Paris, April 9th 2019

Seminar VirtualLab Fusion – Part #1: Introduction und Concepts of Field Tracing Technology

Stefan Steiner
LightTrans International UG

Enabling Innovation in Optics&Photonics by Fast Physical Optics with VirtualLab Fusion

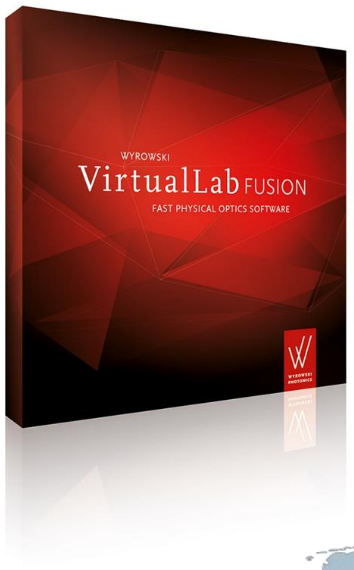
Jena, Germany

LightTrans International

LightTrans

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

Wyrowski Photonics



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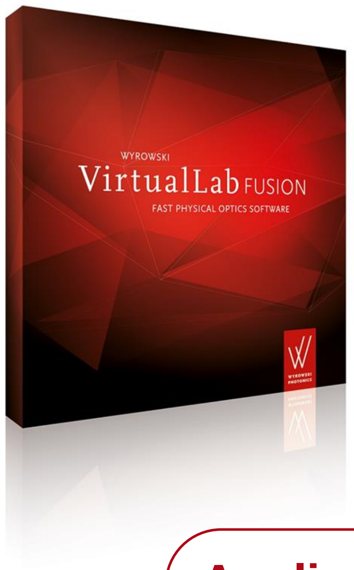
Development of fast physical optics software VirtualLab Fusion

University of Jena



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LIGHTTRANS

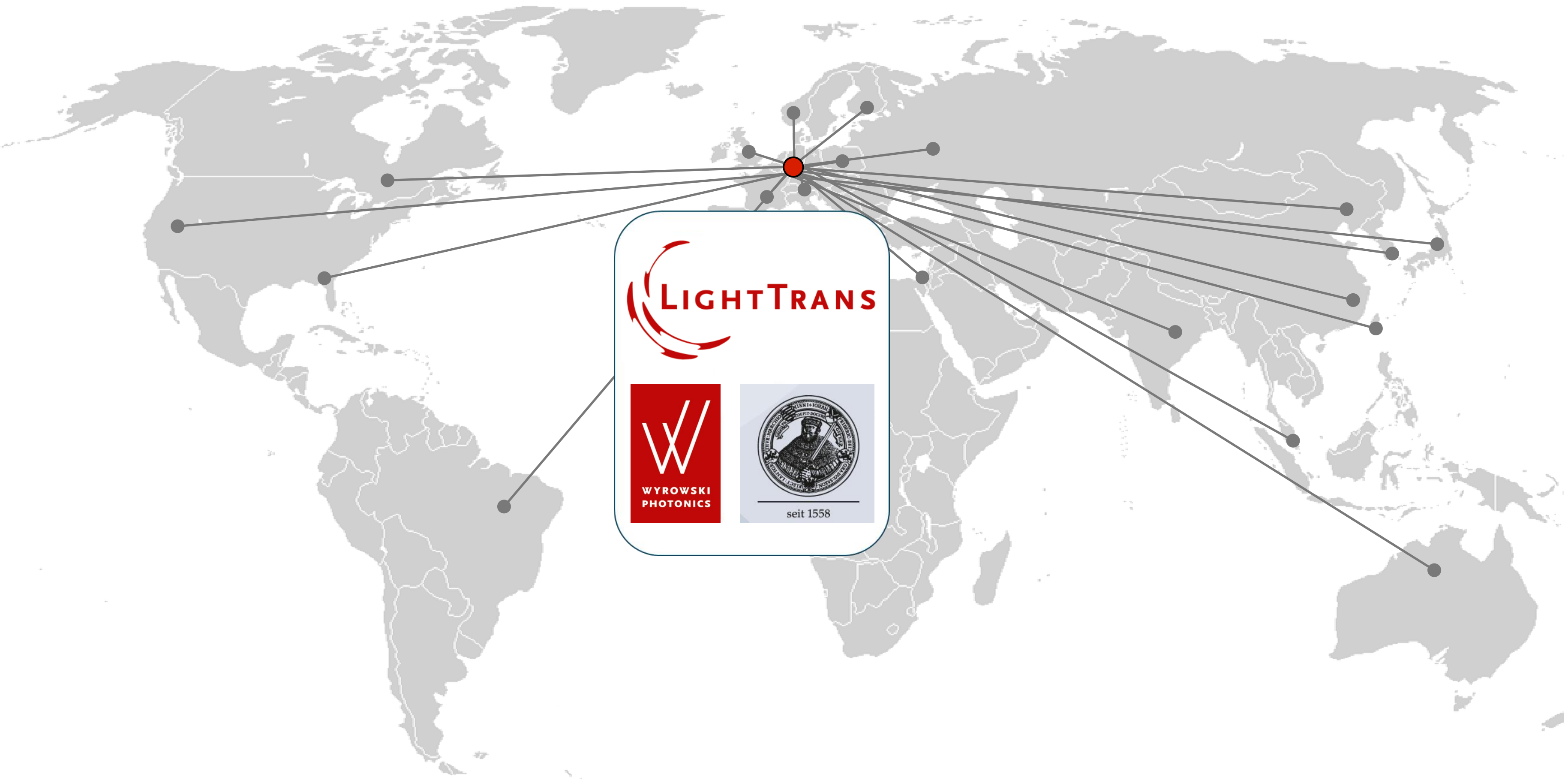
WYROWSKI PHOTONICS

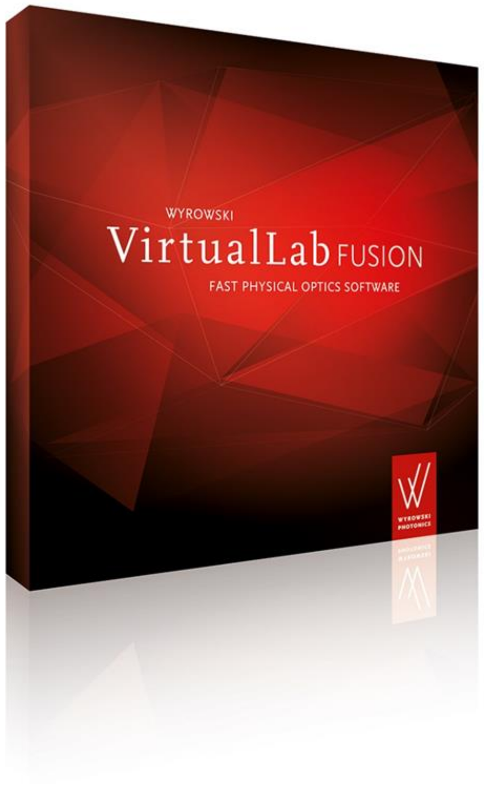
Wyrowski Photonics Development of fast physical optics software VirtualLab Fusion

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

seit 1558

Optical Design Software and Services

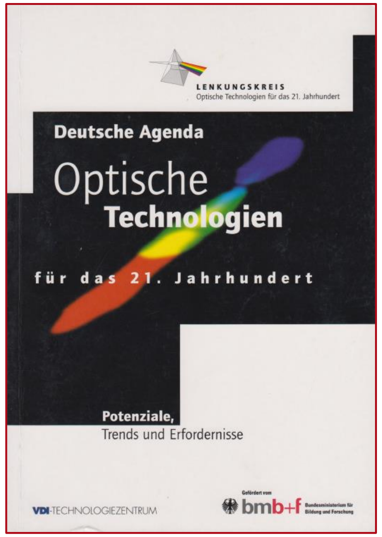




Our Motivation and Key Messages

Motivation

- **Optics and photonics** is **enabling technology** for the development of innovative commercial and industrial products.



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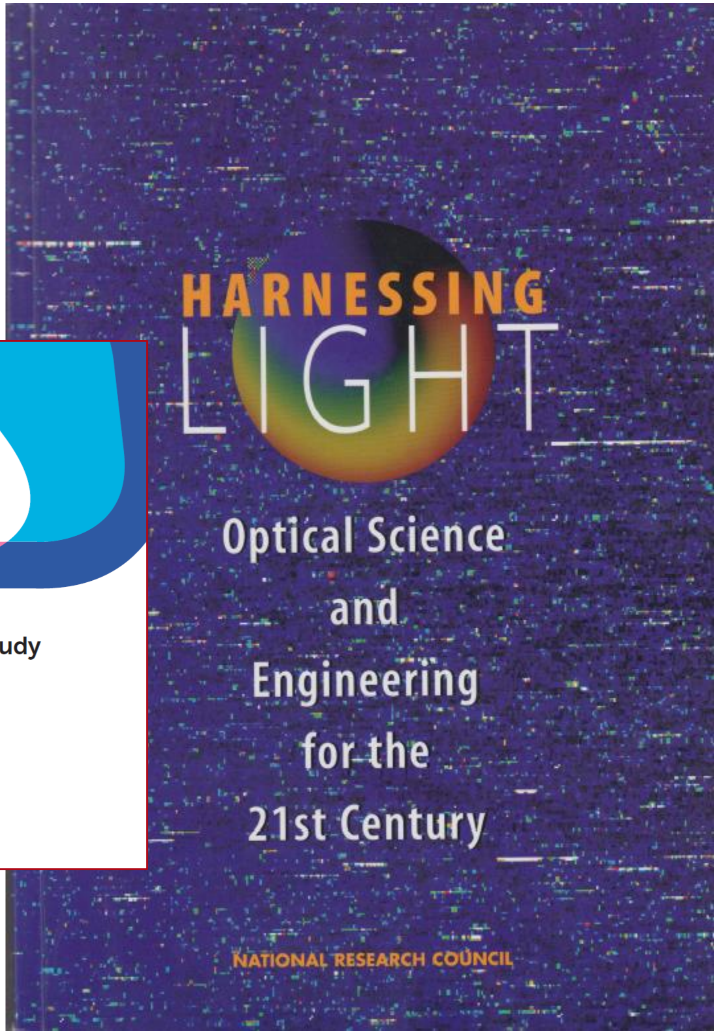

1998

Motivation

- **Optics and photonics** is **enabling technology** for the development of innovative commercial and industrial products.

- This development demands sophisticated **optical modeling and design software**.

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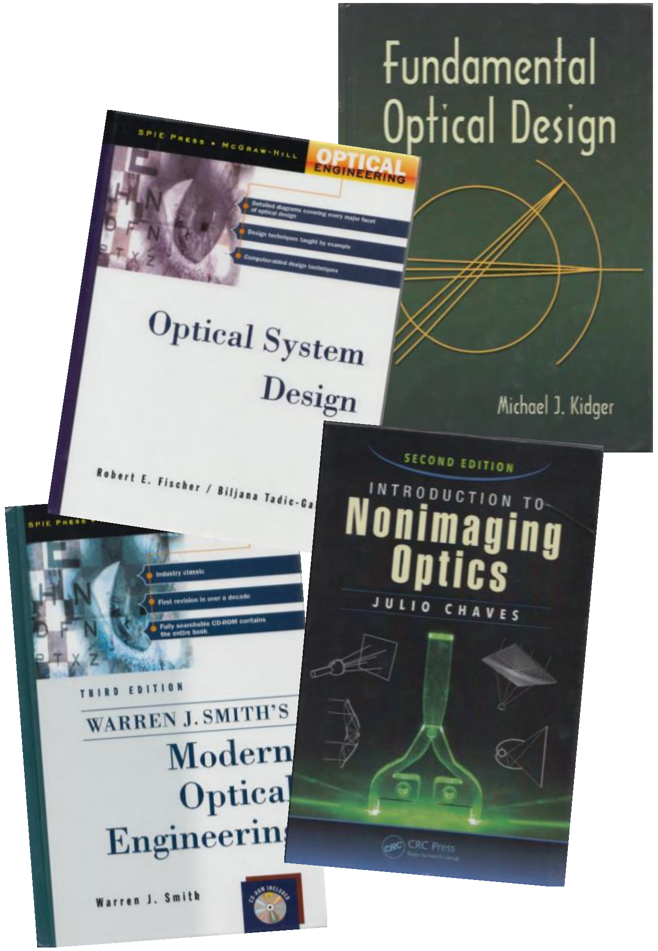
- This development demands sophisticated **optical modeling and design software**.

Challenge

- **Modeling:** Ray optics is currently used as the platform in optical modeling. Physical optics “patches” are added where most needed. This approach becomes an obstacle for innovation.

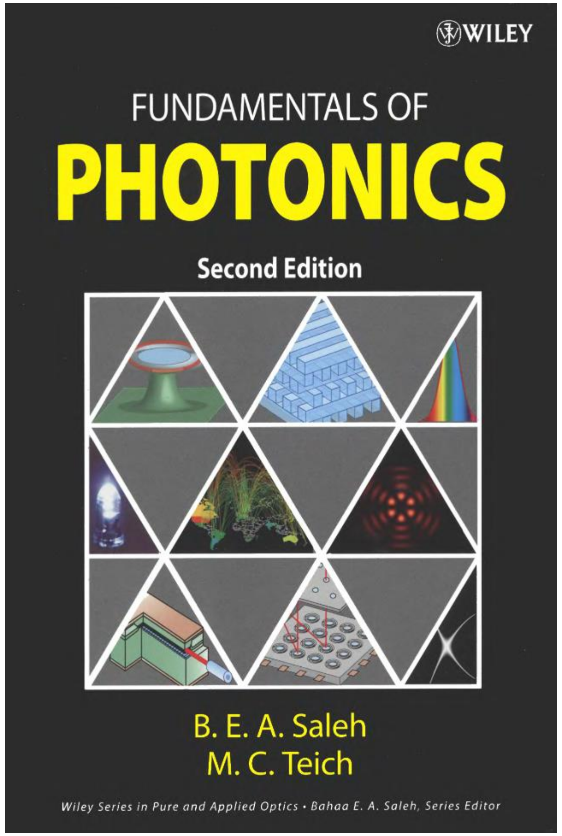
How to tackle this challenge?

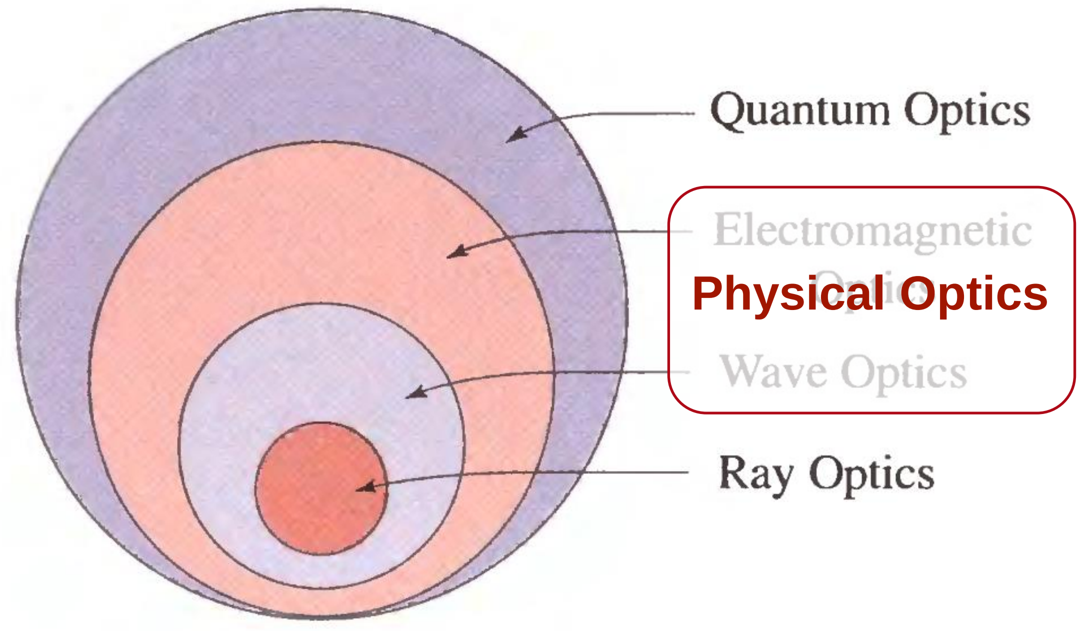
Here is our approach in three key messages!



Paradigm Shift in Optical Modeling Needed

- **Status quo:** Ray optics is currently used as the platform in optical modeling. Physical optics “patches” are added where most needed.





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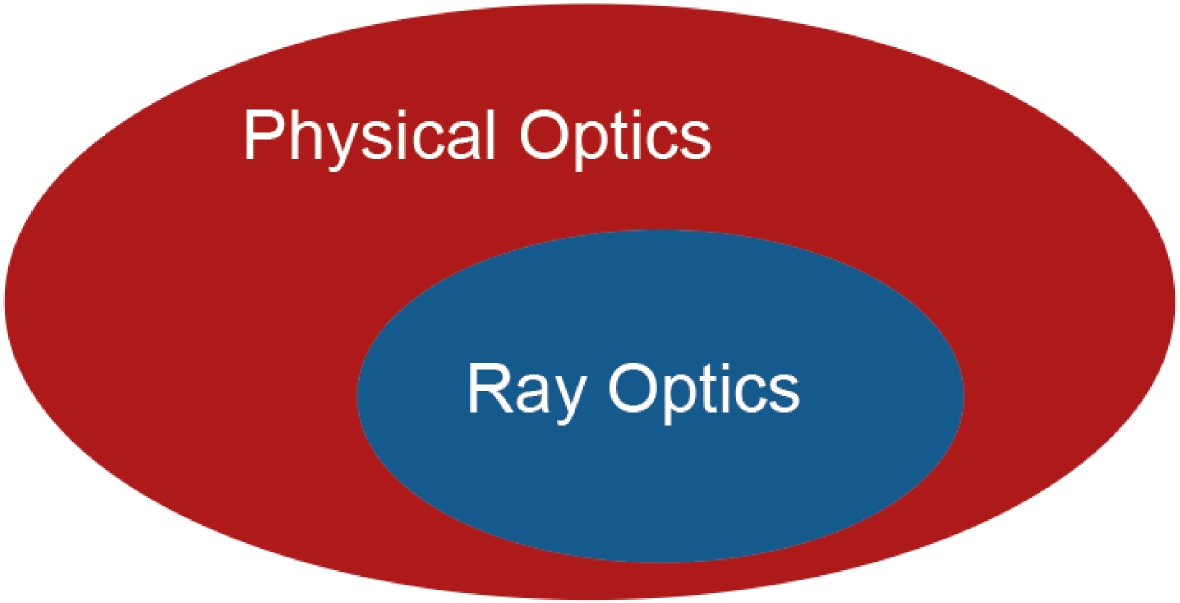

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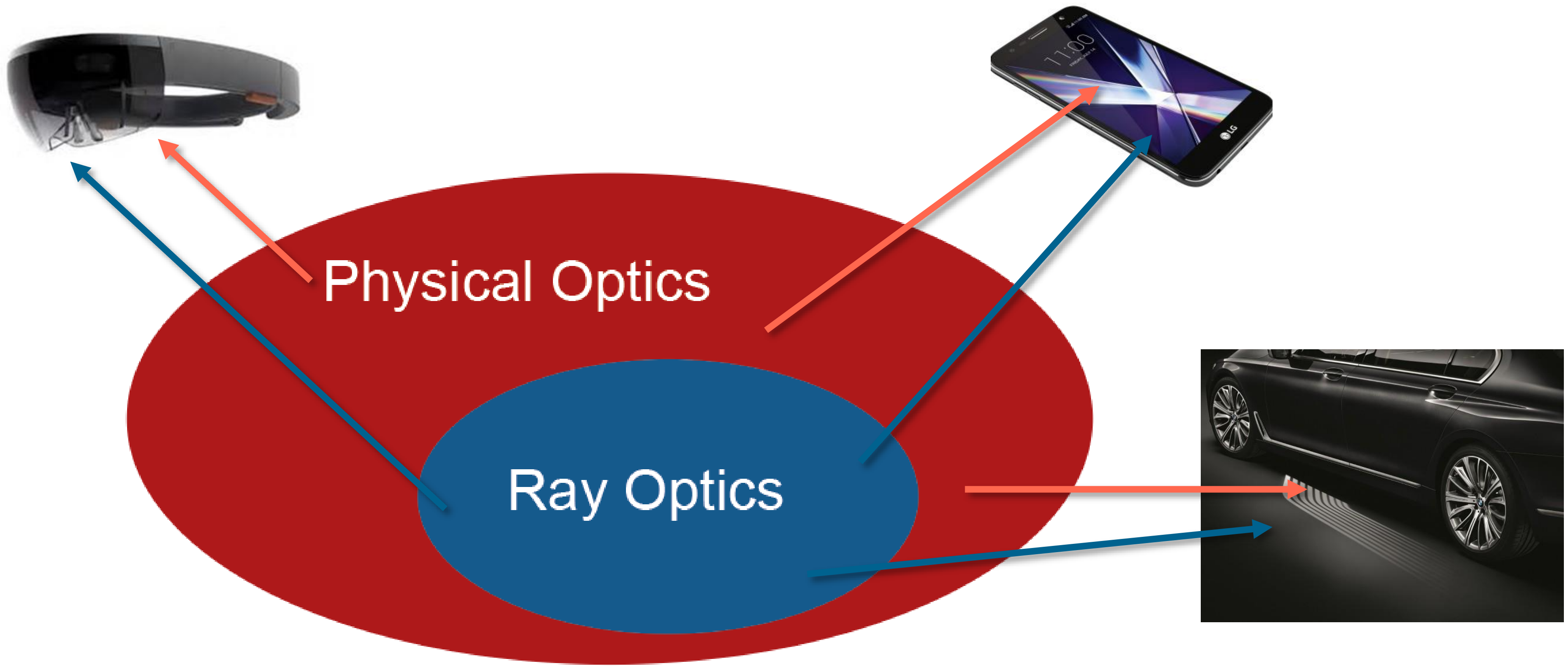

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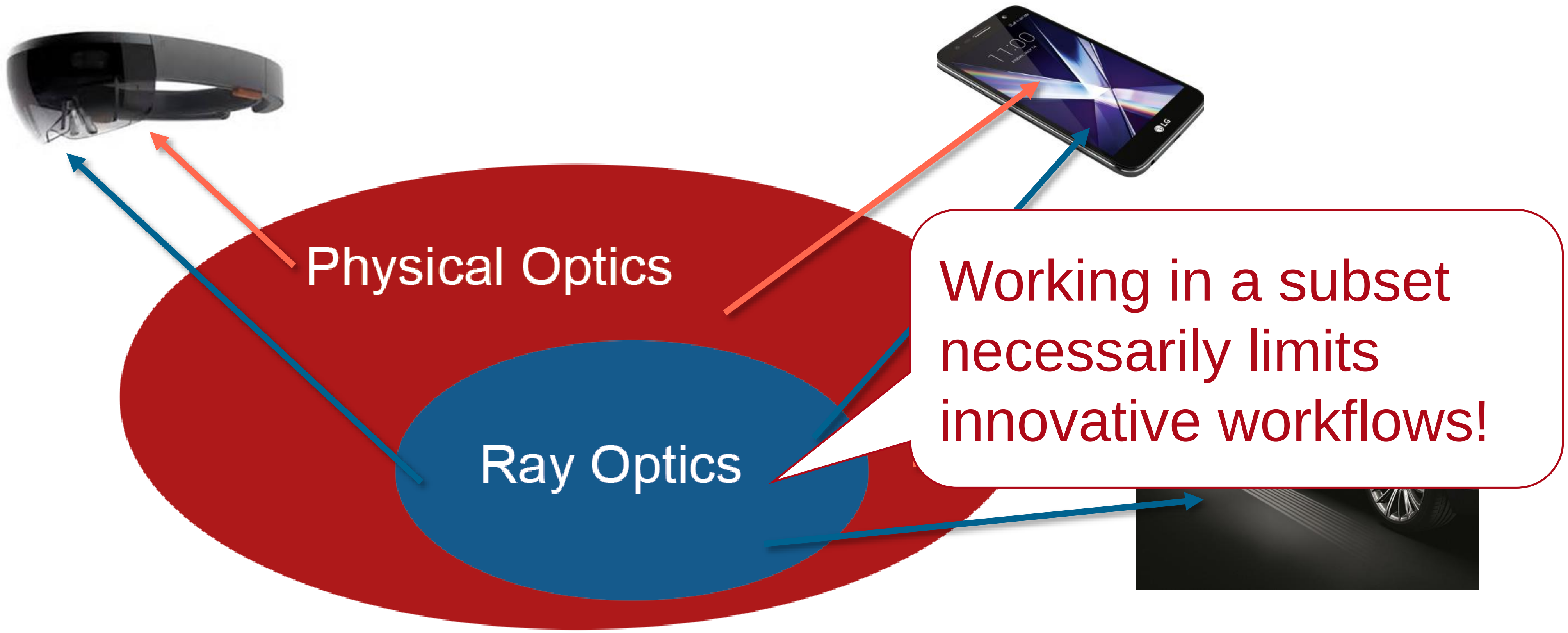
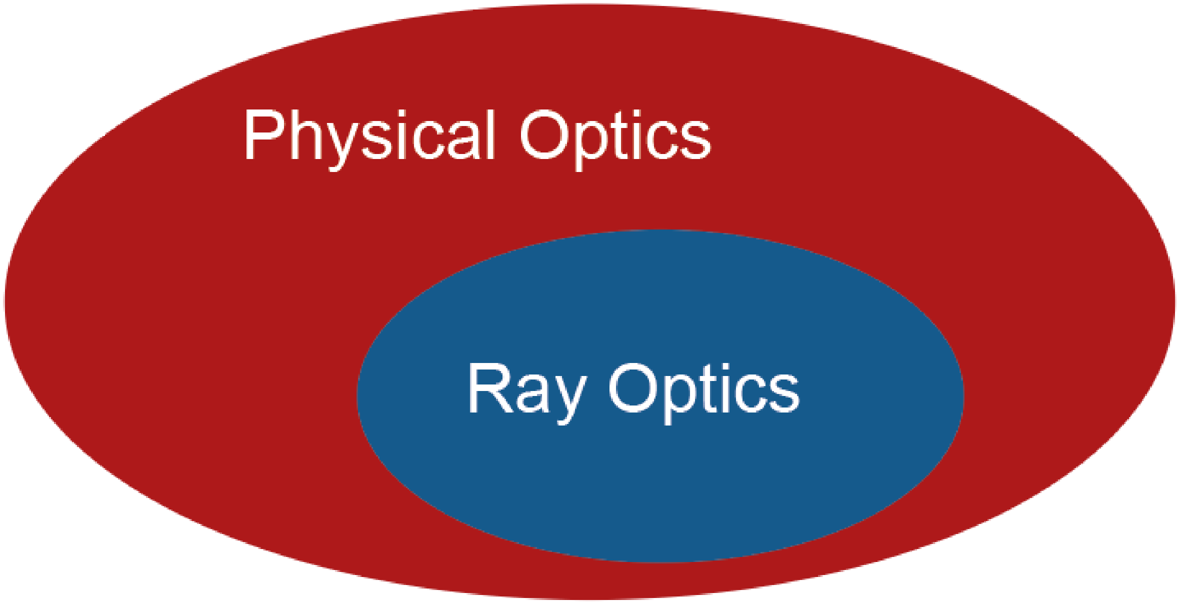


Message #1

Make physical optics the platform in optical modeling

#1: Make Physical Optics the Platform in Optical Modeling

- **Status quo:** Ray optics is currently used as the platform in optical modeling. Physical optics “patches” are added where most needed.
- **Our proposal:** To make physical optics the platform in optical modeling, with ray tracing solidly embedded within.



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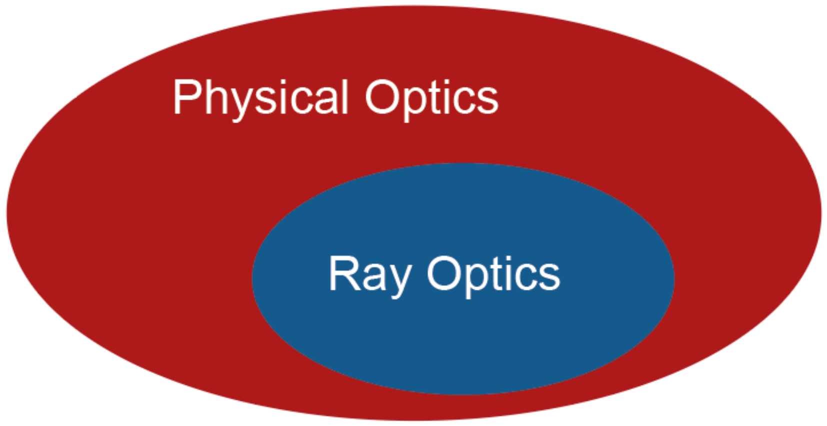
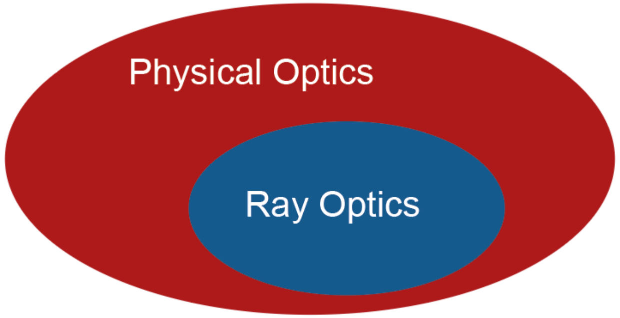
For this paradigm shift physical optics must be **fast** in practice!



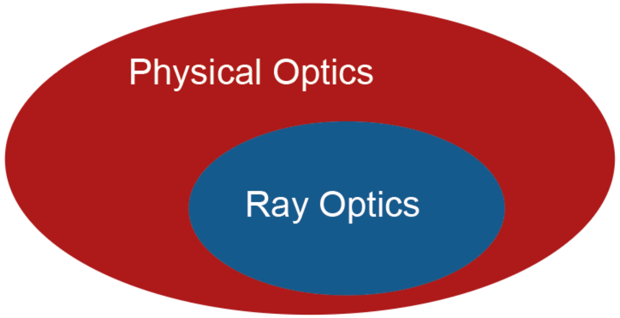
Fast Electromagnetic Modeling Required

- Physical optics modeling must be based on **solutions of Maxwell's equations**.



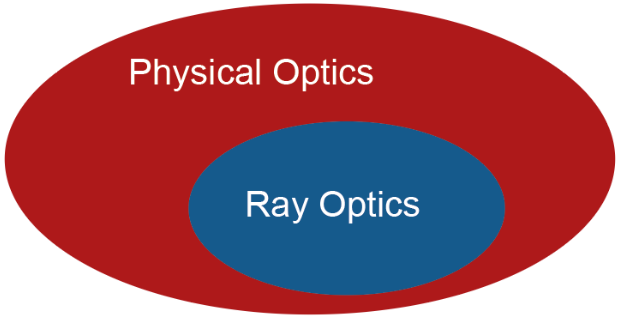
Fast Electromagnetic Modeling Required

- Physical optics modeling must be based on **electromagnetic field solvers**.



Fast Electromagnetic Modeling Required

- Physical optics modeling must be based on **electromagnetic field solvers**.
- Physical optics modeling must be **fast**. It should be even as fast as ray tracing wherever possible.



How to realize a fast electromagnetic modeling in optics?

Message #2

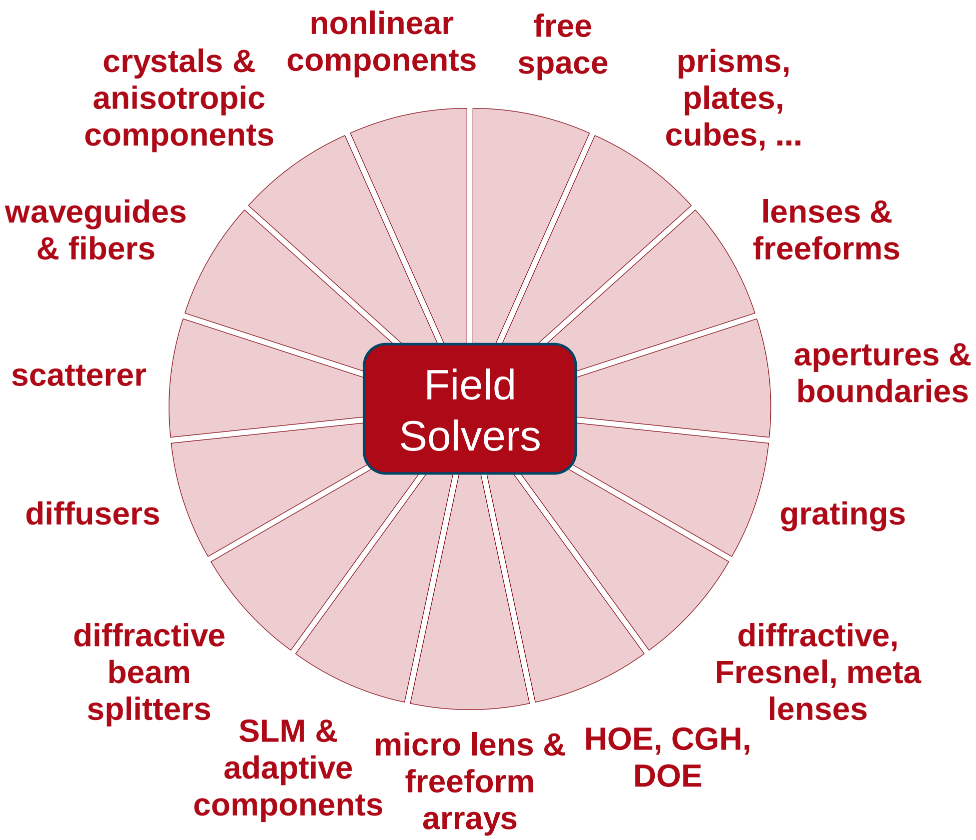
Field tracing enables **fast** physical optics

#2: Field Tracing Enables Fast Physical Optics

Theory peek

Field Tracing comprises:

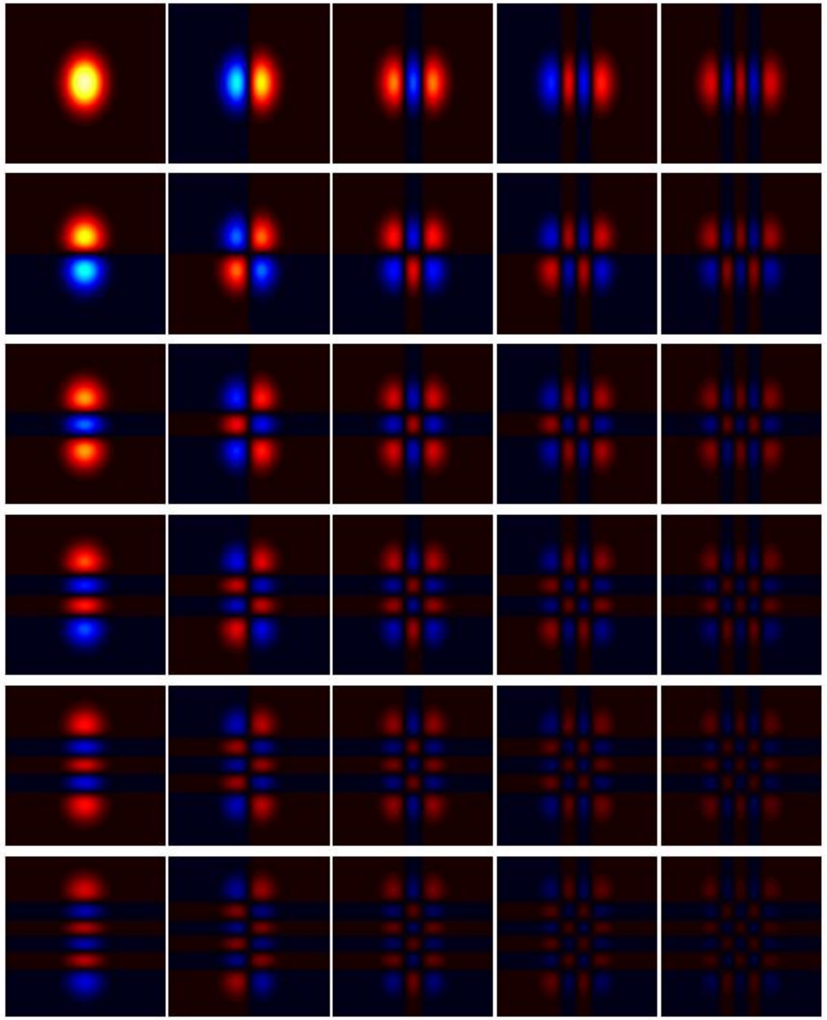
- Application of different electromagnetic field solvers in different regions of one system.
- Interconnection of any type of general and specialized field solver.



