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VirtualLab Fusion Applications, Technology & Workflows

Extended Hands-on Training with VirtualLab Fusion

LightTrans International UG

Presenter: Sohrab Sangini & Hartwig Craisheim

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-

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Introduction to the Teams

Who We Are



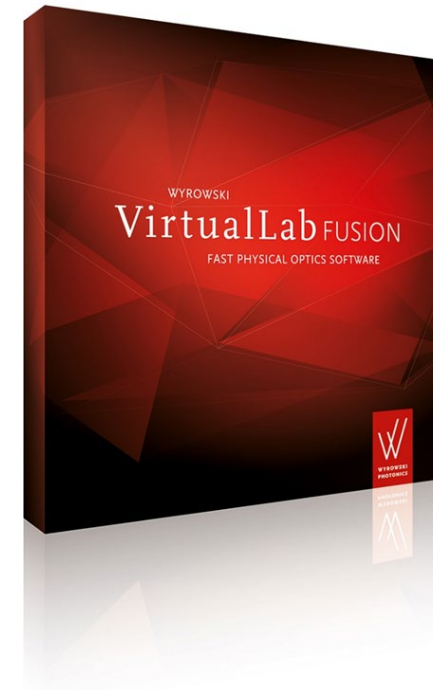
Founded 1999

General Distributor of the
Fast Physical Optics Software
VirtualLab Fusion

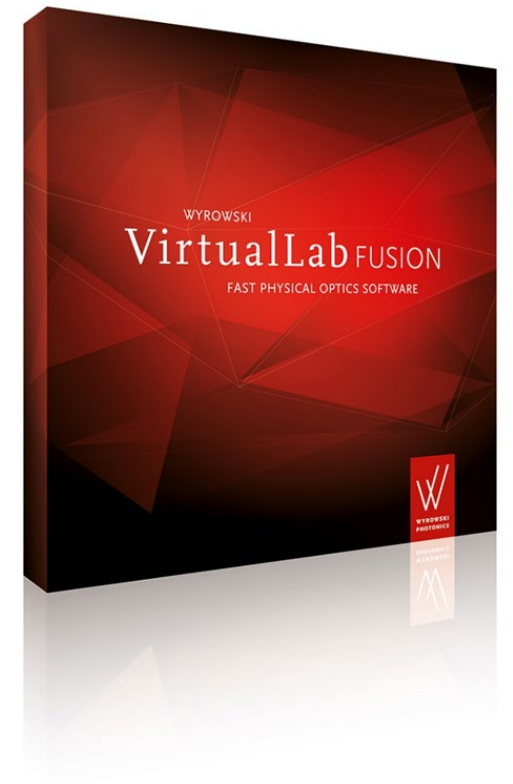
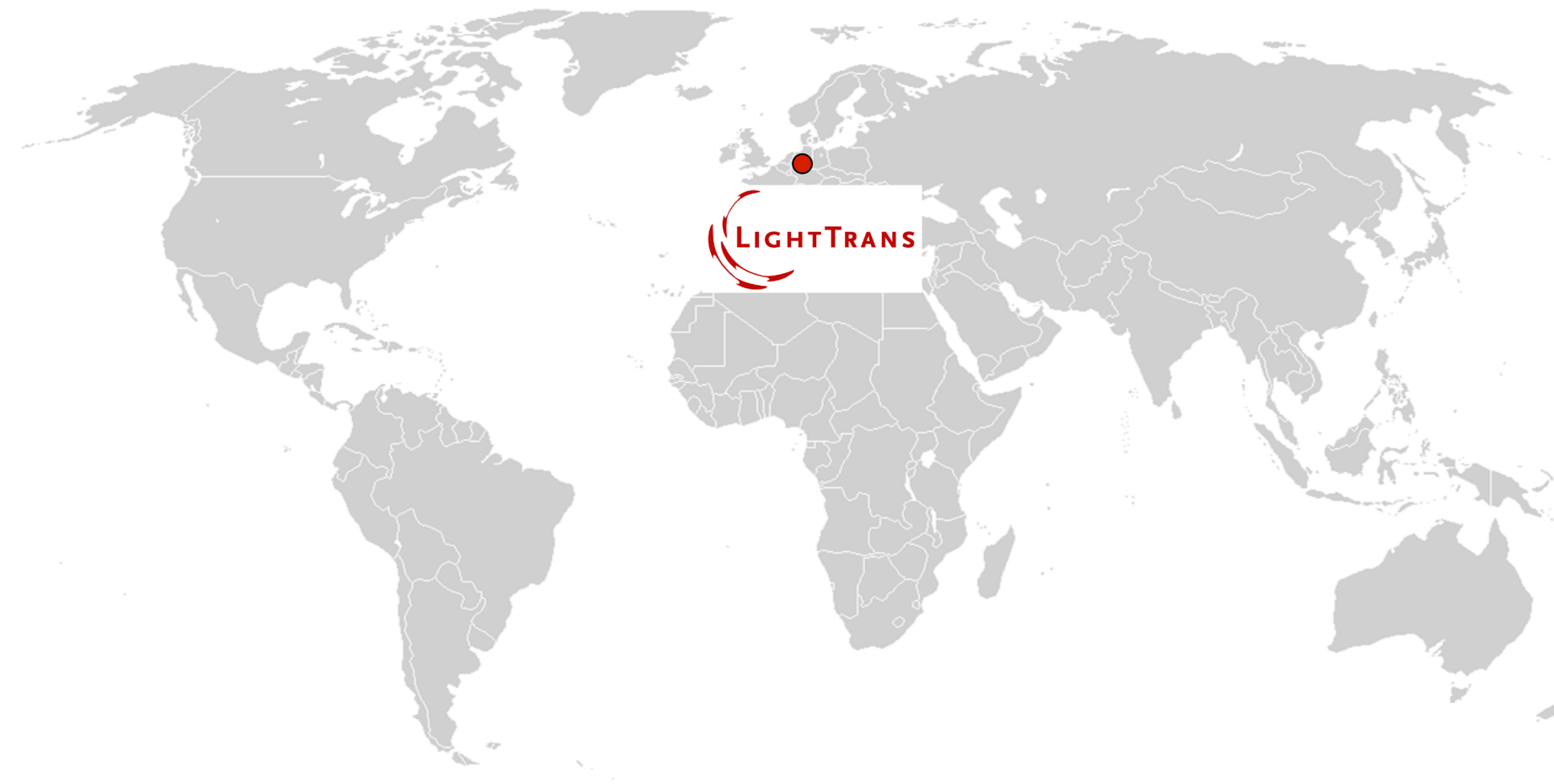


Founded 2014

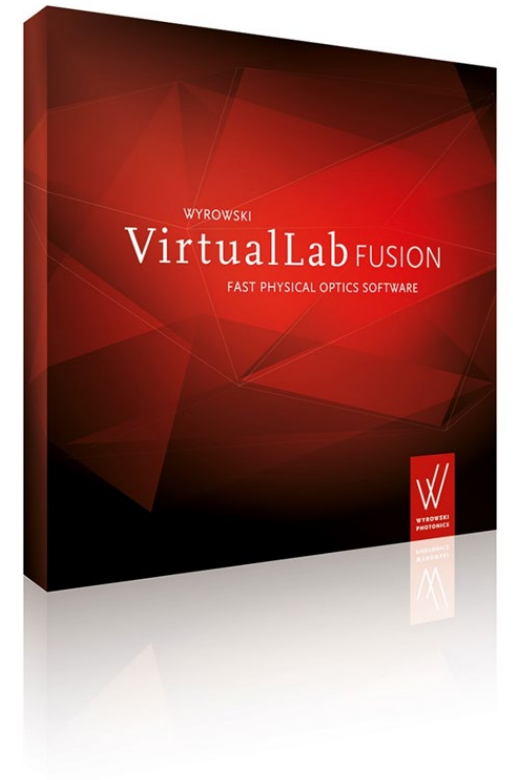
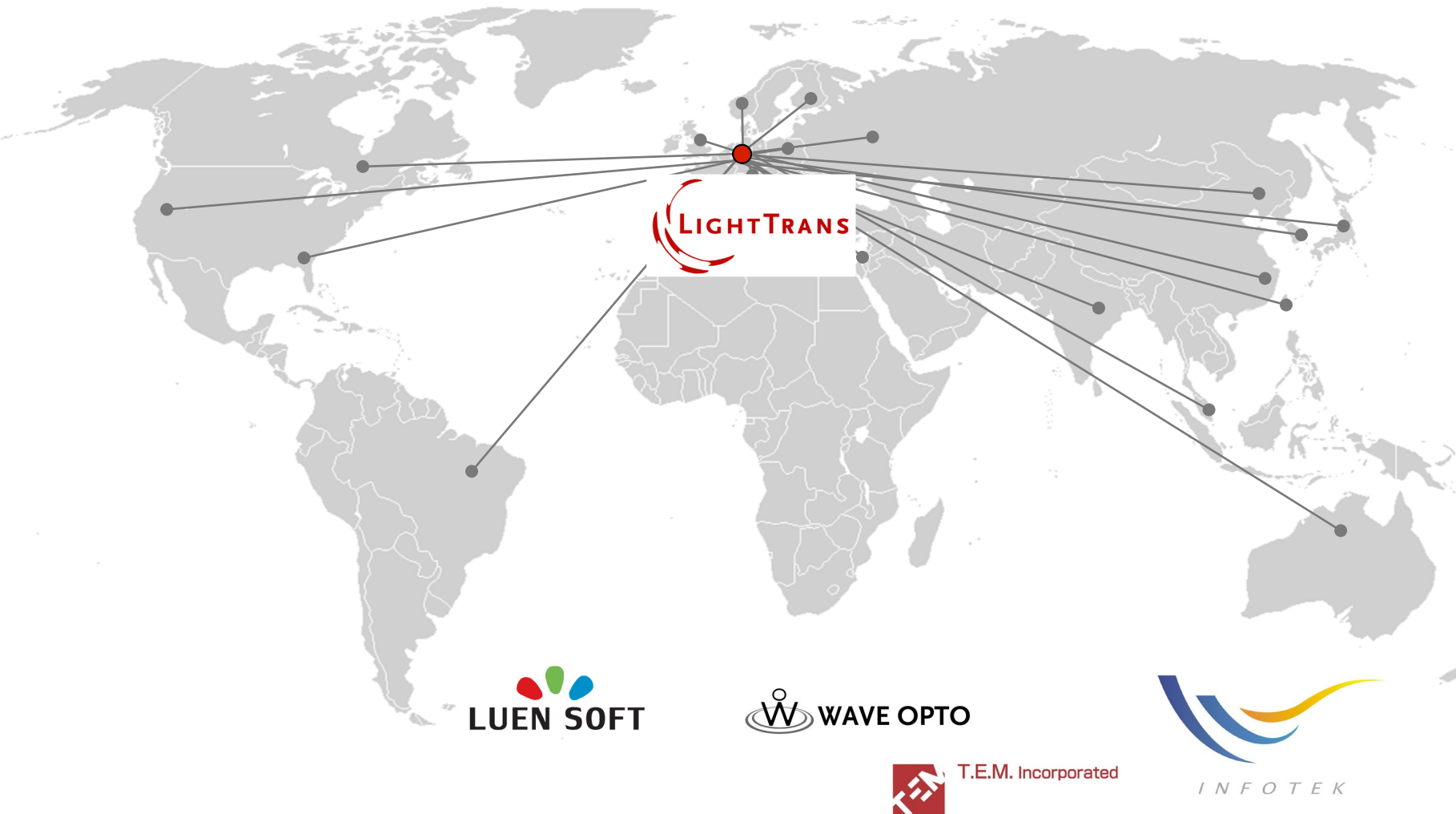
Developer of the
Fast Physical Optics Software
VirtualLab Fusion



Fast Physical Optics Modeling and Design Software



Fast Physical Optics Modeling and Design Software



Part 1

Light as an Electromagnetic Field



The Objective Behind VirtualLab Fusion

To perform physical optics simulations of arbitrary optical systems

The Objective Behind VirtualLab Fusion

To perform **physical optics simulations** of arbitrary optical systems

The Objective Behind VirtualLab Fusion

To perform **physical optics simulations** of arbitrary optical systems

Finding the expression of the **six-dimensional vector field that solves Maxwell's equations** under the conditions imposed by the system in question

The Objective Behind VirtualLab Fusion

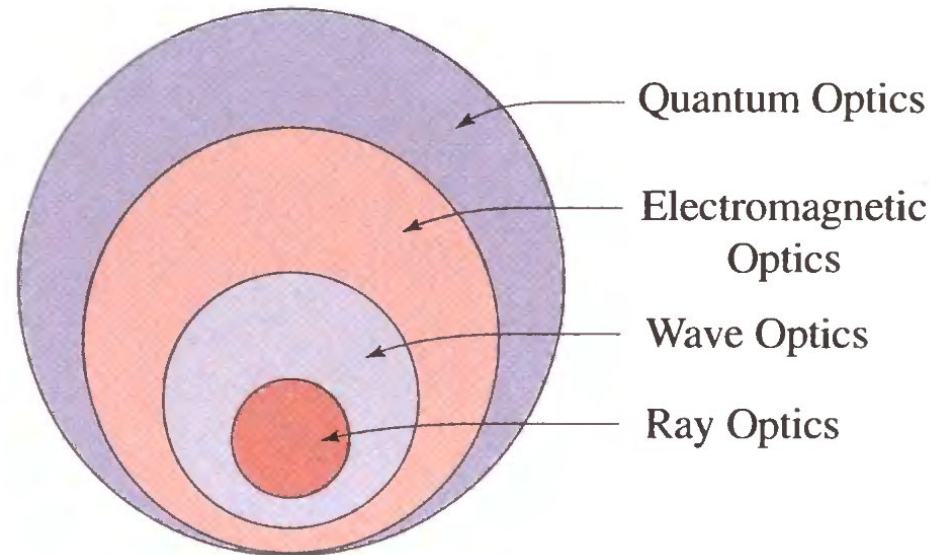
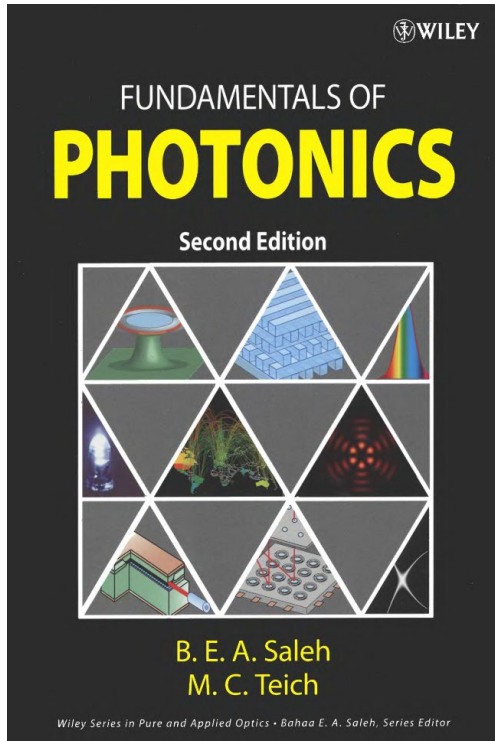
To perform **physical optics simulations** of arbitrary optical systems

Finding the expression of the **electromagnetic field** for the system in question

The Objective Behind VirtualLab Fusion

To perform **physical optics simulations** of arbitrary optical systems

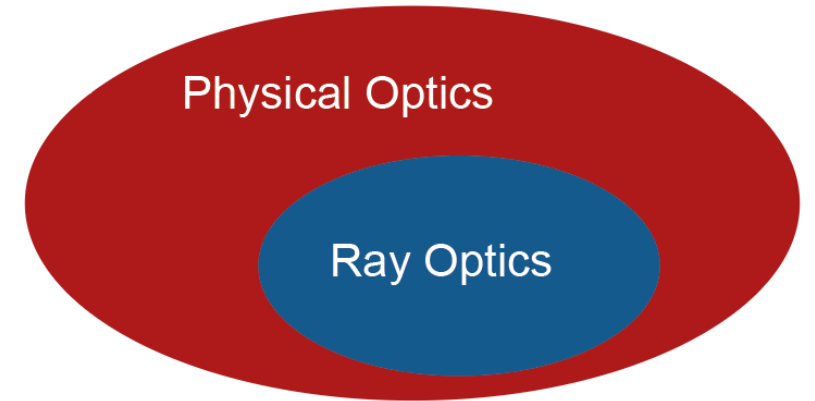
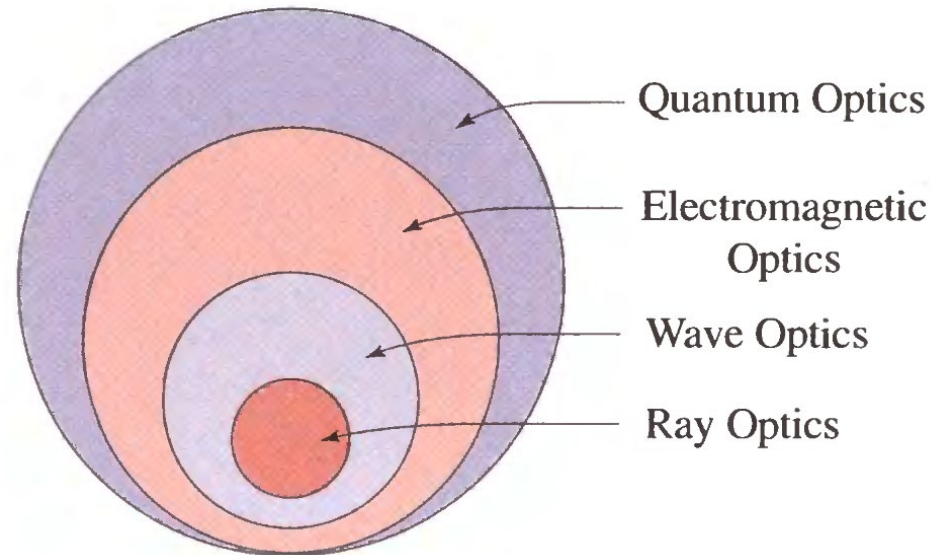
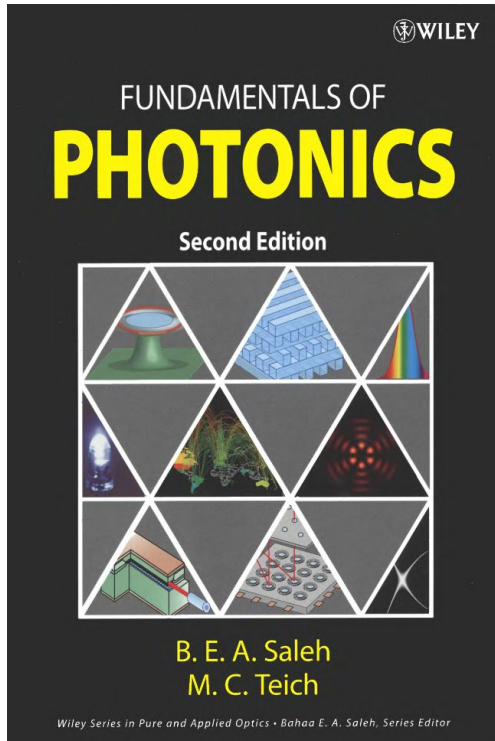
Finding the expression of the **electromagnetic field** for the system in question



The Objective Behind VirtualLab Fusion

To perform **physical optics simulations** of arbitrary optical systems

Finding the expression of the **electromagnetic field** for the system in question



... in VirtualLab Fusion

The Objective Behind VirtualLab Fusion

To perform **physical optics simulations** of arbitrary optical systems

Finding the expression of the **electromagnetic field** for the system in question

Quantum Optics

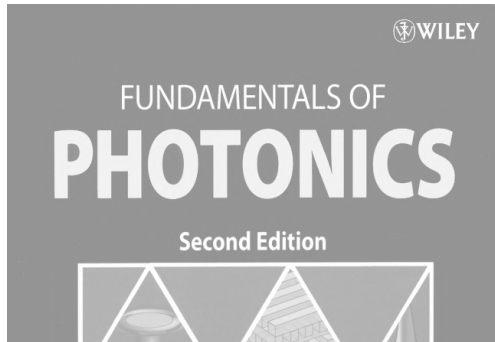
Physical Optics

Ray Optics

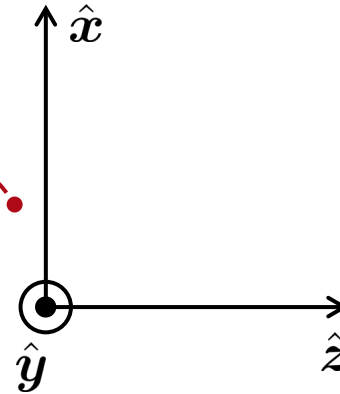
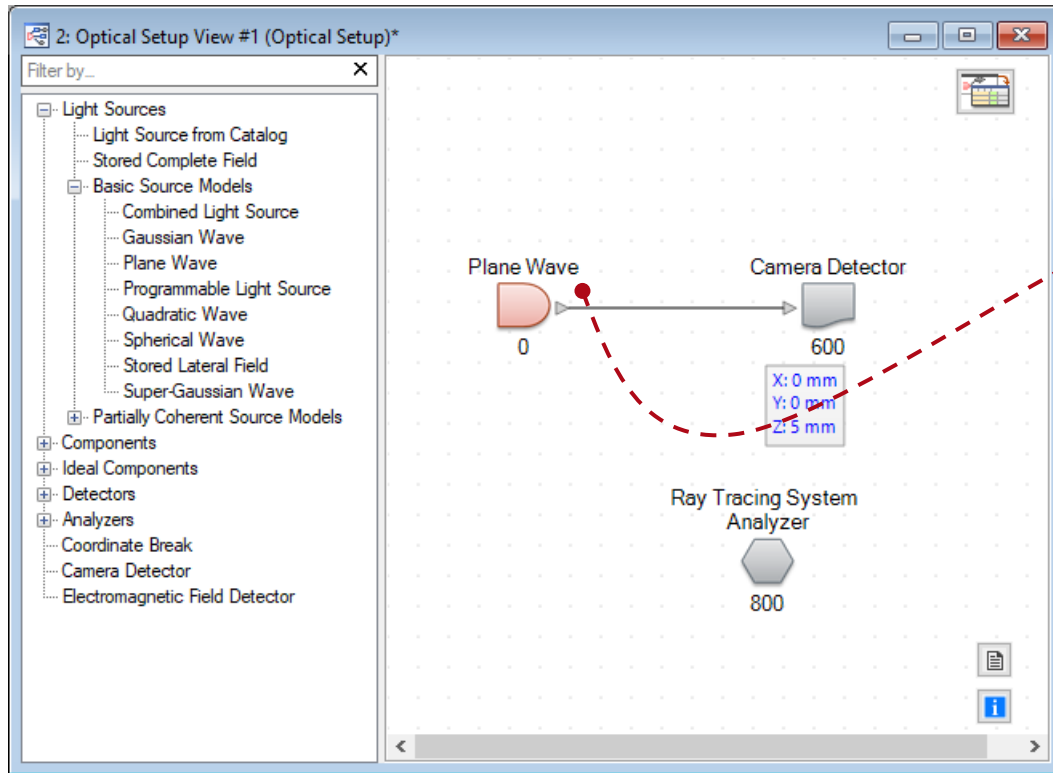
Important:

no distinction between physical optics and electromagnetic optics.
We never use the scalar approximation!

... in VirtualLab Fusion

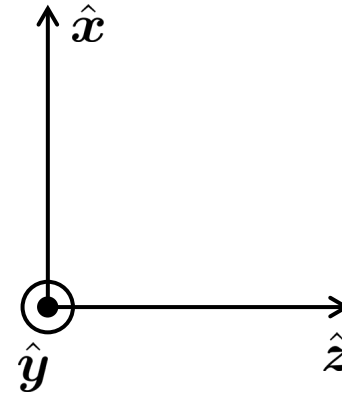
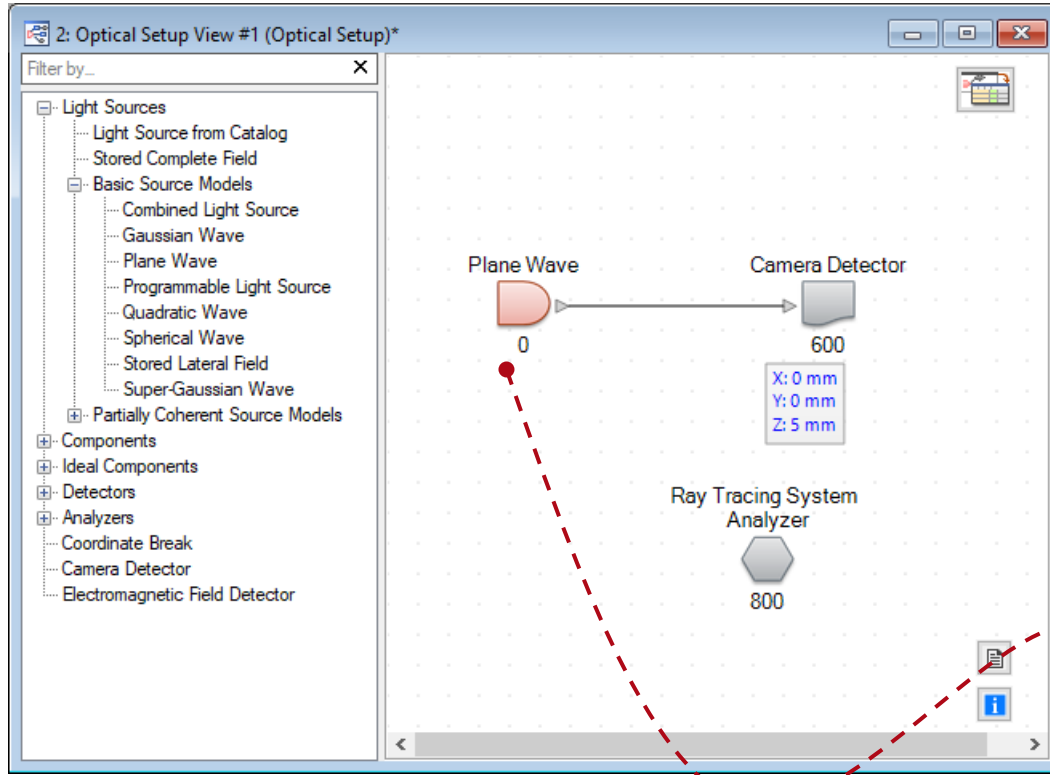


How Is Light Generated in the System? (Basics)



In VirtualLab Fusion, the source establishes the **global coordinate system** of the optical setup

How Is Light Generated in the System? (Basics)

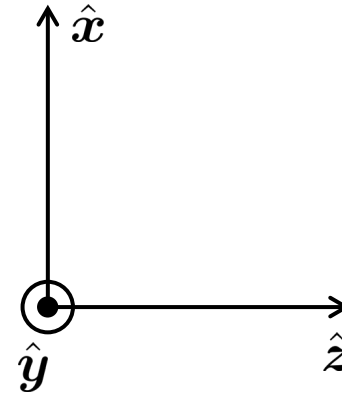
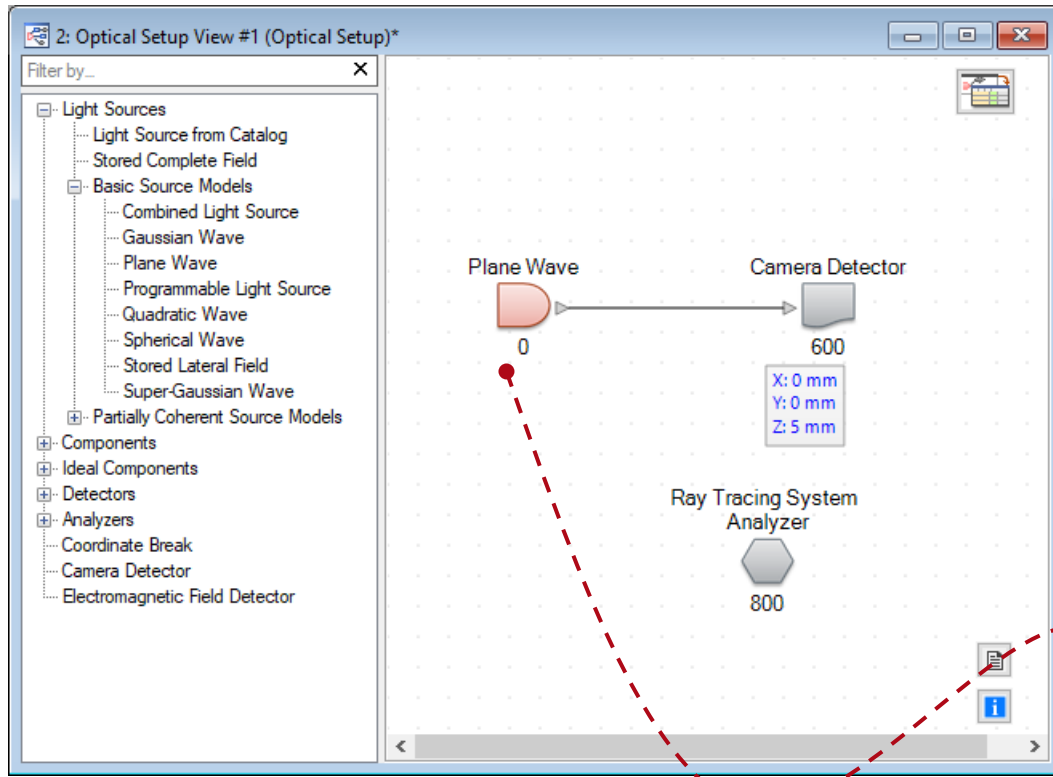


In VirtualLab Fusion, the source establishes the **global coordinate system** of the optical setup

$$\begin{cases} E_x(x, y) \\ E_y(x, y) \end{cases}$$

The source needs to define, per wavelength, the **function that spatially describes the x and y components** of the electric field at the input plane

How Is Light Generated in the System? (Basics)



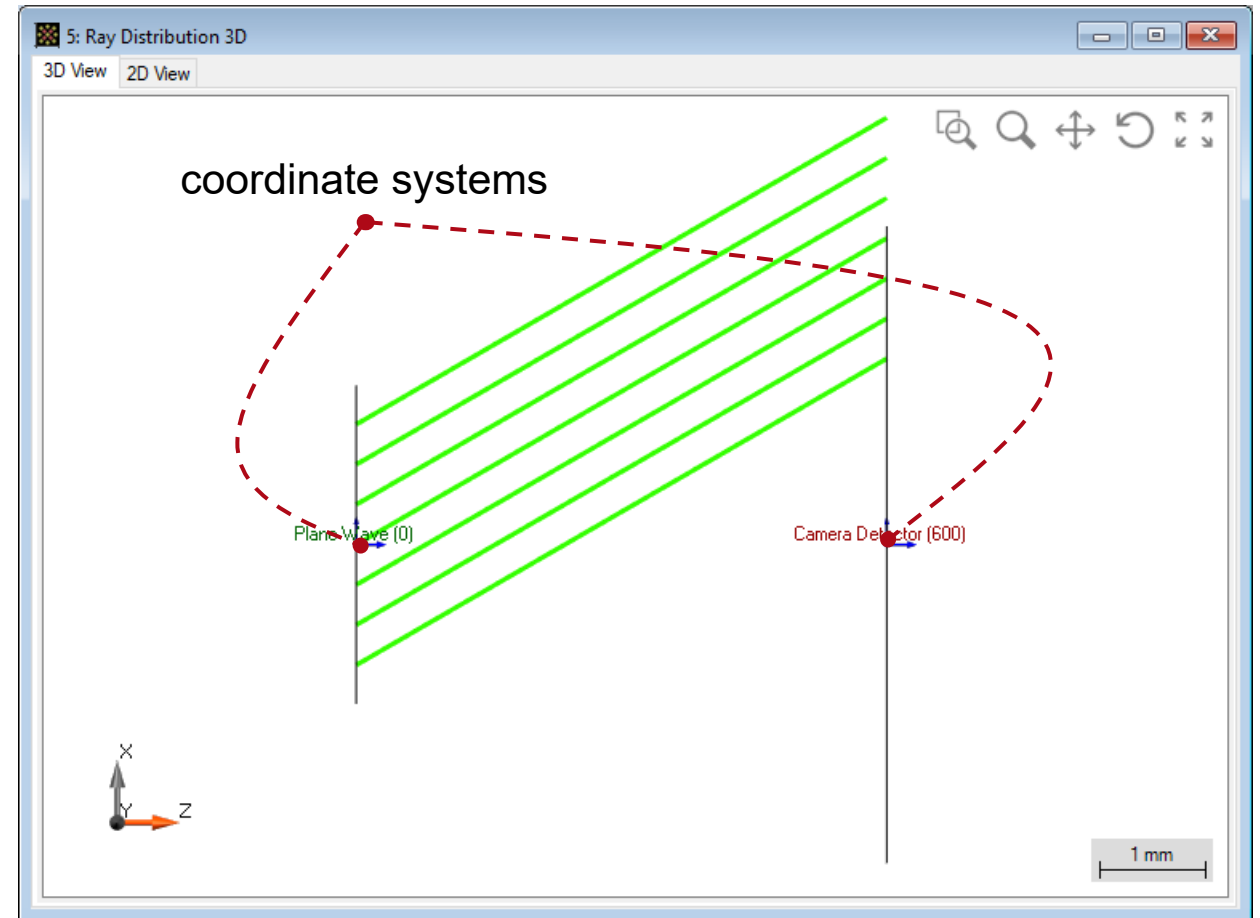
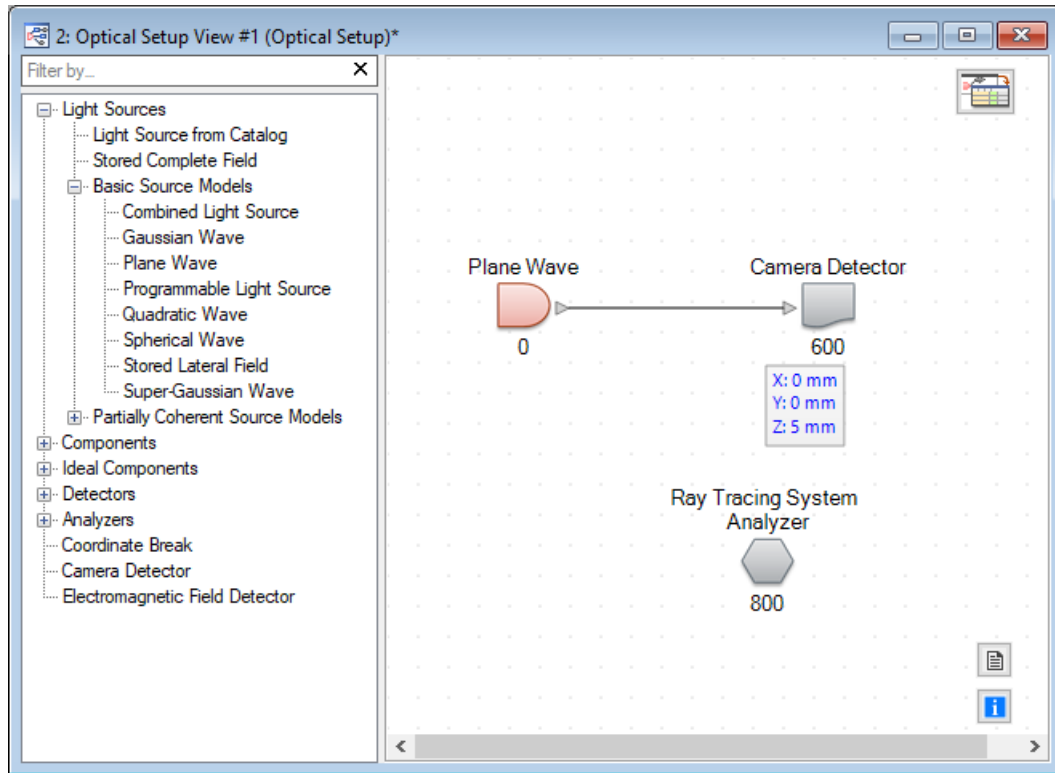
In VirtualLab Fusion, the source establishes the **global coordinate system** of the optical setup

$$\begin{cases} E_x(x, y) \\ E_y(x, y) \end{cases}$$

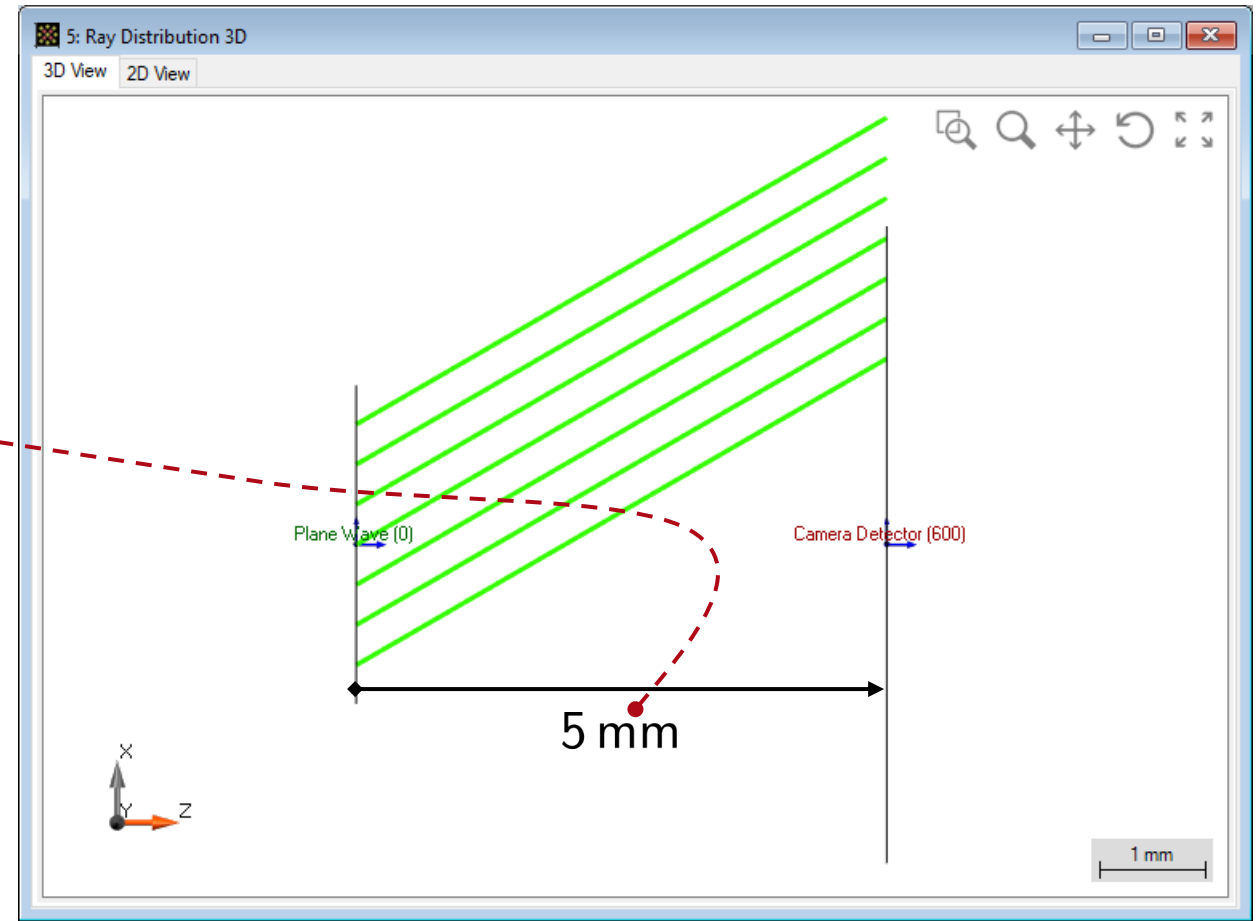
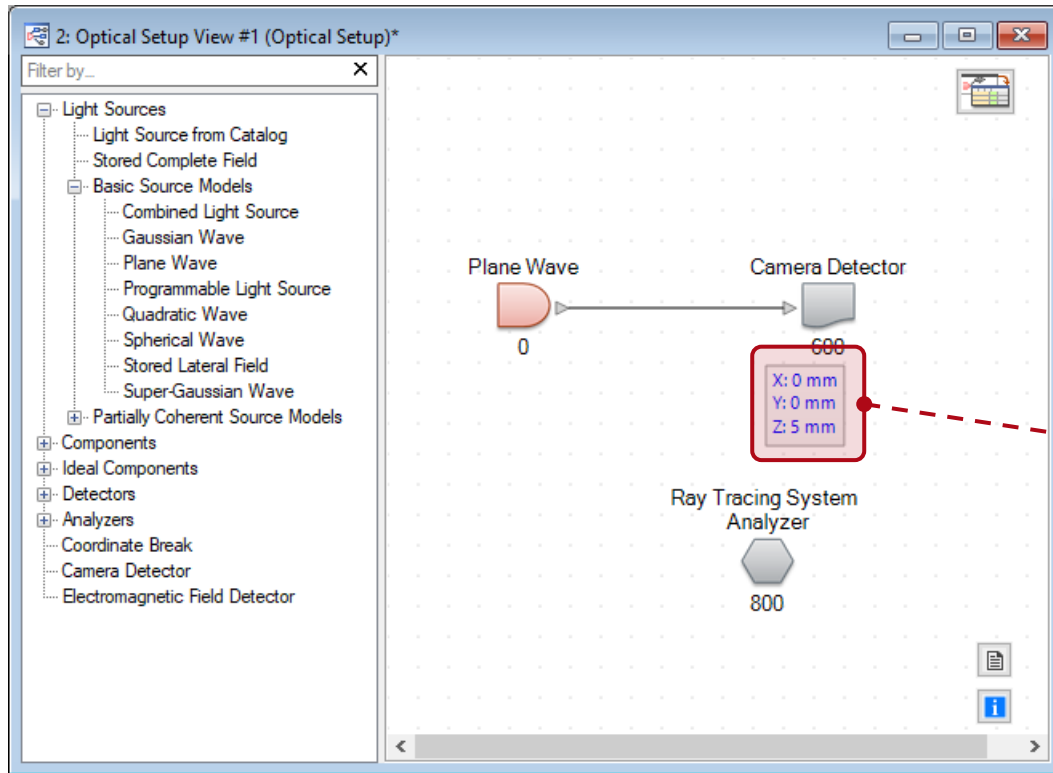
The source needs to define, per wavelength, the **function that spatially describes the x and y components** of the electric field at the input plane

According to Maxwell's equations, **only two of the six electromagnetic components are independent** in a homogeneous, isotropic medium → we arbitrarily select E_x and E_y ; other components calculated on demand

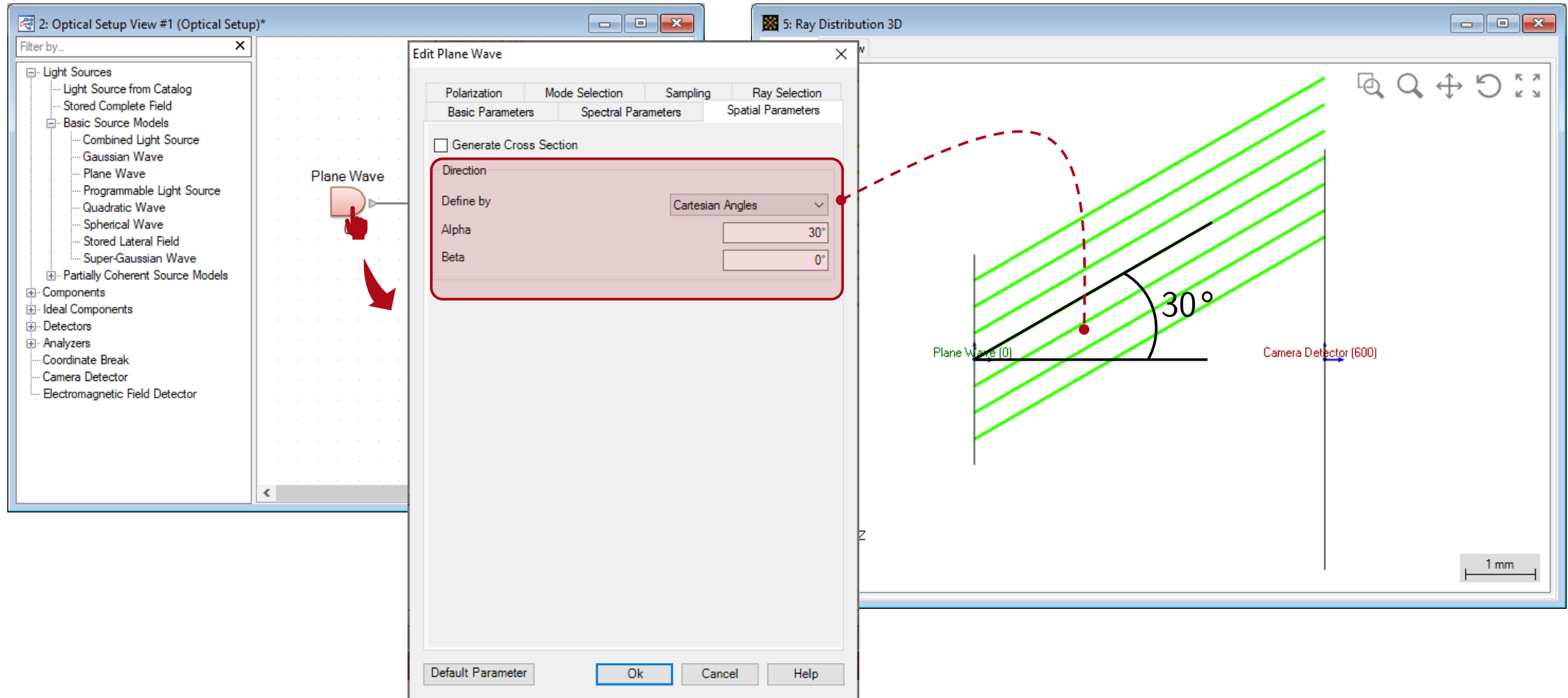
How Is Light Generated in the System? (Basics)



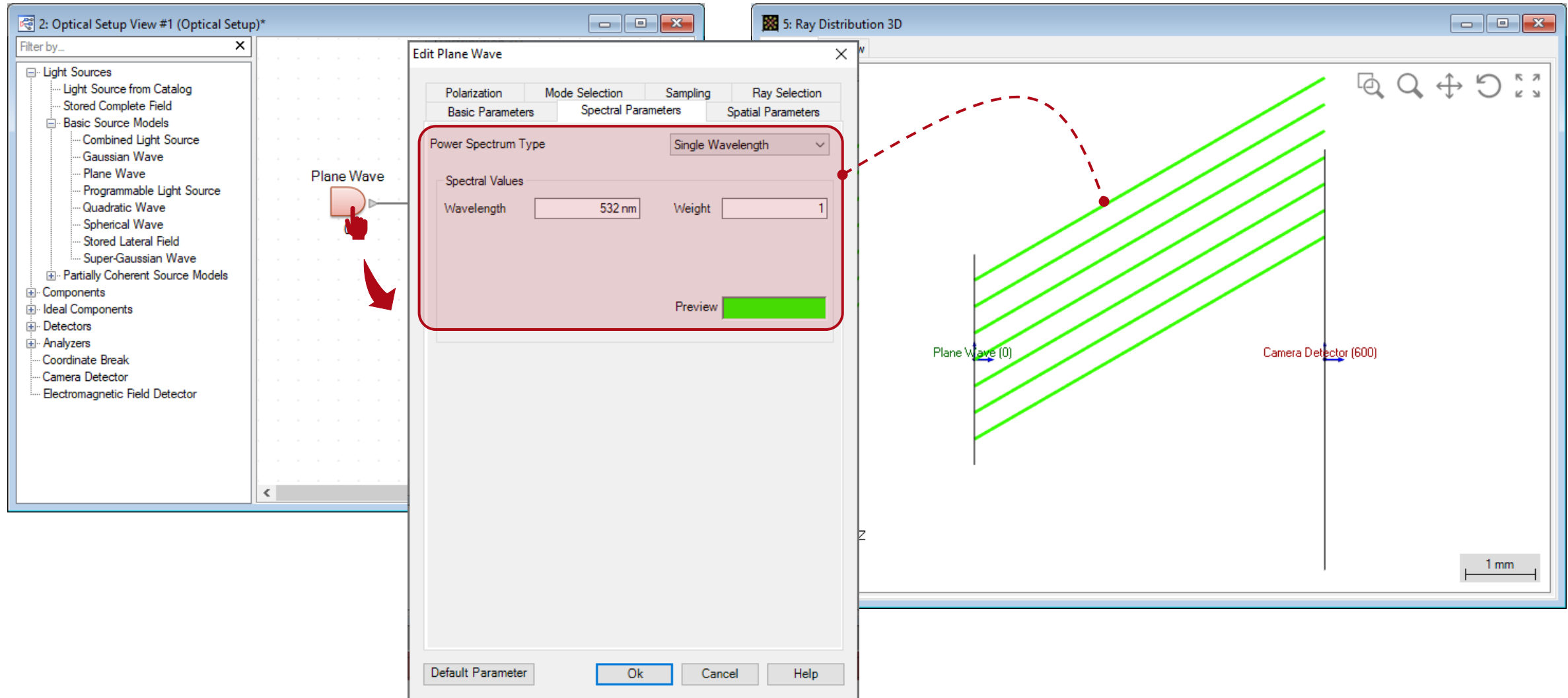
How Is Light Generated in the System? (Basics)



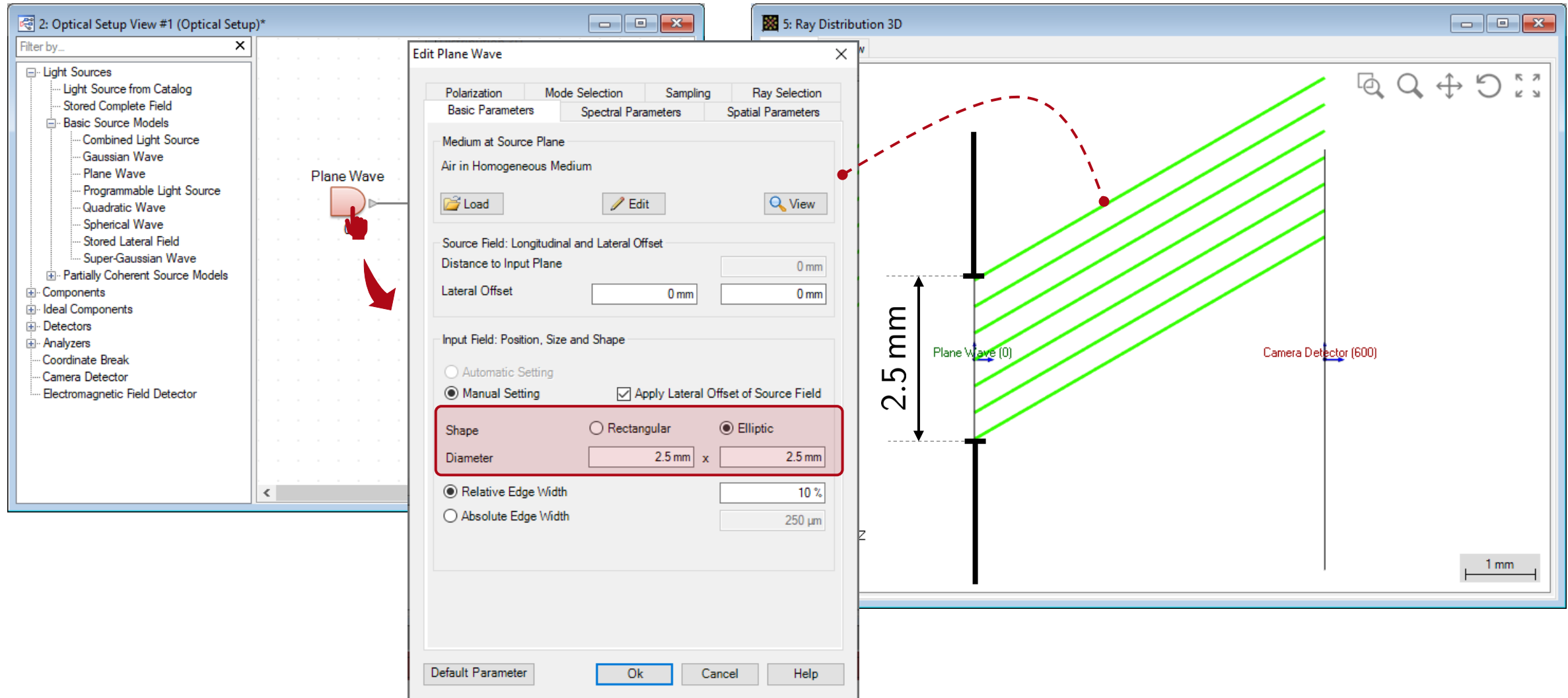
How Is Light Generated in the System? (Basics)



How Is Light Generated in the System? (Basics)



How Is Light Generated in the System? (Basics)



How Is Light Generated in the System? (Basics)

The image displays a software interface for optical simulation, showing the configuration of a light source and the resulting ray distribution.

2: Optical Setup View #1 (Optical Setup)*

- Filter by...
- Light Sources
 - Light Source from Catalog
 - Stored Complete Field
 - Basic Source Models
 - Combined Light Source
 - Gaussian Wave
 - Plane Wave
 - Programmable Light Source
 - Quadratic Wave
 - Spherical Wave
 - Stored Lateral Field
 - Super-Gaussian Wave
 - Partially Coherent Source Models
- Components
 - Ideal Components
 - Detectors
 - Analyzers
 - Coordinate Break
 - Camera Detector
 - Electromagnetic Field Detector

Edit Plane Wave

Polarization | Mode Selection | Sampling | Ray Selection

Basic Parameters | Spectral Parameters | Spatial Parameters

Medium at Source Plane
Air in Homogeneous Medium

Load | Edit | View

Source Field: Longitudinal and Lateral Offset
Distance to Input Plane: 0 mm
Lateral Offset: 0 mm

Input Field: Position, Size and Shape

☐ Automatic Setting
☒ Manual Setting ☒ Apply Lateral Offset of Source Field

Shape: ☐ Rectangular ☒ Elliptic
Diameter: 2.5 mm x 2.5 mm

☒ Relative Edge Width: 10 %
☐ Absolute Edge Width: 250 μm

Default Parameter | Ok | Cancel | Help

5: Ray Distribution 3D

Plane Wave (0)

10: "Camera Detector" (# 600) after "Plane Wav..."

Chromatic Fields Set

Data for Wavelength of 532 nm $[(V/m)^2]$

Y [mm] X [mm]

1.2
0.62
-2.9E-07

1 mm

The screenshot illustrates the configuration of a plane wave source in an optical simulation. The 'Edit Plane Wave' dialog box is open, showing the 'Basic Parameters' tab. The 'Medium at Source Plane' is set to 'Air in Homogeneous Medium'. The 'Source Field' is configured with a 'Distance to Input Plane' of 0 mm and a 'Lateral Offset' of 0 mm. The 'Input Field' is set to 'Position, Size and Shape' with 'Manual Setting' selected and 'Apply Lateral Offset of Source Field' checked. The 'Shape' is set to 'Elliptic' with a 'Diameter' of 2.5 mm x 2.5 mm. The 'Relative Edge Width' is set to 10%, which is highlighted with a red box and a red arrow pointing to the 'Camera Detector' window. The 'Camera Detector' window shows the resulting light distribution, a circular spot, with a color scale ranging from -2.9E-07 to 1.2. The 'Ray Distribution 3D' window shows the light rays as green lines. A red dashed line connects the 'Relative Edge Width' setting to the 'Camera Detector' window.

How Is Light Generated in the System? (Basics)

The image displays a software interface for optical simulation, showing the configuration of a light source and the resulting field distribution.

2: Optical Setup View #1 (Optical Setup)*

- Filter by...
- Light Sources
 - Light Source from Catalog
 - Stored Complete Field
 - Basic Source Models
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 - Gaussian Wave
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 - Stored Lateral Field
 - Super-Gaussian Wave
 - Partially Coherent Source Models
- Components
 - Ideal Components
 - Detectors
 - Analyzers
 - Coordinate Break
 - Camera Detector
 - Electromagnetic Field Detector

Edit Plane Wave

Polarization | Mode Selection | Sampling | Ray Selection

Basic Parameters | Spectral Parameters | Spatial Parameters

Medium at Source Plane
Air in Homogeneous Medium

Load Edit View

Source Field: Longitudinal and Lateral Offset
Distance to Input Plane: 0 mm
Lateral Offset: 0 mm

Input Field: Position, Size and Shape

☐ Automatic Setting
☒ Manual Setting ☒ Apply Lateral Offset of Source Field

Shape: ☐ Rectangular ☒ Elliptic
Diameter: 2.5 mm x 2.5 mm

☒ Relative Edge Width: 10 %
☐ Absolute Edge Width: 250 μm

Default Parameter Ok Cancel Help

5: Ray Distribution 3D

Plane Wave (0)

10: "Camera Detector" (# 600) after "Plane Wav..."

Chromatic Fields Set

Data for Wavelength of 532 nm $[(V/m)^2]$

Y [mm]: -1, -0.5, 0, 0.5, 1
X [mm]: -1, -0.5, 0, 0.5, 1

1.2

The diagram illustrates the generation of light in the system. A **Plane Wave** is selected from the **Light Sources** list. The **Edit Plane Wave** dialog box shows the configuration for the **Plane Wave (0)**. The **Relative Edge Width** is set to **10 %**. The resulting field distribution is shown in the **5: Ray Distribution 3D** view, and the **10: "Camera Detector" (# 600) after "Plane Wav..."** view displays the **Chromatic Fields Set** for a wavelength of 532 nm, showing the intensity distribution $[(V/m)^2]$ on a grid.

How Is Light Generated in the System? (Basics)

The image displays a software interface for configuring an optical system. The main window, titled "2: Optical Setup View #1 (Optical Setup)*", shows a tree view of components on the left. A red arrow points to the "Plane Wave" component under "Basic Source Models".

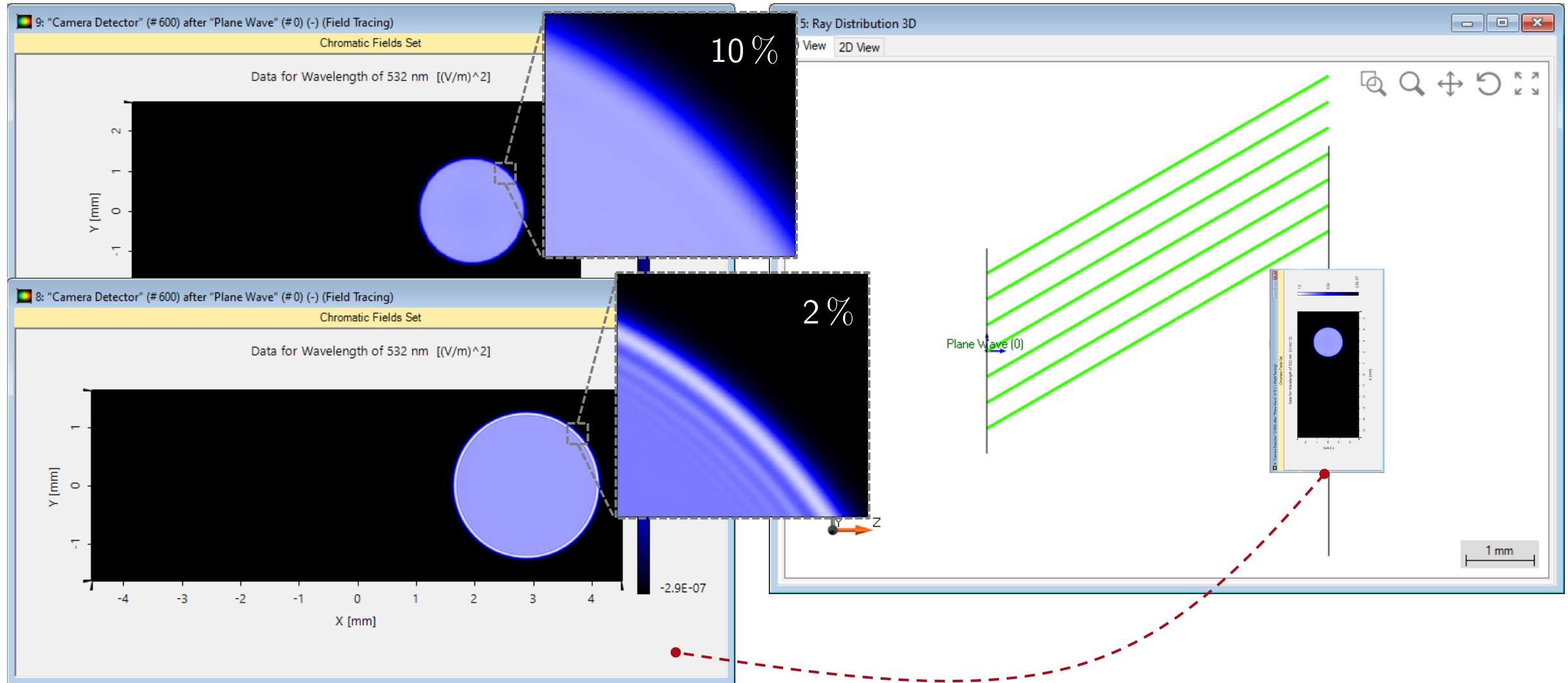
The "Edit Plane Wave" dialog box is open, showing the "Basic Parameters" tab. The "Medium at Source Plane" is set to "Air in Homogeneous Medium". The "Source Field: Longitudinal and Lateral Offset" section shows "Distance to Input Plane" and "Lateral Offset" both set to 0 mm. The "Input Field: Position, Size and Shape" section shows "Automatic Setting" selected, "Apply Lateral Offset of Source Field" checked, and "Shape" set to "Elliptic" with a "Diameter" of 2.5 mm x 2.5 mm. A red box highlights the "Relative Edge Width" setting, which is set to 10 %.

Below the dialog box, the text "Relative Edge Width: 2 %" is displayed in a large font.

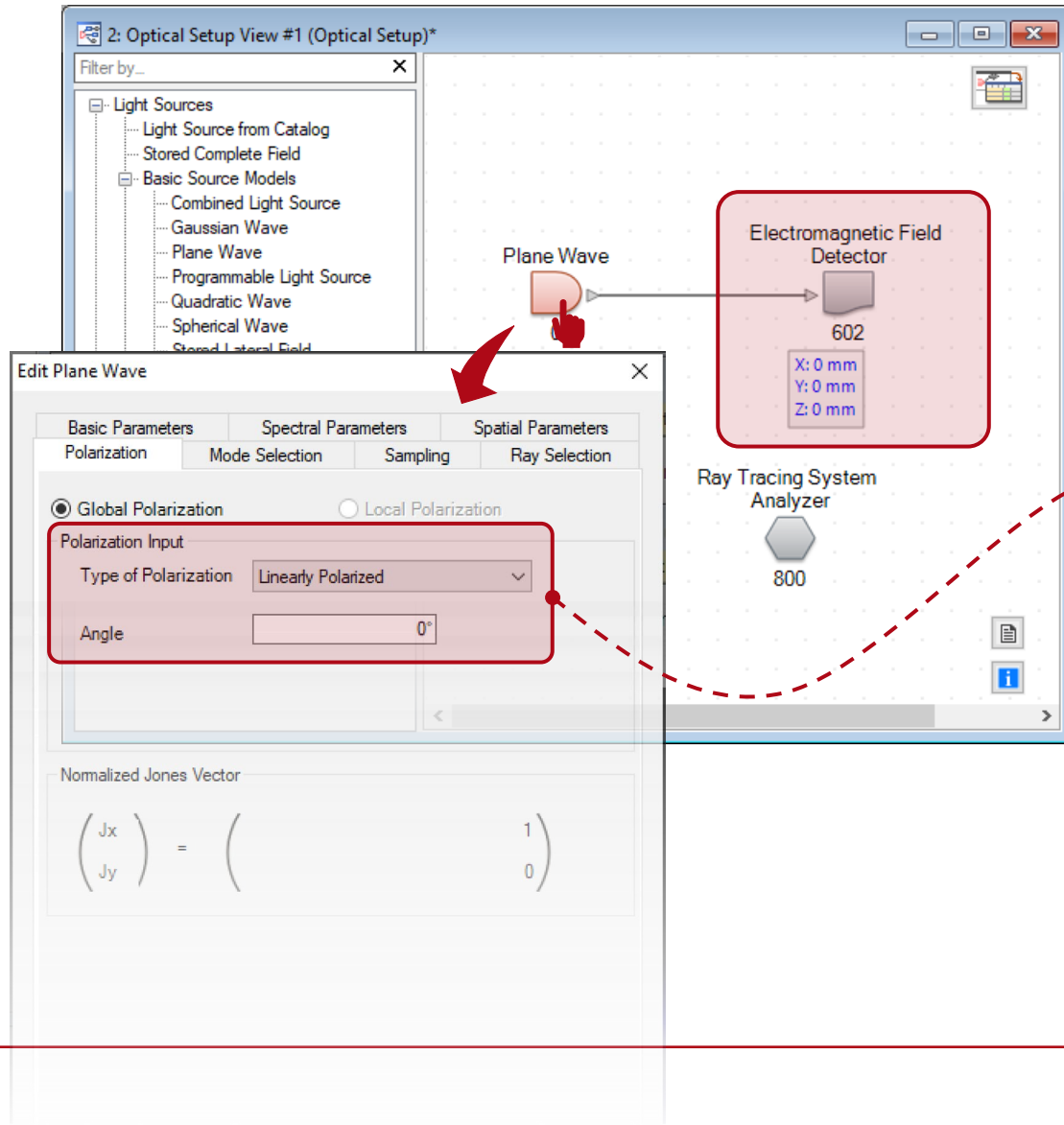
The "5: Ray Distribution 3D" window shows a 3D visualization of the light rays, which are green lines originating from a point labeled "Plane Wave (0)".

The "11: 'Camera Detector' (# 600) after 'Plane Wav..." window shows a 2D plot of the "Chromatic Fields Set" for a wavelength of 532 nm. The plot shows a blue circular field of view on a black background, with a red dot indicating the center of the field.

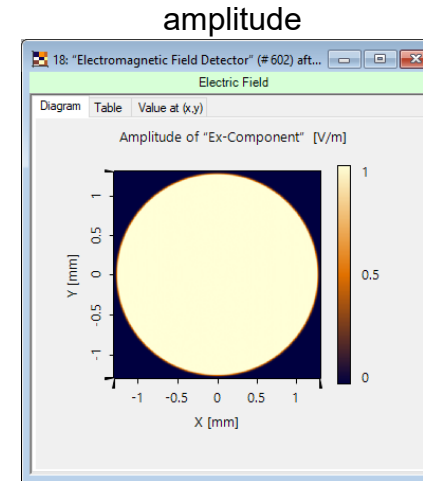
How Is Light Generated in the System? (Basics)



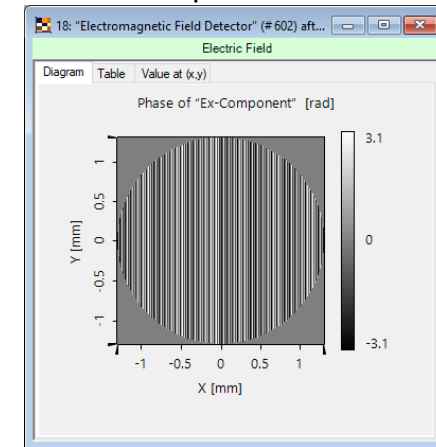
How Is Light Generated in the System? (Basics)



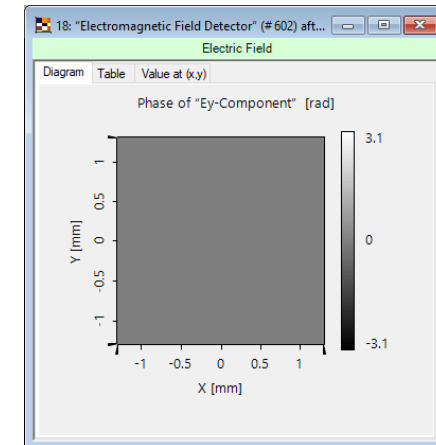
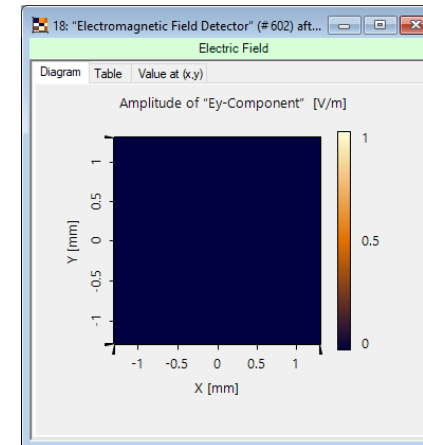
E_x



phase



E_y

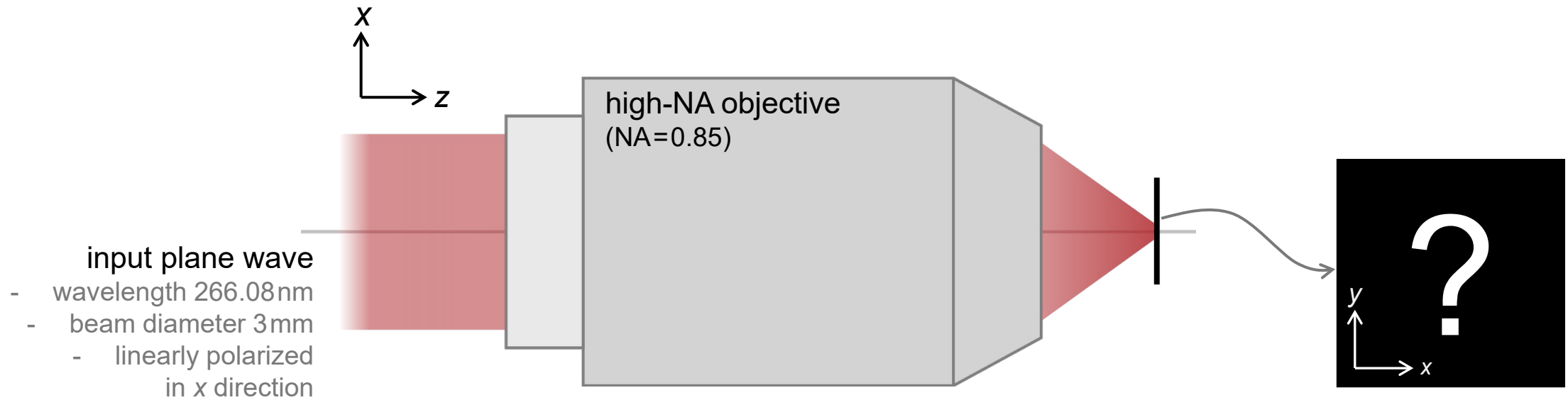


Example 1

Analyzing High-NA Objective Lens Focusing

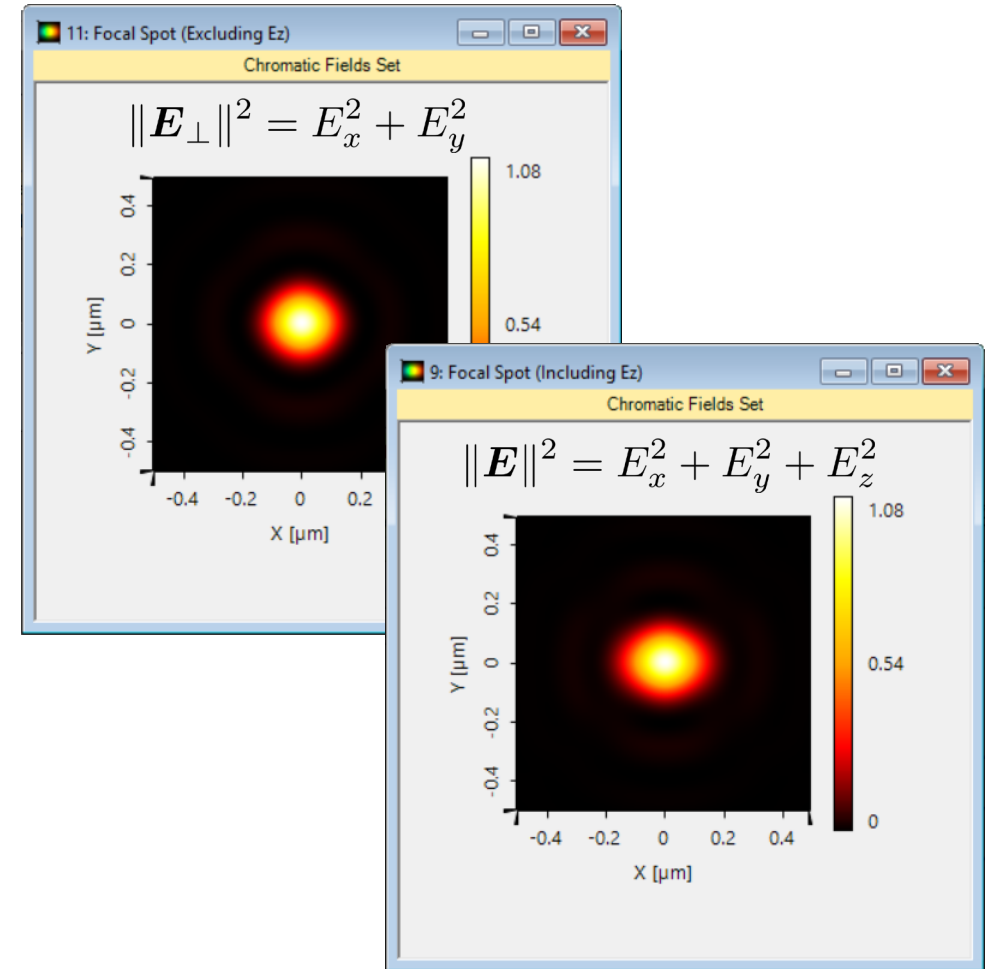


Modeling Task



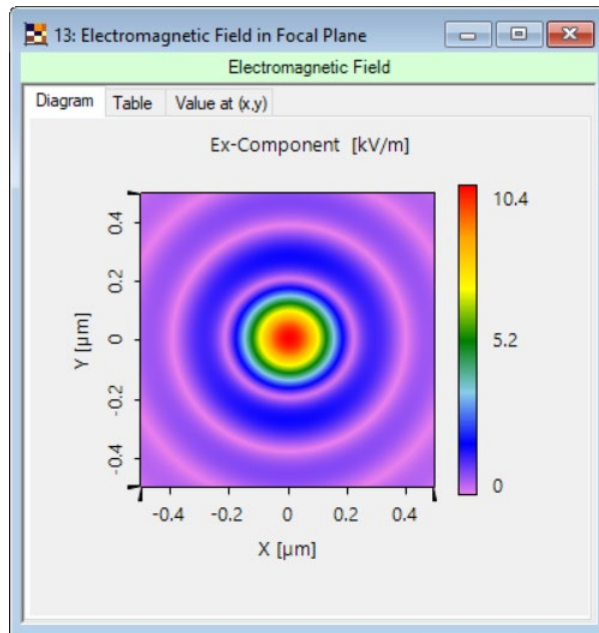
Field Tracing Results (Camera Detector)

- The top figure shows the intensity by integrating E_x and E_y field components only.
- The bottom figure shows the intensity by integrating E_x , E_y and E_z components: an obvious asymmetry is seen due to the relatively large E_z component in high-NA situation.

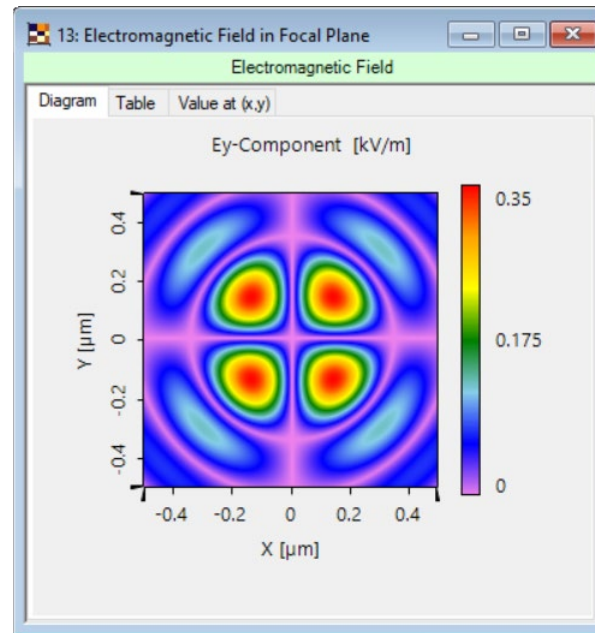


Field Tracing Results (Electromagnetic Field Detector)

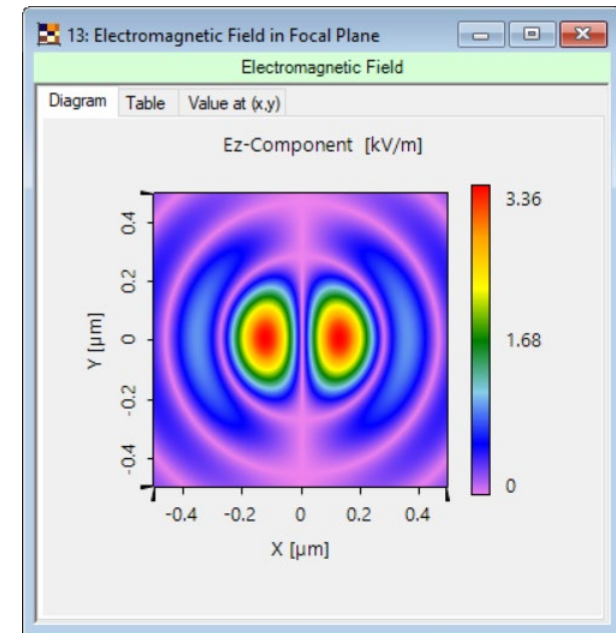
- All electromagnetic field components are obtained by using the Electromagnetic Field Detector.



amplitude of E_x



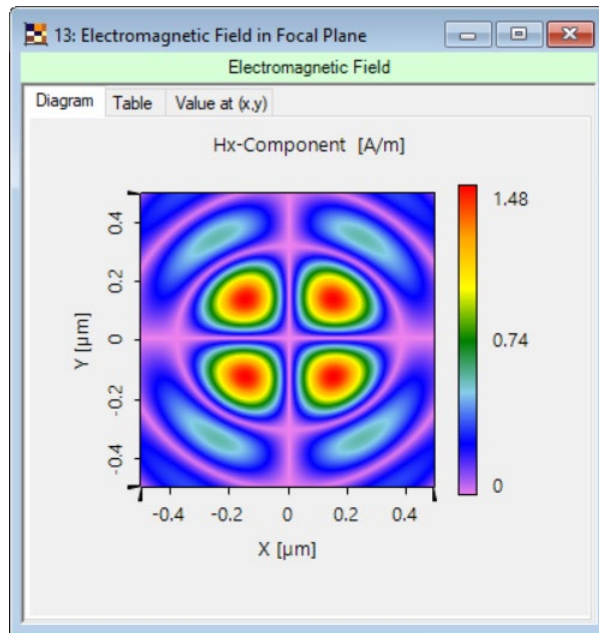
amplitude of E_y



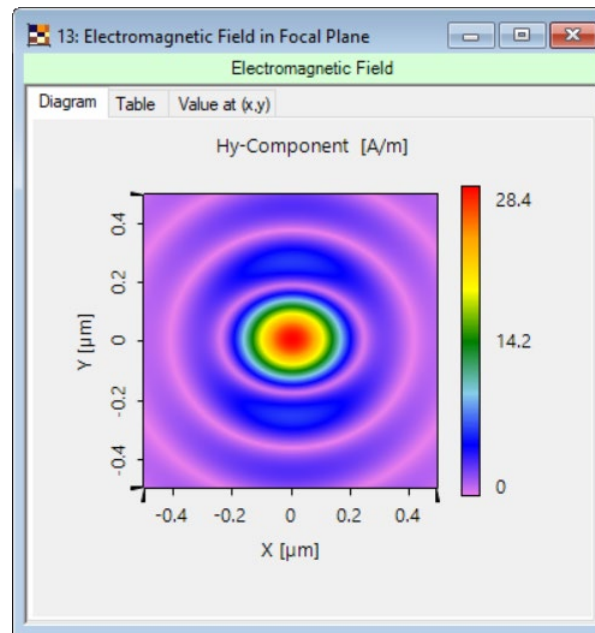
amplitude of E_z

Field Tracing Results (Electromagnetic Field Detector)

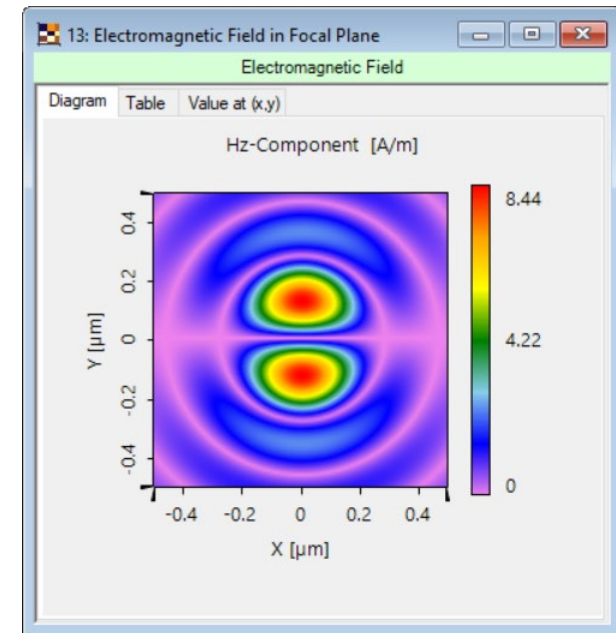
- All electromagnetic field components are obtained by using the Electromagnetic Field Detector.



amplitude of H_x



amplitude of H_y



amplitude of H_z

Part 2

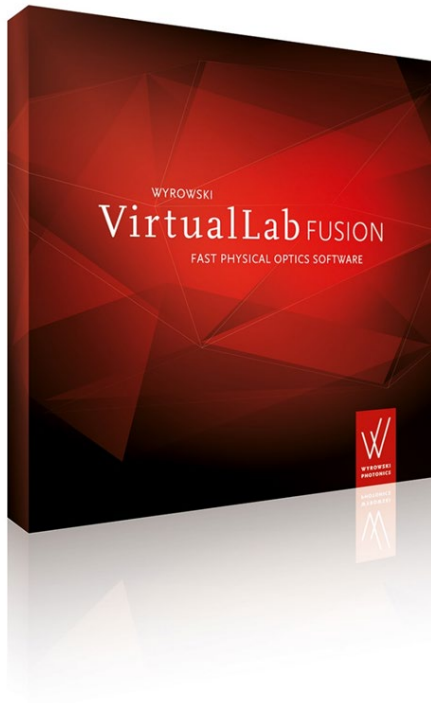
The Electromagnetic Field Solvers



One Platform, Many Solvers

Fast physical optics simulations...

... made possible by **connecting field solvers!**



VirtualLab Fusion acts a software platform to connect electromagnetic field solvers in a **seamless, fully non-sequential manner**



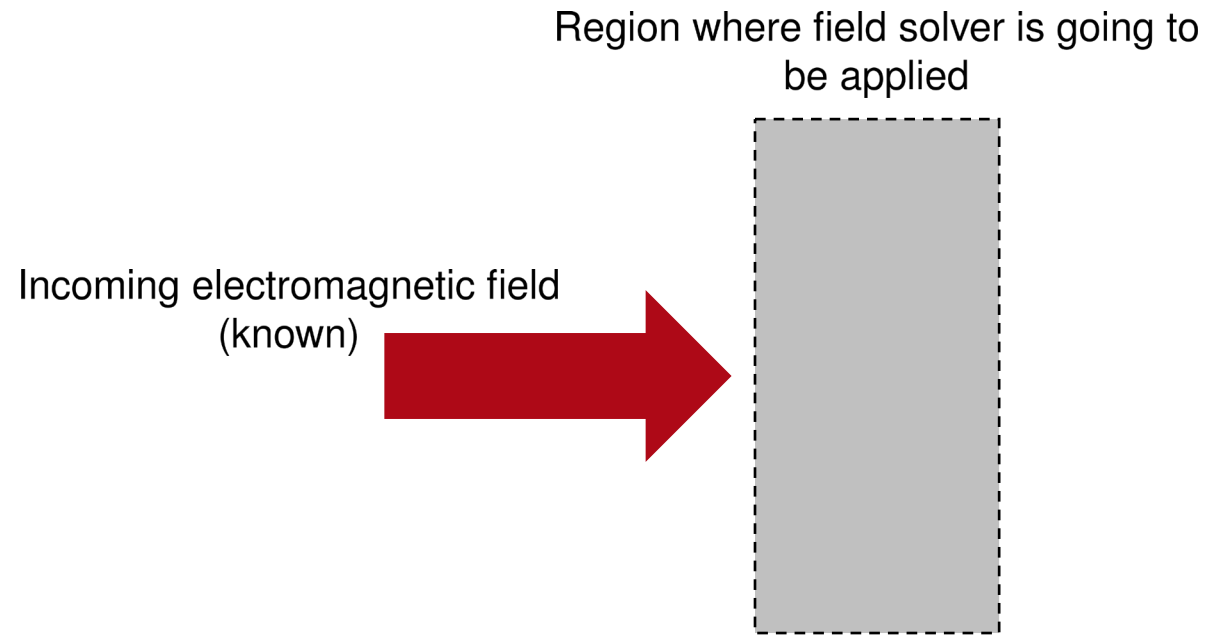
solving Maxwell's equations for the whole system!

Electromagnetic Field Solvers

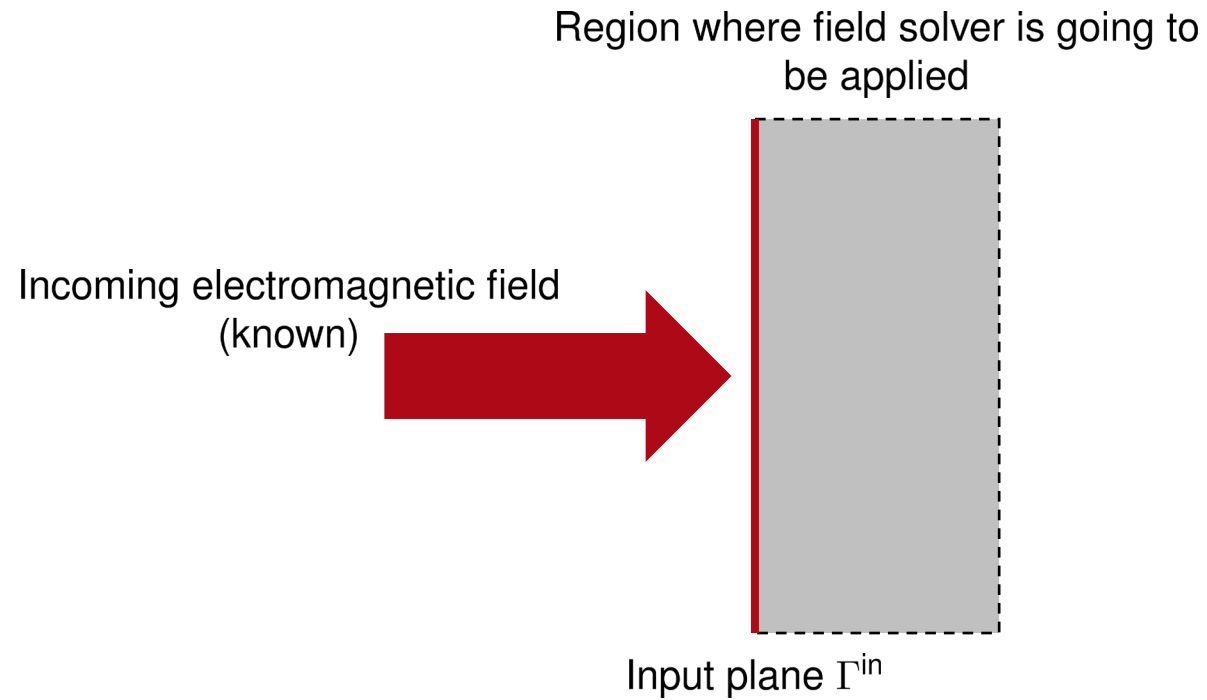
Region where field solver is going to
be applied



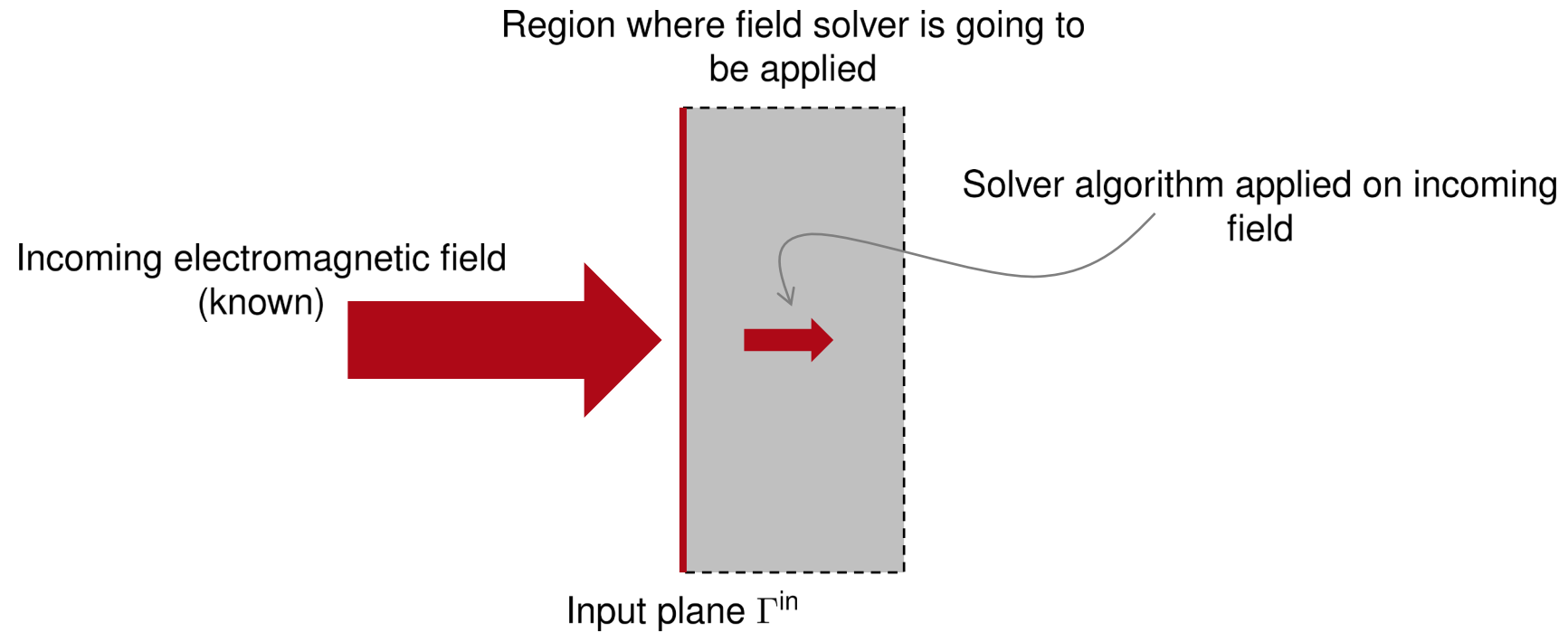
Electromagnetic Field Solvers



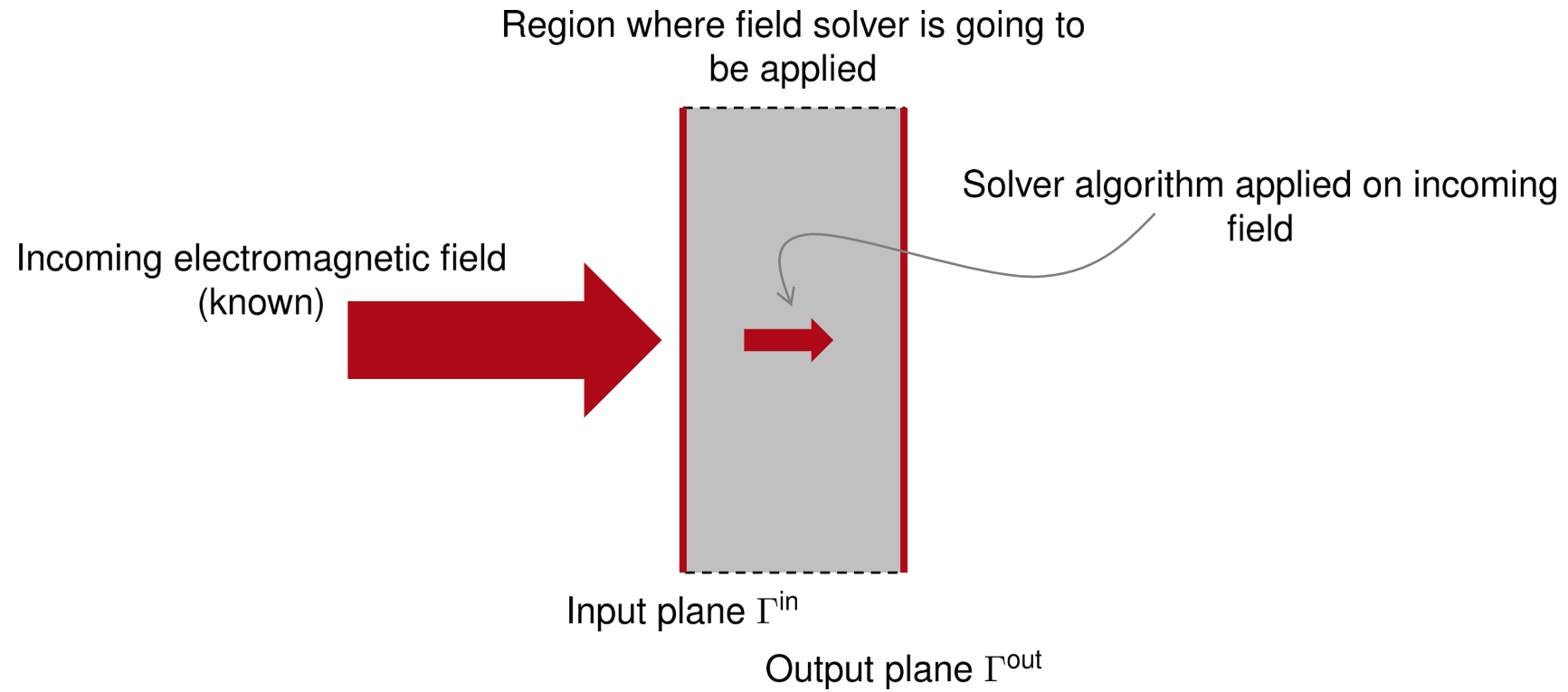
Electromagnetic Field Solvers



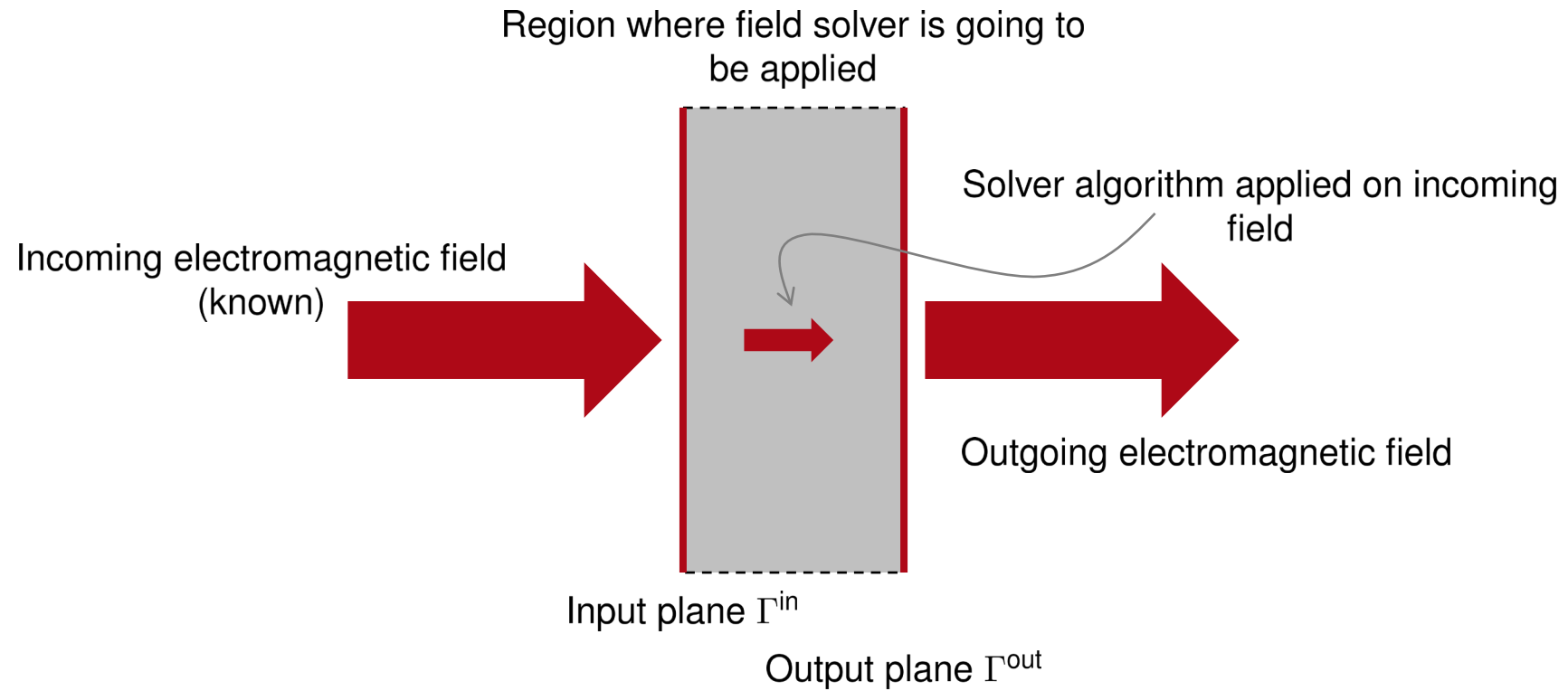
Electromagnetic Field Solvers



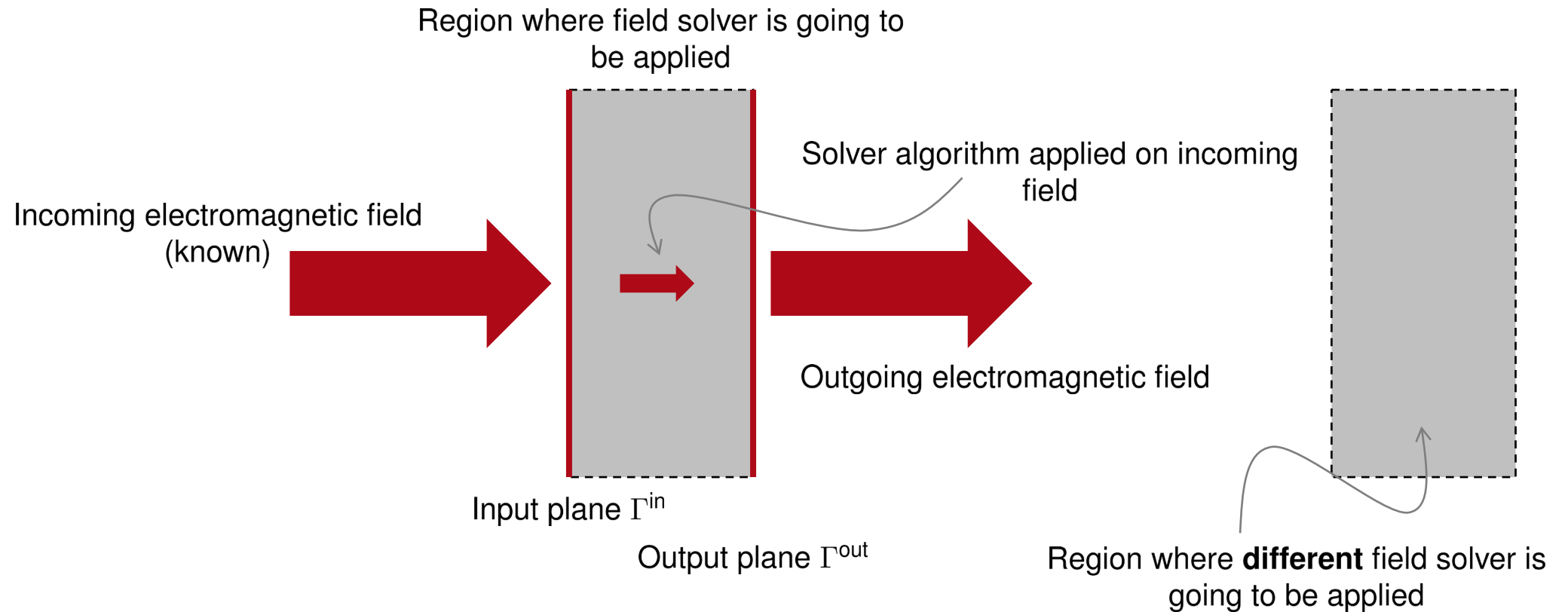
Electromagnetic Field Solvers



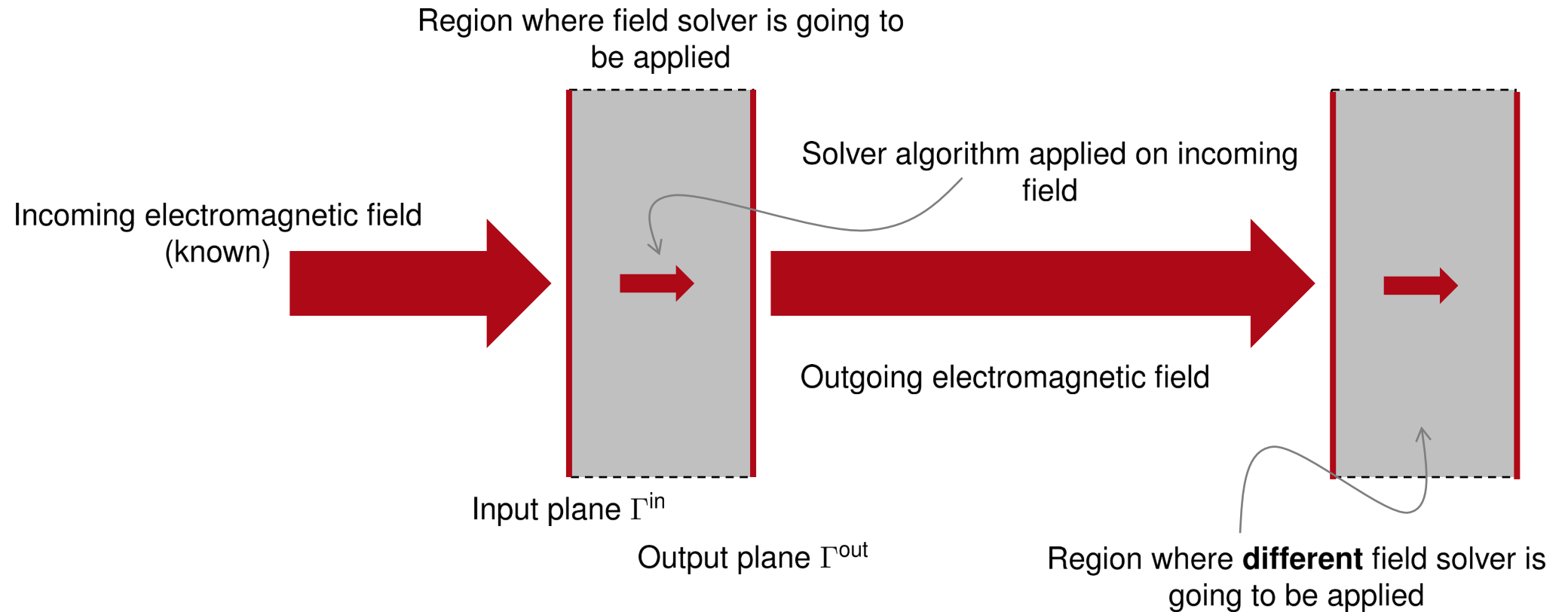
Electromagnetic Field Solvers



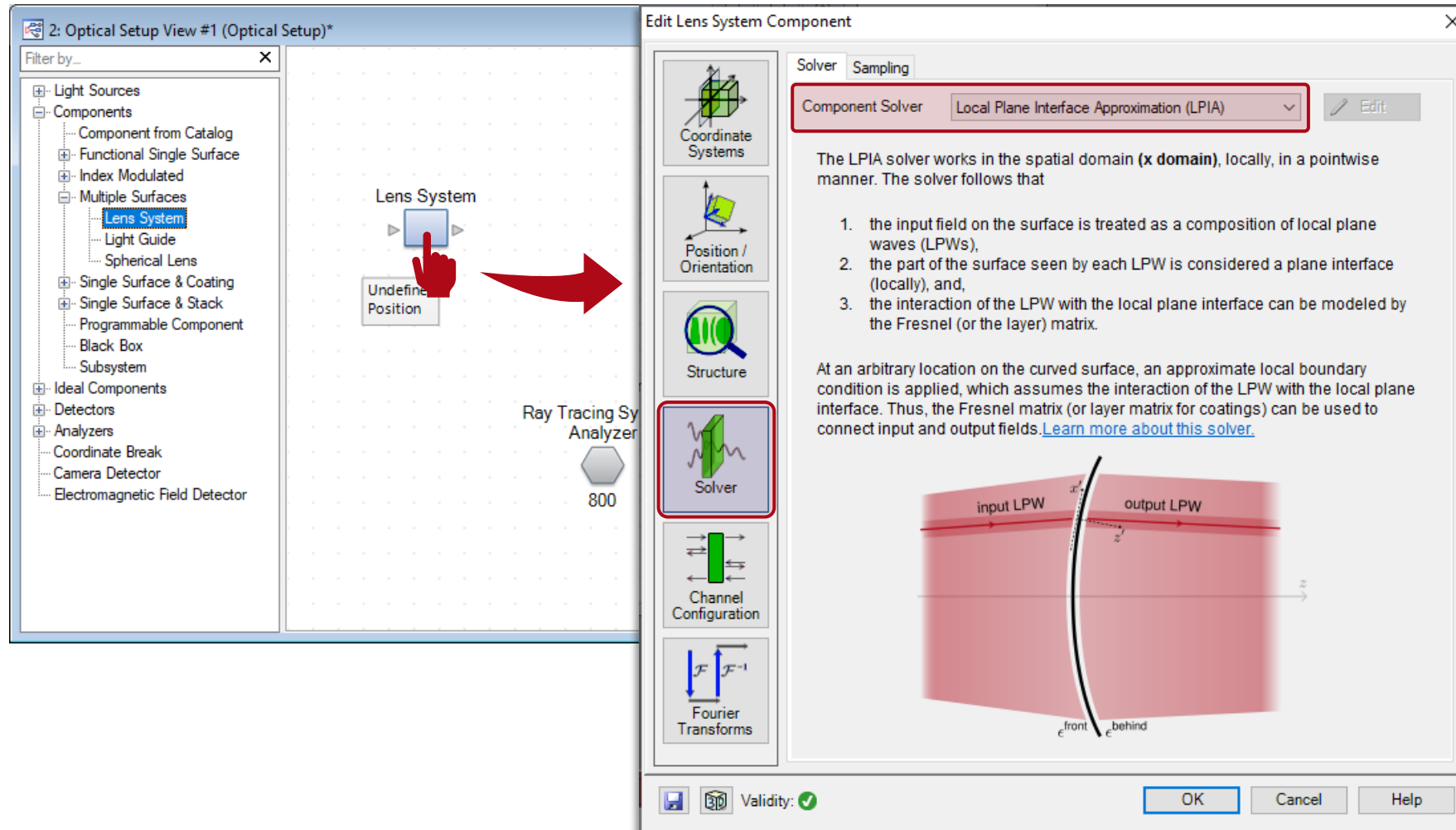
Electromagnetic Field Solvers



Electromagnetic Field Solvers

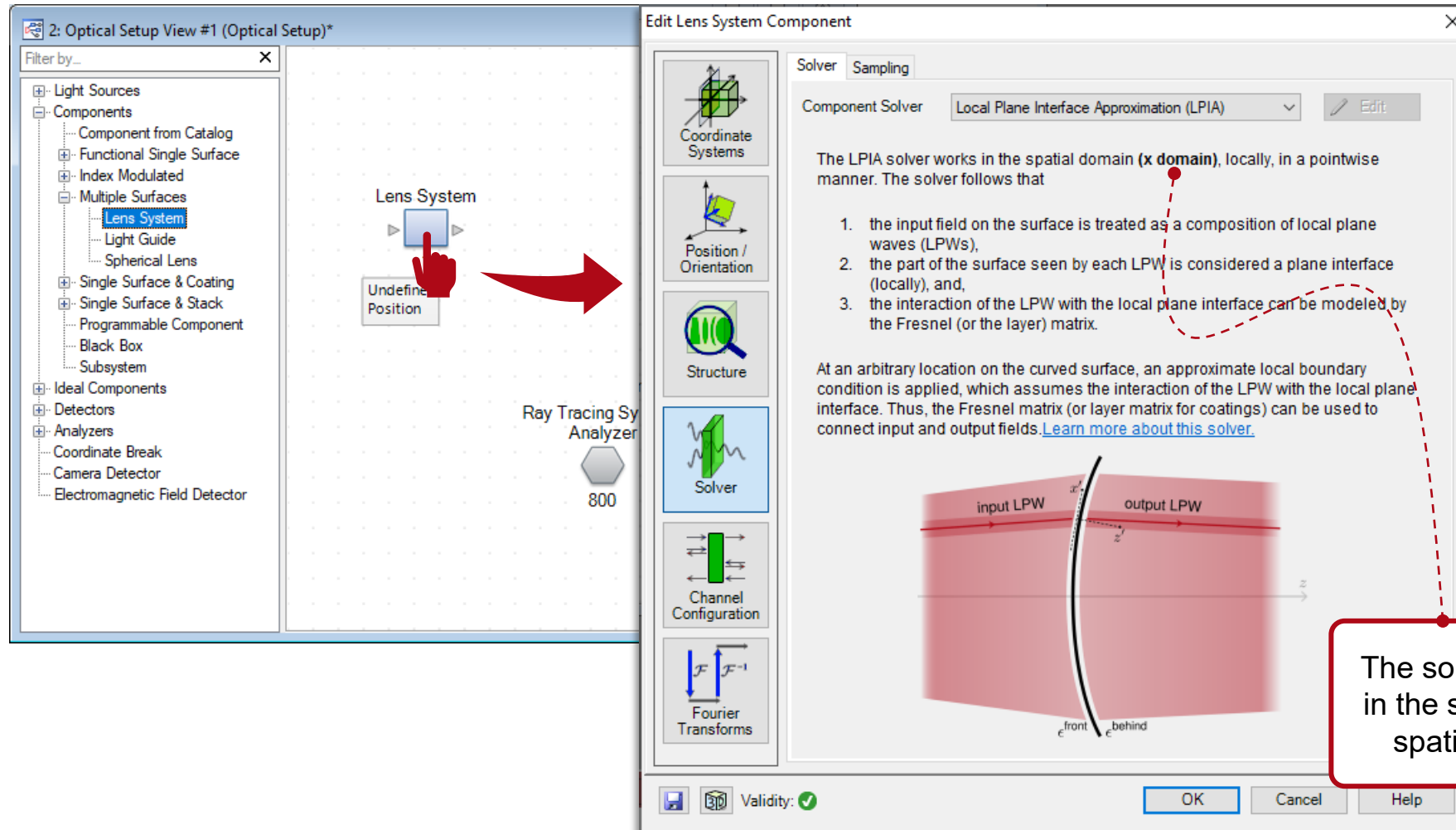


Components & Solvers



In VirtualLab Fusion, including a certain type of component in your system means, in practice, selecting an **electromagnetic field solver** to model that part of the system

