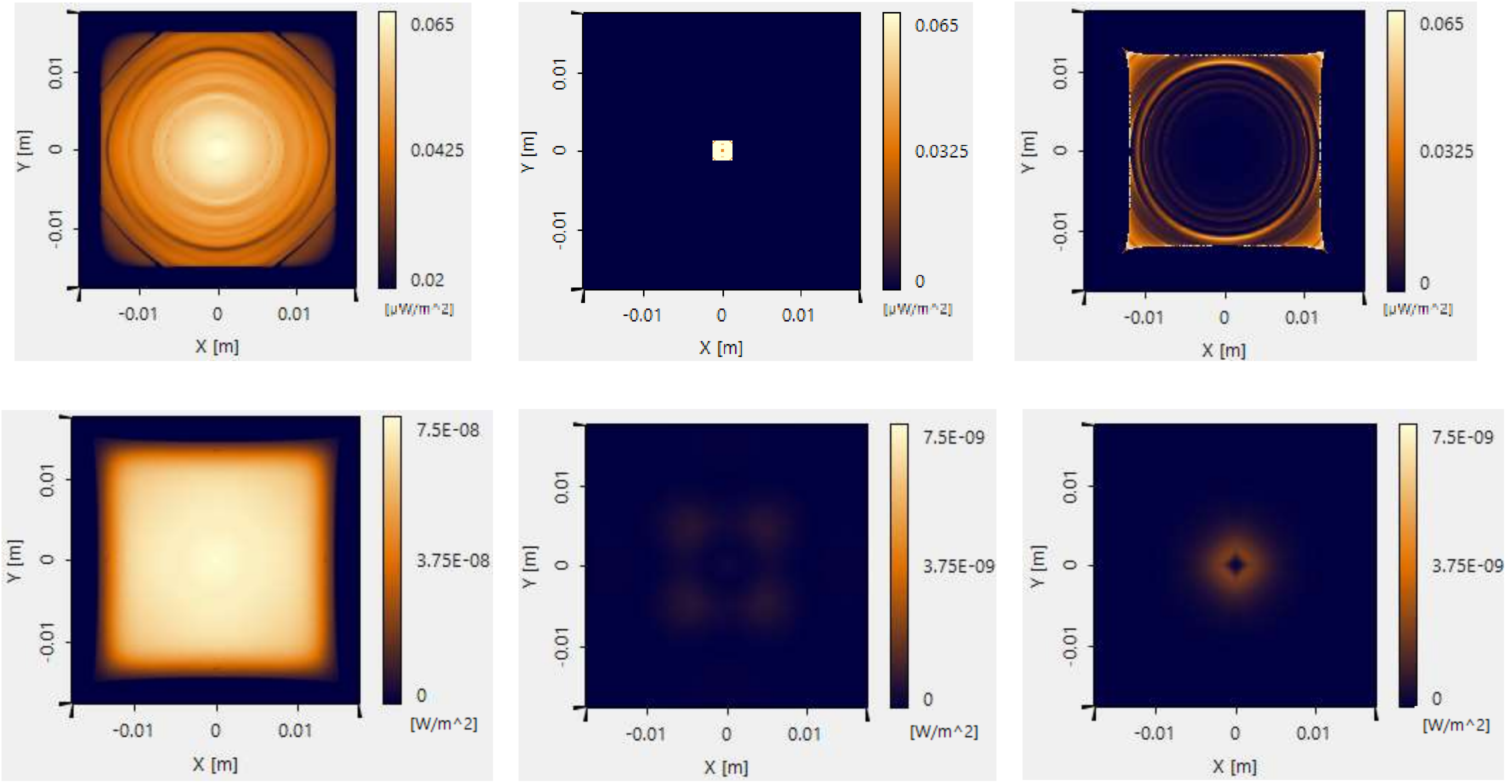


Gaussian to Top-Hat: Lens + HOE

The result irradiance on target plane is compared with the previous case without the lens.

without the lens

with the lens



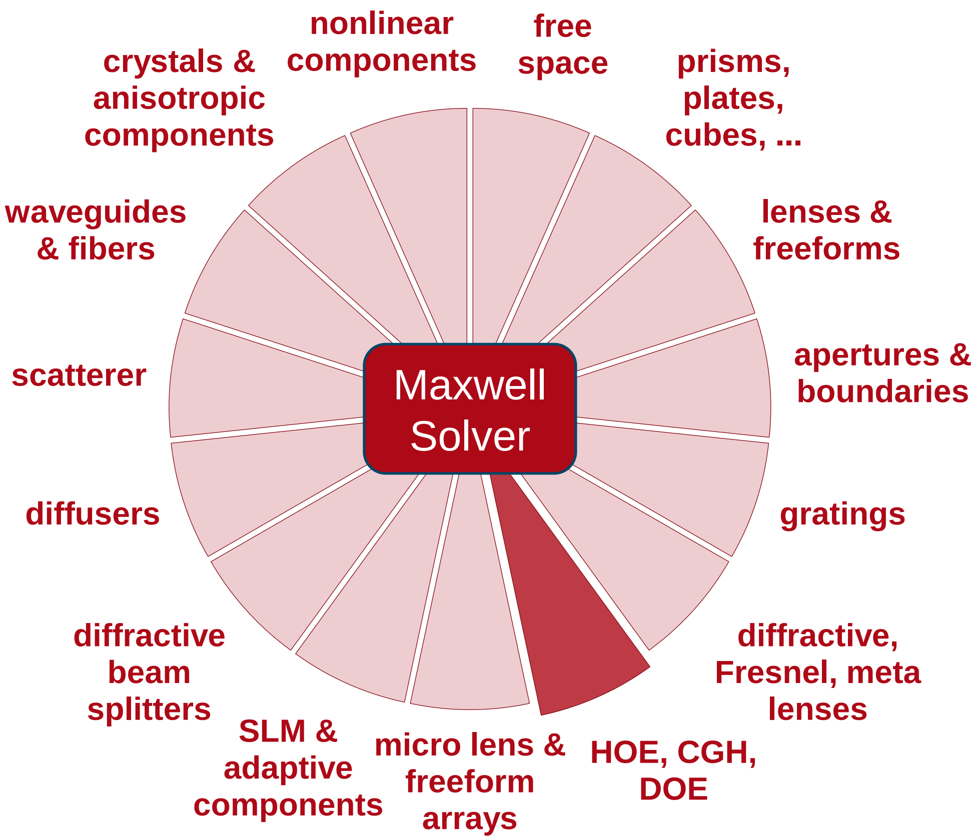
-1order

0 order

+1order

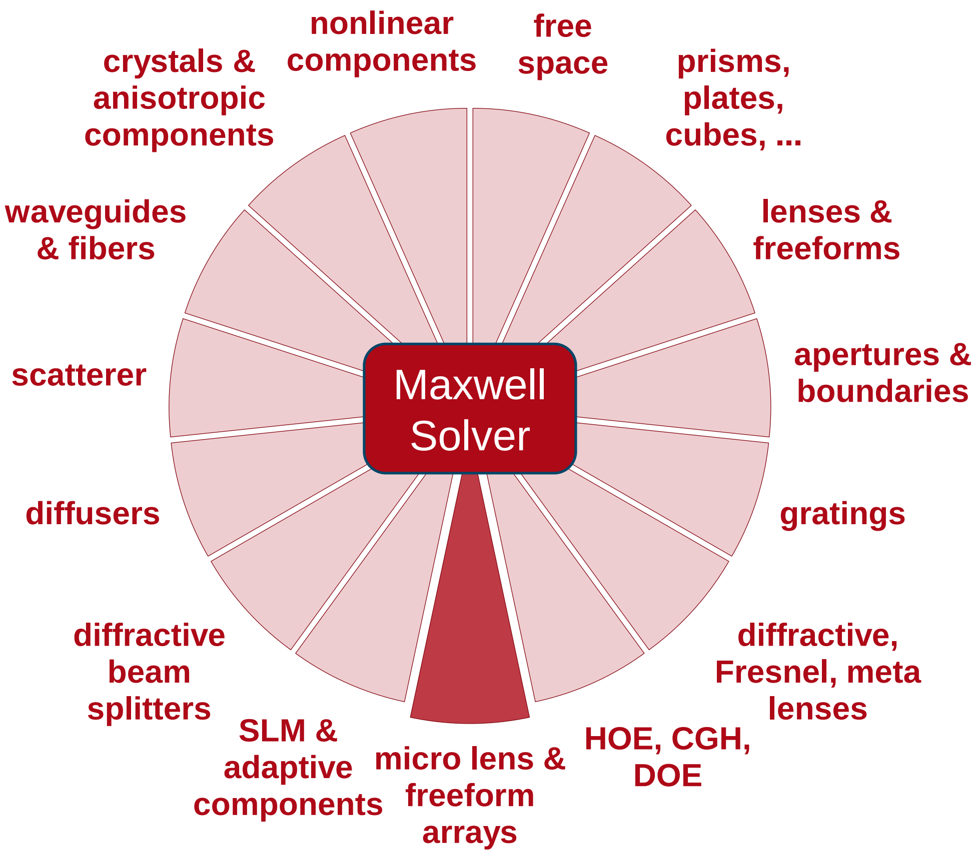
HOE, CGH, DOE

- For small apertures rigorous modeling, e.g. by FMM.
- For most practical situations local assumption of linear grating or specific nanostructures.
- In order to investigate stray light use of LPIA/TEA or split-step techniques.
- Further techniques under development.



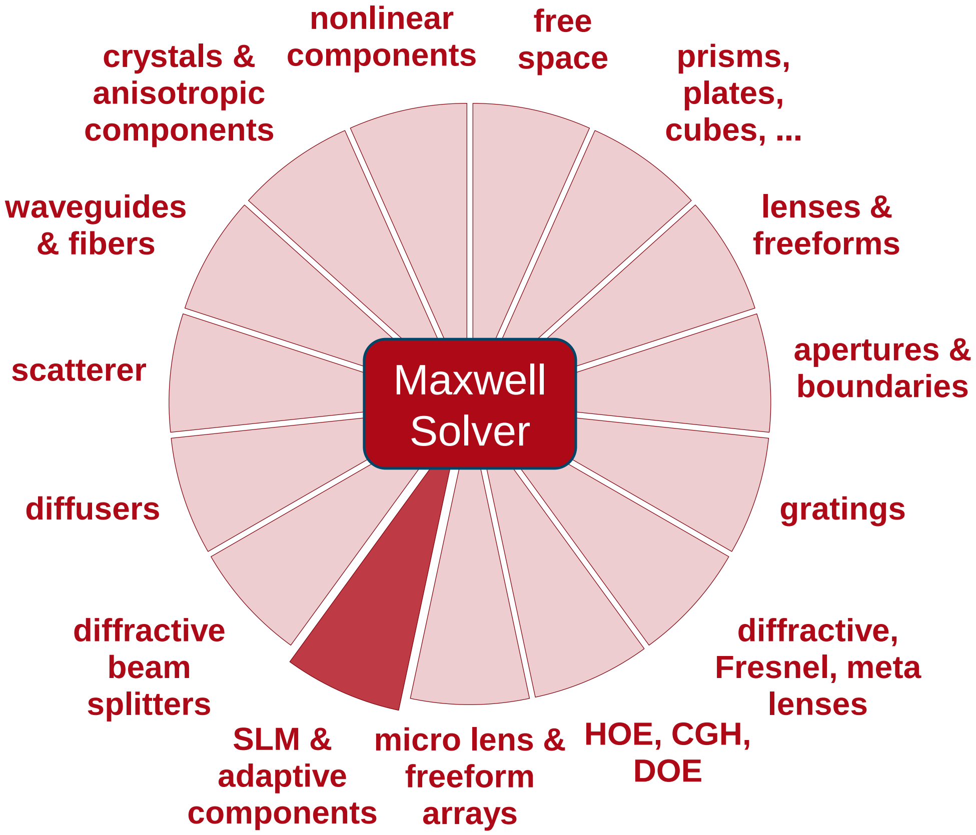
Micro Lens and Freeform Arrays

- Space domain approach: LPIA/TEA for entire array.
- For arrays with small pitch it is better to consider array as grating and apply grating modeling in k-domain.
- Under development: Space domain approach with separated channels for lenses in array.



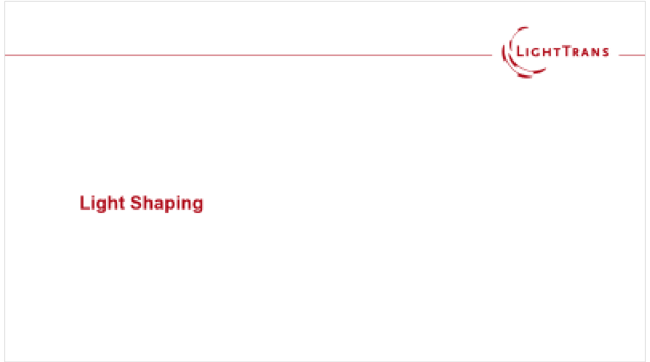
SLM & Adaptive Optics Components

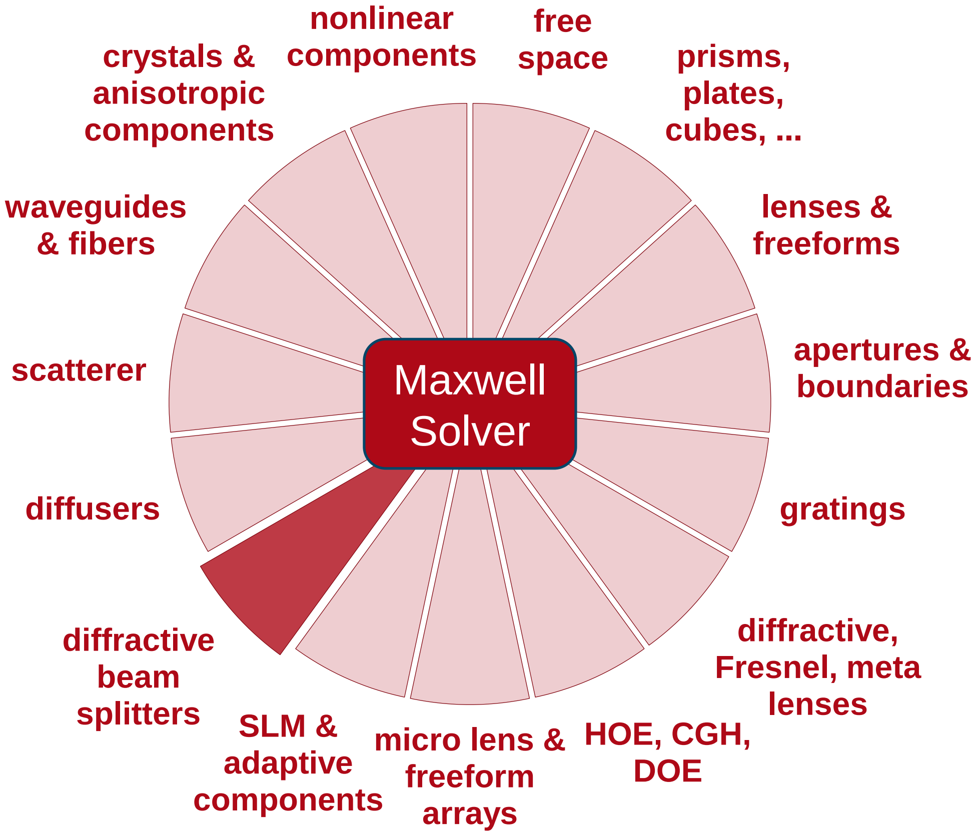
- Space domain approach: LPIA/TEA for entire array.
- For arrays with small pitch it is better to consider array as grating and apply grating modeling in k-domain.
- Under development: Space domain approach with separated channels for structures in array.



Diffractive Beam Splitter

- Gratings modeling technqiues: FMM and LPIA/TEA
- For high NA beam splitter split-step techniques.





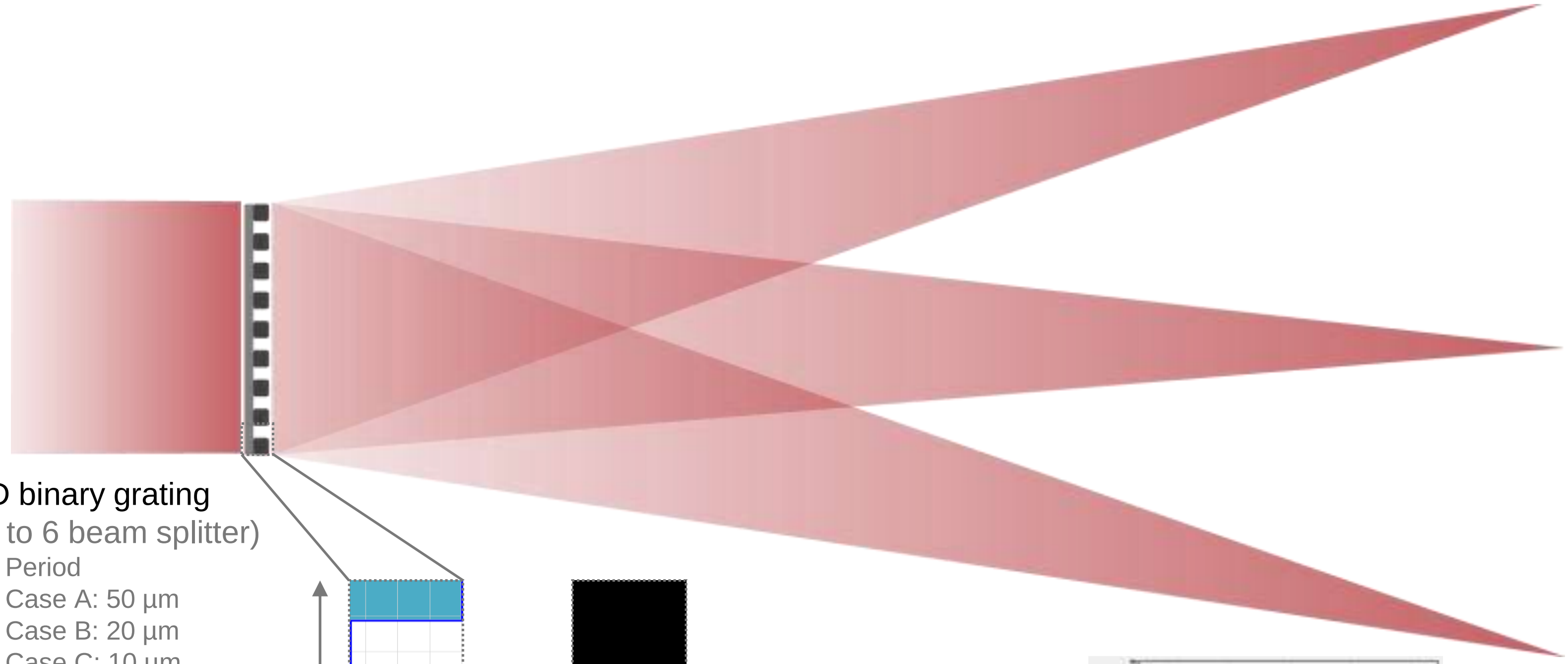
Comparison of Different Method of Modeling Binary Grating

Huiying Zhong

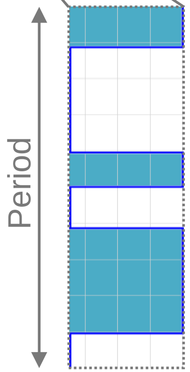
The sample comes from 2018-01-10_Hartwig_Crailsheim_FieldInside&Efficiency-Comparison

Task Description

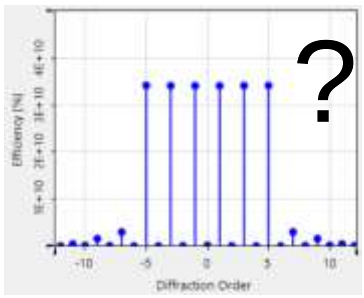
Ideal plane wave
- Wavelength is 632.8 nm
- Polarization state:
  - Case A to D: E_x –polarized
  - Case E: E_y –polarized



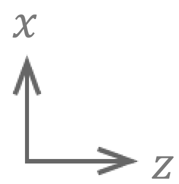
1D binary grating
(1 to 6 beam splitter)
- Period
- Case A: 50 µm
- Case B: 20 µm
- Case C: 10 µm
- Case D&E: 5 µm



To be calculated:
field inside
the grating

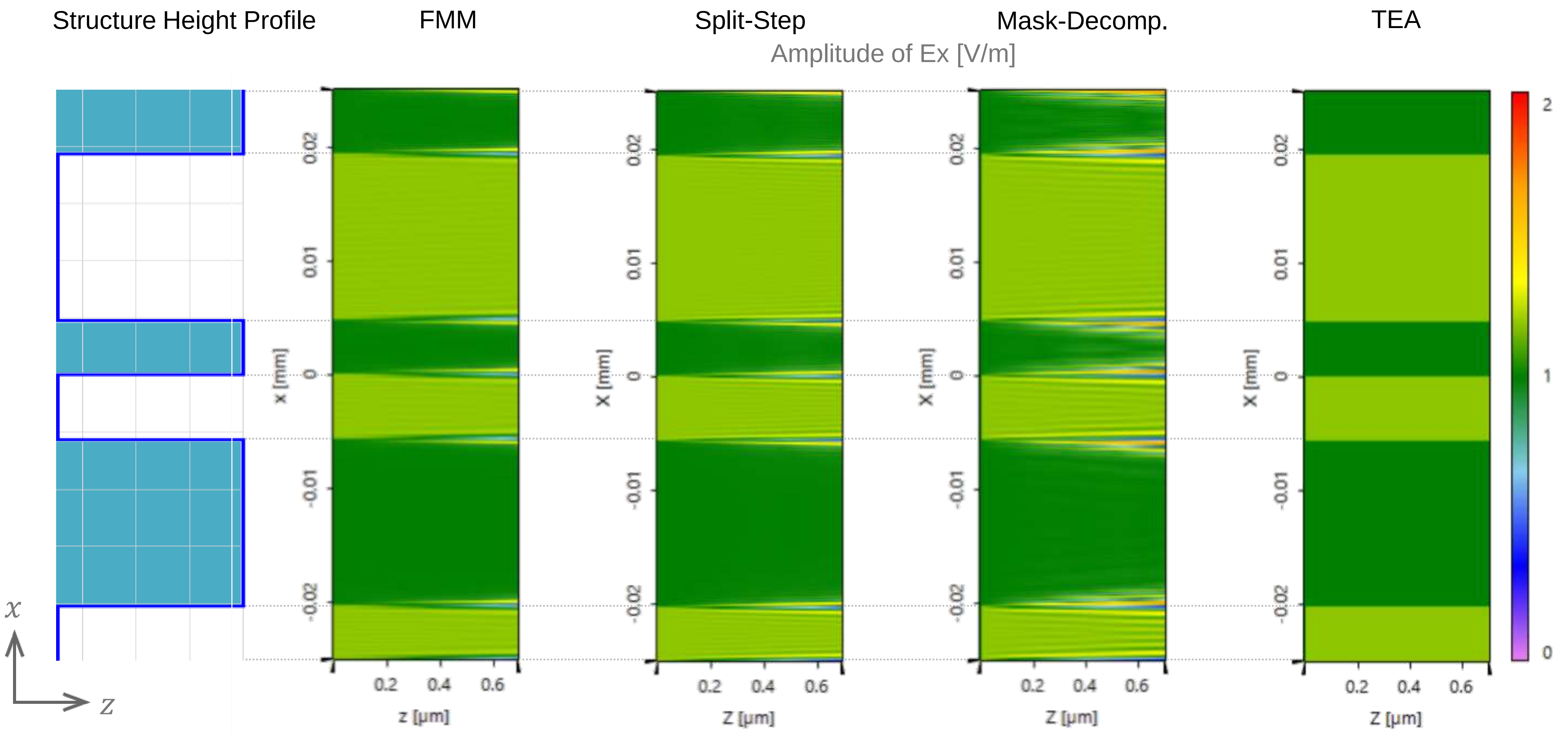


To be calculated:
diffraction efficiency

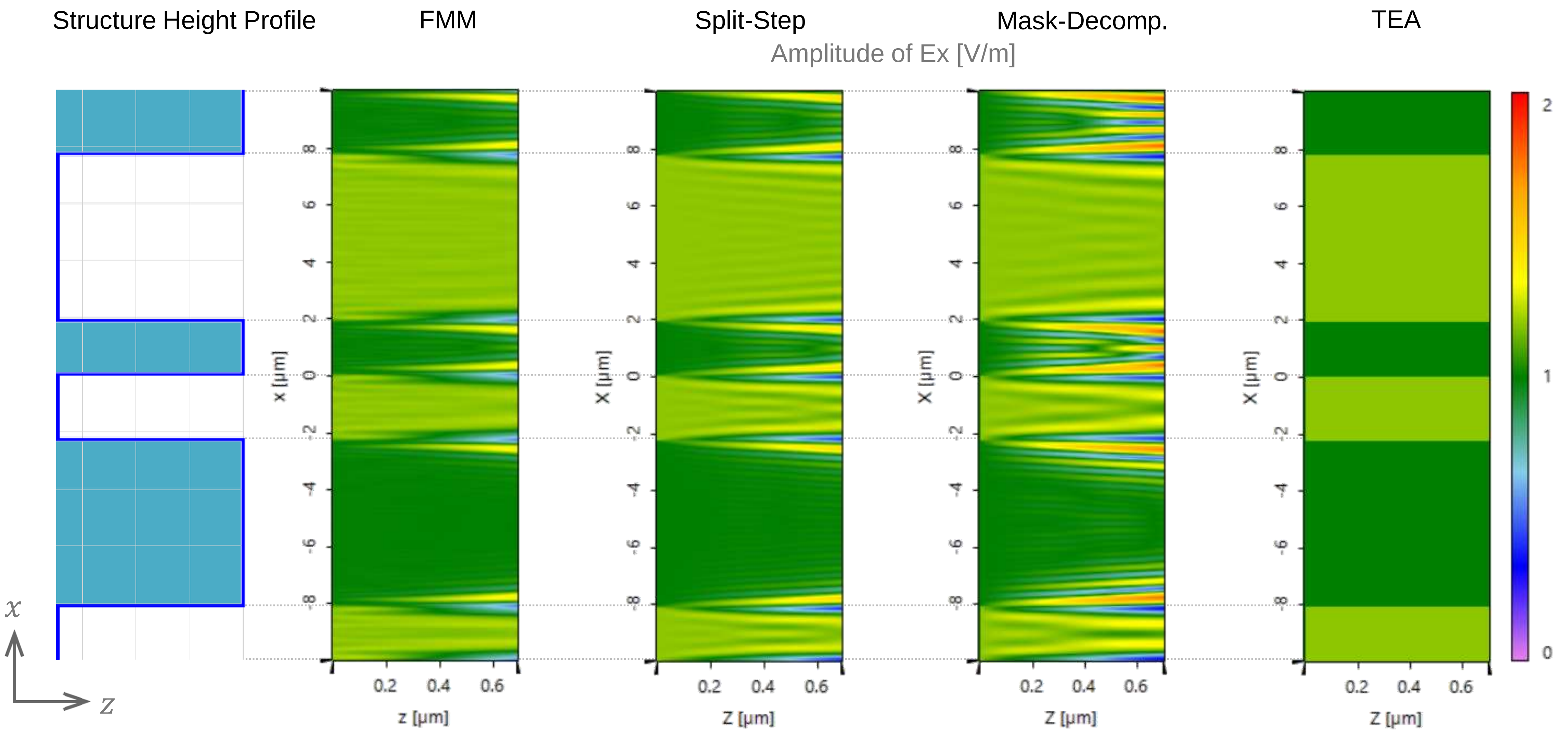


- Calculation of ideal plane wave propagation through a binary grating by using Fourier modal method, split-step method, split step mask decomposition, and thin element approximation.
- Comparison of field inside grating and diffraction efficiency calculated by different methods.

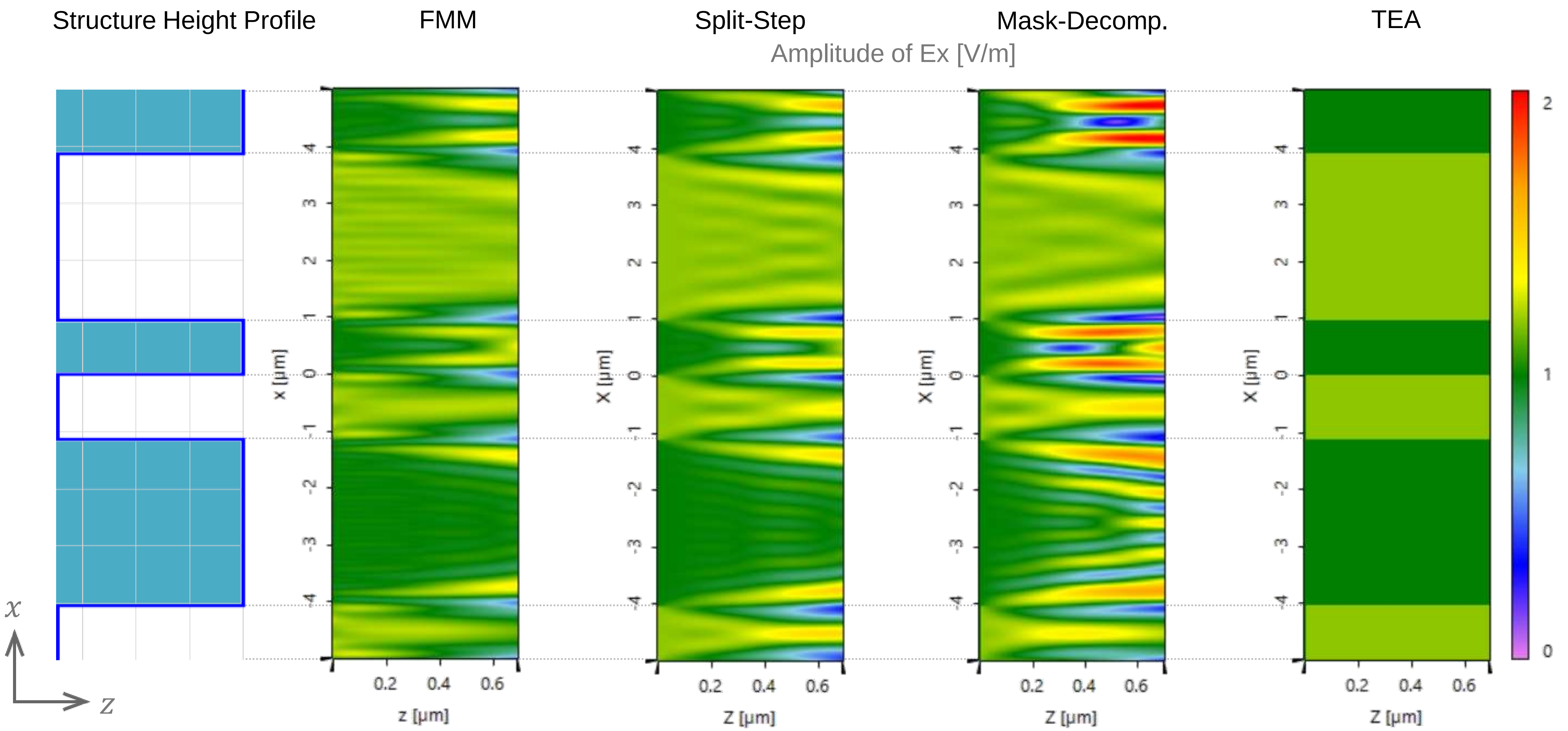
Case A Amplitude: Period=50 µm, Smallest Feature = 4.7410µm



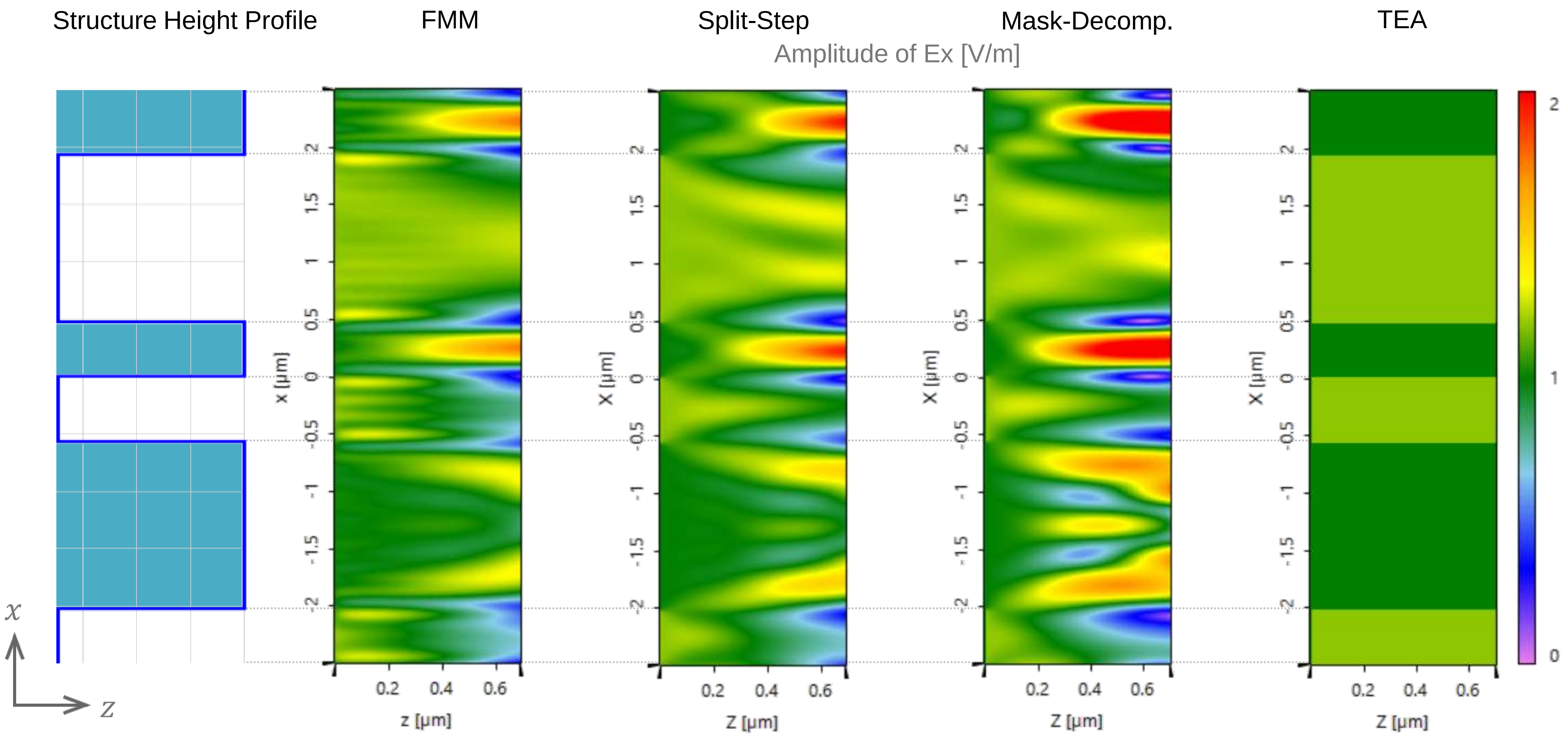
Case B Amplitude: Period=20 µm, Smallest Feature = 1.8964µm



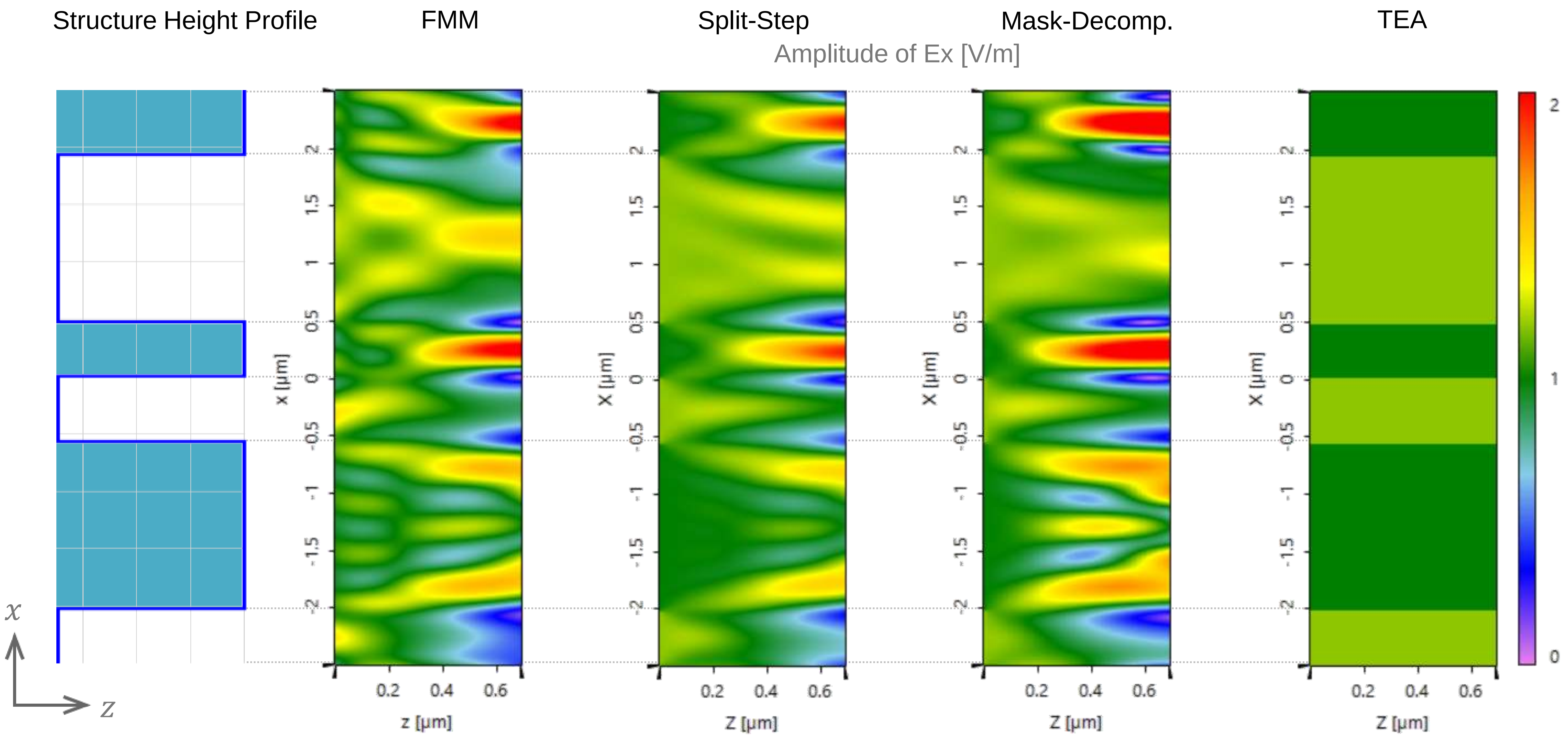
Case C Amplitude: Period=10 µm, Smallest Feature = 0.9482 µm



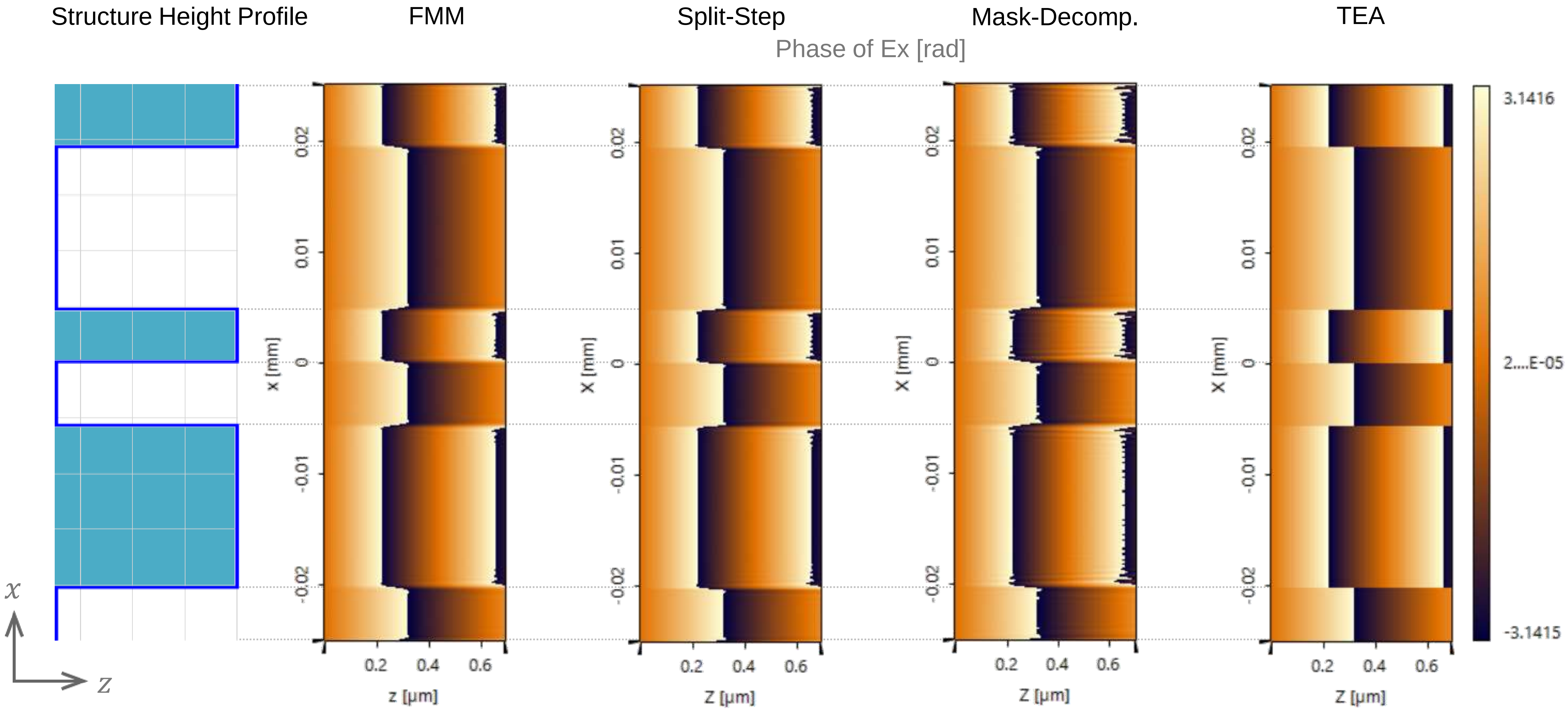
Case D Amplitude: Period=5 µm, Smallest Feature = 0.4741 µm



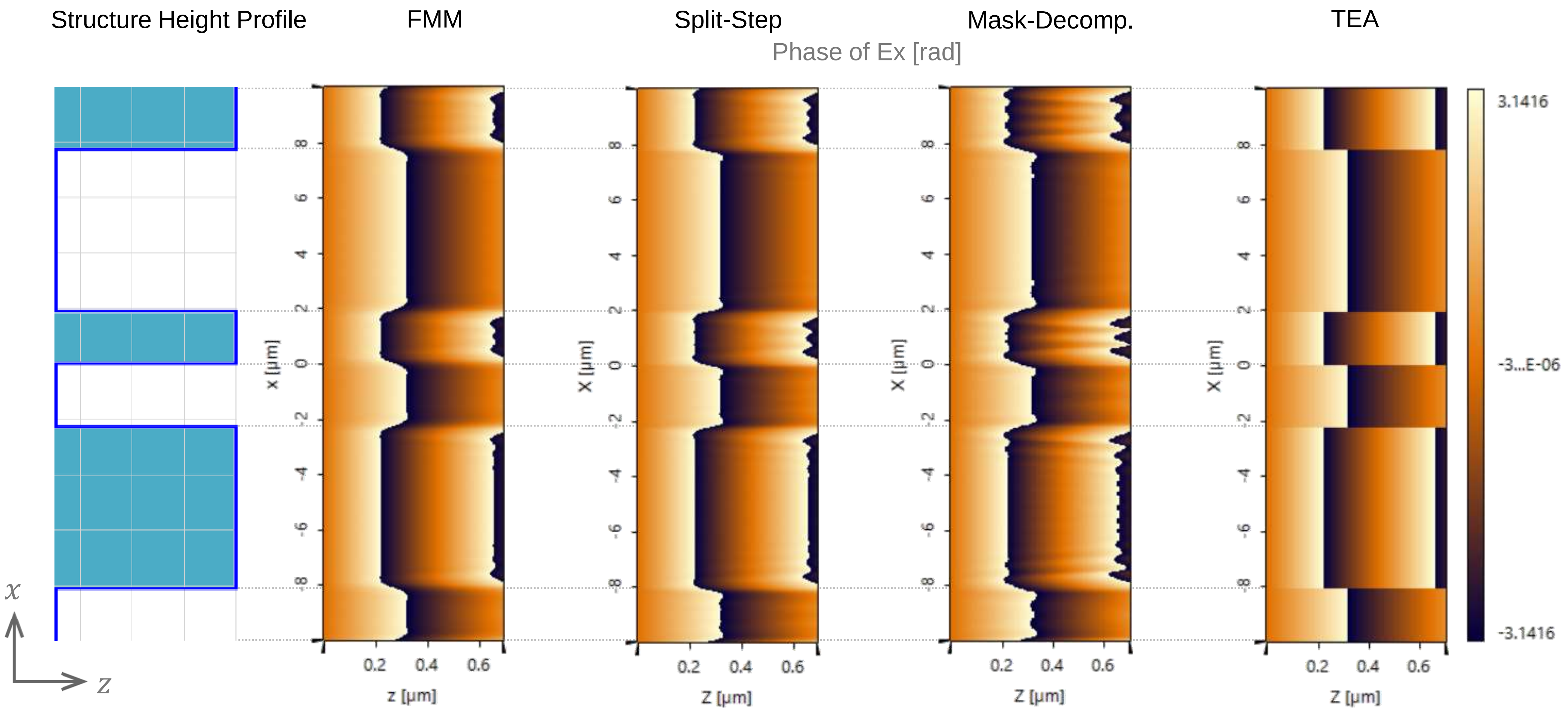
Case E Amplitude: Period=5 µm, Smallest Feature = 0.4741 µm



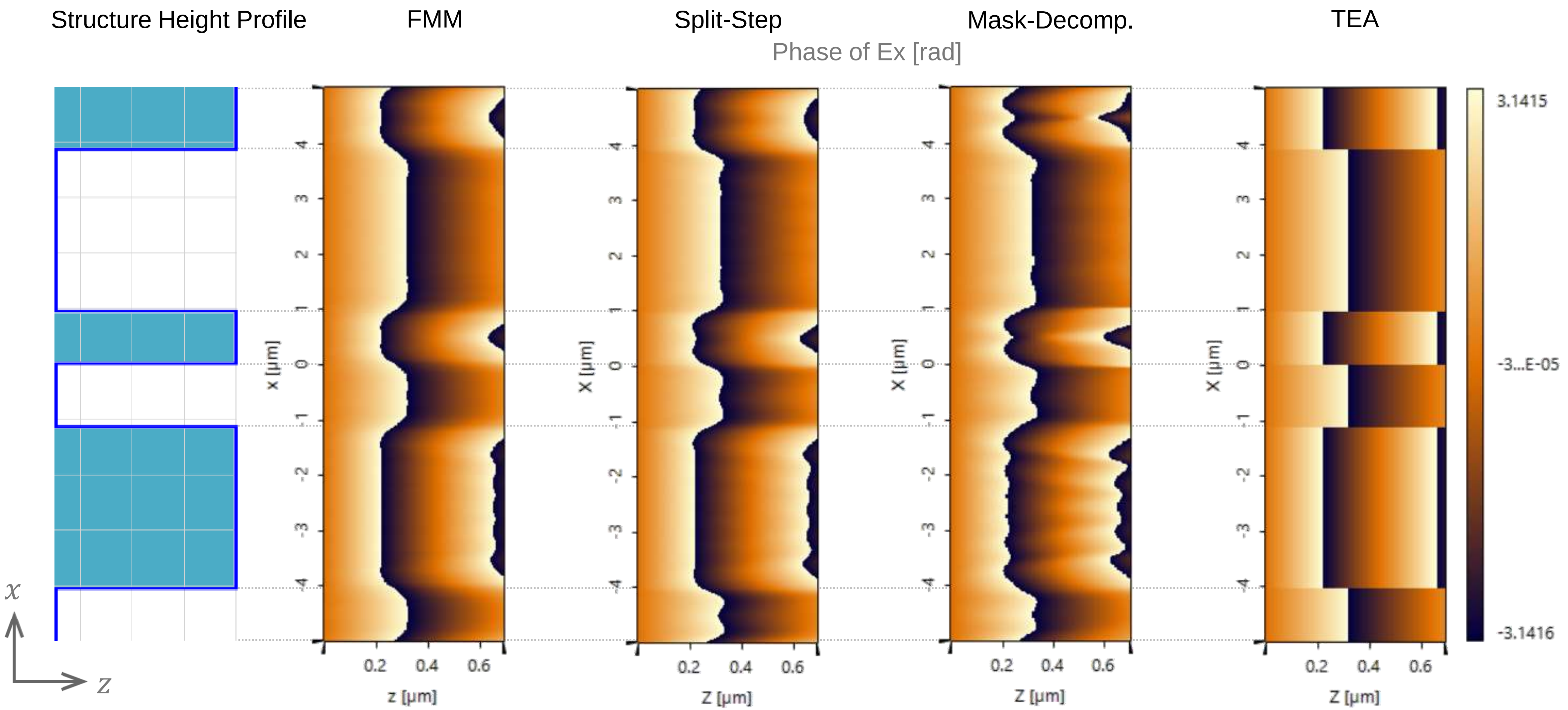
Case A Phase: Period=50 µm, Smallest Feature = 4.7410µm



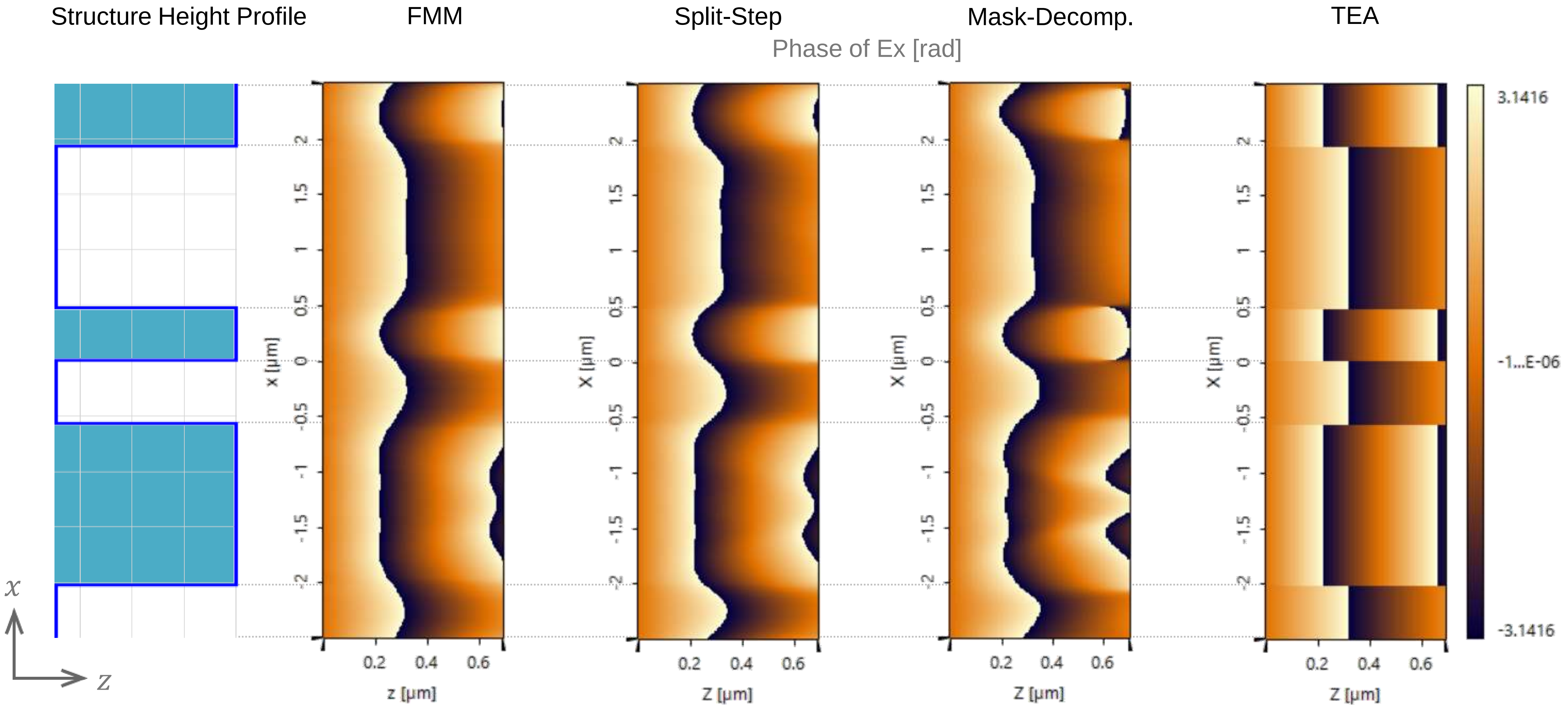
Case B Phase: Period=20 µm, Smallest Feature = 1.8964µm



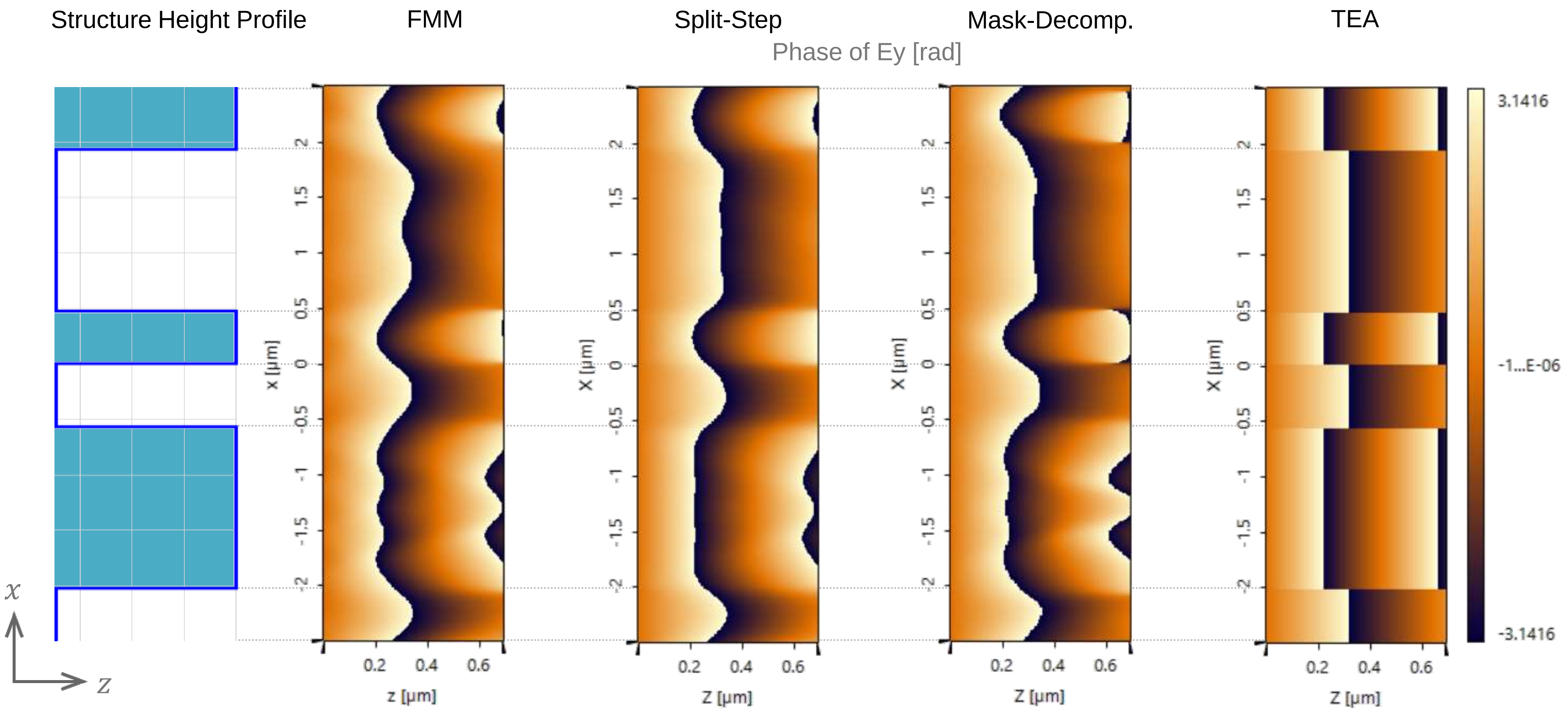
Case C Phase: Period=10 µm, Smallest Feature = 0.9482 µm



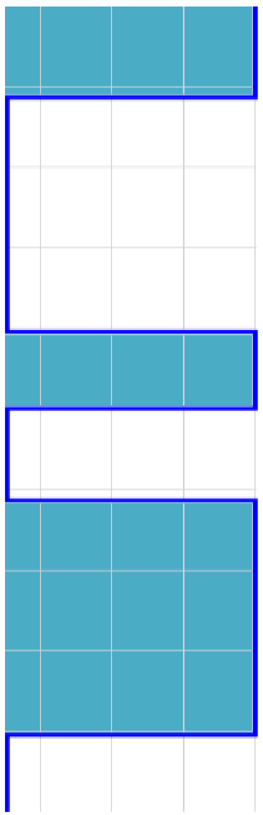
Case D Phase: Period=5 µm, Smallest Feature = 0.4741 µm

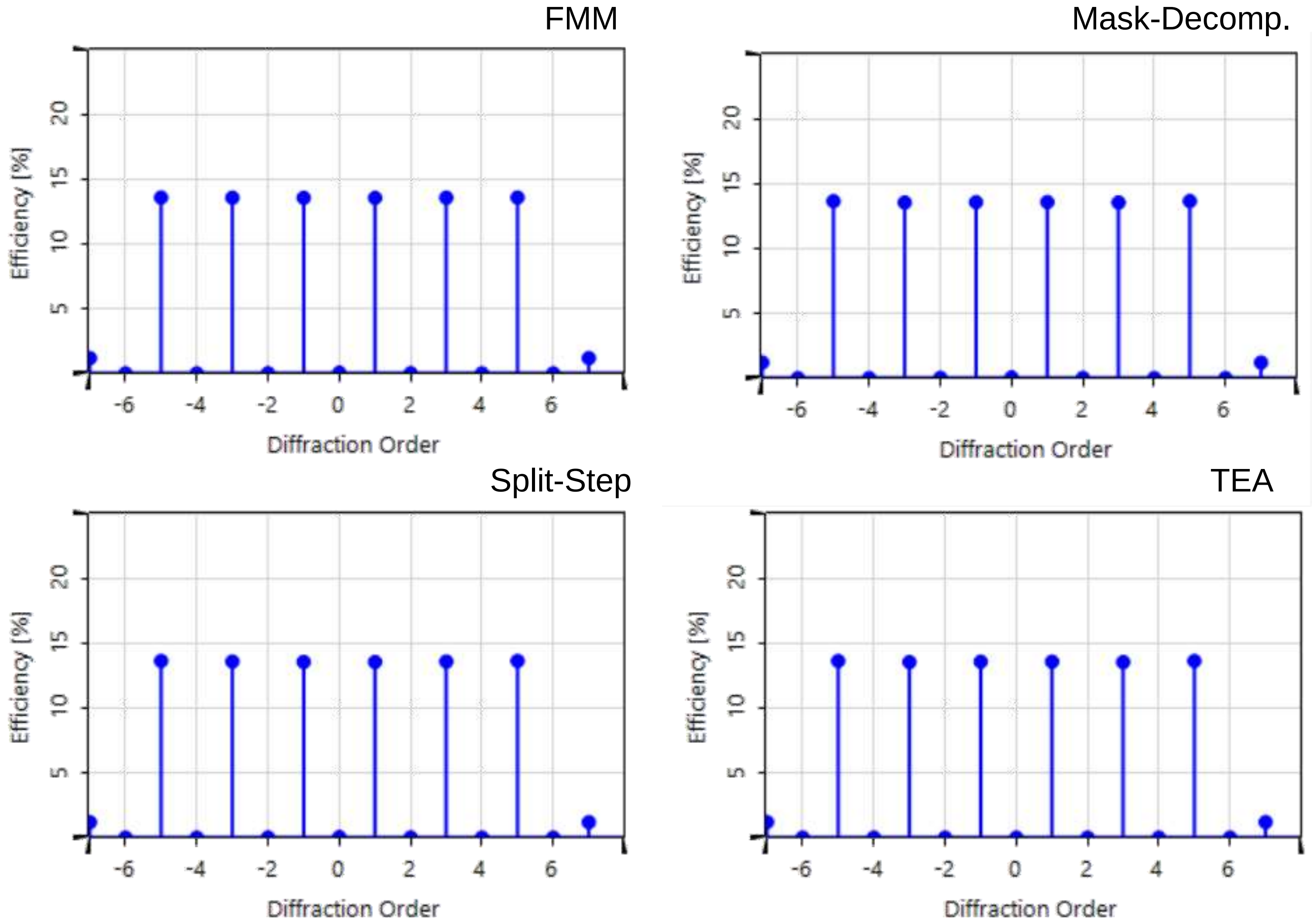


Case E Phase: Period=5 µm, Smallest Feature = 0.4741µm

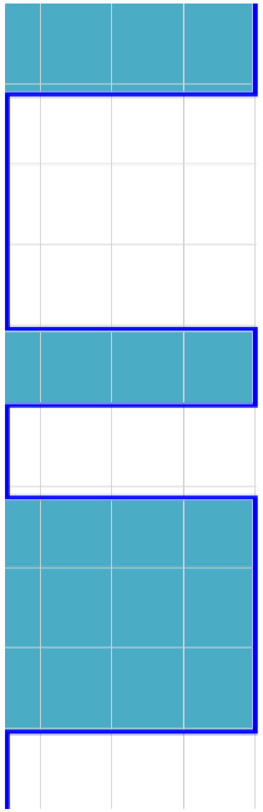


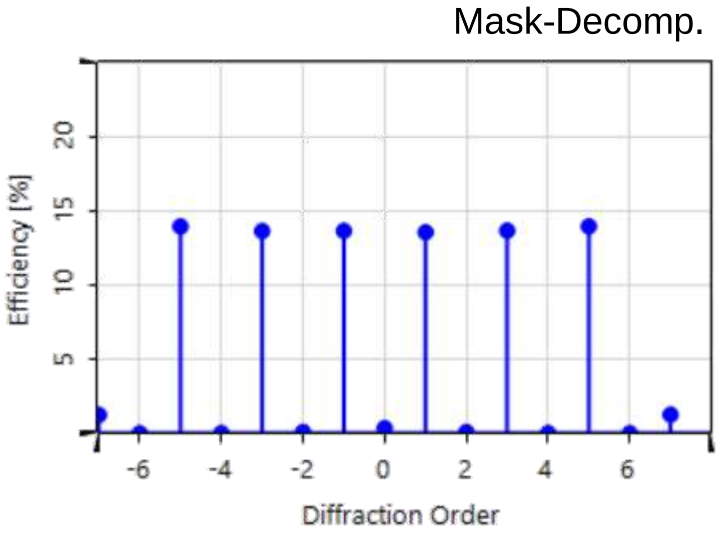
Case A Efficiency: Period=50 µm, Smallest Feature = 4.7410µm

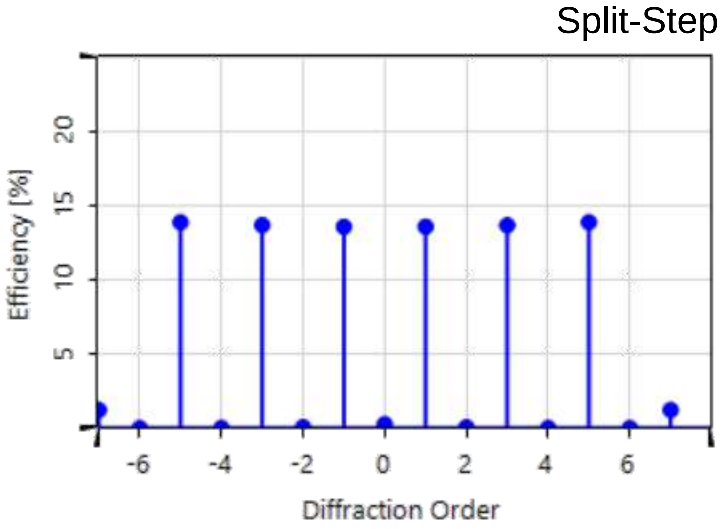




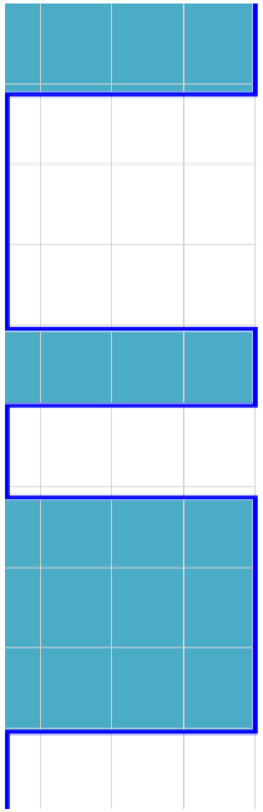
Case B Efficiency: Period=20 µm, Smallest Feature = 1.8964µm

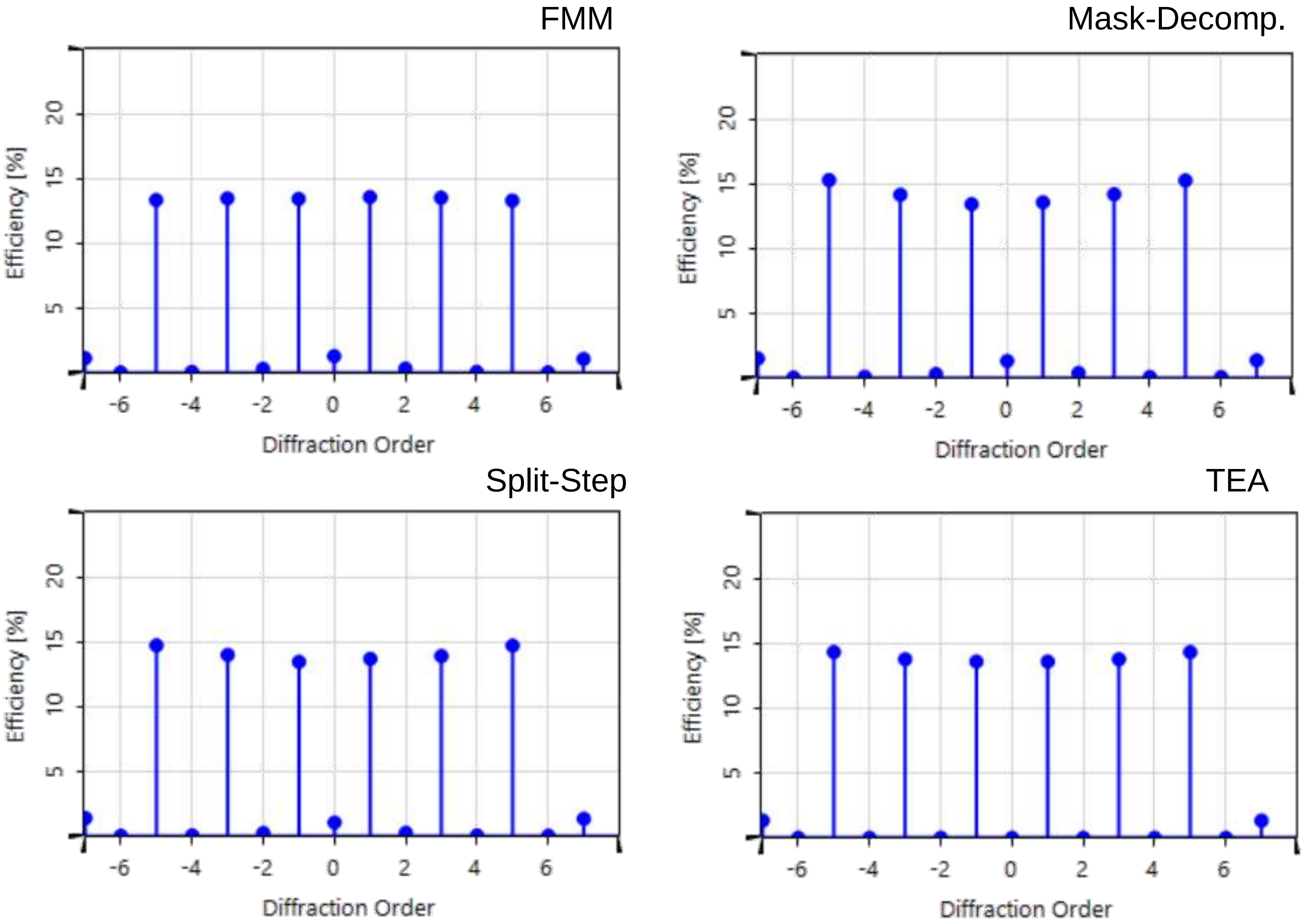




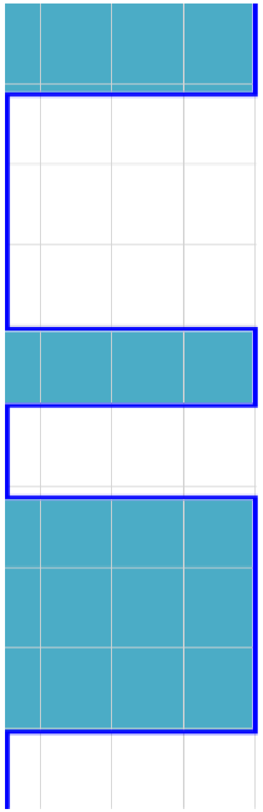


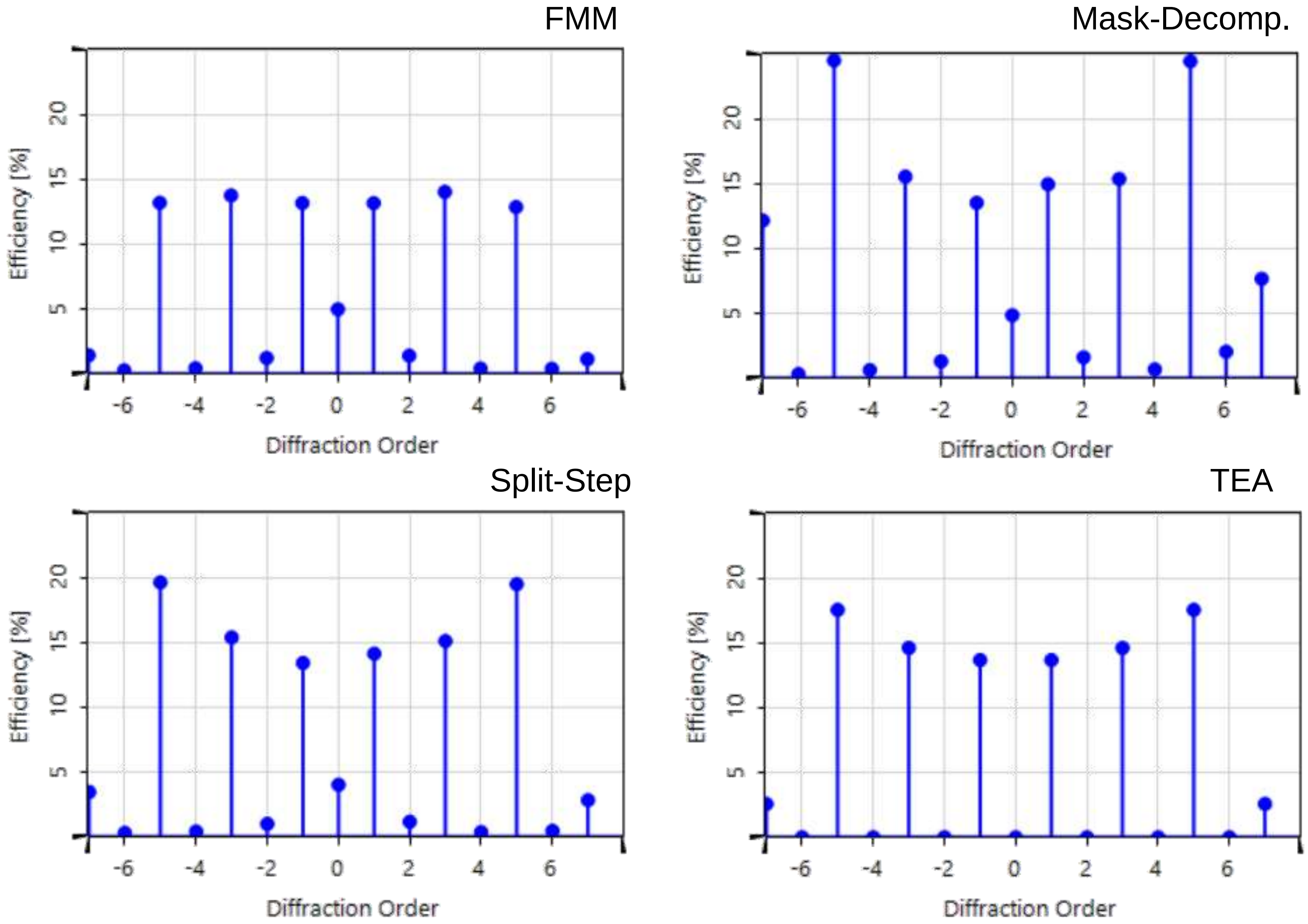
Case C Efficiency: Period=10 µm, Smallest Feature = 0.9482 µm



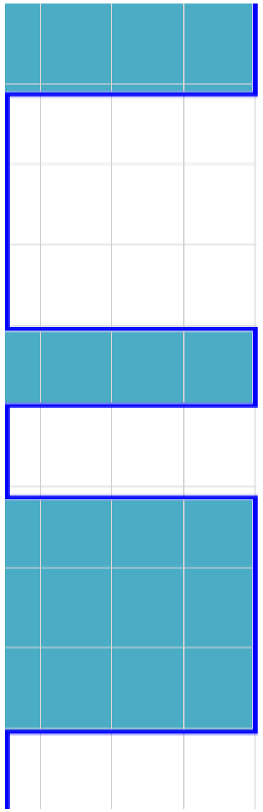


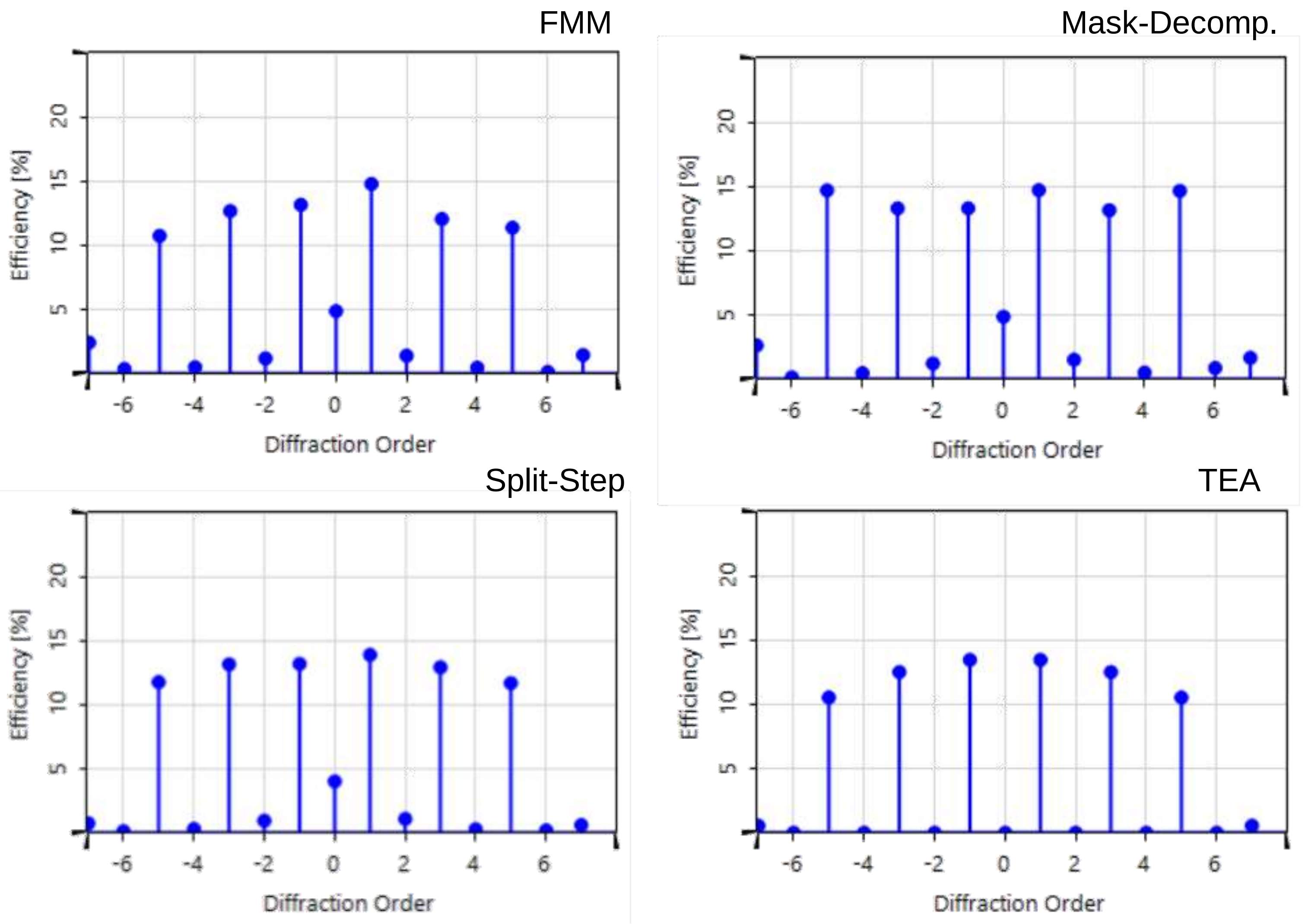
Case D Efficiency: Period=5 µm, Smallest Feature = 0.4741 µm





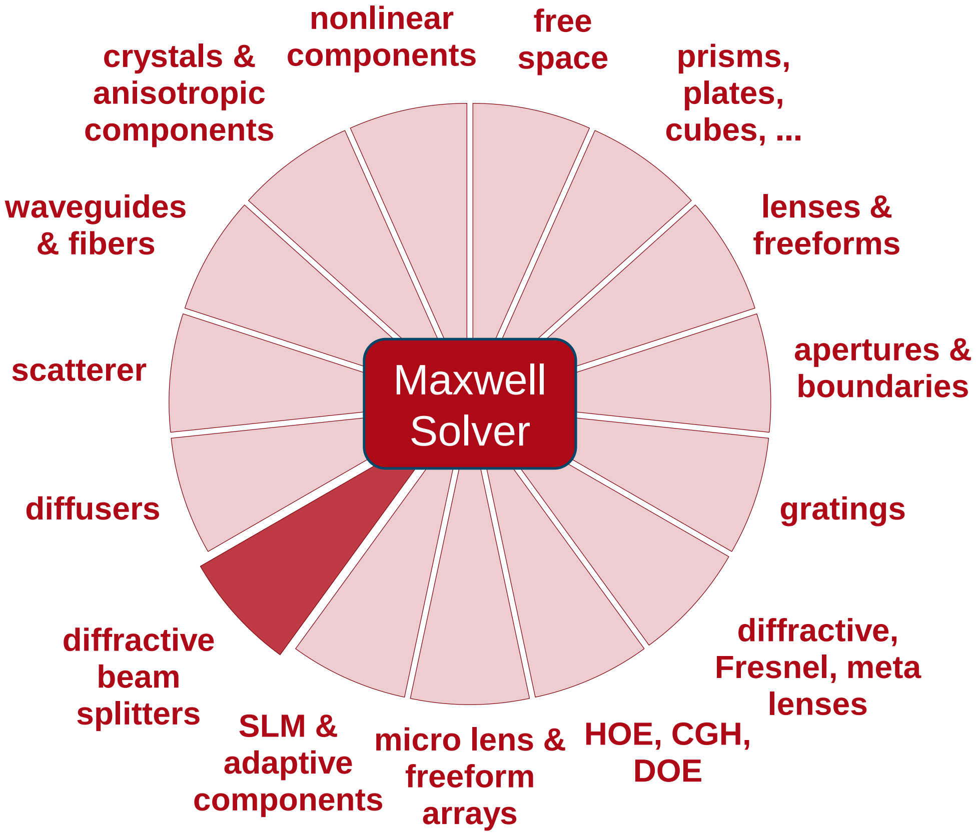
Case E Efficiency: Period=5 μm, Smallest Feature = 0.4741 μm





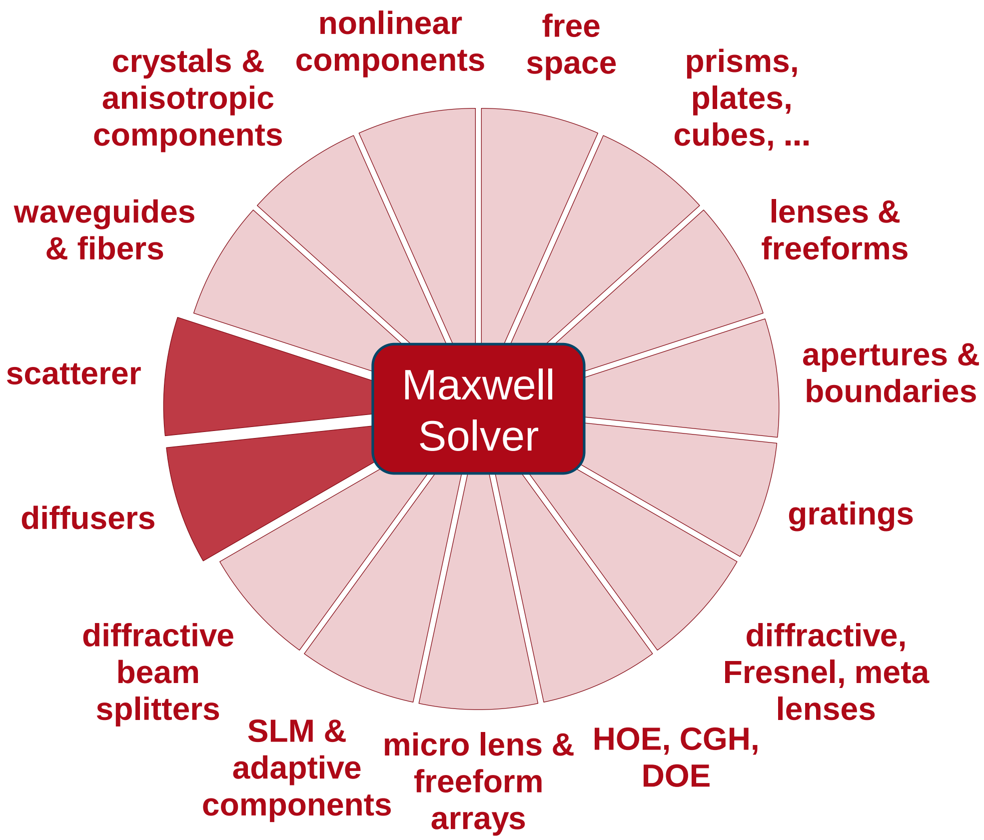
Diffractive Beam Splitter

- Gratings modeling technqiues: FMM and LPIA/TEA
- For high NA beam splitter split-step techniques.