#2: Field Tracing Enables Fast Physical Optics

Field Tracing comprises:

- Application of different electromagnetic field solvers in different regions of one system.
- Interconnection of any type of general and specialized field solver.
- Source mode concept to represent coherent, partially coherent, and incoherent sources.



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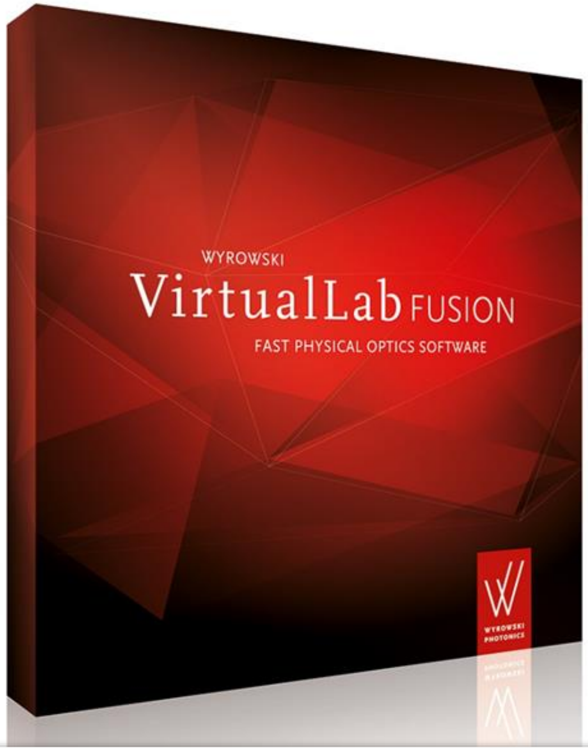
- … and many more techniques



Fast Physical Optics Software!

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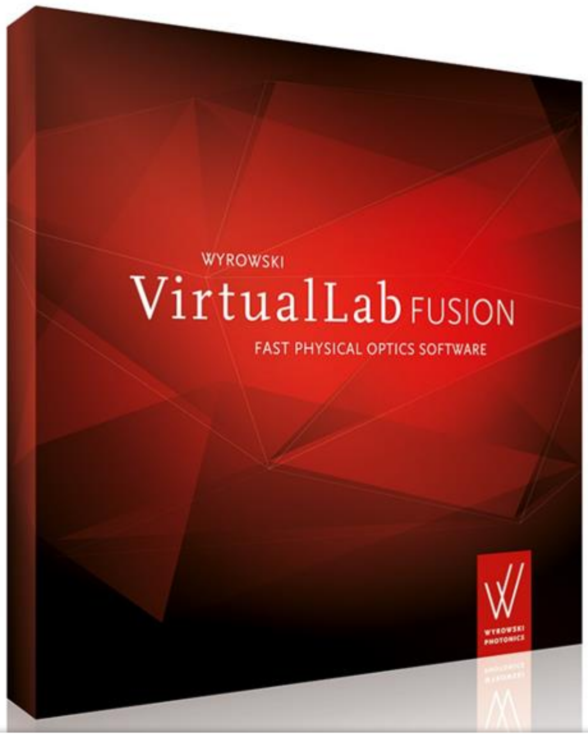
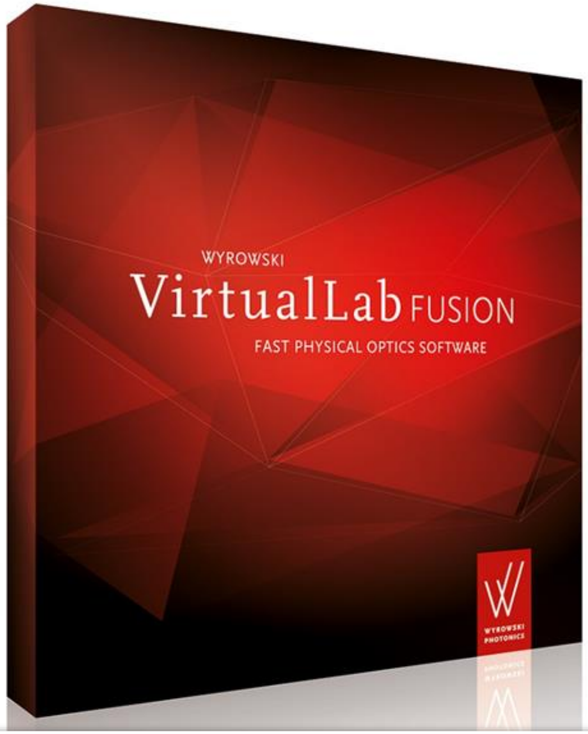


Platform to interconnect any type of general and specialized field solver:

- In-built solvers
- Customized solvers

#2: Field Tracing Enables Fast Physical Optics

VirtualLab enables the incorporation of any solver and interconnects all needed solvers with field tracing technology!



Platform to interconnect any type of general and specialized field solver:

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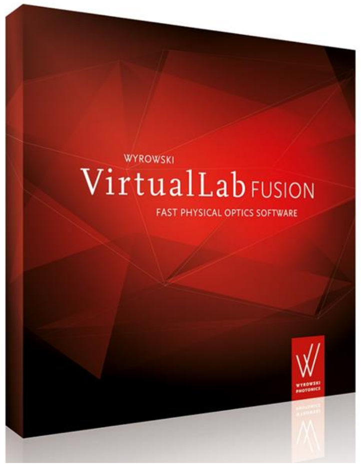
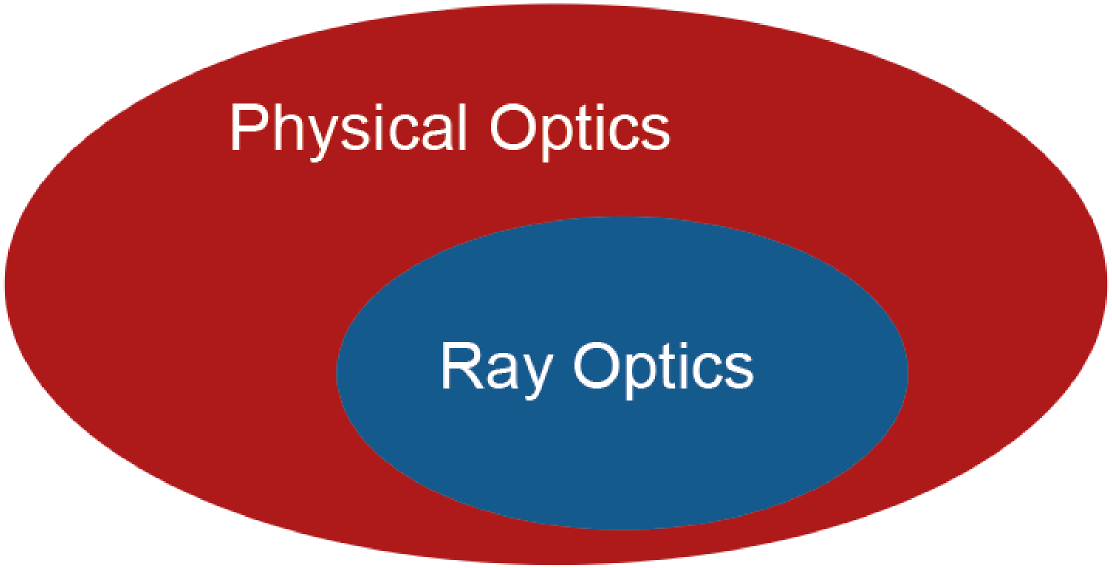
Message #3

Ray tracing is embedded in fast physical optics

#3: Ray Tracing Embedded in Fast Physical Optics

- Fast physical optics does not replace ray tracing, but enriches our way to do optical modeling and design.
- We can just win!





Field Tracing

… from field tracing other techniques can be deduced mathematically, e.g. …

Unified Optical Modeling

Field Tracing

Polarization Ray Tracing

Paraxial Field Tracing

Gaussian Beam Propagation

Flux Ray Tracing

Ray Tracing

Paraxial Ray Tracing

Monte Carlo Field Tracing

Monte Carlo Ray Tracing

Unified Optical Modeling

Field Tracing

Paraxial Field Tracing

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Monte Carlo Field Tracing

Polarization Ray Tracing

Flux Ray Tracing

Ray Tracing

Paraxial Ray Tracing

Monte Carlo Ray Tracing

No physical model assumptions, but pure mathematical arguments.

Our Key Messages on Modeling

#1: Make physical optics the platform in optical modeling.

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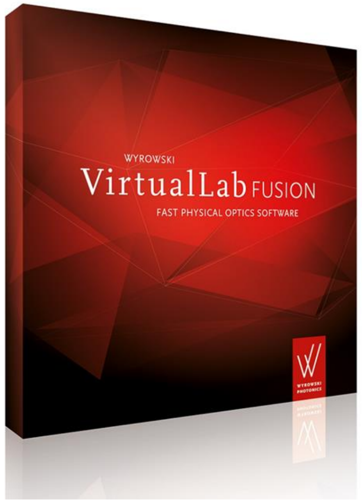


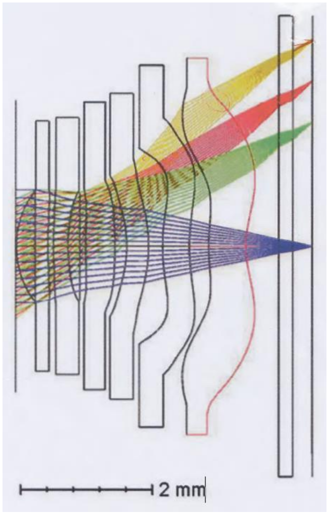
Fast Physical Optics Software!

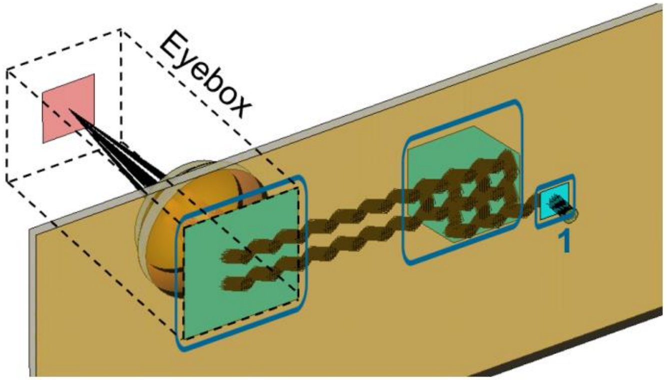
Fast physical optics does not replace ray tracing, but enriches our way to do optical modeling and design.

Optical Design beyond Parametric Optimization

Challenge

- **Design:** Parametric optimization is the standard optical design technique. This approach fails in ever more cases because of the growing complexity of components and systems.





Challenges

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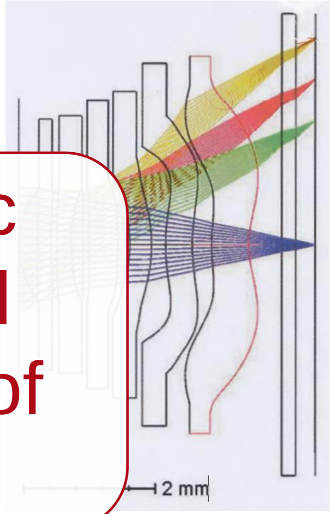
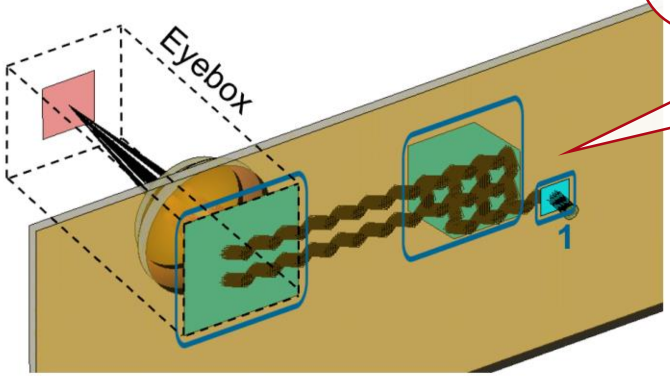


Full design by parametric optimization not practical because of high number of free parameters.



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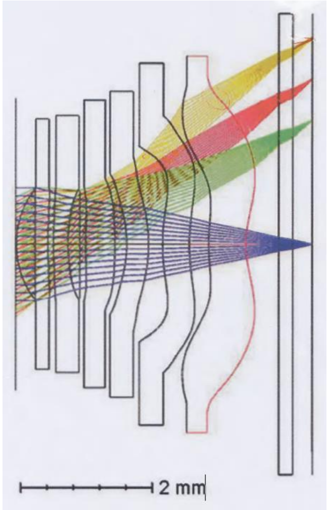

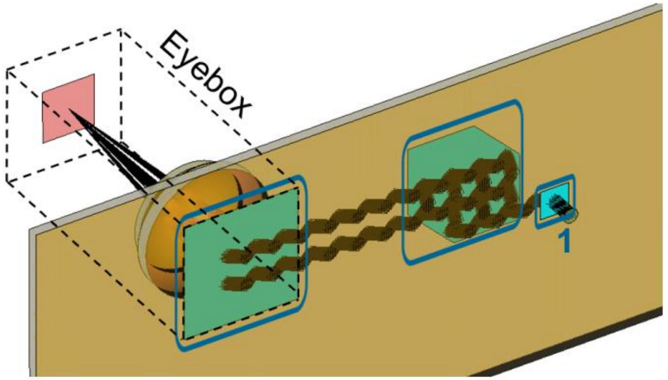

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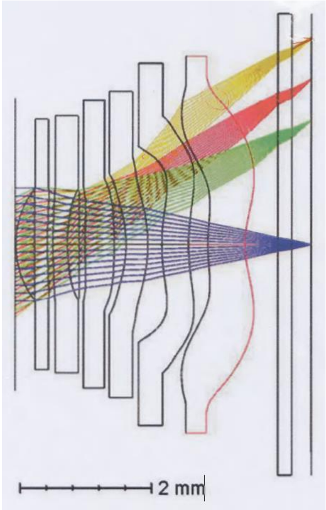
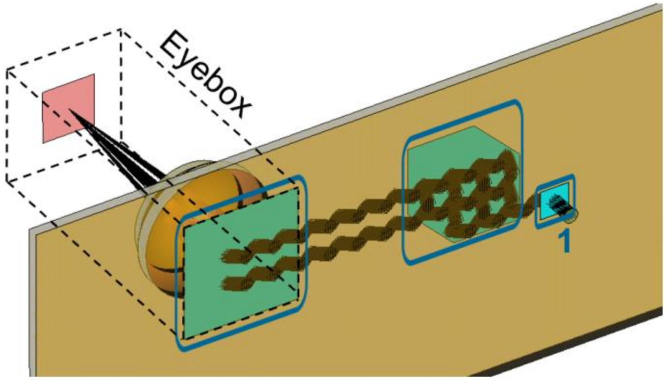


- We propose to accompany parametric optimization with systematic design approaches.



Parametric Optimization and Systematic Design

Parametric optimization

How to find a good initial system for final parametric optimization?

Parametric Optimization and Systematic Design

Functional design

Where and what should be done with incident light to obtain a desired function?

Parametric optimization

Parametric Optimization and Systematic Design

Functional design

Result: Set of positions and ideal responses of optical components.

Parametric optimization

Parametric Optimization and Systematic Design

Functional design

Structural design

Design of structures which enable the required responses.

Parametric optimization

Parametric Optimization and Systematic Design

Functional design

In suitable combination

Structural design

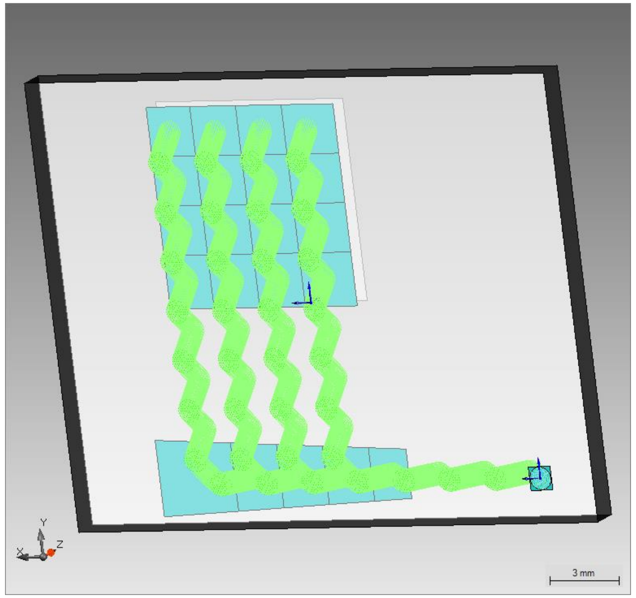
- Freeform surfaces
- Diffractive surfaces
- Metalayers
- GRIN layers

Parametric optimization

Per source mode and in combination of all source modes!

Systematic Design

- This is a new R&D topic, but already starts to be fruitful in some applications, e.g. waveguide design in AR/MR, diffractive optics, and freeform design.
- Though it works with ray and physical optics, its full benefit is available on the physical otpics platform.



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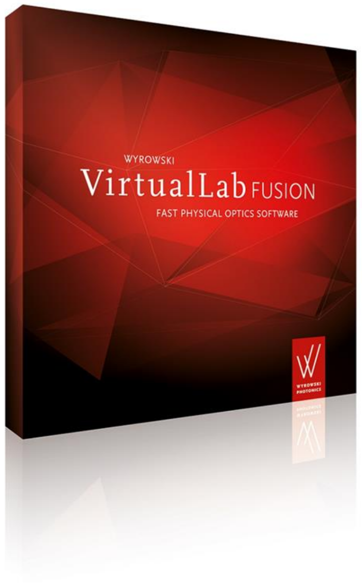

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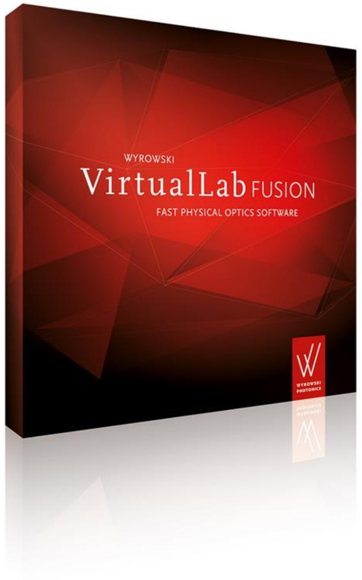

Lens design and physical optics

Status quo in ray tracer software

Physical Optics in Lens Design

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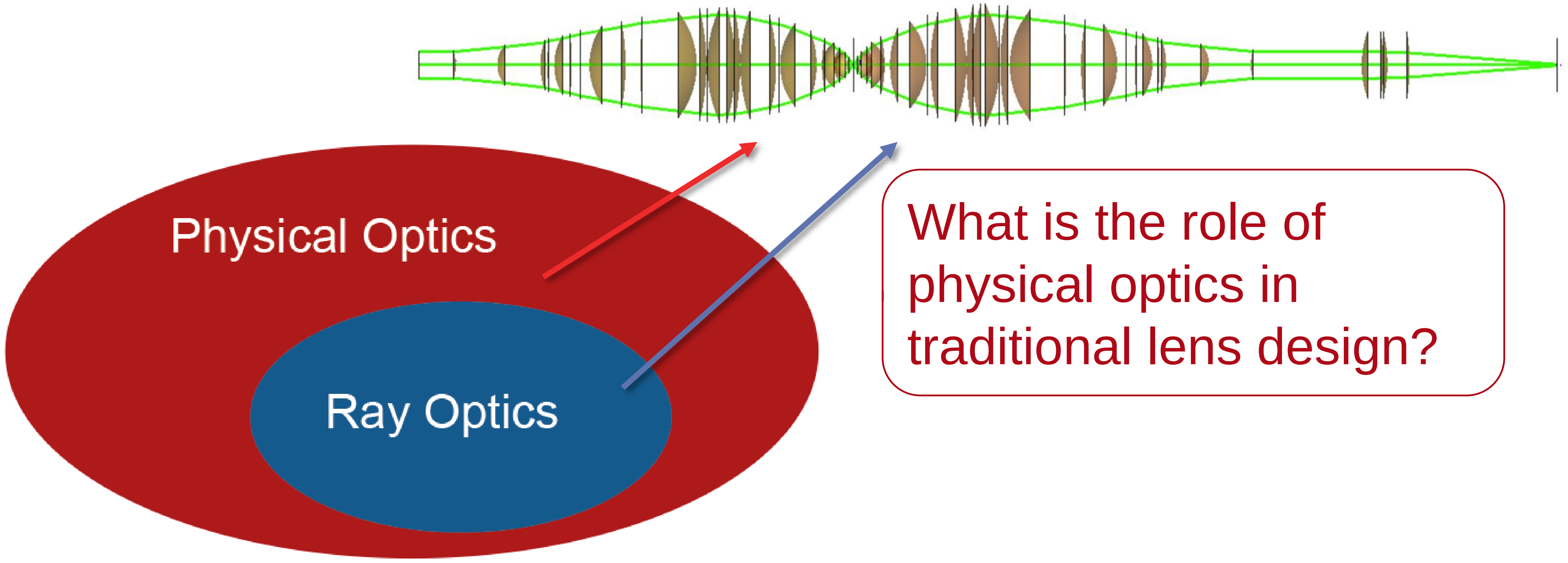
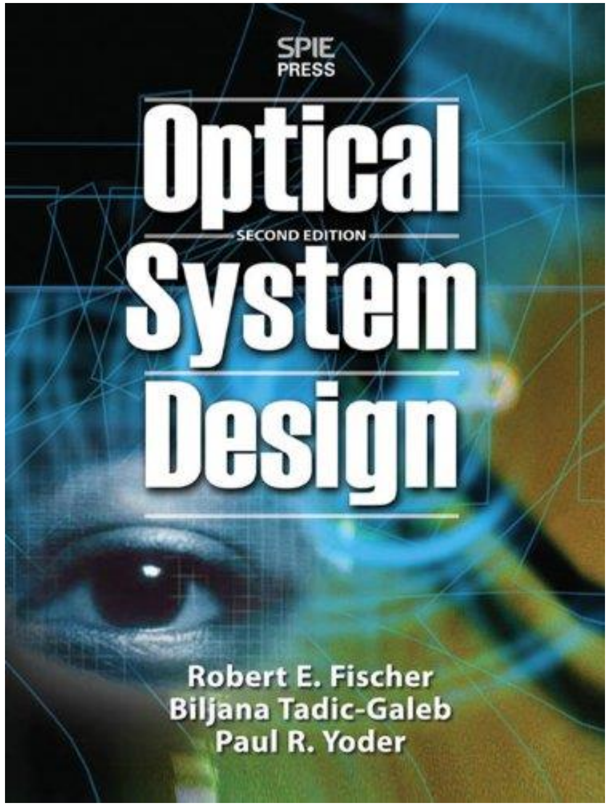


What is the role of physical optics in traditional lens design?

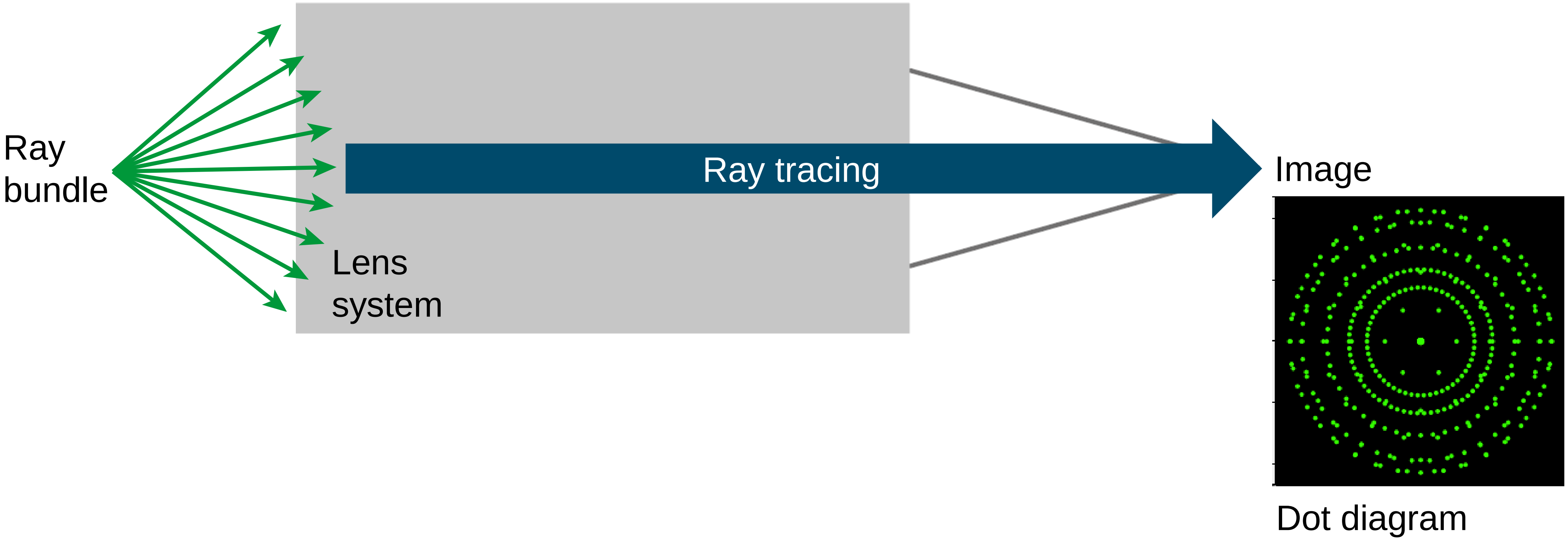
Modeling Lens Systems



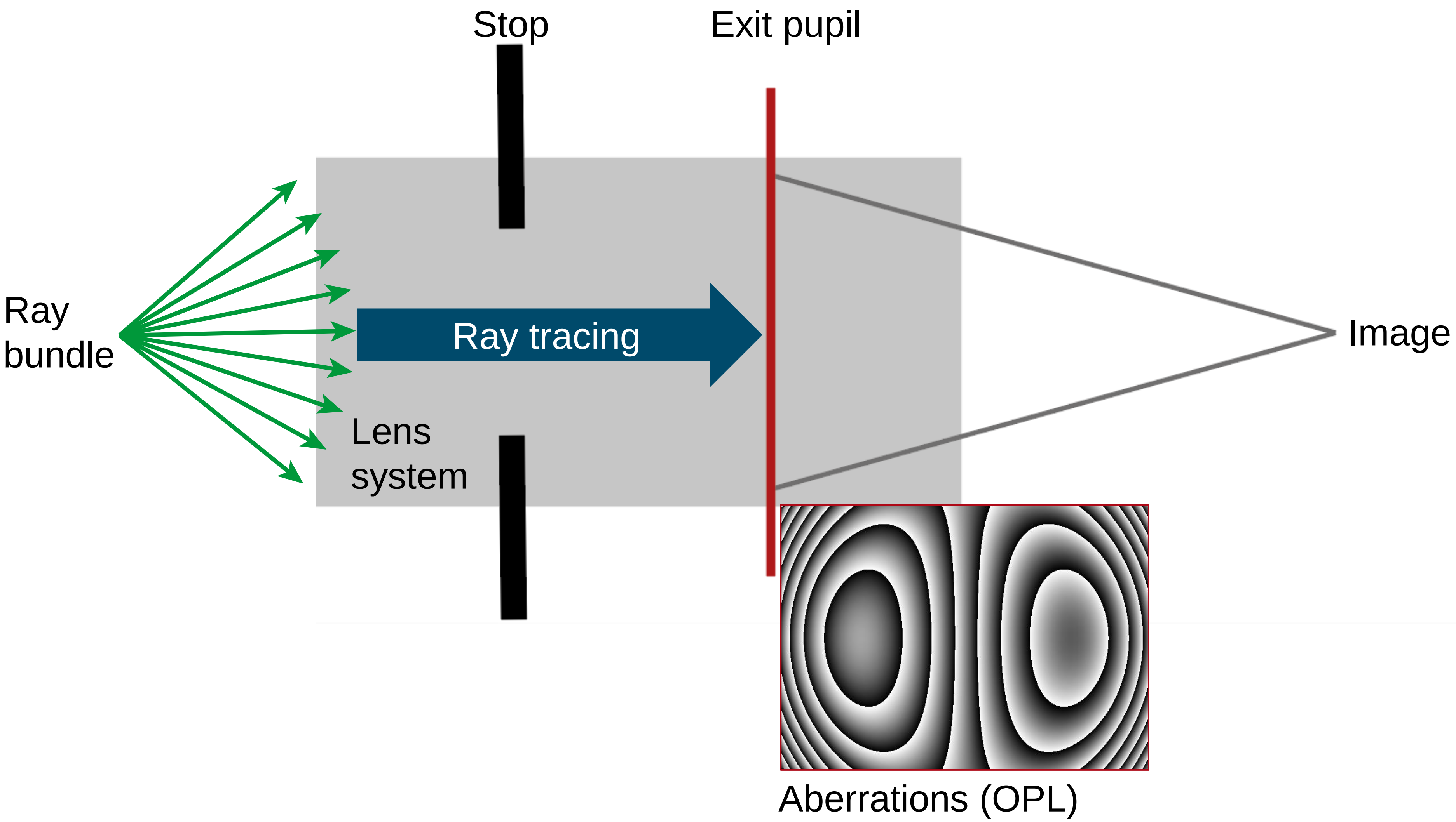
Modeling Lens Systems

Modeling Lens Systems

Modeling Lens Systems: Ray Tracing



Modeling Lens Systems: Ray Tracing



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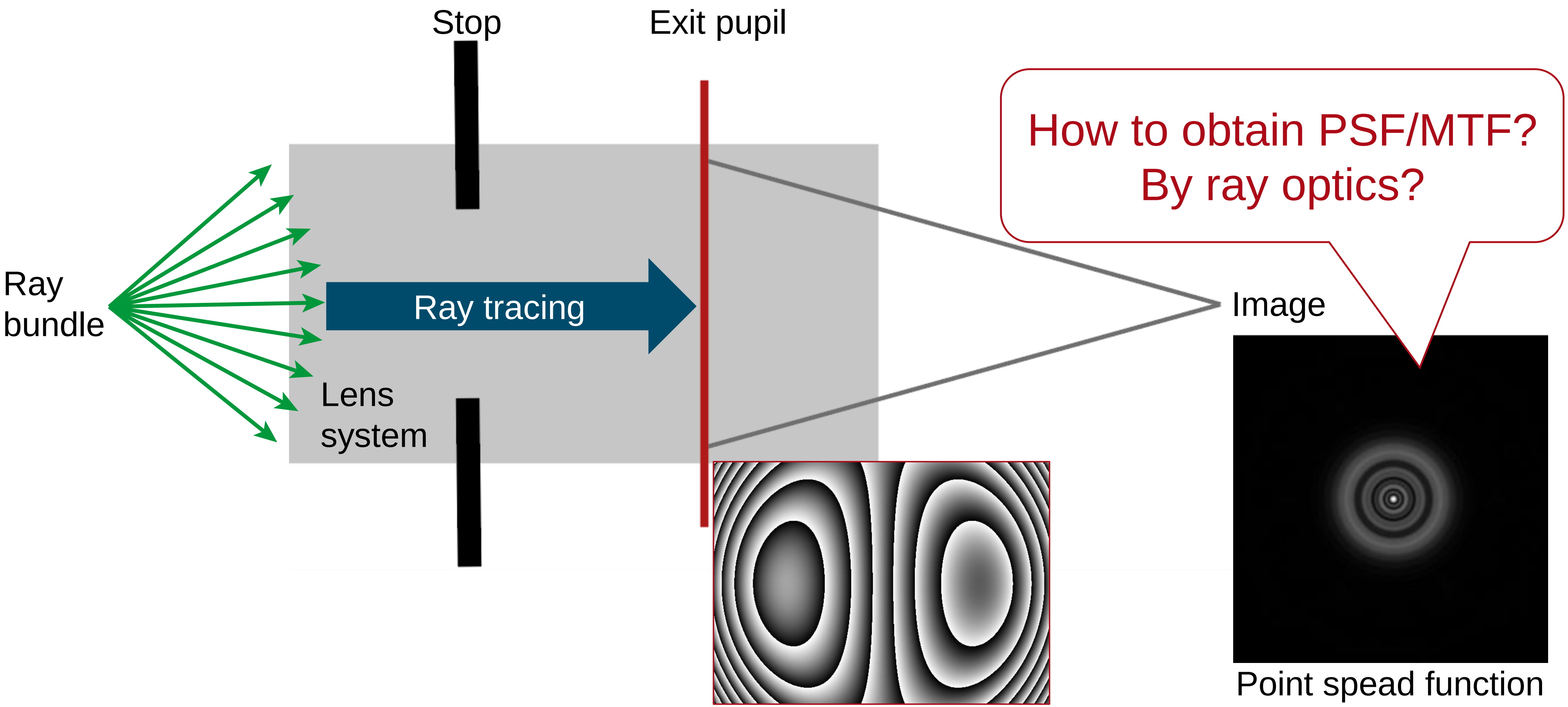
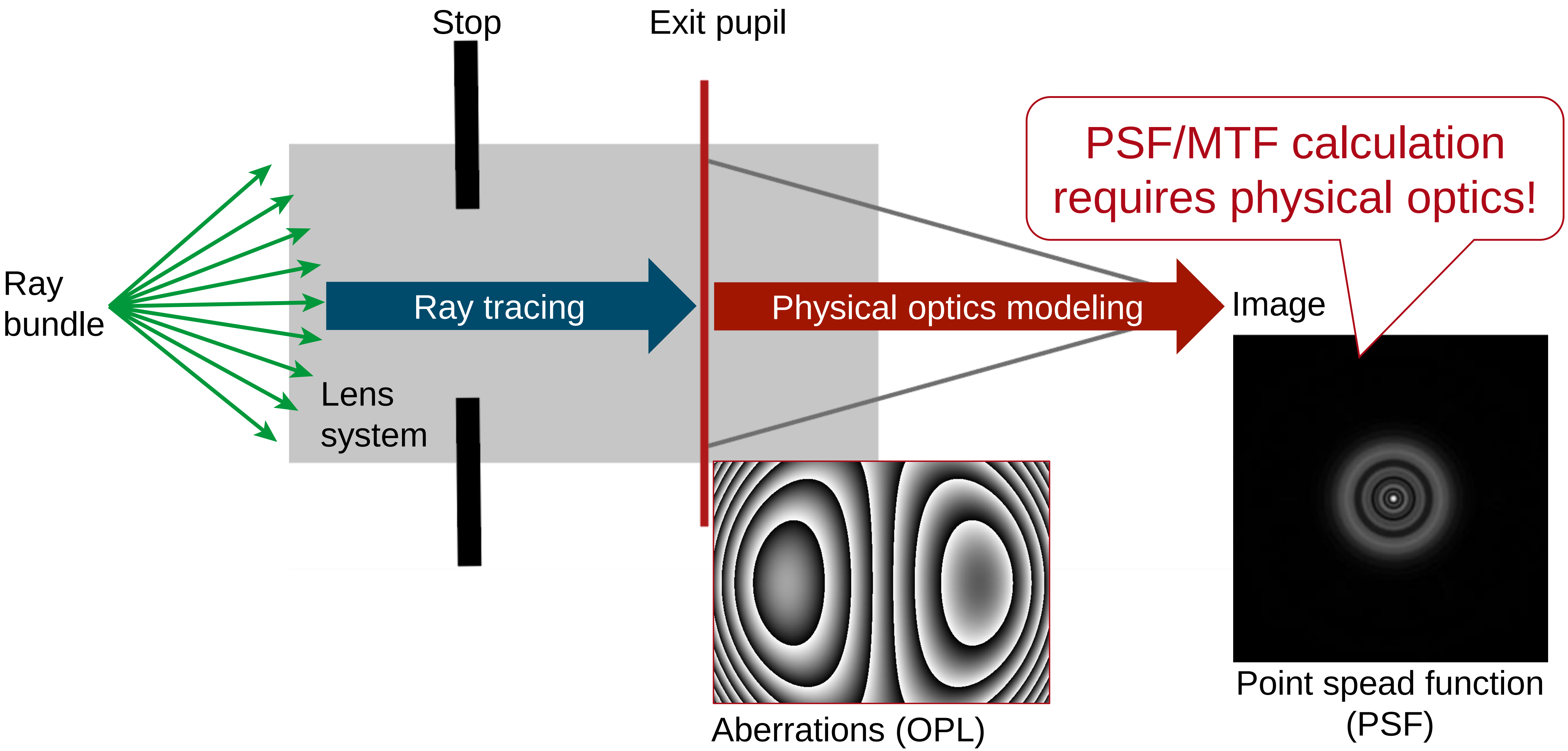


Aberrations (OPL)

Point spread function (PSF)

Modeling Lens Systems



Imaging Optics: Ray Optics + PSF/MTF

Euclid of Alexandria

c. 325 BC - 265 BC

Pierre de Fermat

1601-1665

James Clerk Maxwell

1831-1879

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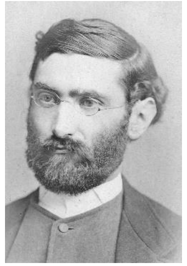

1840-1905

Diffraction limited resolution

Imaging Optics: Ray Optics + PSF/MTF

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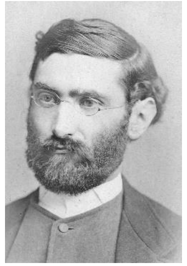


Peter Debye

c. 325 BC - 265 BC

1601-1665

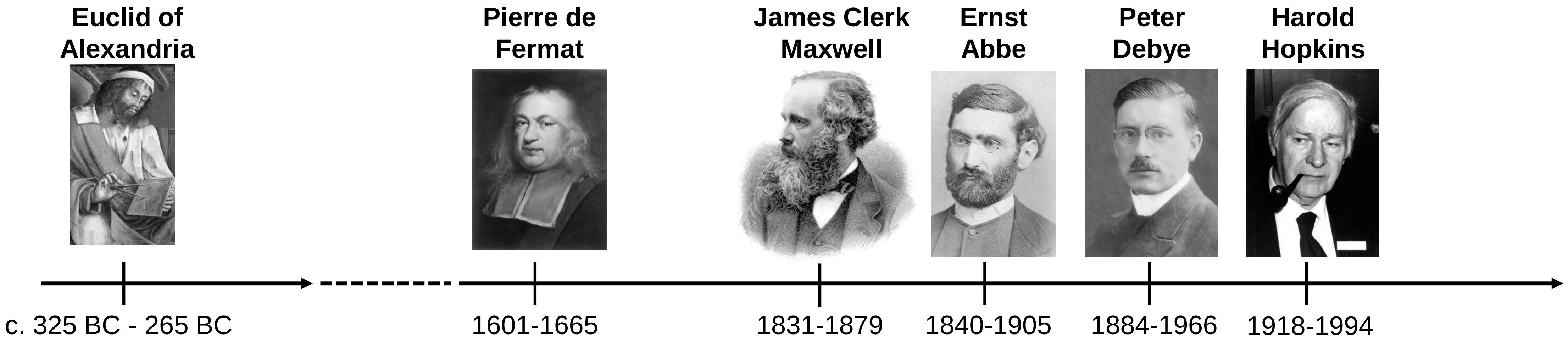
1831-1879

1840-1905

1884-1966

Light in focal regions

Imaging Optics: Ray Optics + PSF/MTF



Wave theory of aberrations

Imaging Optics: Ray Optics + PSF/MTF

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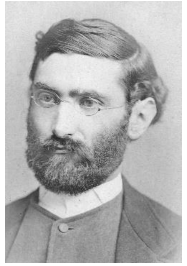


1840-1905

Peter Debye

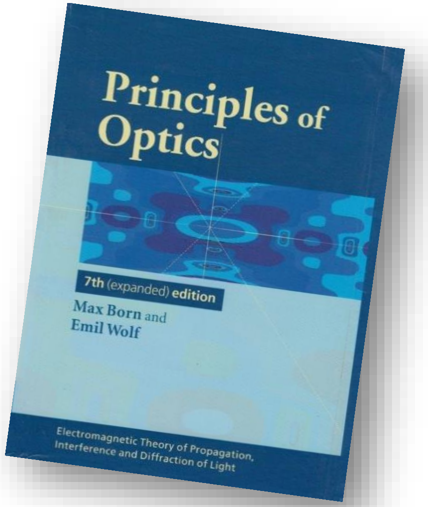
1884-1966

Harold Hopkins

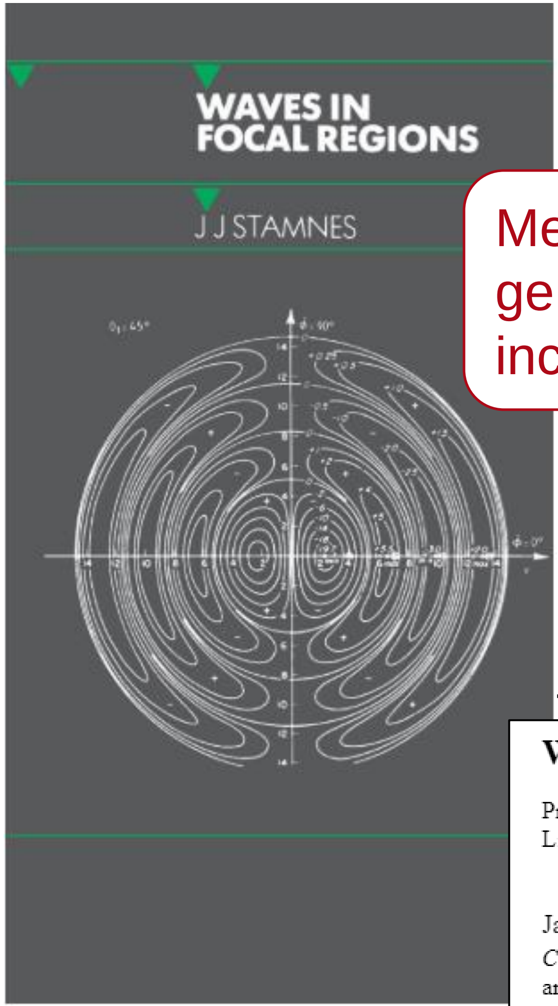
1918-1994

Emil Wolf

1922-2018



Modeling Lens Systems: Diffraction Theory of Lens Systems



Methods are generalized and included in VirtualLab!