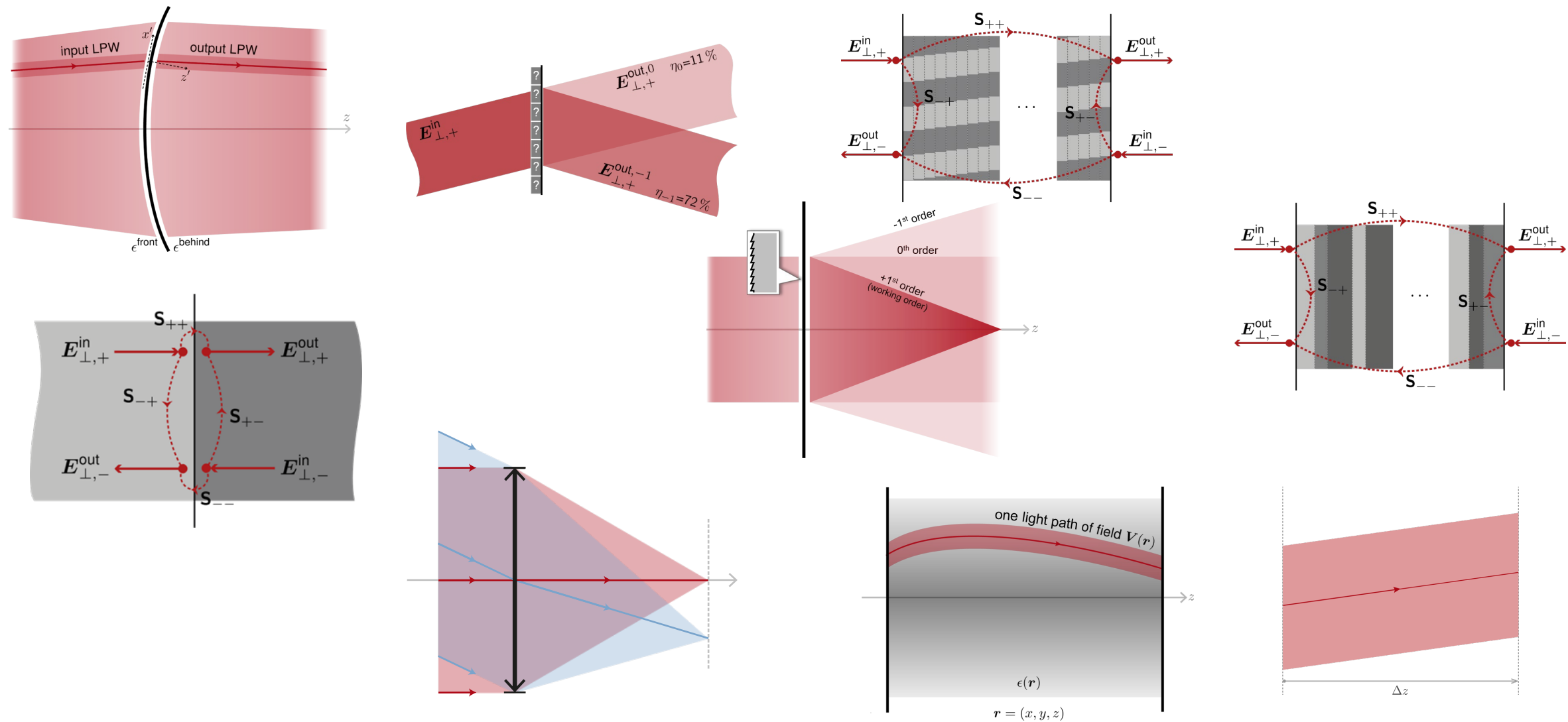
Components & Solvers



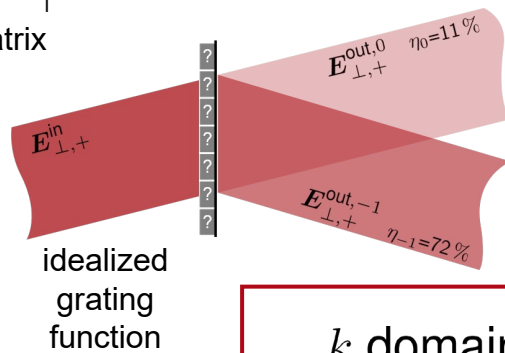
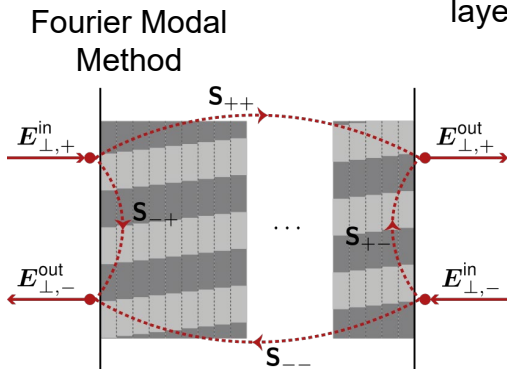
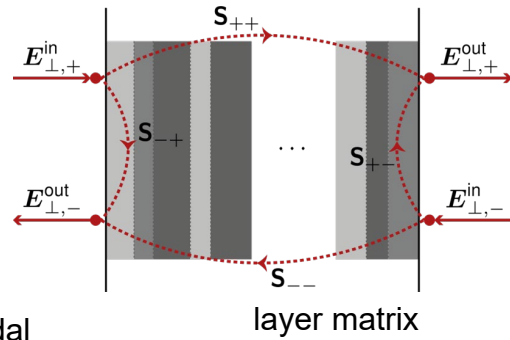
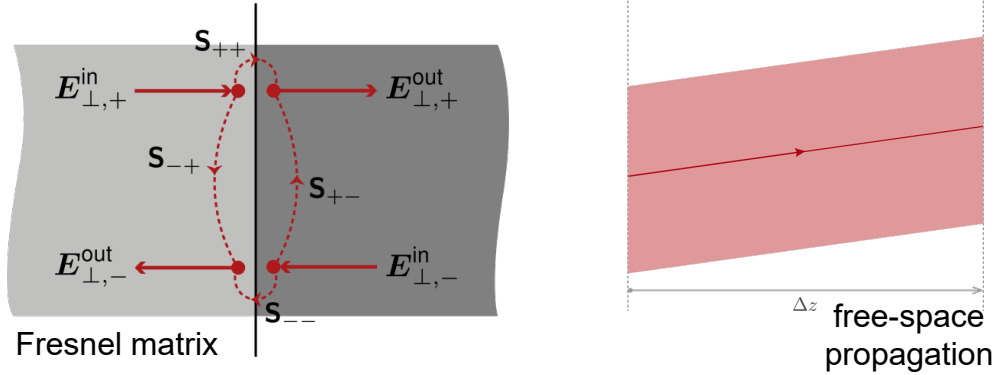
In VirtualLab Fusion, including a certain type of component in your system means, in practice, selecting an **electromagnetic field solver** to model that part of the system

The solvers may be implemented in the space (x) domain, or in the spatial-frequency (k) domain

Why Different Domains?

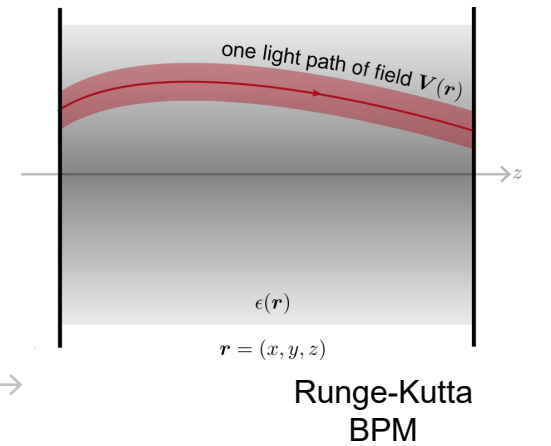
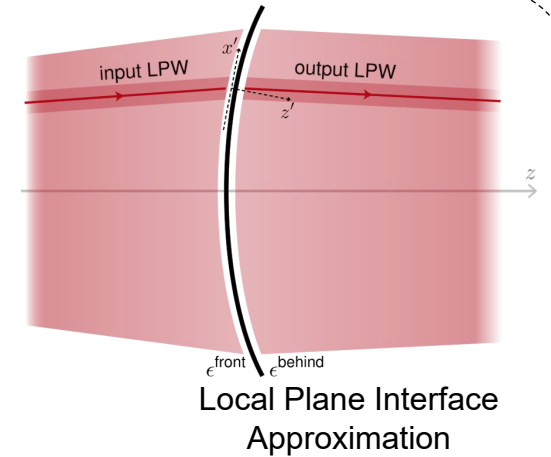
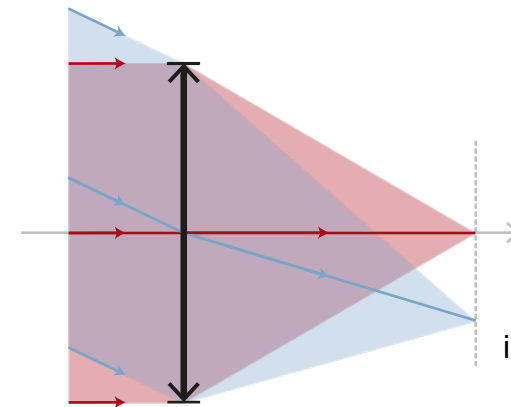
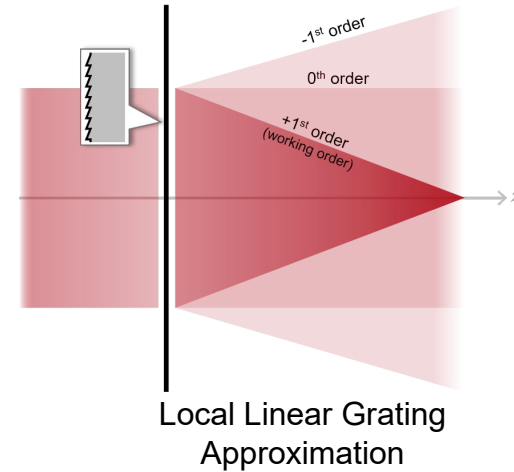


Why Different Domains?



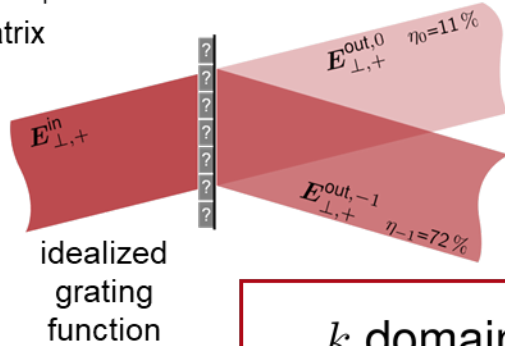
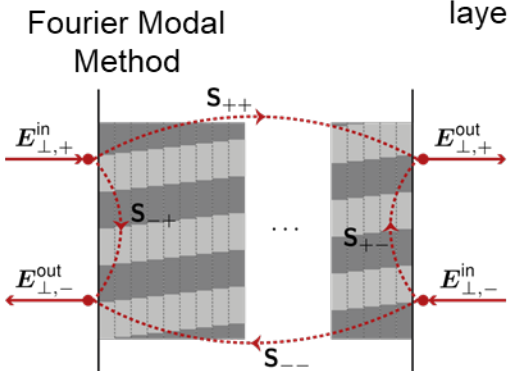
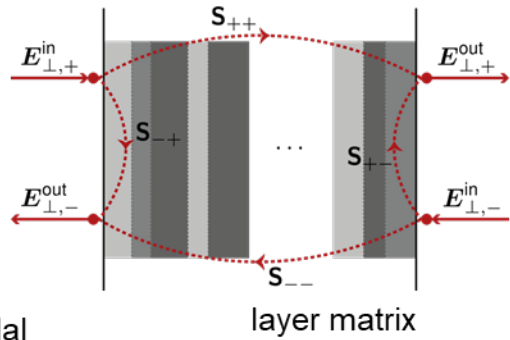
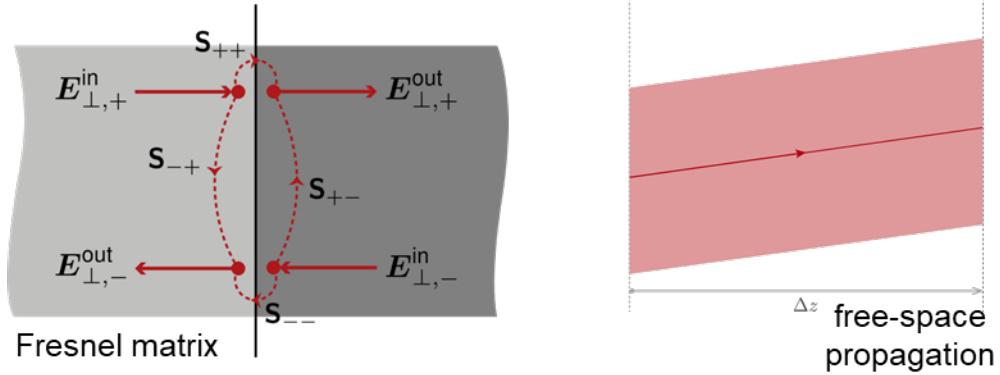
k domain

x domain



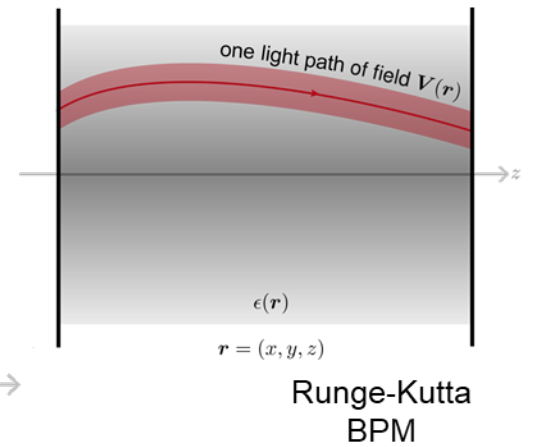
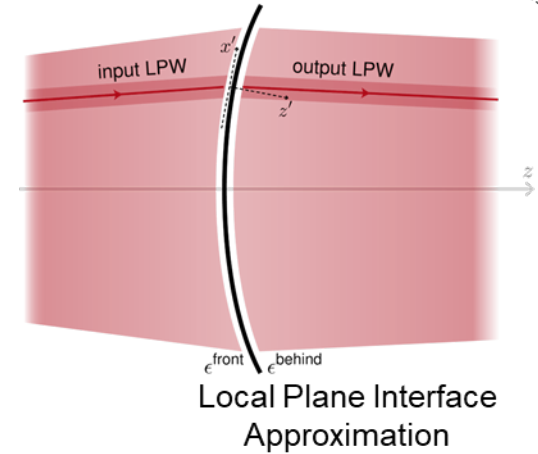
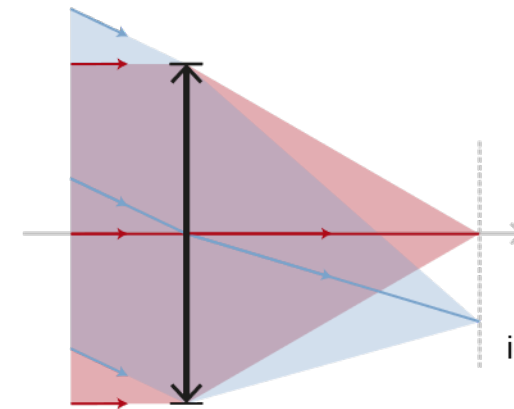
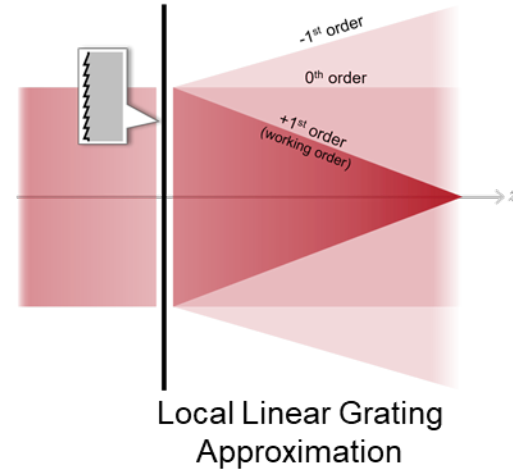
Hint: click on the logos for additional documentation on the solvers!

Why Different Domains?

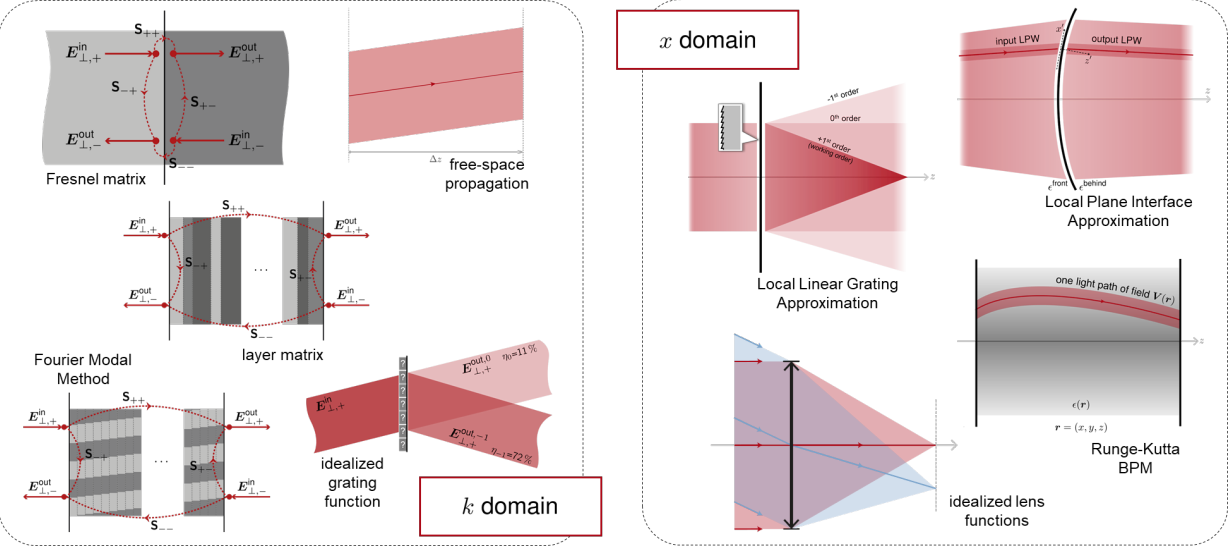


k domain

x domain

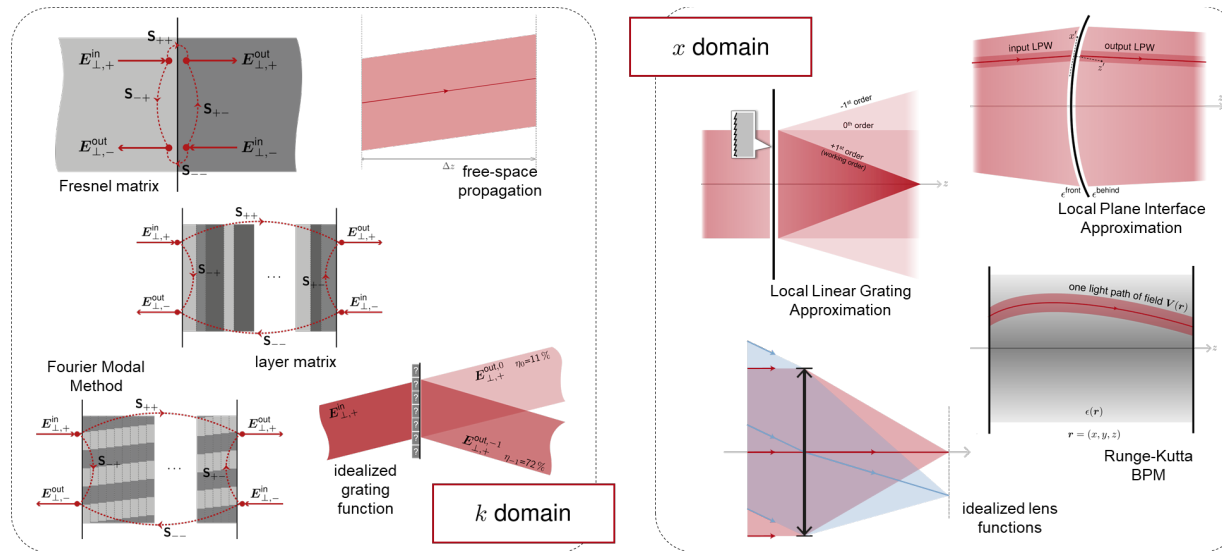


Why Different Domains?



Why Different Domains?

Although, in general, electromagnetic field solvers have an **integral** behaviour, with the resulting high numerical complexity, the characteristics of some of the most common optical components mean they can be modeled with **pointwise** operators in one of the Fourier domains – when this happens, it entails a **massive computational advantage**!



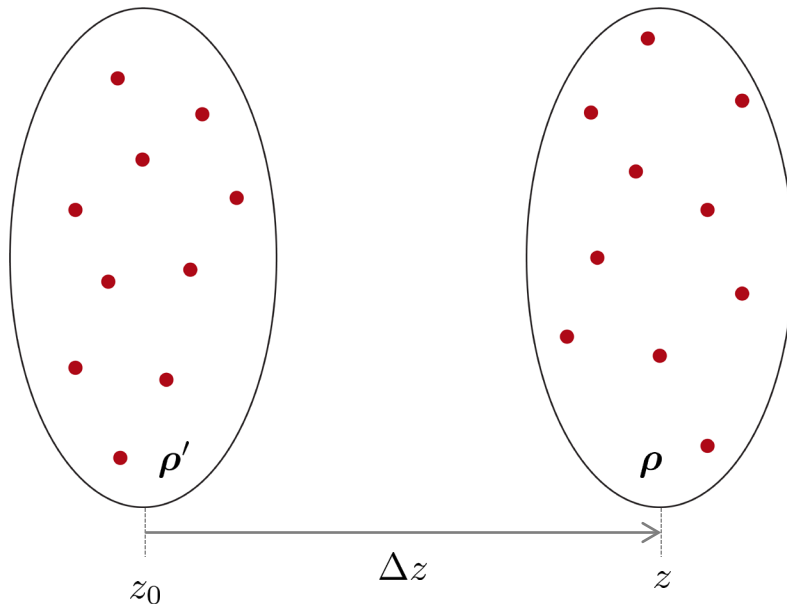
Example: Free-Space Propagation

Space domain

Rayleigh-Sommerfeld integral:

$$V_{\ell}^{\text{out}}(\boldsymbol{\rho}, z) \propto \iint_{-\infty}^{+\infty} V_{\ell}^{\text{in}}(\boldsymbol{\rho}', z_0) \frac{e^{ik_0 n R}}{R} \left(ik_0 n - \frac{1}{R} \right) \frac{\Delta z}{R} d^2 \rho'$$

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



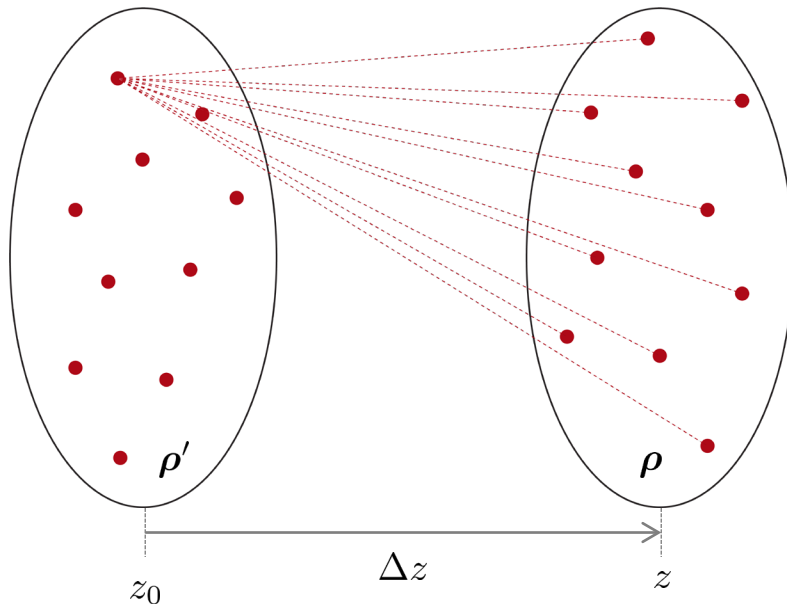
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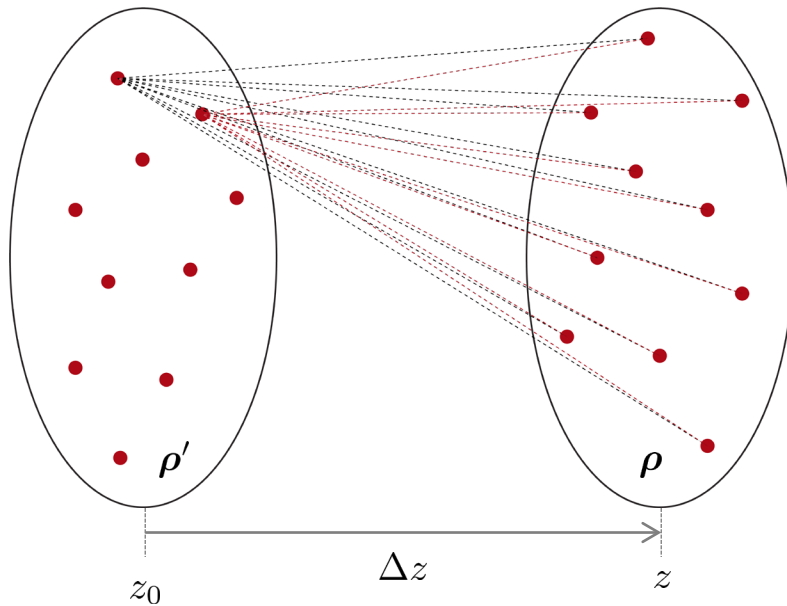
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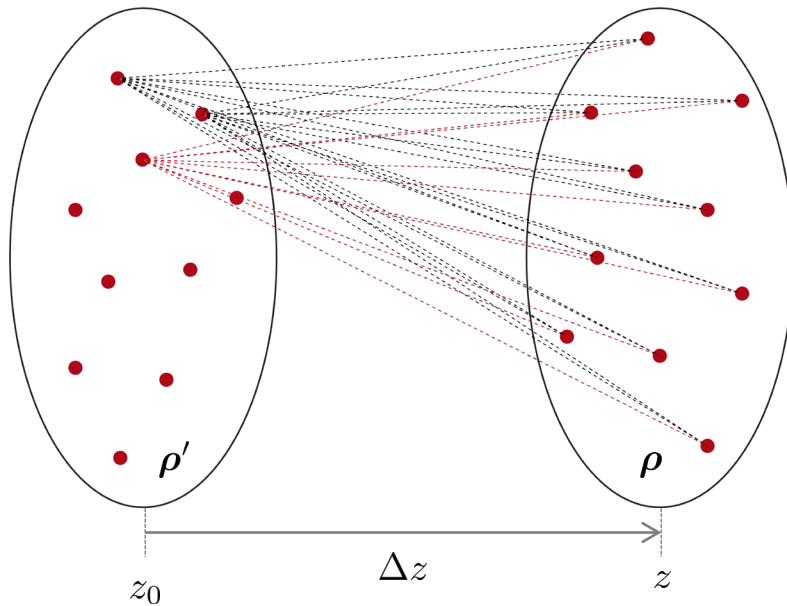
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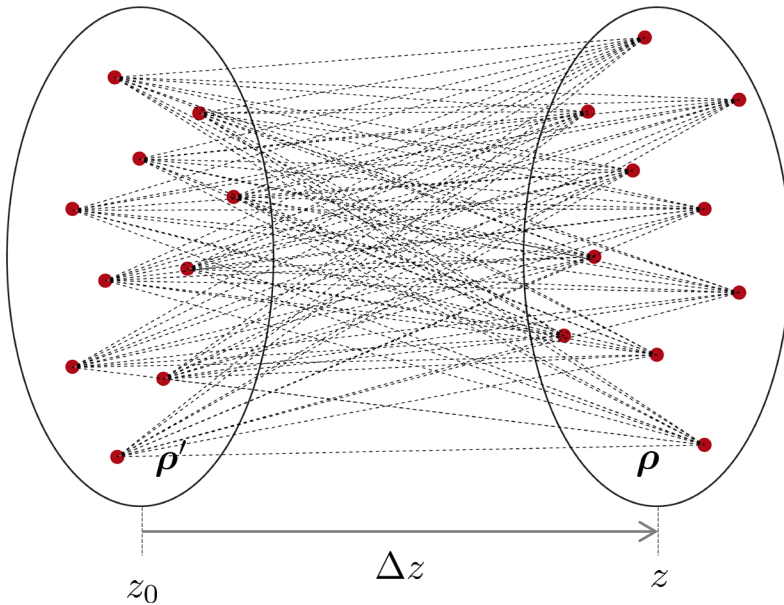
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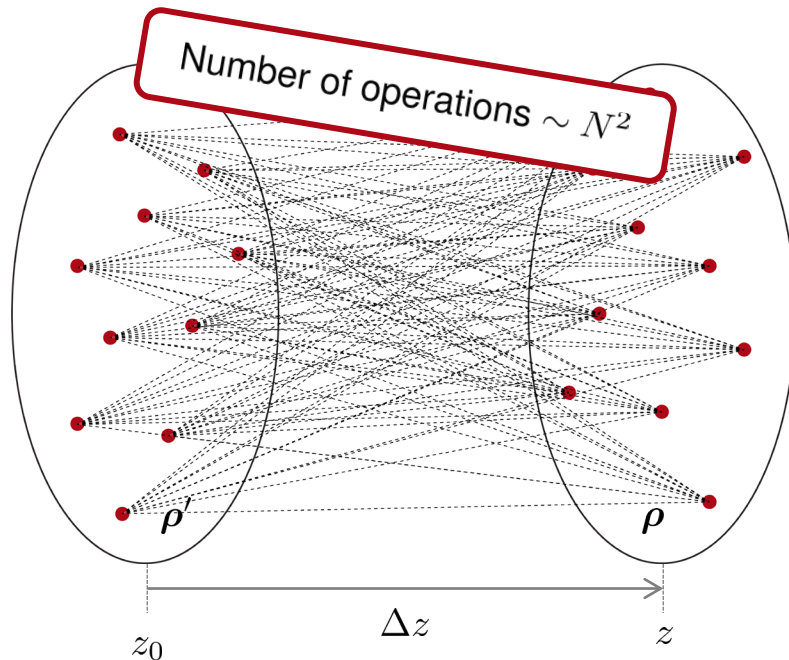
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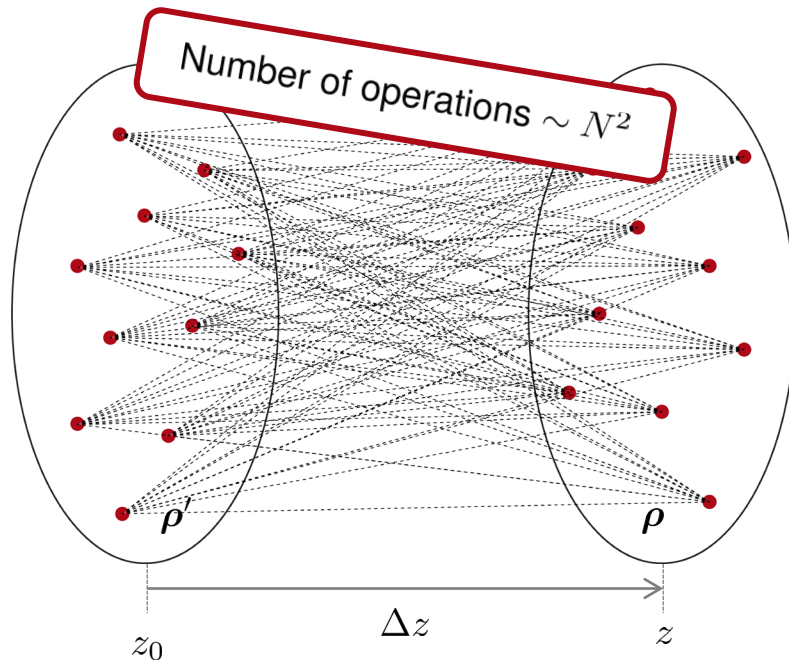
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Spatial-frequency domain

Plane-wave propagation operator:

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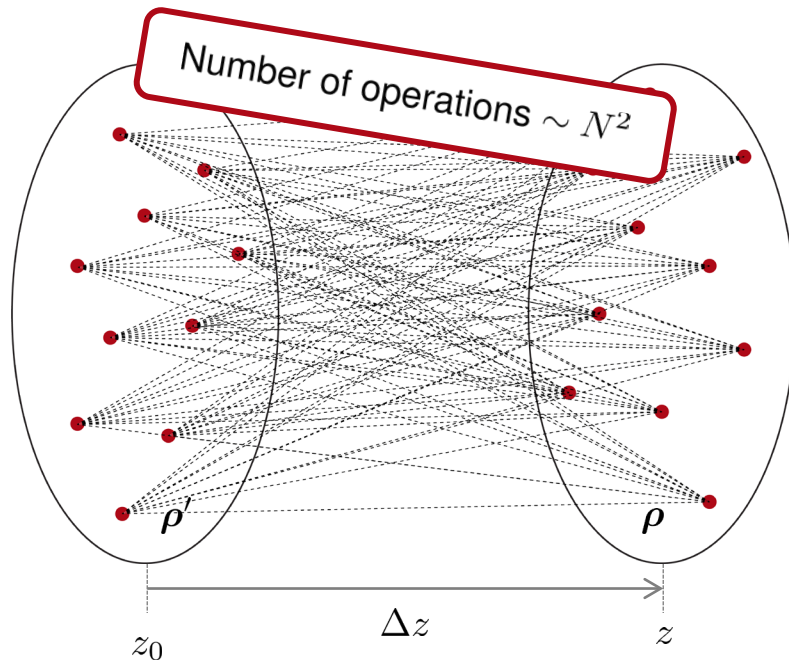
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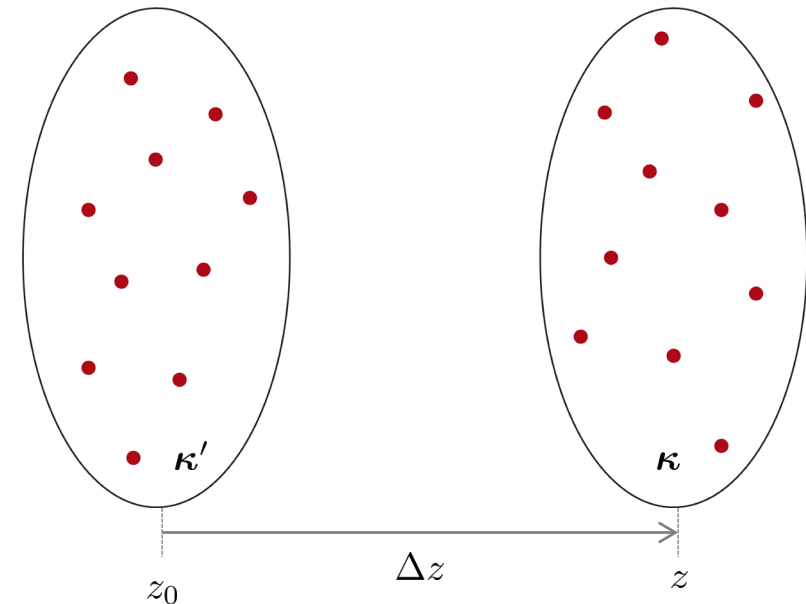
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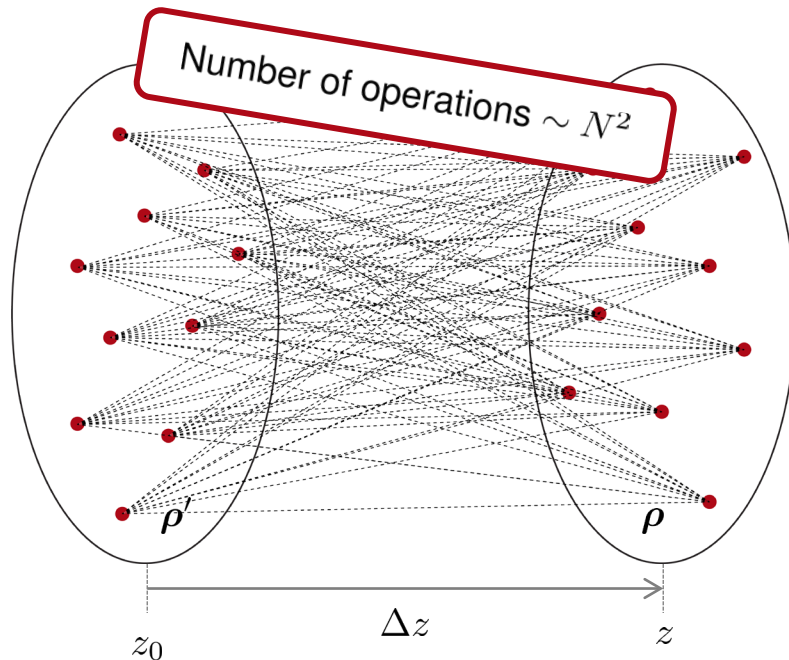
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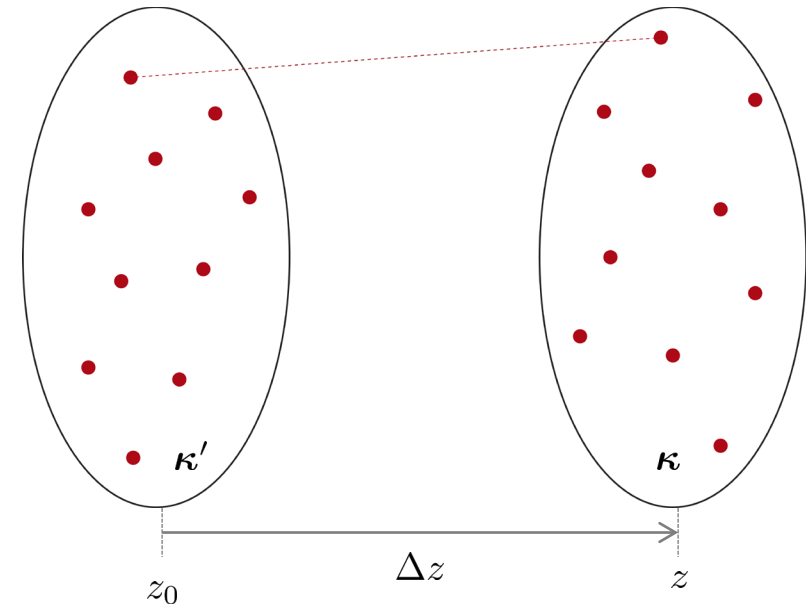
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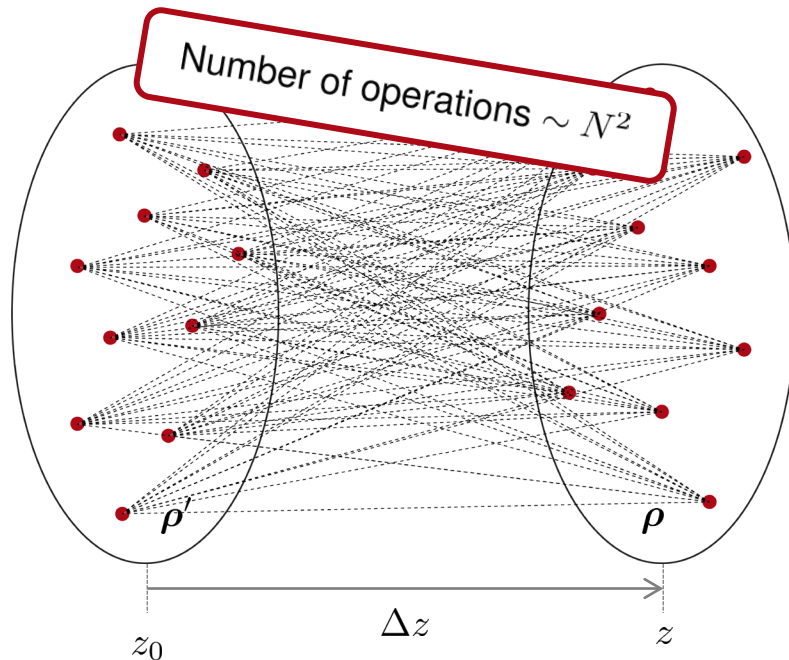
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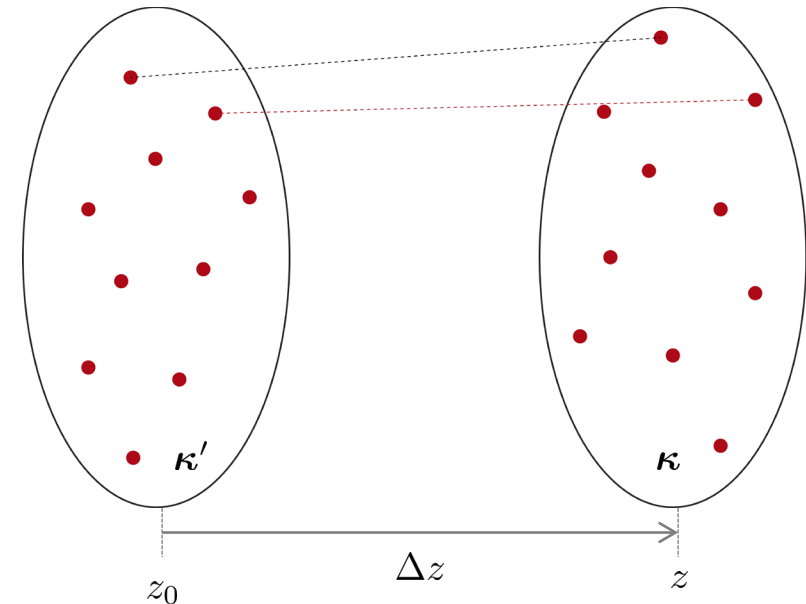
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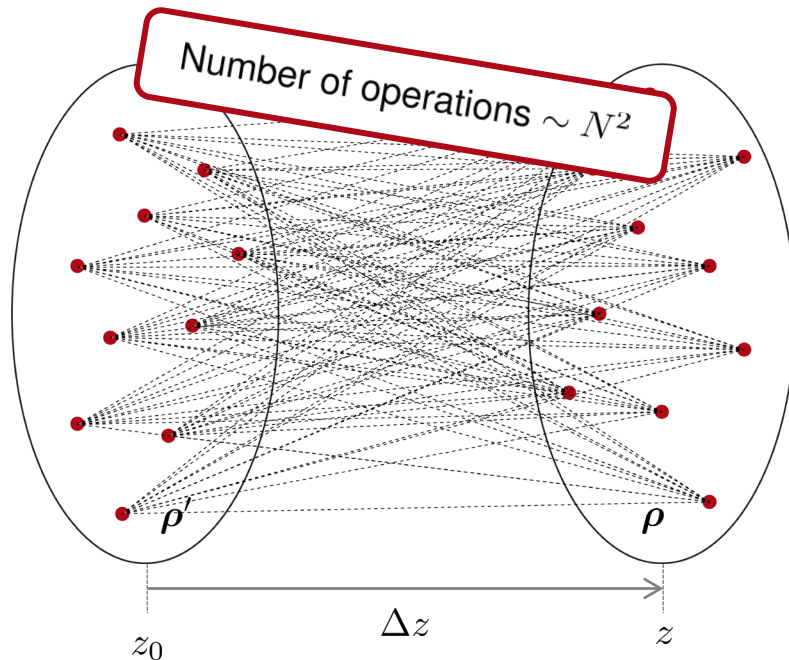
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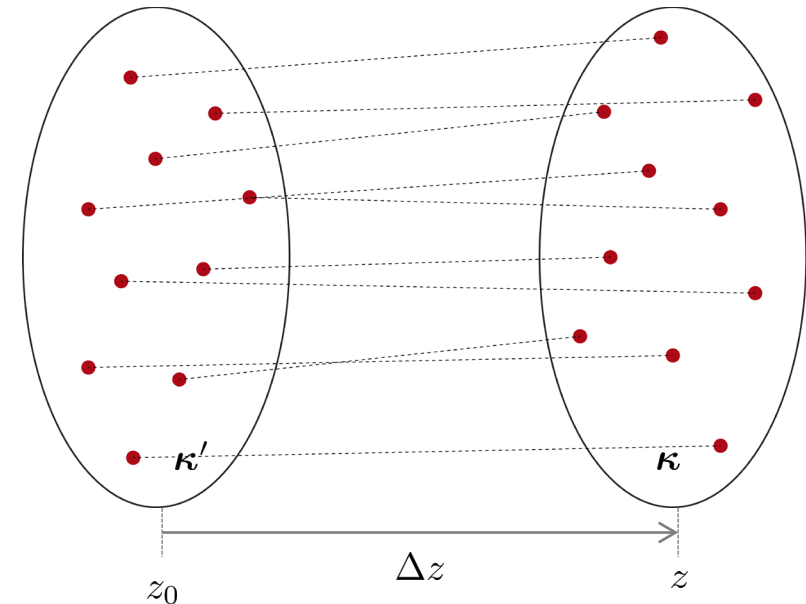
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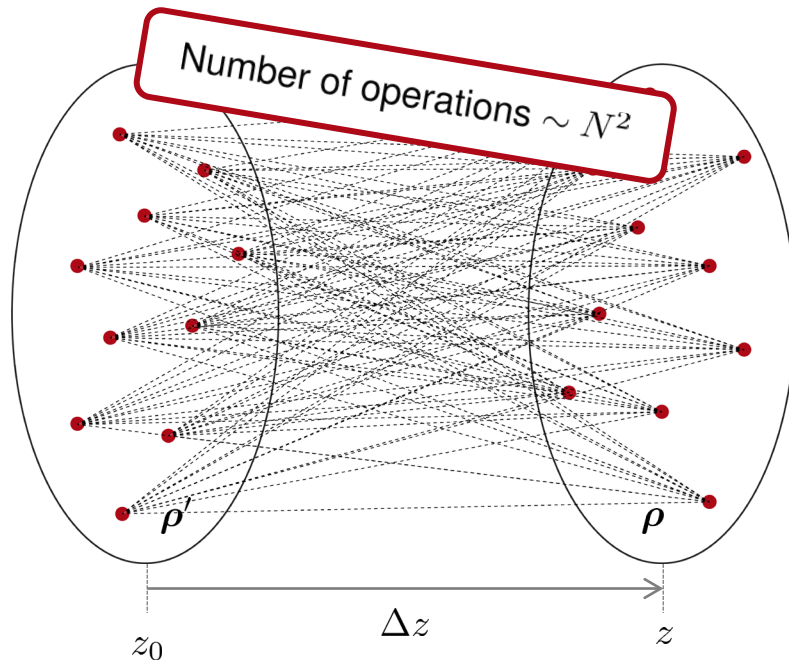
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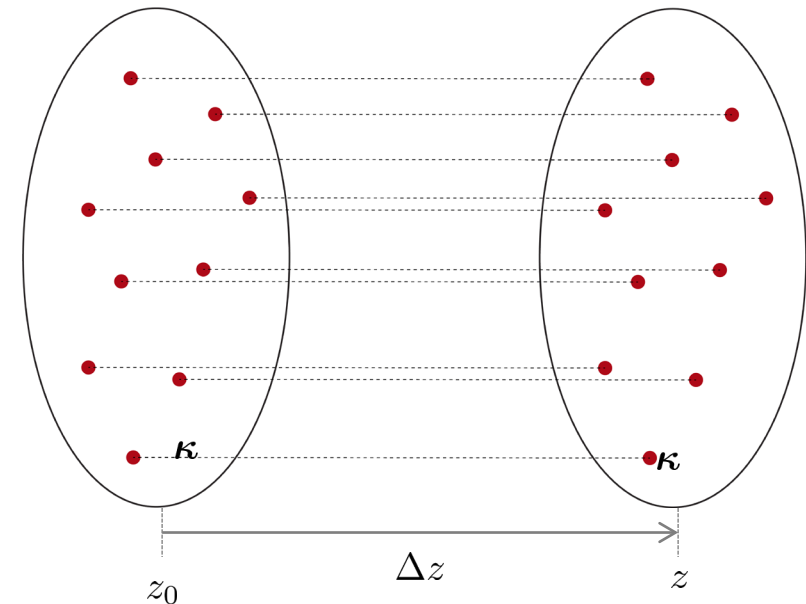
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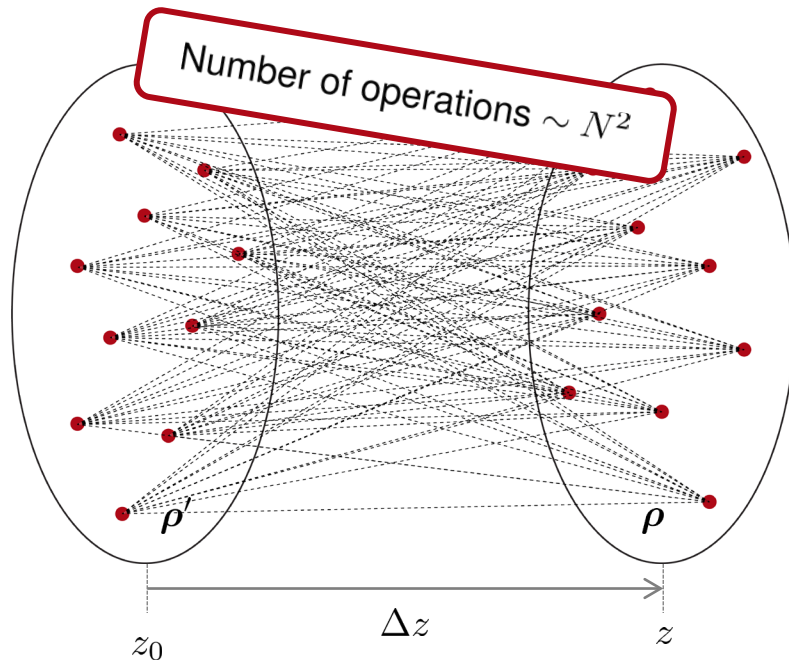
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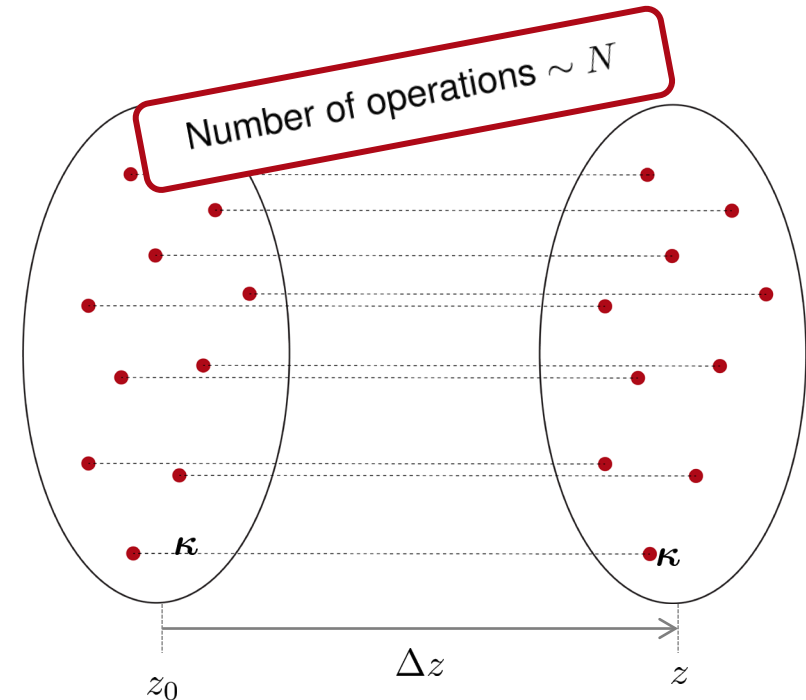
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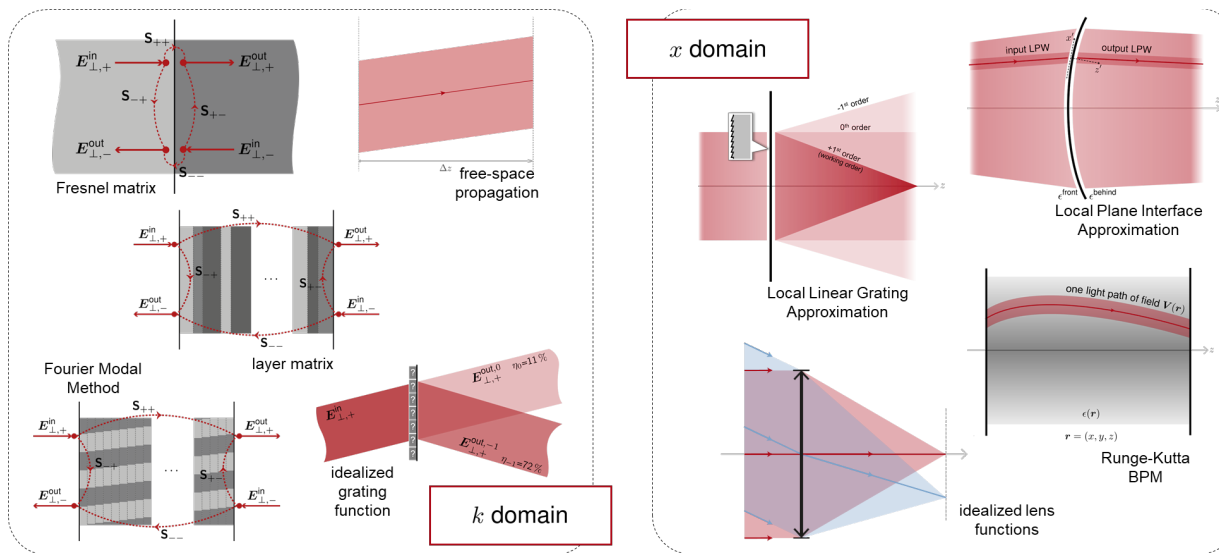
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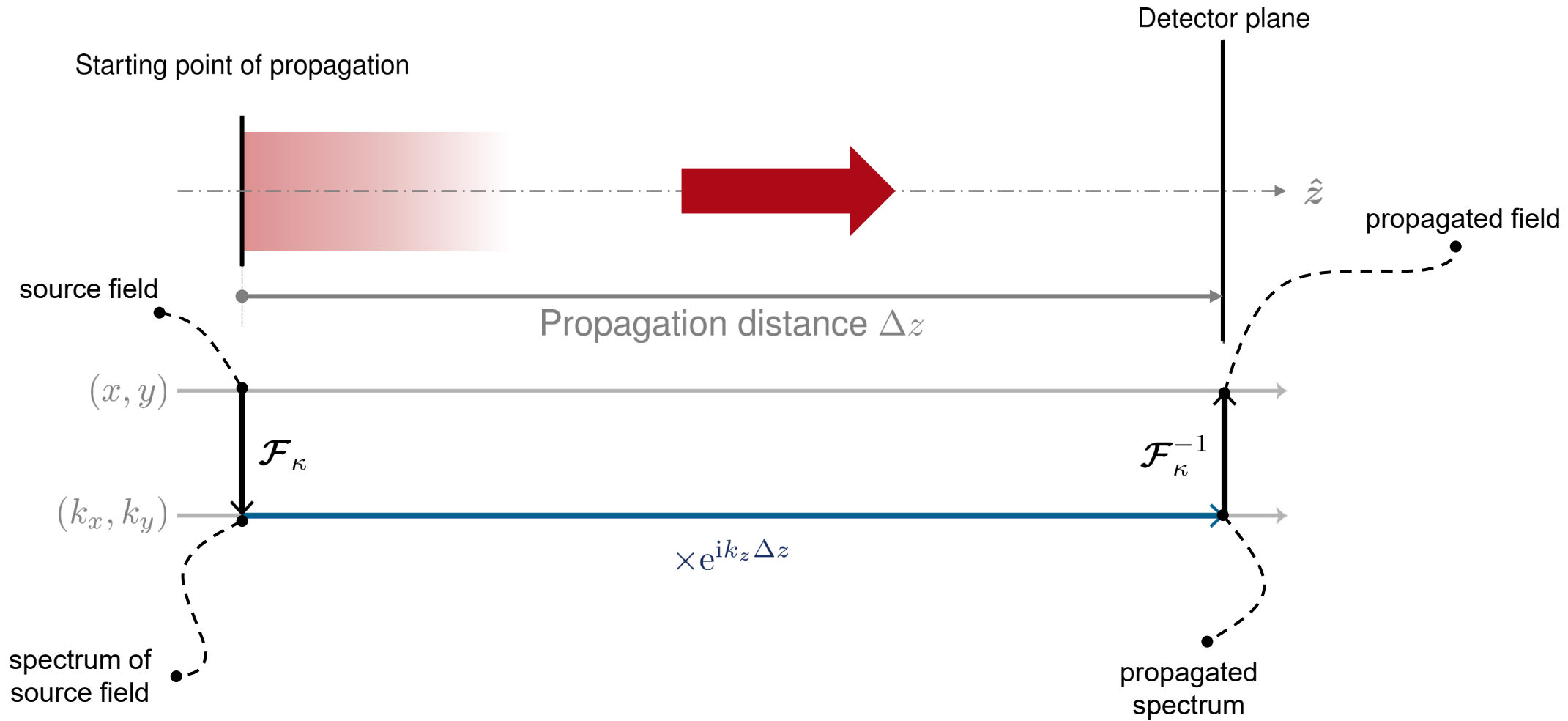
Why Different Fourier Domains?

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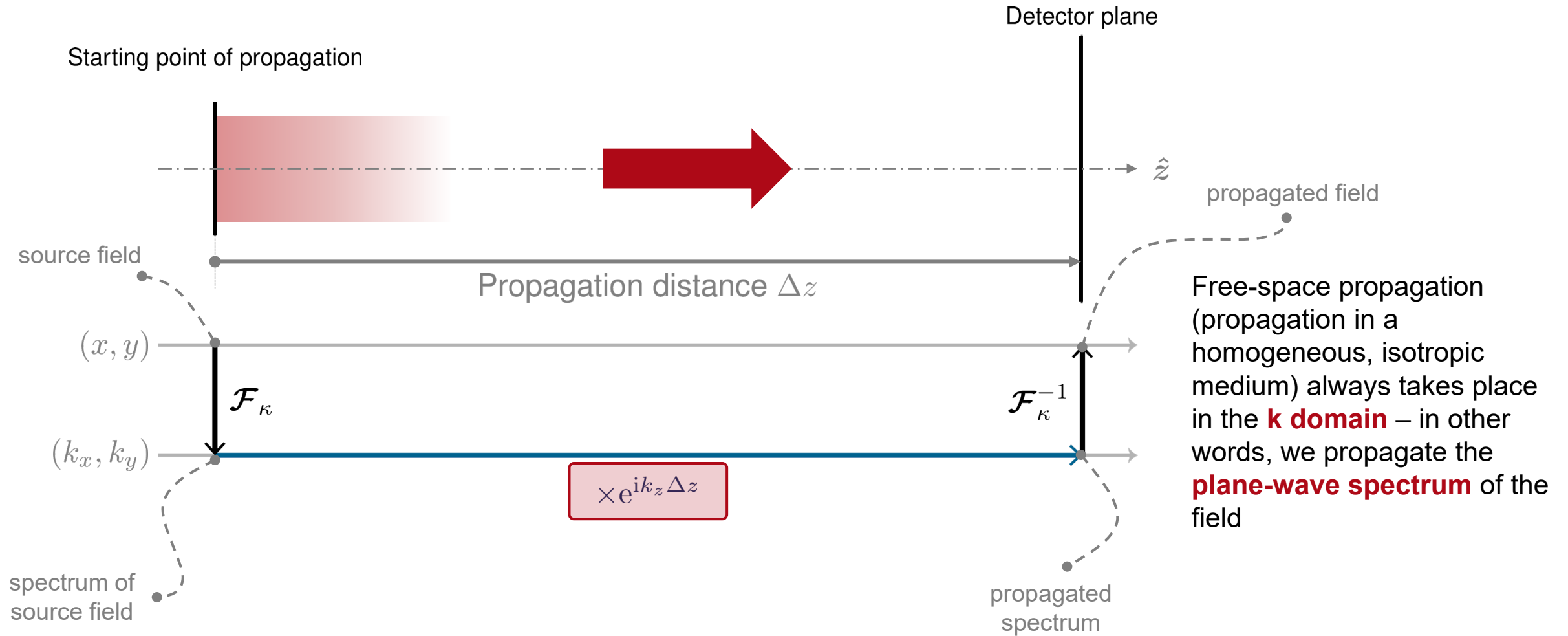


Conclusion: Whenever this mathematical property presents itself, we implement the solver in the domain where it exhibits **pointwise behaviour**!

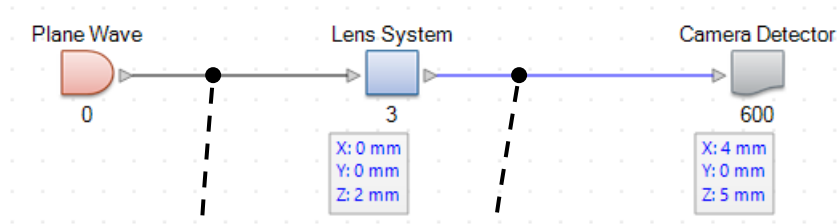
Free-Space Propagation



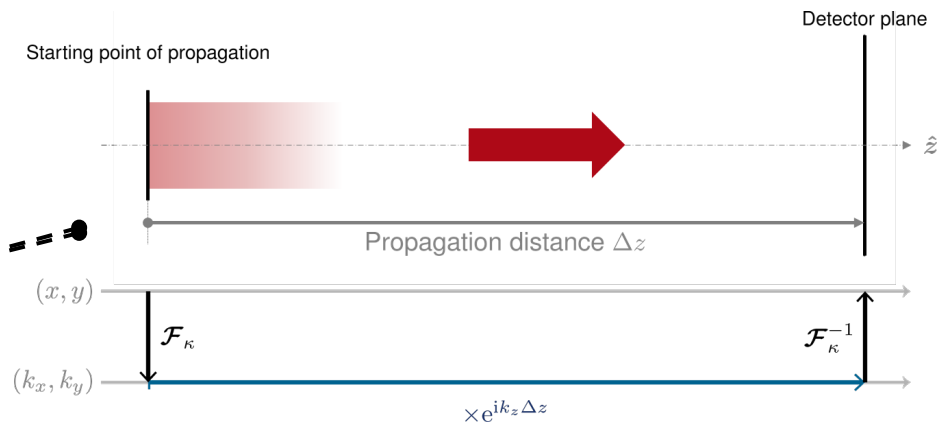
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Free-Space Propagation

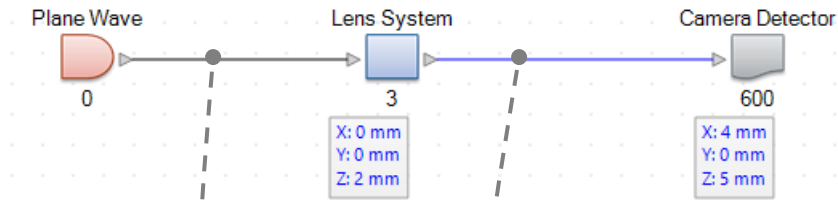


This refers to propagation between elements of an optical system...

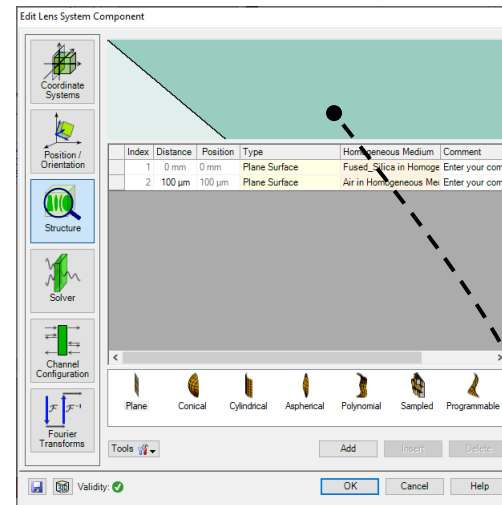


Free-space propagation (propagation in a homogeneous, isotropic medium) always takes place in the **k domain** – in other words, we propagate the **plane-wave spectrum** of the field

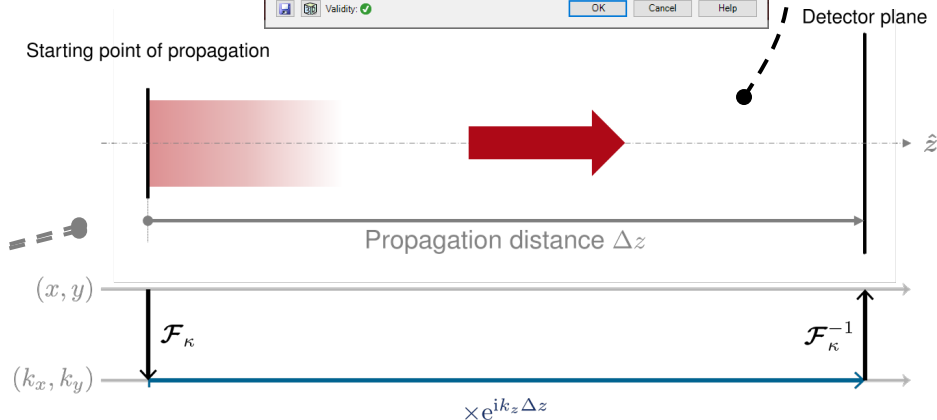
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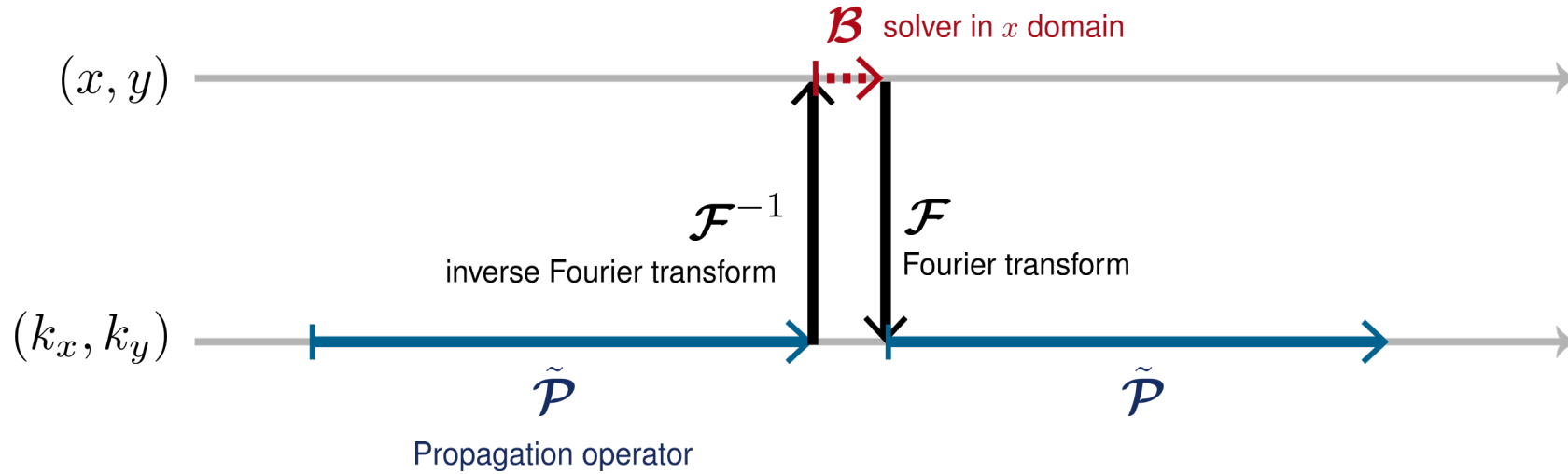


... as well as to internal propagation between surfaces in some cases, like the *Lens System* component



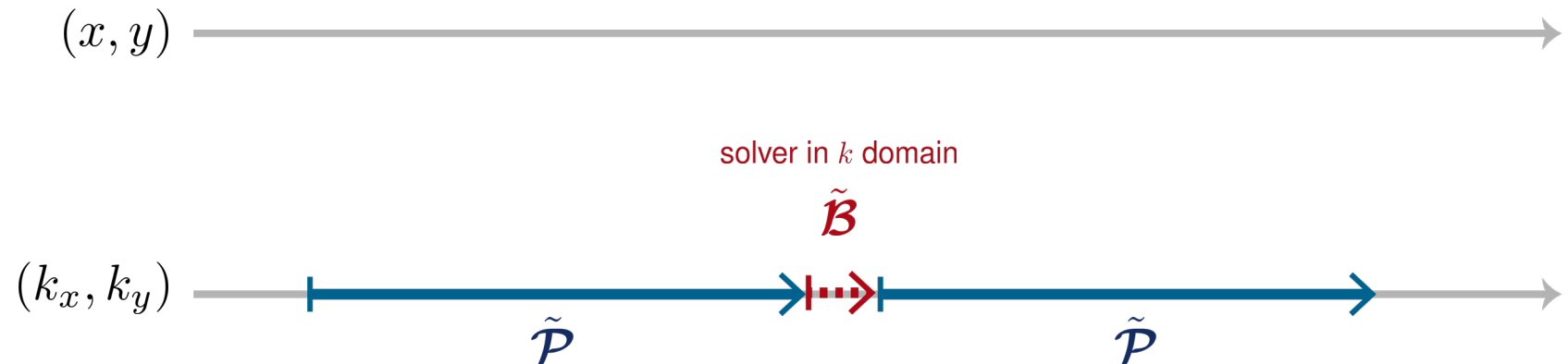
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Domain of Application of the Solvers

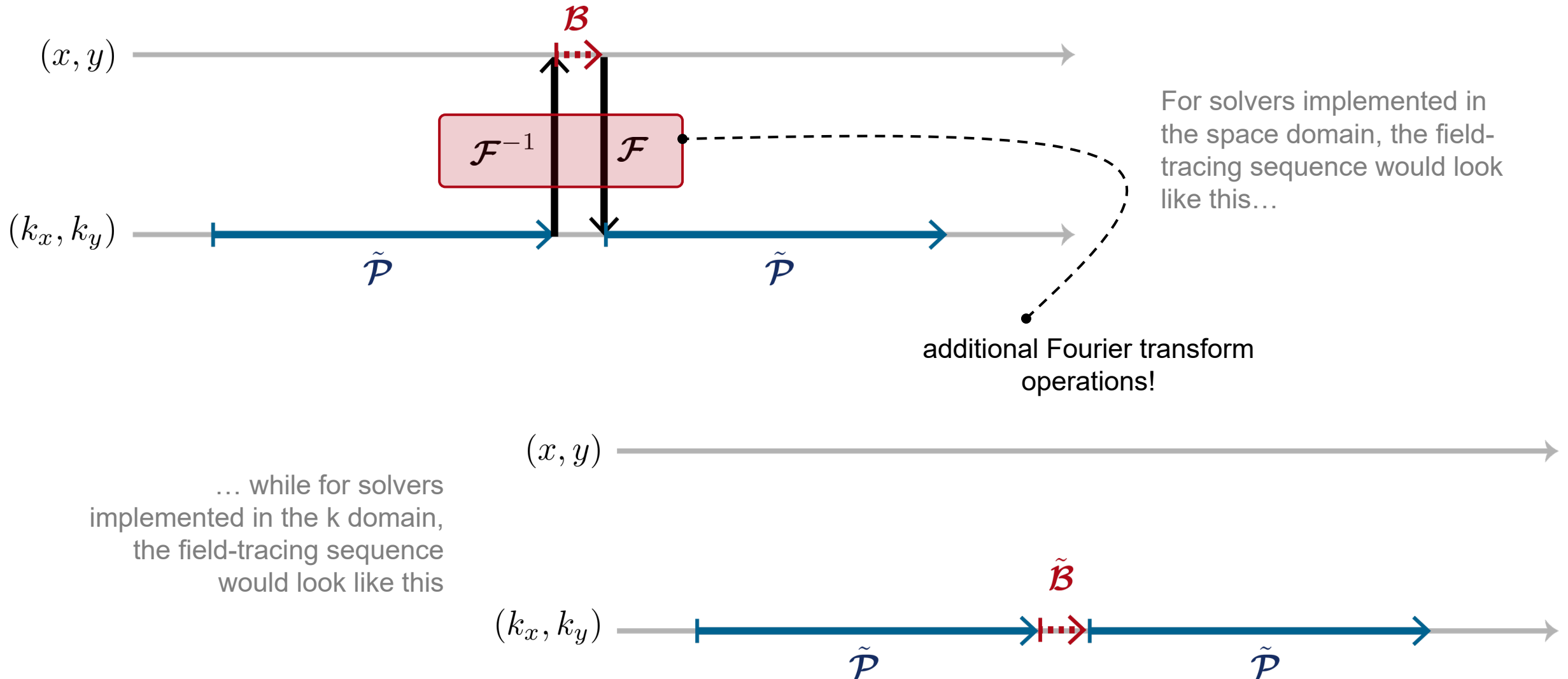


For solvers implemented in the space domain, the field-tracing sequence would look like this...

... while for solvers implemented in the k domain, the field-tracing sequence would look like this



Domain of Application of the Solvers

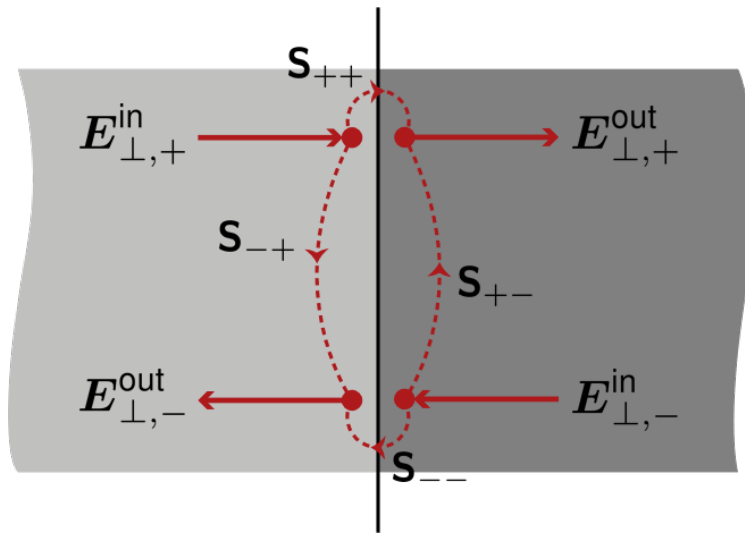


The Special Case of the Plane Surface

Possible Field Solvers for Plane Surfaces

- As an infinitely extended ideal plane surface → **Fresnel Matrix**

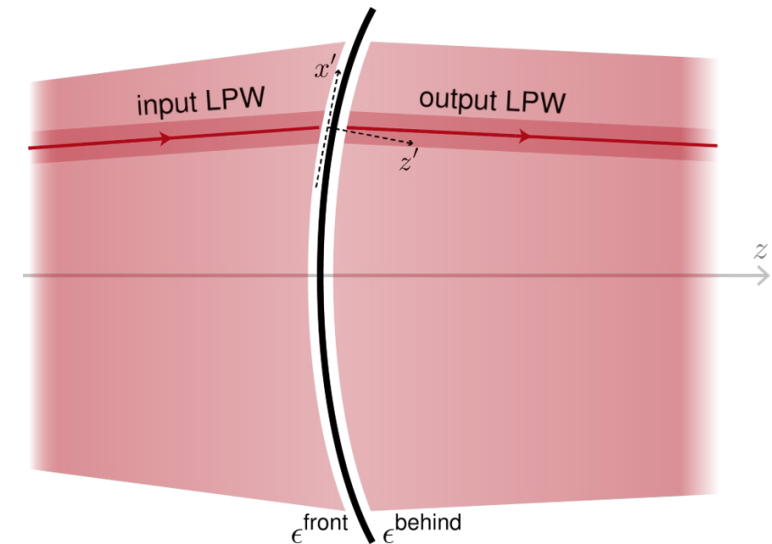
- Solver in **k domain**



- Implemented in *Plane Surface* component

- As a curved surface without curvature → **Local Plane Interface Approximation (LPIA)**

- Solver in **x domain**



- Implemented in *Lens System* and *Curved Surface* components, among others

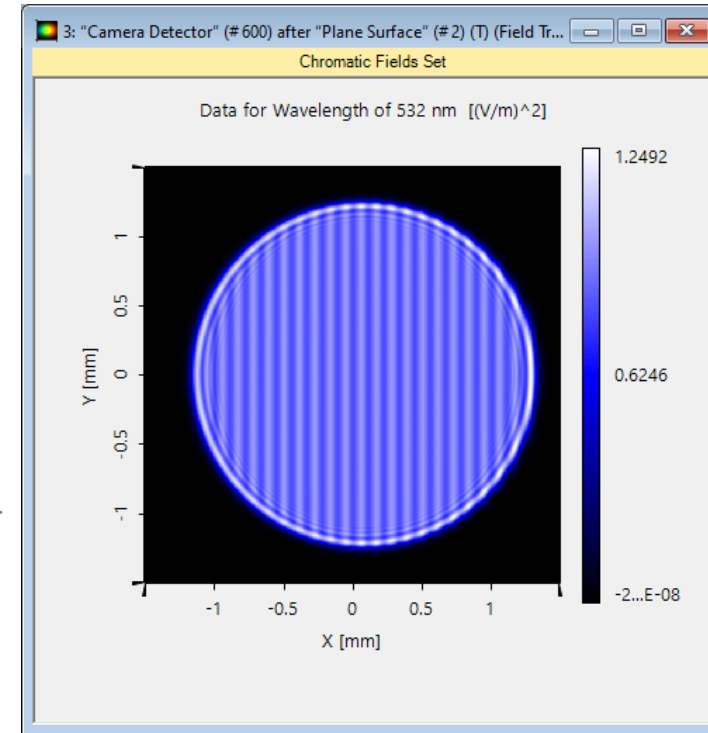
Modeling an Etalon with Plane Interfaces...

etalon configuration
planar-planar (tilted)

- center thickness $100\mu\text{m}$
- tilt of first surface 0.1°

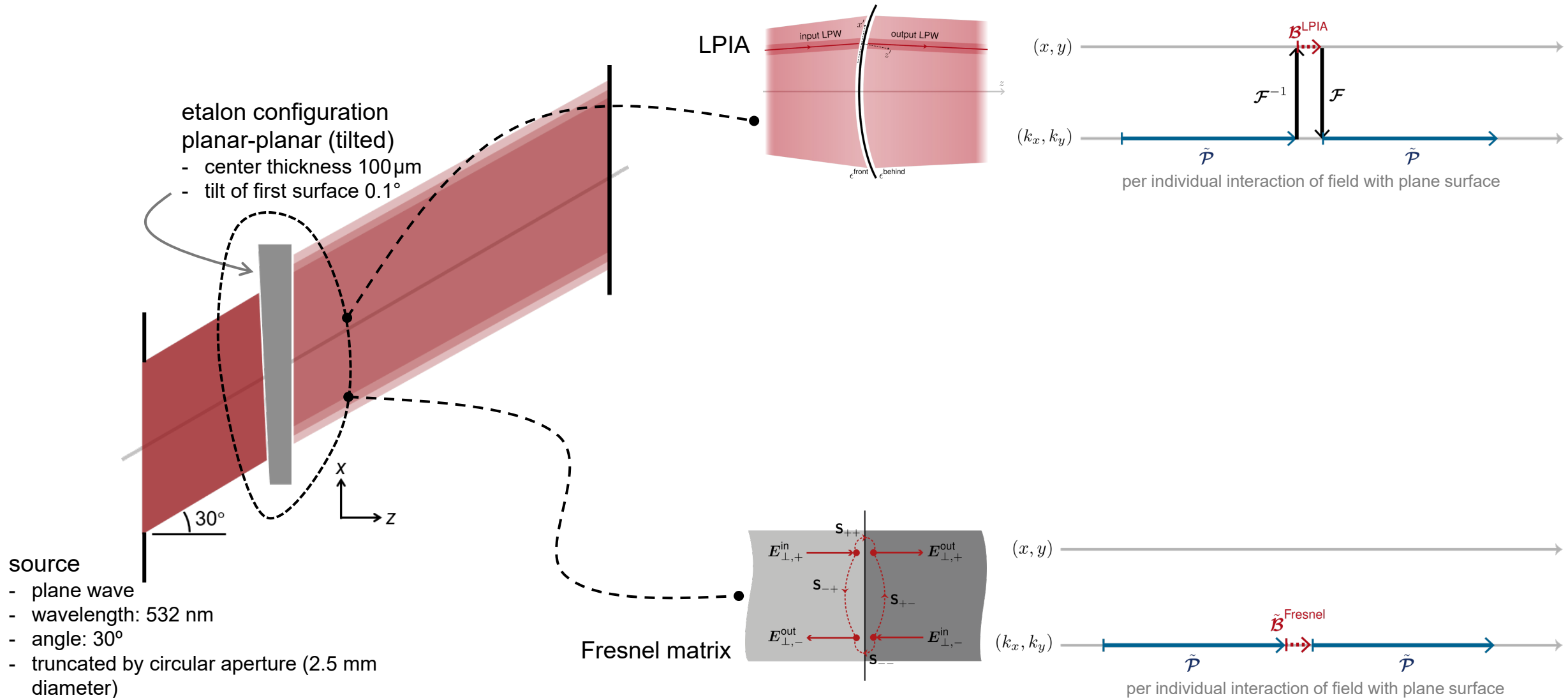
source

- plane wave
- wavelength: 532 nm
- angle: 30°
- truncated by circular aperture (2.5 mm diameter)



 [see the full Application Use Case:
"Modeling of Etalon with Planar or Curved Surfaces"](#)

... Two Ways



... Two Ways

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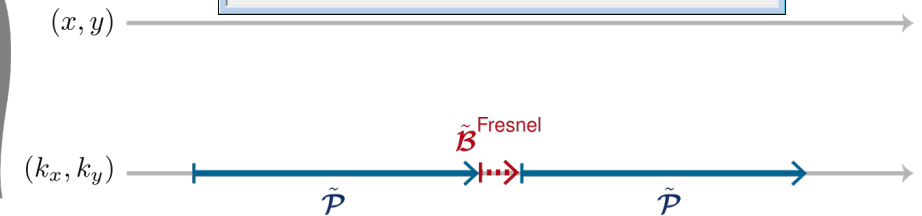
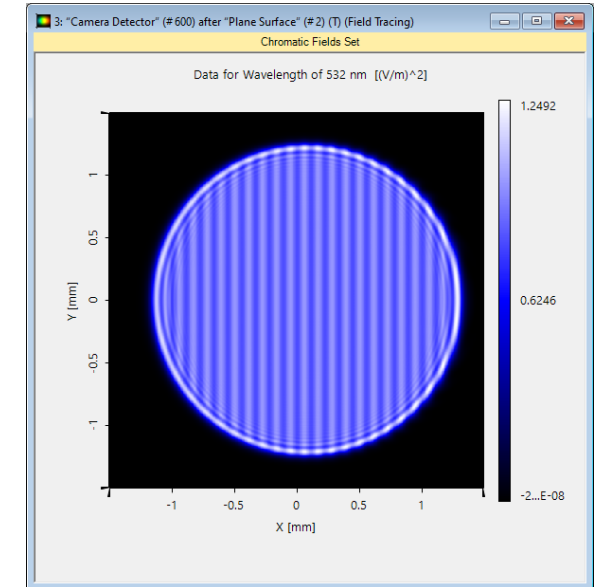
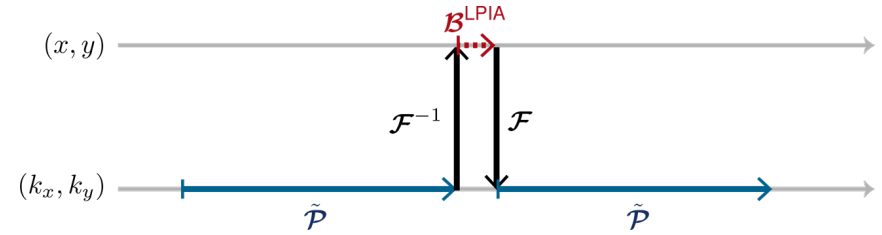
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LPIA

$\Delta t_{\text{simulation}} \sim 1.5\text{ min (*)}$

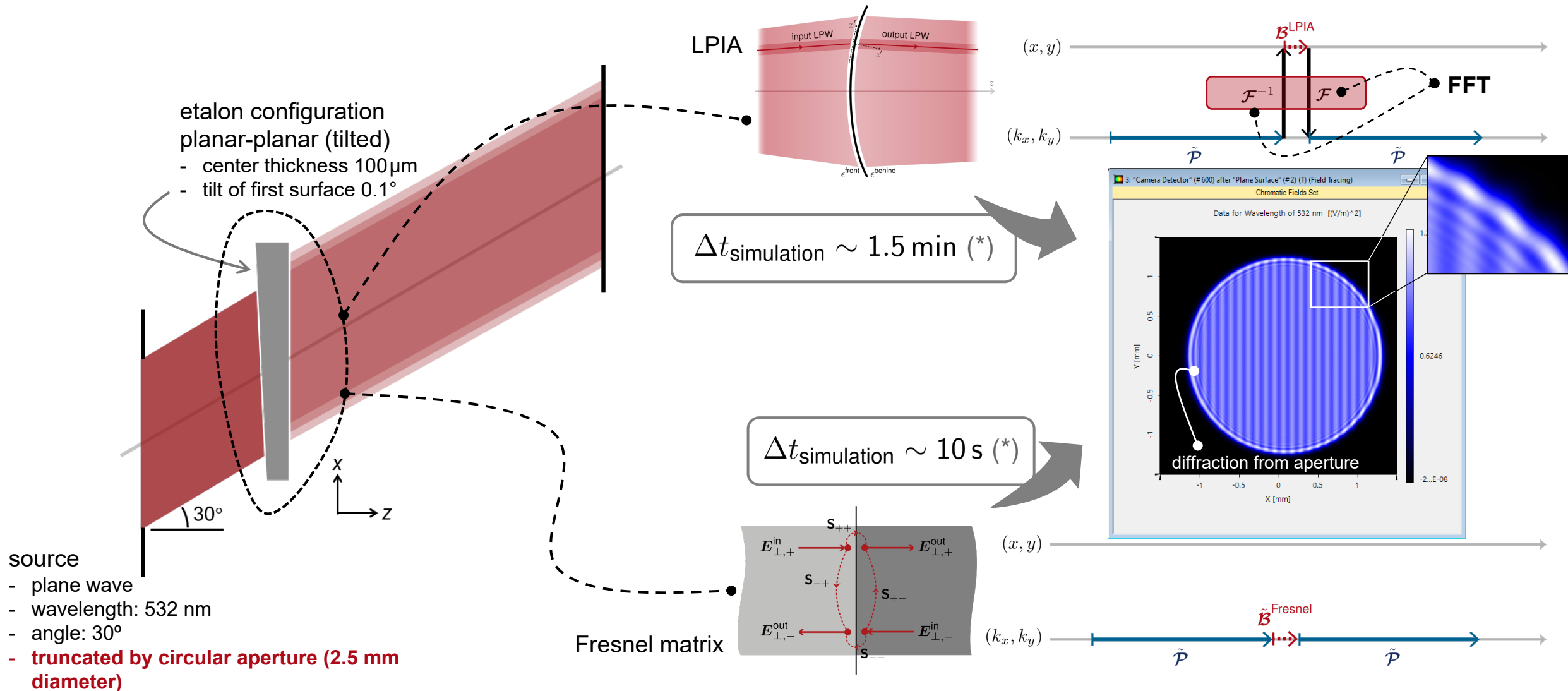
$\Delta t_{\text{simulation}} \sim 10\text{ s (*)}$

Fresnel matrix



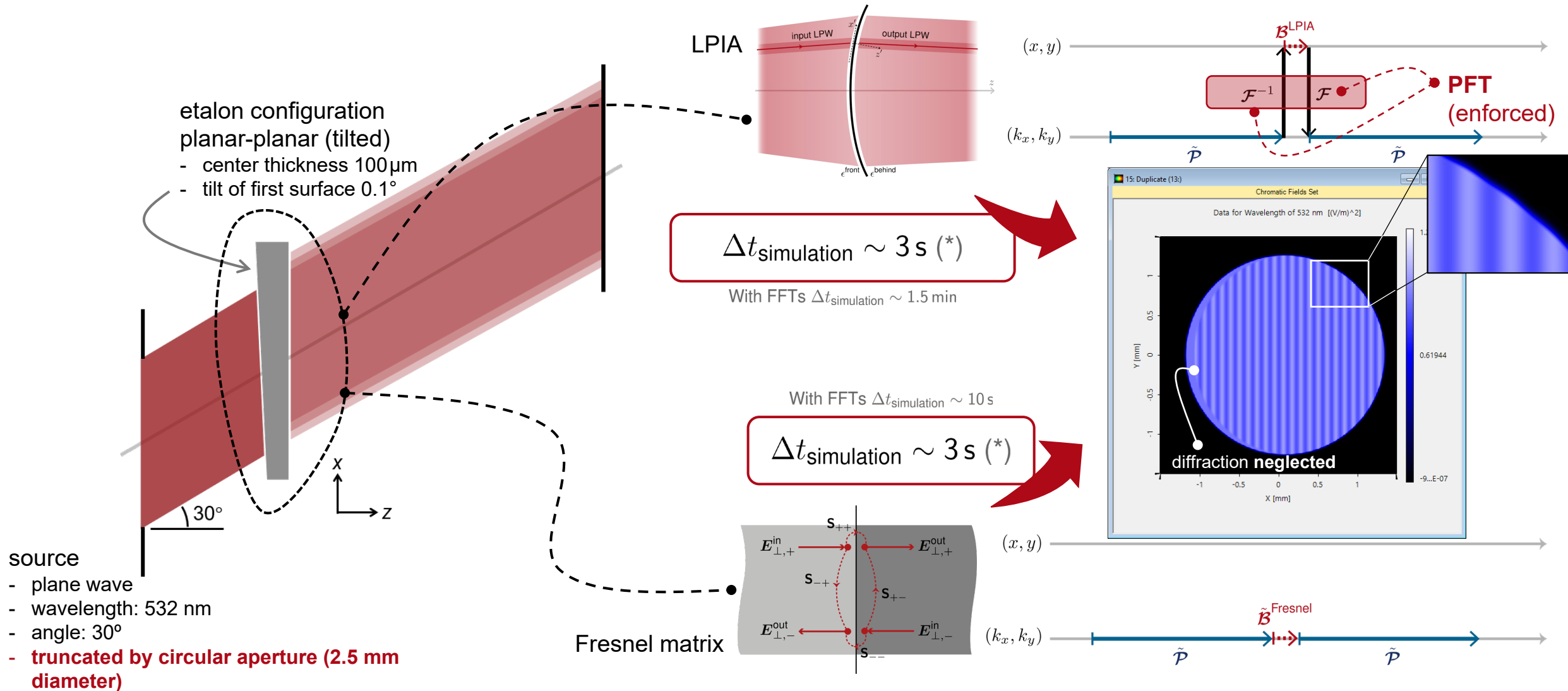
(*) Approximate simulation times on a PC with the following technical specs: processor Intel(R) Core(TM) i7-7700HQ CPU @ 2.80GHz and 32 GB RAM

The Importance of the Fourier Transform



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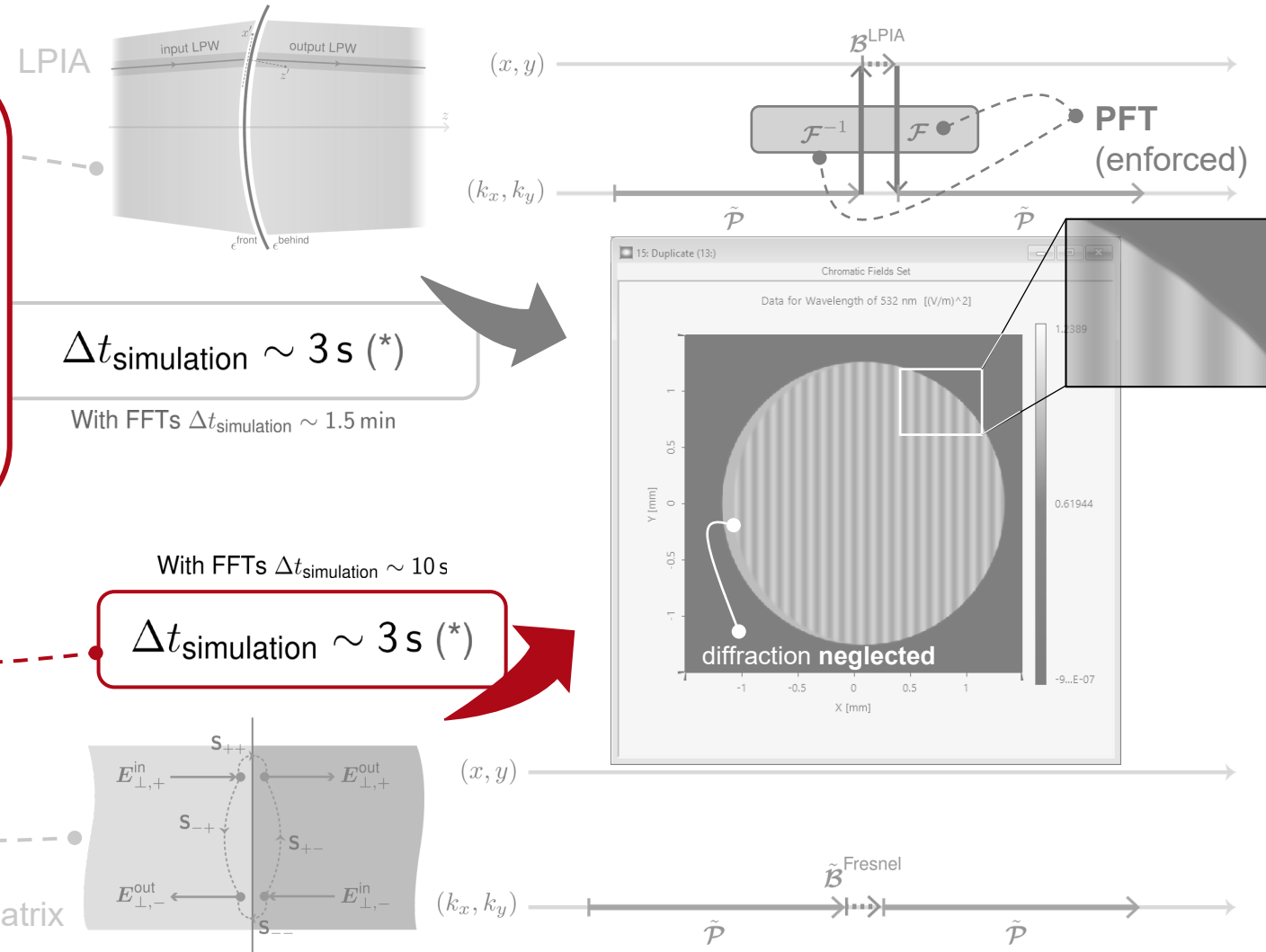
The Importance of the Fourier Transform



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The Importance of the Fourier Transform

Note: Fourier transforms are also performed at the source and detector planes, hence there is also a slight time improvement in the Fresnel Matrix case when the **Pointwise Fourier transform is enforced** across the system



More information about our catalog of Fourier transform algorithms in our use case “[Fourier Transform Settings Discussion at Examples](#)”

Practical Conclusions: Which Solver Do I Use?