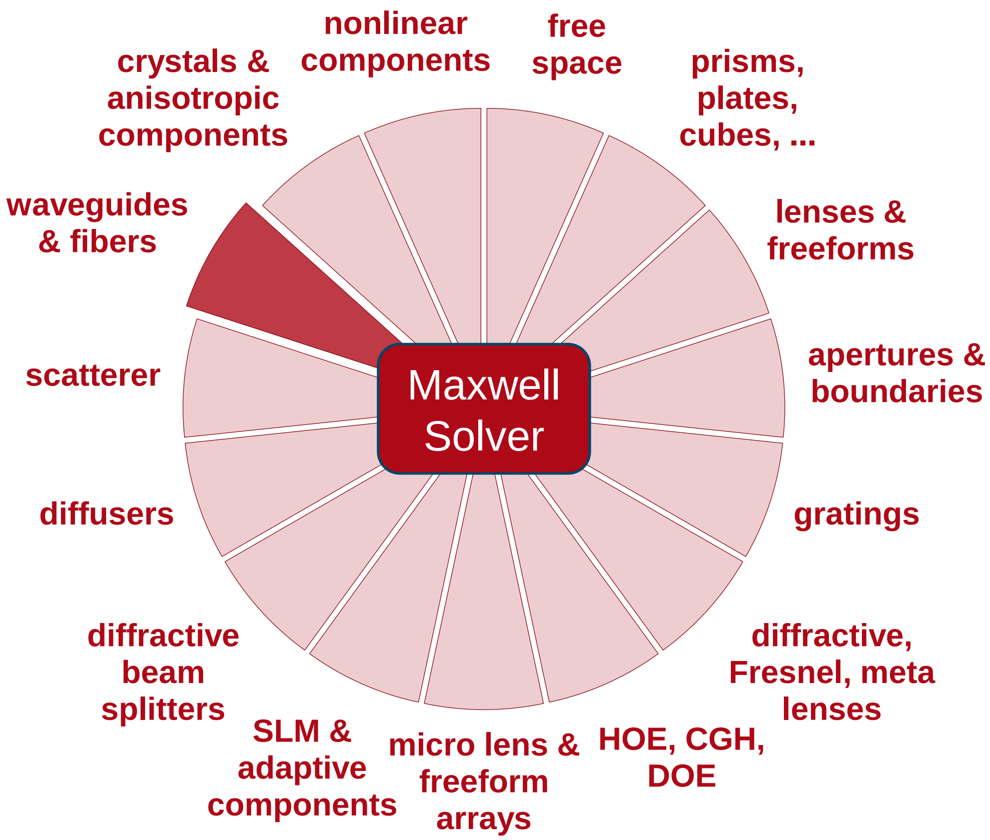
Diffuser and Scatterer

- If numerically feasible FMM
- Standard: LPIA/TEA
- For high NA scattering split-step techniques.
- Under development: Import and usage from BSDF data from measurement

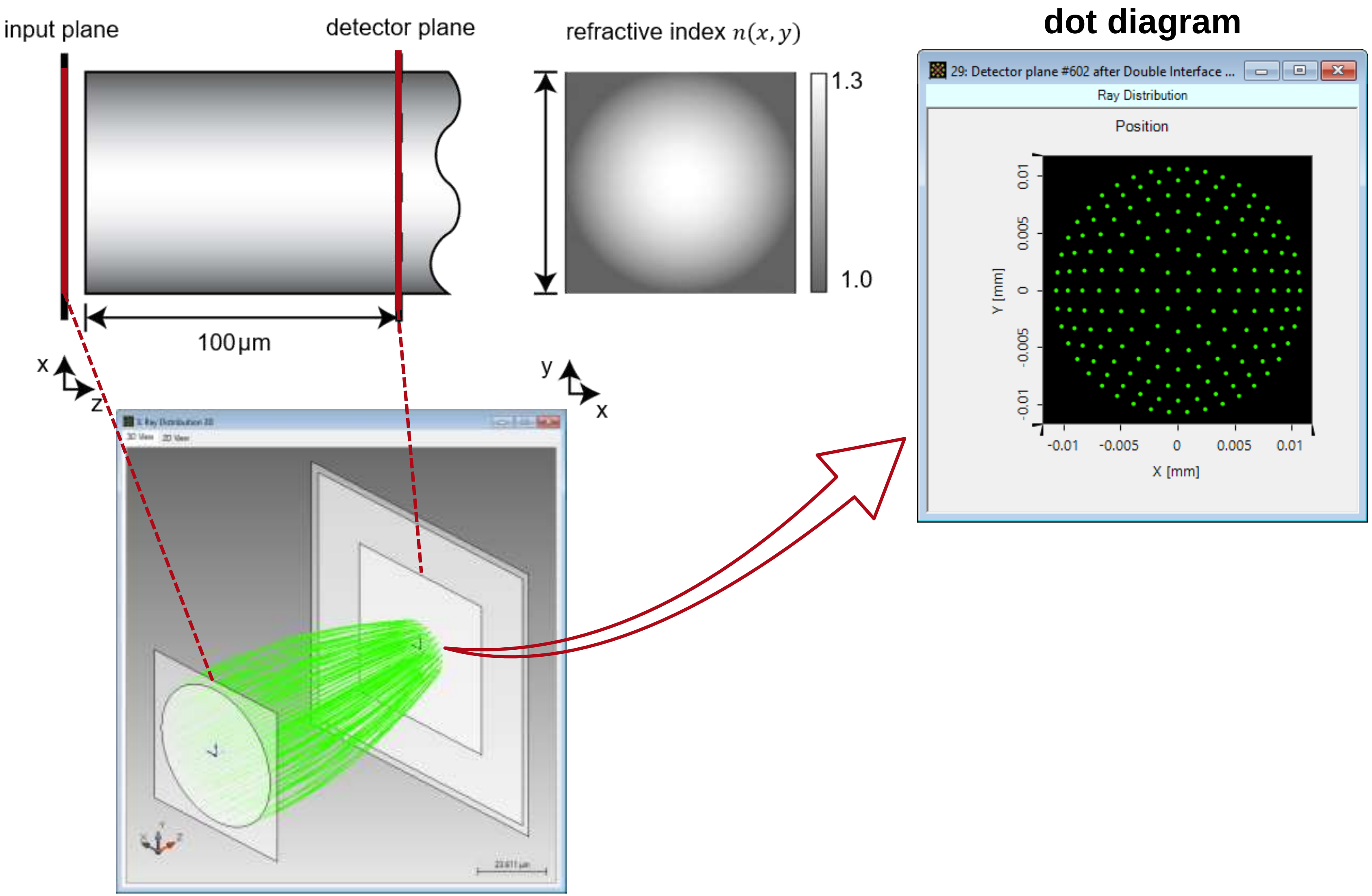


Waveguides and Fibers

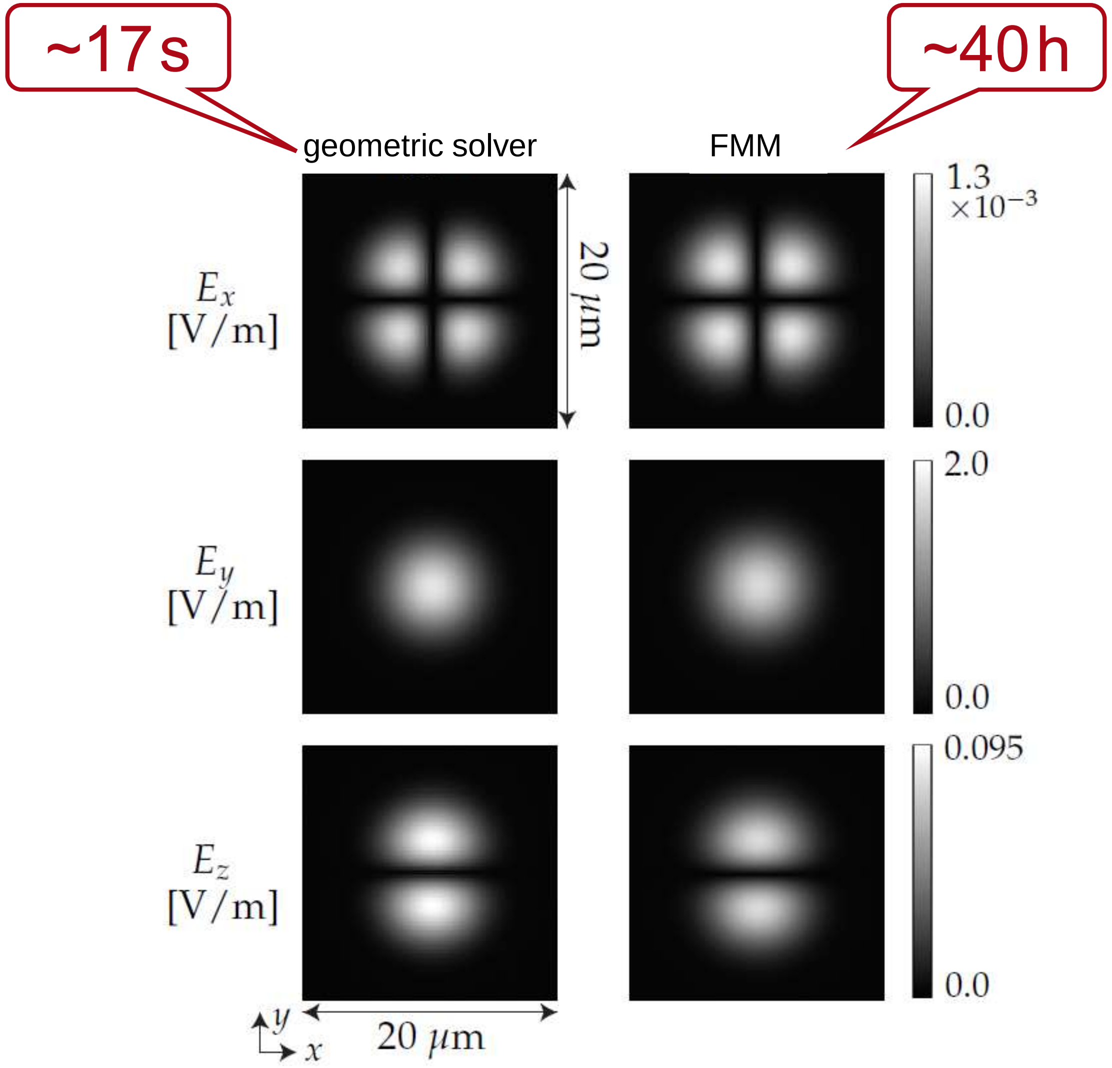
- Mode solver by FMM
- Runge-Kutta type solver
- Split-step techniques
- Under development: mode solver for rectangular and cylindrical waveguides
- Zigzag techniques for waveguide/lightplates: combination of free-space propagation and planar surfaces



GRIN Medium: 3D System Ray Tracing



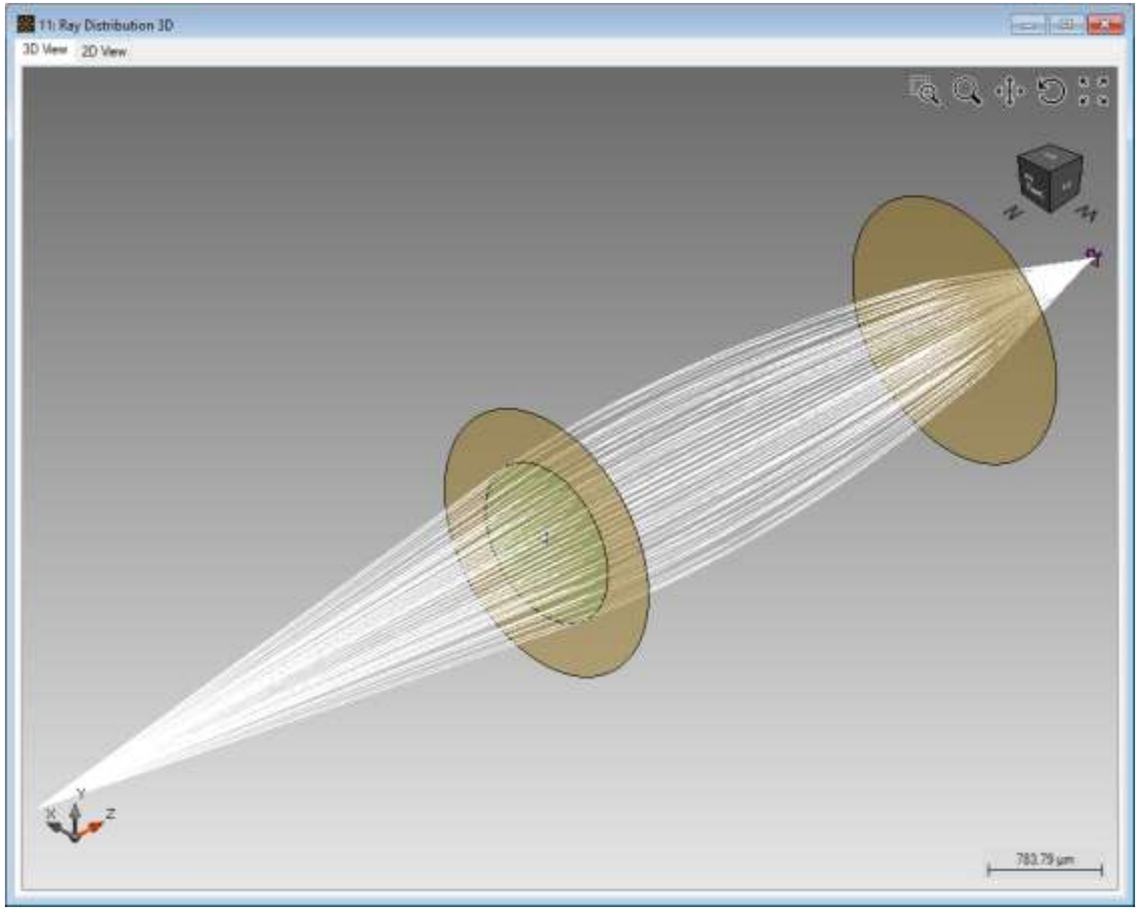
Rung-Kutta Solver vs FMM



Deviation between results of both approaches is ~1%

Construction and Modeling of a Graded-Index Lens

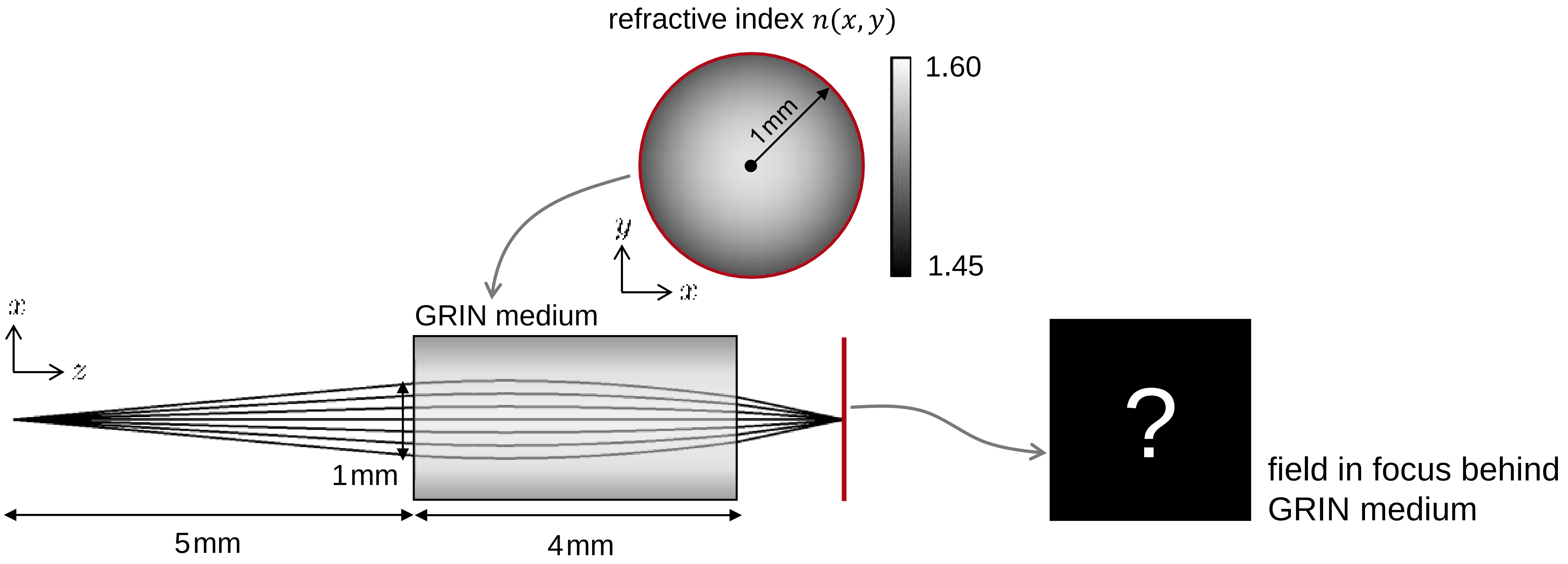
Abstract



VirtualLab allows the specification of a graded-index lens in a very user friendly way. In addition such index modulated lenses can be analyzed by ray tracing as well as field tracing. Within this use case we will show how easy it is to configure a graded-index lens in VirtualLab and show also simulation results for analysis by different propagation engines. For the illustration of this technology a simple setup is used, which includes a spherical wave, a graded-index lens component and a detector to show the electromagnetic field component in the focus and directly after the lens.

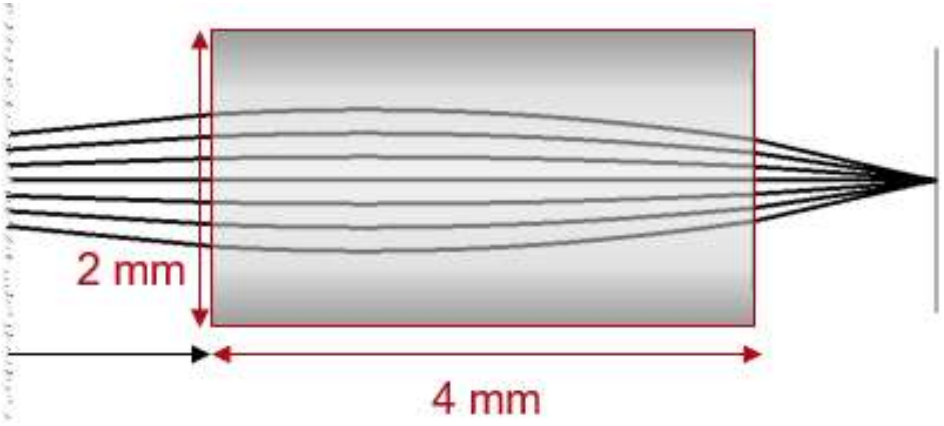
Modeling Task

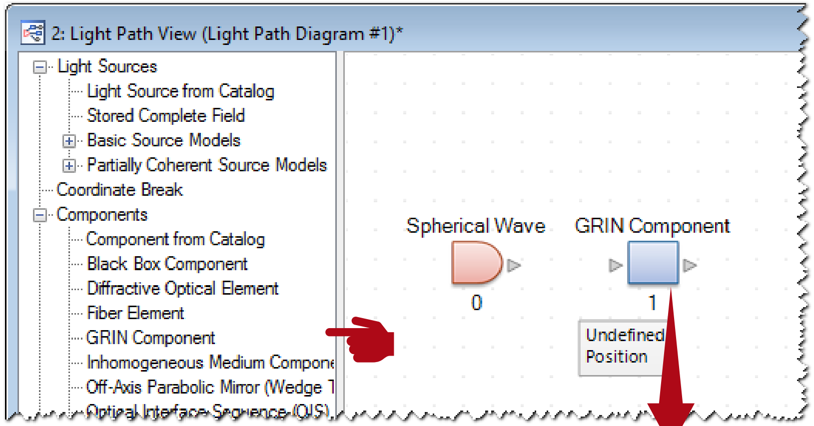
- how to construct a GRIN lens.
- how to perform both ray and field tracing analysis of it.

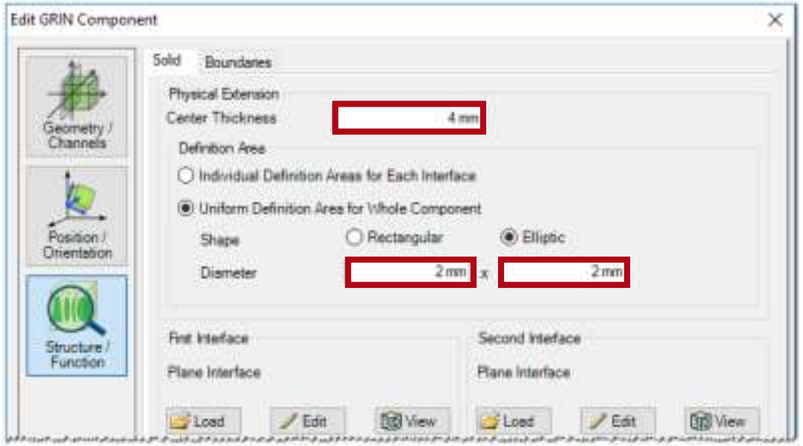


Construction of a GRIN Lens

- Specifications of the GRIN lens
  - Components ➔ *GRIN Component* is used to model the GRIN lens.







GRIN Lens: GRIN Medium

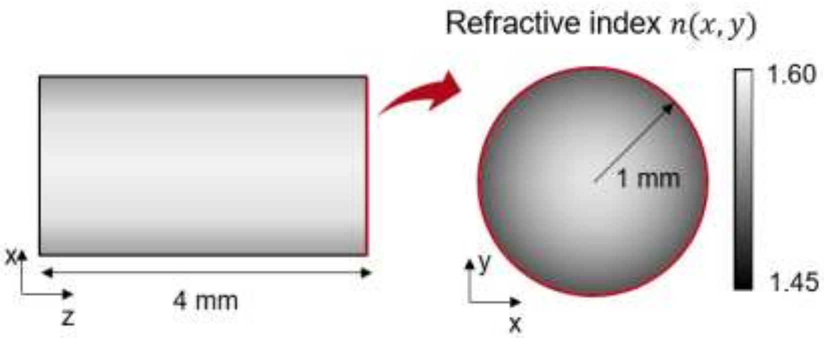
- Refractive index $n(x,y)$

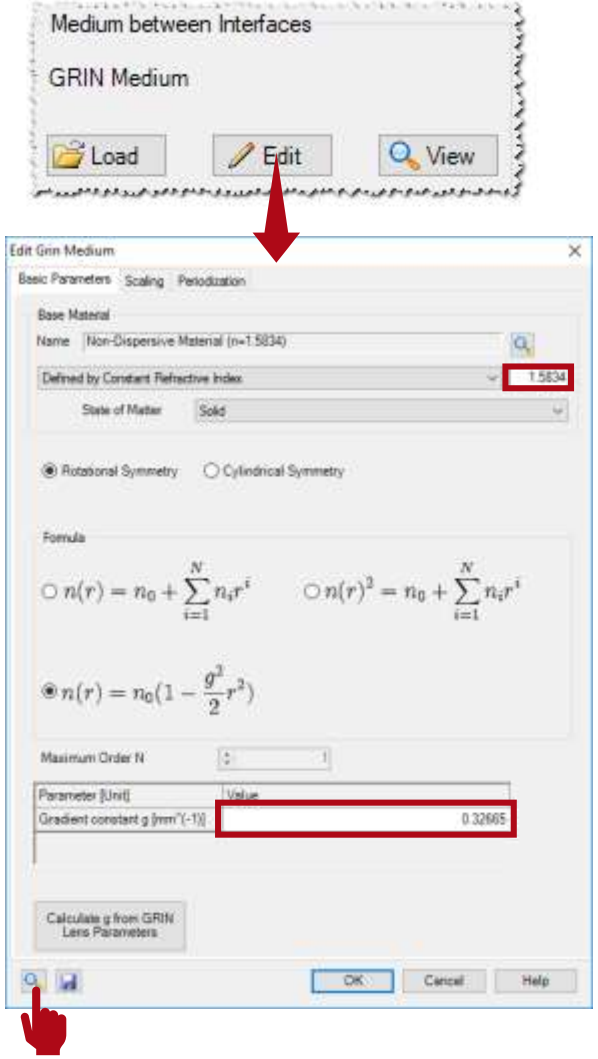
$$n(x,y) = n_0\left(1 - \frac{g^2}{2}\cdot r^2\right)$$

with $r = \sqrt{x^2 + y^2}$.

- In this case [1]:

$$n_0 = 1.5834$$
$$g = 0.32665\,\mathrm{mm}^{-1}$$





[1] Riedl, M.J., *Optical Design Fundamentals,* SPIE Press (2001)

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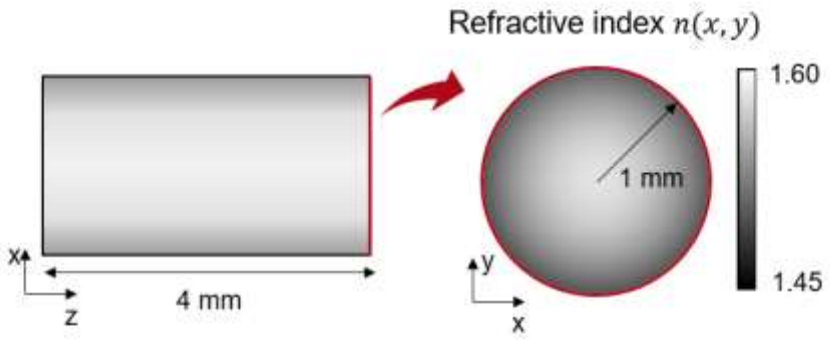
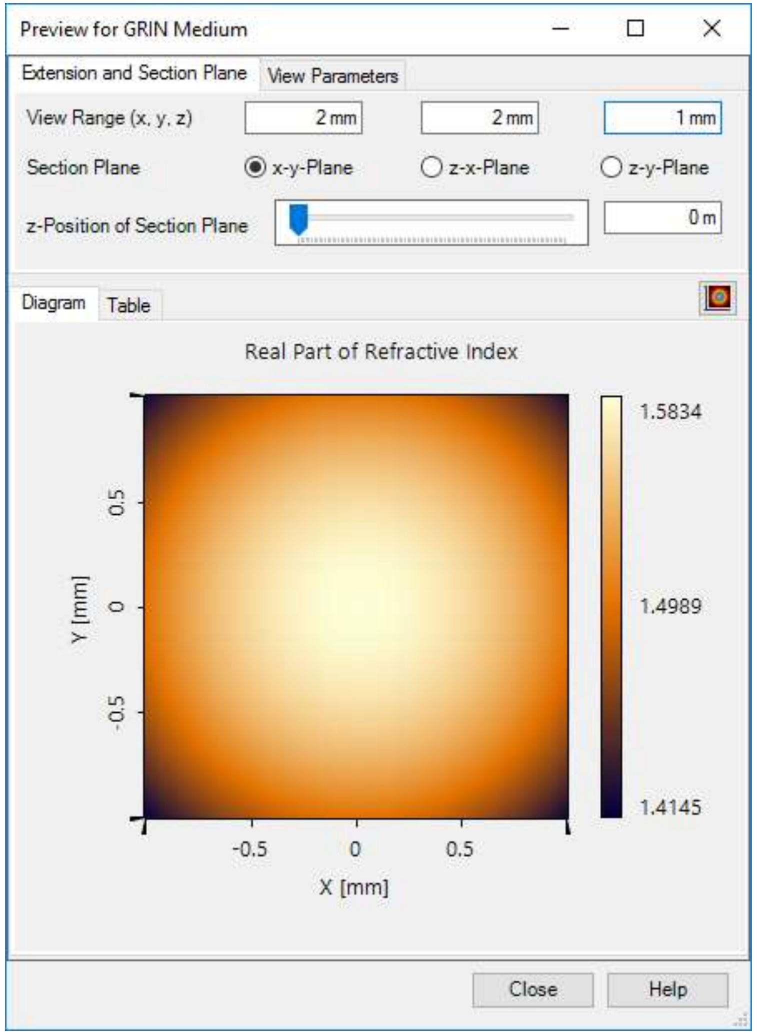
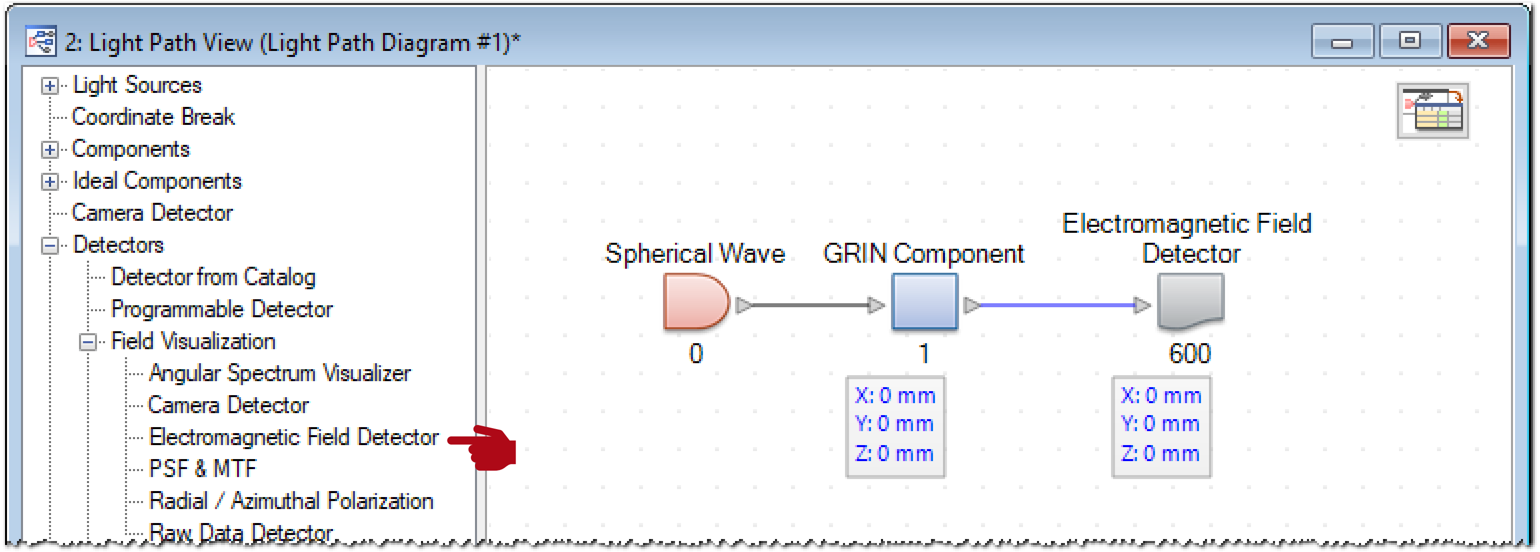




[1] Riedl, M.J., *Optical Design Fundamentals,* SPIE Press (2001)

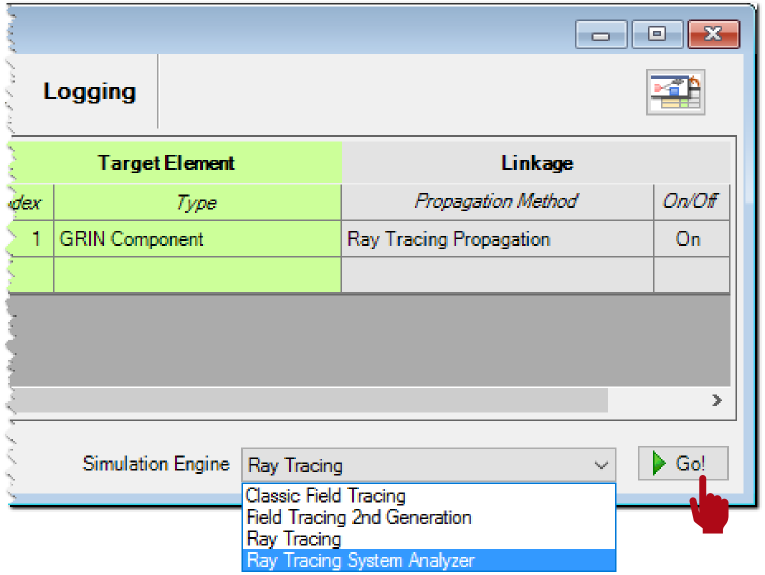
System Setup: Detector and Linkage

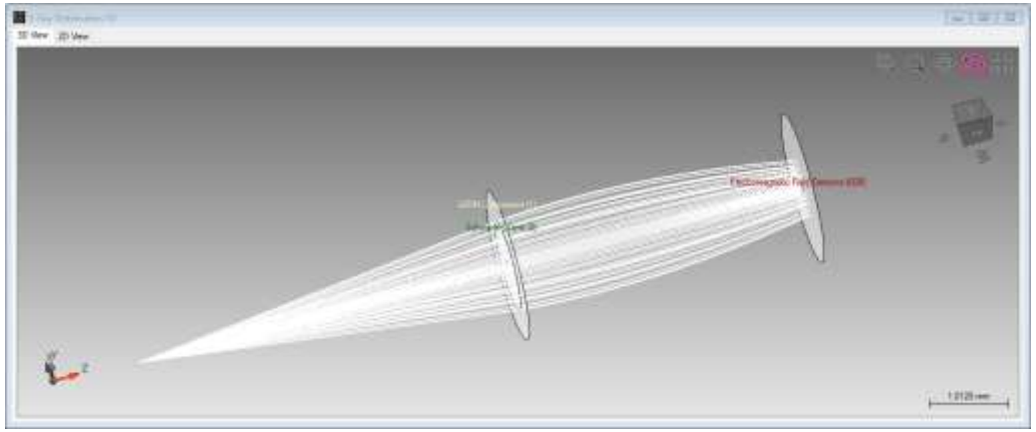
- Specifications of detector:
  - *Electromagnetic Field Detector* is used to detect the image.



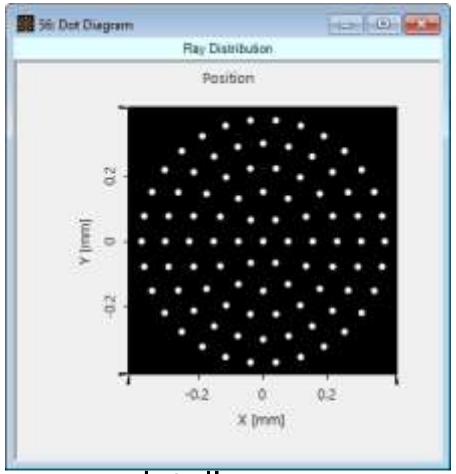
Simulation Results: Ray Tracing Analysis

- Simulation engine:
  - Choose *Ray Tracing System Analyzer*
  - Click Go!





ray tracing analysis of the imaging system

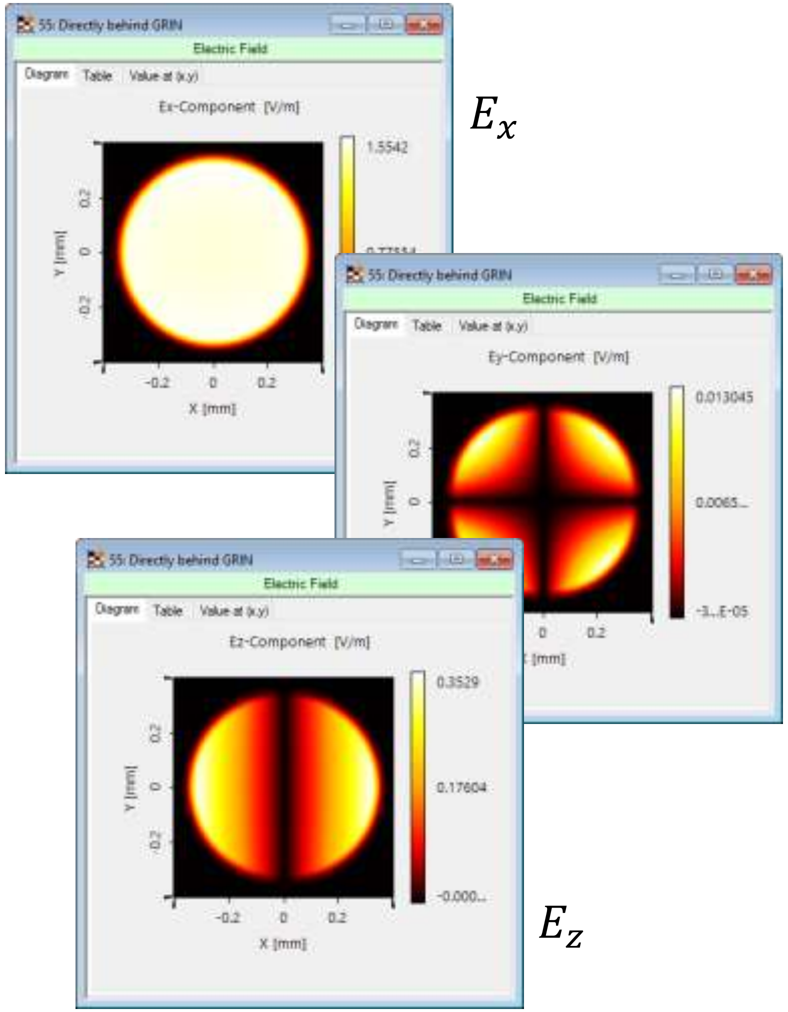


dot diagram

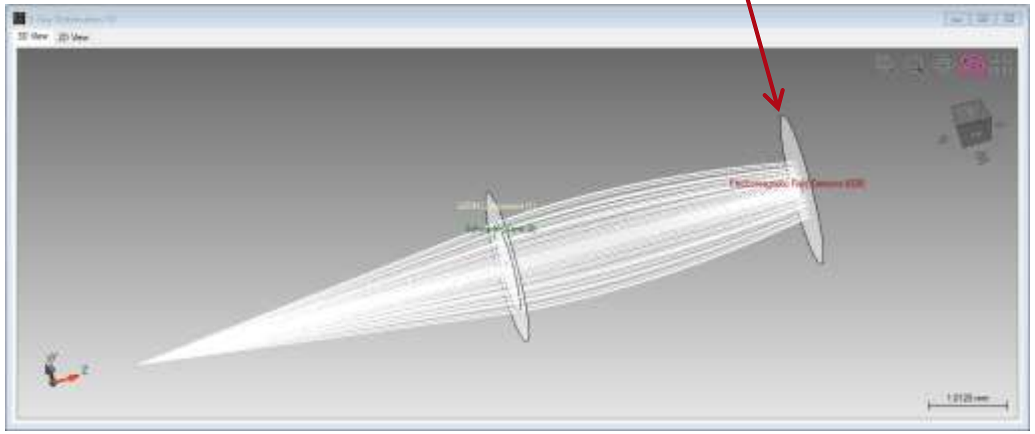
Simulation Results: Field Tracing Analysis

- Simulation engine:
  - Choose *Field Tracing 2nd Generation*.
  - Click Go!

amplitude of fields

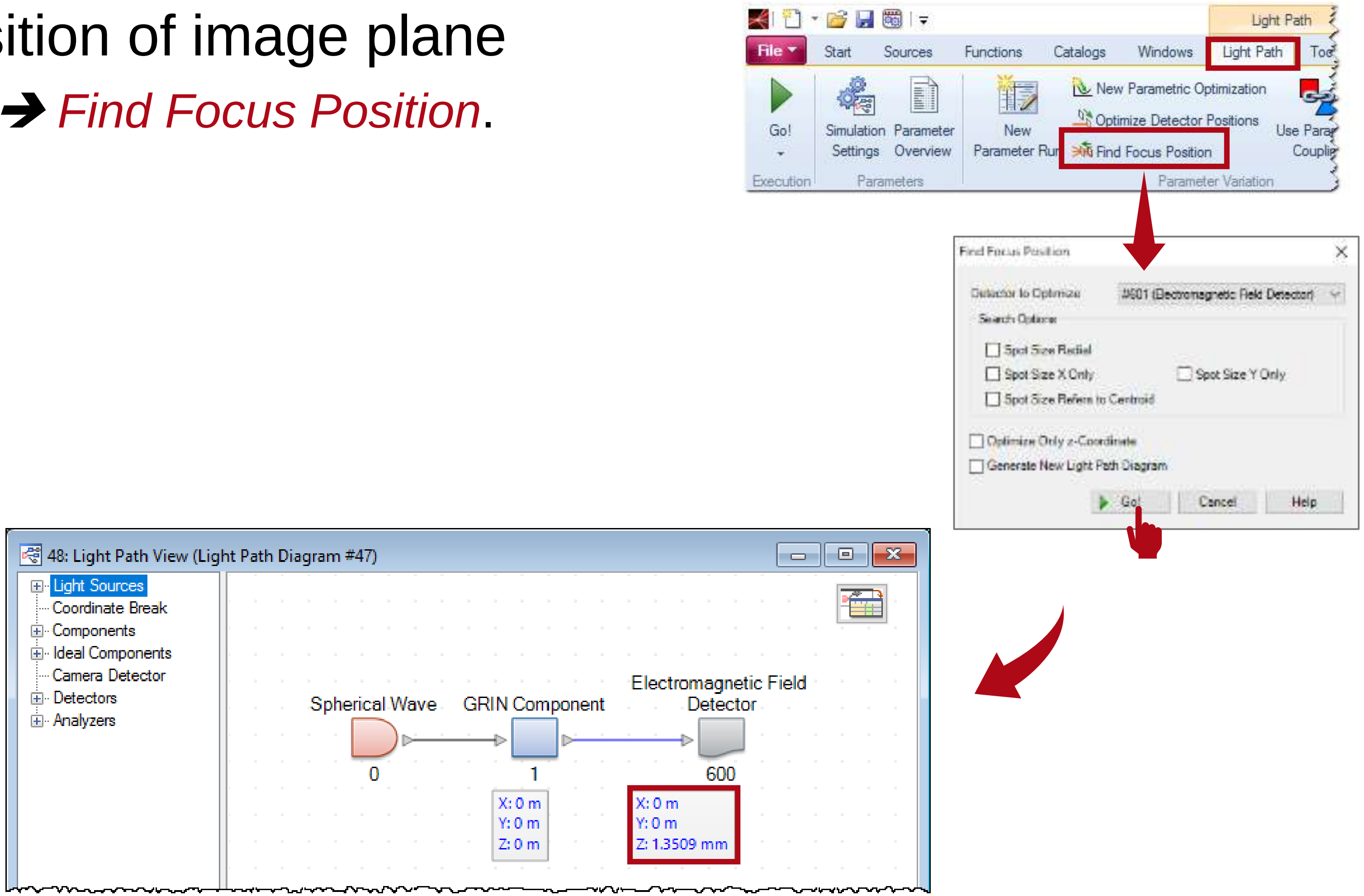


field distribution
on this plane



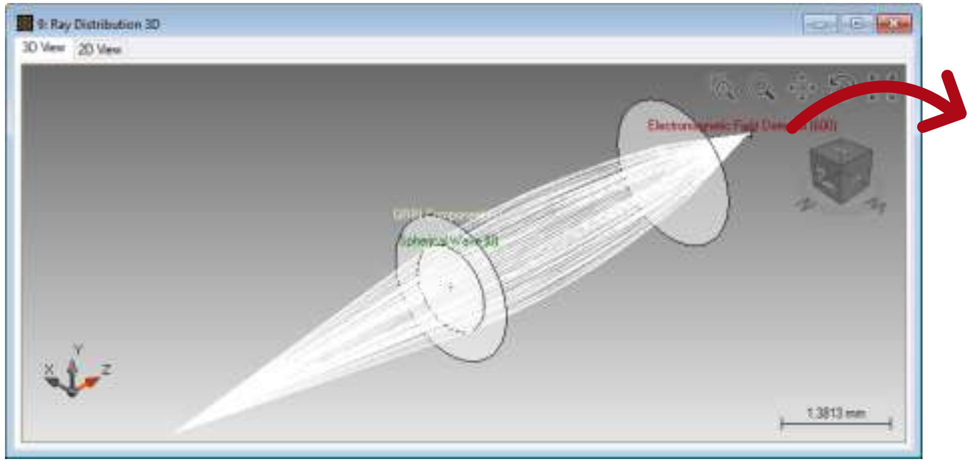
System Setup: Find the Image Plane

- Find the position of image plane
  - *Light Path* ➔ *Find Focus Position*.

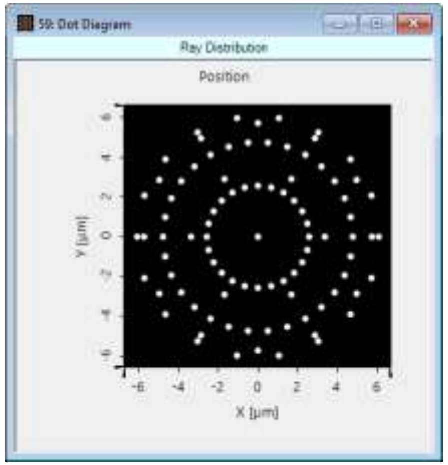


Simulation Results: Ray and Field Tracing

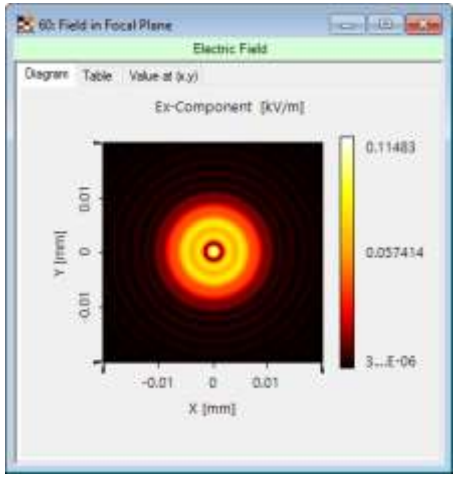
ray tracing analysis of the imaging system



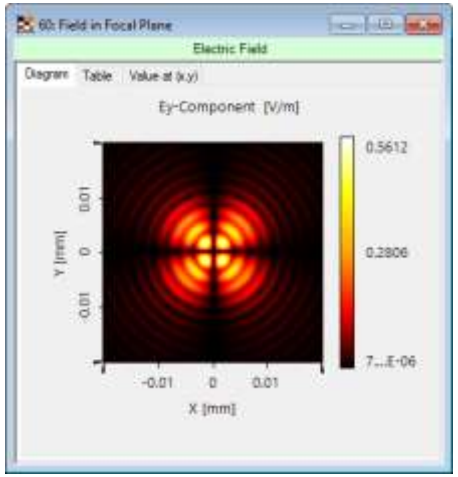
dot diagram



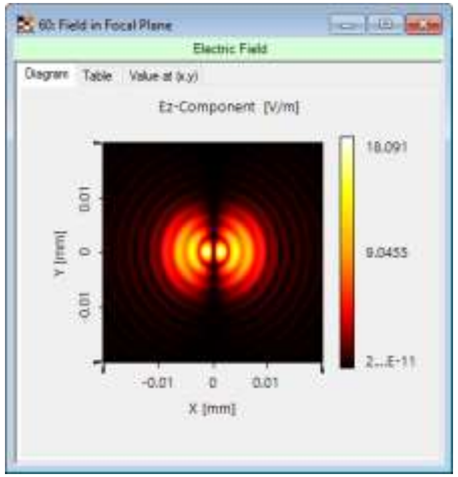
field tracing results in focal plane



E_x

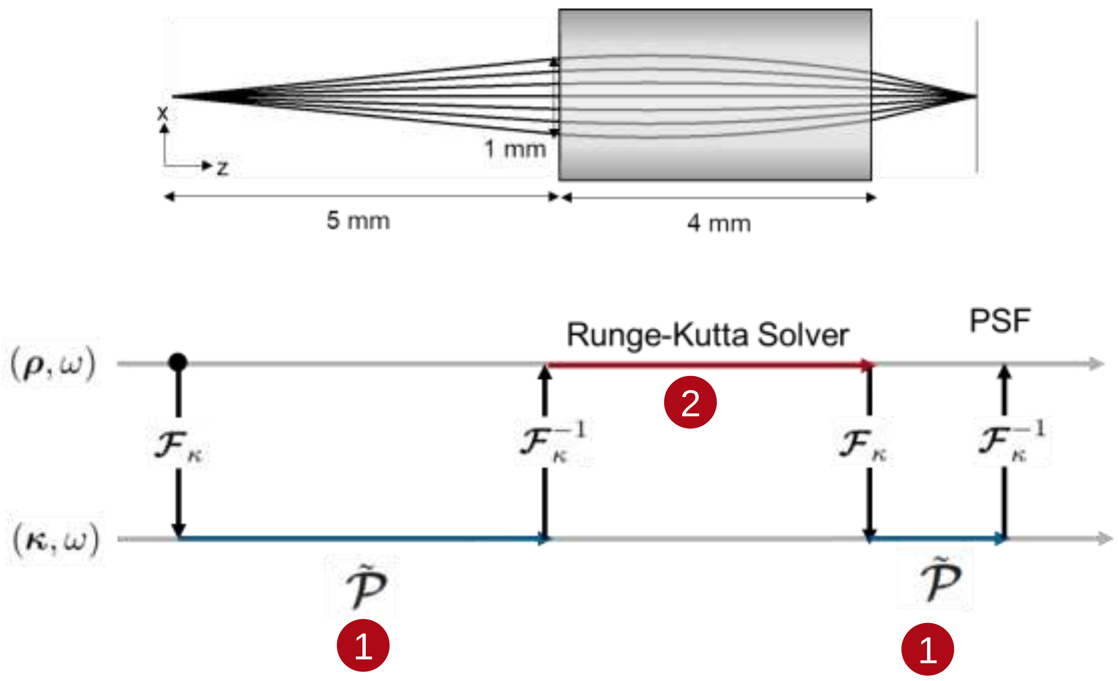


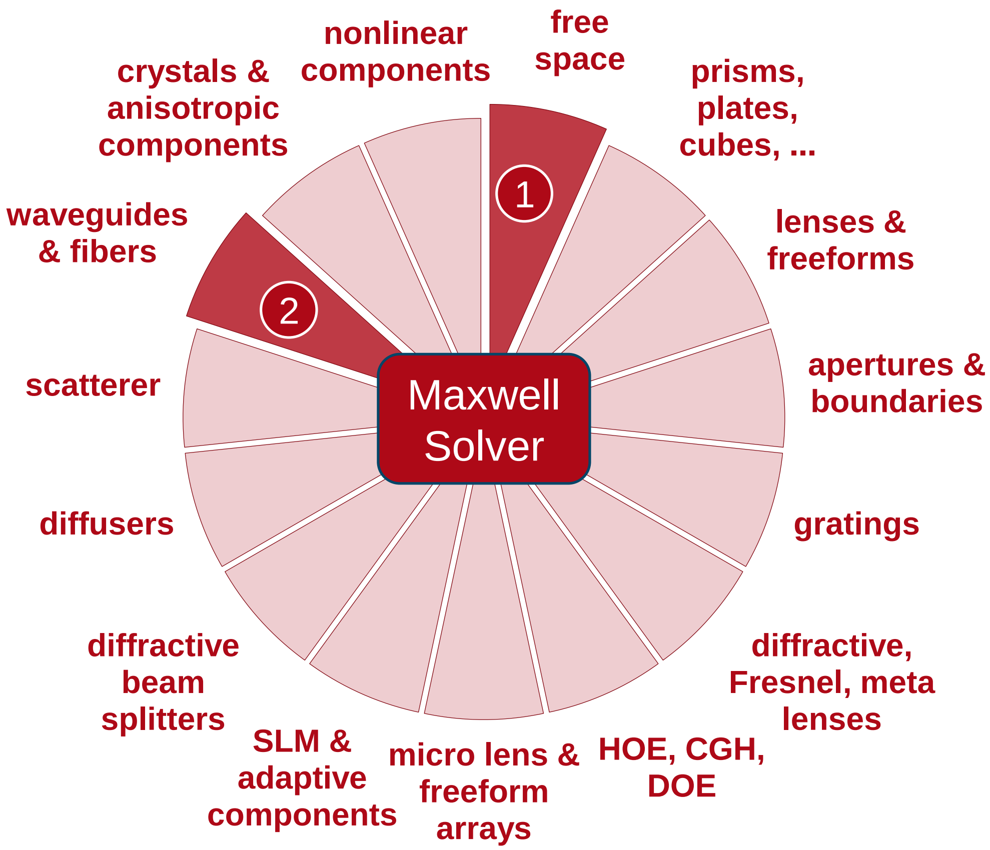
E_y



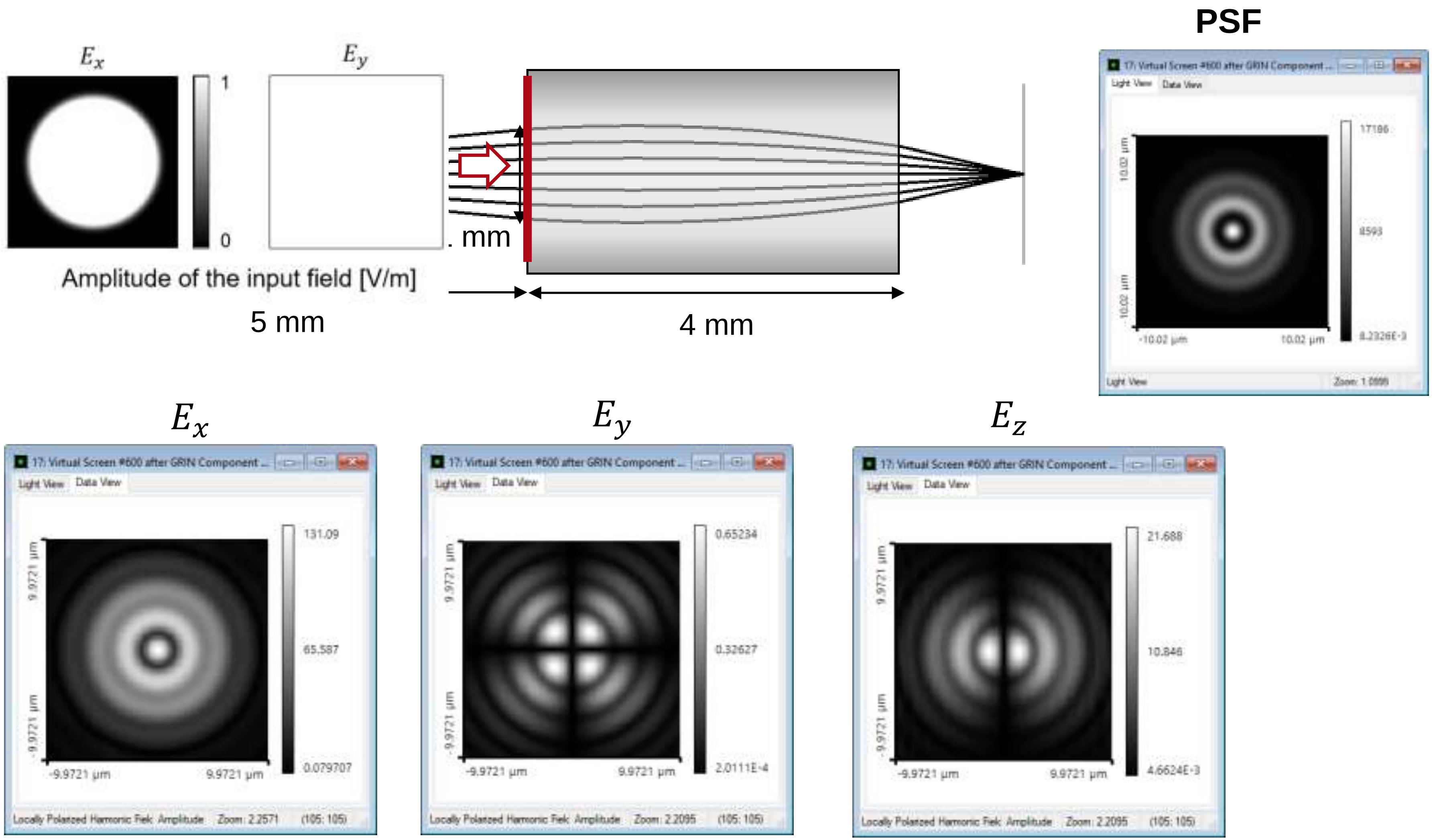
E_z

Waveguides and Fibers





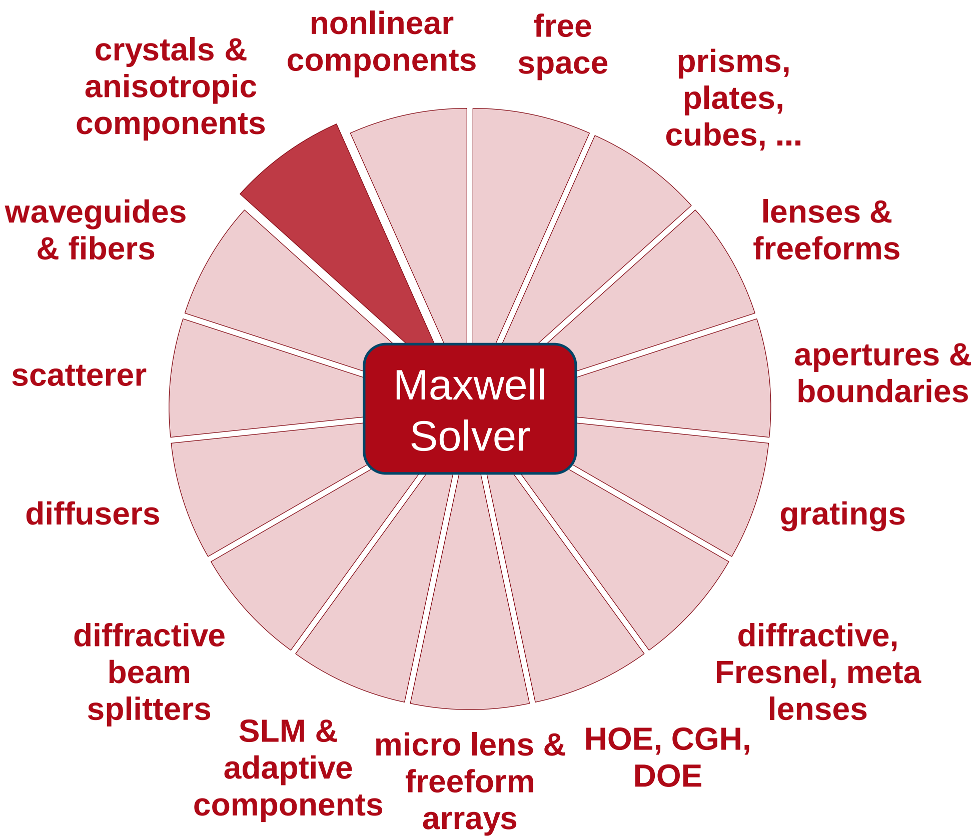
Example: PSF of GRIN Lens



Amplitude of the image [V/m]

Crystals & Anisotropic Components

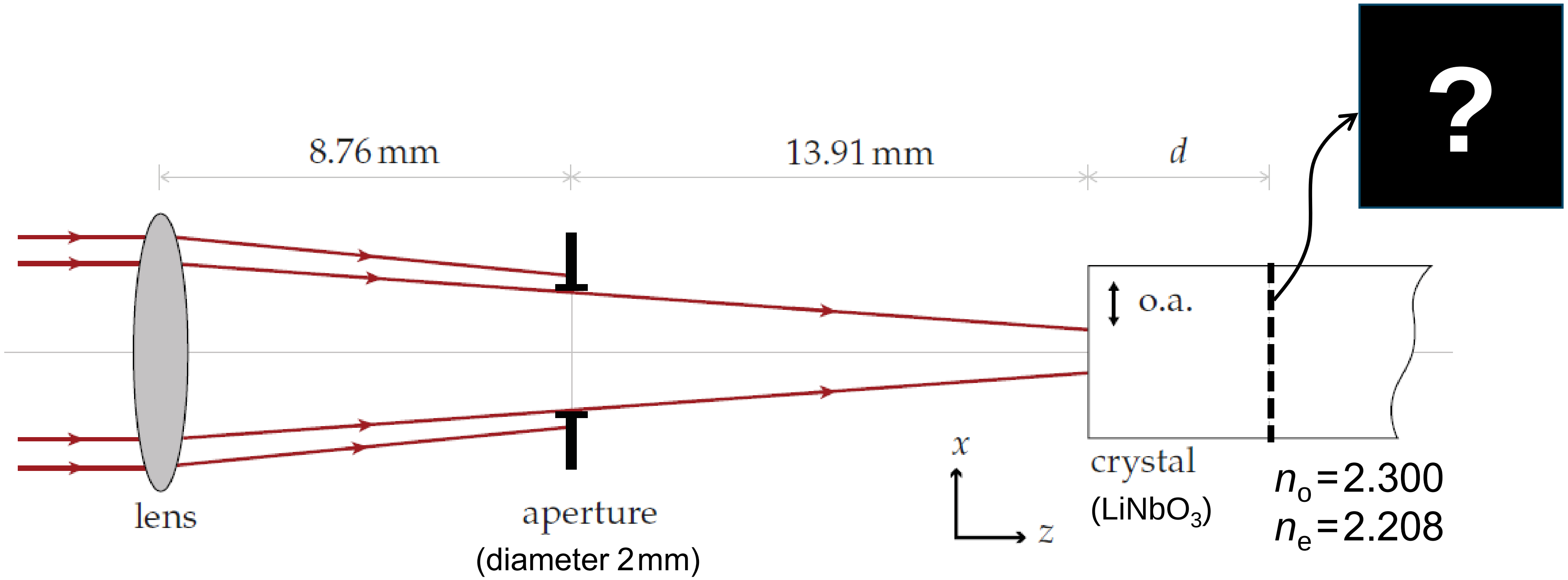
- Fully rigorous solver for general crystals with planar surfaces
- Solver for anisotropic layers
- Under development:
  - Anisotropic media adn curved surfaces
  - Inhomogeneous (GRN) anisotroic media



Example: Focusing into Uniaxial Crystal

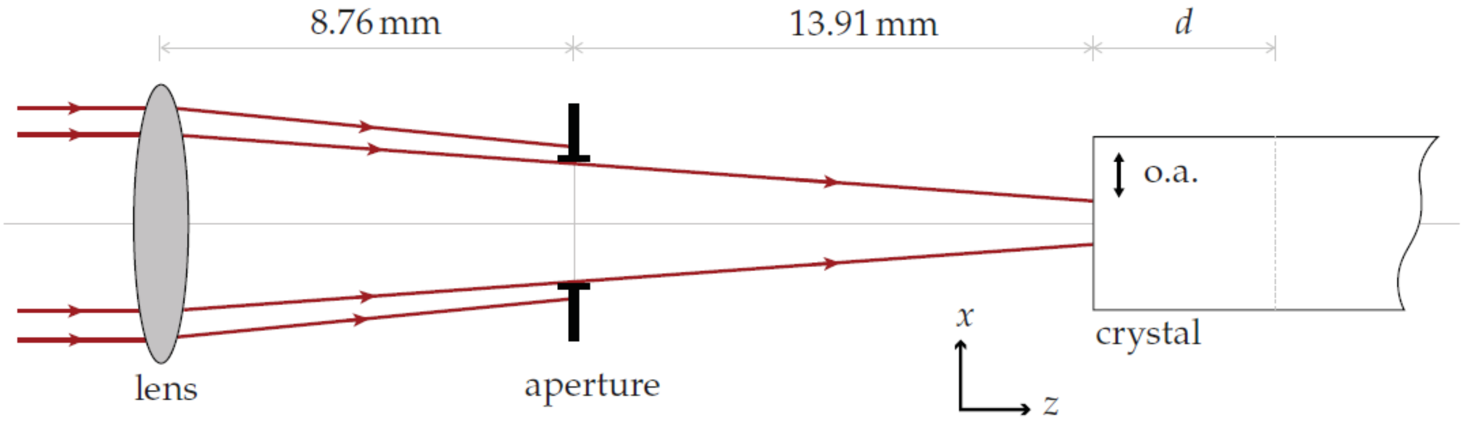
observe focused field distributions inside $LiNbO_3$ crystal, at different depths

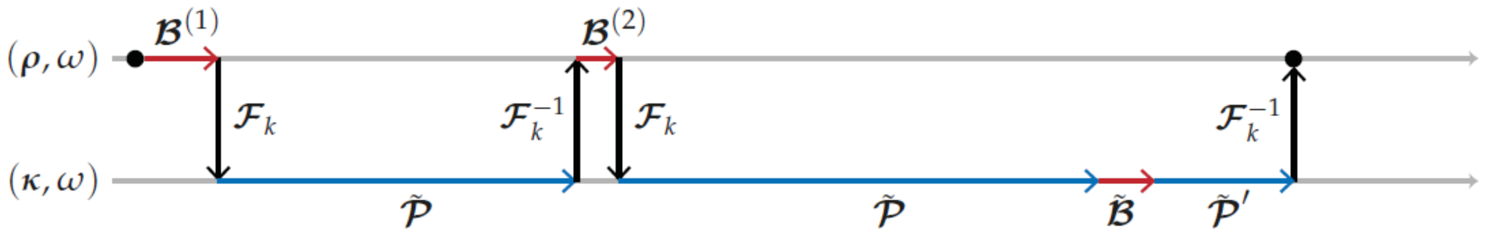
input field
- plane wave
- wavelength 633 nm
- diameter 4 mm
- linearly polarized along *x* direction



Reference: [Jain 2009] Jain *et al*., J. Opt. Soc. Am. A **26**, 691-698 (2009)

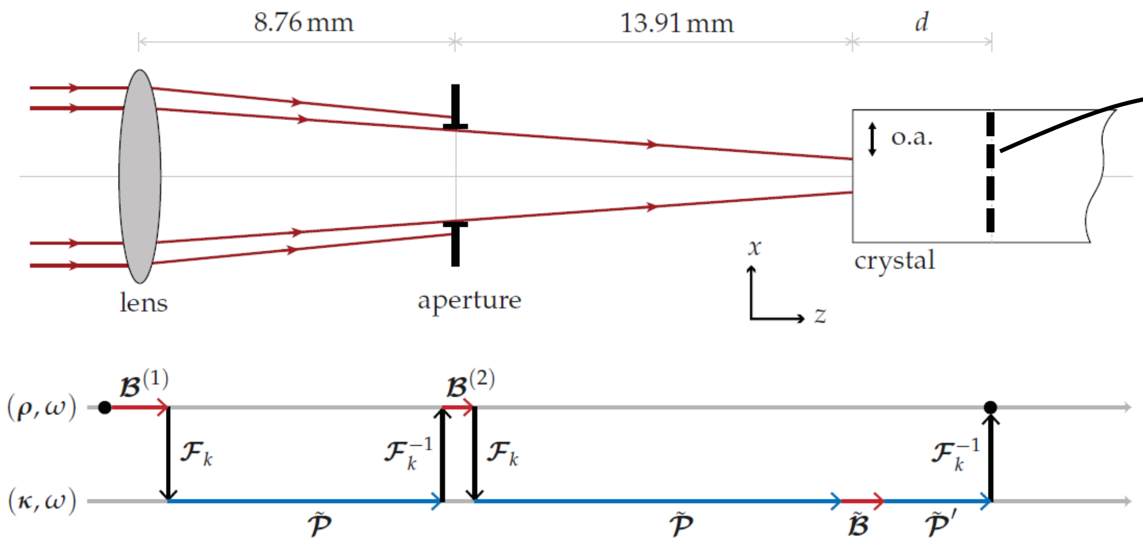
Example: Focusing into Uniaxial Crystal



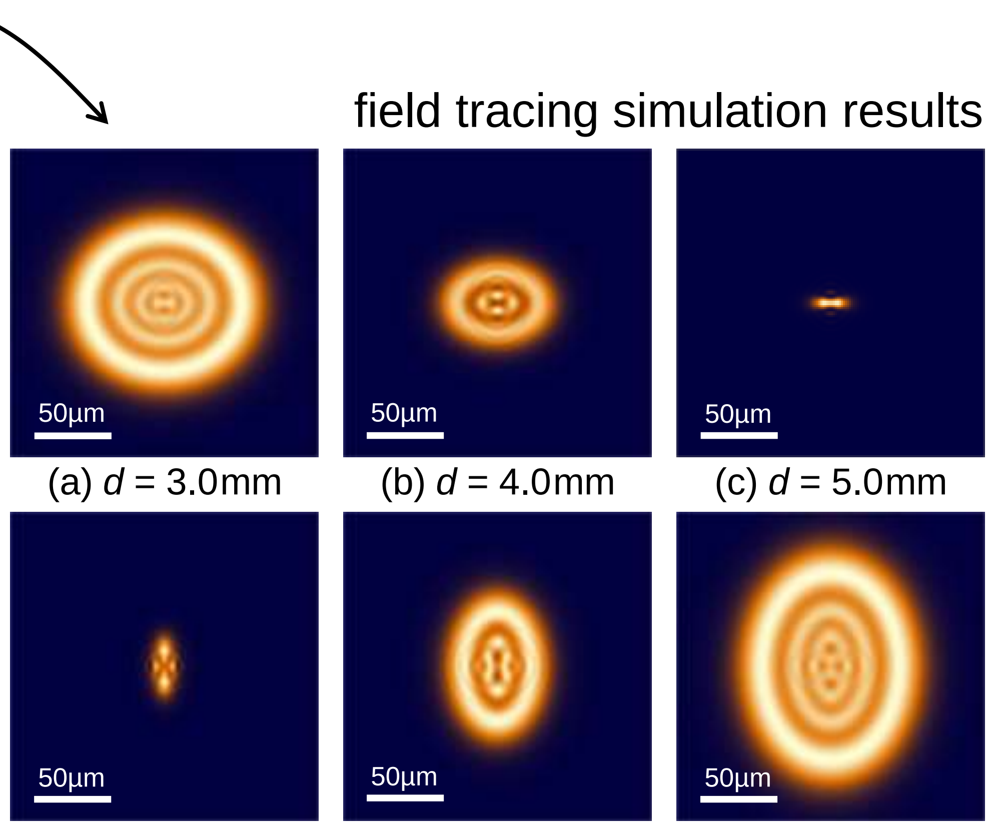


Operator	Description
$\mathcal{B}^{(1)}$	idealized lens model
$\mathcal{B}^{(2)}$	idealized aperture model
$\tilde{\mathcal{P}}$ / $\tilde{\mathcal{P}}'$	free-space propagation (isotropic / anisotropic)
$\tilde{\mathcal{B}}$	planar surface operator

Example: Focusing into Uniaxial Crystal



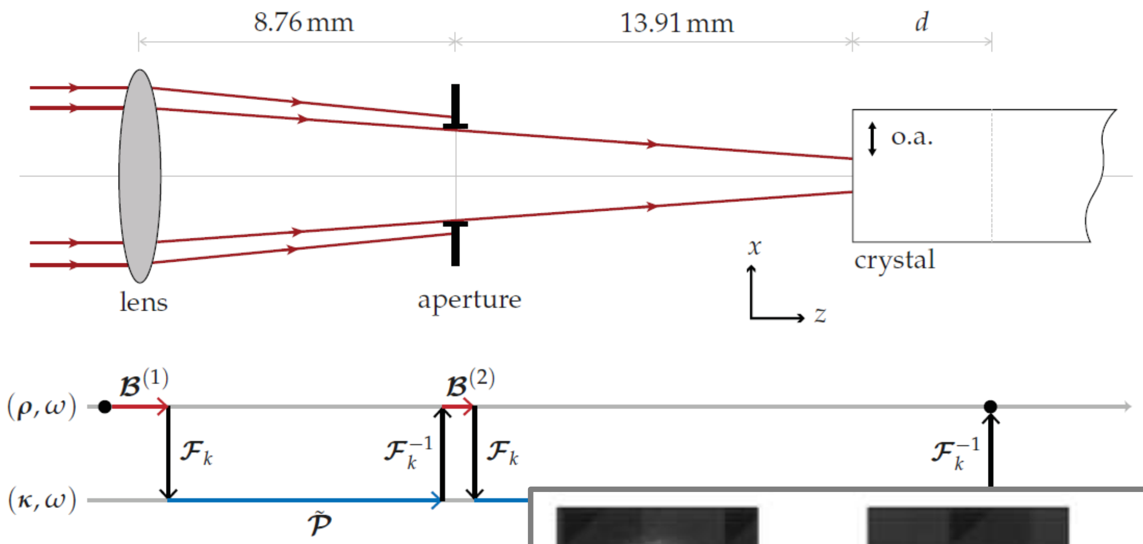
field tracing simulation results



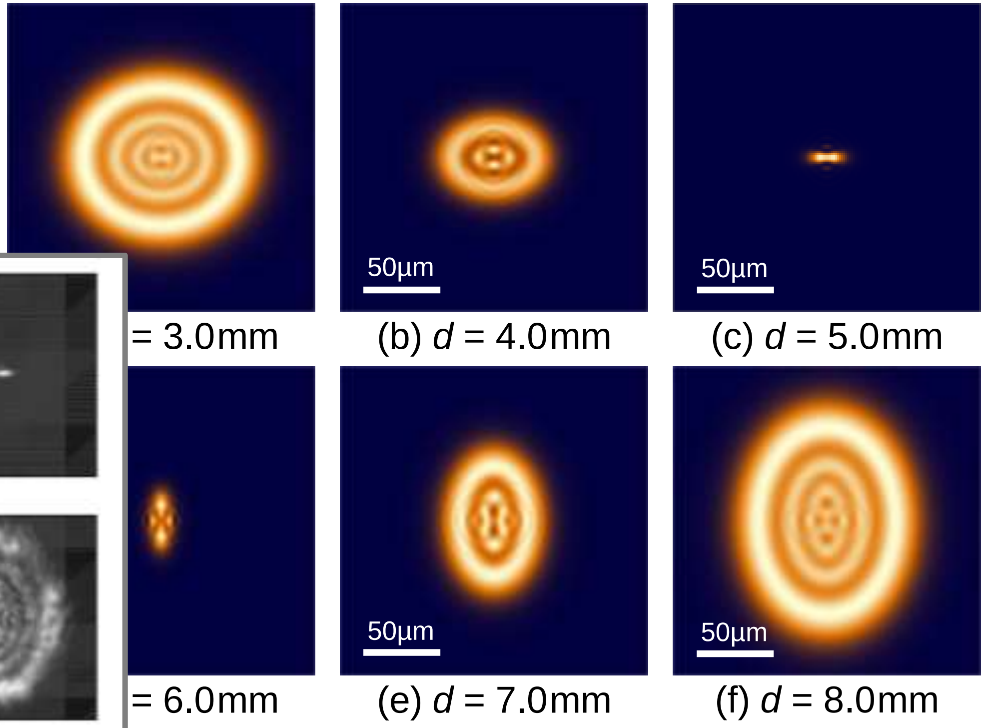
(a) d = 3.0mm (b) d = 4.0mm (c) d = 5.0mm

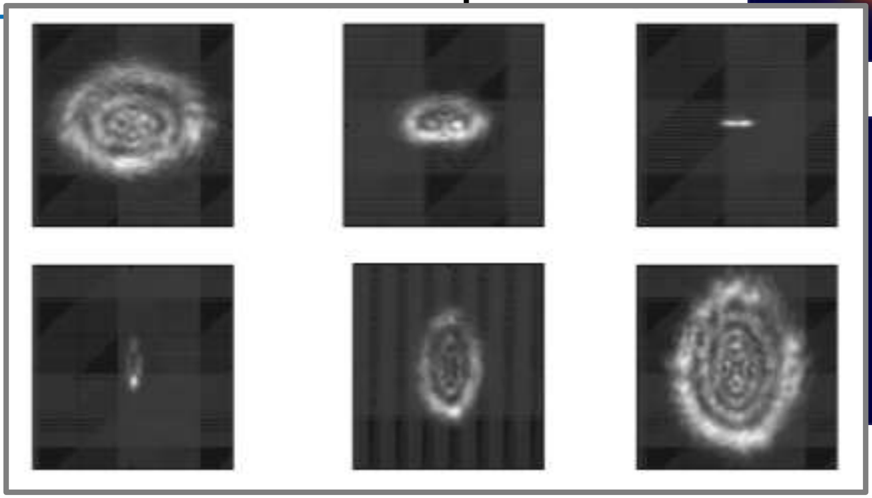
(d) d = 6.0mm (e) d = 7.0mm (f) d = 8.0mm

Example: Focusing into Uniaxial Crystal



field tracing simulation results



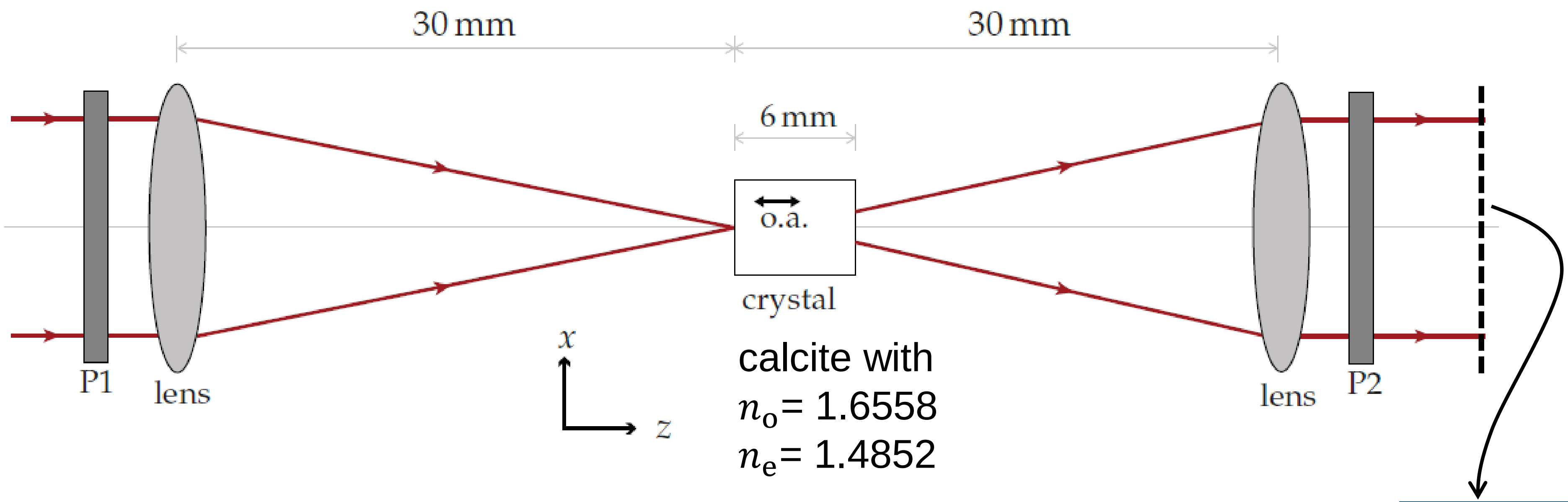


experimental measurement from [Jain 2009]

Example: Polarization Conversion

input field

- fundamental Gaussian field
- wavelength 633 nm
- diameter 3 mm
- linearly polarized along *x* direction



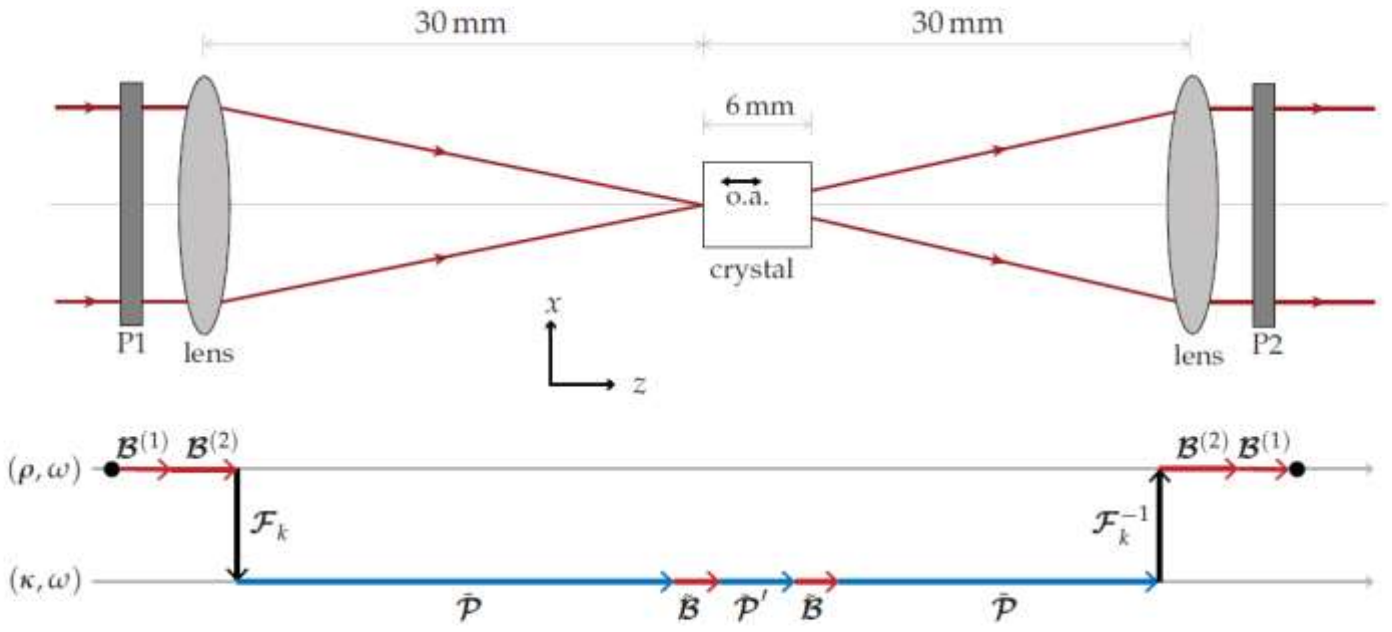
calcite with
n_o= 1.6558
n_e= 1.4852

Reference: [Izdebskaya 2009] Izdebskaya *et al.*, Opt. Express **17**, 18196-18208 (2009)

calculate field behind polarizer P2, when it is either parallel or orthogonal to P1

?