1986; 603 pages

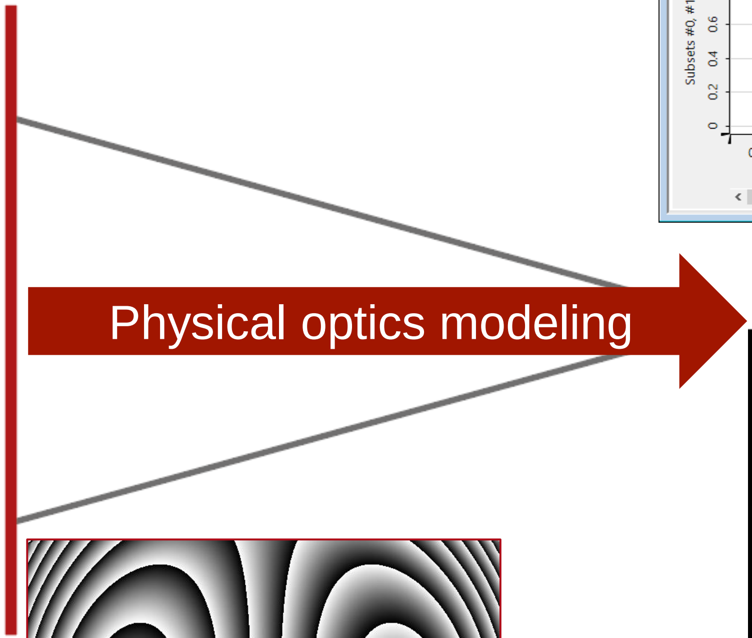
Waves in Focal Regions

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

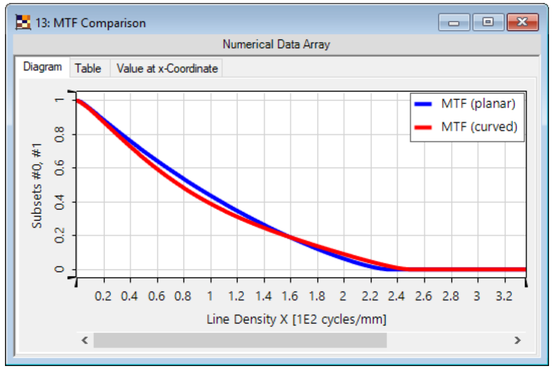
Jakob J Stamnes

Center for Industrial Research, Oslo
and
Norwave AS

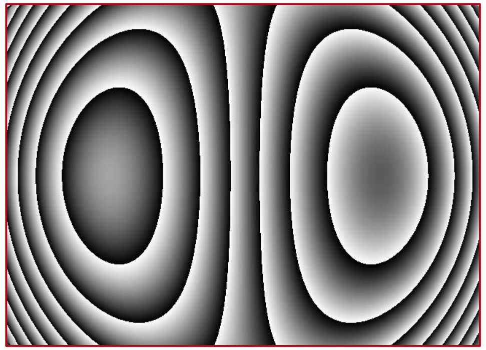
Exit pupil



MTF

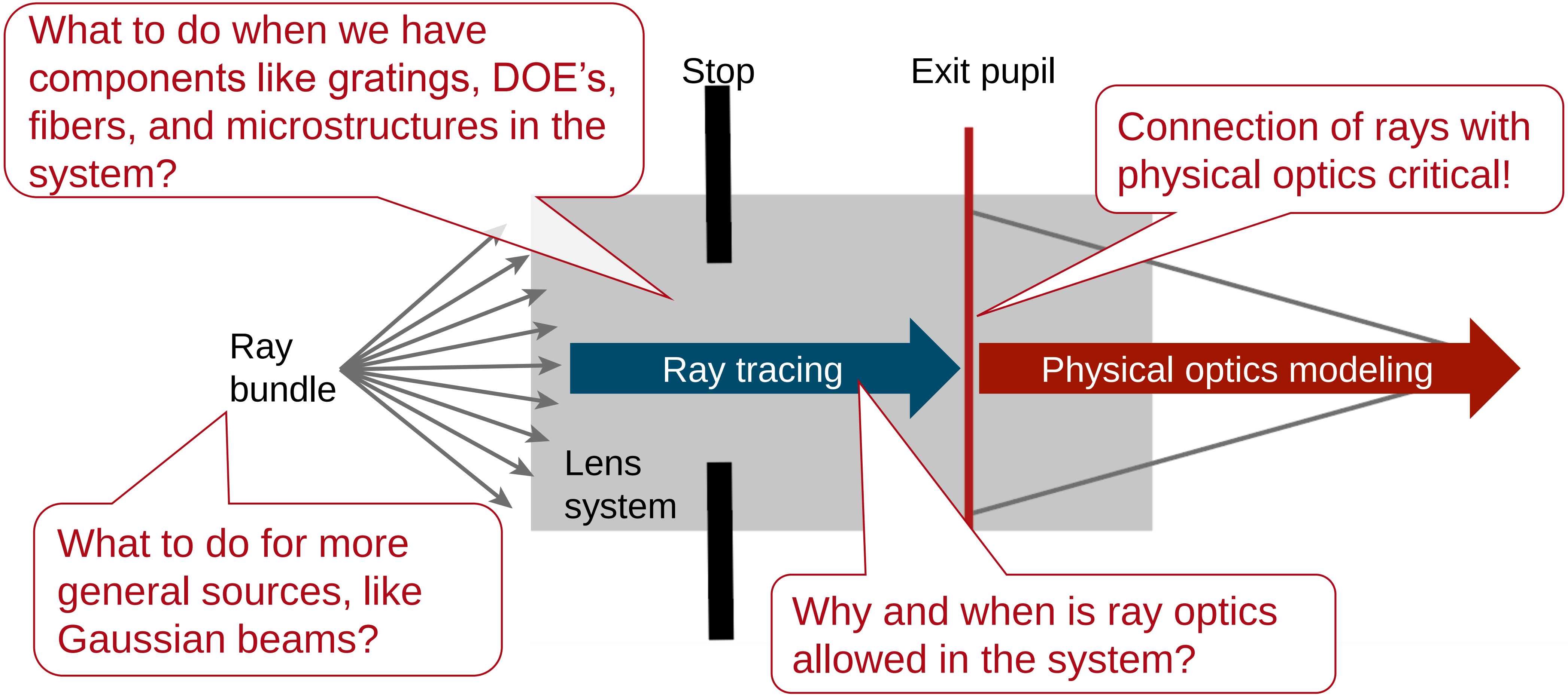


Point spead function

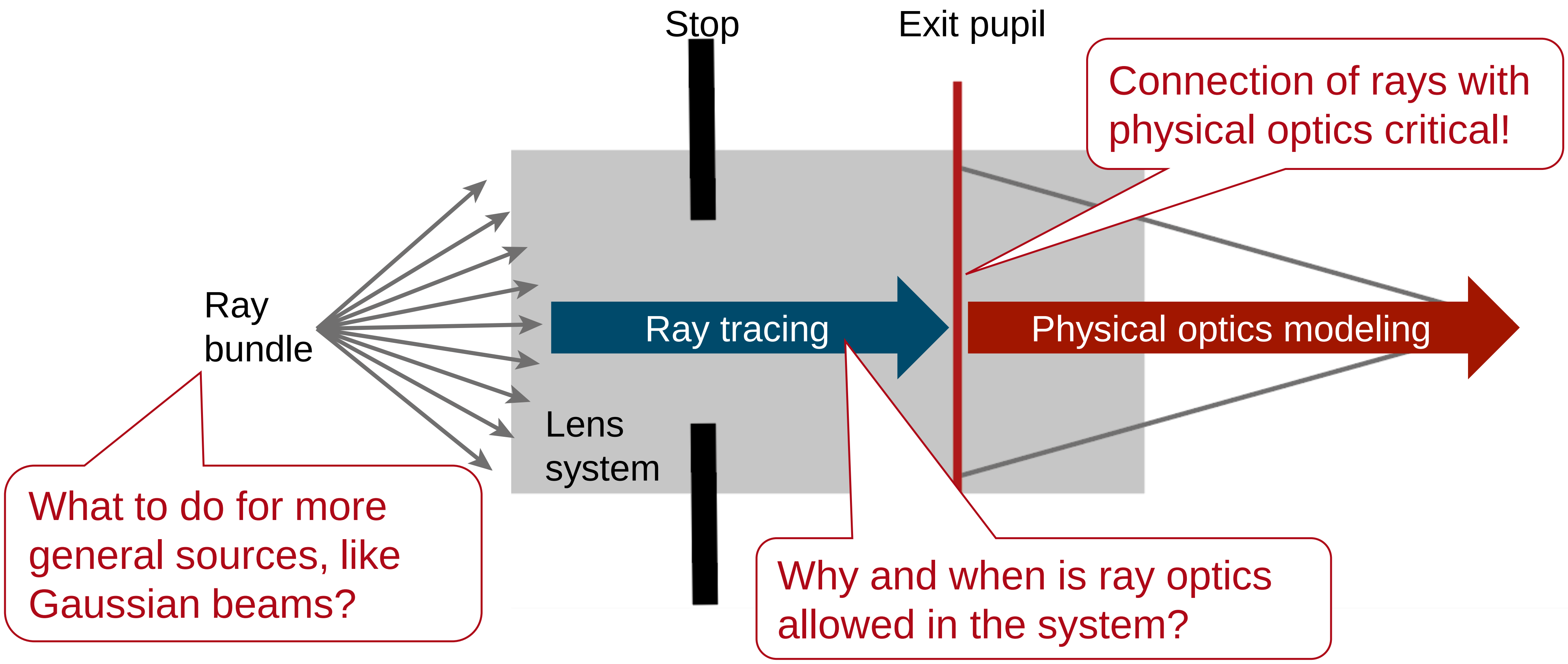


Aberrations (OPL)

Modeling Lens Systems: Ray and Physical Optics

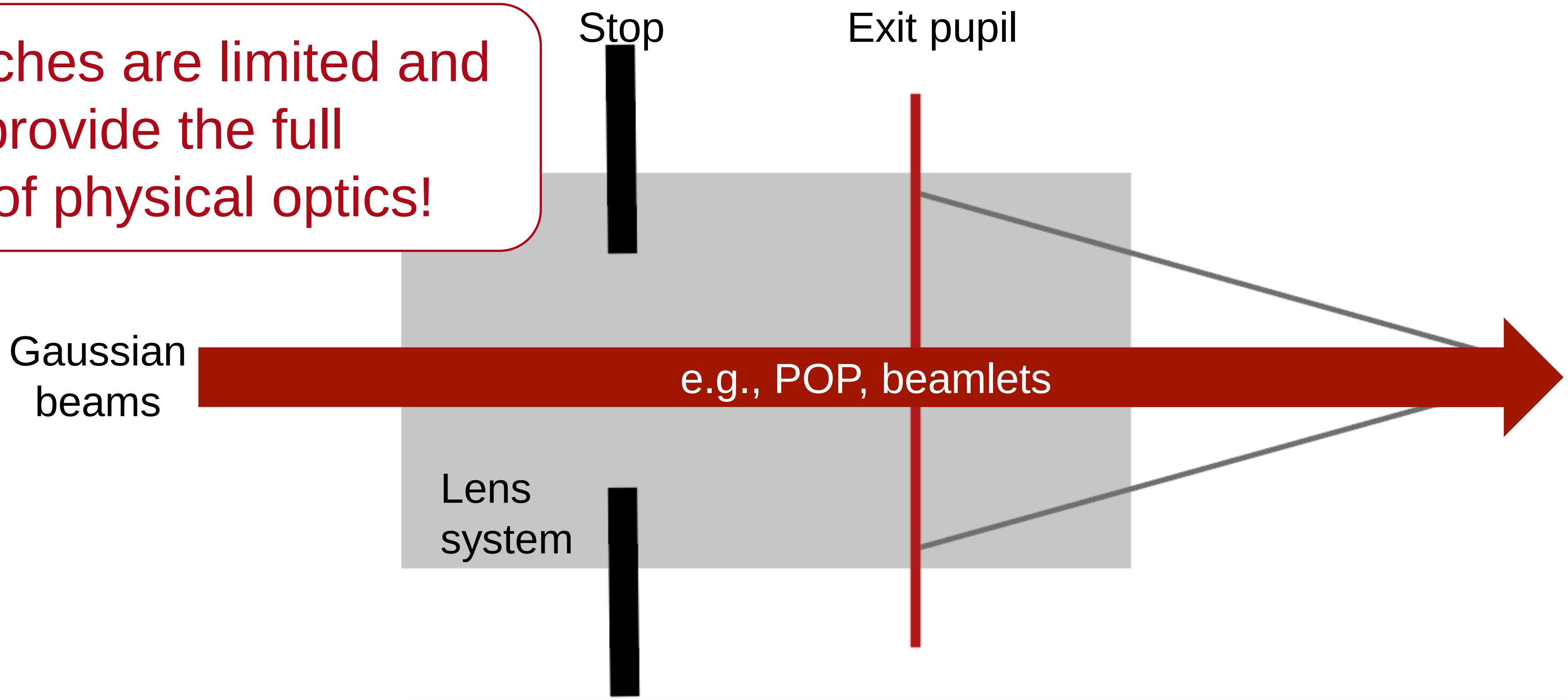


Modeling Lens Systems: Ray and Physical Optics



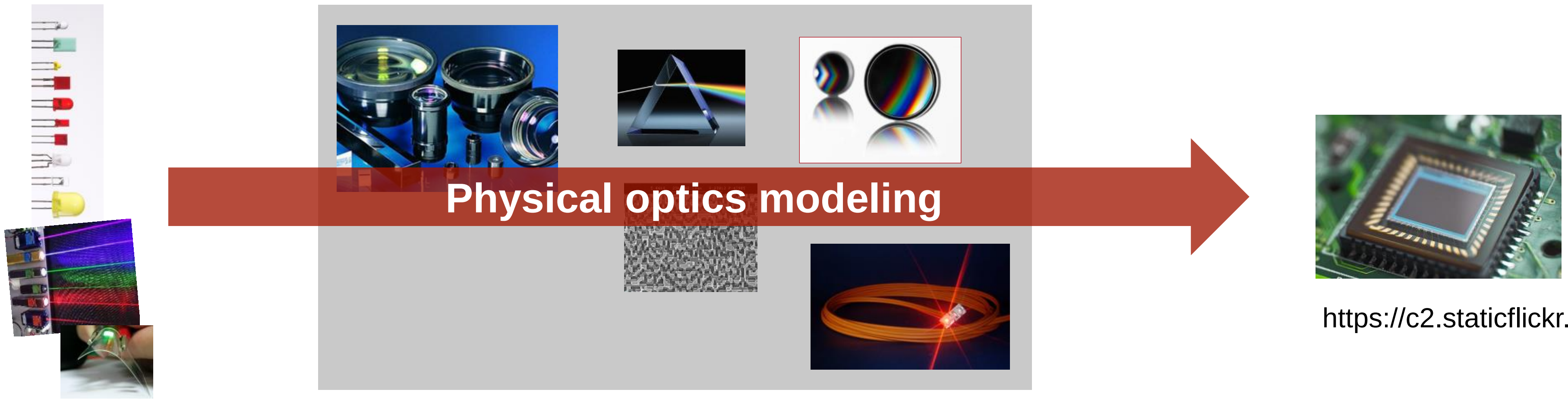
Ray Tracer: Physical-Optics Add-Ons

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



General Physical-Optics System Modeling

Sources Components Detectors



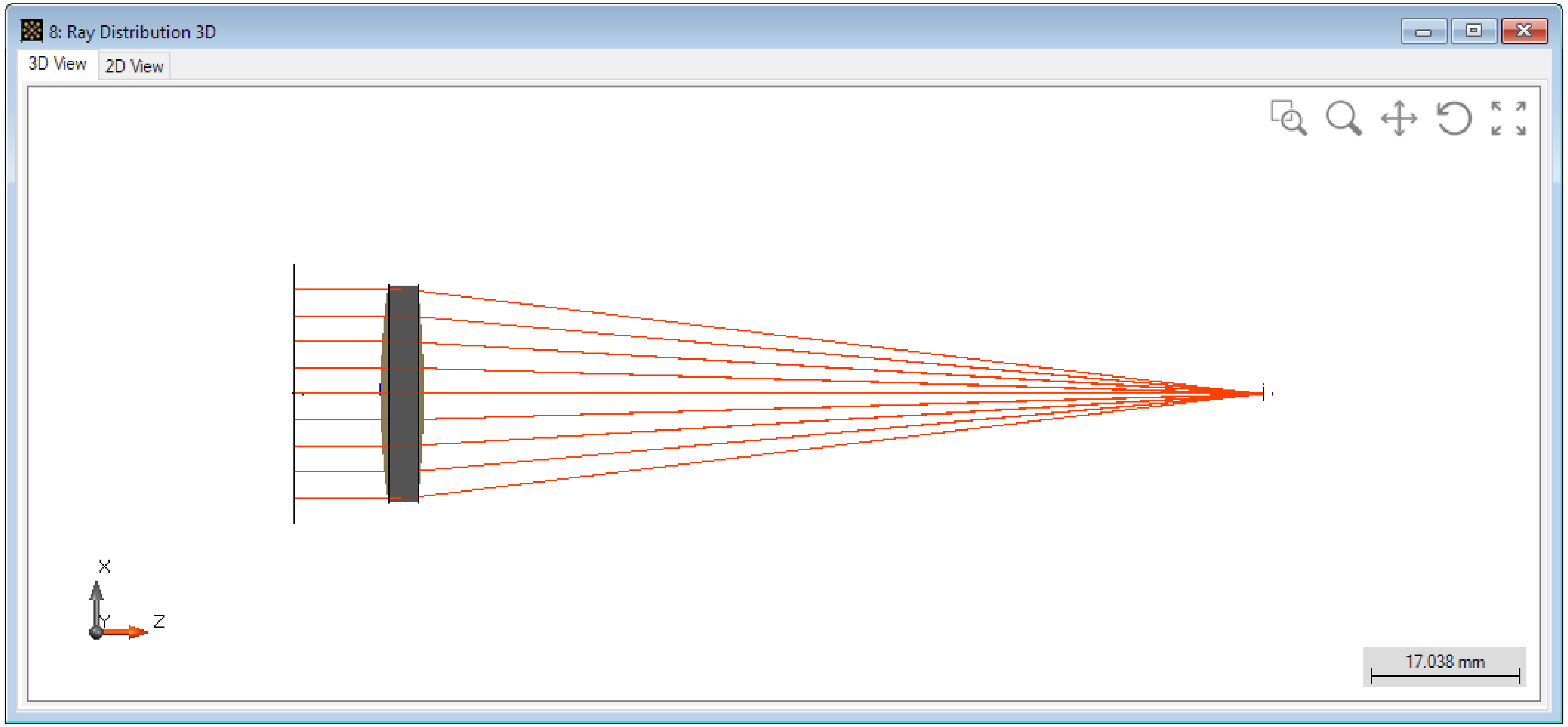
https://c2.staticflickr.com

VirtualLab Fusion: To make physical optics the platform in optical modeling, with ray tracing solidly embedded within.

Live example: Investigation of Focal Region of a Singlet Lens

Example: Singlet

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



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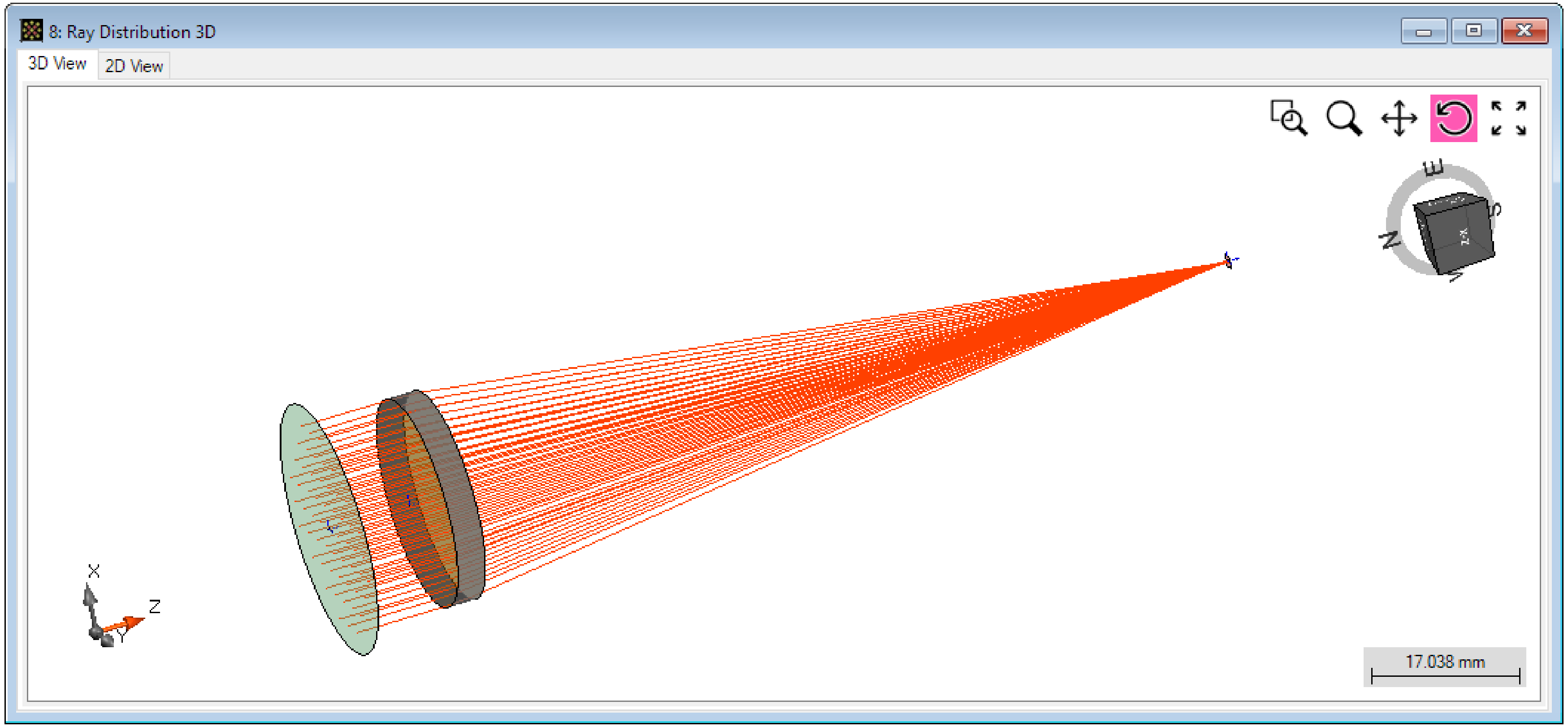
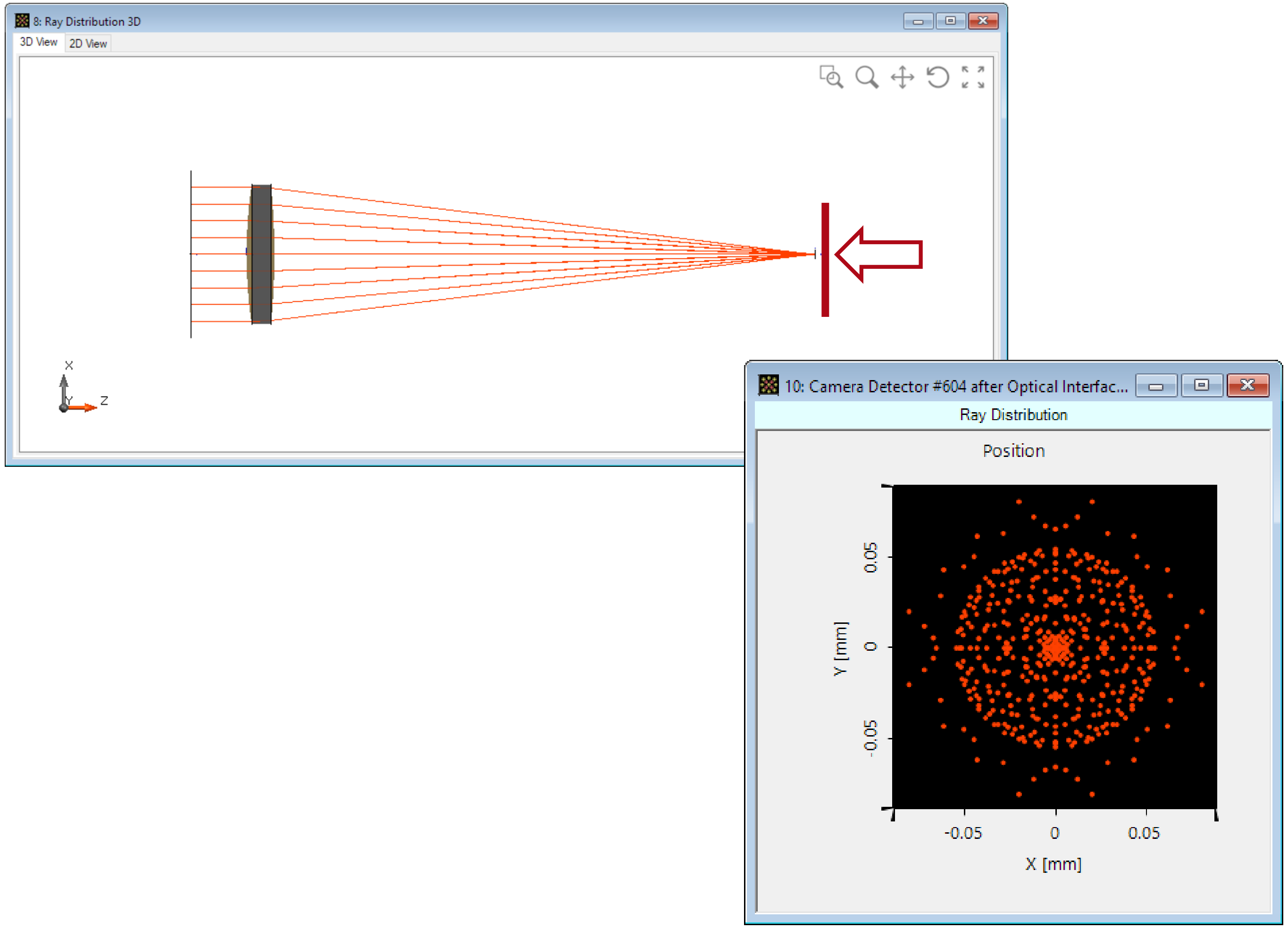
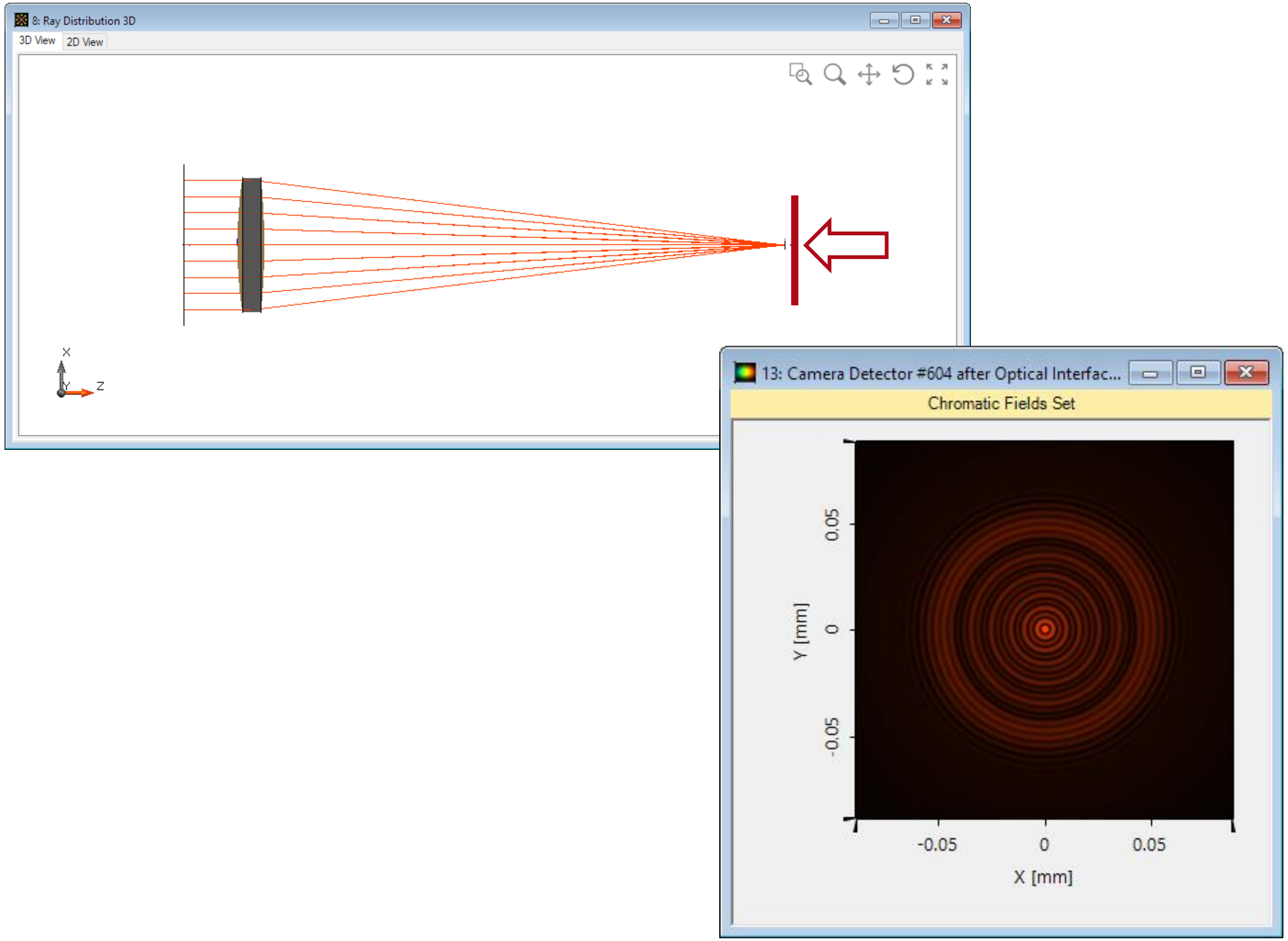