Two possible solvers for plane interfaces in an optical system: the Fresnel Matrix and the Local Plane Interface Approximation (LPIA). Which one is more appropriate for your system depends on the circumstances:

Fresnel Matrix:

- Rigorous solver for ideal plane surface
- Works in spatial-frequency (k) domain
- Fewer Fourier transforms to be calculated
→ potential numerical gain
- Assumes infinite surface

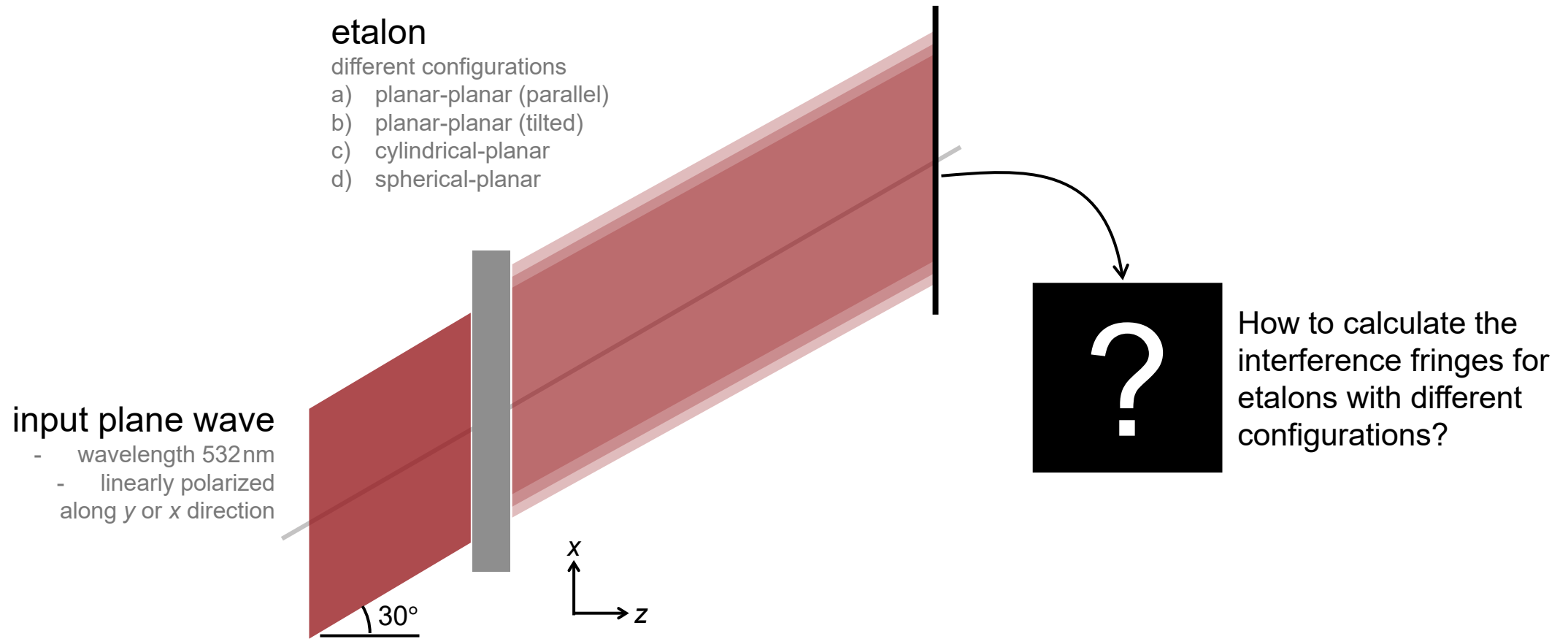
LPIA:

- Solver for curved surfaces
 - Works in space (x) domain
 - Requires computation of additional Fourier transforms
 - Considers finite size (aperture) of surface
-

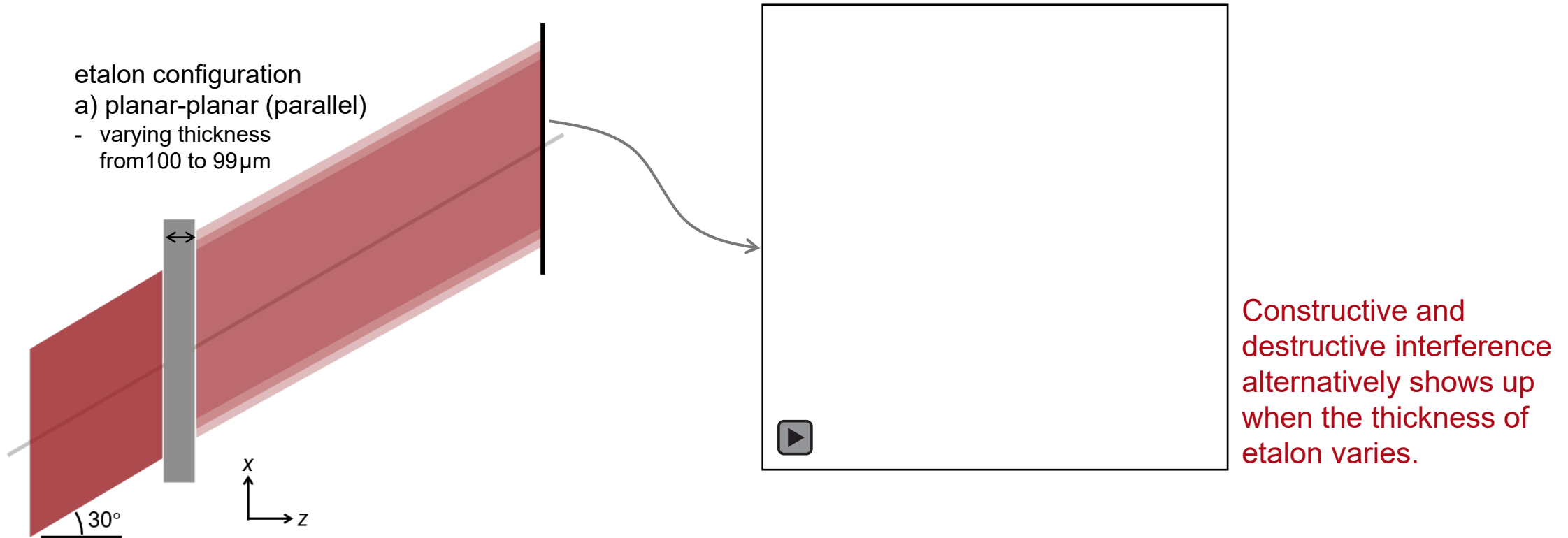
Modeling of Etalon with Planar or Curved Surfaces



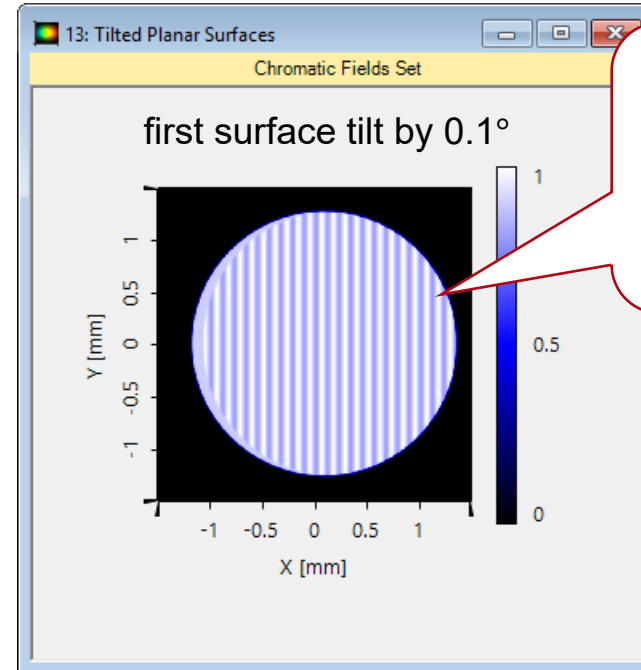
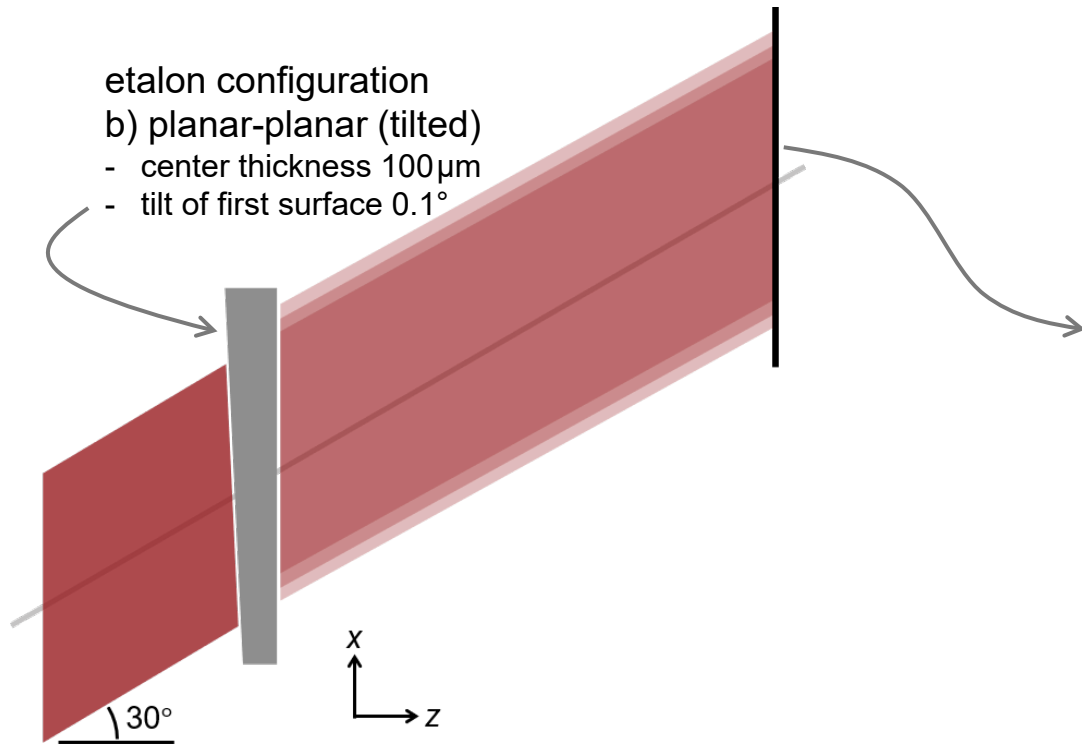
Modeling Task



Parallel Planar-Planar Surfaces

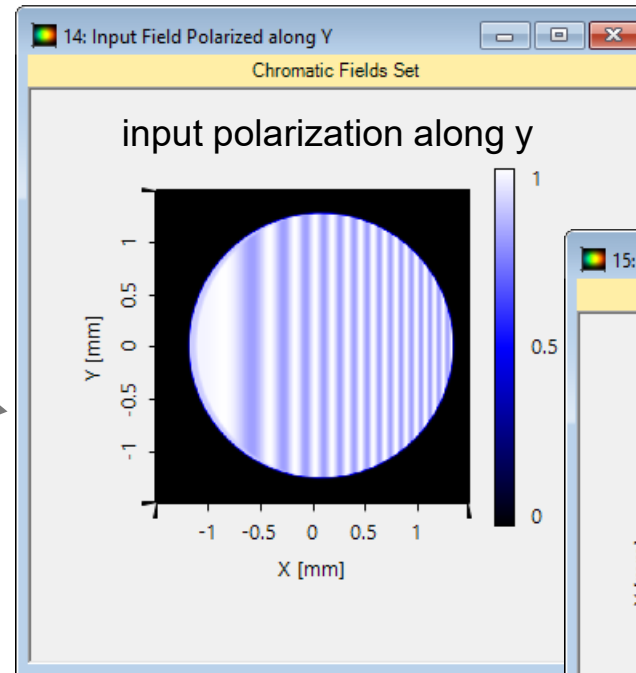
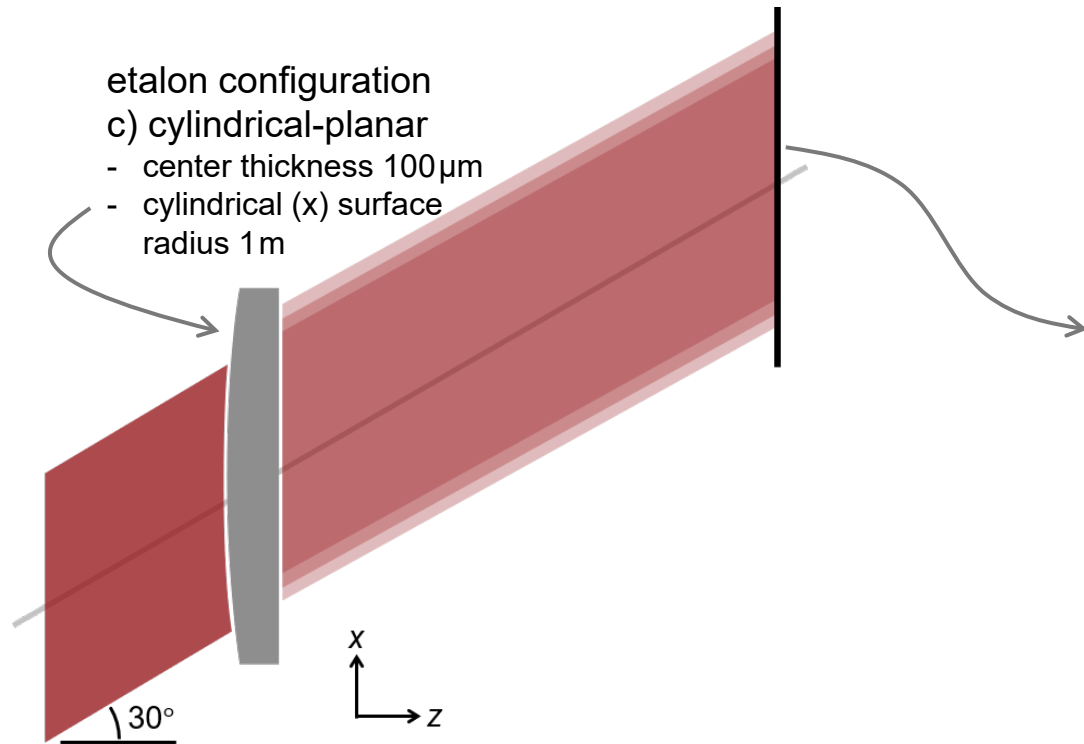


Tilted Planar-Planar Surfaces

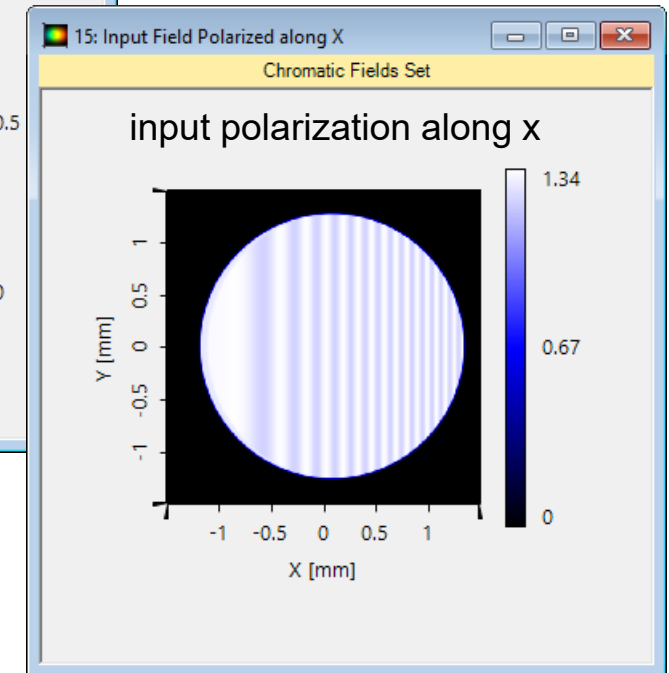


Linear interference fringes appear due to linear change of etalon thickness.

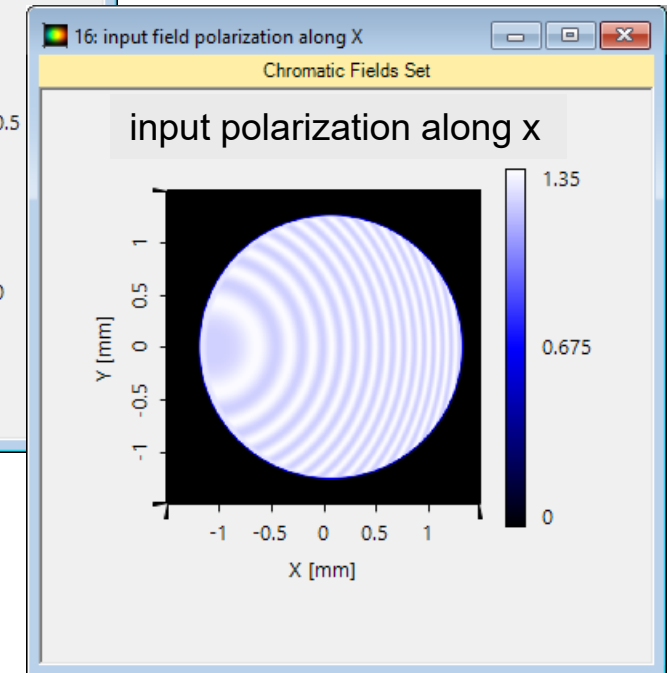
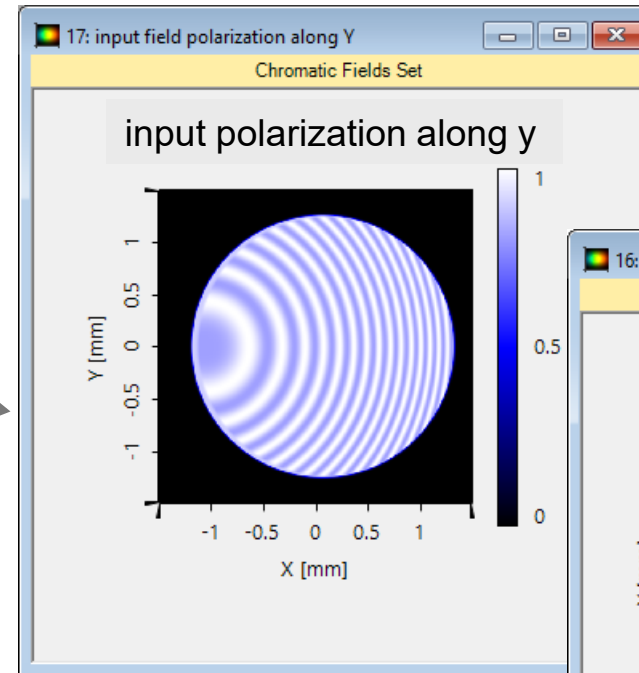
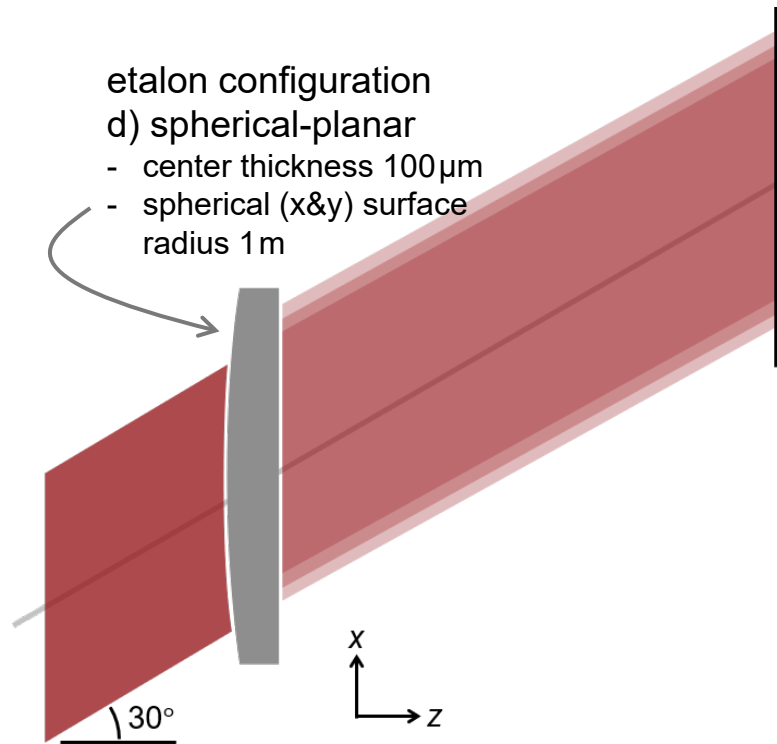
Cylindrical-Planar Surfaces



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

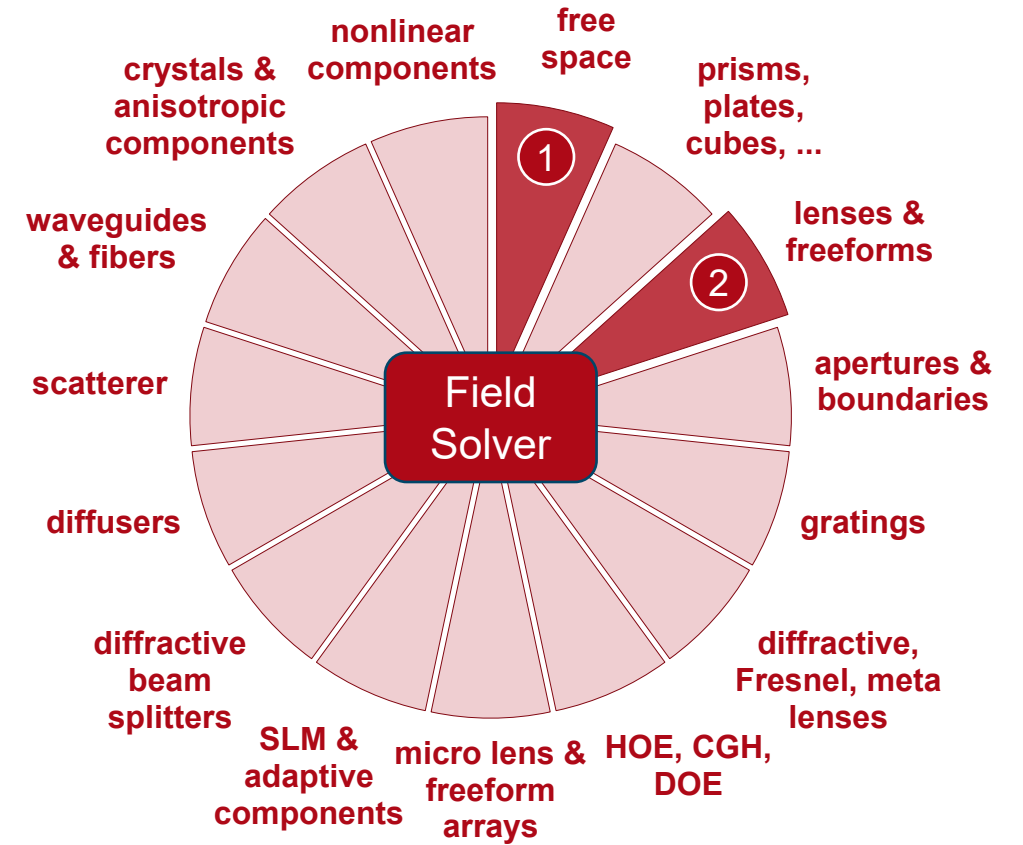
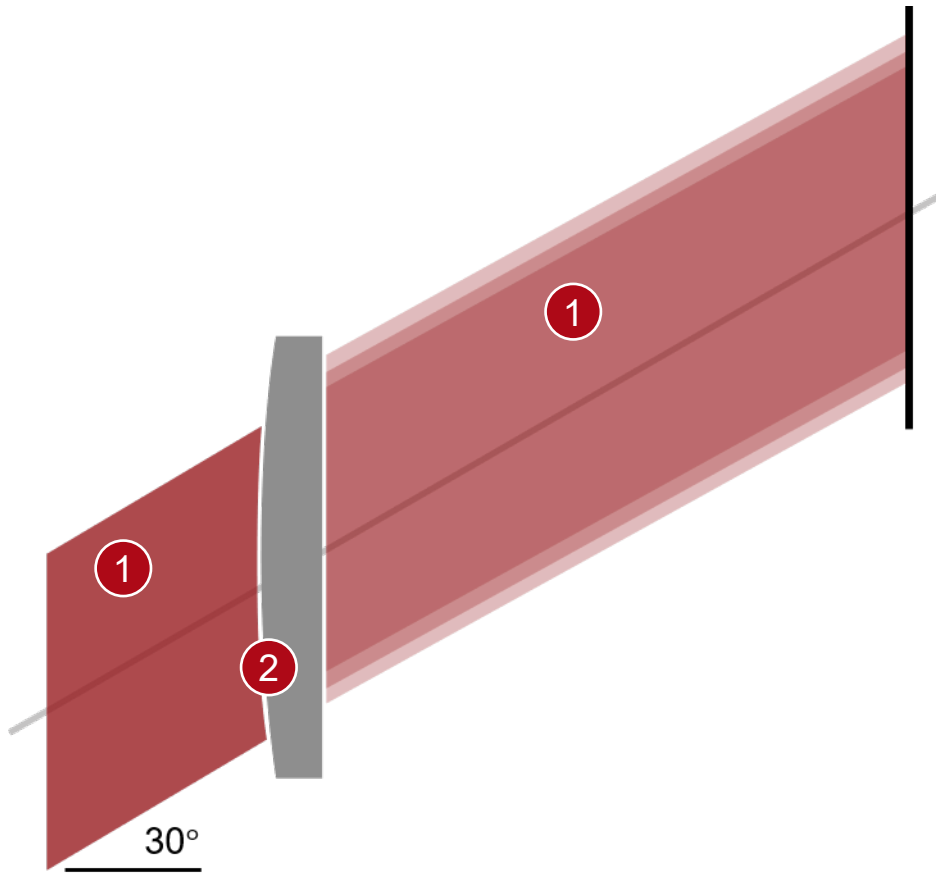


Spherical-Planar Surfaces



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

VirtualLab Fusion Technologies

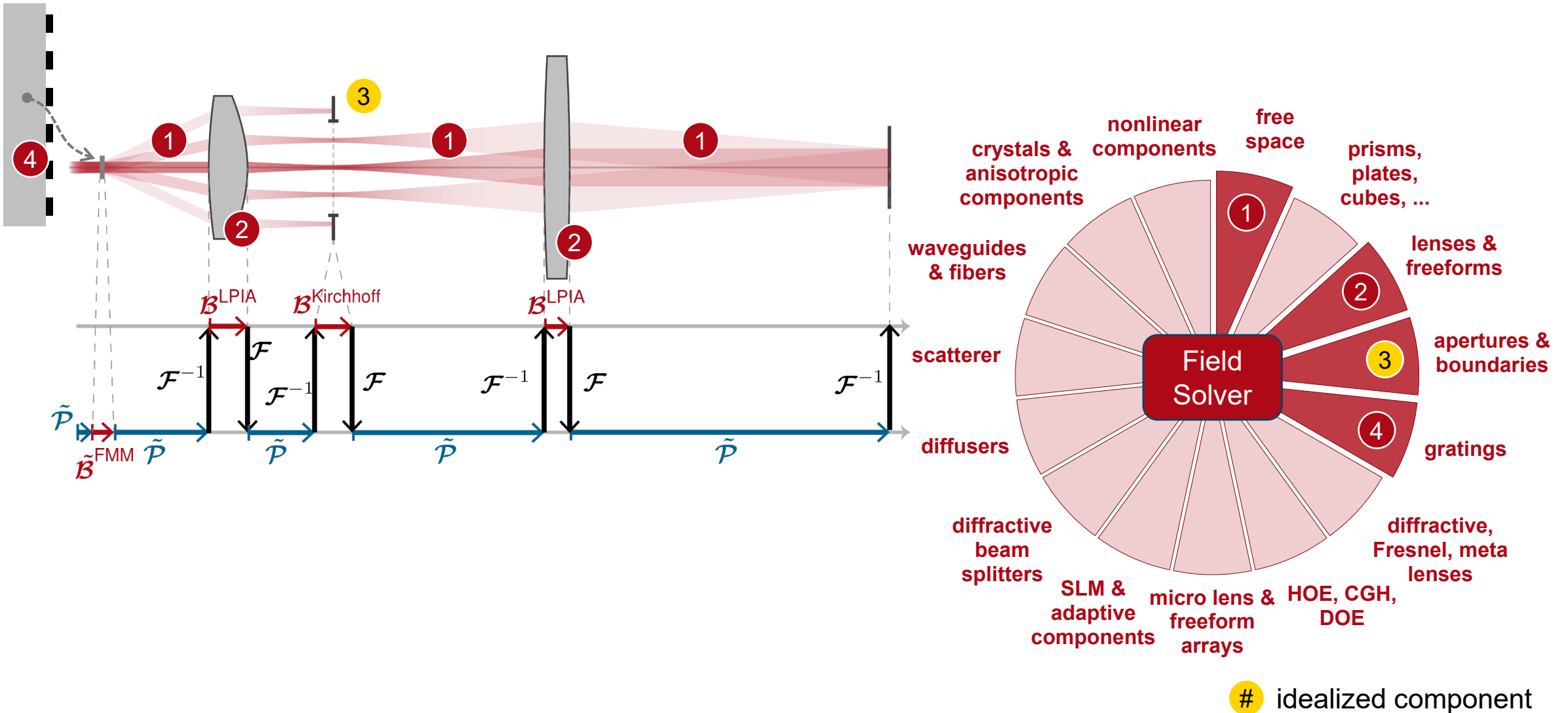


Part 3

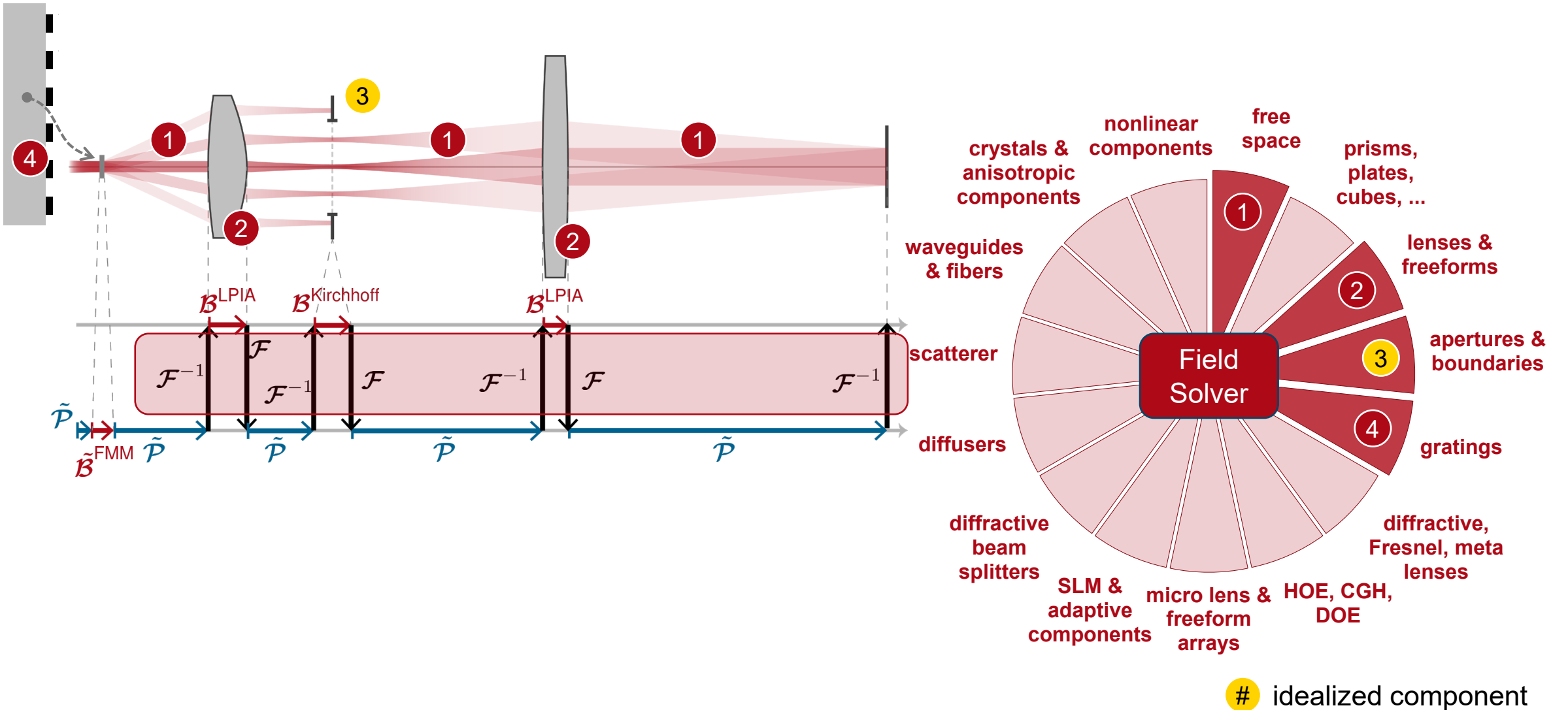
The Fourier Transform



Field Tracing Diagram

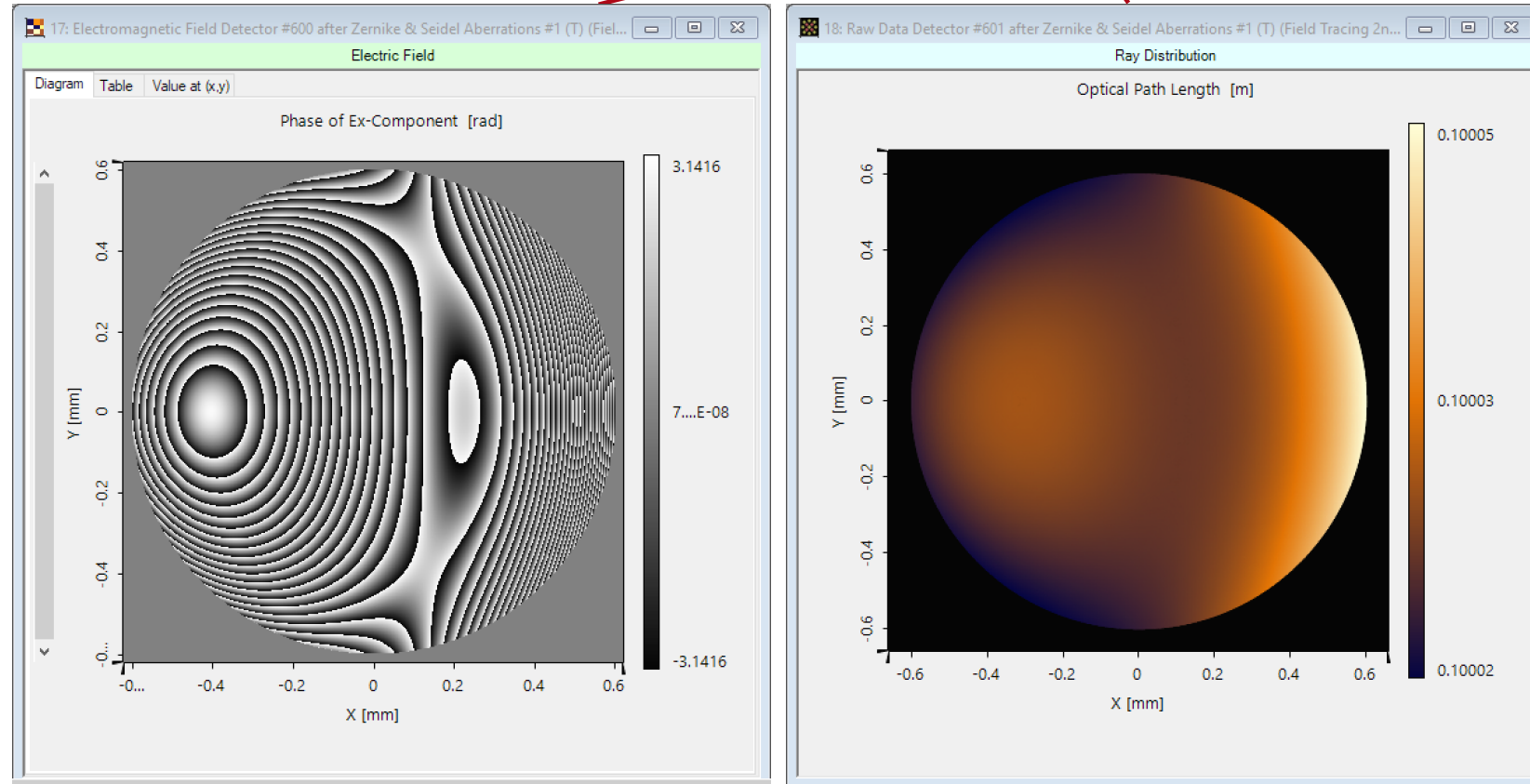


Field Tracing Diagram



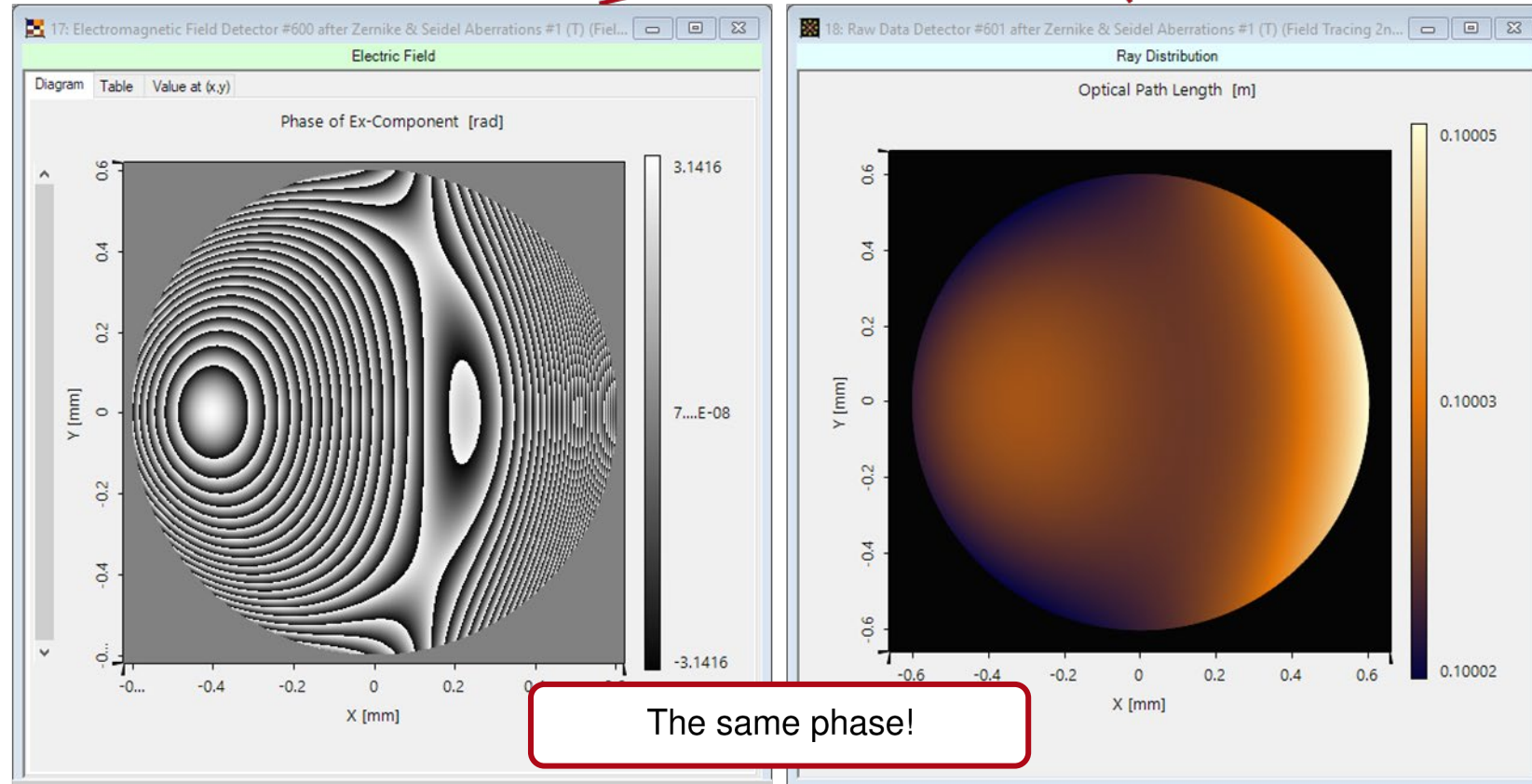
Fourier-Transforming an Arbitrary Field

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



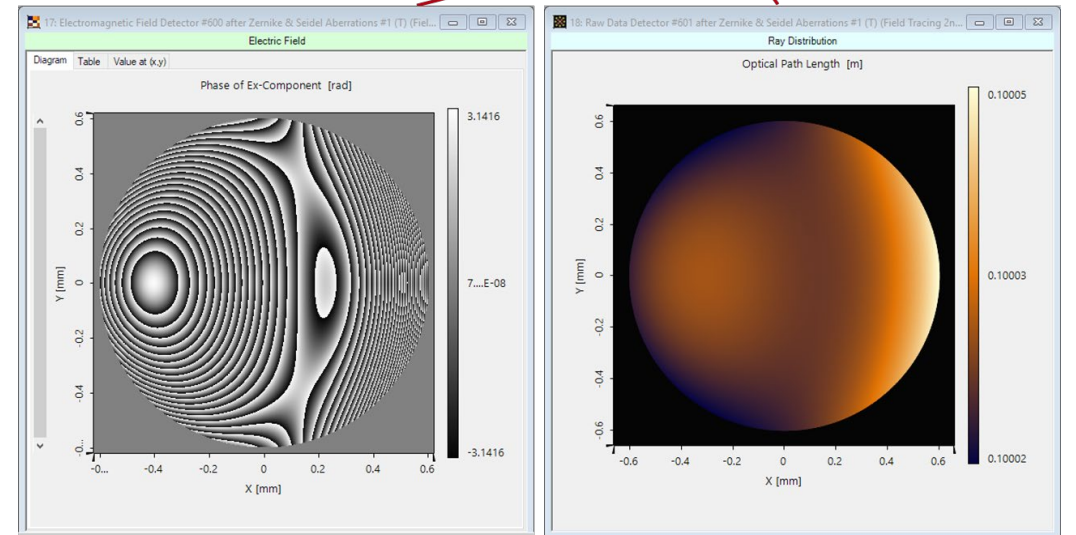
Fourier-Transforming an Arbitrary Field

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



Fourier-Transforming an Arbitrary Field

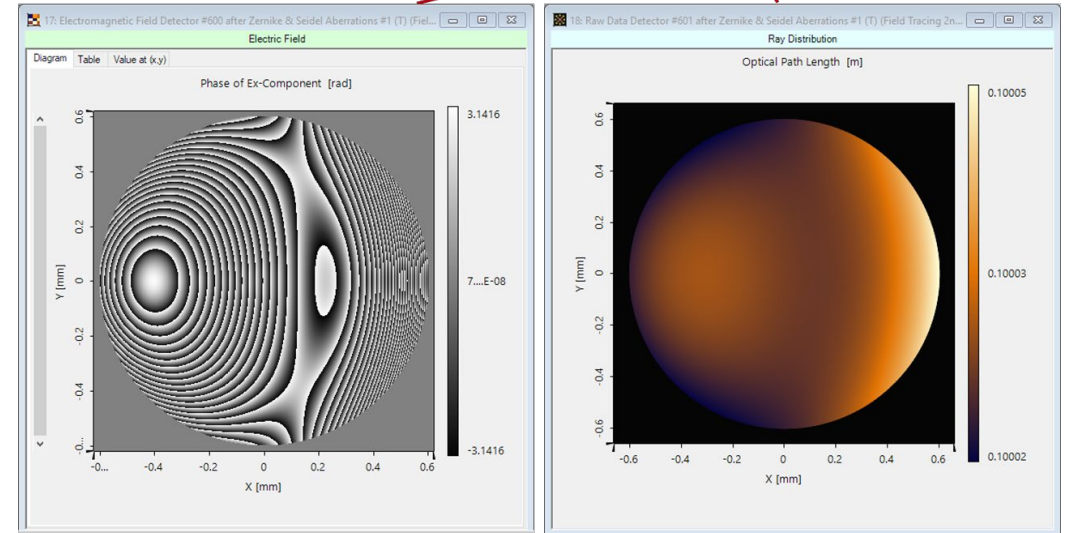
$$V_\ell(\boldsymbol{\rho}, z, \omega) = |V_\ell(\boldsymbol{\rho}, z, \omega)| \exp(i\varphi_\ell(\boldsymbol{\rho}, z, \omega)) \exp(i\psi(\boldsymbol{\rho}, z, \omega))$$



Fourier-Transforming an Arbitrary Field

- Direct discretization of Fourier integral \rightarrow DFT (Discrete Fourier Transform): numerical complexity $\sim N^2$

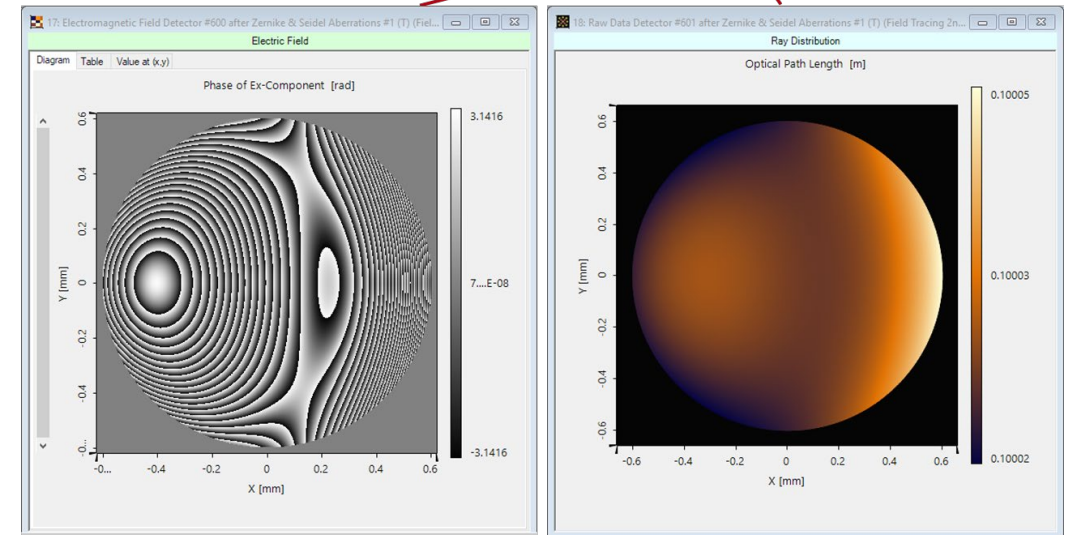
$$V_\ell(\boldsymbol{\rho}, z, \omega) = |V_\ell(\boldsymbol{\rho}, z, \omega)| \exp(i\varphi_\ell(\boldsymbol{\rho}, z, \omega)) \exp(i\psi(\boldsymbol{\rho}, z, \omega))$$



Fourier-Transforming an Arbitrary Field

- Direct discretization of Fourier integral \rightarrow DFT (Discrete Fourier Transform): numerical complexity $\sim N^2$
- Numerical trick in Fast Fourier Transform (FFT) brings down computational effort to $\sim N \log N \rightarrow \sim N$

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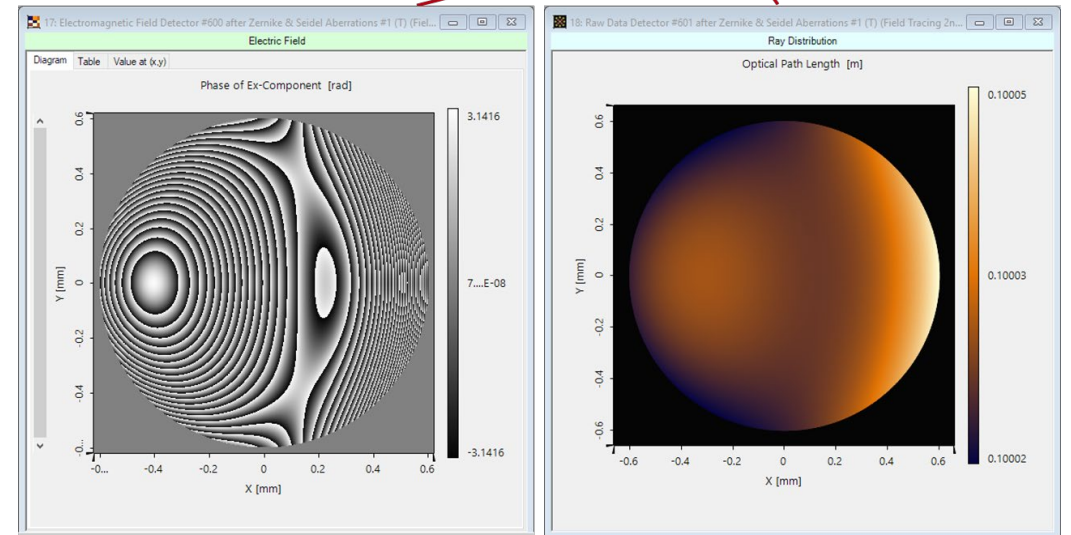


Fourier-Transforming an Arbitrary Field

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This already means **pointwise** operation, right?
Job done! ✓

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

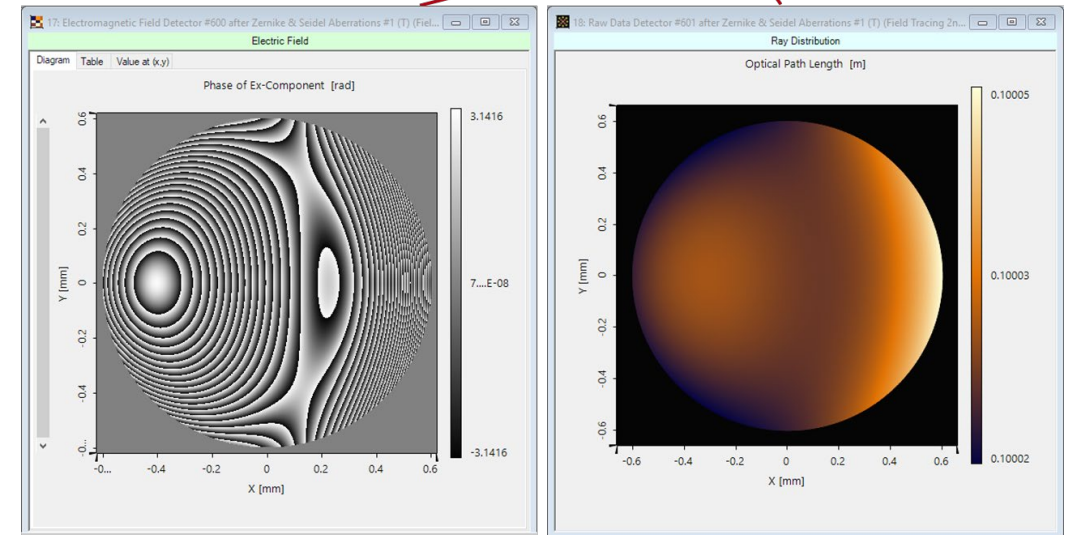


Fourier-Transforming an Arbitrary Field

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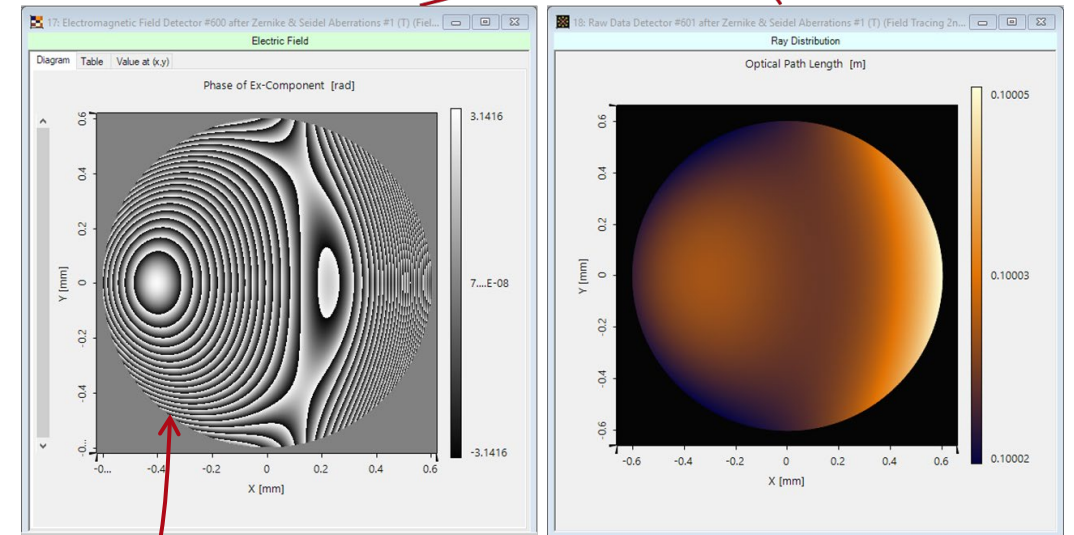
Fourier-Transforming an Arbitrary Field

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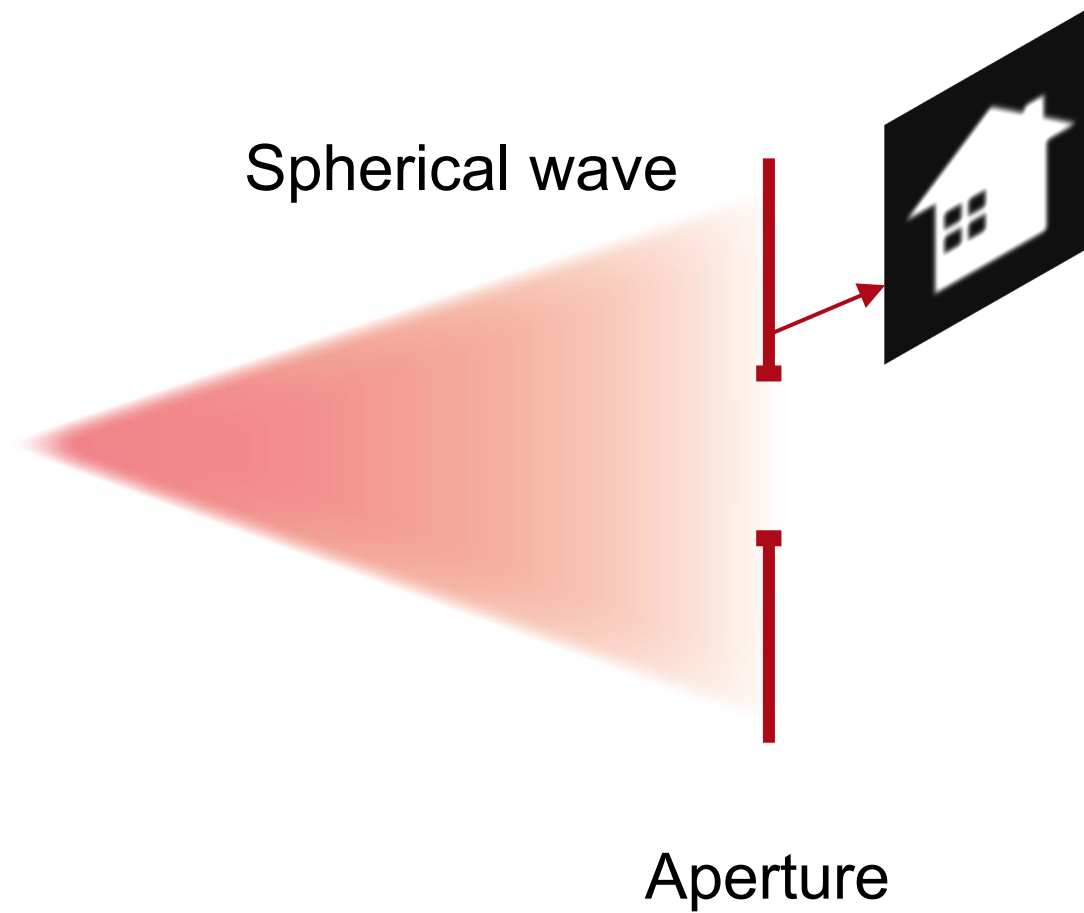
$$V_\ell(\boldsymbol{\rho}, z, \omega) = |V_\ell(\boldsymbol{\rho}, z, \omega)| \exp(i\varphi_\ell(\boldsymbol{\rho}, z, \omega)) \exp(i\psi(\boldsymbol{\rho}, z, \omega))$$

The FFT requires fulfilment of the Nyquist-Shannon sampling theorem \Rightarrow wrapped phase **must** be well resolved!

\Downarrow
Huge sample number N



Modeling the Propagation Through an Aperture

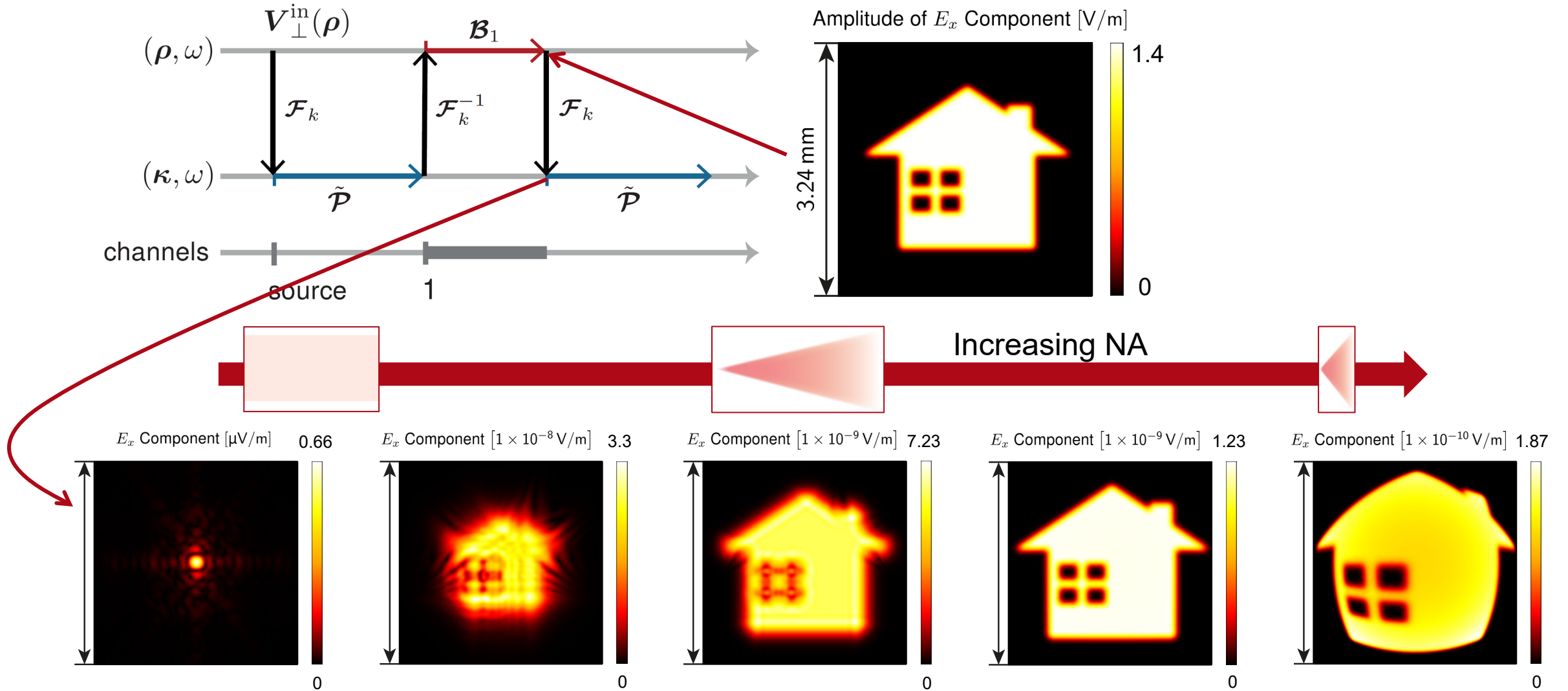


Field after the aperture

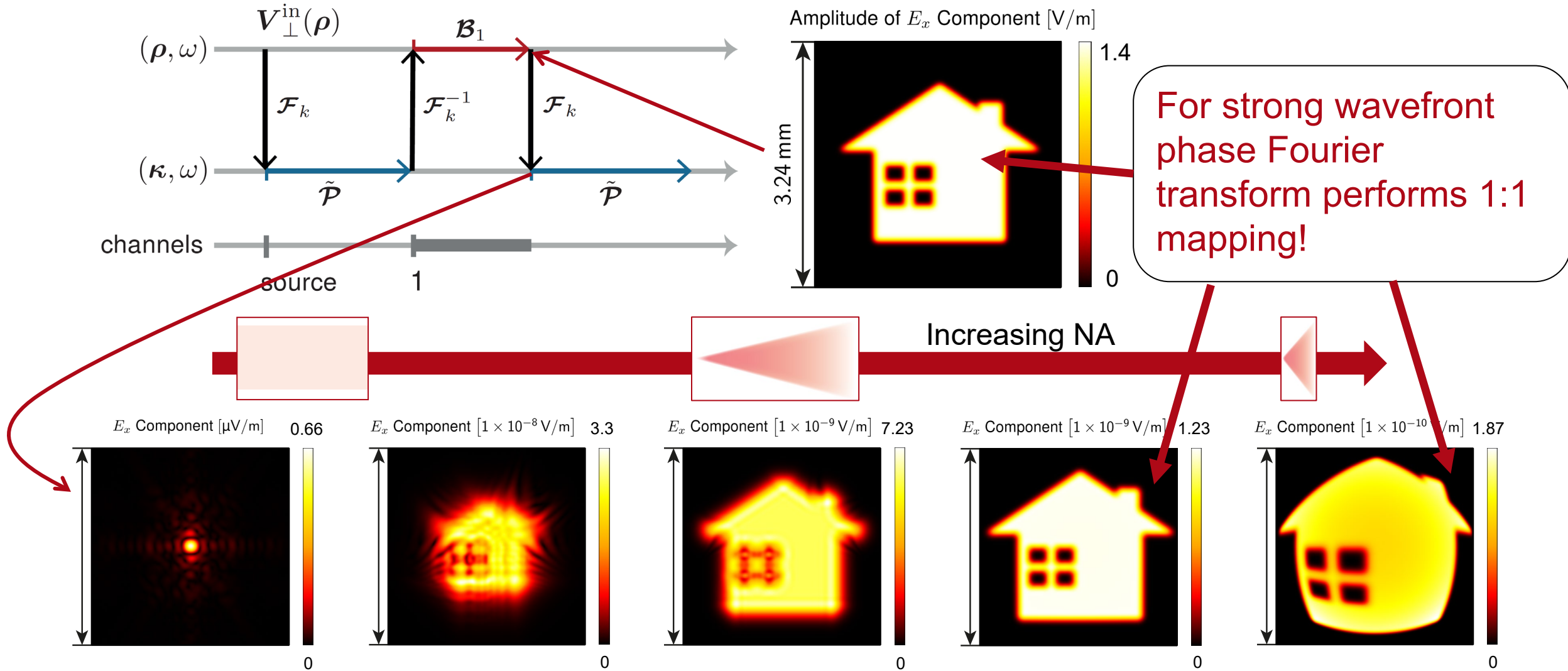
Amplitude of E_x Component [V/m]



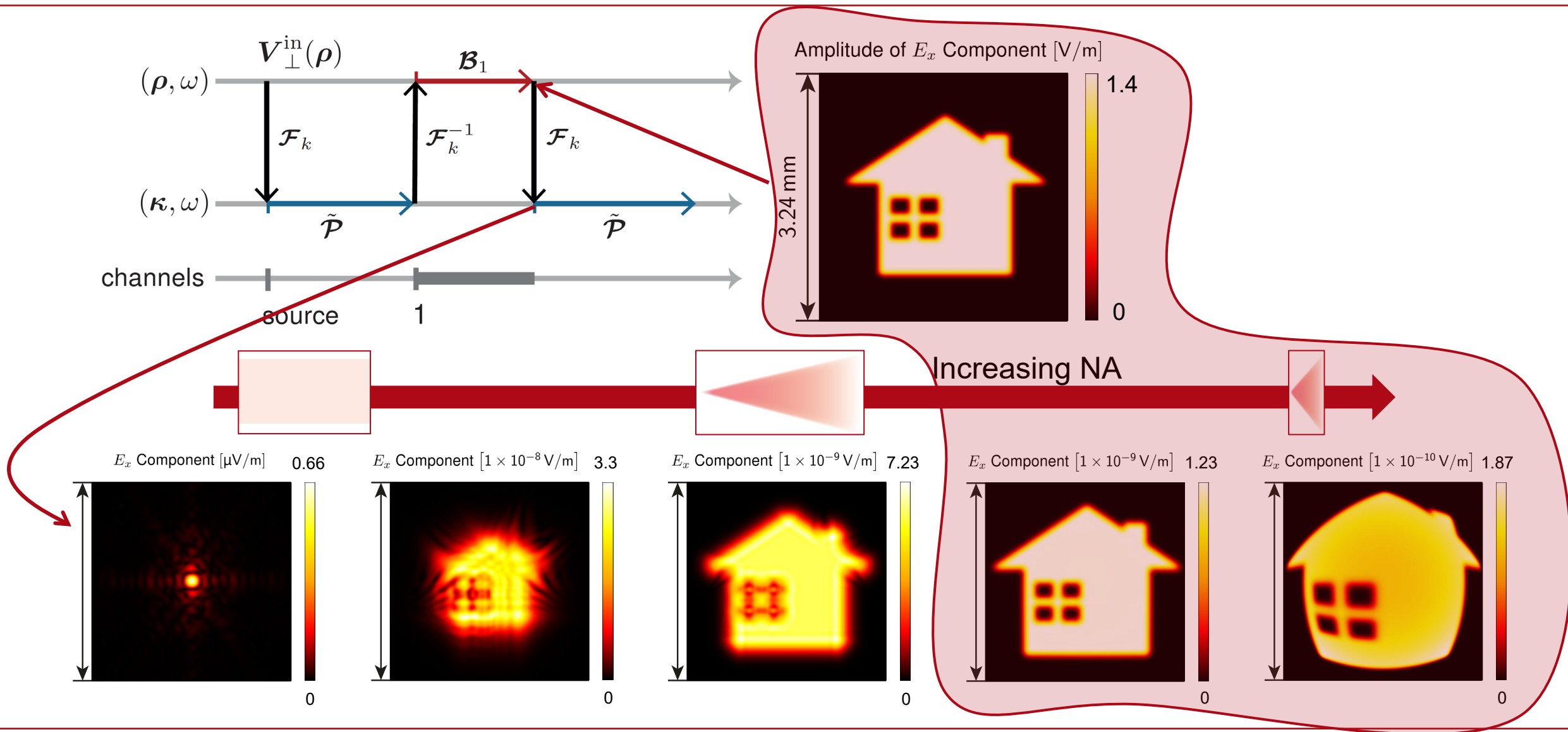
Results of Fourier Transform



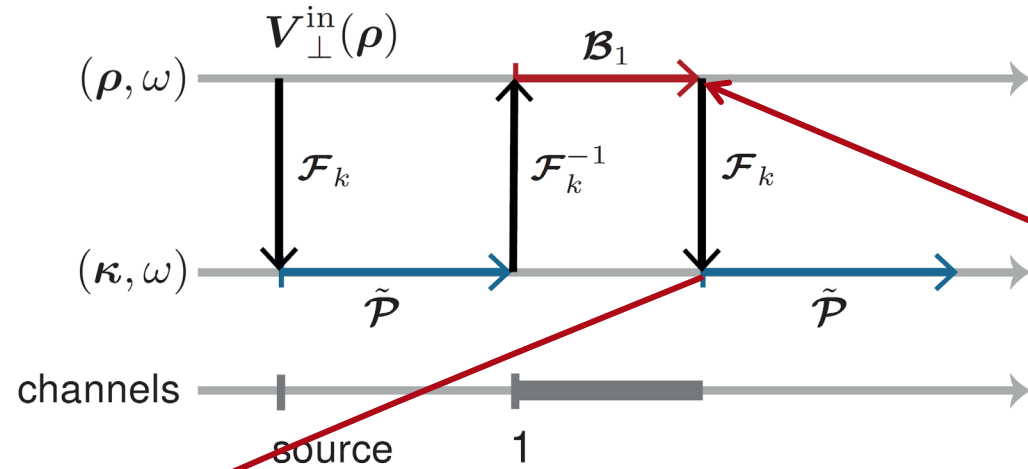
Results of Fourier Transform



Results of Fourier Transform



Results of Fourier Transform

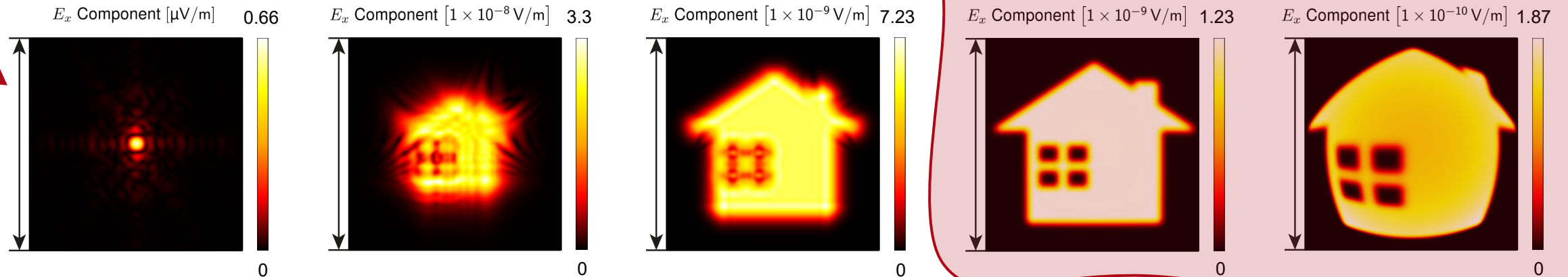


Amplitude of E_x Component [V/m]

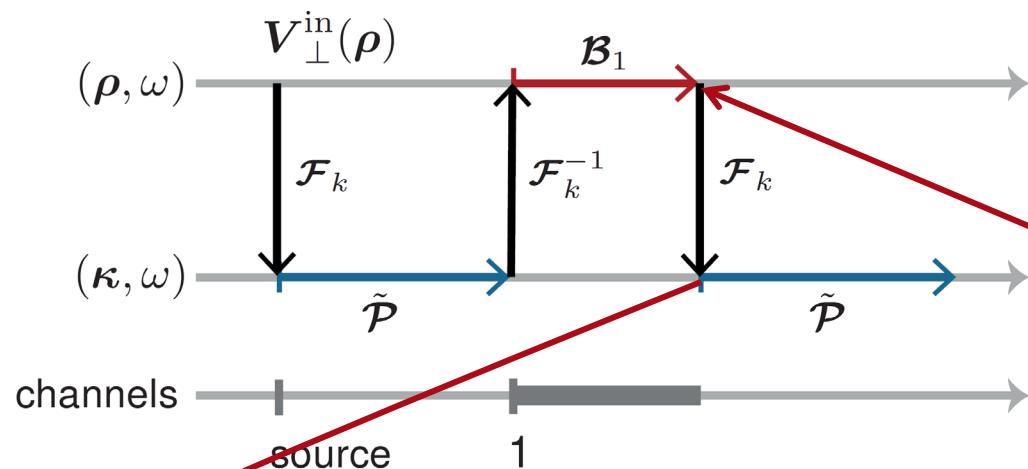


This behaviour can be used to develop an approximate algorithm to compute the Fourier transform that is **extremely accurate** when the field exhibits this behaviour, and **extremely fast**

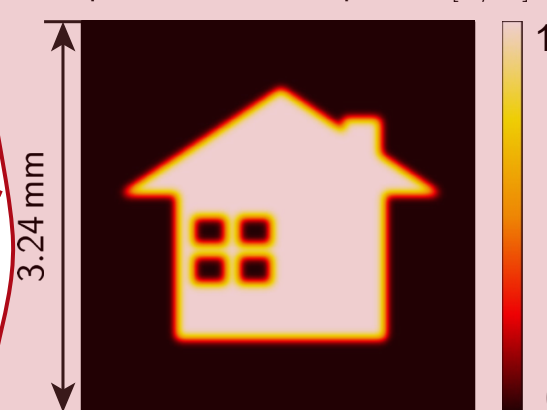
Increasing NA



Results of Fourier Transform



Amplitude of E_x Component [V/m]

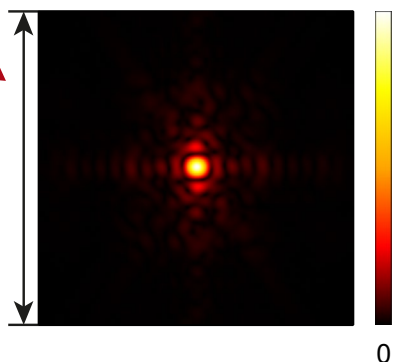


This behaviour can be used to develop an approximate algorithm to compute the Fourier transform that is **extremely accurate** when the field exhibits this behaviour, and **extremely fast**

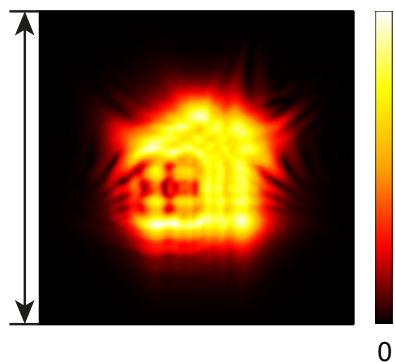
pointwise Fourier transform

Increasing NA

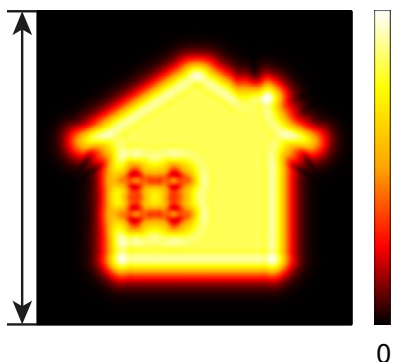
E_x Component [$\mu\text{V/m}$] 0.66



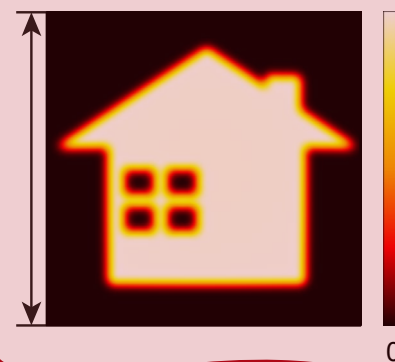
E_x Component [$1 \times 10^{-8} \text{ V/m}$] 3.3



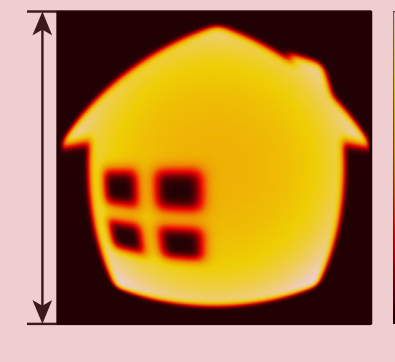
E_x Component [$1 \times 10^{-9} \text{ V/m}$] 7.23



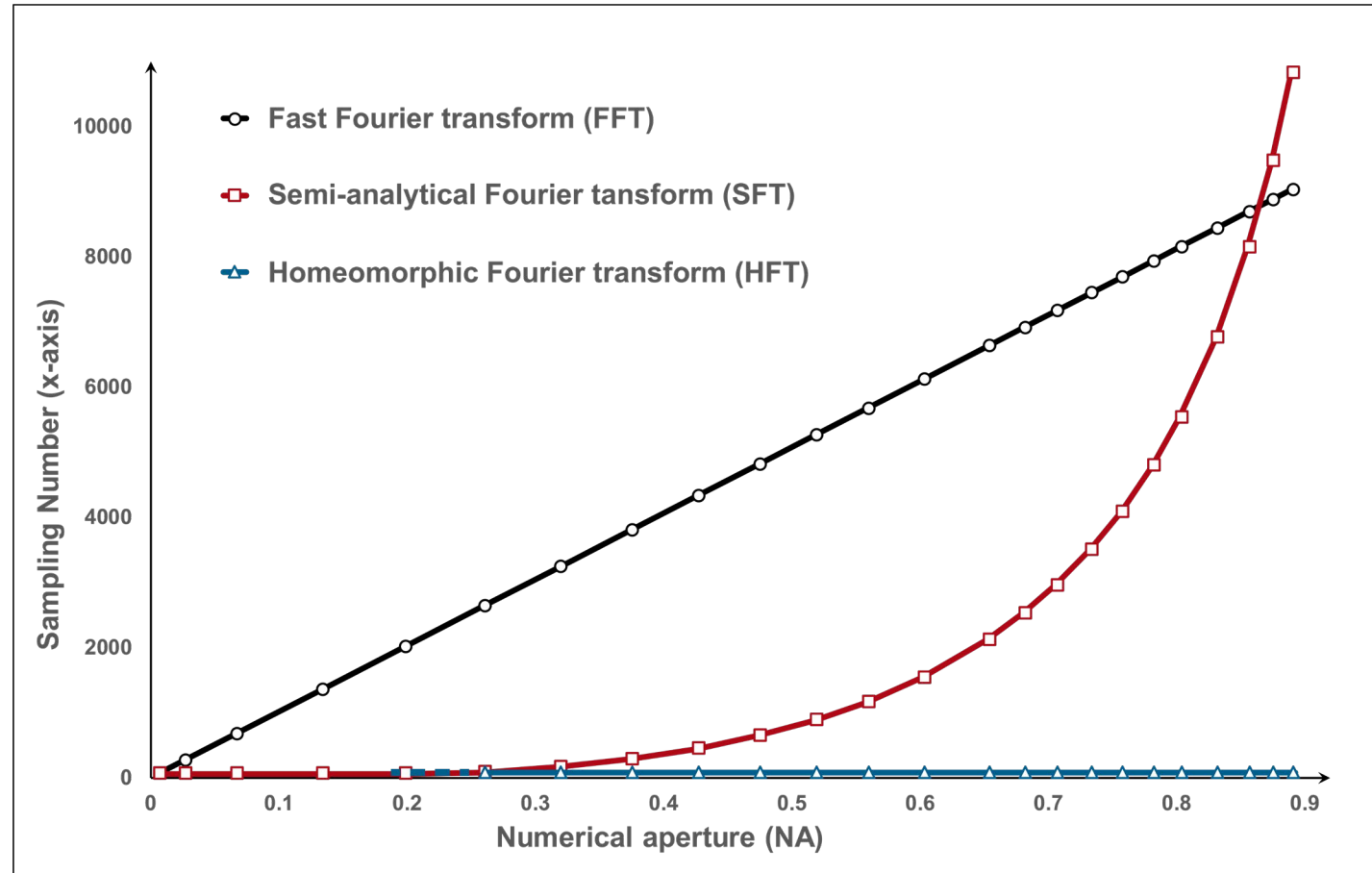
E_x Component [$1 \times 10^{-9} \text{ V/m}$] 1.23



E_x Component [$1 \times 10^{-10} \text{ V/m}$] 1.87

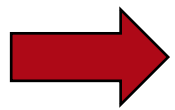


Comparison of the Sampling Effort

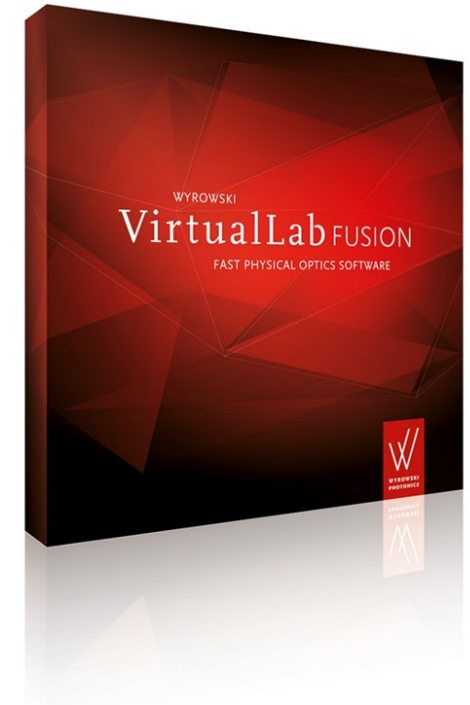


Types of Fourier Transform Algorithms in VirtualLab Fusion

- Fast Fourier Transform (FFT)
 - Fast for weak wavefront phase
- Semianalytical Fourier transform (SFT)
 - Fast for wavefront phase with medium local gradient
- Pointwise Fourier transform (PFT)
 - Accurate for strong wavefront phase



Combination of Fourier transform algorithms essential for fast physical optics!



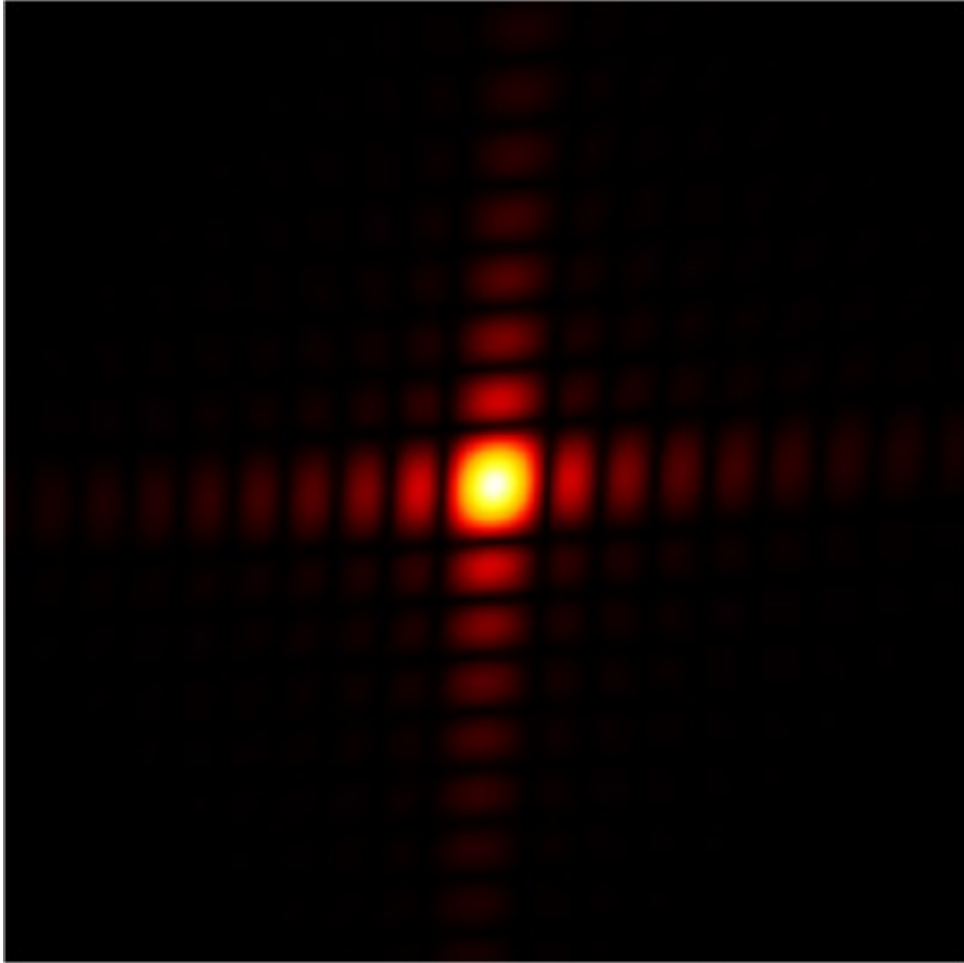
References to Our Fourier Transform Publications

- *Theory and algorithm of the homeomorphic Fourier transform for optical simulations*, Z. Wang et al, Optics Express, **28**, 7, 2020
- *Application of the semi-analytical Fourier transform to electromagnetic modeling*, Z. Wang et al, Optics Express, **27**, 11, 2019

Automatic Selection of Fourier Transform Techniques in Free-Space Propagation Operator

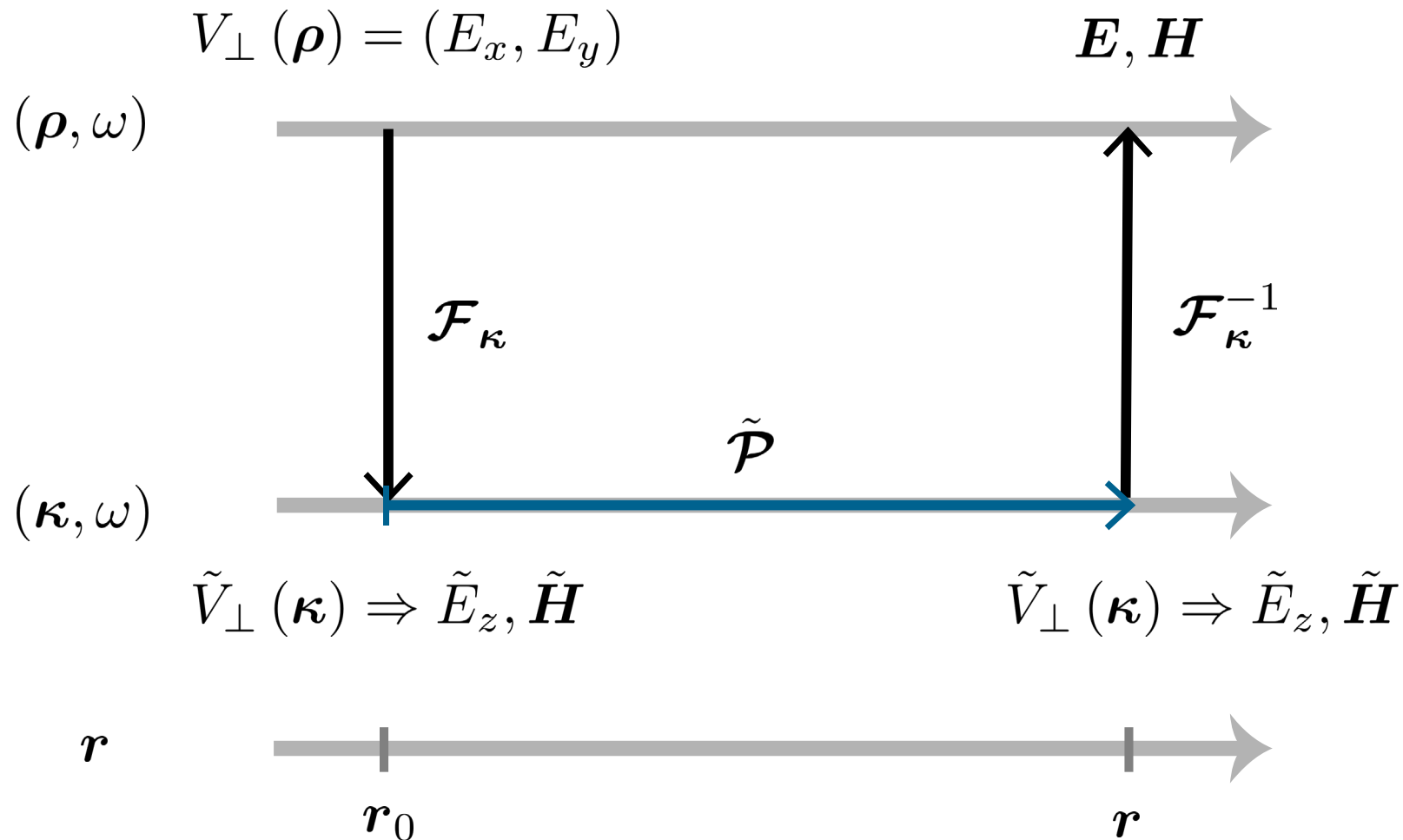


Abstract



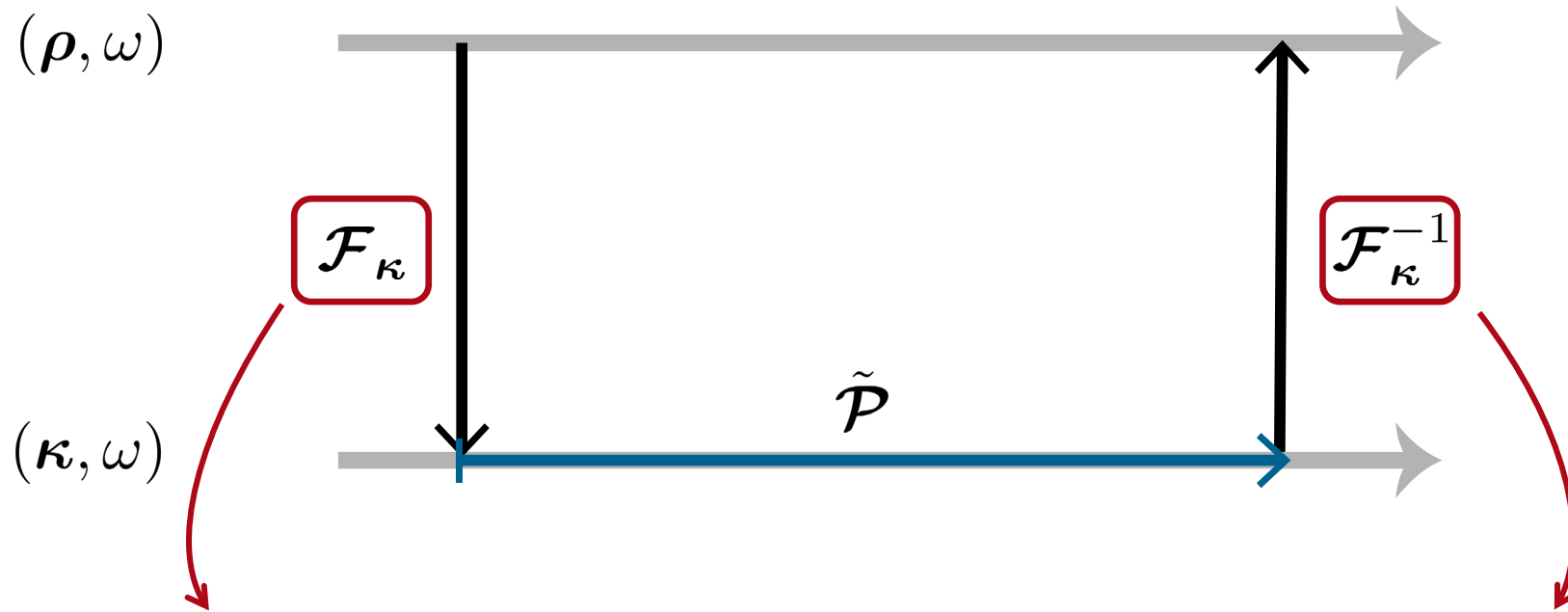
Accurate and efficient simulation of free-space propagation of electromagnetic fields is essential for physical optics modeling and design. VirtualLab Fusion has a unified free-space propagation concept. It is based on the spatial-frequency domain (k -domain) analysis. In combination with different Fourier transform techniques, it delivers numerical efficient solutions for different situations of free-space propagations. The selection of appropriate Fourier transform is automatic according to the situation.