Example: Polarization Conversion



Operator	Description
$\mathcal{B}^{(1)}$	Jones matrix model
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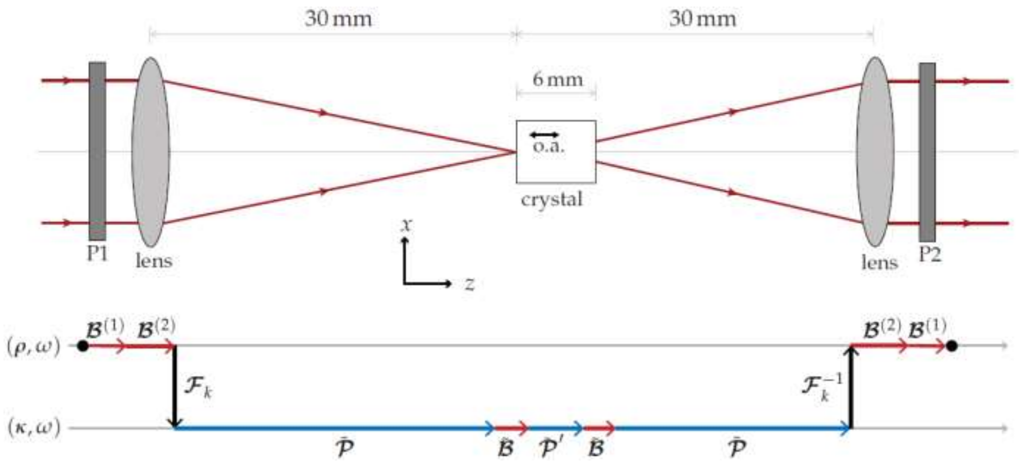
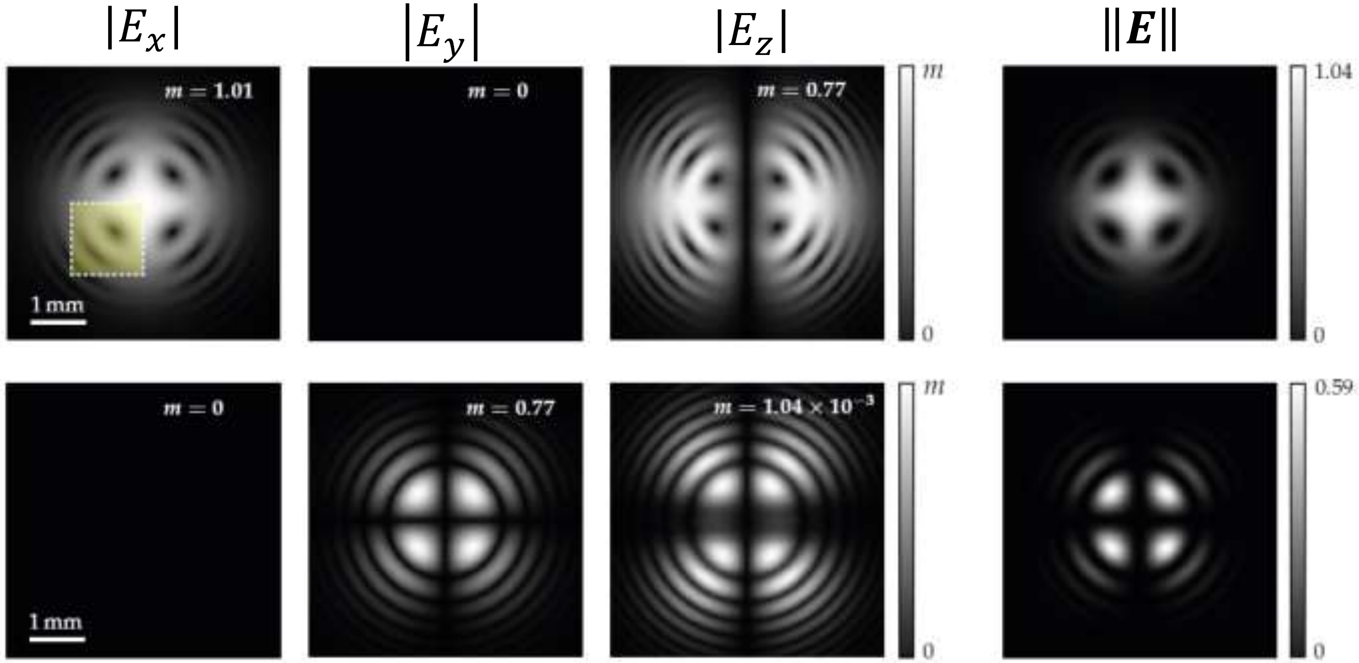
Example: Polarization Conversion

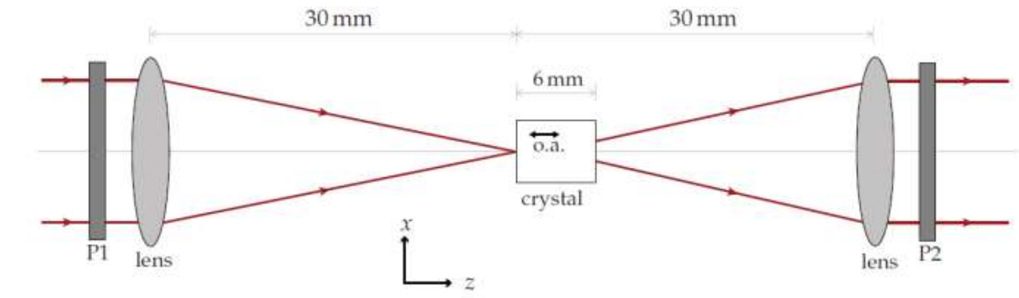


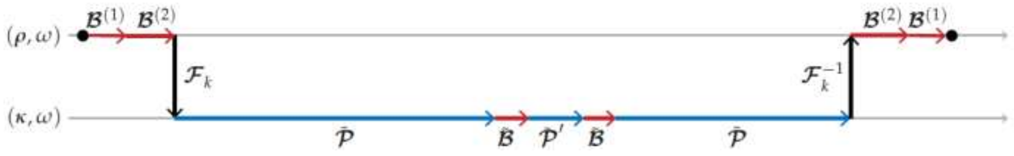


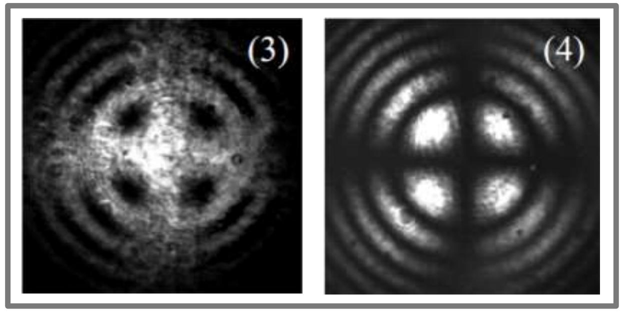
P2 parallel to P1

P2 orthogonal to P1

Example: Polarization Conversion

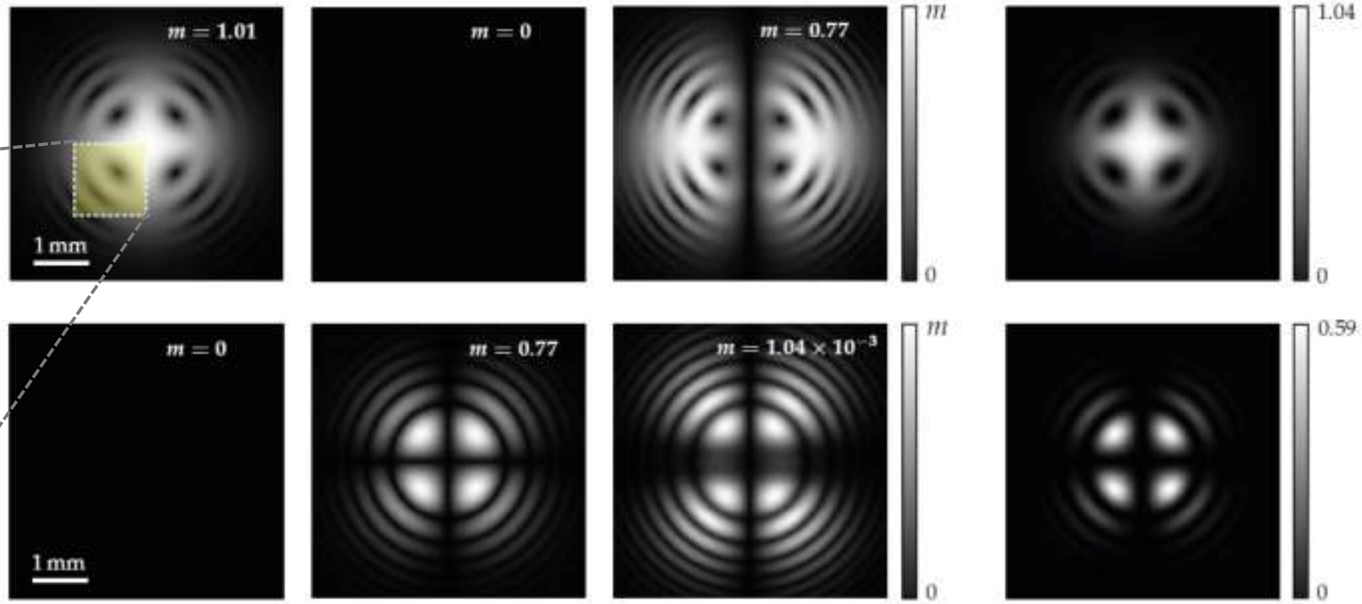


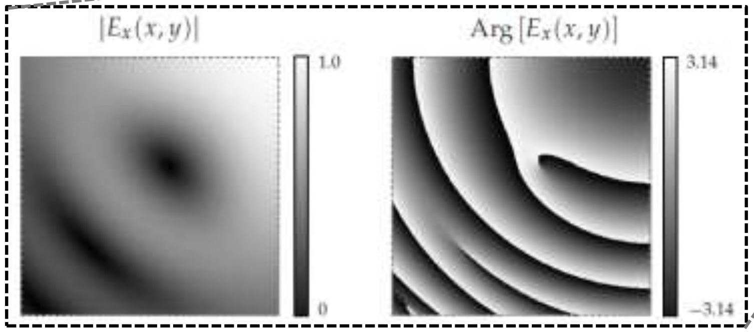




experimental measurement from [Izdebskaya 2009]

field tracing simulation results





Example – Stress Birefringence

- Laser-based soldering
  - Contact free heating, versatile to use
  - Localized and minimized input of energy
  - Flux-free processing, no contamination

P. Ribes-Pleguezuelo *et al*., Opt. Express **25**, 5927-5940 (2017)

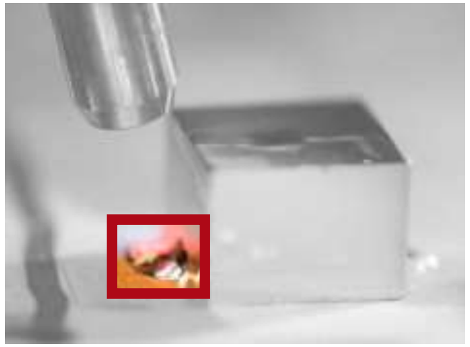


Photo from Fraunhofer IOF

- ANSYS
  - Structural/material definition
  - Transient thermal analysis
  - Stress simulation inside crystal component
- VirtualLab
  - Convert stress into optical permittivity data
  - Simulation of field propagation through birefringent materials

From Stress to Birefringence

- Convert stress to optical permittivity
  (for each layer inside stratified medium)

Stress tensor

$$\begin{pmatrix} \sigma_1 & \sigma_6 & \sigma_5 \\ \sigma_6 & \sigma_2 & \sigma_4 \\ \sigma_5 & \sigma_4 & \sigma_3 \end{pmatrix} \xrightarrow{\quad ? \quad} \begin{pmatrix} \epsilon_1 & \epsilon_6 & \epsilon_5 \\ \epsilon_6 & \epsilon_2 & \epsilon_4 \\ \epsilon_5 & \epsilon_4 & \epsilon_3 \end{pmatrix}$$

Permittivity tensor

From Stress to Birefringence

- Convert stress to optical permittivity
  (for each layer inside stratified medium)

Stress tensor

$$\begin{pmatrix} \sigma_1 & \sigma_6 & \sigma_5 \\ \sigma_6 & \sigma_2 & \sigma_4 \\ \sigma_5 & \sigma_4 & \sigma_3 \end{pmatrix}$$

Piezo-optic constant

$$\Delta B_m = \pi_{mn} \sigma_n$$

Changes in impermeability tensor

$$\begin{pmatrix} \Delta B_1 & \Delta B_6 & \Delta B_5 \\ \Delta B_6 & \Delta B_2 & \Delta B_4 \\ \Delta B_5 & \Delta B_4 & \Delta B_3 \end{pmatrix}$$

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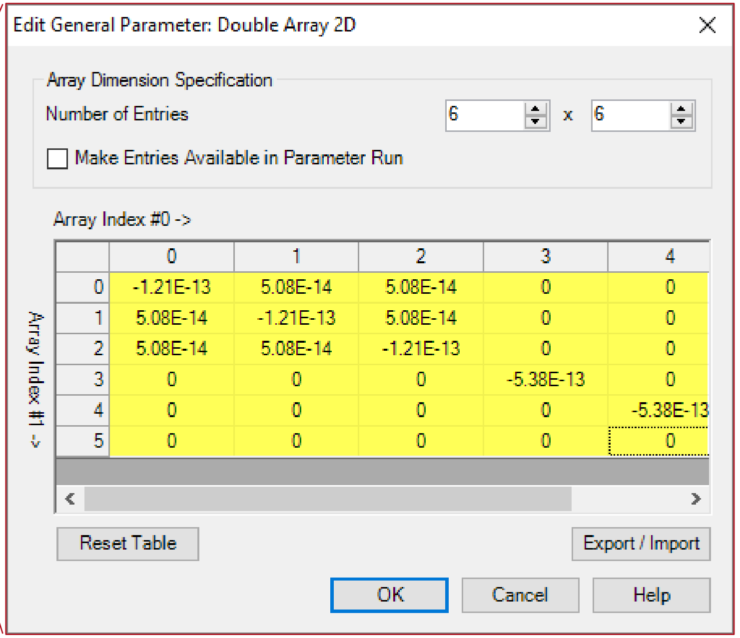


	0	1	2	3	4
0	-1.21E-13	5.08E-14	5.08E-14	0	0
1	5.08E-14	-1.21E-13	5.08E-14	0	0
2	5.08E-14	5.08E-14	-1.21E-13	0	0
3	0	0	0	-5.38E-13	0
4	0	0	0	0	-5.38E-13
5	0	0	0	0	0

Example: piezo-optic constant tensor for YAG crystal

From Stress to Birefringence

- Convert stress to optical permittivity
  (for each layer inside stratified medium)

Stress tensor

$$\begin{pmatrix} \sigma_1 & \sigma_6 & \sigma_5 \\ \sigma_6 & \sigma_2 & \sigma_4 \\ \sigma_5 & \sigma_4 & \sigma_3 \end{pmatrix}$$

$$\Delta B_m = \pi_{mn}\sigma_n$$

Changes in impermeability tensor

$$\begin{pmatrix} \Delta B_1 & \Delta B_6 & \Delta B_5 \\ \Delta B_6 & \Delta B_2 & \Delta B_4 \\ \Delta B_5 & \Delta B_4 & \Delta B_3 \end{pmatrix}$$

$$B_m = \boxed{B_{0,m}} + \Delta B_m$$

Stress-free values
(related to refractive index/indicies)

Impermeability tensor

$$\begin{pmatrix} B_1 & B_6 & B_5 \\ B_6 & B_2 & B_4 \\ B_5 & B_4 & B_3 \end{pmatrix}$$

From Stress to Birefringence

- Convert stress to optical permittivity
  (for each layer inside stratified medium)

Stress tensor

$$\begin{pmatrix} \sigma_1 & \sigma_6 & \sigma_5 \\ \sigma_6 & \sigma_2 & \sigma_4 \\ \sigma_5 & \sigma_4 & \sigma_3 \end{pmatrix}$$

$$\Delta B_m = \pi_{mn}\sigma_n$$

Changes in impermeability tensor

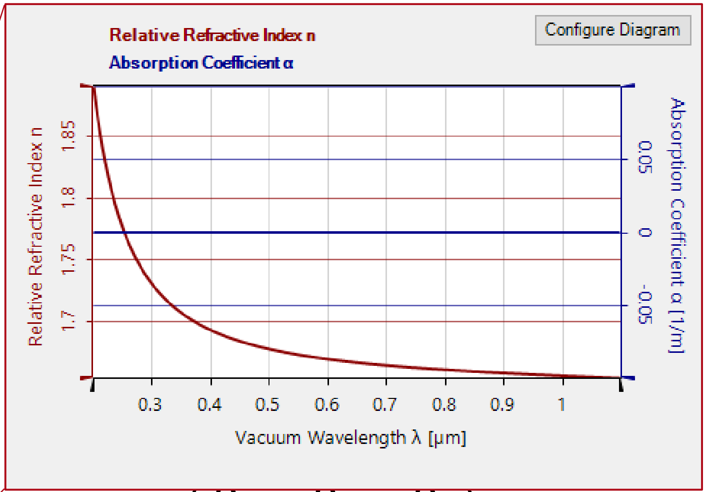
$$\begin{pmatrix} \Delta B_1 & \Delta B_6 & \Delta B_5 \\ \Delta B_6 & \Delta B_2 & \Delta B_4 \\ \Delta B_5 & \Delta B_4 & \Delta B_3 \end{pmatrix}$$

$$B_m = B_{0,m} + \Delta B_m$$

$$\begin{pmatrix} B_1 & B_6 & B_5 \\ B_6 & B_2 & B_4 \\ B_5 & B_4 & B_3 \end{pmatrix}$$

Stress-free values
(related to refractive index/indicies)

Example: ordinary refractive index for BBO crystal



From Stress to Birefringence

- Convert stress to optical permittivity
  (for each layer inside stratified medium)

Stress tensor

$$\begin{pmatrix} \sigma_1 & \sigma_6 & \sigma_5 \\ \sigma_6 & \sigma_2 & \sigma_4 \\ \sigma_5 & \sigma_4 & \sigma_3 \end{pmatrix}$$

$$\Delta B_m = \pi_{mn}\sigma_n$$

Piezo-optic constant (π_{mn})

Changes in impermeability tensor

$$\begin{pmatrix} \Delta B_1 & \Delta B_6 & \Delta B_5 \\ \Delta B_6 & \Delta B_2 & \Delta B_4 \\ \Delta B_5 & \Delta B_4 & \Delta B_3 \end{pmatrix}$$

$$B_m = B_{0,m} + \Delta B_m$$

Stress-free values ($B_{0,m}$)
(related to refractive index/indicies)

Impermeability tensor

$$\begin{pmatrix} B_1 & B_6 & B_5 \\ B_6 & B_2 & B_4 \\ B_5 & B_4 & B_3 \end{pmatrix}$$

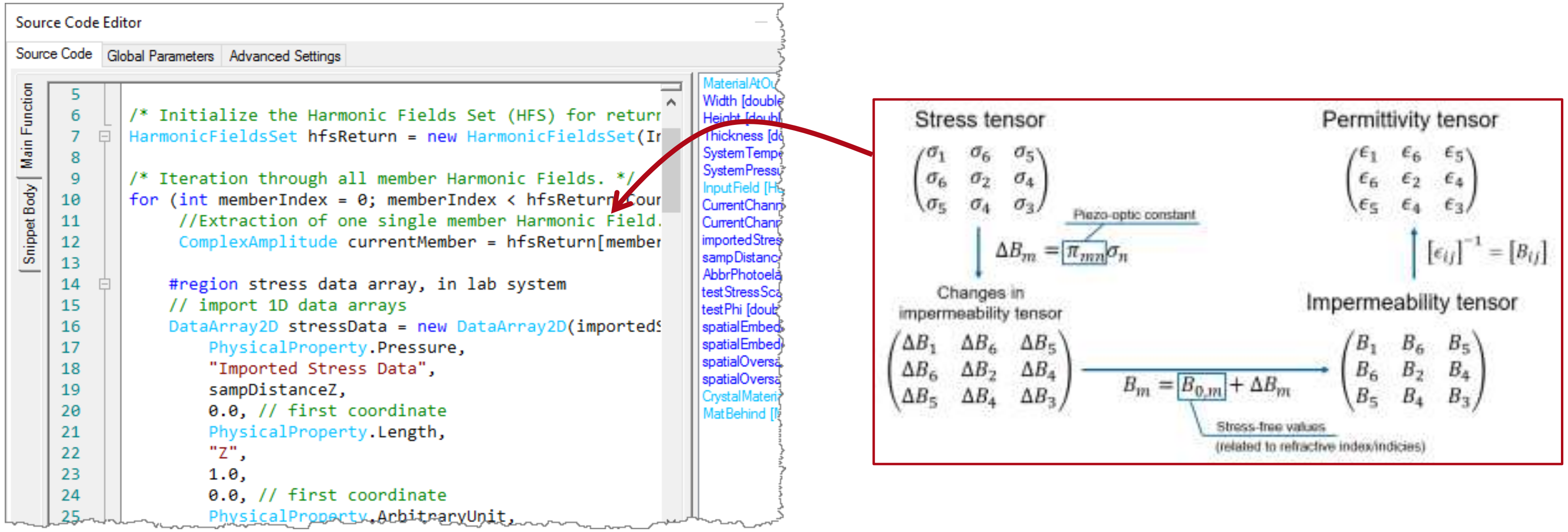
$$[\epsilon_{ij}]^{-1} = [B_{ij}]$$

Permittivity tensor

$$\begin{pmatrix} \epsilon_1 & \epsilon_6 & \epsilon_5 \\ \epsilon_6 & \epsilon_2 & \epsilon_4 \\ \epsilon_5 & \epsilon_4 & \epsilon_3 \end{pmatrix}$$

VirtualLab Simulation

- Convert stress to optical permittivity

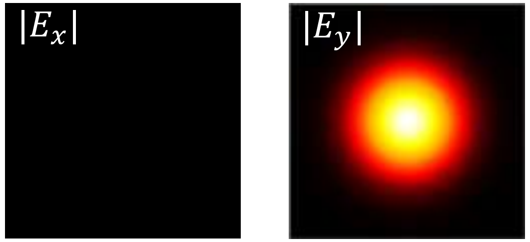


Conversion from stress tensor to the corresponding permittivity tensor is implemented by using the programmable component in VirtualLab

Simulation Results

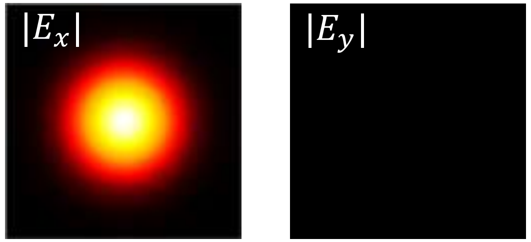
- Input field

1) @1064 nm



(waist radius 50 µm)

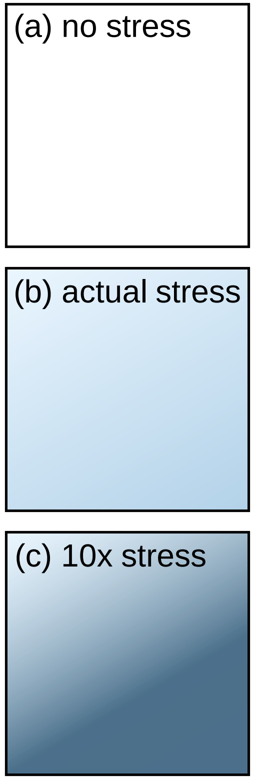
2) @532 nm



(waist radius 50 µm)

Note: we set the polarization according to the SHG configuration

- Applied stress

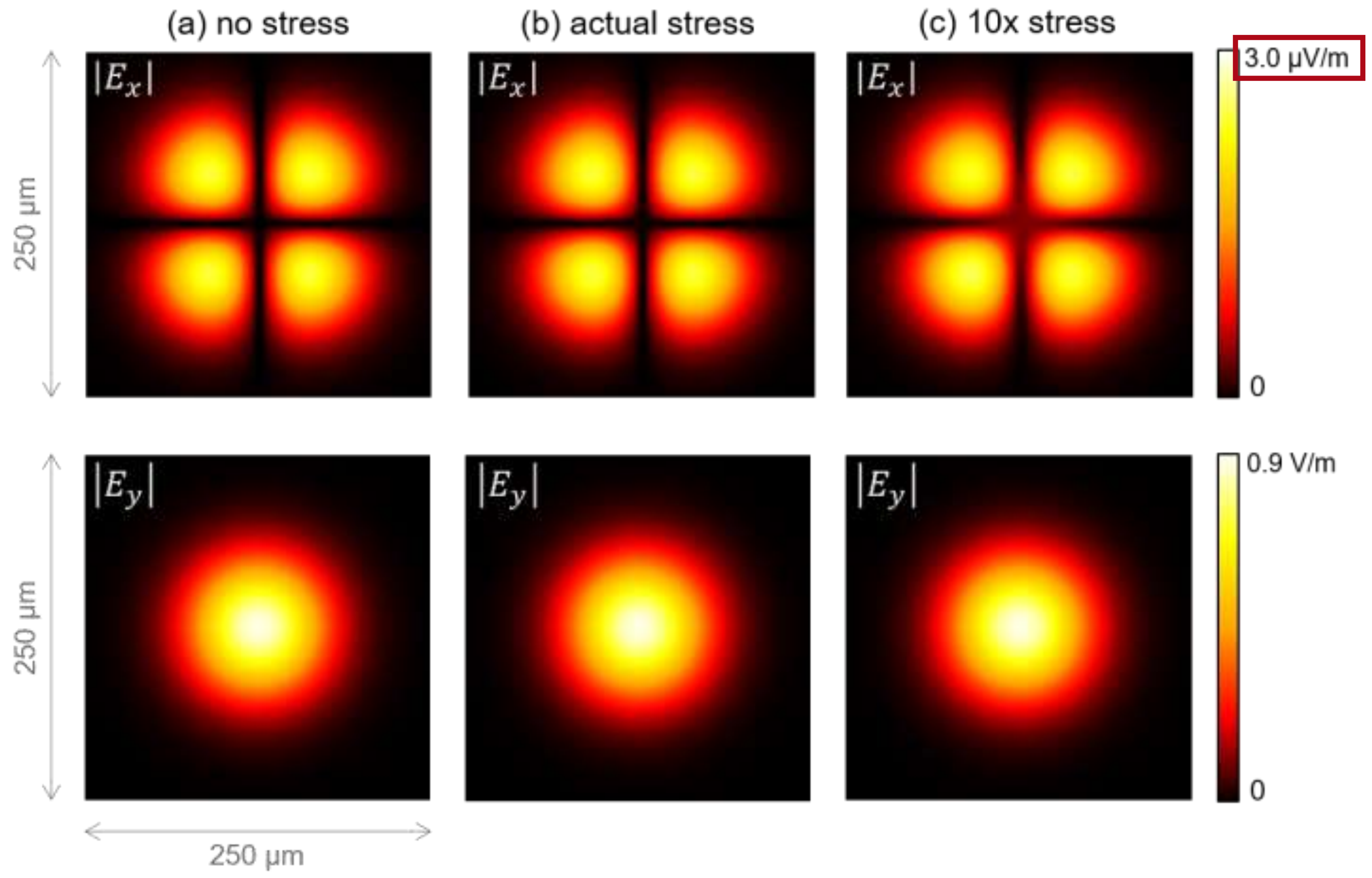


- Output field

?

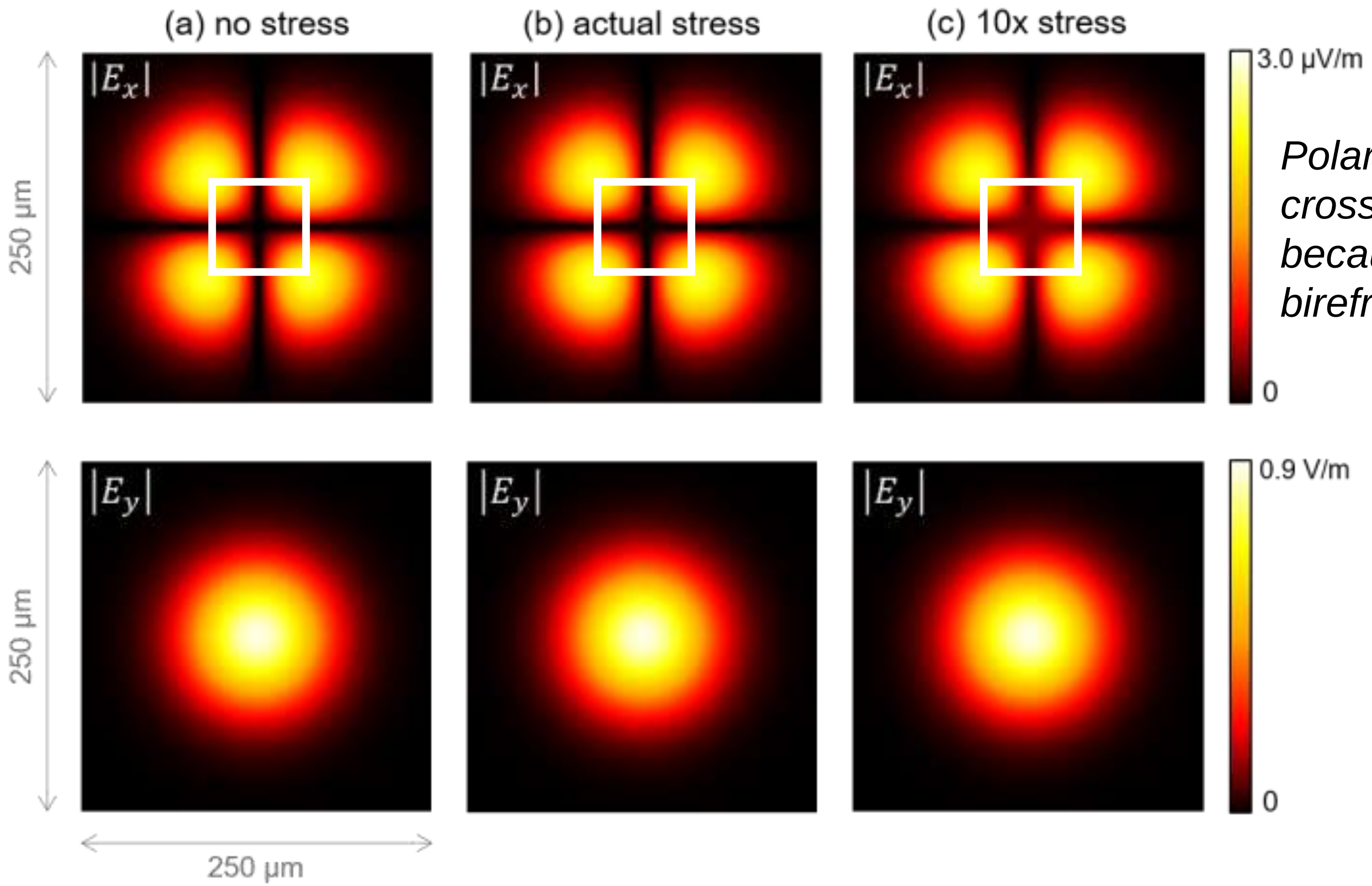
Simulation Results

- YAG crystal with 1064 nm input field (Ey)



Simulation Results

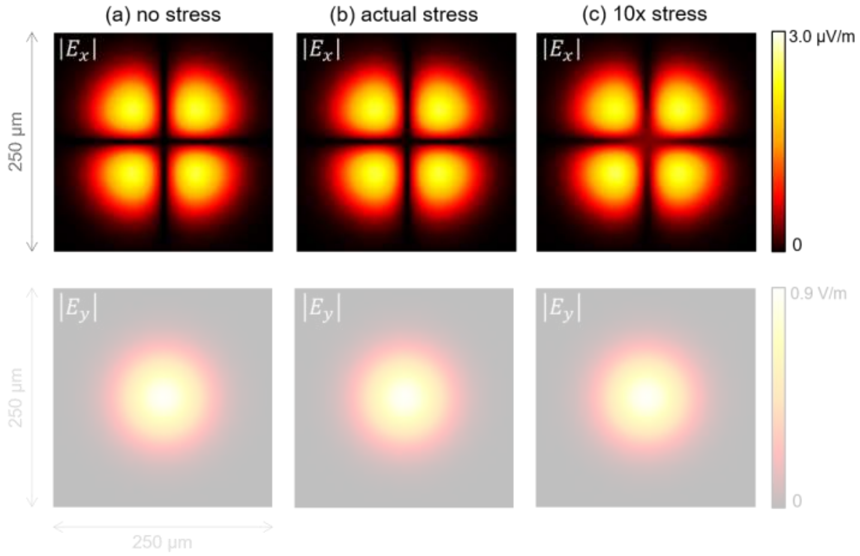
- YAG crystal with 1064 nm input field (Ey)



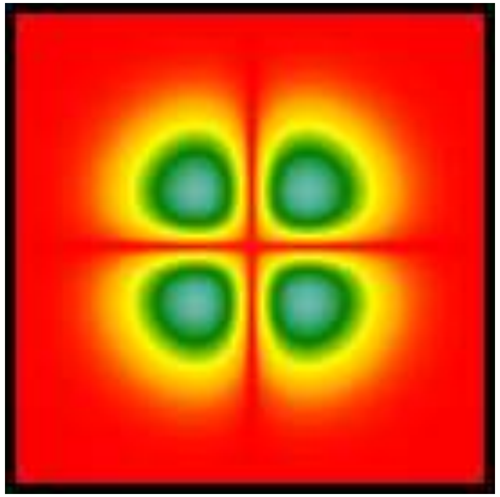
Polarization crosstalk (center) because of birefringence

Simulation Results

- YAG crystal with 1064 nm input field (Ey)
  - Further check on the influence of stress-induced birefringence, we perform parameter run from 1x to 201x stresses (with 101 steps)



from 1x to 201x stress

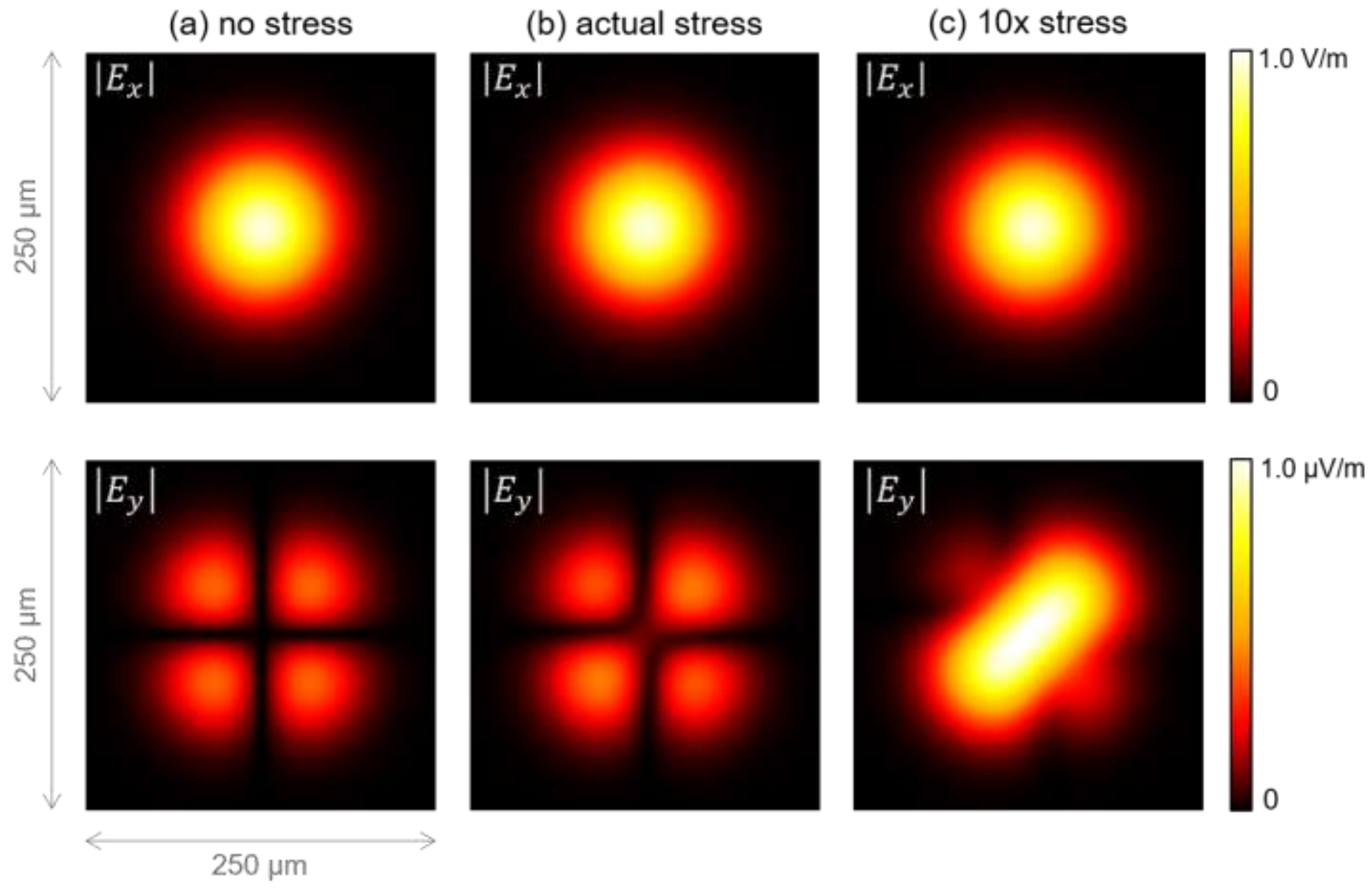


(logarithm color for better visibility)

Calculation of 101 steps: ~ **90** s
with Intel Core i7-4910MQ

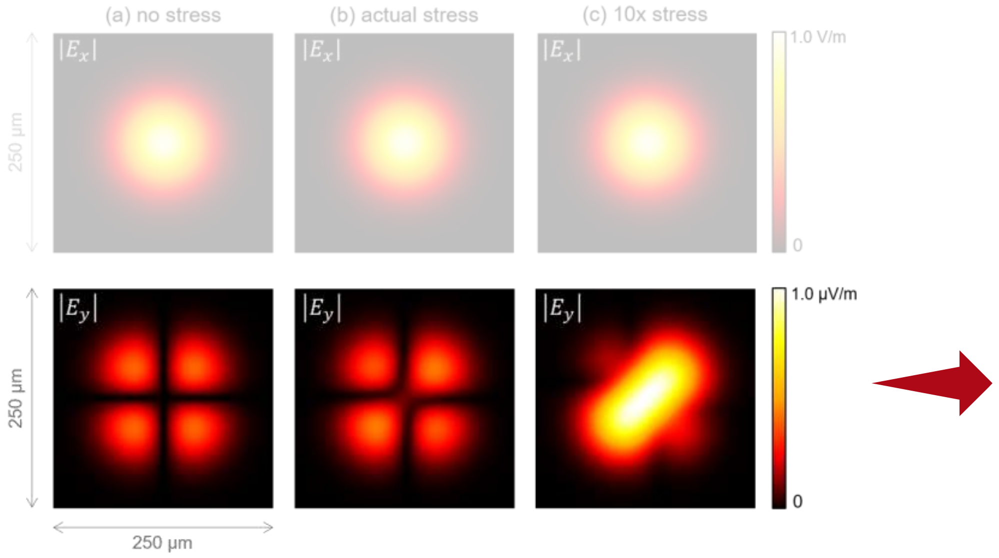
Simulation Results

- YAG crystal with 532 nm input field (Ex)

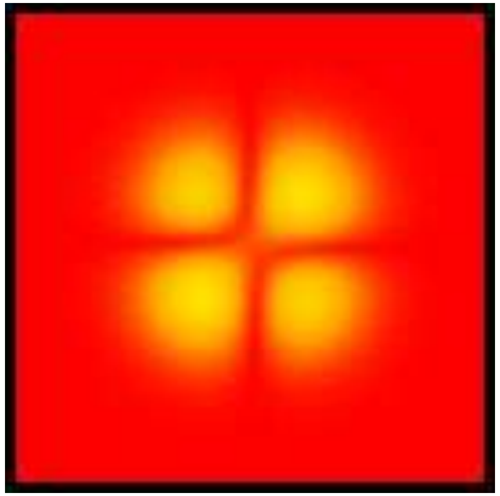


Simulation Results

- YAG crystal with 532 nm input field (Ex)
  - Further check on the influence of stress-induced birefringence, we perform parameter run from 1x to 51x stresses (with 101 steps)



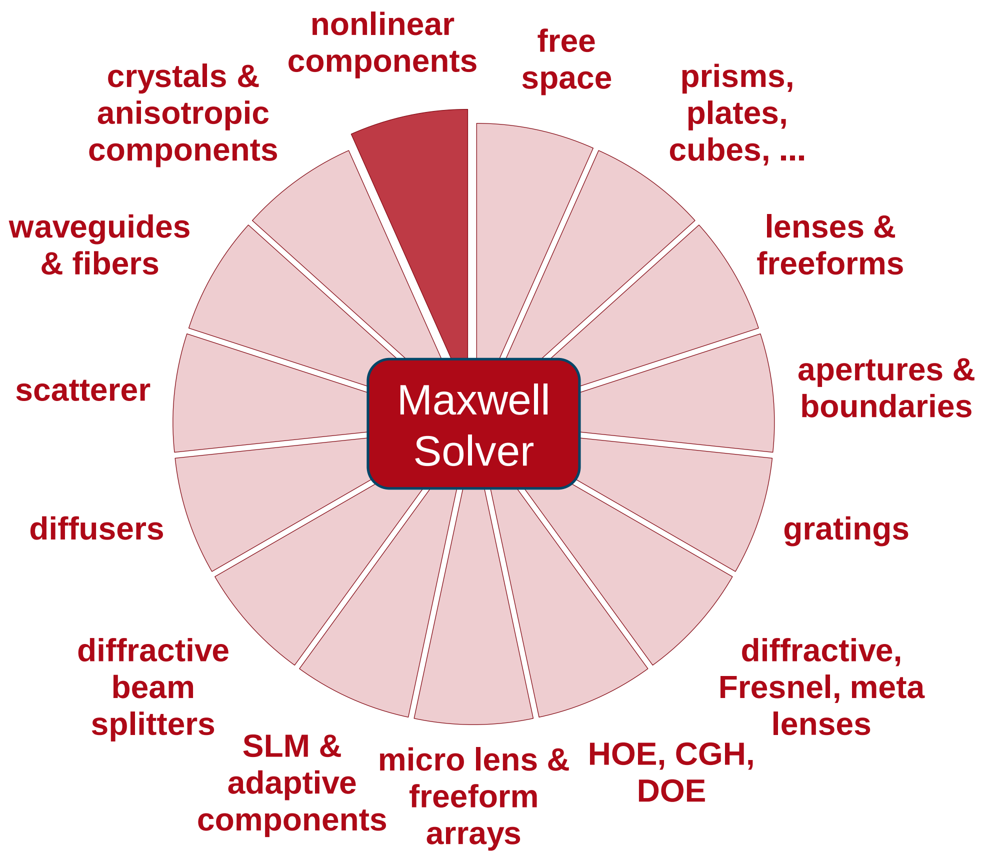
from 1x to 51x stress



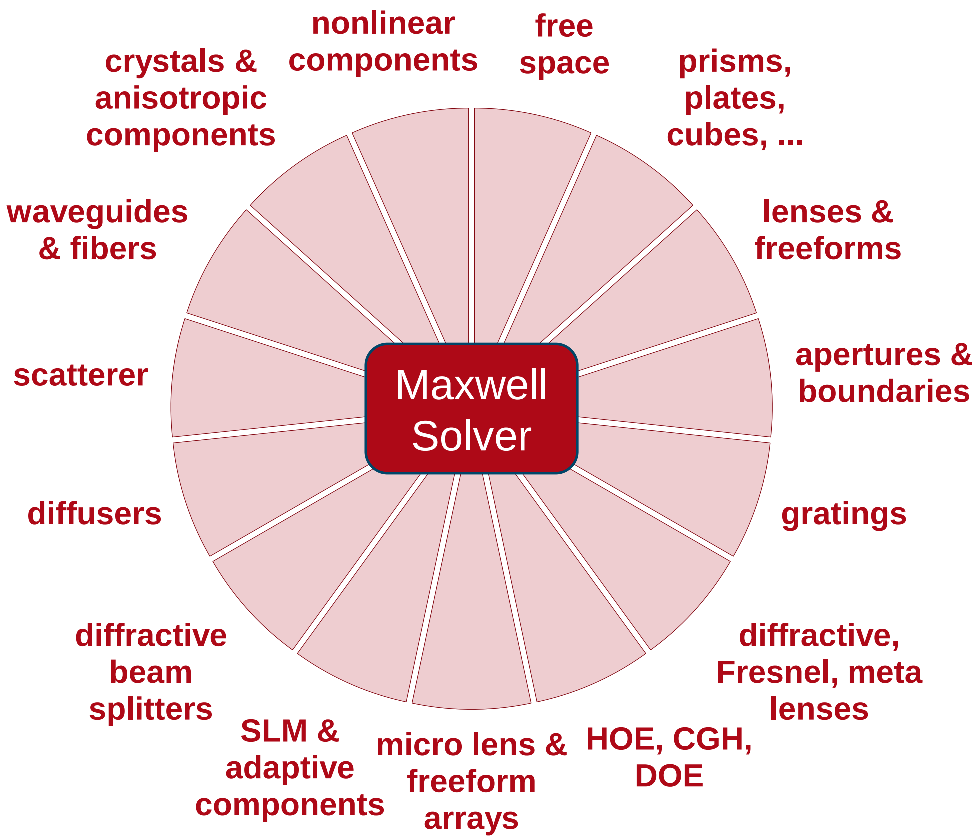
(logarithm color for better visibility)

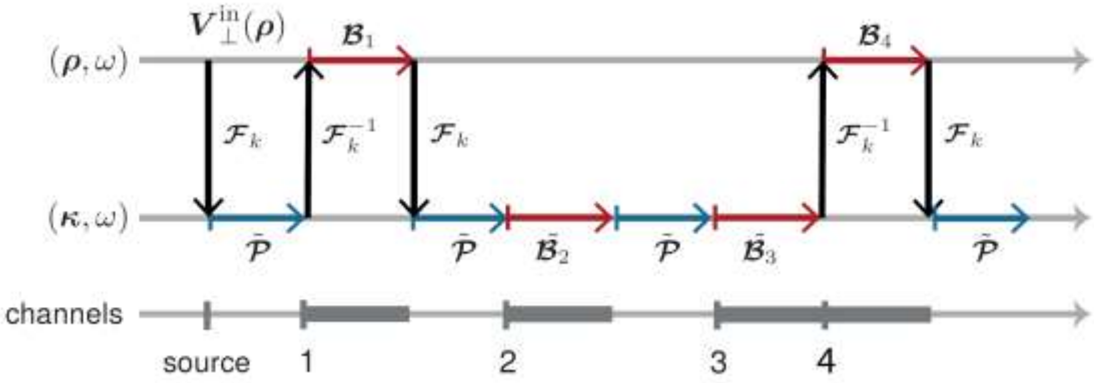
Nonlinear Components

- Ongoing R&D in field of nonlinear optics.
- Paraxial SHG and Kerr effect modeling available.
- More to come later in 2019.



Physical-Optics System Modeling: Regional Maxwell Solver





- All techniques can be combined in field tracing with VirtualLab Fusion.
- Steady in-house R&D and software development.
- Cooperation with experts worldwide to include more techniques in VLF.

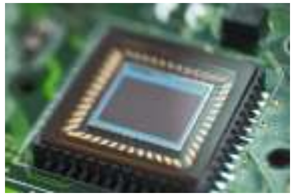
General Physical-Optics System Modeling

Sources

Components

Detectors

Physical optics modeling



https://c2.staticflickr.com

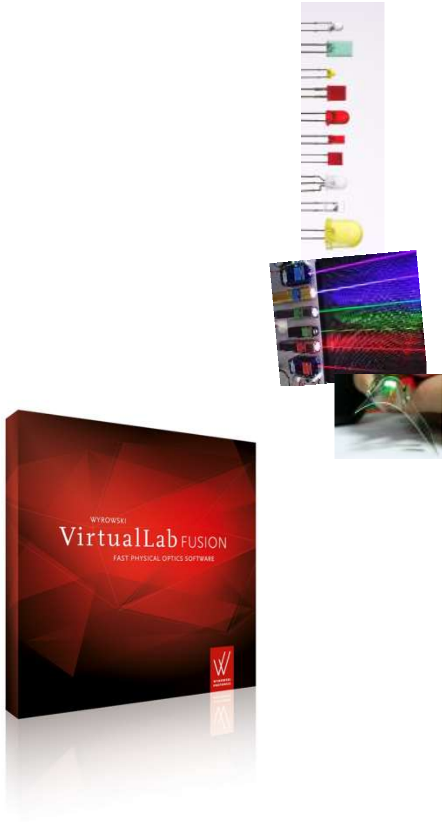
We demand full flexibility in physical optics modeling.

General Physical-Optics System Modeling

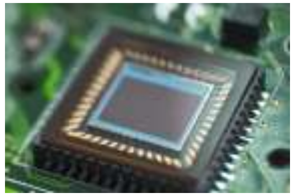
Sources

Components

Detectors



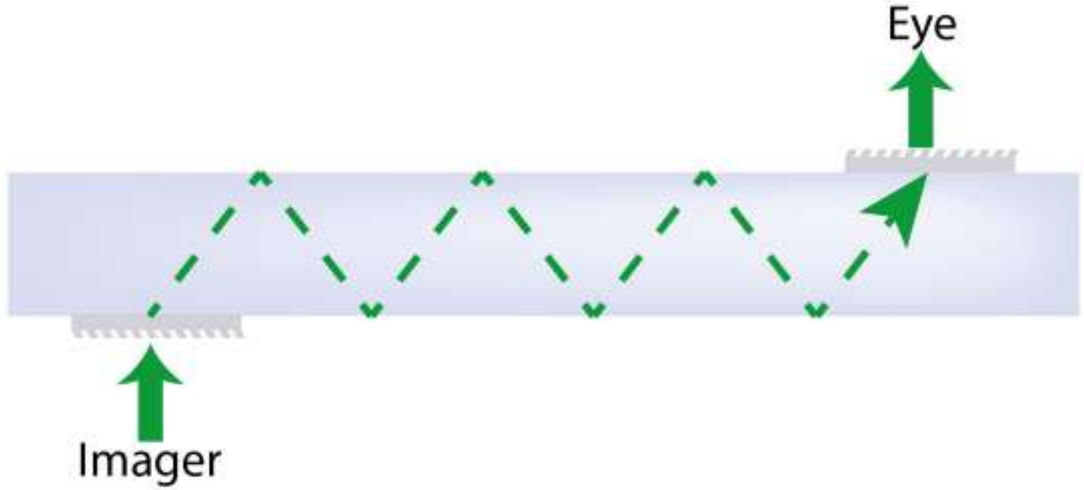
Physical optics modeling

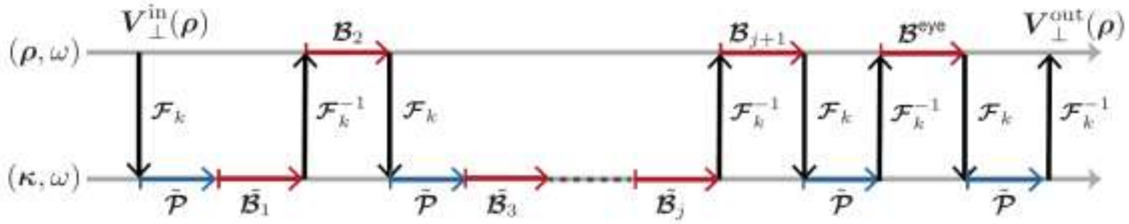


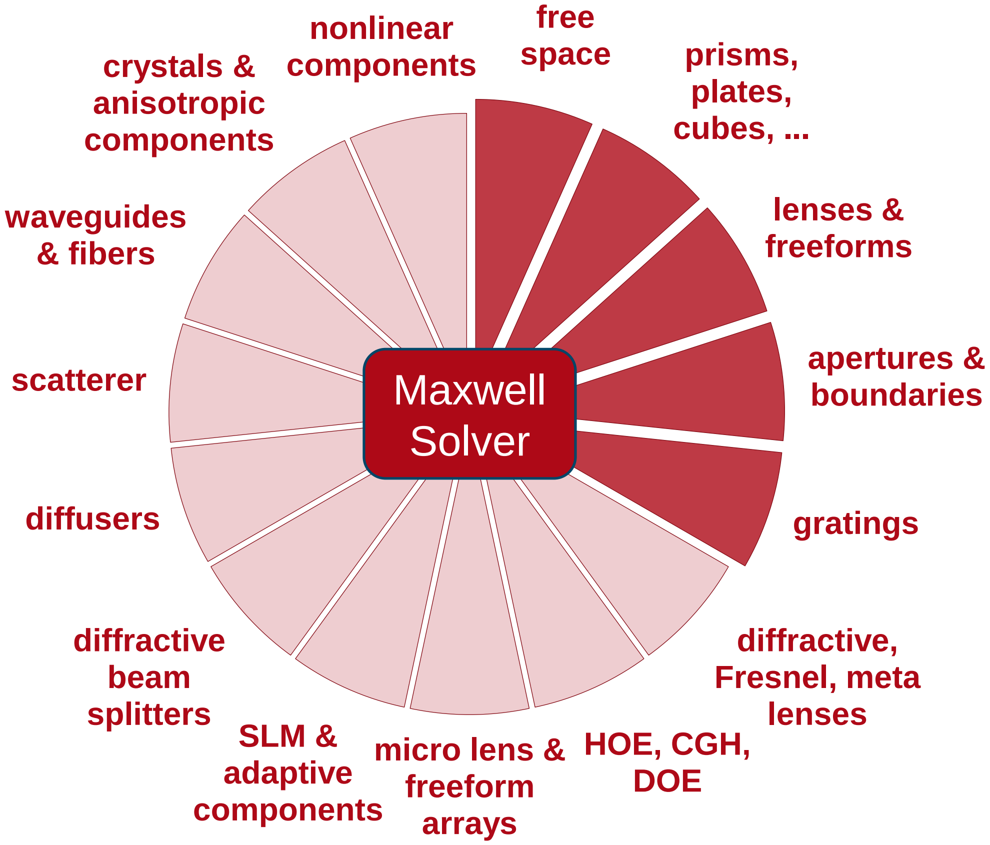
https://c2.staticflickr.com

Physical optics modeling should be as fast as ray tracing wherever possible!

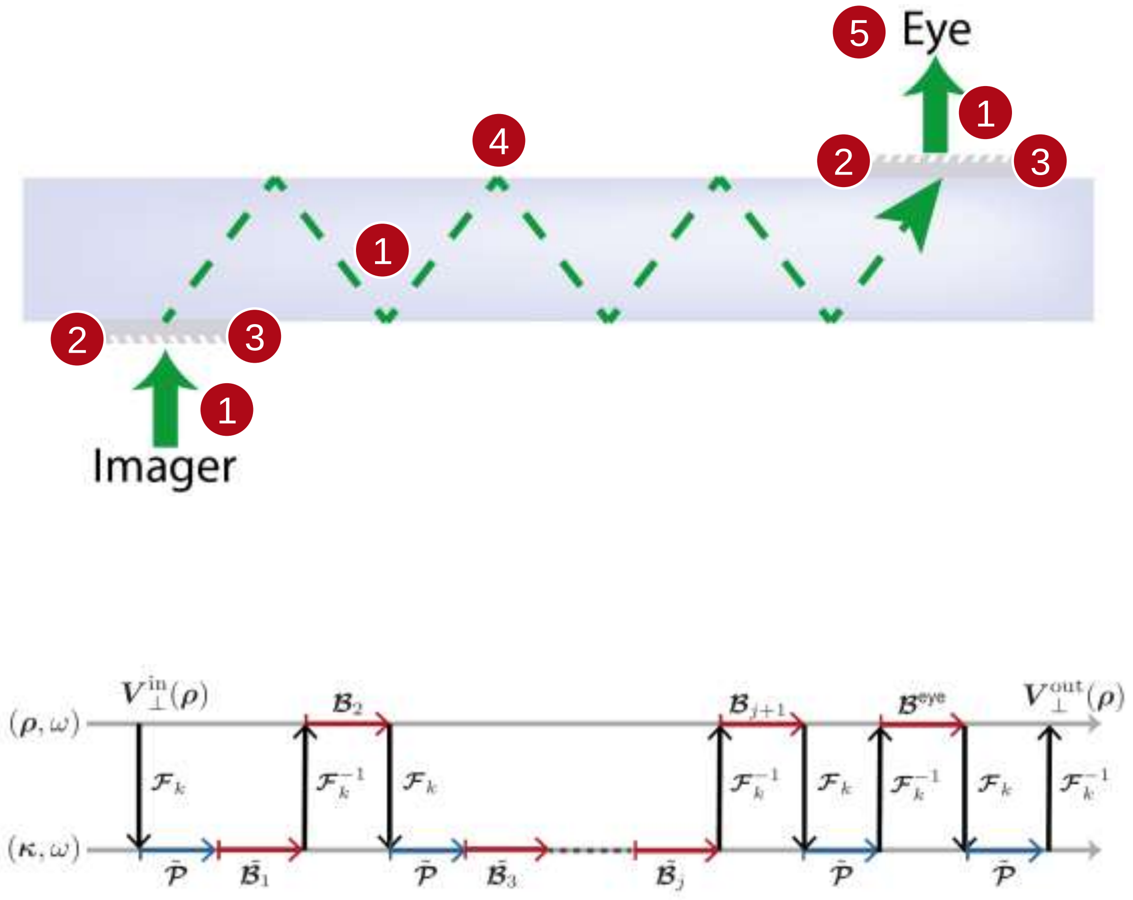
Typical Modeling Situation for AR&MR Waveguide

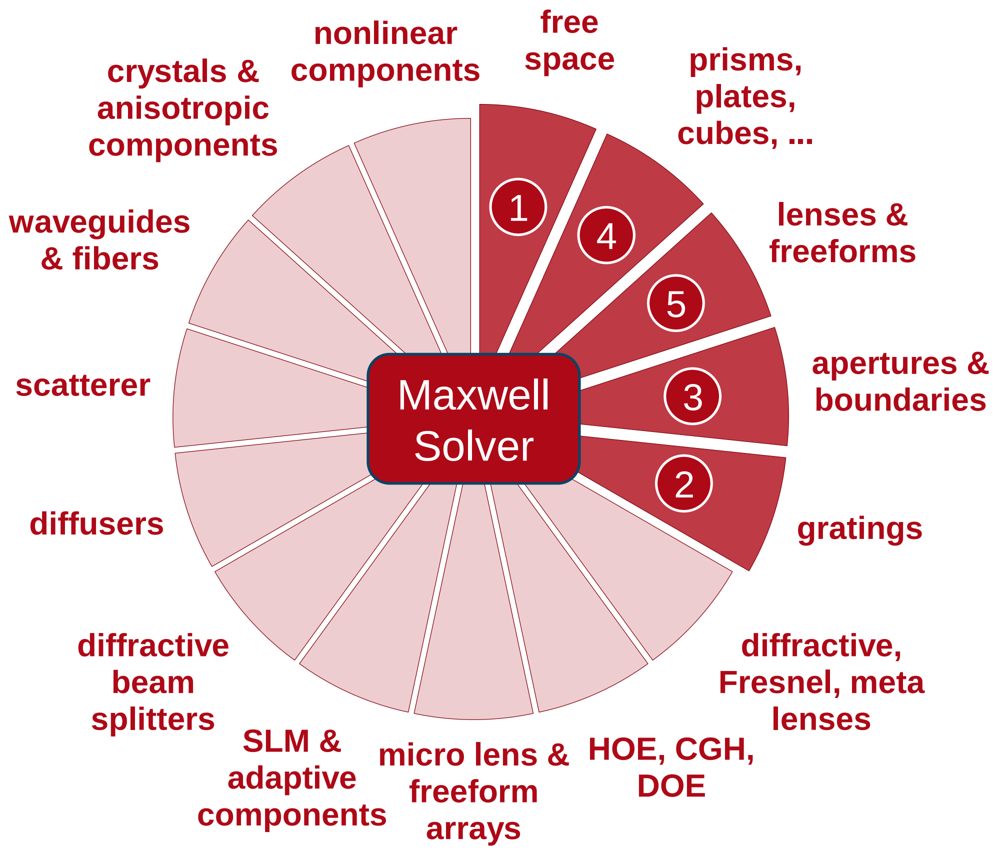




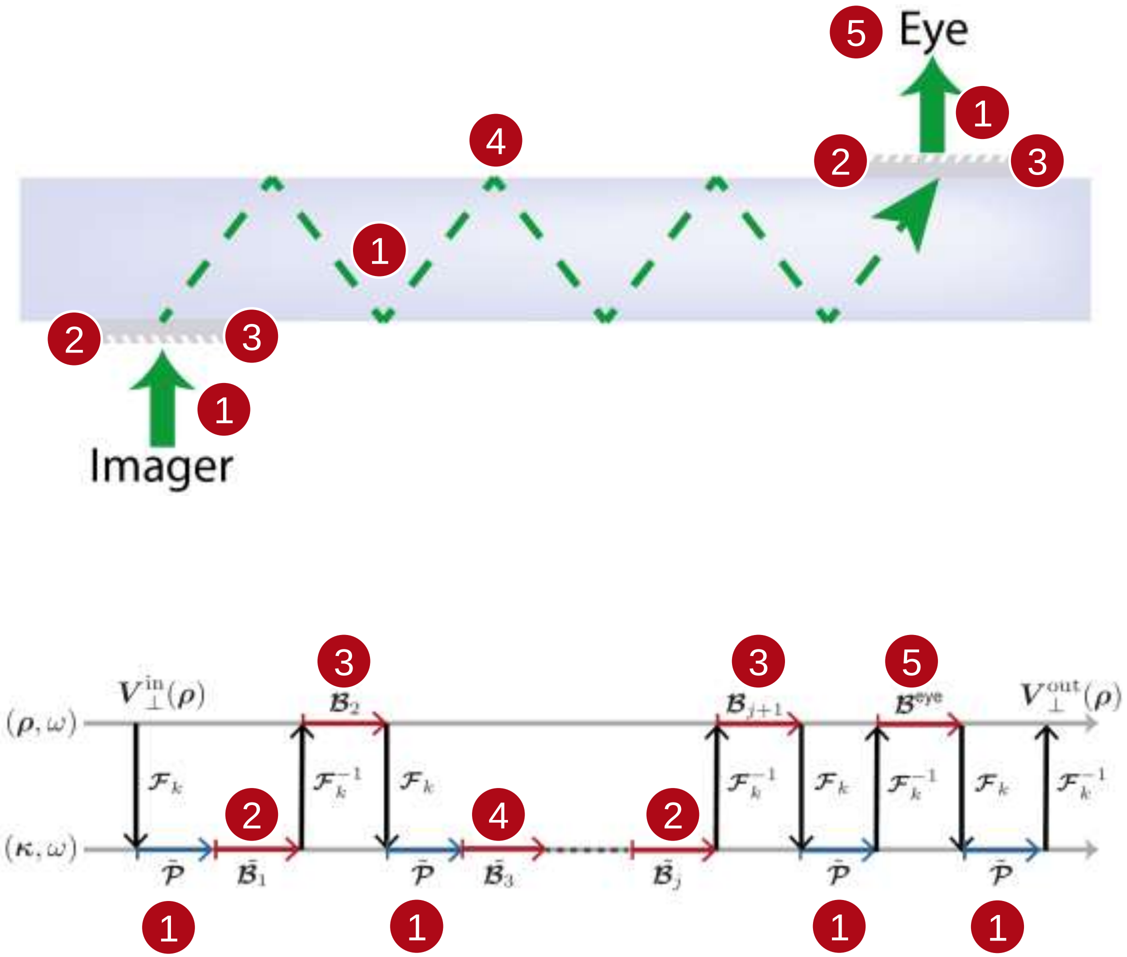


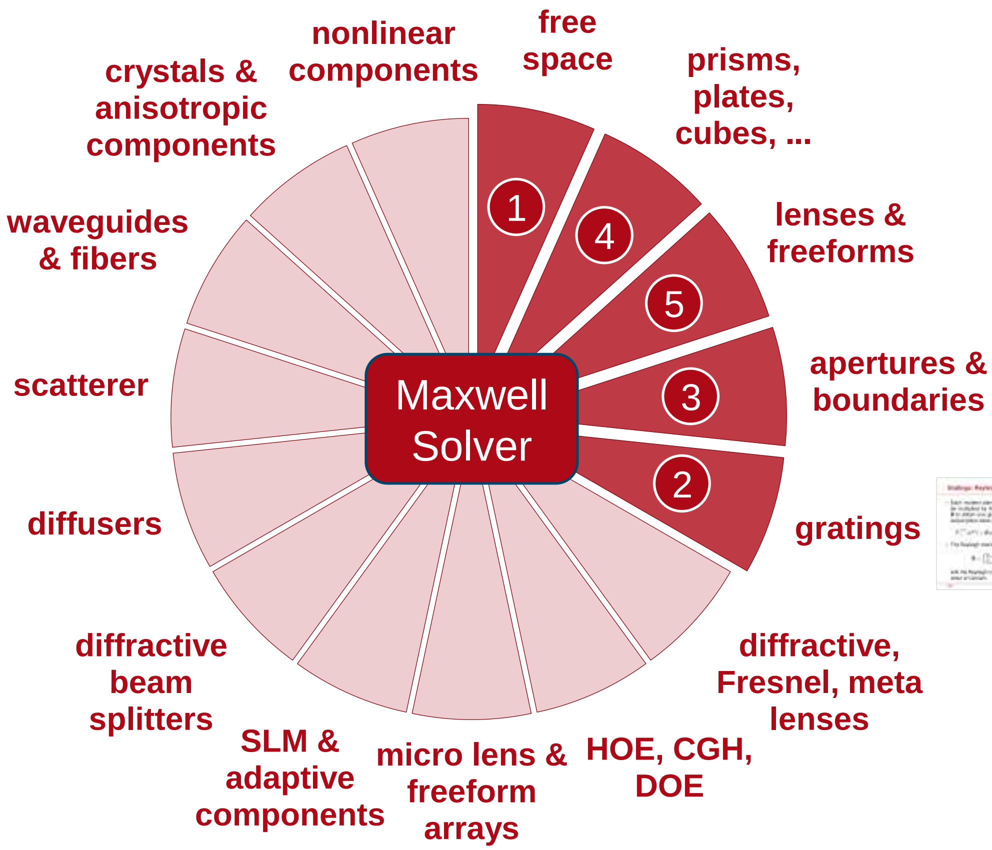
Typical Modeling Situation for AR&MR Waveguide



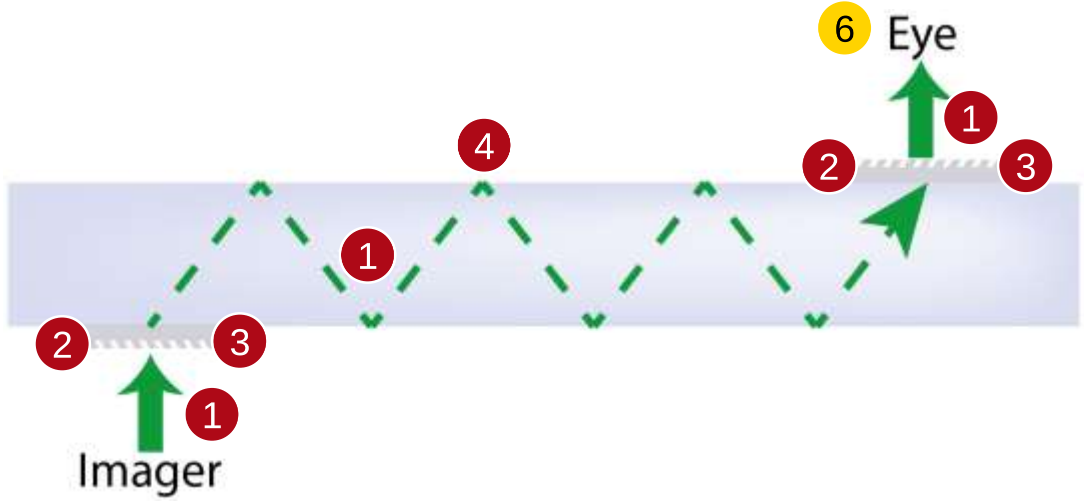


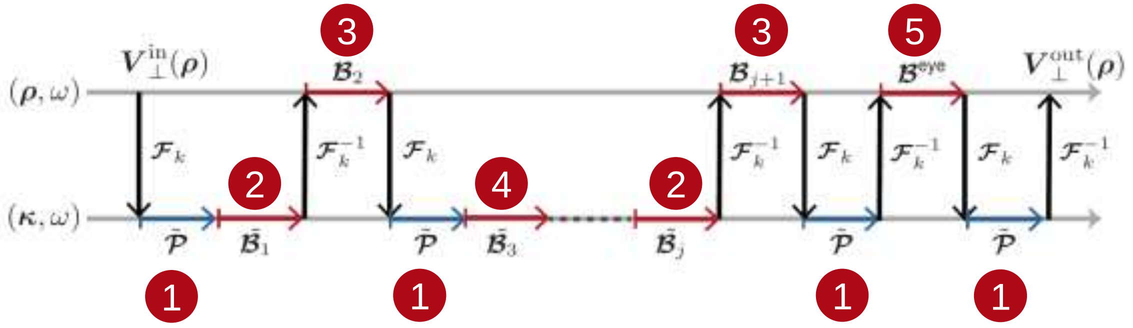
Typical Modeling Situation for AR&MR Waveguide

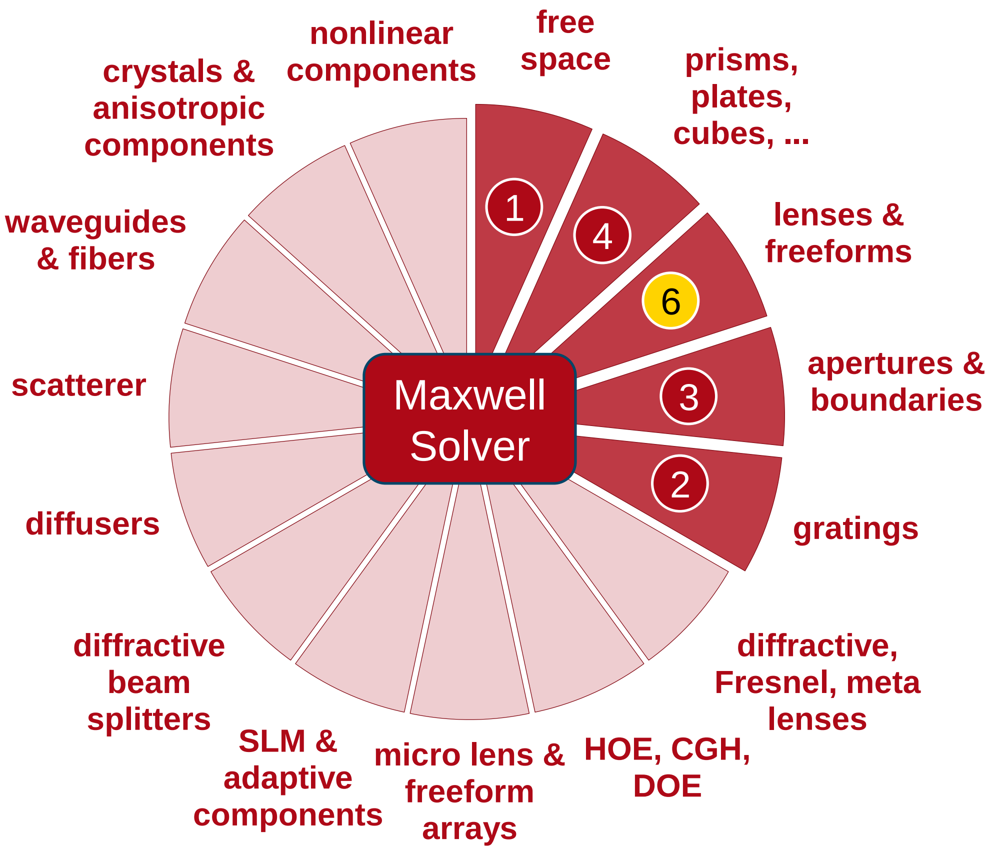




Typical Modeling Situation for AR&MR Waveguide

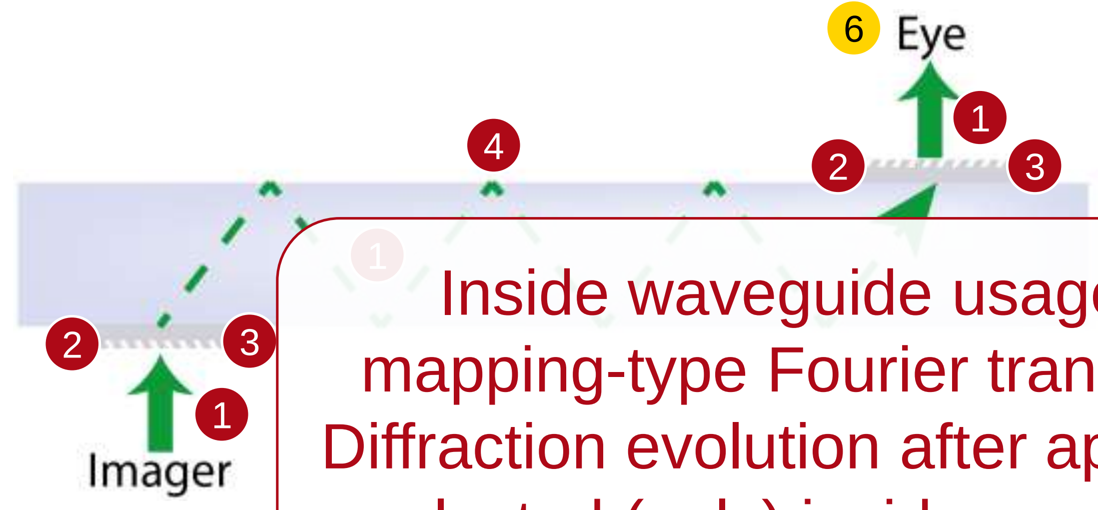




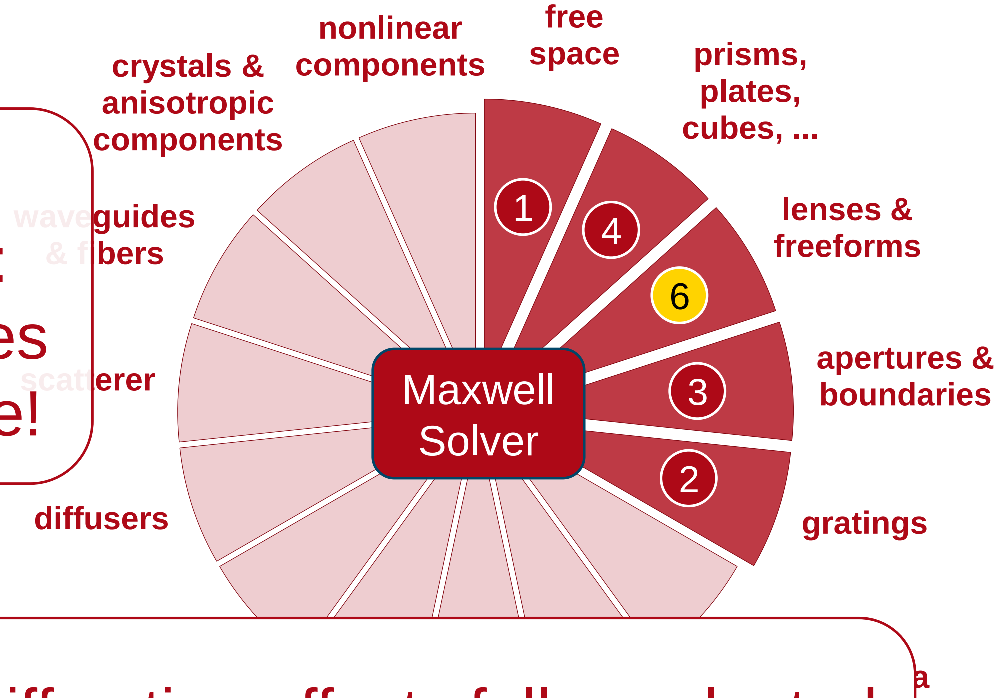


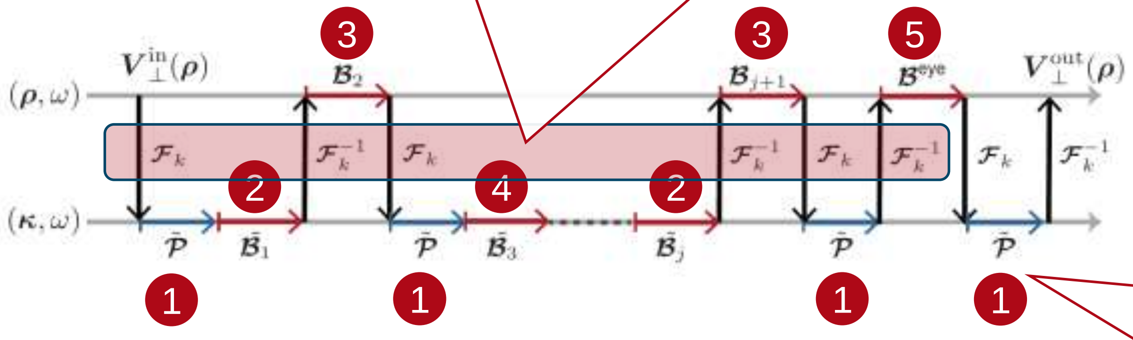
6 Idealized lens model

Typical Modeling Situation for AR&MR Waveguide



Inside waveguide usage of mapping-type Fourier transform: Diffraction evolution after apertures neglected (only) inside waveguide!





Diffraction effects fully evaluated in last propagation step, which provides the PSF!

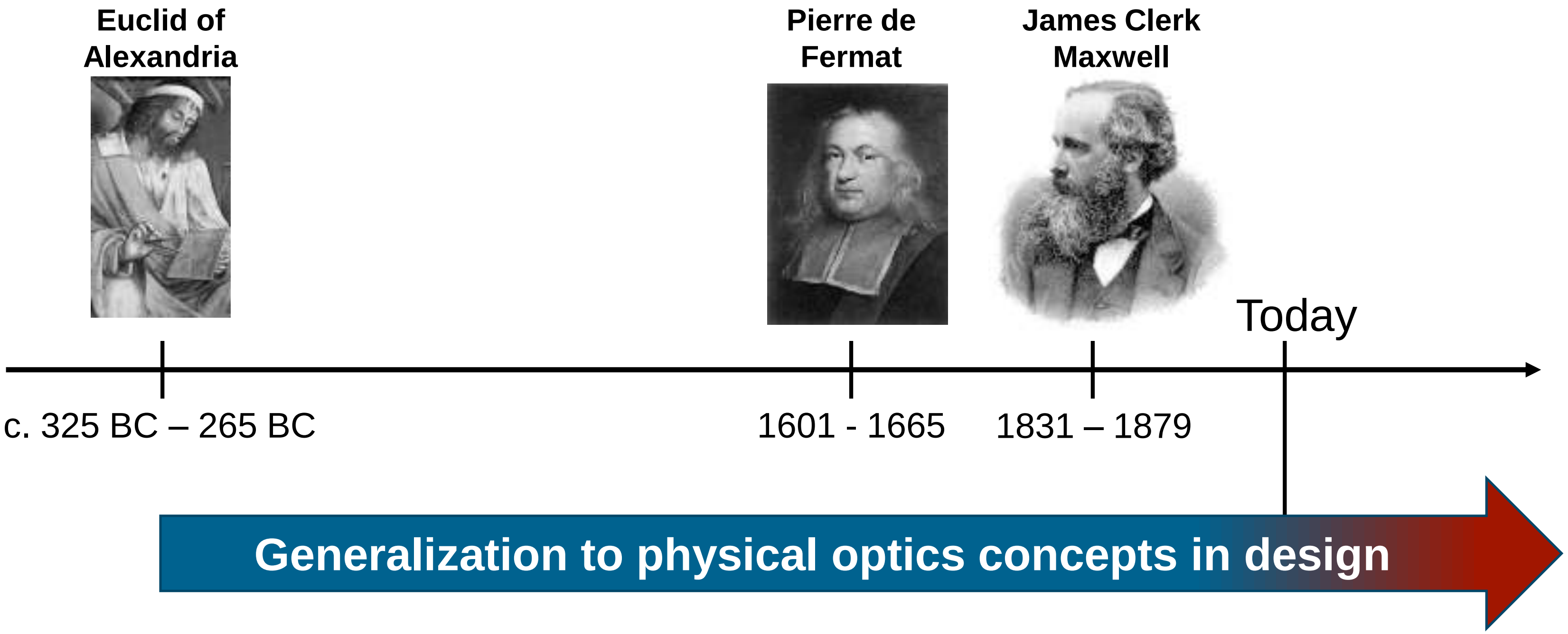
Modeling and Design with Fast Physical Optics

- 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

Modeling and Design with Fast 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 gain 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 enable new optical design concepts and by that innovative optical solutions

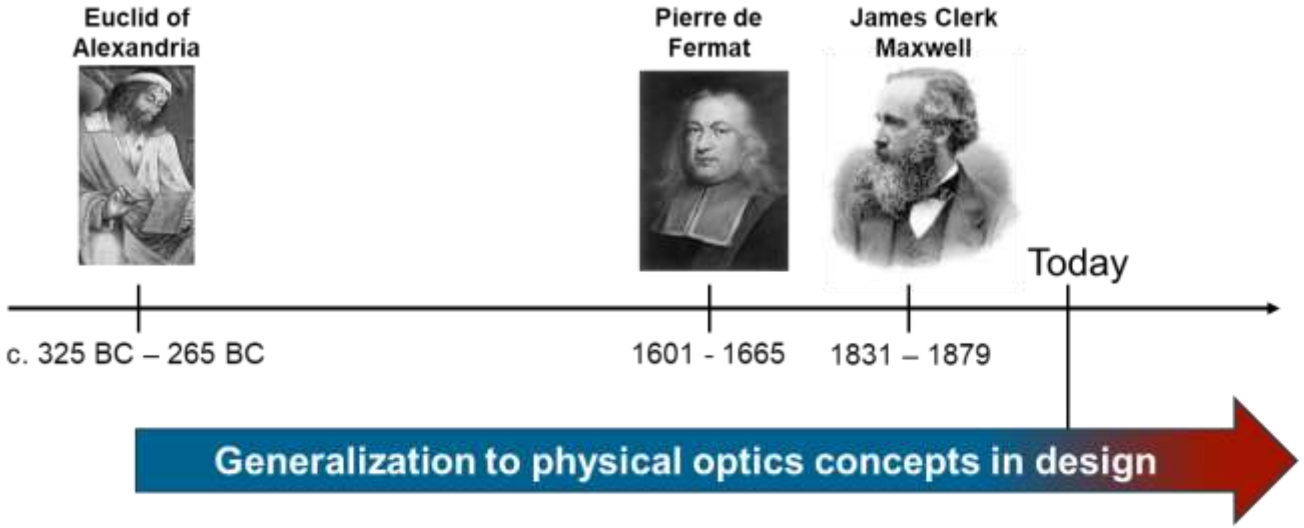
Fast Physical Optics with VirtualLab Fusion



It’s time for a paradigm shift!

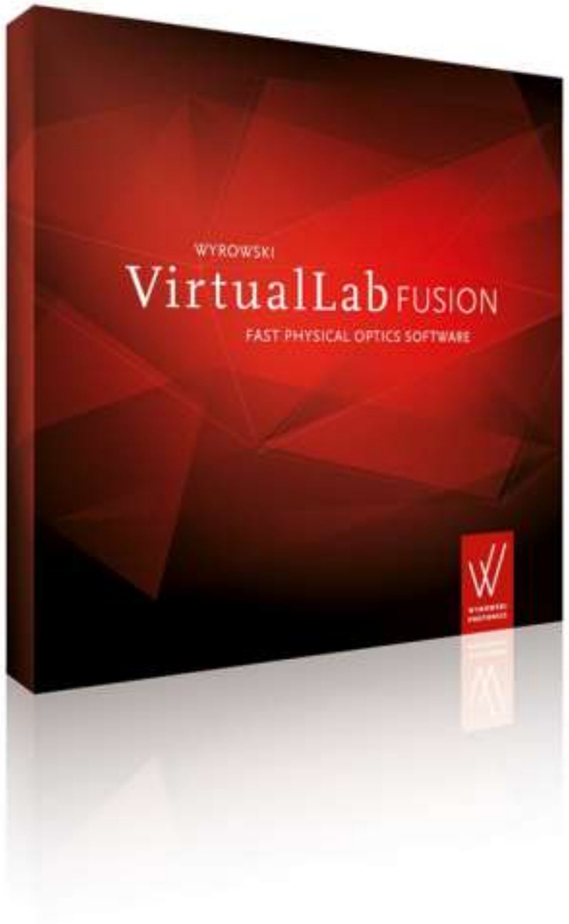
Physical optics do not replace ray tracing, but enriches our way to do optical design. We can just win – **if we do it smart!**

Fast Physical Optics with VirtualLab Fusion



It's time for a paradigm shift!