Ray Tracing: Dot Diagram



Physical Optics: Intensity



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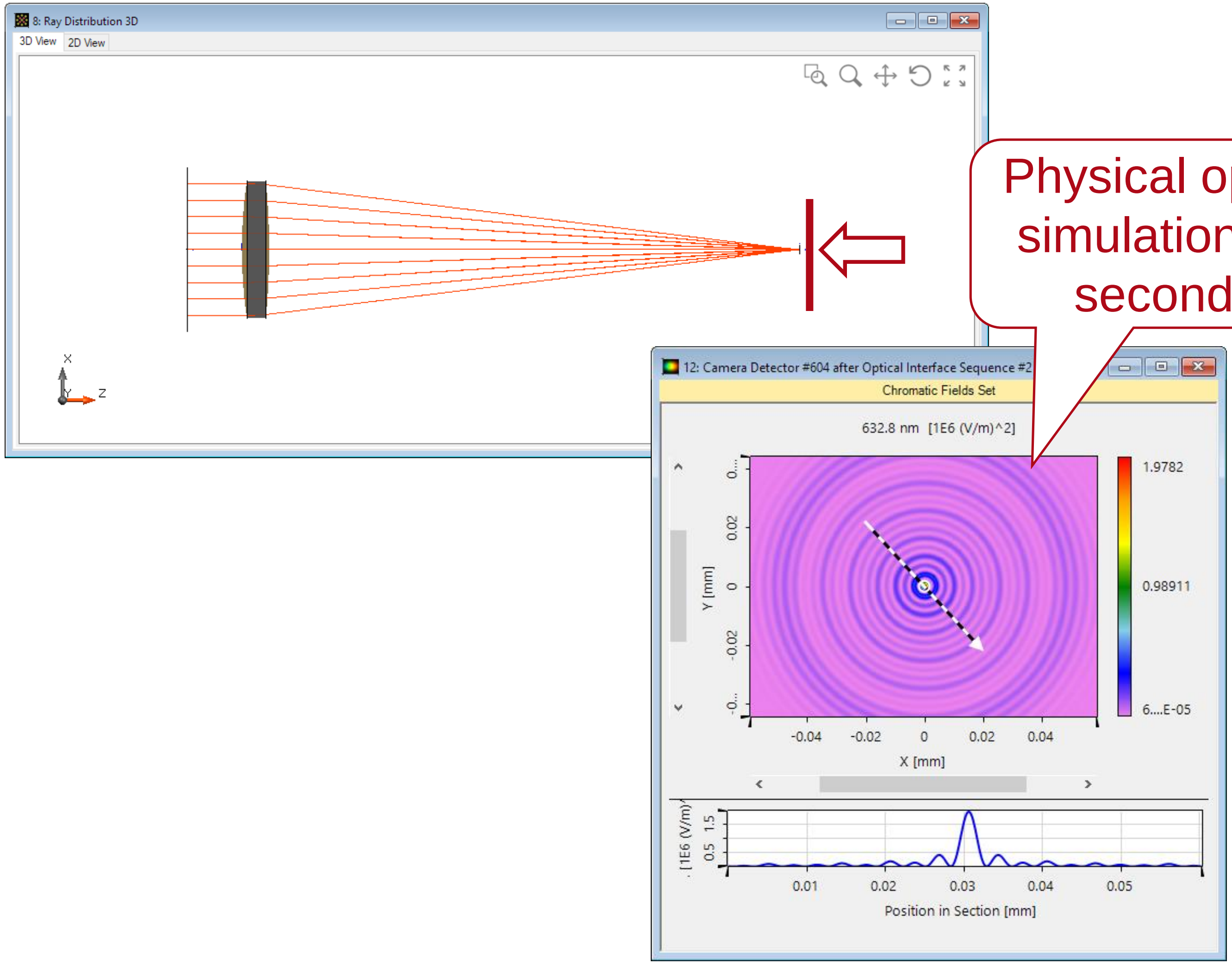
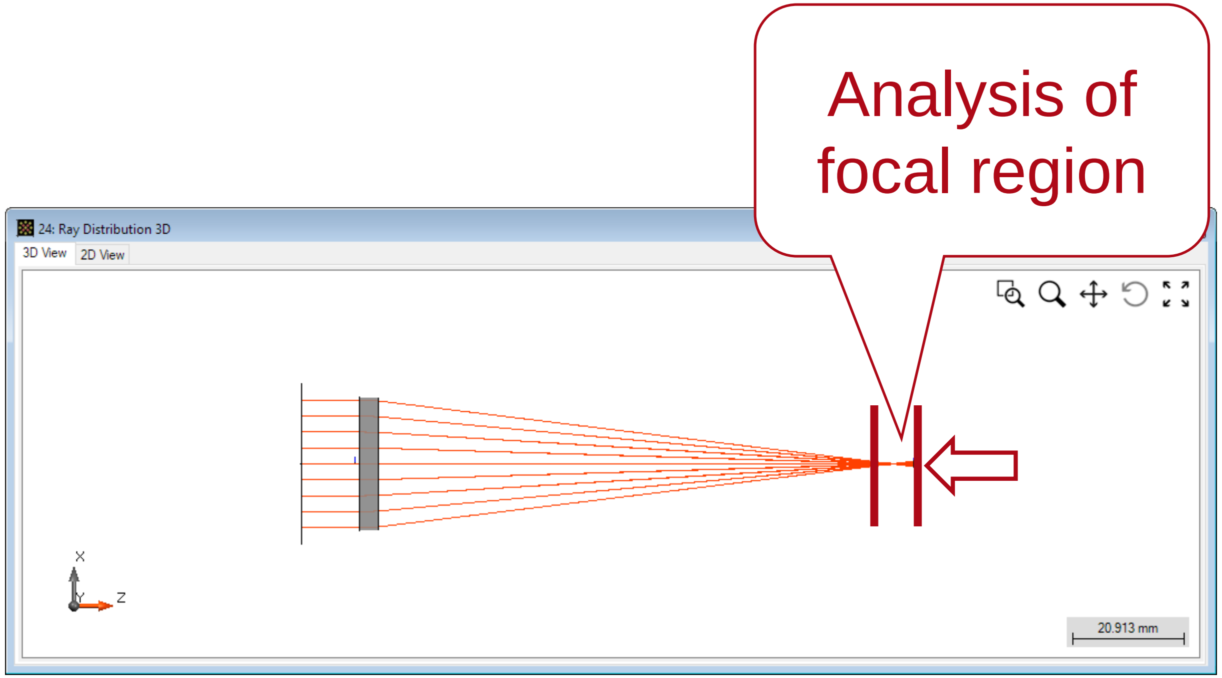
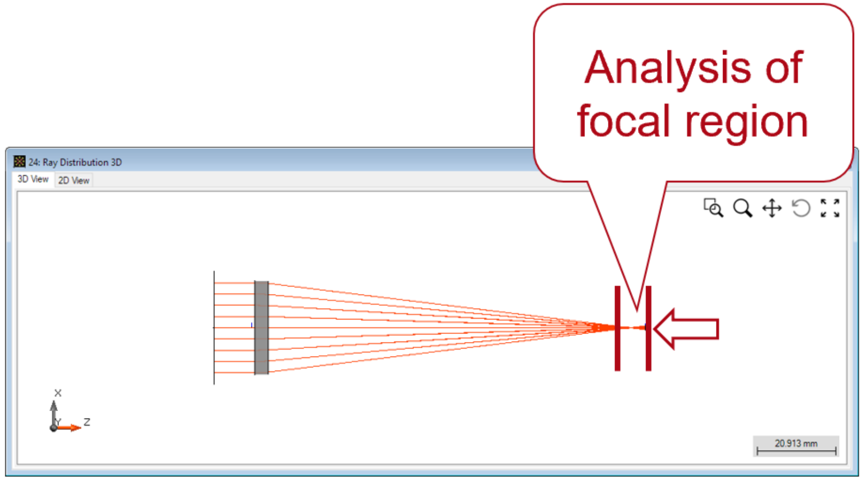


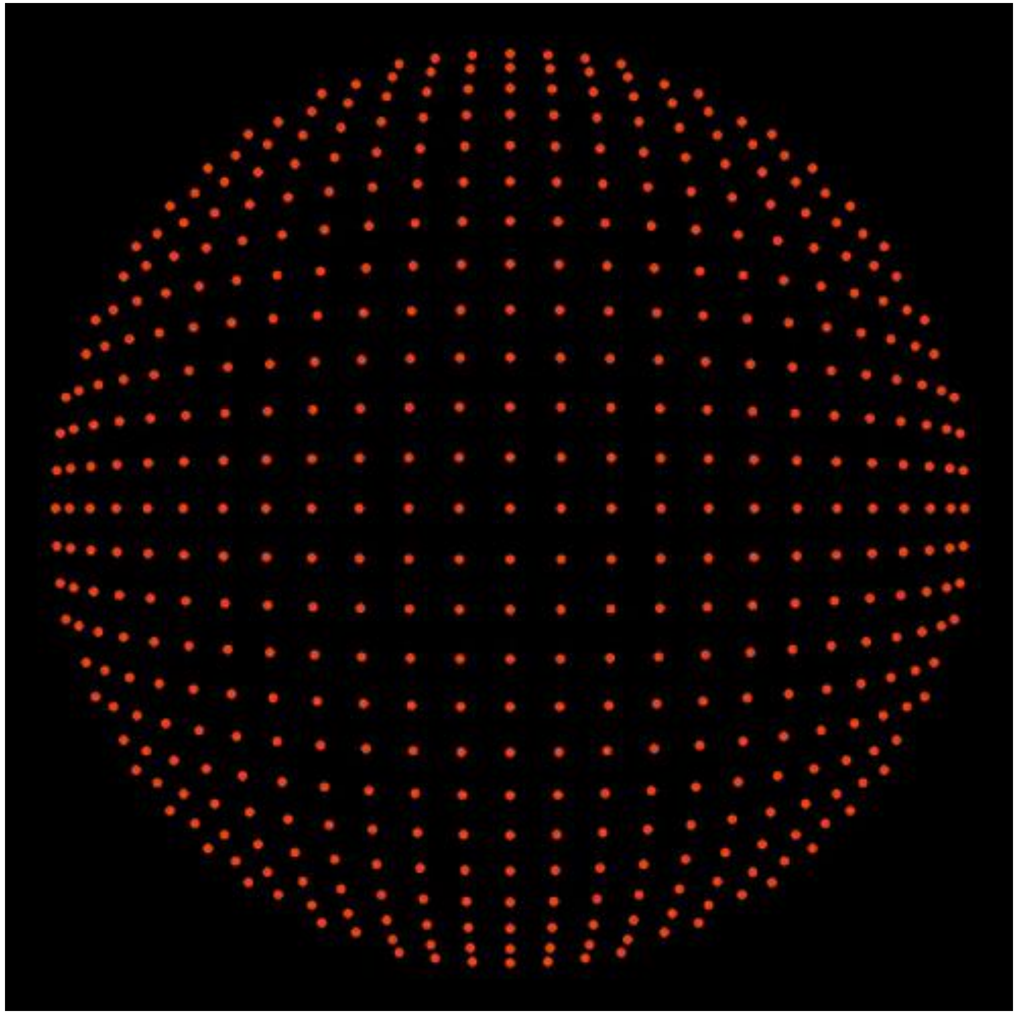
Physical optics simulations in seconds

Analysis of Focal Region



Ray Tracing: 91 - 100 mm





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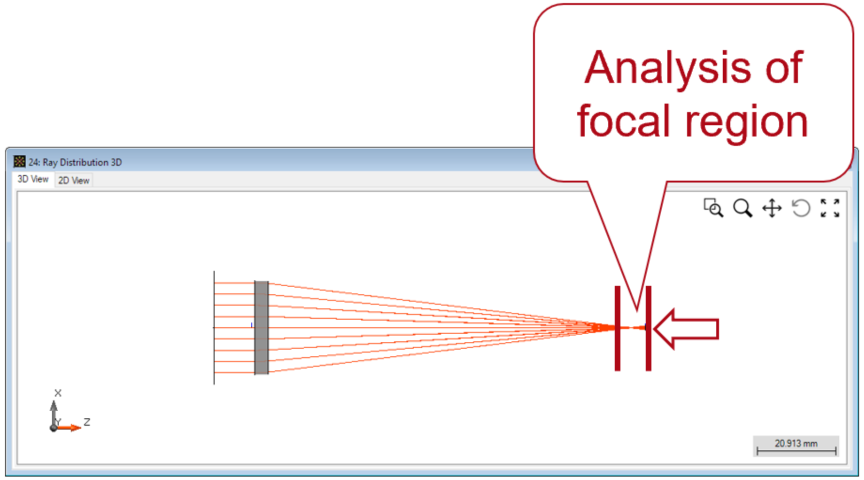

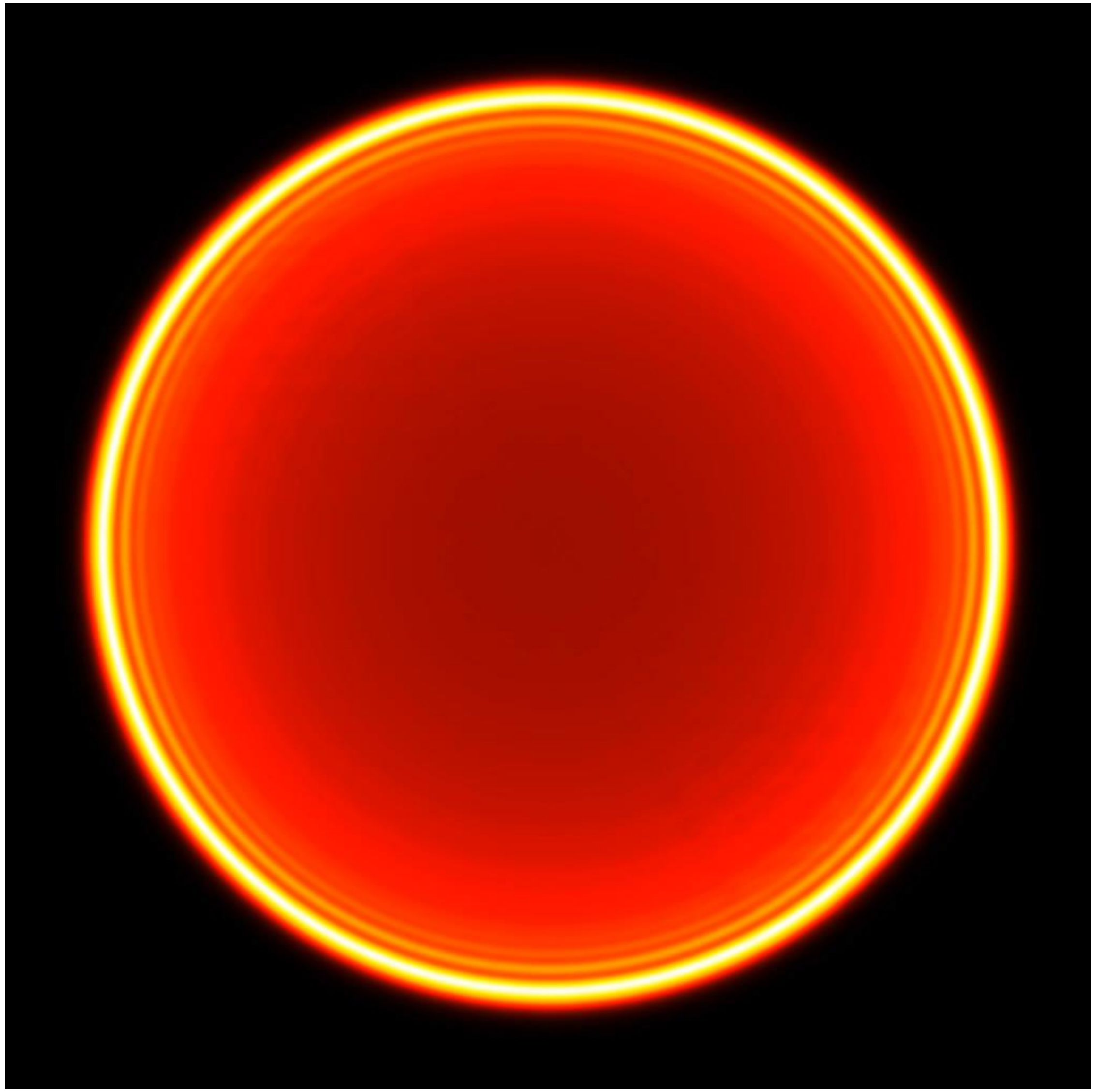

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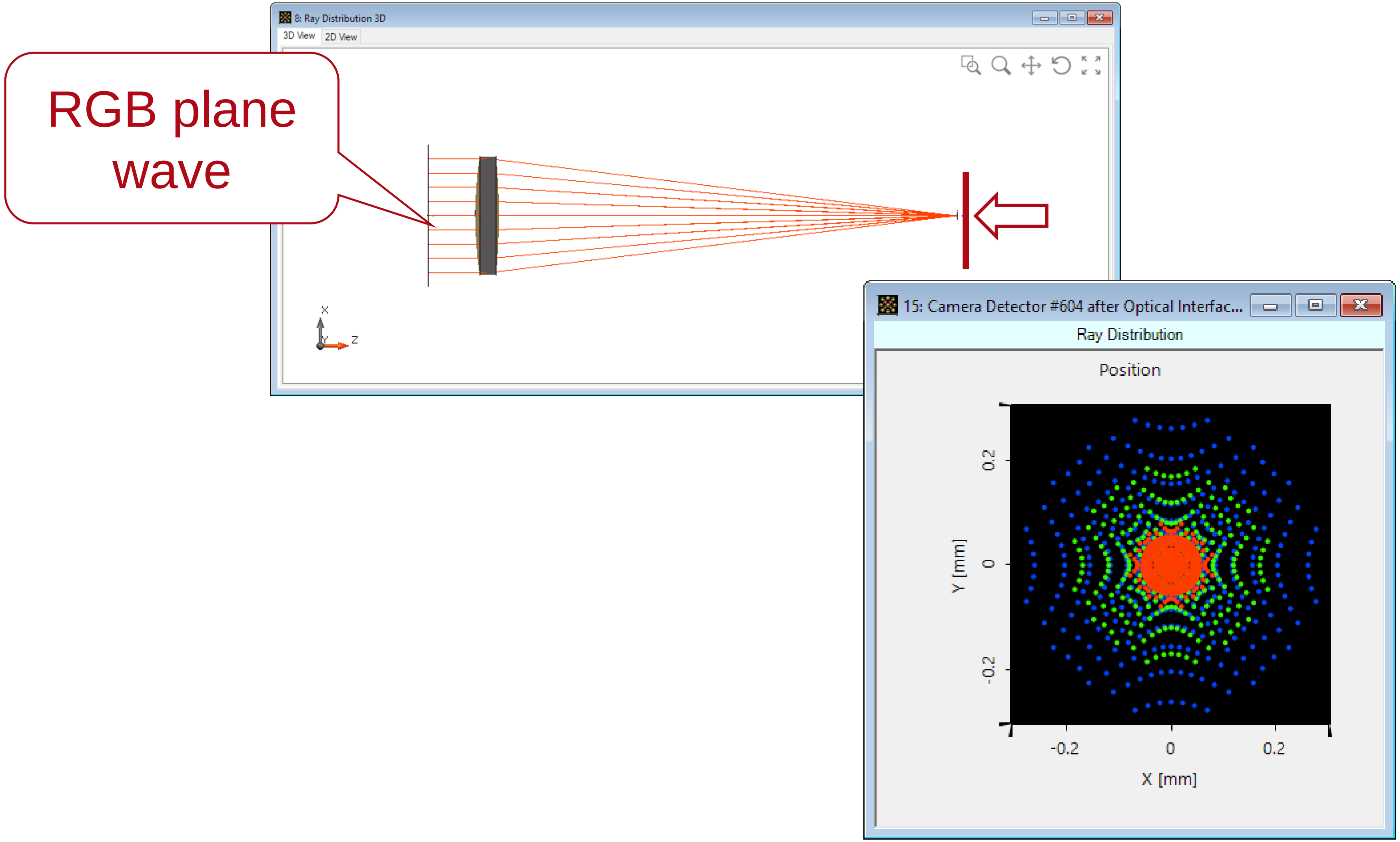

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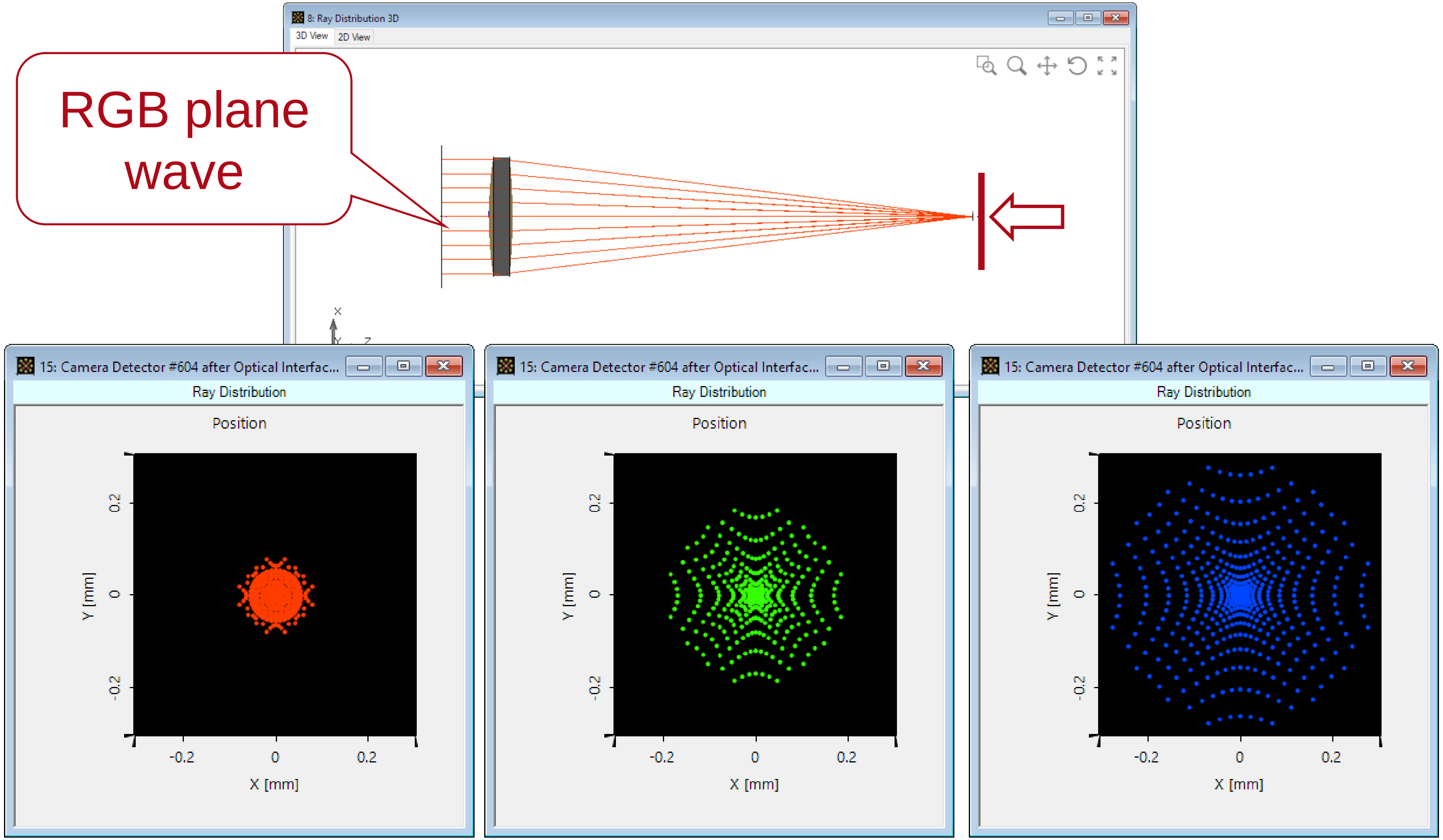

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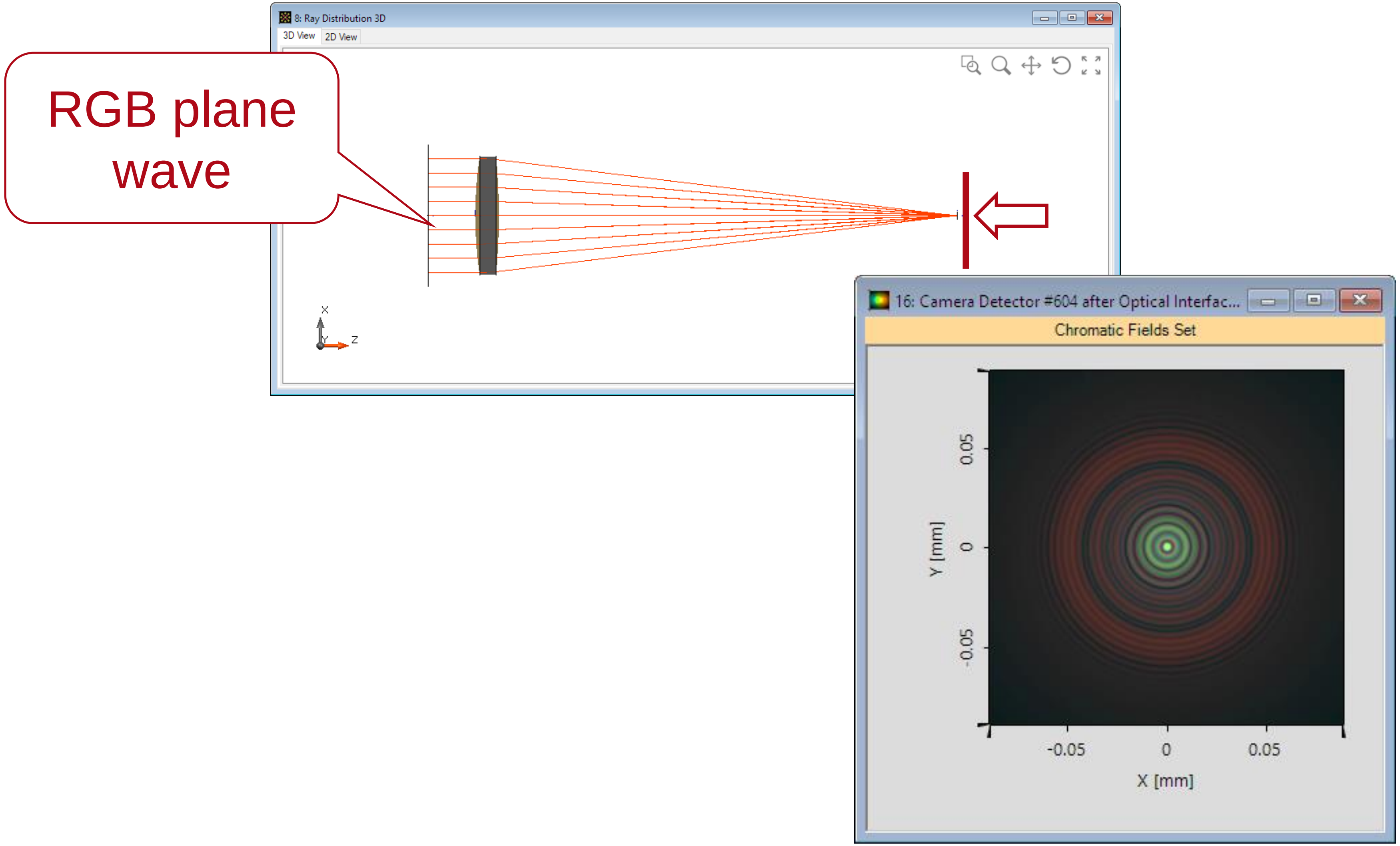

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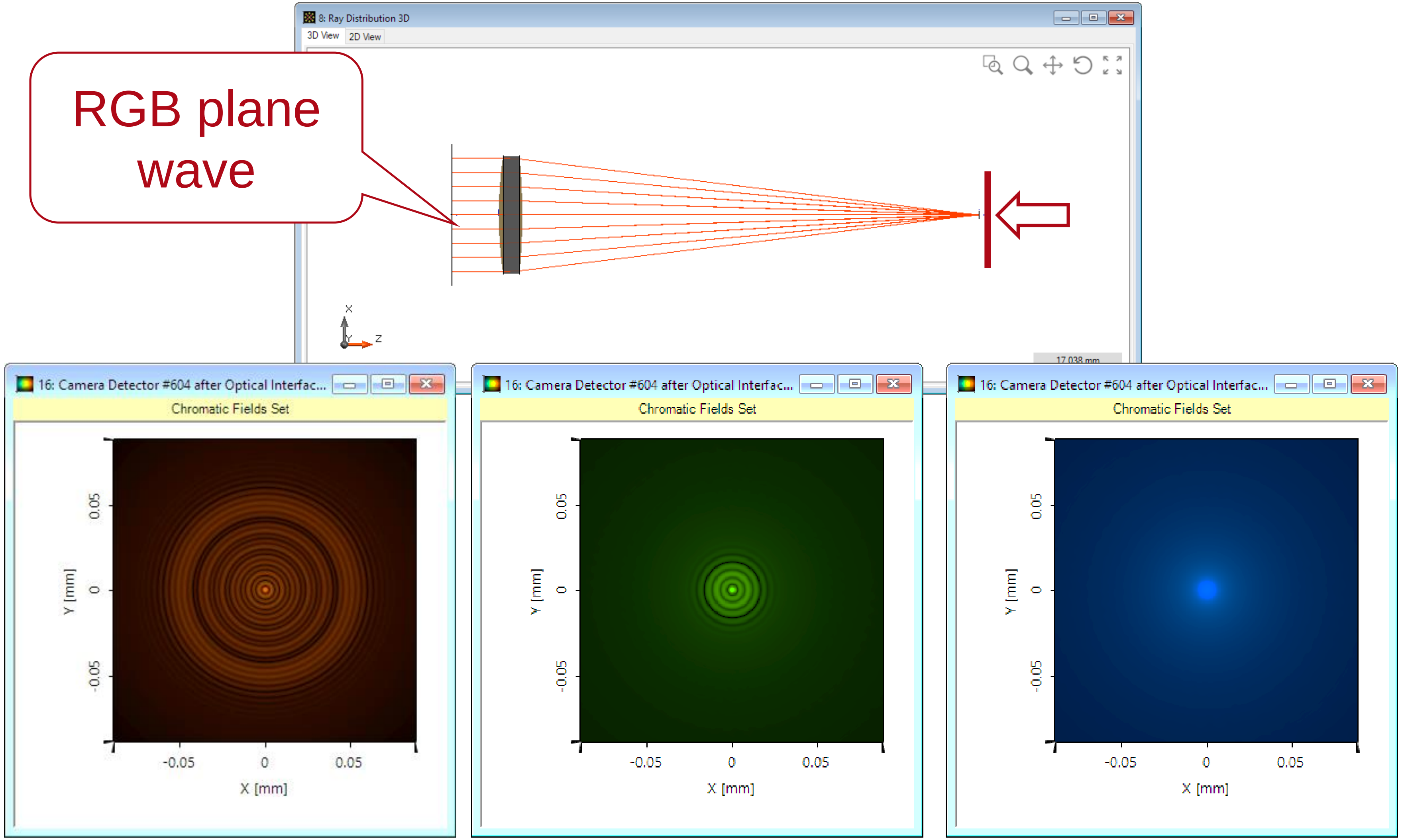
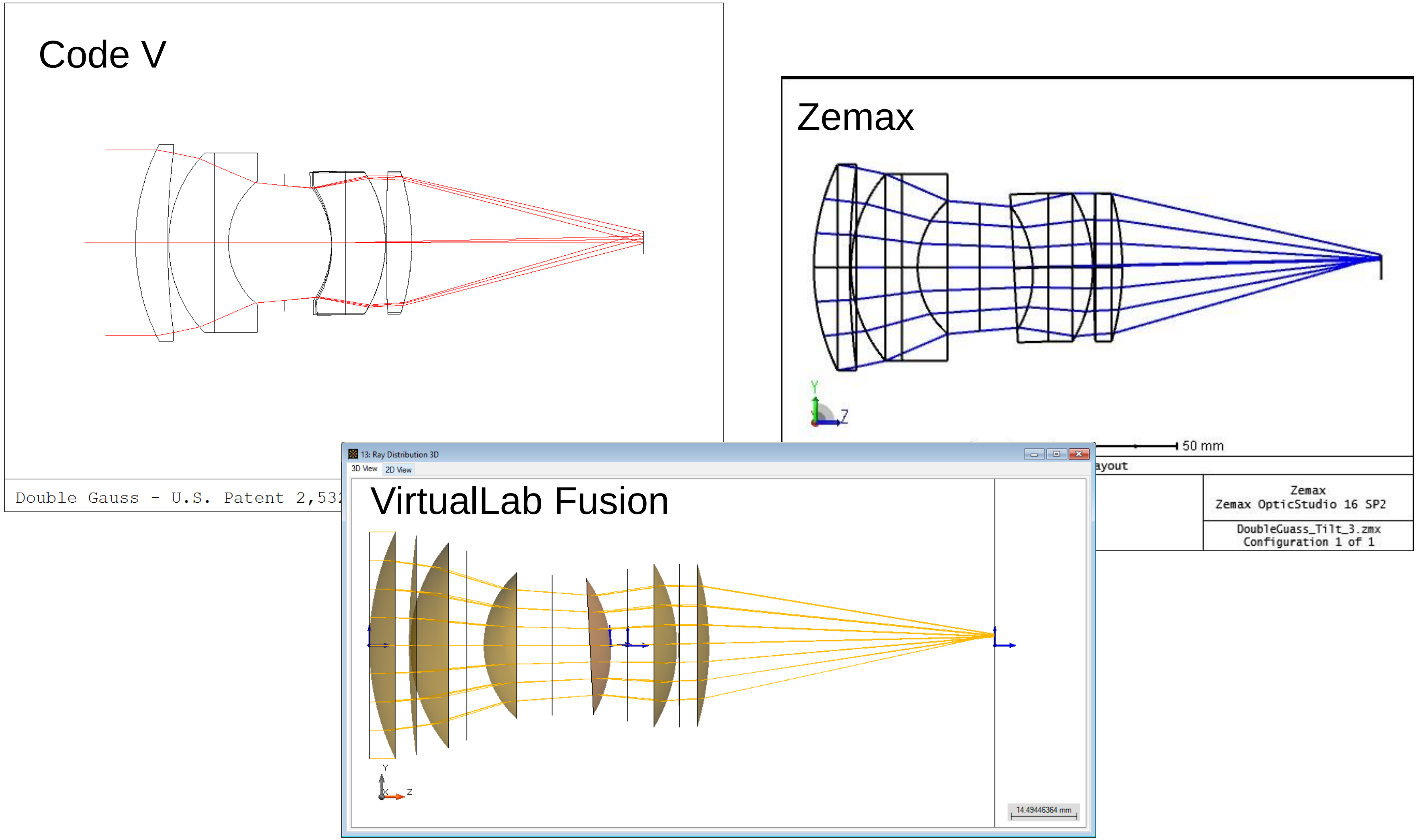


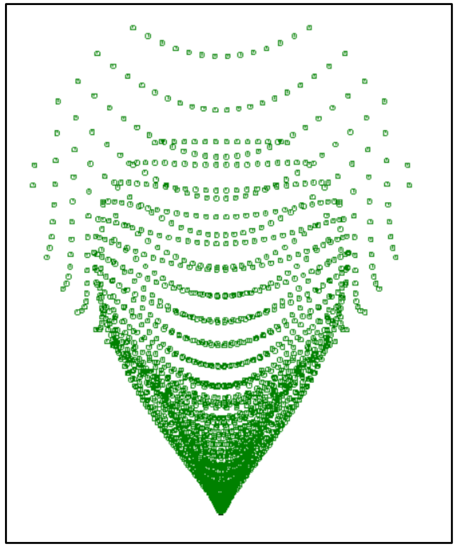
Lens modeling in VirtualLab Fusion

From ray tracing to field tracing

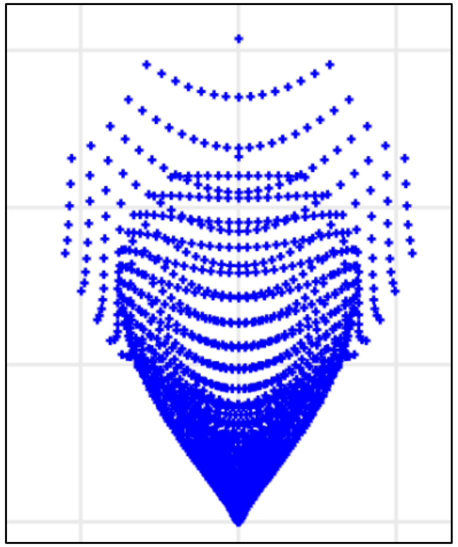
System Illustration



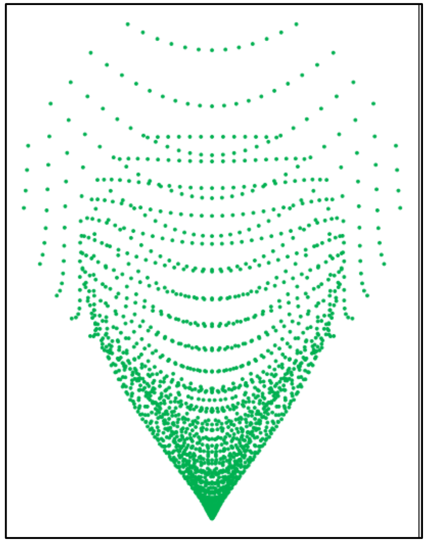
Dot Diagram Comparison: Target Plane



Code V



Zemax



VirtualLab

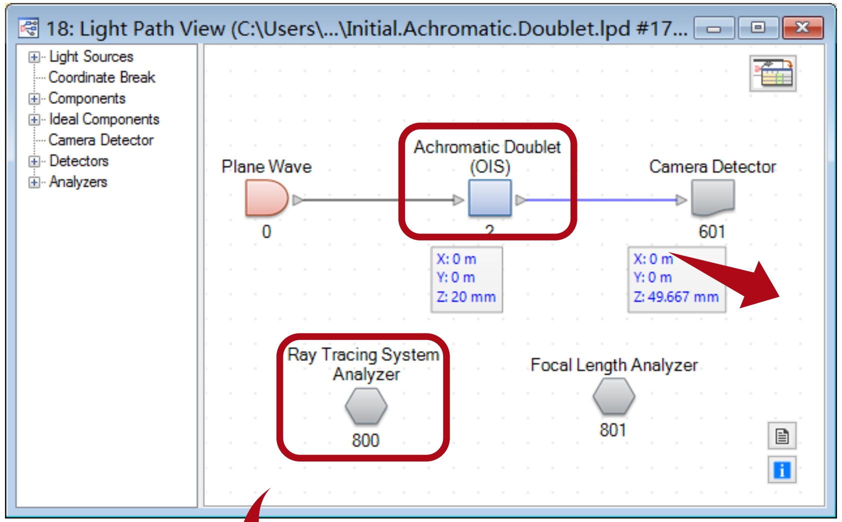
Precise Comparison: Position

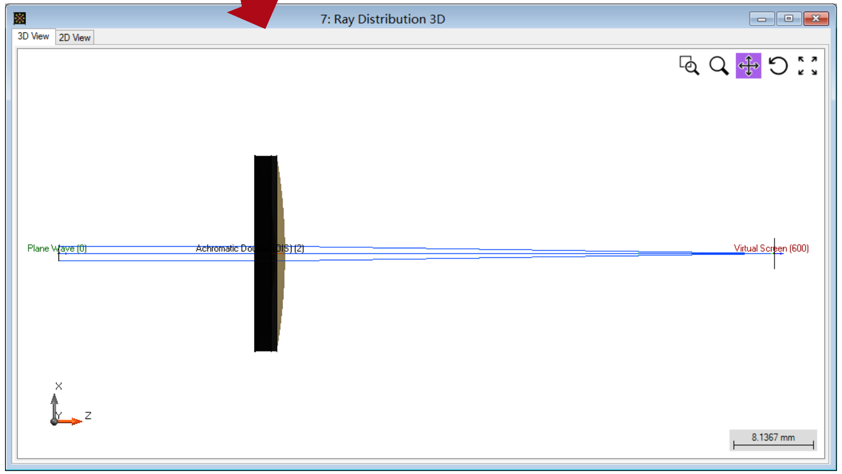
Ray position at initial plane			
No.	**Lateral coordinates**	**No.**	**Lateral coordinates**
1	(0, 15 mm)	4	(0, 7.5 mm)
2	(0, -15 mm)	5	(0, -7.5 mm)
3	(7.5 mm, 7.5 mm)	6	(7.5 mm, -7.5 mm)