Concept of Free-Space Propagation Operator



- Unified propagation operator in the k-domain
- Applicable for arbitrarily oriented planes
- Switching between two domains via Fourier transform
- References
 - F. Wyrowski, "Unification of the geometric and diffractive theories of electromagnetic fields" Proc. DGaO, (2017)
 - Z. Wang *et al.*, "Application of the semi-analytical Fourier transform to electromagnetic modeling," Opt. Express 27, 15335-15350 (2019)

Available Fourier Transform Techniques in VirtualLab Fusion

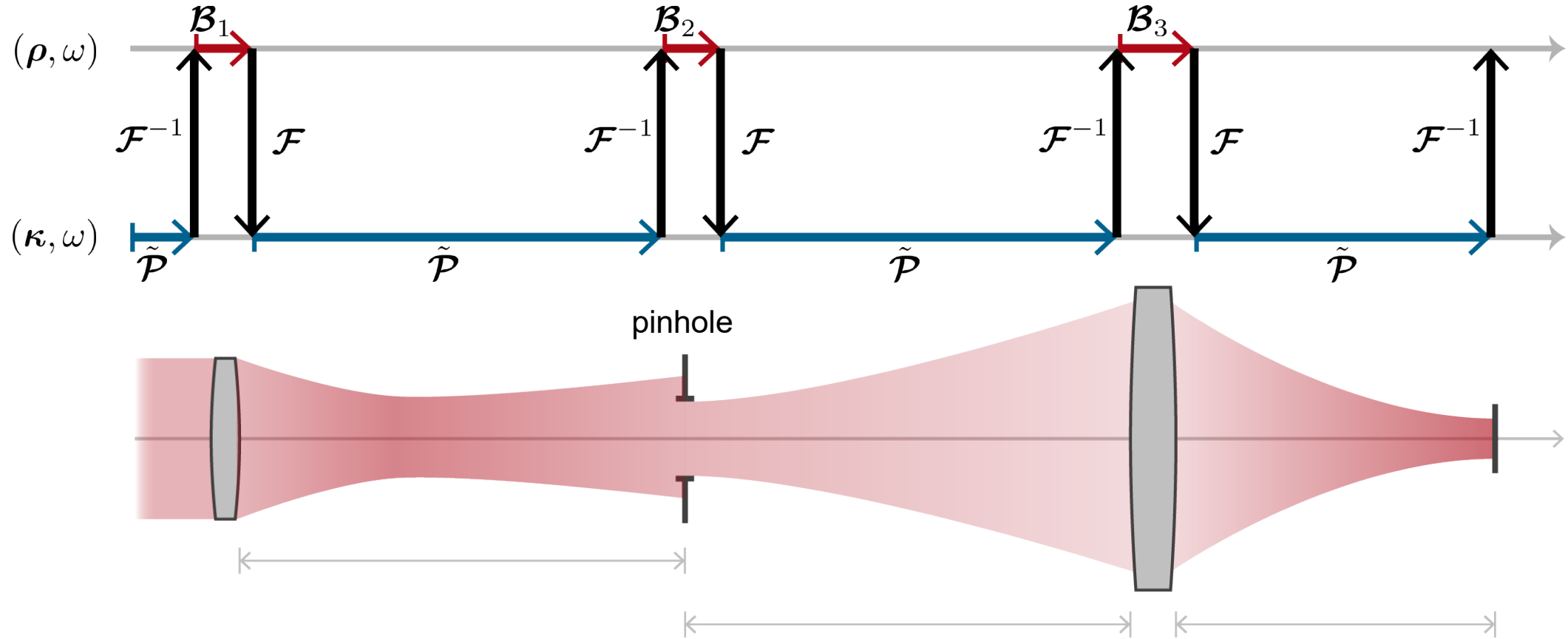


- \mathcal{F}_κ : fast Fourier transform (FFT)
- $\mathcal{F}_\kappa^{\text{semi}}$: semi-analytical Fourier transform (SFT)
- $\mathcal{F}_\kappa^{\text{h}}$: homeomorphic Fourier transform (HFT)

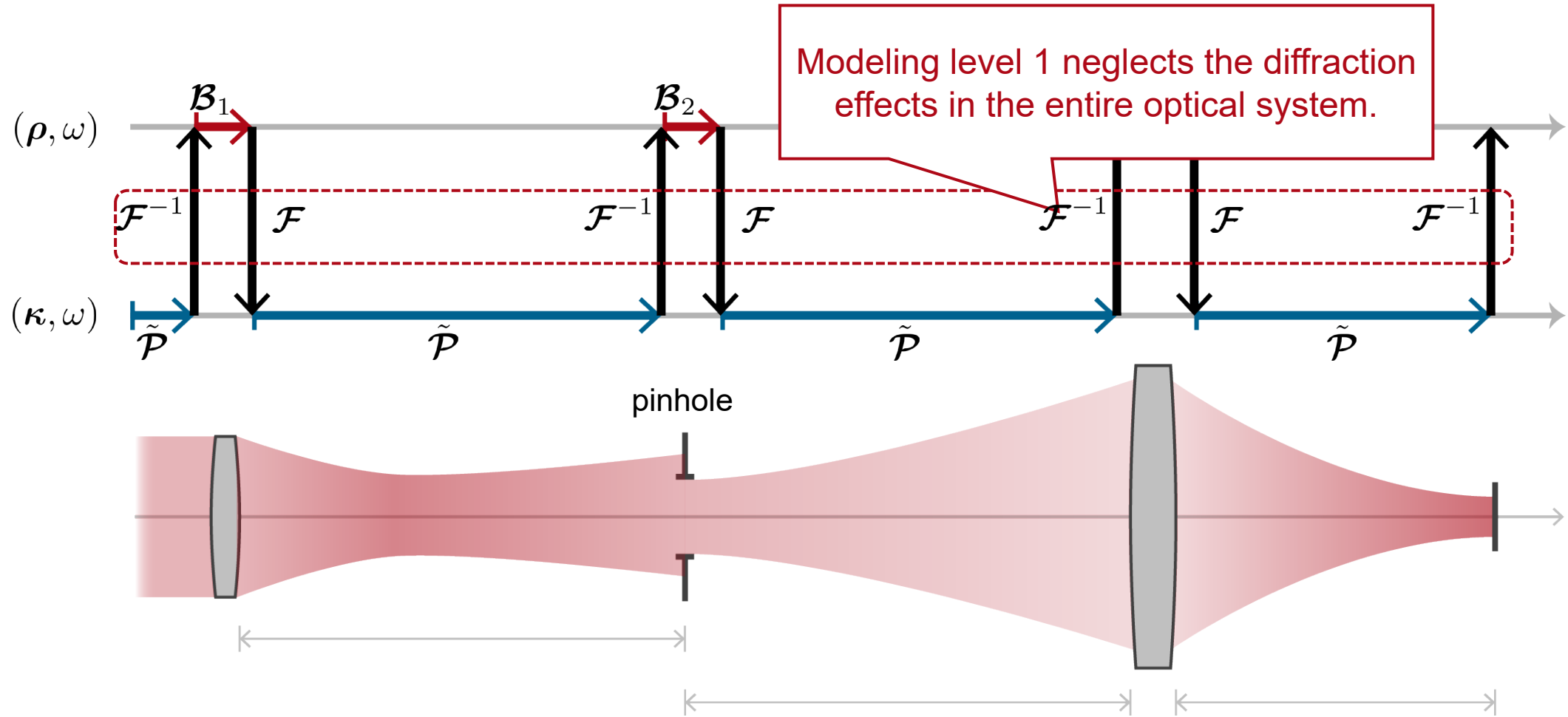
- \mathcal{F}_κ^{-1} : inverse fast Fourier transform (IFFT)
- $\mathcal{F}_\kappa^{-1, \text{semi}}$: inverse semi-analytical Fourier transform (ISFT)
- $\mathcal{F}_\kappa^{-1, \text{h}}$: inverse homeomorphic Fourier transform (IHFT)

Modeling Levels Definitions

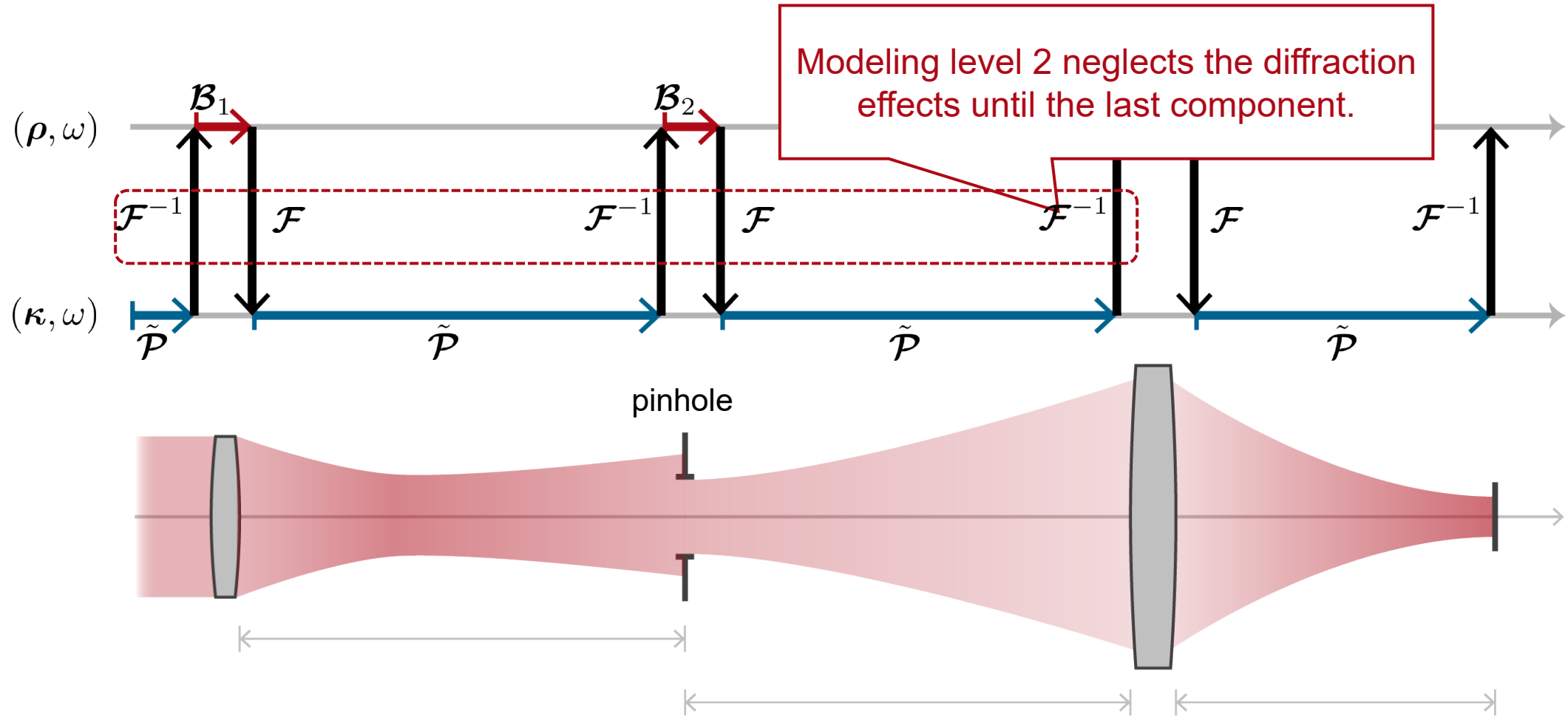
Available Modeling Levels For an Arbitrary System



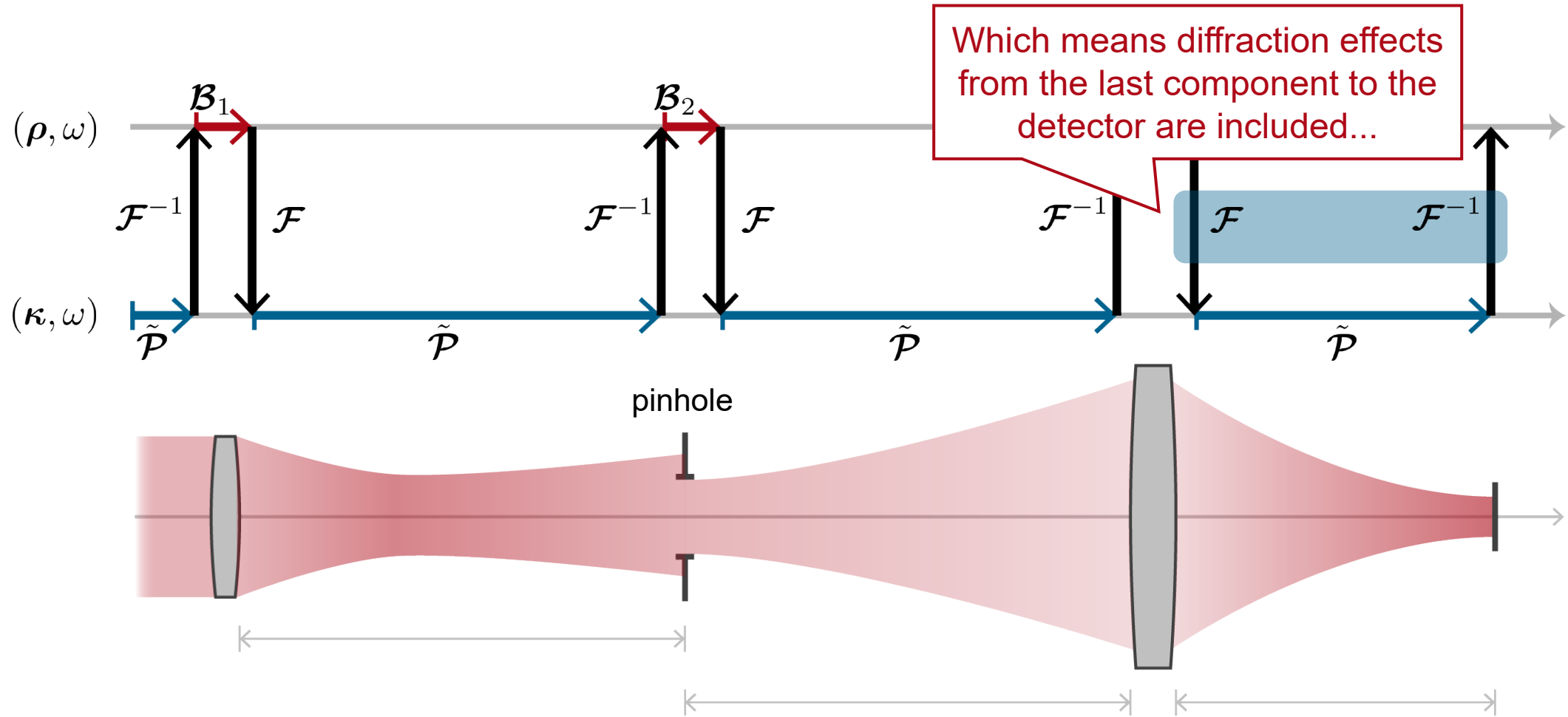
Modeling Level 1



Modeling Level 2



Modeling Level 2



Modeling Level 3

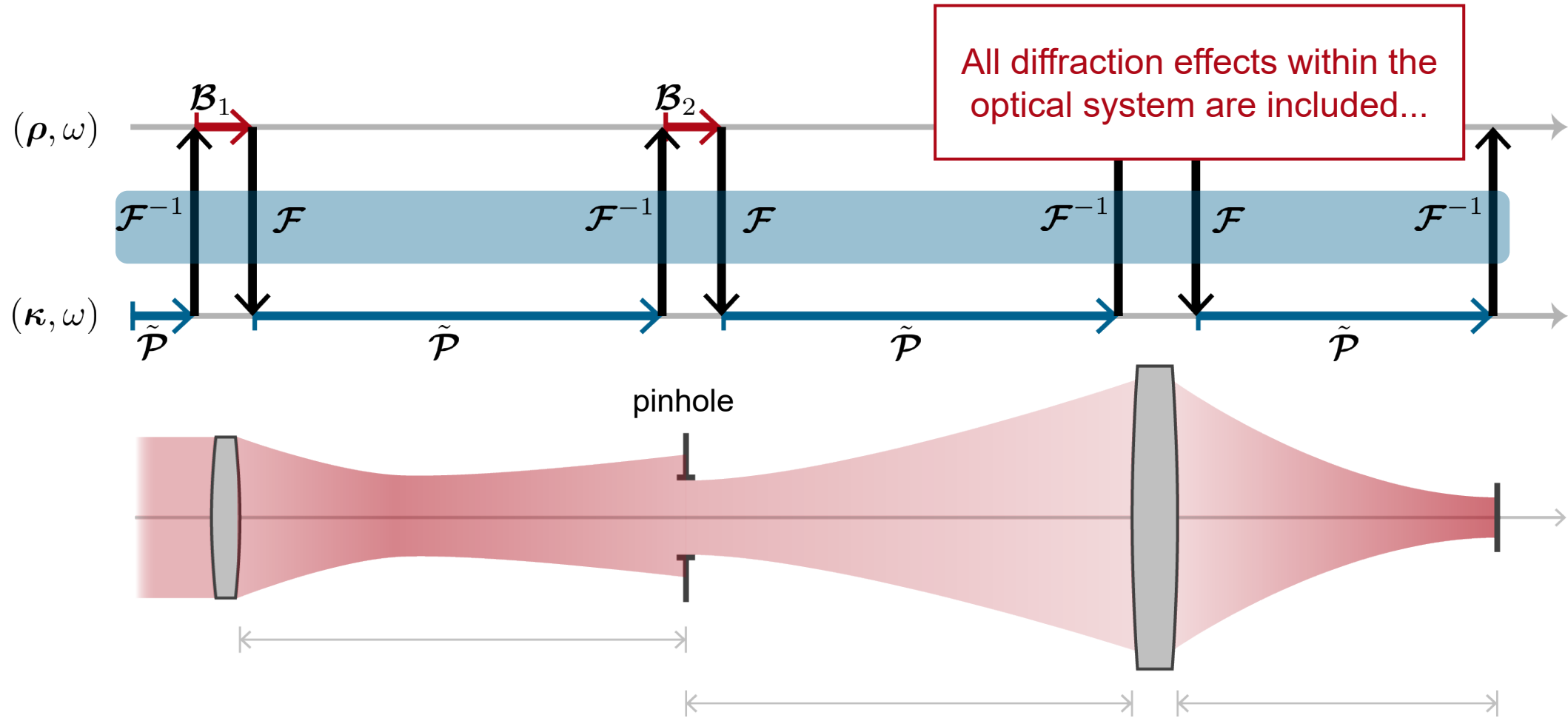
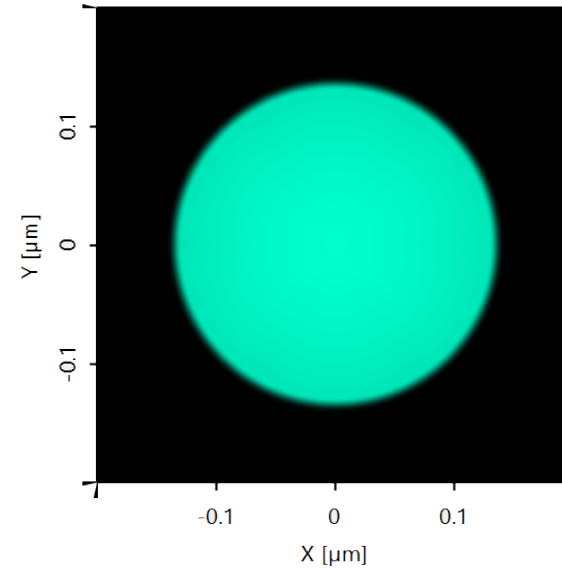
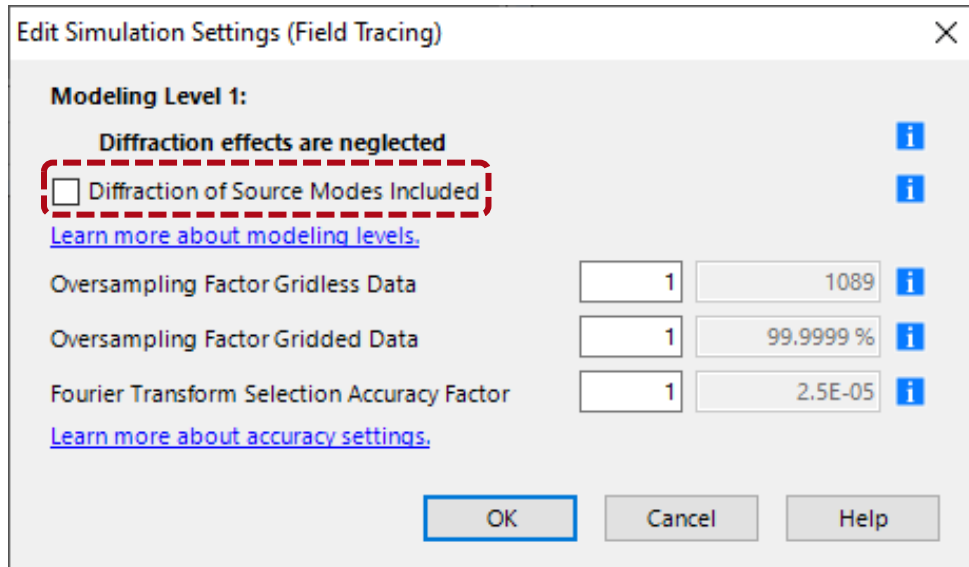
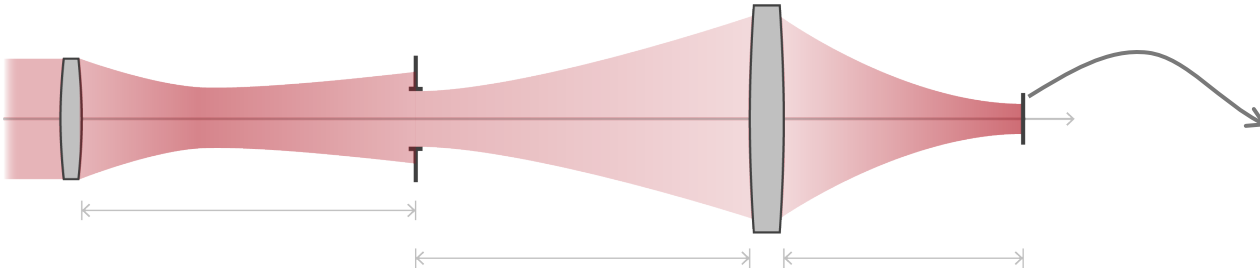


Image Evaluation by Modeling Level 1



Focal spot

Image Evaluation by Modeling Level 2

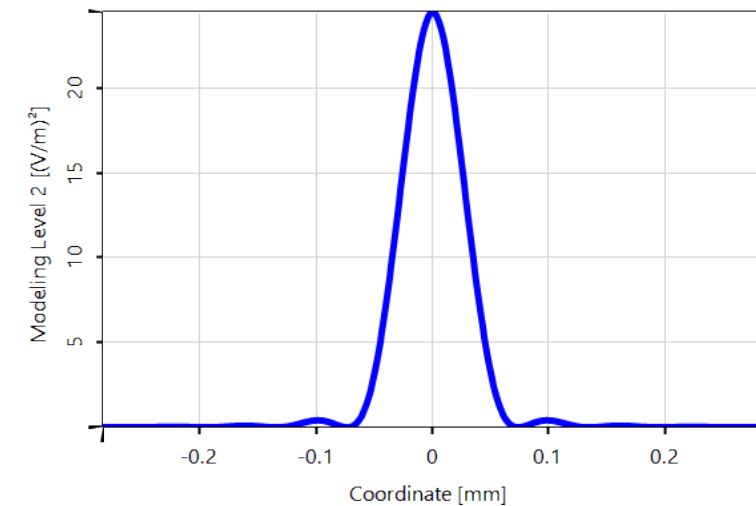
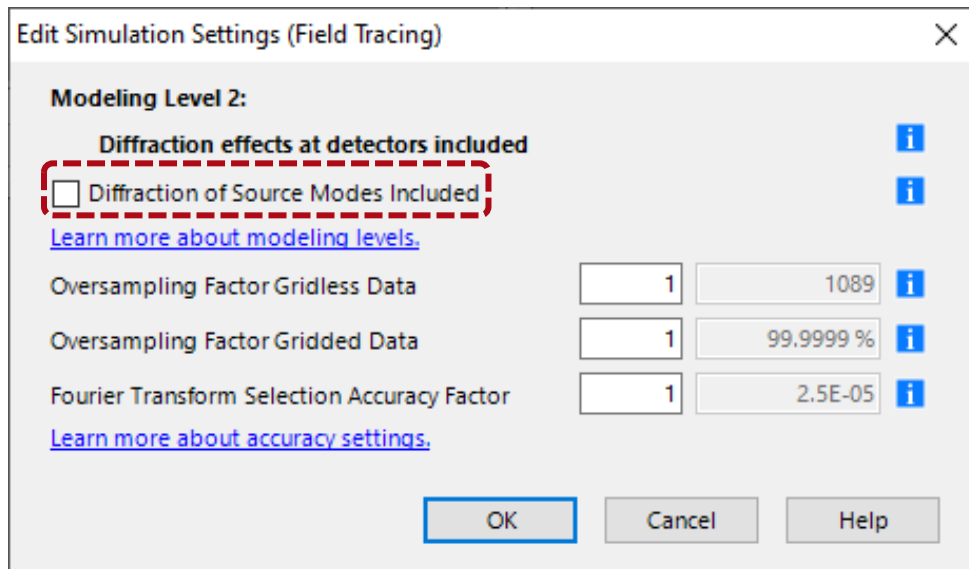
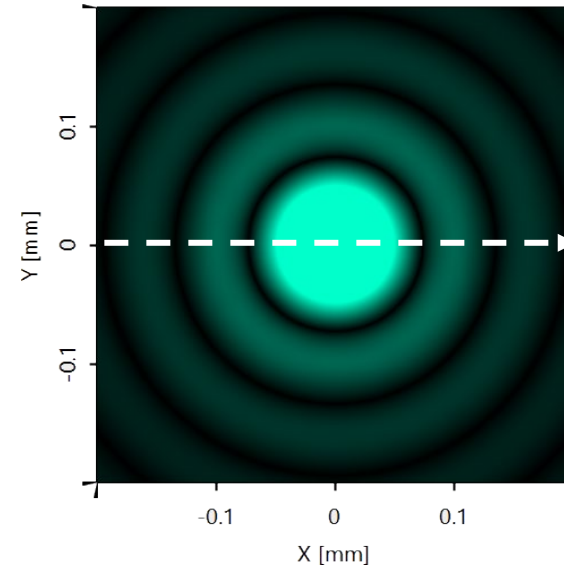
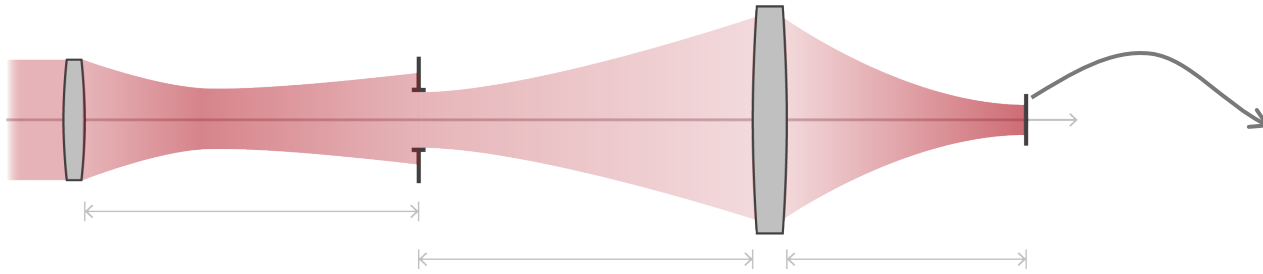
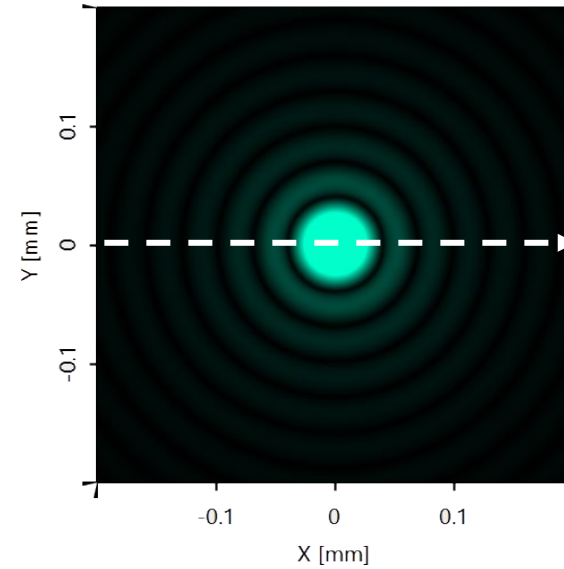
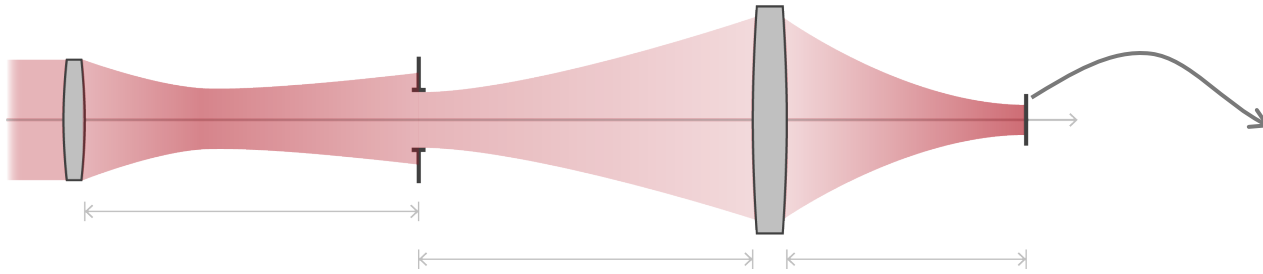


Image Evaluation by Modeling Level 3



Edit Simulation Settings (Field Tracing) ✕

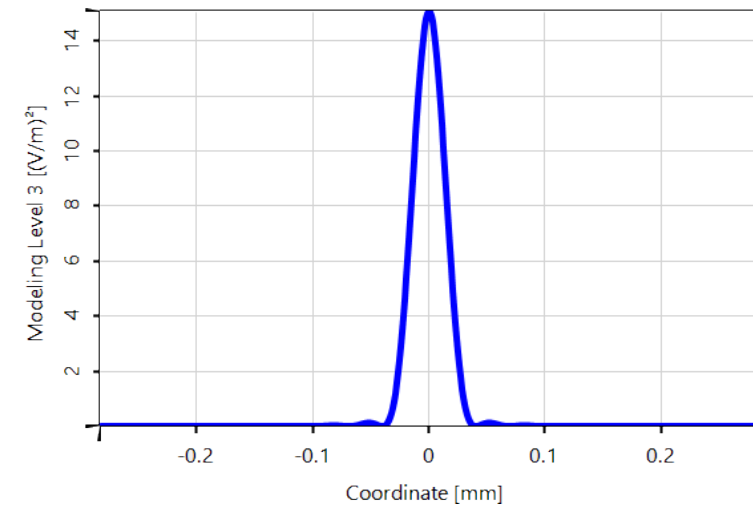
Modeling Level 3:

All diffraction effects in system included i

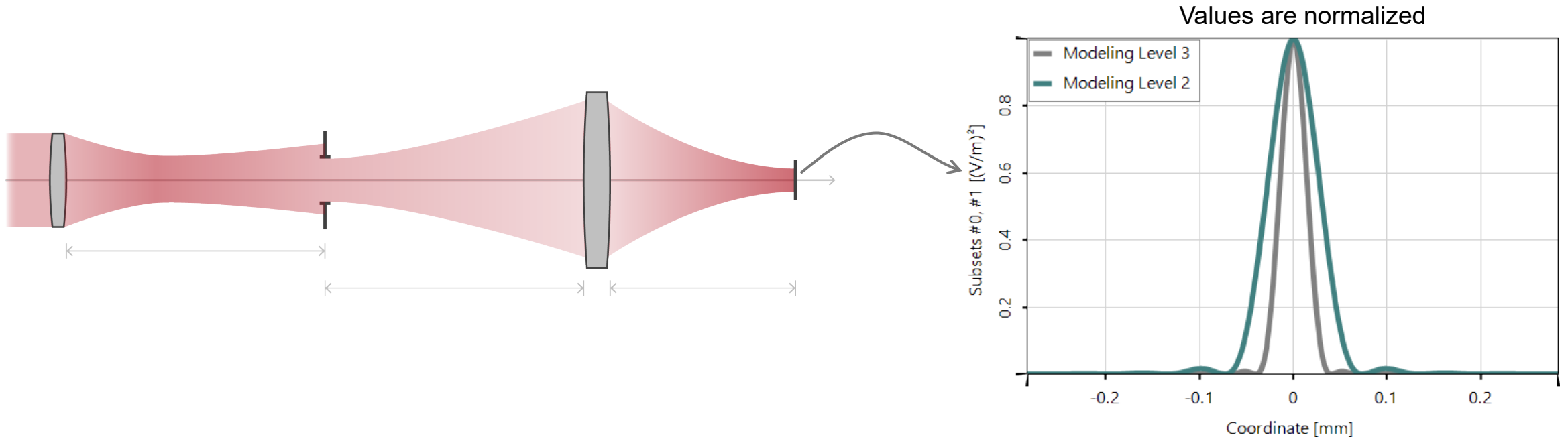
[Learn more about modeling levels.](#)

Oversampling Factor Gridless Data	<input type="text" value="1"/>	<input type="text" value="1089"/>	i
Oversampling Factor Gridded Data	<input type="text" value="1"/>	<input type="text" value="99.9999 %"/>	i
Fourier Transform Selection Accuracy Factor	<input type="text" value="1"/>	<input type="text" value="2.5E-05"/>	i

[Learn more about accuracy settings.](#)



Comparison between Modeling Level 2 & 3

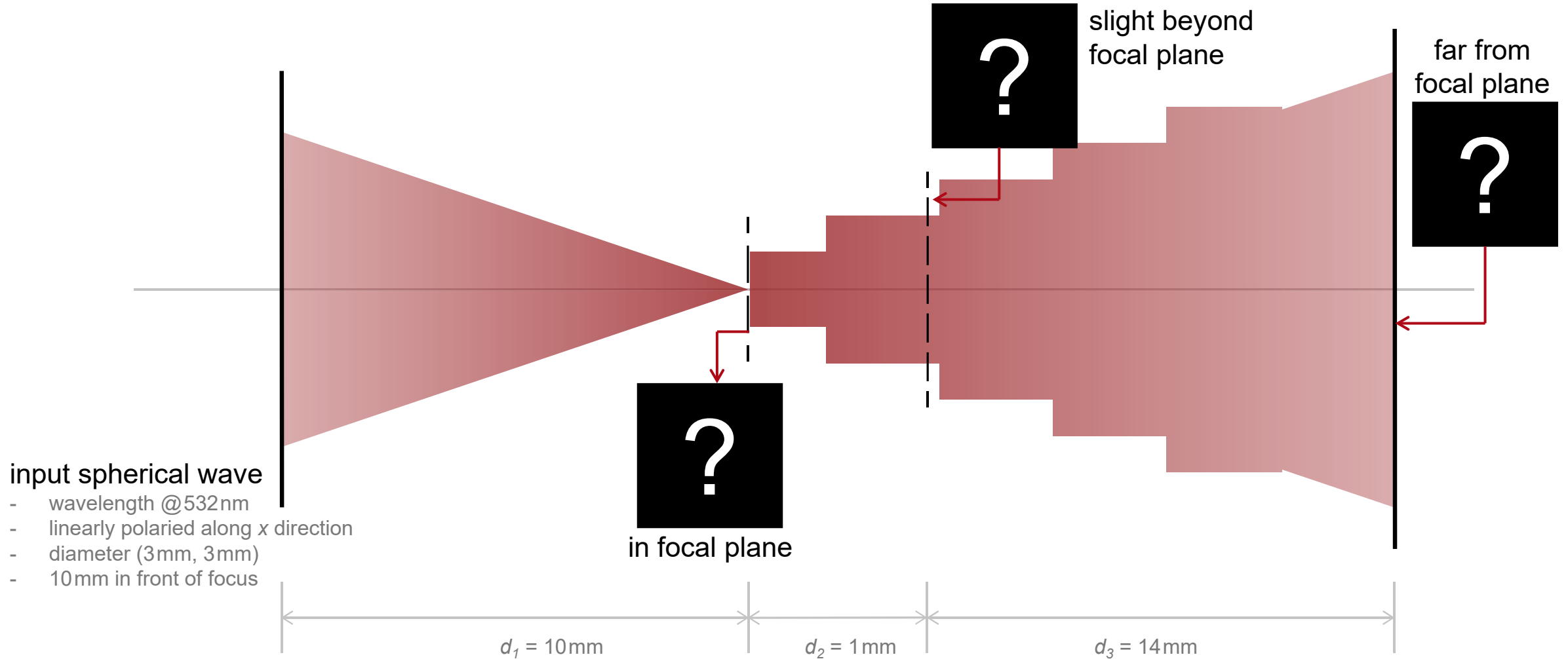


Using rigorous Fourier transform in the whole system results in truncation of a large amount of energy by the pinhole!

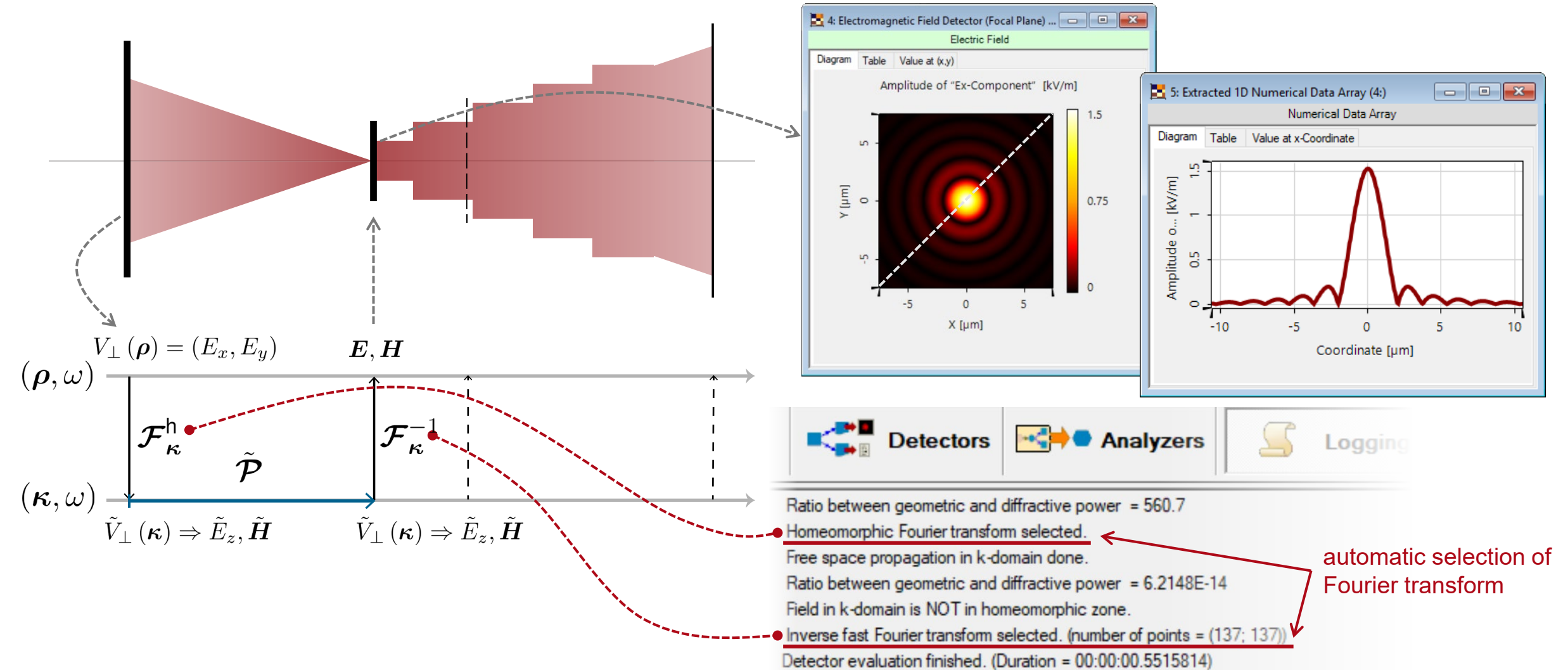
Example 1: Propagation of a Spherical Wave

 [see the full Application Use Case](#)

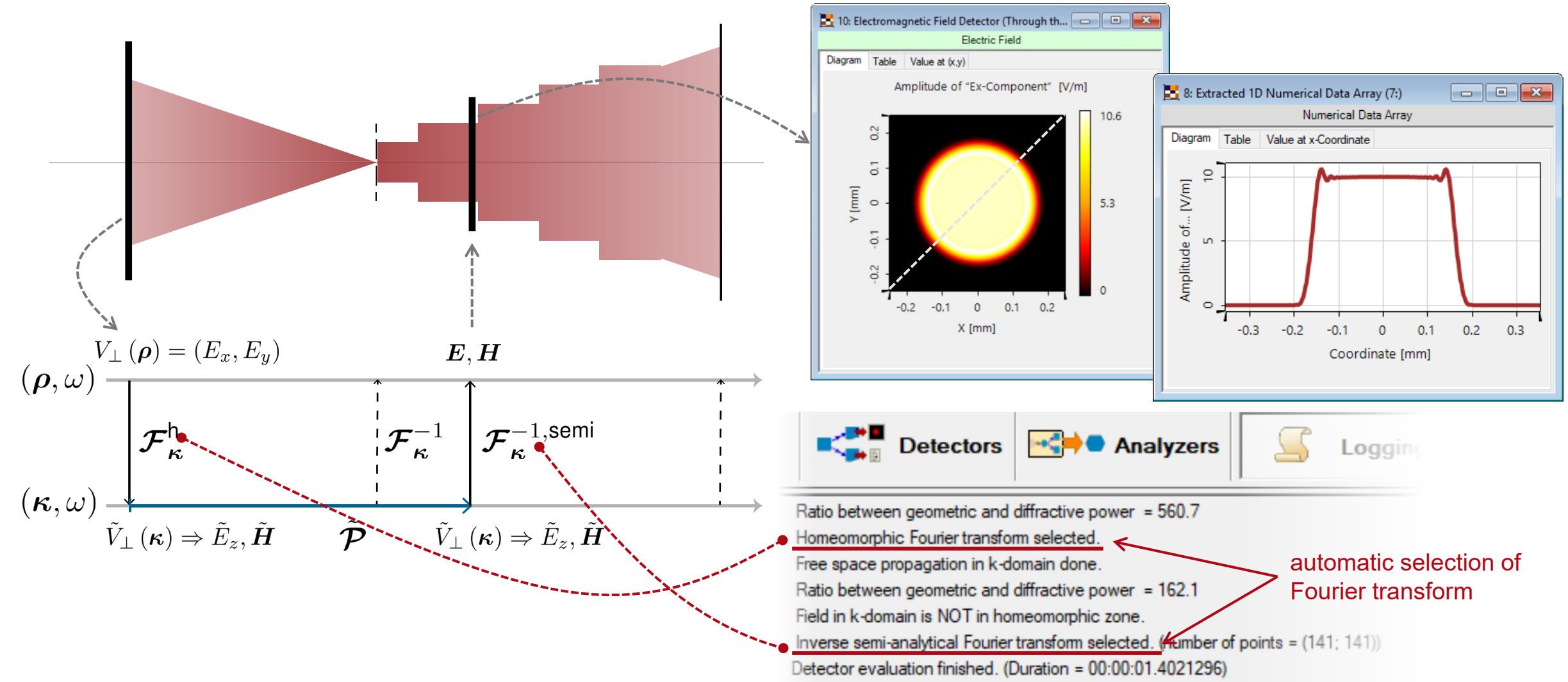
Modeling Task



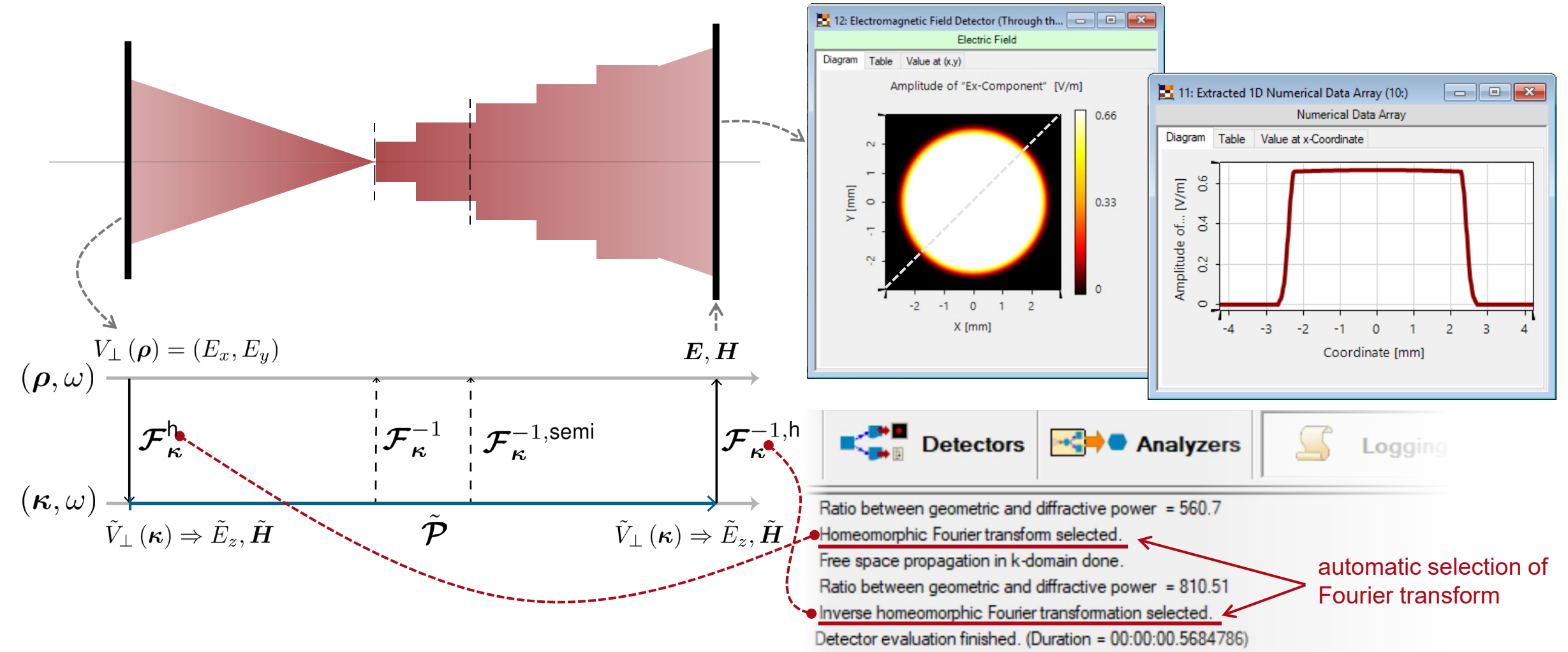
Simulation Result: in Focal Plane



Simulation Result: Slightly beyond Focal Plane



Simulation Result: Far from Focal Plane



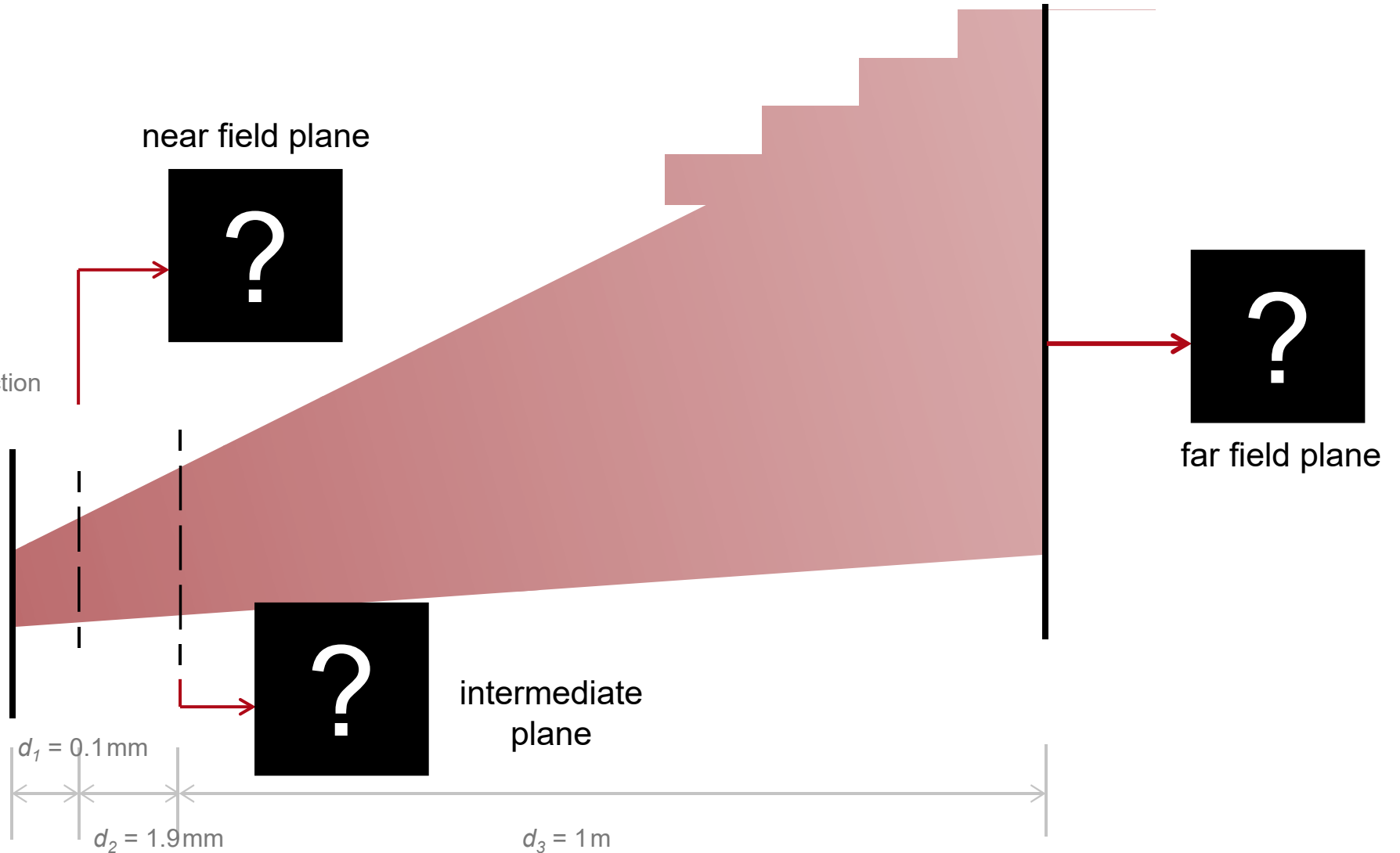
Example 2: Propagation of a Truncated Plane Wave

 [see the full Application Use Case](#)

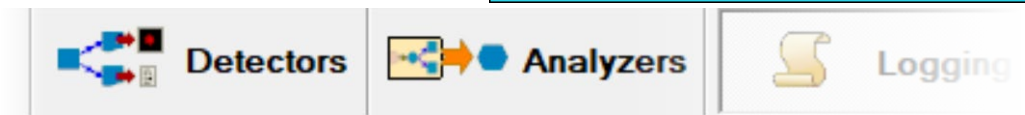
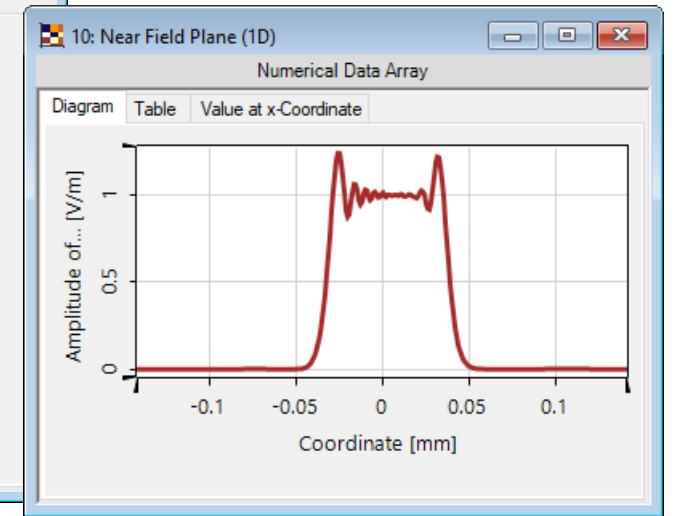
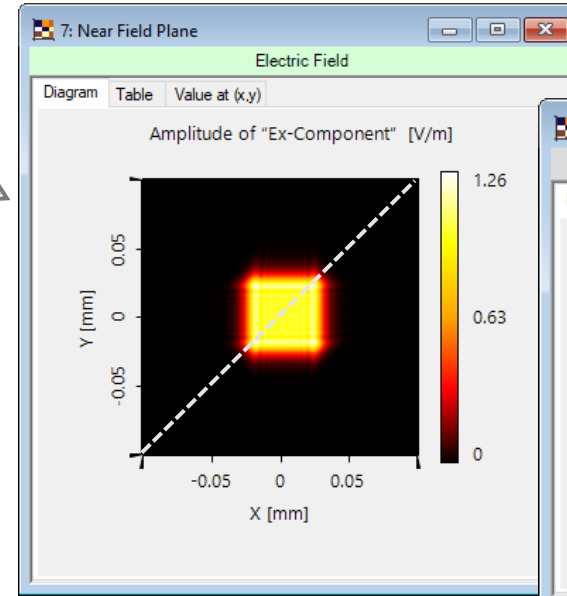
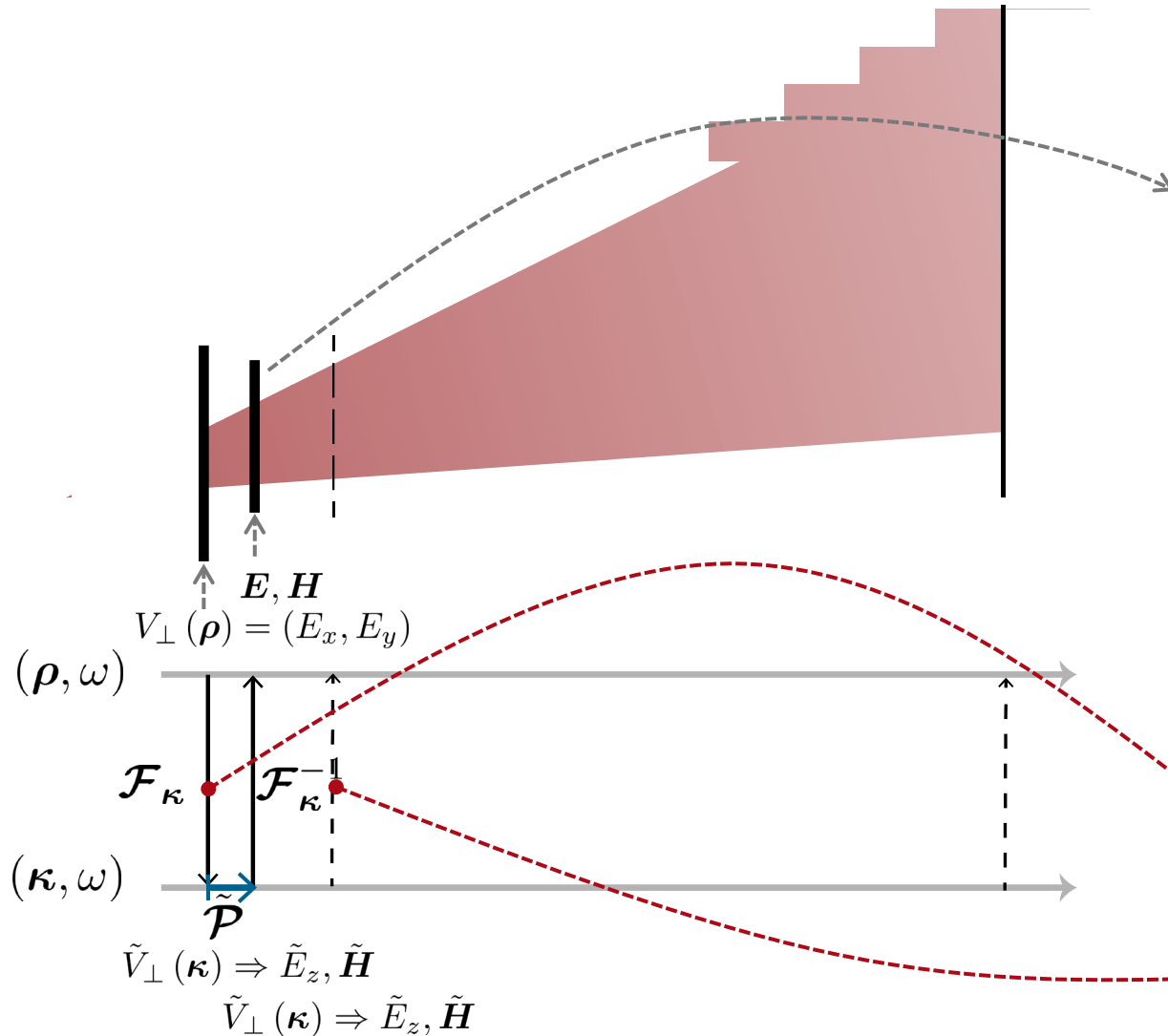
Modeling Task

truncated plane wave

- wavelength @532nm
- linearly polarized along x direction
- shape: rectangular
- diameter: (50 μ m, 50 μ m)
- inclination(10°, 20°)



Simulation Result: Near Field Plane



Ratio between geometric and diffractive power = 1.0774E-13

Field in x-domain is NOT in homeomorphic zone.

Fast Fourier transform selected. (number of points = (137; 137))

Free space propagation in k-domain done.

Ratio between geometric and diffractive power = 0.042497

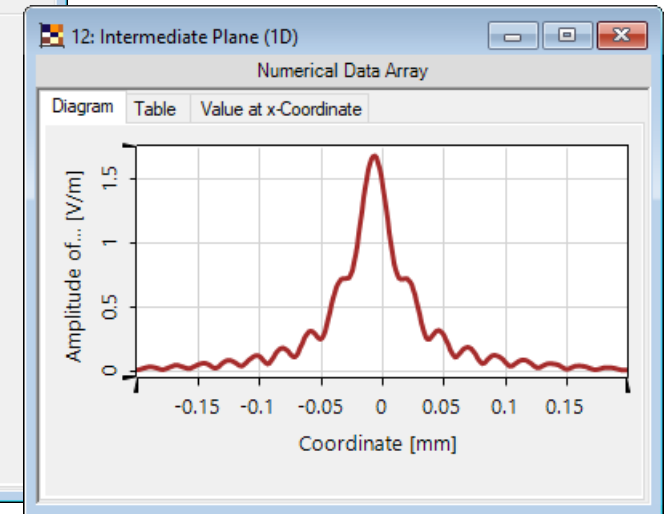
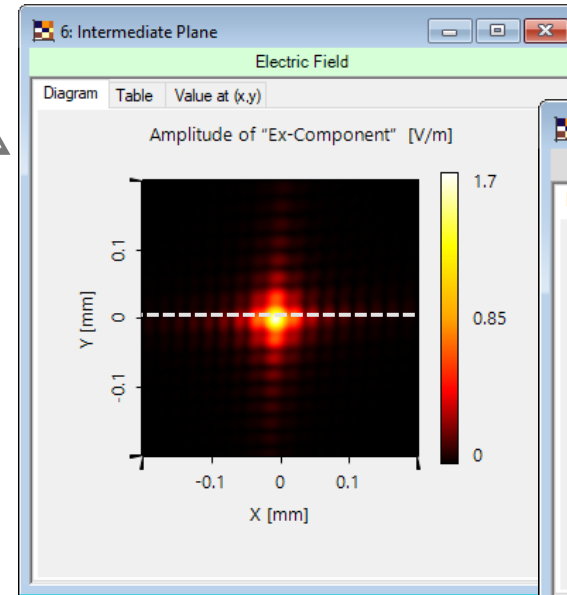
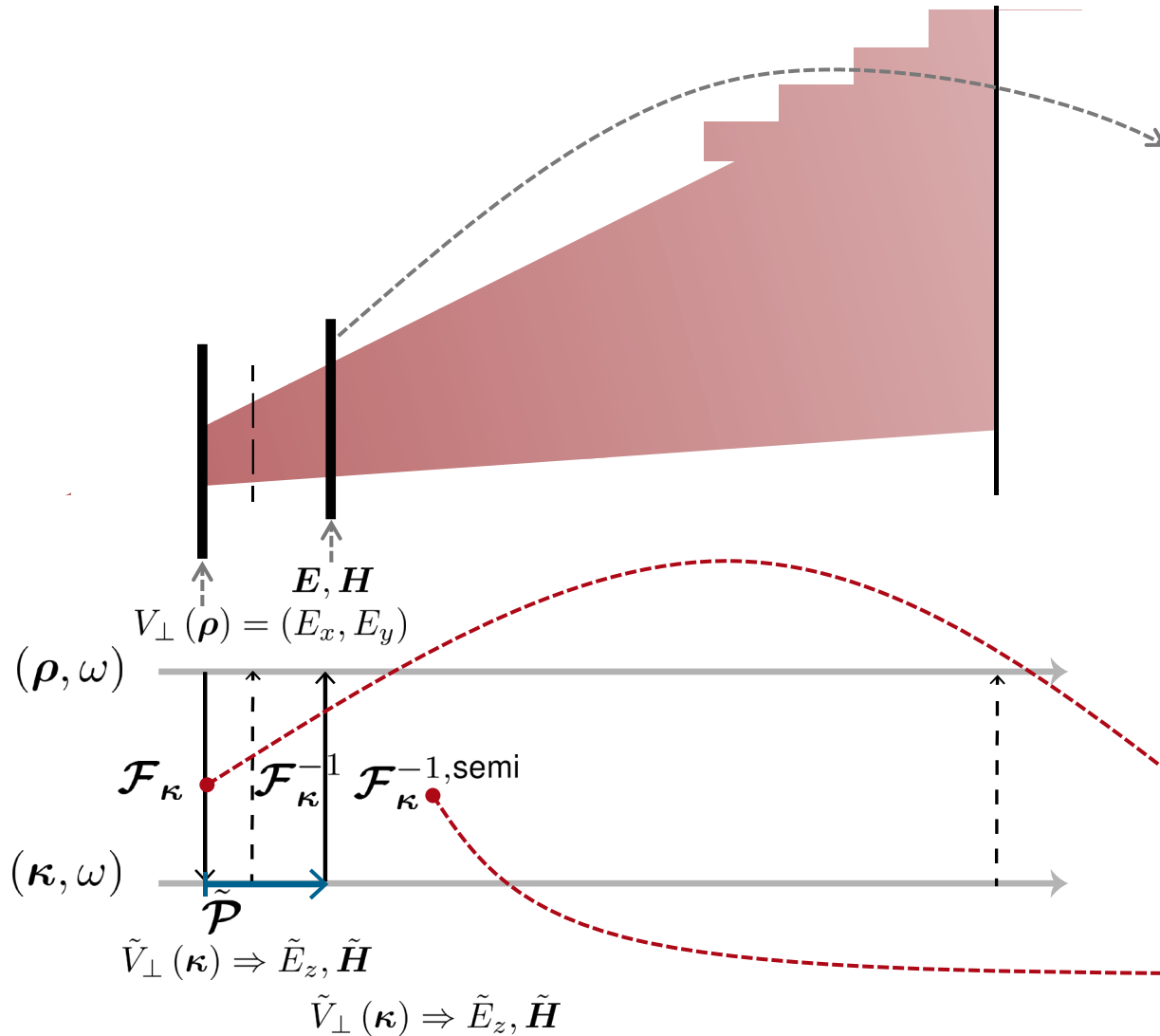
Field in k-domain is NOT in homeomorphic zone.

Inverse fast Fourier transform selected. (number of points = (1005; 1055))

Detector evaluation finished. (Duration = 00:00:02.3430915)

automatic selection of
Fourier transform

Simulation Result: Intermediate Plane

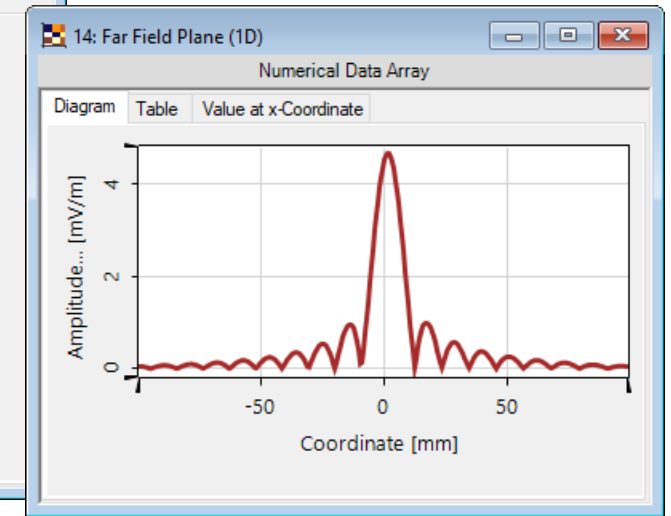
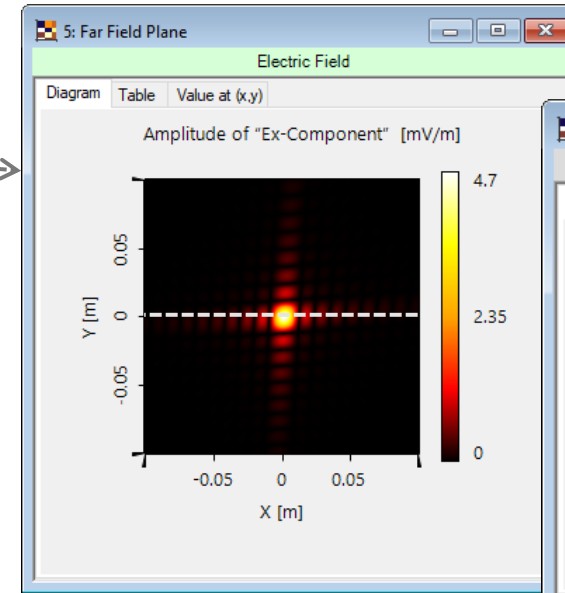
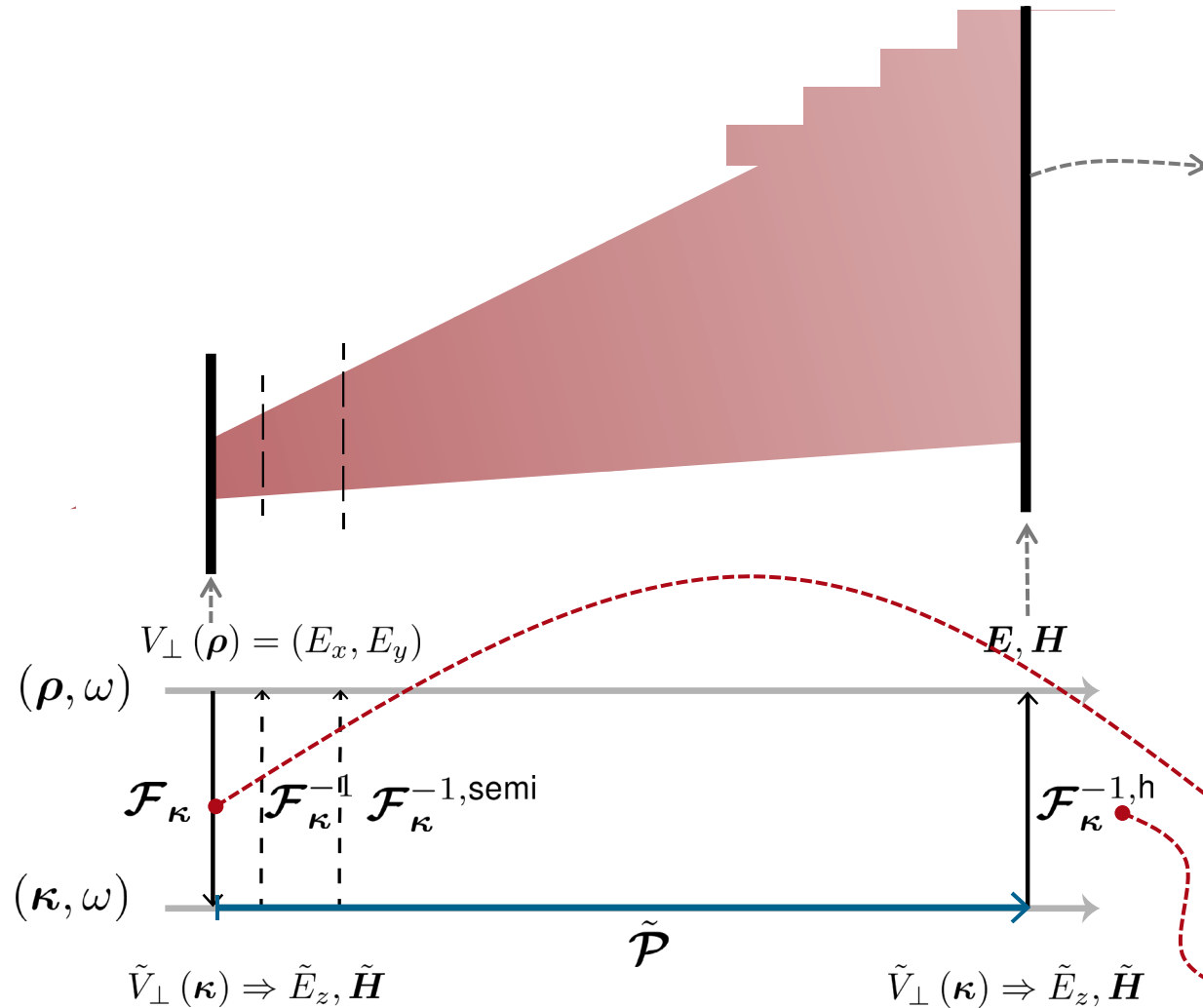


Detectors **Analyzers** **Logging**

Ratio between geometric and diffractive power = 1.3091E-13
 Field in x-domain is NOT in homeomorphic zone.
Fast Fourier transform selected. (number of points = (137; 137))
 Free space propagation in k-domain done.
 Ratio between geometric and diffractive power = 0.84993
 Field in k-domain is NOT in homeomorphic zone.
Inverse semi-analytical Fourier transform selected. (number of points = (1195; 1663))
 Detector evaluation finished. (Duration = 00:00:15.7667738)

automatic selection of Fourier transform

Simulation Result: Far Field Plane



Detectors Analyzers Logging

Ratio between geometric and diffractive power = 1.2744E-13

Field in x-domain is NOT in homeomorphic zone.

Fast Fourier transform selected. (number of points = (137; 133))

Free space propagation in k-domain done.

Ratio between geometric and diffractive power = 431.71

Inverse homeomorphic Fourier transformation selected.

Detector evaluation finished. (Duration = 00:00:00.9925490)

automatic selection of Fourier transform

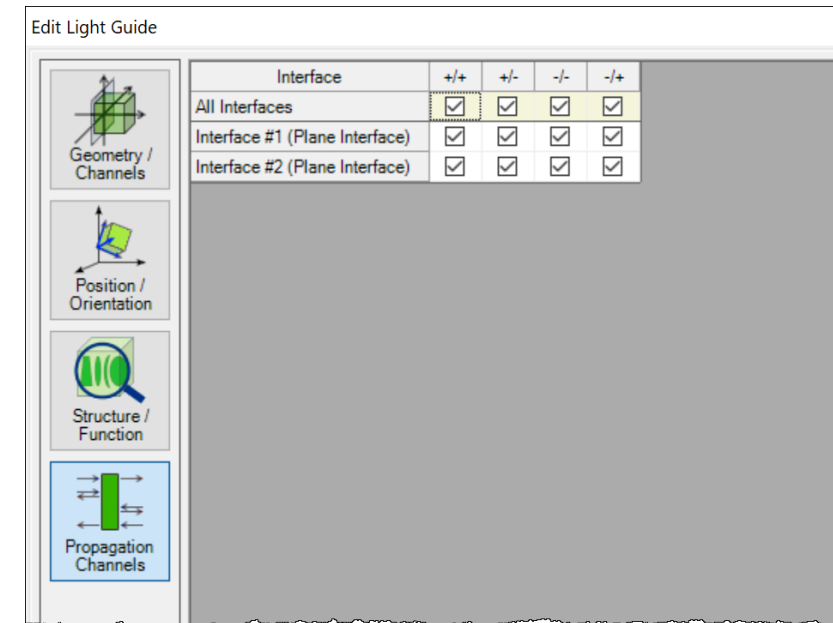
Part 4

The Channel Concept



Surface Channels

- Channel definition
 - There are four possible channels for each surface, at least one should be activated for the tracing.
 - Channels can be defined for each surface individually.
 - Different settings on channels leads to different modeling schemes.

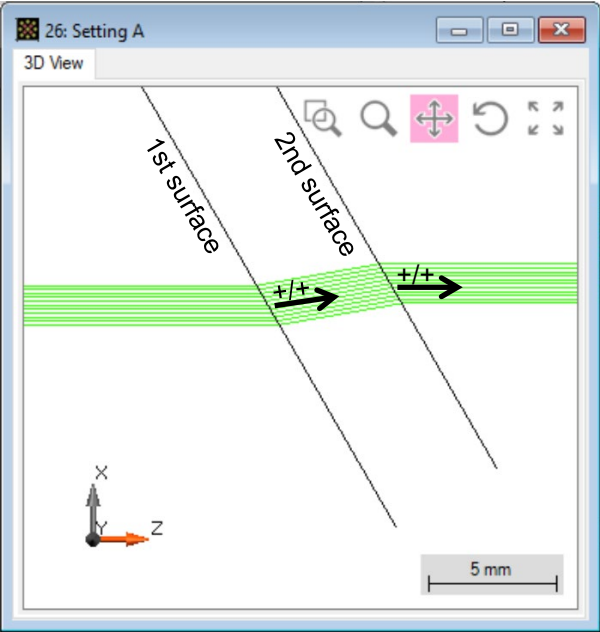


Channel Description

+/+	transmission (forward)
+/-	reflection (forward)
-/+	reflection (backward)
-/-	transmission (backward)

Surface Channels

Setting A

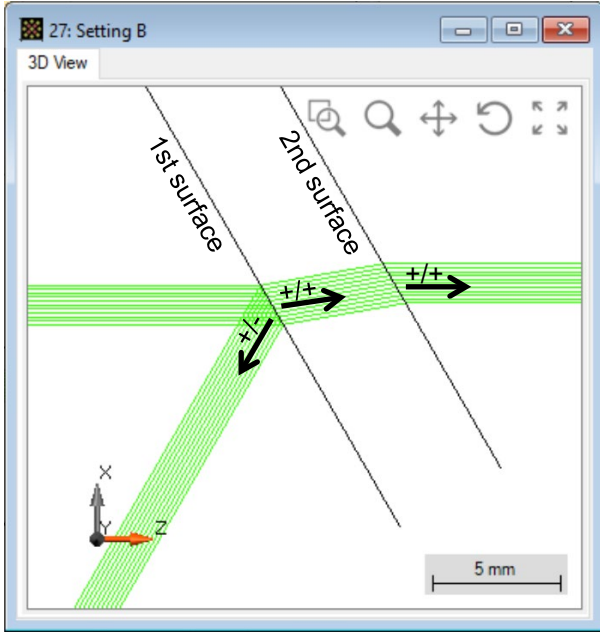


Surface	± 0.1	± 0.05	± 0.02	± 0.01
---------	-----------	------------	------------	------------

1st	\times			
-----	----------	--	--	--

2nd	\times			
-----	----------	--	--	--

Setting B

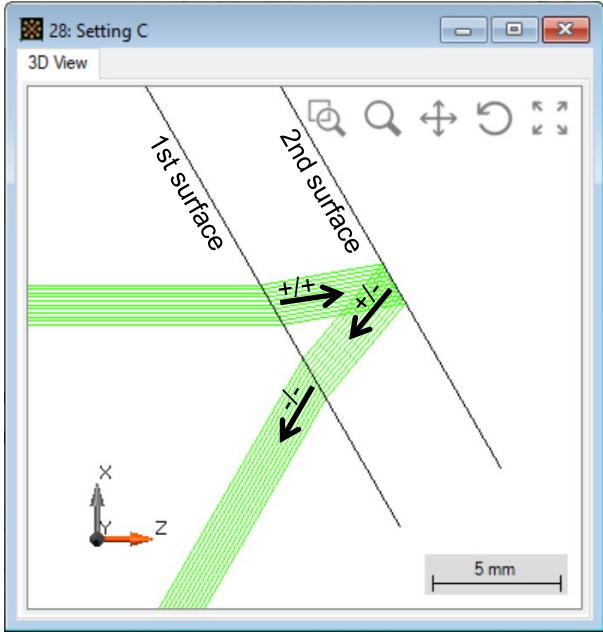


Surface	± 0.1	± 0.05	± 0.02	± 0.01
---------	-----------	------------	------------	------------

1st	\times	\times		
-----	----------	----------	--	--

2nd	\times			
-----	----------	--	--	--

Setting C



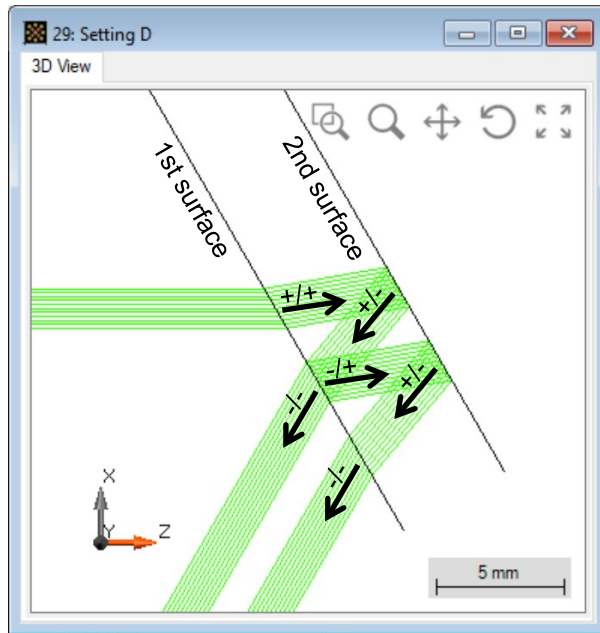
Surface	± 0.1	± 0.05	± 0.02	± 0.01
---------	-----------	------------	------------	------------

1st	\times		\times	
-----	----------	--	----------	--

2nd		\times		
-----	--	----------	--	--

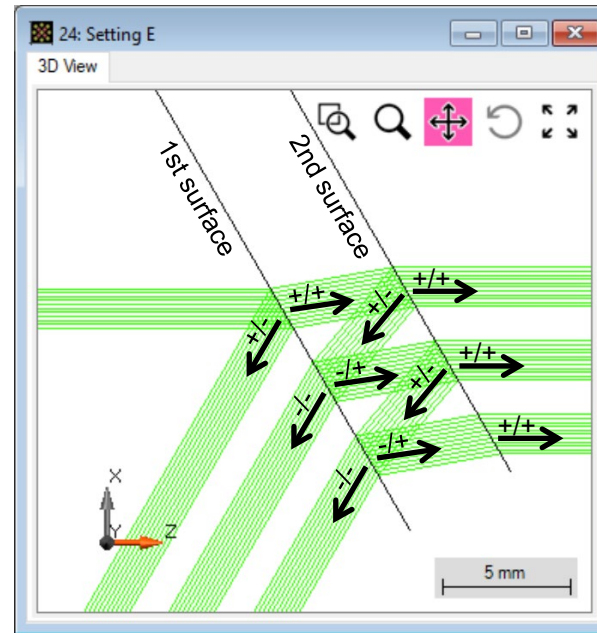
Surface Channels

Setting D



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

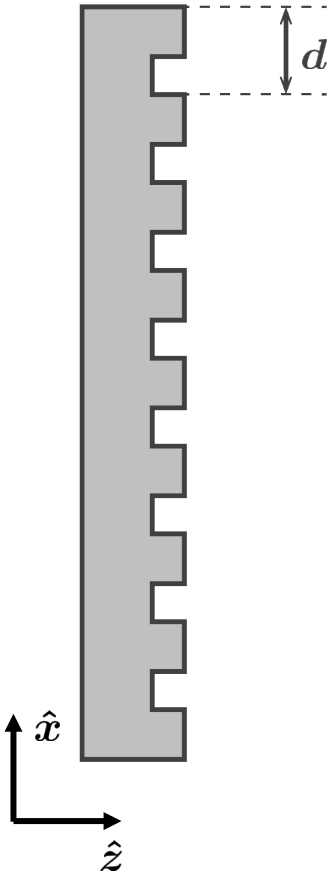
Setting E



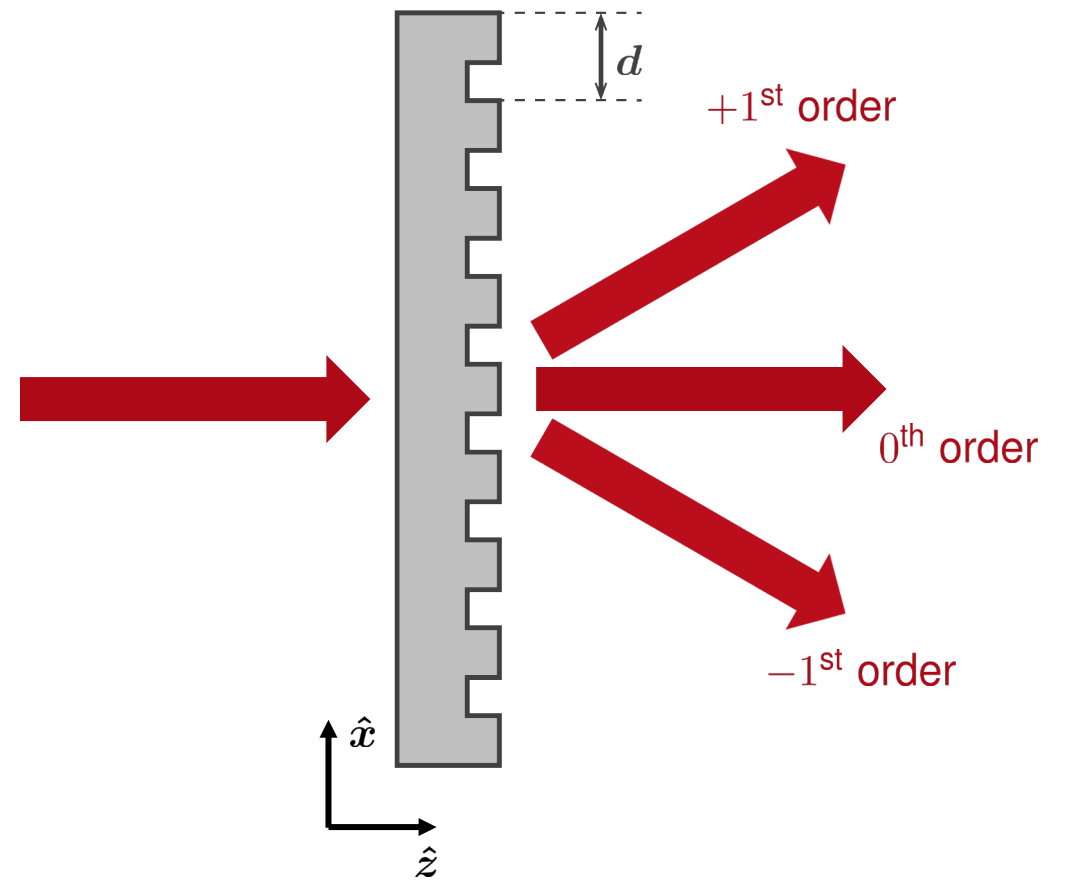
Surface	+/+	+/-	-/-	-/+
1st	×	×	×	×
2nd	×	×	×	×

Note: an activated channel does not necessarily lead to corresponding light path(s). E.g., the -/- and -/+ channel of 2nd interface do not influence the tracing, because there is no backward incidence.

Grating Channels



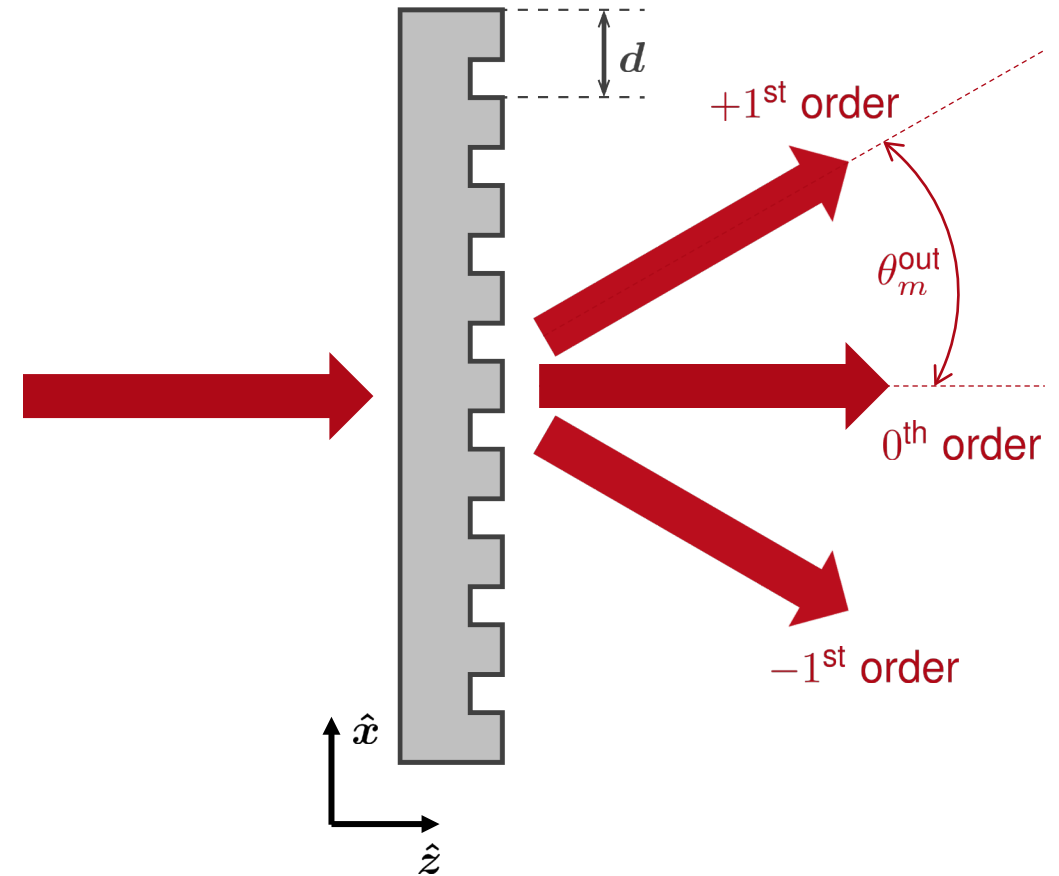
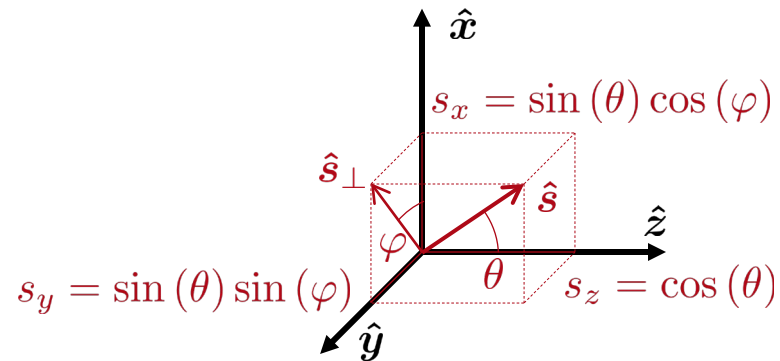
Grating Channels



Grating Channels

Grating equation:

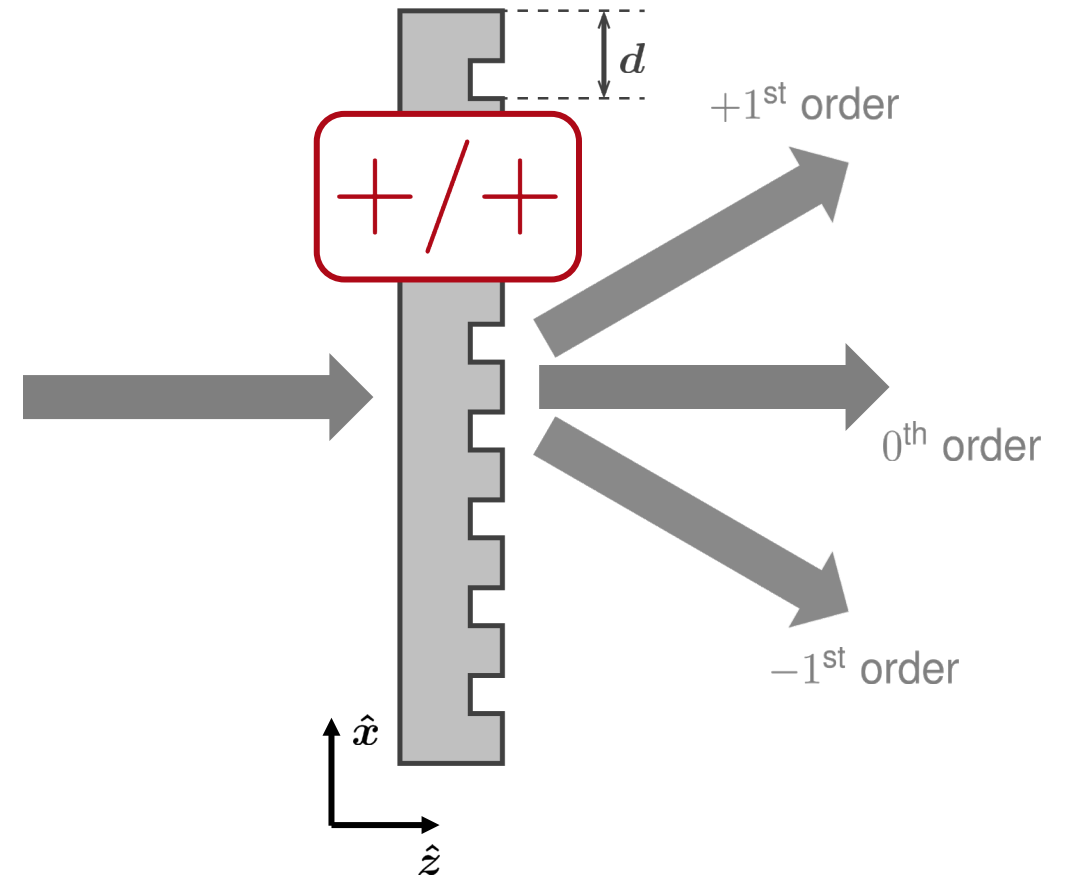
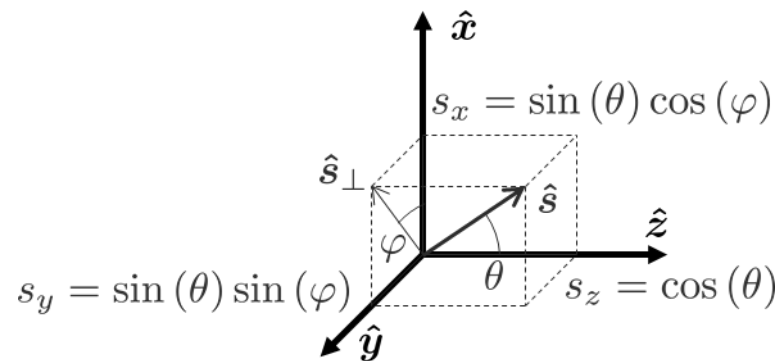
- $\kappa_m^{\text{out}} = \kappa^{\text{in}} + m\Delta\kappa$,
- where $\kappa_m^{\text{out}} = \mathbf{k}_{m,\perp}^{\text{out}} = (k_{m,x}^{\text{out}}, k_{m,y}^{\text{out}}) = nk_0\hat{\mathbf{s}}_{m,\perp}^{\text{out}}$ (with m the order),
- $\kappa^{\text{in}} = \mathbf{k}_{\perp}^{\text{in}} = (k_x^{\text{in}}, k_y^{\text{in}}) = nk_0\hat{\mathbf{s}}_{\perp}^{\text{in}}$ and
- $\Delta\kappa = \frac{2\pi}{d}$



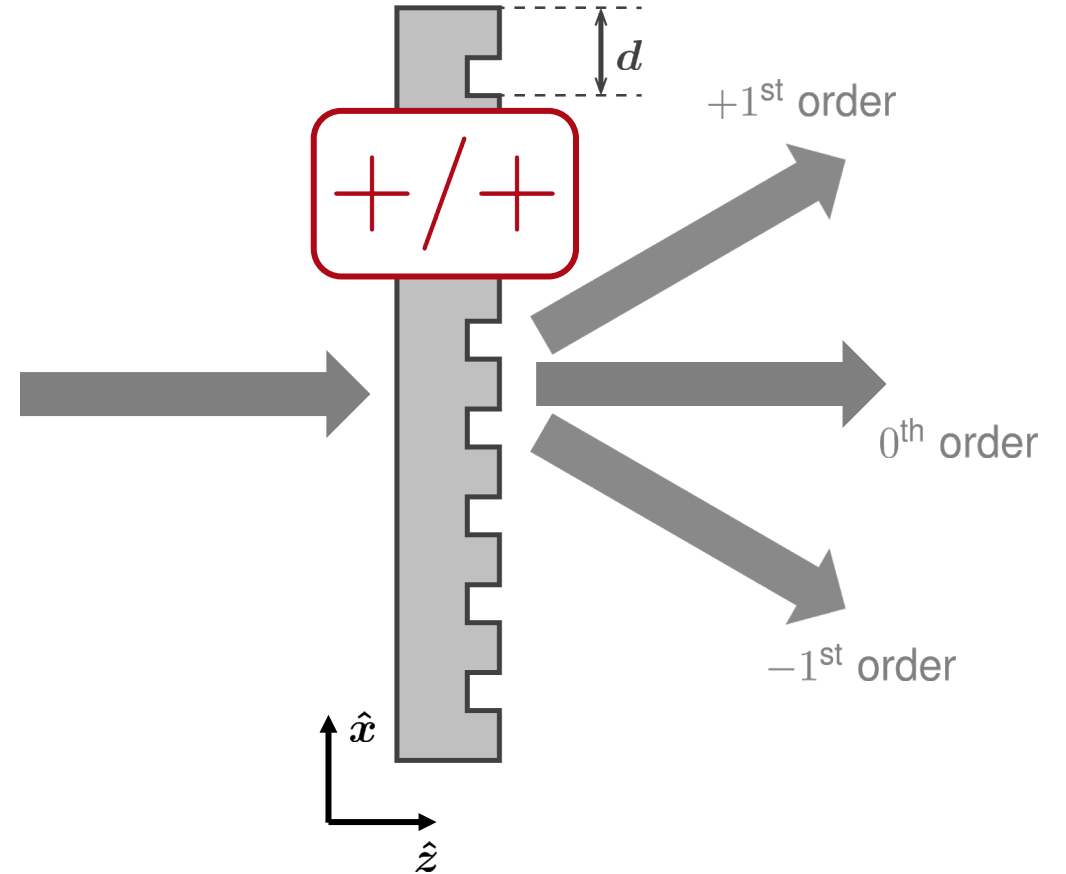
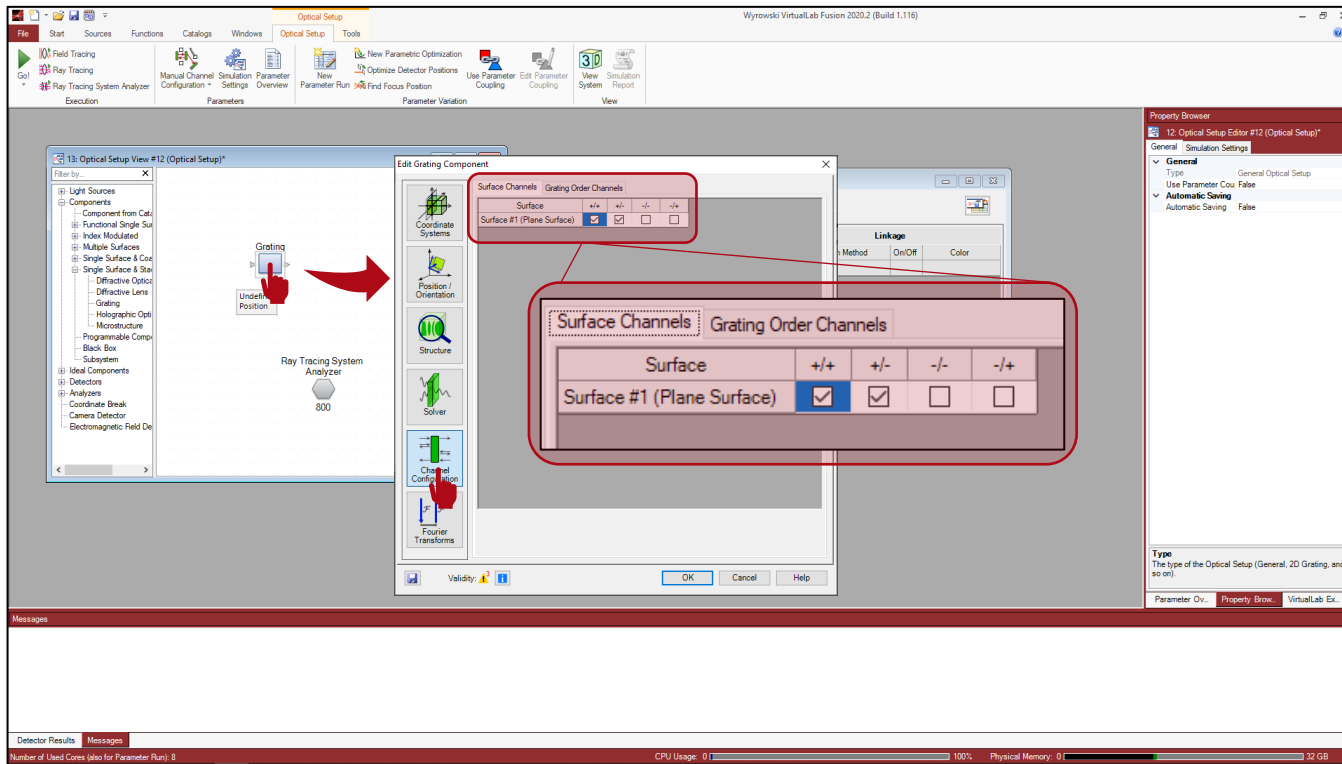
Grating Channels

Grating equation:

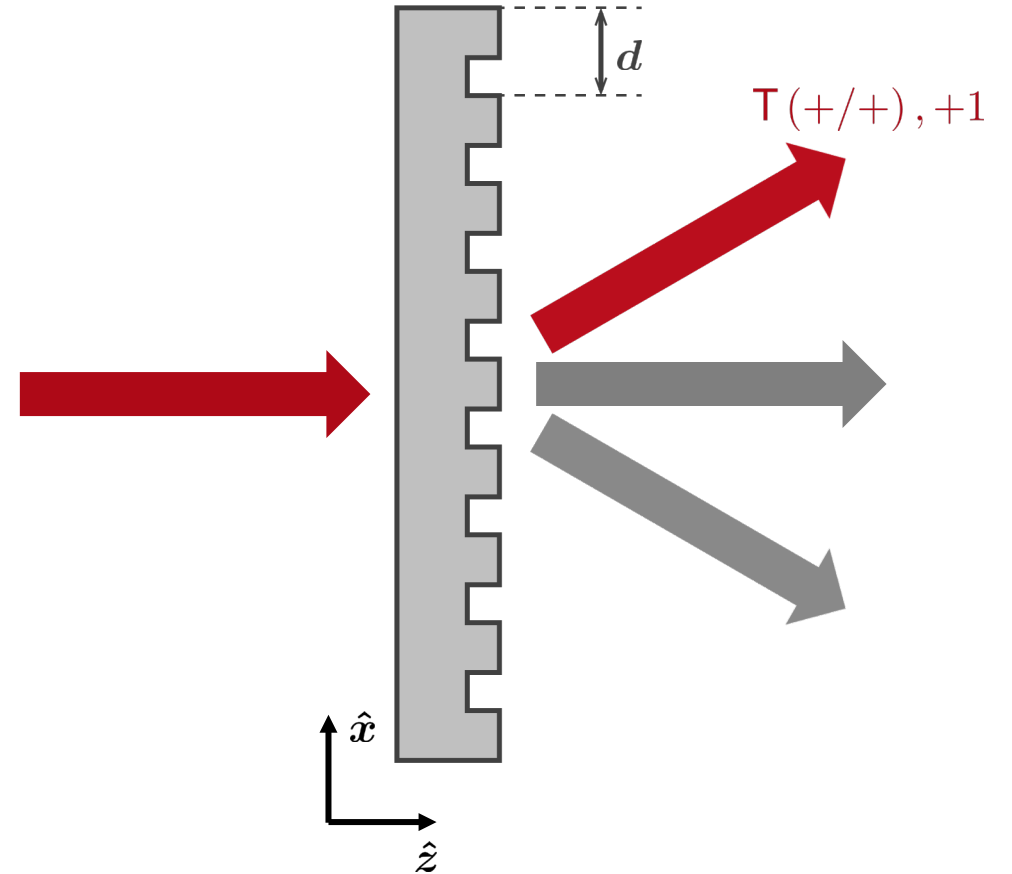
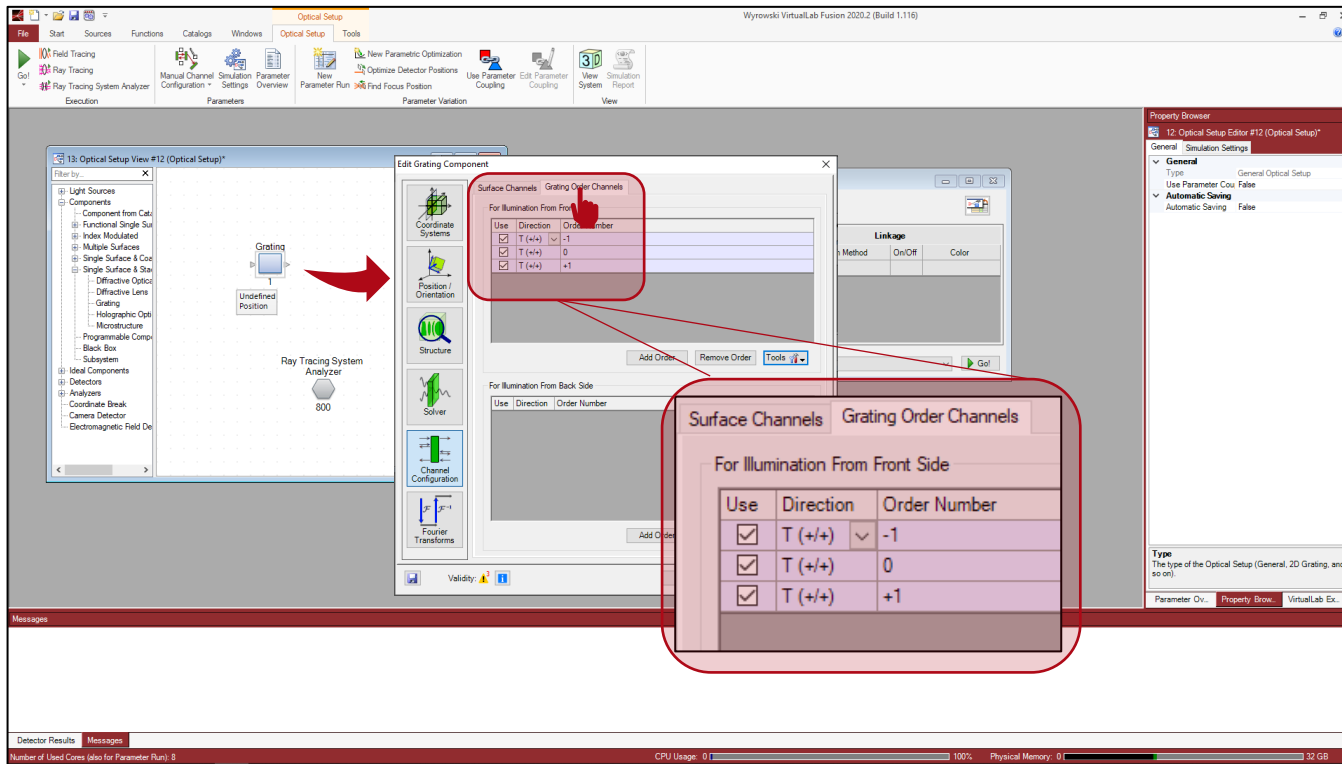
- $\kappa_m^{\text{out}} = \kappa^{\text{in}} + m\Delta\kappa$,
- where $\kappa_m^{\text{out}} = \mathbf{k}_{m,\perp}^{\text{out}} = (k_{m,x}^{\text{out}}, k_{m,y}^{\text{out}}) = nk_0 \hat{\mathbf{s}}_{m,\perp}^{\text{out}}$ (with m the order),
- $\kappa^{\text{in}} = \mathbf{k}_{\perp}^{\text{in}} = (k_x^{\text{in}}, k_y^{\text{in}}) = nk_0 \hat{\mathbf{s}}_{\perp}^{\text{in}}$ and
- $\Delta\kappa = \frac{2\pi}{d}$