Physical optics do not replace ray tracing, but enriches our way to do optical design. We can just win – **if we do it smart!**

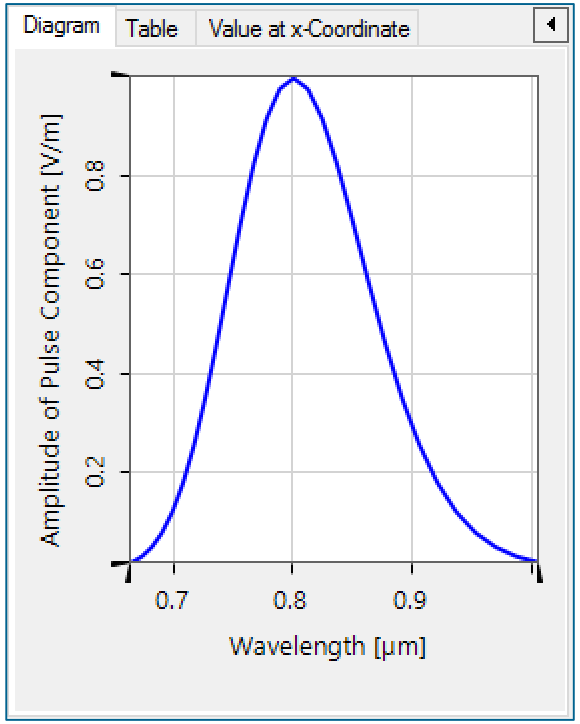


Task N

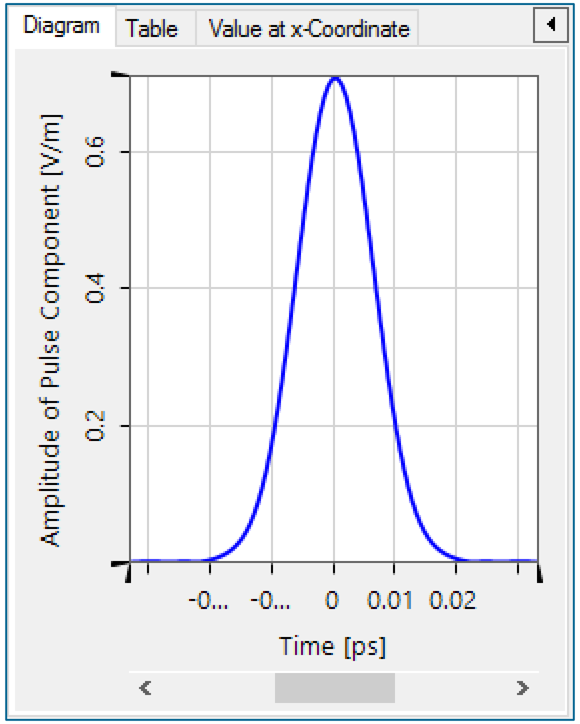
Pulse Broadening and Compression

Pulse in Frequency Domain

- In frequency (wavelength) domain
  - Gaussian pulse

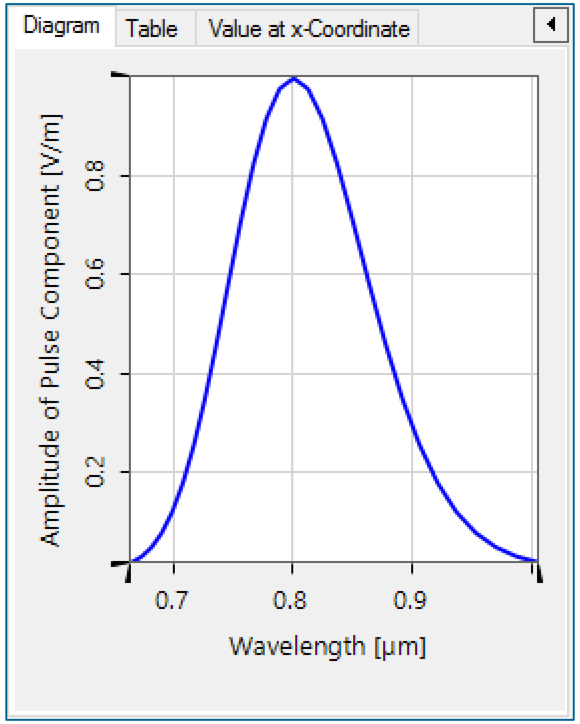


- In time domain (envelop)
  - Fourier transform

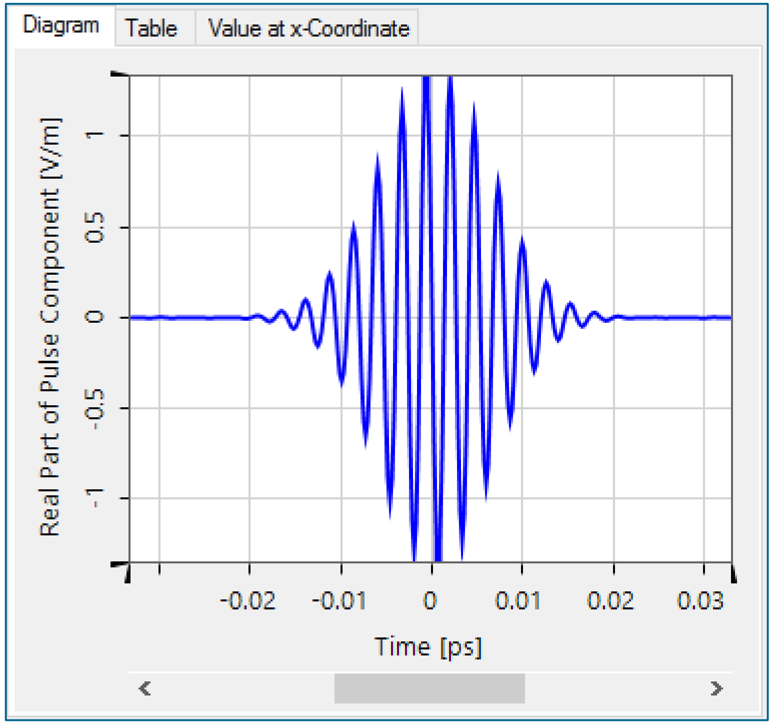


Pulse in Frequency Domain

- In frequency (wavelength) domain
  - Gaussian pulse

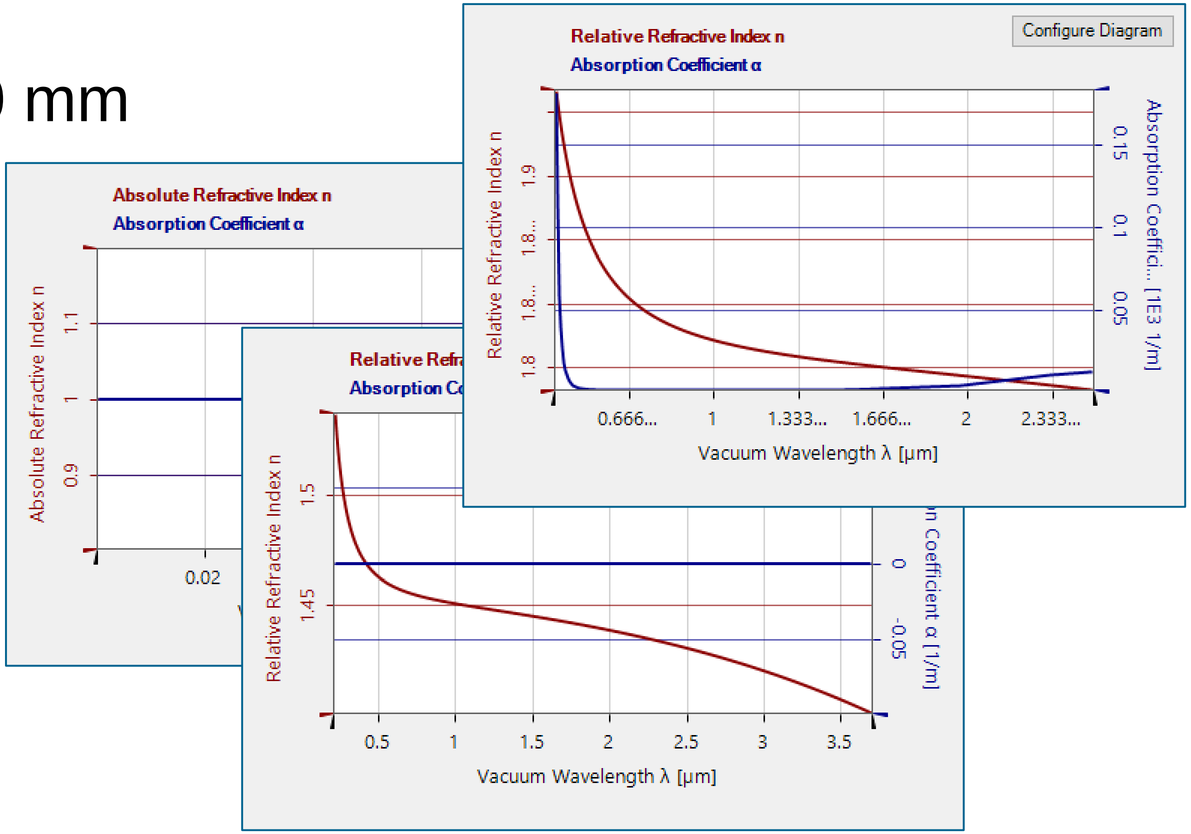


- In time domain
  - Fourier transform



Propagation of Pulse

- Initial pulse
  - Central (carrier) wavelength: 619 nm
  - Pulse duration: 31 fs
- Propagation distance: 180 mm
- Media
  - Vacuum
  - Fused silica
  - SF57



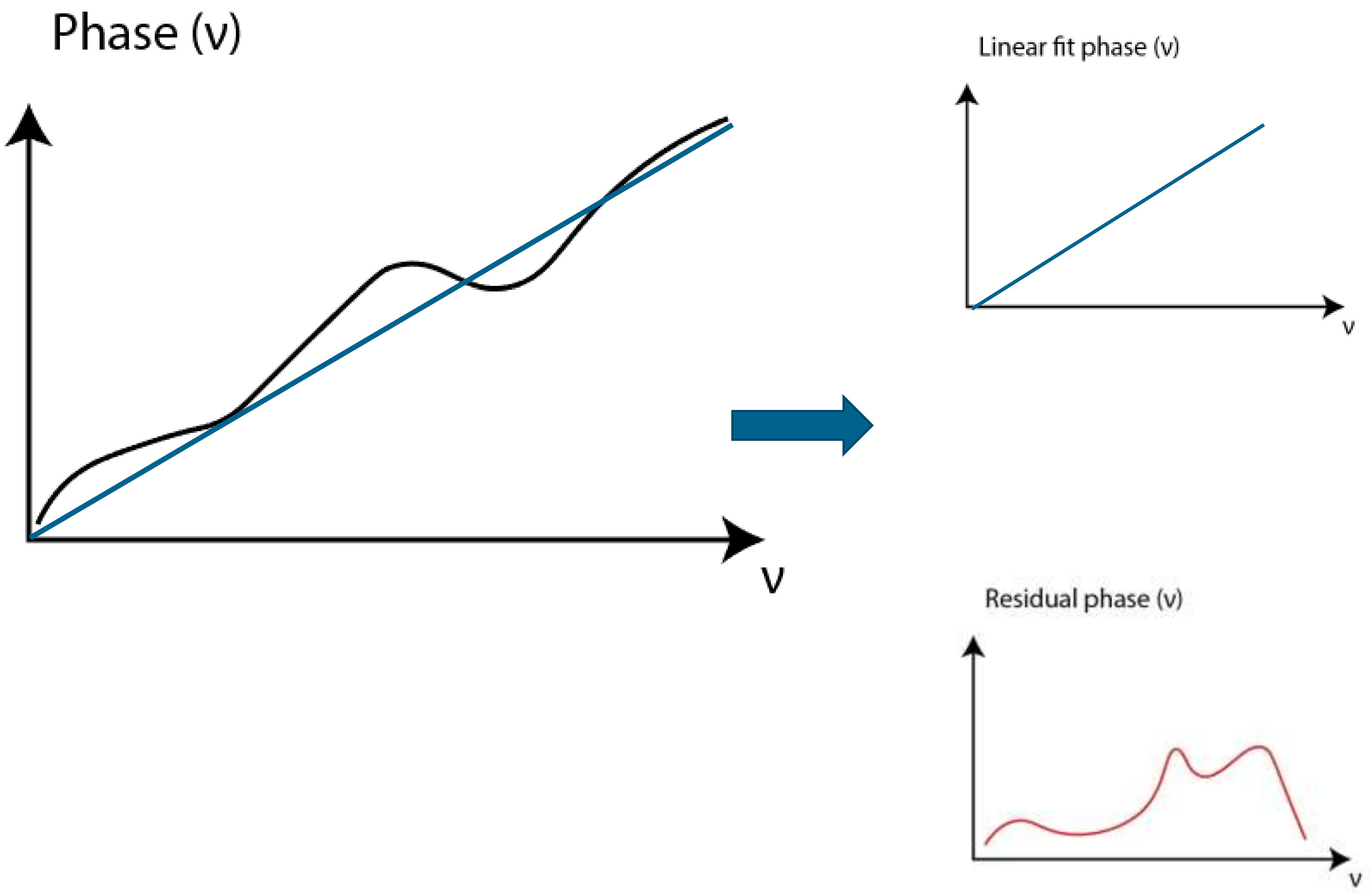
Related files: Material.Dispersion_30fs@619nm.lpd

Pulse Propagation in Vacuum

- Open the related lpd
- Use OIS (Vacuum) as the component
- Simulation
  - Geometric field tracing as the simulation engine
  - OPL Analyzer (OIS)
- Check the pulse in both time and frequency domain
- Detect the pulse duration of output field.

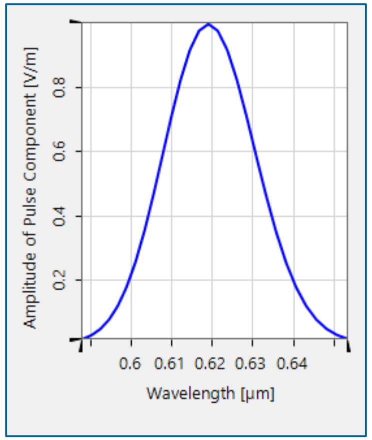
Related files：Material.Dispersion_30fs@619nm.lpd

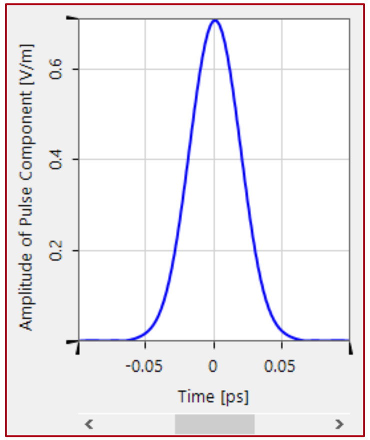
What we will do?



Result

- Input pulse

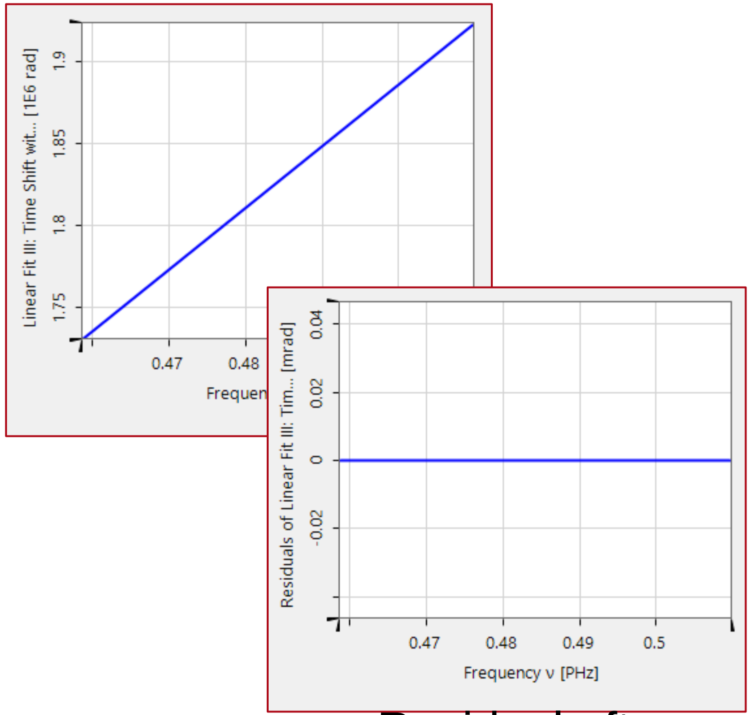




31 fs

- Output pulse

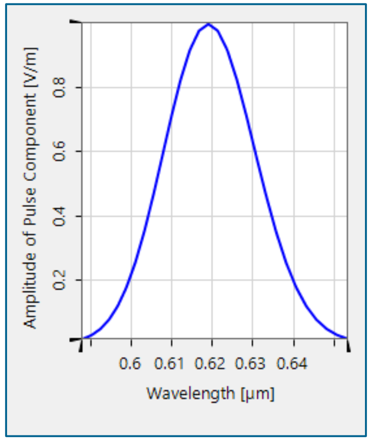
The phase is linear to frequency

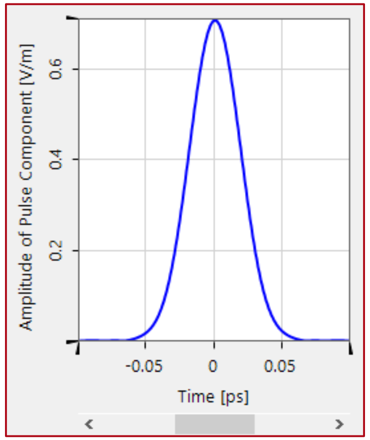


Residual after linear fitting

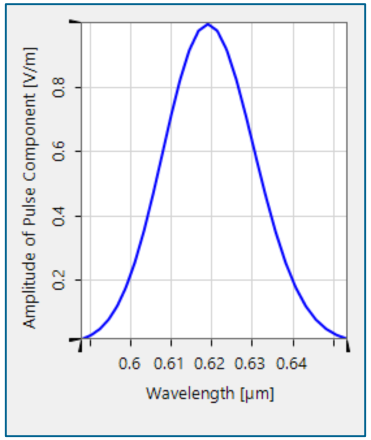
Result

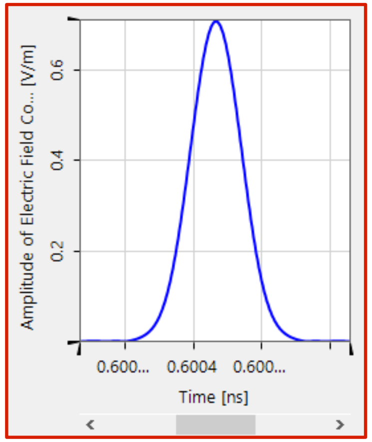
- Input pulse
- Output pulse





31 fs





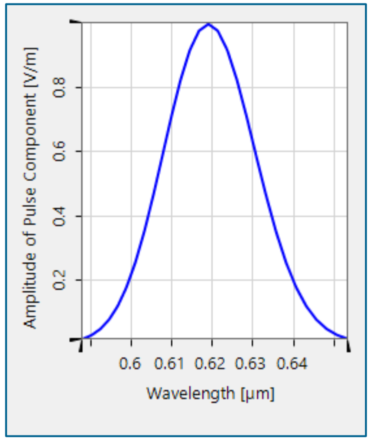
31 fs

Time axis?

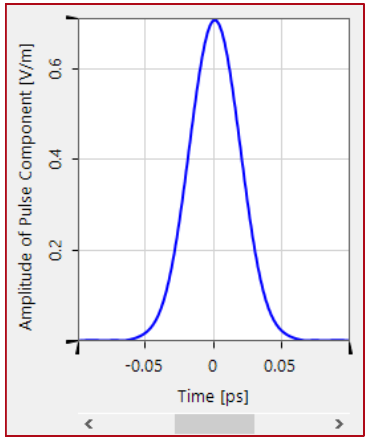
Pulse Propagation in Fused Silica

- Input pulse
- Output pulse
  - Phase v.s. Frequency（Analyzer）

Frequency

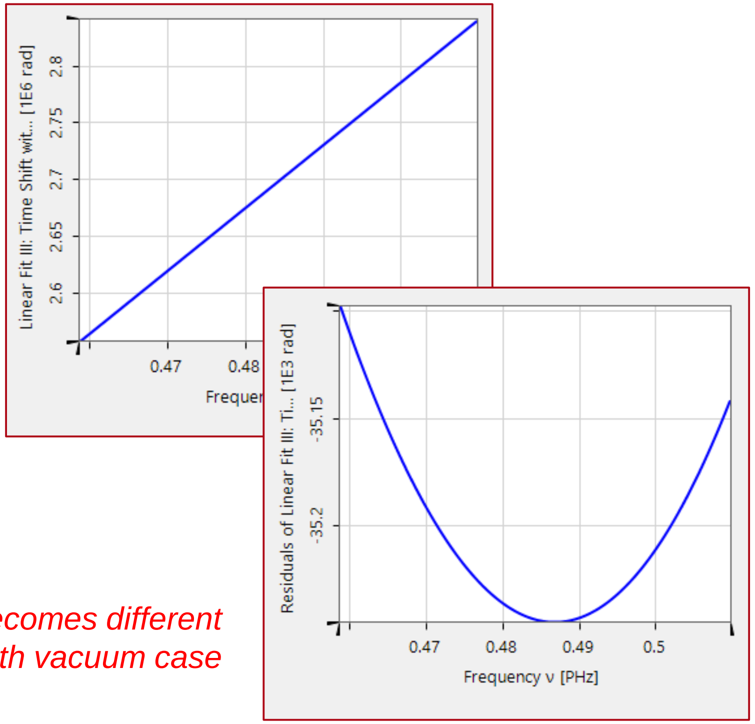


Time



31 fs

Phase



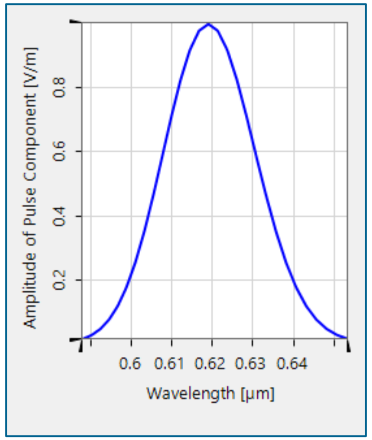
Why the residual becomes different compared with vacuum case

Residual after fitting

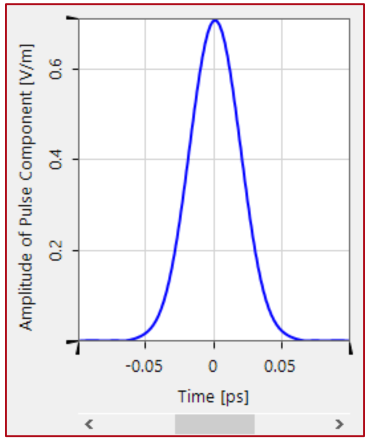
Pulse Propagation in Fused Silica

- Input pulse
- Output pulse

Frequency

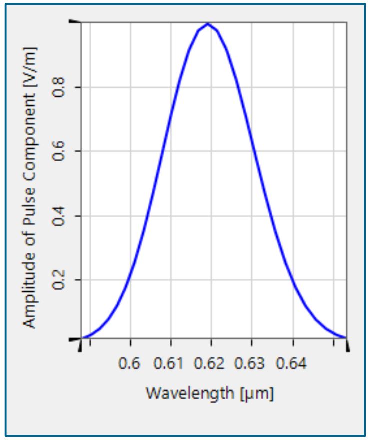


Time

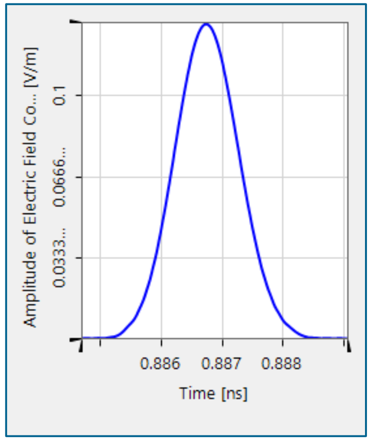


31 fs

Frequency



Time



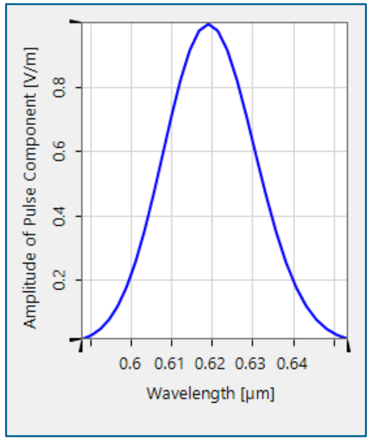
870 fs

Why pulse broadening ?

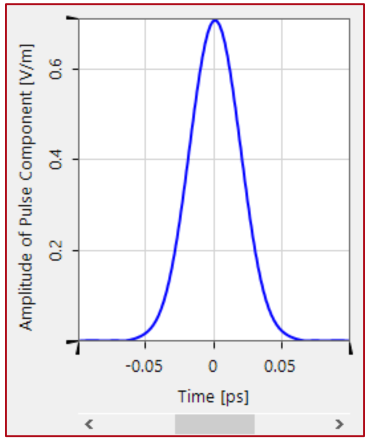
Pulse Propagation in SF57

- Input pulse
- Output pulse

Frequency

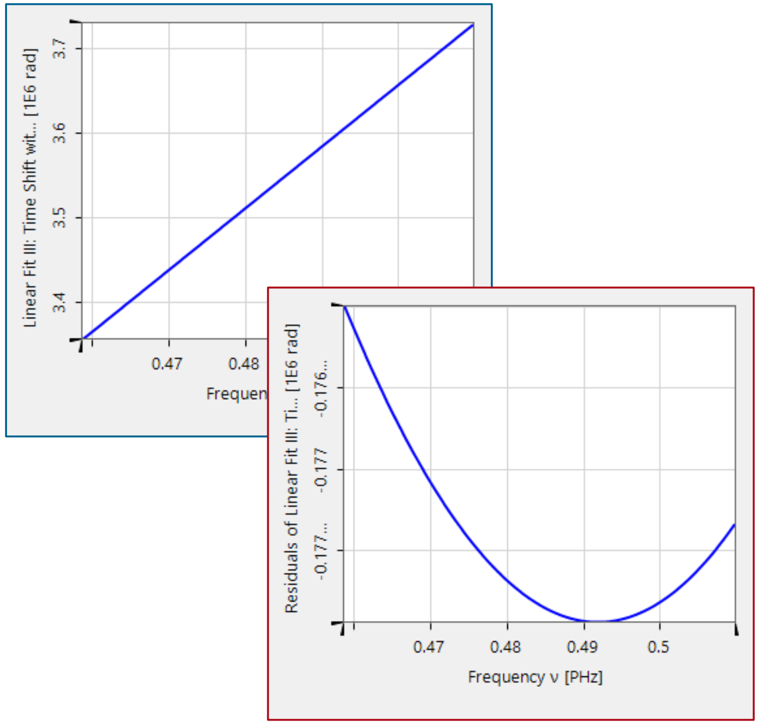


Time



31 fs

Phase v.s. Frequency

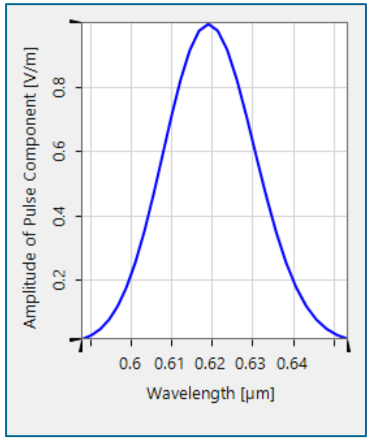


Residual after fitting

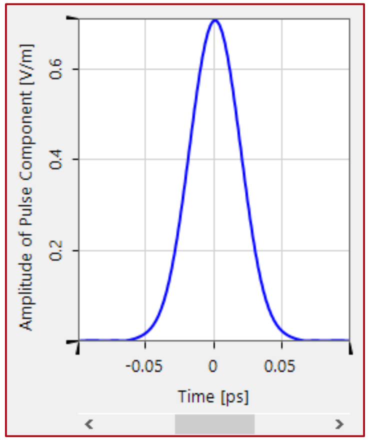
Pulse Propagation in SF57

- Input pulse
- Output pulse

Frequency

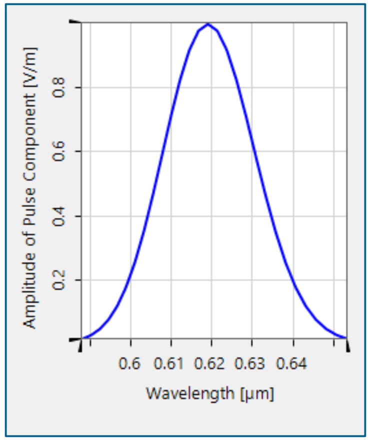


Time

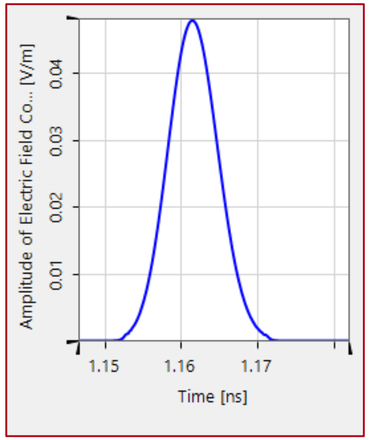


31 fs

Frequency



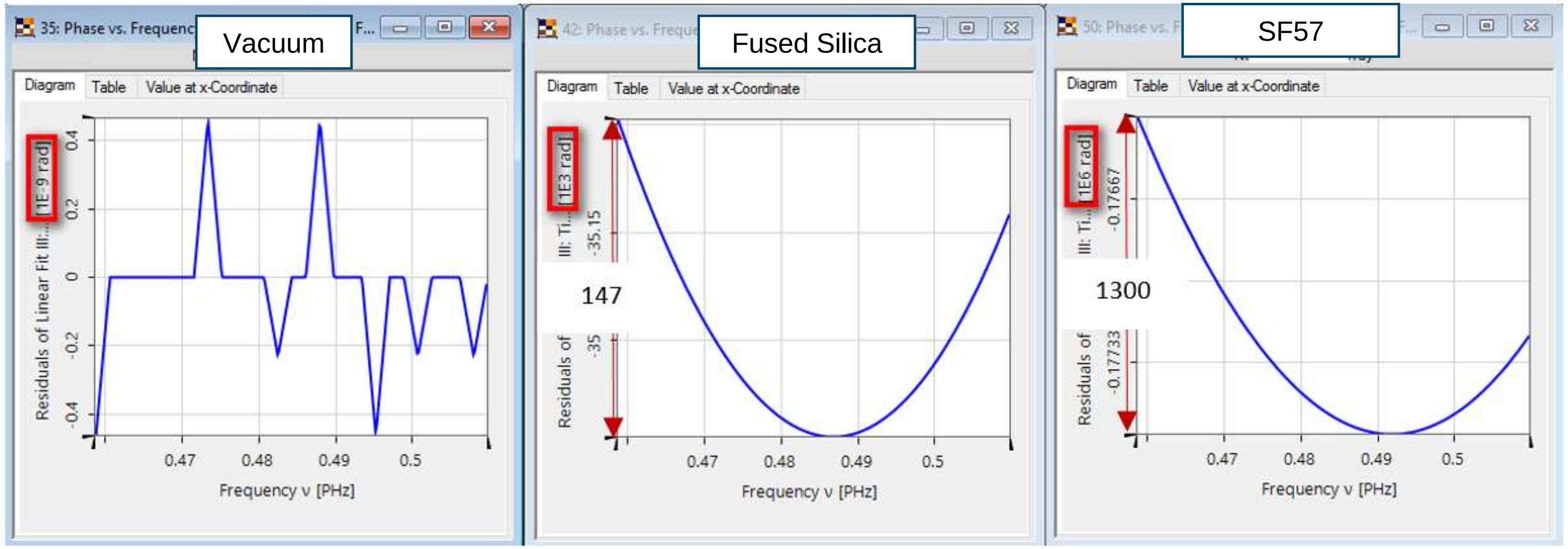
Time



5.4 ps

Short Summary

- Pulse broadening after propagation in dispersive medium
- Why?
- How to compress the output pulse?
  - Method: Compensate the residual phase after fitting



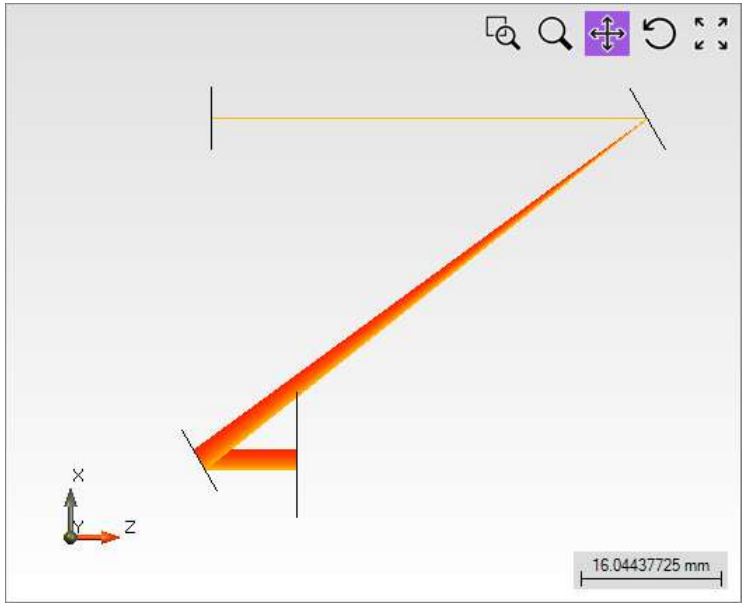
Pulse duration 31 fs 870 fs 5.4 ps

Pulse Propagation after a Grating Pair

- Input pulse
  - Carrier wavelength：619 nm
  - Pulse duration：31 fs

- Spec of gratings pair
  - Period：1.667 µm
  - Rotation angle：30°
  - Diffraction order：+1
  - Distance between two grating：64 mm

- Ray Tracing

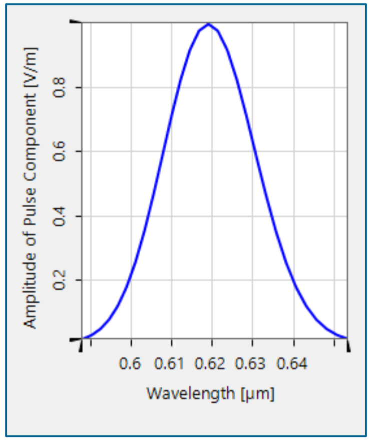


Related file：Compressor.Only_30fs@619nm.lpd

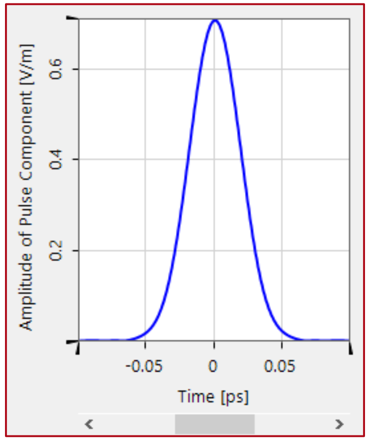
Pulse Propagation after a Grating Pair

- Input pulse

Frequency



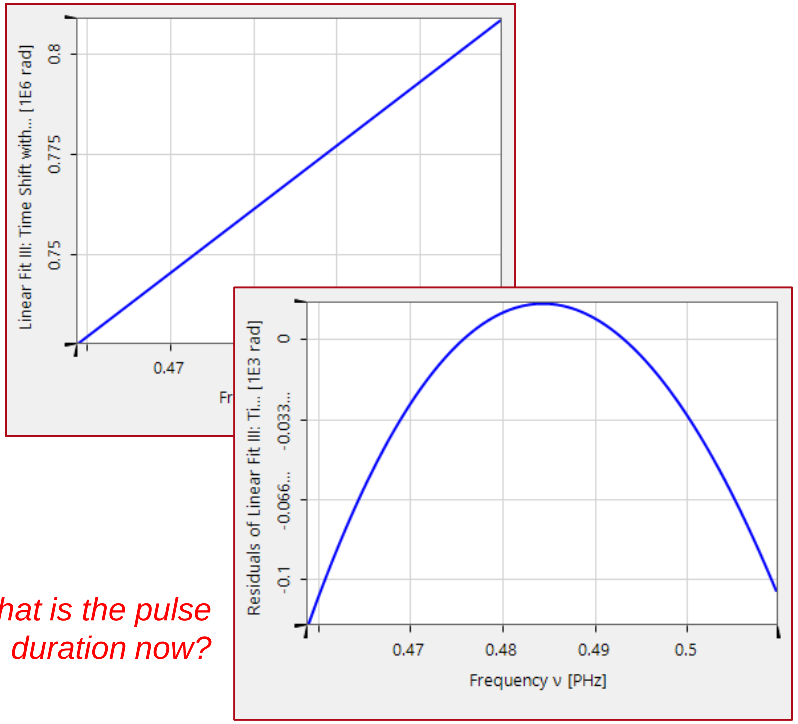
Time



31 fs

- Output pulse

Phase



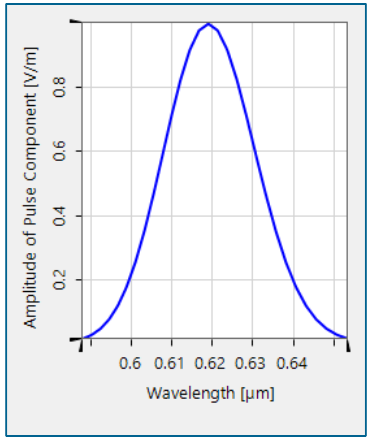
What is the pulse duration now?

Residual after fitting

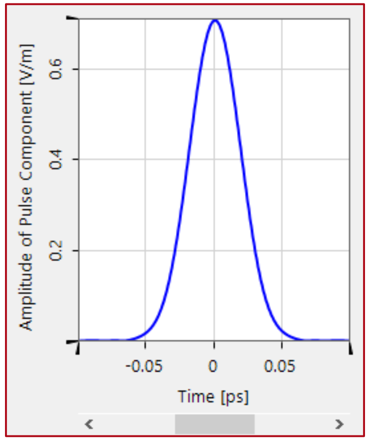
Pulse Propagation through Grating Pair

- Input pulse
- Output pulse

Frequency

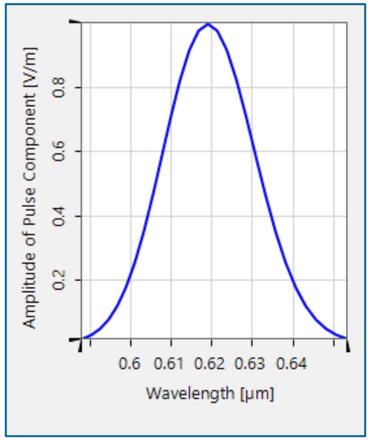


Time

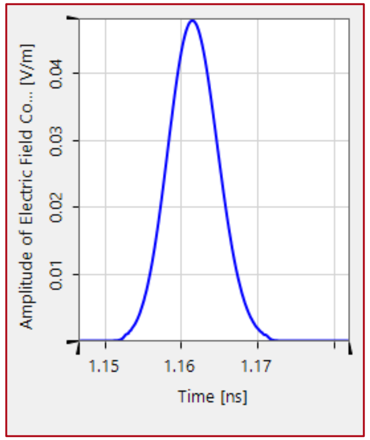


31 fs

Frequency



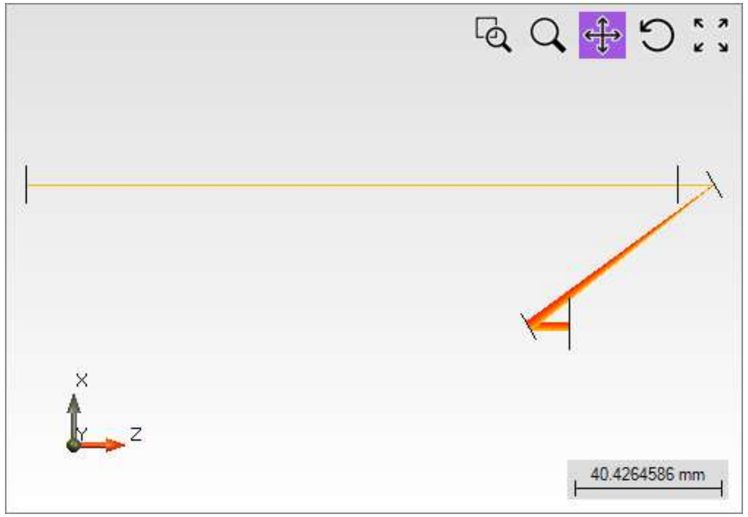
Time



5.4 ps

Combine the Dispersive Medium and Gratings

- Input pulse
  - Carrier wavelength：619 nm
  - Pulse duration：31 fs
- Dispersive medium
  - Thickness：180 mm
  - Fused silica
- Grating pair
  - Period：1.667 μm
  - Rotation angle：30°
  - Diffraction order：+1
  - Distance between two grating：64 mm
- Ray Tracing

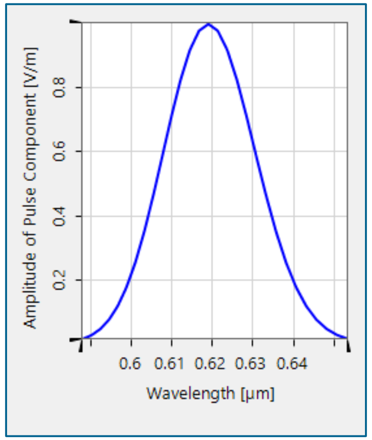


Related file：**Silica.Dispersion+Compressor_30fs@619nm.lpd**

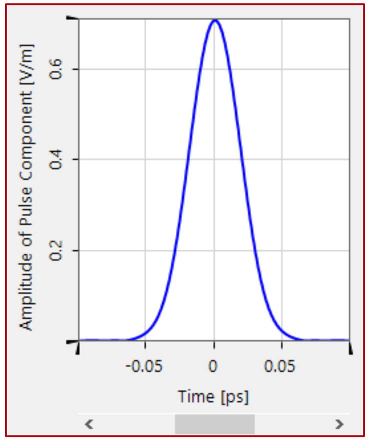
Compressor

- Output pulse
- Input pulse

Frequency

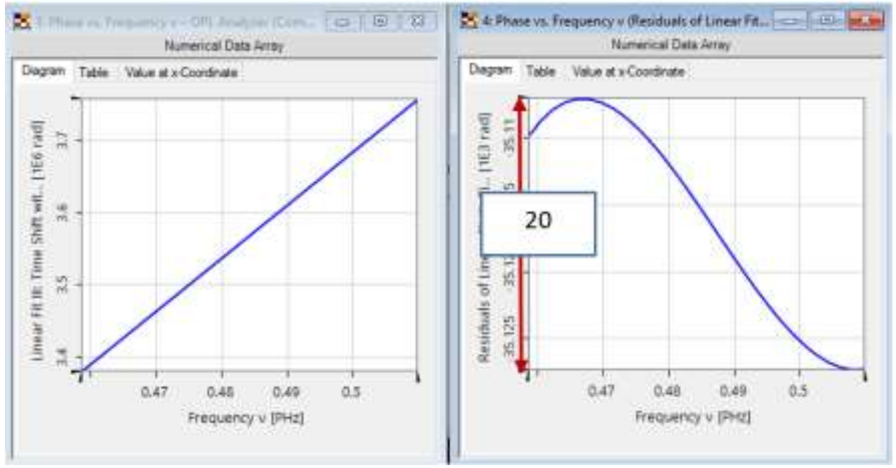


Time



31 fs

Phase v.s. Frequency

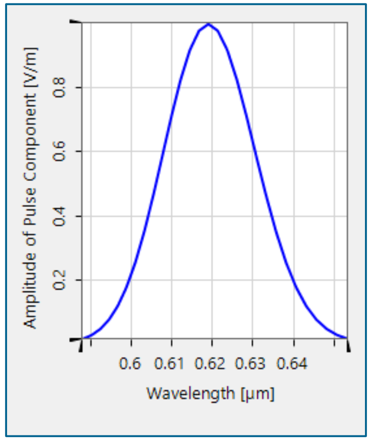


Residual

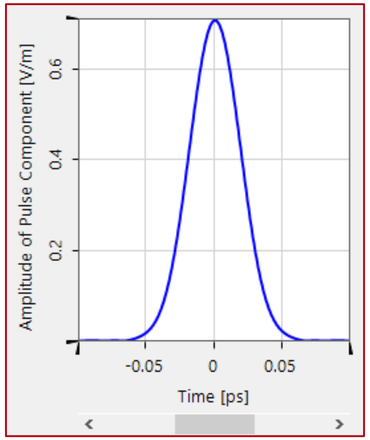
Compressor

- Input pulse
- Output pulse

Frequency

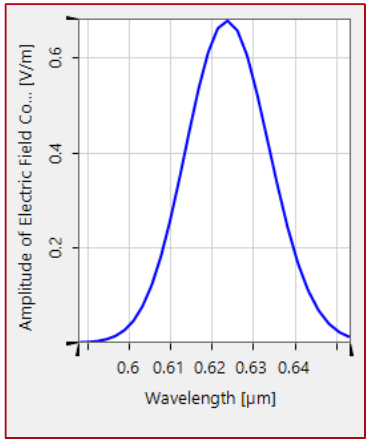


Time

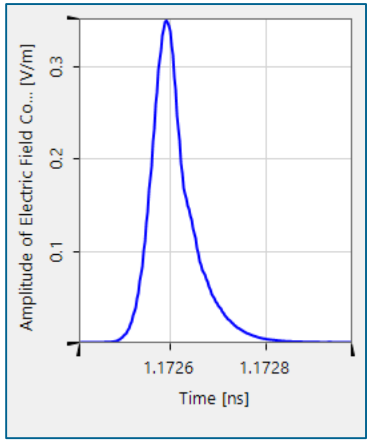


31 fs

Frequency



Time

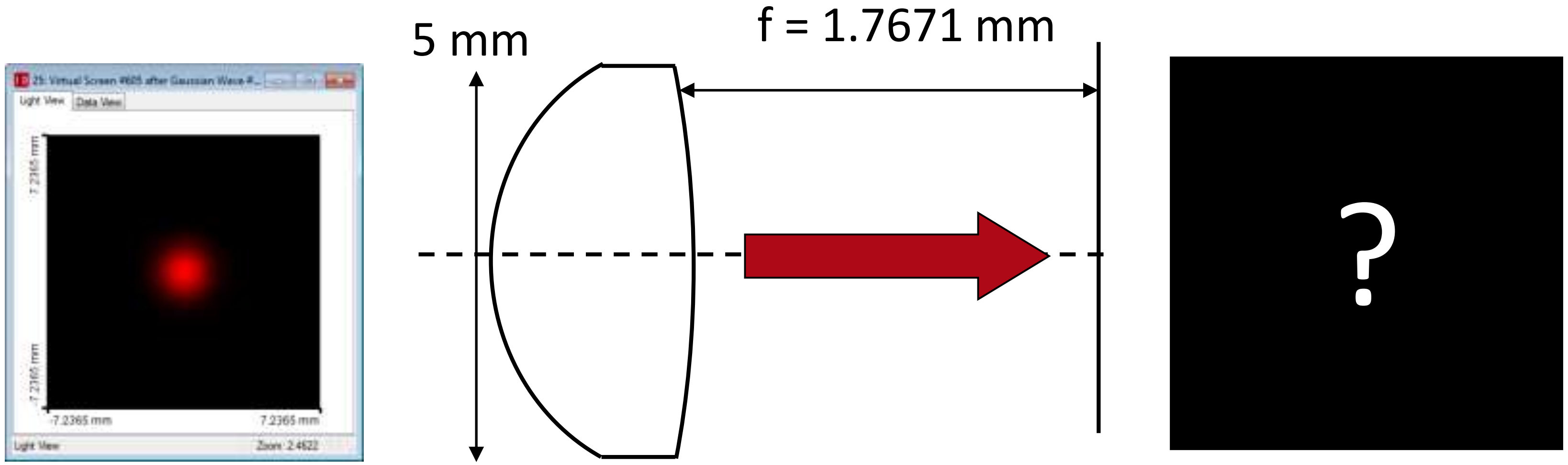


Pulse duration：
47 fs << 870 fs

Experiment 0004

Spatiotemporal Evolution of Femtosecond Pulse Focus

Overview



Laser beam

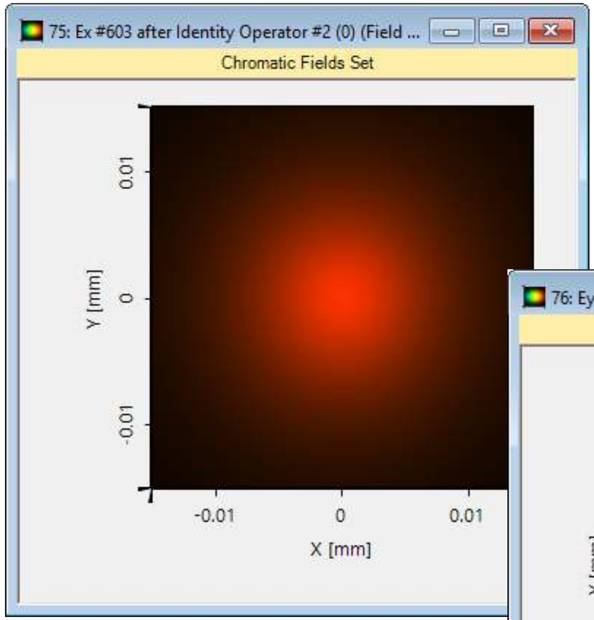
Aspherical lens

Focal plane

NA=0.68

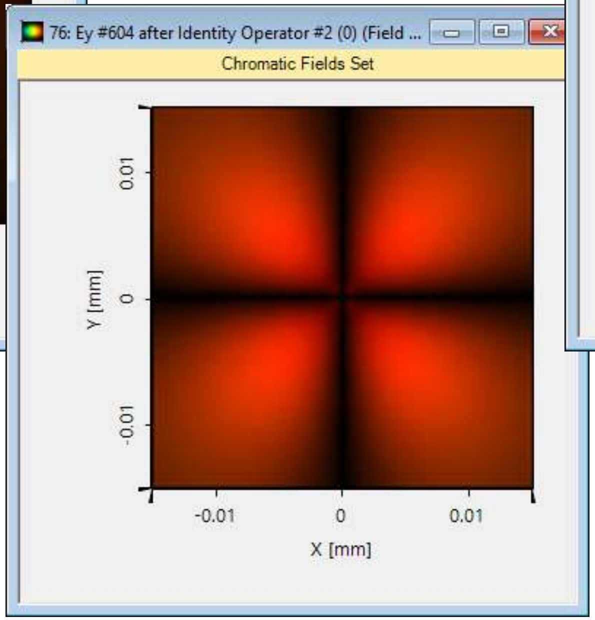
Simulation: Ex, Ey and Ez

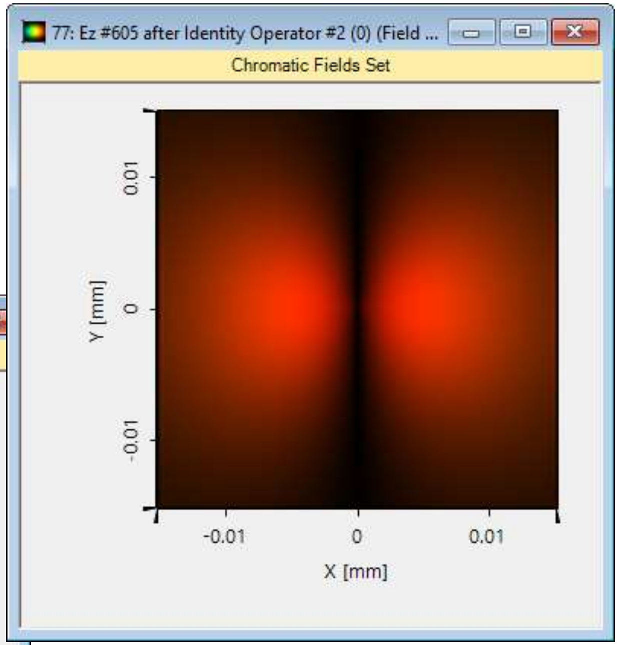
- Enable the detectors Ex, Ey and Ez



E_x

E_y

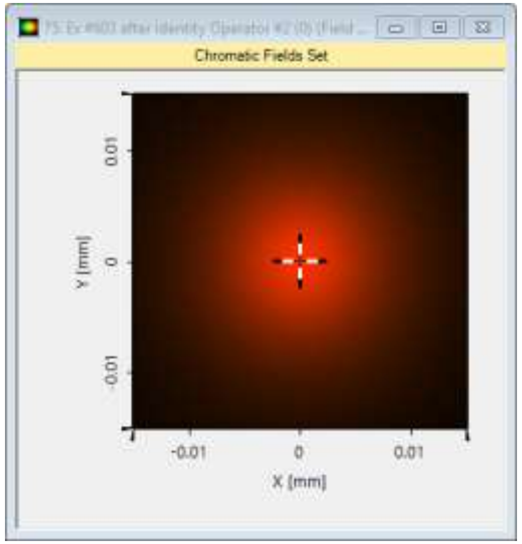




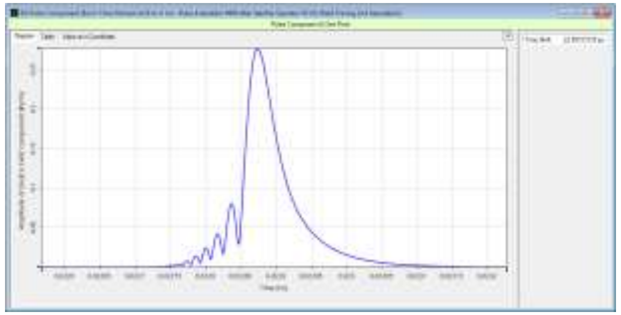
E_z

Simulation: Pulse at Point (0,0)

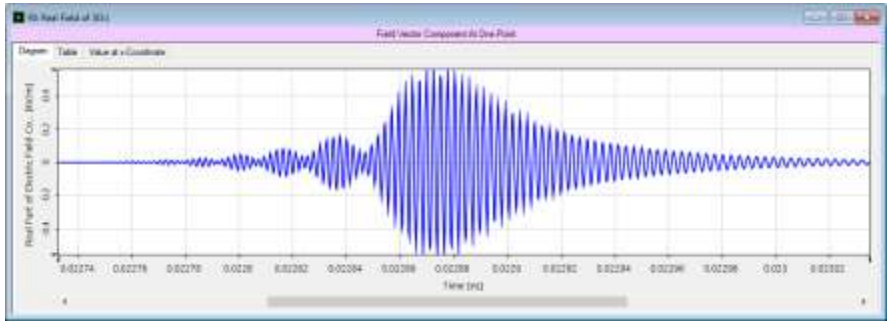
- Enable Detector Pulse Evaluation



E_x

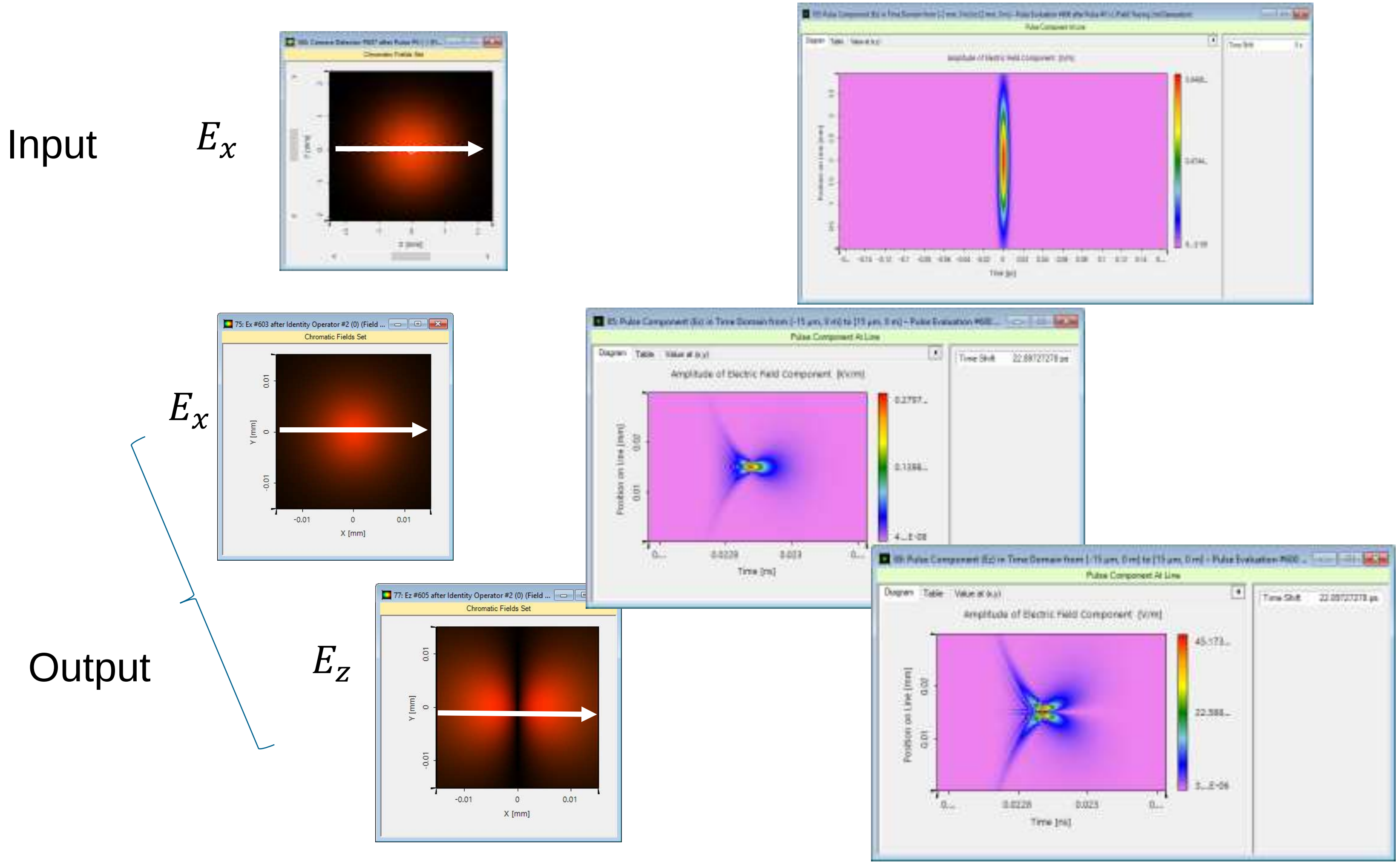


Envelope



Field

Simulation: Pulse along x-Axis

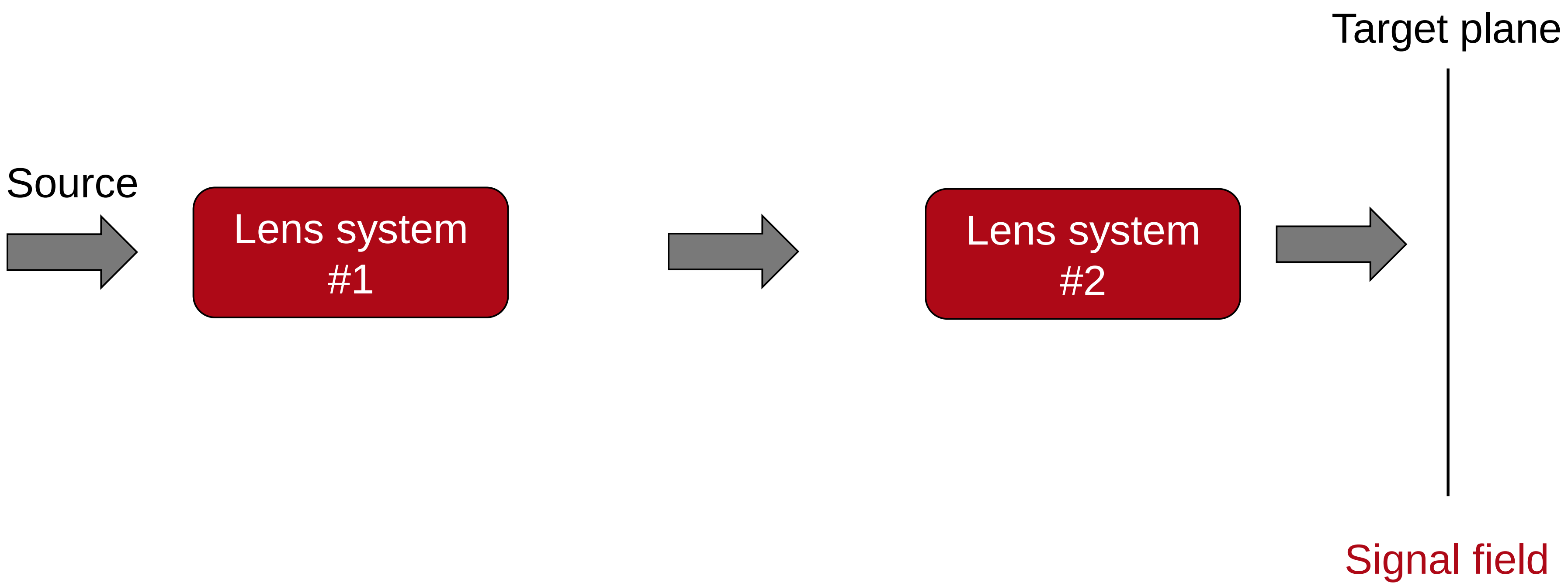


Light Shaping

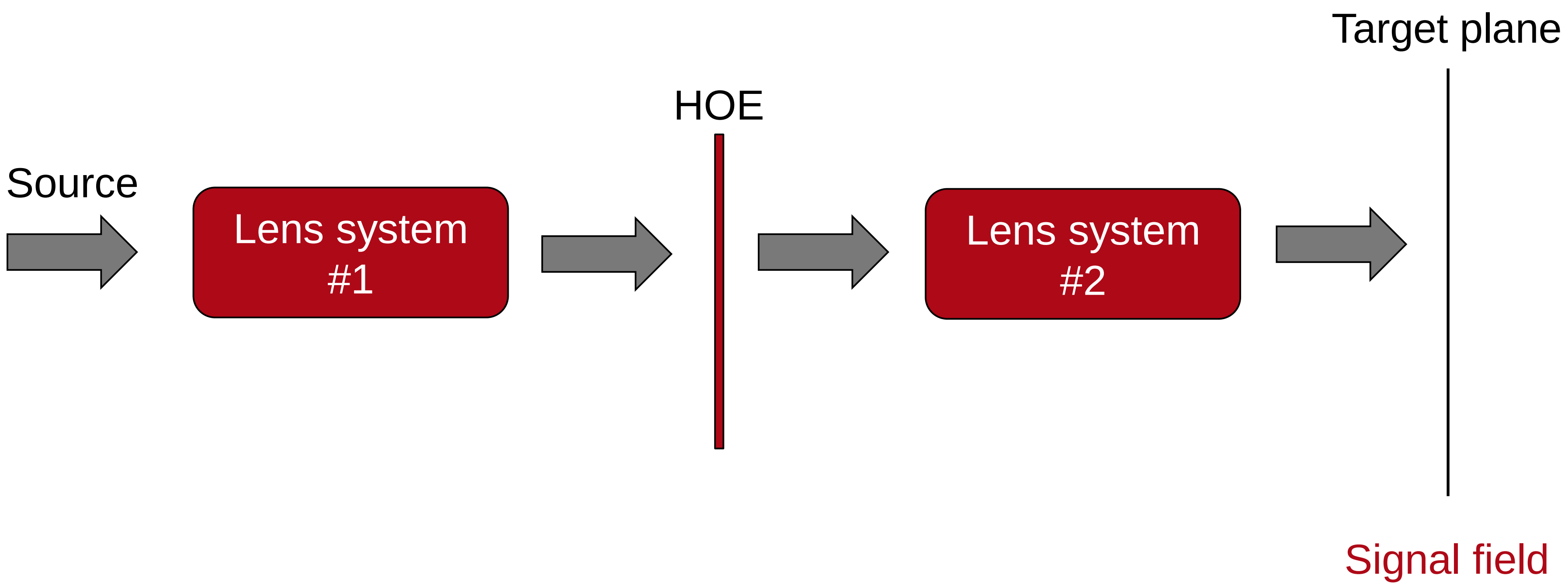
Light shaping by inverse approach

Concept of amplitude matching and consequences

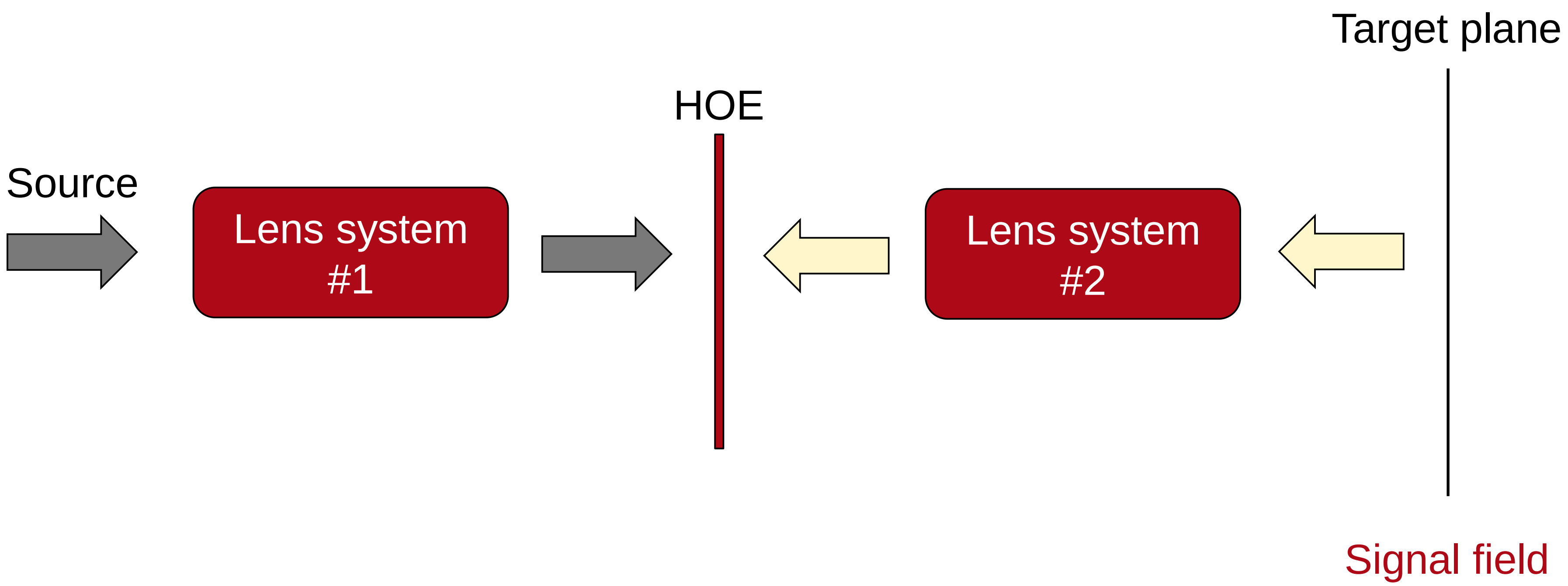
Inverse Design Concept: HOE and Freeform



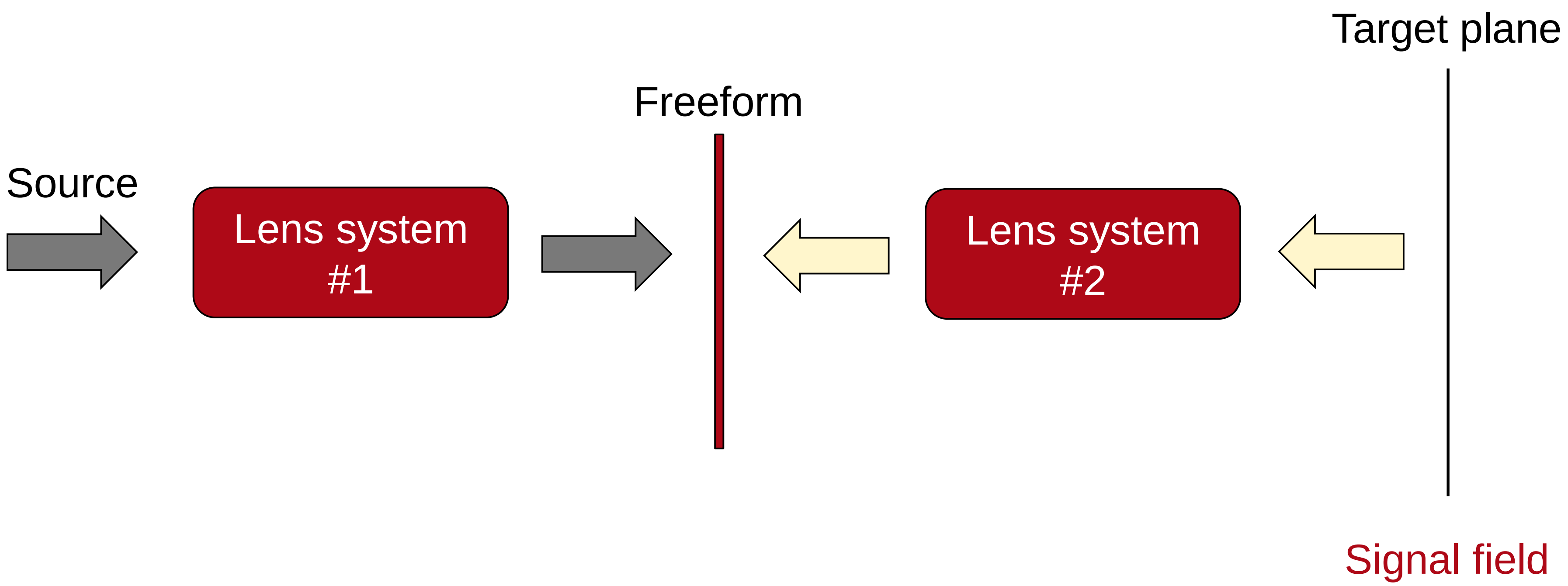
Inverse Design Concept: HOE and Freeform



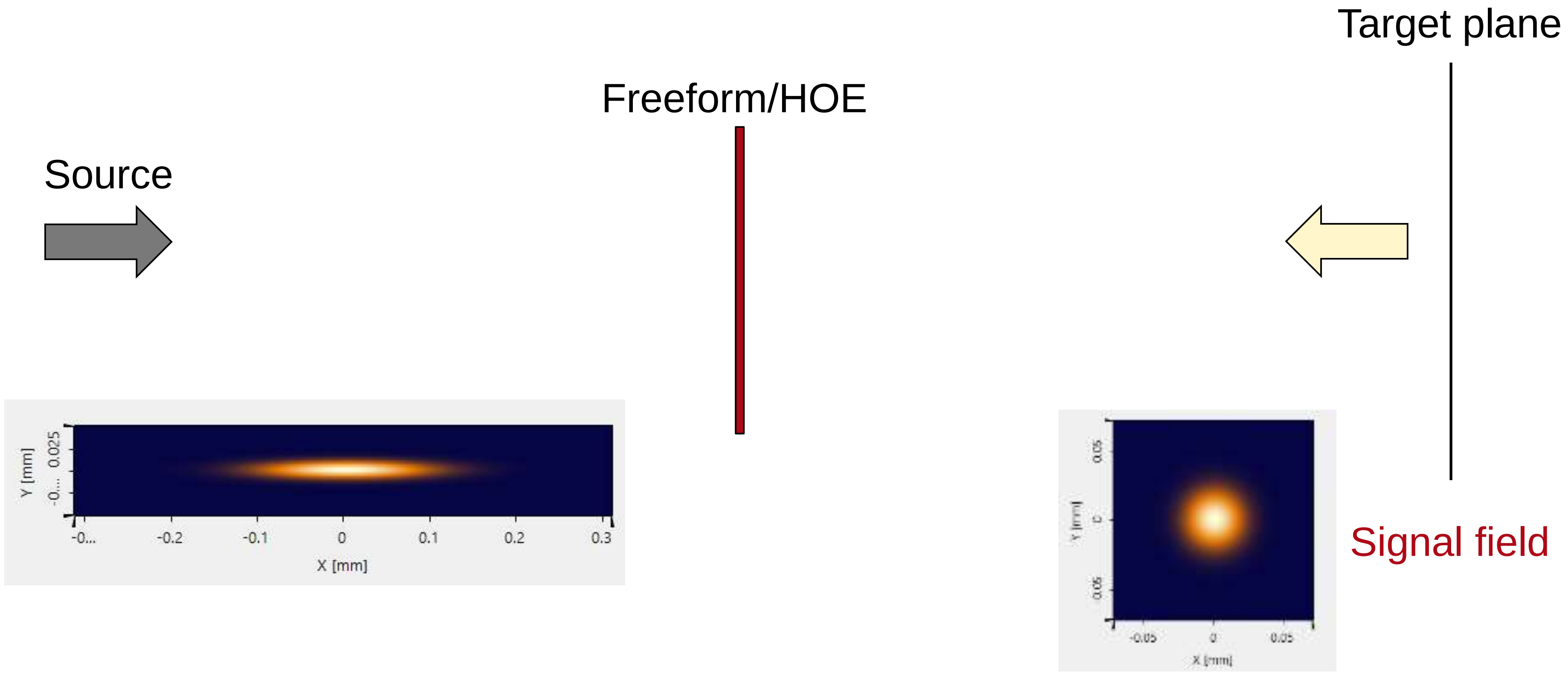
Inverse Design Concept: HOE and Freeform



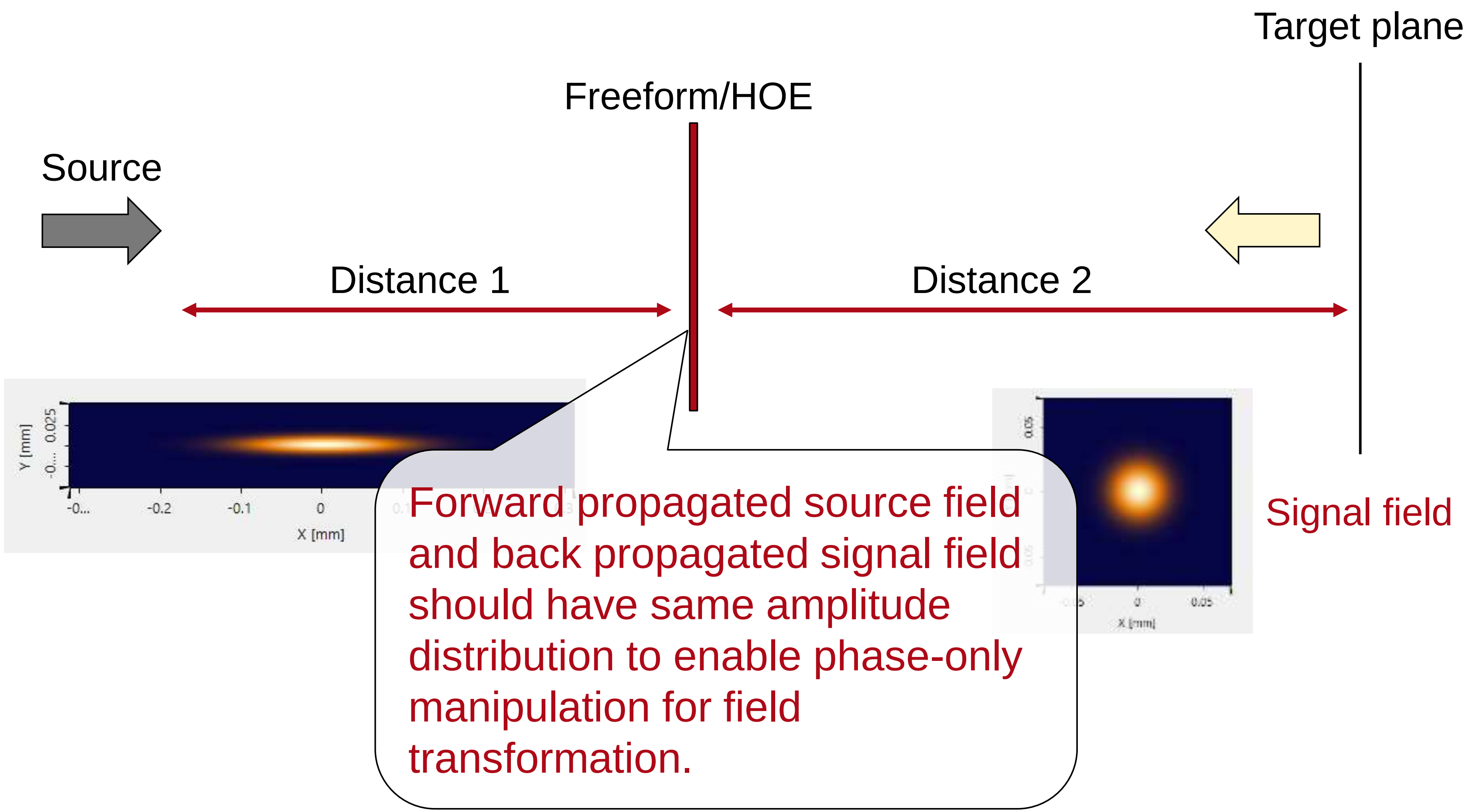
Inverse Design Concept: HOE and Freeform



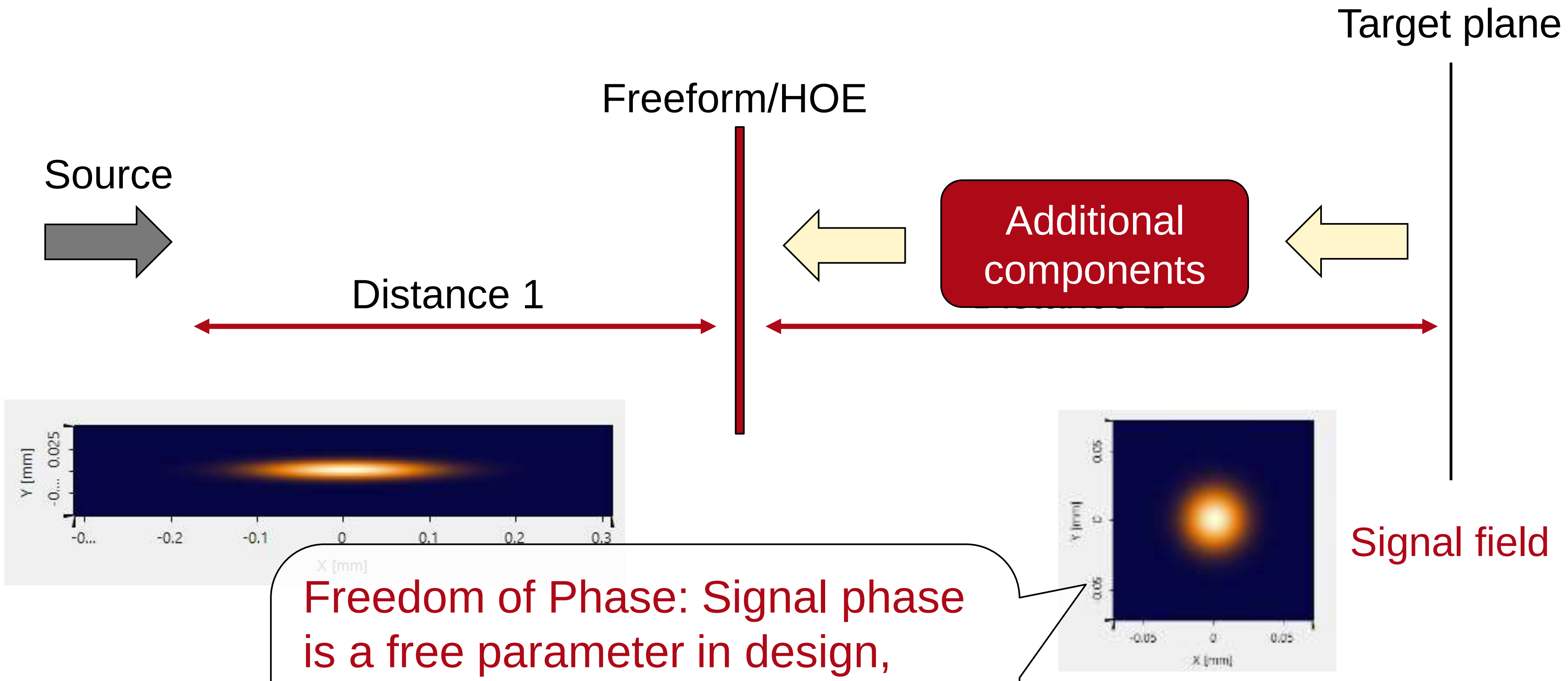
Inverse Design Concept: HOE and Freeform



Inverse Design Concept: HOE and Freeform

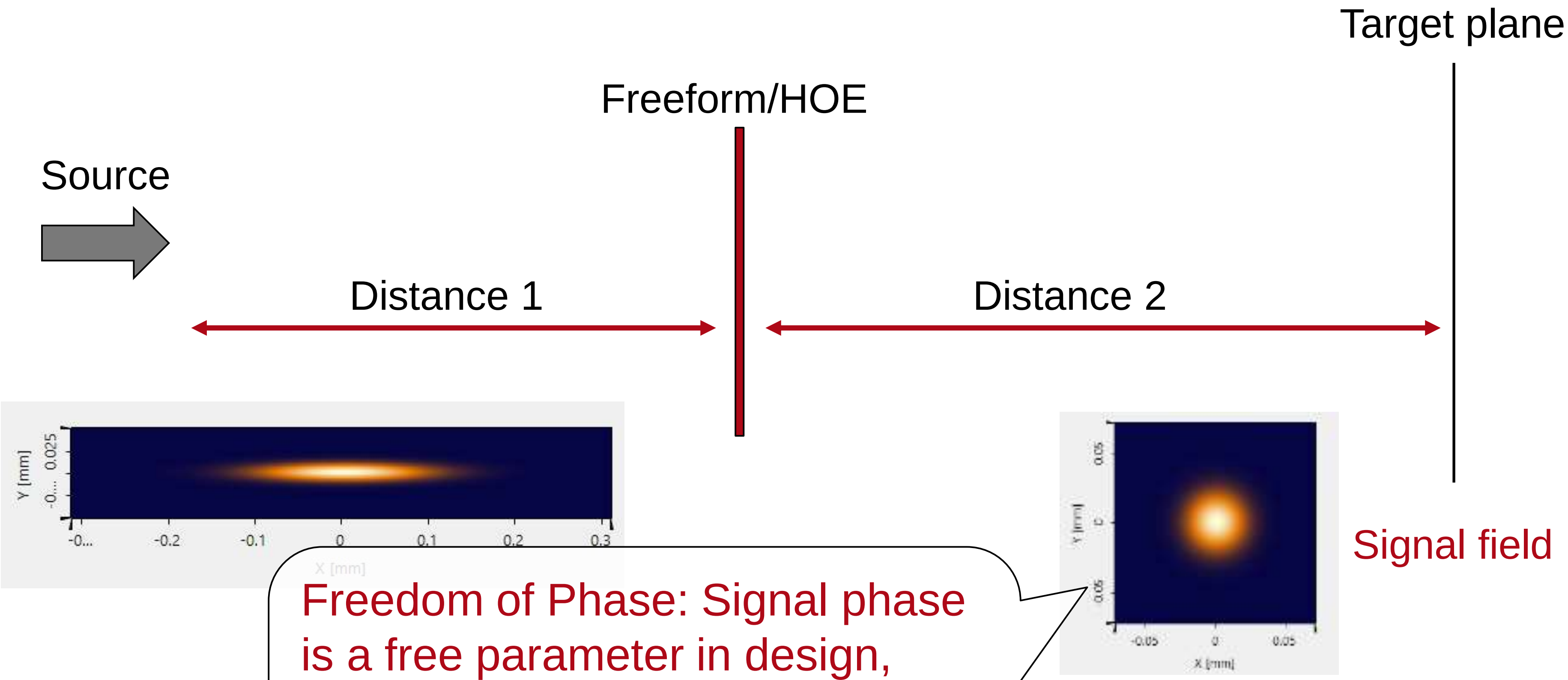


Inverse Design Concept: HOE and Freeform



Freedom of Phase: Signal phase is a free parameter in design, when only the intensity is of concern. Comment: Phase affects the 3D signal behavior.

Inverse Design Concept: HOE and Freeform



Freedom of Phase: Signal phase is a free parameter in design, when only the intensity is of concern. Comment: Phase affects the 3D signal behavior.