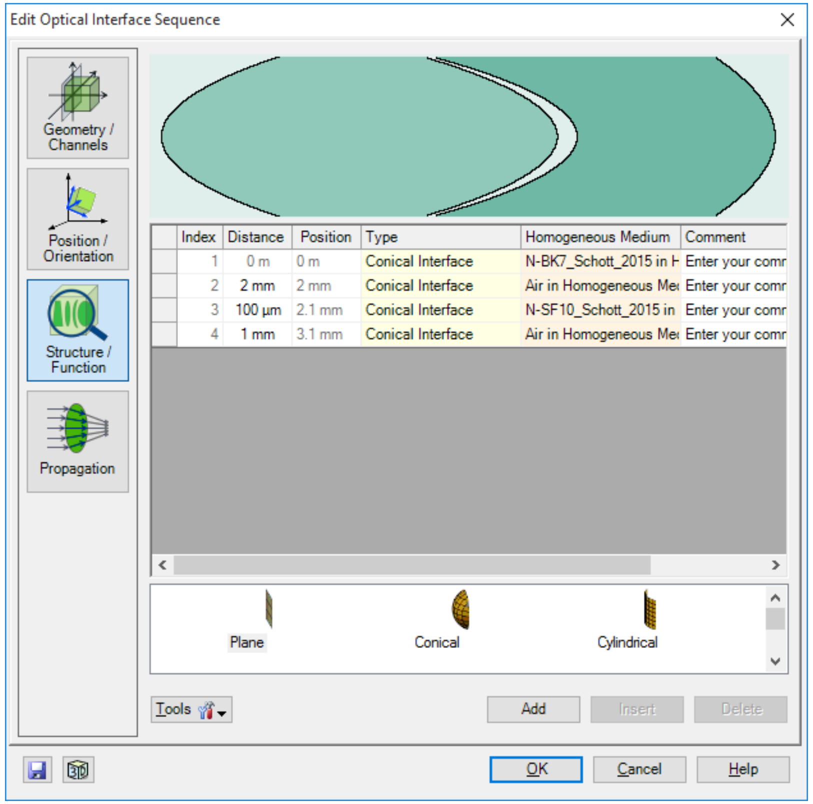
Ray position at imaging plane			
No.	**VLF**	**Code V**	**Zemax**
1	(0, 2.1524 mm)	(0, 2.1524 mm)	(0, 2.1524 mm)
2	(0, 2.1536 mm)	(0, 2.1536 mm)	(0, 2.1536 mm)
3	(52.07 µm, 1.927 mm)	(52.07 µm, 1.927 mm)	(52.07 µm, 1.927 mm)
4	(0, 1.905 mm)	(0, 1.905 mm)	(0, 1.905 mm)
5	(0, 1.8825 mm)	(0, 1.8825 mm)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

Example: Parametric optimization of an achromatic doublet

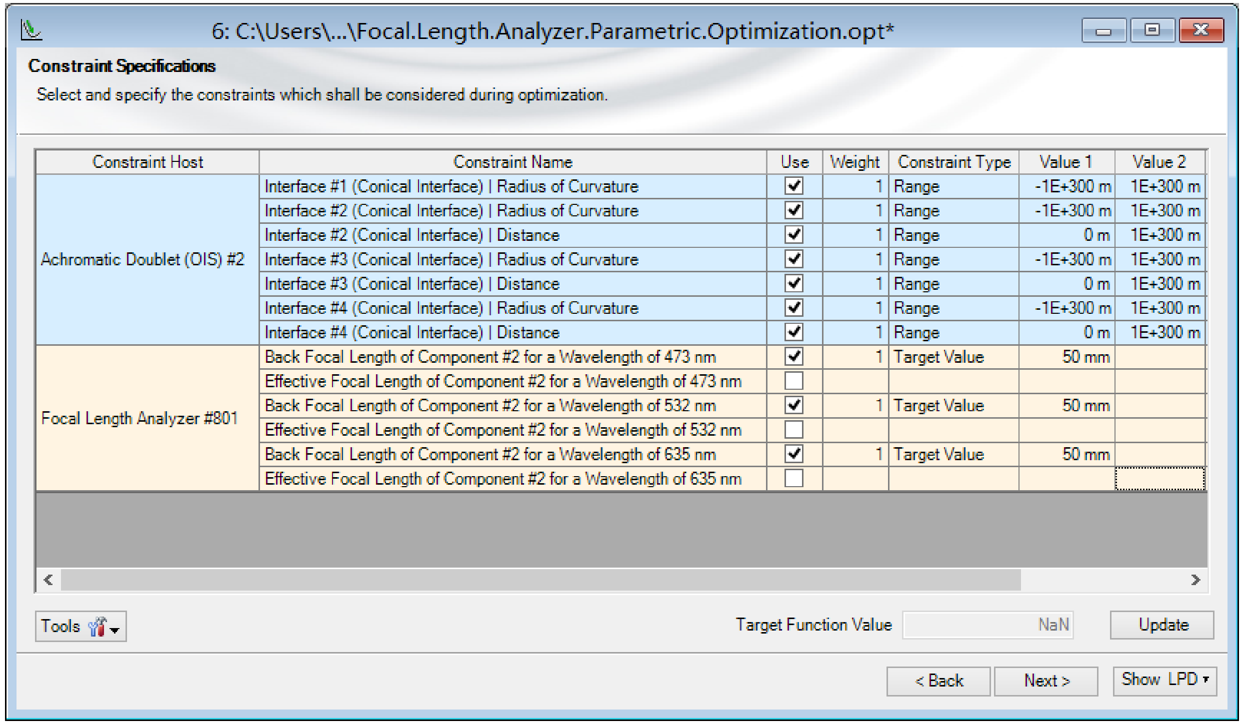
Schematic and Light Path Diagram





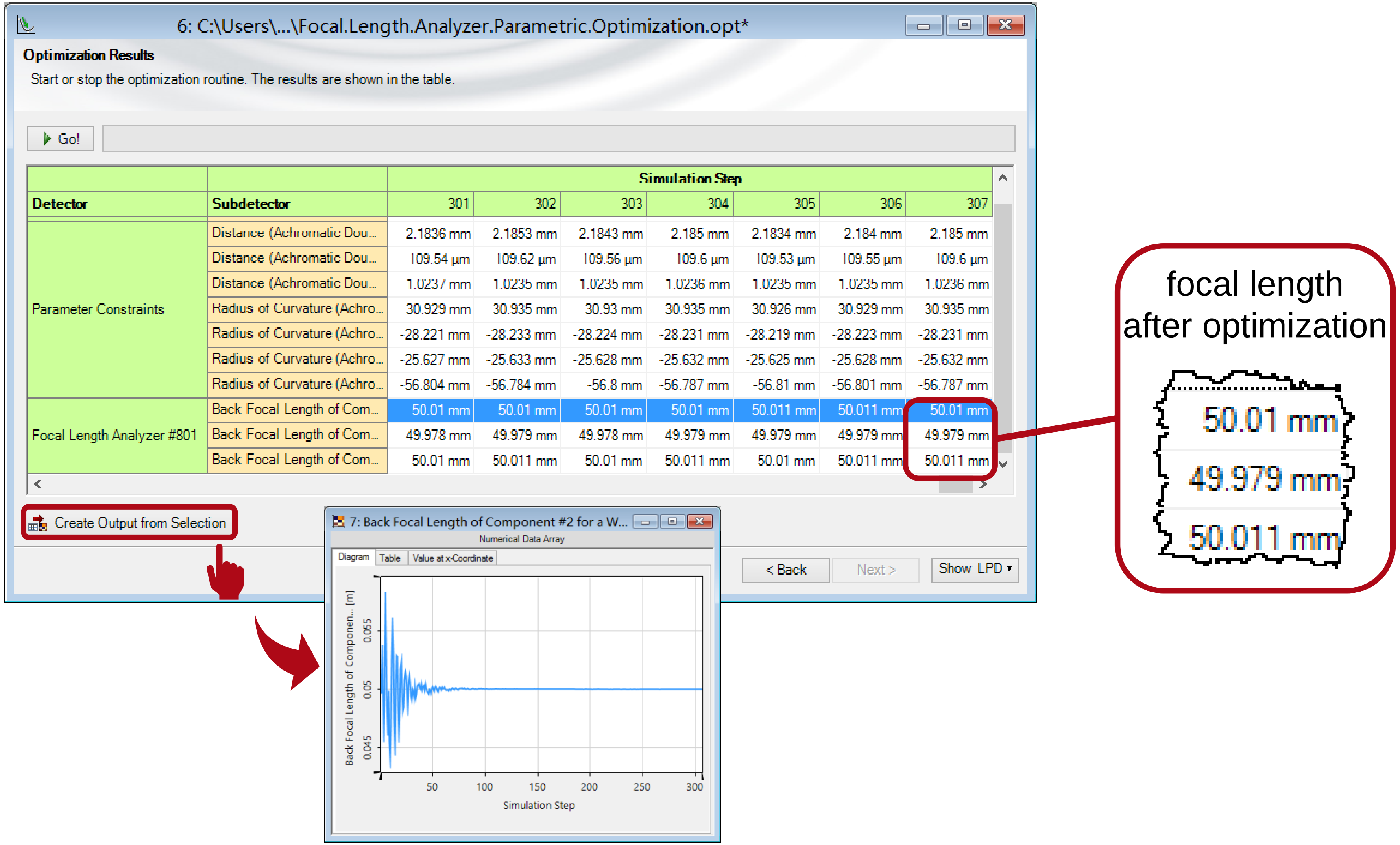


Set Optimization Target



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

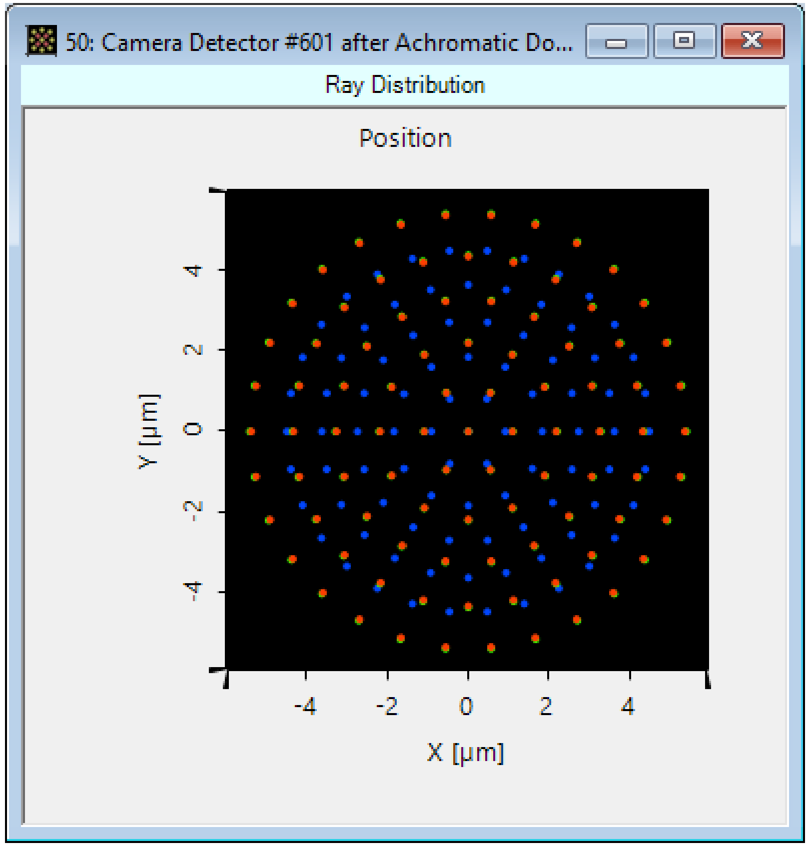
Optimization Result



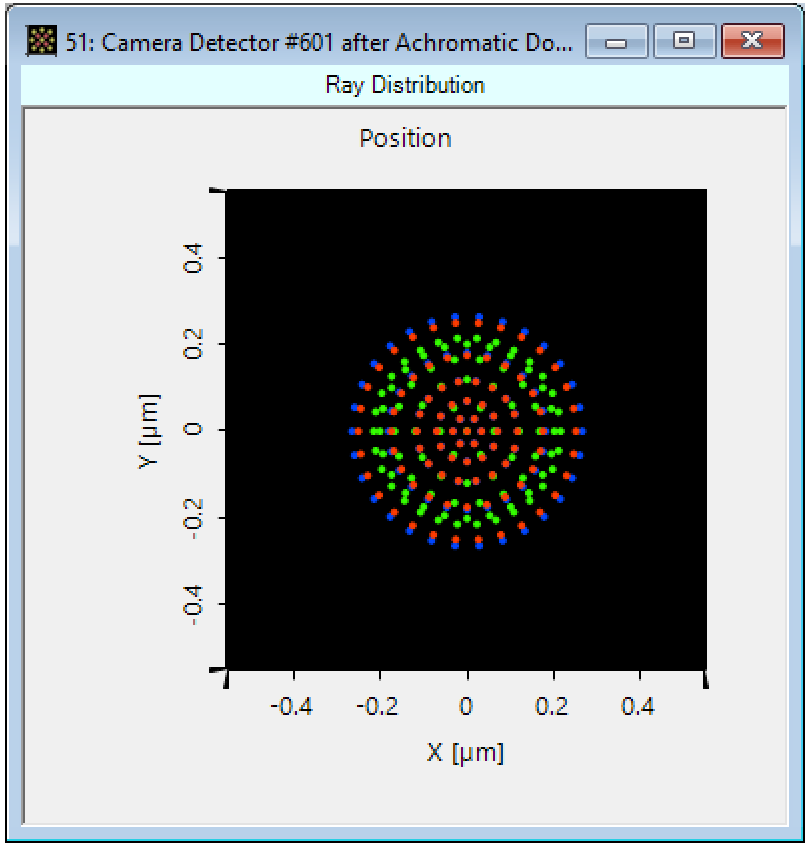
		Simulation Step						
Detector	Subdetector	301	302	303	304	305	306	307
Parameter Constraints	Distance (Achromatic Dou...	2.1836 mm	2.1853 mm	2.1843 mm	2.185 mm	2.1834 mm	2.184 mm	2.185 mm
	Distance (Achromatic Dou...	109.54 µm	109.62 µm	109.56 µm	109.6 µm	109.53 µm	109.55 µm	109.6 µm
	Distance (Achromatic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

Comparison of Results

Dot Diagram (initial setup)

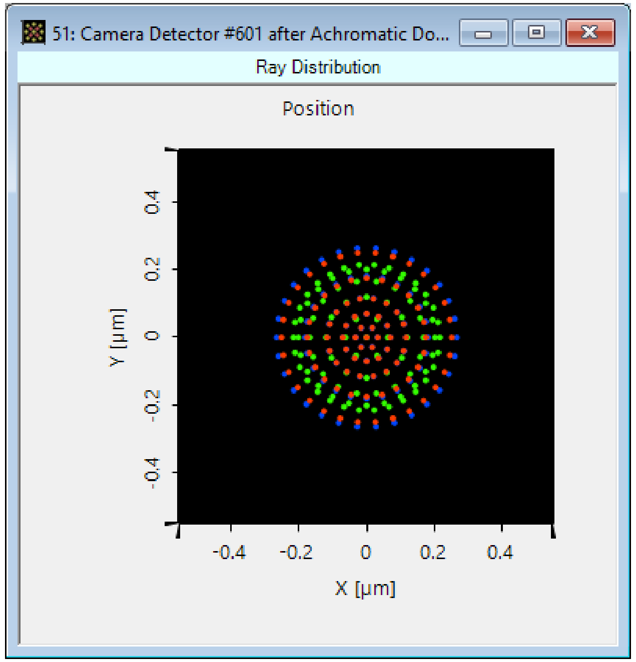


Dot Diagram (optimized)



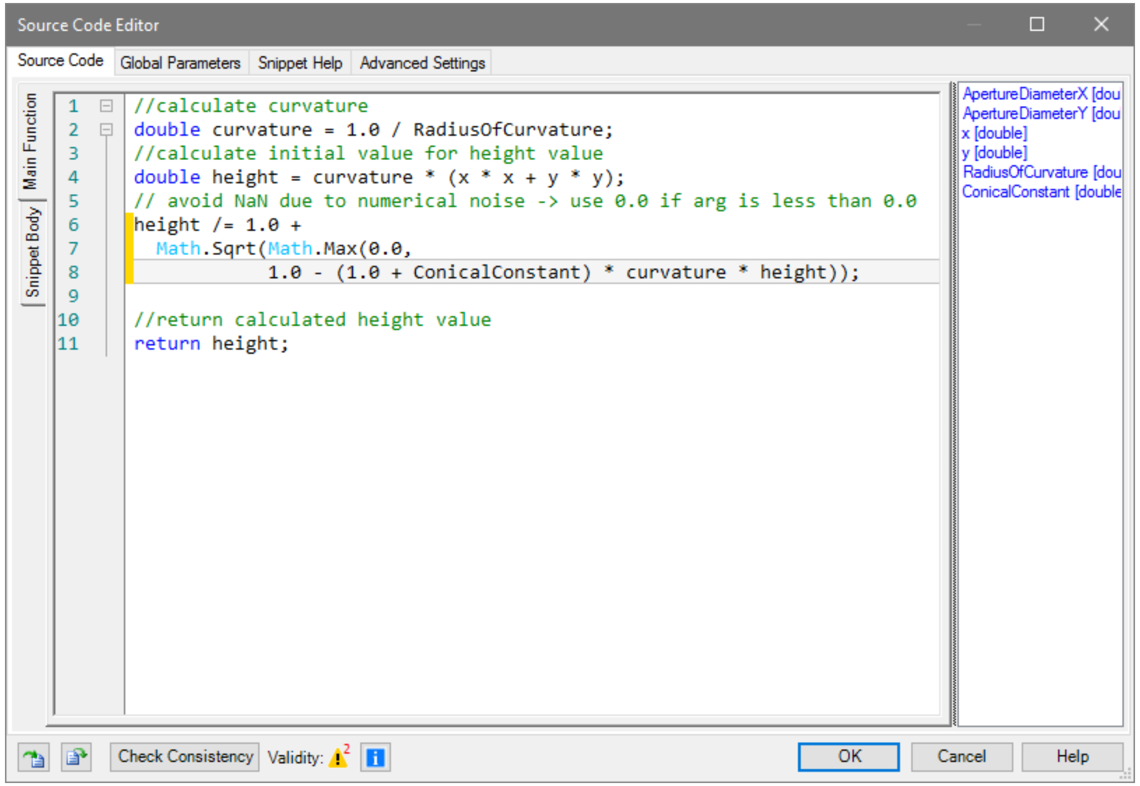
Ray Tracing in VirtualLab Fusion

- Ray tracing engine is included
- Sequential and non-sequential in the same system
- Comment: No CAD system description yet
- More to come to support typical lens designer workflows
- **Easy and fast way of customization!**



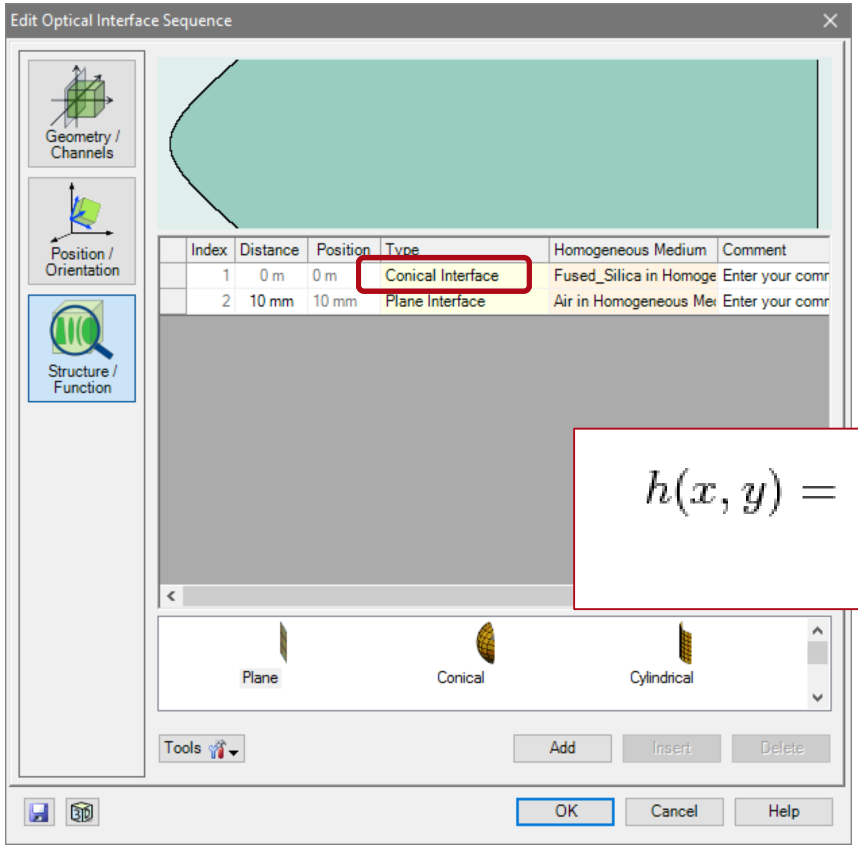
Customization of VirtualLab Fusion

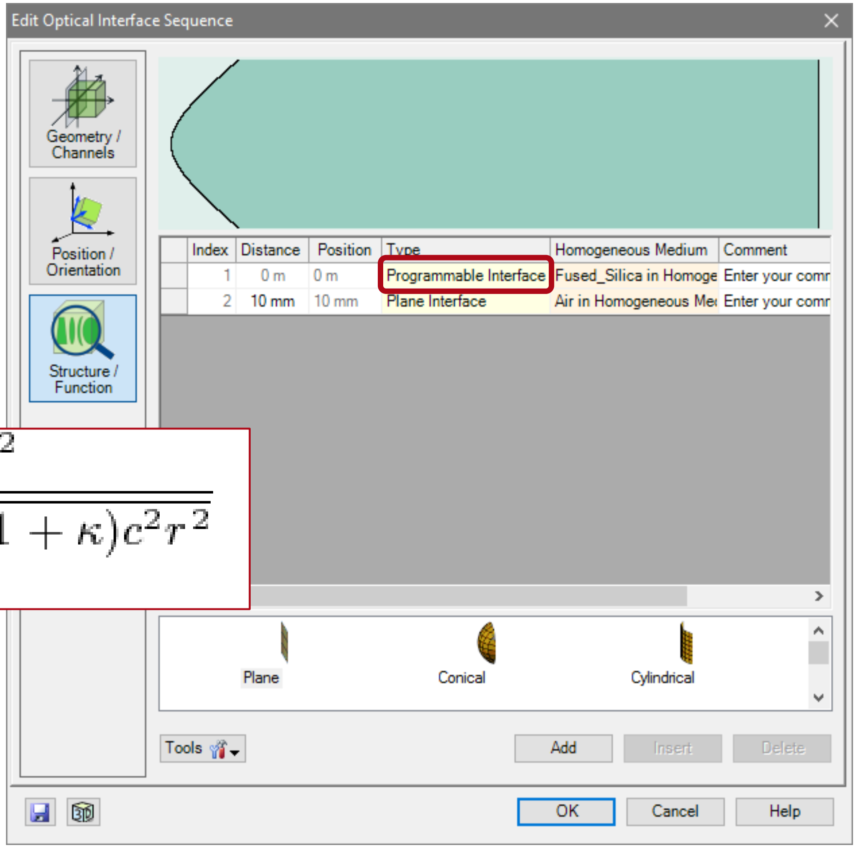
- Import of data for usage in sources, surfaces, media, and any other building block.
- Any building block allows also a customization by programming.
- That can be done by in-built programming editor or externally in e.g. Visual Studio: Language is C#



Almost no loss of performance!

Build-In vs. Customized Surface Description



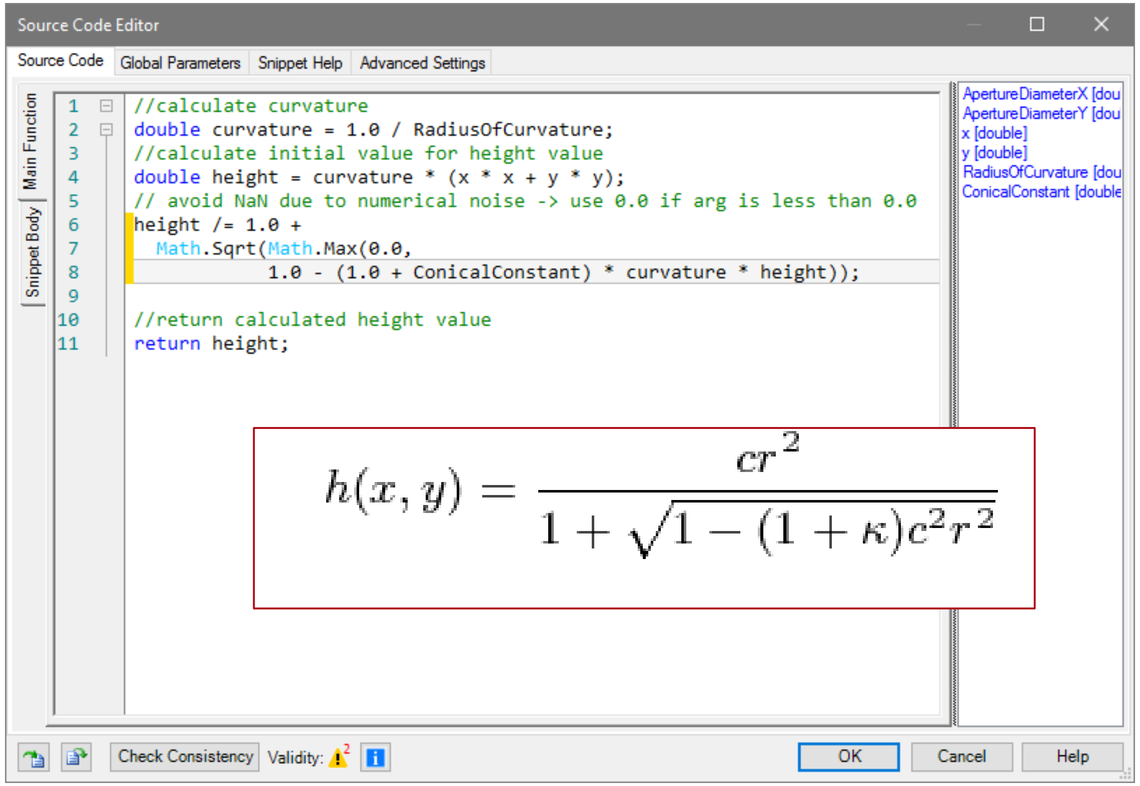


$$h(x,y) = \frac{cr^2}{1+\sqrt{1-(1+\kappa)c^2r^2}}$$

Build-In Surface

Customized Surface

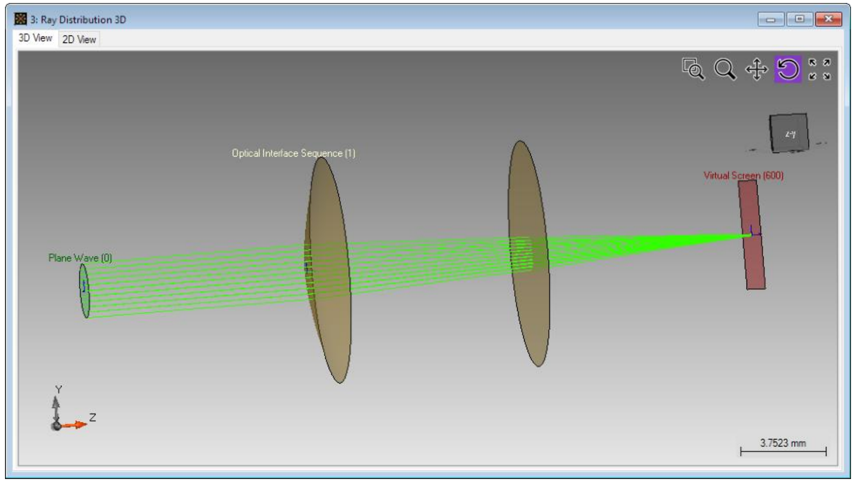
Implementation of Customized Surface



- The source code editor of the programmable surface allow the implementation of any customized profile height formula.
- In addition the user can define global parameters to parametrize the surface.
- These parameters are also available in parameter run and parametric optimization.