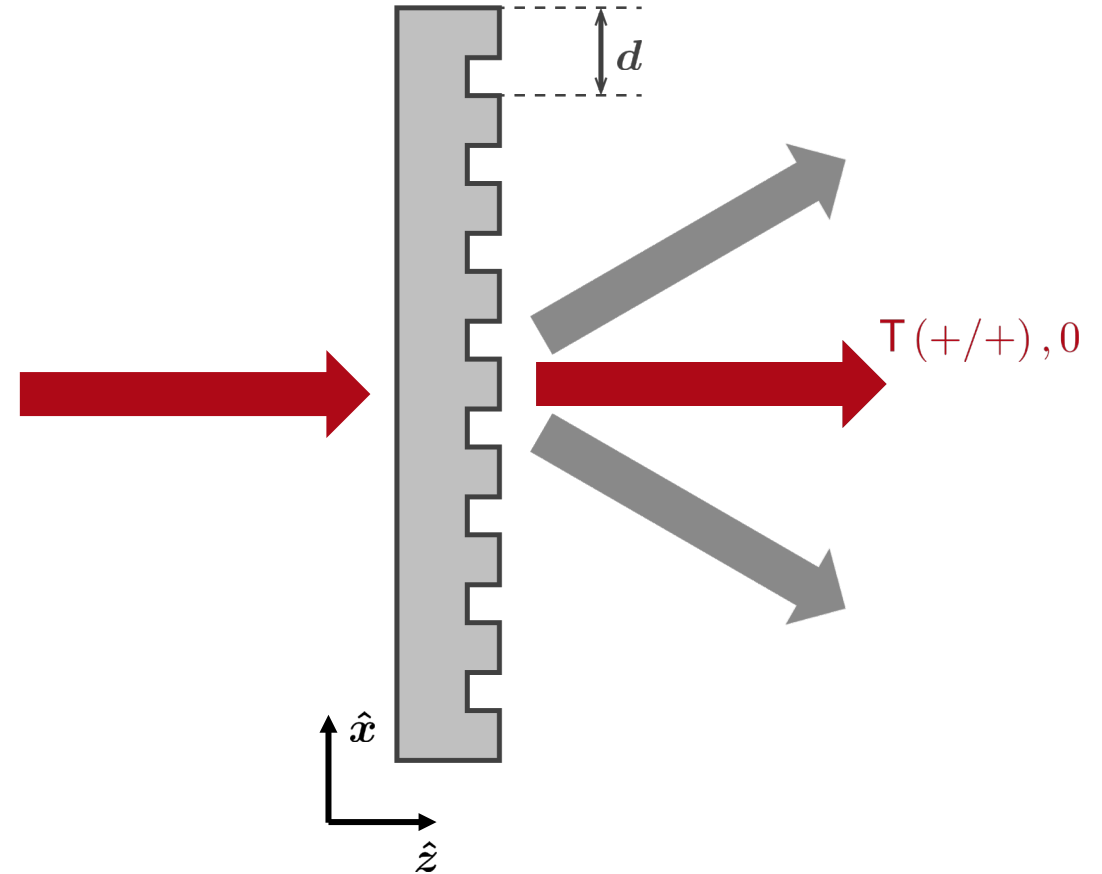
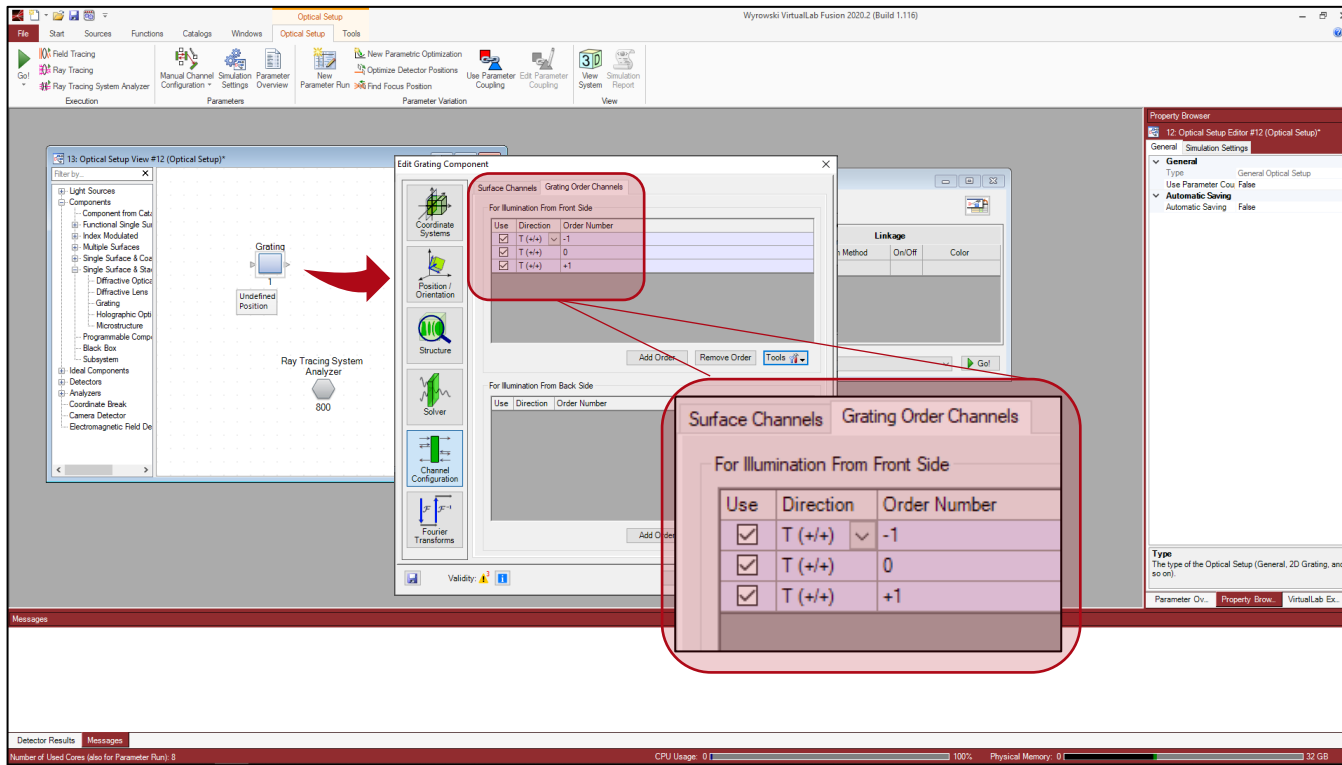
Grating Channels



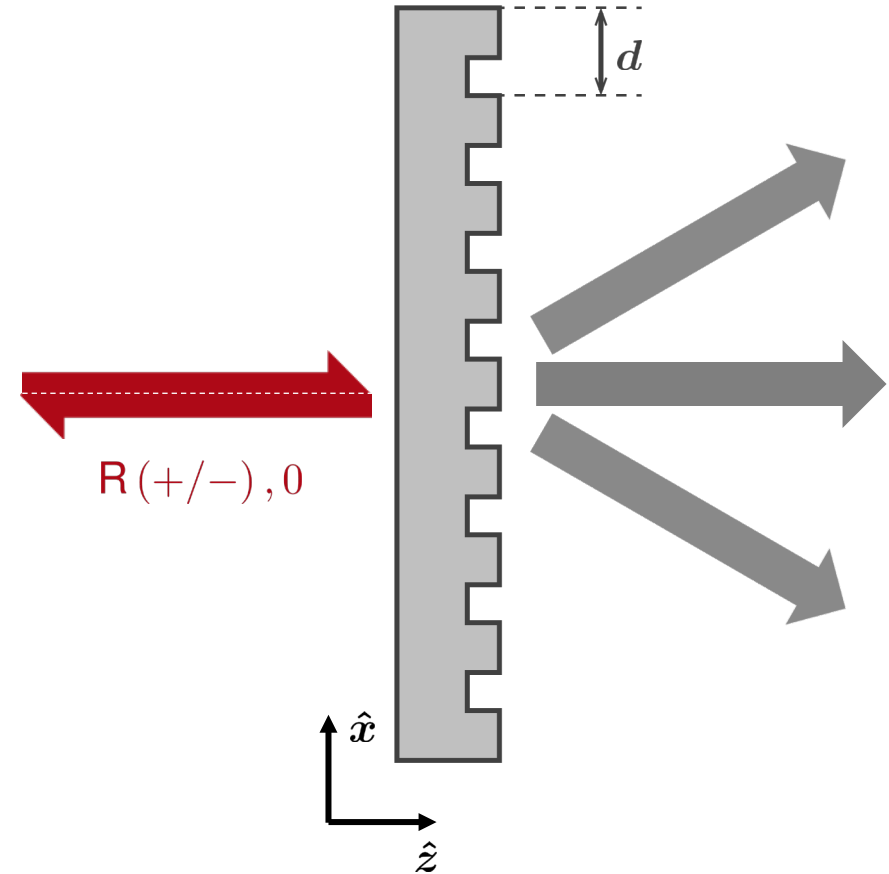
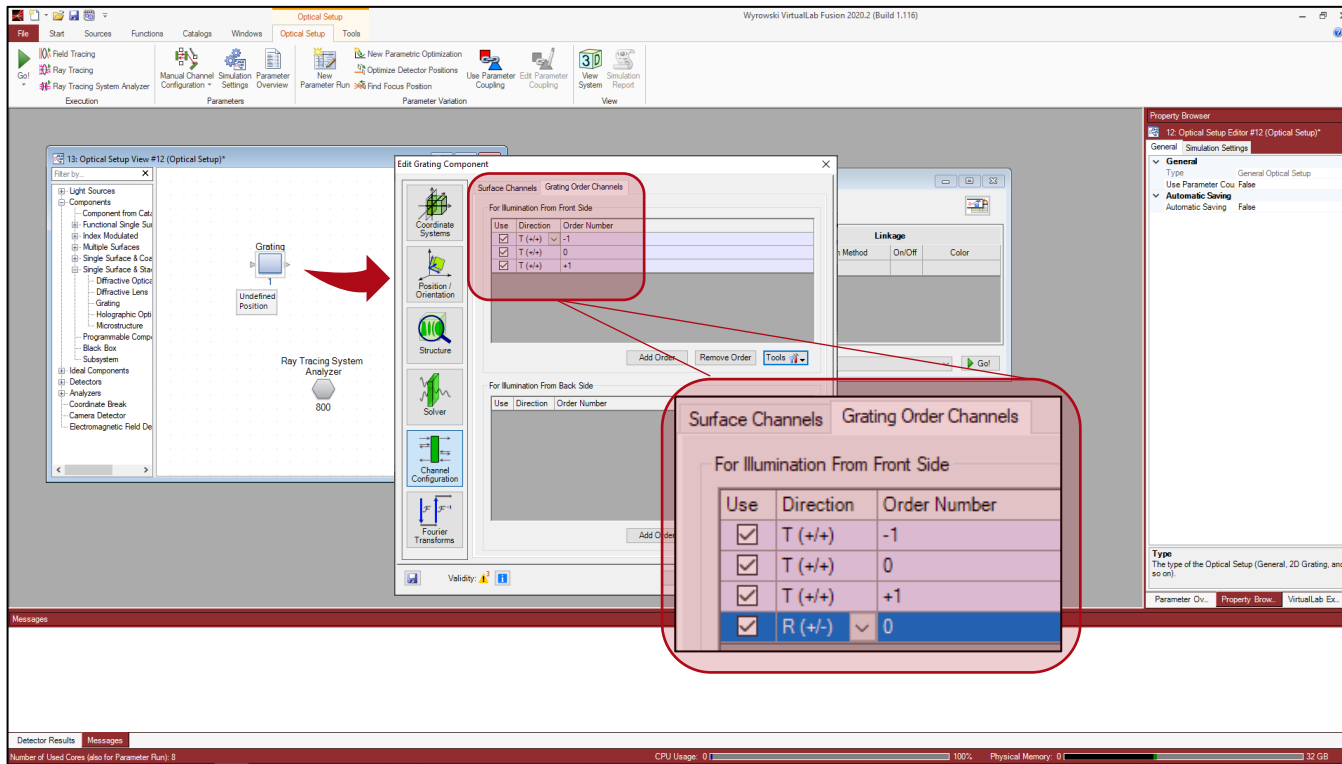
Grating Channels



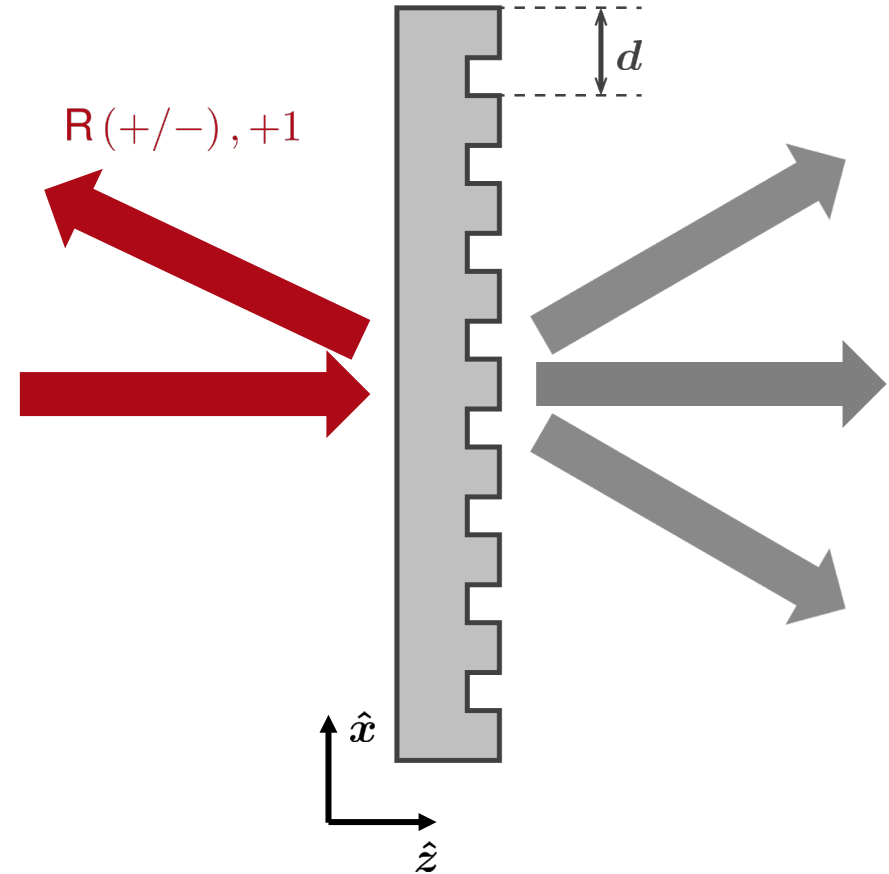
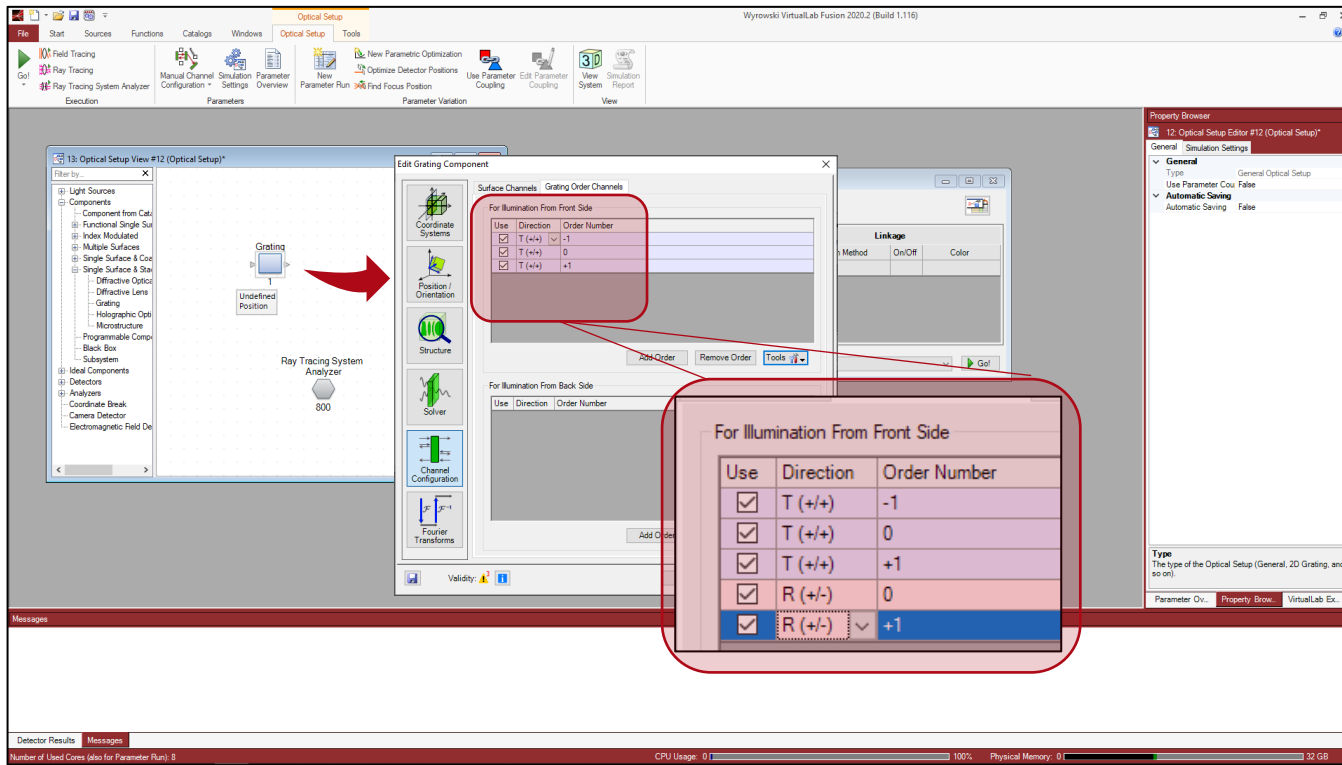
Grating Channels



Grating Channels



Grating Channels



Grating Channels in Abbe's Experiment

26: Ray Distribution 3D

3D View 2D View

grating

How many orders need to be considered in the modeling?

Edit Grating Component

Surface Channels Grating Order Channels

For Illumination From Front Side

Use	Direction	Order Number
<input checked="" type="checkbox"/>	T (+/+)	-5
<input checked="" type="checkbox"/>	T (+/+)	-4
<input checked="" type="checkbox"/>	T (+/+)	-3
<input checked="" type="checkbox"/>	T (+/+)	-2
<input checked="" type="checkbox"/>	T (+/+)	-1
<input checked="" type="checkbox"/>	T (+/+)	0
<input checked="" type="checkbox"/>	T (+/+)	+1
<input checked="" type="checkbox"/>	T (+/+)	+2

Add Order Remove Order Tools

For Illumination From Back Side

Use	Direction	Order Number
-----	-----------	--------------

Add Order Remove Order Tools

Coordinate Systems
Position / Orientation
Structure
Solver
Channel Configuration
Fourier Transforms

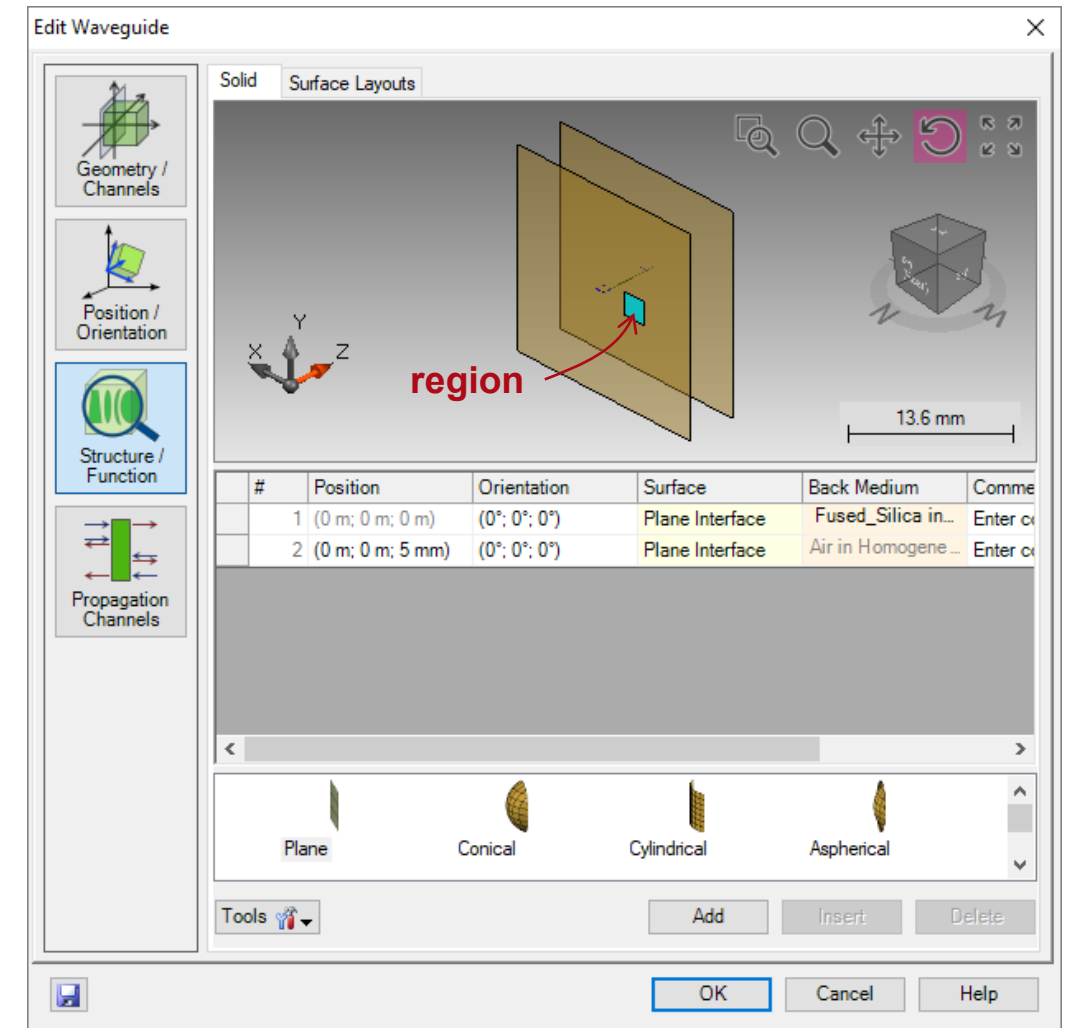
Validity: 3

OK Cancel Help

1 mm

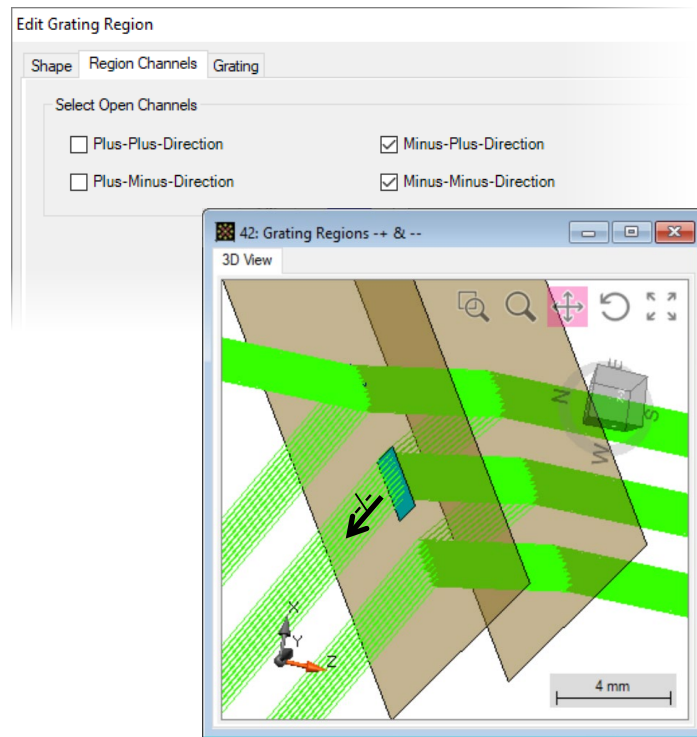
Lateral Channels

- Region(s) on surface
 - It is possible to define individual Regions on a surface and define their optical properties individually, including the channel settings.

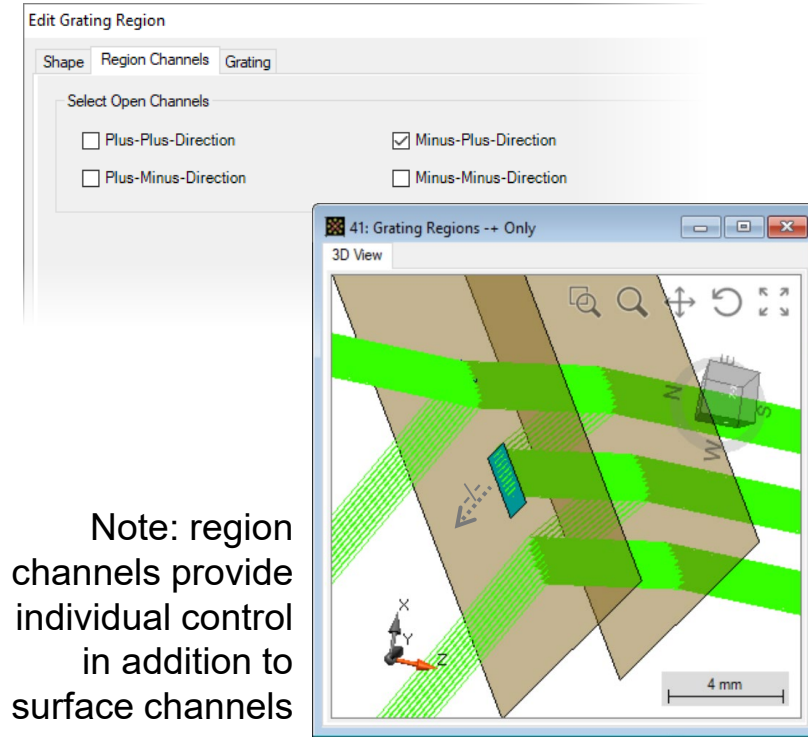


Lateral Channels

- Region definition
 - Set up the channels for this region, following the same rule as for the surfaces.



region channels -/+ , -/- on



Note: region channels provide individual control in addition to surface channels

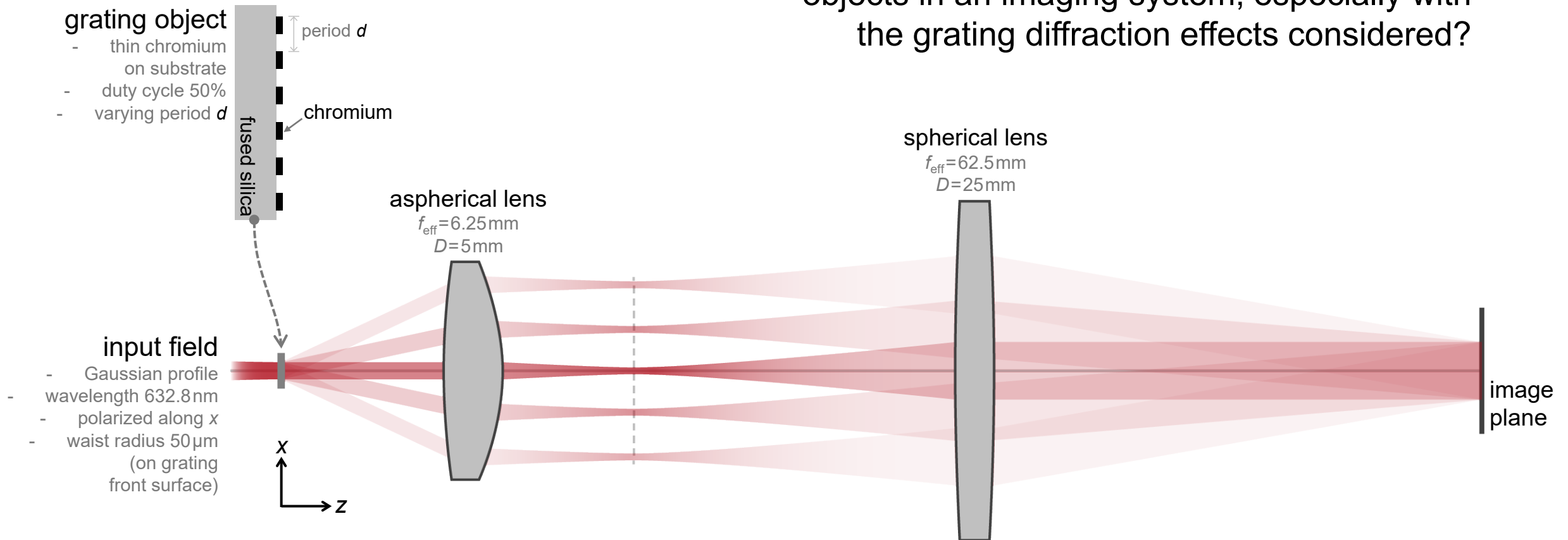
region channel -/+ on

Demonstration of Abbe's Theory of Image Formation

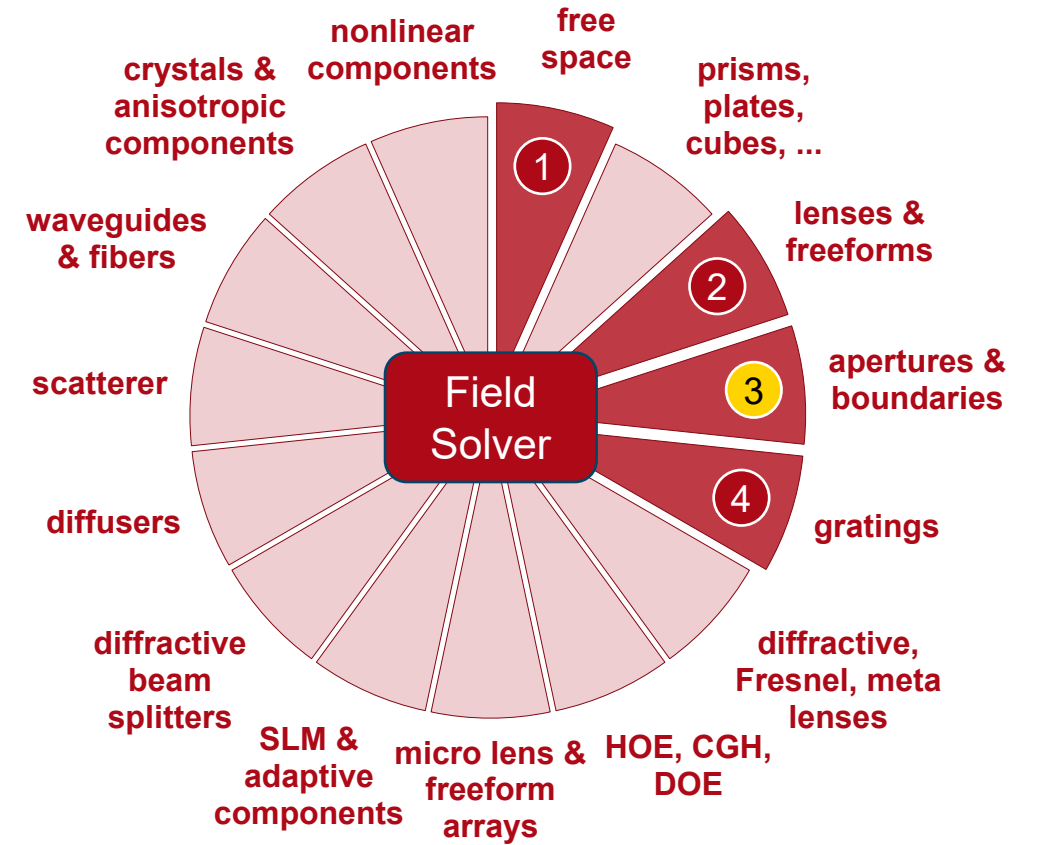
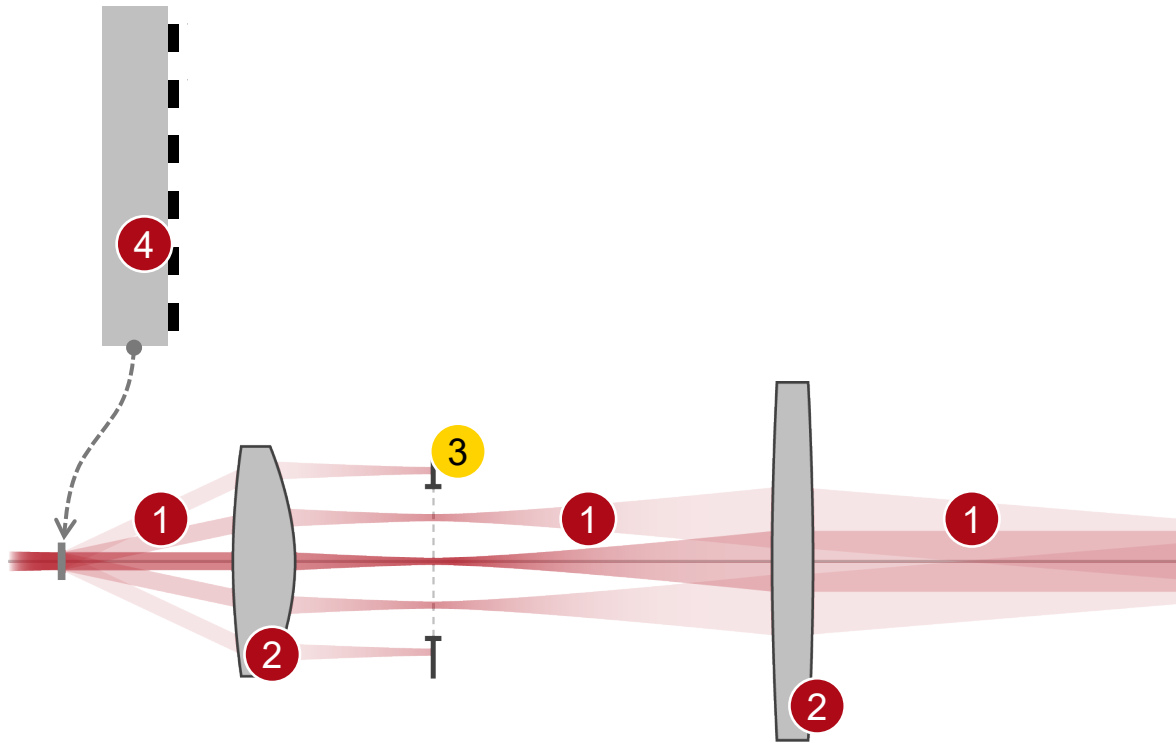


Modeling Task – Imaging with Varying Grating Period

How to simulate the image formation for grating objects in an imaging system, especially with the grating diffraction effects considered?



VirtualLab Fusion Technologies



idealized component

Image Formation Analysis

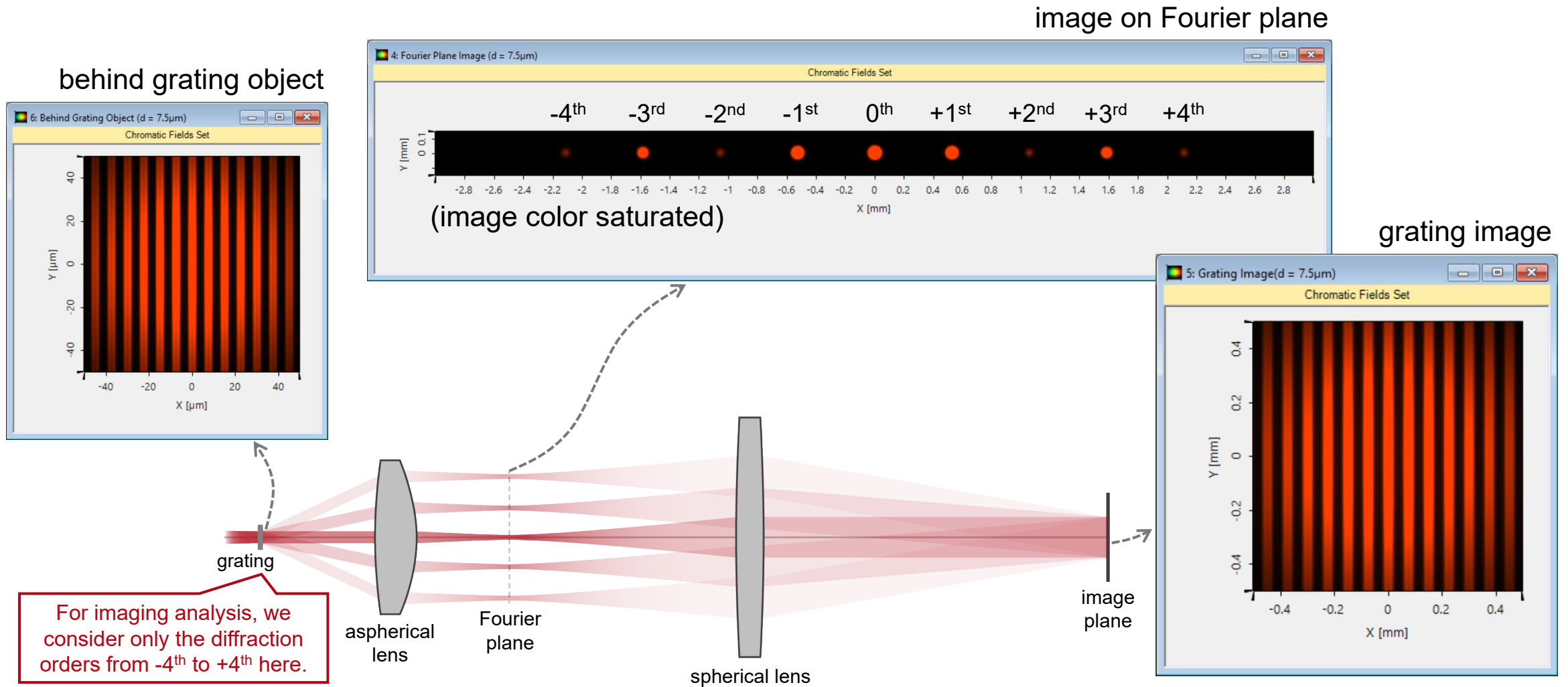
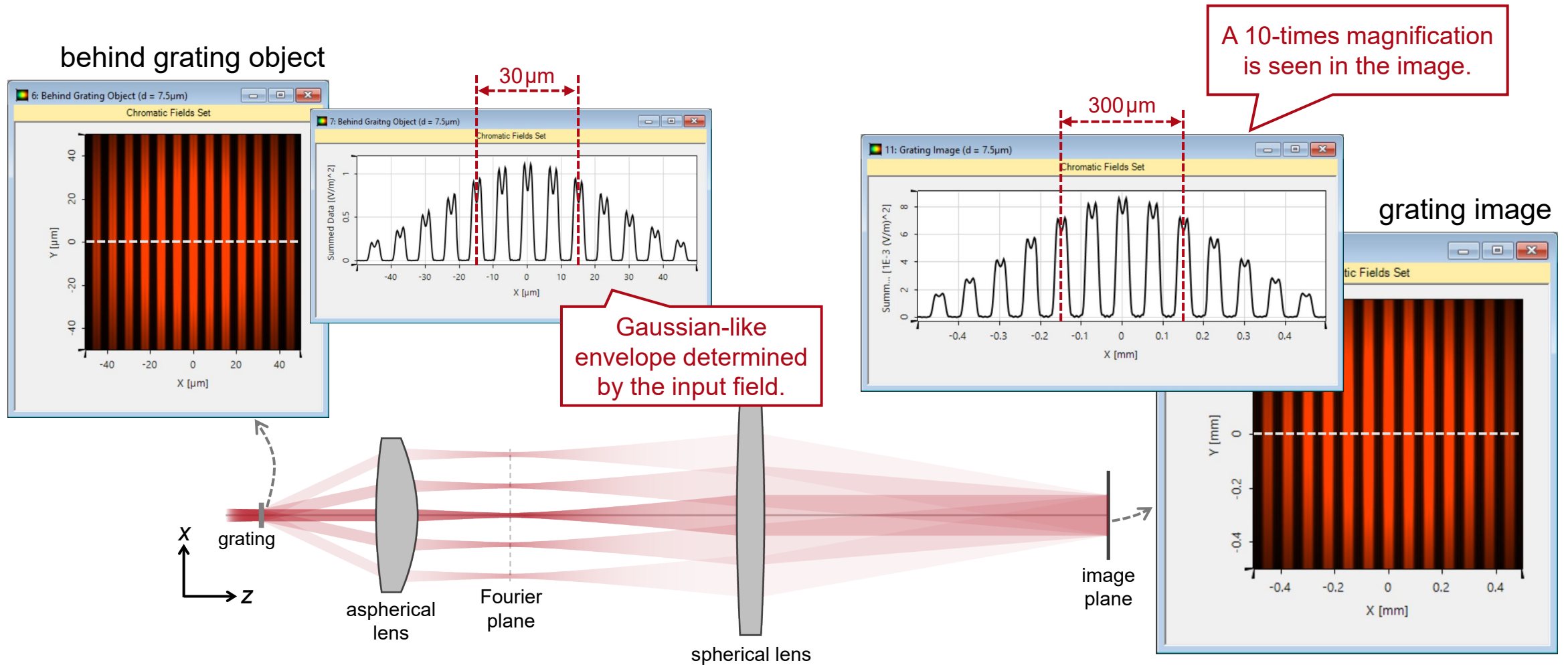
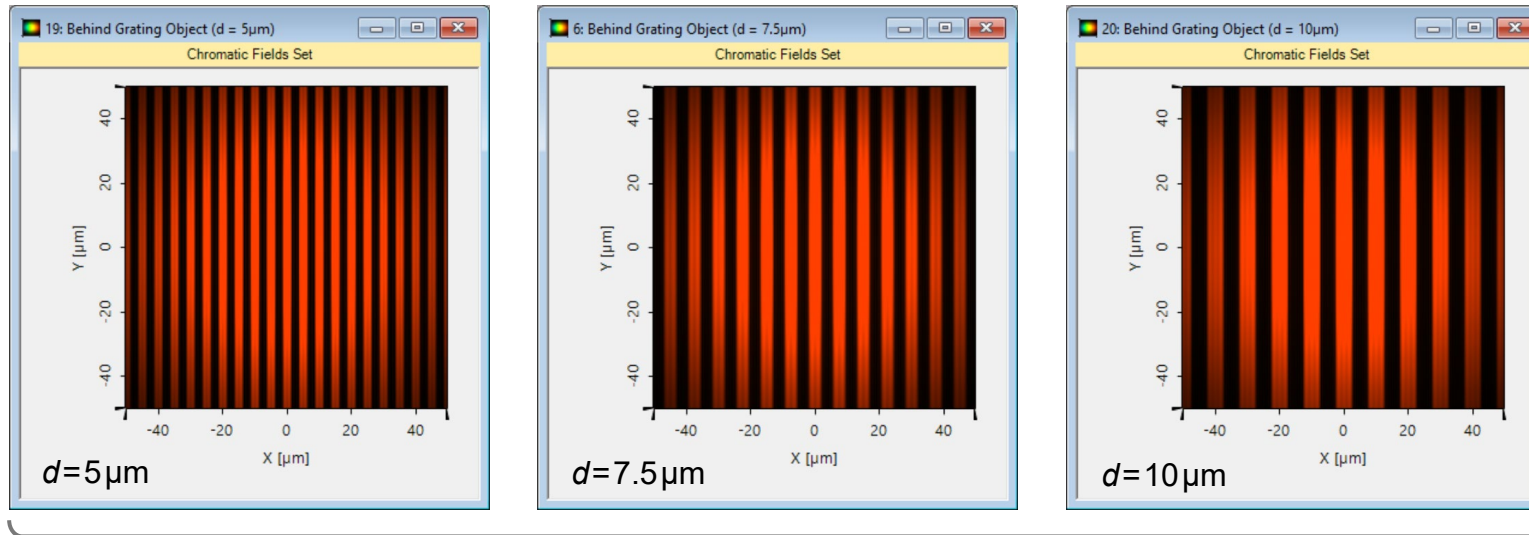


Image Formation Analysis

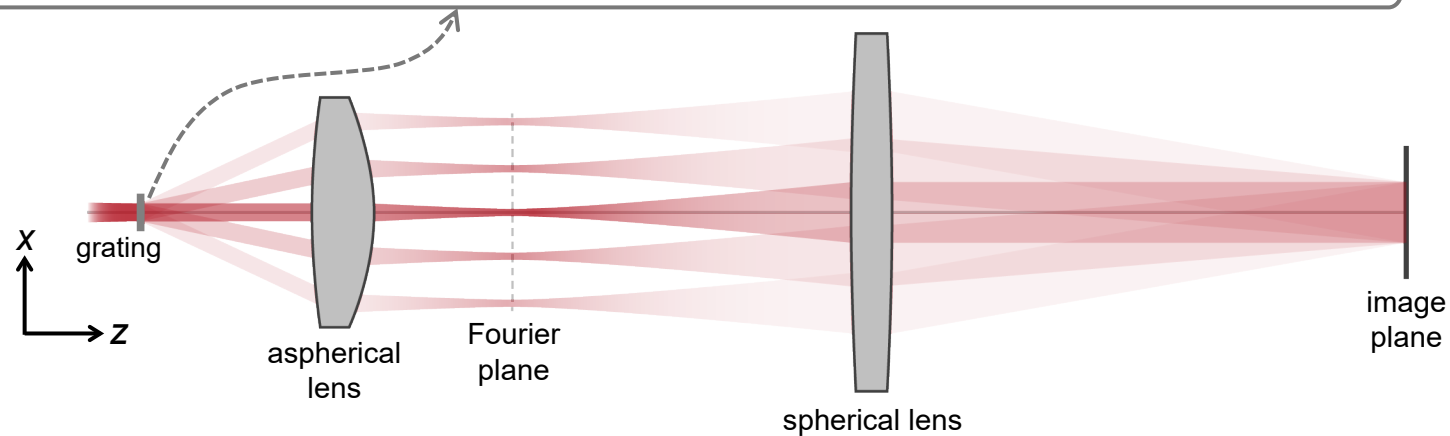


Behind Grating Objects with Different Periods

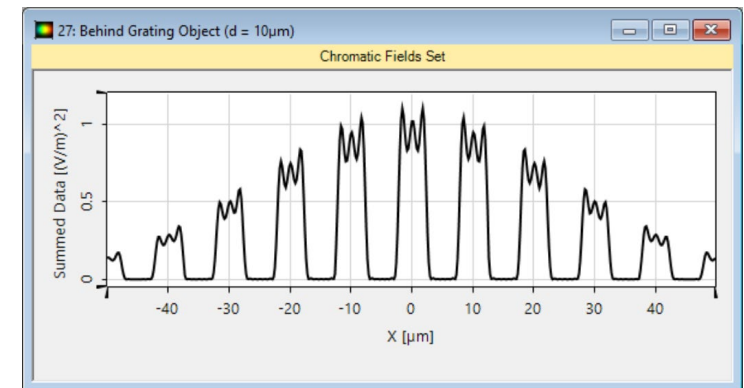
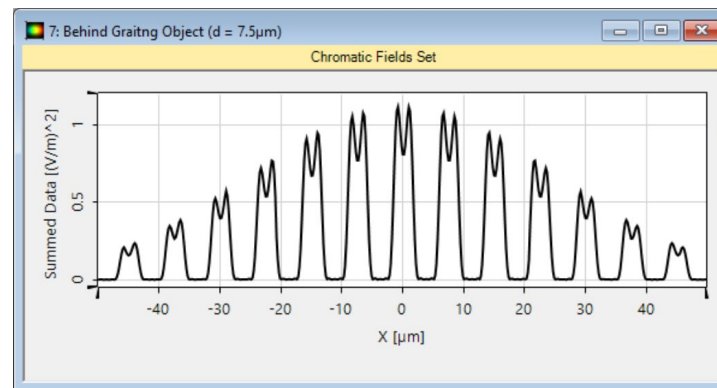
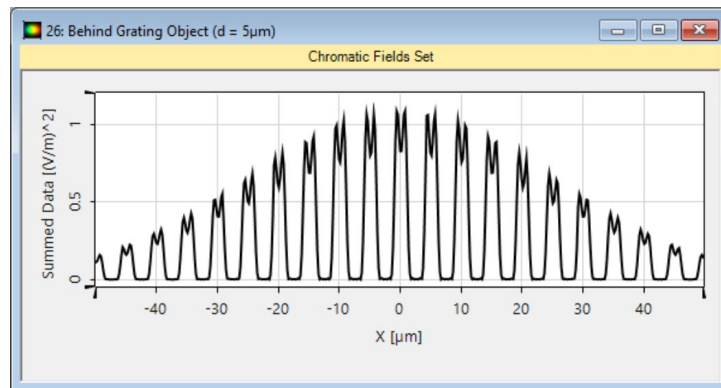
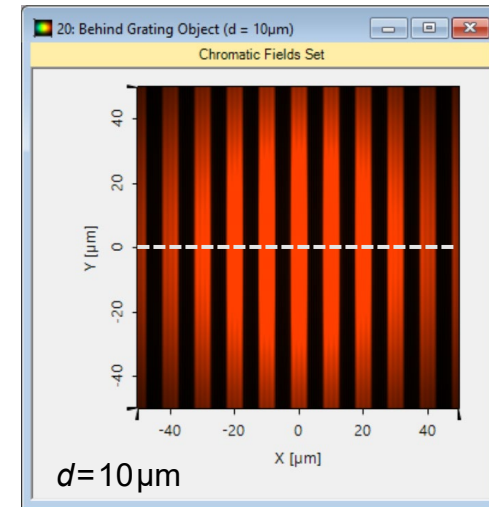
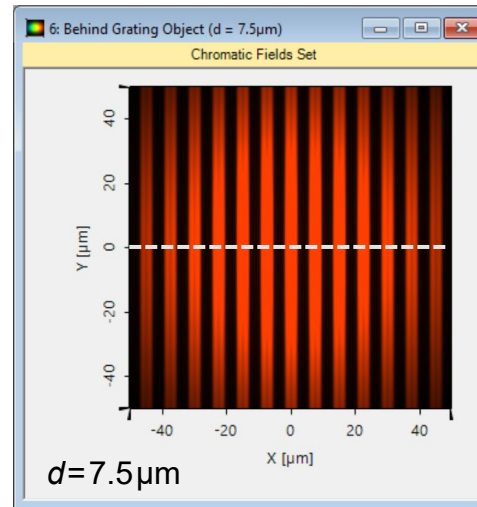
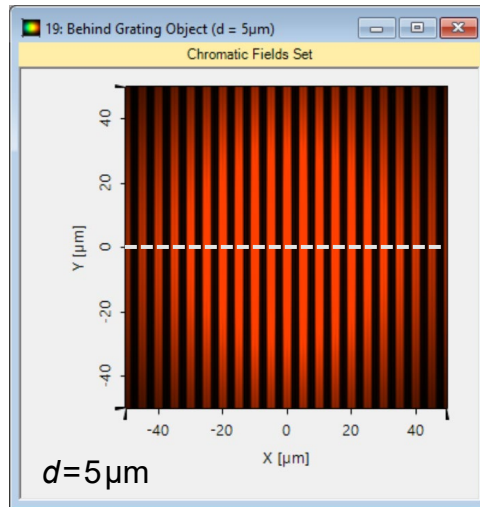


For imaging analysis, we consider only the diffraction orders that will enter the subsequent system:

- $d=5\mu\text{m}$: -3^{rd} to $+3^{\text{rd}}$ orders
- $d=7.5\mu\text{m}$: -4^{th} to $+4^{\text{th}}$ orders
- $d=10\mu\text{m}$: -6^{th} to $+6^{\text{th}}$ orders



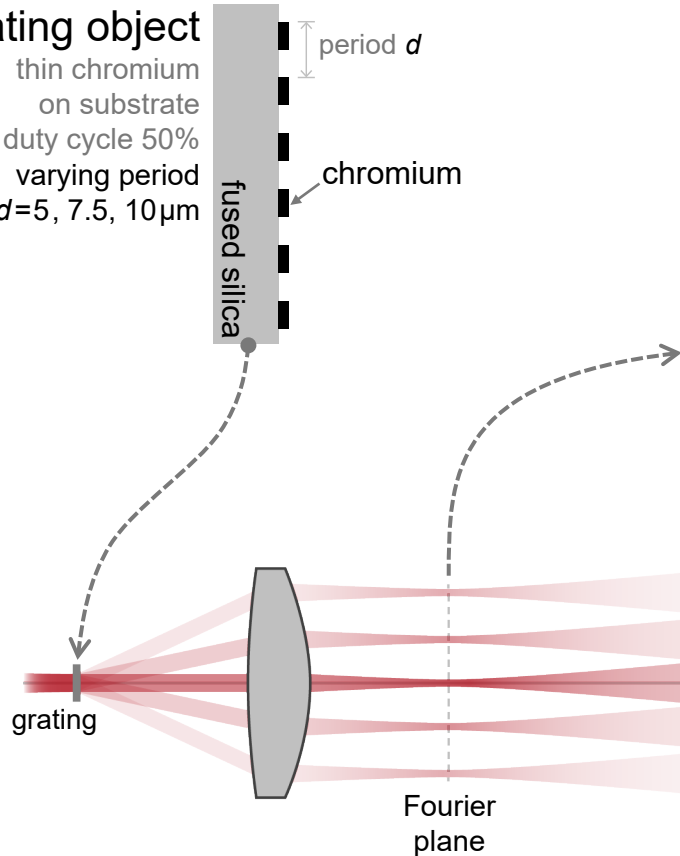
Behind Grating Objects with Different Periods



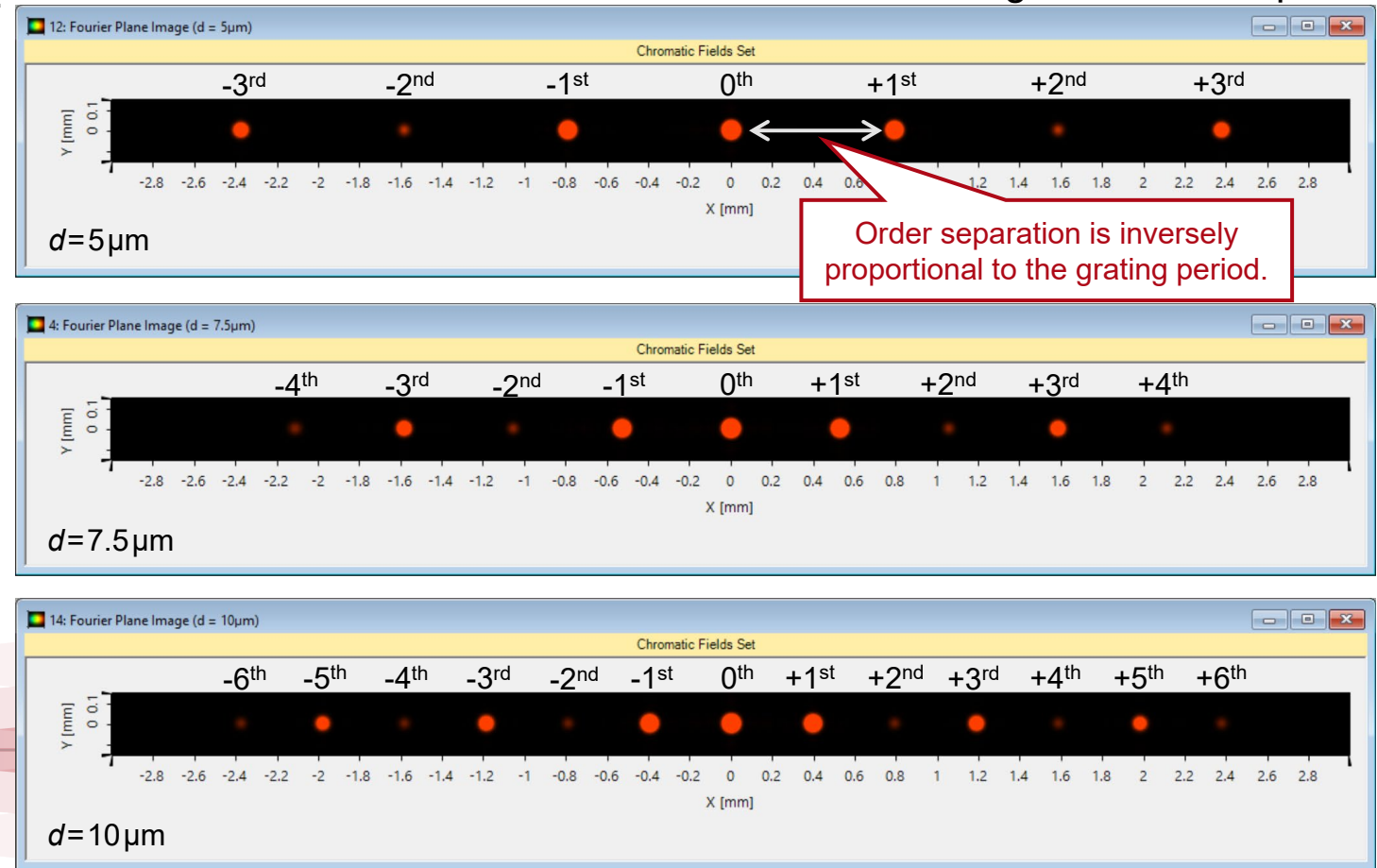
Fourier Plane Images for Different Periods

grating object

- thin chromium on substrate
- duty cycle 50%
- varying period $d=5, 7.5, 10\mu\text{m}$



images on Fourier plane

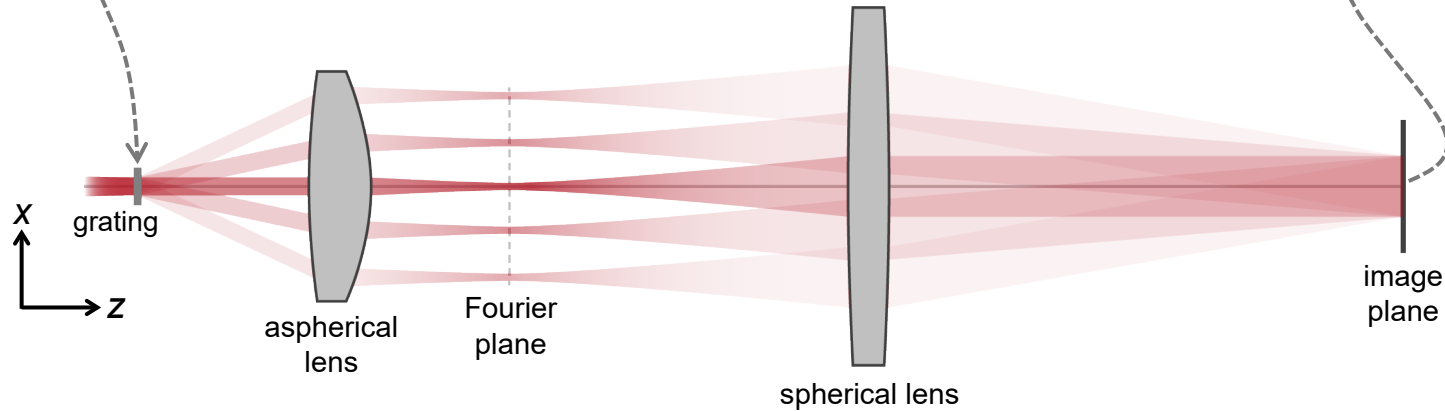
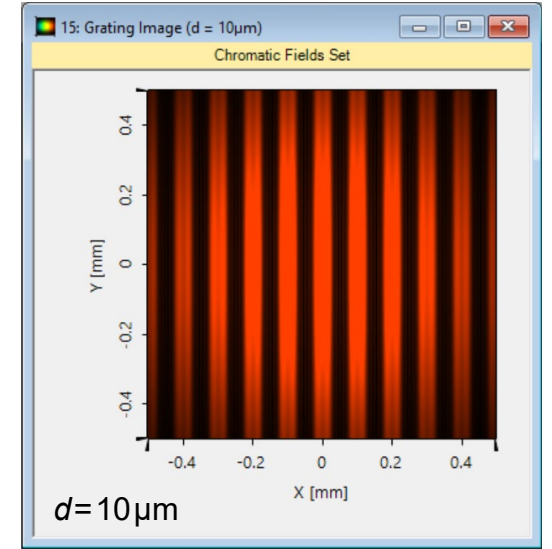
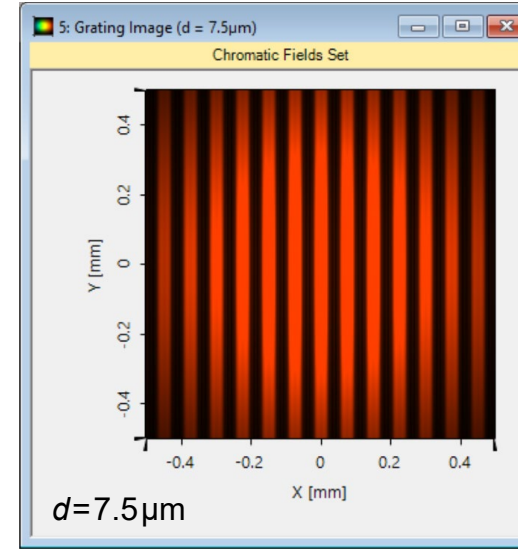
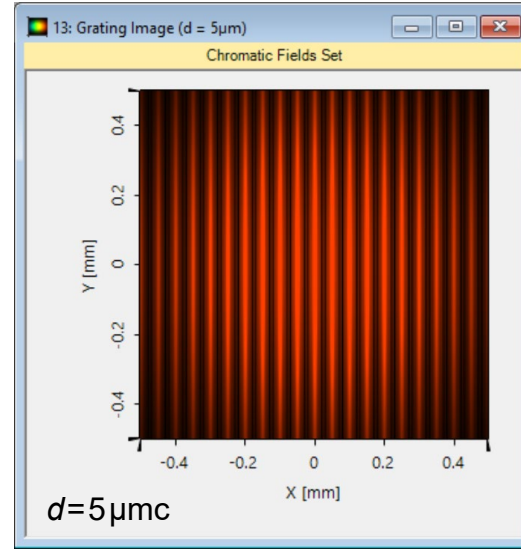
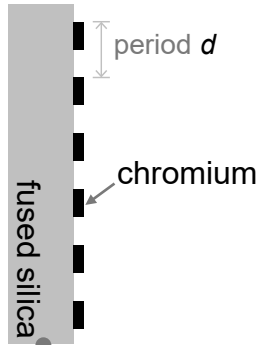


Grating efficiencies – corresponding to the spot brightness – are calculated by Fourier modal method (FMM, also known as RCWA).

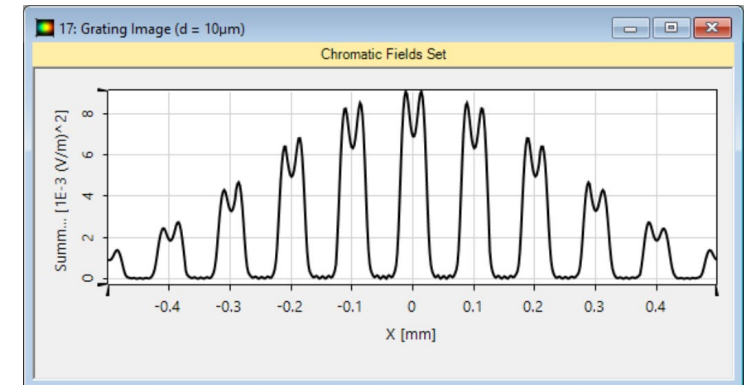
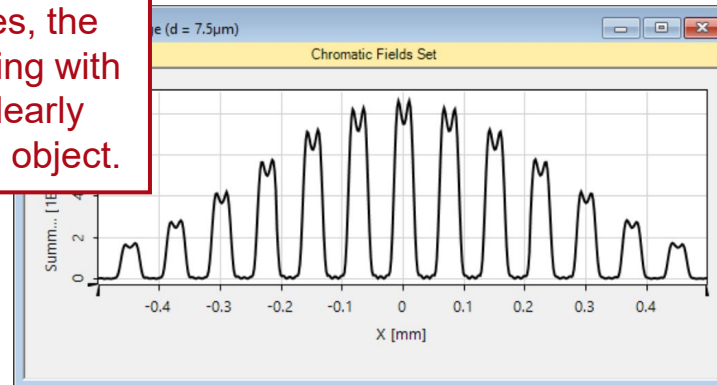
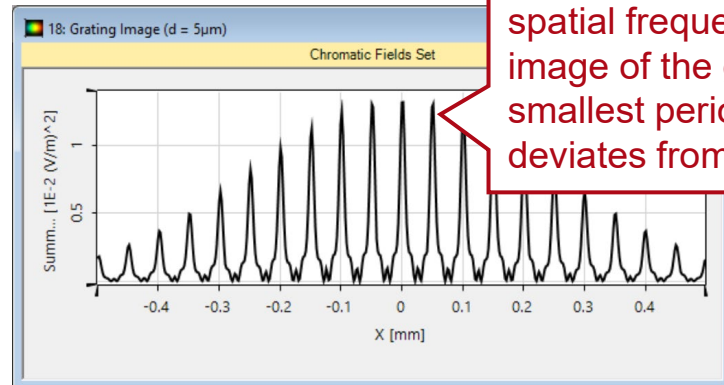
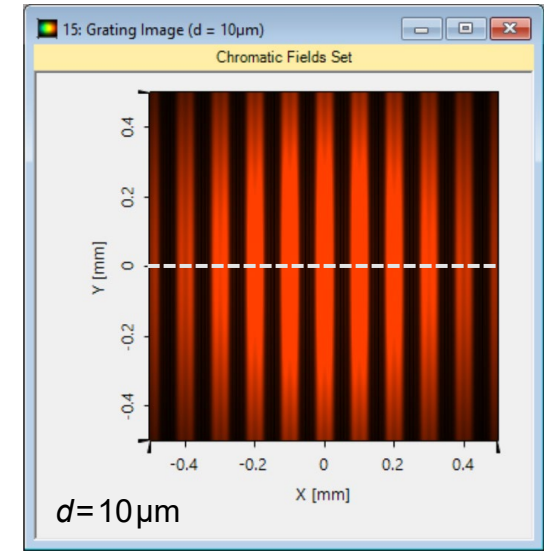
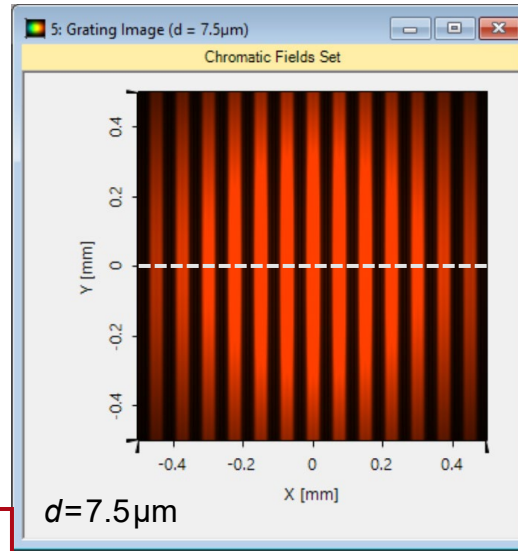
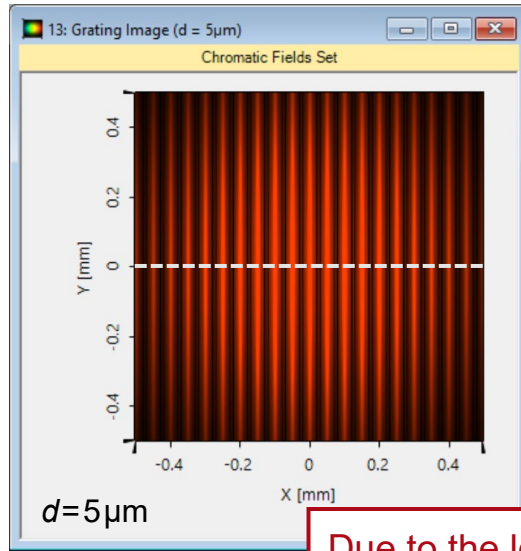
Grating Images for Different Periods

grating object

- thin chromium on substrate
- duty cycle 50%
- varying period $d=5, 7.5, 10\mu\text{m}$



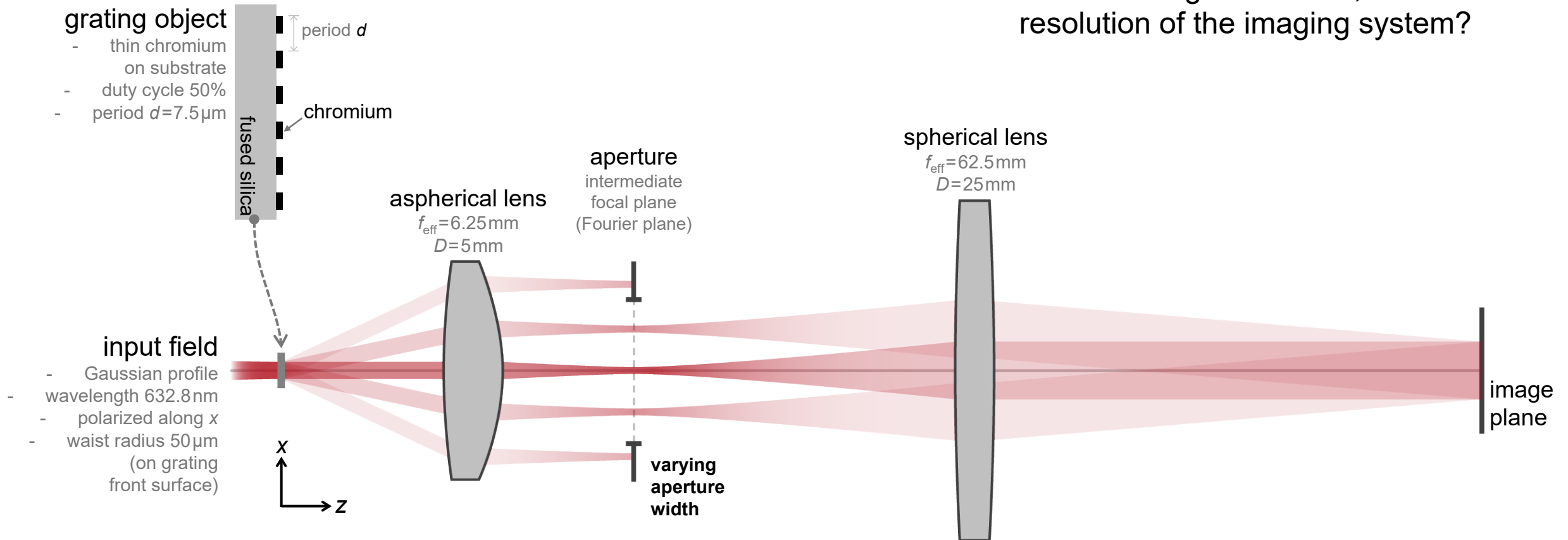
Grating Images for Different Periods



Due to the loss of high spatial frequencies, the image of the grating with smallest period clearly deviates from the object.

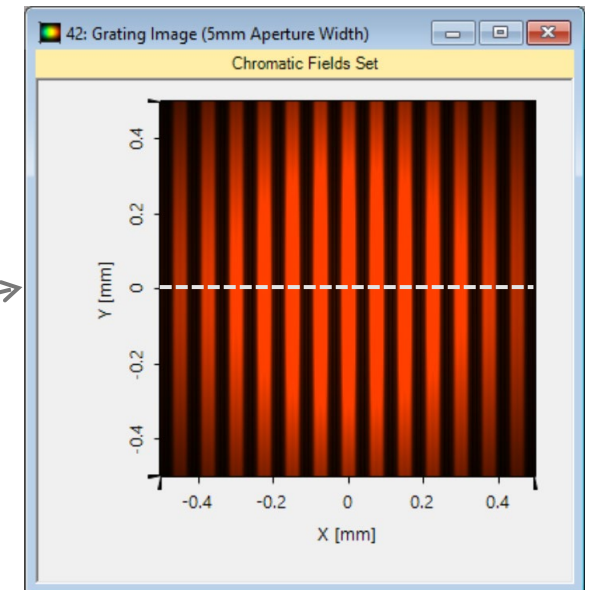
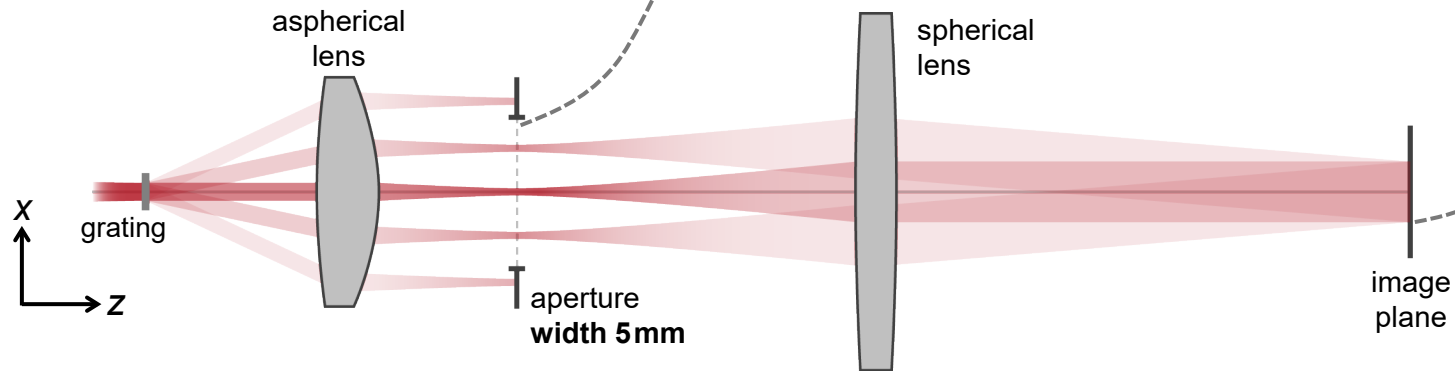
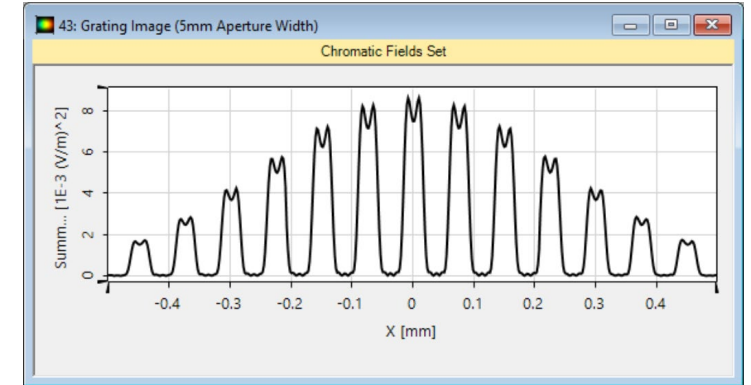
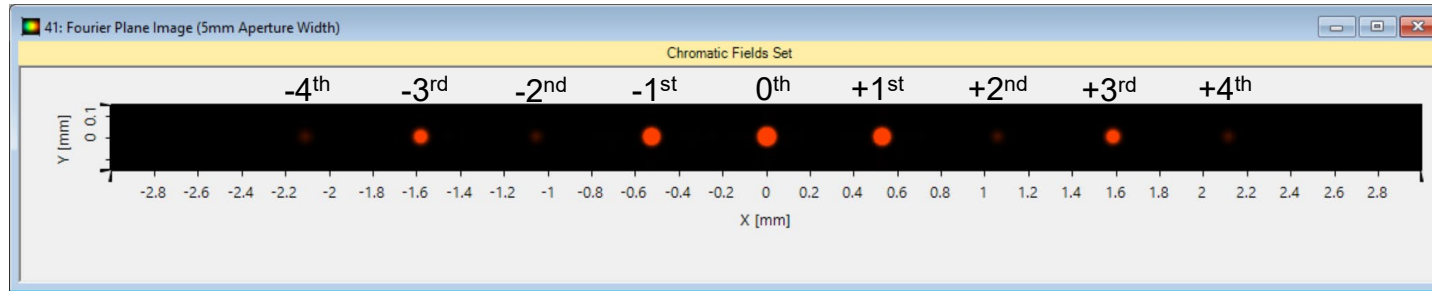
Modeling Task – Aperture Effect in Fourier Plane

How can the aperture in the Fourier plane affect the image formation, and the resolution of the imaging system?



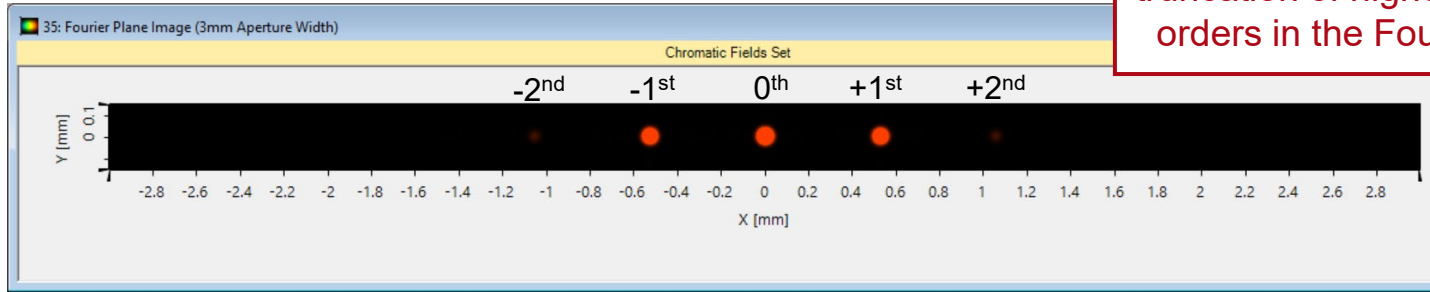
Aperture Width 5mm

images on Fourier plane behind aperture

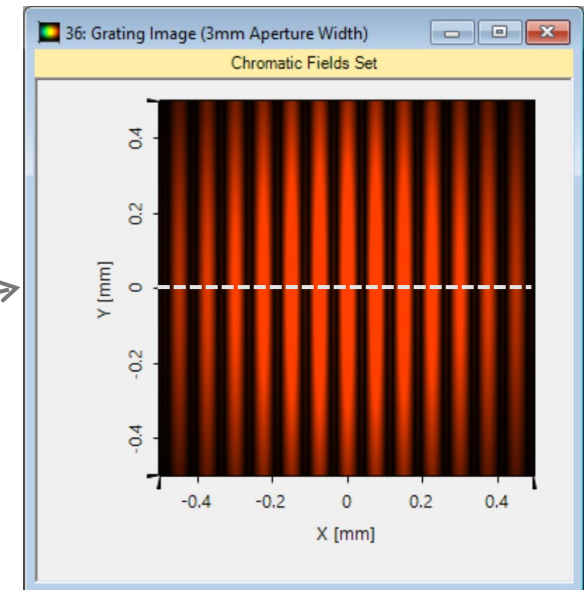
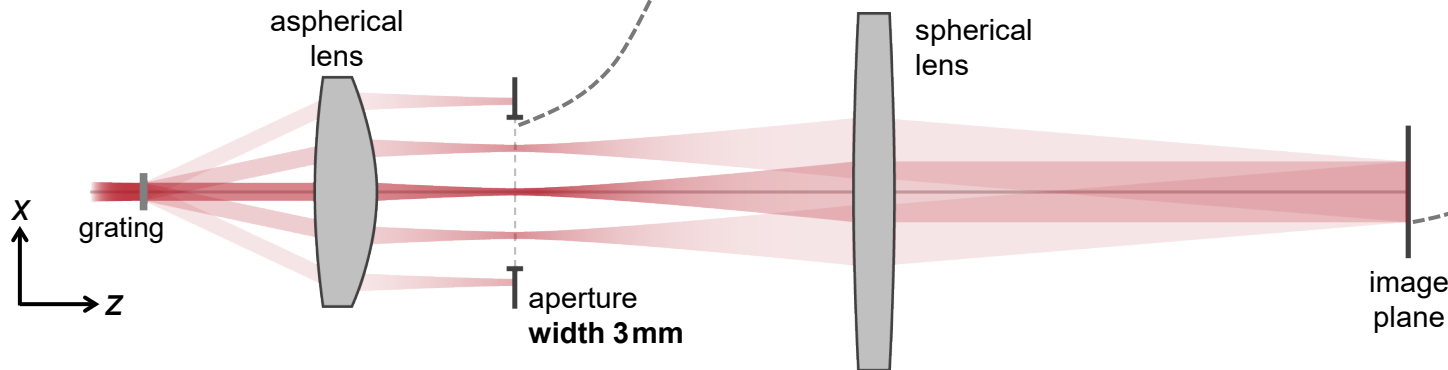
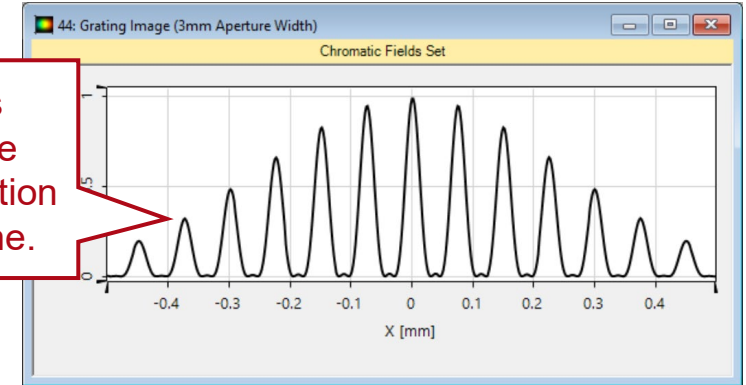


Aperture Width 3mm

images on Fourier plane behind aperture

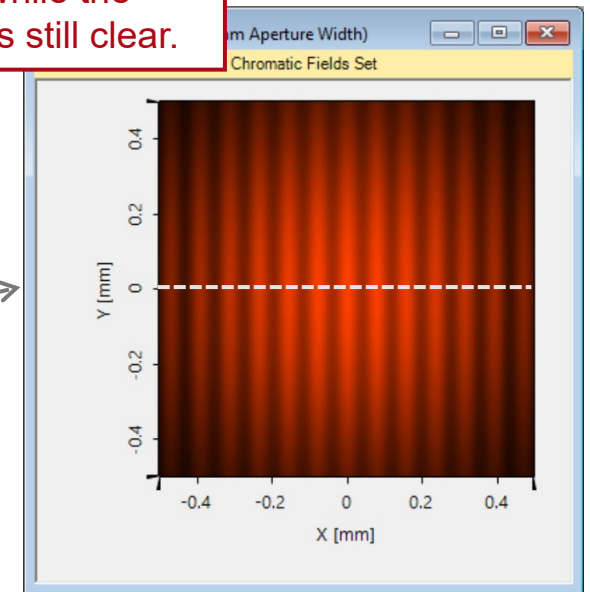
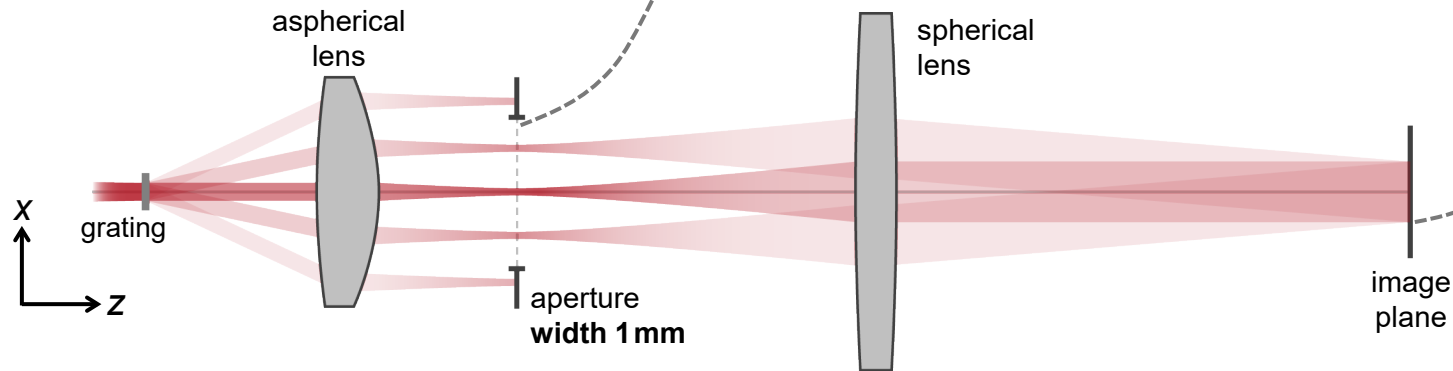
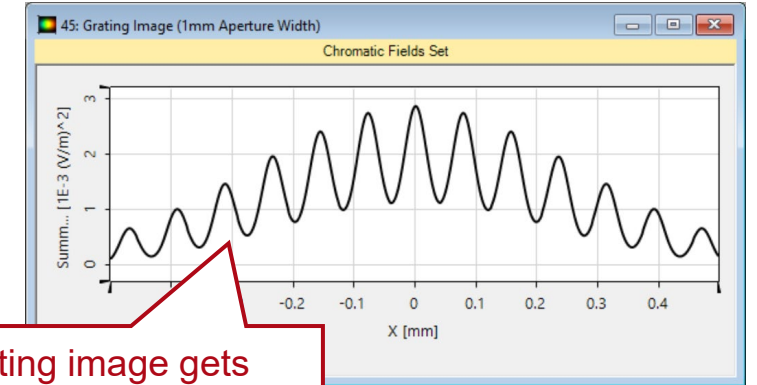
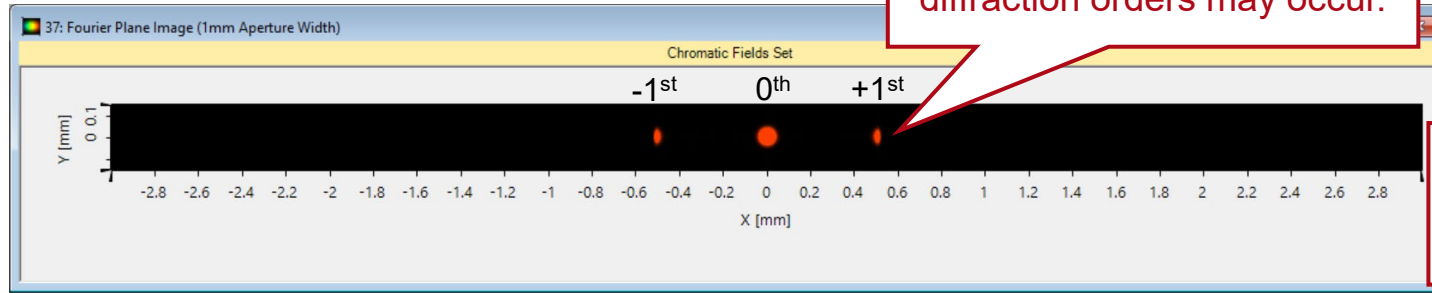


The grating image gets smoother because of the truncation of higher diffraction orders in the Fourier plane.



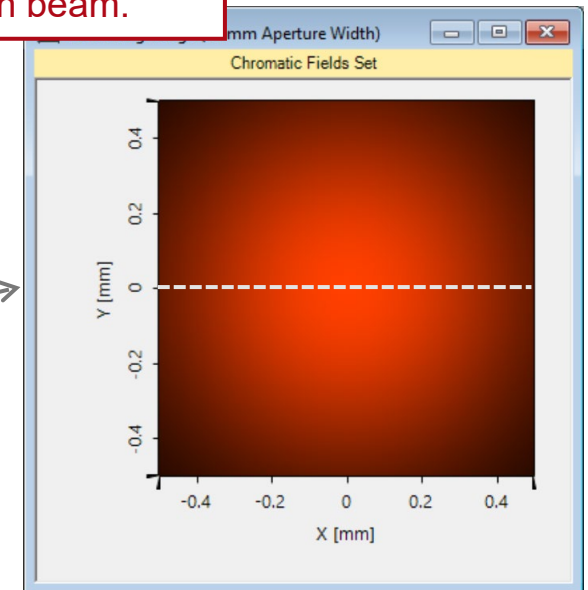
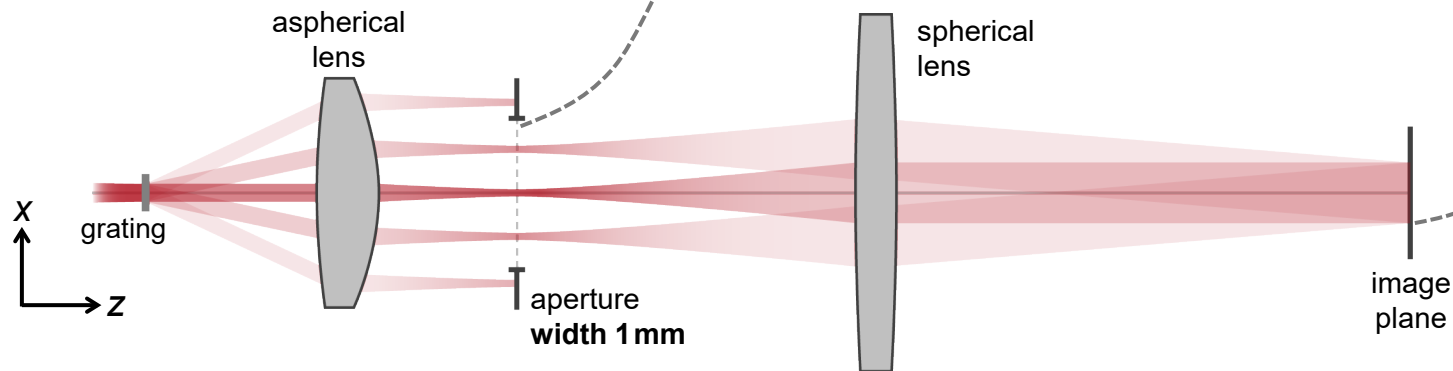
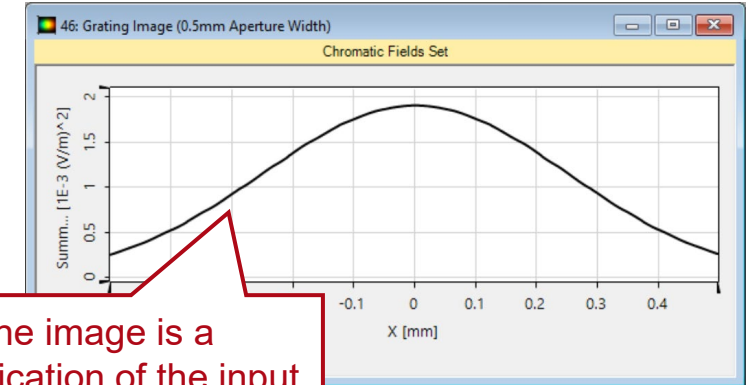
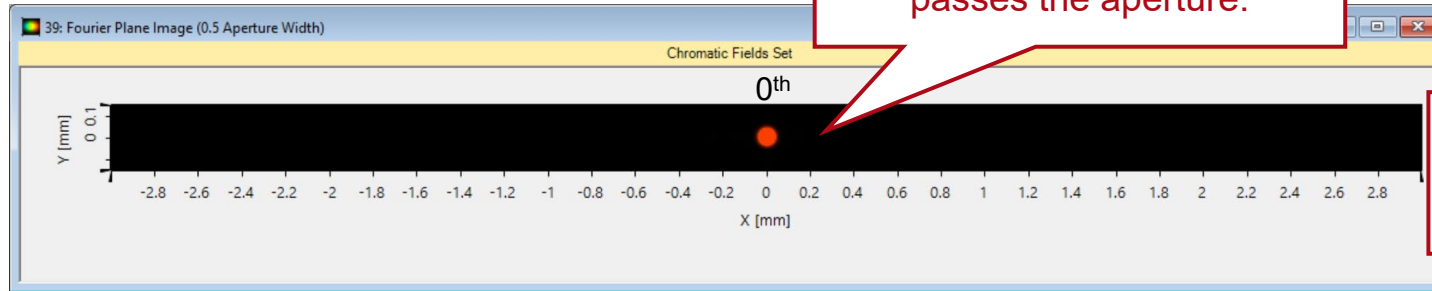
Aperture Width 1 mm

images on Fourier plane behind aperture



Aperture Width 0.5mm

images on Fourier plane behind aperture



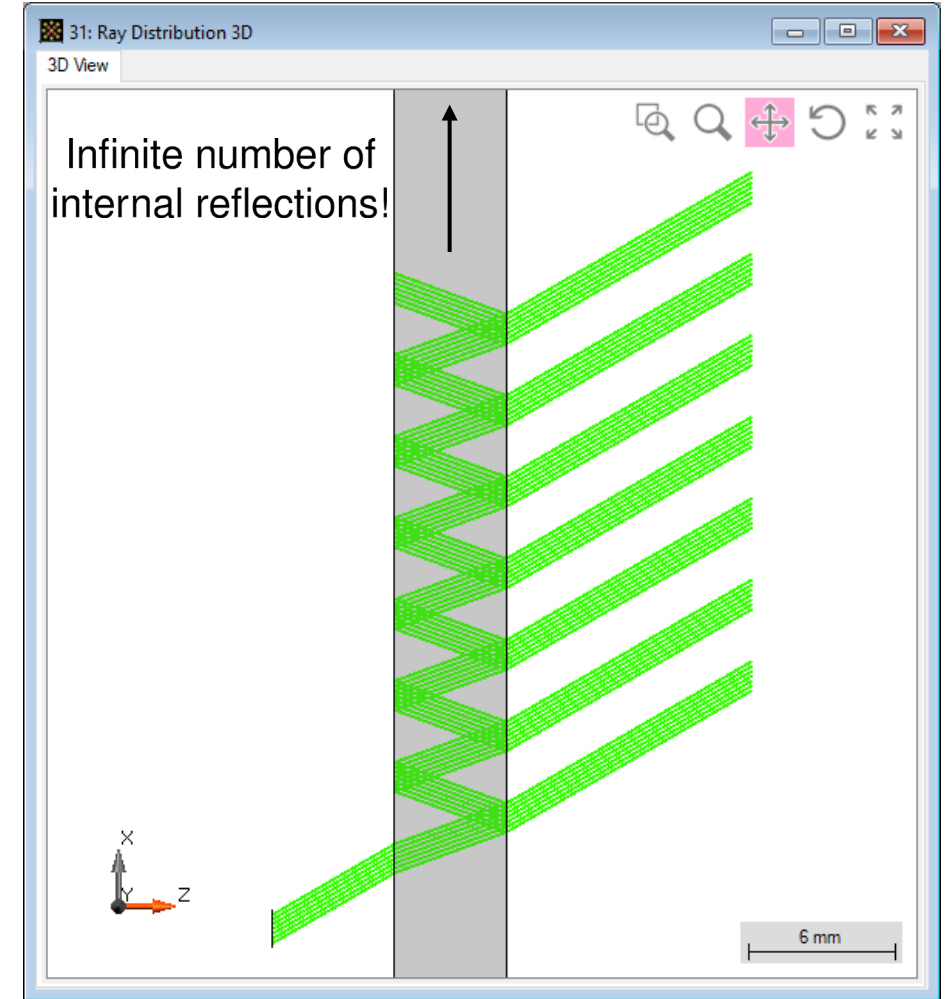
Part 5

The Light Path Finder

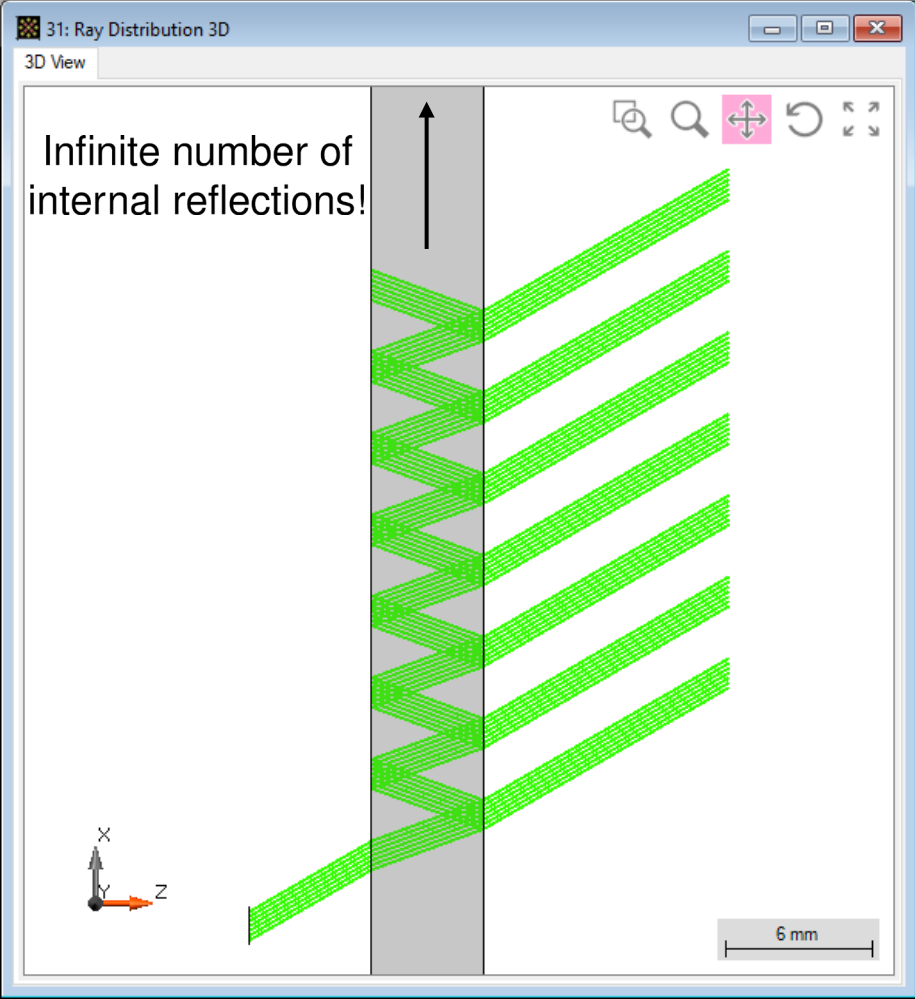
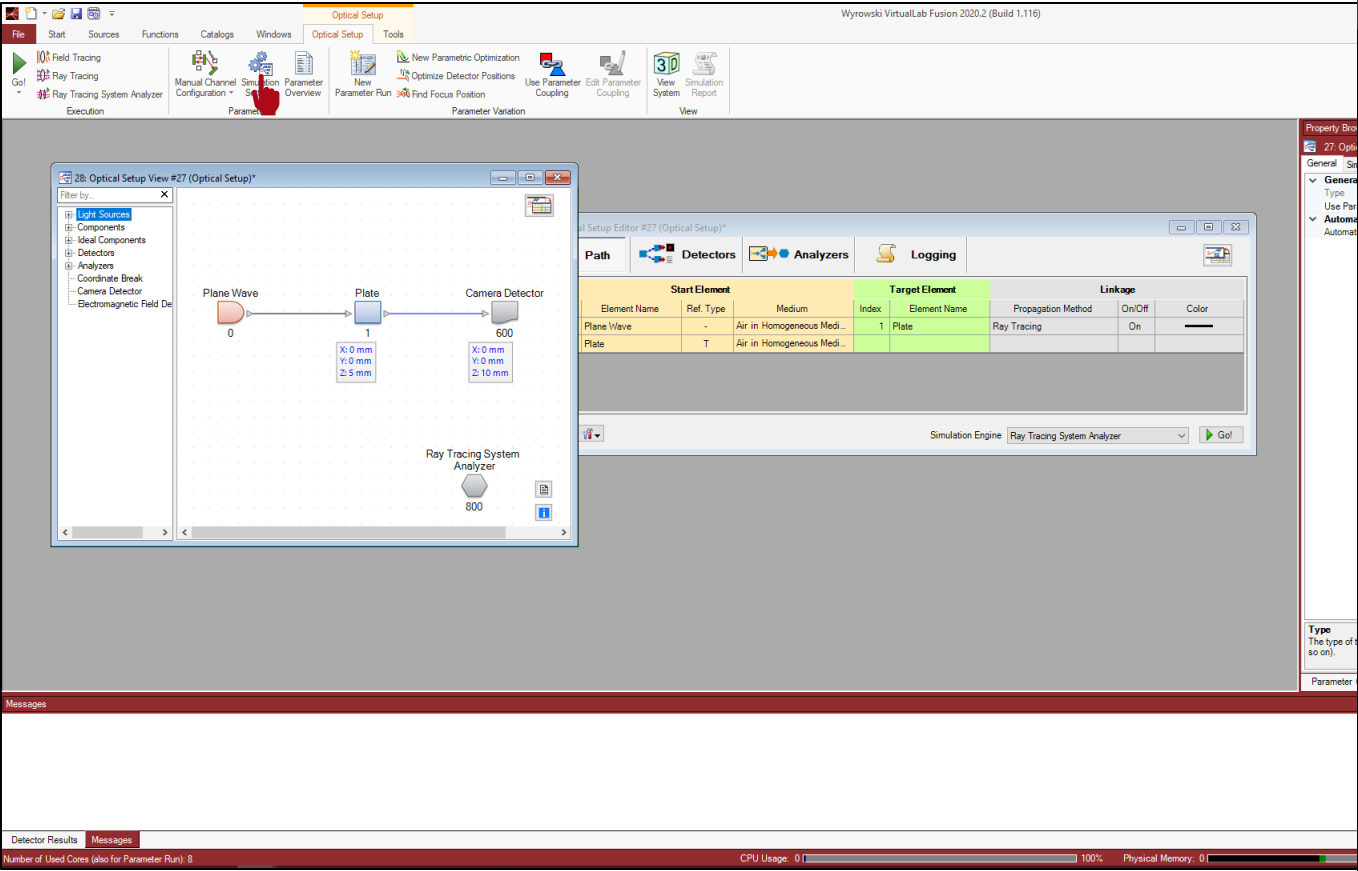


The Light Path Finder

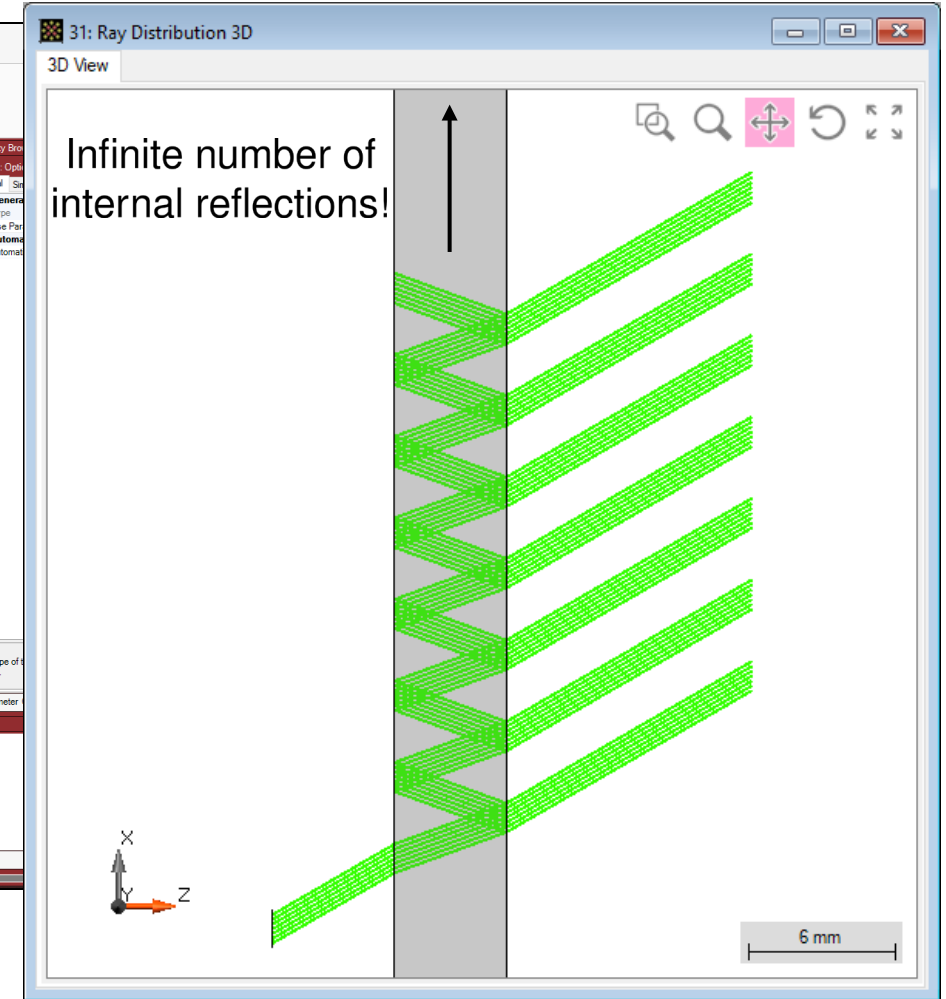
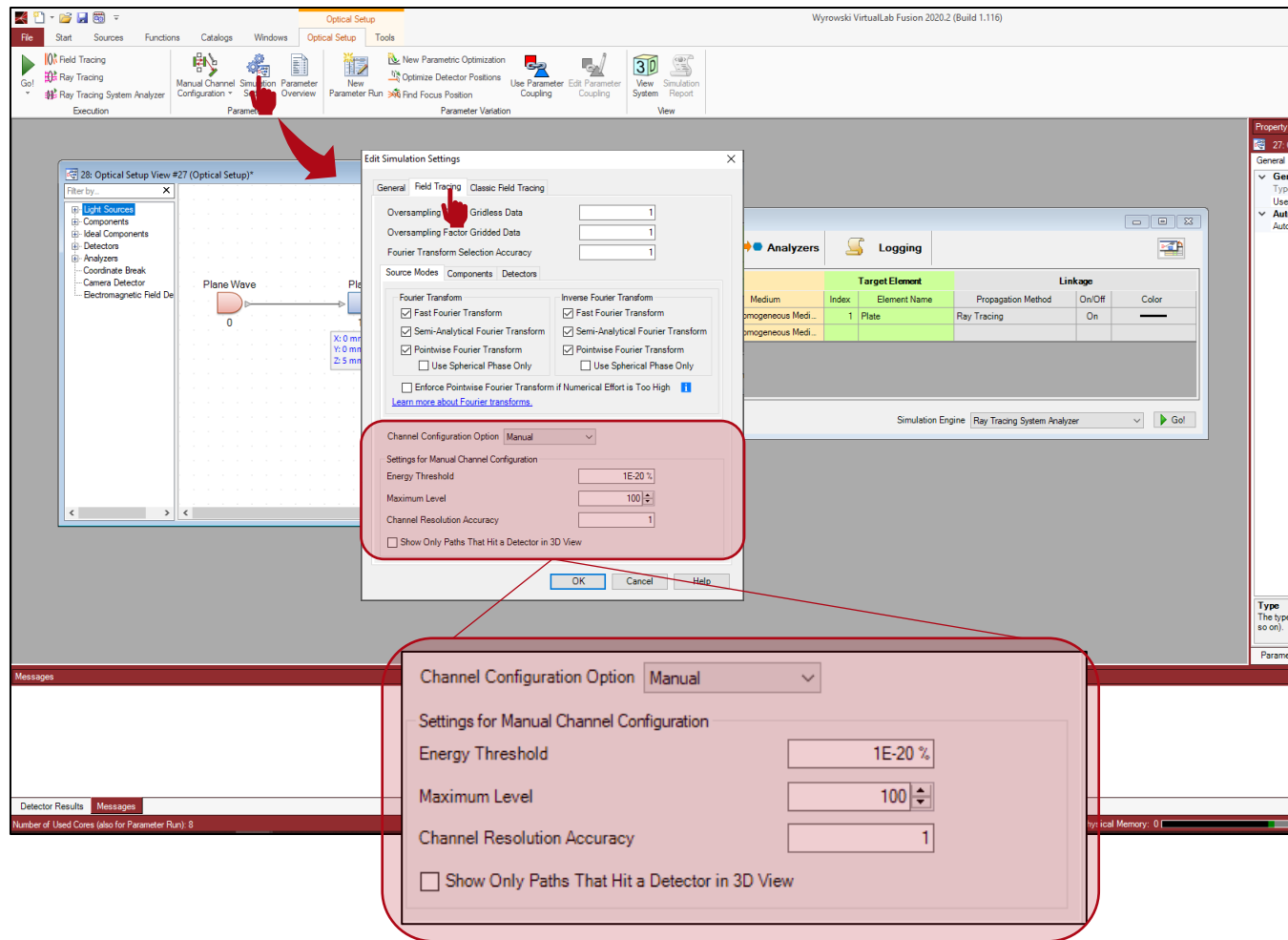
- The Light Path Finder performs a preliminary analysis of the open channels in the system and determines through which of them light will propagate and how.
- The Light Path Finder uses a physical-optics model without diffraction to analyse the system.
- After the Light Path Finder has determined the light paths that the field is going to follow, the Field Tracing engine takes over and simulates the fully fledged physical-optics propagation of the field along those paths.