Light Shaping Concepts

- Tailored aberrations
- Stored scanning process
- Multichannel concept: Single Deflection
- Multichannel concept: General

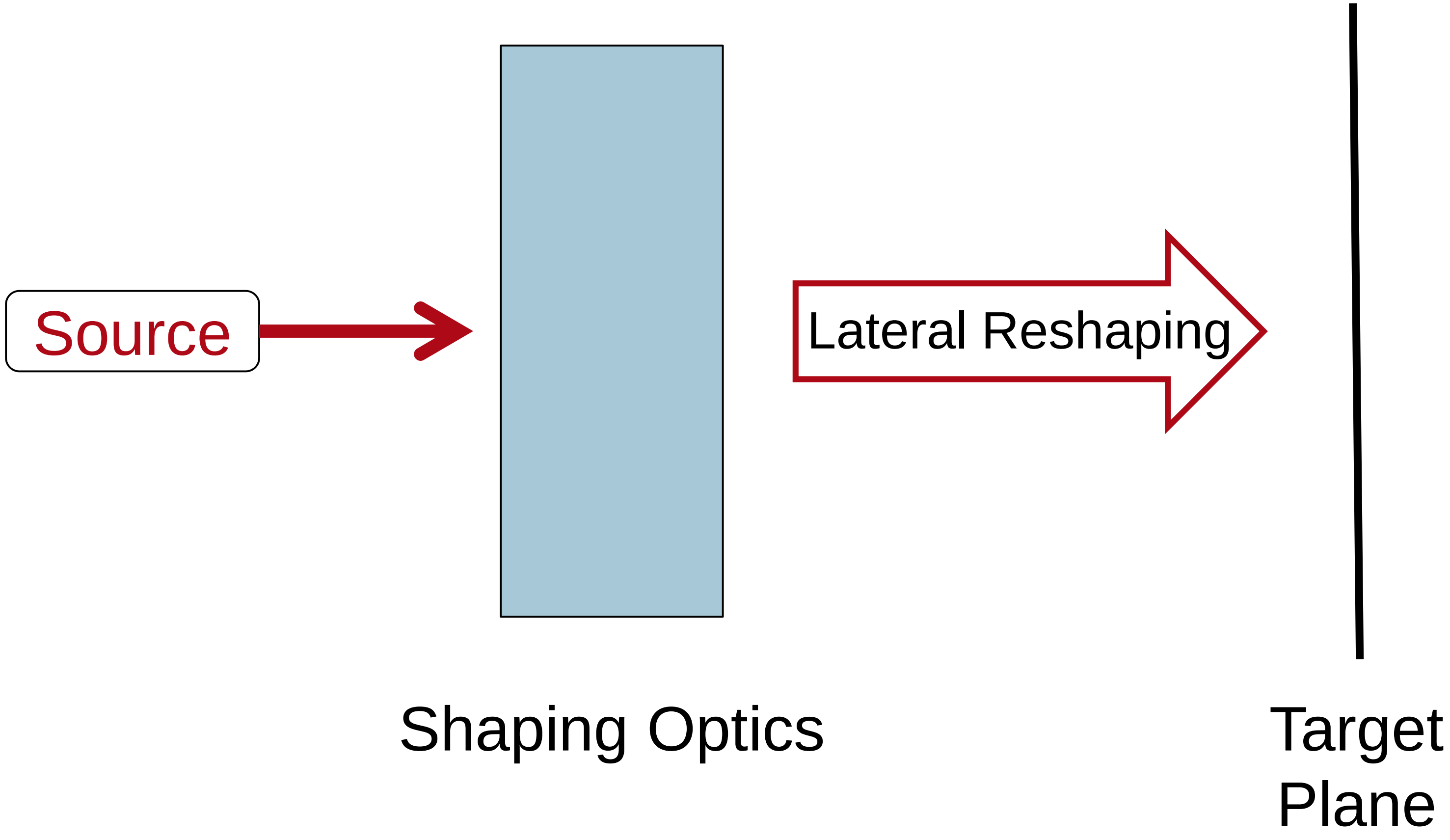
Light Shaping Concepts

- Tailored aberrations
- Stored scanning process
- Multichannel concept: Single Deflection
- Multichannel concept: General

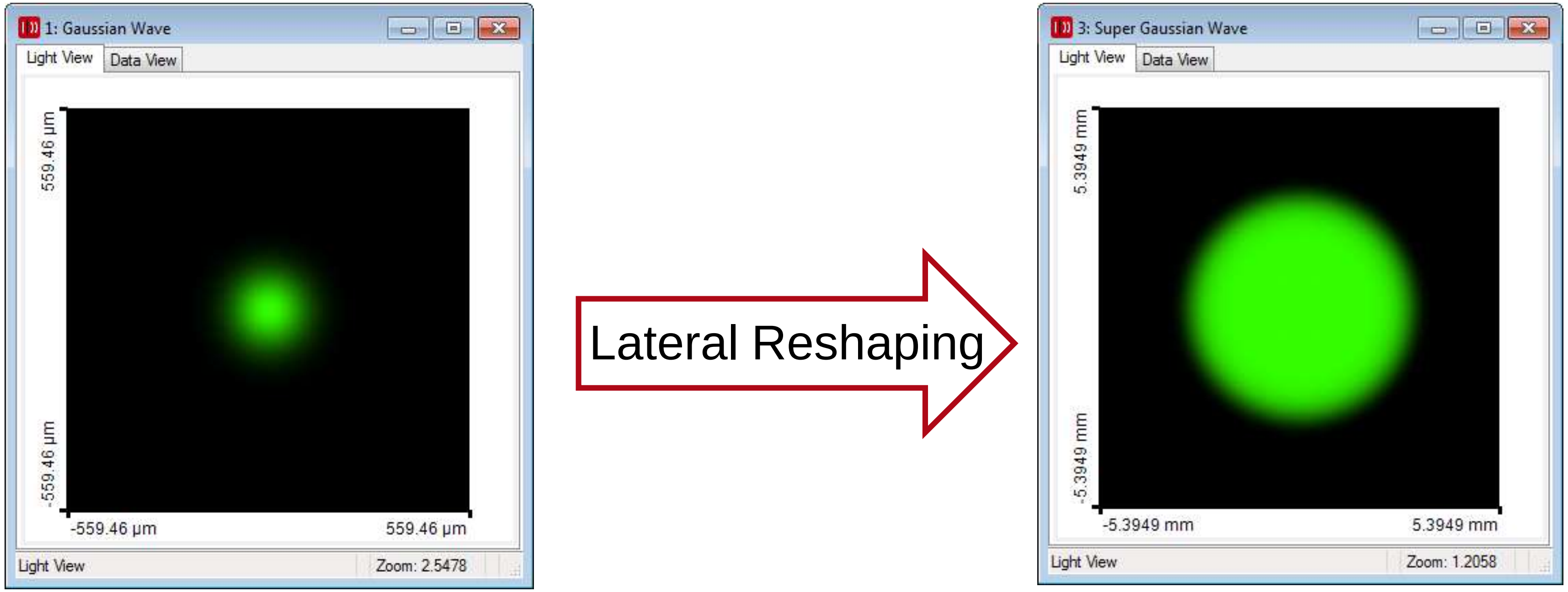
Light shaping by tailored aberrations

Refractive and diffractive optical elements

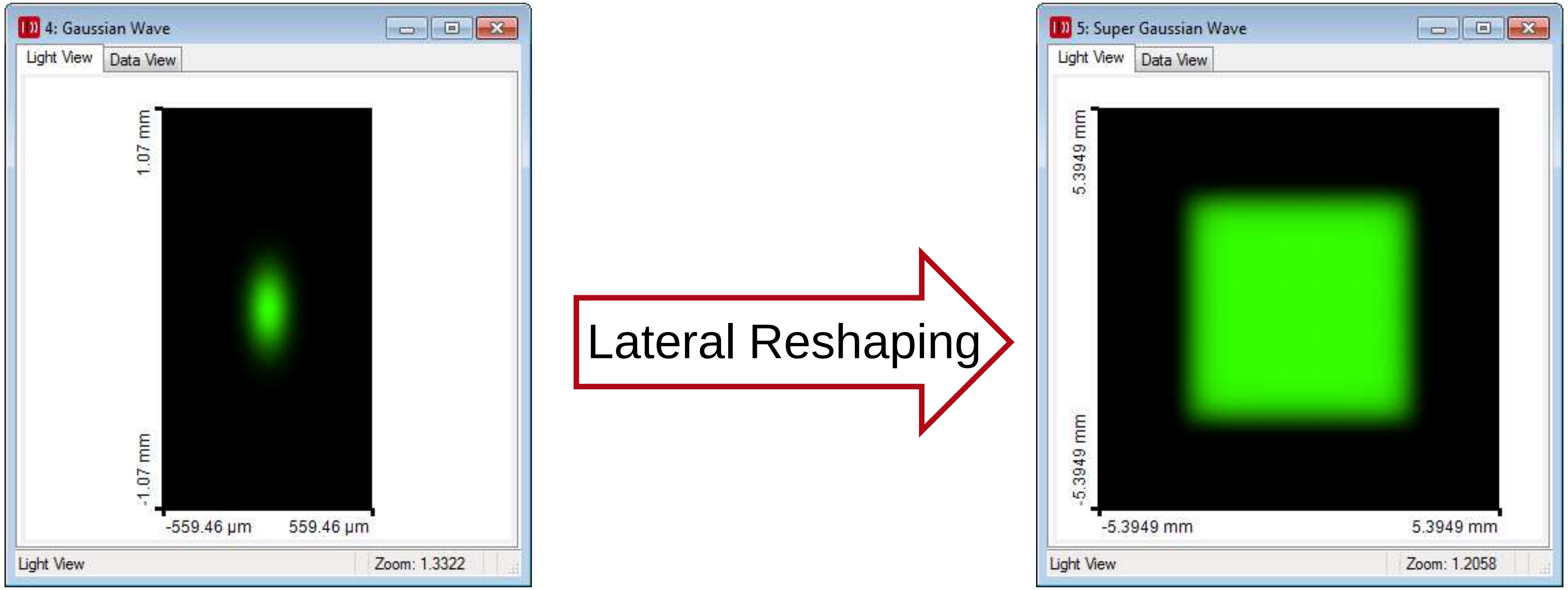
Beam Shaping: The Task



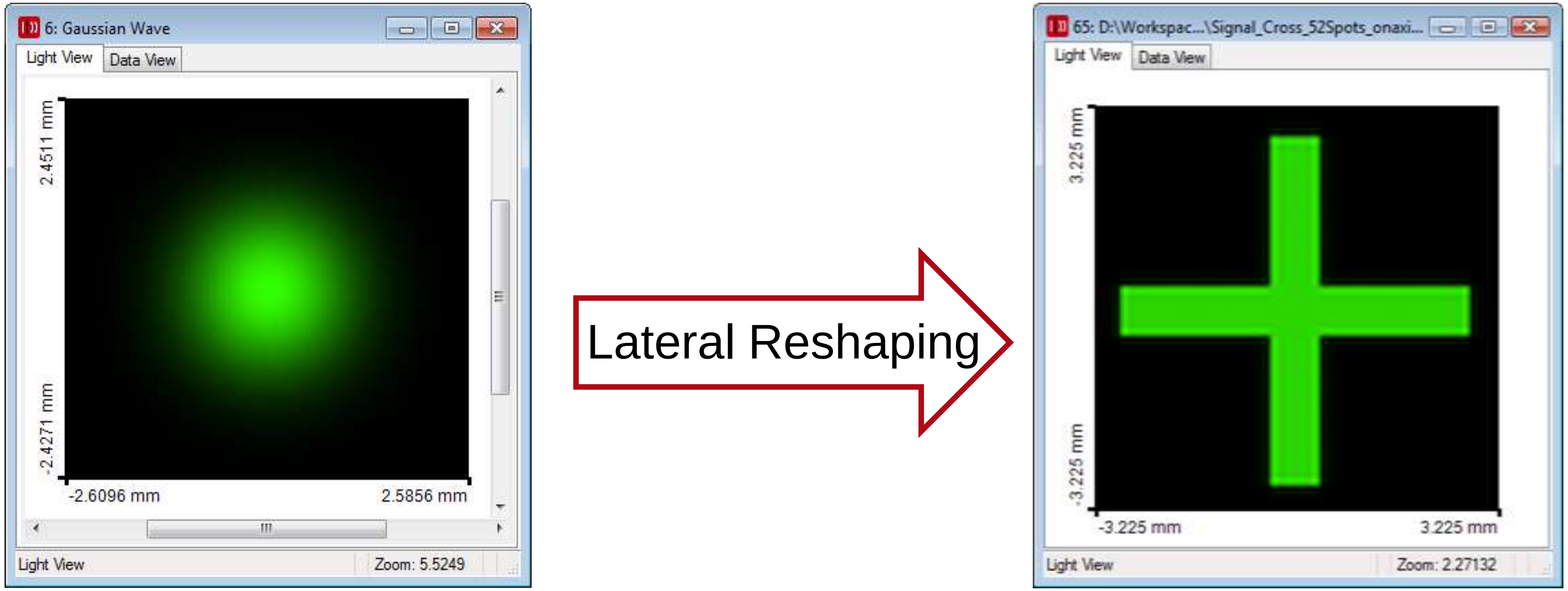
Beam Shaping: The Task



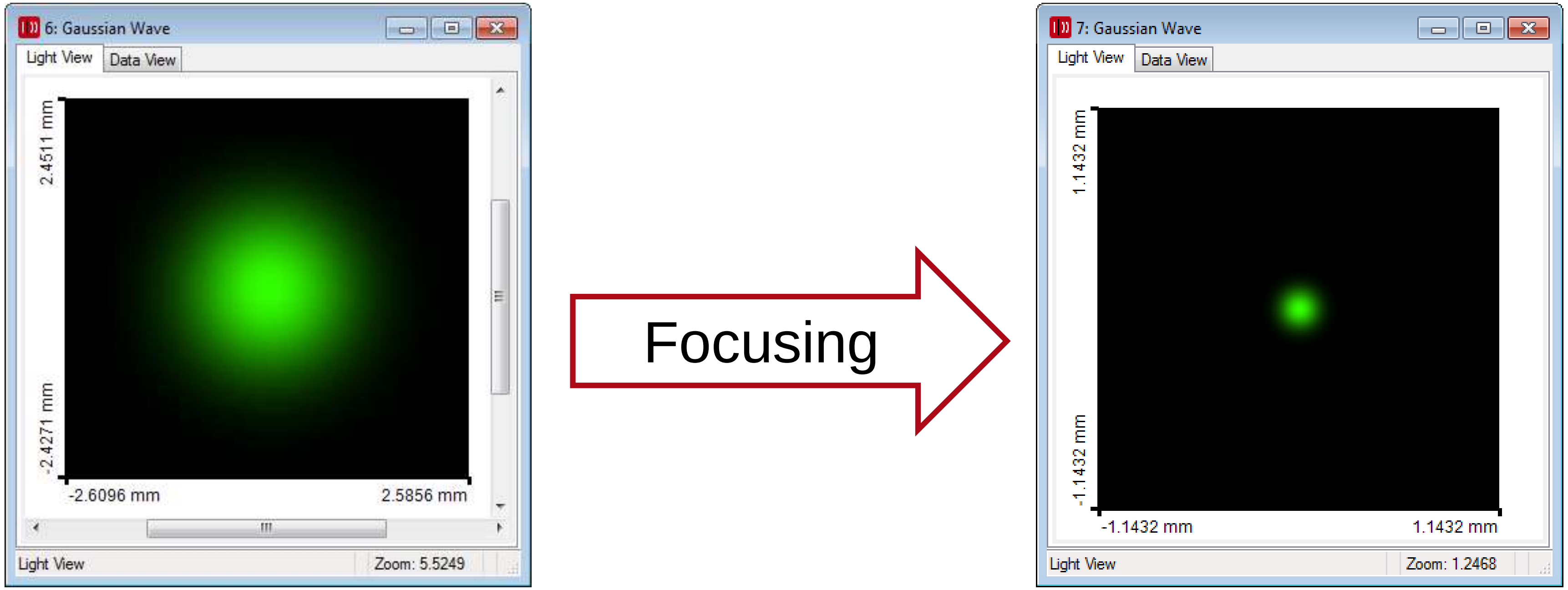
Beam Shaping: The Task



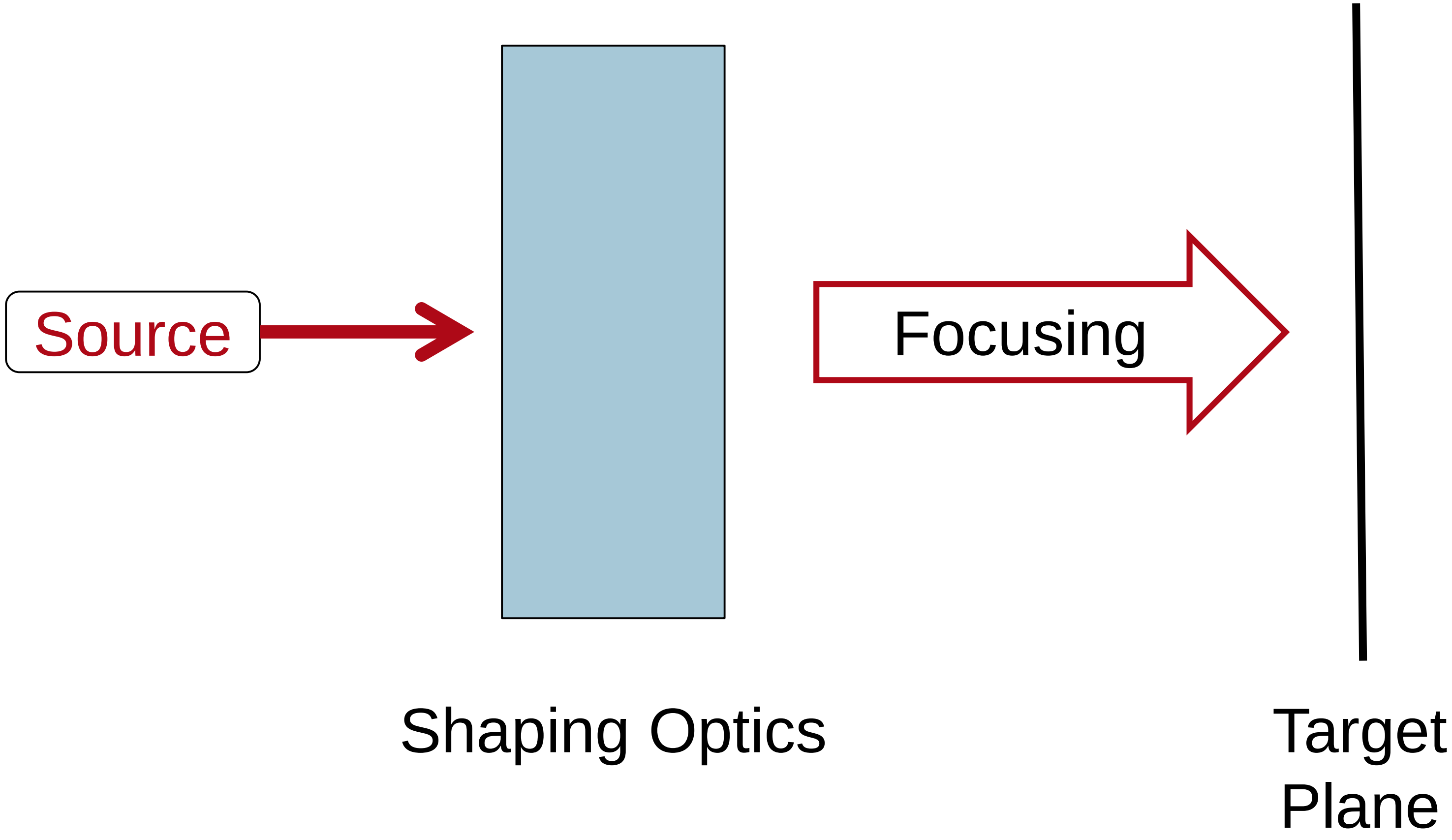
Beam Shaping: The Task



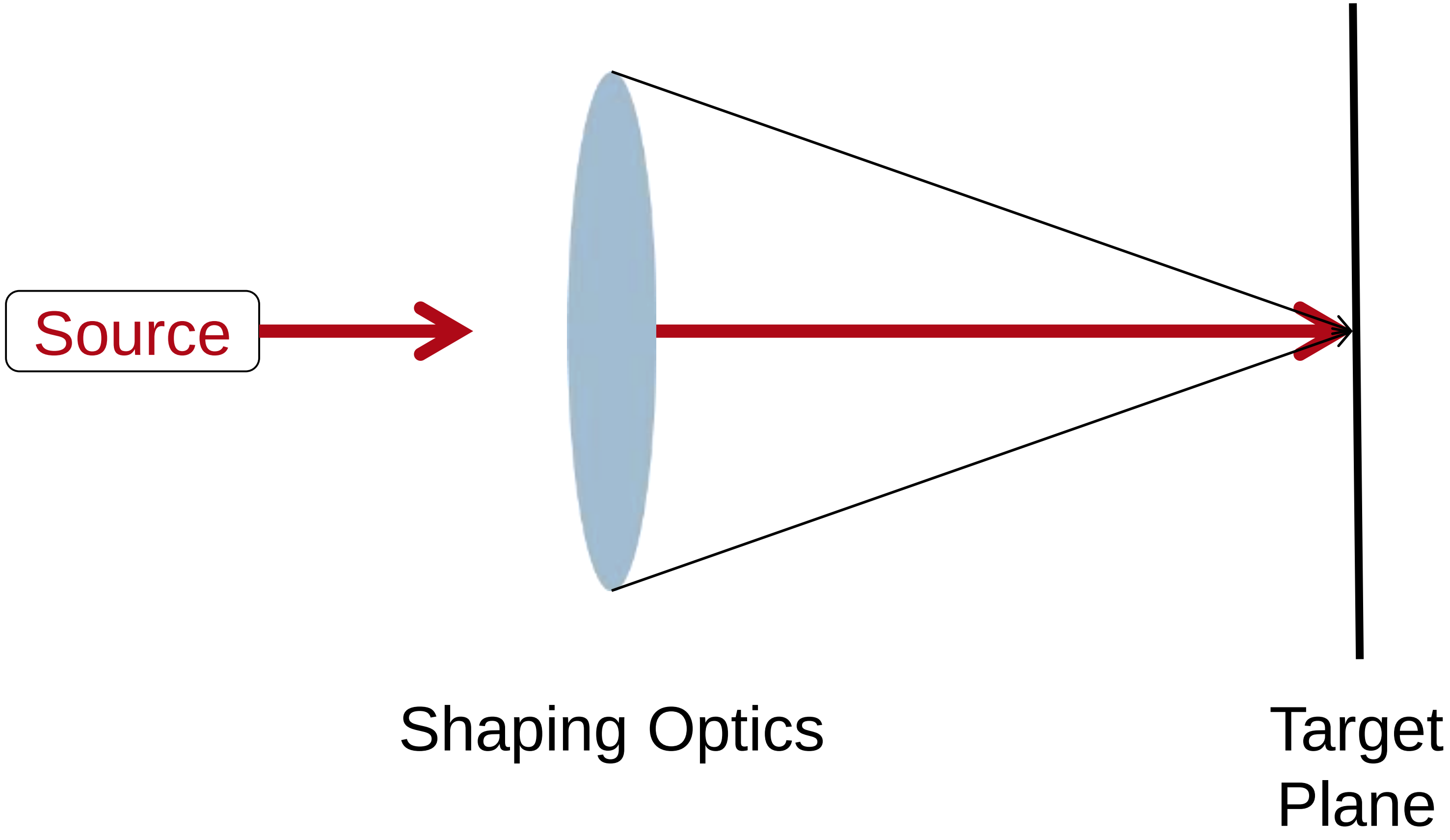
Basic „Beam Shaping“ Task: Focusing



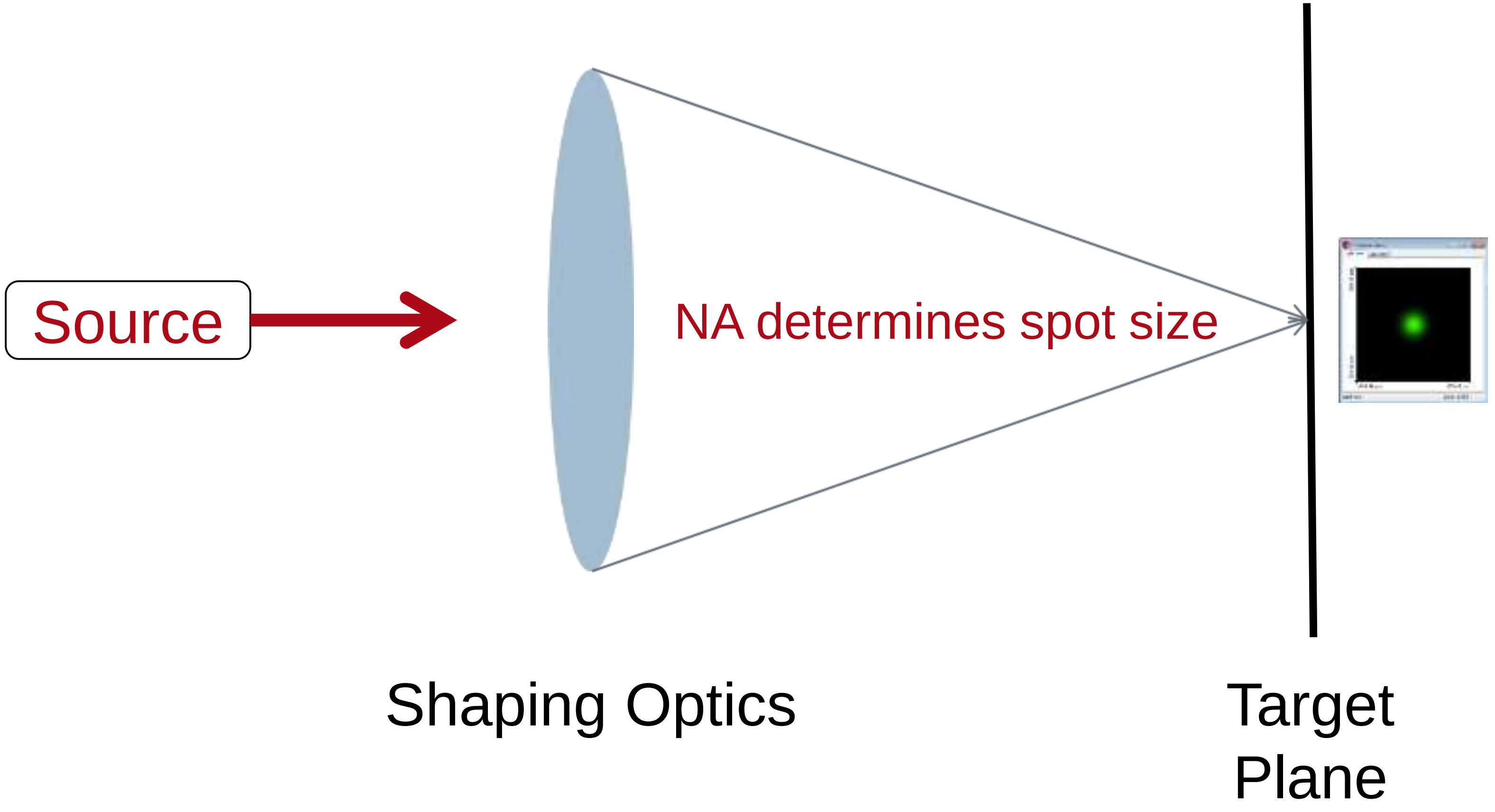
Basic „Beam Shaping“ Task: Focusing



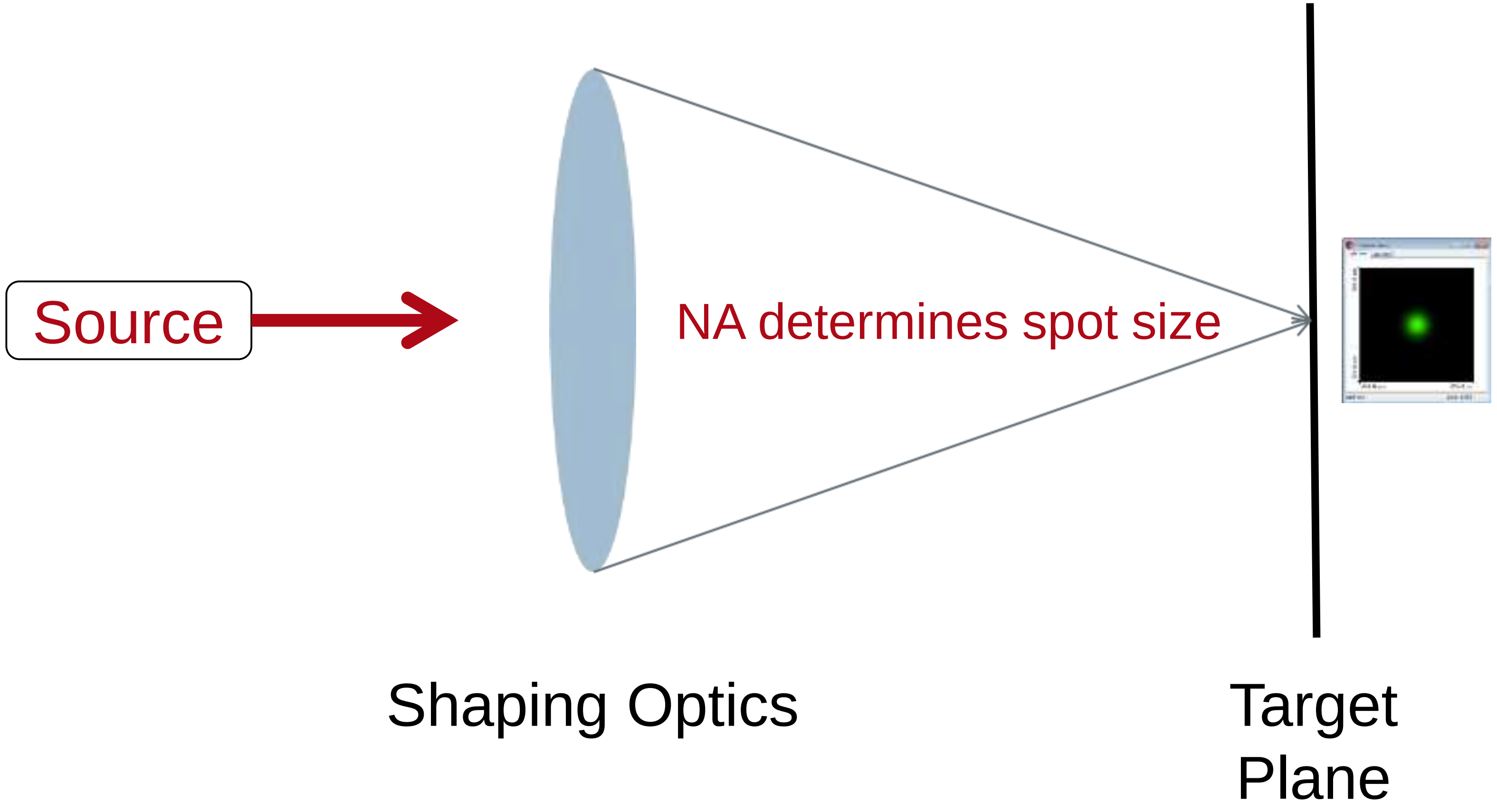
Basic „Beam Shaping“ Task: Focusing



Basic „Beam Shaping“ Task: Focusing

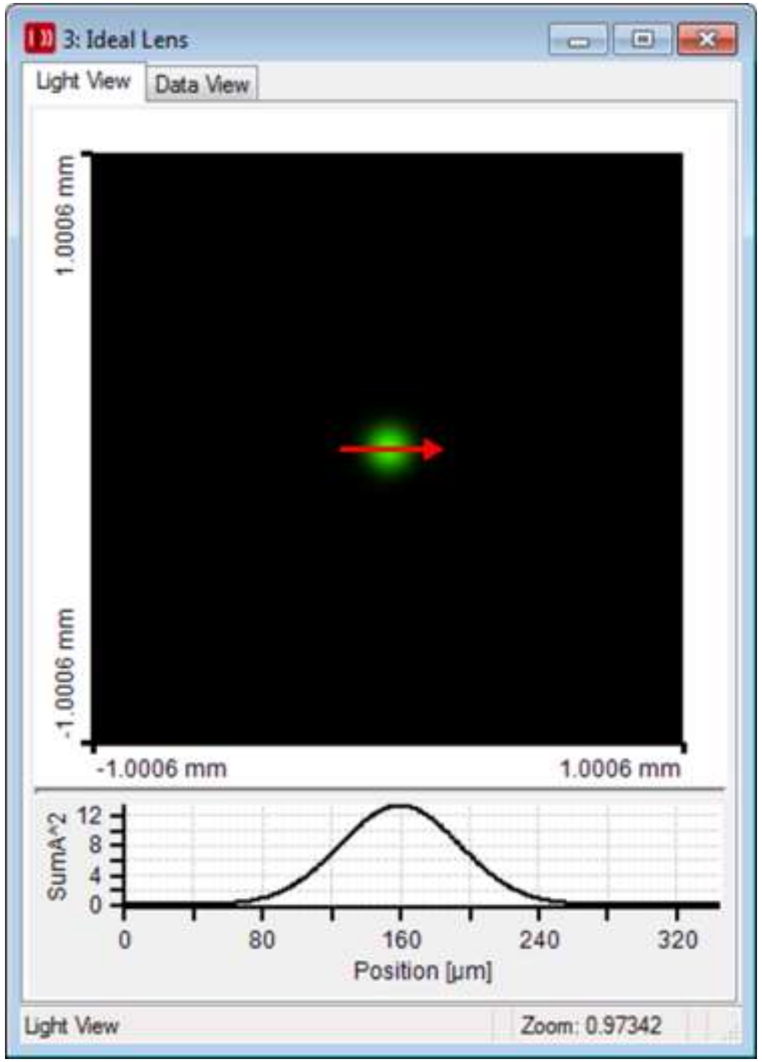


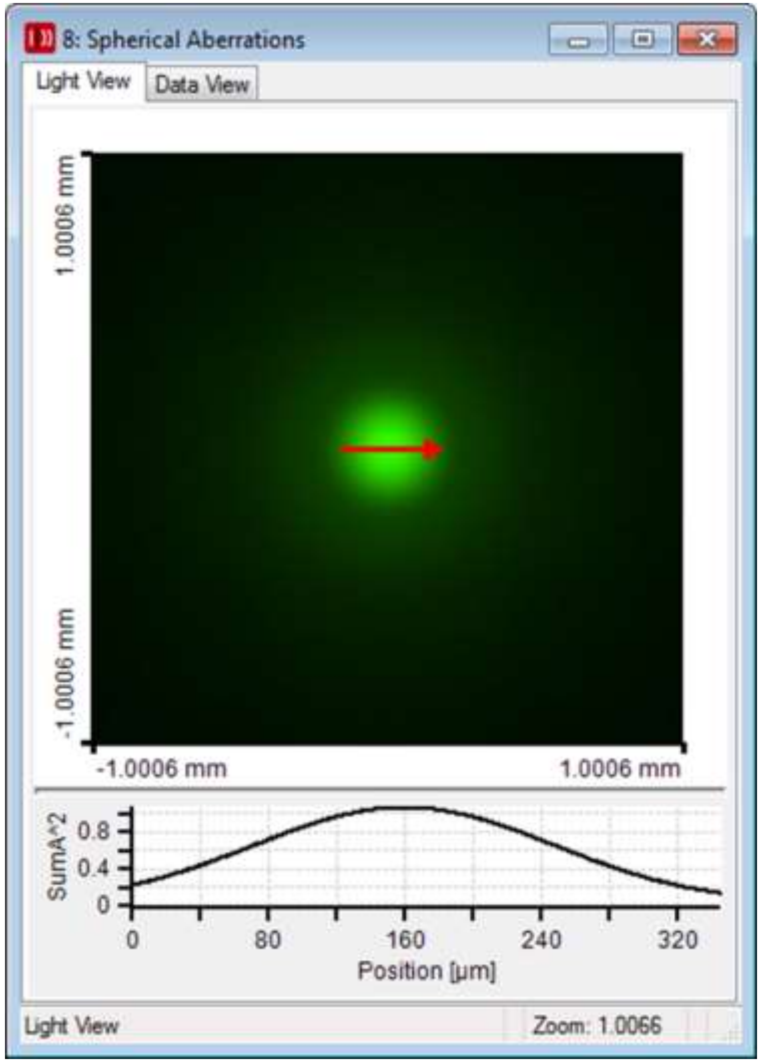
Light Shaping by Aberrations



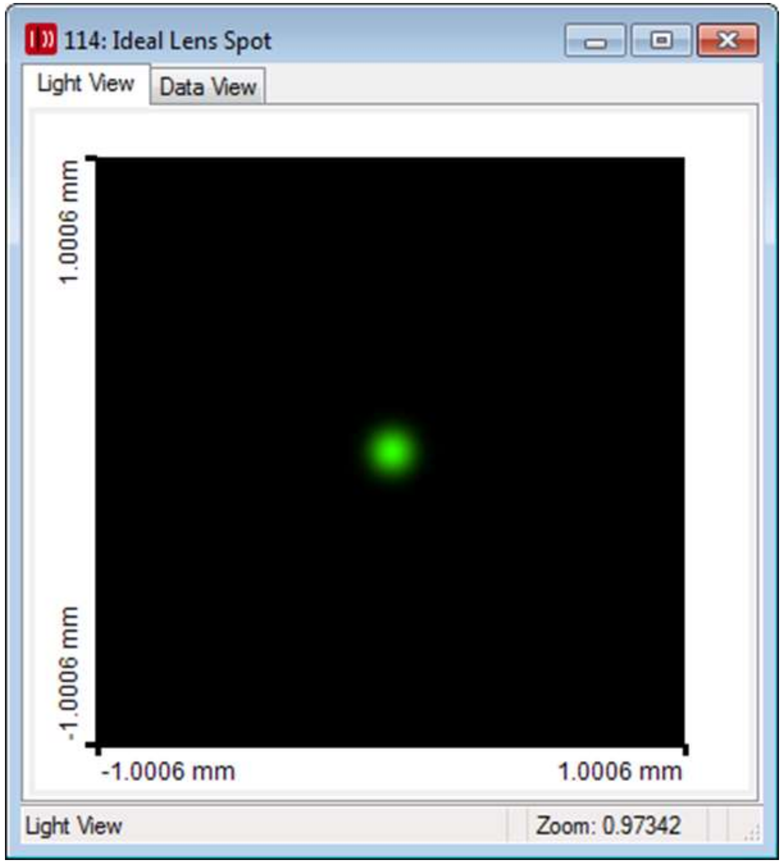
Beam shaping can be understood as the introduction of aberrations to shape the focus!

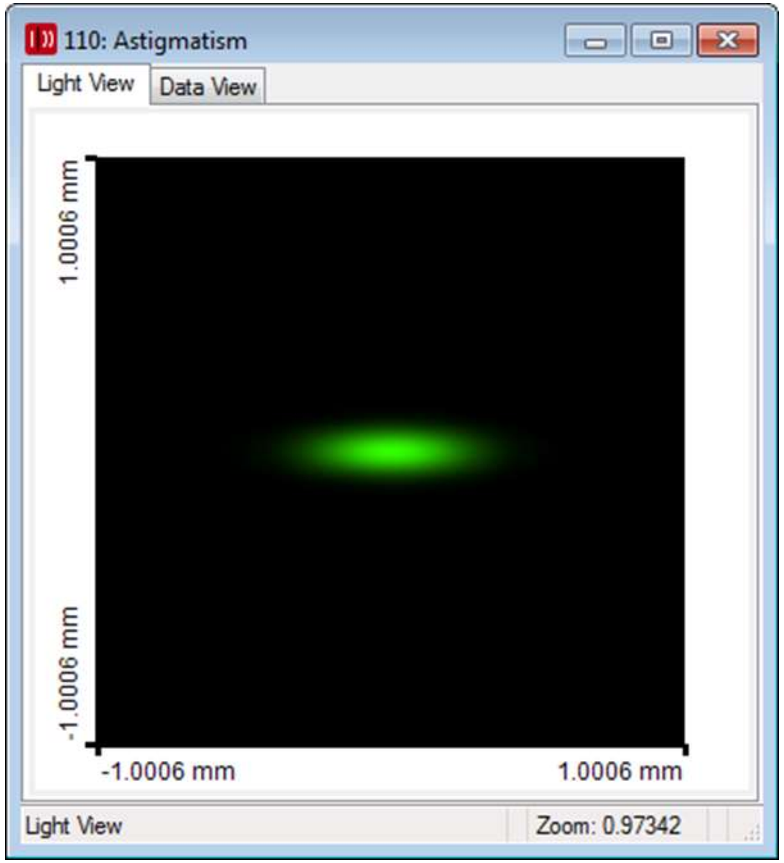
Ideal Lens vs. Spherical Aberrations



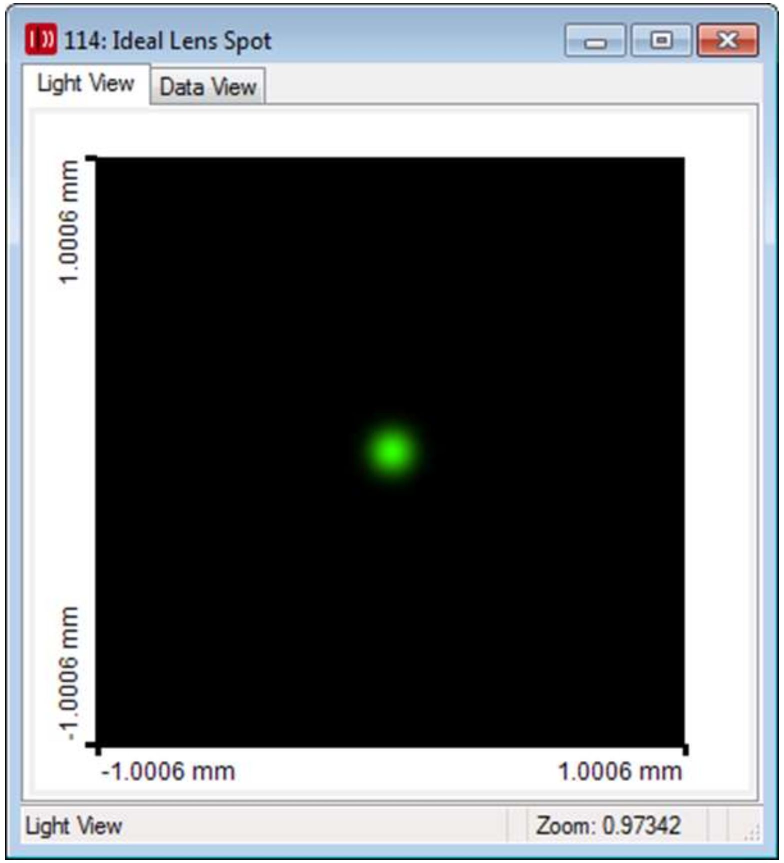


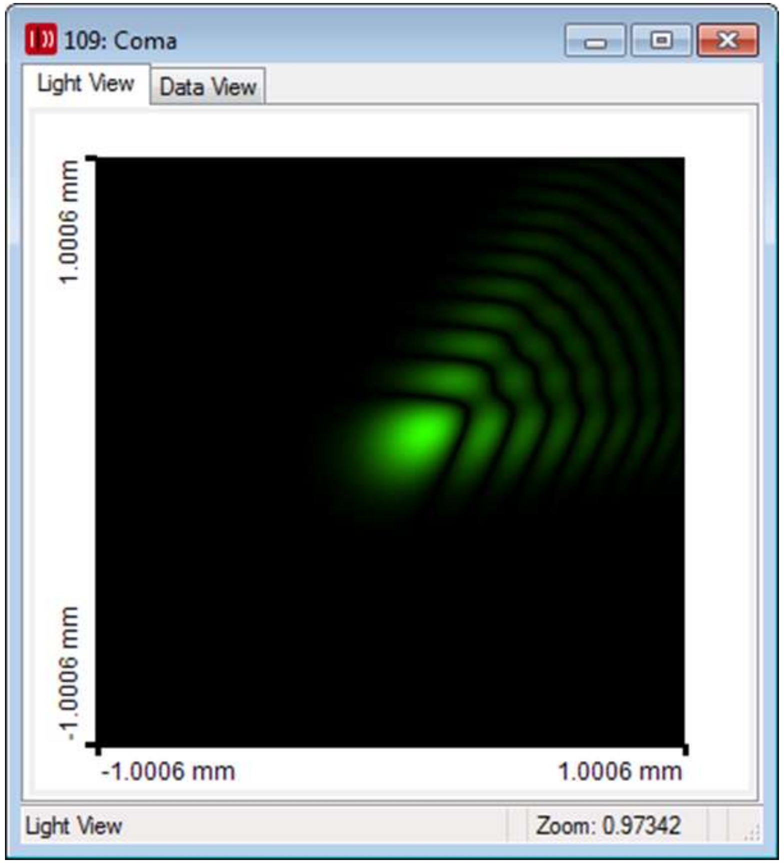
Ideal Lens vs. Astigmatism



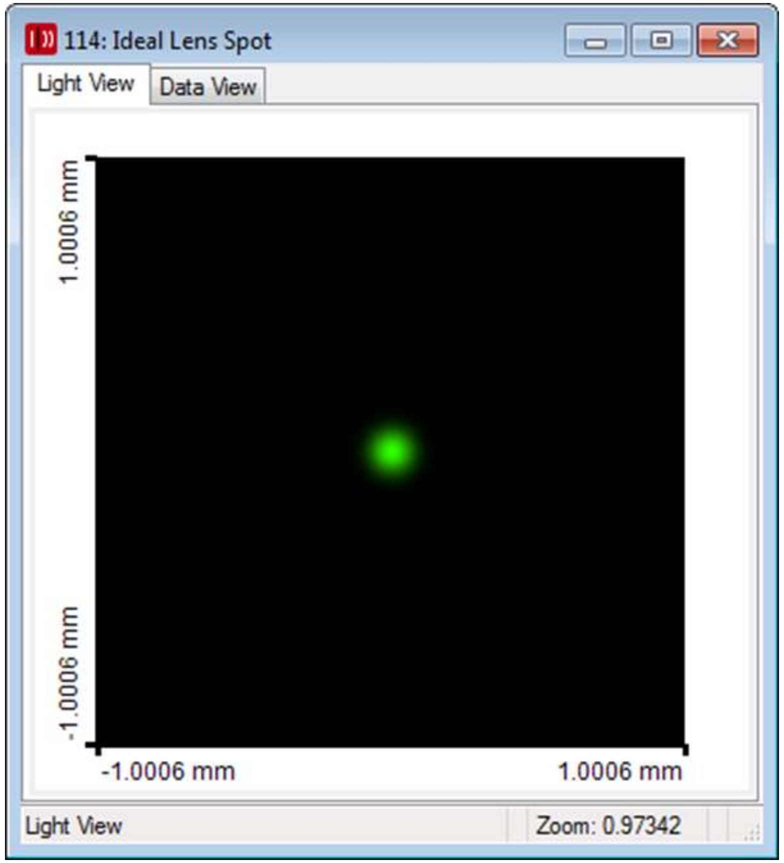


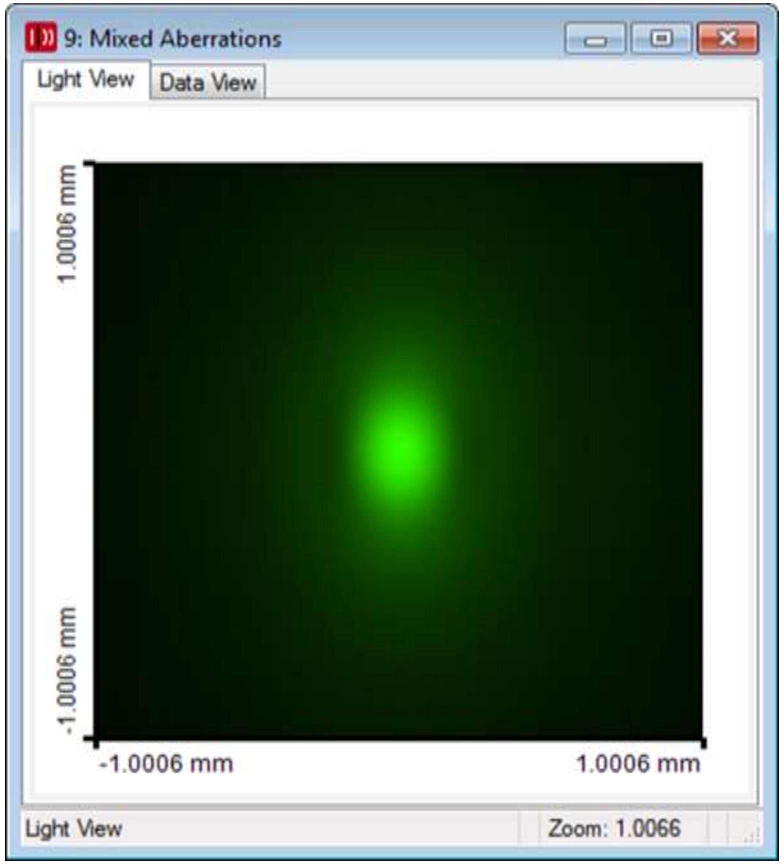
Ideal Lens vs. Coma





Ideal Lens vs. Mixed Aberration



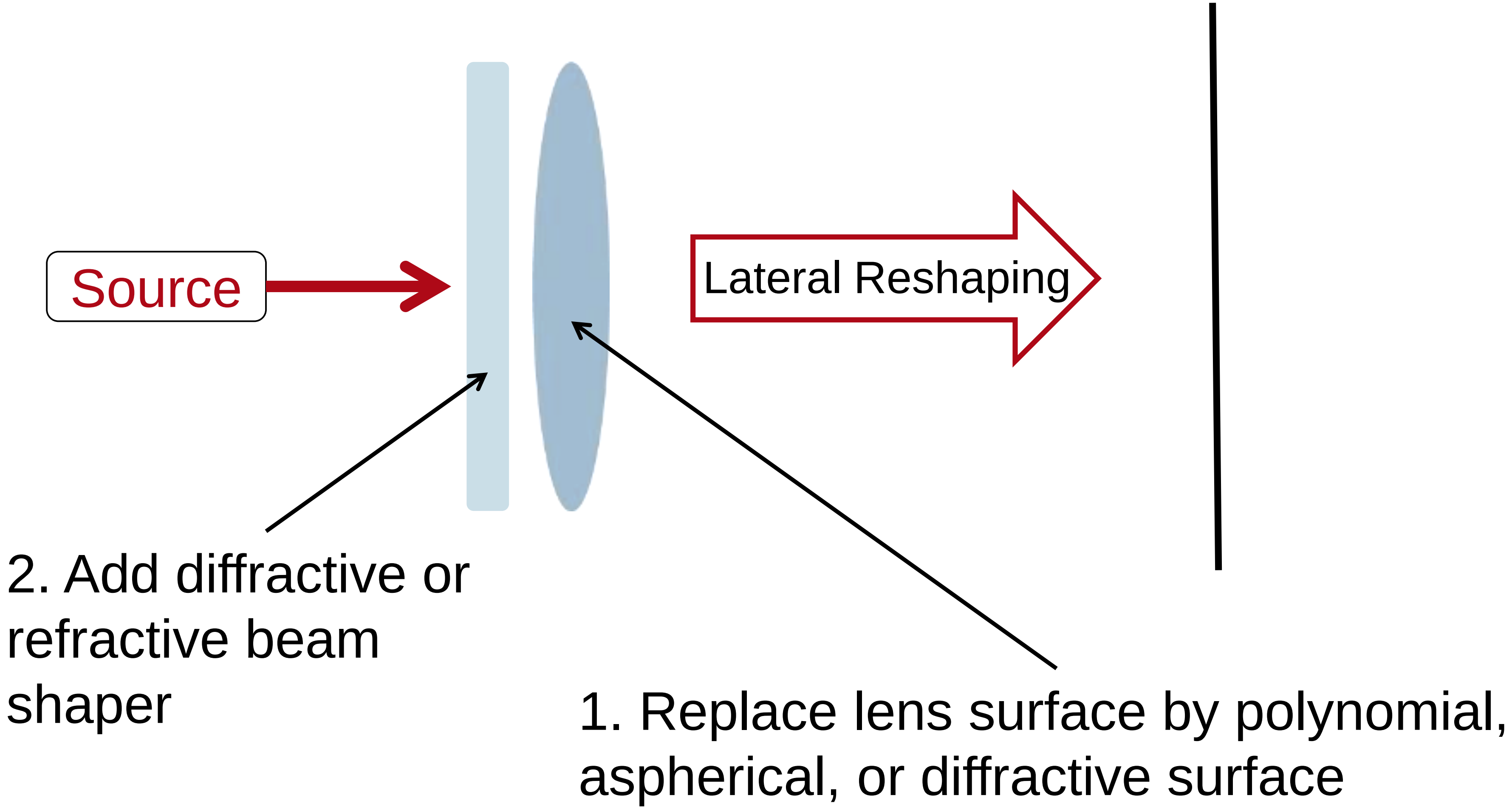


Conclusions for Beam Shaping

- Aberrations enlarge and reshape the focal spot of the ideal lens system

- The focal spot of the ideal lens system must be
  - Smaller than the demanded shaped spot
  - Not bigger than the smallest feature in the shaped spot
- Designing a beam shaping system must always be started with selecting a lens system the NA of which enables the required focal spot size
- Remark: Aberrations of lens systems are allowed, because beam shaper can compensate that

Introduction of Aberrations



What Kind of Aberrations Are Needed?

- Dependent on the input beam and the required beam profile in the target plane aberrations must be introduced
- A basic approach to estimate the required aberrations for a given beam shaping problem is based on
  - Determination of geometrical distortion to redistribute energy
  - Calculation of phase function, which realizes the geometrical distortion

Geometrical Distortion Concept

Analytical beam shaping with application to laser-diode arrays

Harald Aagedal, Michael Schmid, Sebastian Egner, Jörn Müller-Quade, and Thomas Beth

Institut für Algorithmen und Kognitive Systeme, Universität Karlsruhe, Am Fasanengarten 5, D-76128 Karlsruhe, Germany

Frank Wyrowski

Institut für Angewandte Physik, Friedrich-Schiller-Universität, Max-Wien-Platz 1, D-07743 Jena, Germany

Vol. 14, No. 7/July 1997/J. Opt. Soc. Am. A 1549

Geometrical Distortion Concept

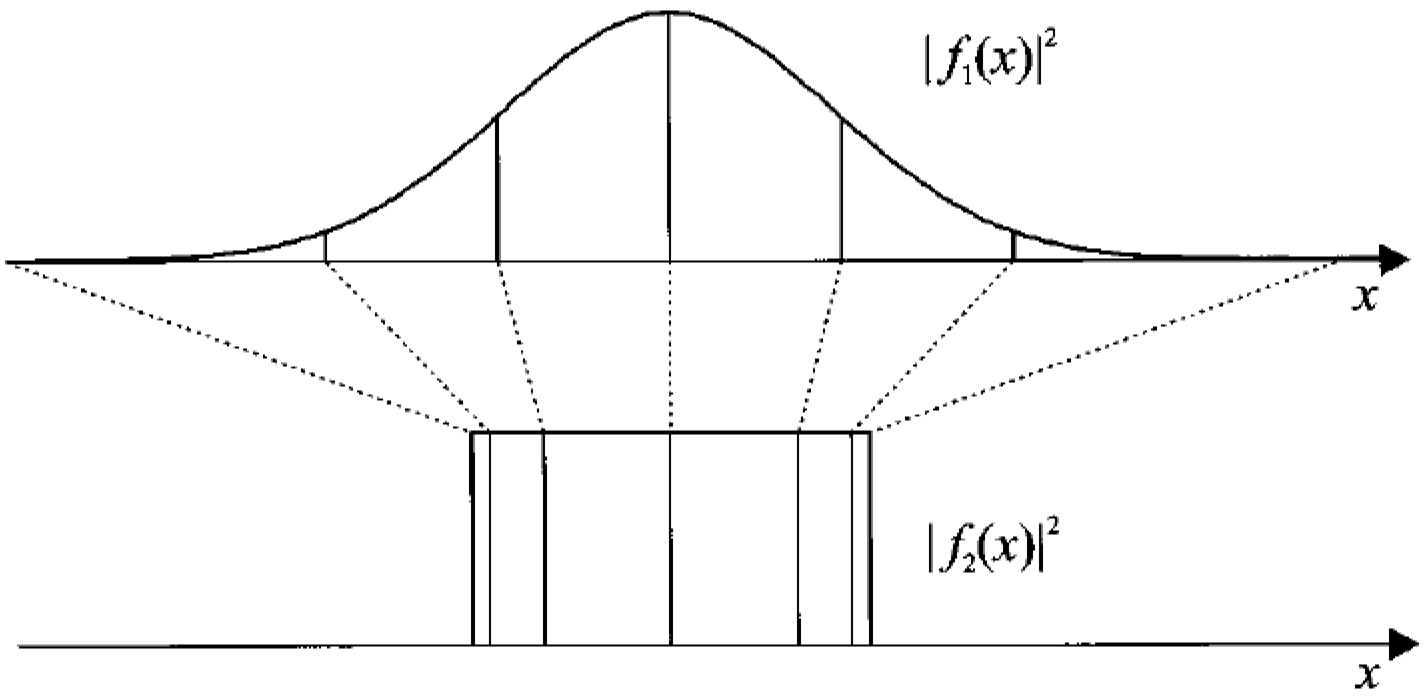


Fig. 1. Distortion transforming a Gaussian beam to a uniform distribution.

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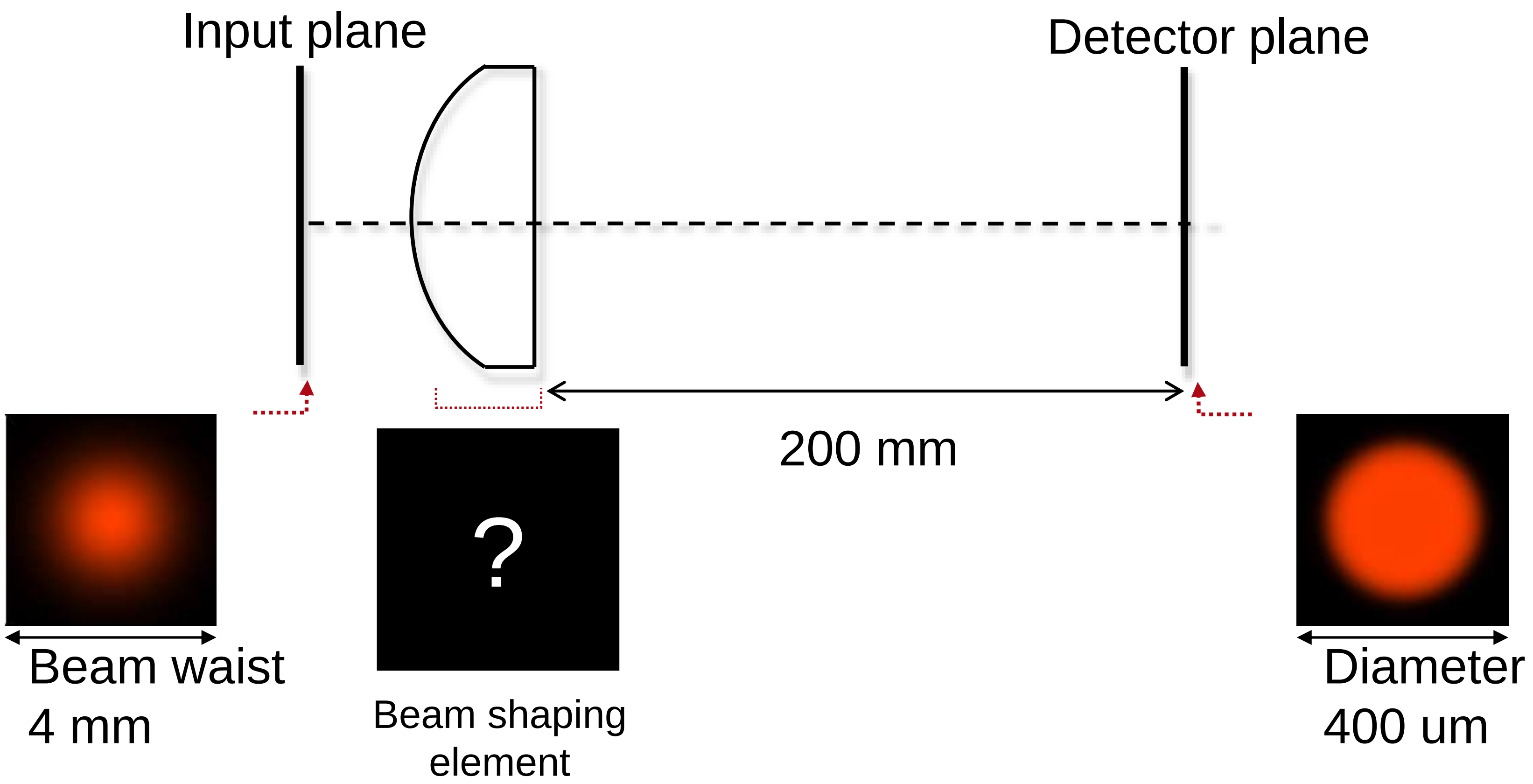
Light Shaping > Refractive Optics

Design of a Refractive Beam Shaper to Generate a Circular Top-Hat

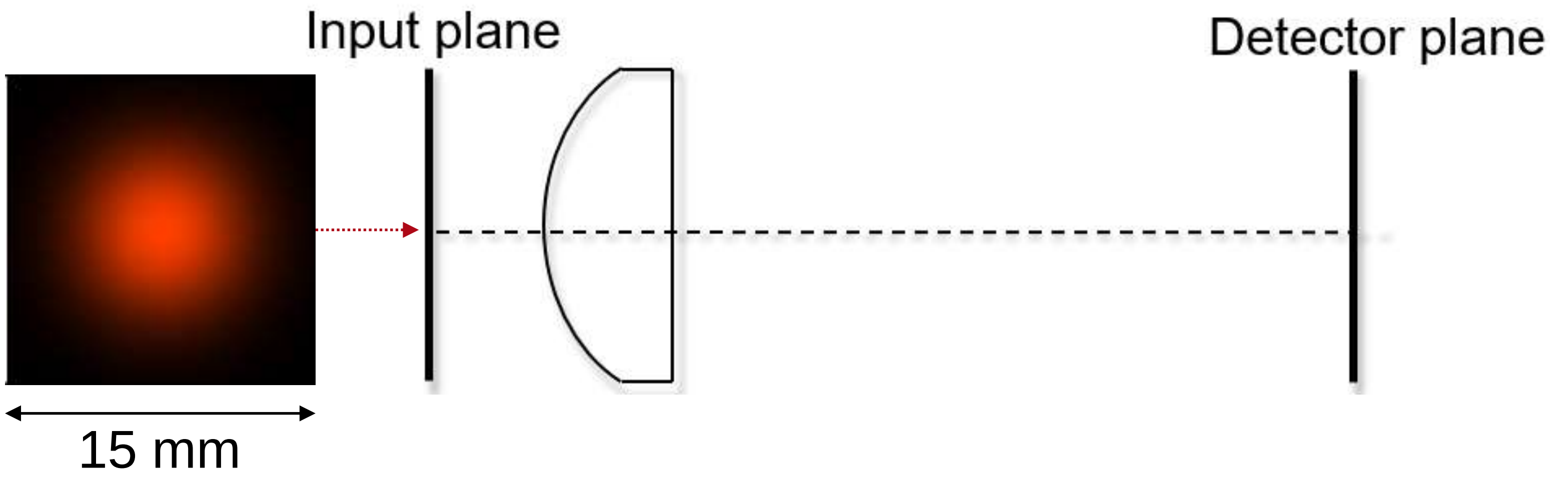
LightTrans International UG

Task 7 Beam Shaper



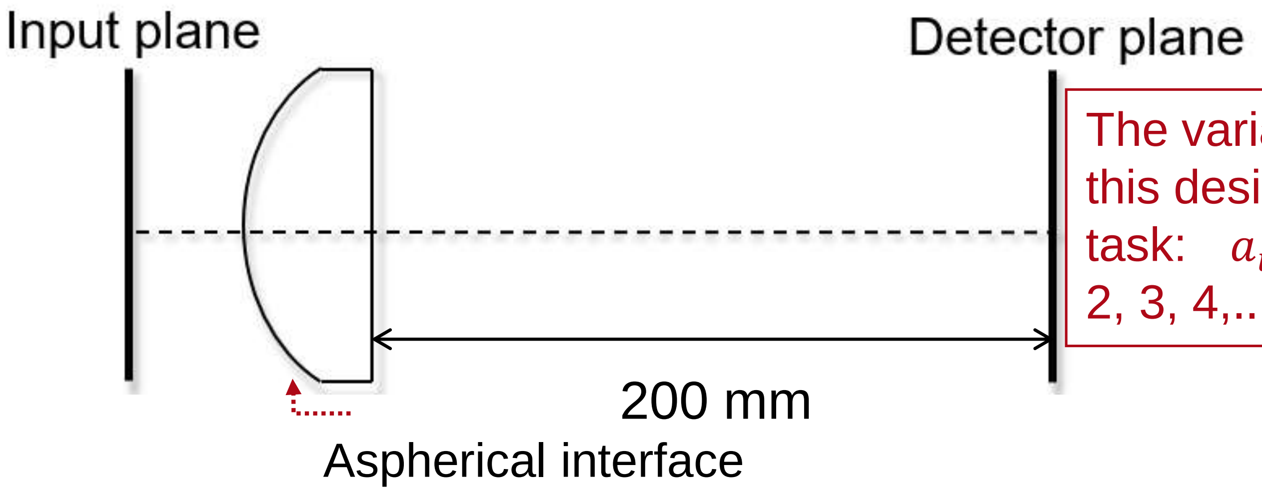
- Design a beam shaping element to shape a laser beam (fundamental mode) to a circular Top-Hat.

Specification: Light Source



Parameter	Description / Value & Unit
type/number	Gaussian beam
coherence/mode	single Hermite Gaussian (0,0) mode
wavelength	632.8 nm
beam diameter ($1/e^2$)	8 mm x 8 mm

Specification: Beam Shaper Element



The variables for this design task: a_i, with i = 2, 3, 4,...,16

- Aspherical interface:

$$h(x,y) = \sum_i a_i r^i$$

with $r = \sqrt{x^2 + y^2}$ and i is polynormial order index

Parameter	Value & Unit
name/type	Aspherical lens
material	N-BK7
thickness	5 mm
size (diameter)	23 mm
Distance to detector	200 mm

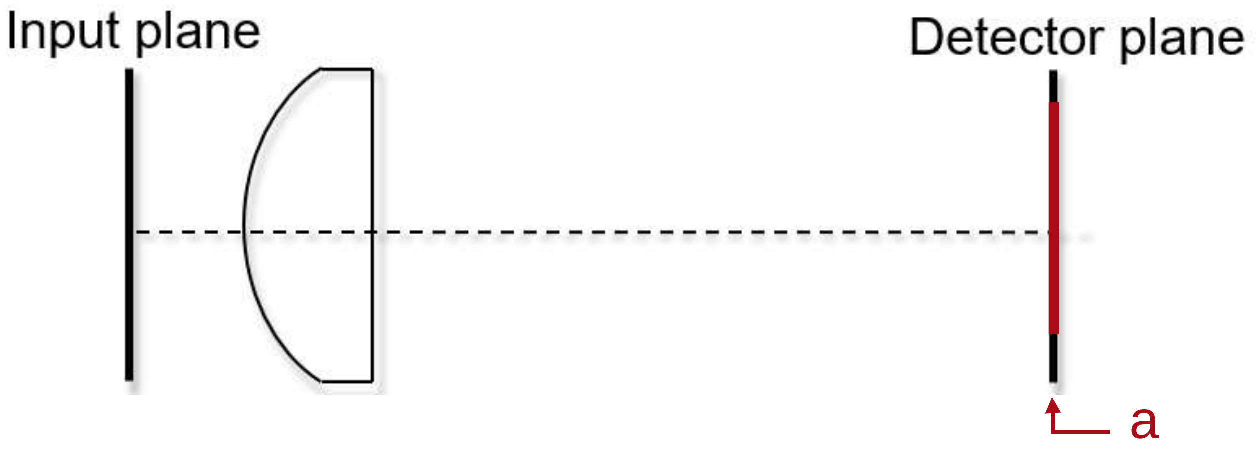
Specification: Desired Pattern

Parameter	Description / Value & Unit
type/number	Top-Hat (Super-Gaussian Wave)
wavelength	632.8 nm
beam diameter (1/e^2)	400 µm x 400 µm
edge width	40 µm

Specifications: Merit Functions for Design

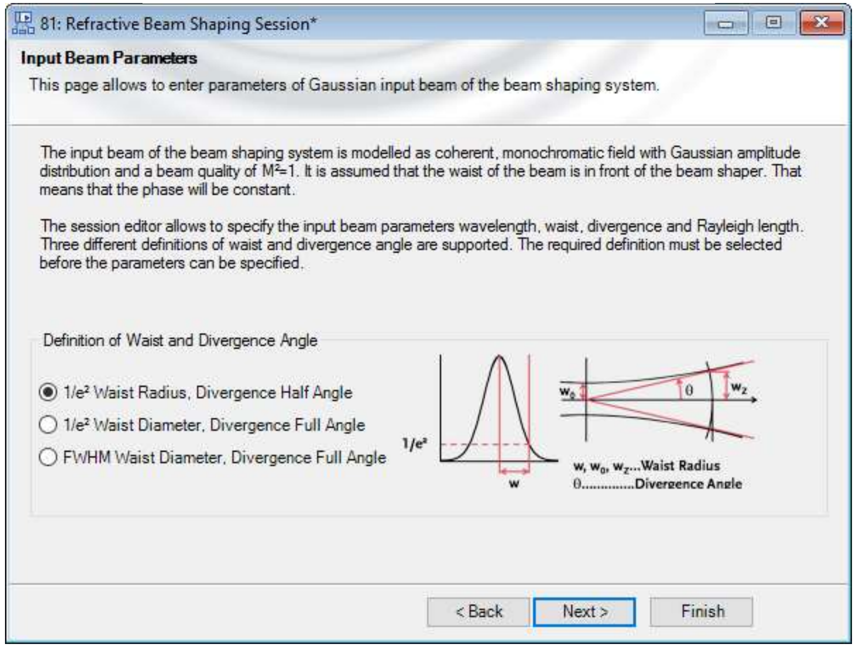
Parameter	Description / Value & Unit
conversion efficiency	> 90%
signal to Noise Radio (SNR)	> 22 dB
maximum relative intensity of stray light	< 10%

Specifications: Detector



Position	Modeling Technique	Detector/Analyzer
a	field tracing	Intensity
b	field tracing	Value of merit functions

Optimization Process

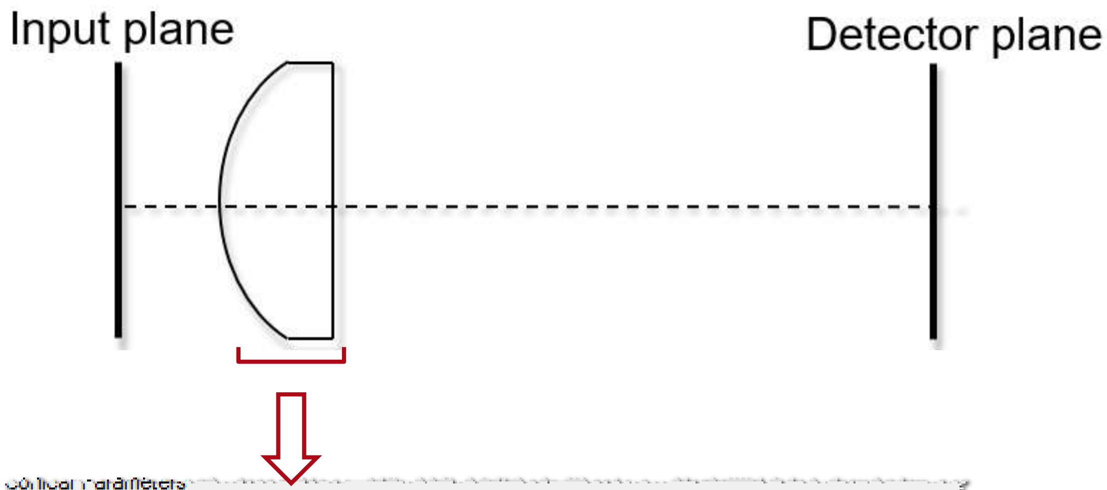


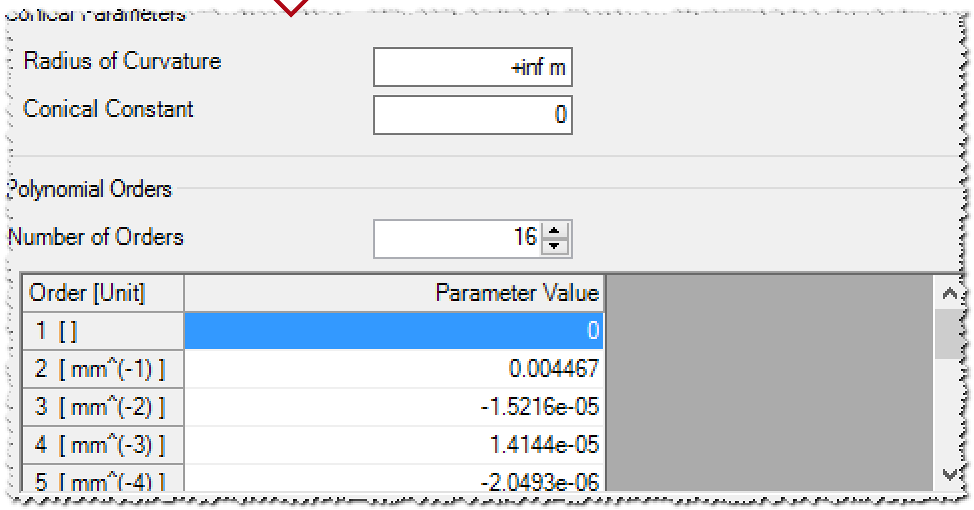
- Design Process is easily done by using the *Refractive Beam Shaping Session*.
  - Fill the parameters in illustration
  - Next!
- Click *Finish*, the beam shaper design is done immediately.

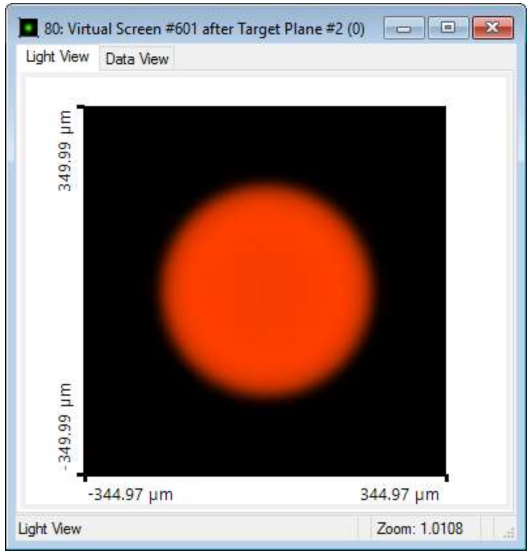
Design time → ~0.016 s !!!