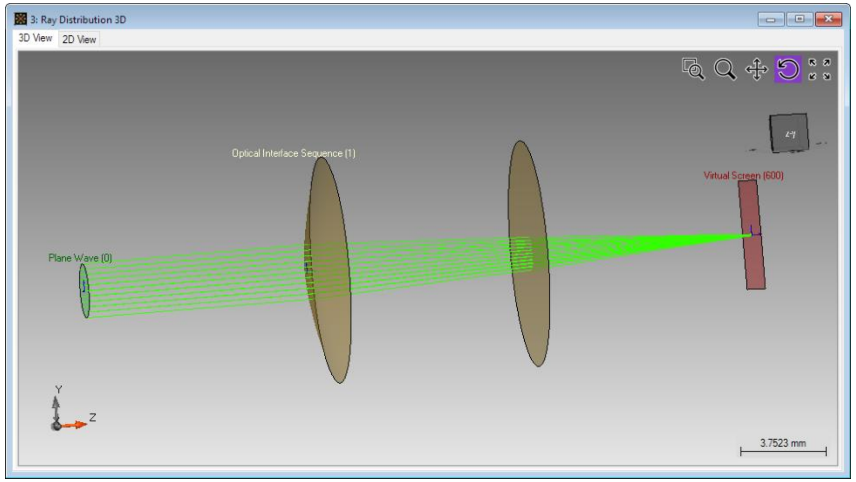
Simulation Result #1: 3D Ray Tracing

Time: about 1 sec



Build-In Surface

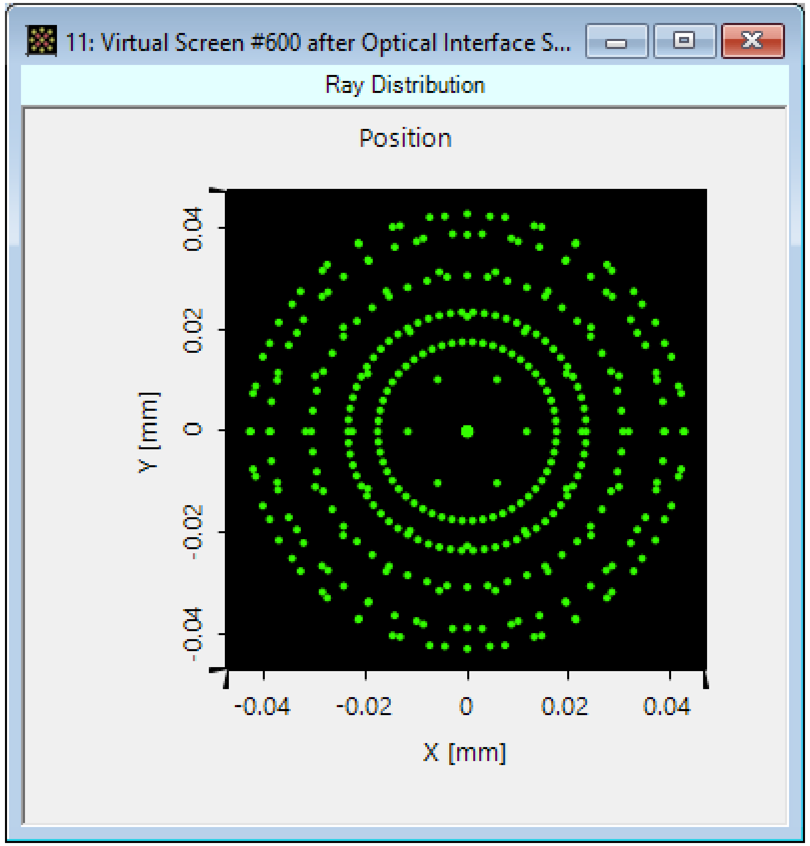
Time: about 1 sec



Customized Surface

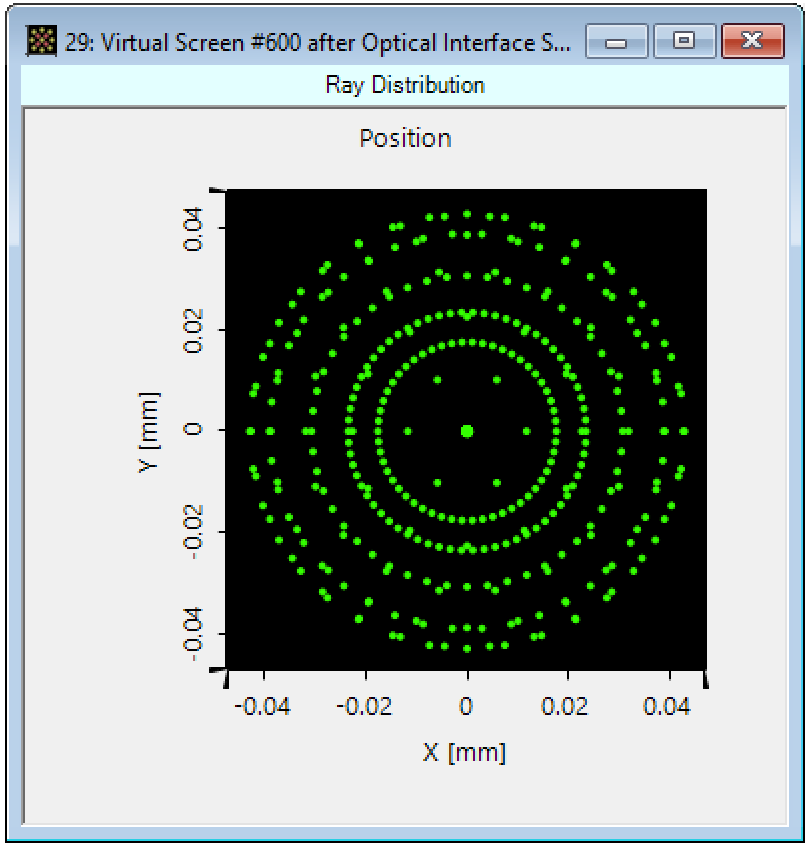
Simulation Result #2: Ray Tracing

Time: about 1 sec



Build-In Surface

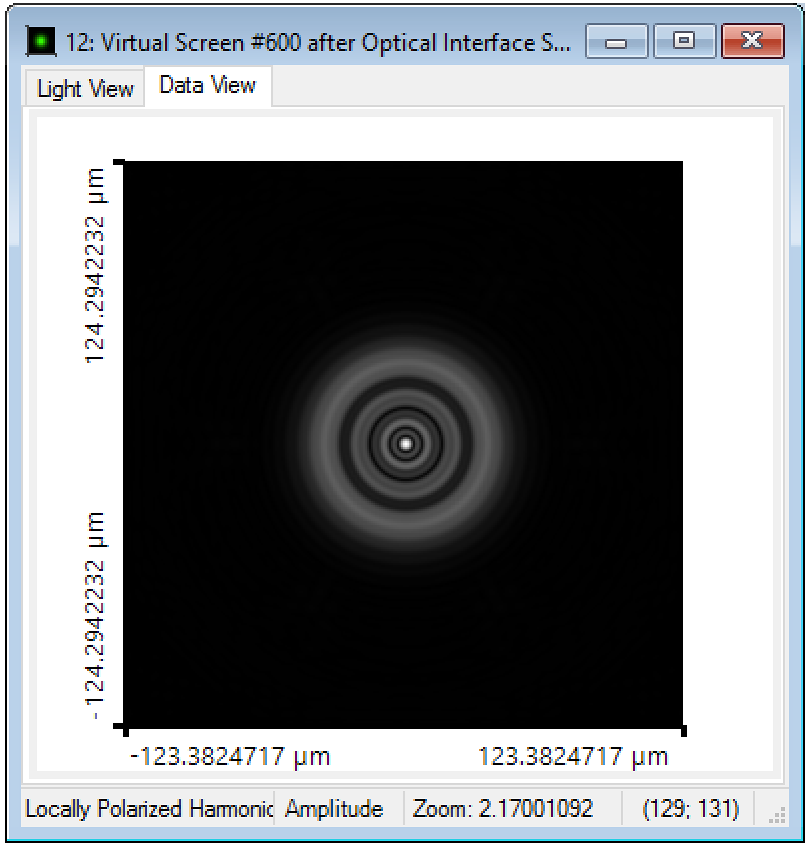
Time: about 1 sec



Customized Surface

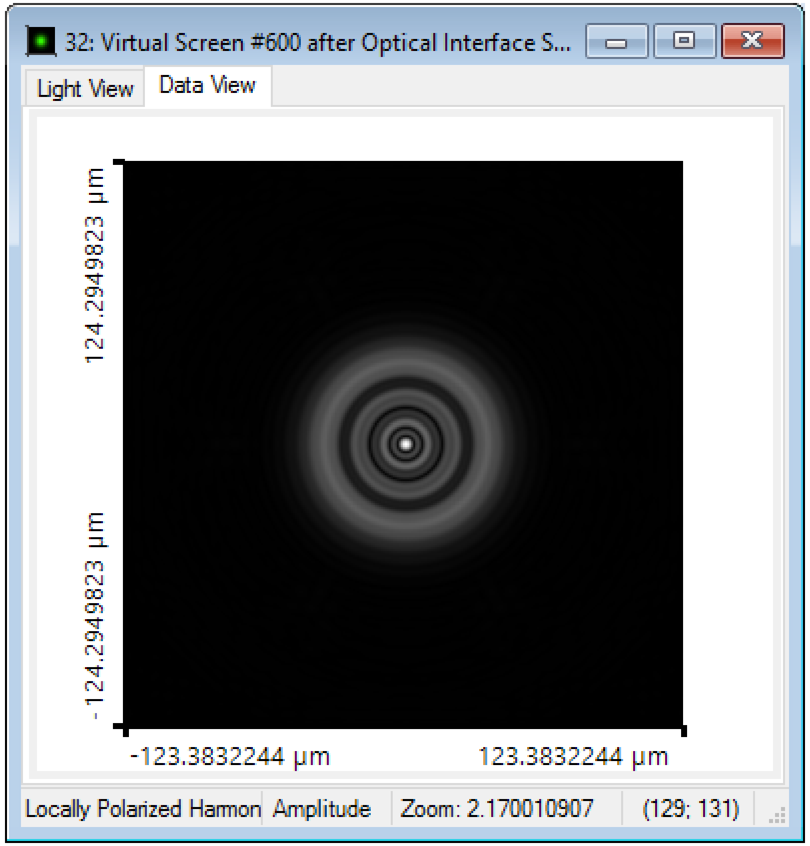
Simulation Result #3: Field Tracing

Time: about 2 sec



Build-In Surface

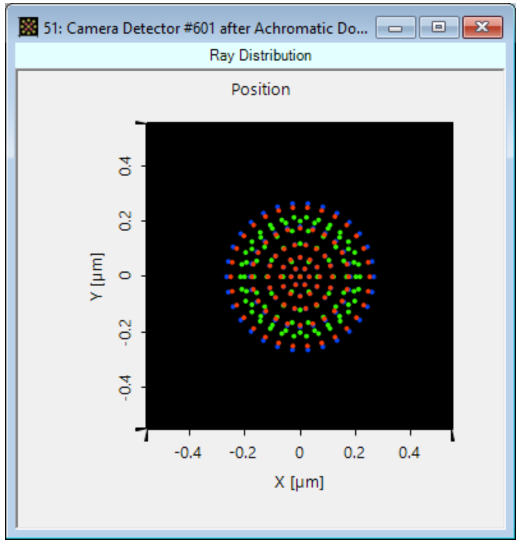
Time: about 2 sec

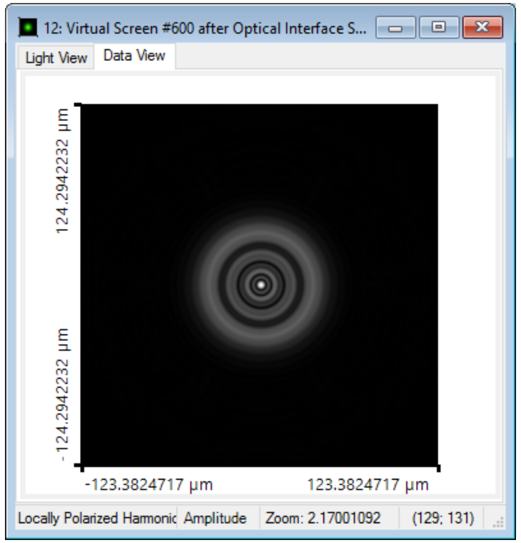


Customized Surface

Ray and Field Tracing in VirtualLab

- Ray tracing engine included
- Sequential and non-sequential in the same system
- Comment: No CAD system description yet
- More to come to support typical lens designer workflows
- Easy and fast way of customization
- VirtualLab Fusion enables switching between ray tracing and physical optics modeling by simply changing the modeling engine
- That enables also fully vectorial and accurate PSF/MTF modeling of lens systems
- Provides solid basis for source models in ray tracing



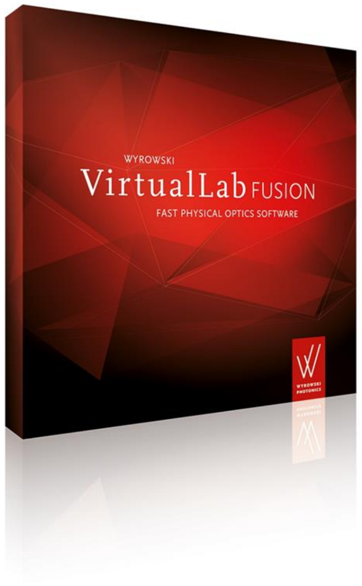


Our Key Messages on Modeling

#1: Make physical optics the platform in optical modeling.

#2: **Field Tracing** enables **Fast Physical Optics**.

#3: Ray tracing is fully embedded in fast physical optics.



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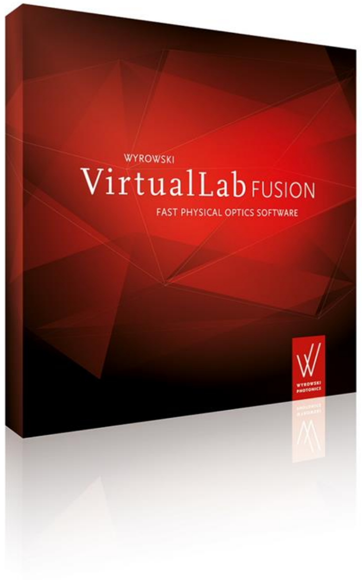


Fast Physical Optics by Field Tracing

Brief introduction of concepts

Physical Optics Often Not Practical because …

- Source modeling by coherence functions with subsequent propagation by four dimensional integral operations: **Unrealistic numerical effort**
- Application of a single field solver, e.g. FEM or FDTD, to the entire system: **Unrealistic numerical effort**
- Field operations of order $O(N^2)$ and higher: **Typically high numerical effort**
- Nyquist sampling of complex field amplitudes: **Often results in high sampling number N**
- Physical optics modeling in one coordinate system: **Often results in high sampling number N**

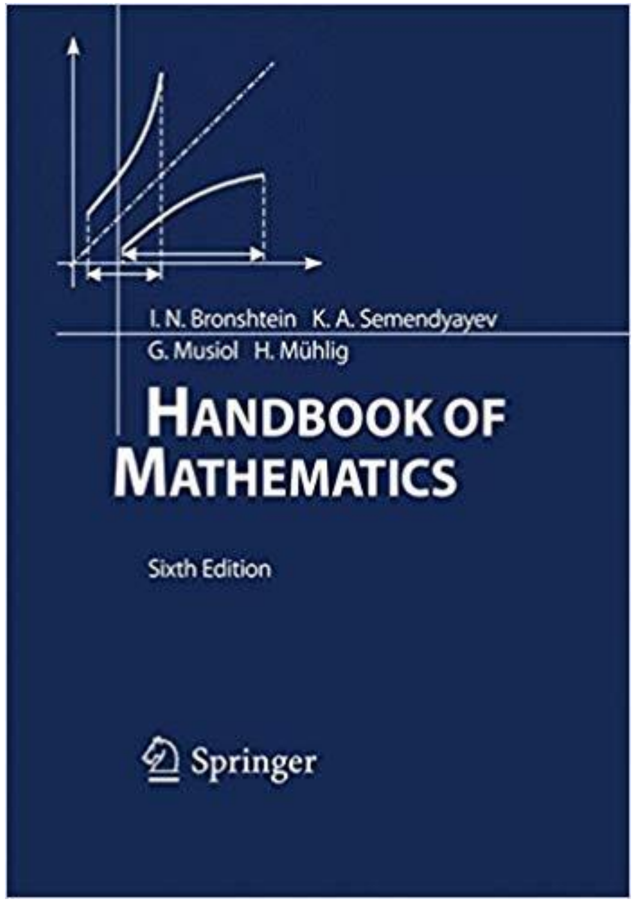
- Physical optics is typically understood as to be too complex, slowly and in general not feasible in practical tasks.
- However, the need for it is growing!
- **Way out of this dilemma?**

Mathematical Concepts for Fast Physical Optics Include …

- **Linear operators and superposition principle**
- **Tearing and interconnection** applied to Maxwell's equations
  - **Tearing**: Application of regional field solver
  - **Interconnection** of solutions in different regions
- **Fourier transform** to change mathematical domain
  - Fast Fourier Transform
  - Shift Theorem
  - Convolution Theorem
  - Q-Integral formula

$$\int_{-\infty}^{\infty} \exp(c'_1 x - c_2 x^2)\,\mathrm{d}x = \sqrt{\frac{\pi}{c_2}} \exp\left(\frac{c'^2_1}{4c_2}\right)$$

- **Stationary phase concept**
- **Transformation between coordinate systems**



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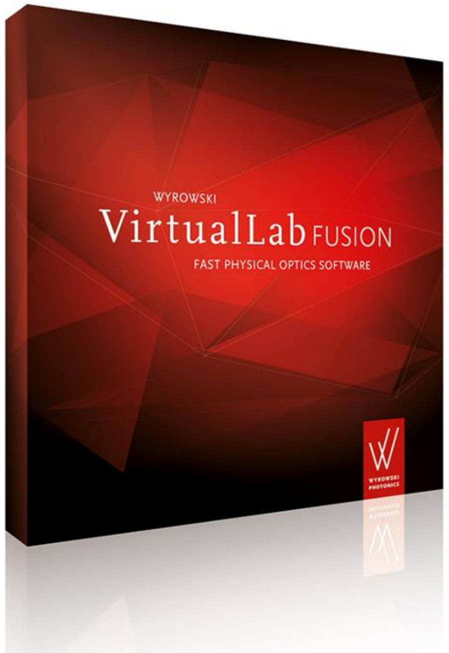

VirtualLab Fusion is based on a sophisticated usage and combination of mathematical concepts.

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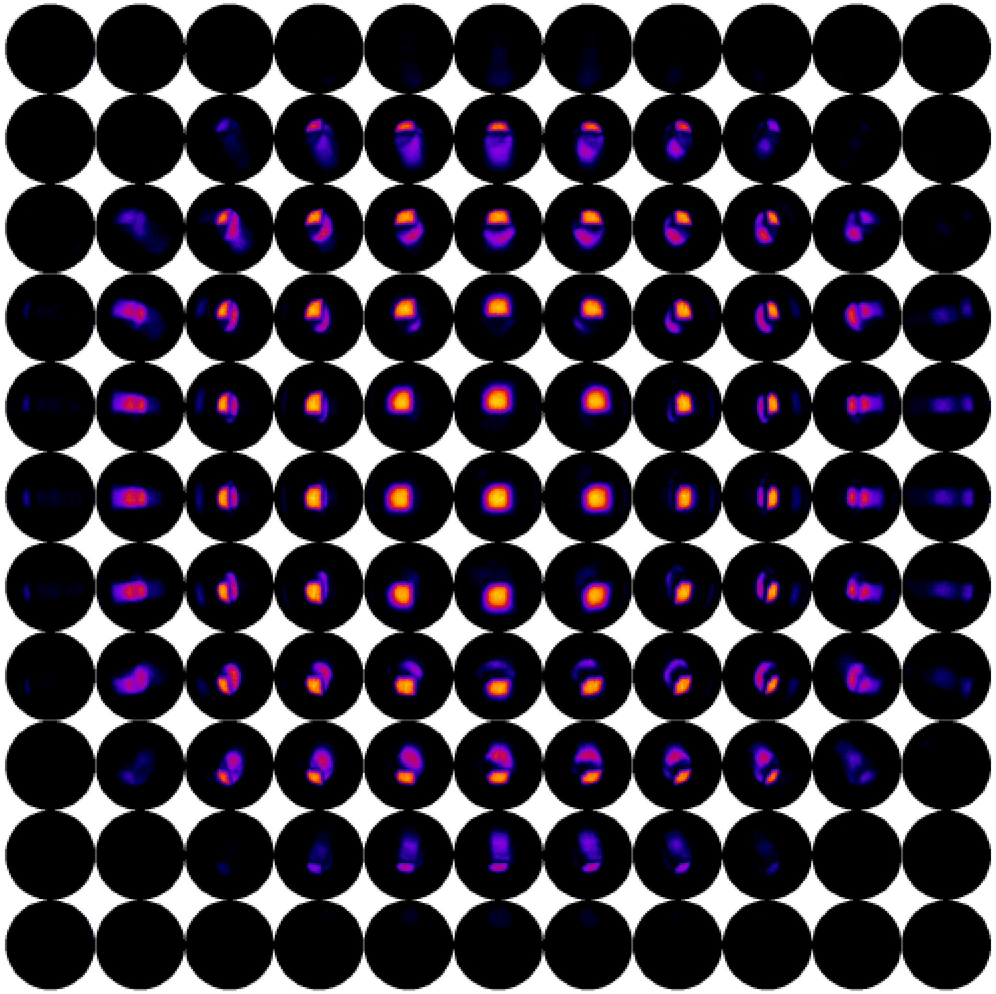
Source Mode Decomposition

Problem:

Source modeling by coherence functions with subsequent propagation by four dimensional integral operations: **Unrealistic numerical effort**

Solution:

Each source field can be decomposed into a set of fully coherent, mutually correlated and uncorrelated **source modes**. Linear operators allow modeling per mode.



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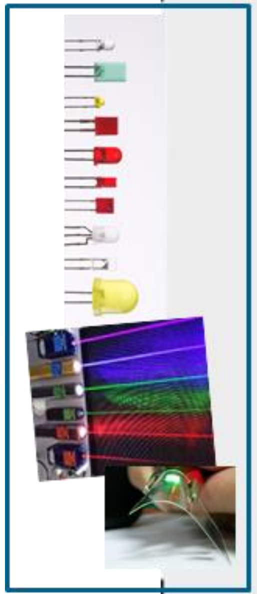
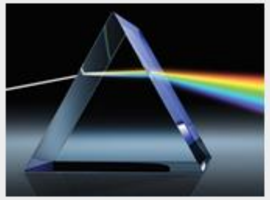
- **Way out of this dilemma?**

Physical-Optics System Modeling



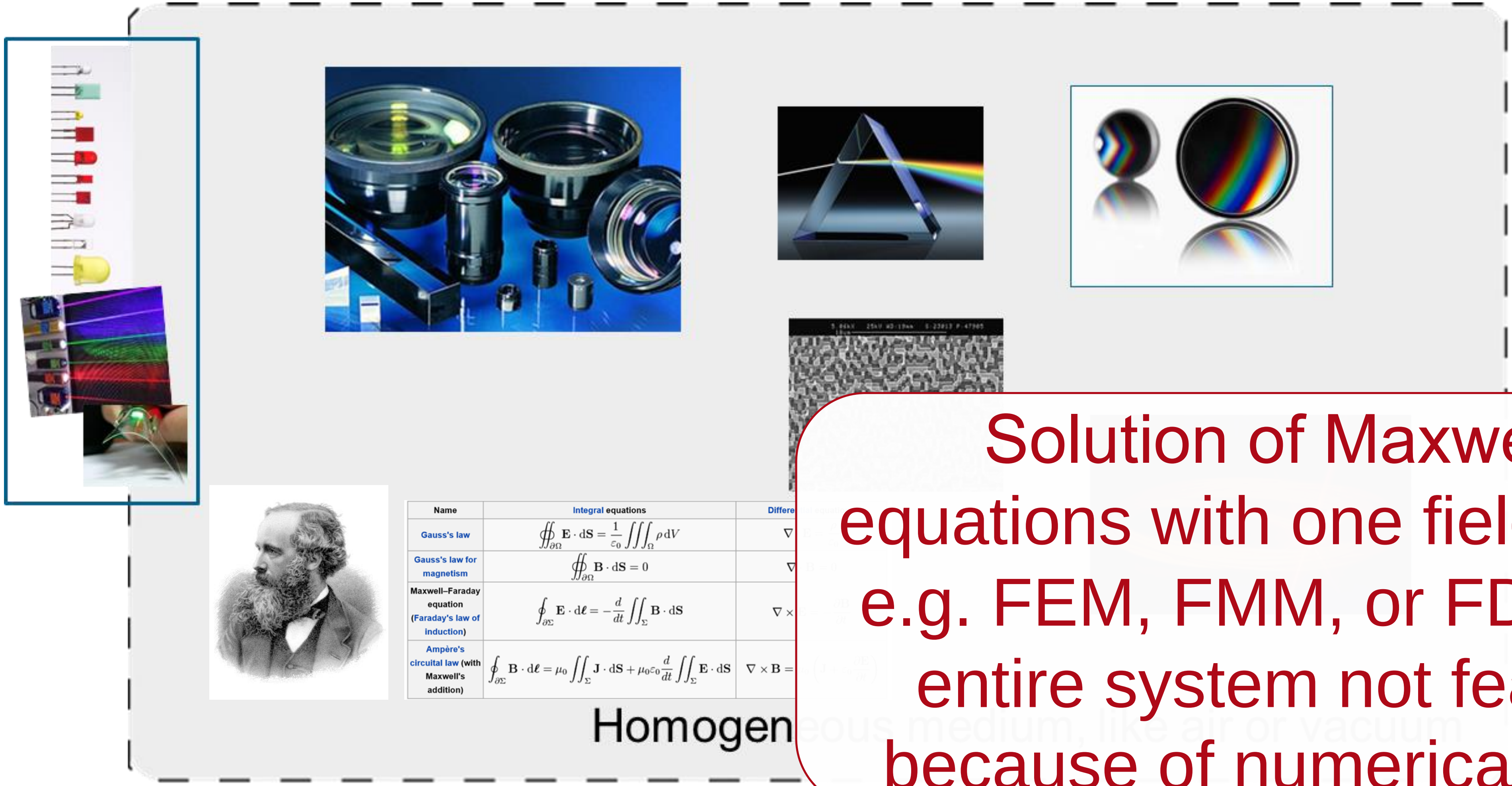


Name	Integral equations	Differential equations
Gauss's law	$\oint\!\!\oint_{\partial\Omega} \mathbf{E}\cdot \mathrm{d}\mathbf{S} = \frac{1}{\varepsilon_0}\iiint_\Omega \rho\,\mathrm{d}V$	$\nabla\cdot\mathbf{E} = \frac{\rho}{\varepsilon_0}$
Gauss's law for magnetism	$\oint\!\!\oint_{\partial\Omega} \mathbf{B}\cdot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

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

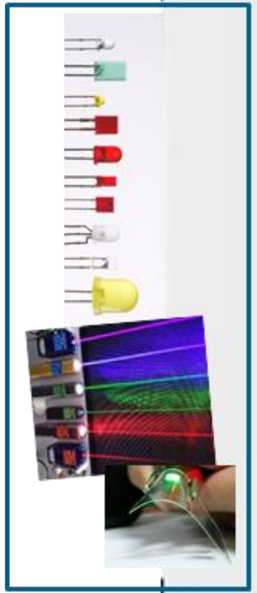
Homogeneous medium, like air or vacuum

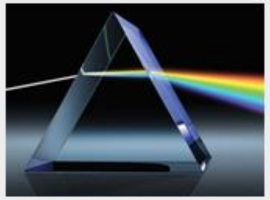
Physical-Optics System Modeling



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

Fast Physical-Optics System Modeling





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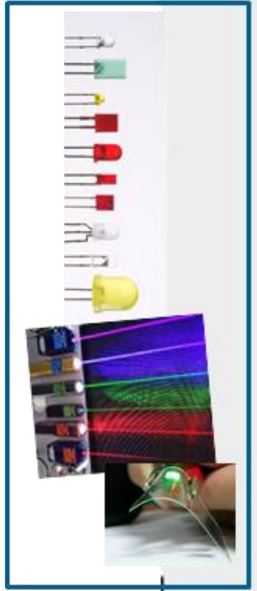
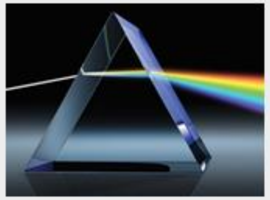
Homog

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

Fast Physical-Optics System Modeling





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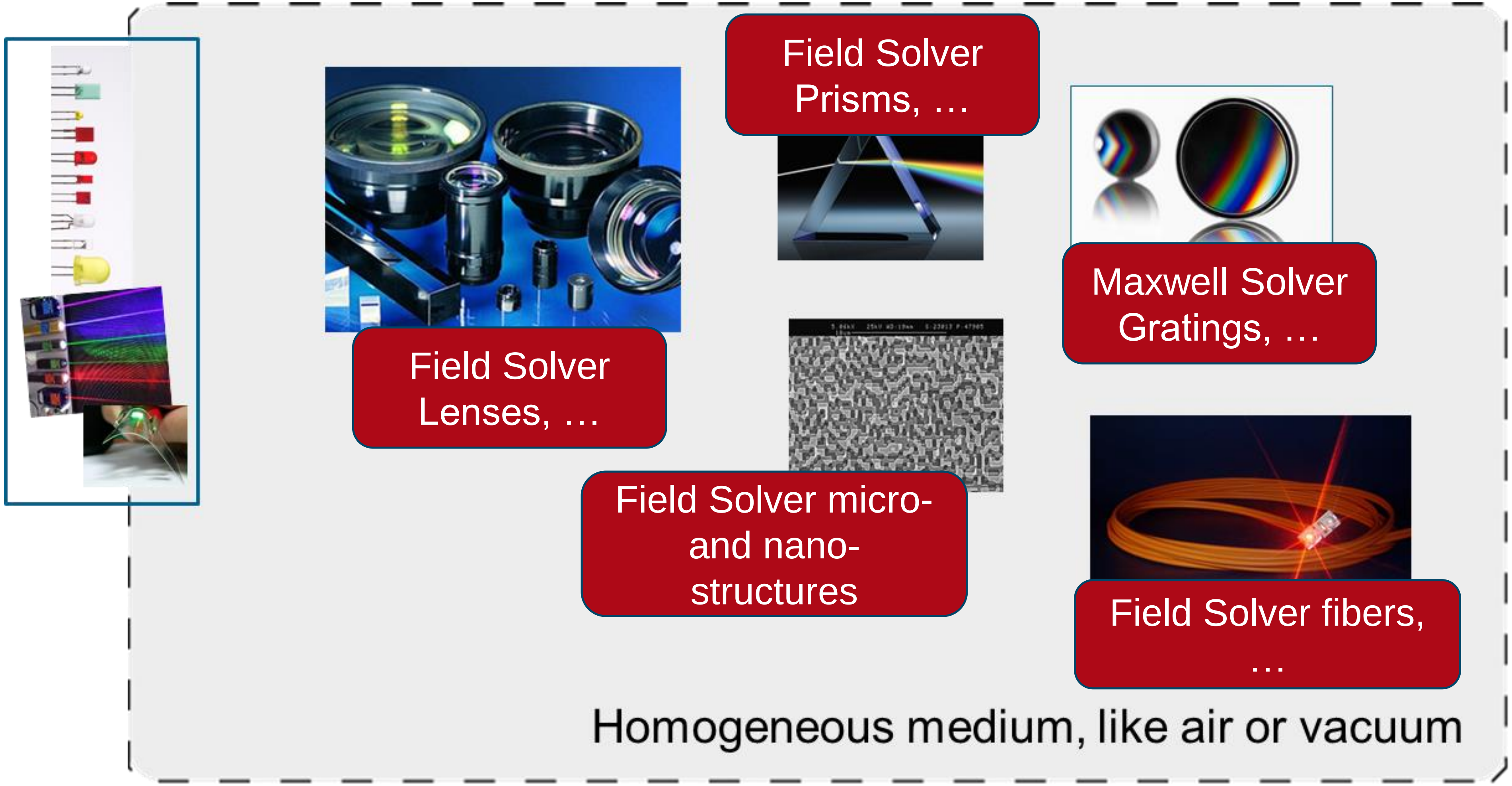
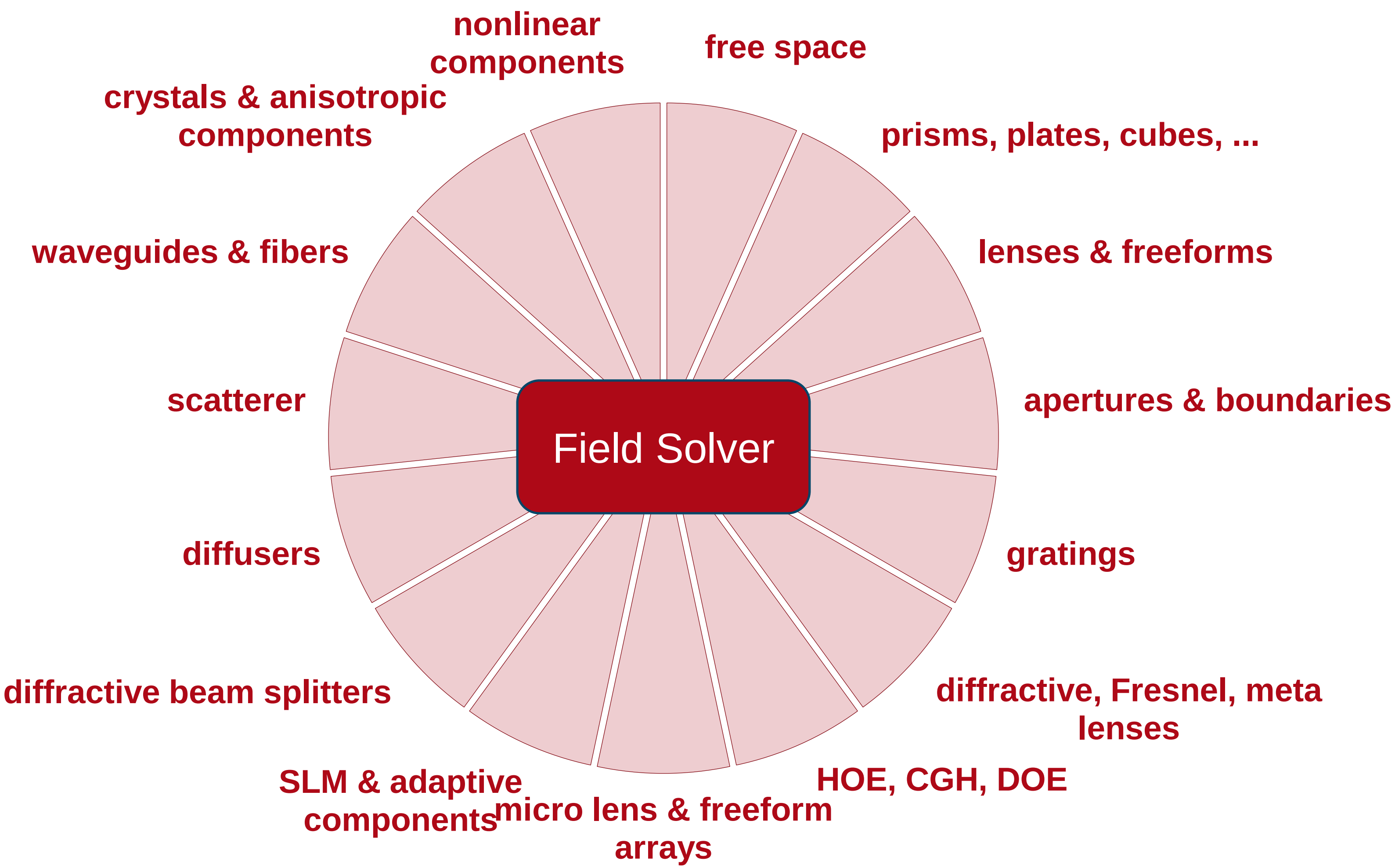
Homogeneous medium, like air or vacuum

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

Physical-Optics System Modeling: Regional Field Solver



Physical-Optics System Modeling: Regional Field Solver



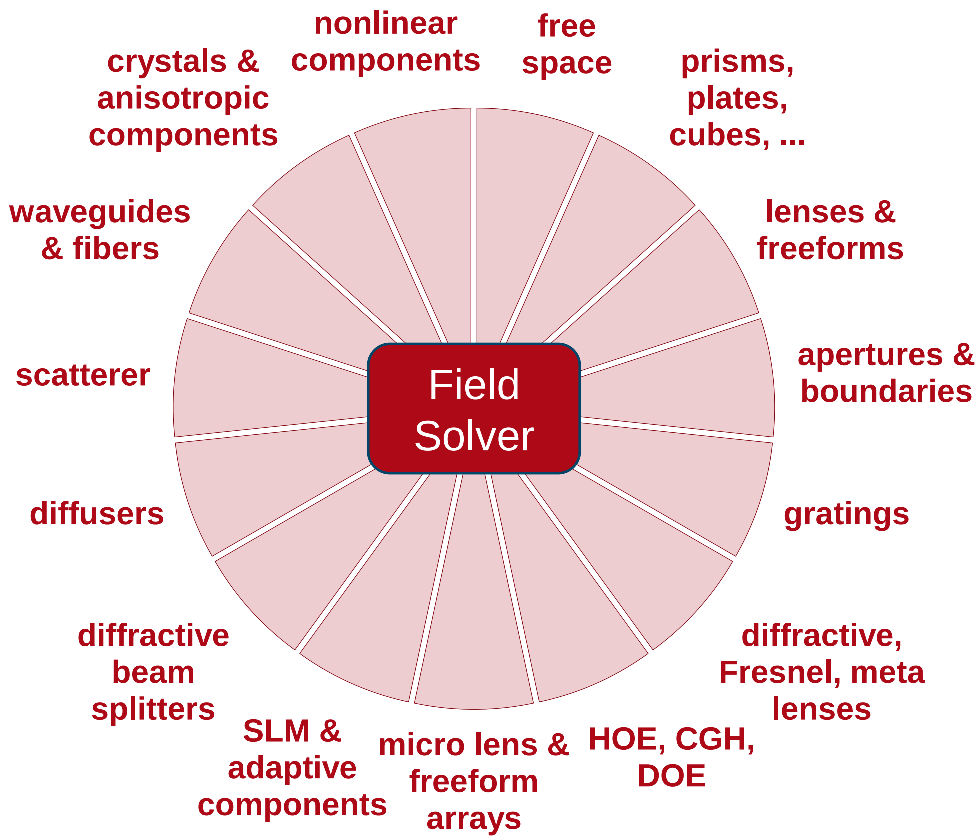
Tearing and Interconnection: Regional Field Solver

Problem:

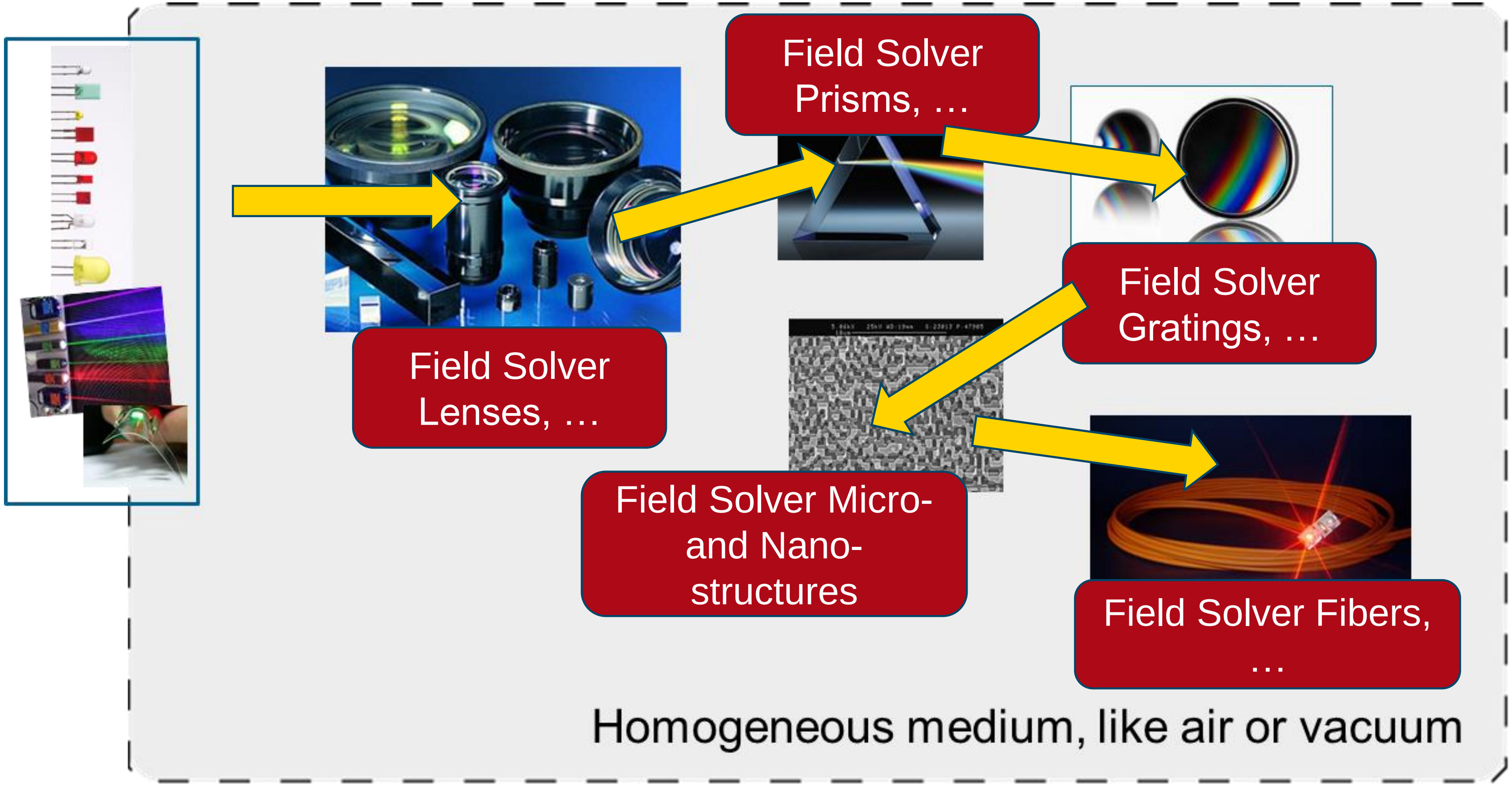
Application of a single field solver, e.g. FEM or FDTD, to the entire system: **Unrealistic numerical effort**

Solution:

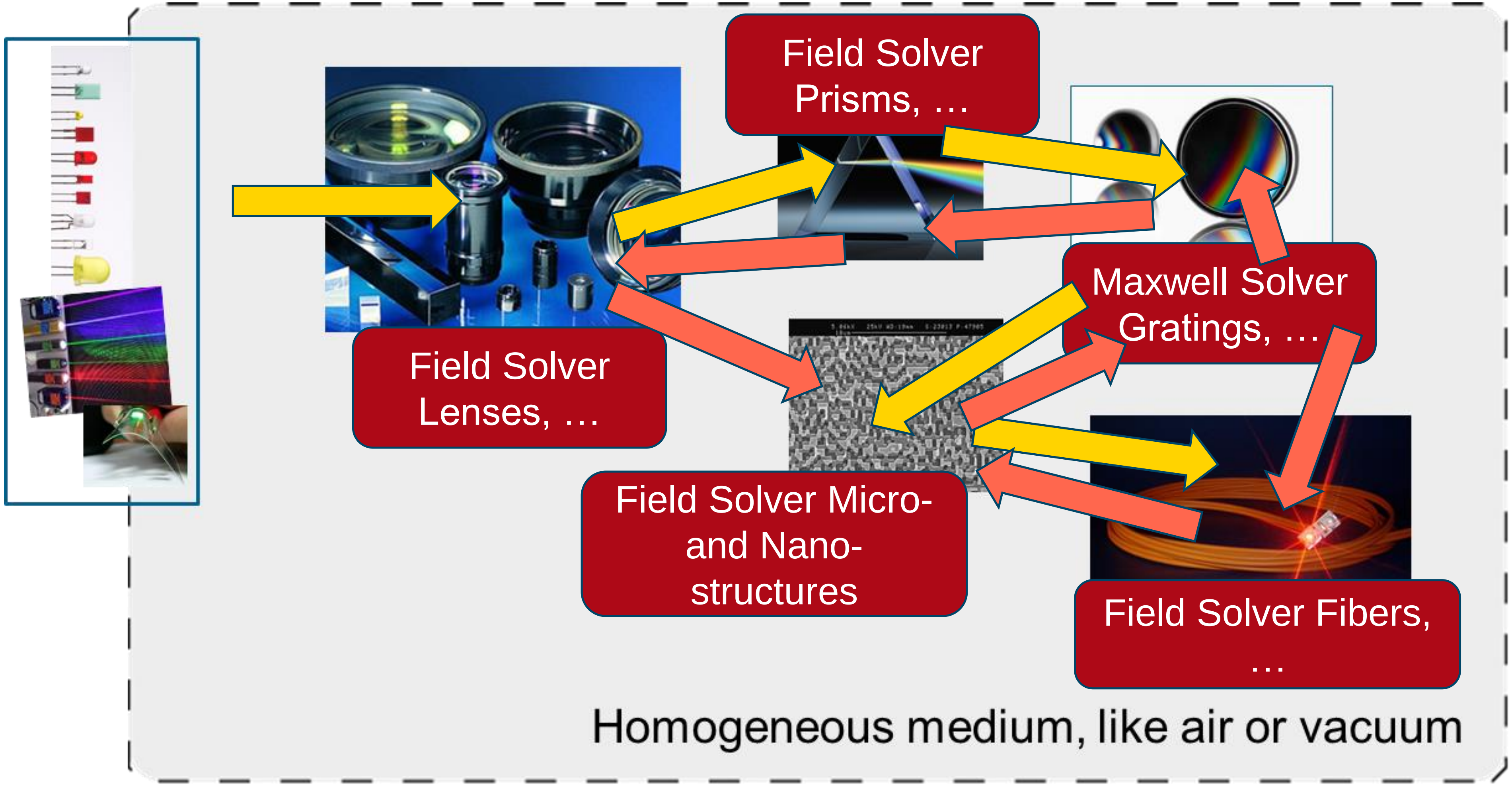
- Decomposition of system and application of regional field solver.
- Interconnection of solver: Channel concept and lightpath decomposition

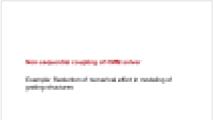


Sequential Connection of Regional Field Solver



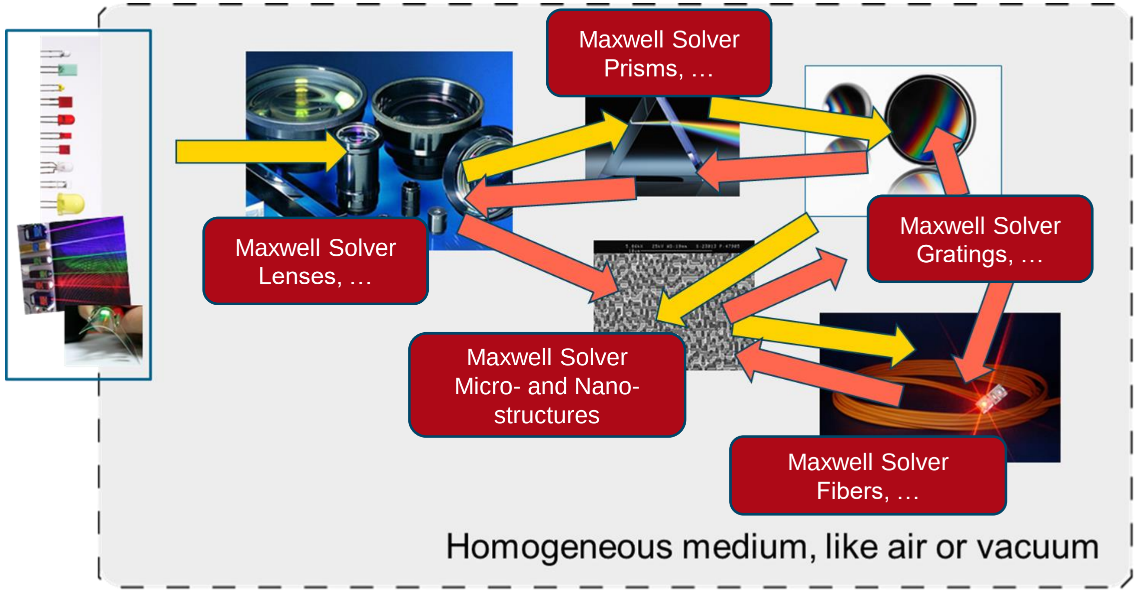
Non-Sequential Connection of Regional Field Solver





Non-sequential Modeling: Algorithm

- VirtualLab analyzes the lightpaths through a system by low sampled physical- optics modeling without diffraction effects at boundaries and apertures.
- Result of lightpath analysis: Set of all relevant (energy threshold) sequential lightpaths.
- Conclusion: VirtualLab decomposes non-sequential modeling into a set of sequential lightpath modeling.



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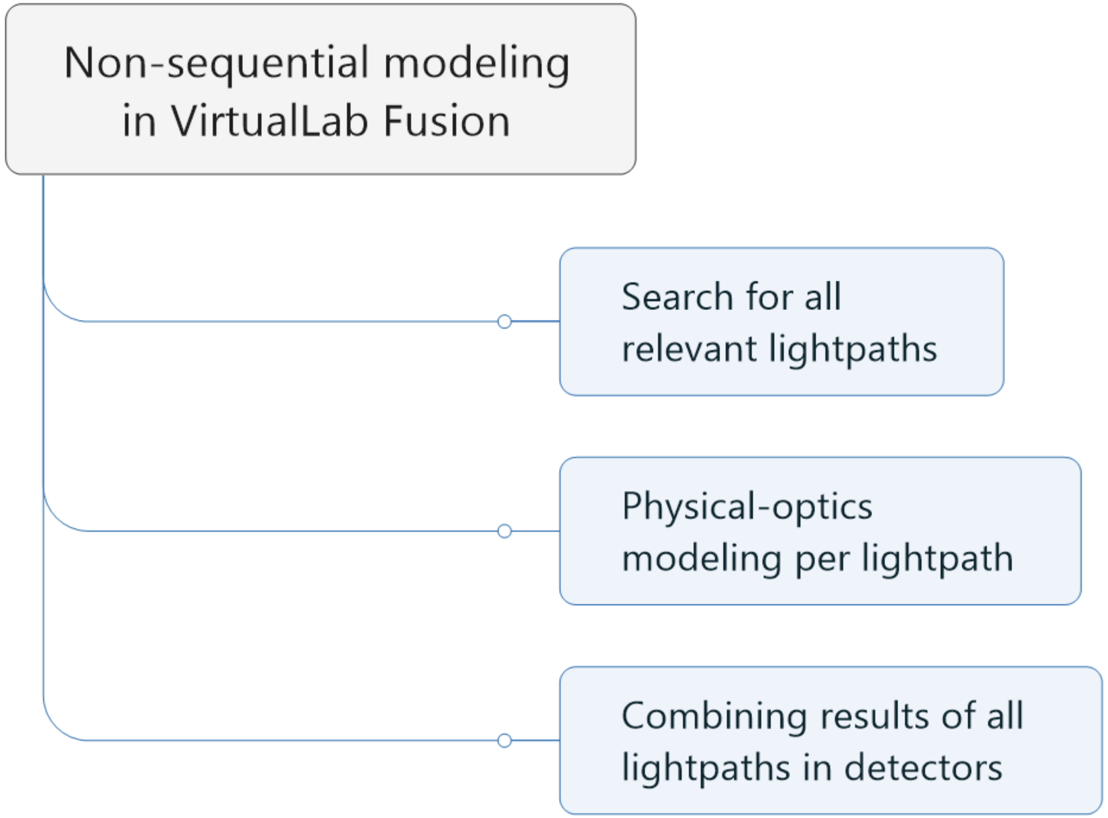

Non-sequential Modeling: Channel Concept

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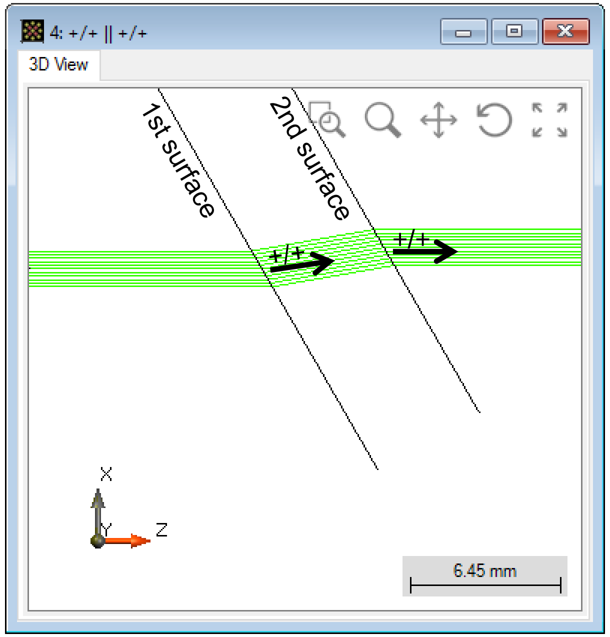
- Result of lightpath analysis: Set of all relevant (energy threshold) sequential lightpaths.
- Conclusion: VirtualLab decomposes non-sequential modeling into a set of sequential lightpath modeling.

- VirtualLab Fusion applies a sophisticated **optical channel concept** to enable the lightpath finder algorithm and by that fast physical optics.

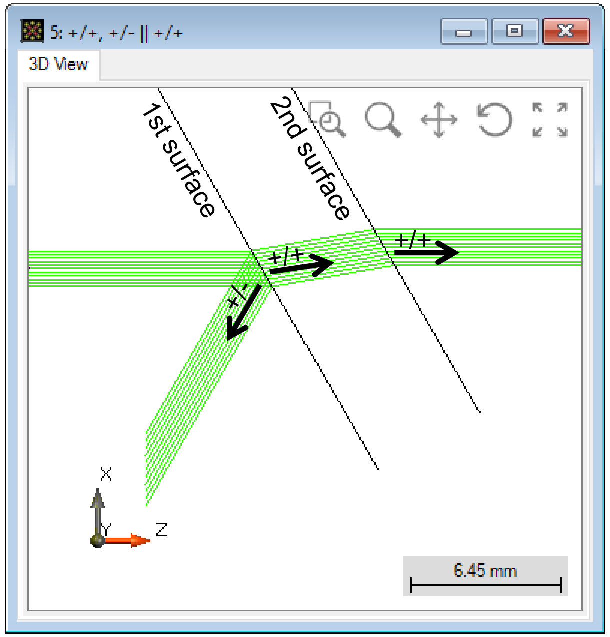
Surface Channels

Setting A



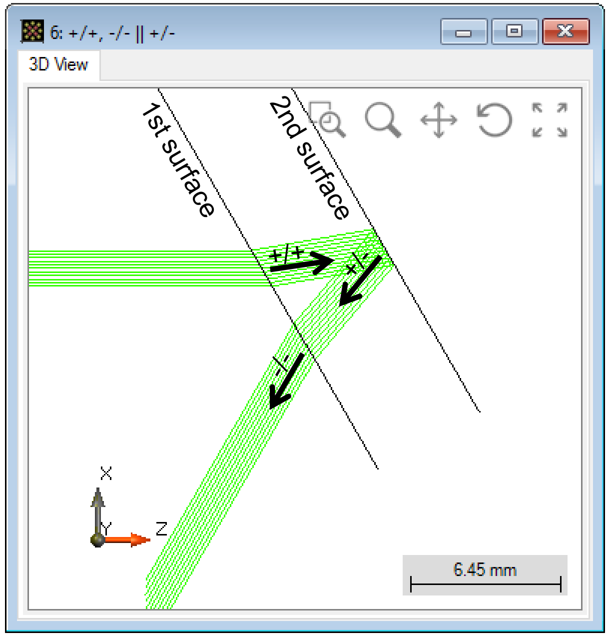
Surface	+/+	+/-	-/-	-/+
1st	×			
2nd	×			

Setting B



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

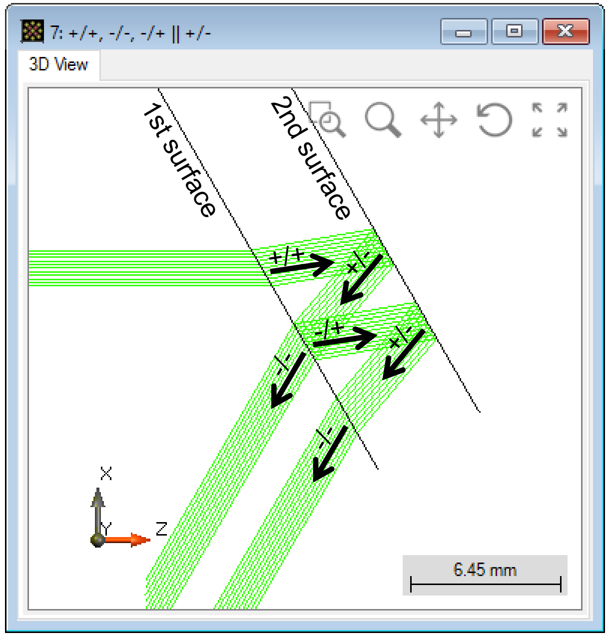
Setting C



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

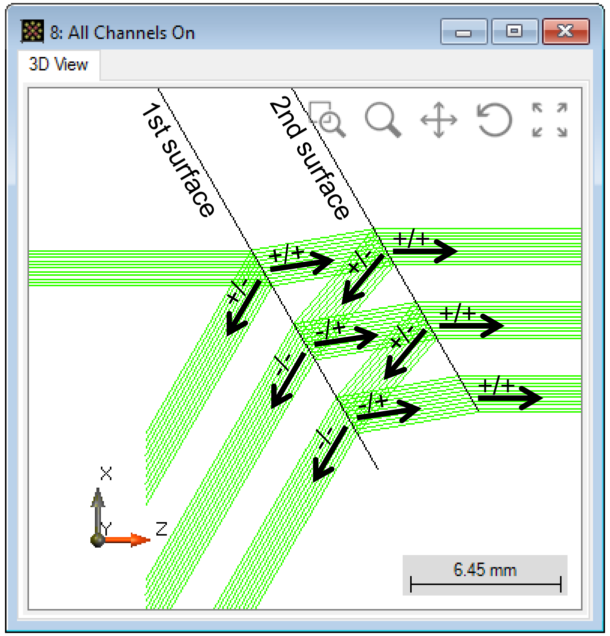
Surface Channels

Setting D



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

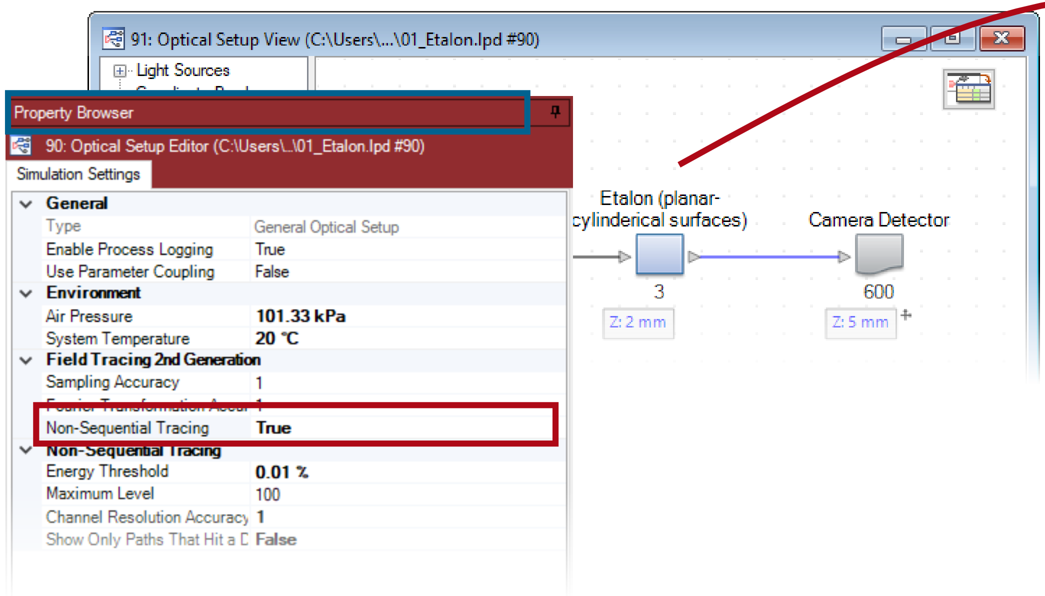
Setting E

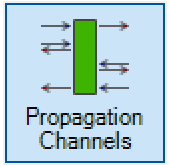


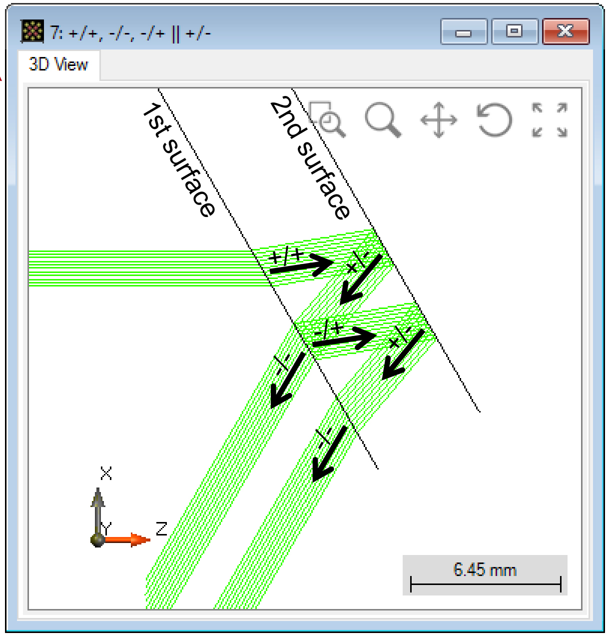
Surface	+/+	+/-	-/-	-/+
1st	×	×	×	×
2nd	×	×	×	×

Non-sequential Extension

- How to enable sequential and non-sequential tracing?



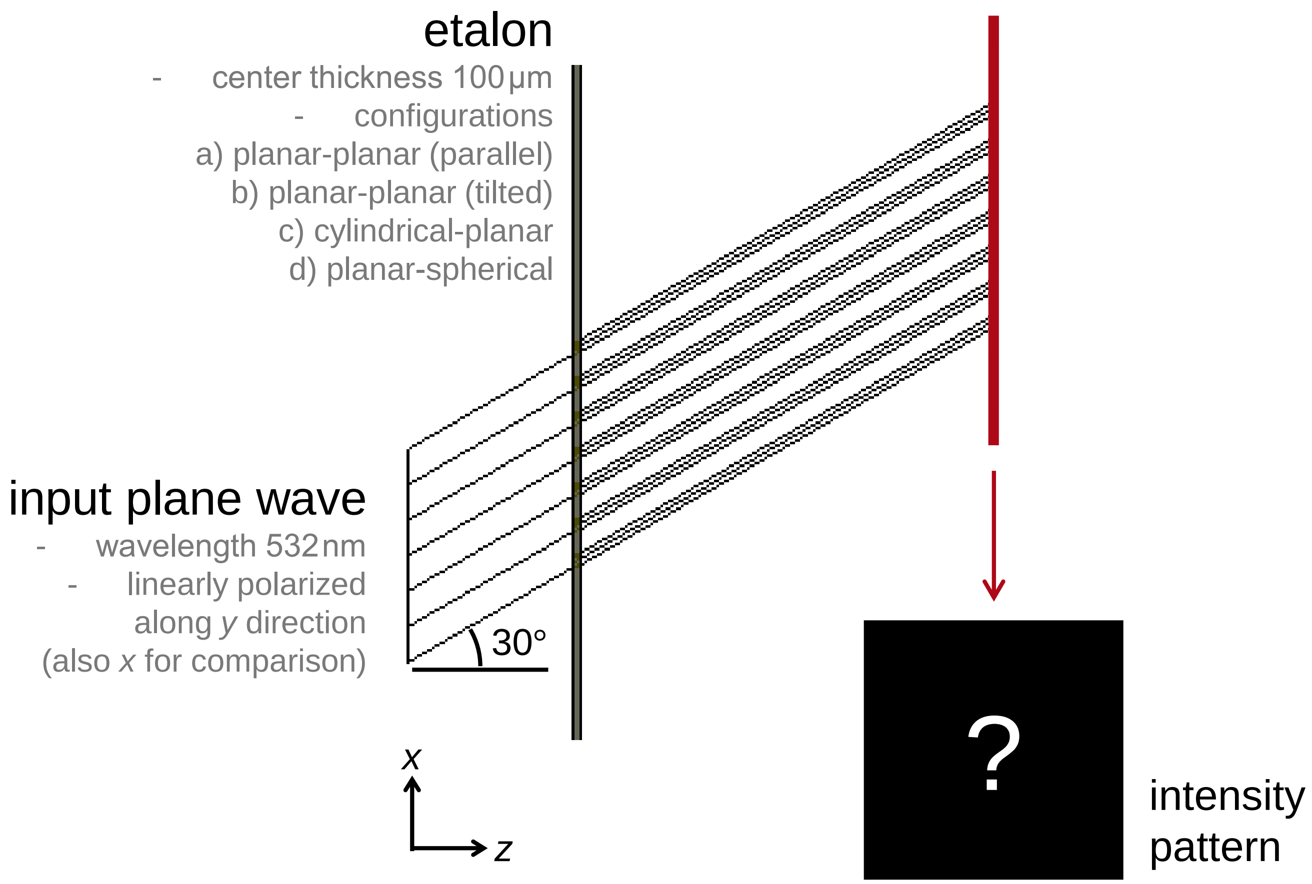




  - For each Optical Setup, enable the term *Non-Sequential Tracing*
  - Four channels can be chosen in each surface/component (+/+, +/-, -/-, -/+)

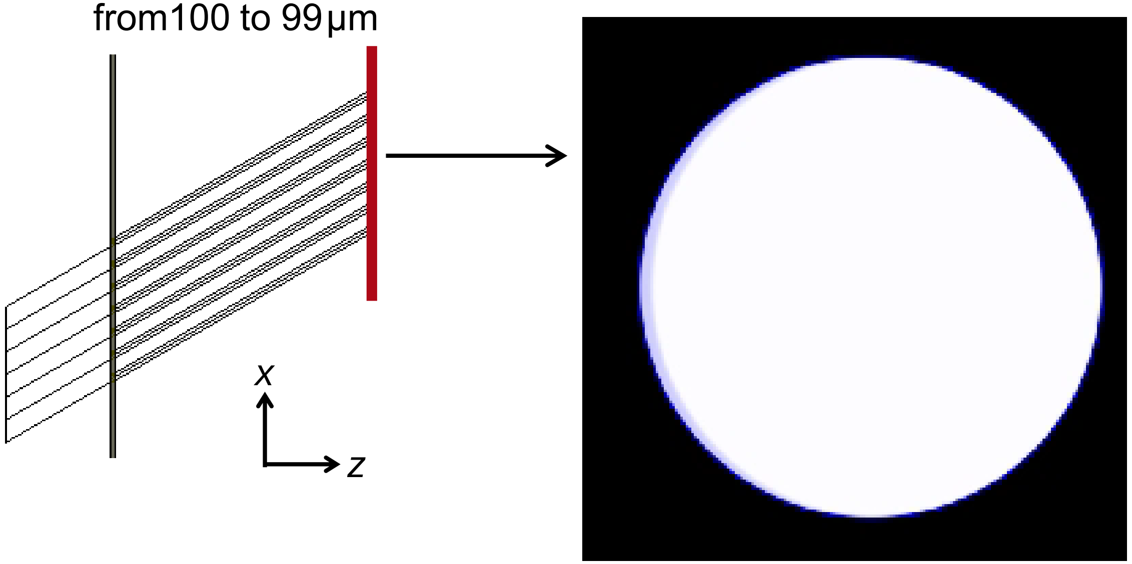
Surface	+/+	+/-	-/-	-/+
1st	×		×	×
2nd		×		

Modeling Task: Interference at Etalon



Results

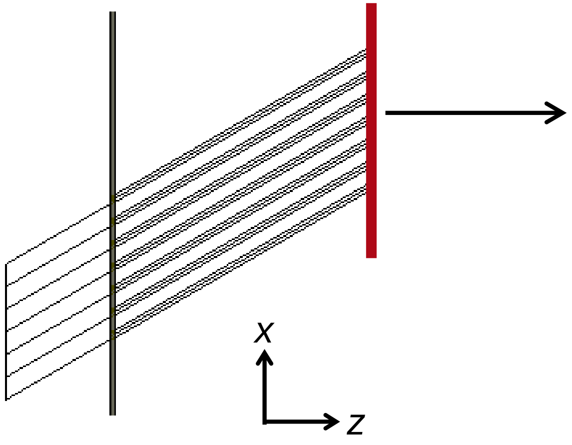
configuration
a) planar-planar (parallel)
- varying thickness from100 to 99 μm

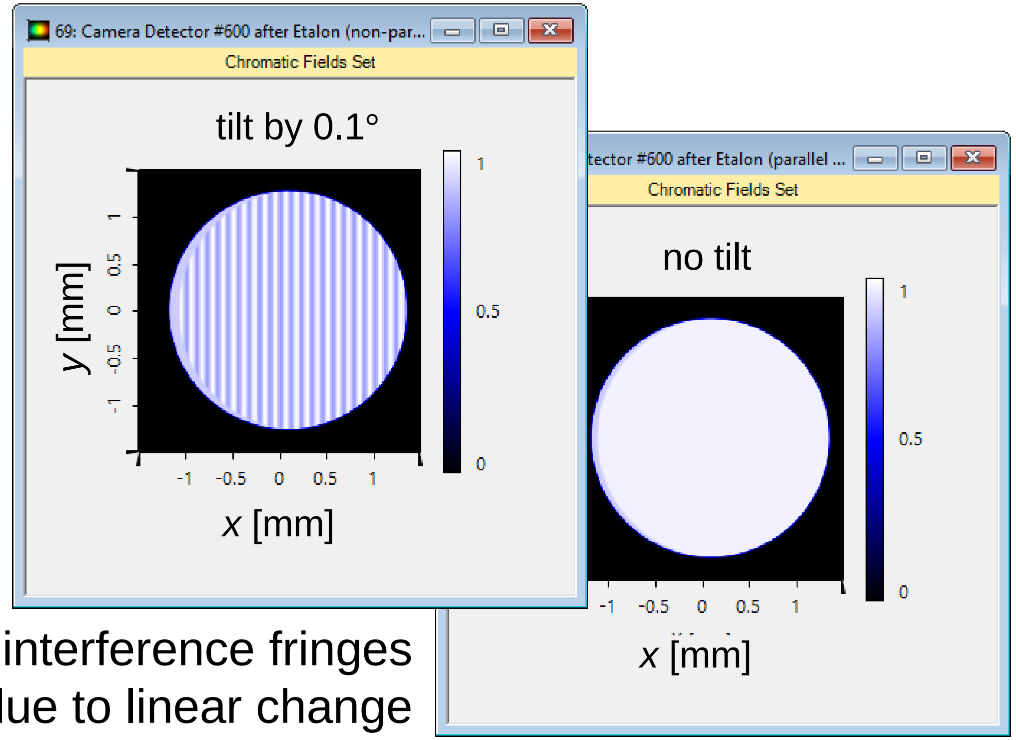


Constructive and destructive interference alternatively shows up when the thickness of etalon varies.

Results

configuration
b) planar-planar (non-parallel)
- center thickness 100 μm
- tilt of first surface

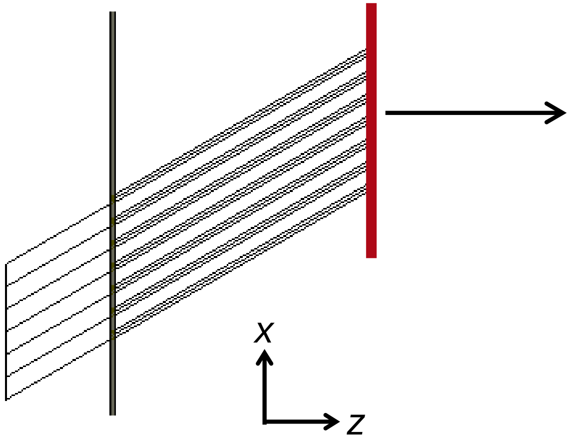


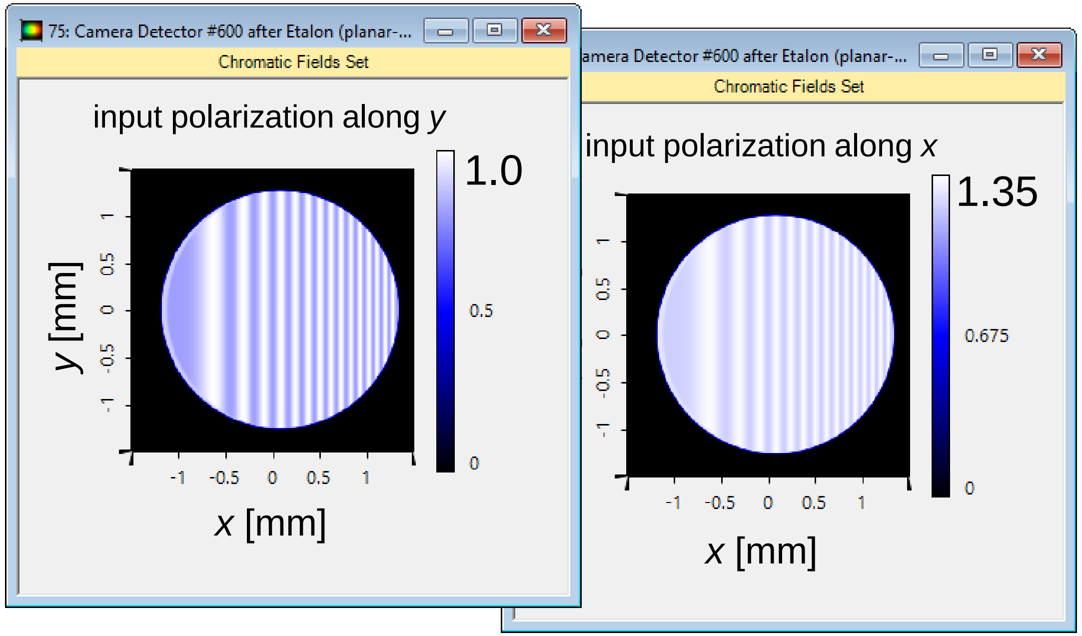


Linear interference fringes appear due to linear change of etalon thickness.

Results

configuration
c) cylindrical-planar
- center thickness 100 µm
- cylindrical surface radius 1 m

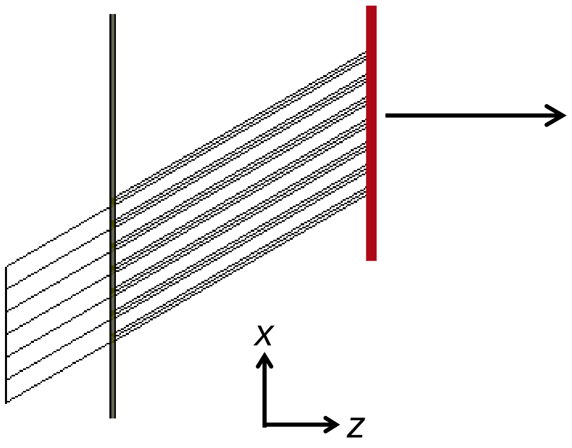


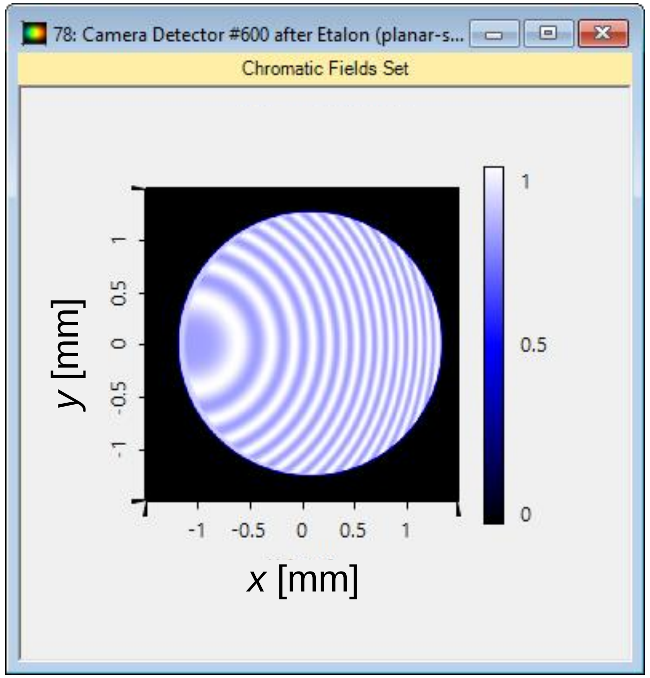


Polarization-dependent effect on the interference is taken into account.

Results

configuration
d) planar-spherical
- center thickness 100 µm
- spherical surface radius -1 m

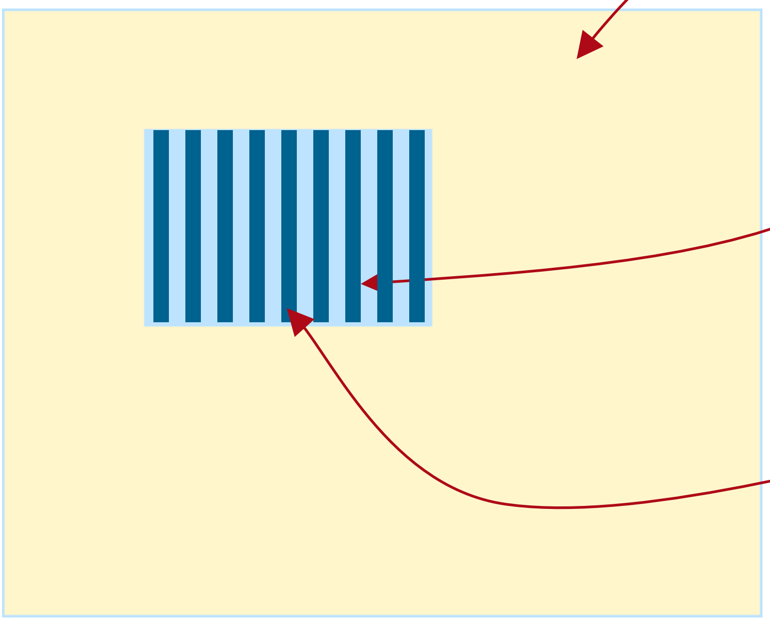




Non-sequential simulation of etalon with curved surfaces takes only 2 seconds.