The Light Path Finder



The Light Path Finder



The Light Path Finder

Pre-Selected Channel Configuration and Manual Channel Configuration are the available choices. In previous versions called *Sequential* and *Non-Sequential* respectively.

Channel Configuration Option: Manual

Settings for Manual Channel Configuration

- Energy Threshold: 1E-20 %
- Maximum Level: 100
- Channel Resolution Accuracy: 1
- ☐ Show Only Paths That Hit a Detector in 3D View

31: Ray Distribution 3D

3D View

Infinite number of internal reflections!

6 mm

The Light Path Finder

The screenshot displays the 'Light Path Finder' software interface. The main window shows a 3D view of a light path simulation. A red arrow points from the 'Optical Setup' menu to the 'Edit Simulation Settings' dialog box. The dialog box has tabs for 'General', 'Field Tracing', and 'Classic Field Tracing'. The 'Field Tracing' tab is selected, showing various Fourier Transform options. A red callout bubble points to the 'Energy Threshold' setting in the 'Channel Configuration Option' section, which is set to '1E-20 %'. Another red callout bubble points to the '31: Ray Distribution 3D' window, which shows a 3D view of the light path with a red arrow indicating the direction of propagation. The text 'Infinite number of internal reflections!' is written in the callout bubble. The 3D view shows a light path entering a structure and reflecting multiple times. A scale bar at the bottom right indicates 6 mm.

Every time the beam interacts with the interface, the energy is split between transmission and reflection, so that each subsequent mode carries ever less energy and is therefore less relevant to the final result!

Infinite number of internal reflections!

Channel Configuration Option: Manual

Settings for Manual Channel Configuration

Energy Threshold: 1E-20 %

Maximum Level: 100

Channel Resolution Accuracy: 1

☐ Show Only Paths That Hit a Detector in 3D View

31: Ray Distribution 3D

3D View

6 mm

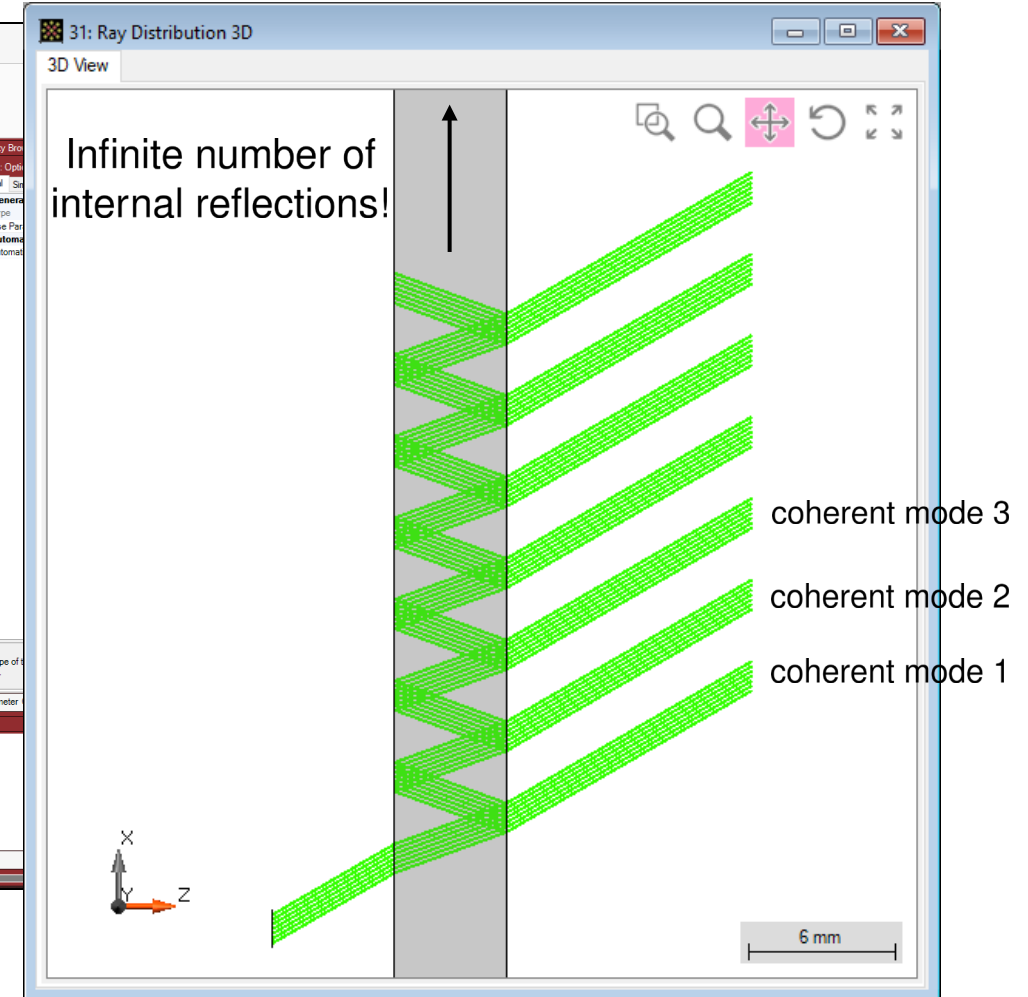
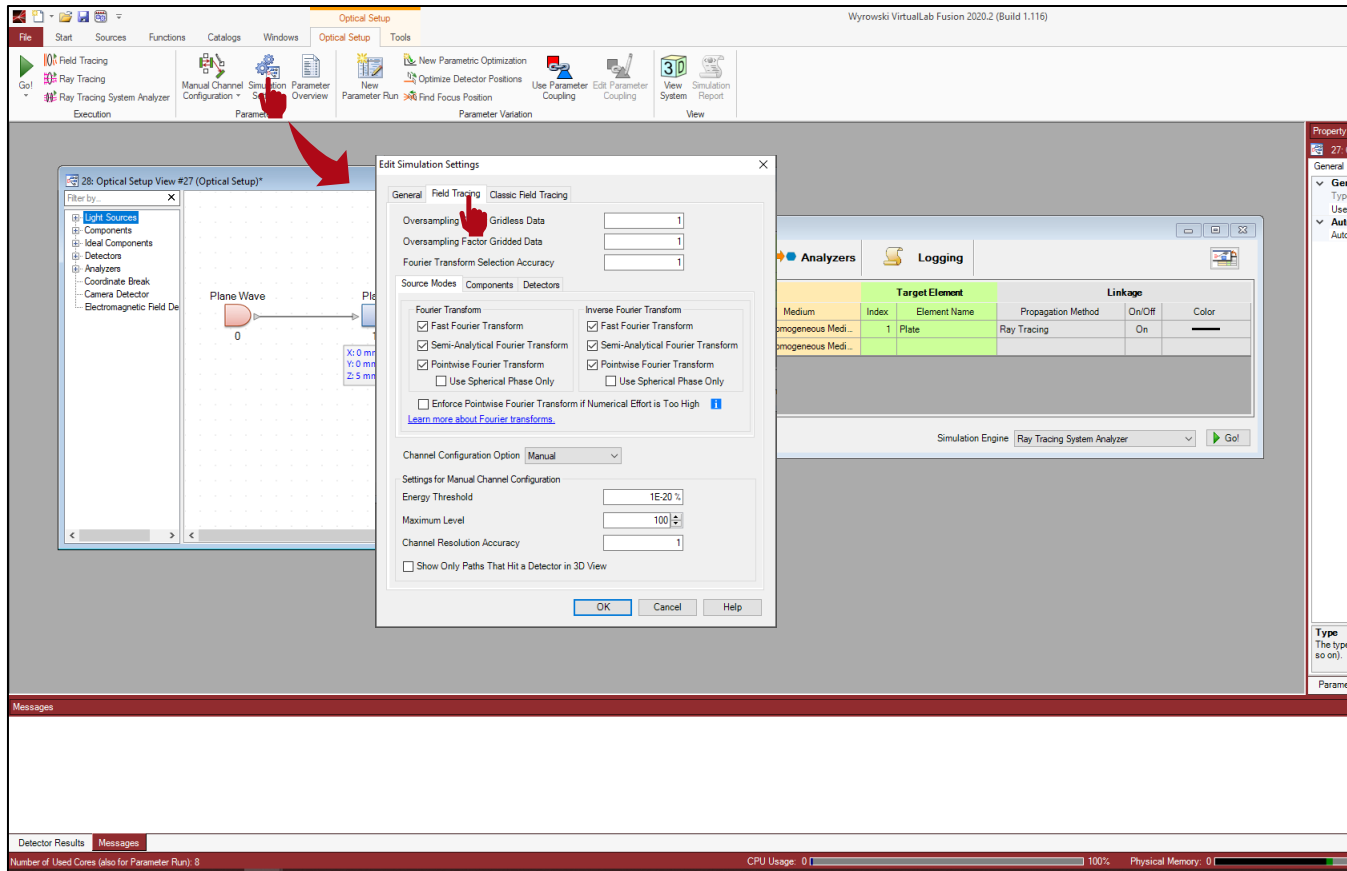
The Light Path Finder

The screenshot displays the Wyrowski VirtualLab Fusion 2020.2 (Build 1.116) interface. The 'Edit Simulation Settings' dialog is open, showing the 'Field Tracing' tab. The 'Channel Configuration Option' is set to 'Manual'. The 'Maximum Level' is set to 100, which is circled in red. The 'Energy Threshold' is set to 1E-20 % and the 'Channel Resolution Accuracy' is set to 1. The 'Show Only Paths That Hit a Detector in 3D View' checkbox is unchecked.

The '31: Ray Distribution 3D' window shows a 3D view of the simulation. A vertical plate is shown with green rays reflecting multiple times. The rays are labeled 'level 1', 'level 2', 'level 3', and 'level 4'. An arrow points upwards with the text 'Infinite number of internal reflections!'. A scale bar at the bottom right indicates 6 mm.

Medium	Index	Element Name	Propagation Method	On/Off	Color
Homogeneous Medi...	1	Plate	Ray Tracing	On	
Homogeneous Medi...					

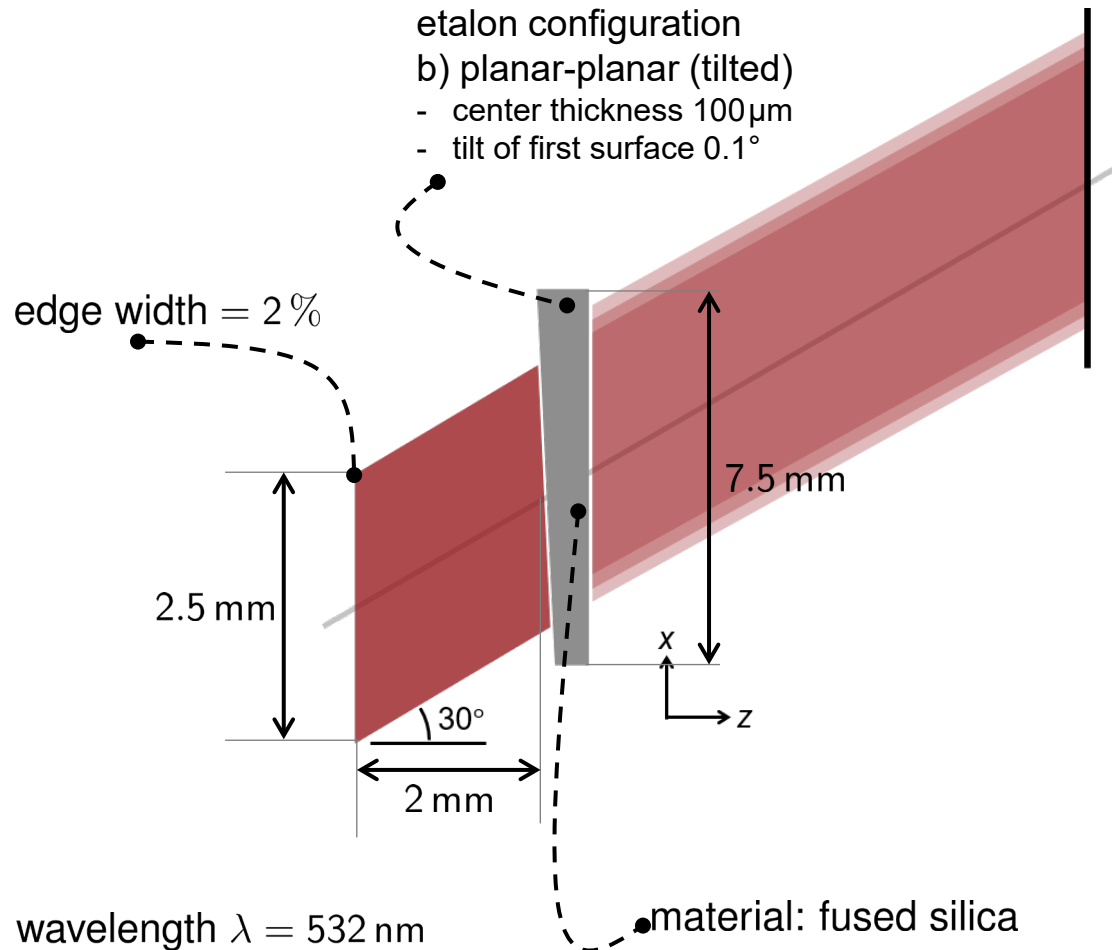
The Light Path Finder and the Modes Reaching the Detector



Exercise 1

Building an Etalon

Build the Following System in VirtualLab Fusion



camera detector

- position $x = 4 \text{ mm}$, $z = 5 \text{ mm}$
- window size $3 \text{ mm} \times 3 \text{ mm}$
- components to integrate E_x , E_y and E_z
- false colour (cold colours) to better visualize interference

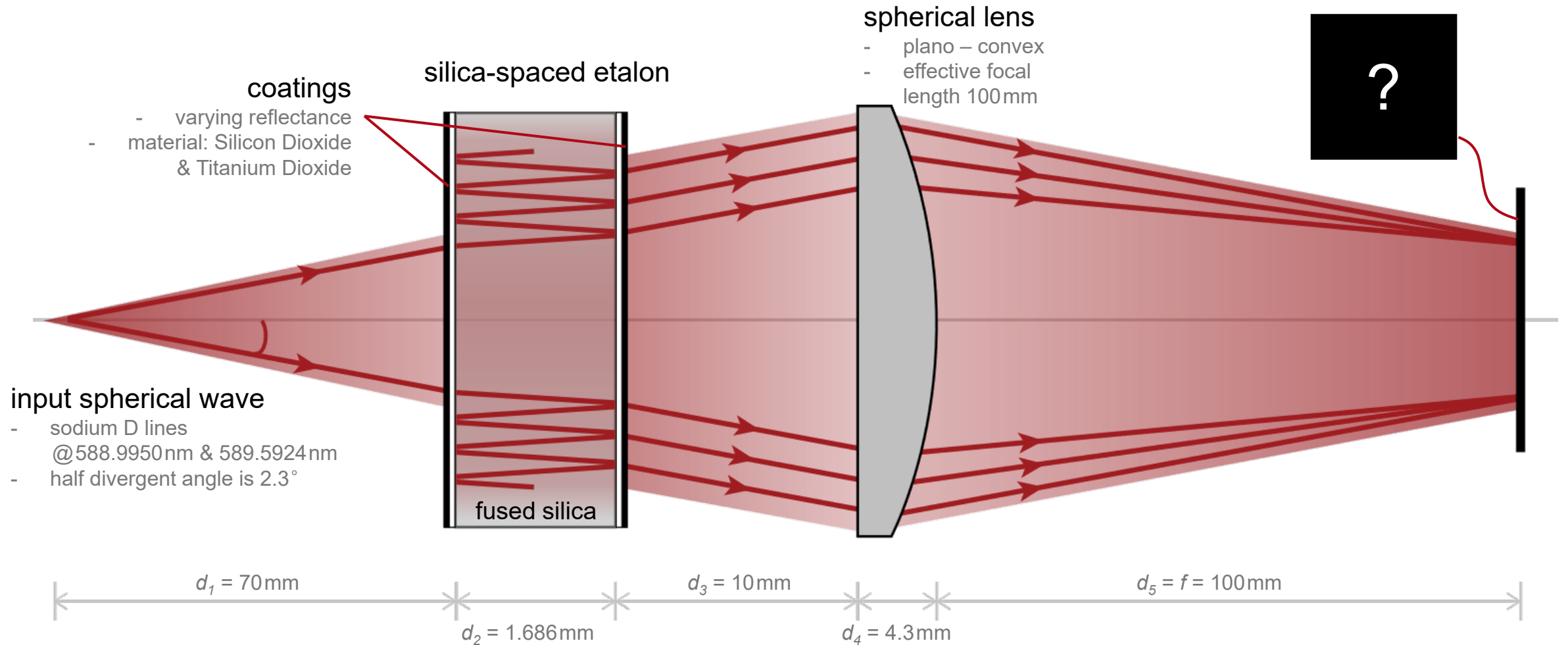
Note:

- Non-sequential simulation – adjust *Channel Configuration Options* to the *Manual* setting and configure surface channels in components.
- Diffraction in the system: play with the Fourier transforms (*Simulation Settings*) to see the role of diffraction.
- Investigate the effects of using different polarization in the source.
- Replace the first surface with others of different shape: spherical, cylindrical... (suggested radius of curvature 1 m).

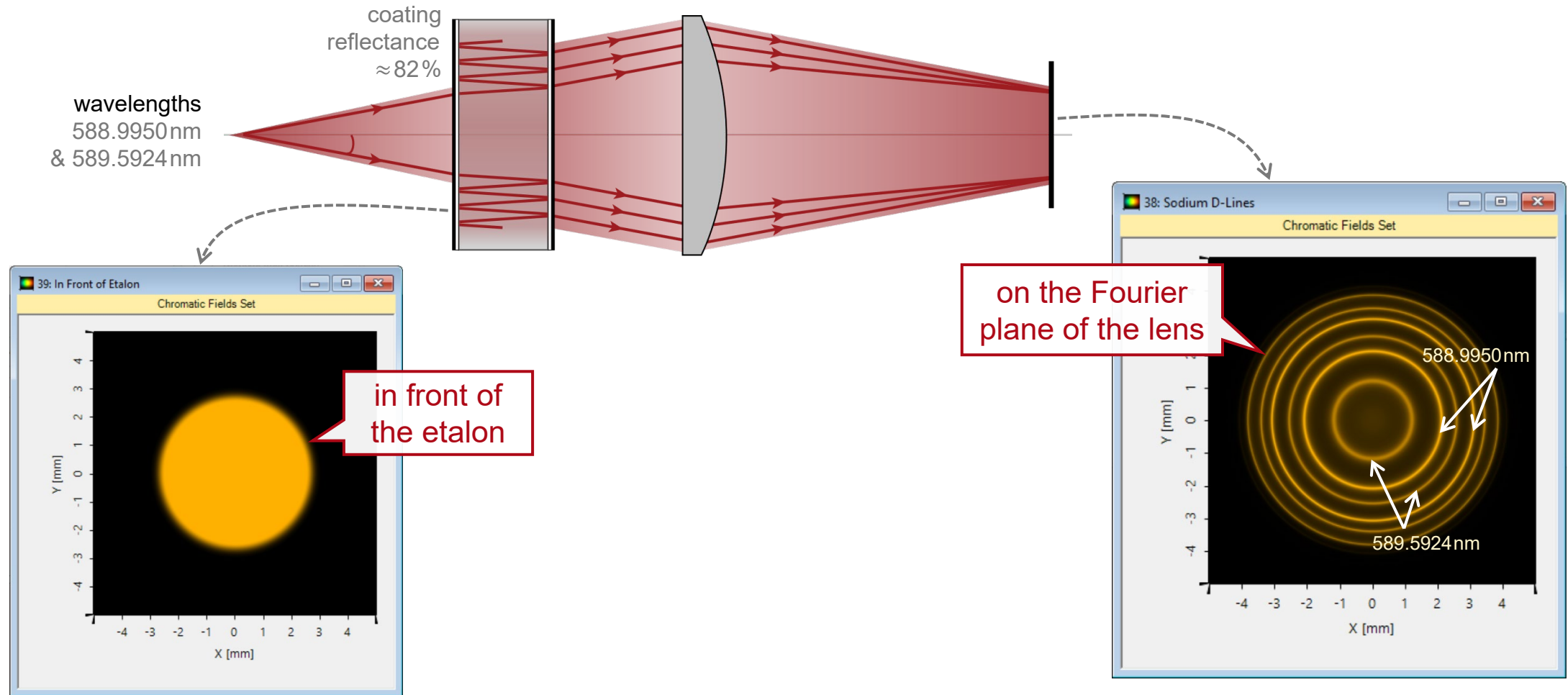
Examination of Sodium D Lines with Fabry-Pérot Etalon



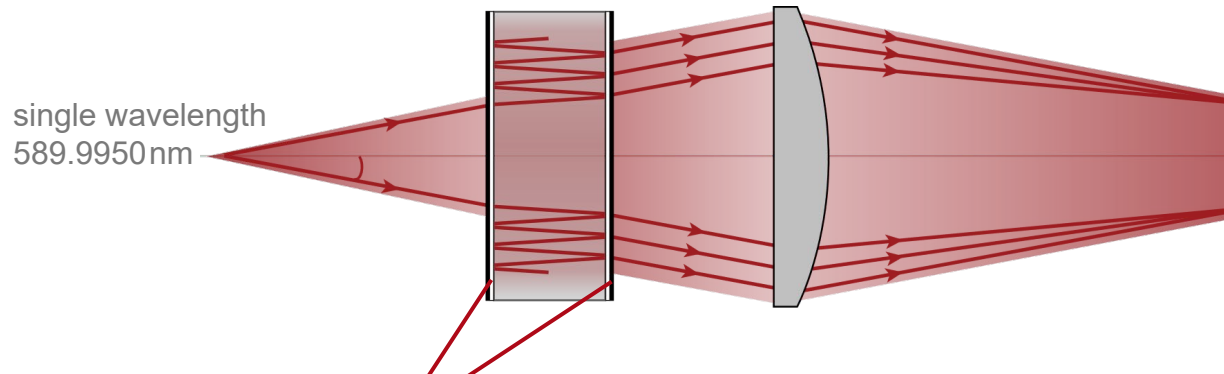
Modeling Task



Visualization of Both Spectrum Lines

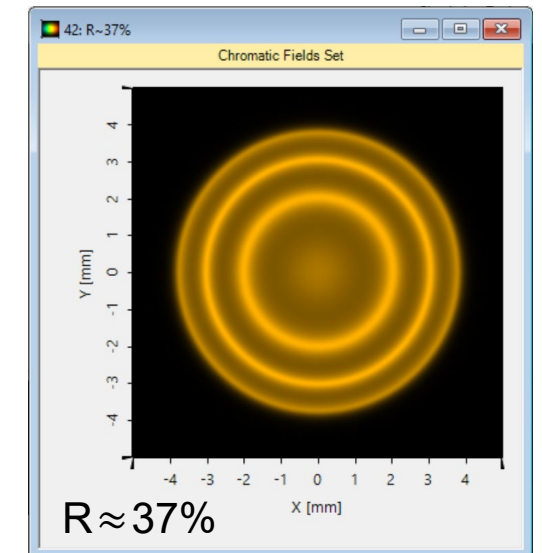
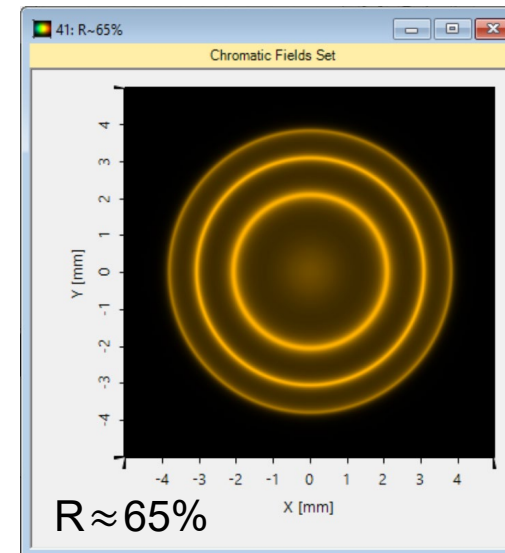
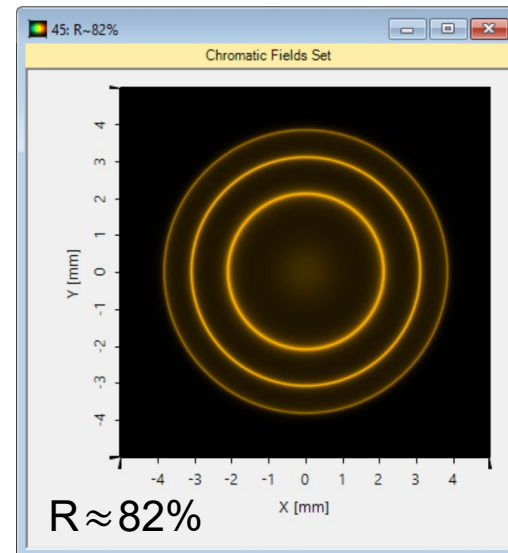


Finesse vs. Coating Reflectance



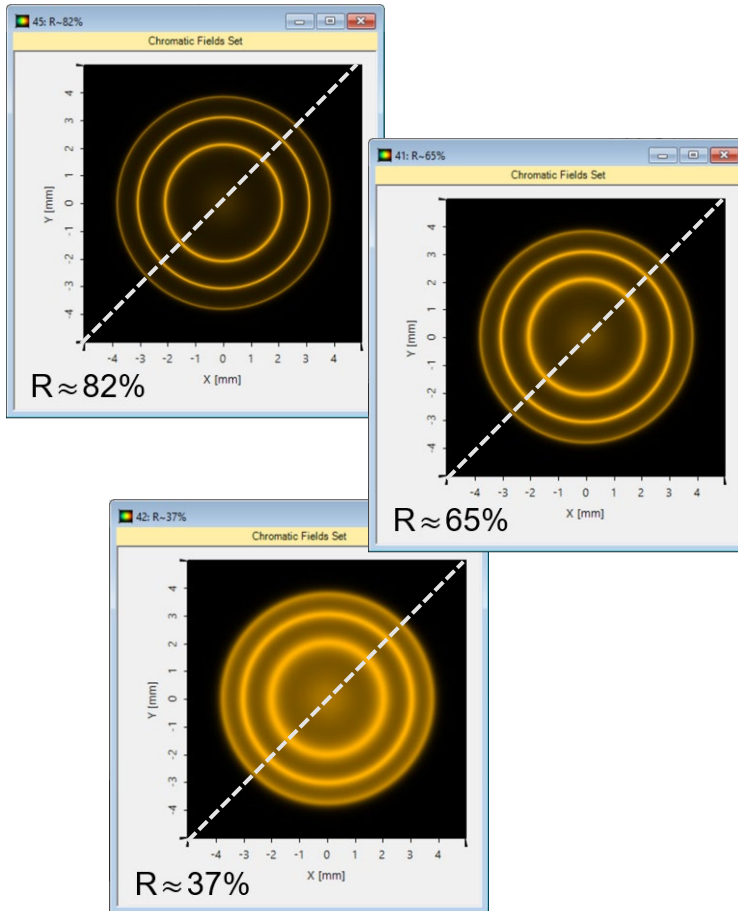
Sharpness of the interference fringes depends on the reflectance of the coatings on the etalon.

- coatings
- varying reflectance:
82%, 65%, 37%

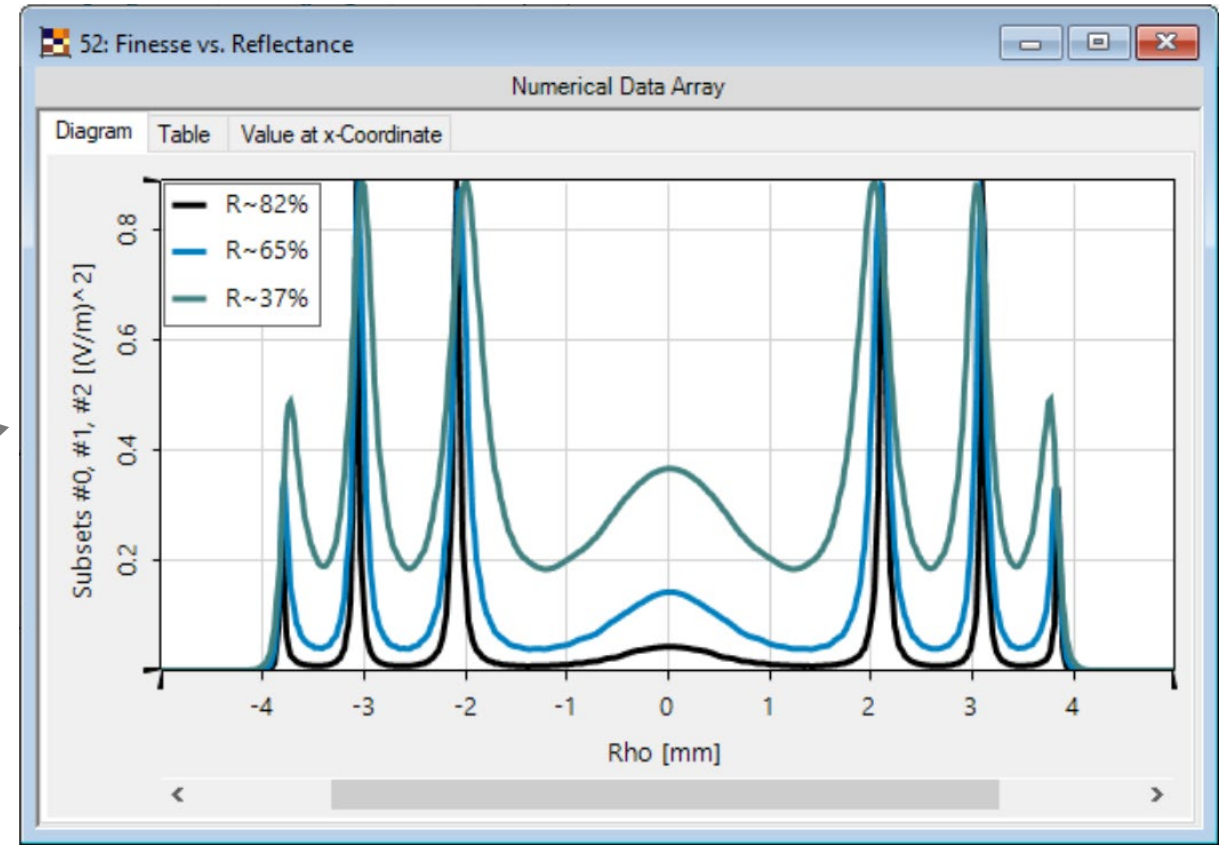


Finesse vs. Coating Reflectance

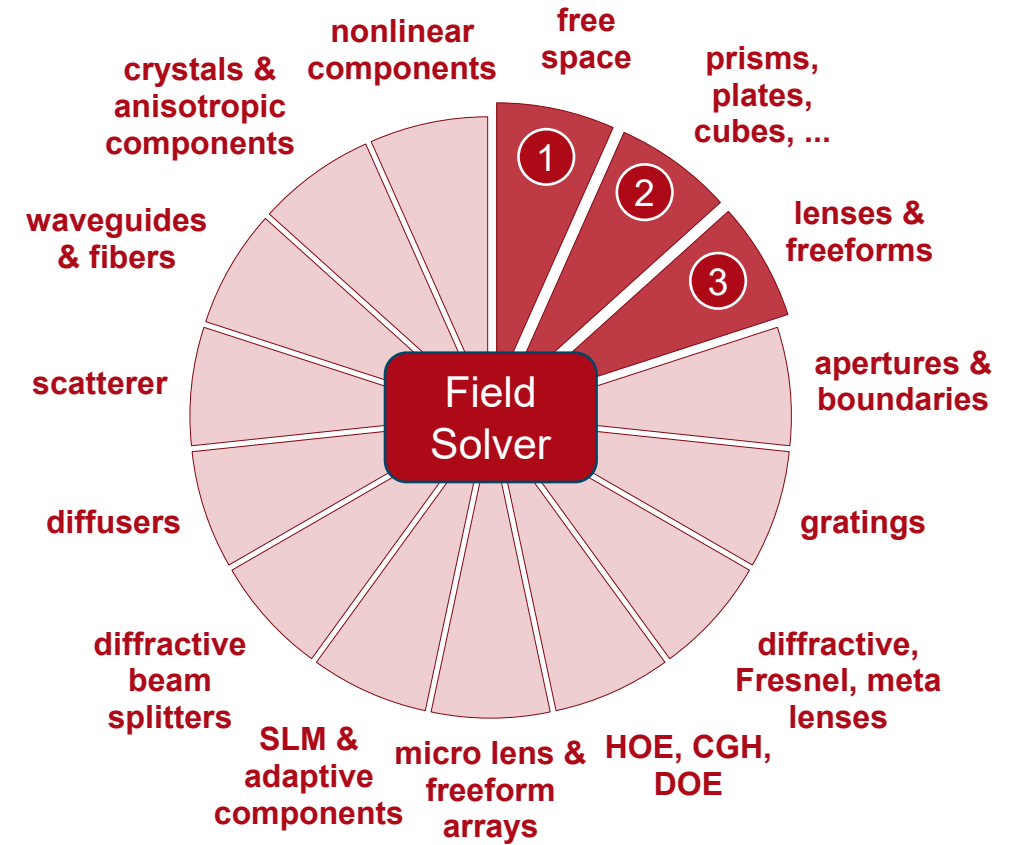
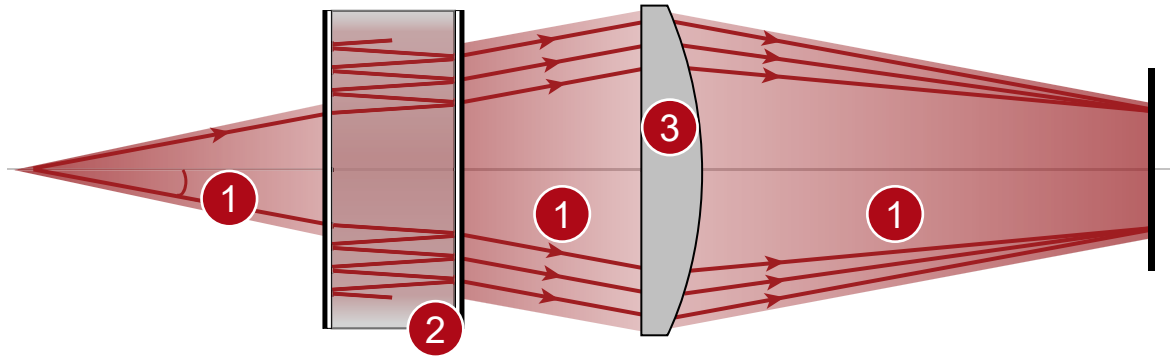
the higher the reflectance, the higher the finesse



1D measurements along the radial direction



VirtualLab Fusion Technologies



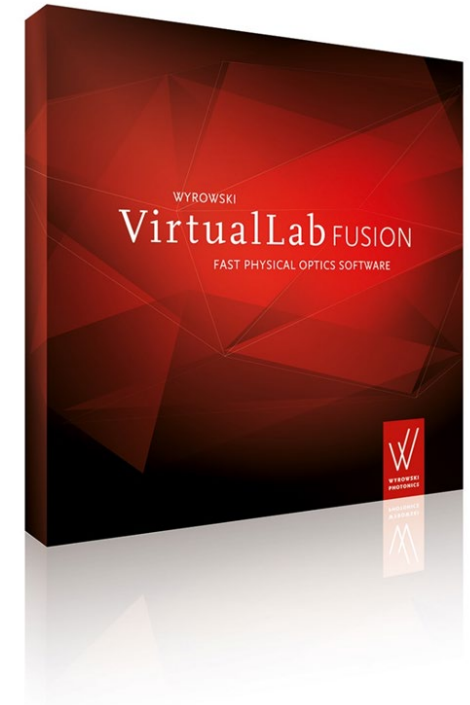
Part 6

The Source Mode Concept



How to Model the Different Properties of Light?

- Being able to replicate the physical **properties of the light** that enters a system is just as important for an optical simulation as being able to model the effect of the different components on the field.
- We are mainly talking about **polarization**, partial **temporal coherence**, partial **spatial coherence**.
- There are different mathematical strategies available.
- In VirtualLab Fusion we follow a single general approach which can be applied to the simulation of all these characteristics: the **source-mode concept**.



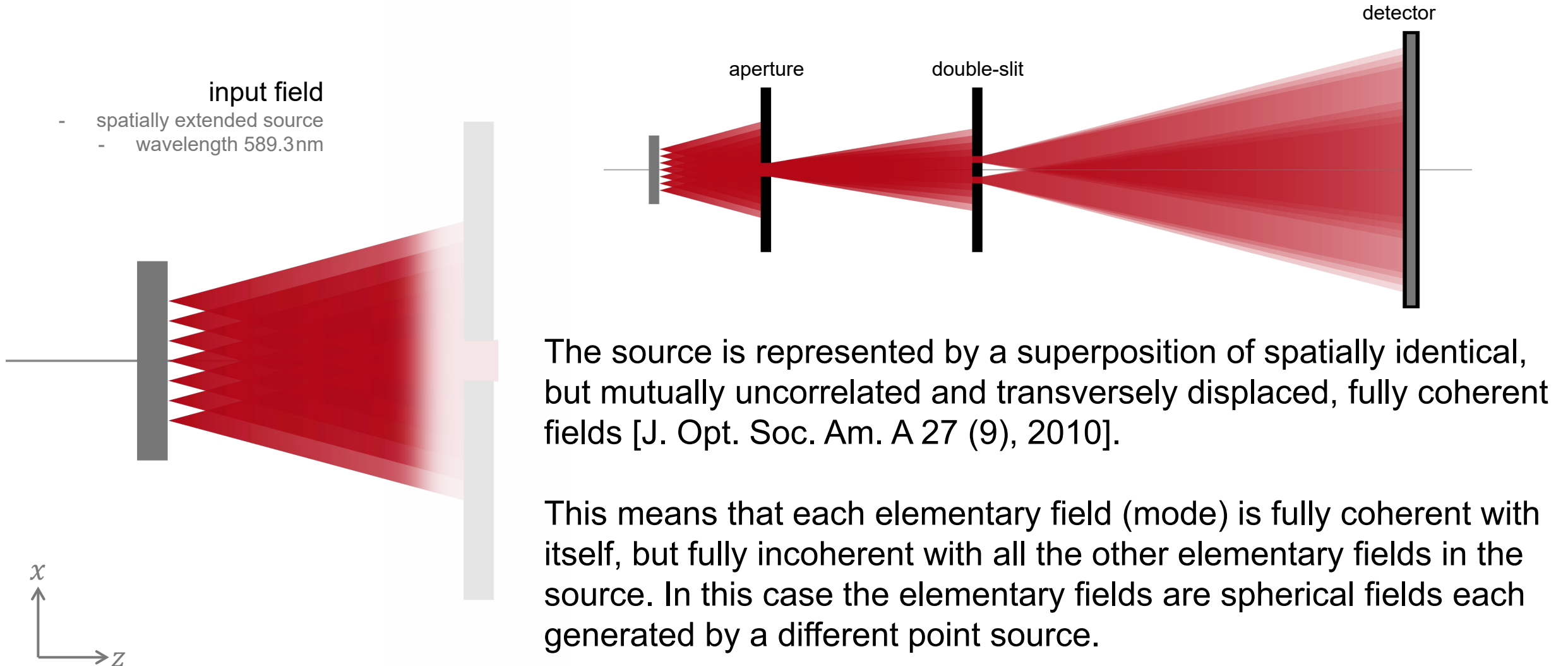
The Source Mode Concept

- The light at the input plane of the system is represented by a finite set of modes.
 - **Each of the modes is fully self-correlated.** This means that, if a source mode is split on its way through the system (for instance, by being partly transmitted and partly reflected at an interface) each of the resulting modes will be coherent to each other, and therefore capable of generating an interference pattern.
 - **Each of the source modes can be coherent or incoherent to each of the other source modes,** depending on the property to be modelled and the characteristics of the source.
 - There are different types of modes: spectral (wavelength) and spatial.
 - **Finding the best set of modes for a given source in a given system is in general not a trivial task!**
-

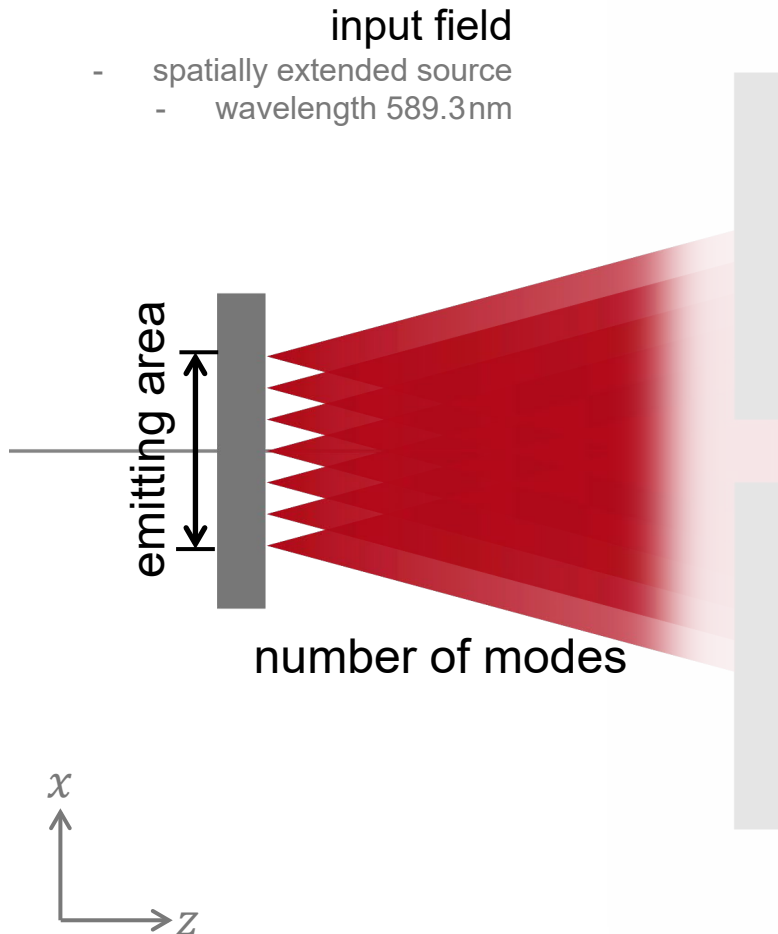
Partial Spatial Coherence with Shifted Elementary Field Method

 [see the full Application Use Case](#)

Shifted Elementary-Field Method



Number of Elementary-Fields (Modes)



- The emitting area is fixed at $800\mu\text{m}$. The point source at the edge of this emitting area gives a weak interference pattern, which is negligible.
- The number of elementary fields (modes) should be large enough to achieve convergent and reliable results.
- So before performing the simulation, **we use a one-dimensional (1D) list of point sources along the x axis to check how many modes give convergent fringes along said axis in the detector.**
- To keep the power of the source constant, the power weight of each point source decreases as the number of modes increases.

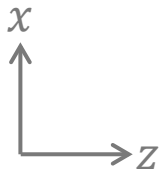
$$\text{weight} = \frac{1.0}{\text{number of modes}}$$

Configuration of Parameter Variation

- input field
 - spatially extended source
 - wavelength 589.3nm

emitting area

number of modes



optical setup

editor of spherical wave

select spherical wave as elementary field

position of source point on x axis

Parameter Run

1	2	*	Object	Category	Parameter	Vary	From	To	Steps	Original Value
					Distance to Input...	<input type="checkbox"/>	-1E+303 mm	1E+303 mm	1	10 mm
					Lateral Offset X	<input checked="" type="checkbox"/>	-400 μ m	400 μ m	5	0 mm
					Lateral Offset Y	<input type="checkbox"/>	-1E+303 mm	1E+303 mm	1	0 mm
			"Spherical Wave" #0		Number of Rays X	<input type="checkbox"/>	1	2E+03	1	31
					Number of Rays Y	<input type="checkbox"/>	1	2E+03	1	31
					Oversampling Fa...	<input type="checkbox"/>	1E+300	1E+300	1	1

source area is 800 μ m

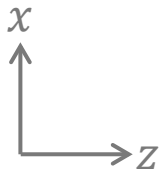
number of modes is 5

Configuration of Parameter Variation

- input field
 - spatially extended source
 - wavelength 589.3 nm

emitting area

number of modes



optical setup

7: Optical Setup View #6 (Optical Setup)*

select spherical wave as elementary field

editor of spherical wave

Generate Spherical Wave

Polarization Mode Selection Sampling Ray Selection

Basic Parameters Spectral Parameters Spatial Parameters

Power Spectrum Type Single Wavelength

Spectral Values

Wavelength 589.3 nm Weight 0.038462

power weight

Preview

Parameter Run

Object Category Parameter Vary From To Steps Original Value

		Wavelength	<input type="checkbox"/>	193 nm	50 μ m	1	589.3 nm
		Weight	<input checked="" type="checkbox"/>	0	1	5	1
		Polarization Angle	<input type="checkbox"/>		360°	1	0°
		Distance to	<input type="checkbox"/>		1E+303 mm	1	10 mm
		Lateral Offset X	<input checked="" type="checkbox"/>	-400 μ m	400 μ m	5	0 mm
		Lateral Offset Y	<input type="checkbox"/>	-1E+303 mm	1E+303 mm	1	0 mm

*Spherical

Show Only Varied Parameters

power weight

Programmable Mode of Parameter Run

Main Function

```
double[,] parameters = new double[NumberOfParameters,NumberOfIterations];

double weight = 1.0 / NumberOfIterations;
for(int Index = 0; Index < NumberOfIterations; Index++)
{
    //power weight
    parameters[0, Index] = weight;
    //position of point source
    parameters[1, Index] = MinimumValues[1] + (MaximumValues[1] - MinimumValues[1]) / (NumberOfIterations - 1.0) * Index;
}

return parameters;
```

$$\text{weight} = \frac{1.0}{\text{number of modes}}$$

Filter by... X ☐ Show Only Varied Parameters

1	2	*	Object	Category	Parameter	Vary	From	To	Steps	Original Value	^
					Wavelength	<input type="checkbox"/>	193 nm	50 µm	1	589.3 nm	
					Weight	<input checked="" type="checkbox"/>	0	1	5	1	
					Polarization Angle	<input type="checkbox"/>	0°	360°	1		
					Distance to Input...	<input type="checkbox"/>	-1E+303 mm	1E+303 mm	1		
					Lateral Offset X	<input checked="" type="checkbox"/>	-400 µm	400 µm	5	0 mm	
					Lateral Offset Y	<input type="checkbox"/>	1E+303 mm	1E+303 mm	1	0 mm	
					Number of ...						
					Number of Rays ...						

"Spherical Wave" #0

NumberOfIterations

MinimumValues[1]

MaximumValues[1]

Display of Resulting Fringe along x Axis

5: D:\OneDrive\...\ParameterRun_5.run*

Results

Start the parameter run and analyze its results

☒ Use Already Calculated Results for Next Run

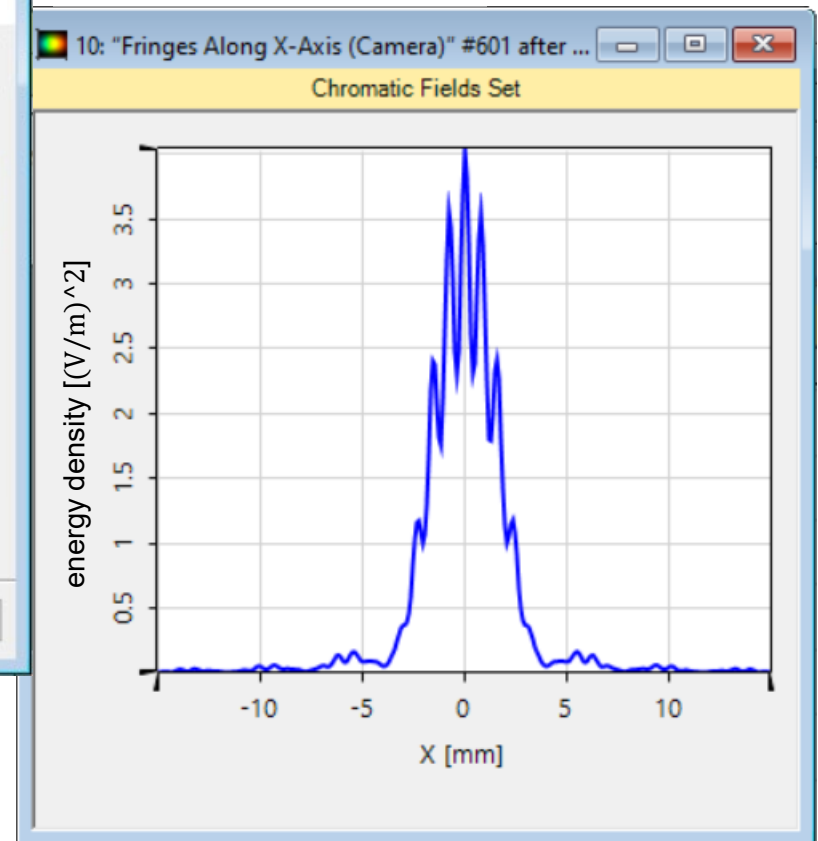
Detector	Subdetector	Combined Output	Iteration Step		
			2	3	4
Varied Parameters	Lateral Offset X ("Spherical...	Data Array	0 μm	0 mm	200 μm
	Weight ("Spherical Wave" ...	Data Array	0.2	0.2	0.2
"Fringe (Camera)" #600 aft...		Animation	s Set	Chromatic Fields Set	Chromatic Fields Set
"Fringes Along X-Axis (Ca...		1D Chromatic	et 1D	Chromatic Fields Set 1D	Chromatic Fields Set 1D

select the row

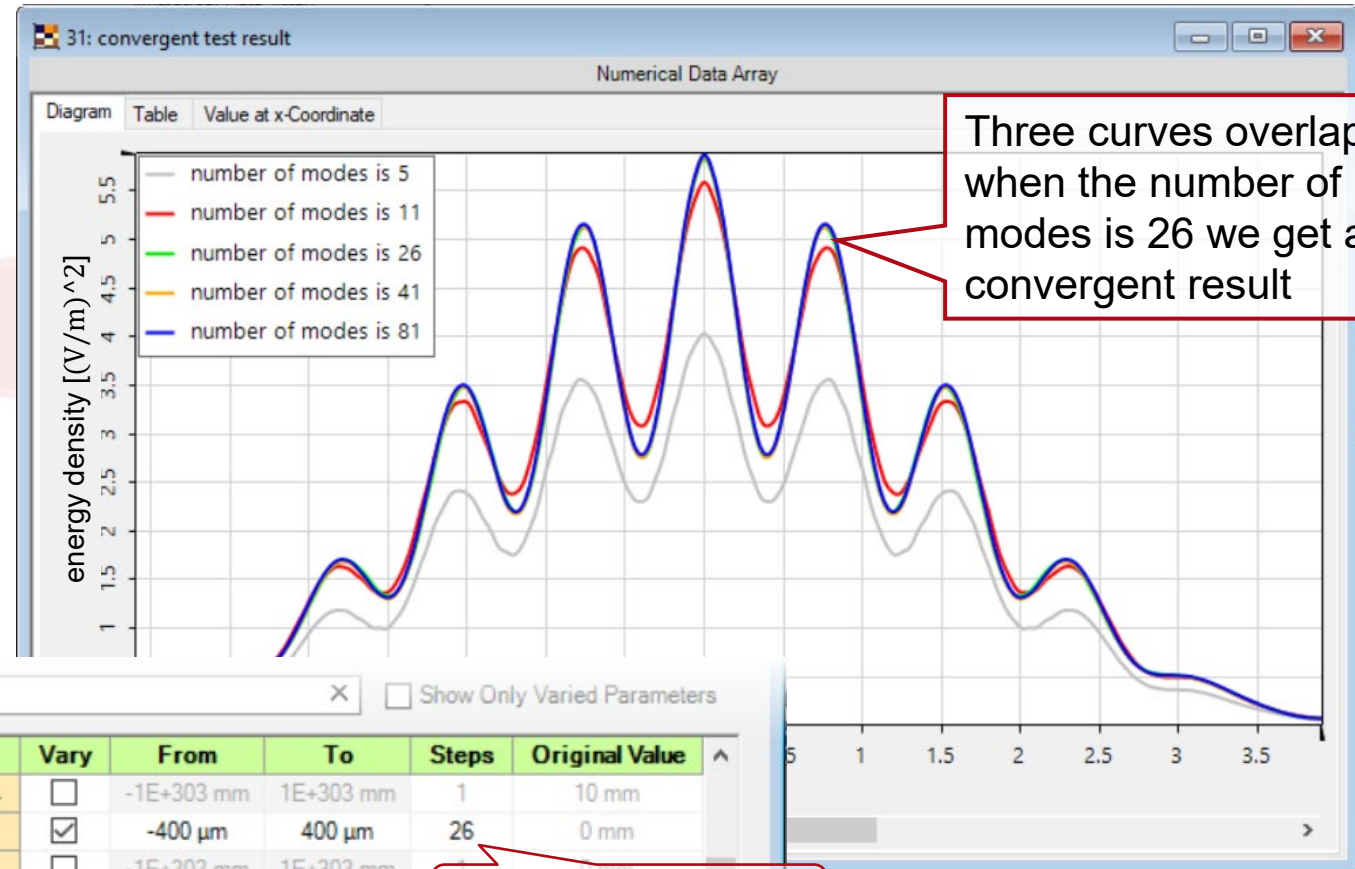
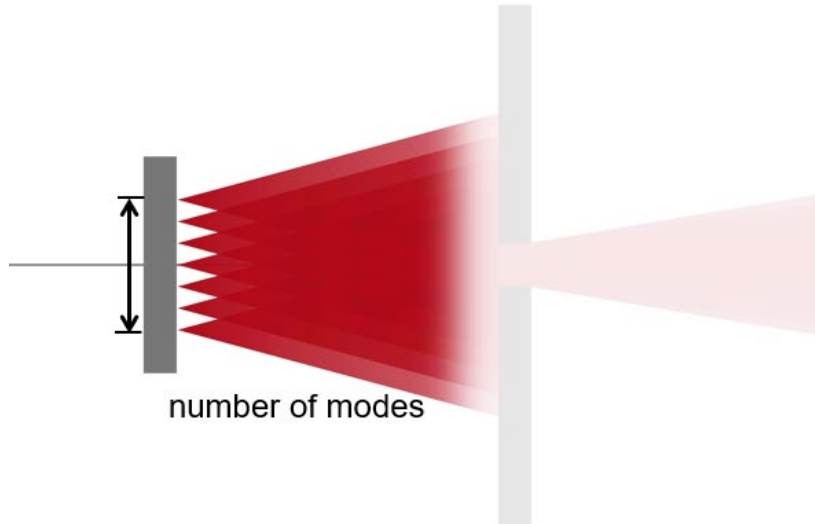
display the resulting fringe

superposition of energy density
from different point sources

fringe along x axis



Fringes with Different Number of Modes



Parameter Run

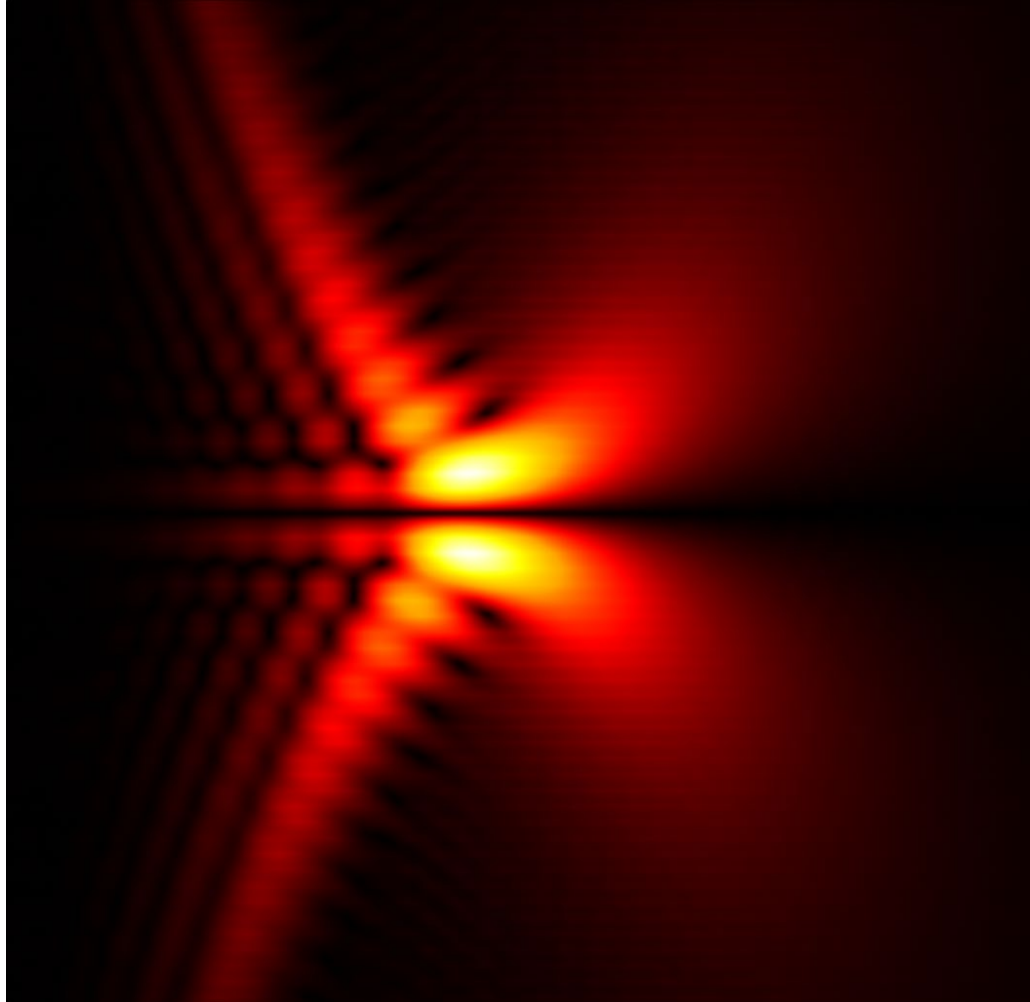
1	2	*	Object	Category	Parameter	Vary	From	To	Steps	Original Value
					Distance to Input...	<input type="checkbox"/>	-1E+303 mm	1E+303 mm	1	10 mm
					Lateral Offset X	<input checked="" type="checkbox"/>	-400 μ m	400 μ m	26	0 mm
					Lateral Offset Y	<input type="checkbox"/>	-1E+303 mm	1E+303 mm	1	0 mm
					Number of Rays X	<input type="checkbox"/>	1	2E+09	1	31
					Number of Rays Y	<input type="checkbox"/>	1	2E+09	1	31
					Oversampling Fa...	<input type="checkbox"/>	1E-300	1E+300	1	1

number of modes

Pulse Focusing with High-NA Lens

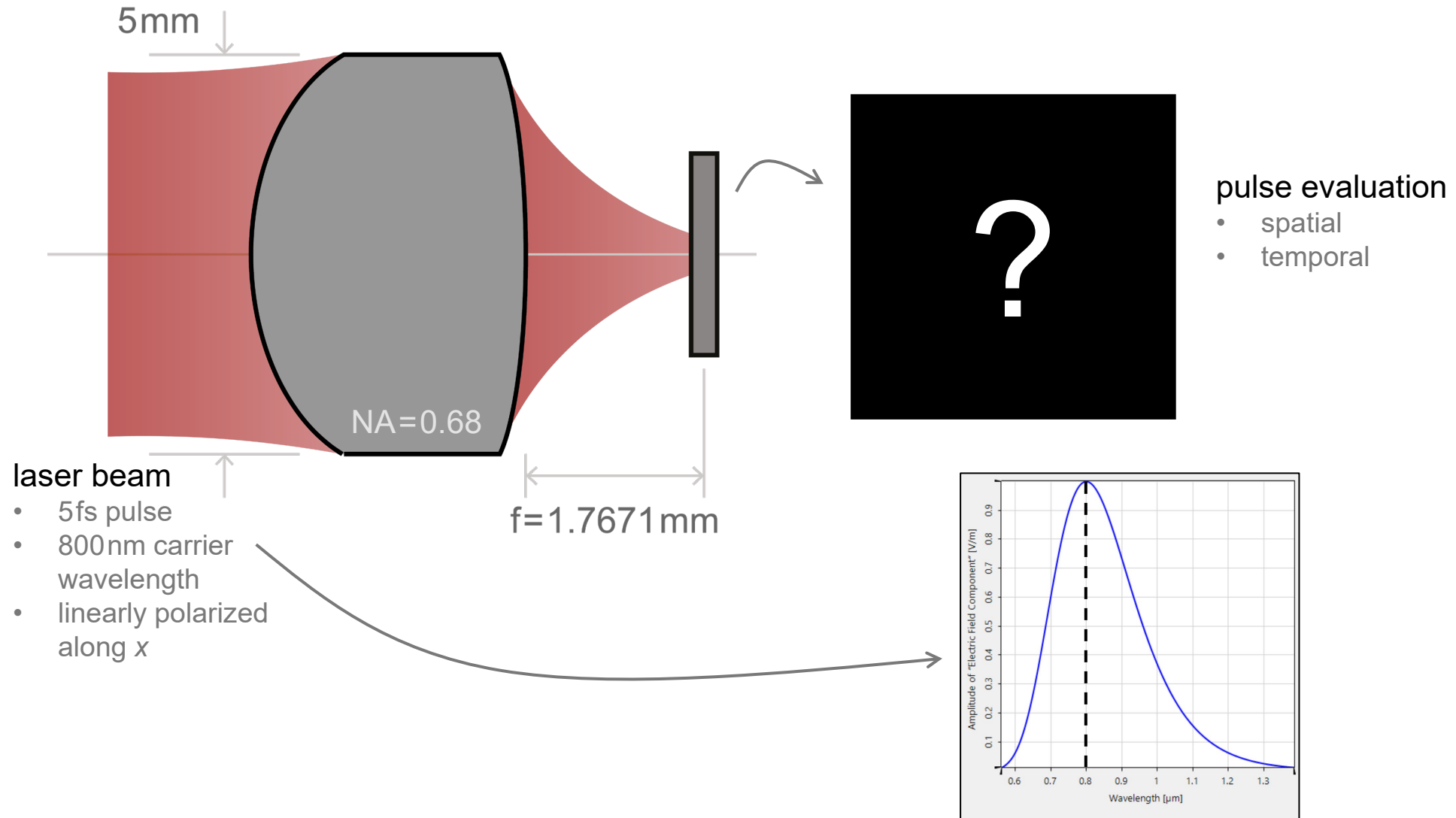


Abstract

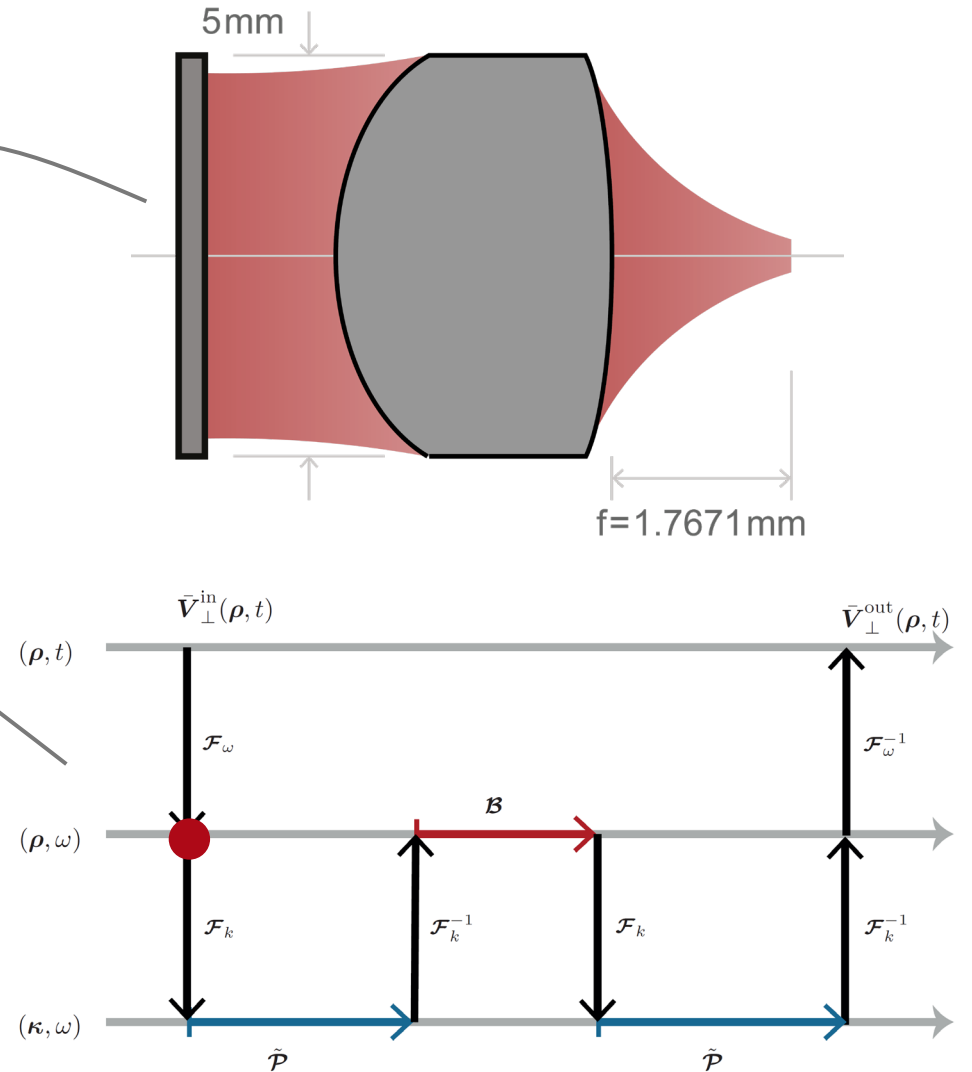
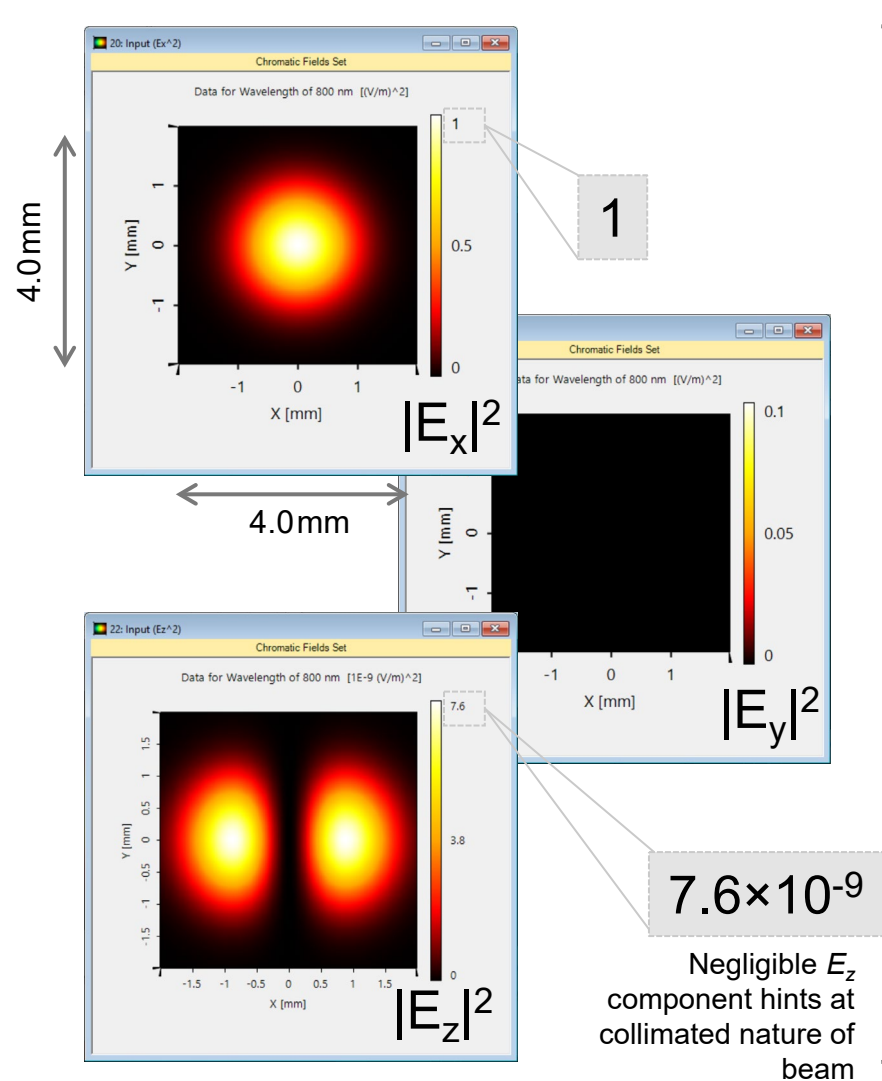


While for most other types of sources it is often accurate enough to labour under the stationary approximation, ultrashort pulses require a somewhat more nuanced approach, where the correlation between the different spectral modes is taken into account. We investigate here the effects of subjecting one such pulse to propagation through a lens with high numerical aperture, in terms of its spatial, as well as of its temporal, profile.

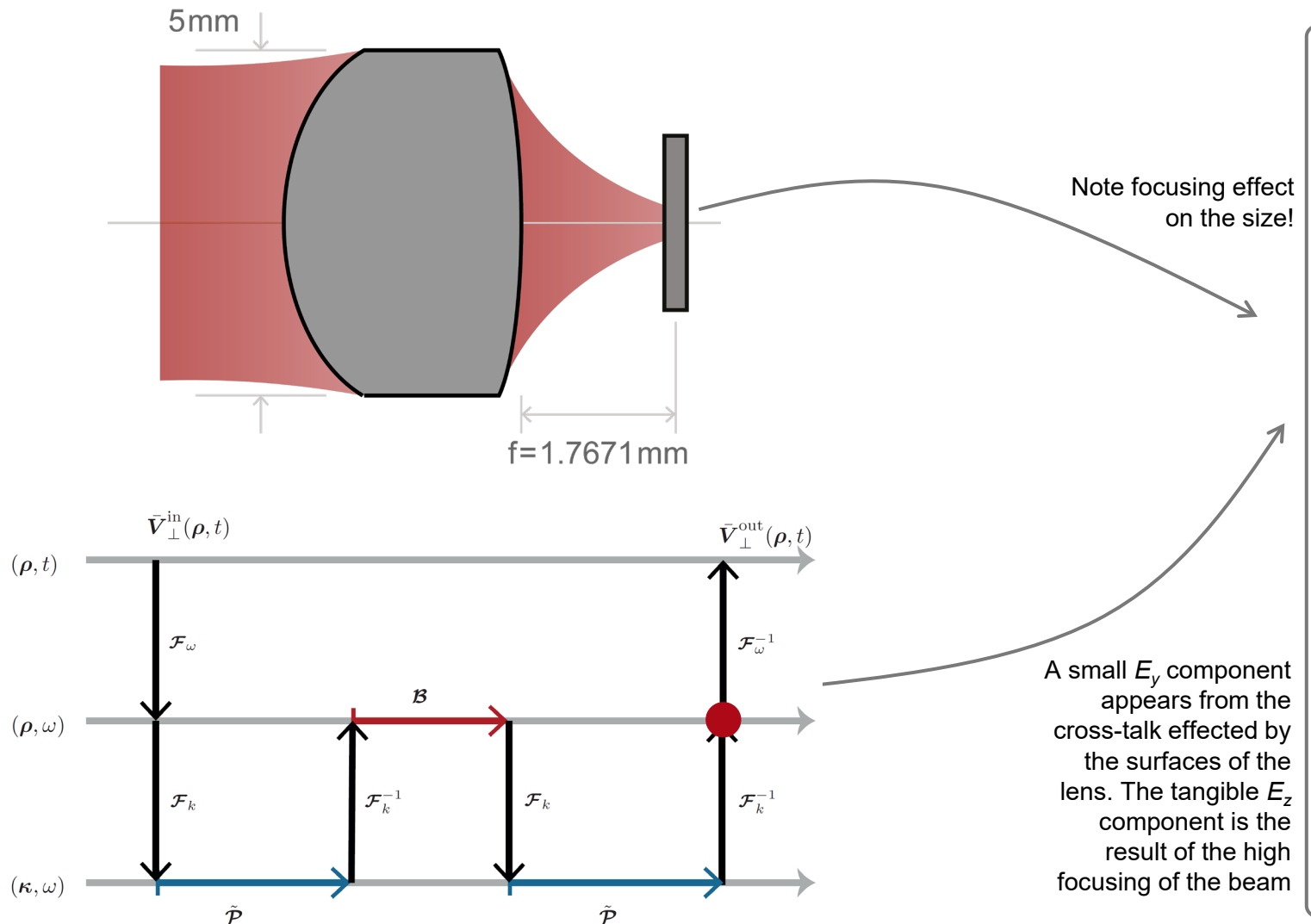
Modeling Task



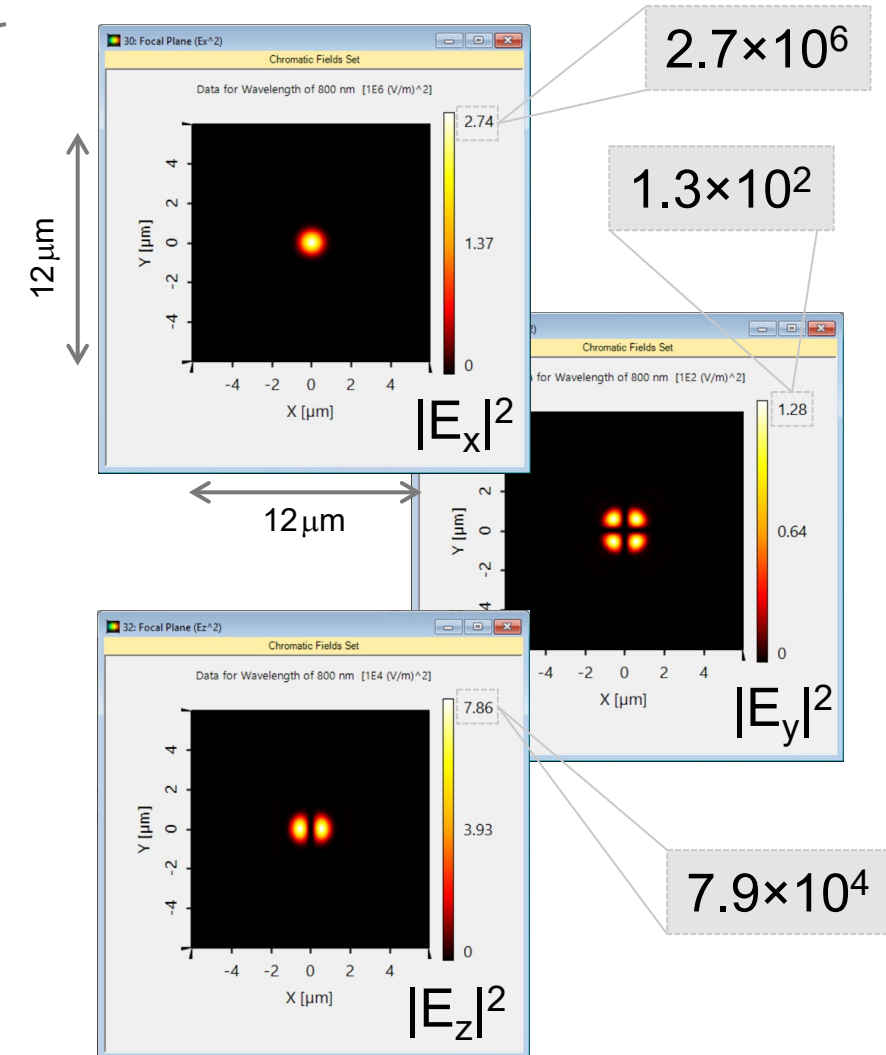
Purely Spatial Analysis: Input Field (Carrier λ)



Purely Spatial Analysis: Field at Focal Plane (Carrier λ)

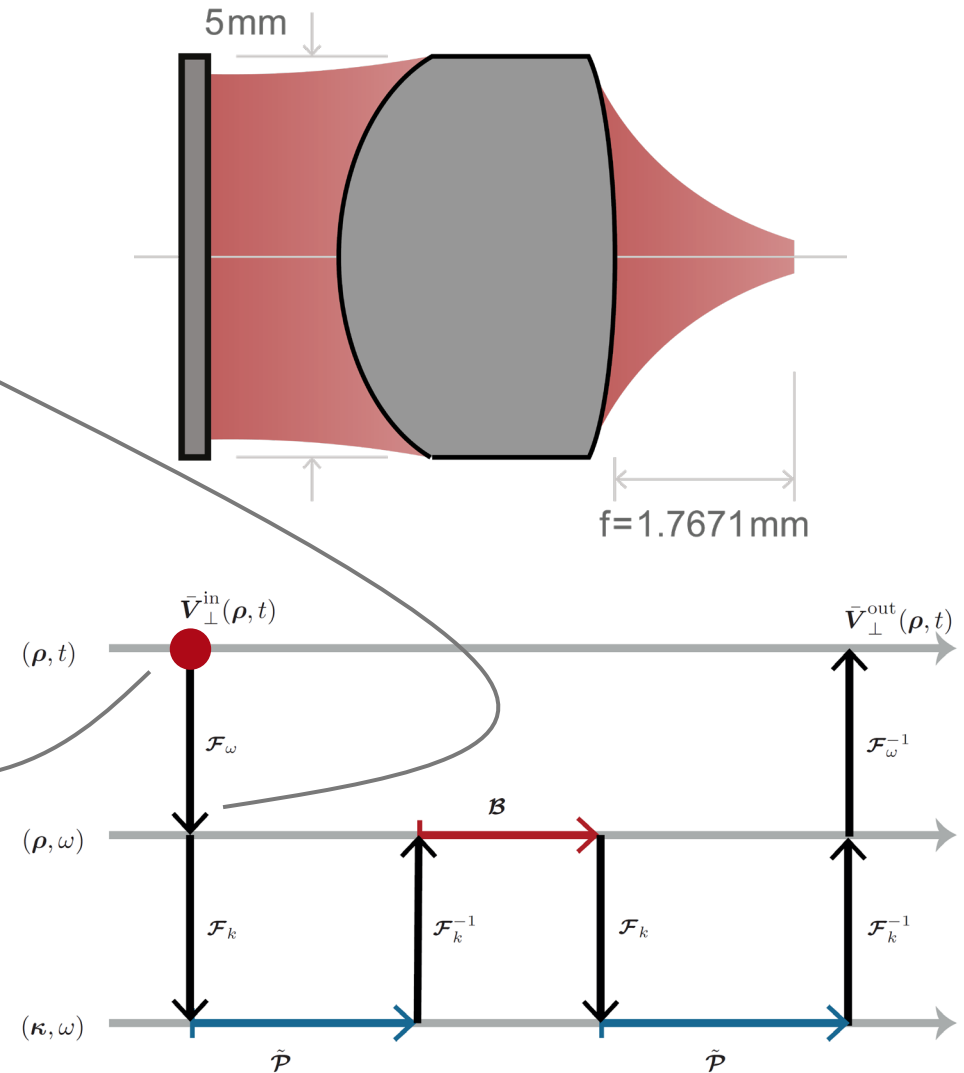
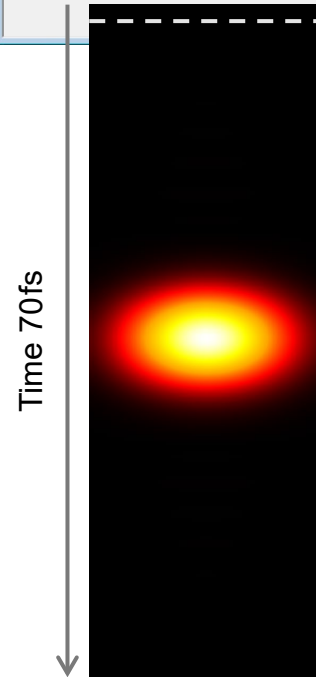
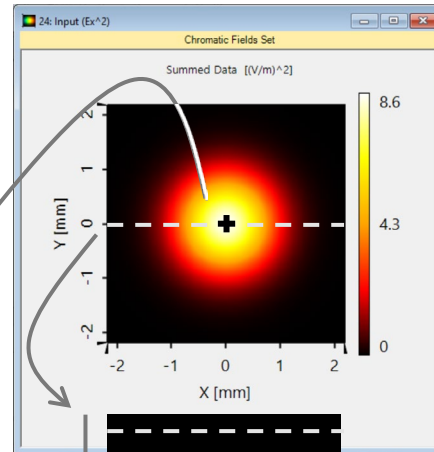
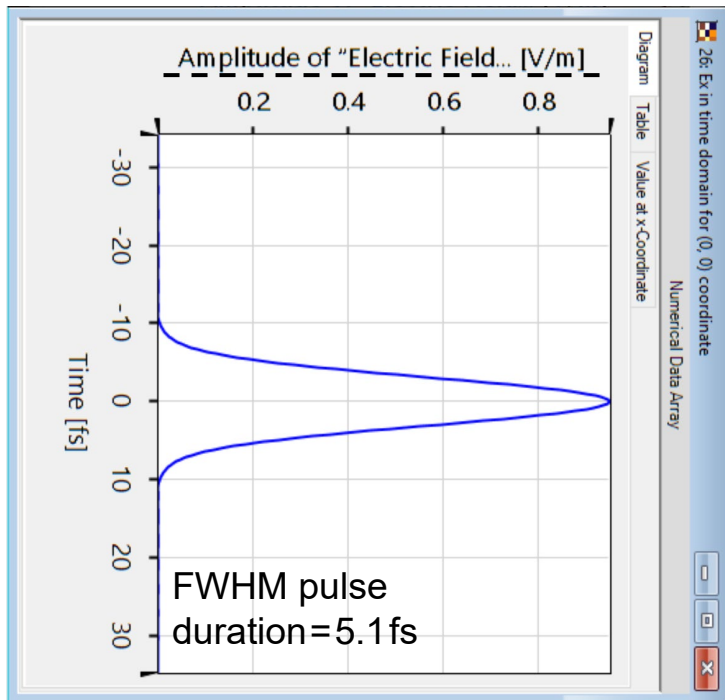


A small E_y component appears from the cross-talk effected by the surfaces of the lens. The tangible E_z component is the result of the high focusing of the beam



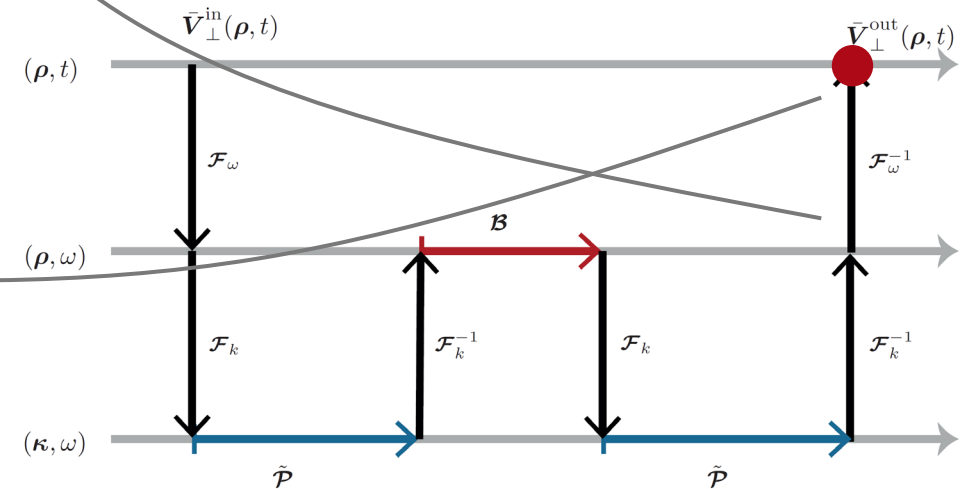
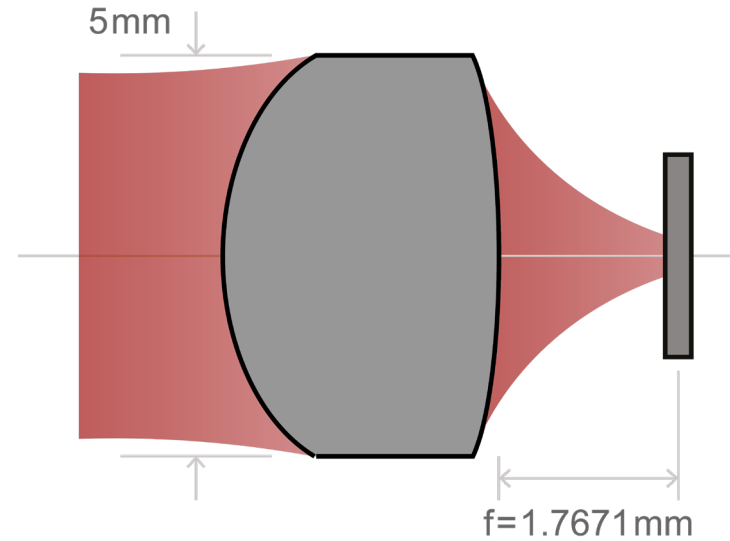
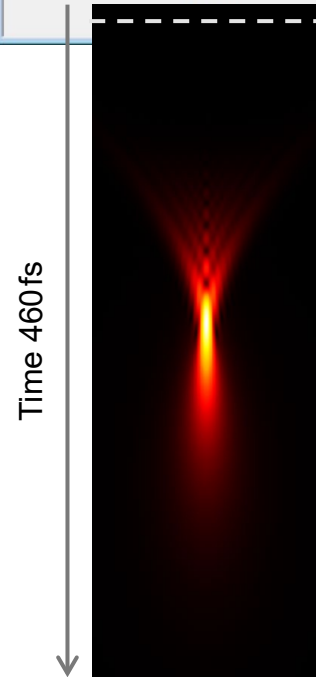
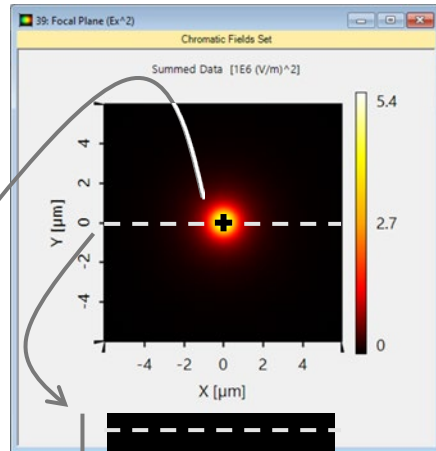
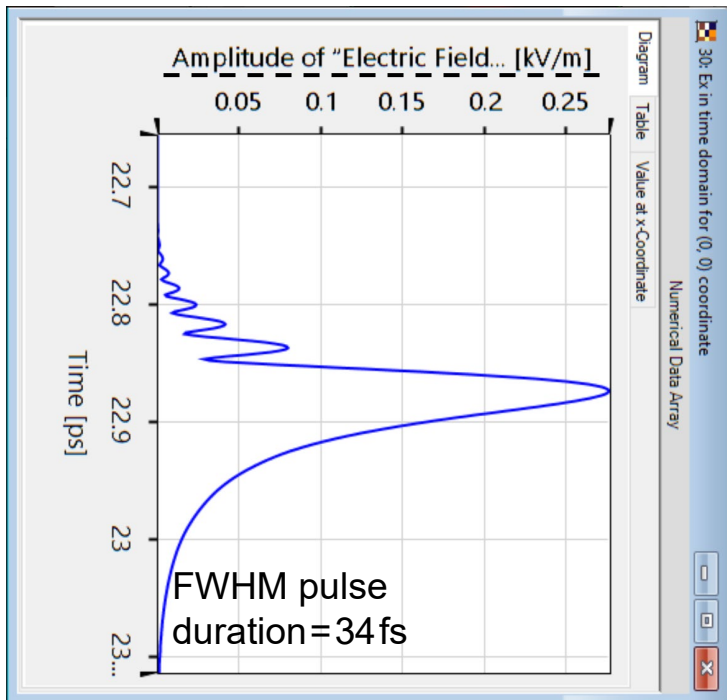
Spatio-Temporal Analysis: Input Field (E_x Component)

The Pulse Evaluation detector in VirtualLab facilitates the visualization of the pulse properties in different domains

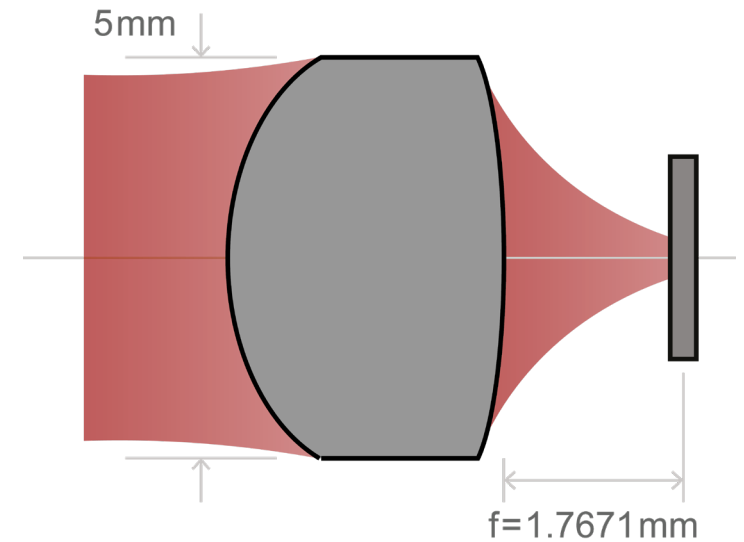
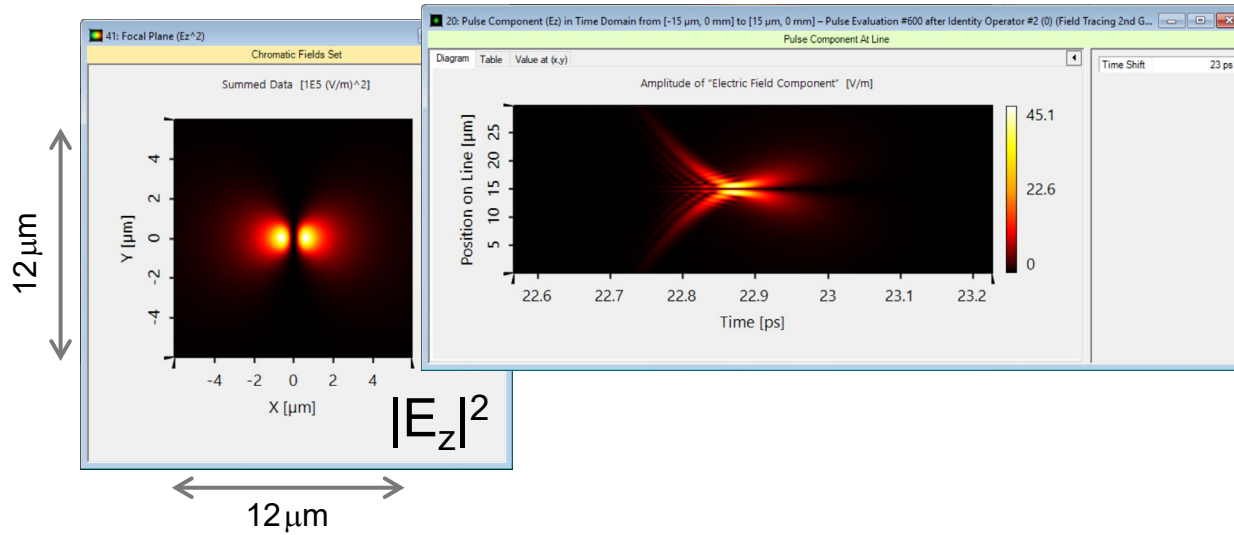
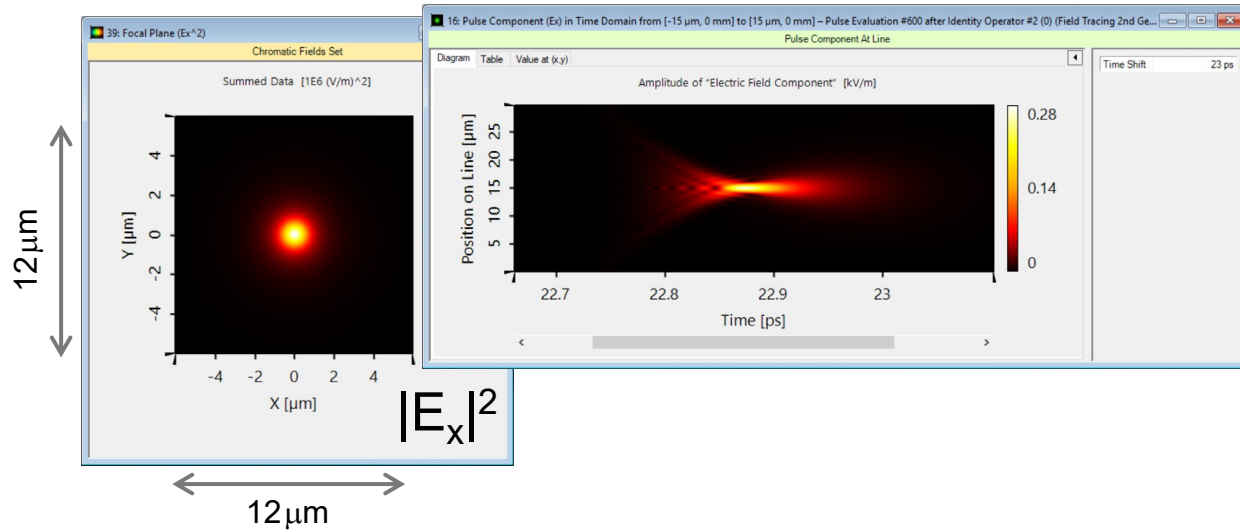


Spatio-Temporal Analysis: Focus (E_x Component)

The Pulse Evaluation detector in VirtualLab facilitates the visualization of the pulse properties in different domains

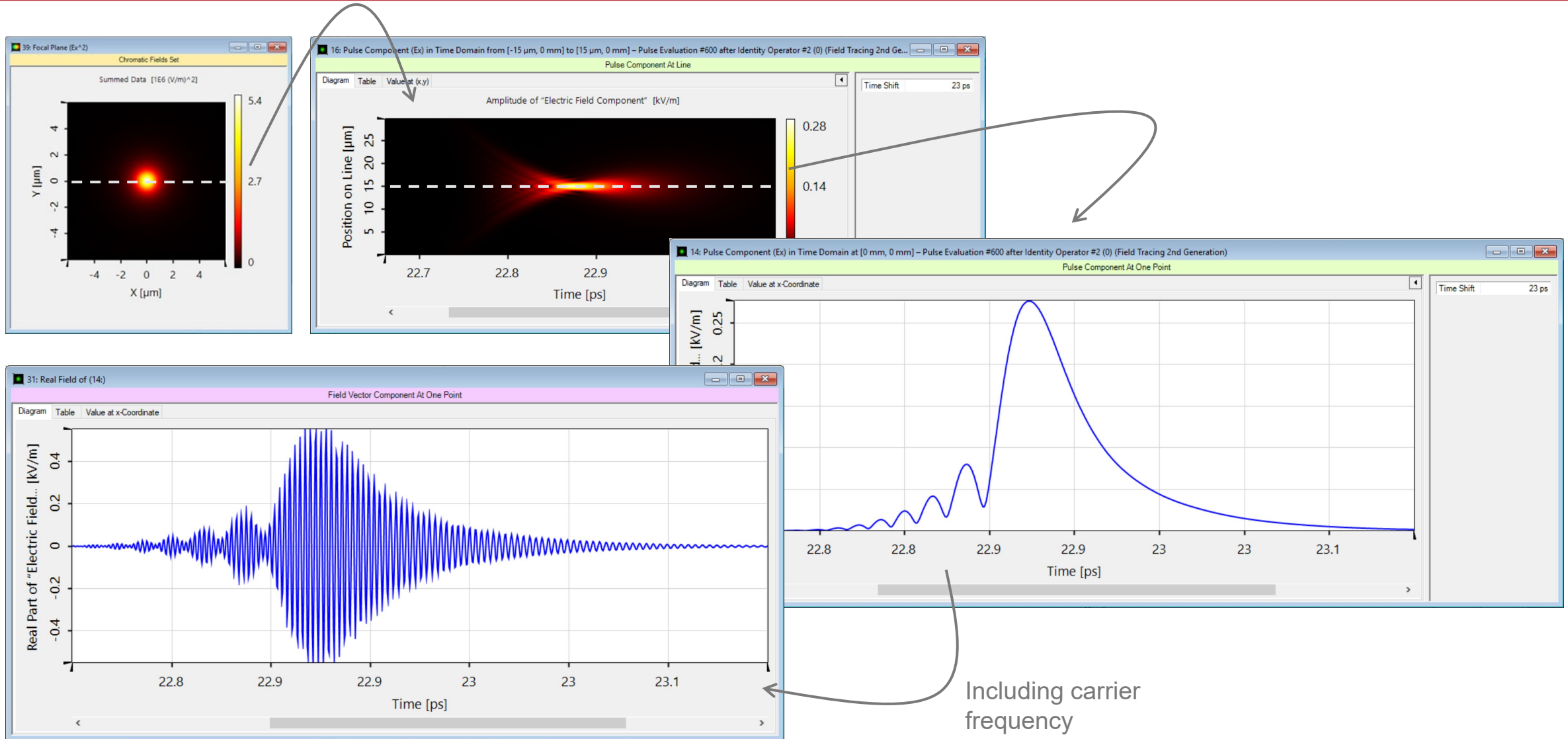


Spatio-Temporal Analysis: Focus (E_x and E_z)