* RO.0001_Refractive_Top_Hat_Beam_Shaper_Session_Editor.seditor

Results: Refractive Beam Shaper







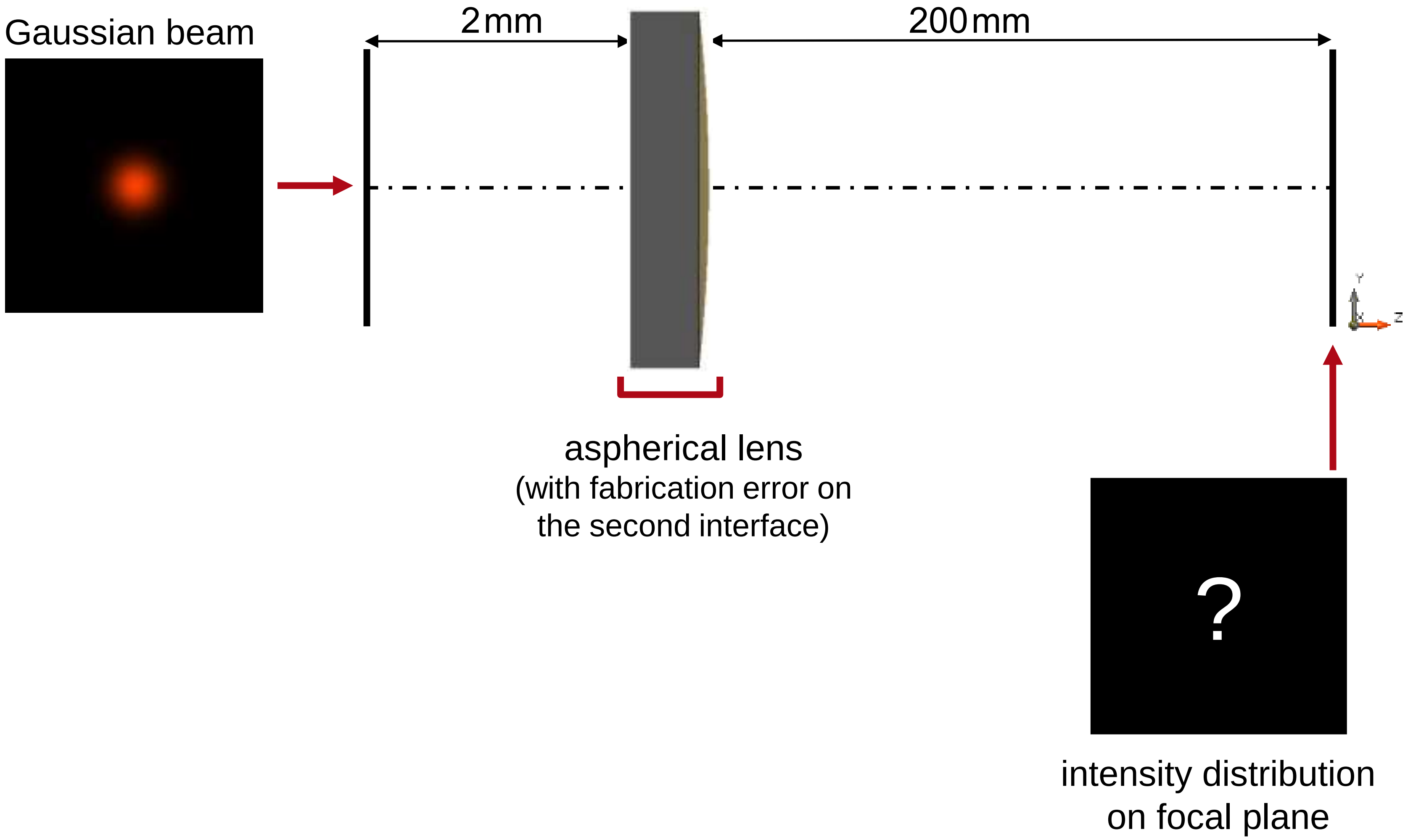
Parameter	Value & Unit
conversion efficiency	90.24%
SNR	22.353 dB
stray light	10.872%

Light Shaping > Refractive Optics

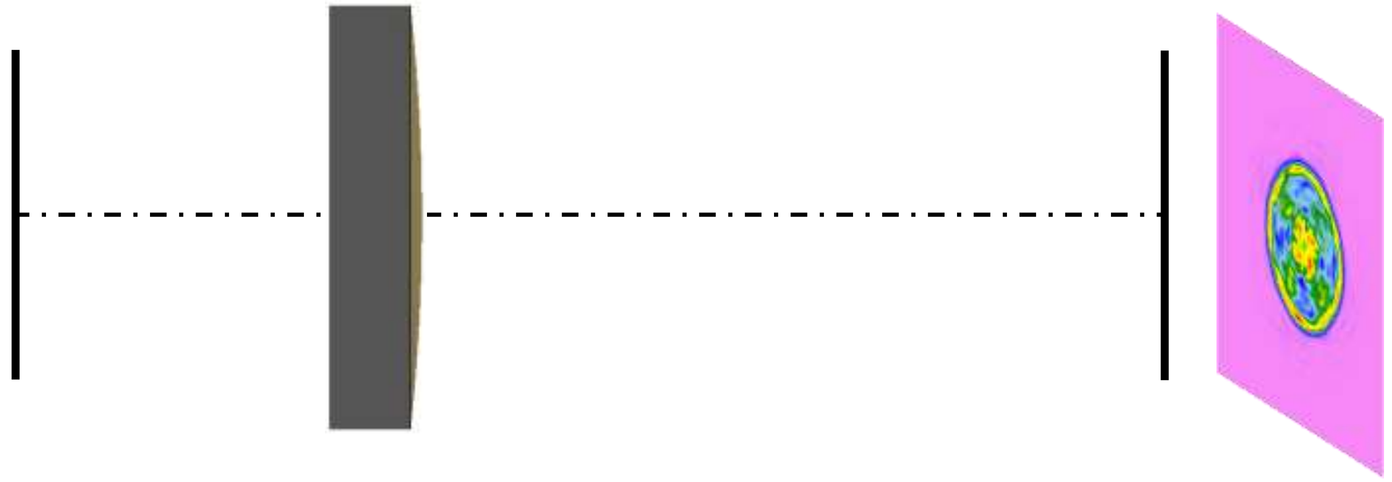
Modeling of a Refractive Beam Shaper with Measured Height Profile

LightTrans International UG

Task/System Illustration

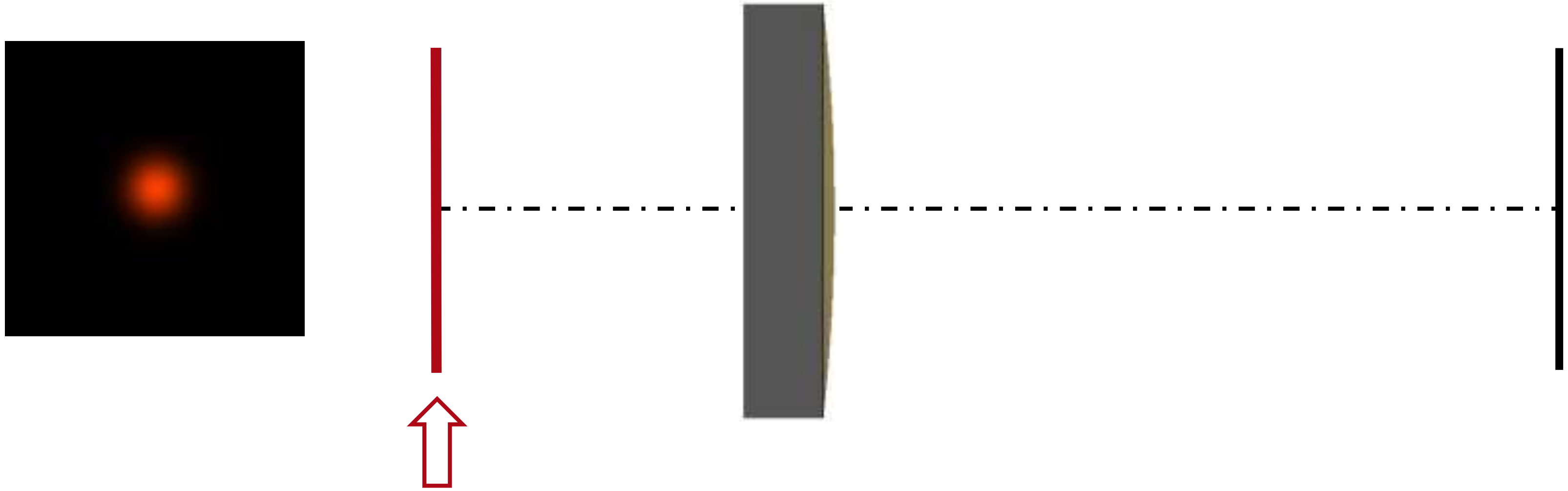


Highlights



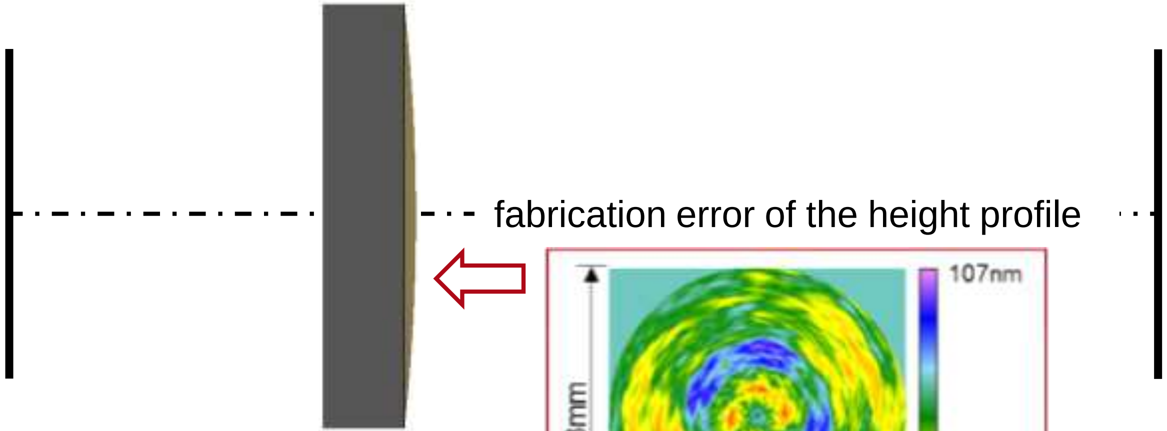
- simulation of fabrication tolerances by importing measurement data of height profiles

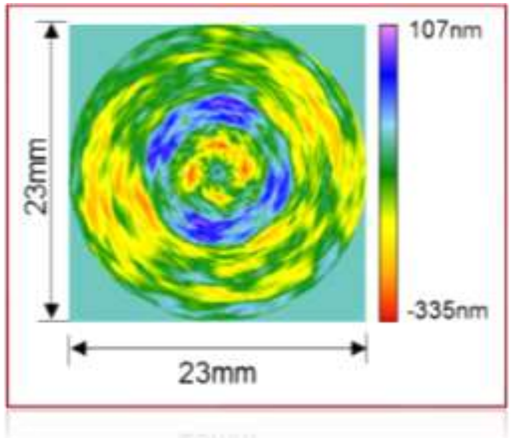
Specification: Light Source



Parameter	Description / Value & Unit
type/number	Gaussian beam
coherence/mode	single Hermite Gaussian (0,0) mode
wavelength	632.8 nm
polarization	linear in x-direction (0°)
waist radius ($1/e^2$)	4 mm × 4 mm

Specification: Focusing Asphere



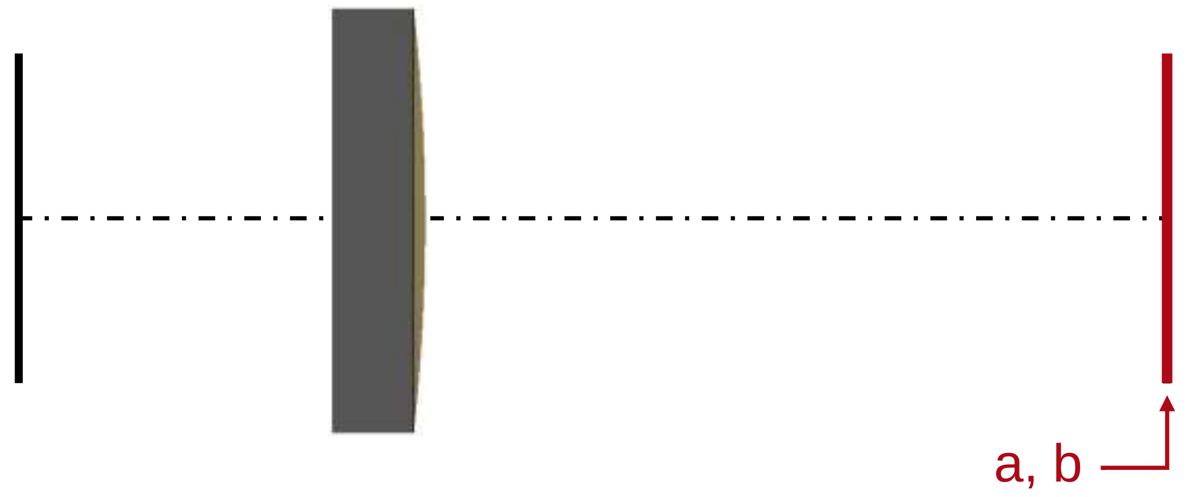


Highlights

- simulation of fabrication tolerances by importing measurement data of height profiles

Parameter	Value & Unit
name/type	convex-plano aspherical lens
first interface	plane interface
second interface	aspherical interface with measured height profile error
material (M)	N-BK7

Specification: Detectors

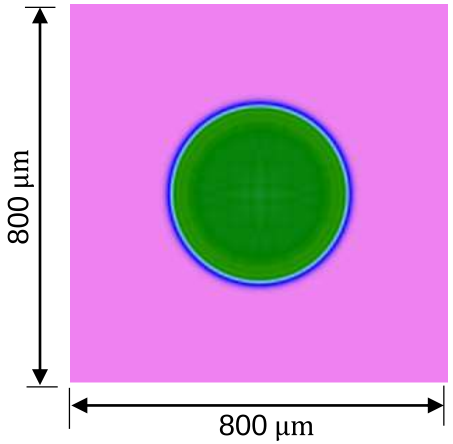


Position	Modeling Technique	Detector/Analyzer
a	field tracing	intensity distribution
b	field tracing	merit function detector

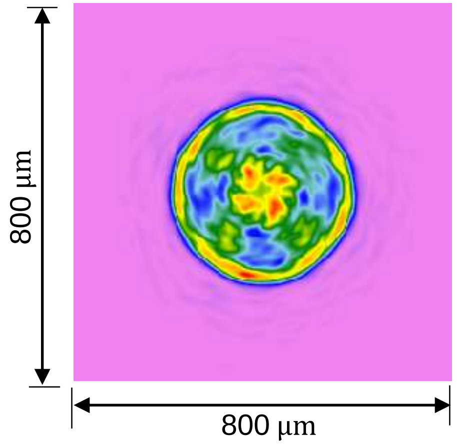
Results: Intensity Distribution

Highlights

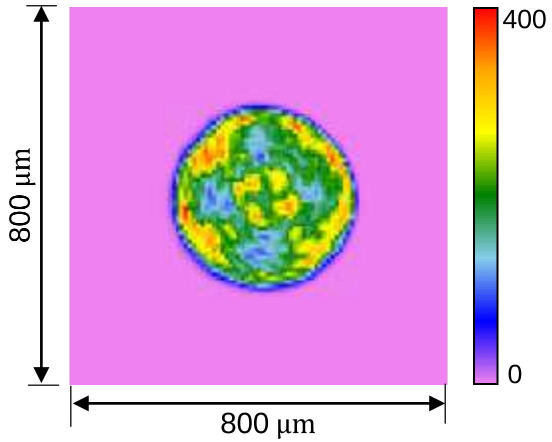
- simulation of fabrication tolerances by importing measurement data of height profiles



intensity of field at focal plane (without fabrication tolerances)



intensity of field at focal plane (with fabrication tolerances)



measured intensity at focal plane (with fabrication tolerances)

Results: Merit Function Detector

Highlights

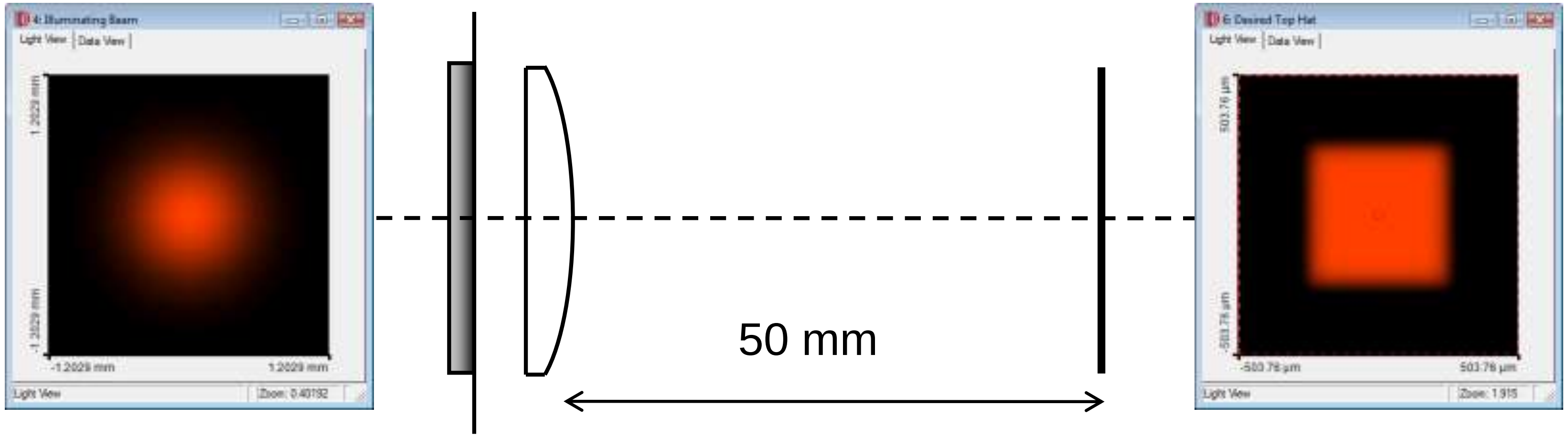
- simulation of fabrication tolerances by importing measurement data of height profiles

Detector/Analyzer	Result (without fabrication error)	Result (with fabrication error)
signal-to-noise ratio (SNR)	26.49 dB	14.66 dB
conversion efficiency	91.21%	87.15%
uniformity error	93.65%	99.73%

Modeling Task

Diffractive Beam shaper
Diameter: 2 × 2 mm
Phase Levels: 16

Target
Plane



Illuminating Beam
Intensity

1f-Setup
Focal Length f=50 mm

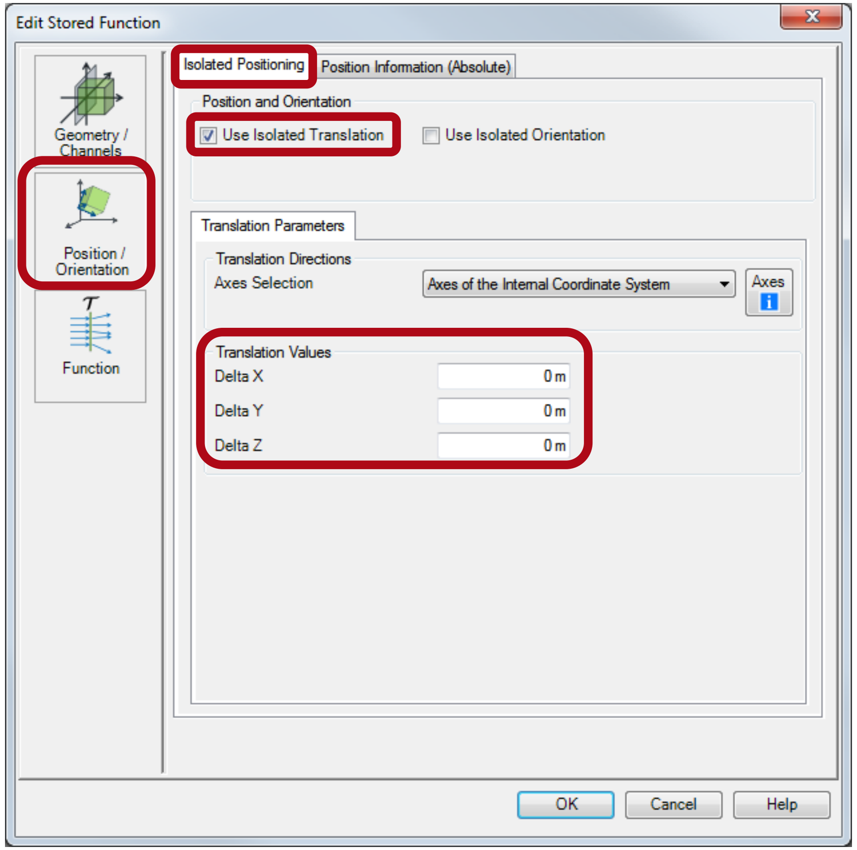
Top Hat Intensity
(free of speckles)

Modeling Task

- The following tolerances of the system are to be analyzed.
- The ± tolerance values are regarded as 3-times ± the standard deviation σ.

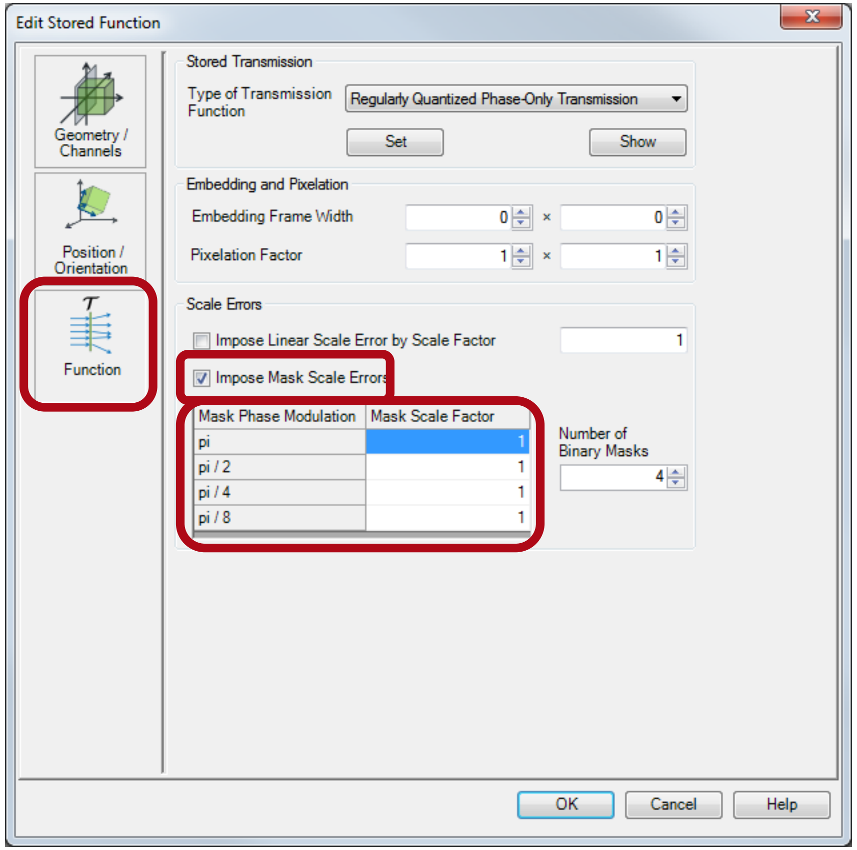
Varied Parameters	**Value and Tolerances**
Waist Radius of Input Beam	(500 ± 25) µm
Etching Depths of all 4 Binary Masks	± 2 % of original height
x-Position of Beam Shaper	(0 ± 10) µm
y-Position of Beam Shaper	(0 ± 10) µm
Focal Length of Lens	(50 ± 0.5) mm

Simulation of Alignment Tolerances



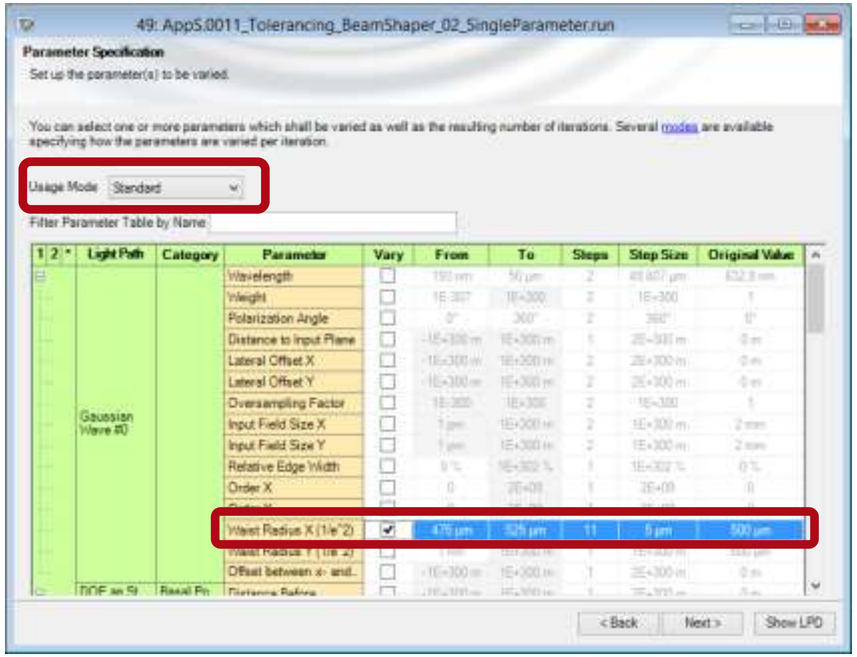
- Simulation of shift tolerances must be activated on *Tolerancing* page of *Stored Function* component and *Target Plane* component.
- Tolerance values are varied by *Parameter Run.* The values set in the component dialog are ignored.

Simulation of Etching Depth Tolerances



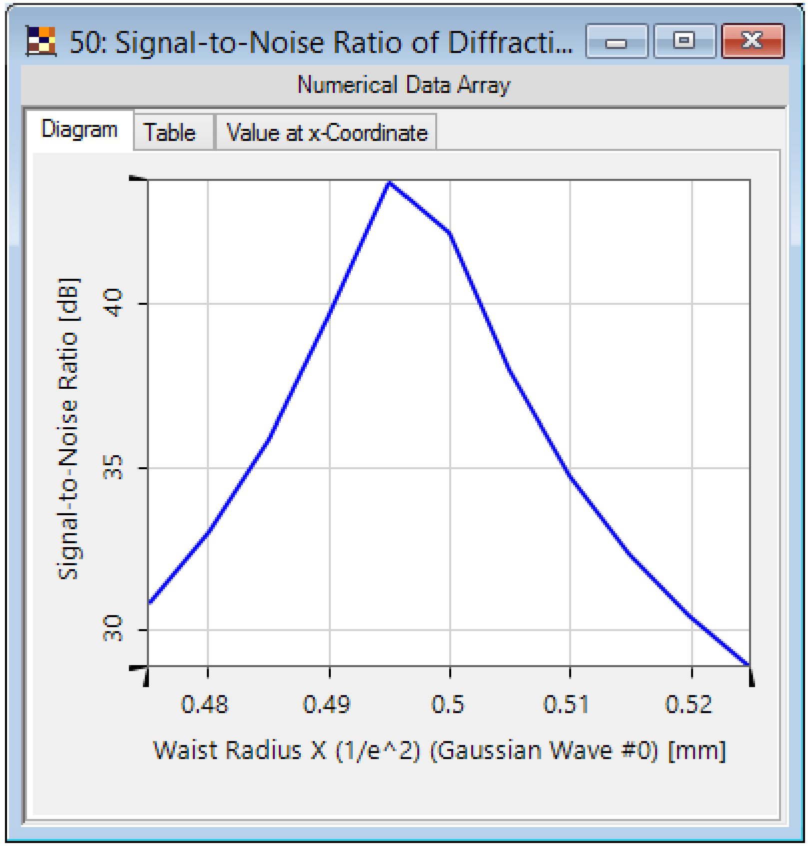
- Simulation of mask etching depth errors must be activated on *Function* page of *Stored Function* component.
- Tolerance values are varied by *Parameter Run*. The respective settings in the component dialog are ignored.
- A tolerance value of 1 represents an optimum etching depth.

Single Parameter Variation



- The laser beam radius has typically a strong influence on the optical performance of a beam shaping system.
- The *Usage Mode: Standard* must be selected for the variation of a single parameter.
- *Waist Radius X* parameter must be selected.

Single Parameter Variation

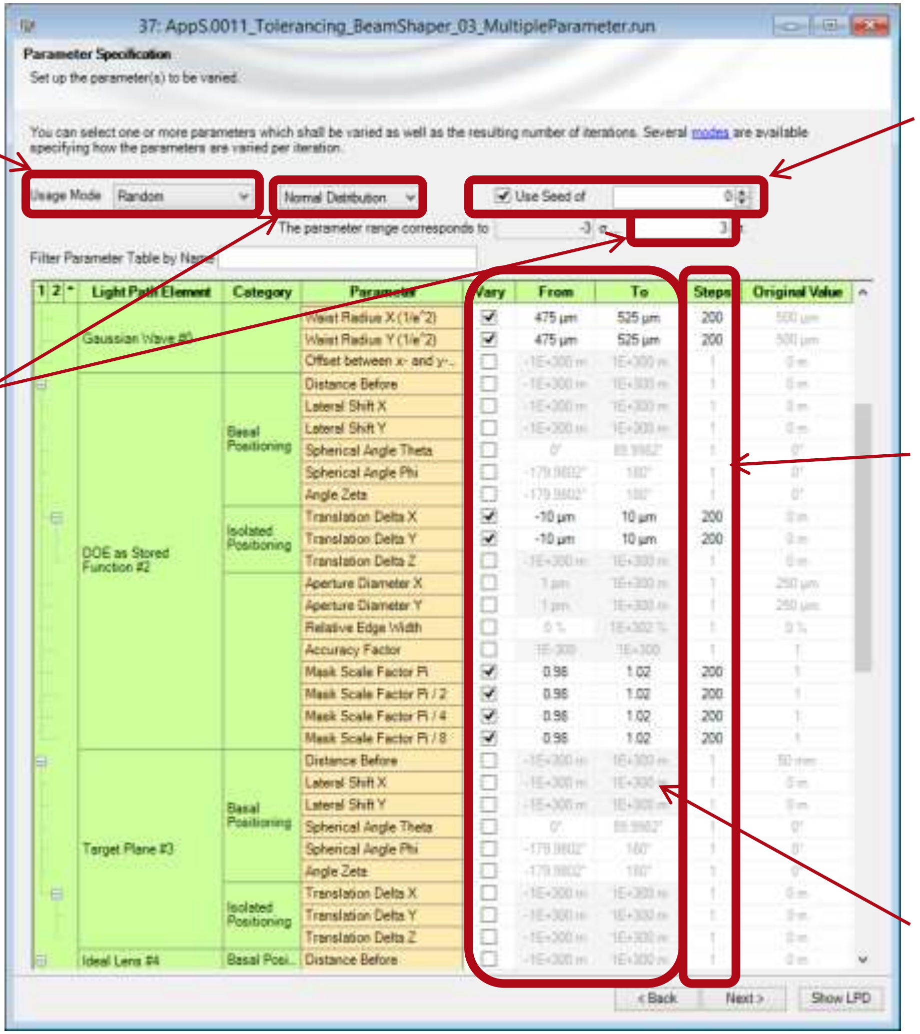


- The beam shaping system shows a strong sensitivity for a variation of the laser beam radius.
- The Signal to Noise Ratio (SNR) will drop to 28.8dB.

Monte-Carlo Simulation

Random mode for Monte Carlo simulation

Parameter Variation has a *Normal Distribution* with a certain standard deviation σ

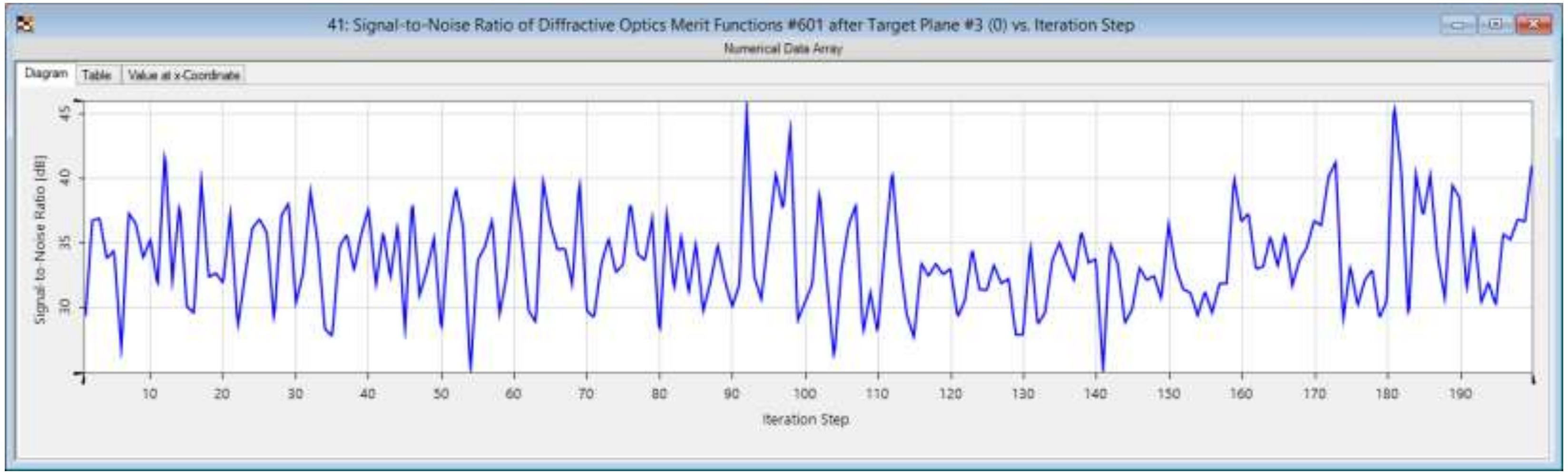


A Seed can be used for reproducible results of the 'random' series.

Total number of variations

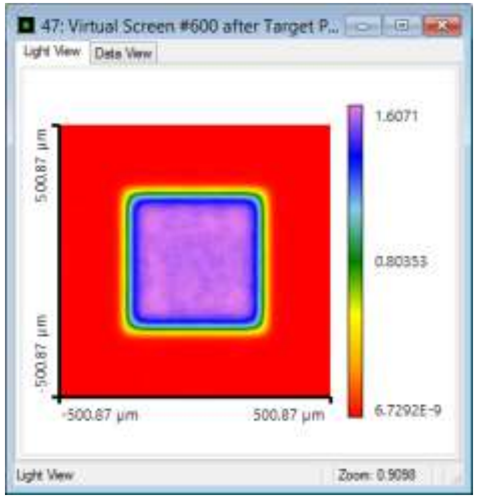
Minimum and maximum value of all tolerances defined by $\pm 3\sigma$

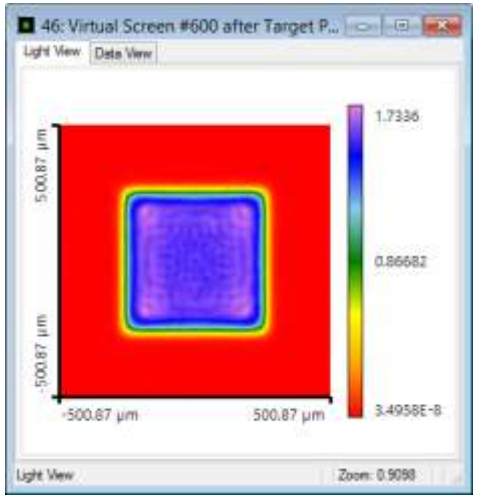
Monte-Carlo Simulation



- Variation of the SNR depending on the random parameter set.
- The minimum SNR can be found from the diagram via the menu entry Detectors > Minimum.
- Minimum SNR: 24.9 dB
- Average SNR: 33.7 dB

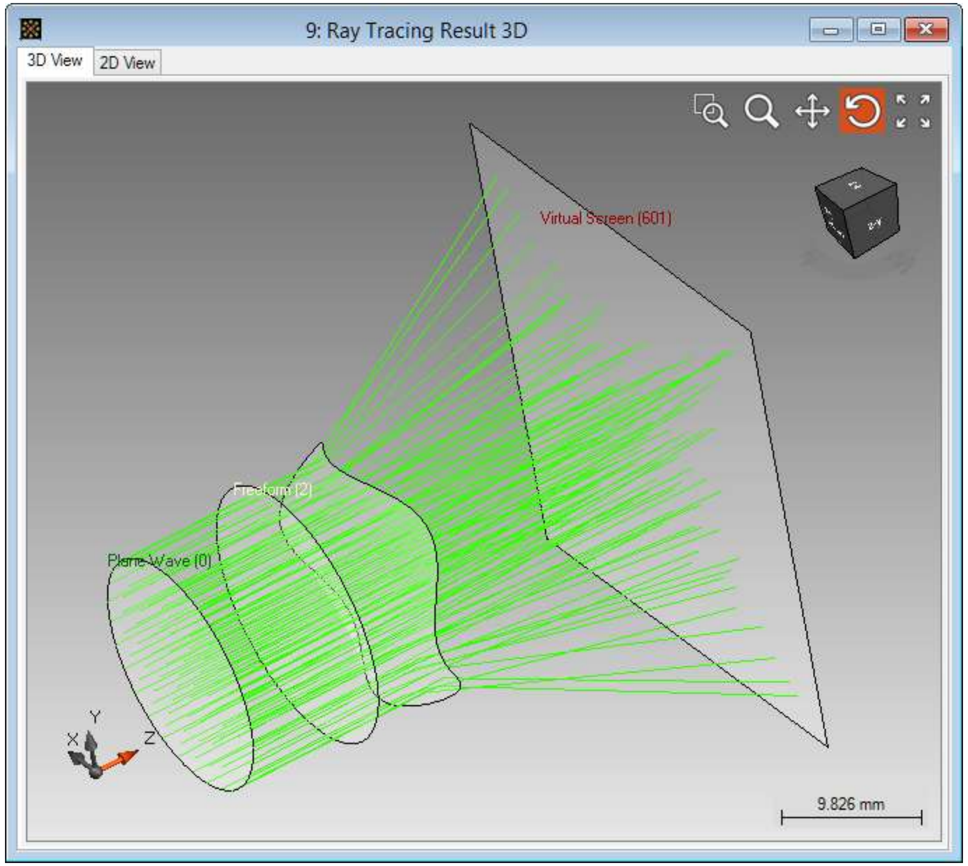
Resulting Field Distributions

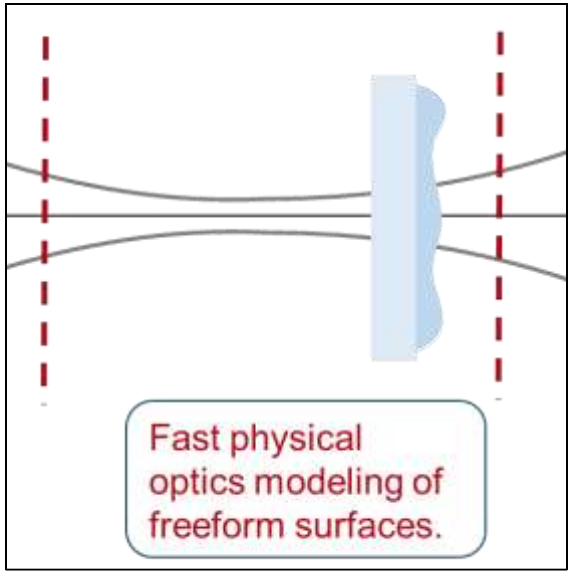




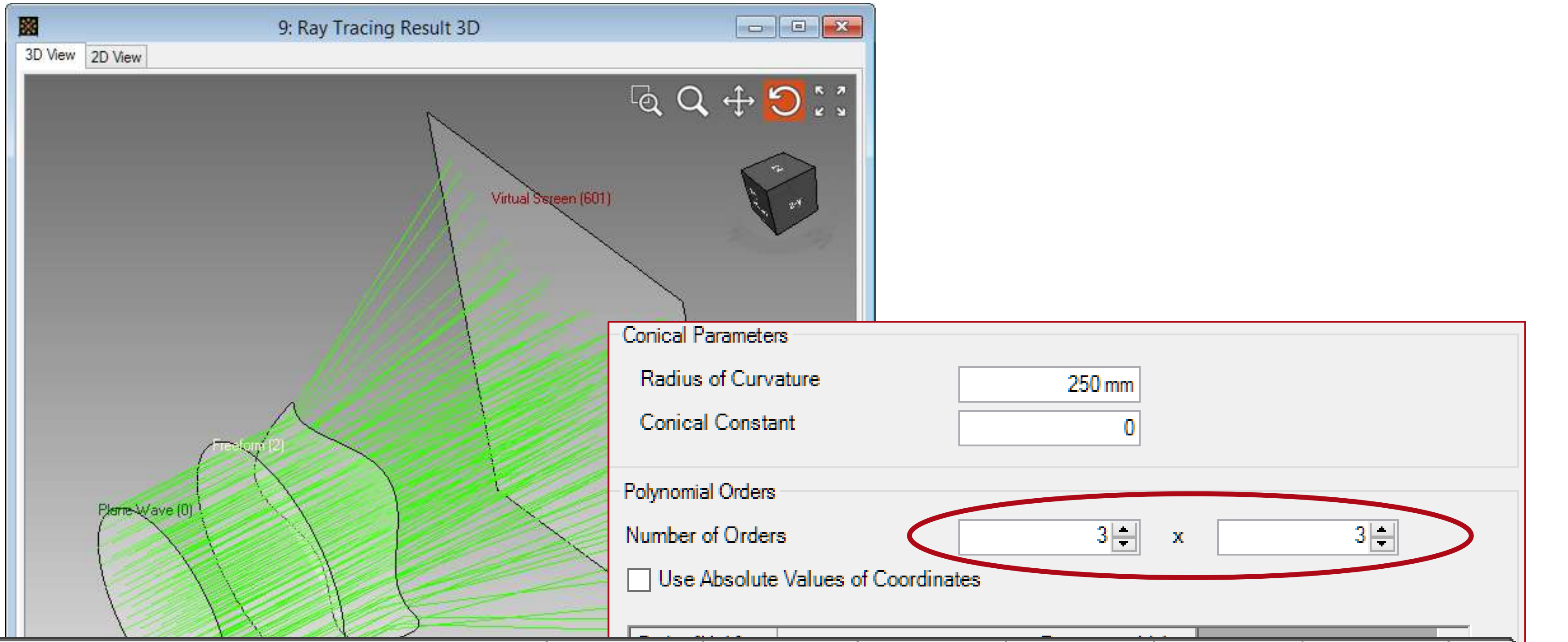
- Left: Ideal output intensity (SNR = 42.2 dB).
- Right: Light pattern with lowest SNR (SNR = 24.9 dB)
- Export of Monte-Carlo simulation results to external software (for example Microsoft Excel) allows further statistical evaluations.

Fast Physical Optics: Freeform Surfaces



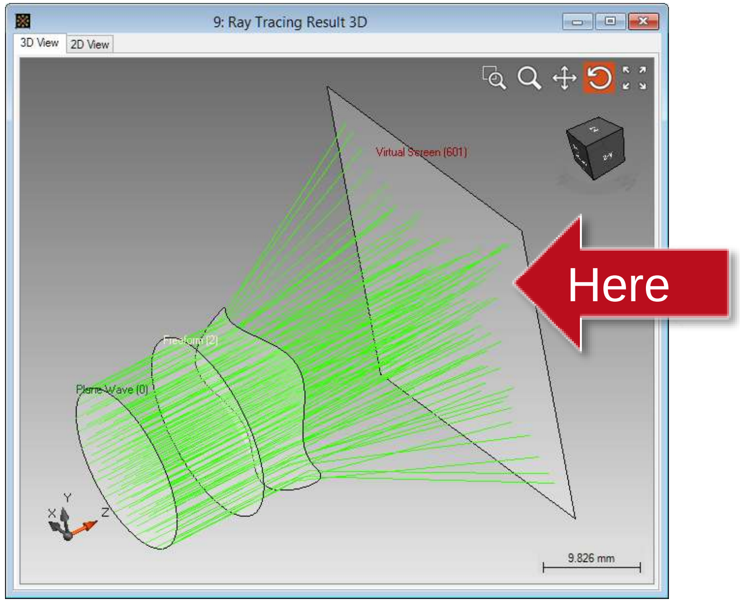


Fast Physical Optics: Freeform Surfaces

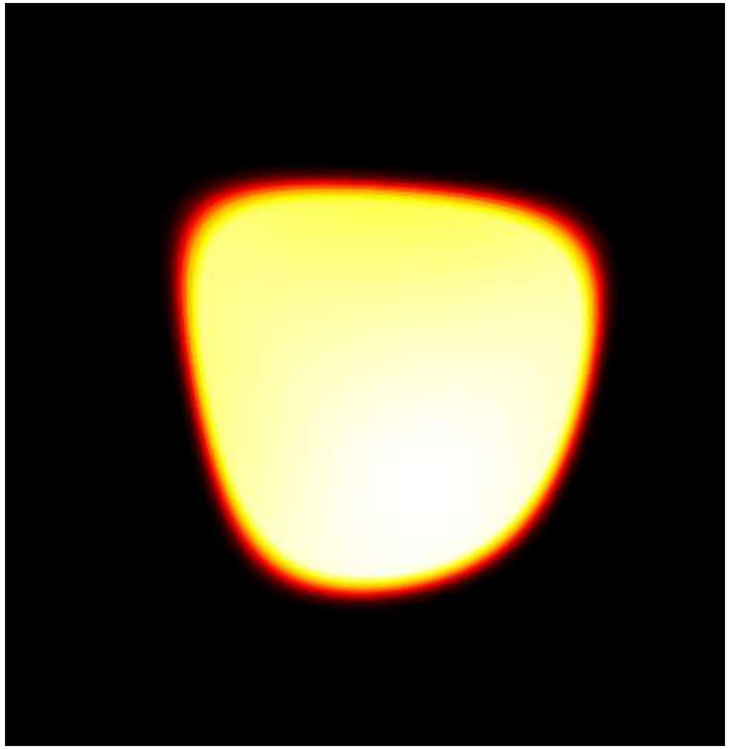


	Iteration Step	1	2	3	4	5	6	7
1	(2,0) [mm^(-1)] (Freeform #2 | Polynomial Interface #1)	0.0024274	0.0031541	0.0041695	0.00035002	0.003082	0.0024793	0.0025
2	(2,1) [mm^(-2)] (Freeform #2 | Polynomial Interface #1)	0.0013393	-0.0017223	0.0020993	0.0010653	-0.0014089	0.0017305	0.0007
3	(0,2) [mm^(-1)] (Freeform #2 | Polynomial Interface #1)	0.0027923	0.0029335	0.			0.0020482	0.00016
4	(1,2) [mm^(-2)] (Freeform #2 | Polynomial Interface #1)	-0.00051556	-9.0126E-05	-0			-0.0010599	-0.002
5	(2,2) [mm^(-3)] (Freeform #2 | Polynomial Interface #1)	0.00016179	0.00013574	0.00012223	0.00017955	0.00039437	4.0504E-05	0.0001
6	Distance Before (Virtual Screen #601 | Basal Positioning)	21.823 mm	25.564 mm	23.586 mm	23.353 mm	26.147 mm	29.382 mm	24.8

Fast Physical Optics: Freeform Surfaces



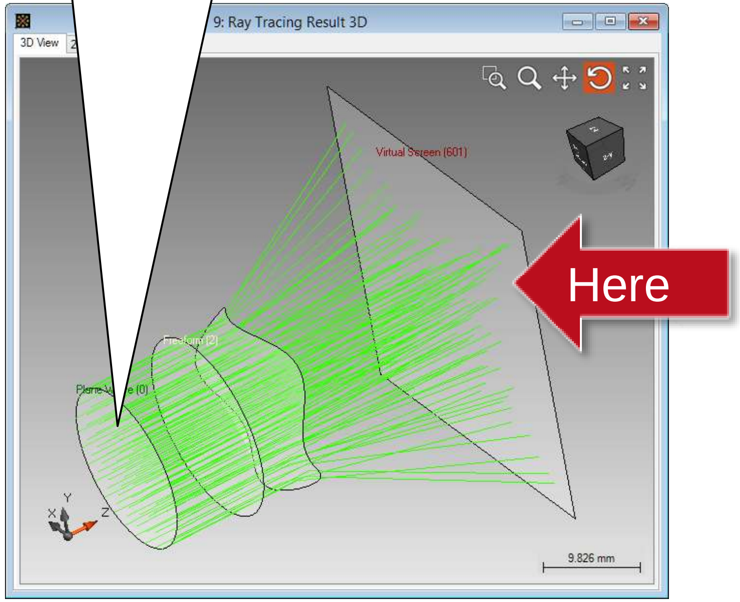
Amplitude $E_x(x,y)$



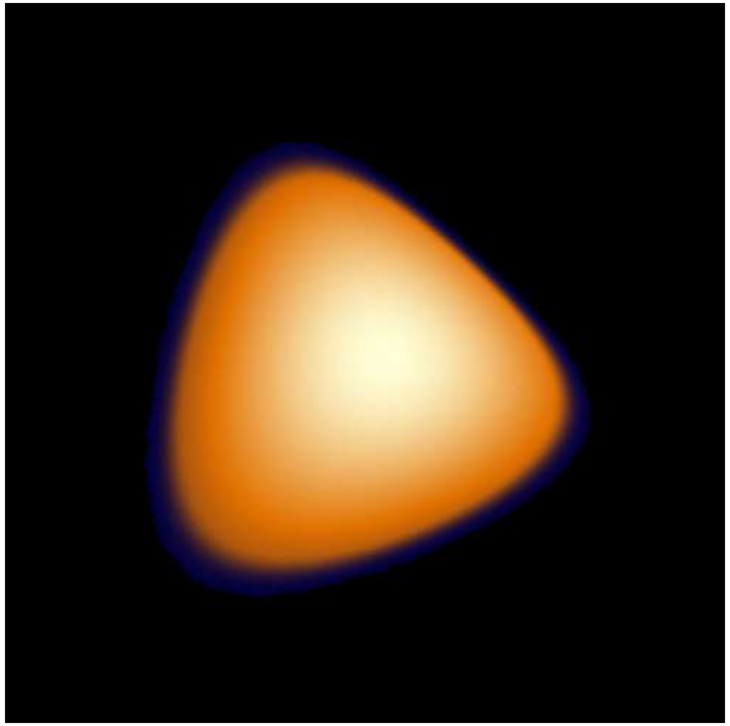
cpu time per simulation < 1 sec

Freeform: Field Tracing

Input: Gaussian beam
Diameter 10 mm



Amplitude $E_x(x,y)$



cpu time per simulation < 1 sec

Geometrical Distortion Concept

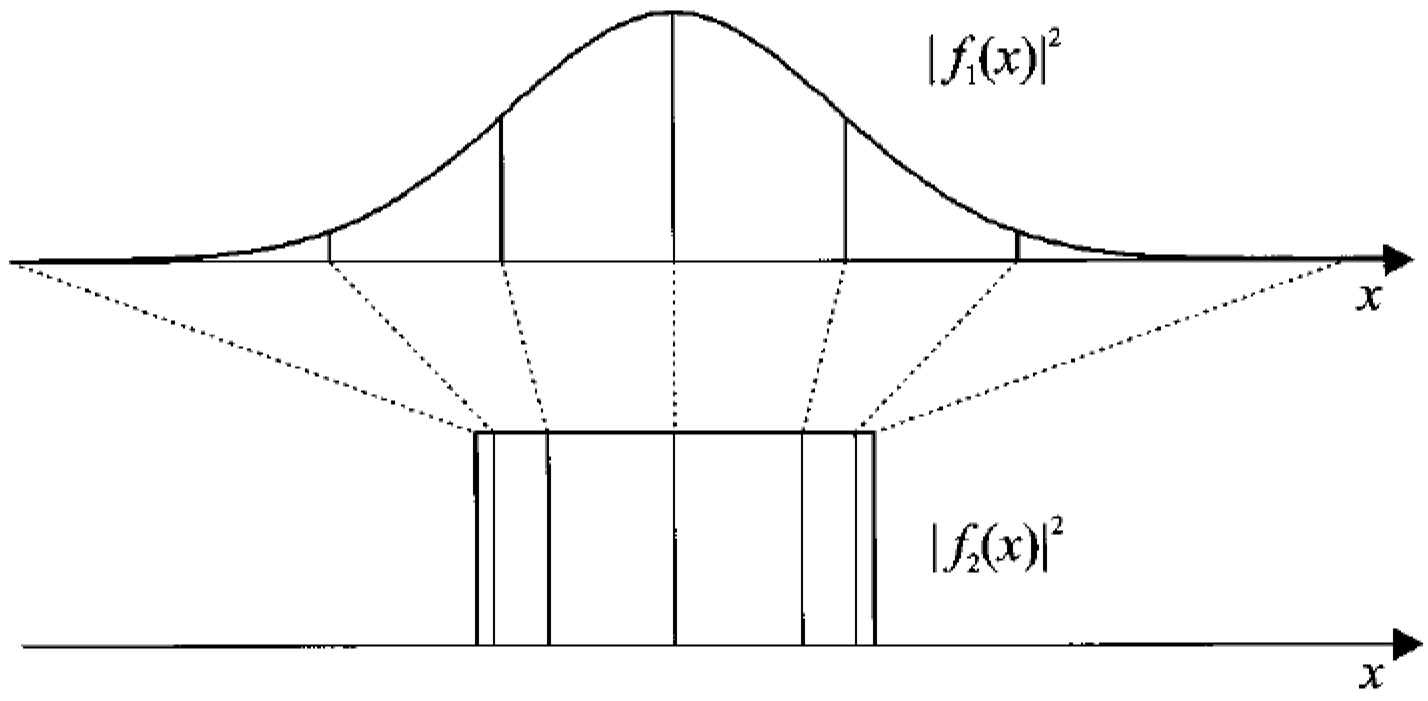


Fig. 1. Distortion transforming a Gaussian beam to a uniform distribution.

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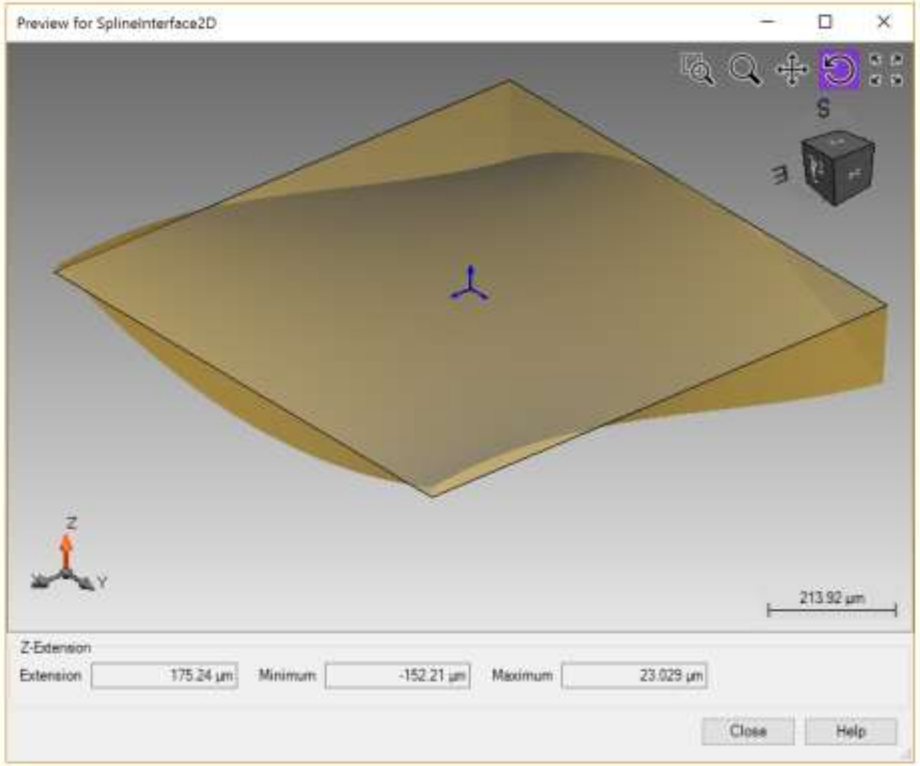
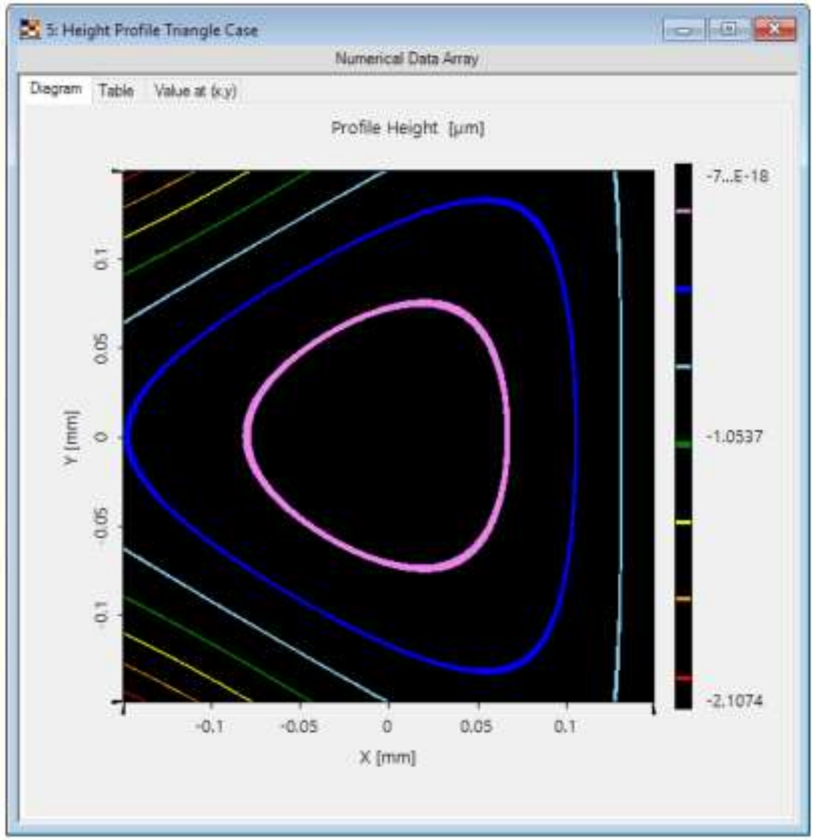
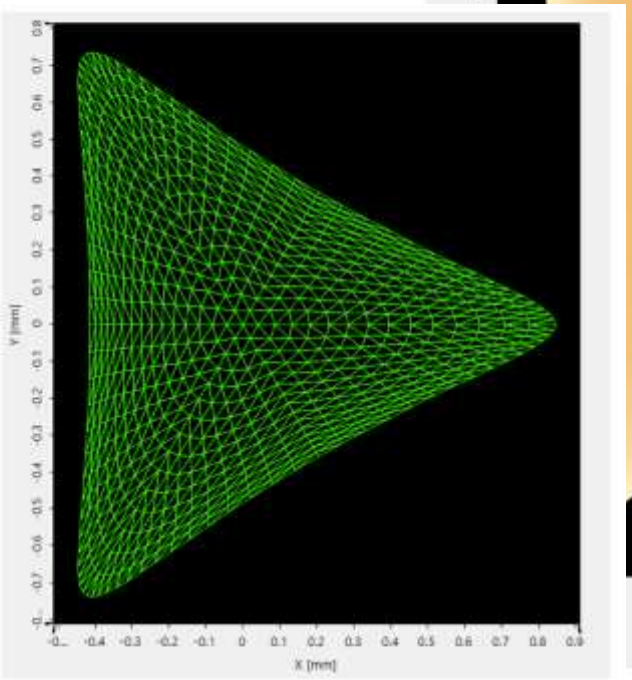
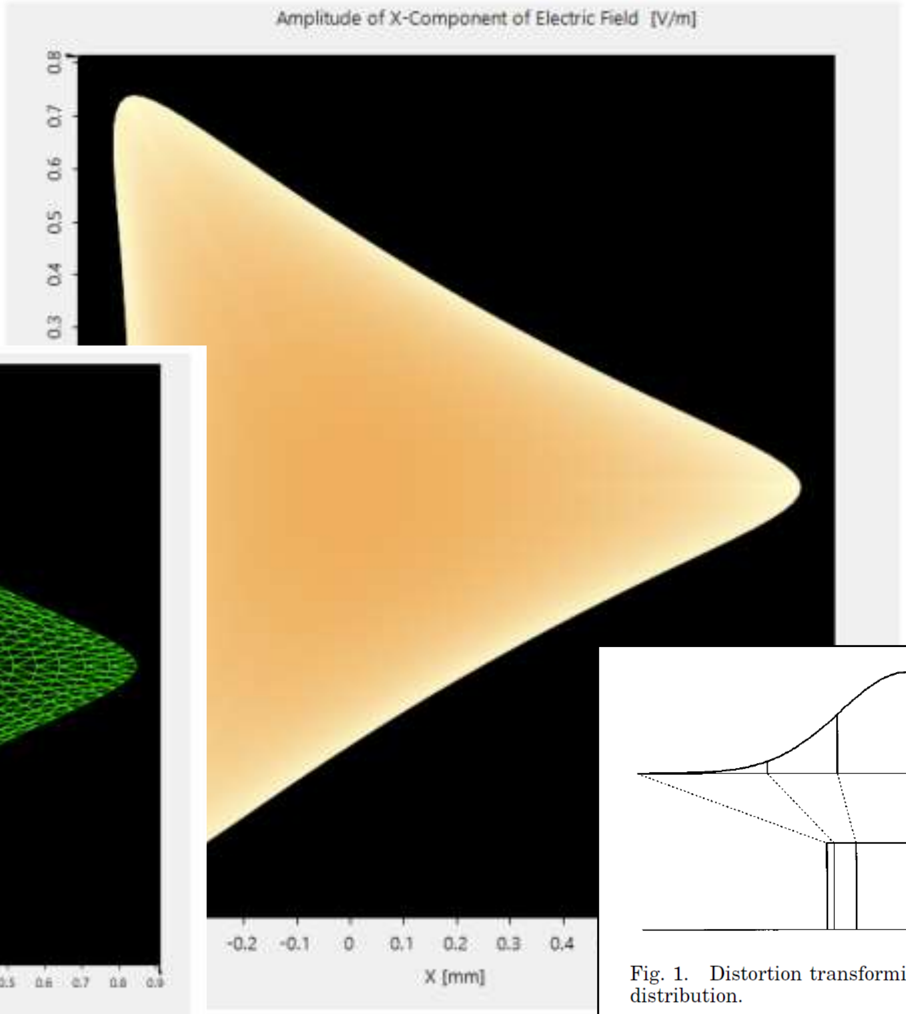
Laser Beam Shaping: R&D





Laser Beam Shaping: R&D





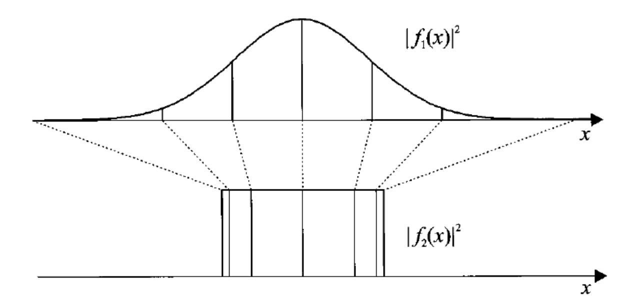
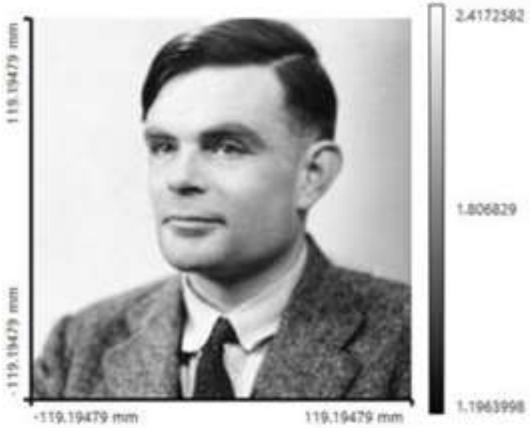
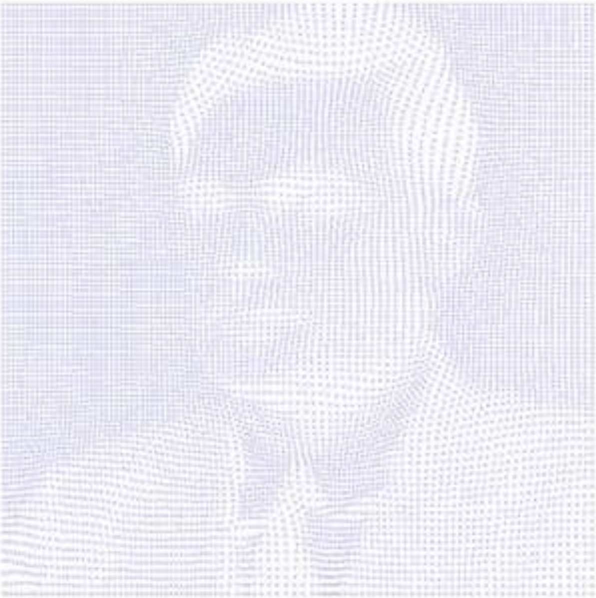
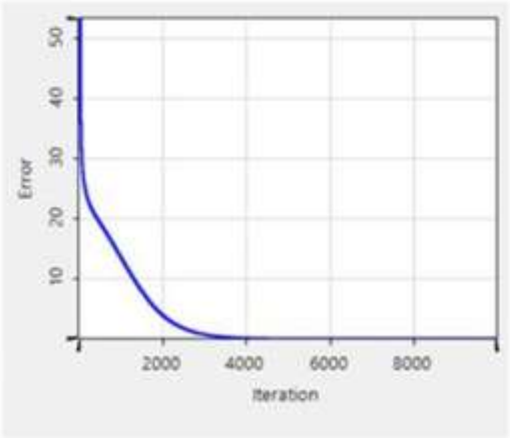


Fig. 1. Distortion transforming a Gaussian beam to a uniform distribution.

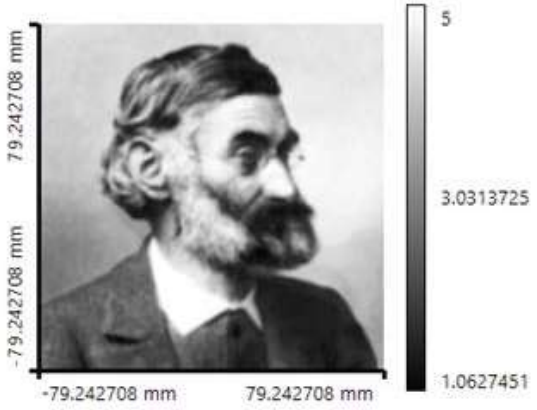
Light Shaping: R&D

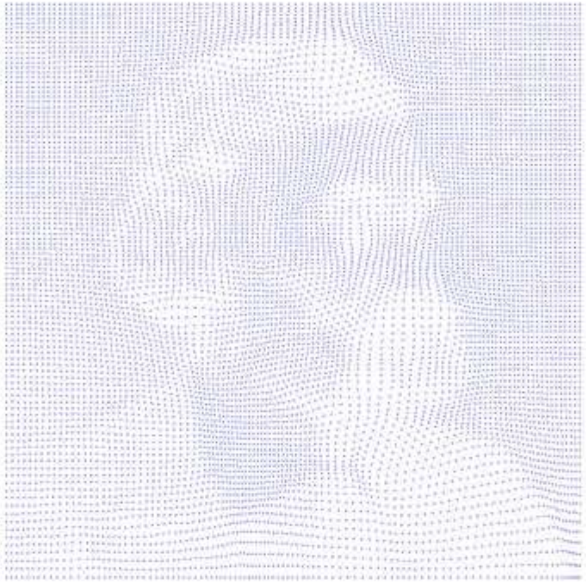


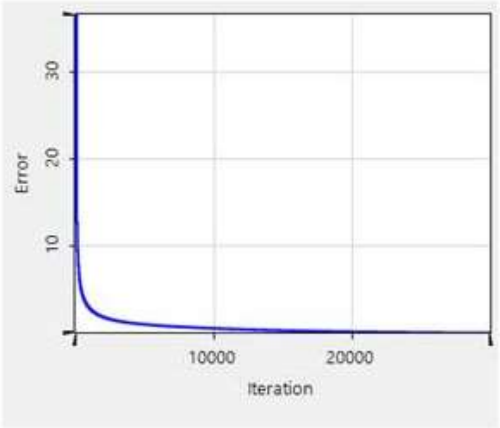




Light Shaping: R&D







Light shaping by stored scanning process

Diffractive optical elements

Light Shaping Concepts

- Tailored aberrations
- Stored scanning process
- Multichannel concept: Single Deflection
- Multichannel concept: General

Light Shaping Concepts

- Tailored aberrations
- Stored scanning process
- Multichannel concept: Single Deflection
- Multichannel concept: General

Function Principle of DOE

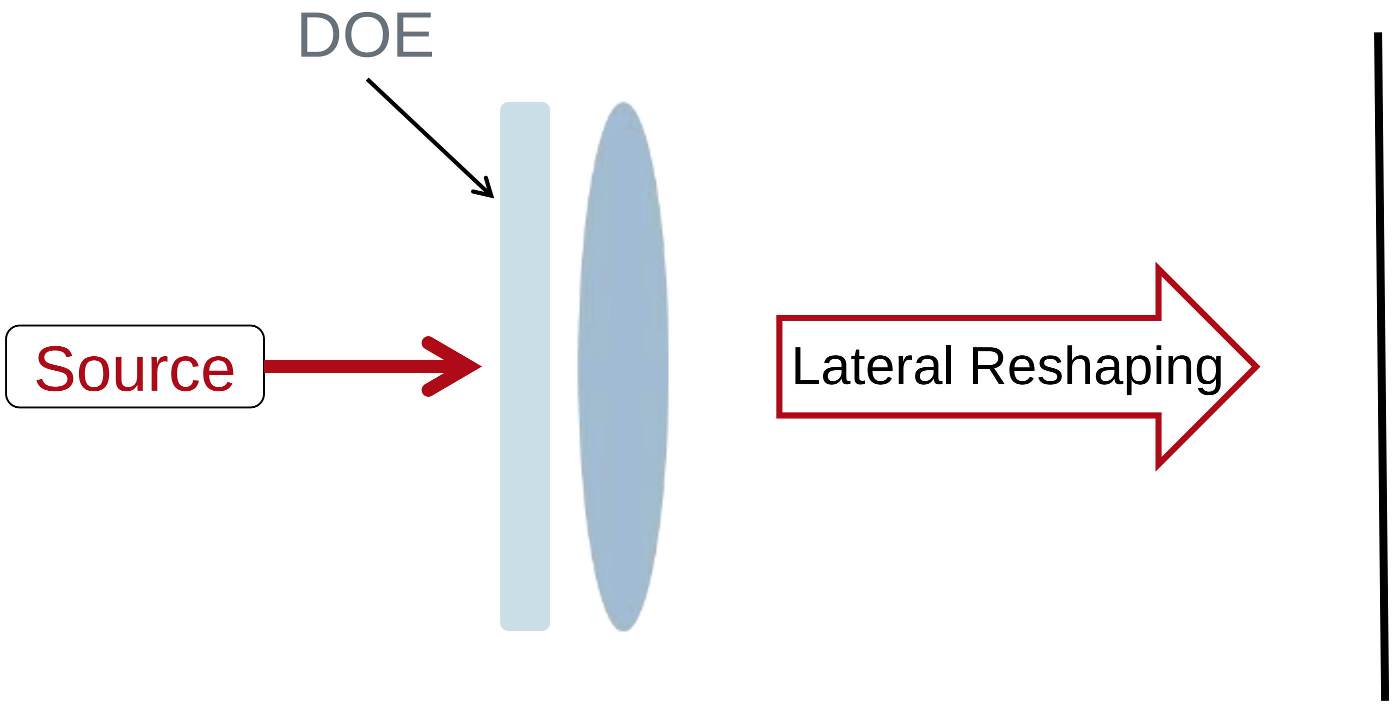
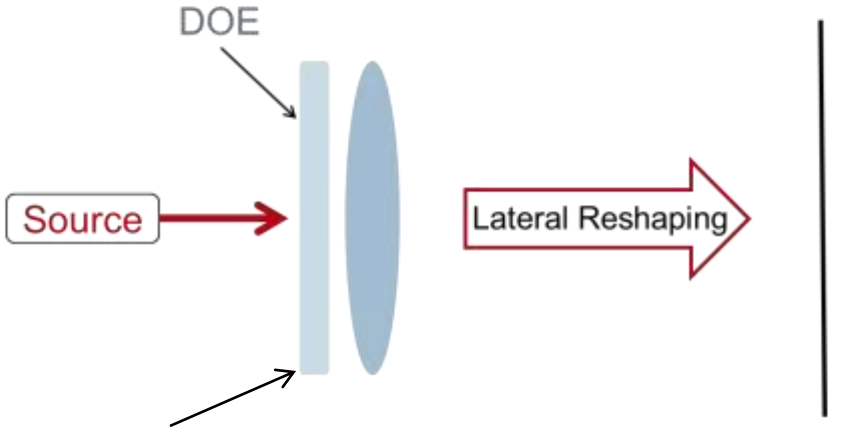
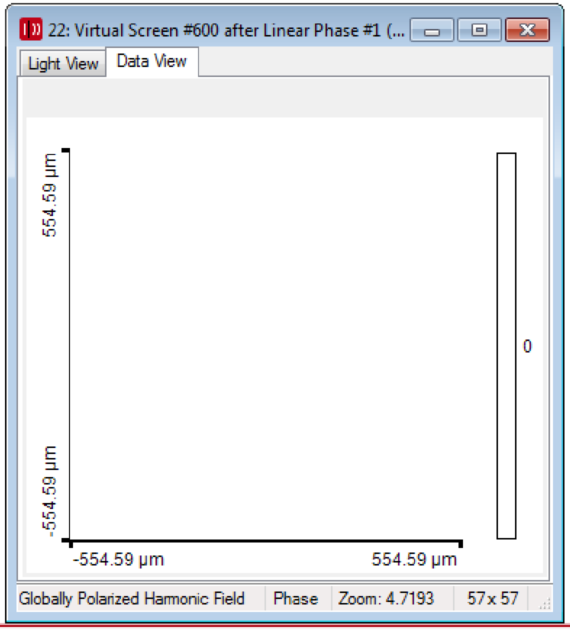


Illustration of Deflection



Phase of transmission



Intensity in target

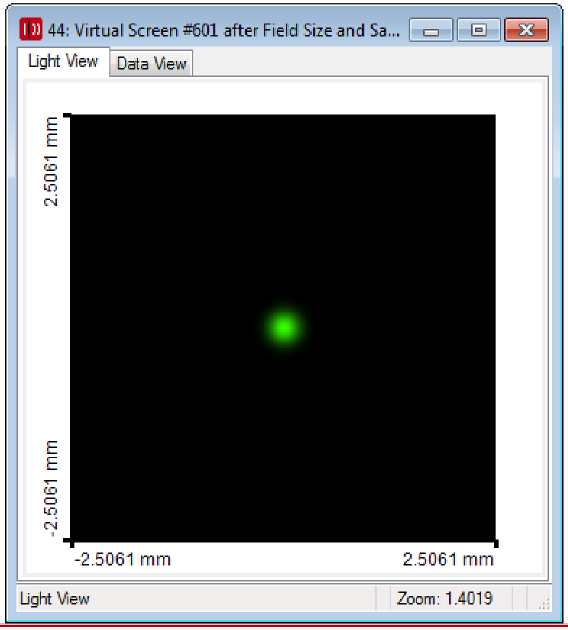
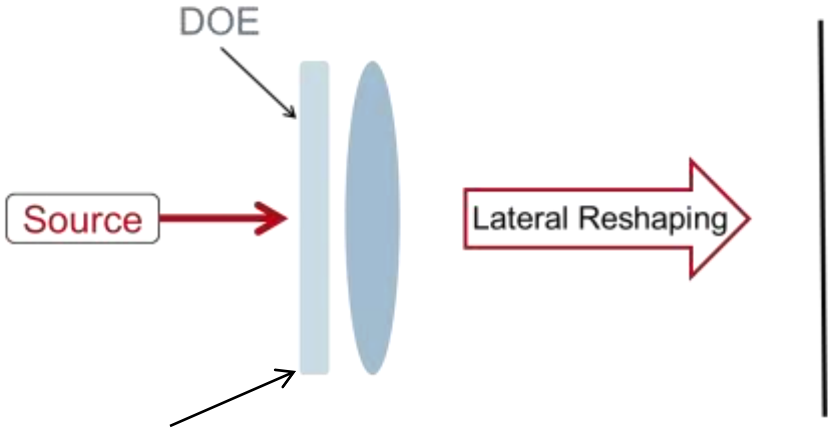
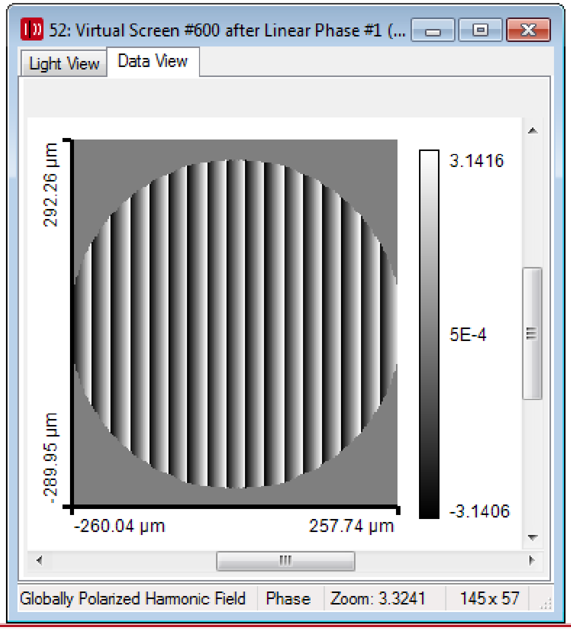


Illustration of Deflection



Phase of transmission

Intensity in target



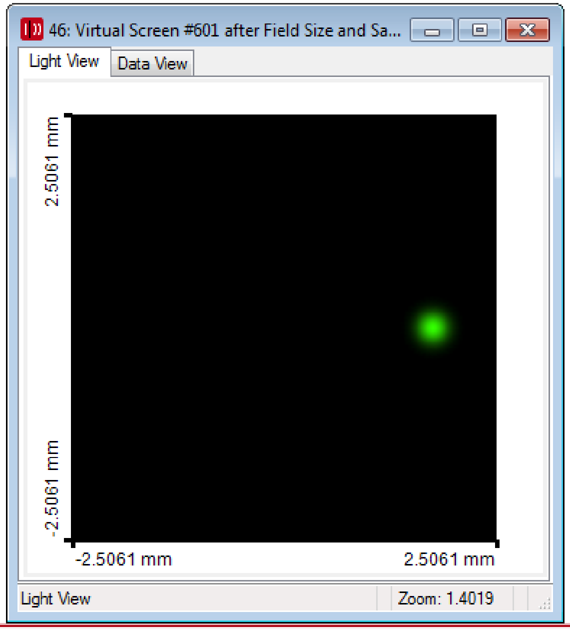
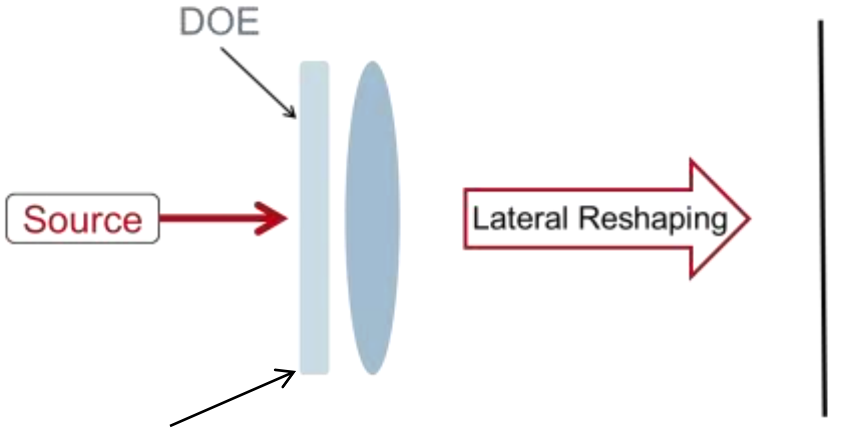
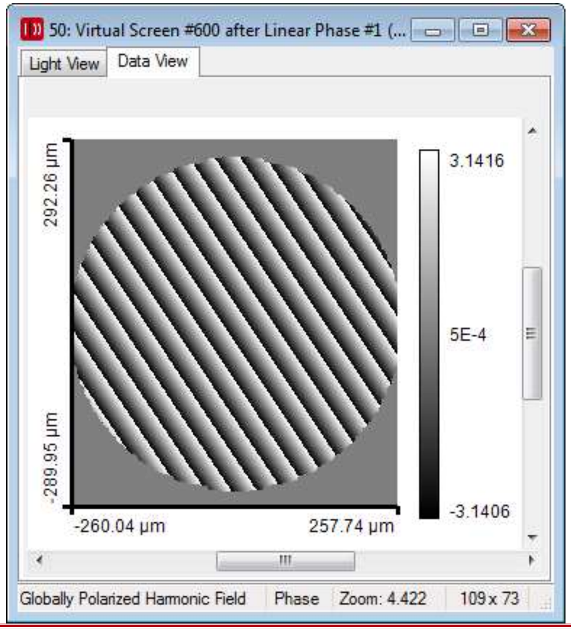


Illustration of Deflection



Phase of transmission

Intensity in target



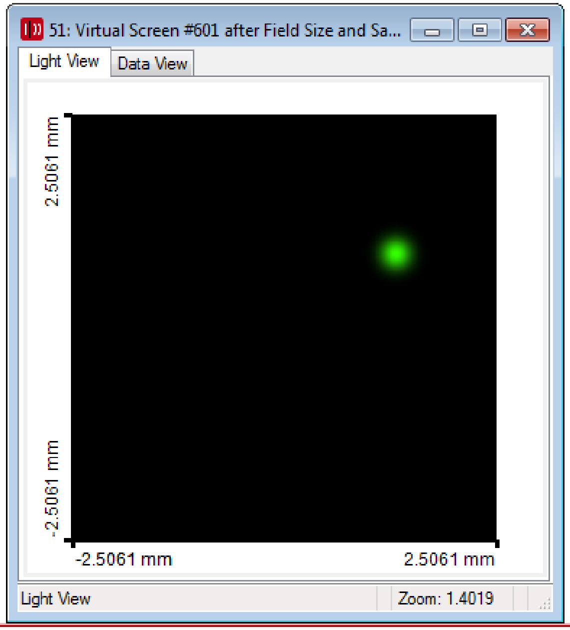


Illustration of Deflection

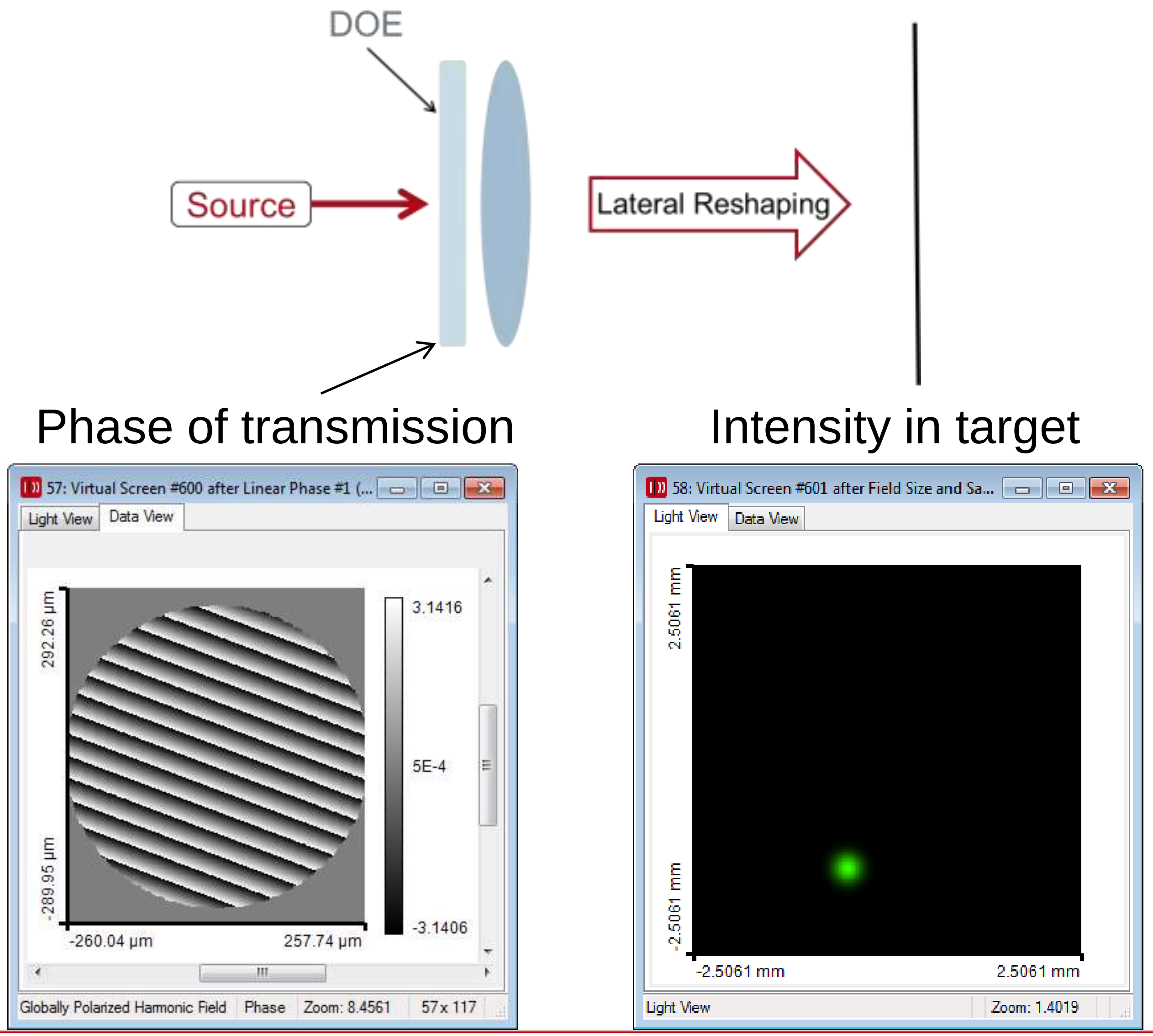
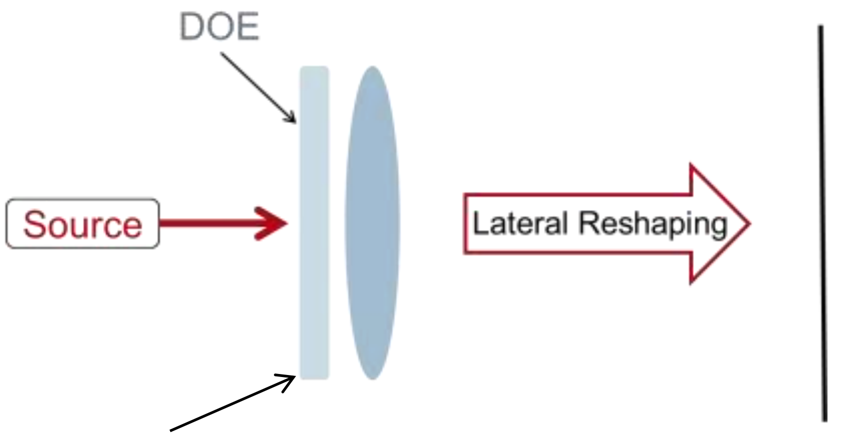
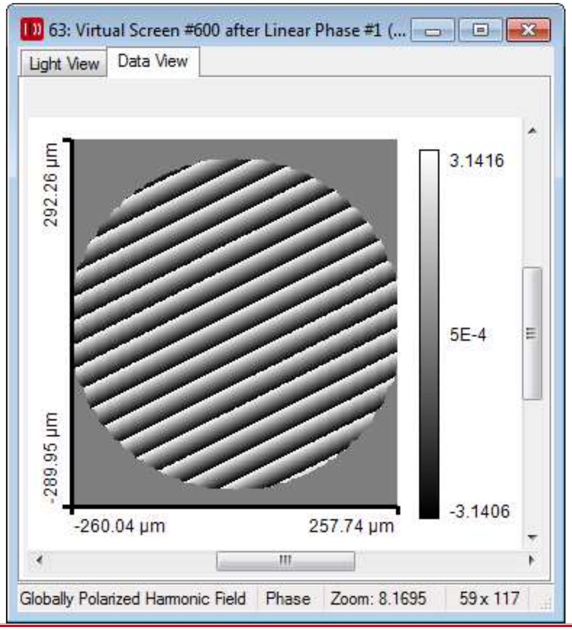


Illustration of Deflection



Phase of transmission



Intensity in target

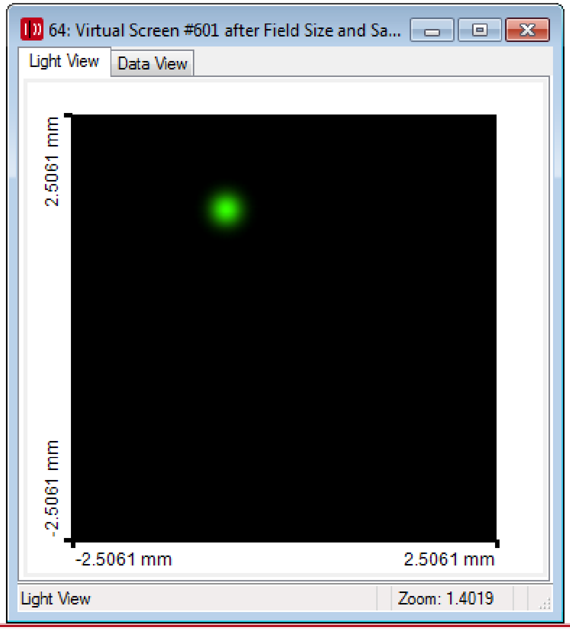
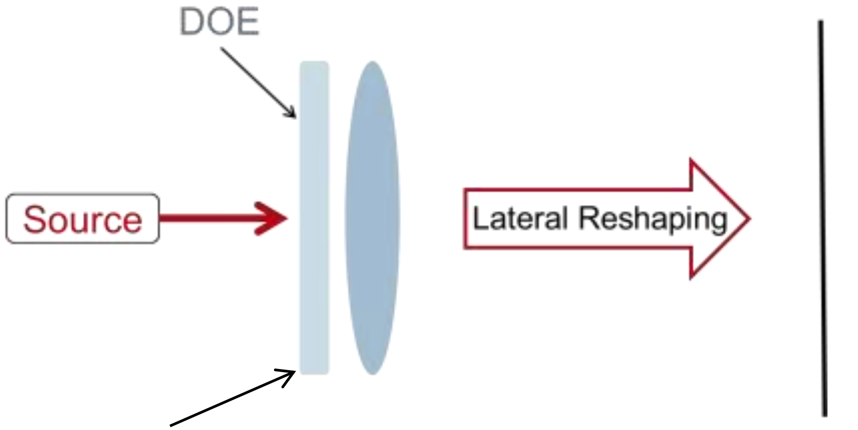
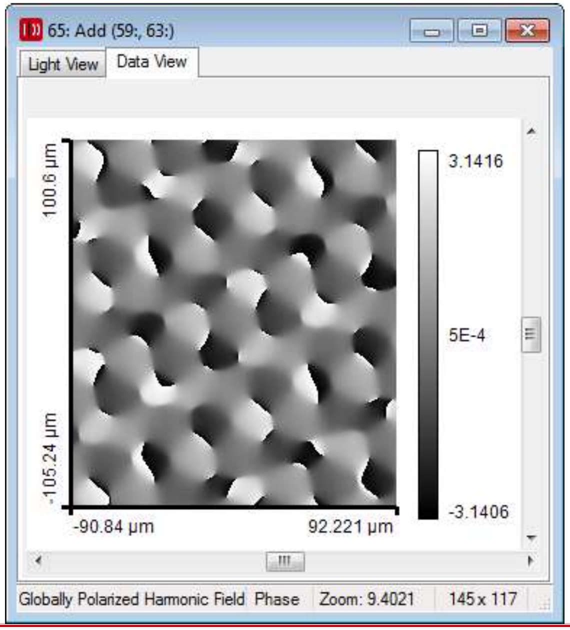


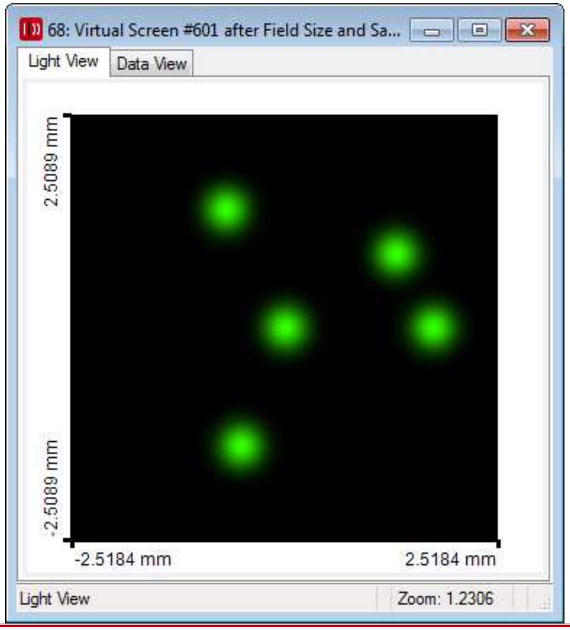
Illustration of Deflection: Sum



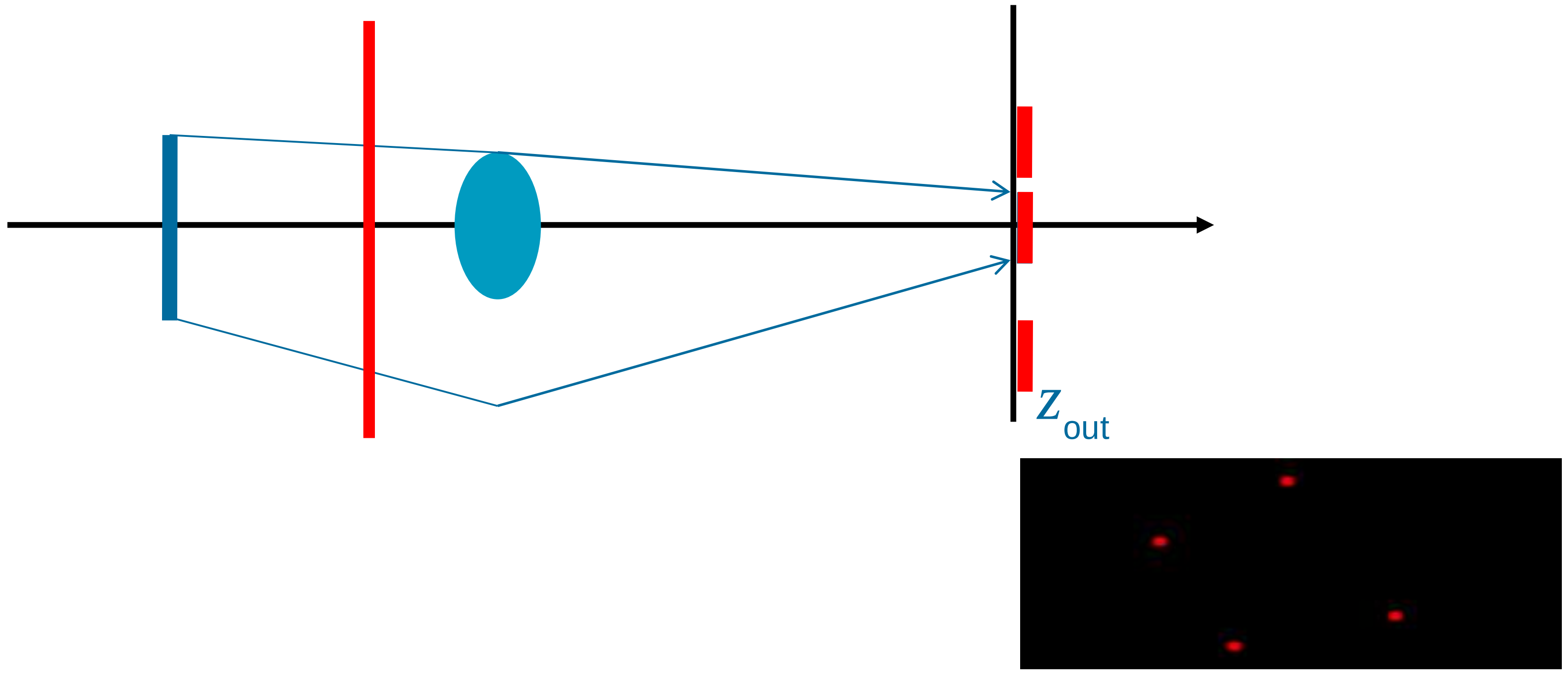
Phase of transmission



Intensity in target

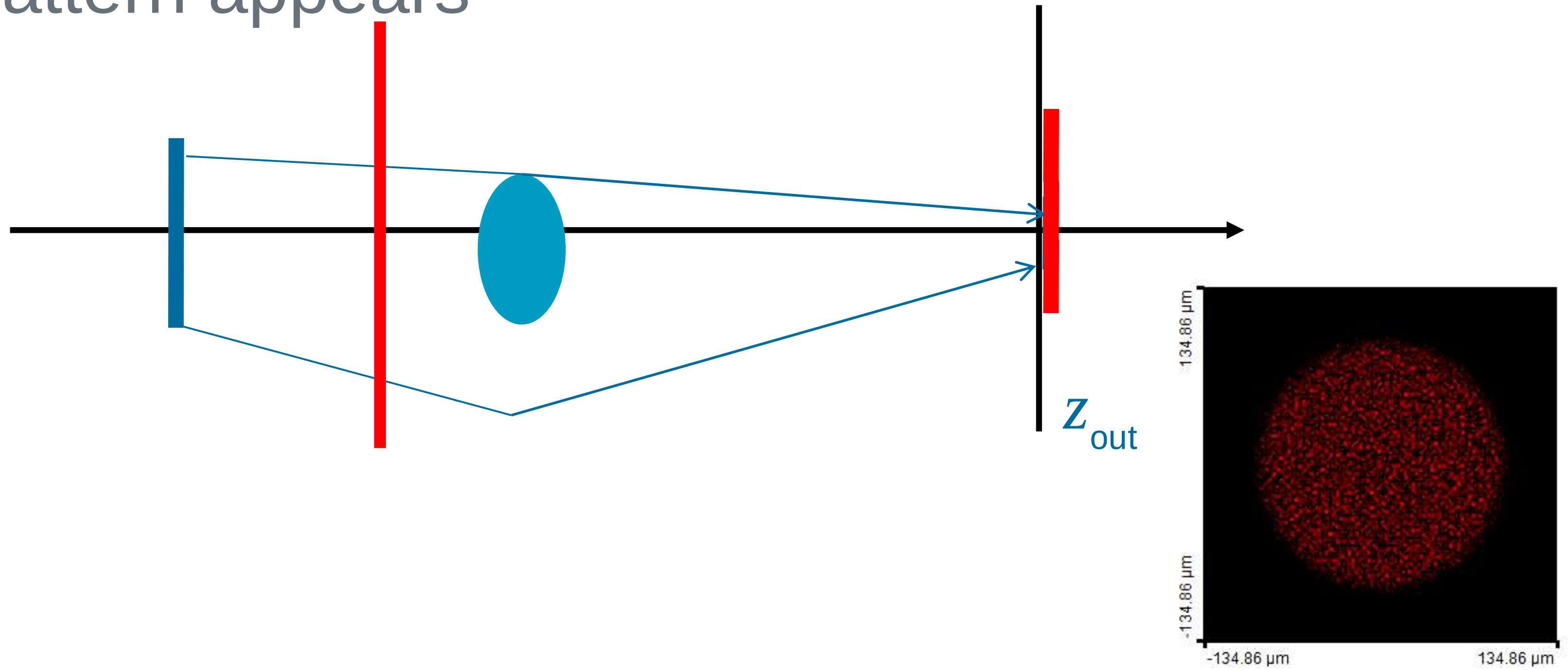


Diffractive Beam Splitting: Deflected output fields (beams) do not overlap



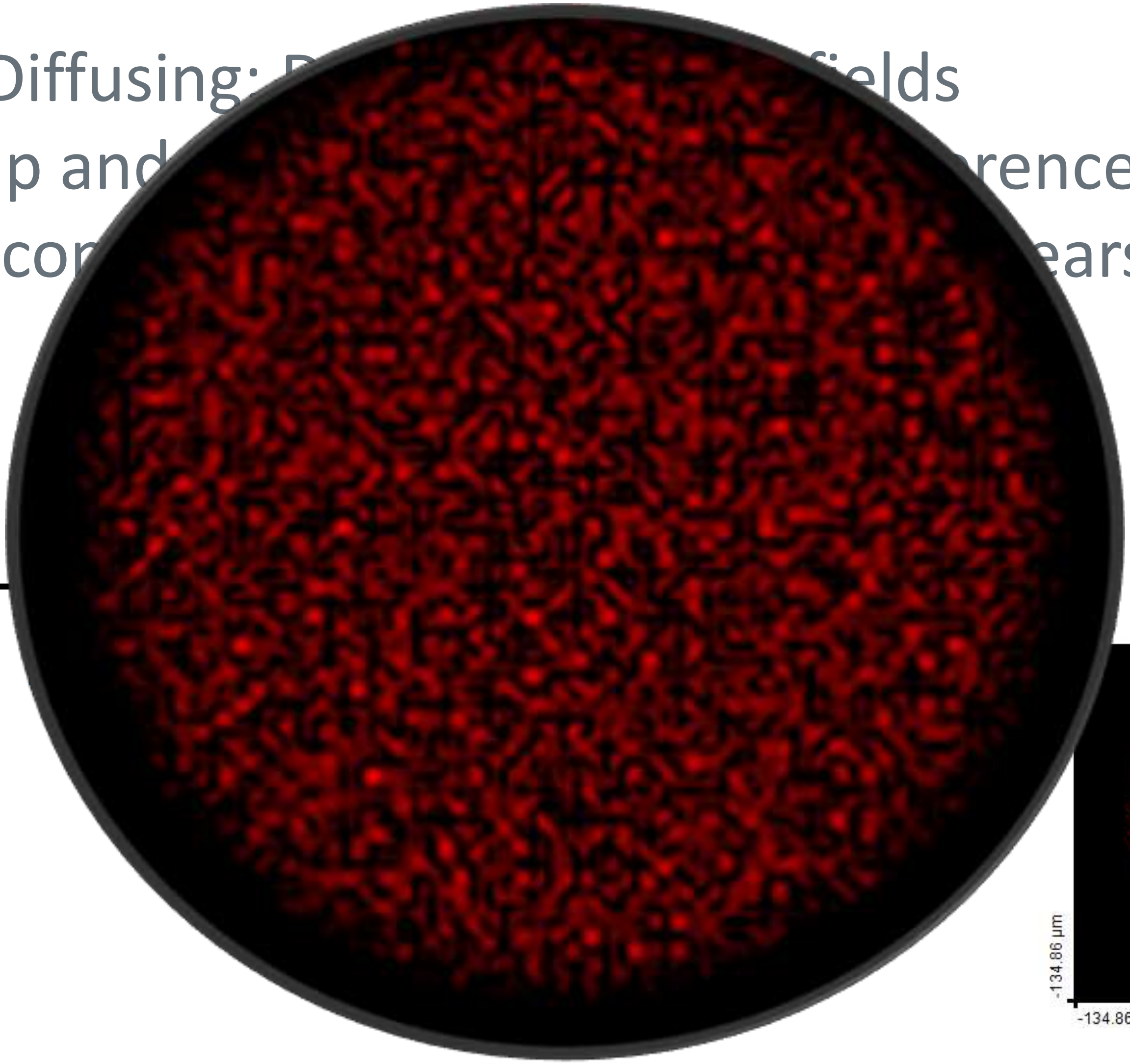
Basic Design Situations: Diffusing

Light Diffusing: Deflected output fields overlap and (partially) coherent interference is not controlled but speckle pattern appears



Basic Design Situations: Diffusing

Light Diffusing: D… …ields
overlap and… …rence
is not co… …ears.



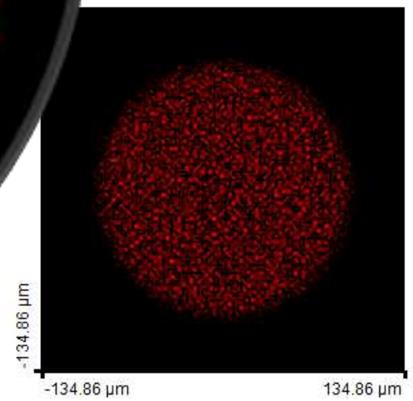


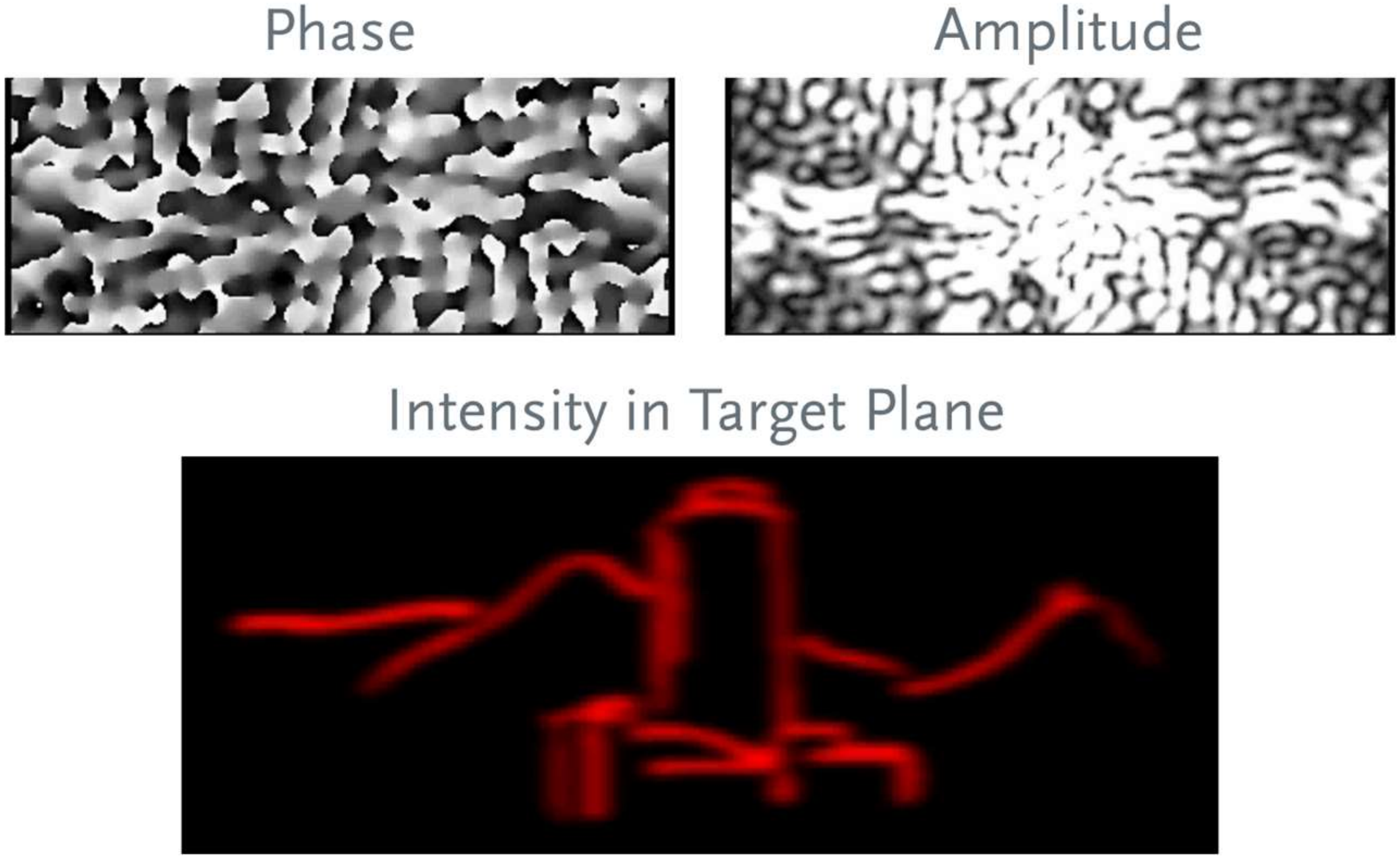
Illustration of Diffuser Concept

Phase

Amplitude

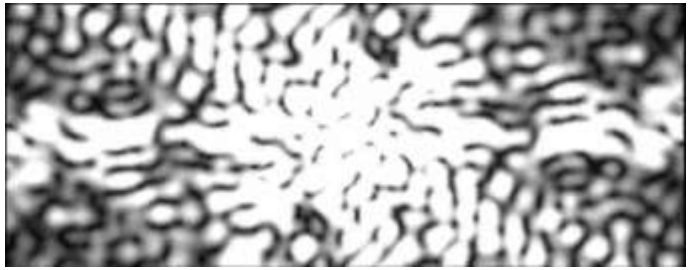
Intensity in Target Plane

Illustration of Diffuser Concept

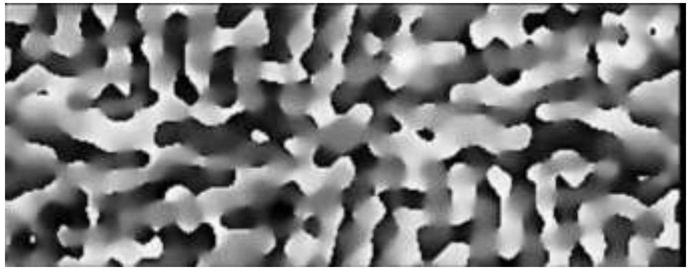


Light Diffusing

Amplitude

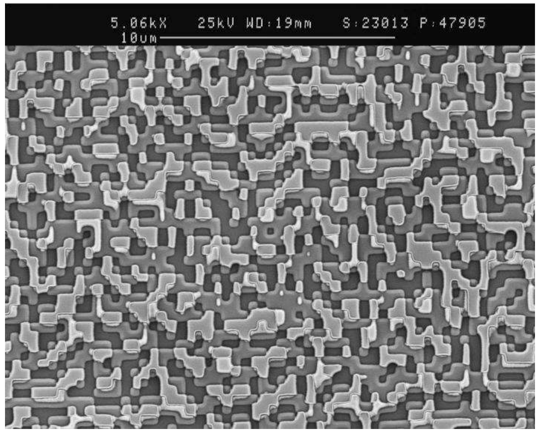


Phase



Advanced diffractive optics design techniques

Design technique (IFTA) implemented in VirtualLab™



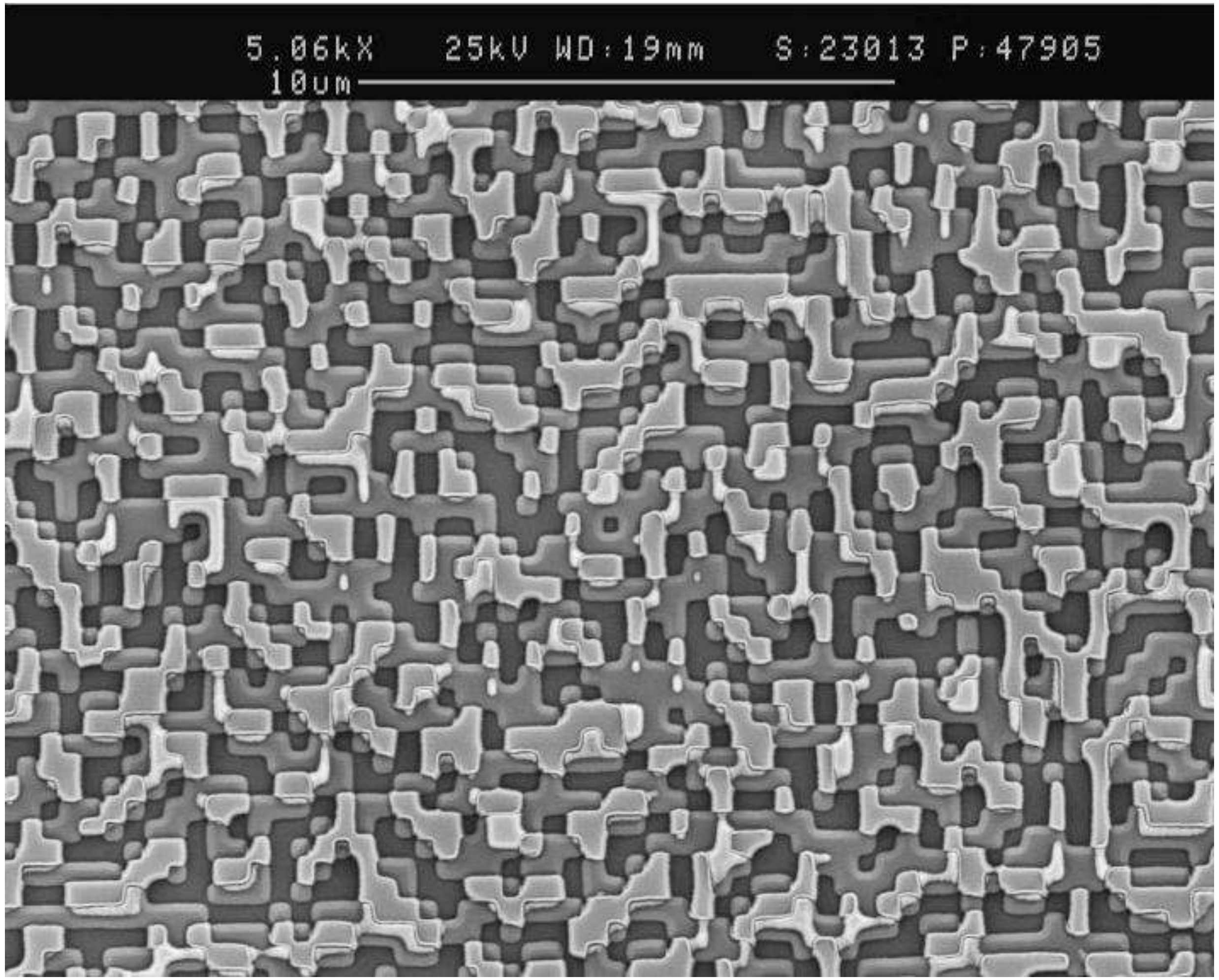
Micro-structured surface profile

Fabricated at IAP, University of Jena

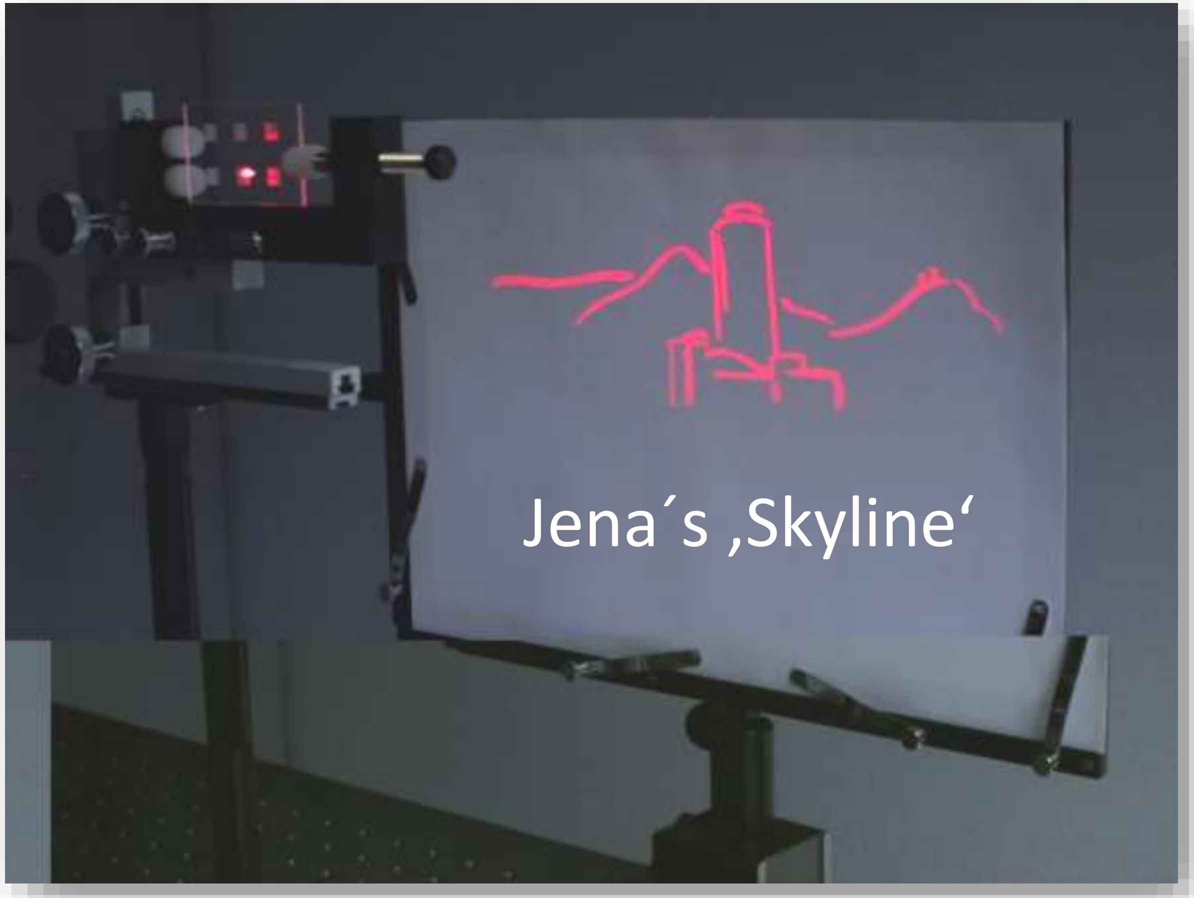
Feature Sizes of Element

Feature size
about 400 nm

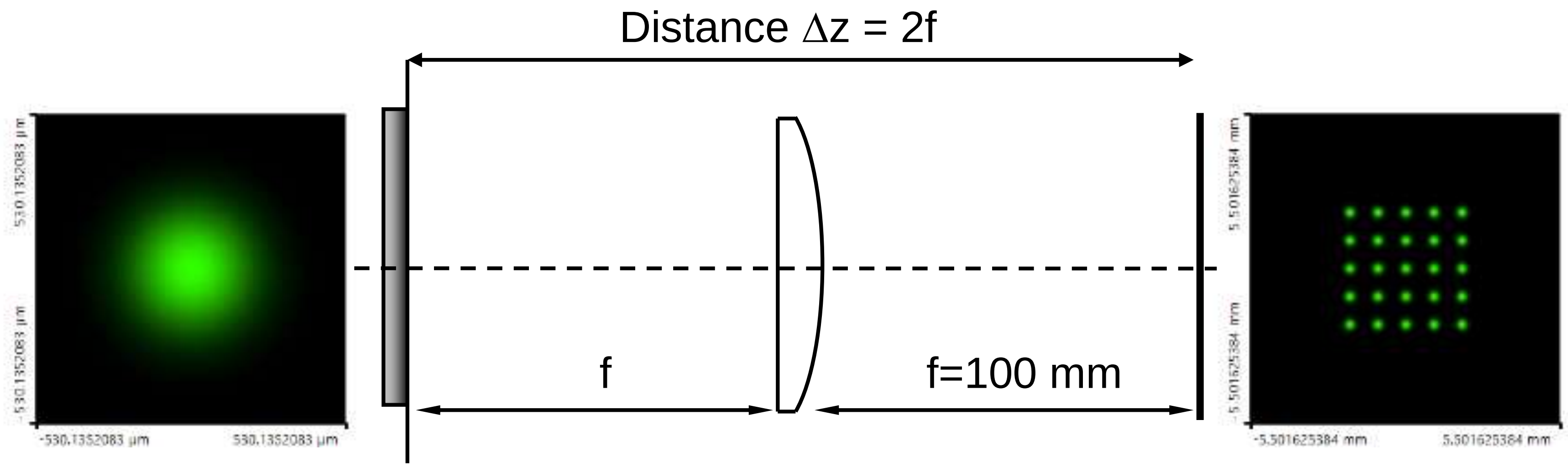
4 height levels



Optical Experiment



Task 8 Beam Splitter



Wavelength: 532nm
Laser Beam Diameter ($1/e^2$): 200µm

Diffractive Beam Splitter Element
4 Phase Levels
rect. 1x1 mm Diameter

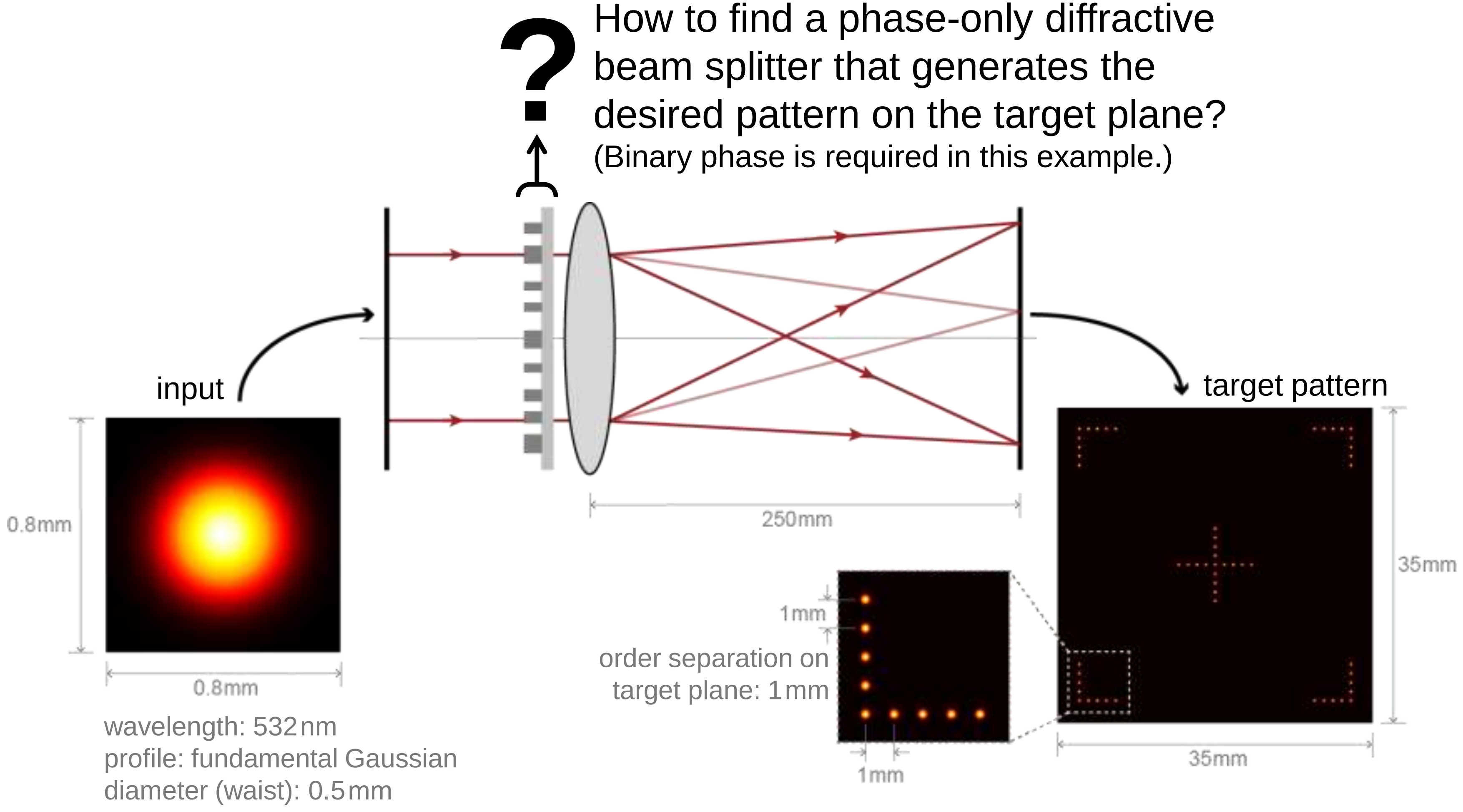
Fourier Lens

Target Plane

Spot Array of 5 x 5 discrete Beam Spots

Design Task

How to find a phase-only diffractive beam splitter that generates the desired pattern on the target plane?
(Binary phase is required in this example.)

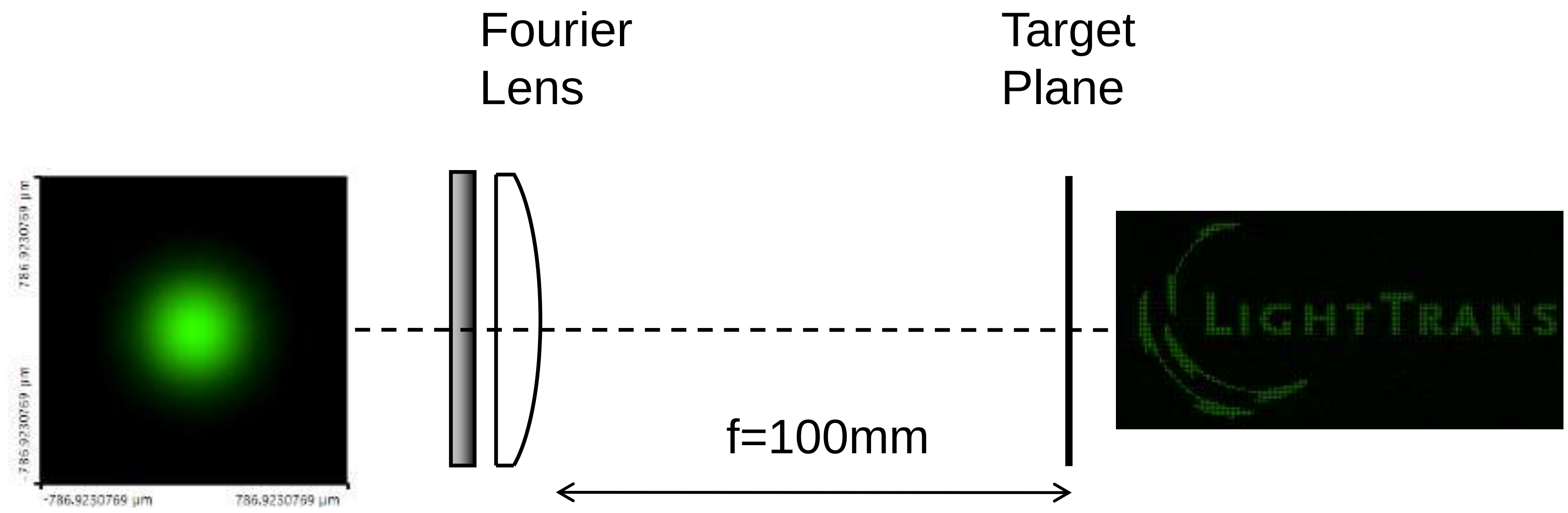


Demo Task 14

Klick the following link to watch the video:

https://youtu.be/9gnYqlB6q08

Modeling Task



Wavelength: 532 nm
Laser Beam Diameter (1/e²): 500 µm

DOE:
Diffractive Beam Splitter
Phase: continuous
Pixel Size: >0.5µm
Diameter: 2 x 2mm

Desired Light Pattern Intensity
Diffraction order distance: 0.1mm x 0.1mm

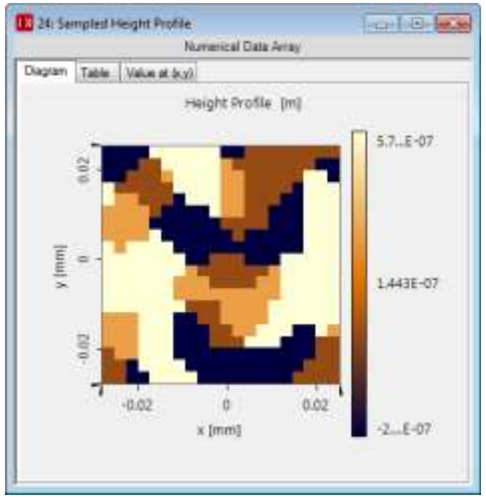
Micro Optical Component

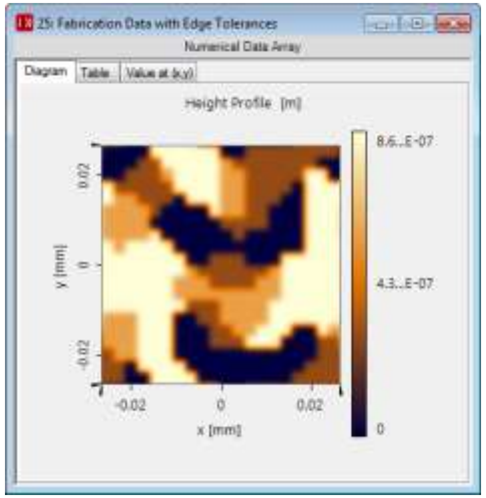
Modeling of Rounding of Pixels

Modeling of Rounding of Pixels

- Several micro structured surfaces consists of rectangular pixels.
- It is typically assumed that pixels have rectangular side walls and sharp edges.
- Exposure and etching processes during the fabrication of micro structured surfaces can lead to a rounding of pixel edges.
- The edge rounding can be modeled in a good approximation by convolution with a Gaussian beam.

Example with Data from Scenario 23.01

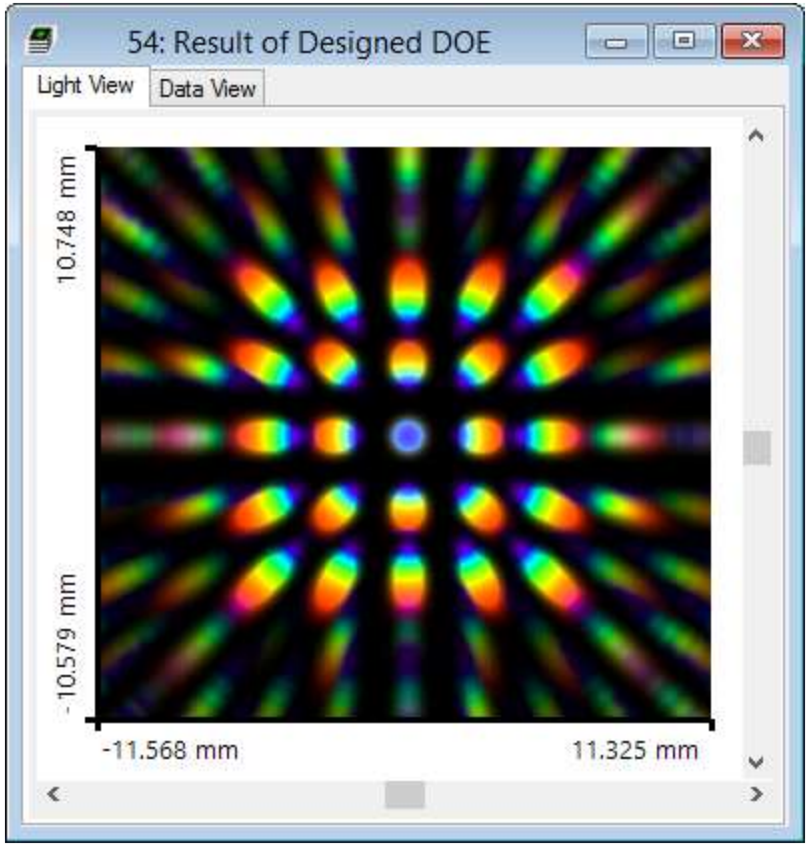




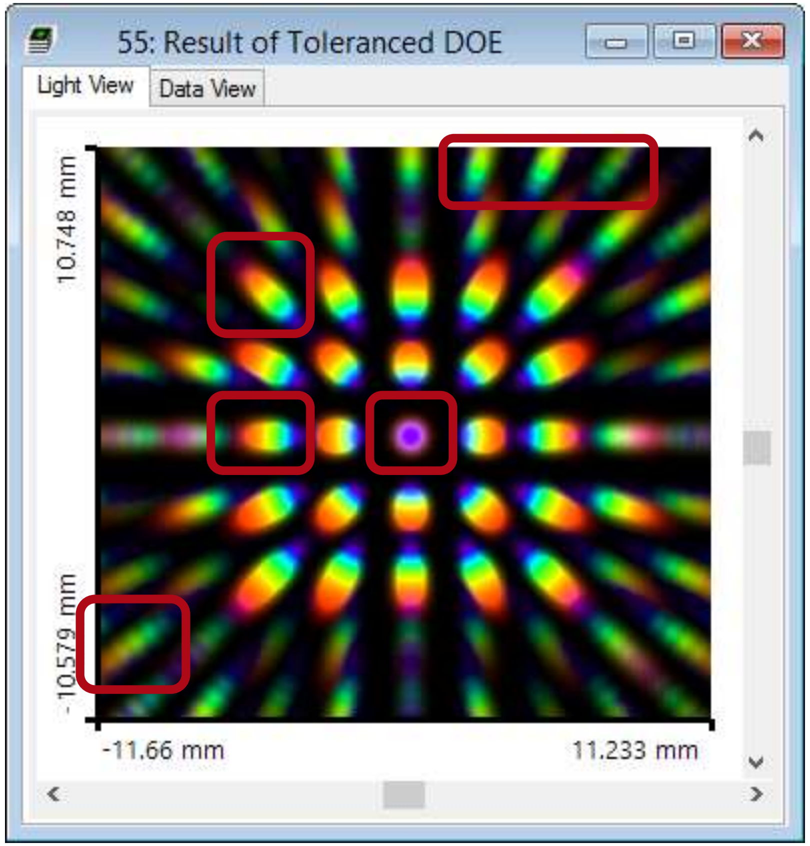
- VirtualLab Module **`Module_RoundedEdge_Tolerances.cs`** can be used to calculate from a perfect profile a profile with rounded edges.
- Calculation steps:
  - Get a *Data Array* with the perfect profile from the sampled interface.
  - Apply the module.
  - Set the *Data Array* with the modified profile into the sampled interface.
- Left side: edge rounding 2 µm, sampling distance 400 nm.

Results with 4x Increased Brightness

Simulation Result of Designed DOE



Simulation Result of DOE with Rounded Edges

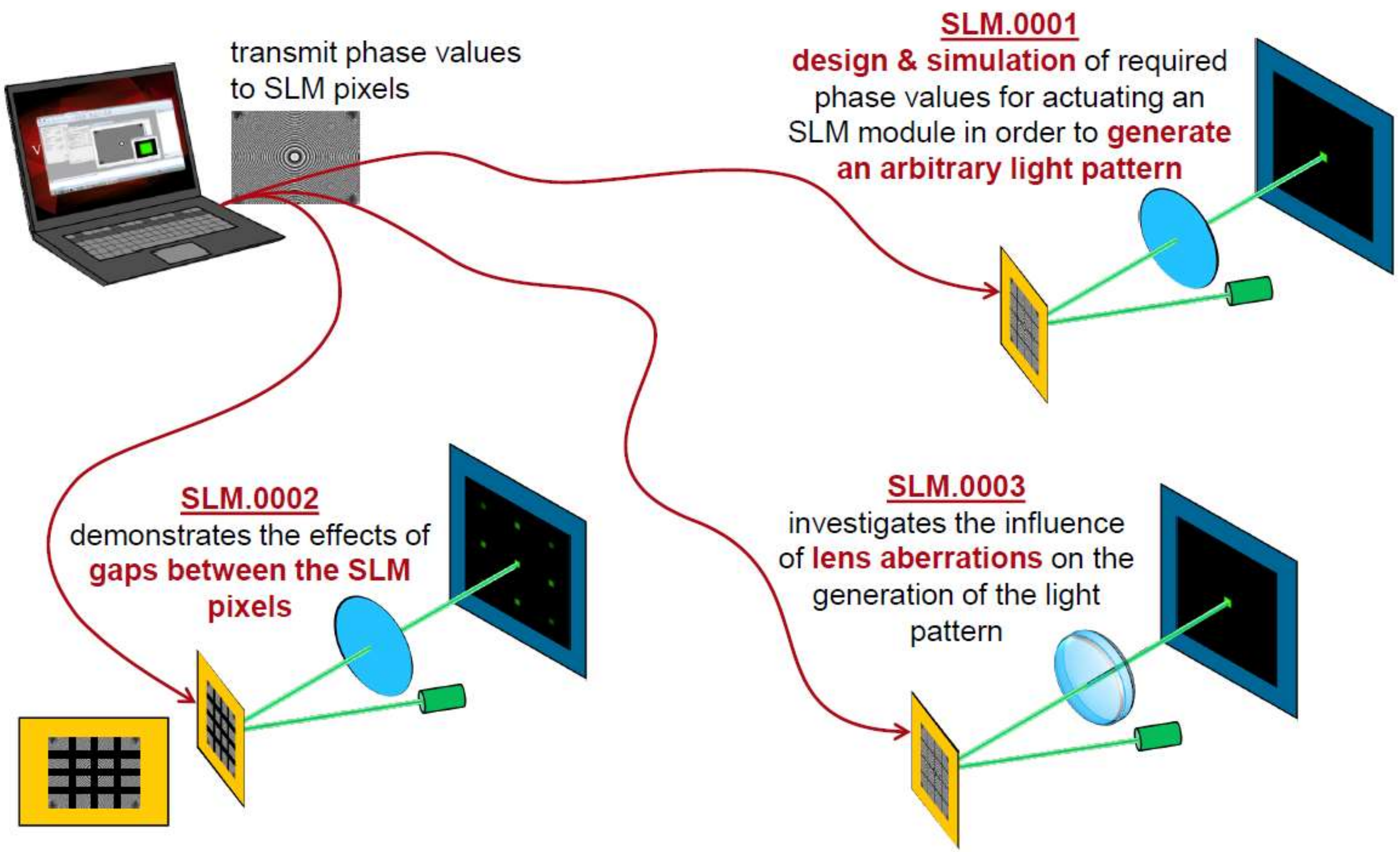


Comments on Diffuser Technology

- Very flexible in light pattern generation
- Robust against adjustment problems
- Coherent light leads to speckle pattern
- Size of speckle features can be adjusted by focusing system
- Diffusers work for partially coherent beams
- Partially coherent beams smooth the speckle pattern; effect can be simulated with VirtualLab™

Laser Show China

Spatial Light Modulator

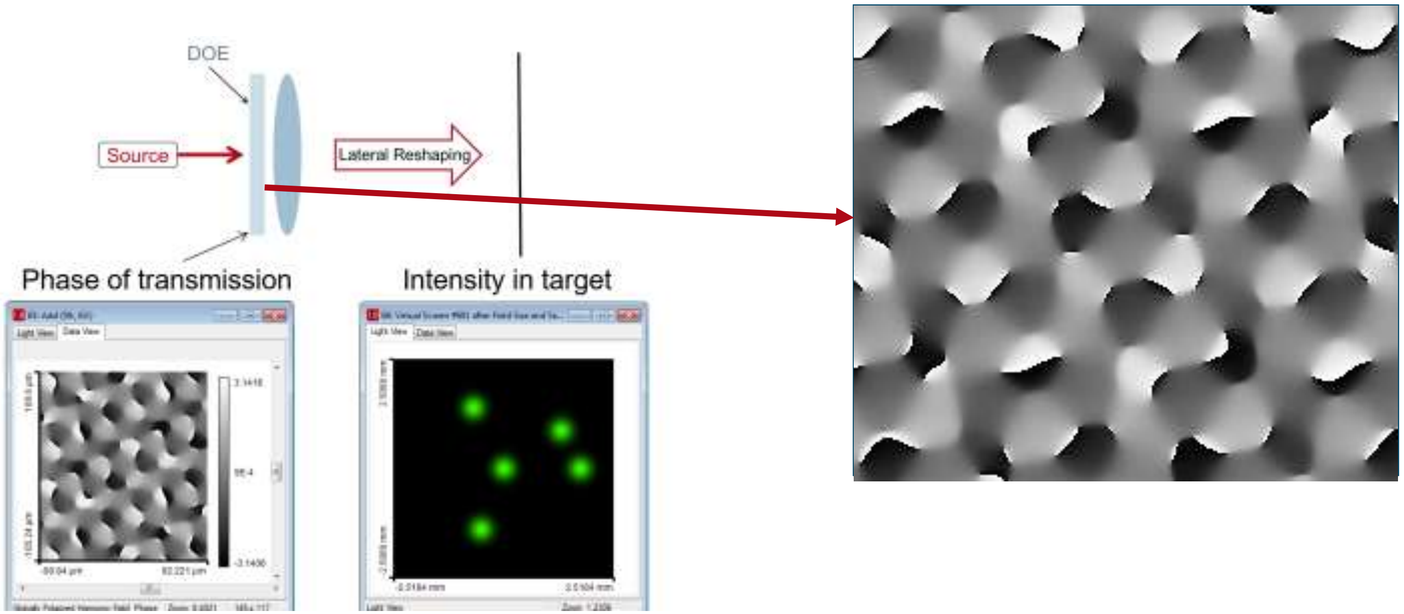


Spatial Light Modulator

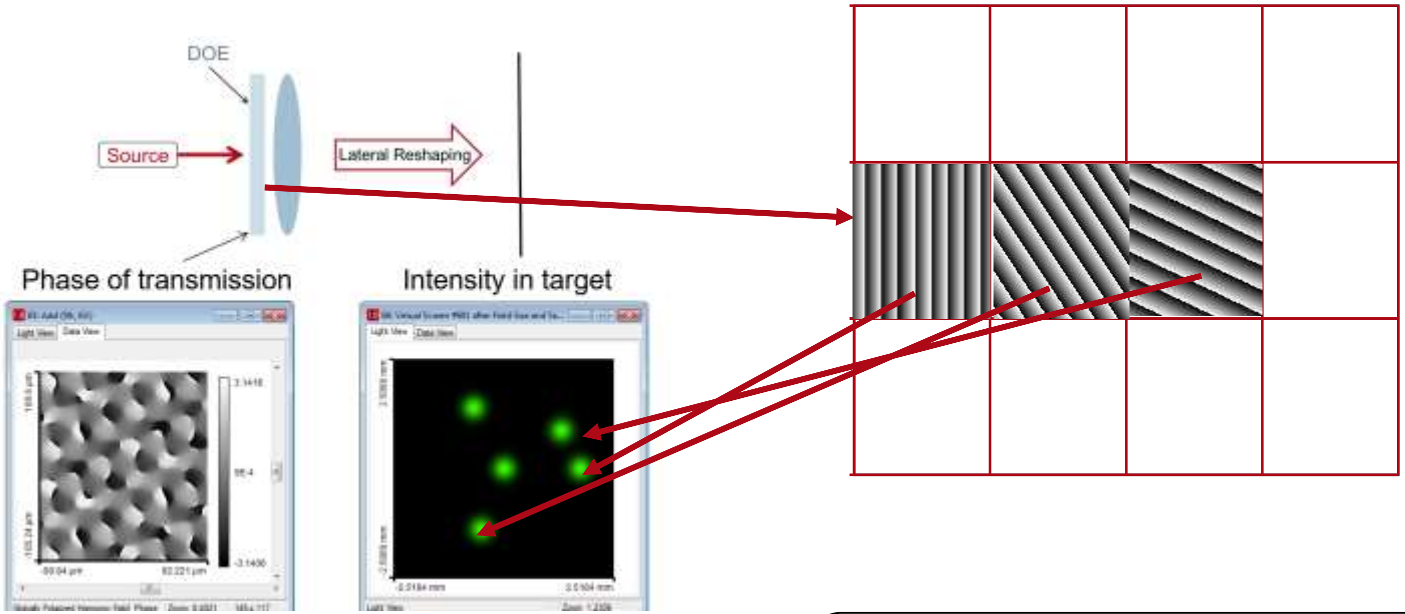
Light shaping by multichannel concept

Diffractive and refractive optical elements

Array of Deflectors

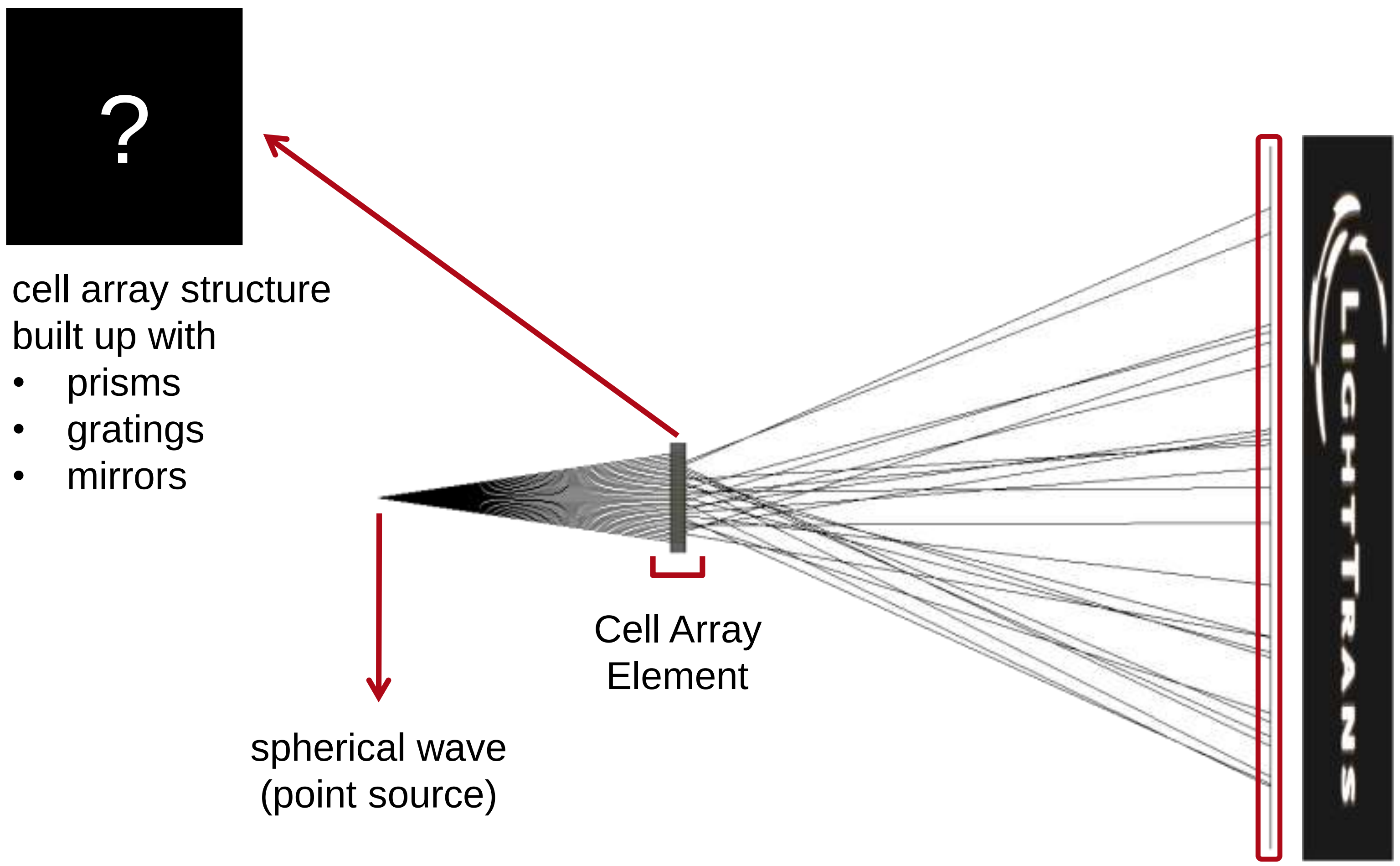


Array of Deflectors

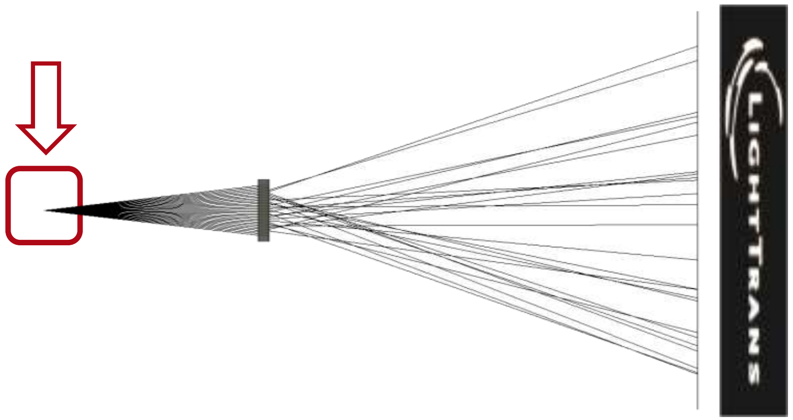


Deflection can be done by gratings, prisms, mirrors.

Task/System Illustration

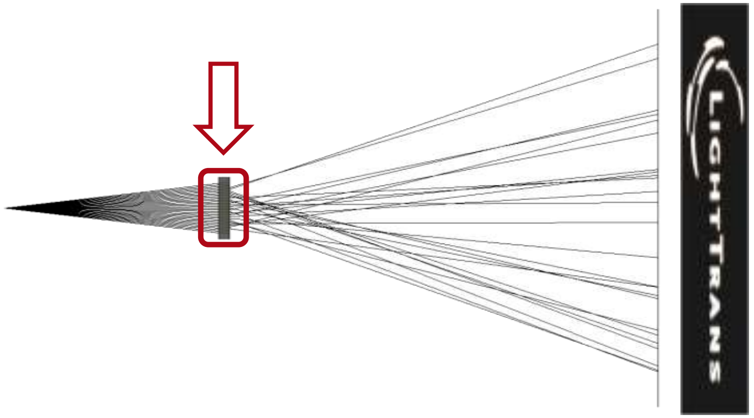


Specification: Light Source



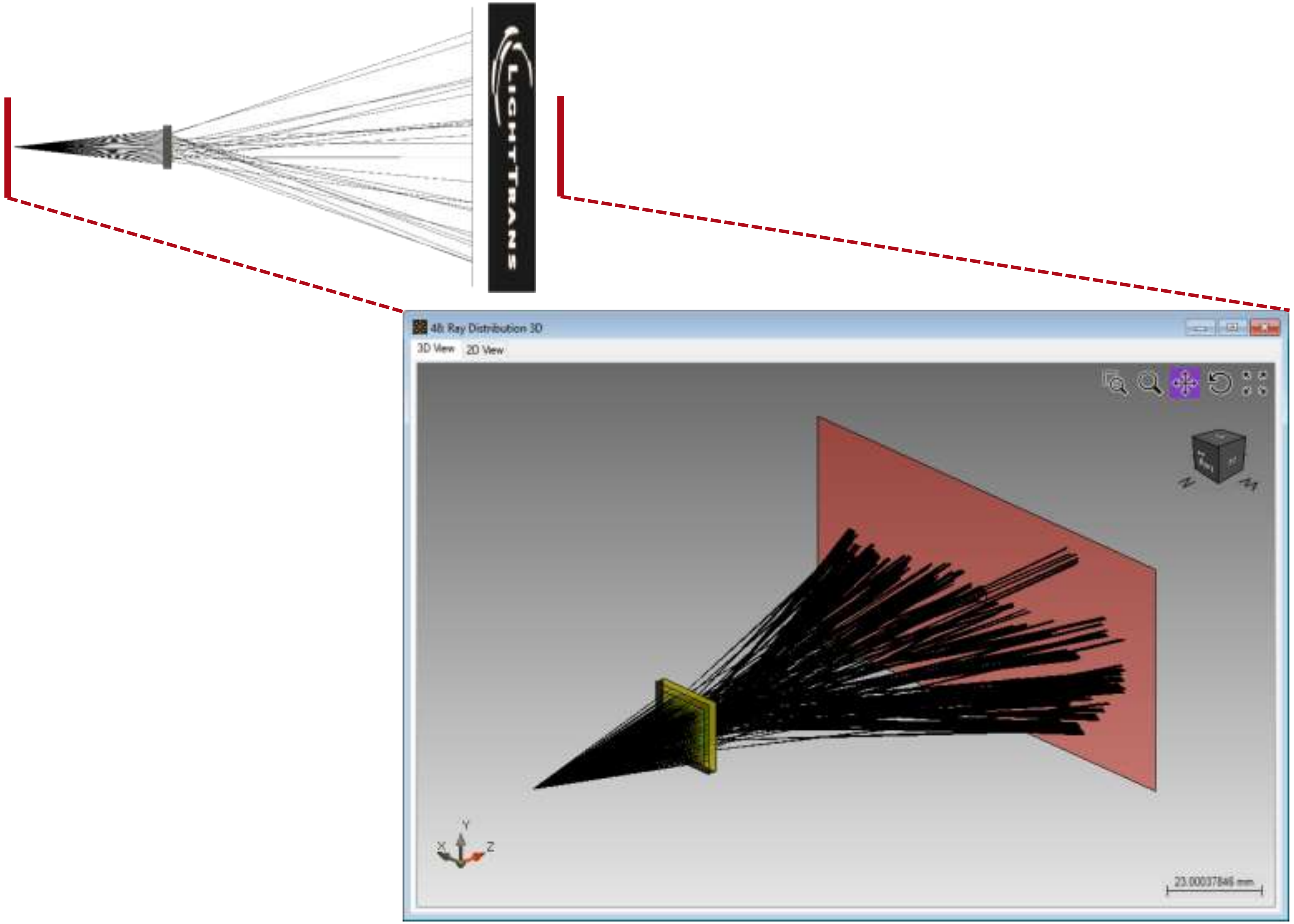
Parameter	Description / Value & Unit
type	RGB LED
emitter size	100x100 µm
wavelength	(473, 532, 635) nm
polarization	right circularly polarized light
number of lateral modes	3x3
Total number of lateral and spectral modes	27

Specification: Cell Array

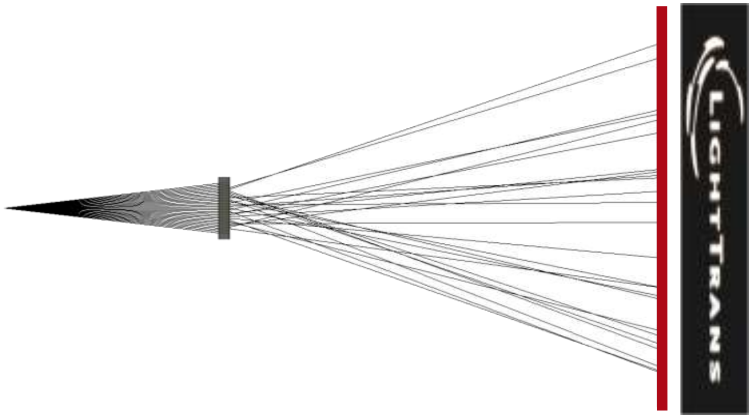


Parameter	Value & Unit
number of cells	100x100
cell size	125x125µm
array aperture	12.5x12.5mm

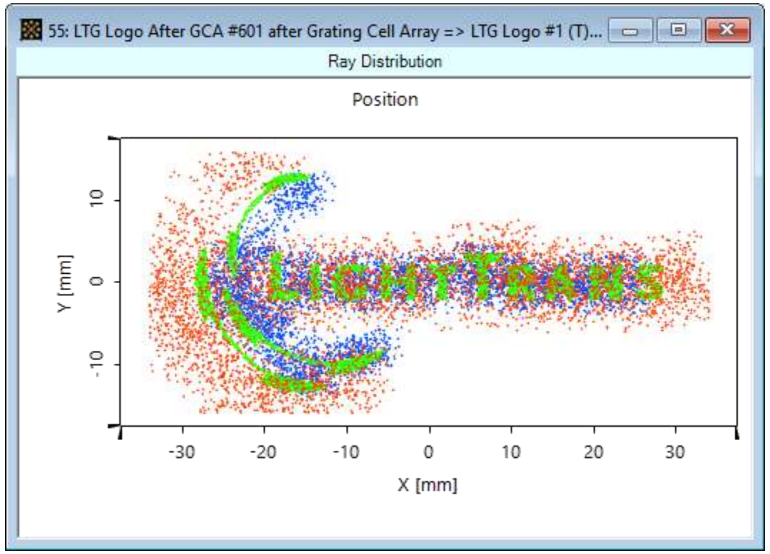
Results: 3D System Ray Tracing

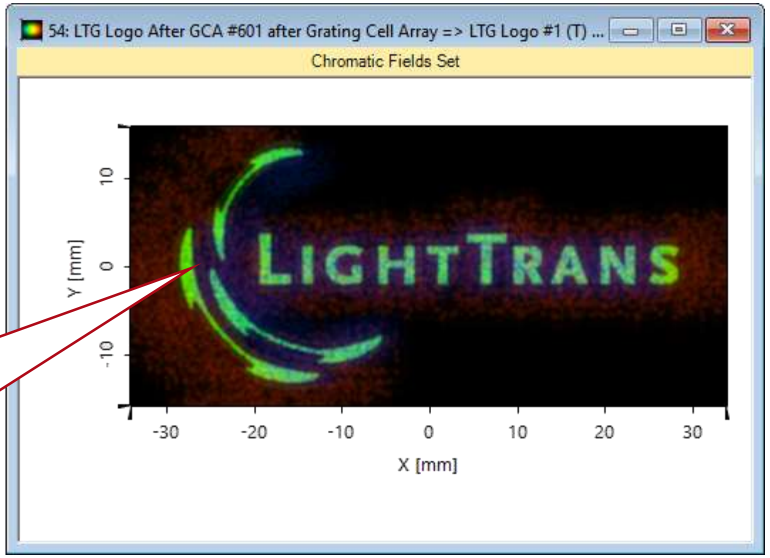


Results: Grating Cells Array



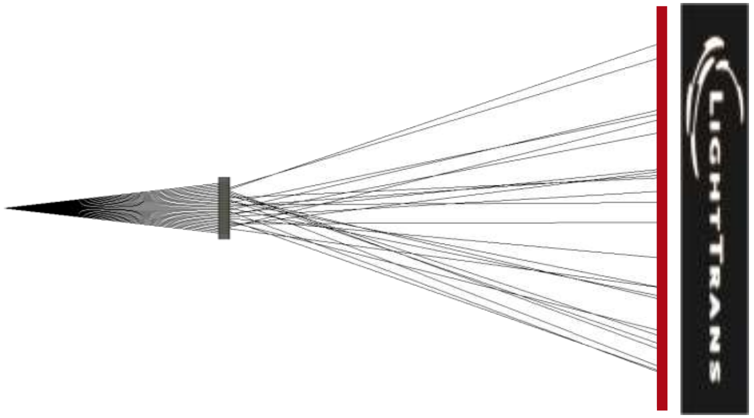
spot diagram



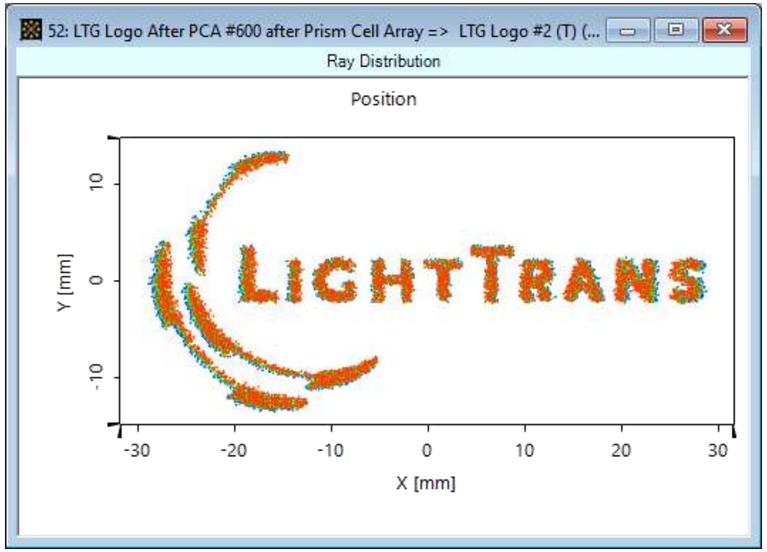


for grating cells array strong dispersion effects occur

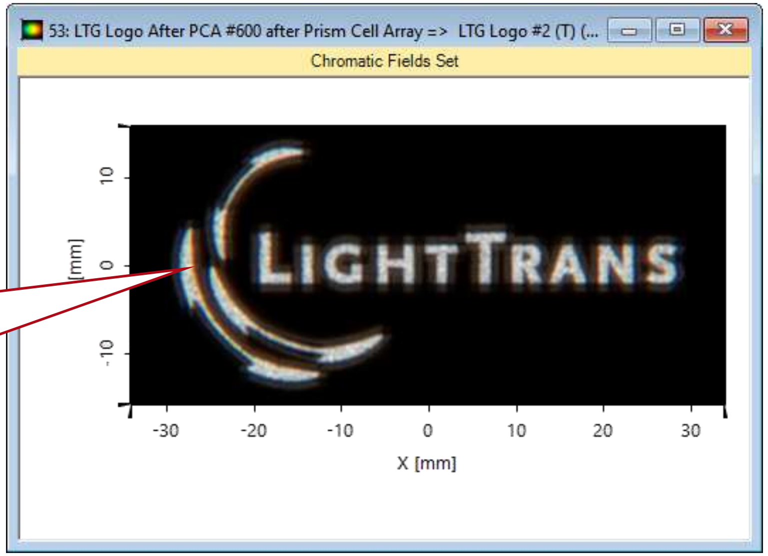
Results: Prism Cells Array



spot diagram

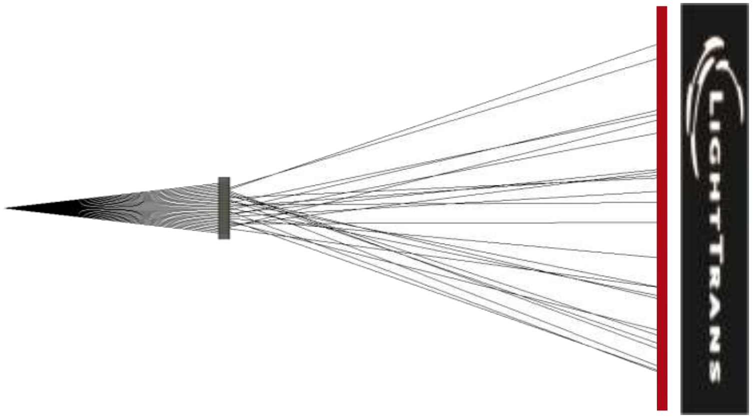


pattern
(real
lor view)

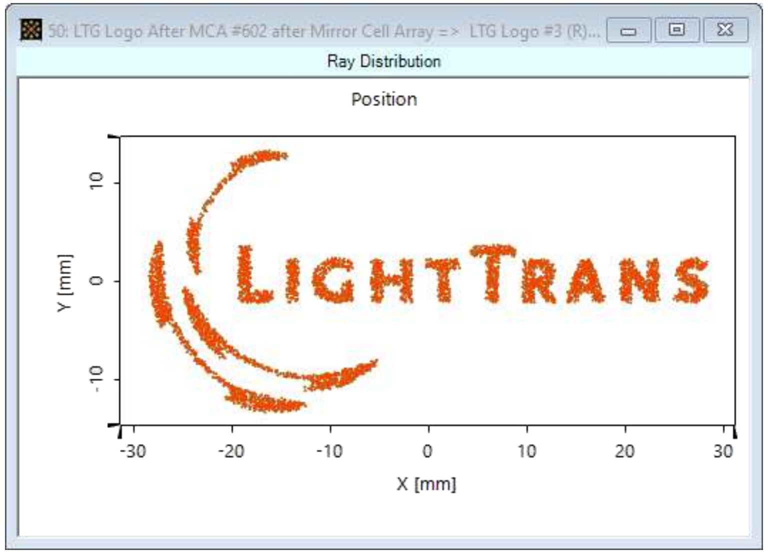


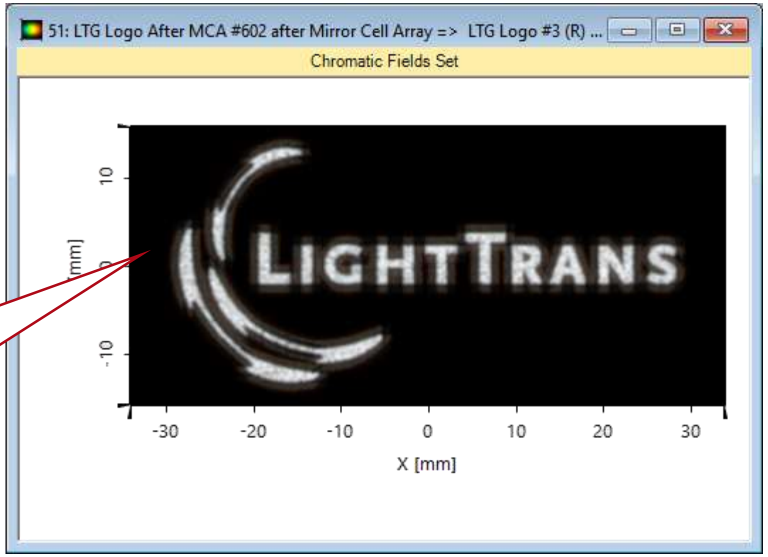
the dispersion is significantly reduced by using prisms

Results: Mirror Cells Array



spot diagram



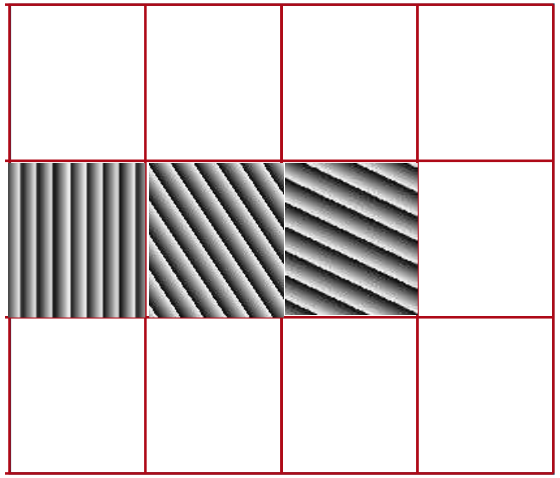


due to reflective approach no dispersion effects occur

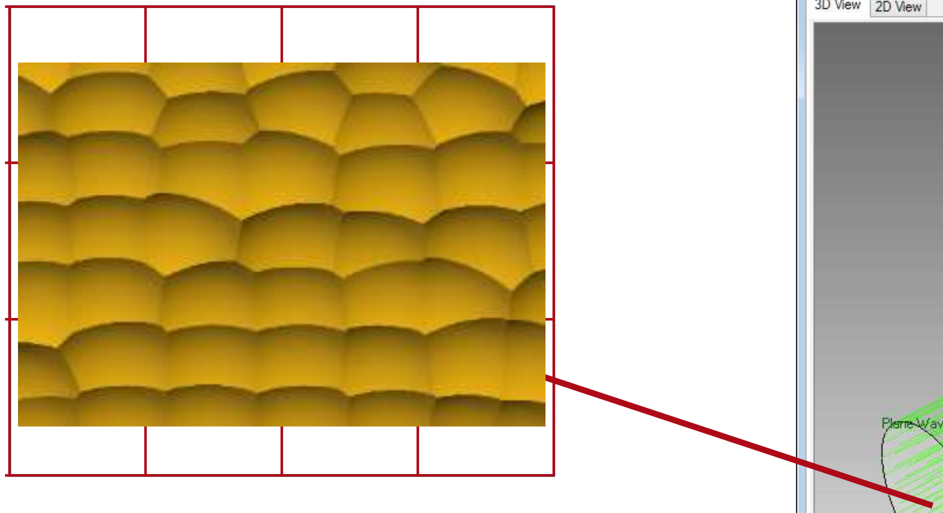
Light shaping by arrays of microoptical components

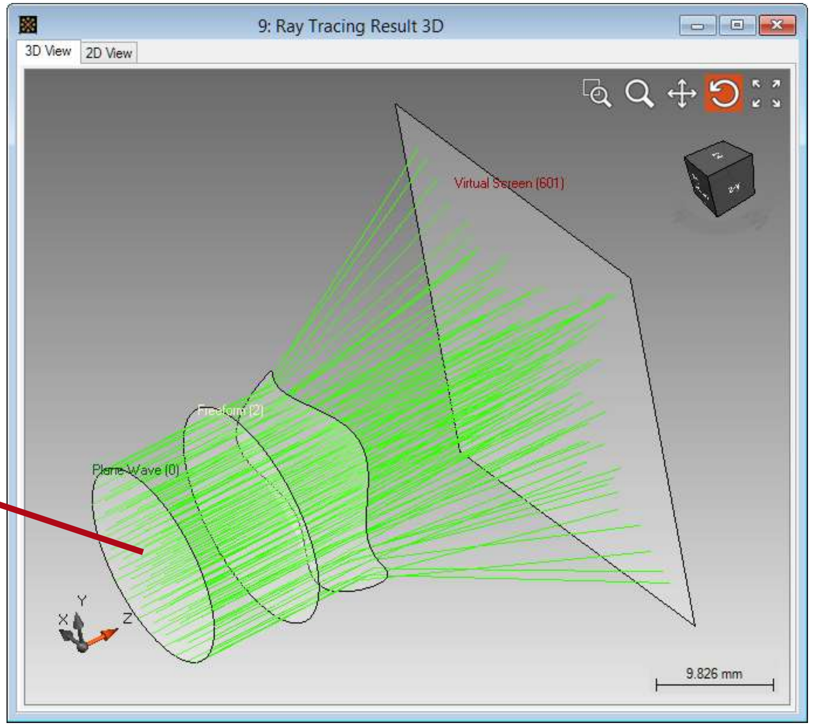
Diffractive and refractive optical elements

Array of Microoptical Components



Array of Microoptical Components

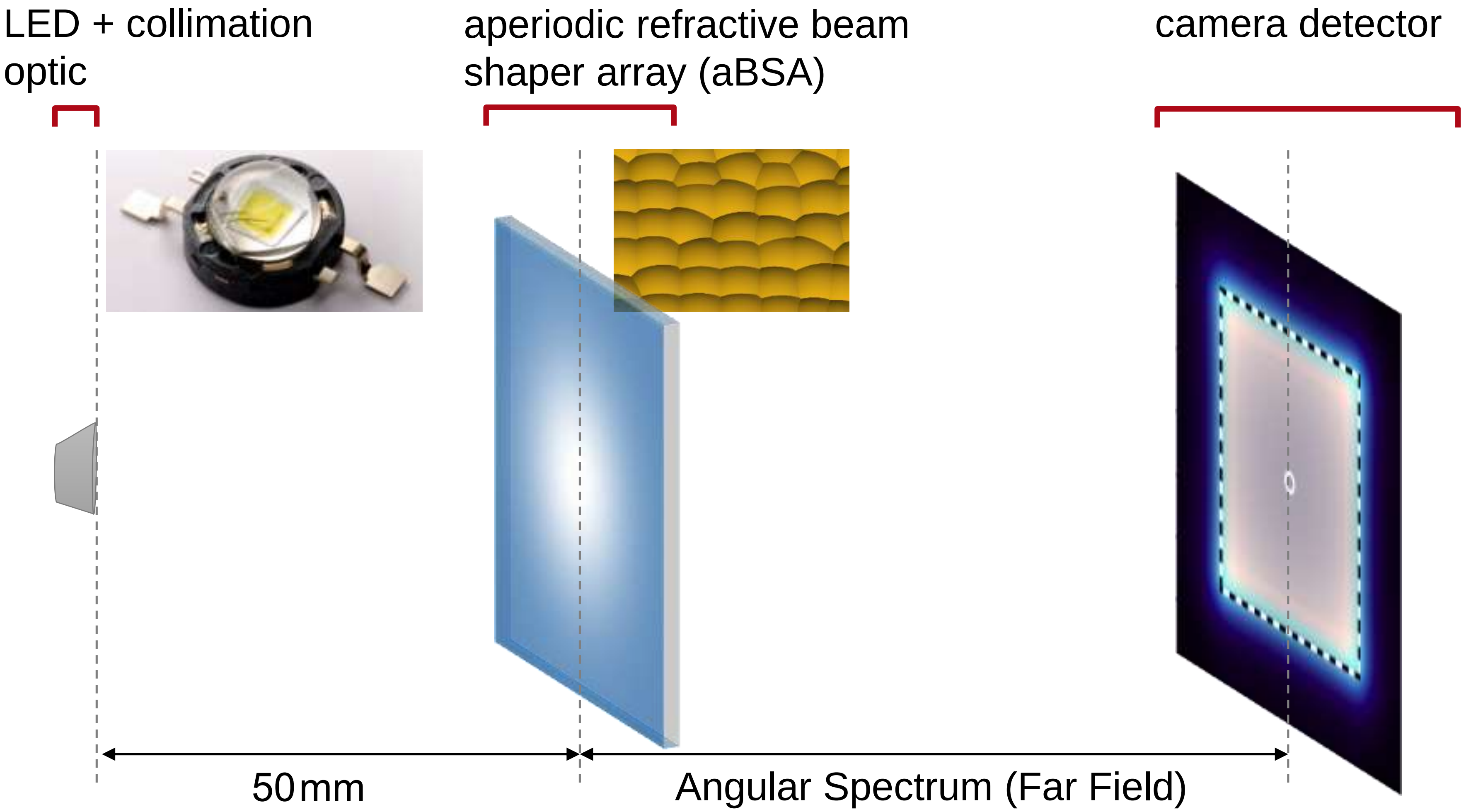




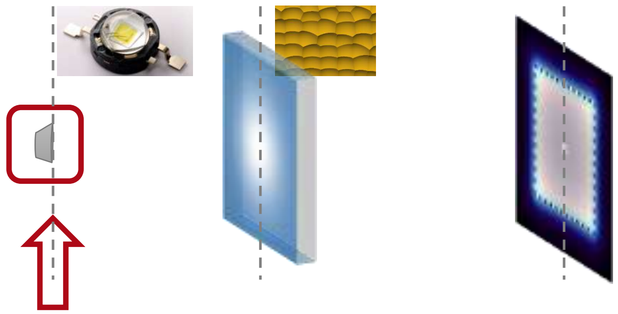
Light Shaping > Aperiodic Microlens Array

LED Top Hat Generation using Aperiodic Refractive Beam Shaper Array

Task/System Illustration



Specs: Light Source



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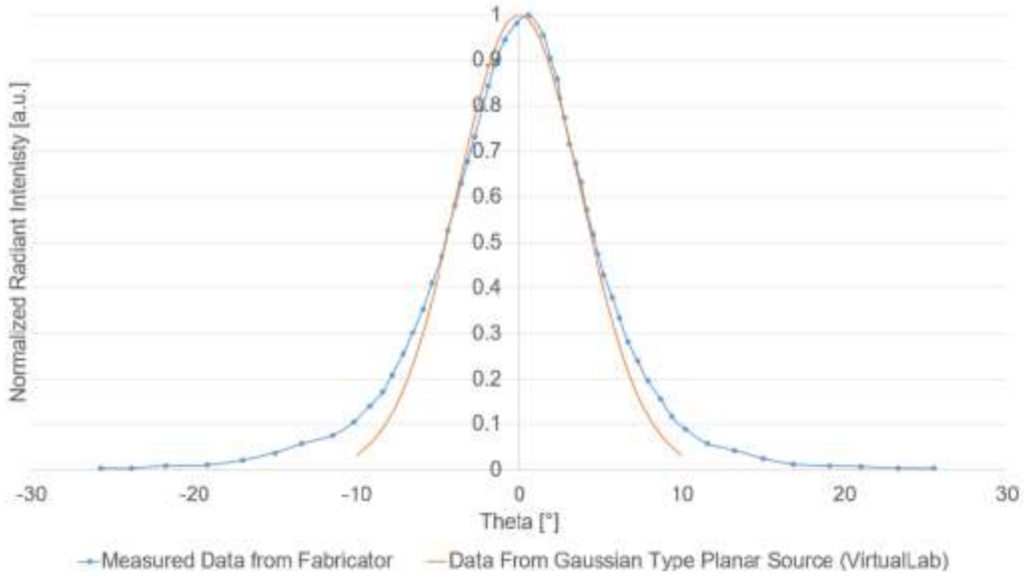
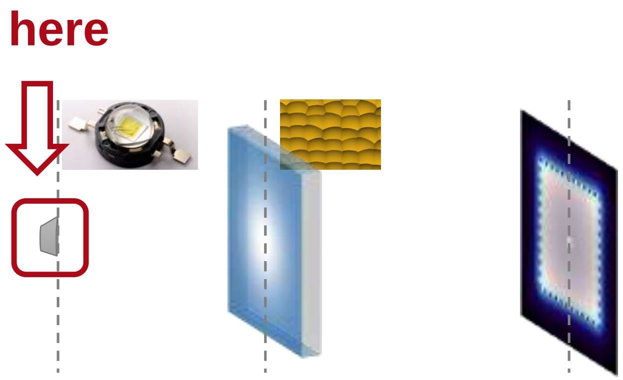