As always, consistent electromagnetic treatment in VirtualLab Fusion allows for the analysis of vectorial effects, also for ultra-short pulses

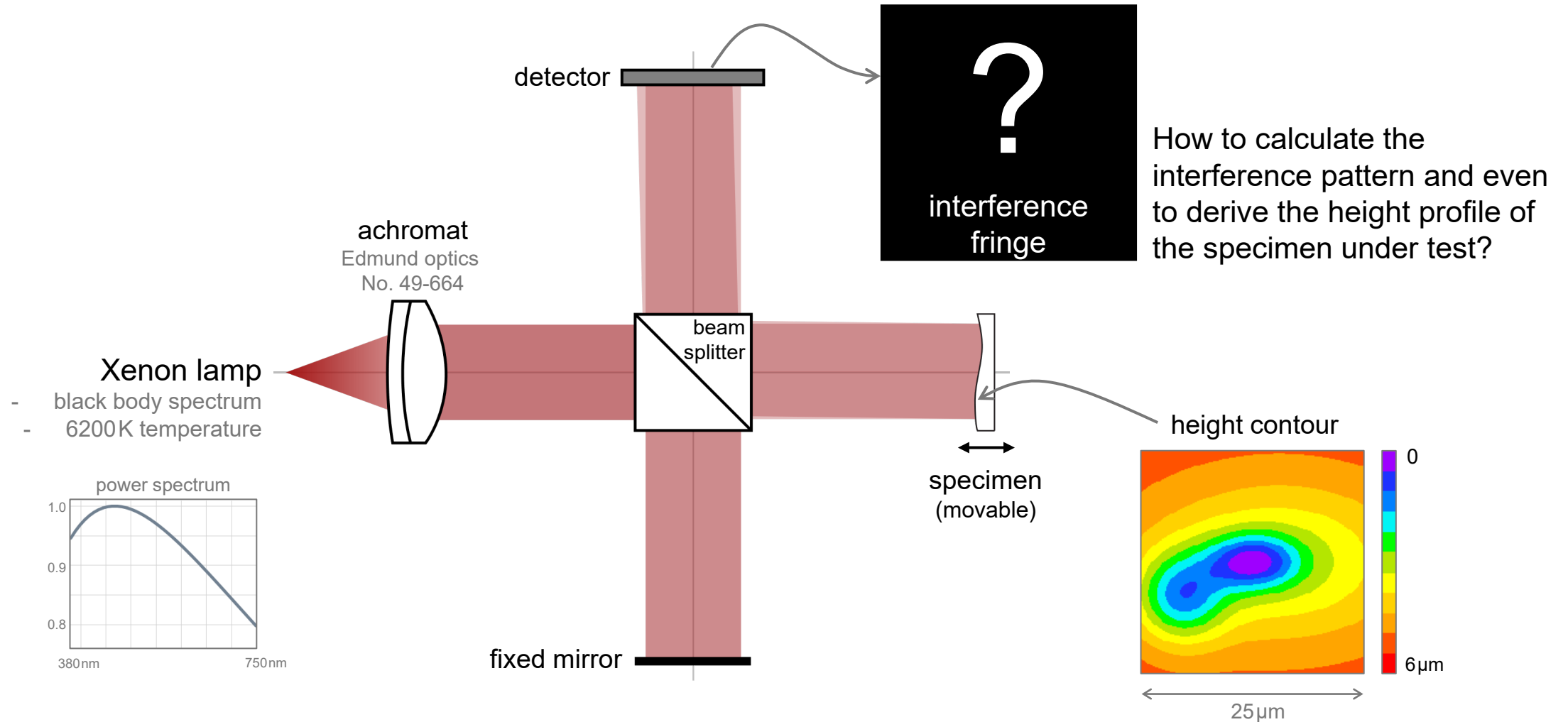
Temporal Analysis: E_x Component with Carrier Frequency



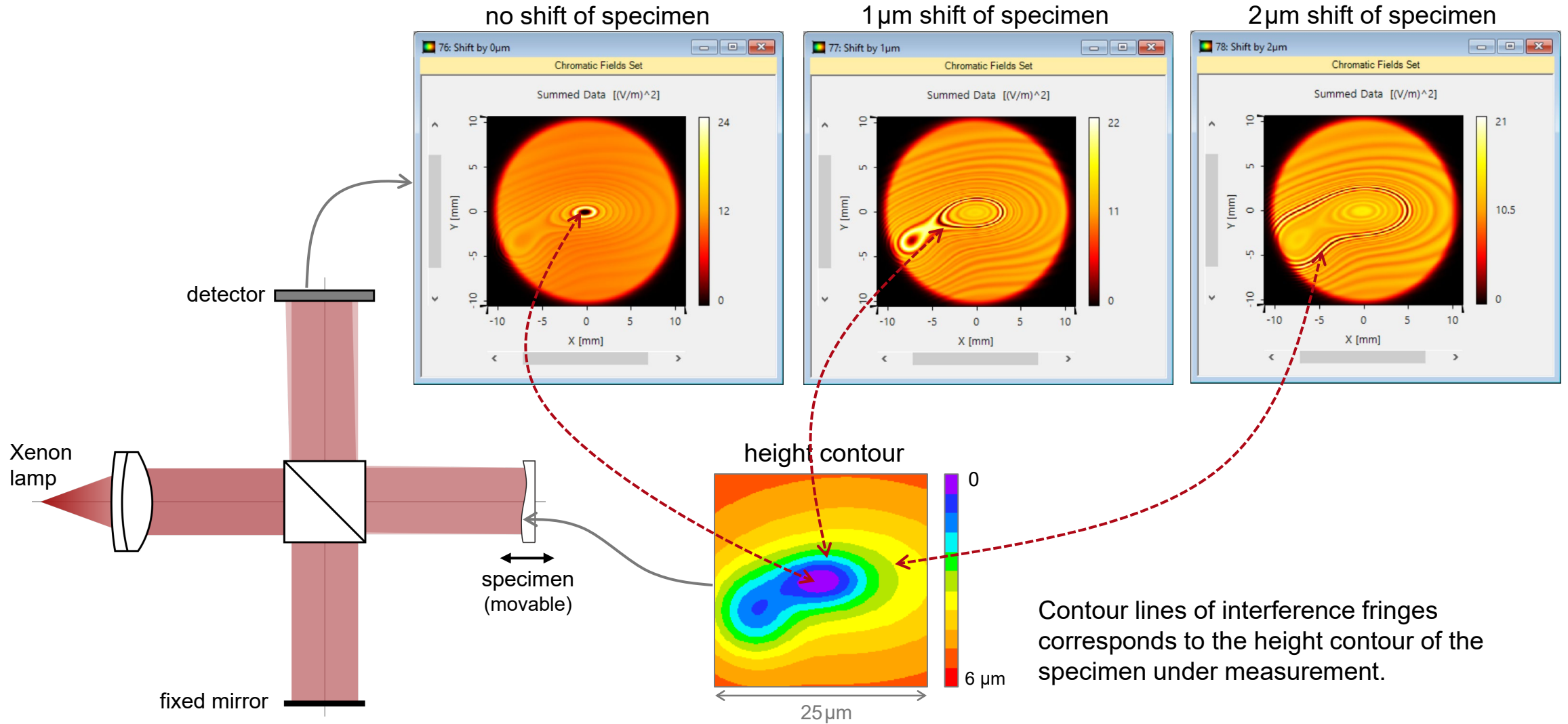
Full-Field Optical Coherence Scanning Interferometry



Modeling Task



Simulated Interference Fringes

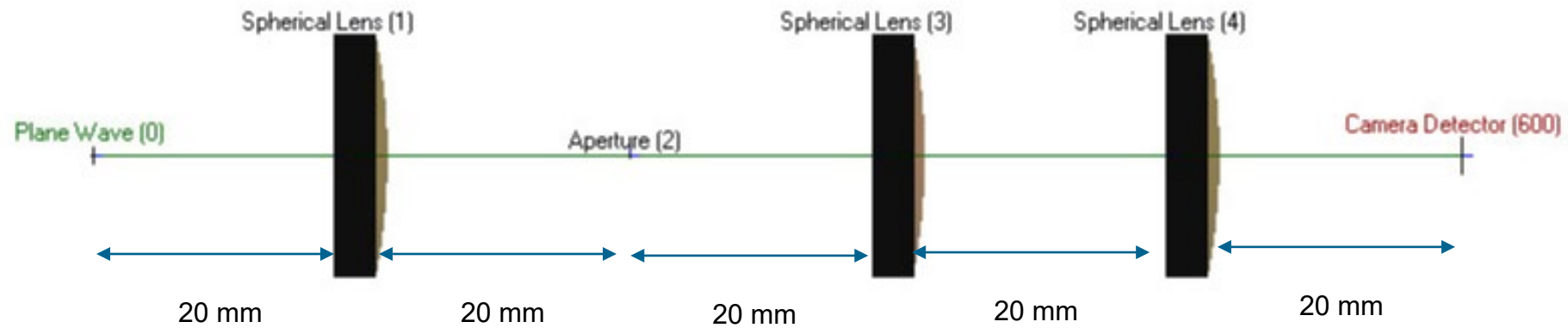


Part 7

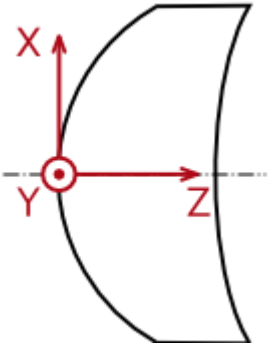
Position and Orientation



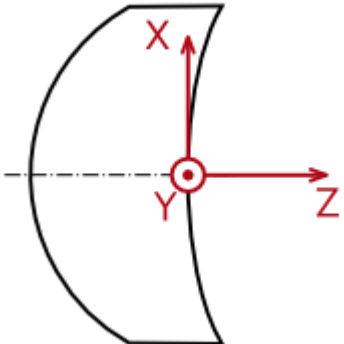
Illustration: Position and Orientation



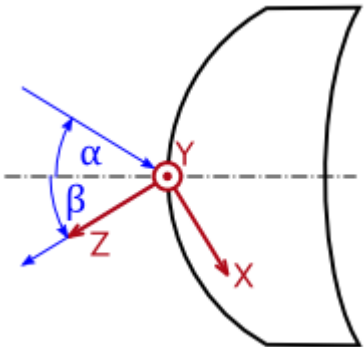
Coordinate Systems



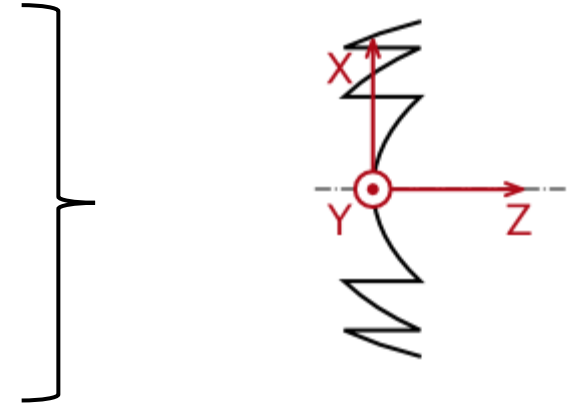
Input coordinate system



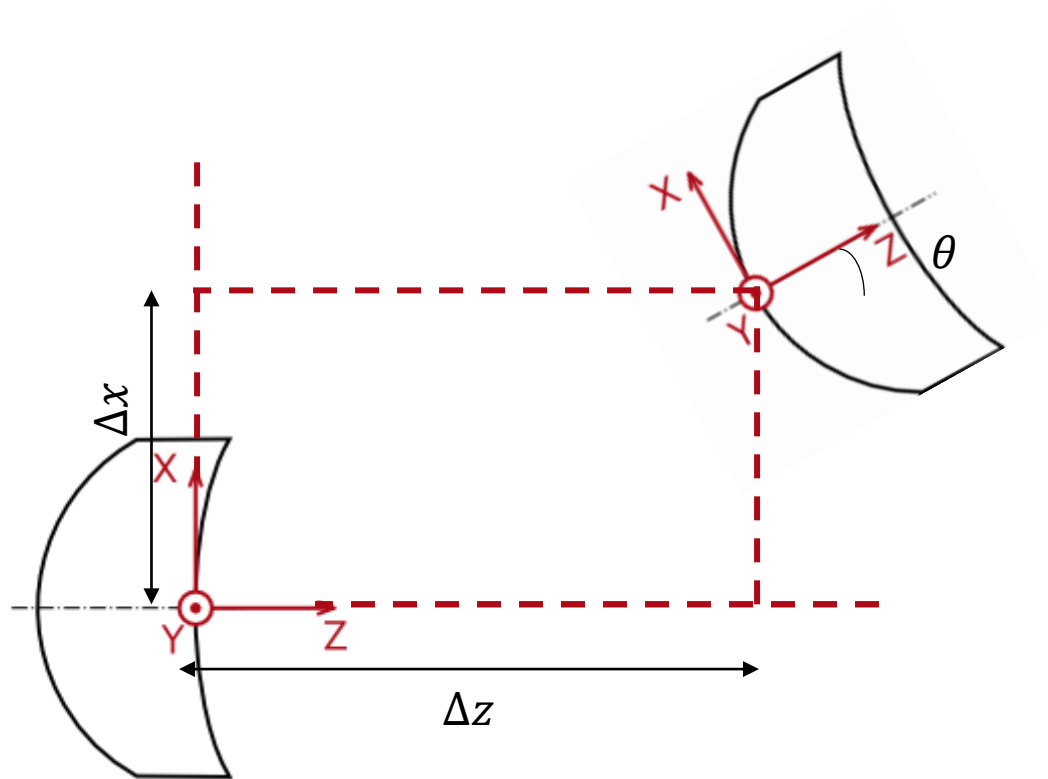
Transmission coordinate system



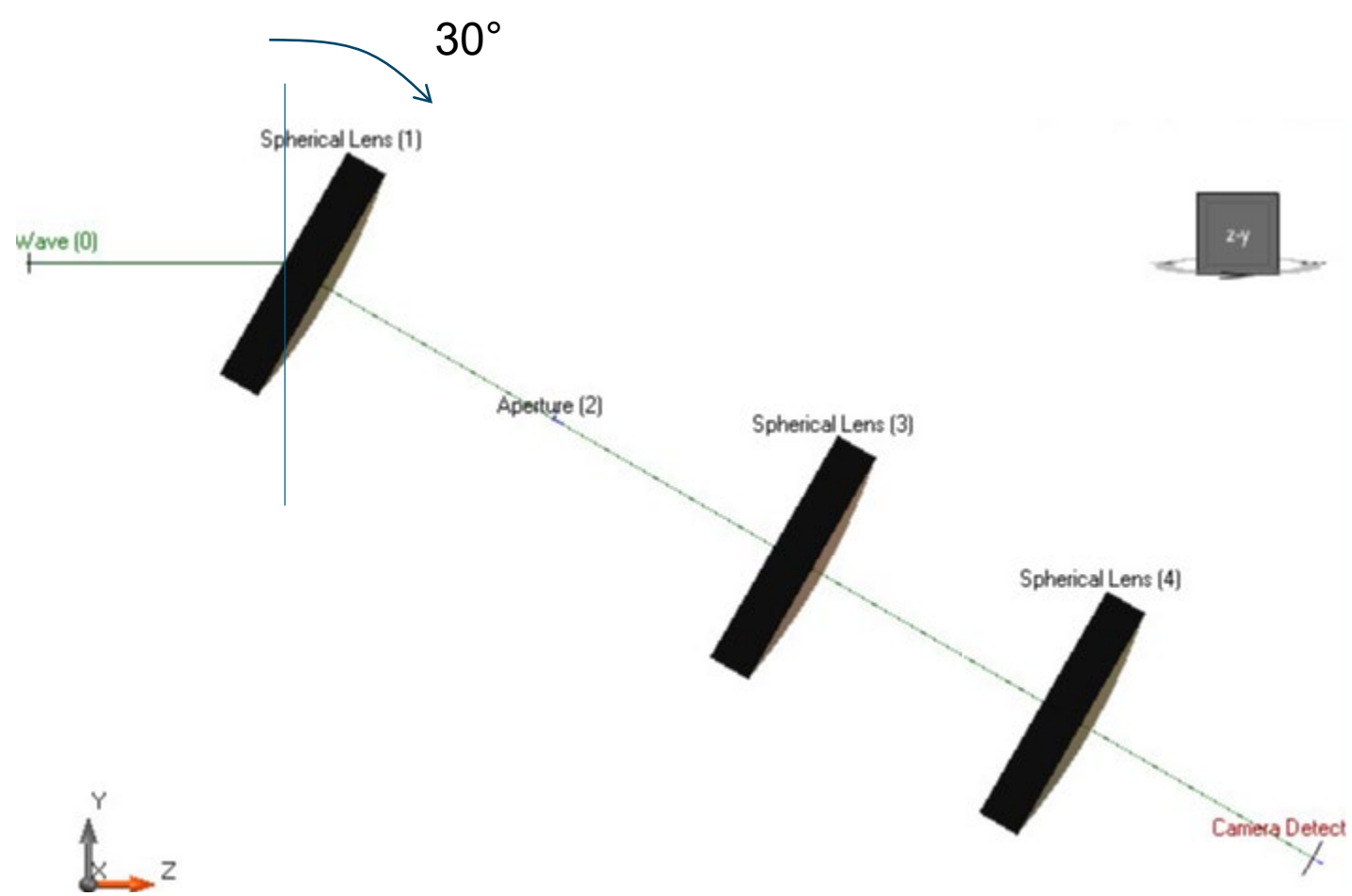
Reflection coordinate system



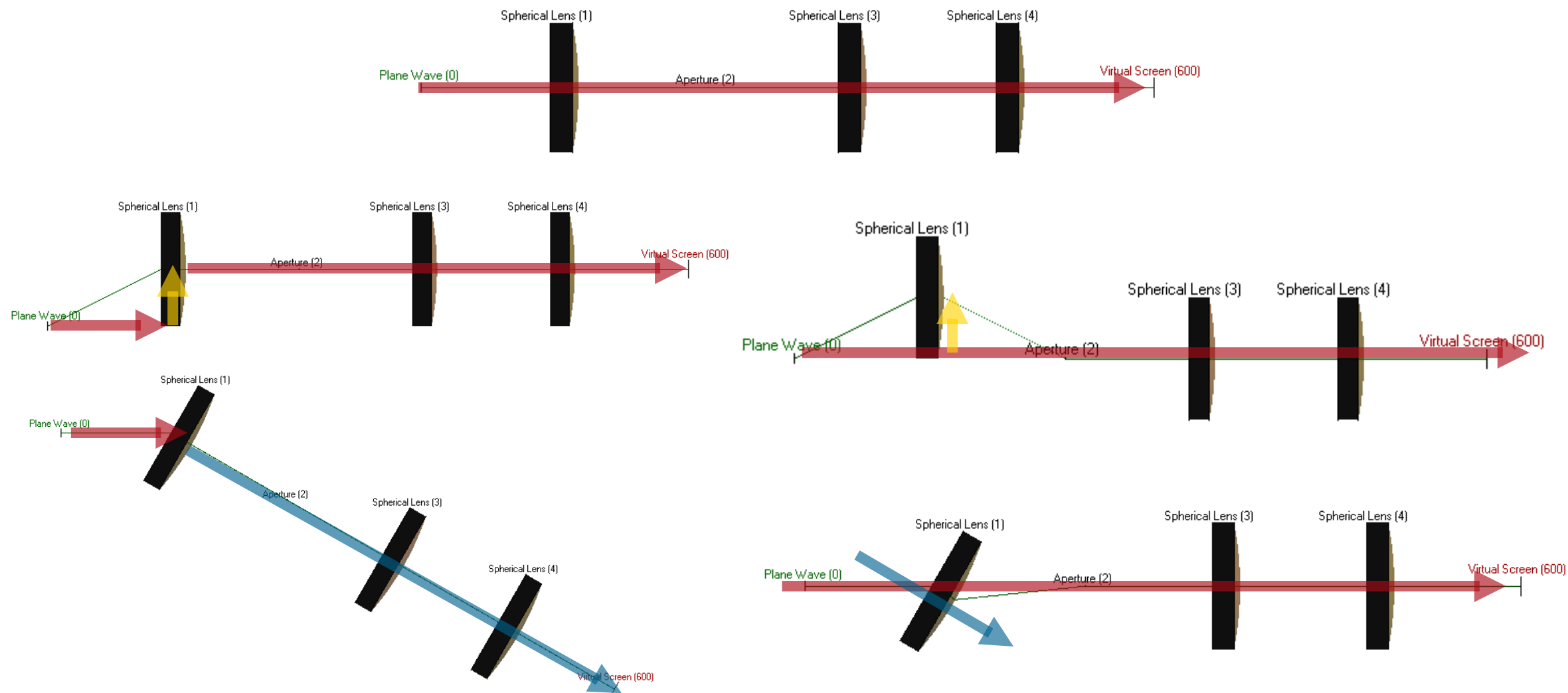
Basal Positioning



Optical Setup



Basal Positioning and Isolated Positioning



Special Components: Mirror

Center Point of Rotations

Reference Point to be Used as Center Point: Reference Point of Input Channel

Orientation Angles

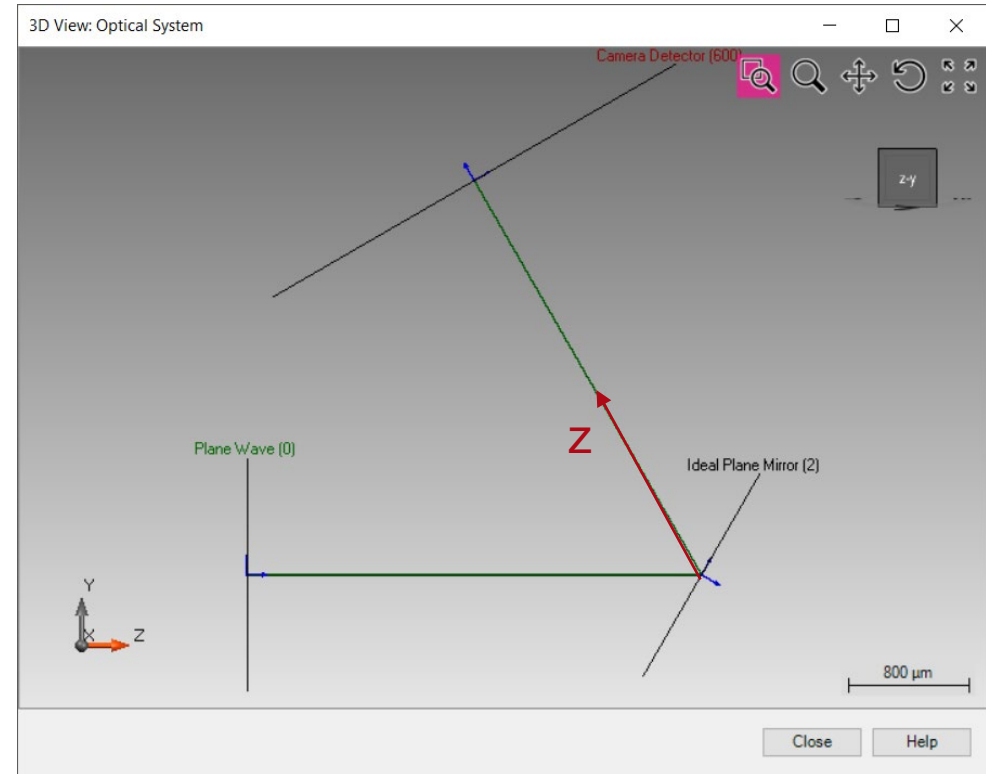
Orientation Definition Type: Sequence of Axis Rotations

☐ Fix Axes

Direction Definition

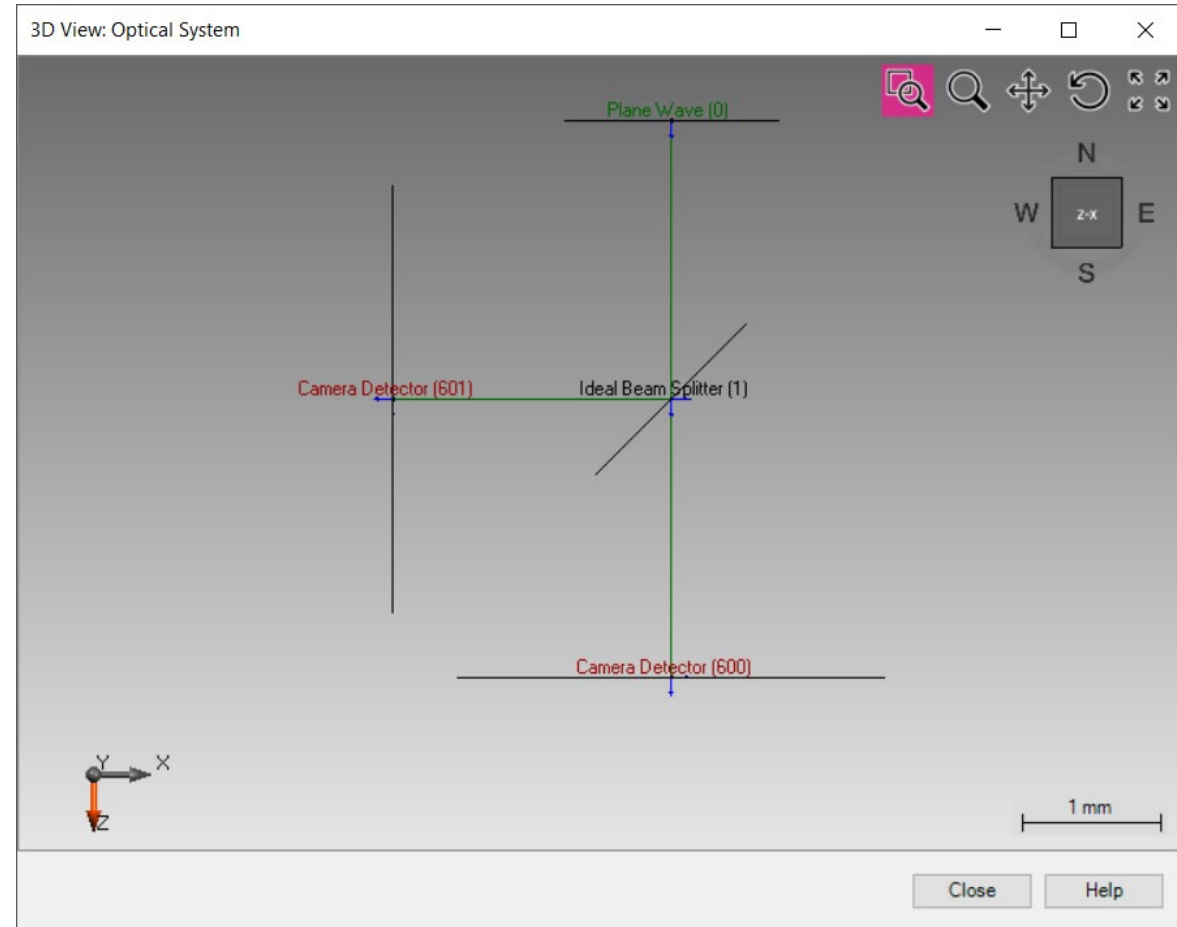
	Angle / Axis	Value
1	X-Axis Rotation	30°

800 μm



Special Components: Ideal Beam Splitter

Two perpendicular output channels are automatically defined.



Several Points about Positioning

- Set position of one component: put the input CS in the output CS of previous component (Basal Positioning)
- Basal position: if one component shift or rotate, all the following path changes
- Isolated position: basal output CS doesn't change
- Special case:
 - Reflection CS: z-axis is calculated by component normal vector and input path
 - Beam splitter: two output CSs > 0 is transmission CS, 1 is reflection CS. Two z-axes are perpendicular

Configuring Reference Type in VirtualLab Fusion

The image displays two windows from the VirtualLab Fusion software. The background window, titled "2: Optical Setup View #1 (Optical Setup)*", shows a schematic of an optical setup on a grid. It includes a "Plane Wave" source (labeled 0), a "Lens System" (labeled 1), a "Camera Detector" (labeled 600), and a "Ray Tracing System Analyzer" (labeled 800). The "Lens System" and "Camera Detector" have coordinate boxes showing X: 0 mm, Y: 0 mm, and Z: 0 mm. A left-hand pane lists various components like "Quadratic Wave", "Spherical Wave", "Stored Lateral", "Super-Gaussian", "Partially Coherent", "Components", "Component from", "Functional Single", "Index Modulated", "Multiple Surfaces", "Lens System", "Light Guide", "Spherical Lens", "Single Surface & Lens", "Single Surface & Lens", "Programmable Coating", "Black Box", "Subsystem", "Ideal Components", "Detectors", "Analyzers", "Coordinate Break", "Camera Detector", and "Electromagnetic Field".

The foreground window, titled "1: Optical Setup Editor #1 (Optical Setup)*", contains a configuration table for the setup. The table has columns for "Start Element" (Index, Element Name, Ref. Type, Medium) and "Target Element" (Index, Element Name, Propagation Method, On/Off, Color). The "Ref. Type" column for the "Lens System" row is highlighted with a red box, and a dropdown menu is open showing options "T" and "R".

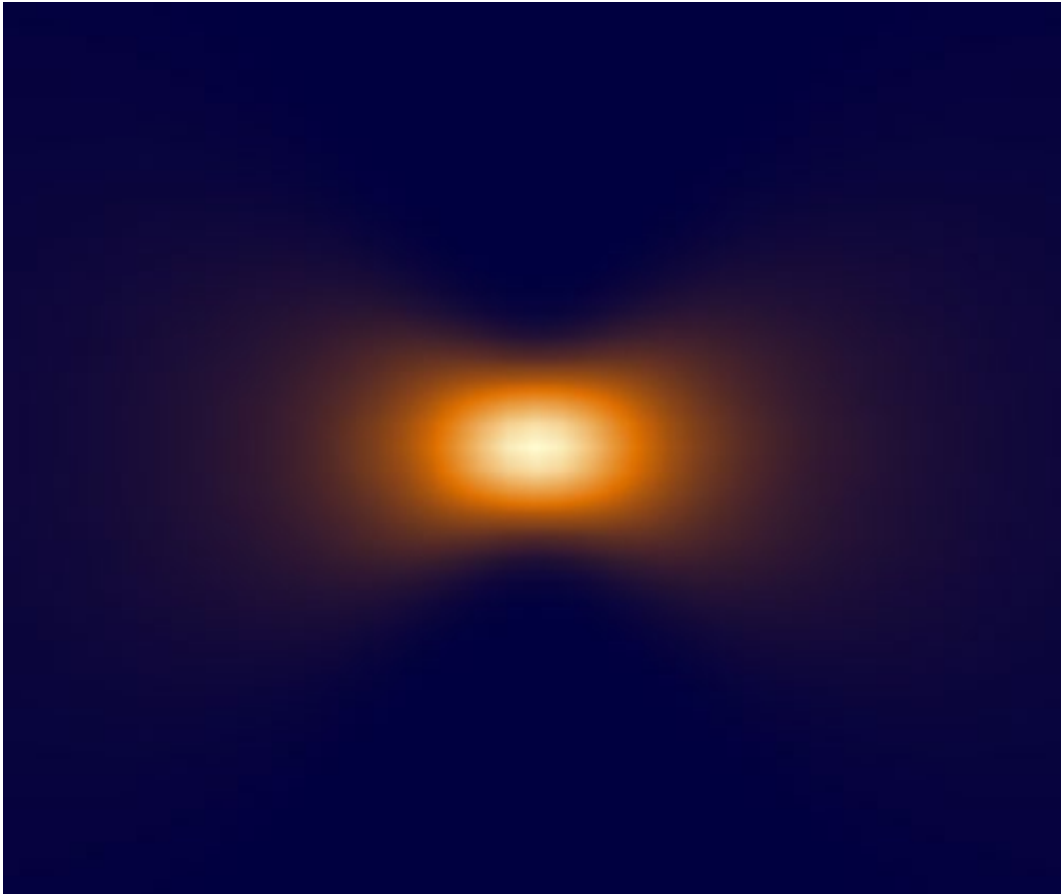
Start Element				Target Element		Linkage		
Index	Element Name	Ref. Type	Medium	Index	Element Name	Propagation Method	On/Off	Color
0	Plane Wave	-	Air in Homogeneous Medi...	1	Lens System	Ray Tracing	On	—
1	Lens System	T	Air in Homogeneous Medi...					

At the bottom of the "1: Optical Setup Editor #1" window, there is a "Simulation Engine" dropdown set to "Ray Tracing" and a "Go!" button.

Tolerance Analysis of a Fiber Coupling Setup

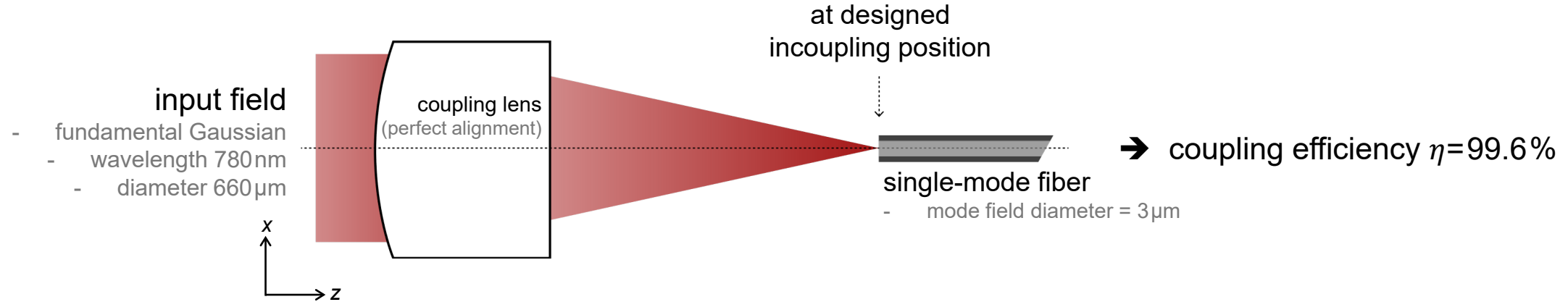


Abstract

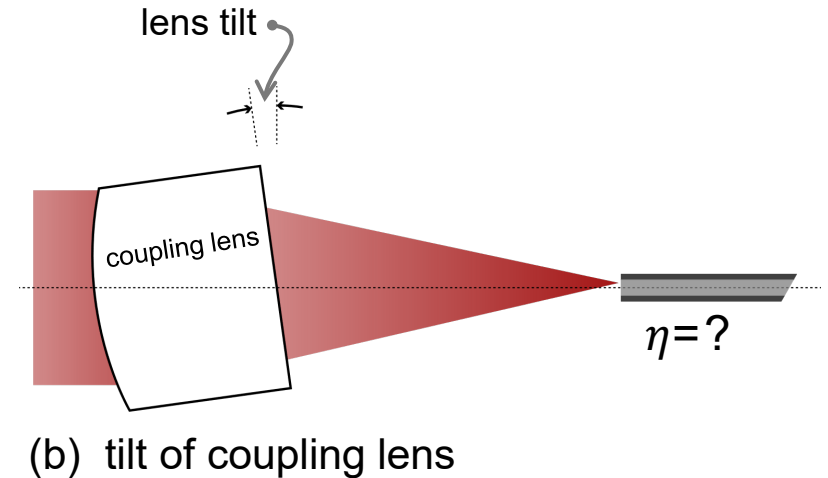
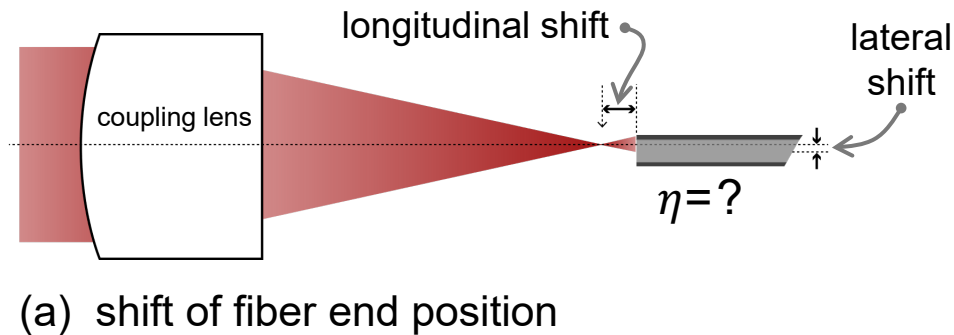


In modern optics, fibers can be found in various optical system, and it is usually of concern how much light can be coupled into fibers. The coupling efficiency can be sensitive to the system alignment, especially for single-mode fibers with relatively small core diameters. In this example, a well-designed fiber coupling lens is selected, and the coupling efficiency is evaluated with respect to different tolerance factors, such as the shift of fiber end position and the tilt of coupling lens.

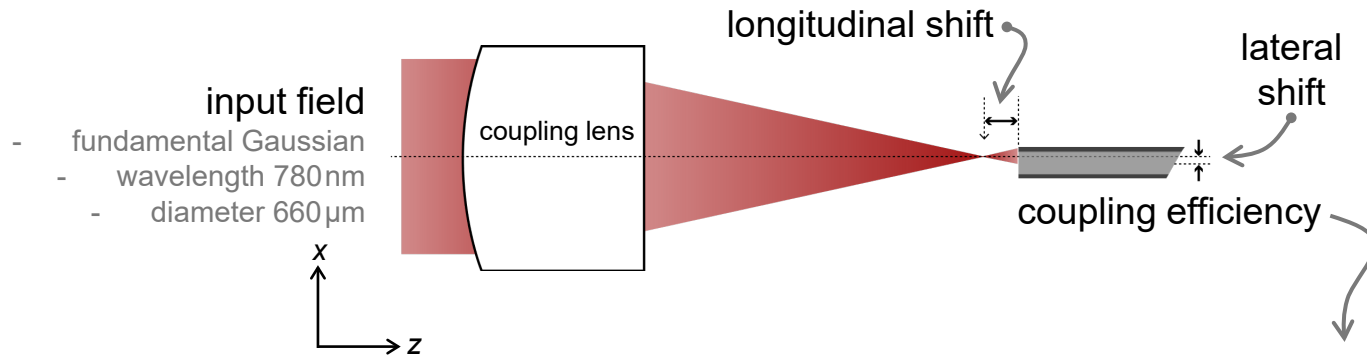
Modeling Task



How does the coupling efficiency change with respect to alignment tolerance factors?

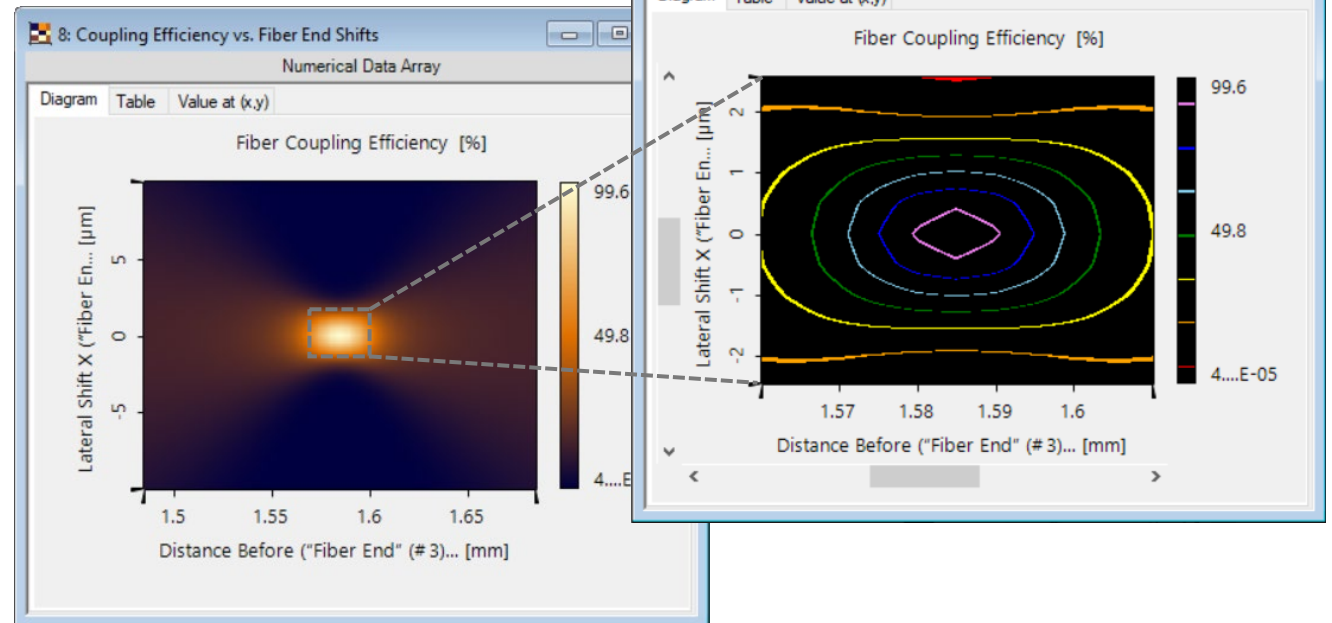


Coupling Efficiency vs. Fiber End Position Shift

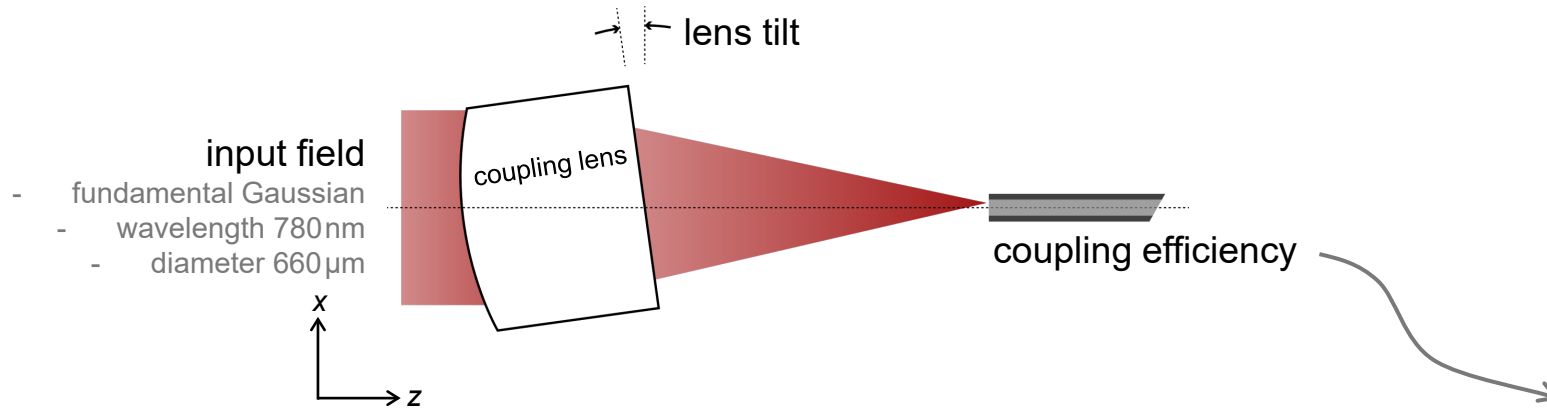


Contour plot helps with the identification of the parameter range for desired coupling efficiency threshold.

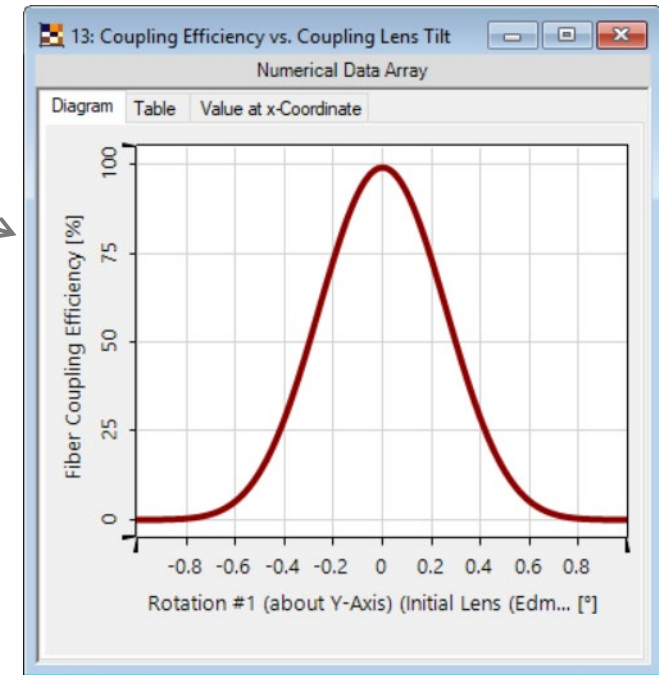
The coupling efficiency is scanned with respect to the fiber position shifts along both axial and lateral directions.



Coupling Efficiency vs. Coupling Lens Tilt



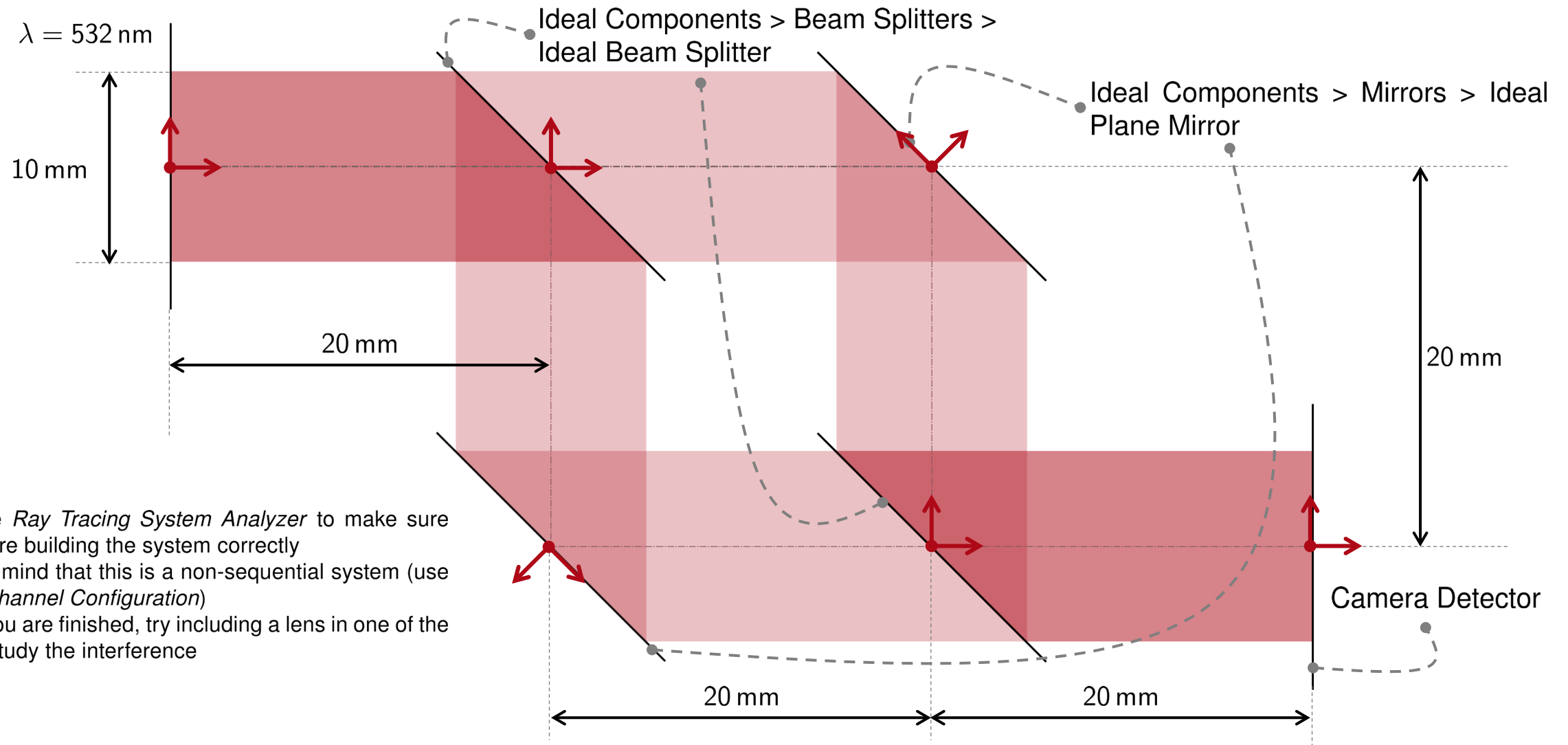
Physical-optics analysis of the coupling efficiency with respect to lens tilt. When lens tilt angle is within 0.1° , the coupling efficiency is still higher than 90%



Exercise 2

Build a Mach-Zehnder Interferometer

Build the Following System in VirtualLab Fusion

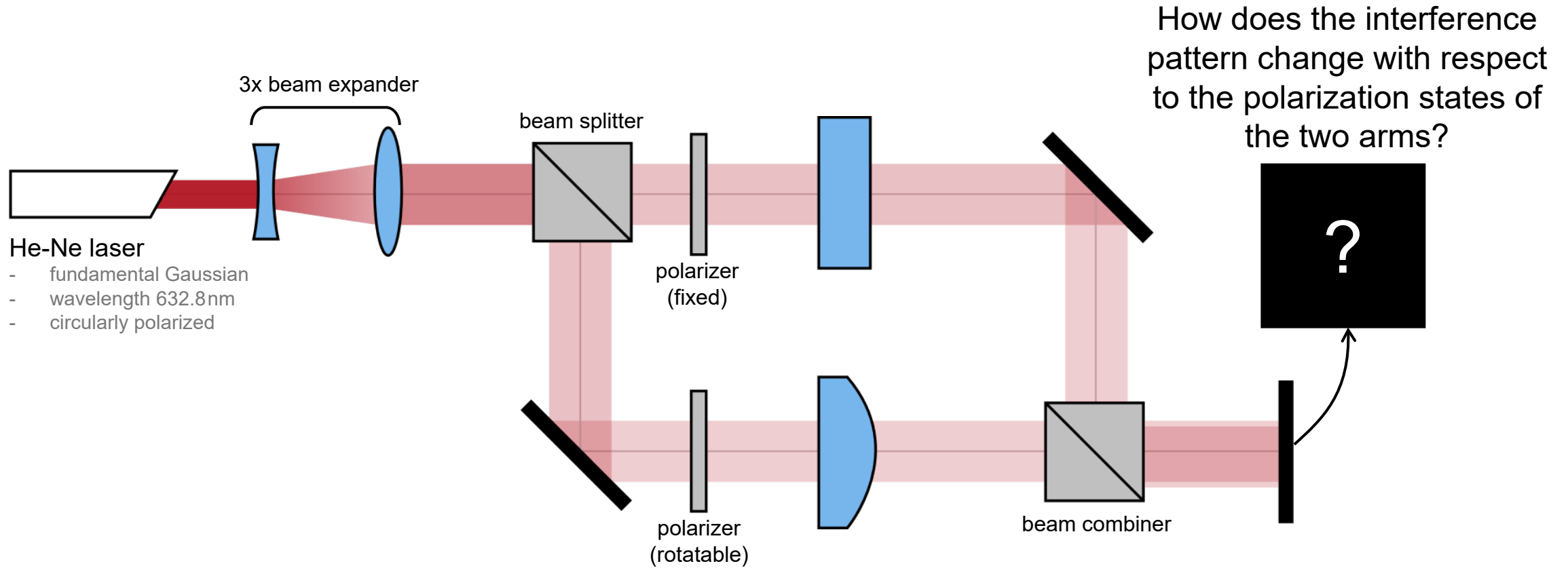


- Use the *Ray Tracing System Analyzer* to make sure that you are building the system correctly
- Keep in mind that this is a non-sequential system (use *Manual Channel Configuration*)
- When you are finished, try including a lens in one of the paths to study the interference

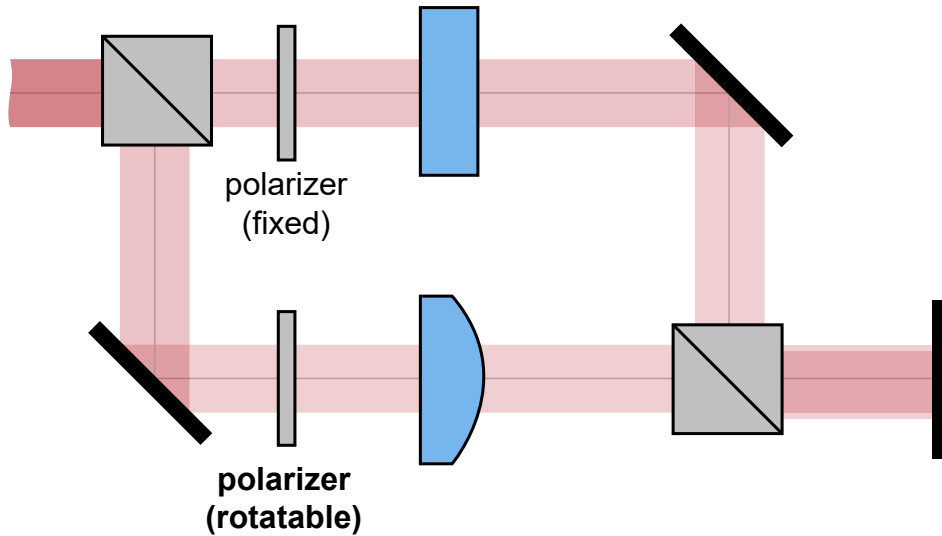
Generation of Spatially Varying Polarization by Interference with Polarized Light



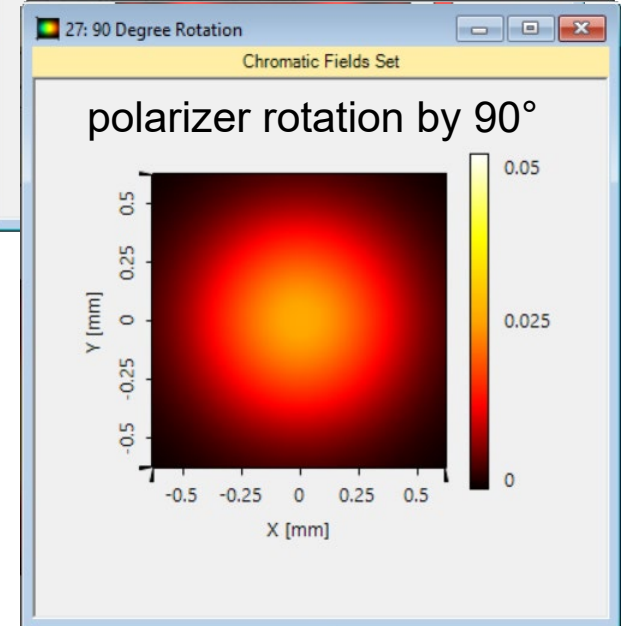
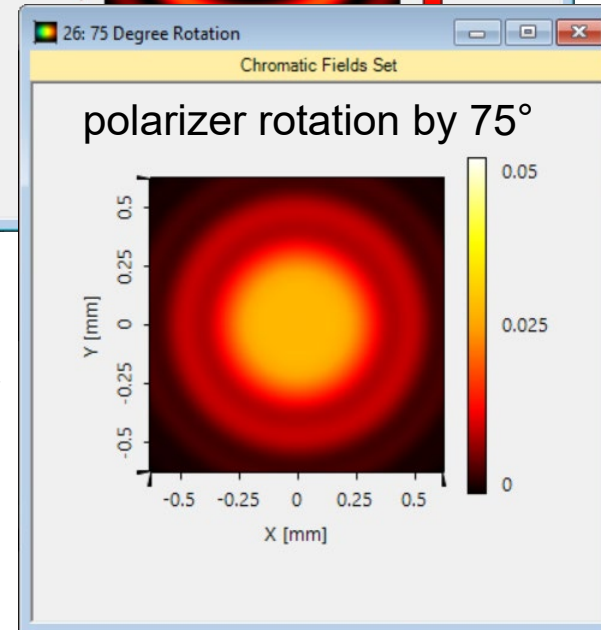
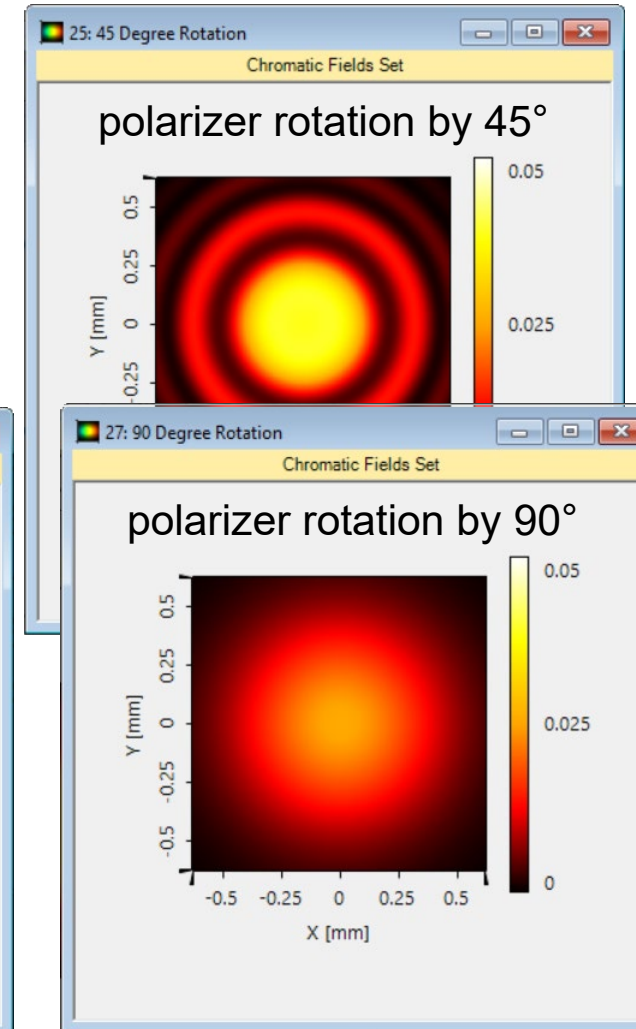
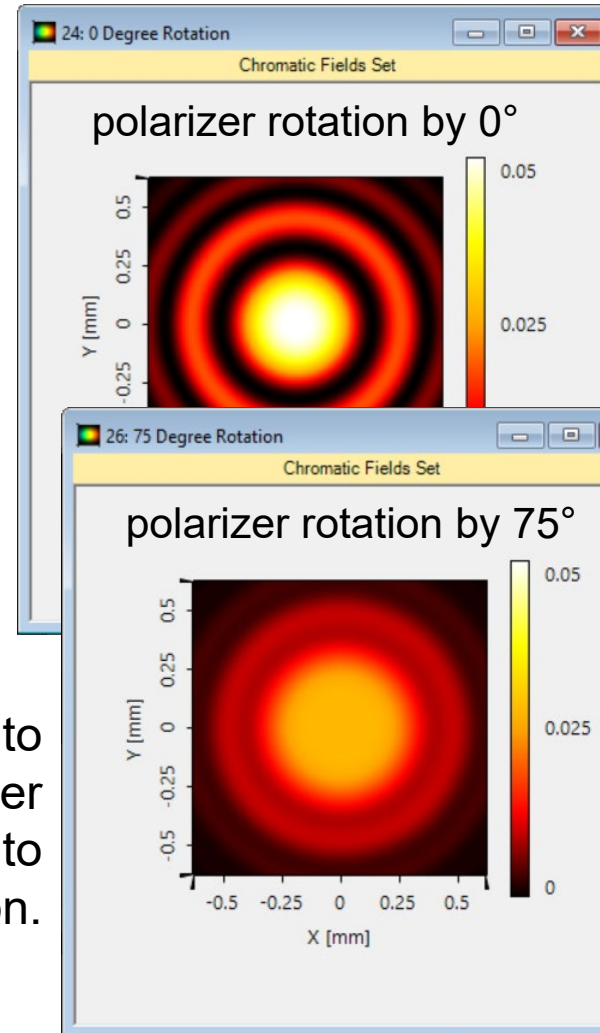
Modeling Task



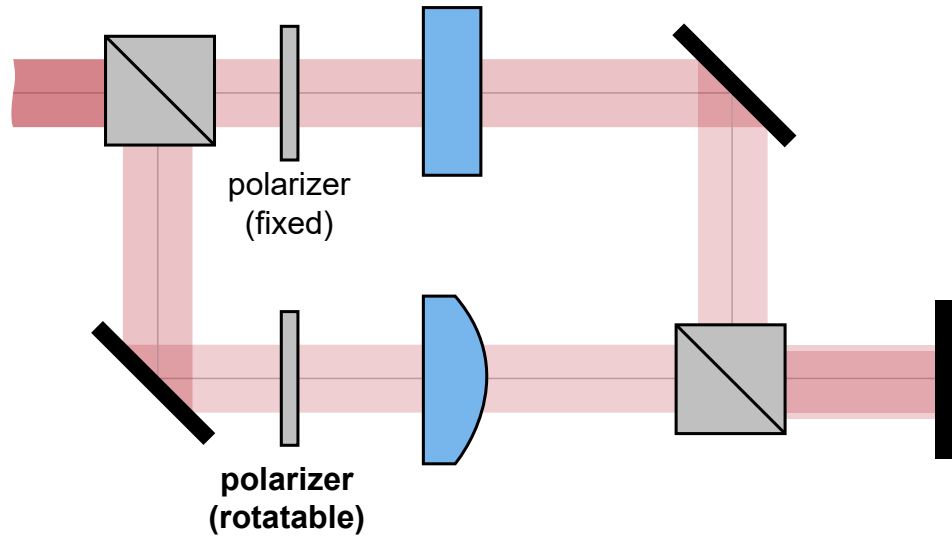
Interference Pattern Changes with Polarizer Rotation



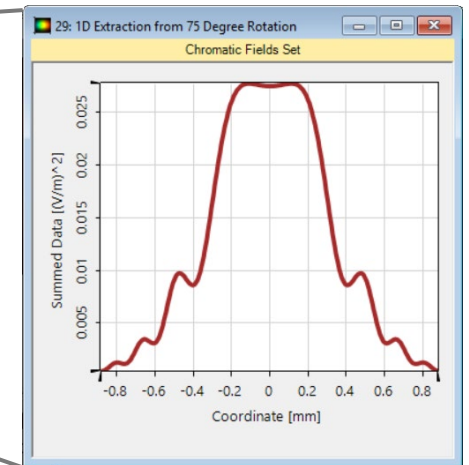
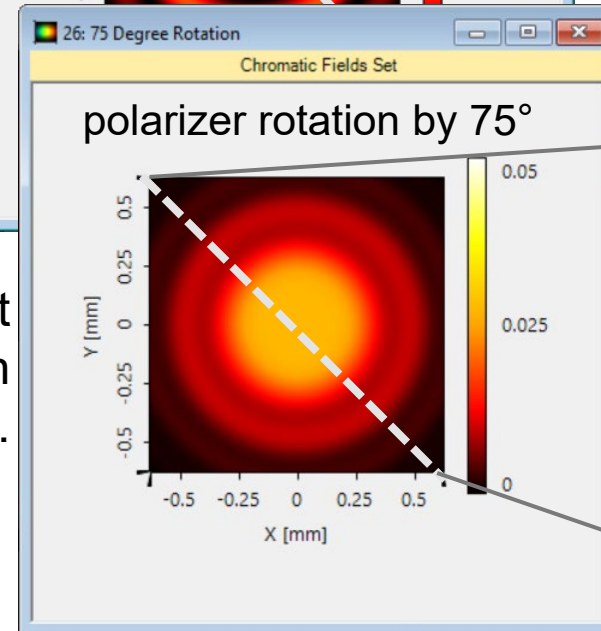
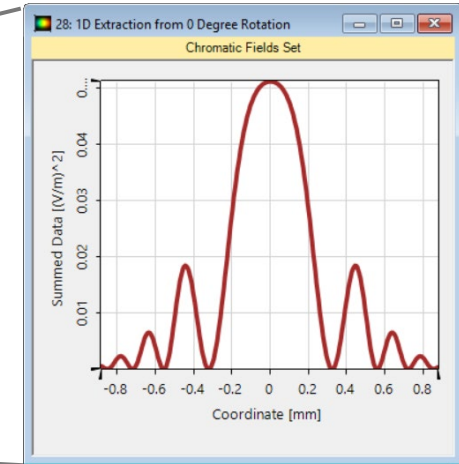
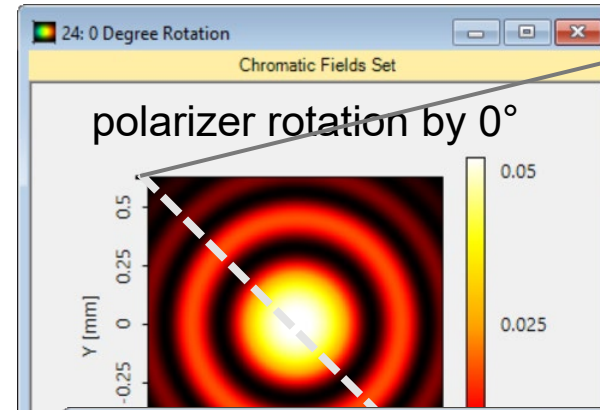
Interference fringes start to disappear, when polarizer rotates from parallel to orthogonal orientation.



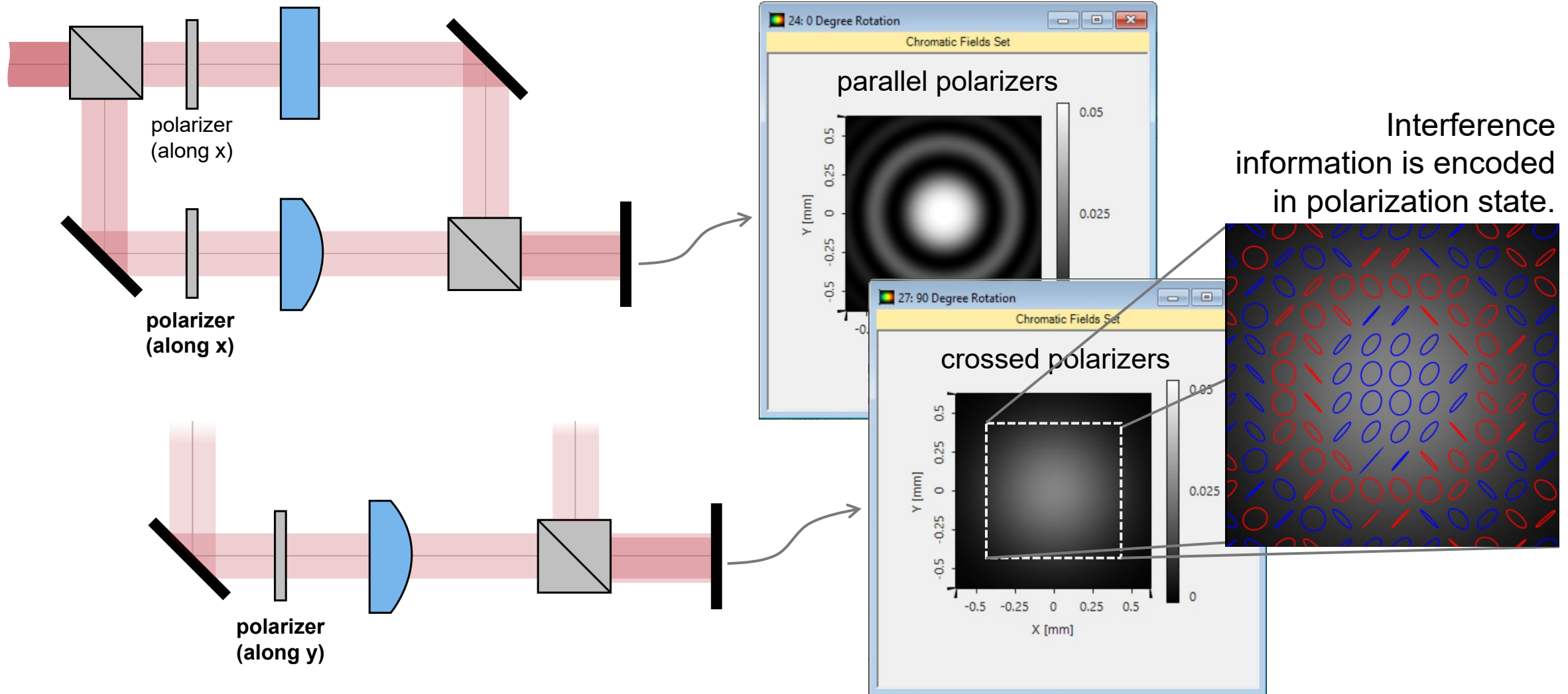
Interference Pattern Changes with Polarizer Rotation



Fringe contrast changes with polarizer rotation.



Interference Pattern

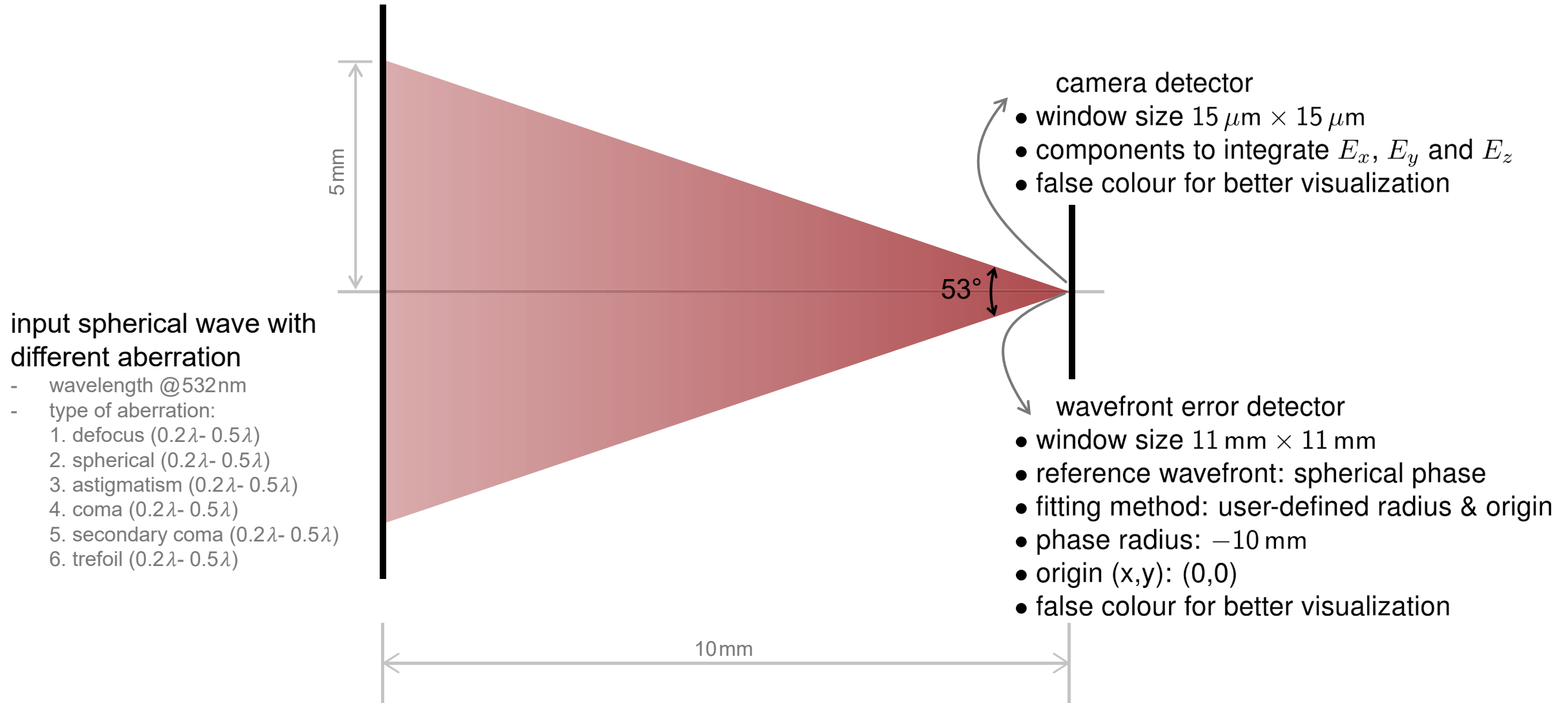


Hands-on Sessions Exercises

Exercise1

Evaluate the Focal Spot for Different Aberrations

Build the Following System in VirtualLab Fusion

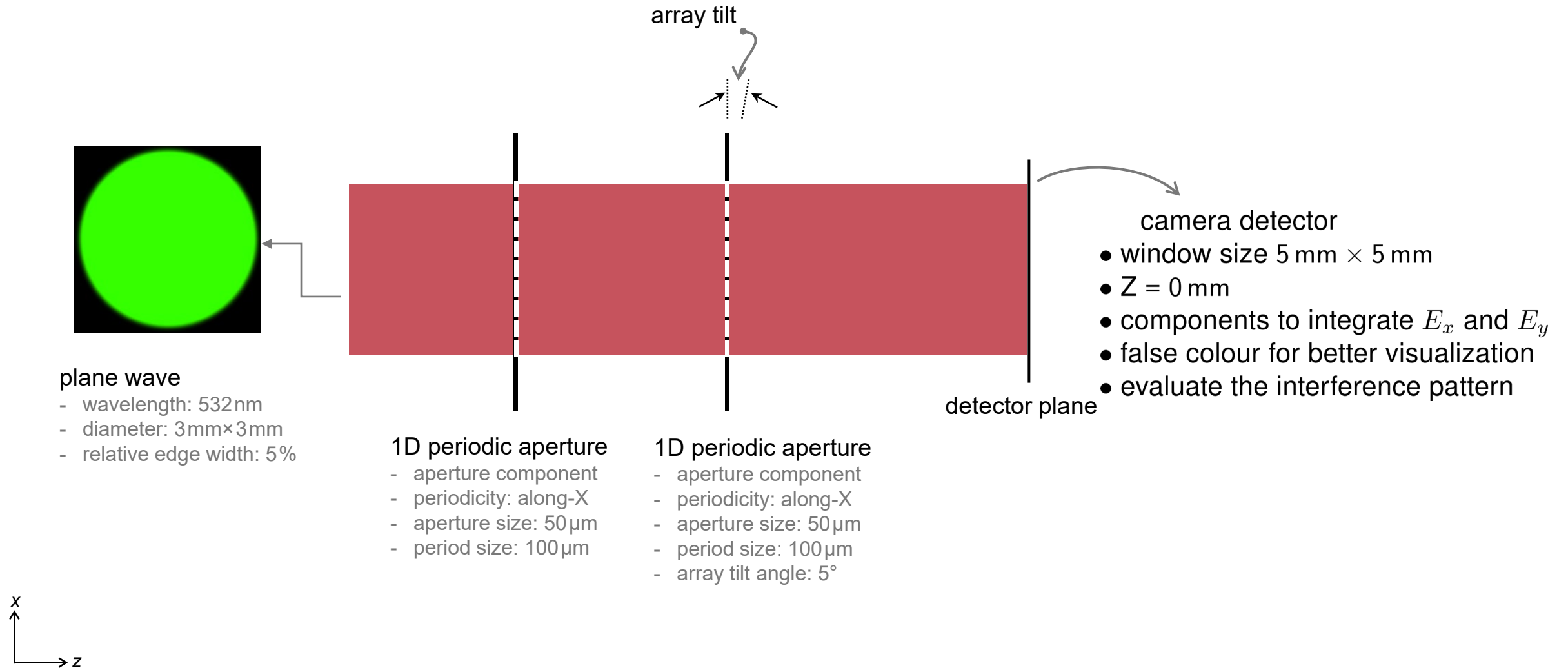


Note: The aberrations can be introduced to the wavefront by using the “Zernike & Seidel Aberrations” component.

Exercise 2-a

Generate Moiré Fringes with Periodic Apertures

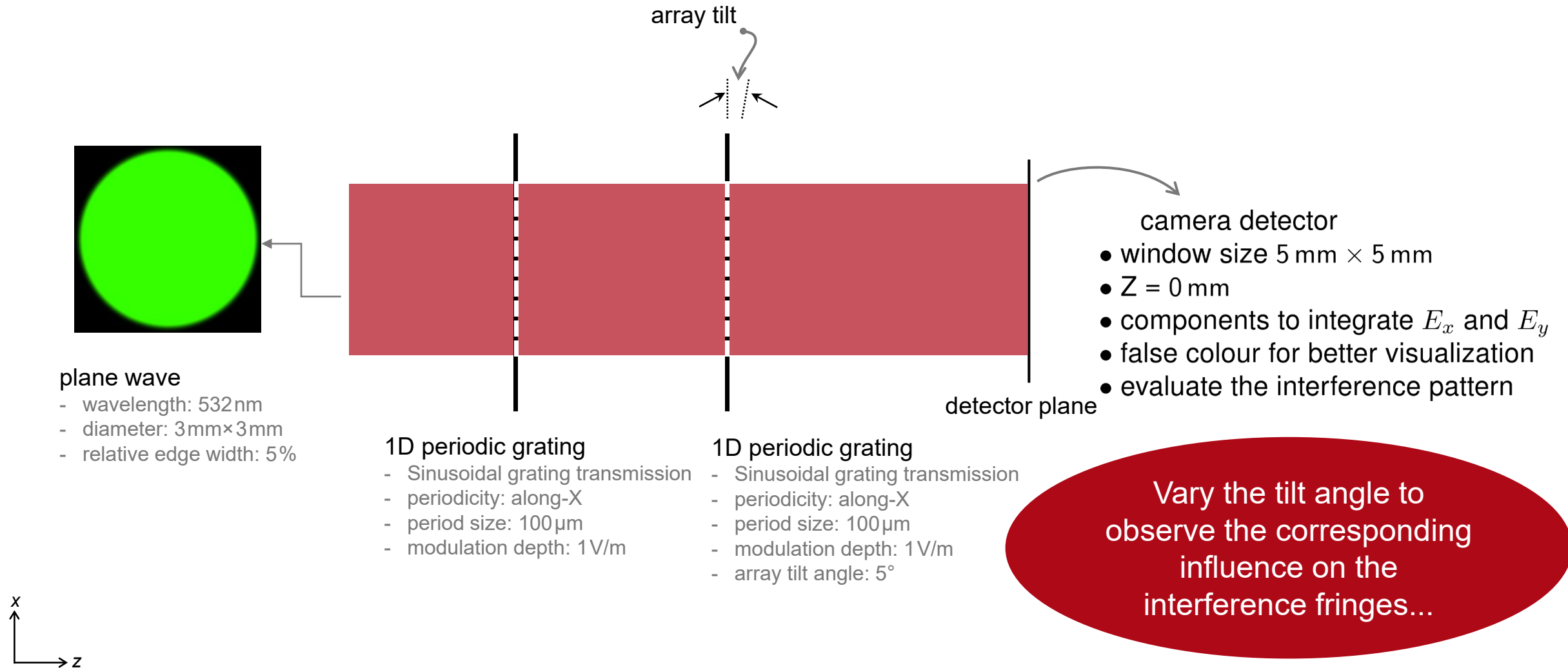
Build the Following System in VirtualLab Fusion



Exercise 2-b

Generate Moiré Fringes with Sinusoidal Gratings

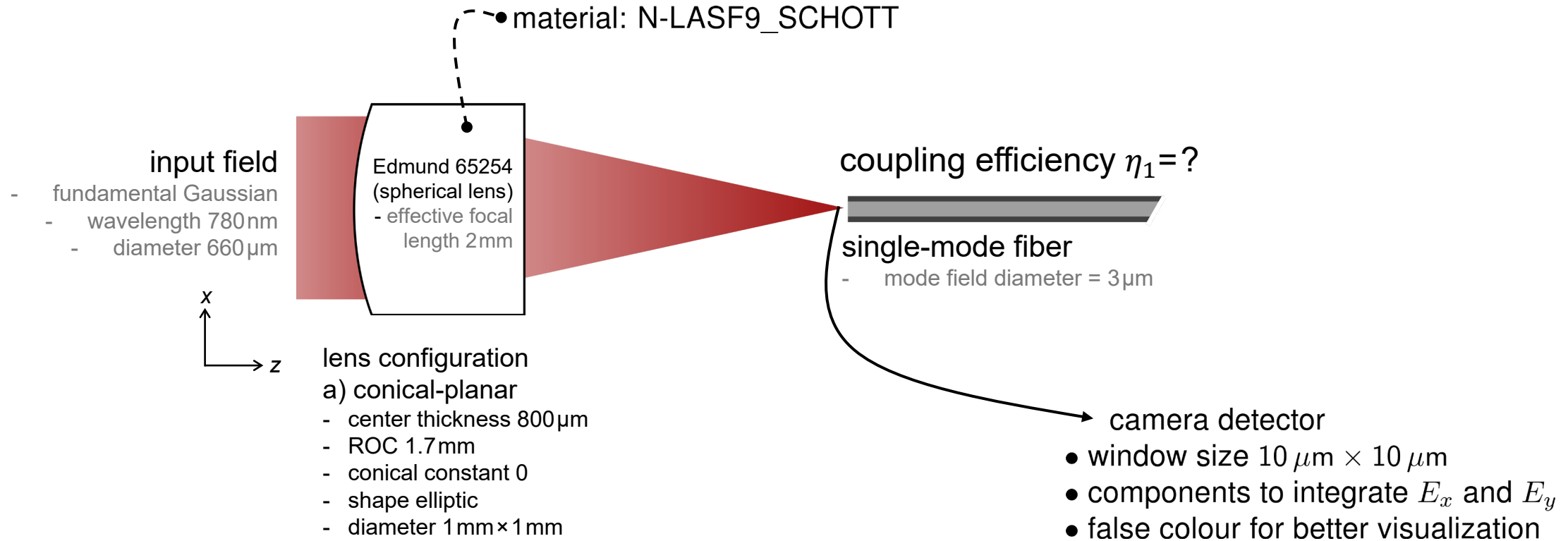
Build the Following System in VirtualLab Fusion



Exercise 3-a

Evaluate The Coupling Efficiency of Different Lenses

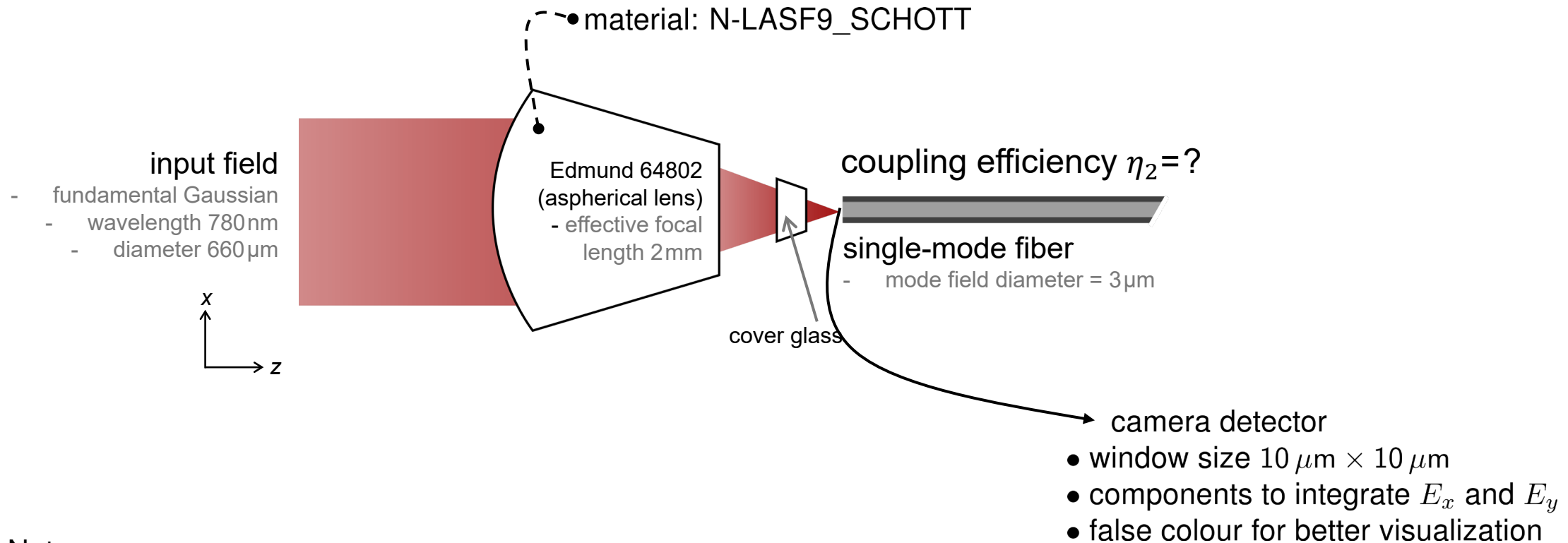
Build the Following System in VirtualLab Fusion



Note:

- Take care of the diffraction in the system.
- Use Single-mode Fiber Coupling Efficiency detector.

Build the Following System in VirtualLab Fusion



Note:

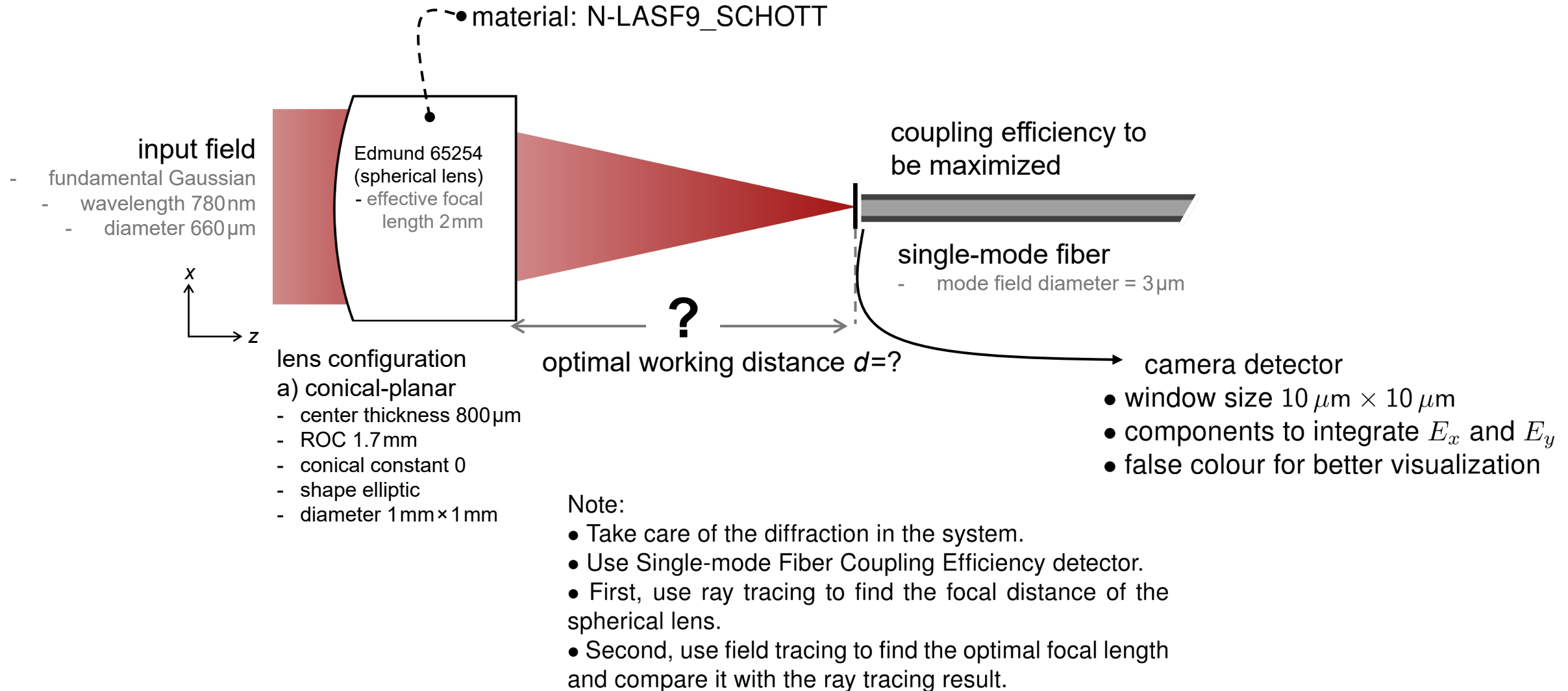
- Take care of the diffraction in the system.
- The lens configuration can be imported into VirtualLab Fusion components catalog. (file name: Edmund_64802_Aspherical Lens.ctlg)
- Use Single-mode Fiber Coupling Efficiency detector.

Exercise 3-b

Find The Optimal Working Distance For Coupling Light into a Single-Mode Fiber

 [see the full Application Use Case](#)

Schematic View of The Optical Setup

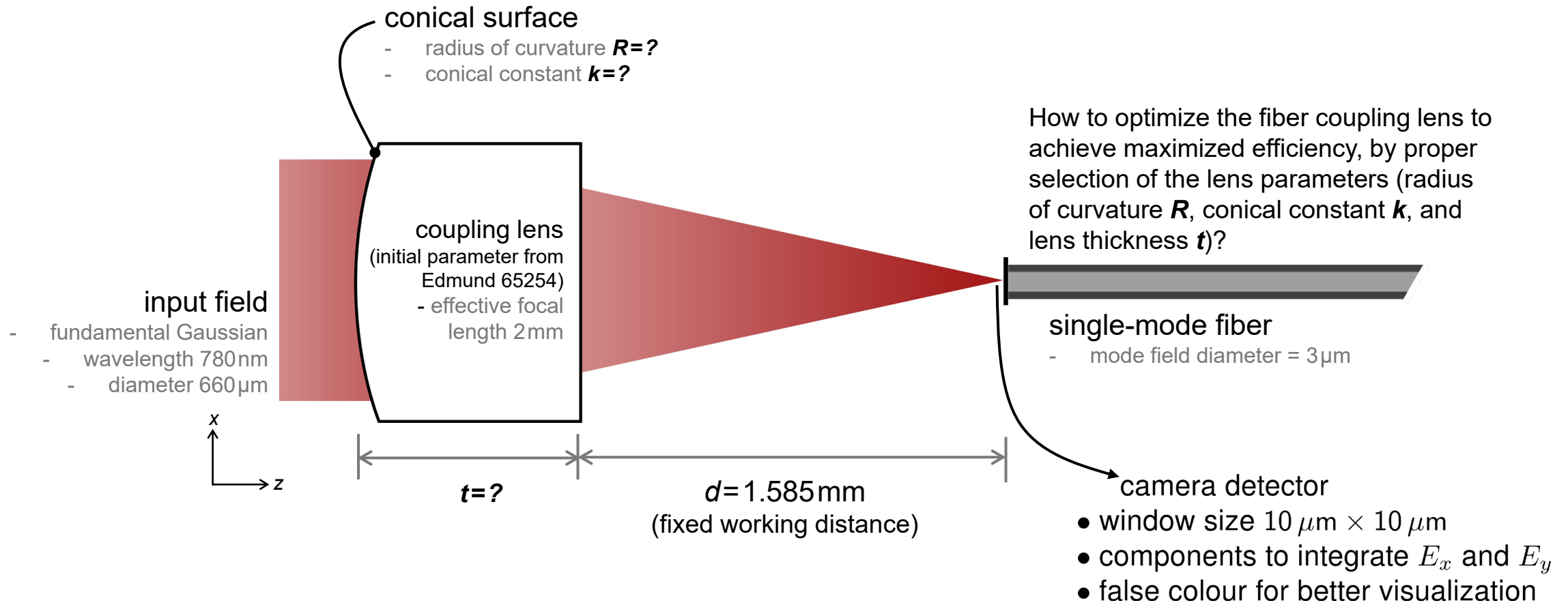


Exercise 3-c

Apply Parametric Optimization to The Fiber Coupling Lens

 [see the full Application Use Case](#)

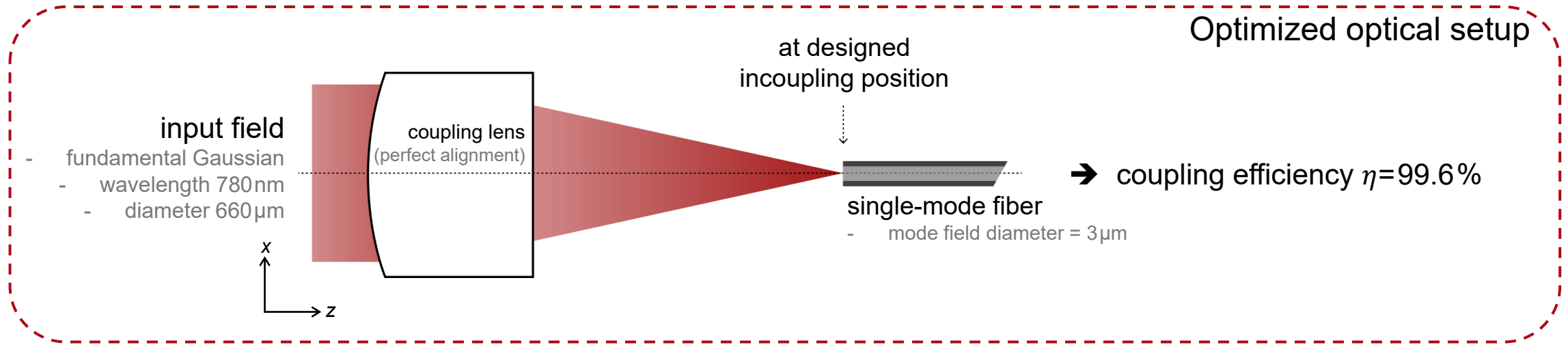
Build the Following System in VirtualLab Fusion



Exercise 3-d

Analyze The Tolerances Induced to The Fiber Coupling Lens

Schematic View of The Optical Setup



misalignment configuration

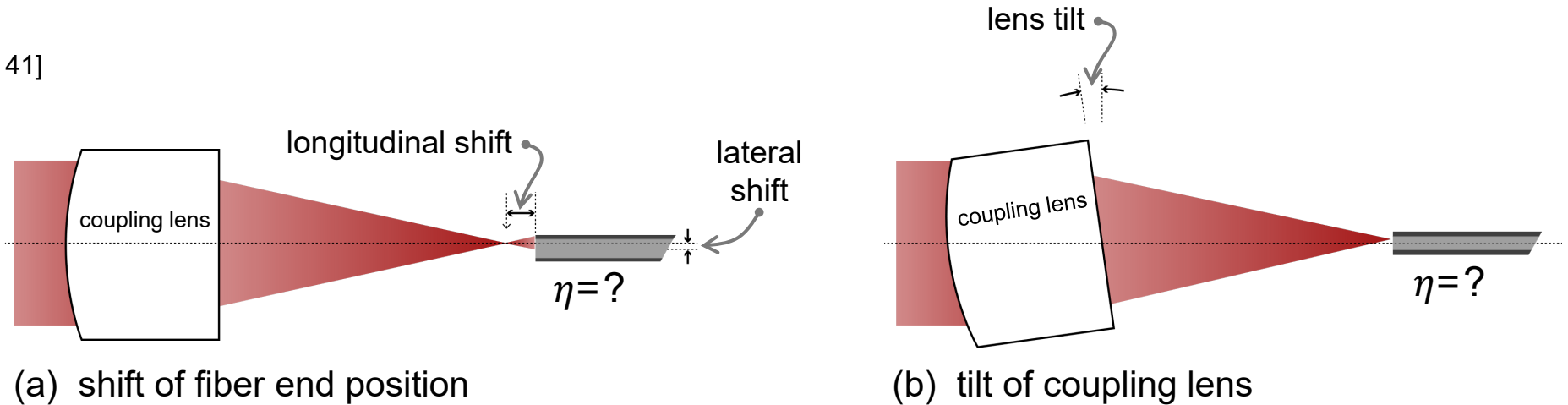
a) longitudinal* & lateral shift**

- shift range* [1.485mm, 1.485mm, 41]
- shift range** [-10 μ m, 10 μ m, 41]

b) tilt along Y-axis

- tilt range [-1°, +1°, 201]

Number of steps



Exercise 4-a

Build A Mach-Zehnder Interferometer with Ideal Beam Splitters

 [see the full Application Use Case](#)

Build the Following System in VirtualLab Fusion

beam expander configuration (part 1)

- a) ROC -20.772 mm & ROC +20.772 mm
- b) material: N-BK7_SCHOTT
- c) diameter 5mm×5mm
- d) thickness 1mm

beam expander configuration (part 2)

- a) ROC 61.072mm & ROC -61.072mm
- b) material: N-BK7_SCHOTT
- c) diameter 10mm×10mm
- d) thickness 4.3mm

1 glass plate configuration

- a) thickness 2mm
- b) material: N-BK7_SCHOTT
- c) diameter 10mm×10mm

2 test object configuration (spherical lens)

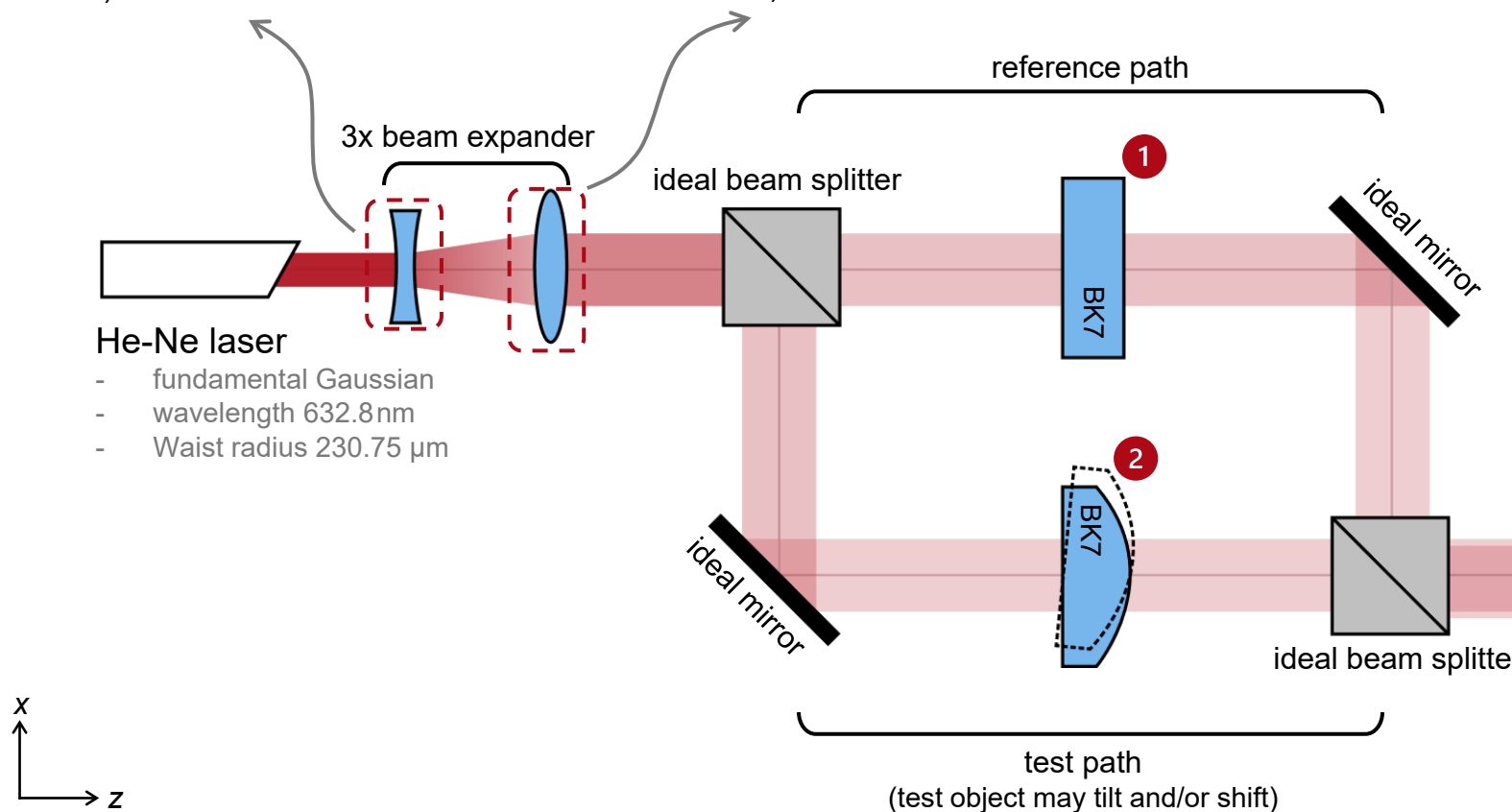
- a) thickness 2mm
- b) material: N-BK7_SCHOTT
- c) diameter 10mm
- d) plano-convex (radius 100mm)

misalignment configuration

- a) lateral shift
 - shift range [0mm, 1mm, 5]
- b) tilt along Y-axis
 - tilt range [3°, 10°, 3]

camera detector

- window size 2 mm × 2 mm
- Z = 20 mm
- components to integrate E_x , E_y and E_z



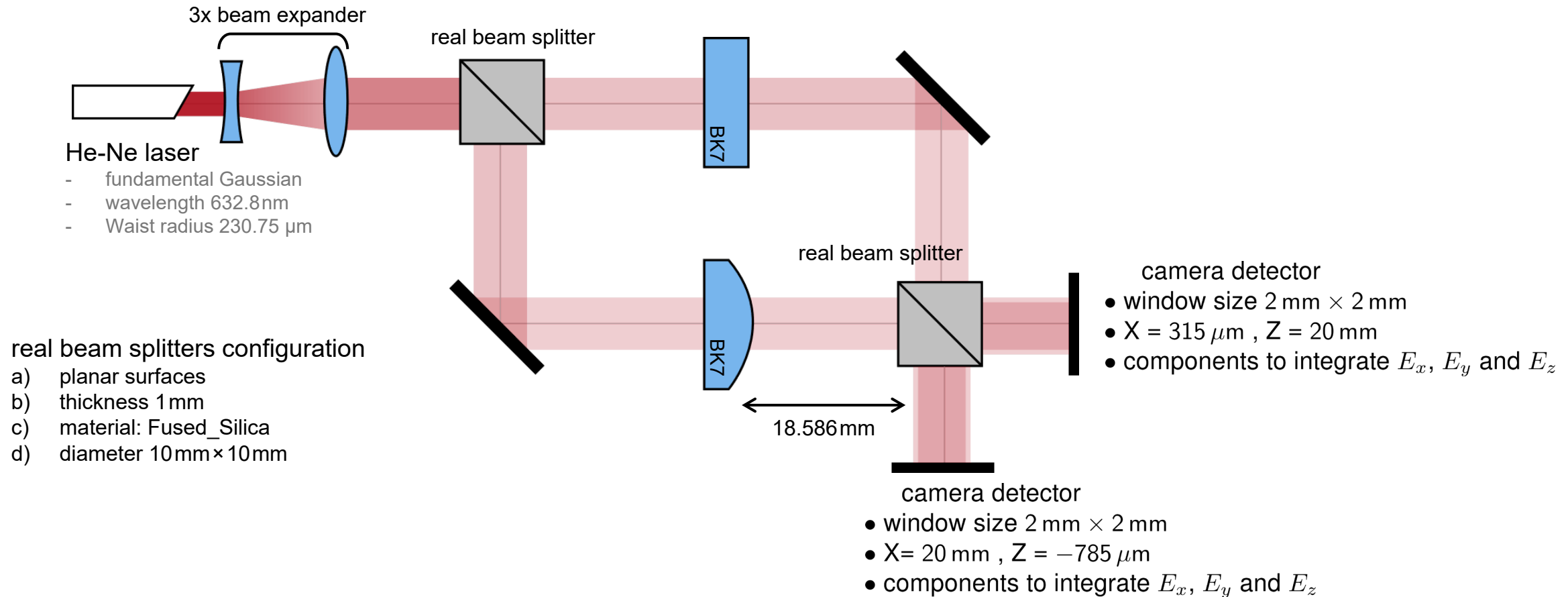
Note: The distances between the components are 20 mm.