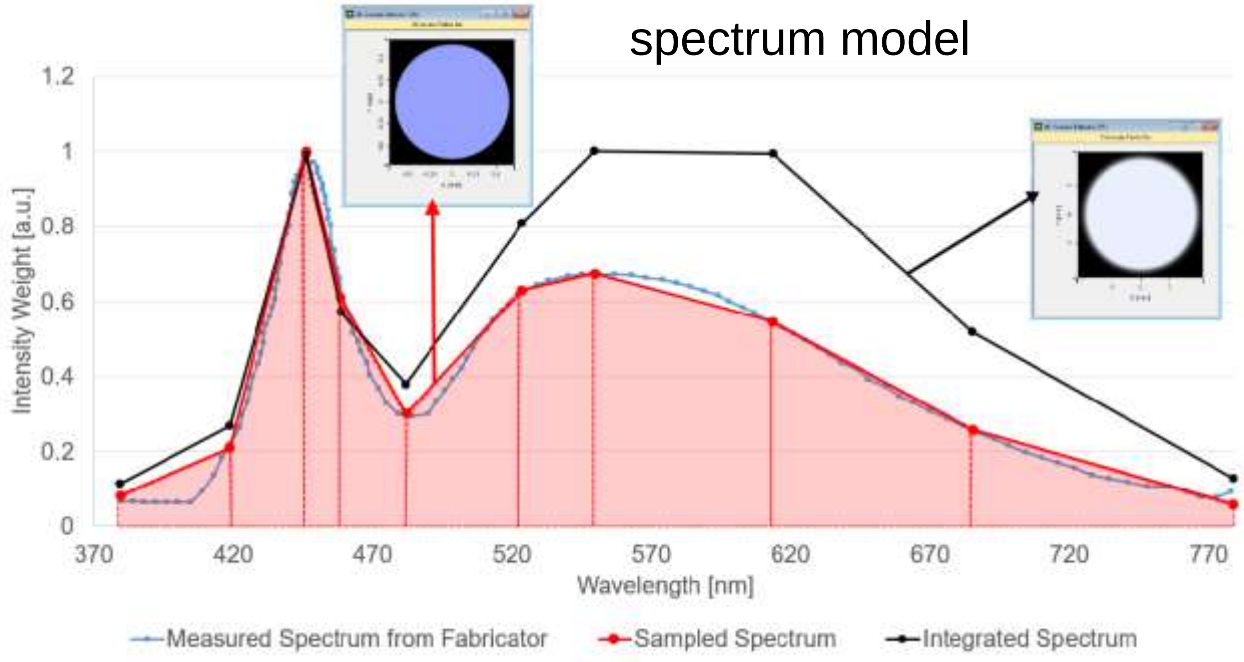
Parameter	Description / Value & Unit
name/type	Seoul Z-LED P4 from Seoul Semiconductors
partially coherent source type	Gaussian type planar source
collimation	TIR lens from Carclo Optics (part no. 10003)
spectrum	pure white light spectrum
FWHM radiant intensity	9°

Specs: Light Source



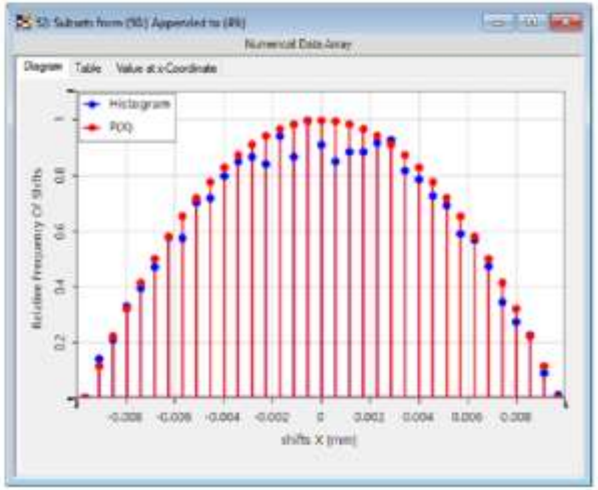
Highlights
- fast and accurate modeling of a white light LED
- design and analysis an aperiodic refractive beam shaper array to optimize a top hat intensity pattern

spectrum model

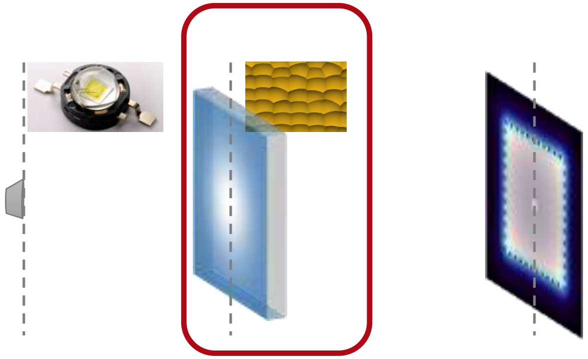


significant performance improvement
non-equidistant sampling of the spectrum

Specs: Aperiodic Refractive Beam Shaper Array



Histogram of Cell Distribution Function



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here

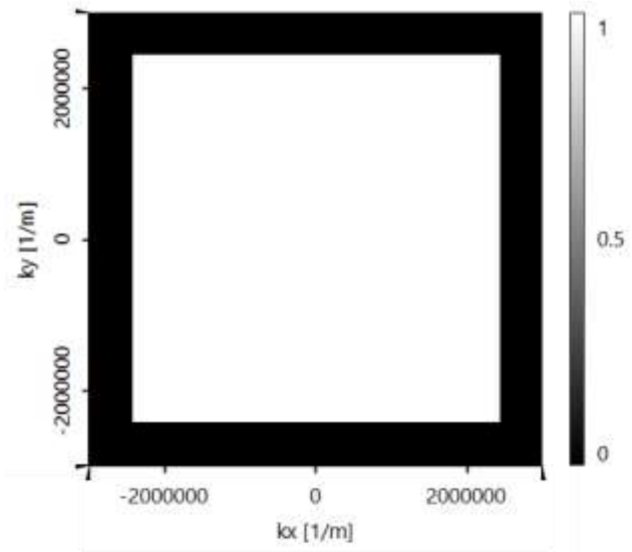
Parameter	**Description / Value & Unit**
cell array aperture	20x20 mm
number of cells	124x124
cell distribution function	quadratic polynomial
substrate thickness	1 mm
substrate material	fused silica

Highlights

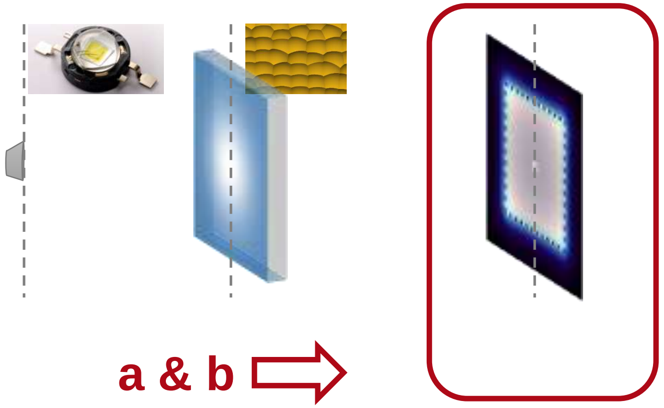
- fast and accurate modeling of a white light LED
- design and analysis an aperiodic refractive beam shaper array to optimize a top hat intensity pattern

parametrization of the distribution function allows optimization regarding a desired target pattern

Specs: Evaluation

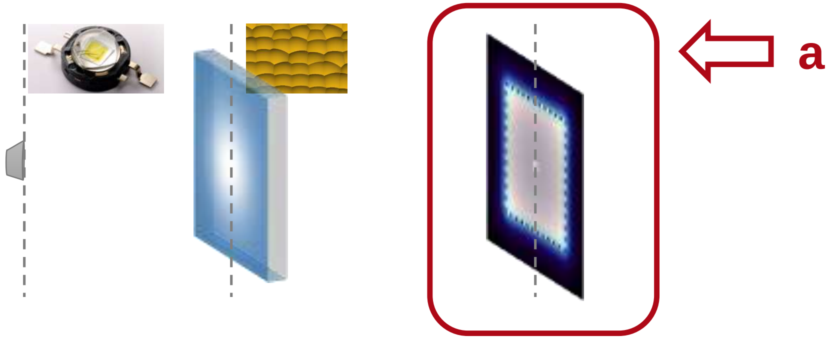


Desired Target Pattern



Position	Type of Evaluation	Description / Value & Unit
a	camera detector	evaluates intensity pattern
b	performance criteria evaluation	evaluates conversion & window efficiency and uniformity error regarding the desired target pattern

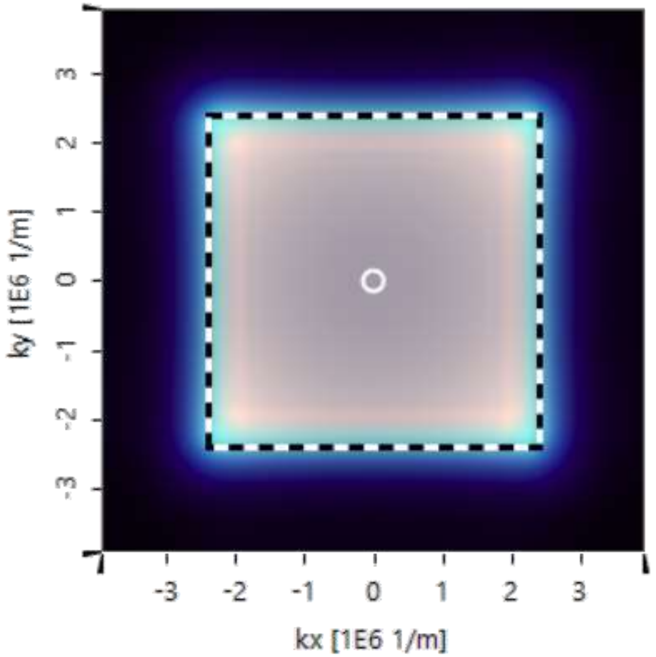
Results: Intensity Pattern (real color view)



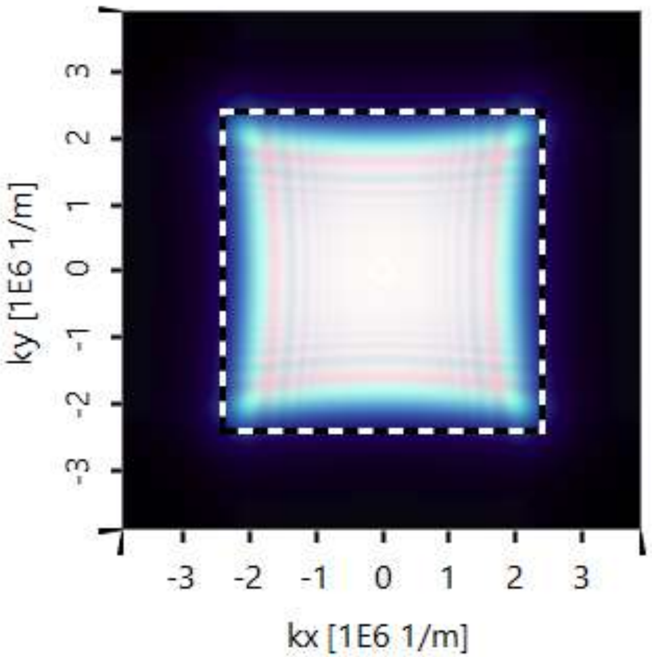
Highlights

- fast and accurate modeling of a white light LED
- design and analysis an aperiodic refractive beam shaper array to optimize a top hat intensity pattern

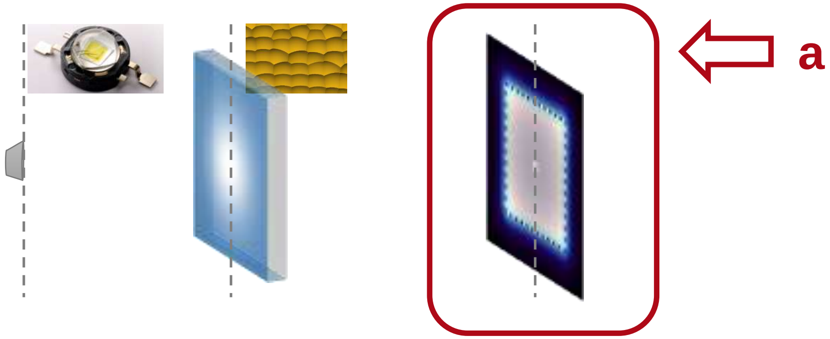
aperiodic beam shaper array



periodic microlens array



Results: Performance Criteria Evaluation



Highlights

- fast and accurate modeling of a white light LED
- design and analysis an aperiodic refractive beam shaper array to optimize a top hat intensity pattern

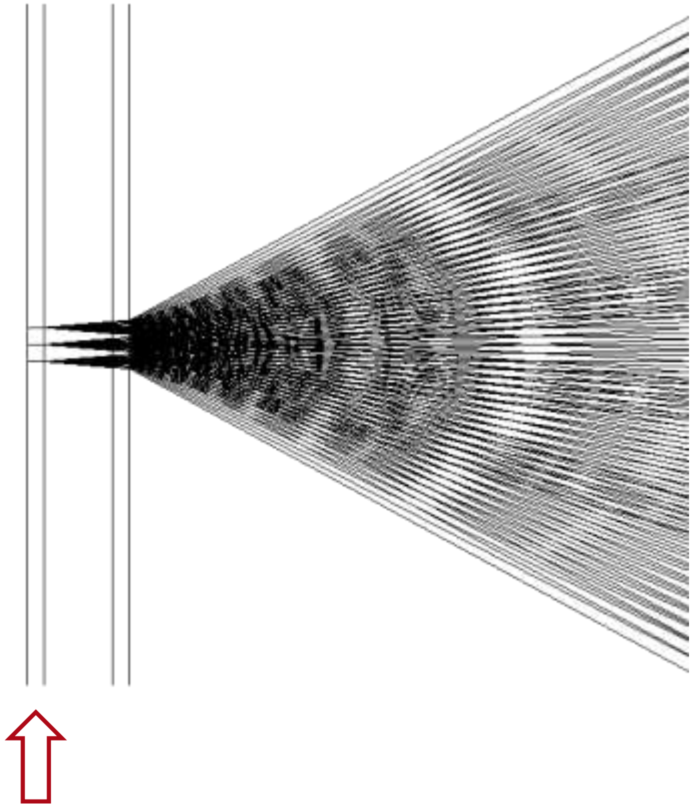
Parameter	Value & Unit Aperiodic Beam Shaper Array	Value & Unit Microlens Array
window efficiency	92.23 %	99.93 %
conversion efficiency	89.34 %	80.18 %
uniformity error	17.92 %	49.08 %

Virtual And Mixed Reality > Pattern Generation

High-NA Pattern Generation Using Two Beam Splitter Elements

LightTrans International UG

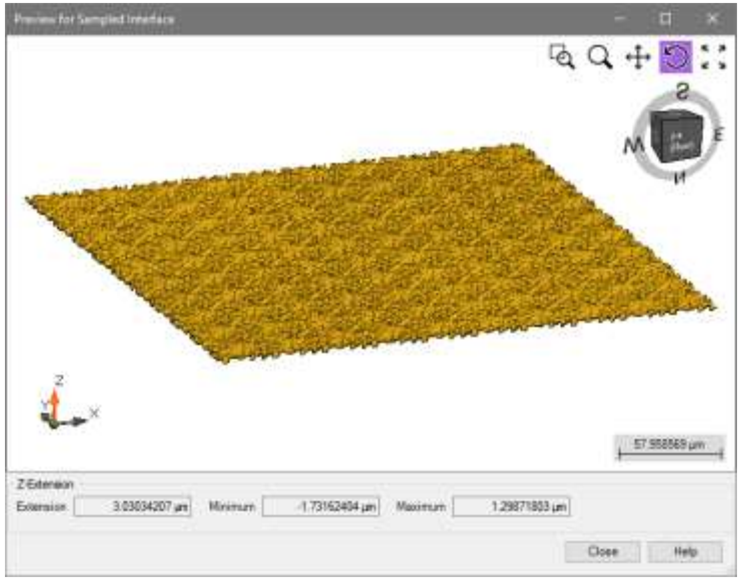
Specification: First Beam Splitter



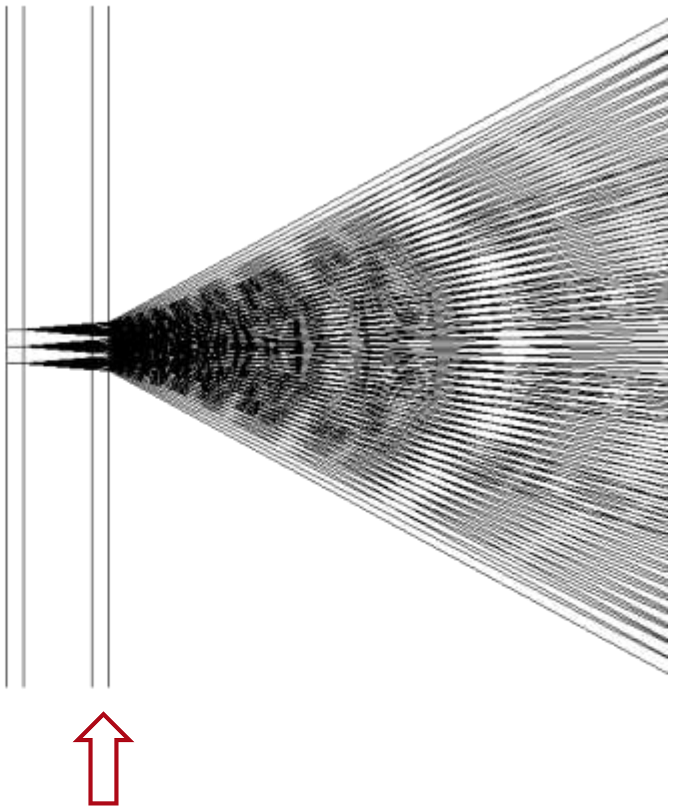
paraxial beam splitter

Parameter	Value & Unit
number of orders	11x11
order separation	1x1°
period	30.35x30.35µm
pixel size	690x690nm
discrete height levels	8
material	fused silica

surface profile

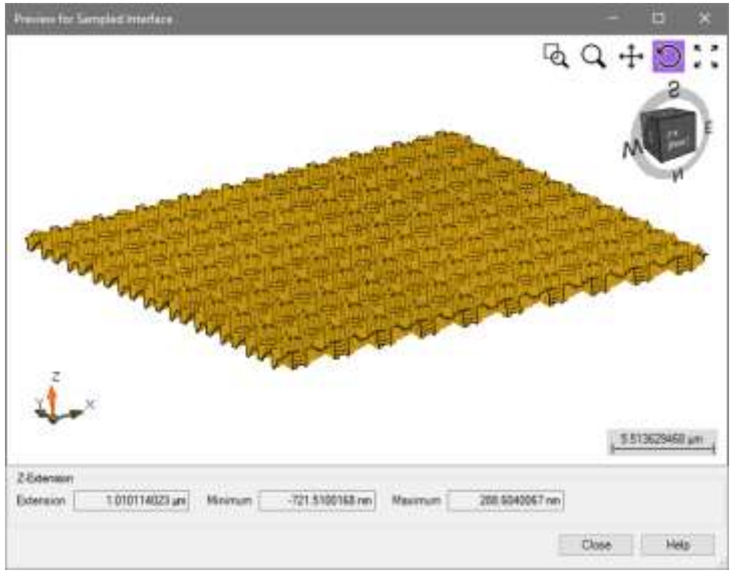


Specification: Second Beam Splitter



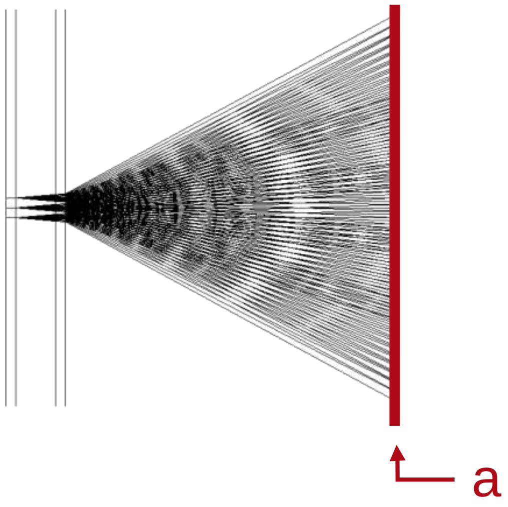
high-NA beam splitter

Parameter	Value & Unit
number of orders	5x5
order separation	11x11°
period	2.73x2.73µm
pixel size	130x130nm
discrete height levels	8
material	fused silica

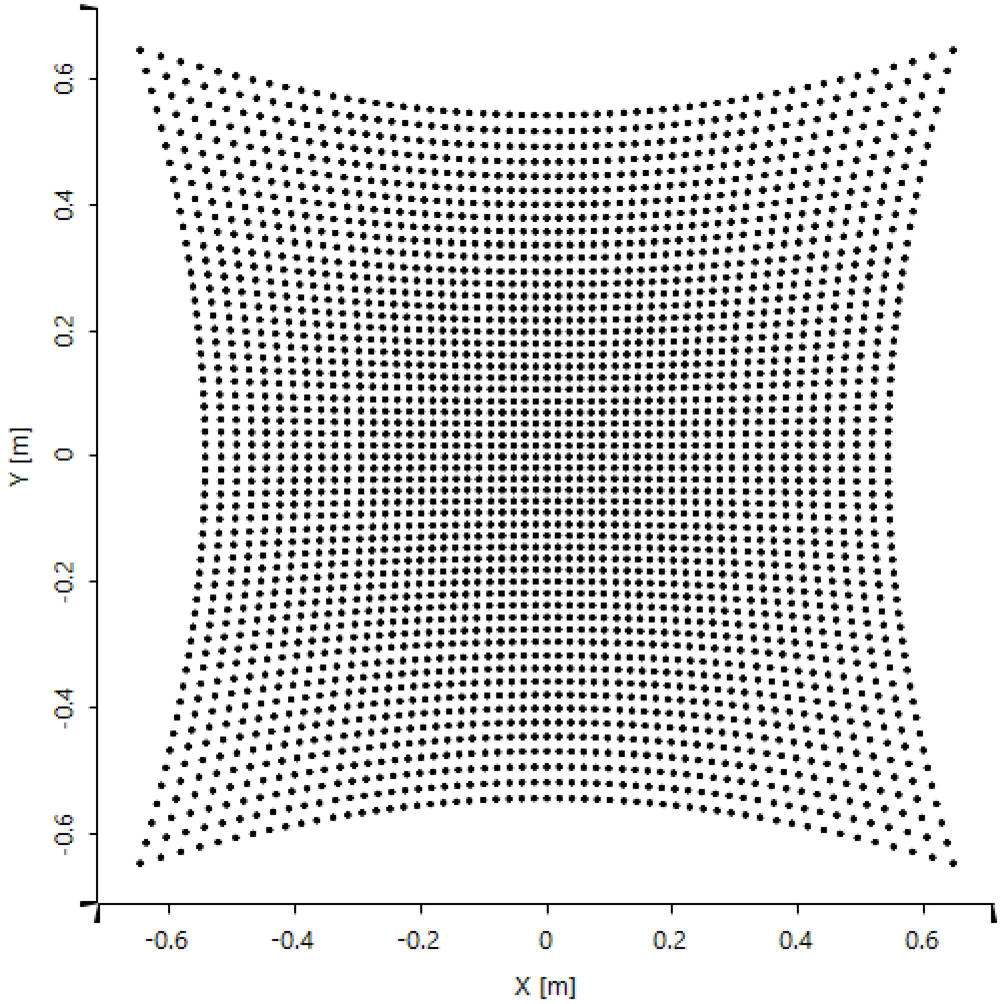


surface profile

Results: Spot Diagram

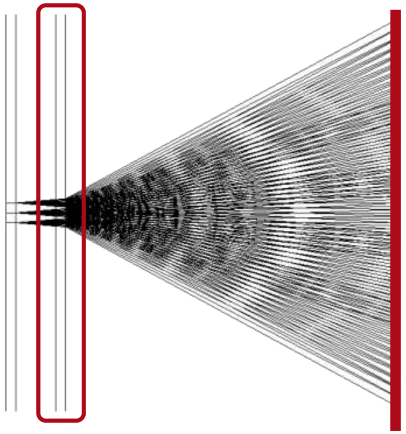


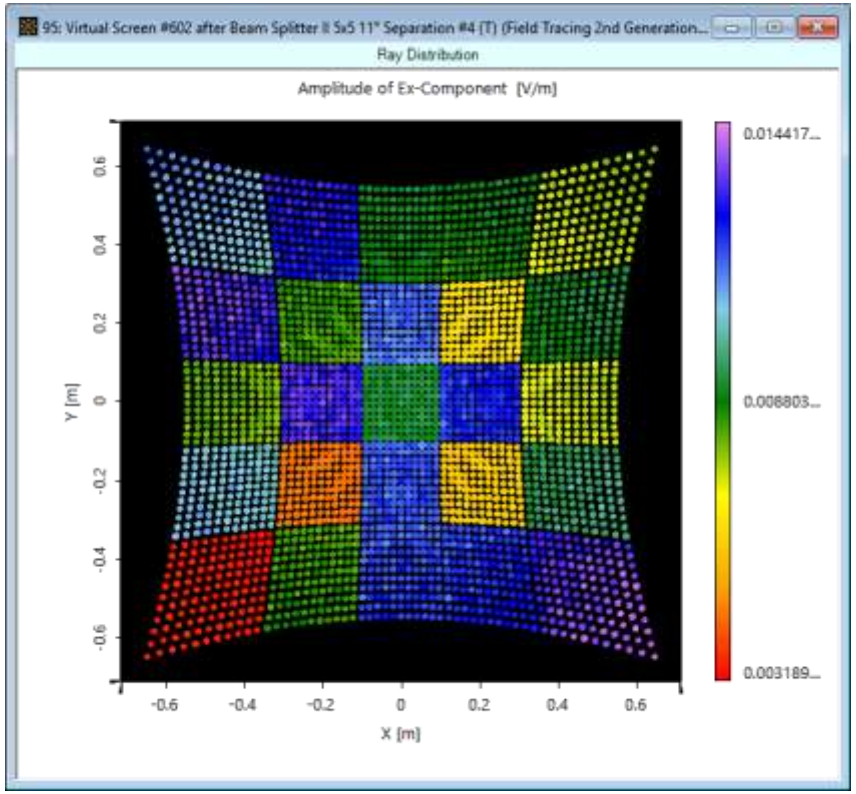
combination of both beam splitter generate **55x55 order** with **55x55° full opening spread**



spot diagram

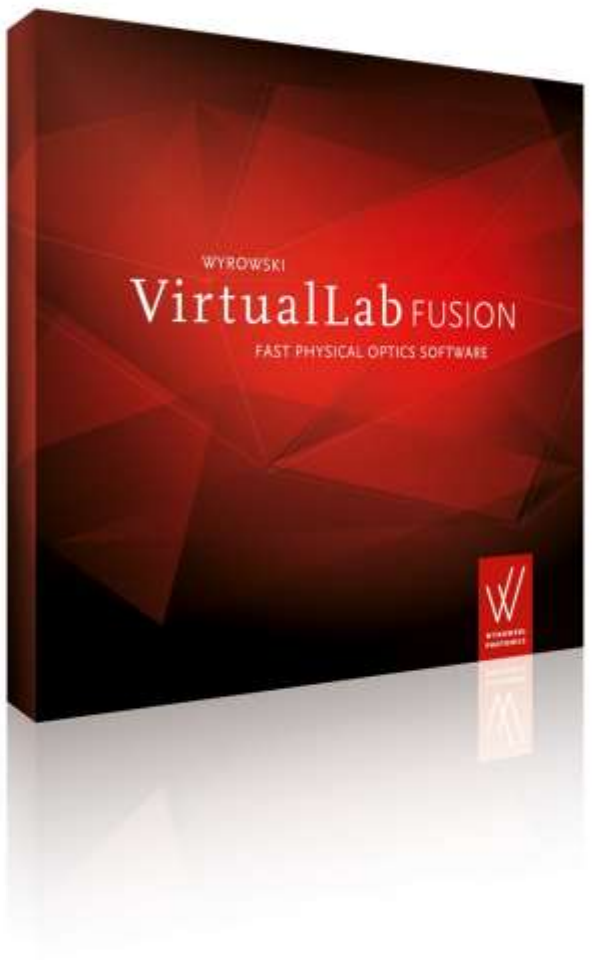
Results: Output Evaluation





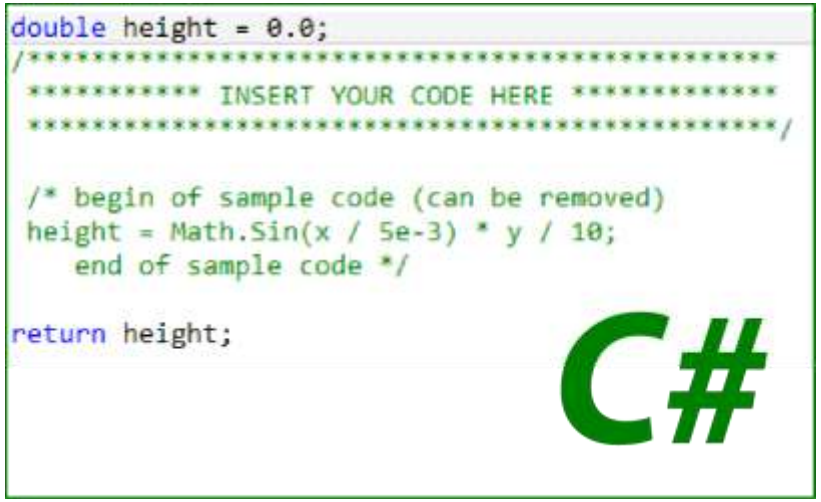
Light Shaping Concepts

- Tailored aberrations
- Stored scanning process
- Multichannel concept: Single Deflection
- Multichannel concept: General



Source Code Editor

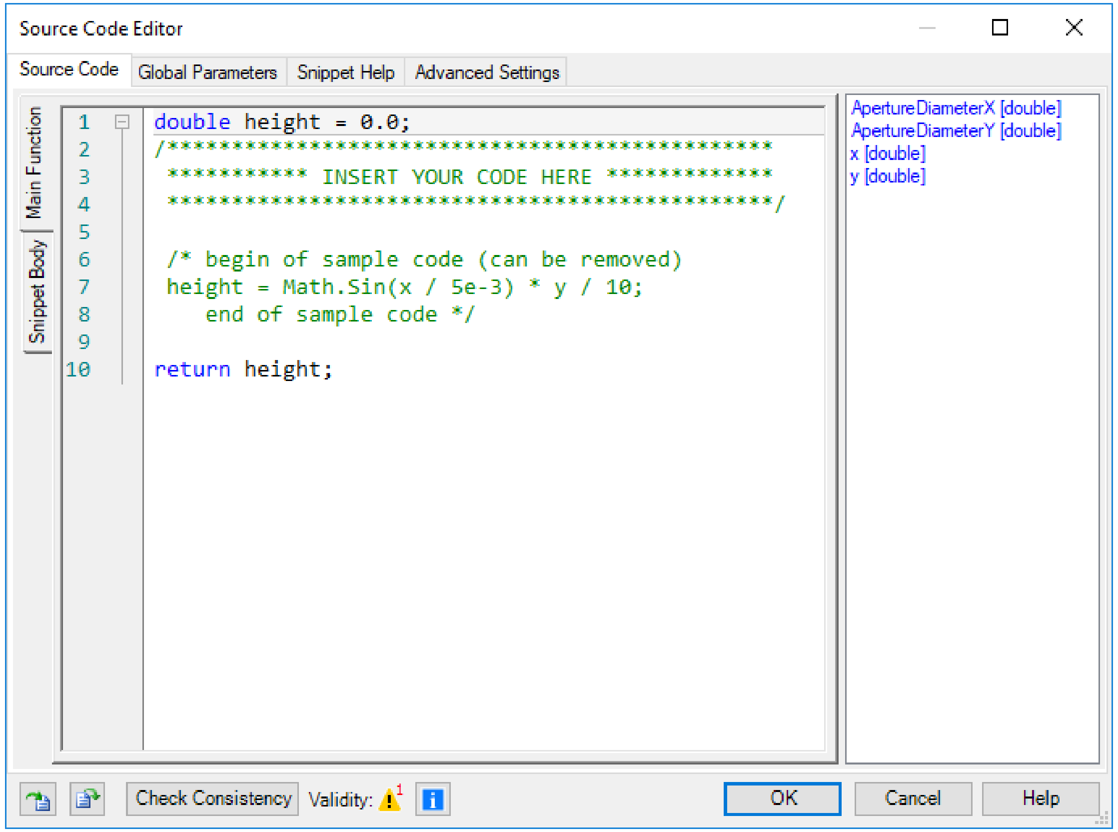
Abstract



For the optical elements, which cannot be found in the catalogs of VirtualLab Fusion, users can create them by using programmable objects, e.g., programmable source, interface, medium, and detector. Also a programmable component is available, which allows users to develop own algorithm, with the access of all optical elements, as well as the implemented functions of VirtualLab. The programming language is C#. The source code editor is the most important structure of all programmable objects. This use case introduces the general structure of the source code editor.

This Use Case Shows...

- the general structure of the *Source Code Editor* of programmable objects.



Tabs: Source Code

- *Source Code* tab :
  - left panel: source code in C# syntax
    - *Main Function*: snippet function to calculate the values this programmable object need to return. For example, in case of programmable interface, the snippet function calculate and return the height profile of this interface $h(x, y)$.
    - *Snippet Body*: specify additional methods, properties or variables, which were initialized once-only by calling the snippet.
  - right panel: global parameters, which can be used within the snippet.

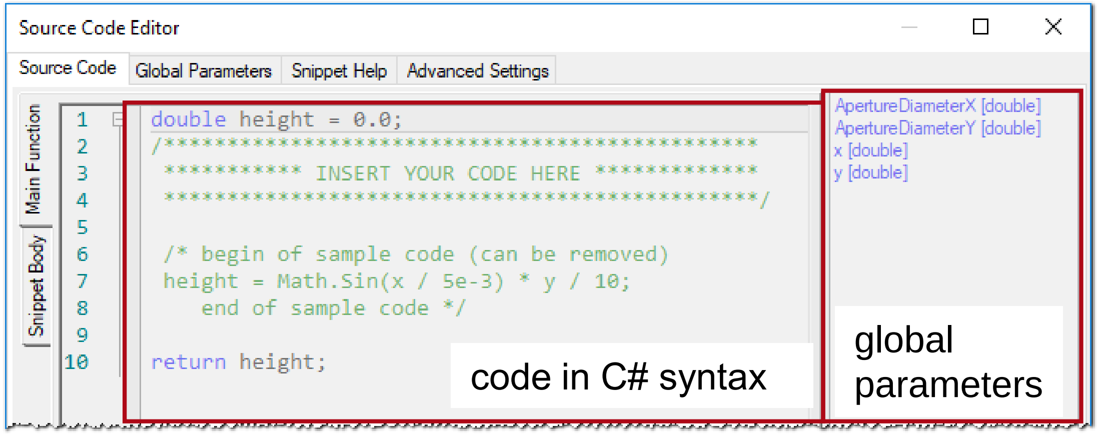


Fig: source code editor of Programmable Interface

Tabs: Source Code

- *Source Code* tab :
  - left panel: source code in C# syntax
  - right panel: global parameters, which can be used in snippet.
  - bottom:
    - *Import Snippet* : import a snippet from a .snp-file.
    - *Export Snippet* : export a snippet into a .snp-file. This file can be used to import the snippet to other programmable objects.
    - *Check Consistency*: check if the snippet is in correct C# syntax. If there is an inconsistency, users will find details by clicking .

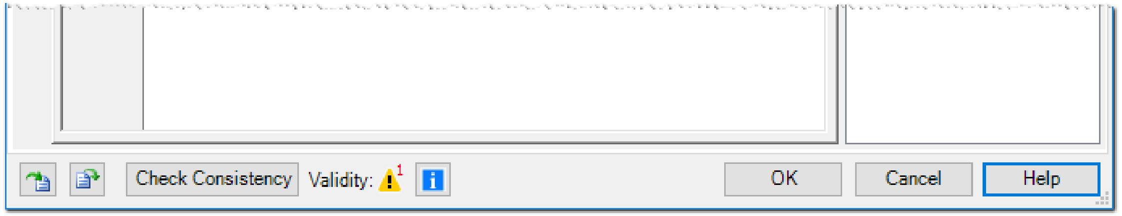
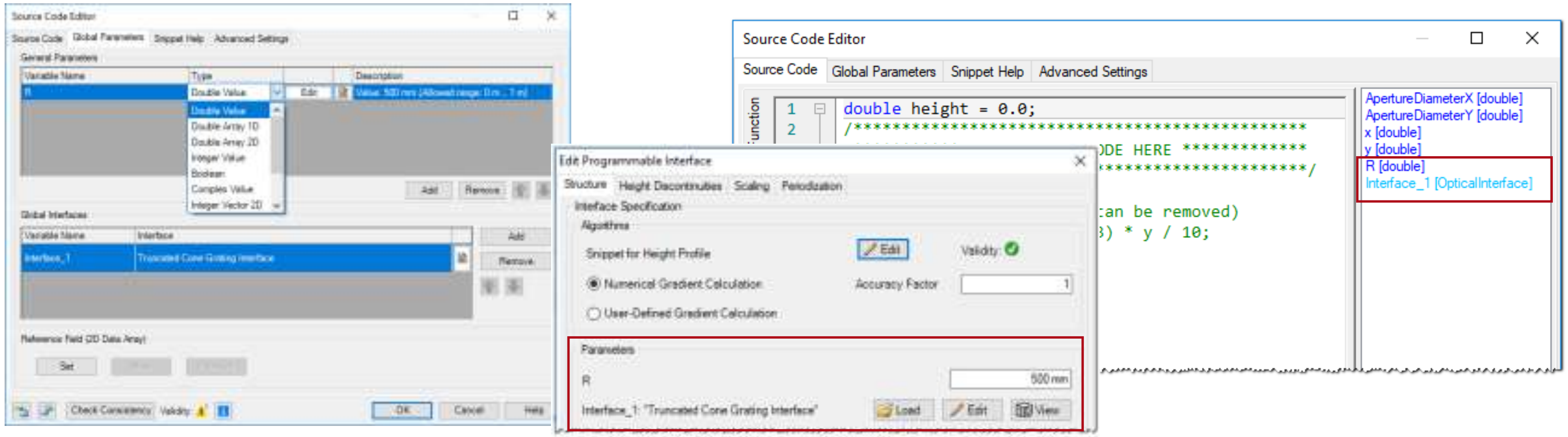


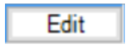
Fig: source code editor of Programmable Interface

Tabs: Global Parameters

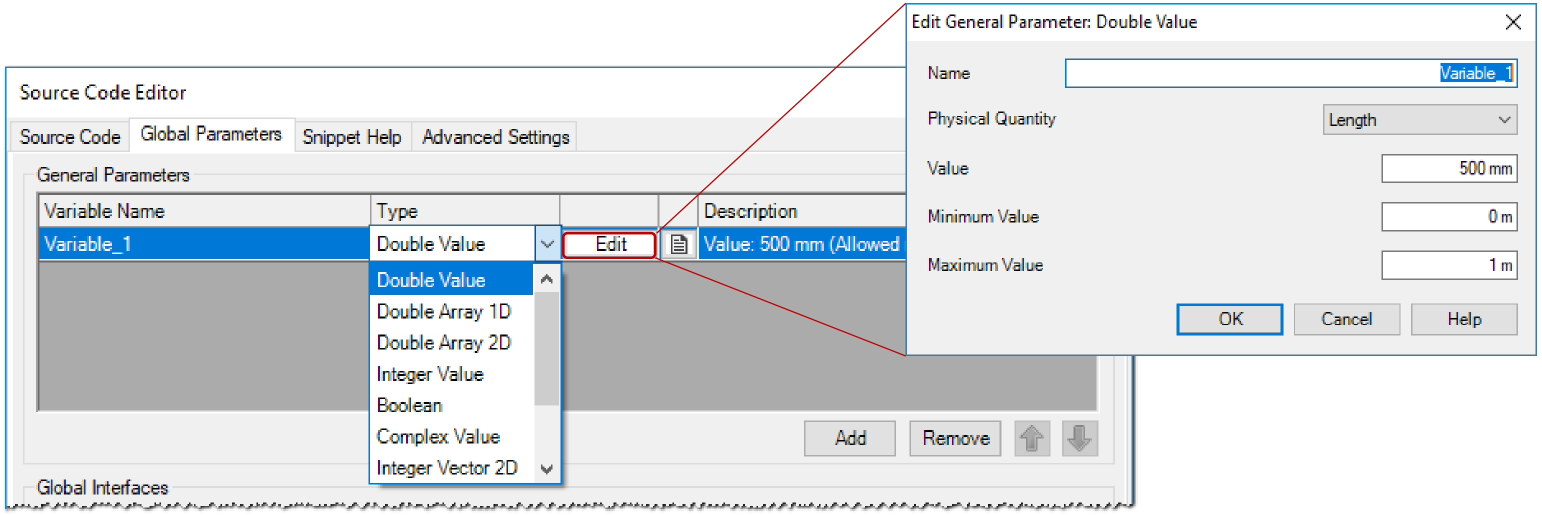
- *Global Parameters* tab allows users to define different types of global parameters, even predefined interfaces, materials and much more.
  - Global parameters can be manually defined within the programmable object, outside the Source Code Editor.
  - Global parameters can be used in Parameter Run and Parametric Optimization.



Global Parameters: General Parameters

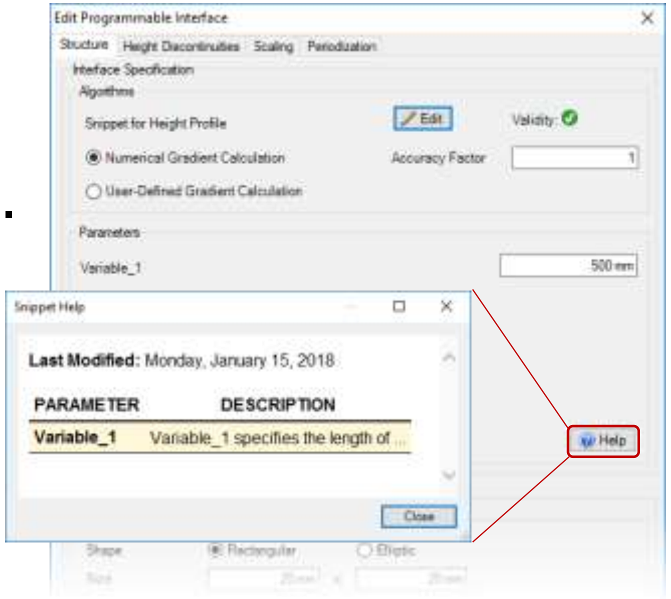
- *General Parameters* support several data types like Double, Integer, Boolean, Complex, Double Vector 2D and much more.
- Users are able to define additional properties for the general parameters like physical unit, minimum and maximum value and the valid range by clicking 

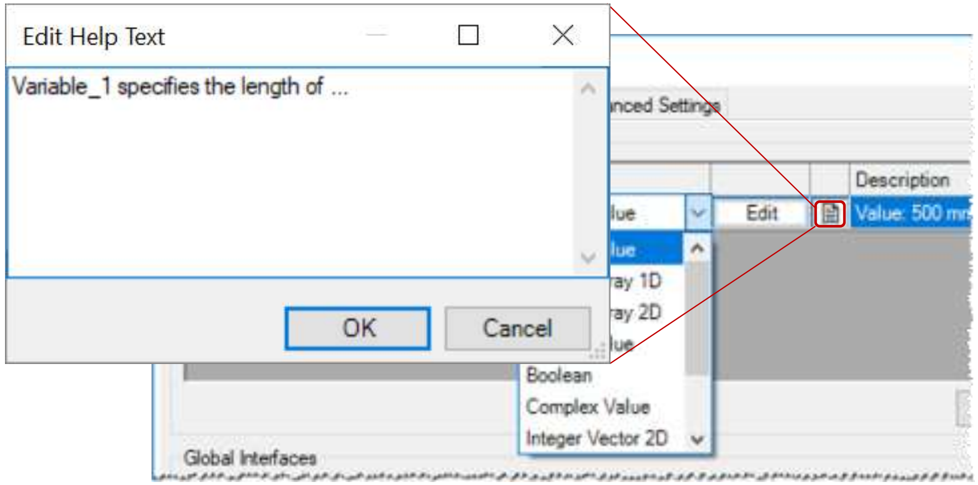
.



Global Parameters: General Parameters

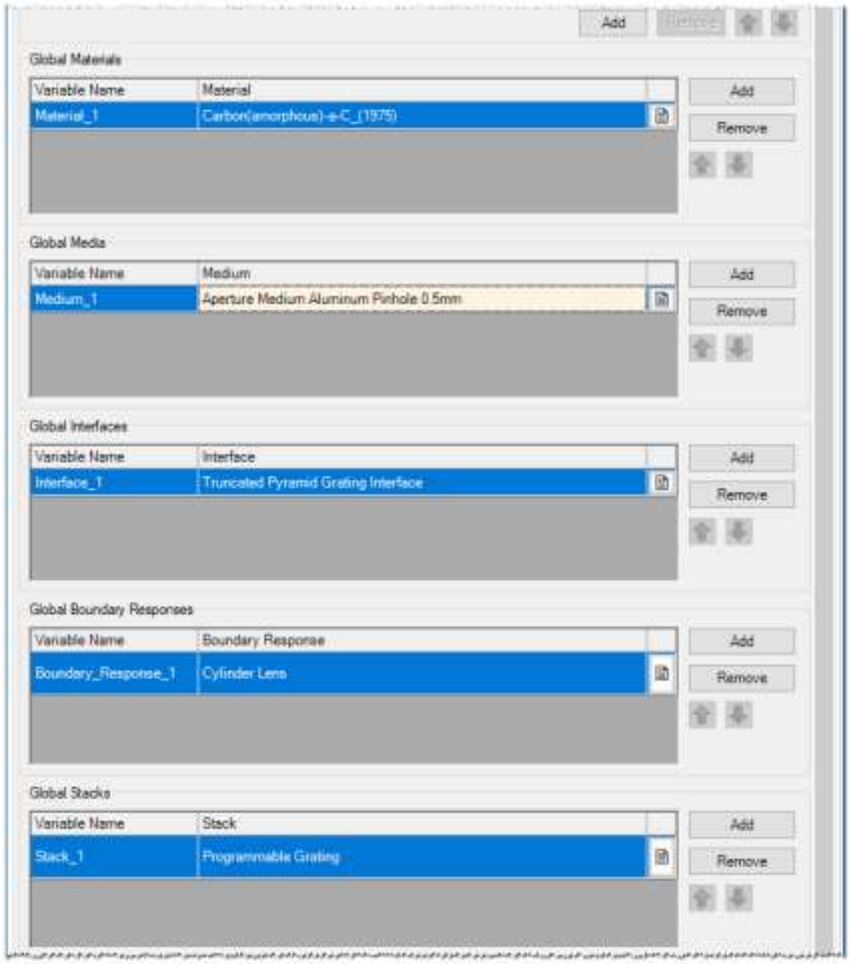
- It is highly recommended to specifiy a help text for each General Parameter by clicking on 🗎 .
- This help text is shown outside the source code editor by clicking Help .





Global Parameters: System Building Blocks

- Any predefined system building blocks in catalogs can be specified as global parameters.
  - materials
  - media
  - interfaces
  - boundary responces, i.e. transmission functions.
  - stacks

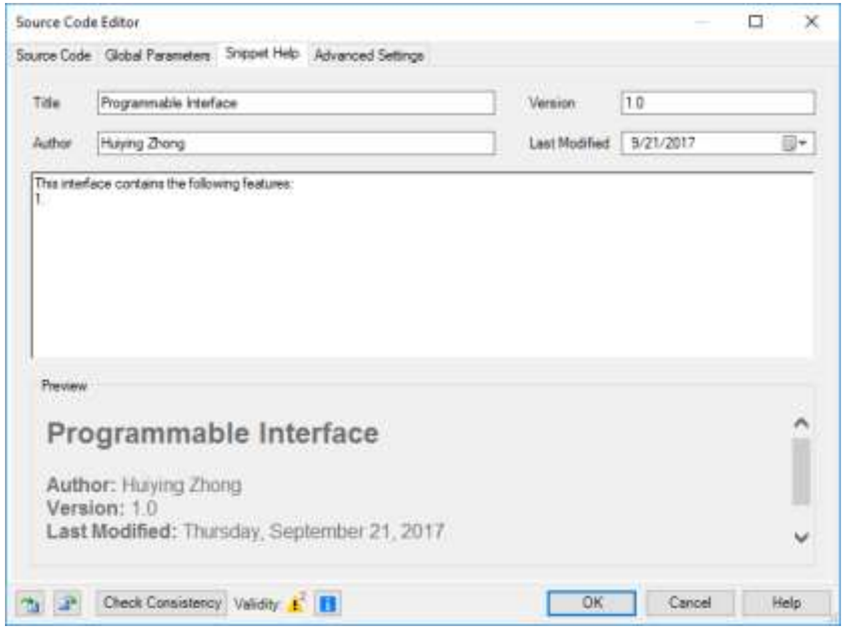


Global Parameters: Reference Field

- Other harmonic field can be used as *Reference Field*, as global parameter.
- It is super useful when users need infomation of both fields. E.g. In programmable detector, the reference field is defined as the desired field pattern. Values of merit functions can be calculated by comparing the detected field and *Reference Field*.

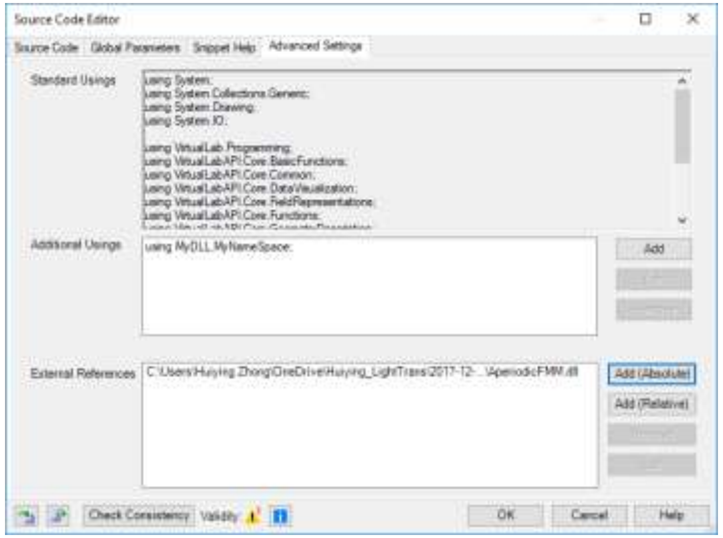
Tab: Snippet Help

- *Snippets Help* tab helps user to record information about the programmable object and specify different parameters.
- Please read the use case *Customizable Help for Programmable Element* for more details.



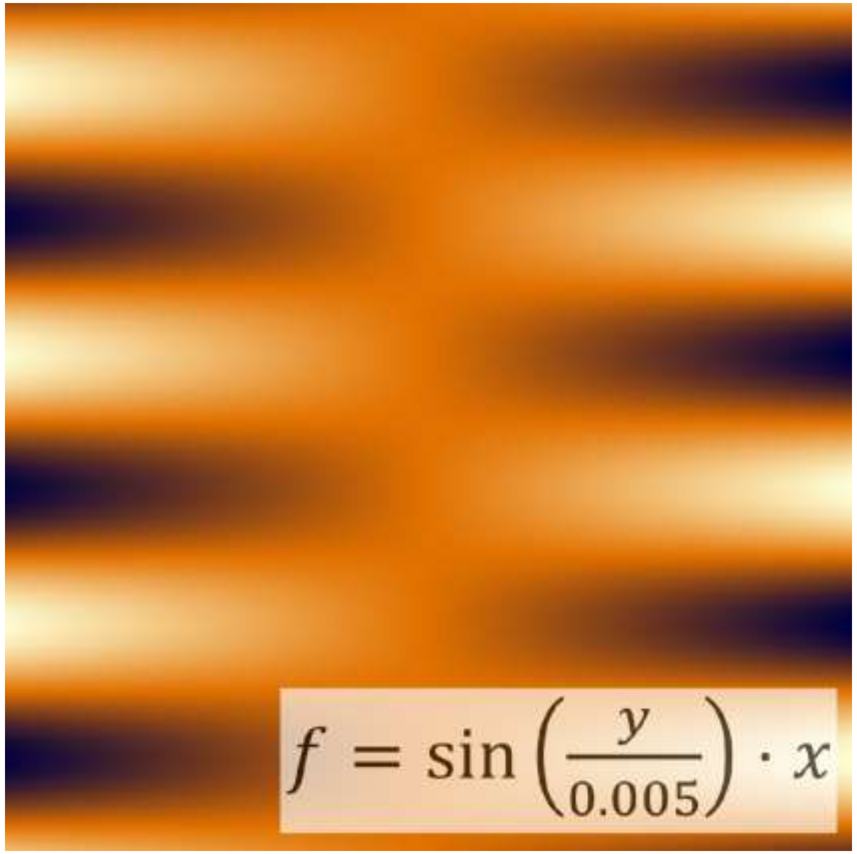
Tab: Advanced Settings

- *Advanced Settings* tab allows you to define additional DLLs and namespaces, which can be used in the snippet.
  - *Standard Usings*: listing standard namespaces, which are used in the snippet
  - *Additional Usings*: user defined additional namespaces of the VirtualLabAPI DLL and the VirtualLab.Programming DLL
  - *External Reference*: importing additional DLLs



Programmable Light Source, Function, Interface and Medium

Abstract



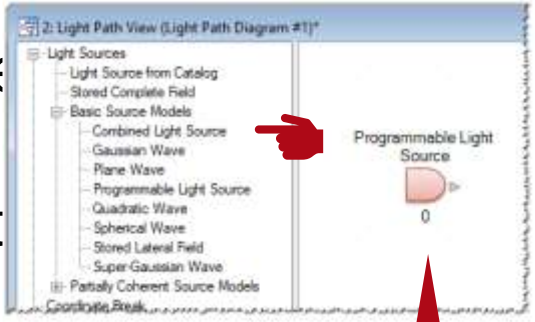
VirtualLab offers always different ways for the specification of optical objects, e.g., light source, interface, and medium. We provide predefined objects, the objects can be specified by measurement data or the object can be described by using programmable objects. The programming language for these customized objects is C#. VirtualLab supports the development of the programmable items by the source code editor. Different object have different input and return parameters. This use case explains the most specific parameters of the programmable light source, interface, function and medium.

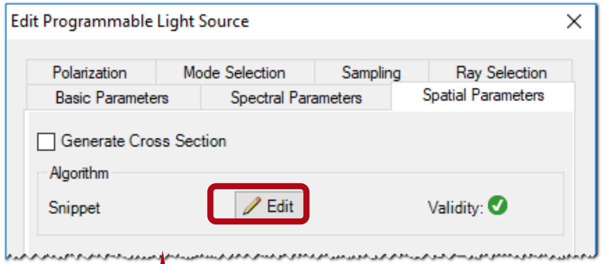
Programmable Light Source

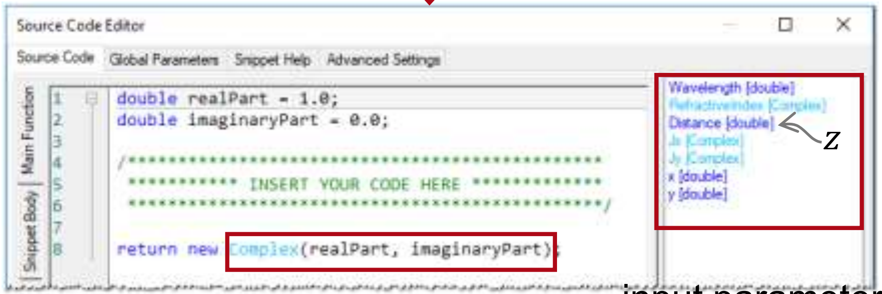
- *Programmable Light Source* allows users to define the spatial distribution of a global polarized light mode in one plane. The mathematical representat is $\breve{E}_0(x, y, z, \breve{\boldsymbol{J}}, \lambda, \breve{n}(\lambda))$
  - (x, y, z) is the spatial coordinators
  - $\breve{\boldsymbol{J}} = \begin{pmatrix} \breve{J}_x \\ \breve{J}_y \end{pmatrix}$ represents the Jones vector

    $$\boldsymbol{E} = \begin{pmatrix} \breve{E}_x \\ \breve{E}_y \end{pmatrix} = \breve{E}_0 \cdot \begin{pmatrix} \breve{J}_x \\ \breve{J}_y \end{pmatrix}$$

  - λ is wavelength
  - $\breve{n}(\lambda)$ is the refractive index of the surrounding medium







$\breve{E}_0$

input parameters: $x, y, z, \boldsymbol{J}, \lambda, \breve{n}(\lambda)$

Example of Programmable Light Source

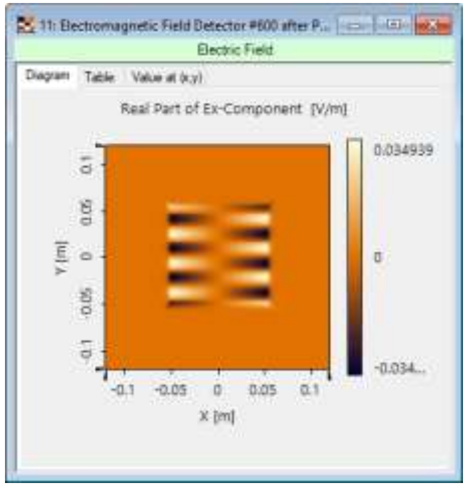
C# snippet

```
double realPart = 1.0;
double imaginaryPart = 0.0;

realPart = Math.Sin(y / 5e-3) * x;

return new Complex(realPart, imaginaryPart);
```

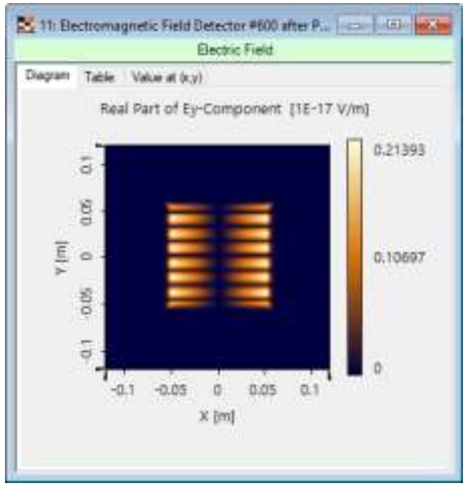
Source parameters

parameter	value
size	100 mm x 100 mm
polarization	right circularly polarized

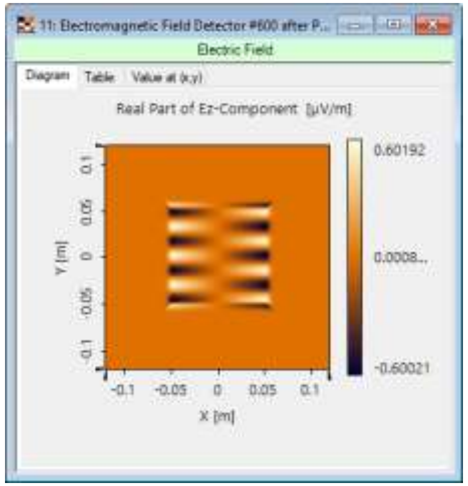
electric field [V/m]



$\Re(E_x)$



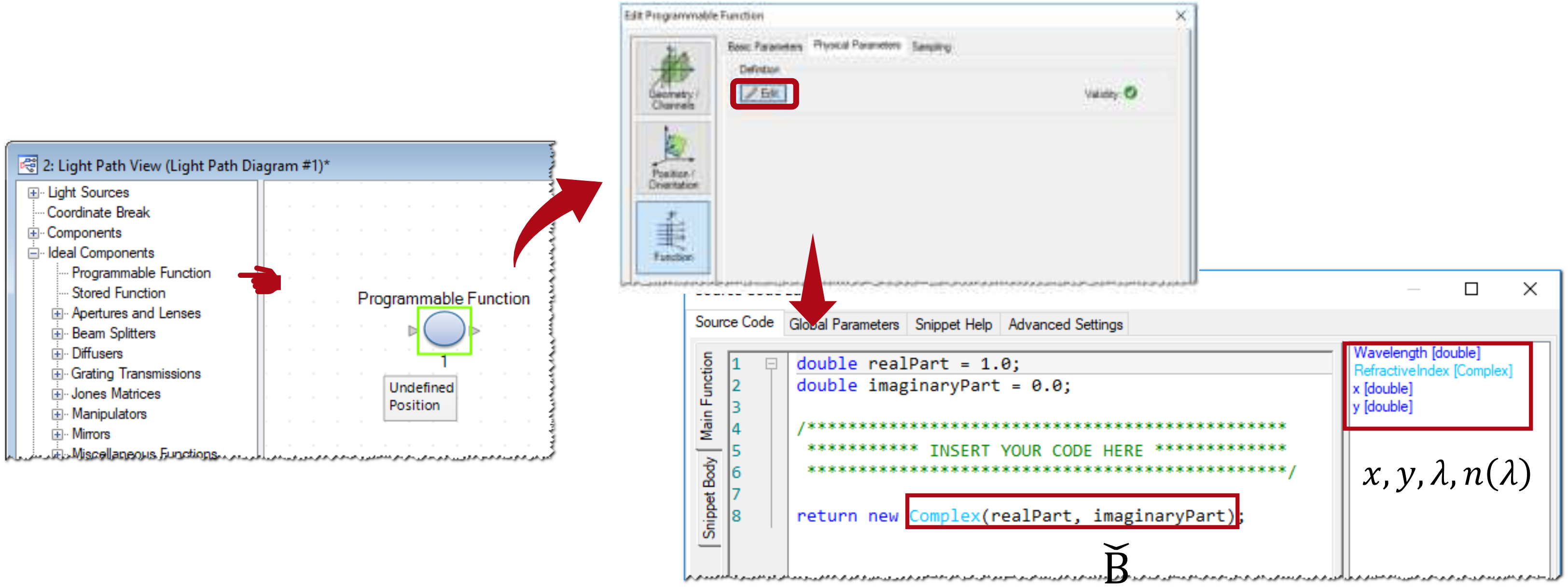
$\Re(E_y)$



$\Re(E_z)$

Programmable Function

- Programmable function allows users to define a specific boundary response, which is mathematically represented as $\breve{\mathrm{B}} = f(x, y, \lambda, \breve{n}(\lambda))$.
- Output field of *Programmable Function* is: $\boldsymbol{E}^{\mathrm{out}}(x, y) = \breve{\mathrm{B}} \cdot \boldsymbol{E}^{\mathrm{in}}(x, y)$



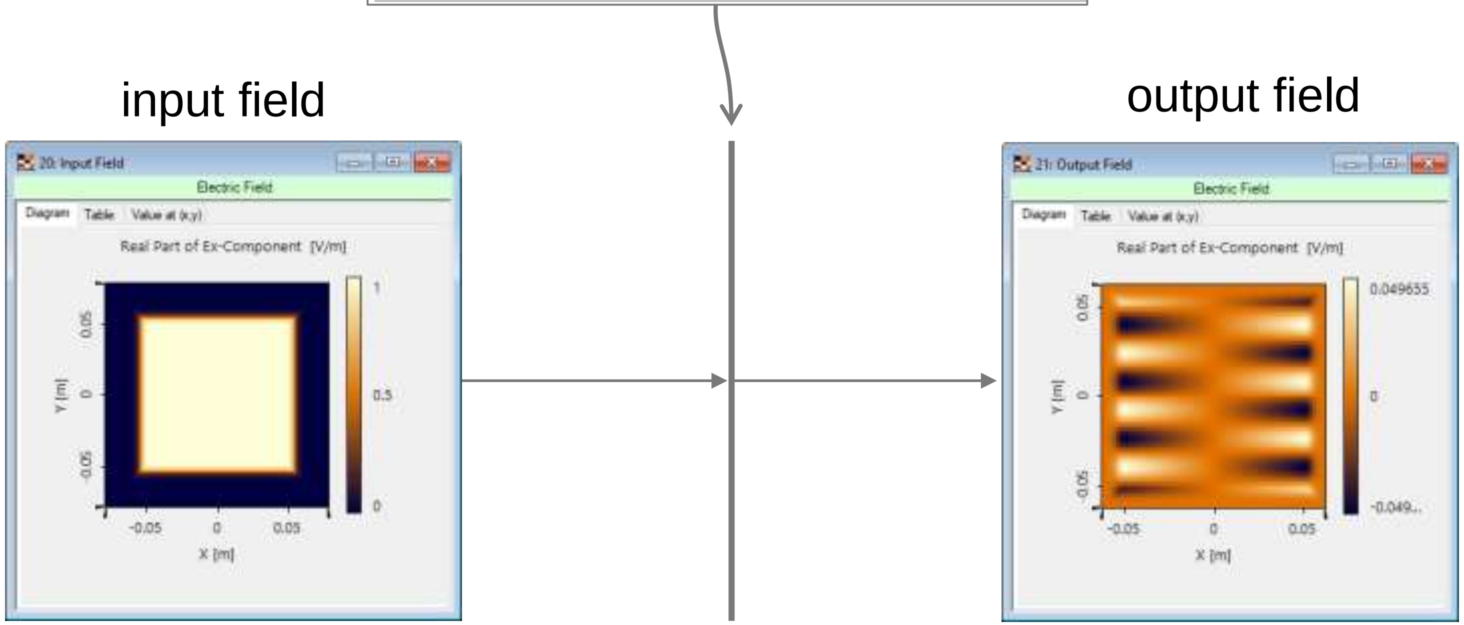
Example of Programmable Function

C# snippet

```
double realPart = 1.0;
double imaginaryPart = 0.0;

realPart = Math.Sin(y / 5e-3) * x;

return new Complex(realPart, imaginaryPart);
```

input field

output field



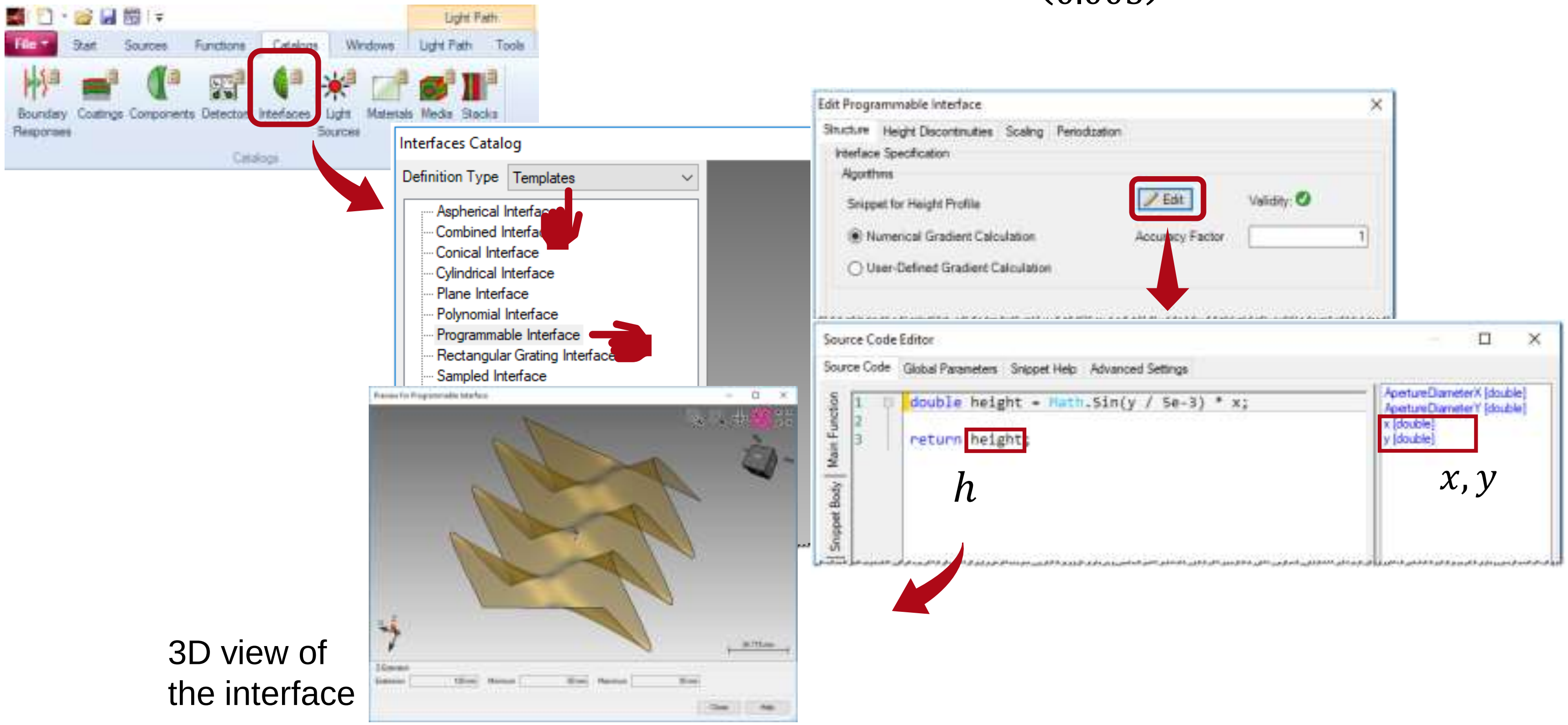
$\Re(E_x^{\text{in}})$

programmable function

$\Re(E_x^{\text{out}})$

Programmable Interface

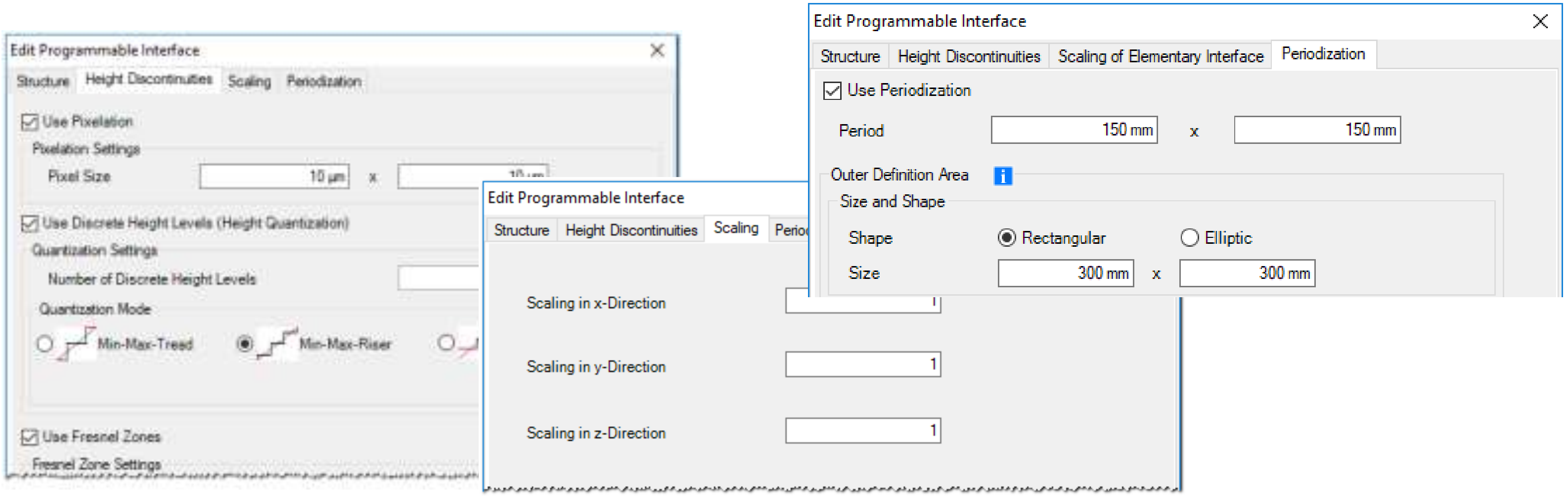
- *Programmable Interface* allows users to define a height profile of an interface.
  - Height profile $h(x,y)$, e.g., $h(x,y) = \sin\left(\frac{y}{0.005}\right) \cdot x$



3D view of the interface

Programmable Interface: Properties

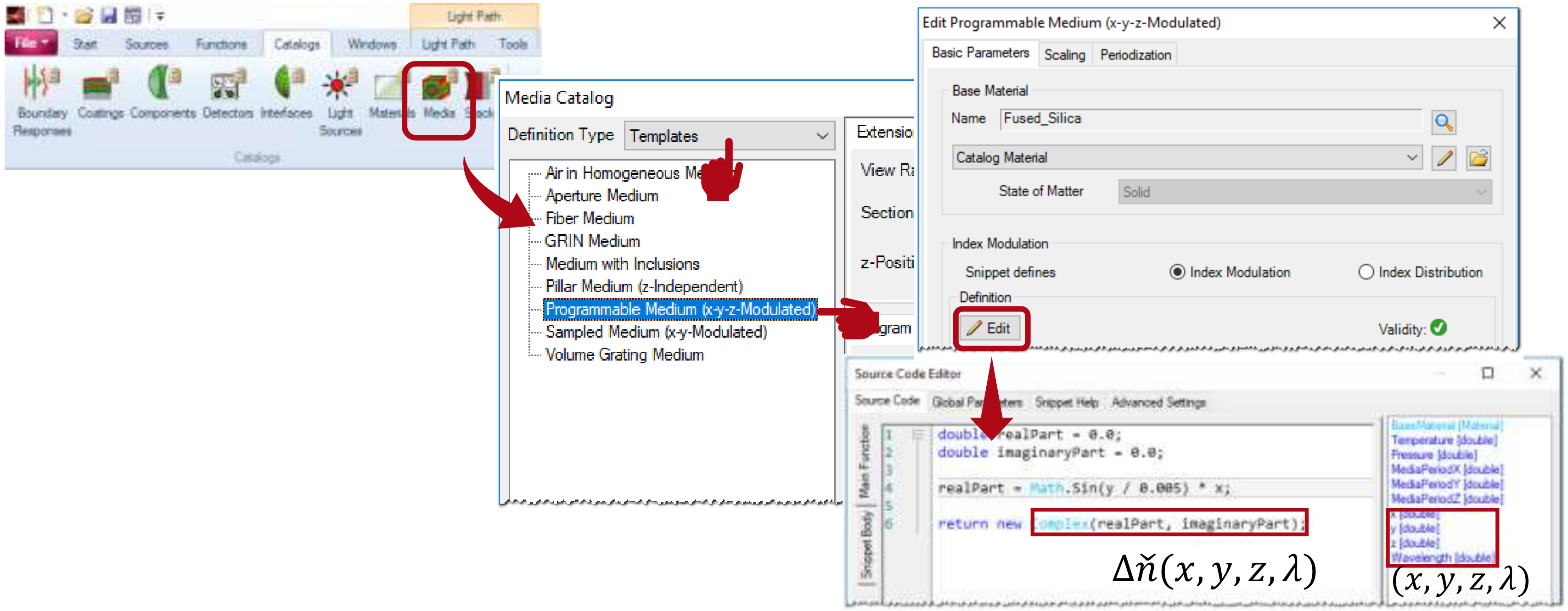
- *Programmable Interface* contains all properties of general interfaces in VirtualLab Fusion.
  - discontinuities: the interface can be quantized
  - scaling: stretch the interface in specific direction
  - periodization: make a repetition of the interface to generate a periodic interface.



More details can be found in "Getting started" tutorial, i.e., Catalogs II: Interfaces

Programmable Medium

- *Programmable Medium* allows users to define an arbitrary, complex-valued refractive index distribution $\breve{n}(x, y, z, \lambda)$. Variance of refractive index $\Delta\breve{n}(x, y, z, \lambda)$ is programmed.



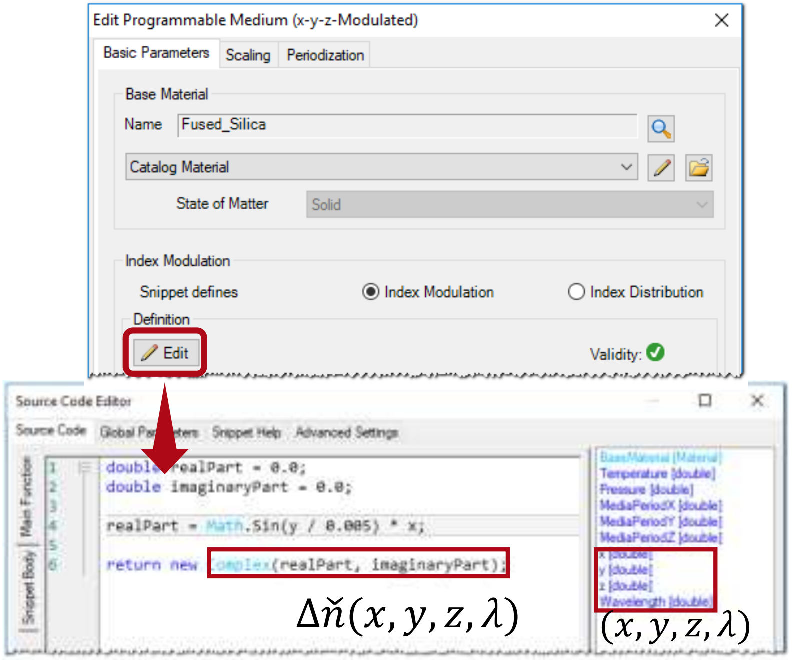
Programmable Medium

- *Programmable Medium* allows users to define an arbitrary, complex-valued refractive index distribution $\breve{n}(x,y,z,\lambda)$. $\Delta\breve{n}(x,y,z,\lambda)$ is programmed.
- There are two ways to define $\breve{n}(x,y,z,\lambda)$:
  - *Index Distribution*:

    $\breve{n}(x,y,z,\lambda) = \Delta\breve{n}(x,y,z,\lambda)$
  - *Index Modulation*:

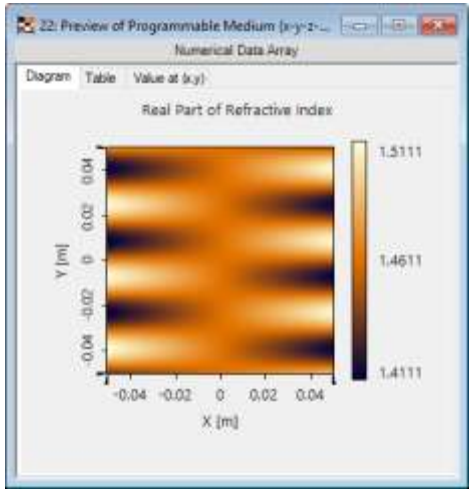
    $\breve{n}(x,y,z,\lambda) = n_0(\lambda) + \Delta\breve{n}(x,y,z,\lambda)$.

    $n_0(\lambda)$ is given by *Base Material*.

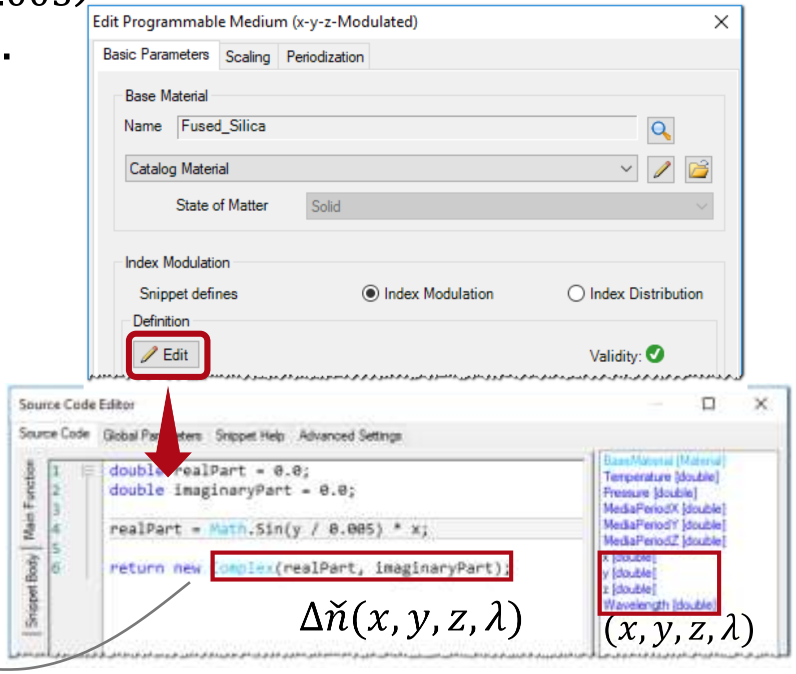


Example of Programmable Medium

- *Programmable Medium* allows users to define an arbitrary, complex-valued refractive index distribution $\breve{n}(x,y,z,\lambda)$.
  - E.g., $\breve{n}(x,y,z,\lambda) = \breve{n}^{\mathrm{FS}}(\lambda) + \sin\left(\frac{y}{0.005}\right) \cdot x$, with $\breve{n}^{\mathrm{FS}}(\lambda)$ denoting the refractive index of fused silica.

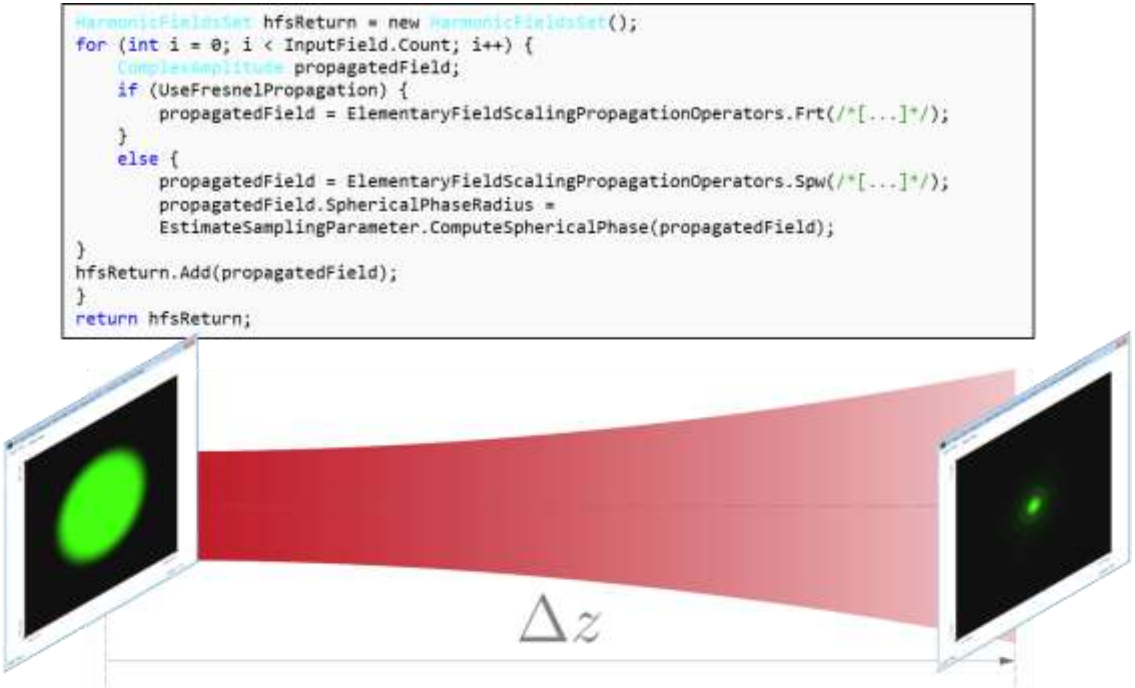


refractive index



Programmable Component for Free-Space Propagation

Abstract



Customization via programming is one of VirtualLab Fusion’s strongest suits. In this example, we present some functions which were used in the Classic Field Tracing engine to propagate an electromagnetic field that was represented in an equidistantly sampled form. We use these functions in a Programmable Component. Please bear in mind that VirtualLab currently offers more evolved propagation algorithms, this use case is merely intended as a programming example.

Programmable Component for Free-Space Propagation

Main Function (Equidistantly Sampled Data)

```
HarmonicFieldsSet hfsReturn = new HarmonicFieldsSet();
for (int i = 0; i < InputField.Count; i++) {
    ComplexAmplitude propagatedField;
    if (UseFresnelPropagation) {
        propagatedField = ElementaryFieldScalingPropagationOperators.Frt(/*[...]*/);
    }
    else {
        propagatedField = ElementaryFieldScalingPropagationOperators.Spw(/*[...]*/);
        propagatedField.SphericalPhaseRadius =
        EstimateSamplingParameter.ComputeSphericalPhase(propagatedField);
}
hfsReturn.Add(propagatedField);
}
return hfsReturn;
```

Task:
Programme a component that propagates an electromagnetic field a given distance Δz.

See sample file for full code!