Exercise 4-b

Build A Mach-Zehnder Interferometer with Real Beam Splitters

 [see the full Application Use Case](#)

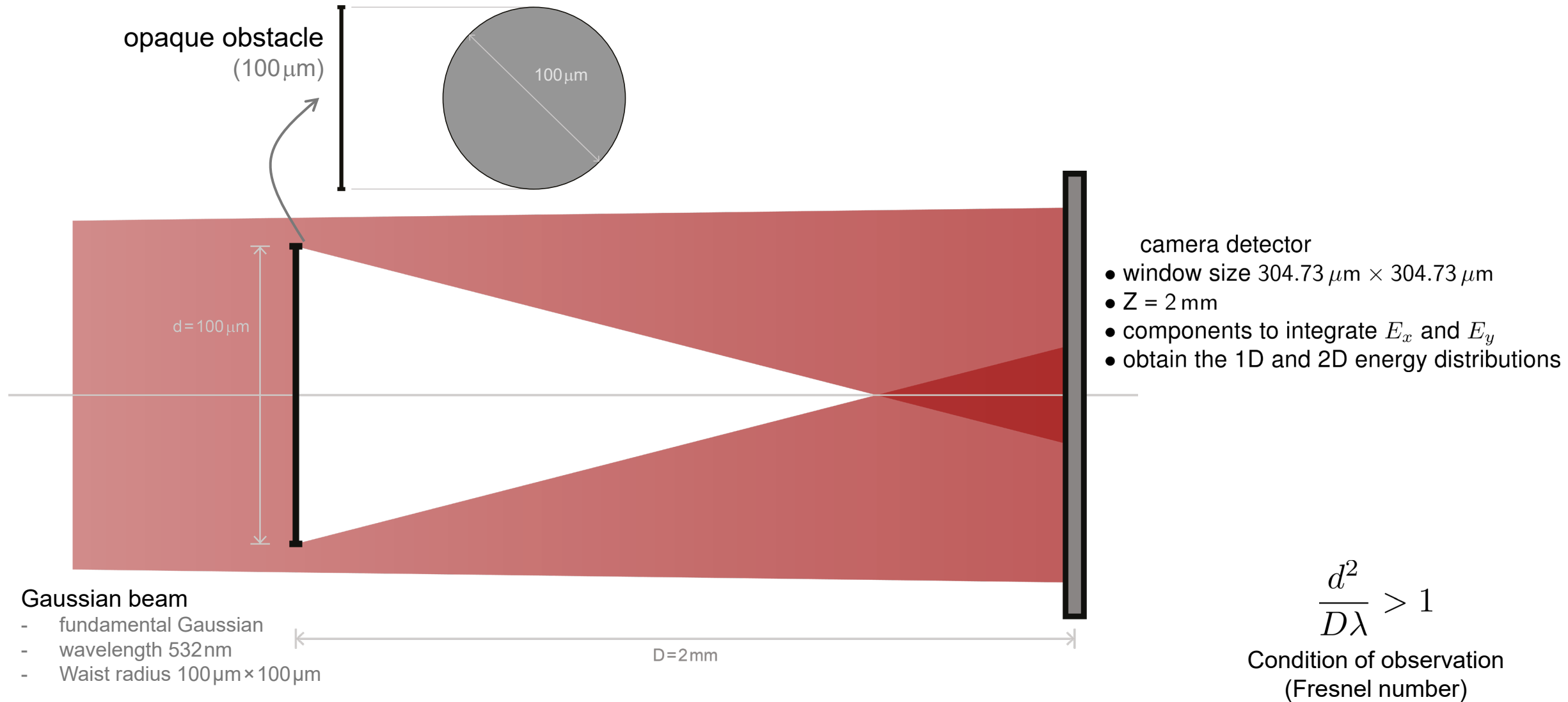
Build the Following System in VirtualLab Fusion



Exercise 5

Observation of the Poisson Spot

Build the Following System in VirtualLab Fusion



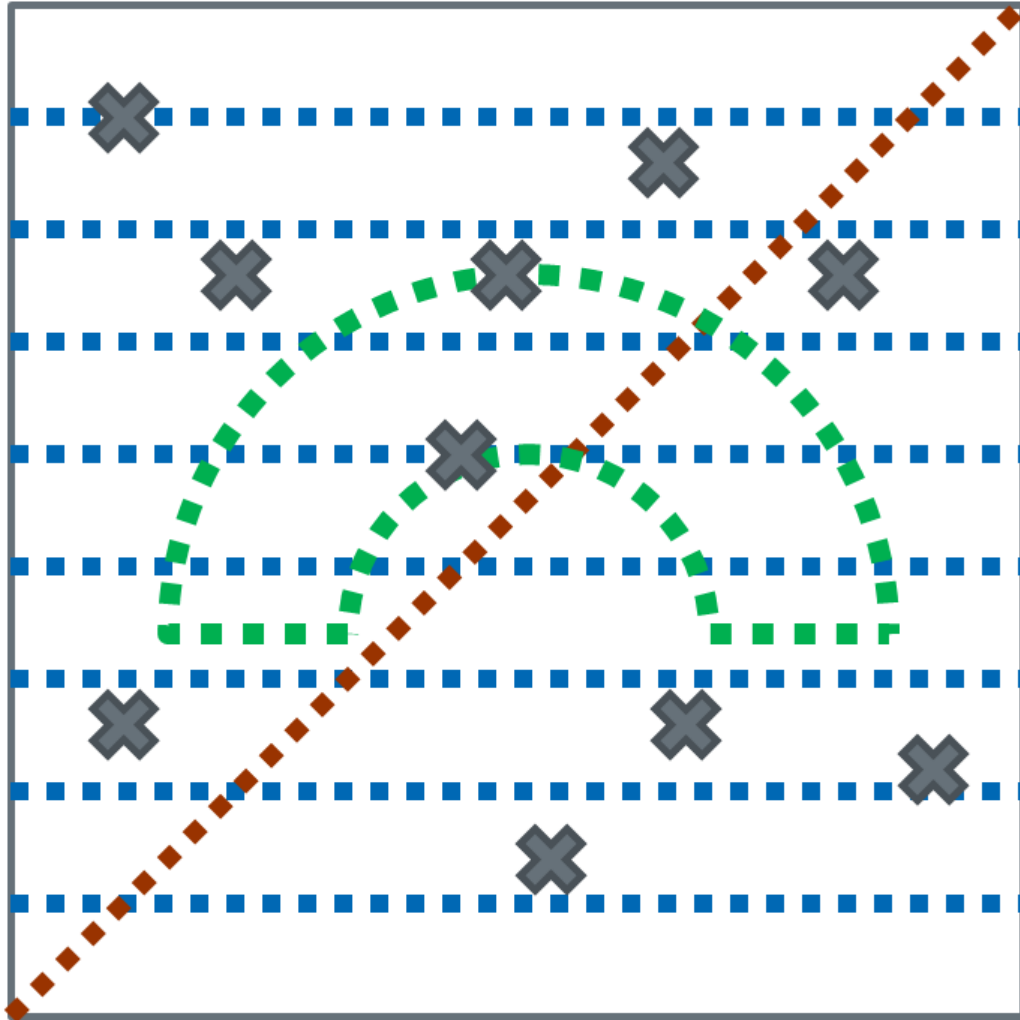
Build the Following System in VirtualLab Fusion

Annex

Some brief guides to useful features

Parameter Run

Abstract



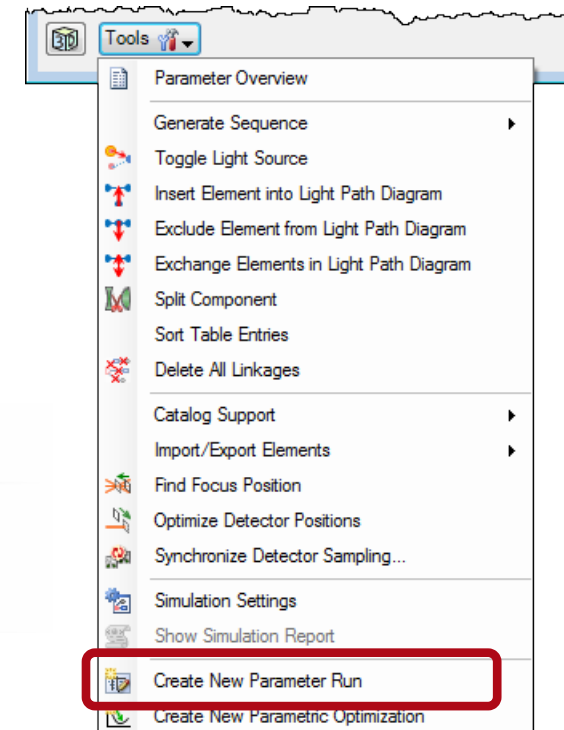
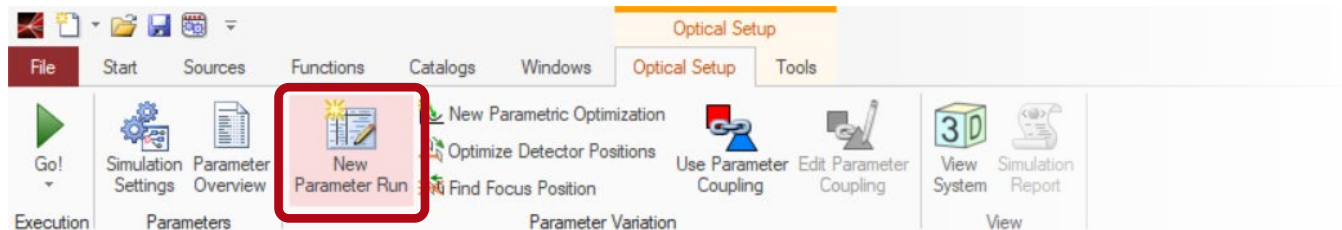
For a given optical system, it is helpful to check its performance by controlling and varying selected parameters. VirtualLab Fusion provides a fully flexible and computationally efficient (via parallelization) Parameter Run, which enables the user specify different manners of parameter variations. As an example, it can be used for the tolerance analysis with respect to any system parameters under investigation. The analysis result can be visualized in different ways, such as single numbers, graphs, or even animations.

Parameter Run Document

- The Parameter Run document allows the variation of the numerical parameters of an Optical Setup.
 - It can be used e. g.
 - to investigate the system's sensitivity for parameter tolerances
 - to optimize parameters
 - to evaluate the changing profile of a beam in the vicinity of a focus
 - ...
 - One or multiple parameters can be varied.
 - Detector results are recorded within the Parameter Run document.
 - A copy of the original Optical Setup is stored in the Parameter Run document.
-

New Parameter Run

- To generate a new Parameter Run an open and activated Optical Setup window is required.
- A new Parameter Run document can be generated via
 - ribbon
 - Optical Setup Tools
 - shortcut Ctrl + P



Parameter Specification Page

5: Parameter Run Example

Parameter Specification
Set up the parameter(s) to be varied.

You can select one or more parameters which shall be varied as well as the resulting number of iterations. Several [modes](#) are available specifying how the parameters are varied per iteration.

Usage Mode: Standard

Filter by: ☐ Show Only Varied Parameters

1	2	Object	Category	Parameter	Vary	From	To	Steps	Step Size	Original Value
<input type="checkbox"/>		Ideal Plane Wave #0		Wavelength	<input checked="" type="checkbox"/>	210.0655221 nm	3.71 μ m	2	3.499934478 μ m	532 nm
<input type="checkbox"/>				Weight	<input type="checkbox"/>	0	1E+300	1	1E+300	1
<input type="checkbox"/>				Polarization Angle	<input type="checkbox"/>	0°	360°	1	360°	0°
<input type="checkbox"/>		Sawtooth Grating #1								
<input type="checkbox"/>			Basal Positioning	Distance Before	<input type="checkbox"/>	-1E+303 mm	1E+303 mm	1	2E+303 mm	0 mm
<input type="checkbox"/>				Window Size Scaling X	<input type="checkbox"/>	1E-300	1E+300	1	1E+300	1
<input type="checkbox"/>		Virtual Screen #600		Window Size Scaling Y	<input type="checkbox"/>	1E-300	1E+300	1	1E+300	1
<input type="checkbox"/>				Resolution Scaling X	<input type="checkbox"/>	1E-300	1E+300	1	1E+300	1
<input type="checkbox"/>				Resolution Scaling Y	<input type="checkbox"/>	1E-300	1E+300	1	1E+300	1
<input type="checkbox"/>			Basal Positioning	Distance Before	<input type="checkbox"/>	-1E+303 mm	1E+303 mm	1	2E+303 mm	0 mm
<input type="checkbox"/>				Window Size Scaling X	<input type="checkbox"/>	1E-300	1E+300	1	1E+300	1
<input type="checkbox"/>		Virtual Screen #601		Window Size Scaling Y	<input type="checkbox"/>	1E-300	1E+300	1	1E+300	1
<input type="checkbox"/>				Resolution Scaling X	<input type="checkbox"/>	1E-300	1E+300	1	1E+300	1
<input type="checkbox"/>				Resolution Scaling Y	<input type="checkbox"/>	1E-300	1E+300	1	1E+300	1

< Back Next > Show ▾

- This page allows you to select the parameters that should be varied.
- The parameter range and the number of steps can be specified.
- Four different Usage Modes (Standard, Programmable, Scanning, Random) will be Explained later.

Parameter Specification Page

You can

- filter for specific parameters
- show only the ones that are already set for variation
- fold/unfold the parameter list for a clearer representation by using the first three columns

5: Parameter Run Example

Parameter Specification
Set up the parameter(s) to be varied.

You can select one or more parameters which shall be varied as well as the resulting number of iterations. Several [modes](#) are available specifying how the parameters are varied per iteration.

Usage Mode: Standard

Filter by: ☐ Show Only Varied Parameters

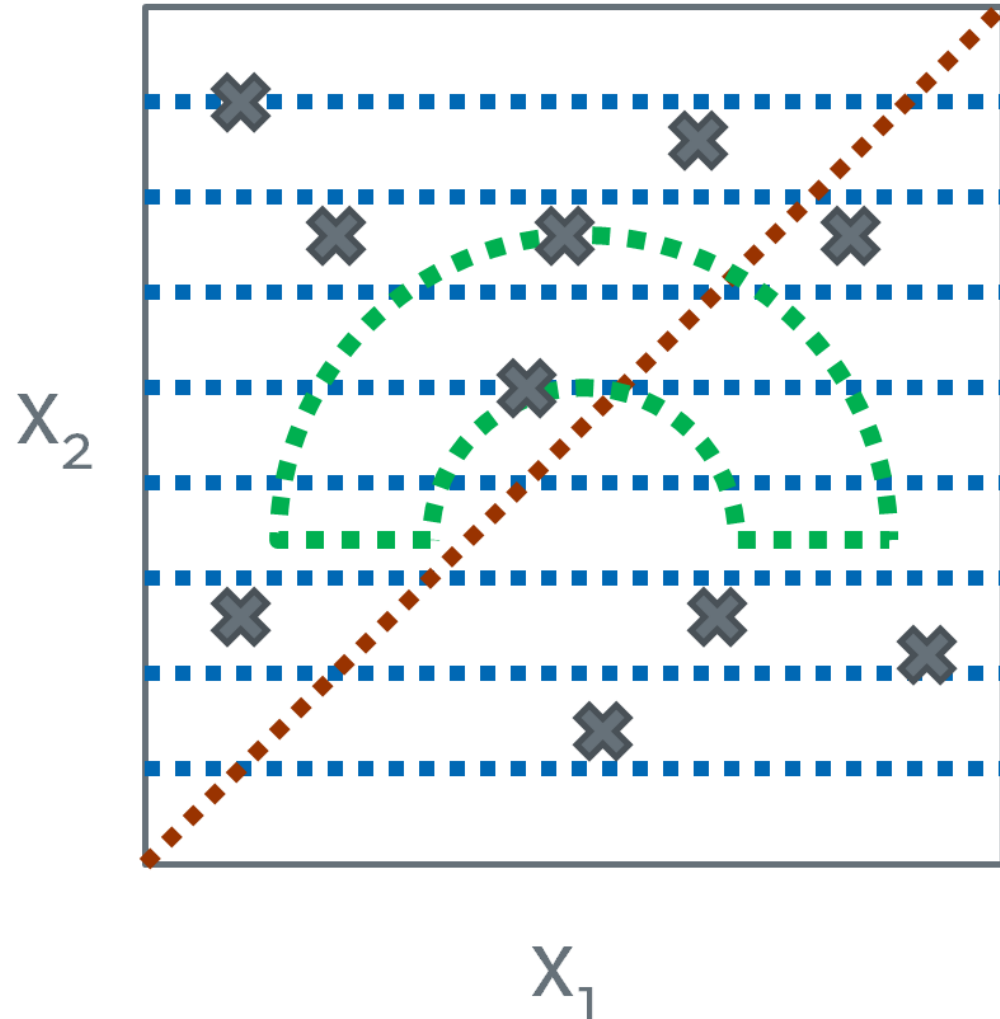
1	2	Object	Category	Parameter	Vary	From	To	Steps	Step Size	Original Value
<input type="checkbox"/>		Ideal Plane Wave #0		Wavelength	<input checked="" type="checkbox"/>	210.0655221 nm	3.71 μ m	2	3.499934478 μ m	532 nm
				Weight	<input type="checkbox"/>	0	1E+300	1	1E+300	1
				Polarization Angle	<input type="checkbox"/>	0°	360°	1	360°	0°
<input type="checkbox"/>		Sawtooth Grating #1								
<input type="checkbox"/>			Basal Positioning	Distance Before	<input type="checkbox"/>	-1E+303 mm	1E+303 mm	1	2E+303 mm	0 mm
				Window Size Scaling X	<input type="checkbox"/>	1E-300	1E+300	1	1E+300	1
				Window Size Scaling Y	<input type="checkbox"/>	1E-300	1E+300	1	1E+300	1
				Resolution Scaling X	<input type="checkbox"/>	1E-300	1E+300	1	1E+300	1
				Resolution Scaling Y	<input type="checkbox"/>	1E-300	1E+300	1	1E+300	1
<input type="checkbox"/>		Virtual Screen #600								
			Basal Positioning	Distance Before	<input type="checkbox"/>	-1E+303 mm	1E+303 mm	1	2E+303 mm	0 mm
				Window Size Scaling X	<input type="checkbox"/>	1E-300	1E+300	1	1E+300	1
				Window Size Scaling Y	<input type="checkbox"/>	1E-300	1E+300	1	1E+300	1
				Resolution Scaling X	<input type="checkbox"/>	1E-300	1E+300	1	1E+300	1
				Resolution Scaling Y	<input type="checkbox"/>	1E-300	1E+300	1	1E+300	1

< Back Next > Show ▾

Usage Modes

- **Standard Mode:**
Linear variation of all selected parameters between minimum and maximum value.
 - **Programmable Mode:**
Customized parameter values per variation step. A table with the parameter values per variation step is filled by a snippet.
 - **Scanning Mode:**
Scan of parameter space – all possible parameter combinations are simulated.
 - **Random Mode:**
Random variation of parameters between minimum and maximum value. Sometimes also called Monte-Carlo-Simulation. A seed can be used for reproducible results.
-

Usage Modes



- Illustration of the different usage modes for the parameter run. A two-dimensional parameter space defined by two parameters X_1 and X_2 is shown.
- **Red:** Resulting parameter sets for the standard mode.
- **Green:** Example how the parameter sets can be generated by a snippet in the programmable mode.
- **Blue:** Resulting parameter sets for the scanning mode.
- **Grey:** Some randomly generated parameter sets.

Detecting Devices Specification Page

3: Parameter Run from 1: Light Path Editor (Light Path Diagram #1)*

Detecting Devices Specification
Set up the detecting devices whose results you want to analyze

This page allows you to select one or more detecting devices (detectors, analyzers, or virtual screens). At least one detecting device must be selected. If you click on the "Open" button of one detecting device, the corresponding edit dialog is displayed.

In the upper part you can select the simulation engine(s) that shall be executed in the parameter run. Furthermore you can select the detectors that shall be evaluated by the selected simulation engine(s).

☒ Unified Field Tracing

Detecting Device		Edit Dialog
Virtual Screen #600	<input checked="" type="checkbox"/>	Open
Virtual Screen #601	<input checked="" type="checkbox"/>	Open

In the lower part you can select the analyzers that shall be executed in the parameter run. They are independent from the simulation engine(s) selected above.

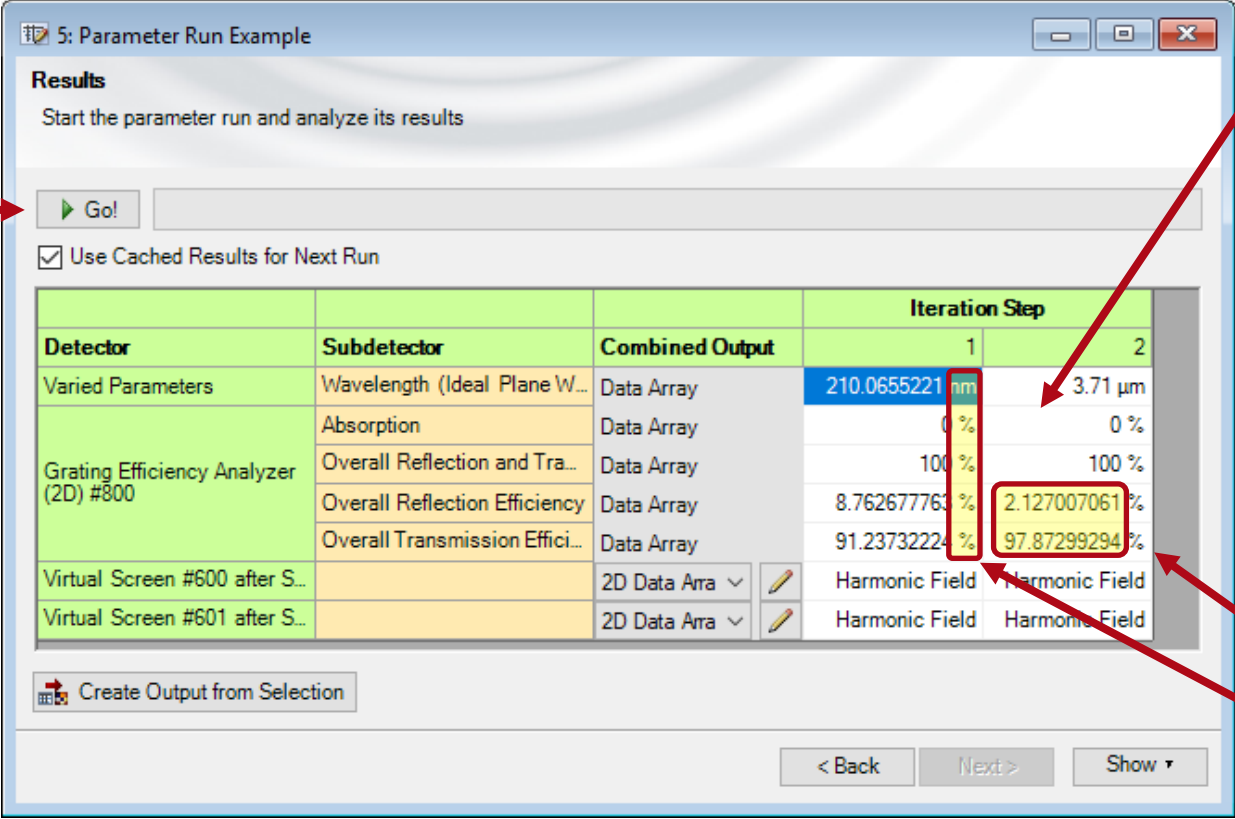
Analyzer		Edit Dialog
Grating Efficiency Analyzer (2D) #800	<input checked="" type="checkbox"/>	Open

< Back Next > Show LPD

- This page allows to select which simulation engines, detectors, screens and analyzers are evaluated.
- The detecting devices can be configured after clicking Open to get to the edit dialog.

Results Page

Starts and stops the parameter variation.



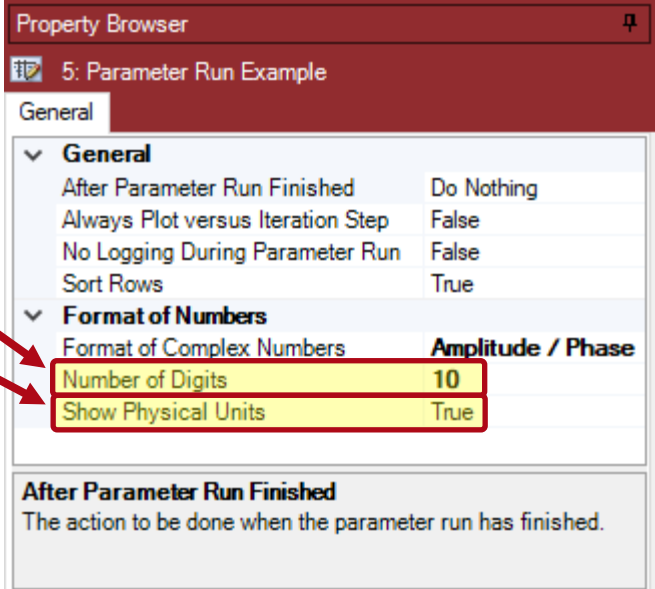
Results
Start the parameter run and analyze its results

☒ Use Cached Results for Next Run

Detector	Subdetector	Combined Output	Iteration Step	
			1	2
Varied Parameters	Wavelength (Ideal Plane W...	Data Array	210.0655221 nm	3.71 μm
	Absorption	Data Array	0 %	0 %
Grating Efficiency Analyzer (2D) #800	Overall Reflection and Tra...	Data Array	100 %	100 %
	Overall Reflection Efficiency	Data Array	8.762677763 %	2.127007061 %
	Overall Transmission Effici...	Data Array	91.23732224 %	97.87299294 %
Virtual Screen #600 after S...		2D Data Arra ▾	Harmonic Field	Harmonic Field
Virtual Screen #601 after S...		2D Data Arra ▾	Harmonic Field	Harmonic Field

Simulation results:
Double click on a document to view it in a separate window.

In the Property Browser you can change the formatting of the shown physical values (number of digits and whether physical units are shown) so that you can better export them to e.g. spread sheet programs via copy & paste.



Property Browser

5: Parameter Run Example

General

After Parameter Run Finished	Do Nothing
Always Plot versus Iteration Step	False
No Logging During Parameter Run	False
Sort Rows	True

Format of Numbers

Format of Complex Numbers	Amplitude / Phase
Number of Digits	10
Show Physical Units	True

After Parameter Run Finished
The action to be done when the parameter run has finished.

Optical Setups within Parameter Run

The screenshot displays the Wyrowski VirtualLab Fusion software interface. The main window is titled "5: Parameter Run Example". It features a "Results" section with a "Go!" button and a checkbox for "Use Cached Results for Next Run". Below this is a table showing simulation results for a "Grating Efficiency Analyzer (2D) #800". The table has columns for "Detector", "Subdetector", "Combined Output", and "Iteration Step" (1 and 2). The "Show Optical Setup" button is highlighted in the top toolbar. The "Property Browser" on the right shows the "General" tab with settings for "After Parameter Run Finished" (Do Nothing), "Always Plot versus Iteration Step" (False), "No Logging During Parameter Run" (False), "Sort Rows" (True), "Format of Numbers" (Amplitude / Phase), "Number of Digits" (10), and "Show Physical Units" (True). The "After Parameter Run Finished" section is also visible at the bottom of the Property Browser.

Detector	Subdetector	Combined Output	Iteration Step	
			1	2
Varied Parameters	Wavelength (Ideal Plane W...	Data Array	210.0655221 nm	3.71 μm
Grating Efficiency Analyzer (2D) #800	Absorption	Data Array	0 %	0 %
	Overall Reflection and Tra...	Data Array	100 %	100 %
	Overall Reflection Efficiency	Data Array	8.762677763 %	2.127007061 %
	Overall Transmission Effici...	Data Array	91.23732224 %	97.87299294 %
Virtual Screen #600 after S...		2D Data Arra	Harmonic Field	Harmonic Field
Virtual Screen #601 after S...		2D Data Arra	Harmonic Field	Harmonic Field

Displays the optical setup:

- initial
- from any iteration

Logging of Parameter Run Results

The screenshot shows the Wyrowski VirtualLab Fusion (2nd Generation Technology Update [Build 7.4.0.49]) interface. The 'Parameter Run' window is active, displaying a table of results for a 'Grating Efficiency Analyzer (2D) #800'. The 'Property Browser' on the right shows the 'General' tab with the 'No Logging During Parameter Run' option set to 'False'. A red box highlights this option, and a red arrow points to it from the 'Parameter Run' window. Another red box highlights the 'No Logging During Execution' button in the 'Execution' ribbon.

Parameter Run Results Table:

Detector	Subdetector	Combined Output	Iteration Step	
			1	2
Grating Efficiency Analyzer (2D) #800	Wavelength (Ideal Plane W...	Data Array	210.0655221 nm	3.71 μm
	Absorption	Data Array	0 %	0 %
	Overall Reflection and Tra...	Data Array	100 %	100 %
	Overall Reflection Efficiency	Data Array	8.762677763 %	2.127007061 %
	Overall Transmission Effici...	Data Array	91.23732224 %	97.87299294 %
Virtual Screen #600 after S...		2D Data Arra	Harmonic Field	Harmonic Field
Virtual Screen #601 after S...		2D Data Arra	Harmonic Field	Harmonic Field

- For time critical simulations especially for Parameter Runs with many iterations, the simulation time can be reduced by **deactivating the logging**.
- Thus the results are only shown after all iterations are finished.
- In order to see the results of a running Parameter Run document that have been produced so far, you can duplicate the document via the Windows ribbon; then VirtualLab creates a Parameter Run document of the current status with all already calculated results.

Display of Parameter Run Results

The screenshot shows the WYROWSKI VirtualLab Fusion software interface. The 'Parameter Run' window is active, displaying the 'Results' section. A red arrow points to the 'Delete Results' button in the top right corner. Another red arrow points to the 'Results' table, which shows the output of the parameter run. A third red arrow points to the 'Property Browser' on the right side of the interface.

Results Table:

Detector	Subdetector	Combined Output	Iteration Step 1	Iteration Step 2
Varied Parameters	Wavelength (Ideal Plane W...	Data Array	210.0655221 nm	3.71 μm
Grating Efficiency Analyzer (2D) #800	Absorption	Data Array	0 %	0 %
	Overall Reflection and Tra...	Data Array	100 %	100 %
	Overall Reflection Efficiency	Data Array	8.762677763 %	2.127007061 %
	Overall Transmission Effici...	Data Array	91.23732224 %	97.87299294 %
Virtual Screen #600 after S...		2D Data Arra	Harmonic Field	Harmonic Field
Virtual Screen #601 after S...		2D Data Arra	Harmonic Field	Harmonic Field

Property Browser:

- General
 - After Parameter Run Finished: Do Nothing
 - Always Plot versus Iteration Step: False
 - No Logging During Parameter Run: False
 - Sort Rows: True
- Format of Numbers
 - Format of Complex Numbers: Amplitude
 - Number of Digits: 10
 - Show Physical Units: True

After Parameter Run Finished:

The action to be done when the parameter run has finished.

1. It is possible to delete the results in order to save a smaller Parameter Run document (e.g. for email sending).
(Sometimes the saving or opening of a Parameter Run document with many and/or huge results takes longer than the simulation of all iterations.)
2. The user can select different orders for the display of the results.
3. There are different options to display complex numbers.

Saving (& Shutdown) after Parameter Run Completion?

Allows you to save the results after the simulation has finished and then shut down your computer.

The screenshot displays the Wyrowski VirtualLab Fusion software interface. The main window is titled '5: Parameter Run Example'. It features a 'Results' section with a 'Go!' button and a checkbox for 'Use Cached Results for Next Run'. Below this is a table showing simulation results for various detectors and parameters. The 'Property Browser' on the right shows the 'General' tab with a dropdown menu set to 'Do Nothing'.

Table 1: Results Data

Detector	Subdetector	Combined Output	Iteration Step 1	Iteration Step 2
Varied Parameters	Wavelength (Ideal Plane W...	Data Array	210.0655221 nm	3.71 μm
Grating Efficiency Analyzer (2D) #800	Absorption	Data Array	0 %	0 %
	Overall Reflection and Tra...	Data Array	100 %	100 %
	Overall Reflection Efficiency	Data Array	8.762677763 %	2.127007061 %
	Overall Transmission Effici...	Data Array	91.23732224 %	97.87299294 %
Virtual Screen #600 after S...		2D Data Arra	Harmonic Field	Harmonic Field
Virtual Screen #601 after S...		2D Data Arra	Harmonic Field	Harmonic Field

Table 2: Property Browser - General

Property	Value
After Parameter Run Finished	Do Nothing
Always Plot versus Iteration Step	False
No Logging During Parameter Run	False
Sort Rows	True
Format of Complex Numbers	Amplitude / Phase
Number of Digits	10
Show Physical Units	True

Results Page – Combined Outputs

The results for each (sub-)detector can be combined into a Data Array, Animation, Harmonic Fields Set or Ray Distribution. Which combined outputs are available depends on the type and dimensionality of the original documents.

Create the combined output – or stop the creation if it takes too long. Clicking/Double clicking on a cell in the Detector or Subdetector column is a shortcut to selecting the whole row and start the output creation with the current combined output.

Results
Start the parameter run and analyze its results

☒ Use Cached Results for Next Run

Detector	Subdetector	Combined Output	Iteration Step	
			1	2
Varied Parameters	Wavelength (Ideal Plane W...	Data Array	210.0655221 nm	3.71 μ m
Grating Efficiency Analyzer (2D) #800	Absorption	Data Array	0 %	0 %
	Overall Reflection and Tra...	Data Array	100 %	100 %
	Overall Reflection Efficiency	Data Array	8.762677763 %	2.127007061 %
	Overall Transmission Effici...	Data Array	91.23732224 %	97.87299294 %
Virtual Screen #600 after S...		2D Data Arra	Harmonic Field	Harmonic Field
Virtual Screen #601 after S...		2D Data Arra	Harmonic Field	Harmonic Field

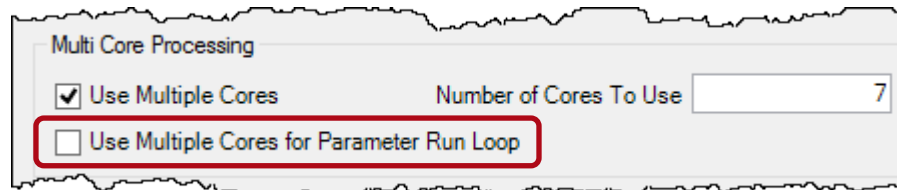
< Back Next > Show ▾

- Select the results to combine.
- Clicking on a cell in the Detector or Subdetector column selects the whole row.

- Choose the desired combined output.
- Several combined outputs can be configured by clicking on the pencil icon.

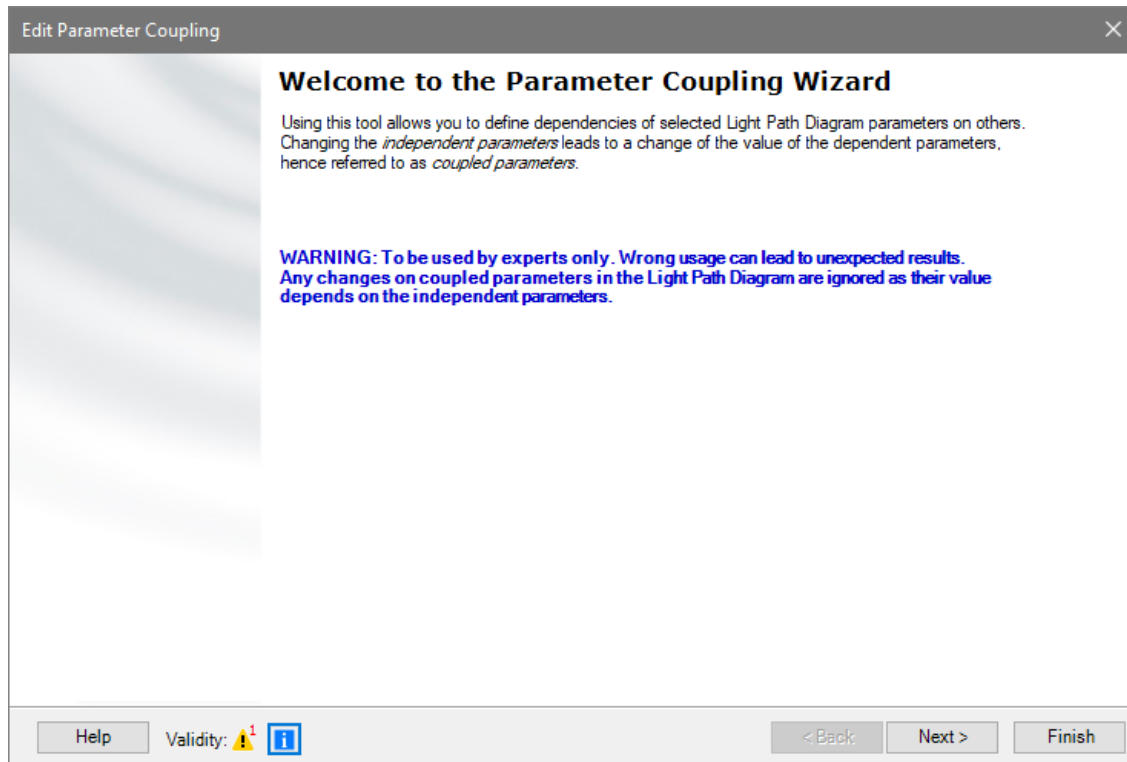
Parallelization & Amount of Data

- The execution of the different iterations of a Parameter Run simulation is very well parallelized. Thus it represents a very efficient method to simulate many different settings very fast.
- But in case already one simulation is extremely memory consuming, parallel executions are out of the question. They would not be possible or slow down the whole process if VirtualLab may swap such large data on hard disc instead of keeping it in the RAM.
- Then the parallelization should be switched off for Parameter Run Loop.
- VirtualLab will still do parallel computations, as parallelization is also used within single system simulations.



Parameter Coupling

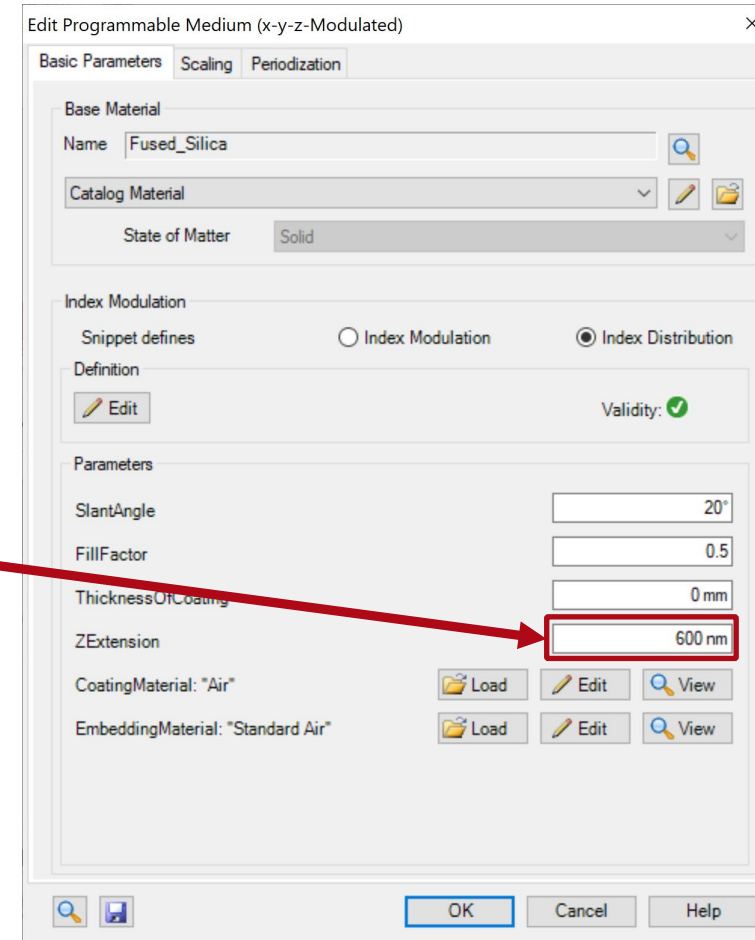
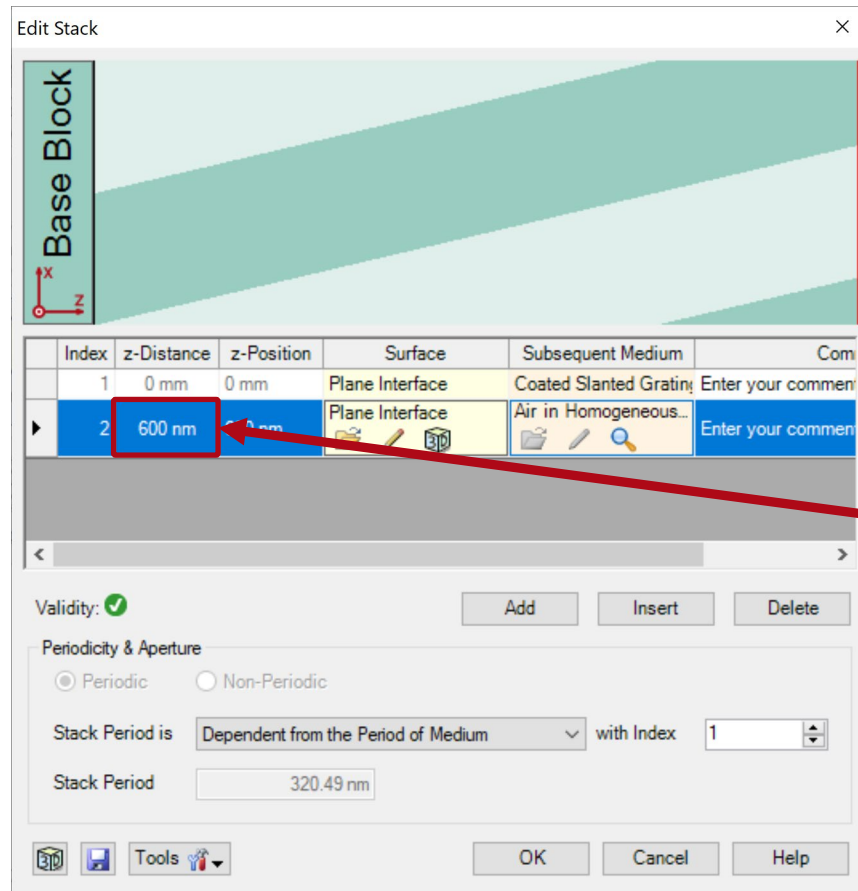
Abstract



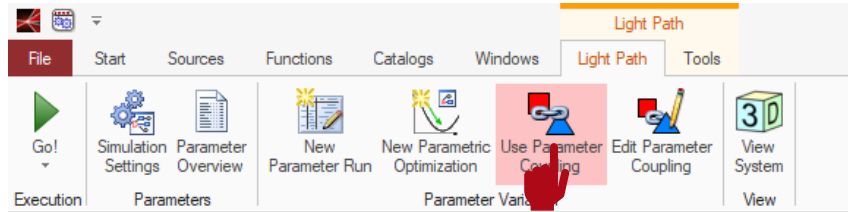
The parameter coupling feature of VirtualLab Fusion enables the coupling of parameters in an optical setup. The values can also be used to re-calculate other parameters of the system, so that a certain relationship between them is automatically maintained. Hence, this feature allows the user to instate complex dependencies for these parameters. For instance, in this example we use the Parameter Coupling to ensure that the z extension of a user-programmed slanted grating medium coincides with the thickness of the structured layer where it is contained.

Task

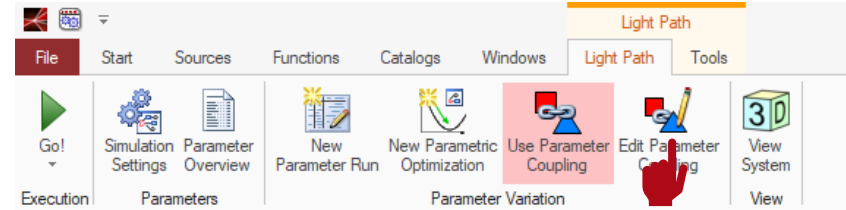
We wish to link two parameters of an optical system, so that they automatically take the same value. For this purpose, VirtualLab's Parameter Coupling feature is used.



Set Up Parameter Coupling

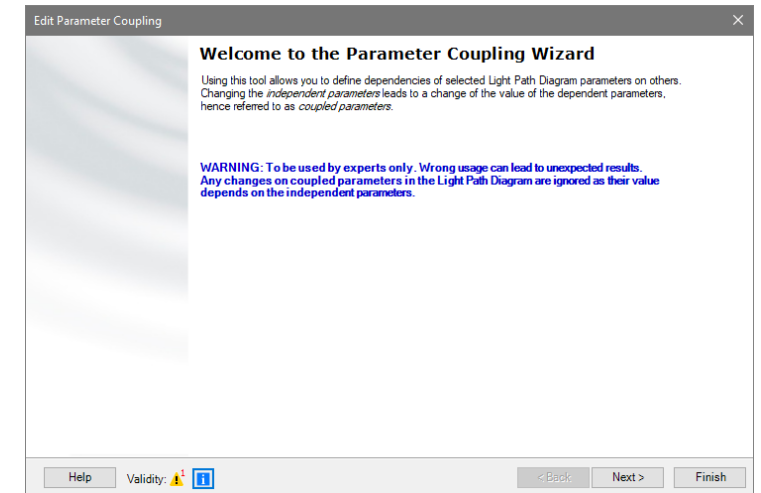


In order to use the parameter coupling feature of VirtualLab Fusion activate the option “*Use Parameter Coupling*” for the optical setup in question.



Afterwards, the “*Edit Parameter Coupling*” button is available.

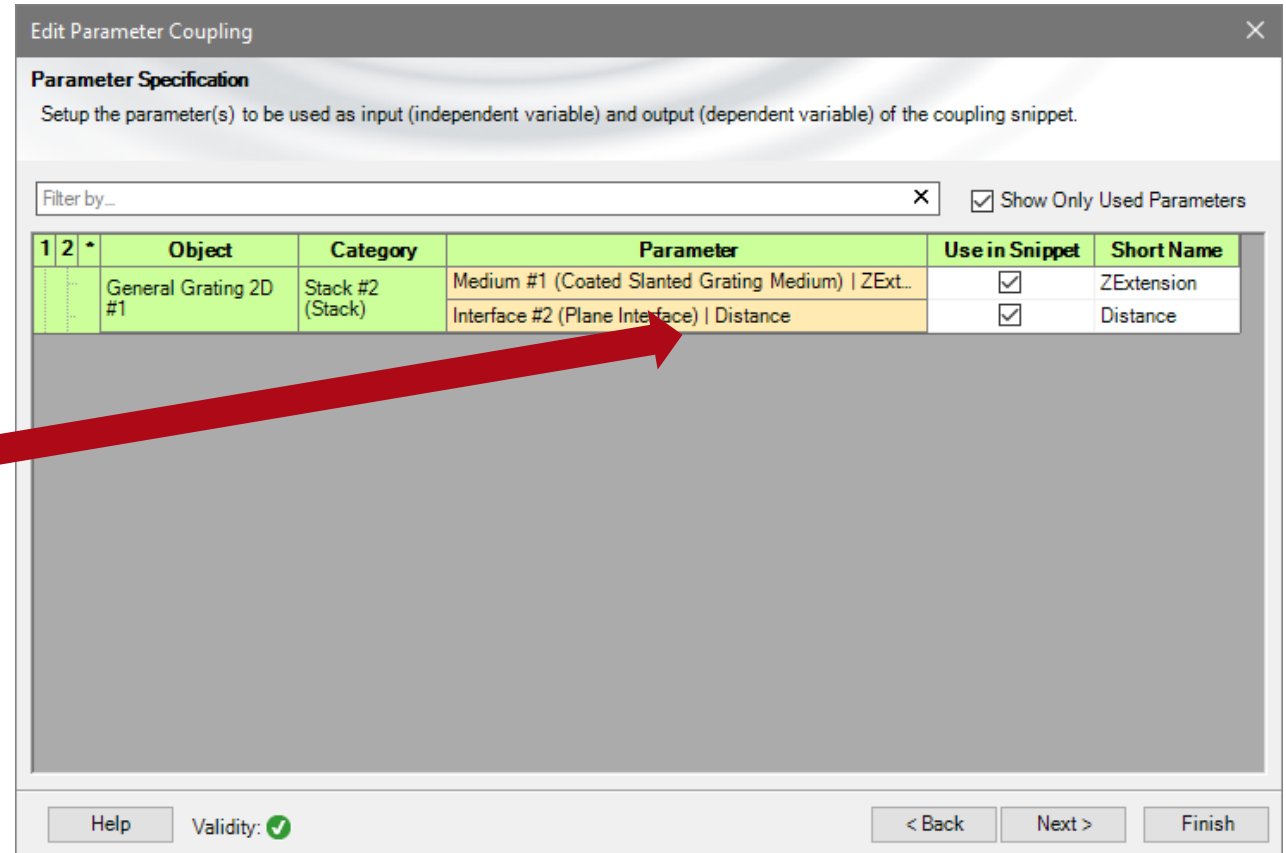
Clicking on the “*Edit Parameter Coupling*” button causes the parameter coupling wizard to appear.



Choose Parameters Involved

By clicking “*Next*”, a table is shown which contains all parameters of the current optical setup.

Please select all the parameters which are relevant for the coupling and necessary calculation. For instance, the parameters “*ZExtension*” and “*Distance*” are chosen in this case.



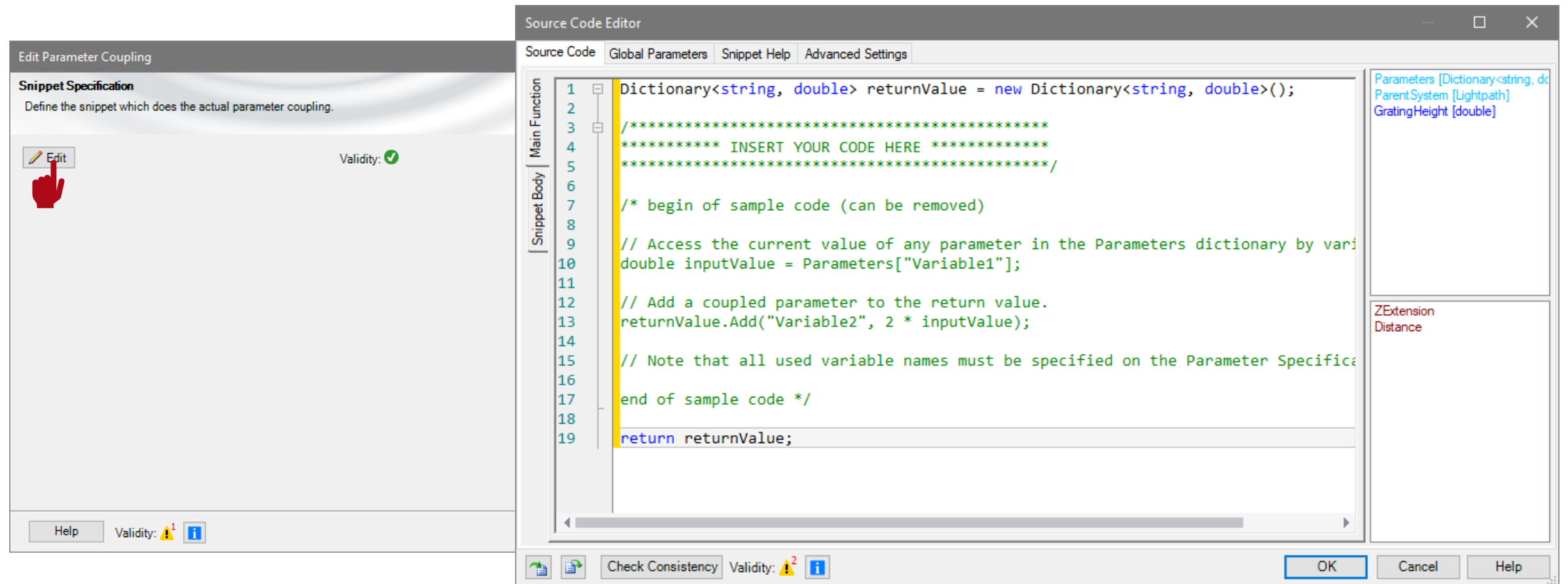
The screenshot shows a software window titled "Edit Parameter Coupling". Inside, there's a section "Parameter Specification" with the instruction: "Setup the parameter(s) to be used as input (independent variable) and output (dependent variable) of the coupling snippet." Below this is a "Filter by..." search bar and a checkbox labeled "Show Only Used Parameters" which is checked. A table lists parameters with columns: "1 2 *", "Object", "Category", "Parameter", "Use in Snippet", and "Short Name".

1 2 *	Object	Category	Parameter	Use in Snippet	Short Name
	General Grating 2D #1	Stack #2 (Stack)	Medium #1 (Coated Slanted Grating Medium) ZExt...	<input checked="" type="checkbox"/>	ZExtension
			Interface #2 (Plane Interface) Distance	<input checked="" type="checkbox"/>	Distance

At the bottom of the window, there are buttons for "Help", "Validity: ✓", "< Back", "Next >", and "Finish". A large red arrow points from the text "Distance" in the paragraph above to the "Distance" parameter row in the table.

Configure the Coupling of the Parameters

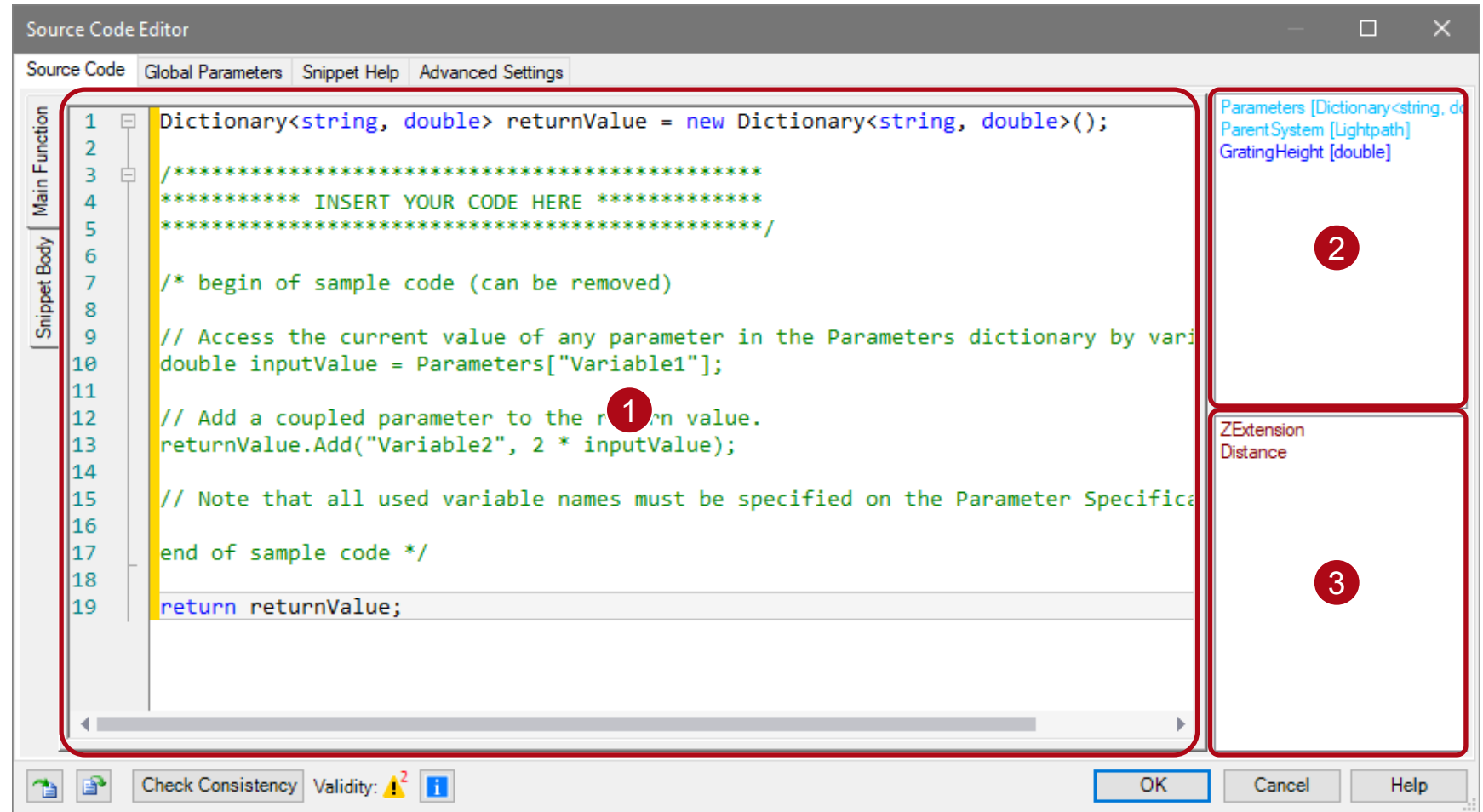
After choosing the parameters, the snippet which controls the coupling has to be set. By clicking on “*Edit*” the source code editor opens.



Configure the Coupling of Parameters

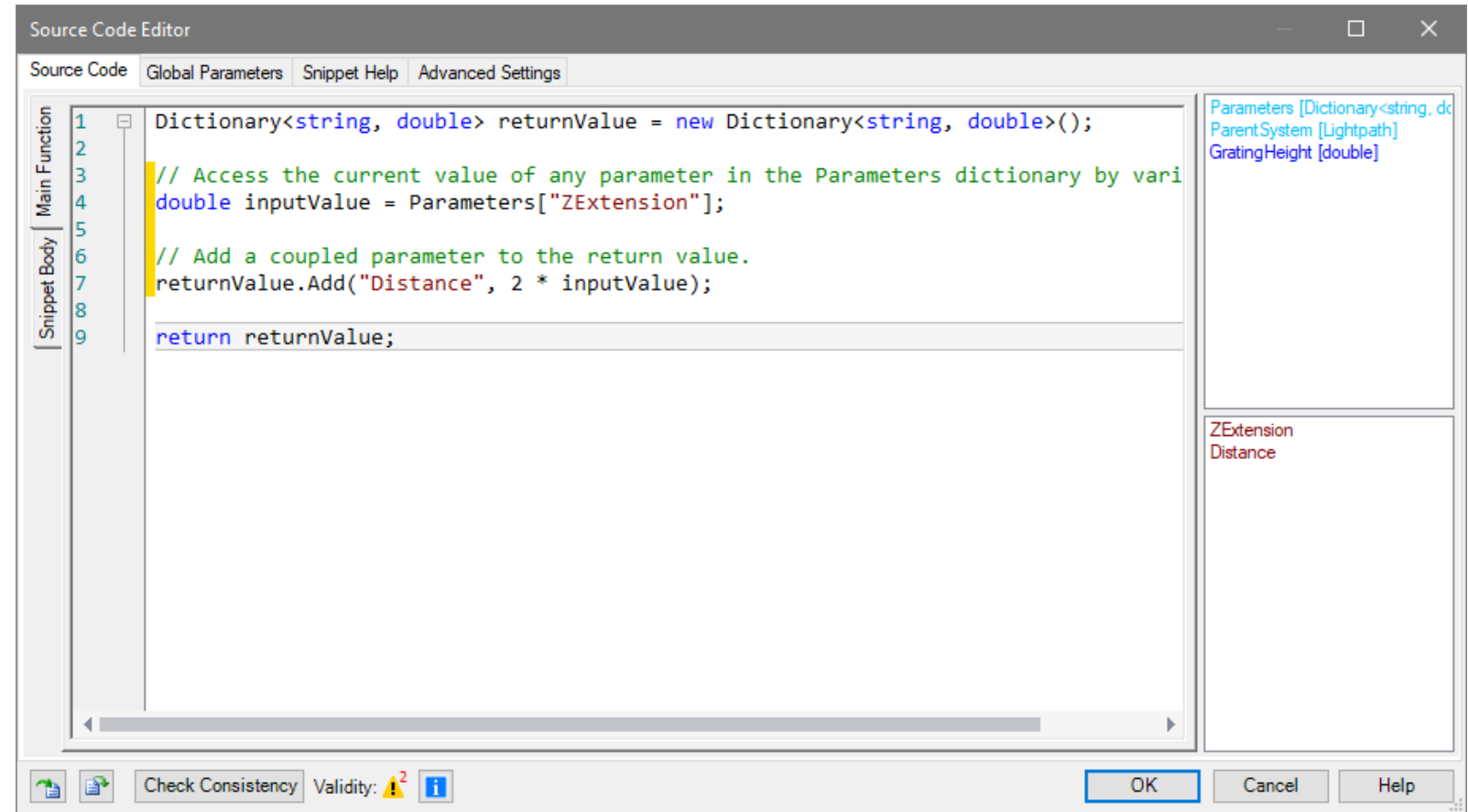
The source code tab contains three areas:

- 1 the source code (center area)
- 2 global variables/parameters (upper right area)
- 3 chosen system parameters (lower right)



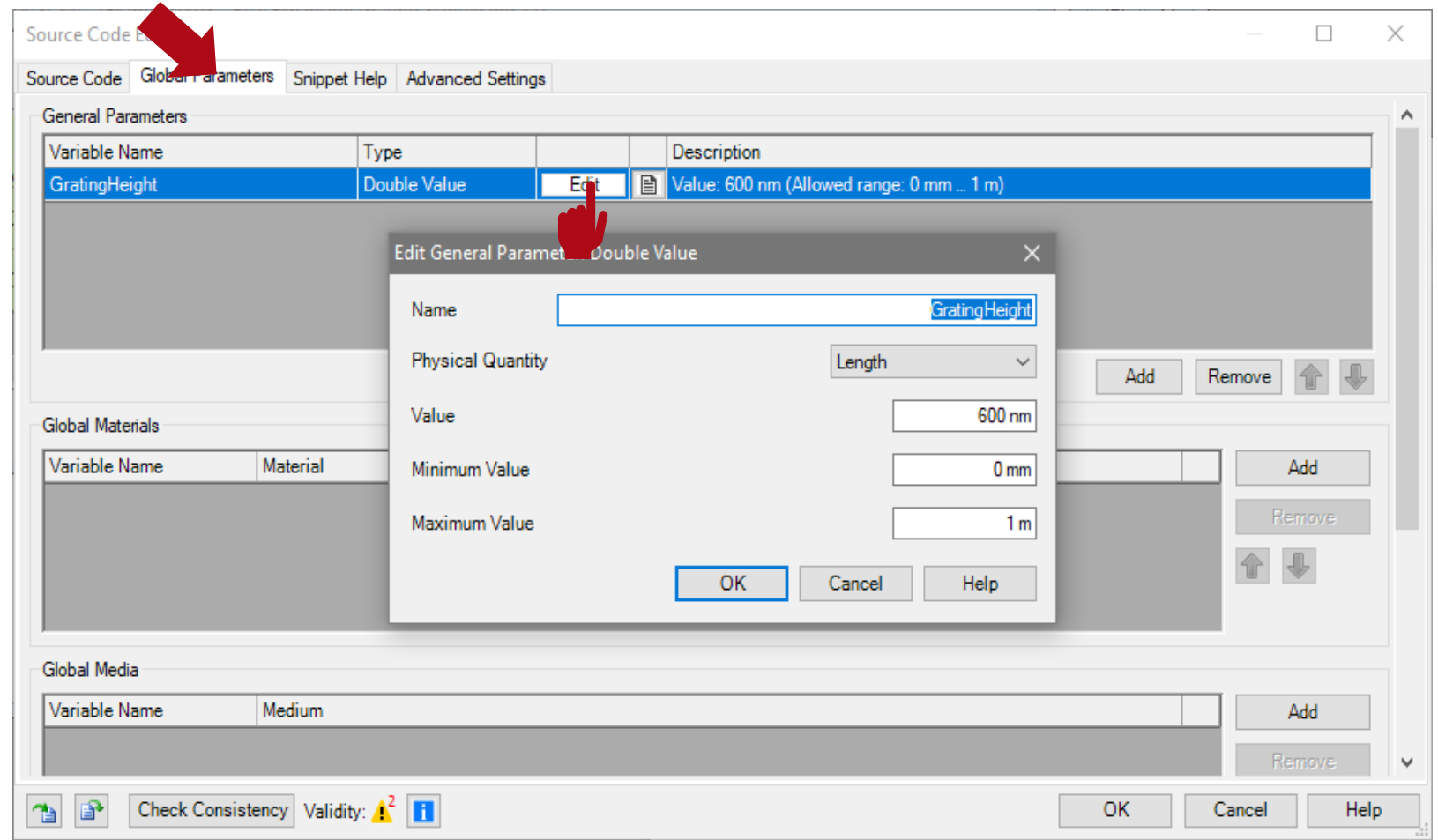
General Example of Parameter Coupling

- In general, the chosen parameters have to be read from the dictionary and saved to a variable (line 4).
- Afterwards, that value can be used as output for another parameter, or play a role in its calculation, e.g. be doubled (line 7).



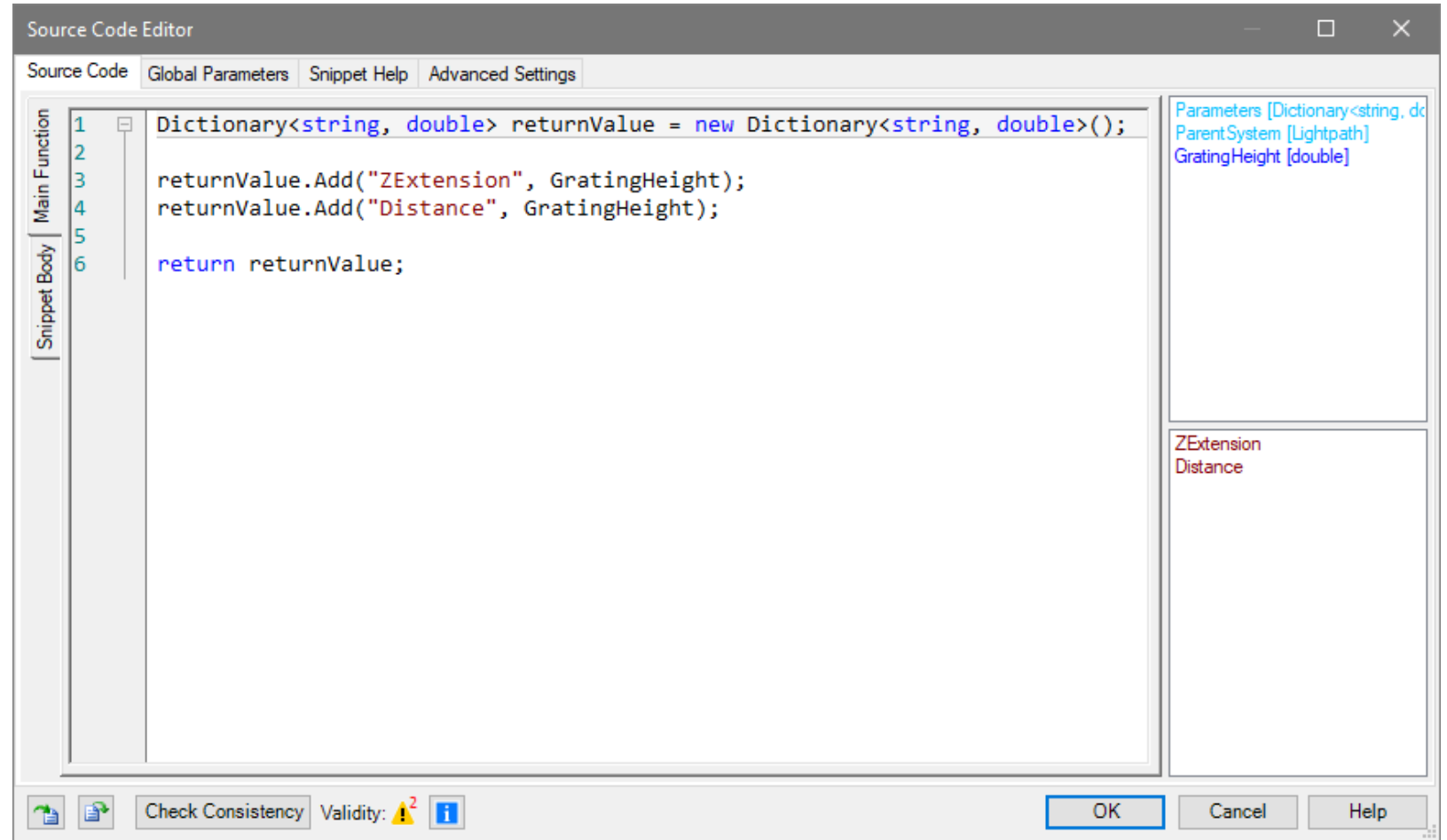
Definition of Global Parameters

- In this particular example, it is helpful to define a new global variable, which later appears on the parameter coupling window.
- This can be done in the “*Global Parameters*” tab.
- The variable can be of different types and have different physical quantities attached.



Particular Example of Parameter Coupling

- In this example, the global variable is used to return its value to both chosen parameters of the system.
- Thus, no parameter has to be read from the dictionary or re-calculated.



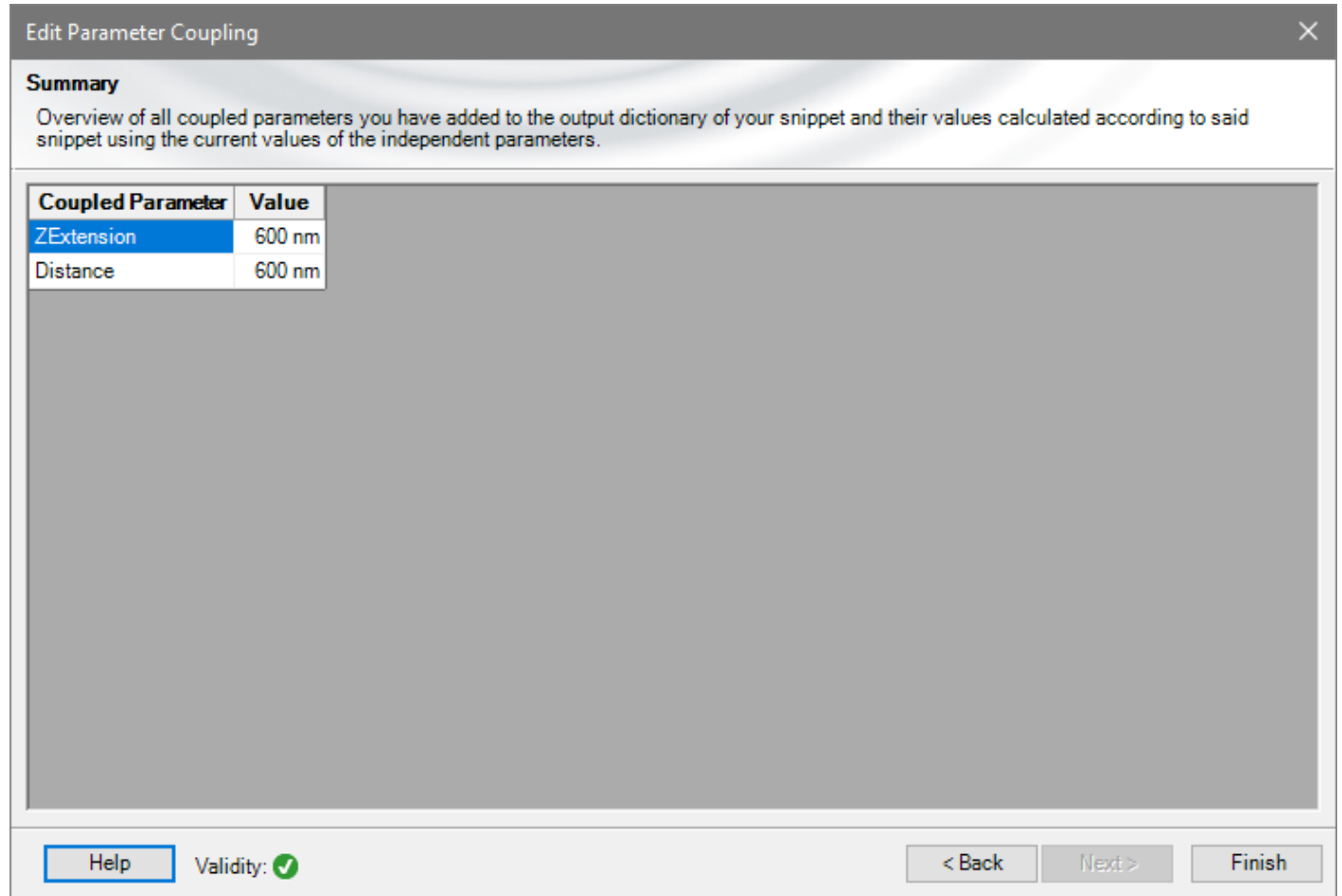
Particular Example of Parameter Coupling

- After closing the source code editor, the defined global variable “*GratingHeight*” appears.
- When working with the system later on, the user will only be able to modify the value of this variable, which will in turn automatically affect the value of the system parameters. Trying to modify the value of the parameters themselves will have no effect.

The screenshot shows a software window titled "Edit Parameter Coupling". Inside, there is a section labeled "Snippet Specification" with the instruction "Define the snippet which does the actual parameter coupling." Below this, there is an "Edit" button with a pencil icon. To the right of the button, it says "Validity: ✓". In the center, the variable name "GratingHeight" is displayed next to a text input field containing the value "600 nm". At the bottom of the window, there is a footer bar containing a "Help" button, a "Validity: ⚠️ 1" indicator, an information icon, and three navigation buttons: "< Back", "Next >", and "Finish".

Final Check of the Set-up Parameter Coupling

- On the last page of the wizard, the returned parameters and values can be checked.



The screenshot shows a software window titled "Edit Parameter Coupling". It contains a "Summary" section with a descriptive text and a table of coupled parameters. The table has two columns: "Coupled Parameter" and "Value". It lists "ZExtension" and "Distance", both with a value of "600 nm". The "ZExtension" row is highlighted. At the bottom, there is a "Help" button, a "Validity" status with a green checkmark, and navigation buttons for "< Back", "Next >", and "Finish".

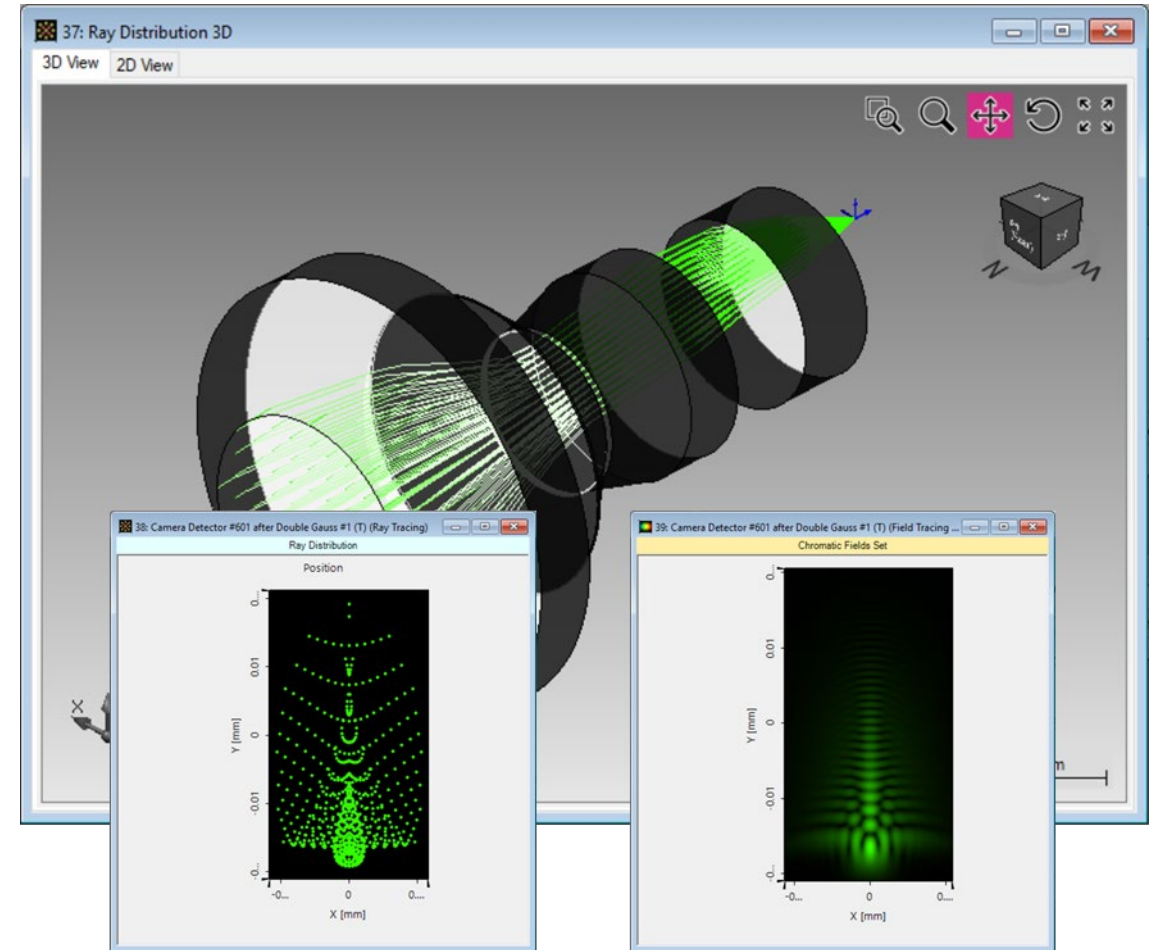
Coupled Parameter	Value
ZExtension	600 nm
Distance	600 nm

Zemax Import

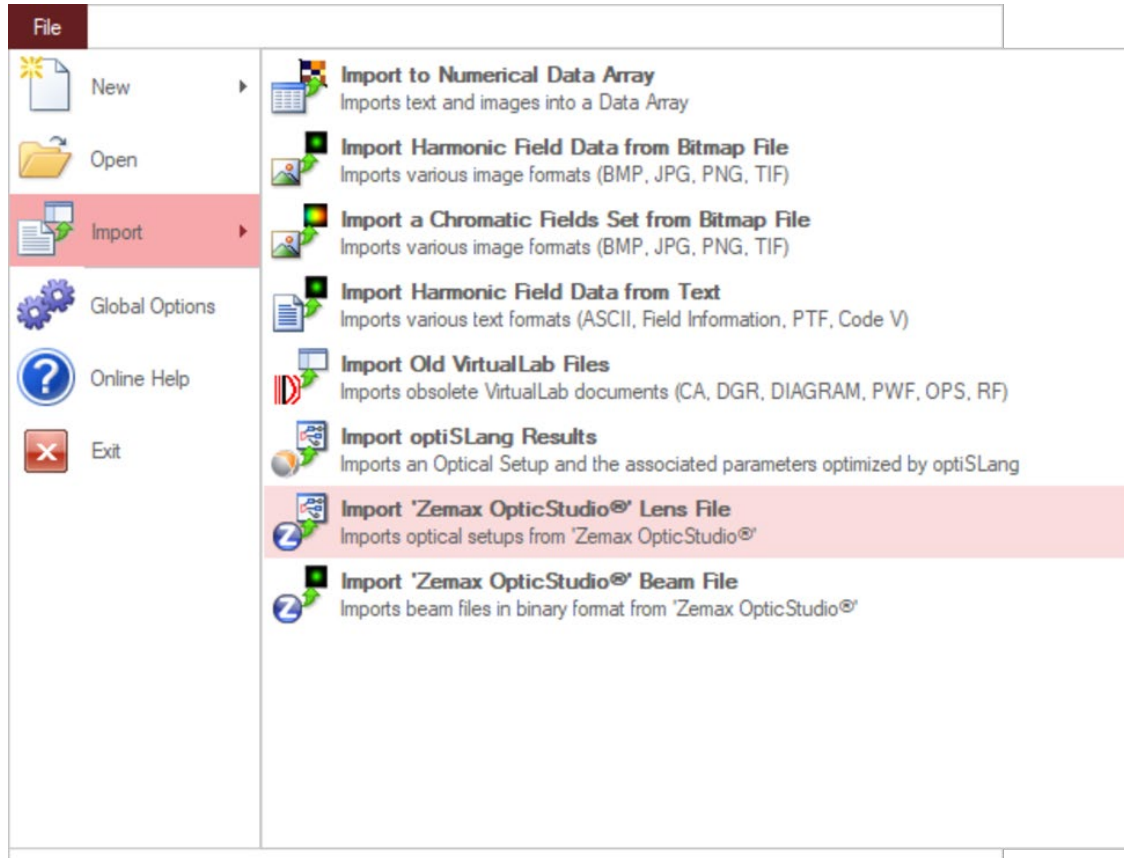
Importing Zemax Files

Being able to import Zemax files into VirtualLab constitutes an interesting feature for several reasons:

- Using field tracing in VirtualLab to simulate a system previously constructed in OpticStudio
- Some hardware manufacturers provide only Zemax files of their products



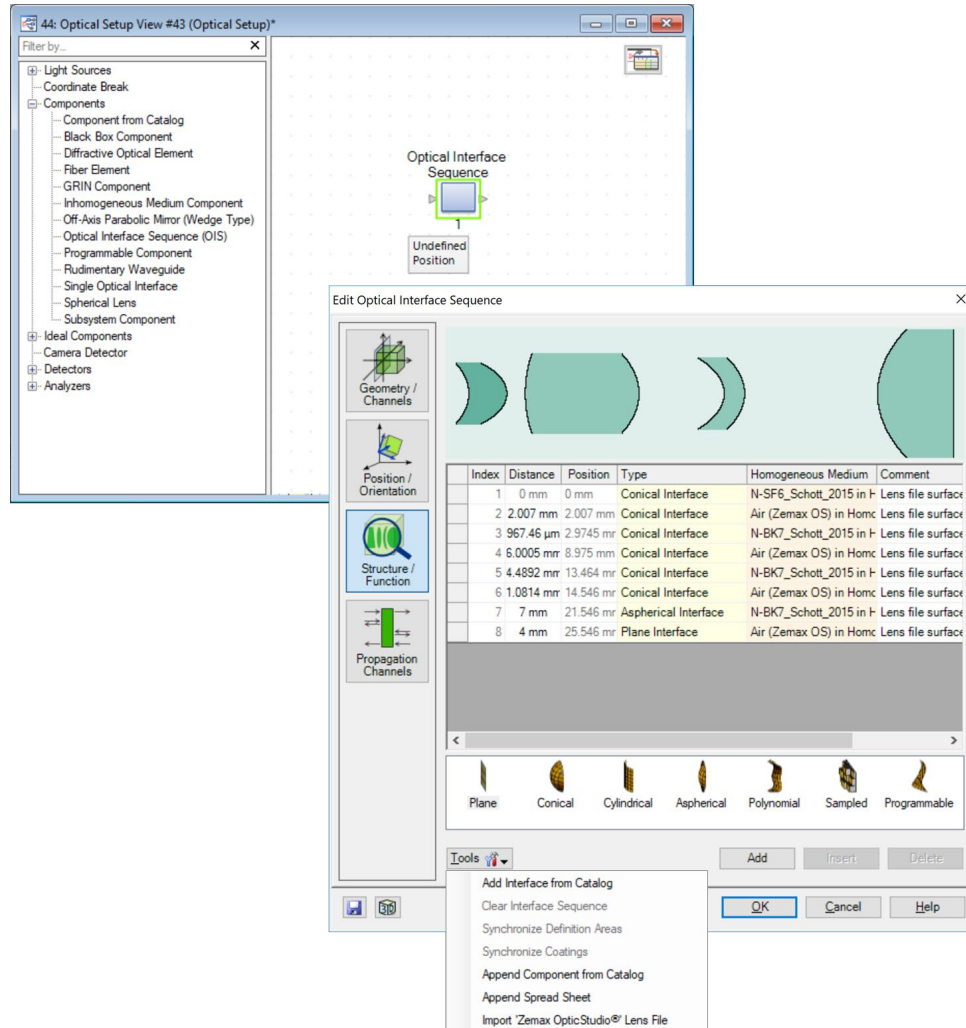
Importing Zemax Files



There are two ways to go about importing a Zemax OpticStudio file into VirtualLab Fusion:

- Importing the full system file into VirtualLab Fusion

Importing Zemax Files



There are two ways to go about importing a Zemax OpticStudio file into VirtualLab Fusion:

- Importing the full system file into VirtualLab Fusion
- Importing the system into an Optical Interface Sequence component in VirtualLab Fusion

Two Zemax Import Mechanisms: Elementary and Advanced

In general the user has three workflow options to trigger the import:

- drag and drop a ZMX file into your VirtualLab window
- go via File menu → Import → Import Zemax OpticStudio Lens File
- use the Tools button in the configuration dialogue of the Optical Interface Sequence (OIS) component into which the system is to be imported

Which import mechanism is used depends only on whether Zemax is installed on the computer in question and on whether there is a valid running licence or not:

- The advanced import mechanism needs access to the Zemax installation to extract more detailed information of the system which is to be imported
 - The elementary import mechanism needs only the Zemax glass catalogue directory in order to load the pertinent materials for the system
-

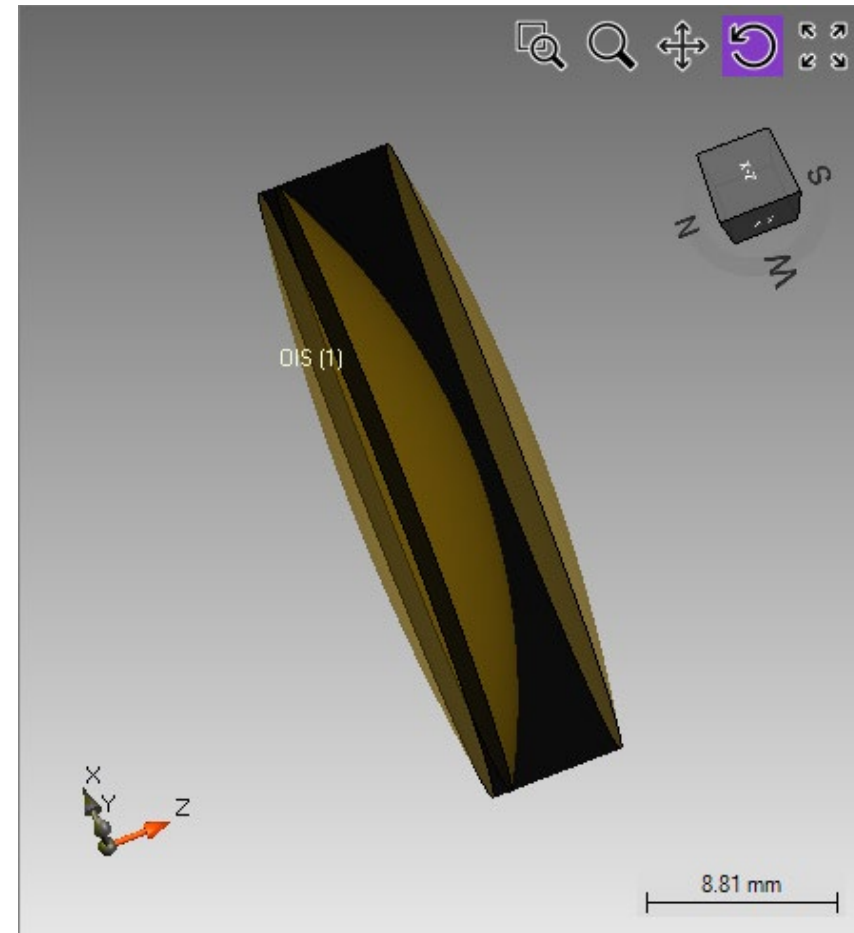
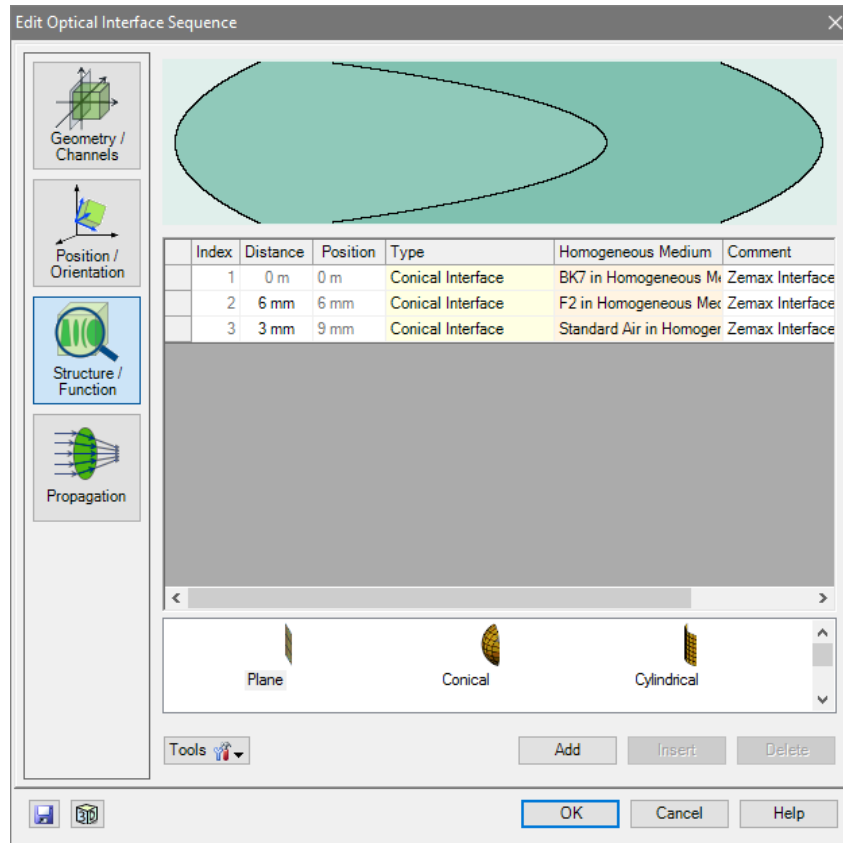
Elementary Zemax Import

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

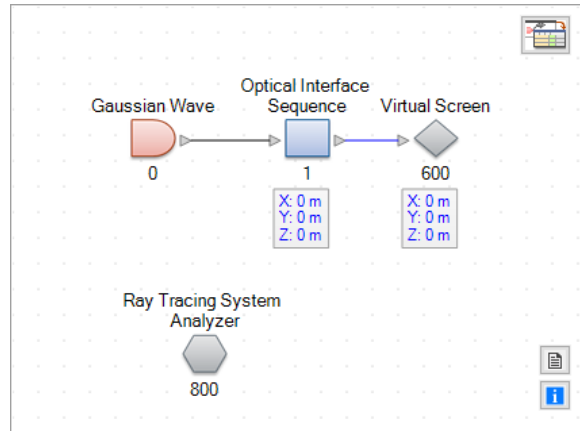
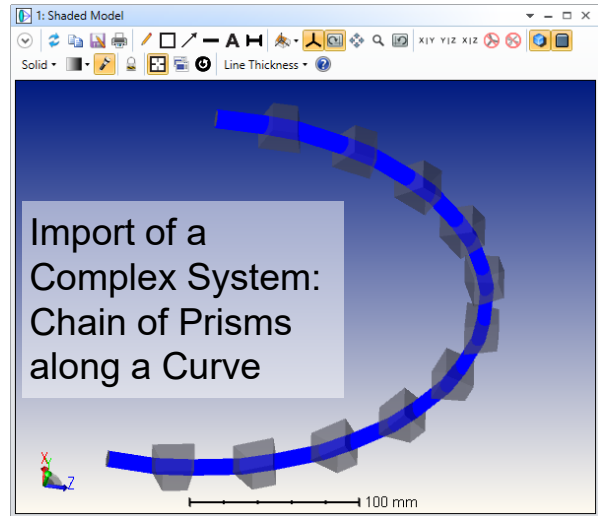
Even though manufacturers also start to provide VirtualLab files, Zemax files are still a standard.

Elementary Zemax Import

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



Limits of the Elementary Zemax Import



Index	Distance	Position	Type	Homogeneous Medium	Comment
1	0 m	0 m	Plane Interface	Air (Zemax) in Homogen	Zemax Interf
2	1 m	1 m	Plane Interface	Air (Zemax) in Homogen	Zemax Interf
3	30 mm	1.03 m	Plane Interface	N-BK7_SCHOTT in Hom	Zemax Interf
4	20 mm	1.05 m	Plane Interface	Air (Zemax) in Homogen	Zemax Interf
5	0 m	1.05 m	Plane Interface	Air (Zemax) in Homogen	Zemax Interf
6	30 mm	1.08 m	Plane Interface	N-BK7_SCHOTT in Hom	Zemax Interf
7	20 mm	1.1 m	Plane Interface	Air (Zemax) in Homogen	Zemax Interf
8	0 m	1.1 m	Plane Interface	Air (Zemax) in Homogen	Zemax Interf
9	30 mm	1.13 m	Plane Interface	N-BK7_SCHOTT in Hom	Zemax Interf
10	20 mm	1.15 m	Plane Interface	Air (Zemax) in Homogen	Zemax Interf
11	0 m	1.15 m	Plane Interface	Air (Zemax) in Homogen	Zemax Interf
12	30 mm	1.18 m	Plane Interface	N-BK7_SCHOTT in Hom	Zemax Interf
13	20 mm	1.2 m	Plane Interface	Air (Zemax) in Homogen	Zemax Interf

Plane Conical Cylindrical

Tools Add Insert Delete

OK Cancel Help

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).

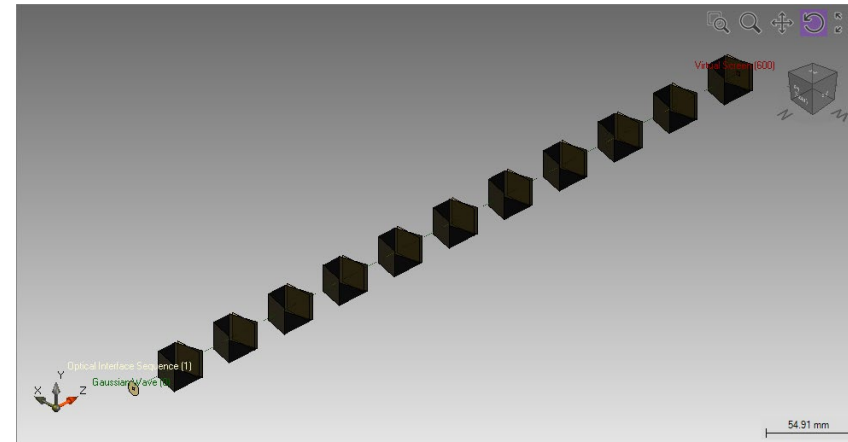
[08/09/2016 17:55:07] Zemax Interface #31: unsupported type COORDBRK, using plane interface

[08/09/2016 17:55:07] Warning: Aperture diameter ZERO detected at Zemax interface 31 (default will be used).

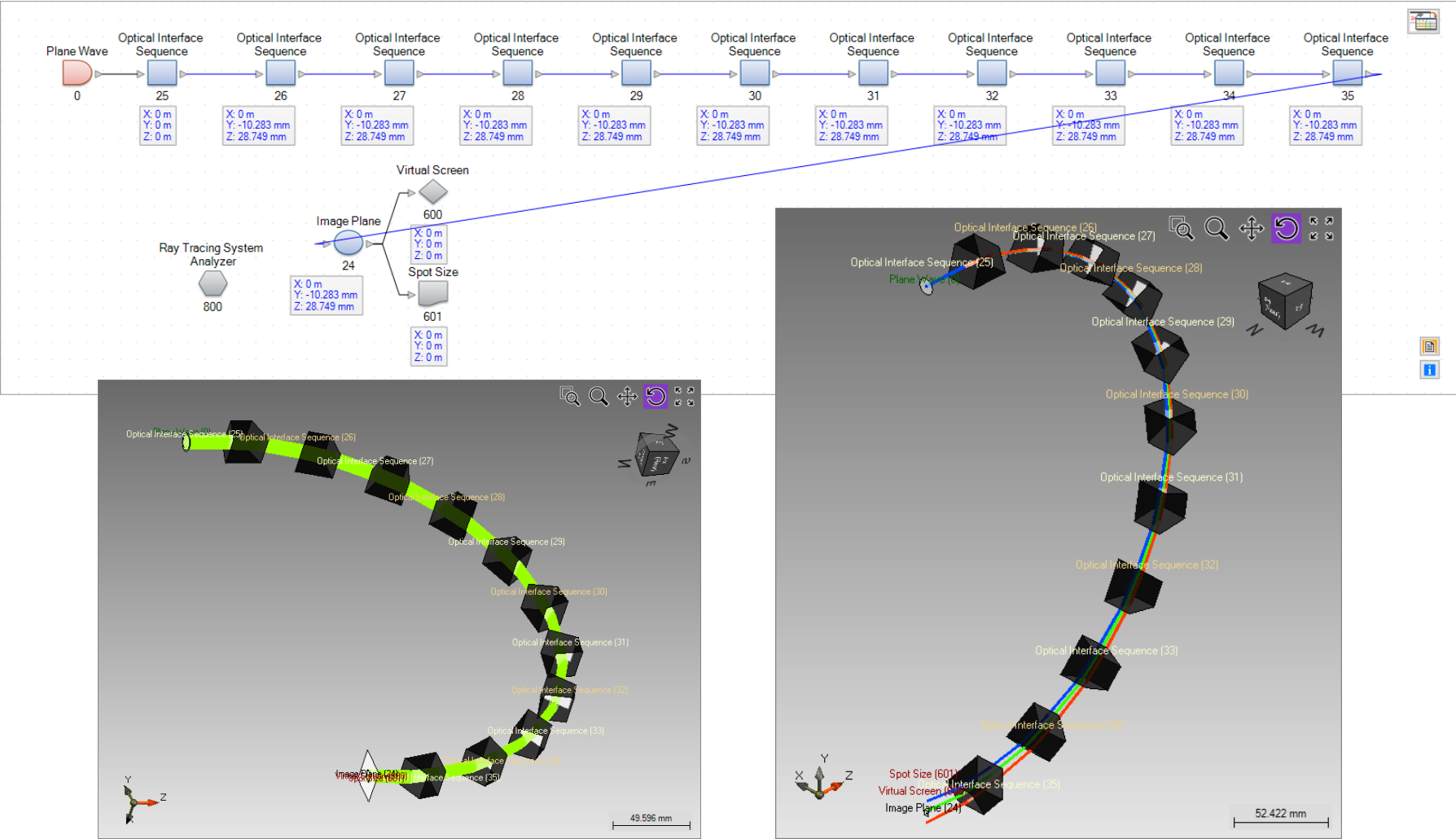
[08/09/2016 17:55:07] Zemax Interface #34: unsupported type COORDBRK, using plane interface

[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.