Modeling of Etalon …

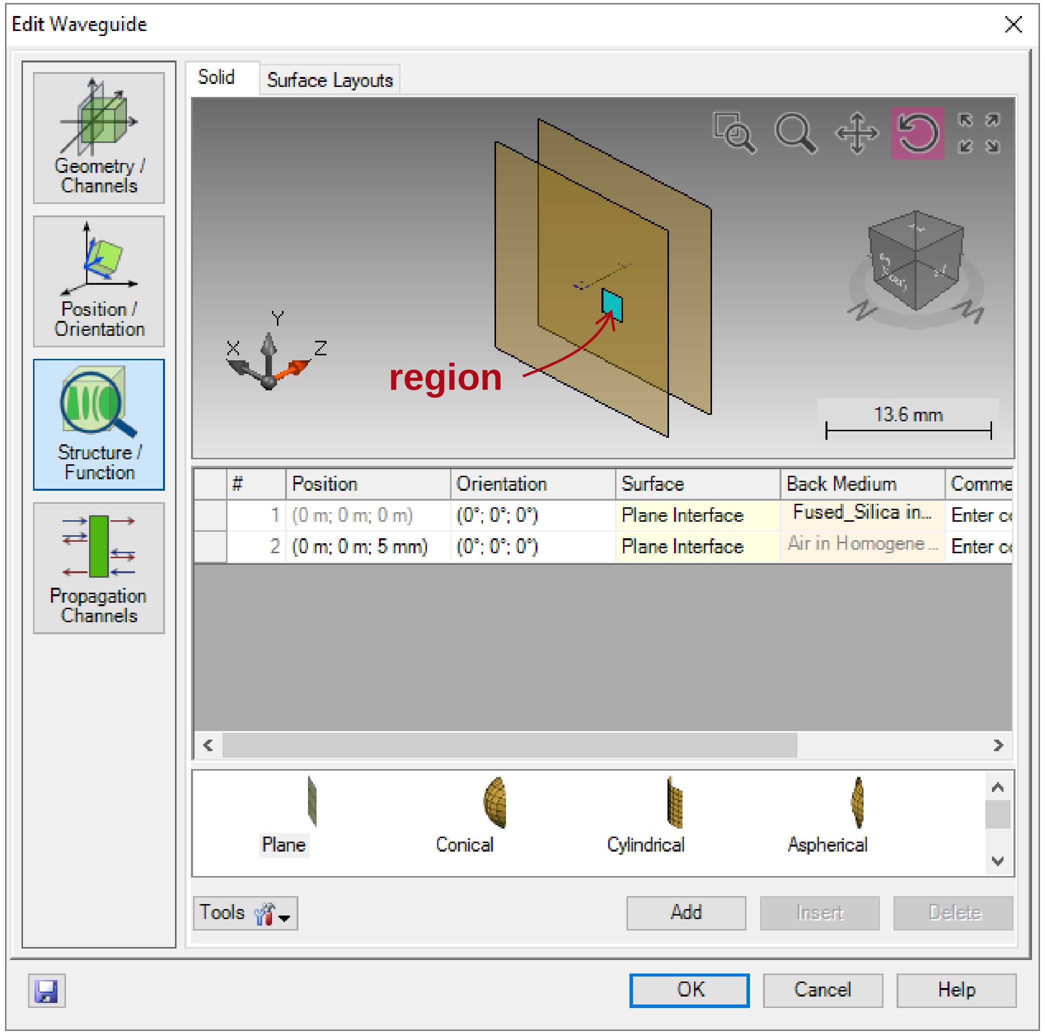
Surface Regions and Channels



- Surfaces have four default channels.
- On surfaces regions of any shape can be defined. Per region the four default channels can be chosen differently than for the entire surface.
- Per region ideal or real gratings, via. stacks, can be specified.
- Channel orders define channels.

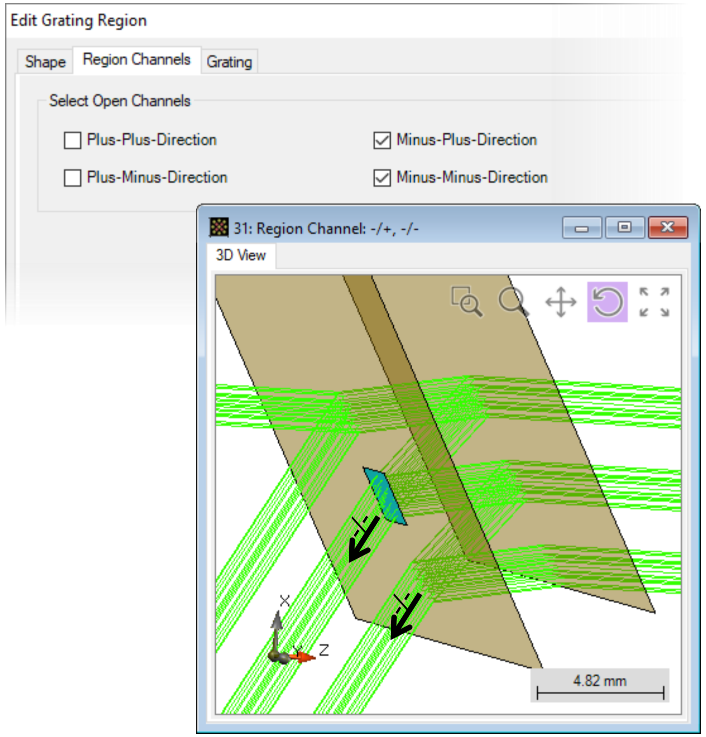
Region Channels

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



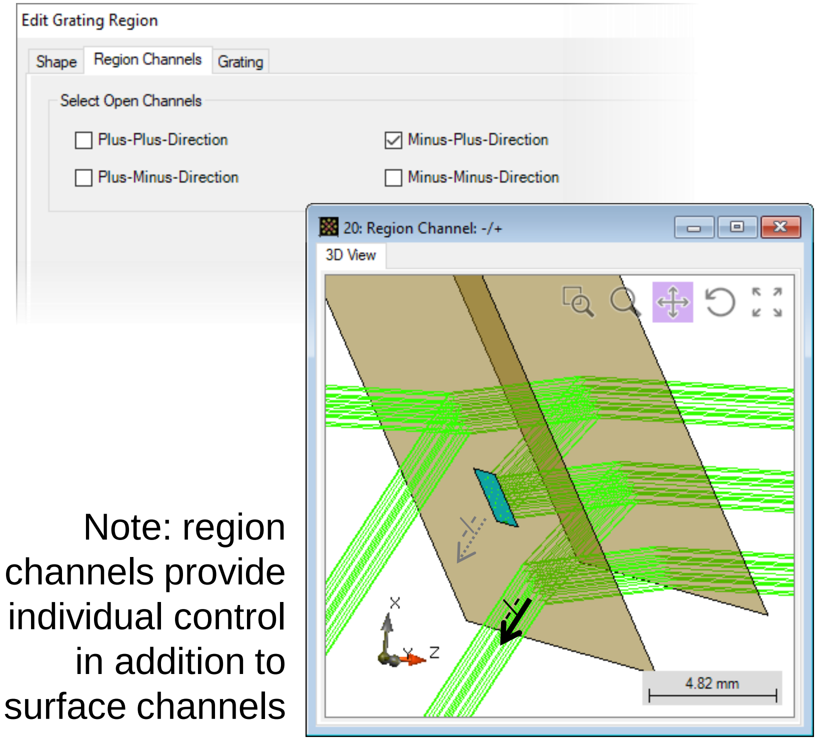
Region Channels

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



region channels -/+, -/- on

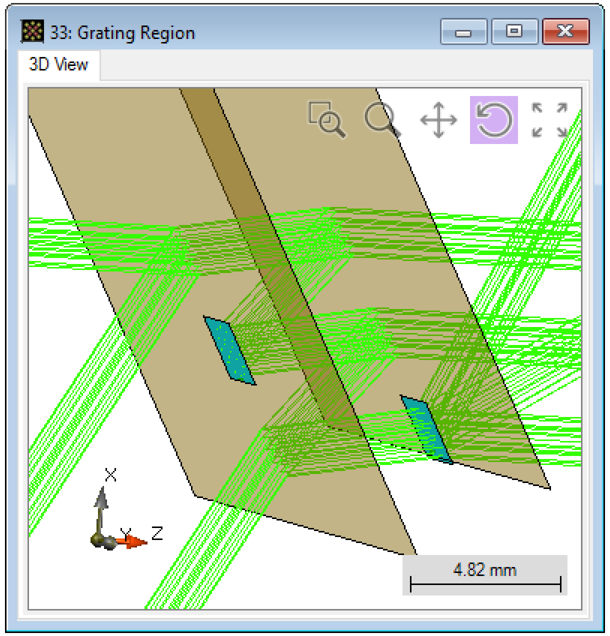
Note: region channels provide individual control in addition to surface channels



region channel -/+ on

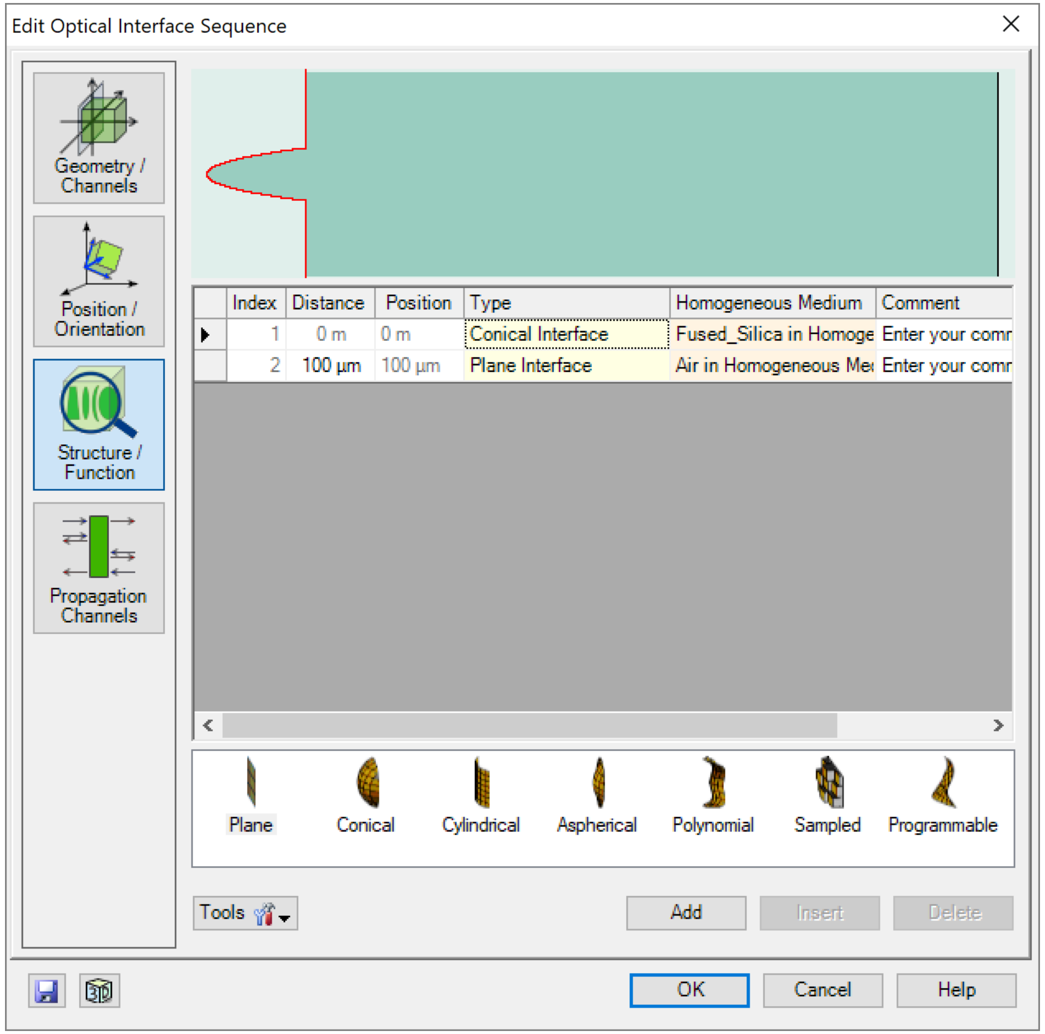
Region Channels with Grating

- Per region ideal and real gratings can be specified.
- Comments:
  - The shape of the regions can be chosen freely.
  - The region concept will be further extended in VirtualLab Fusion as a universonal surface add-on!



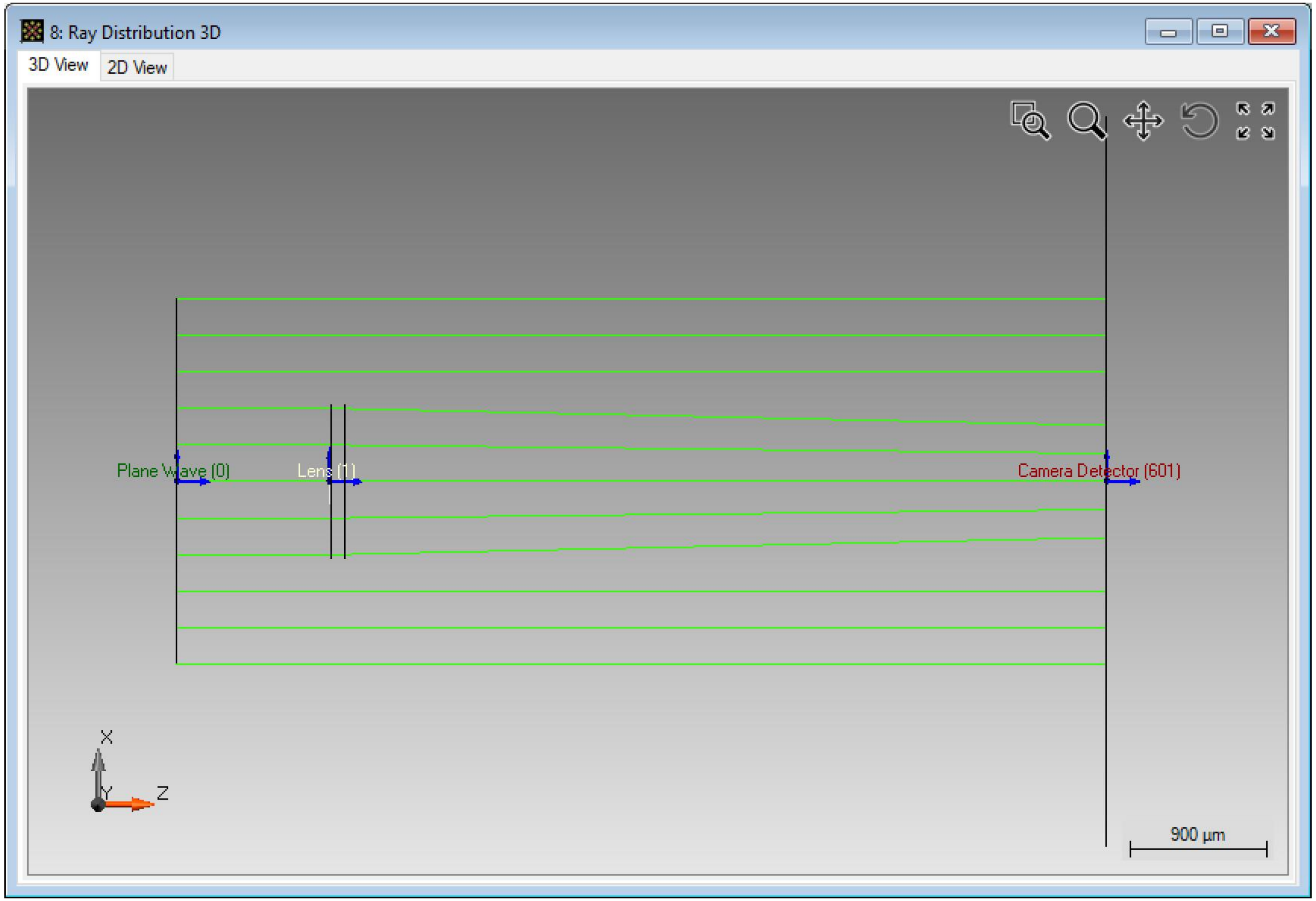
Region on surface 1: -/+ channel on
Region on surface 2: +/+ channel on
[with T0, T+1, T+2 diffraction orders]

Modeling Task: Microlens on Plate

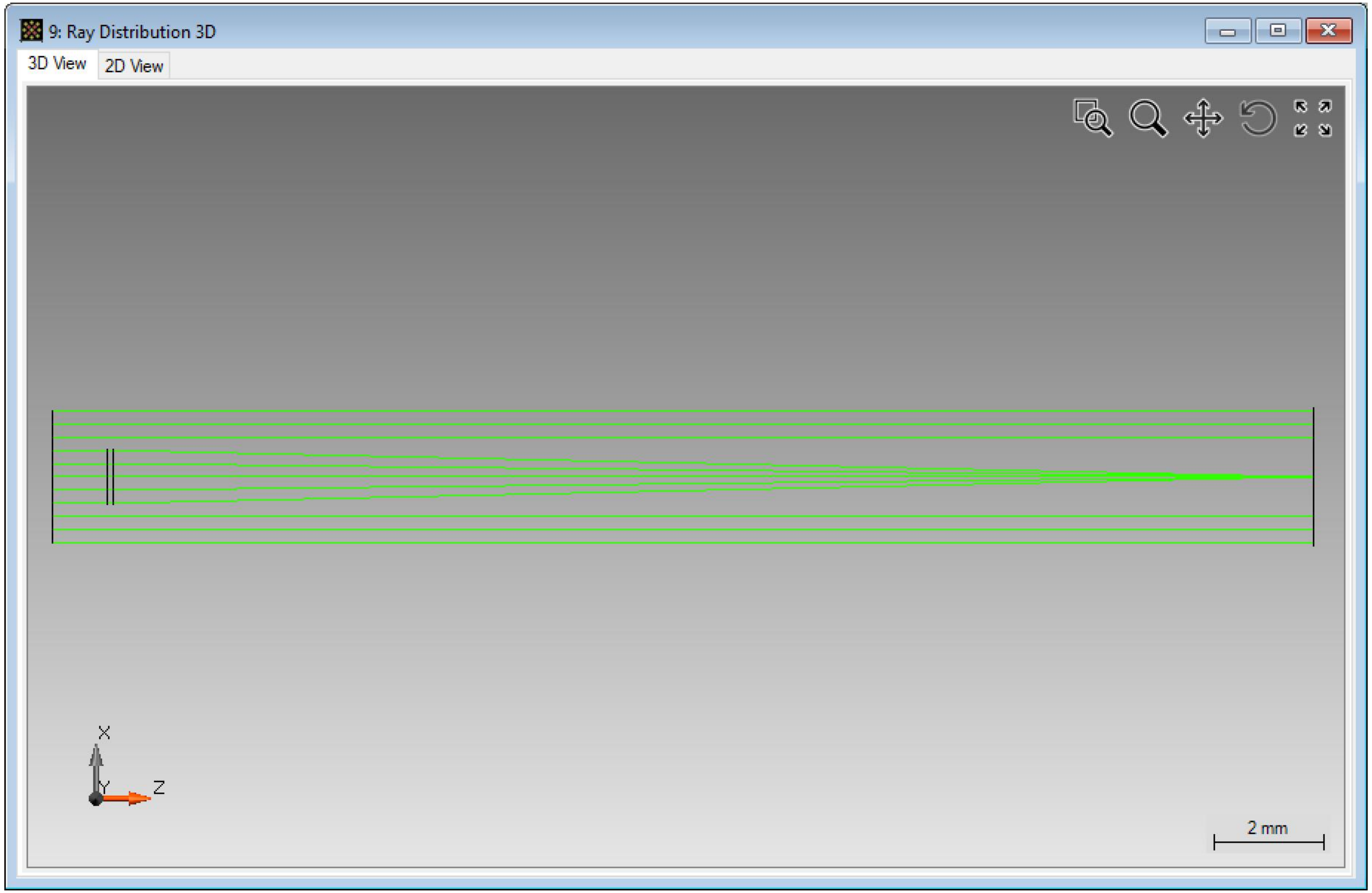


- A lens should be illuminated with a plane wave.
- The lens is smaller than the illuminating beam.
- Outside the lens the surface is planar and it is configured that the light paths the plane (no absorption).

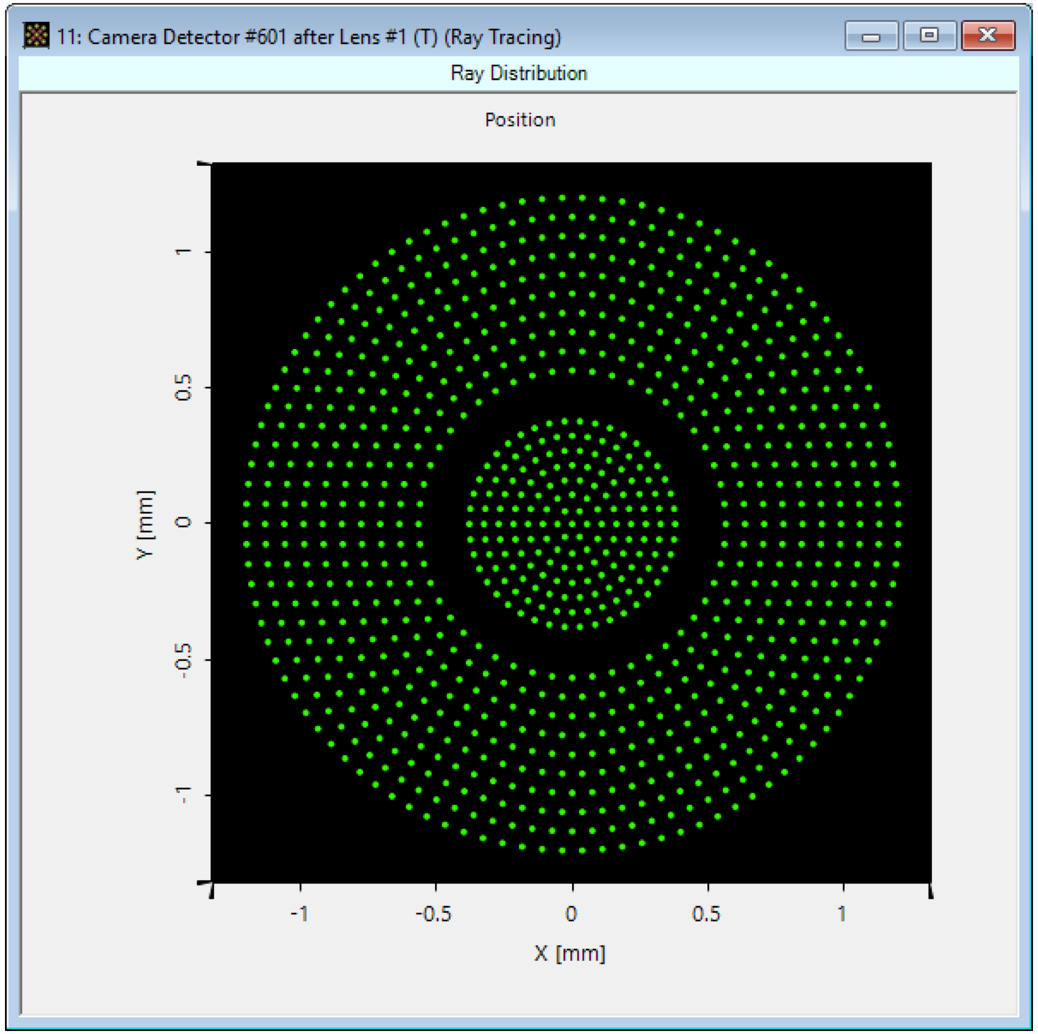
Ray Tracing Simulation (3D)

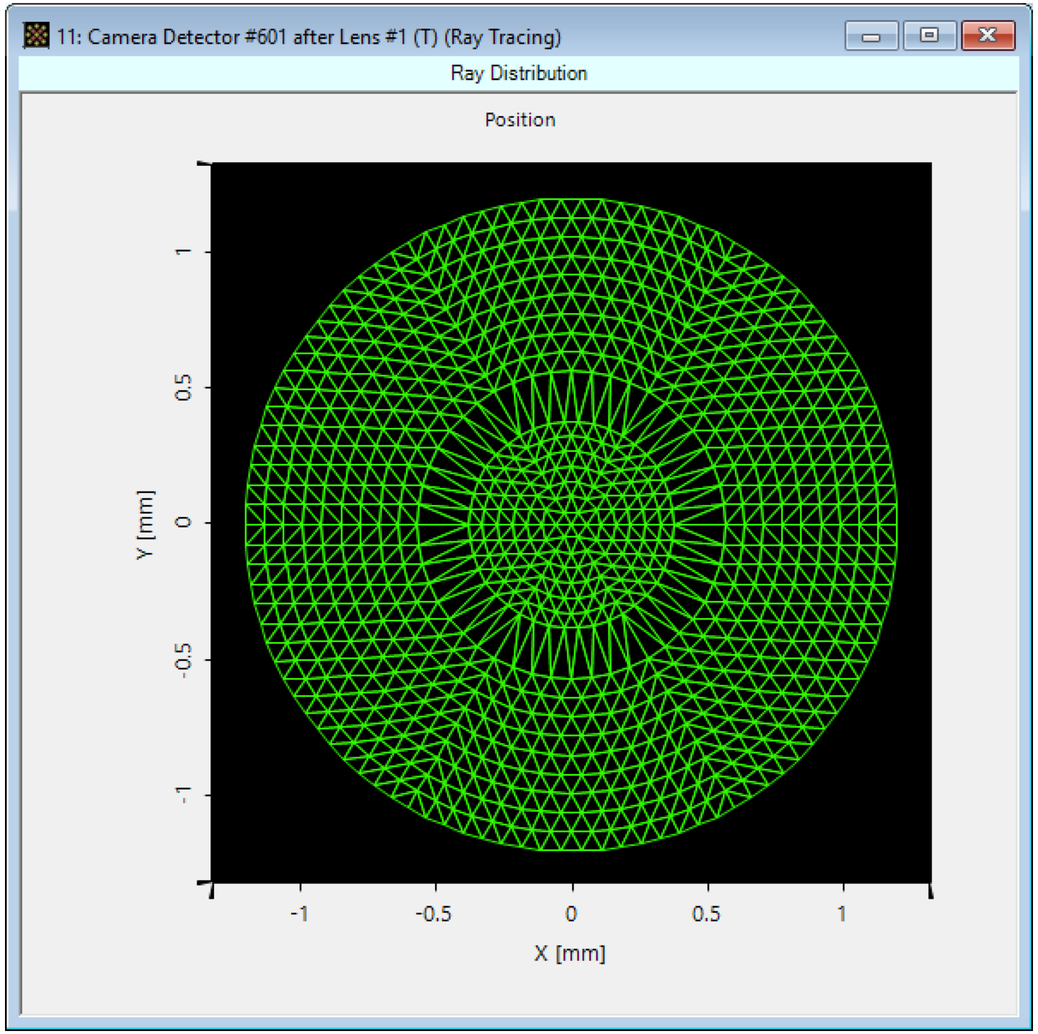


Ray Tracing Simulation (3D) - Focus

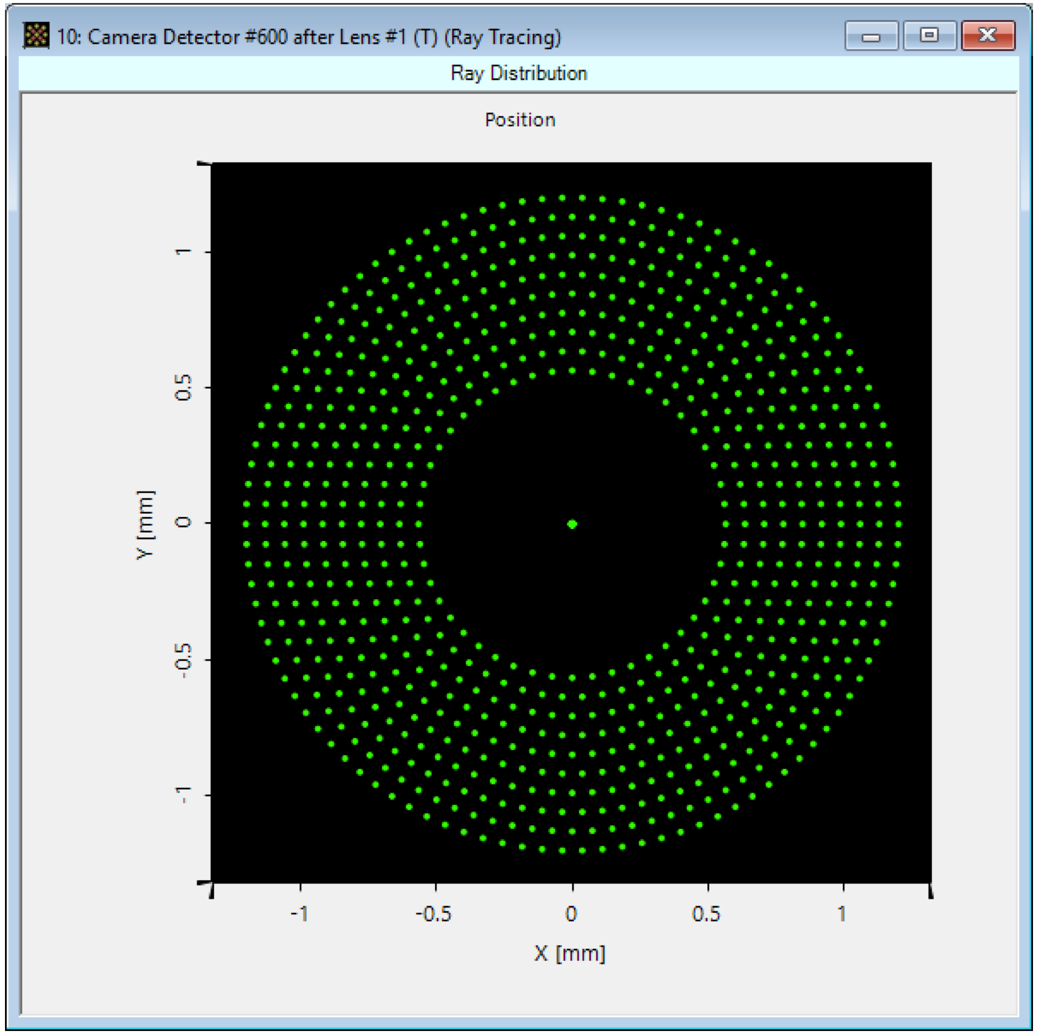


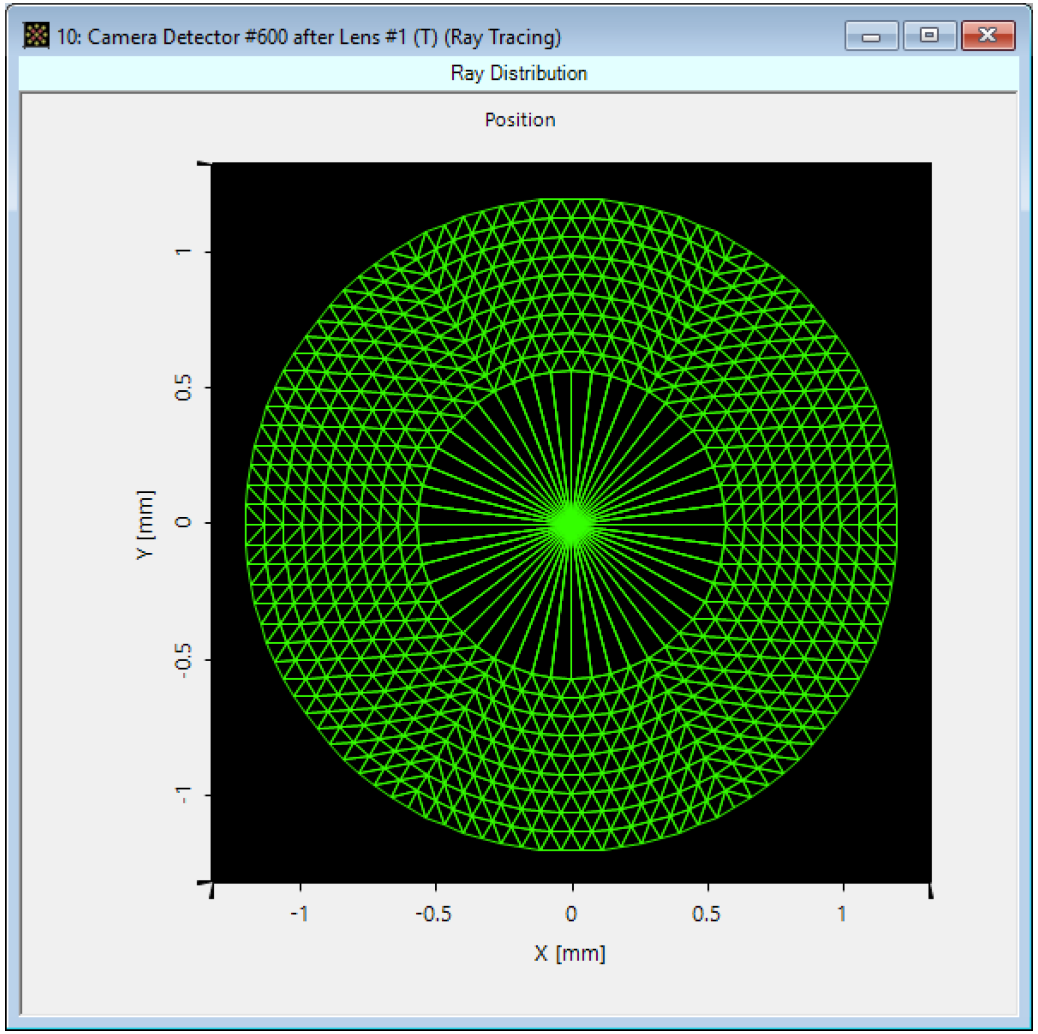
Ray Tracing Result (5mm behind Lens)



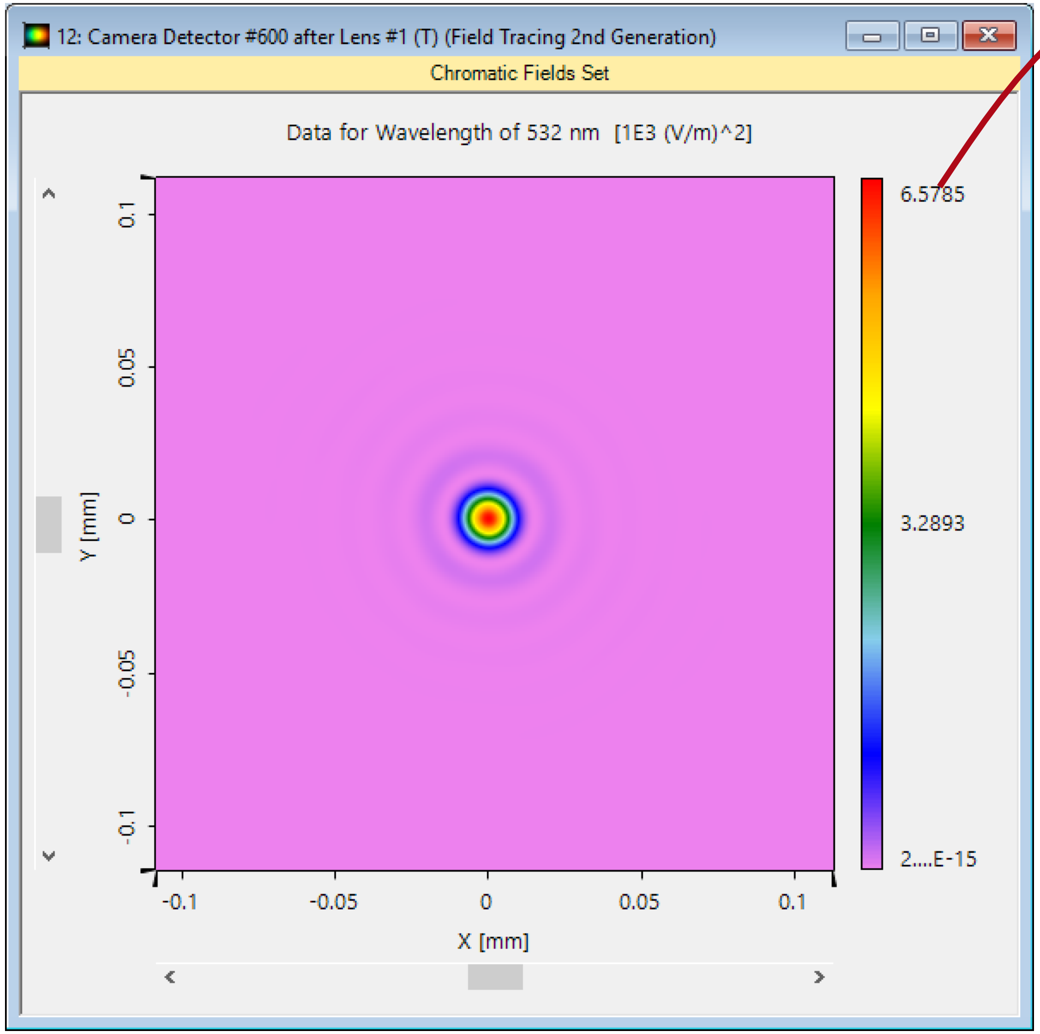


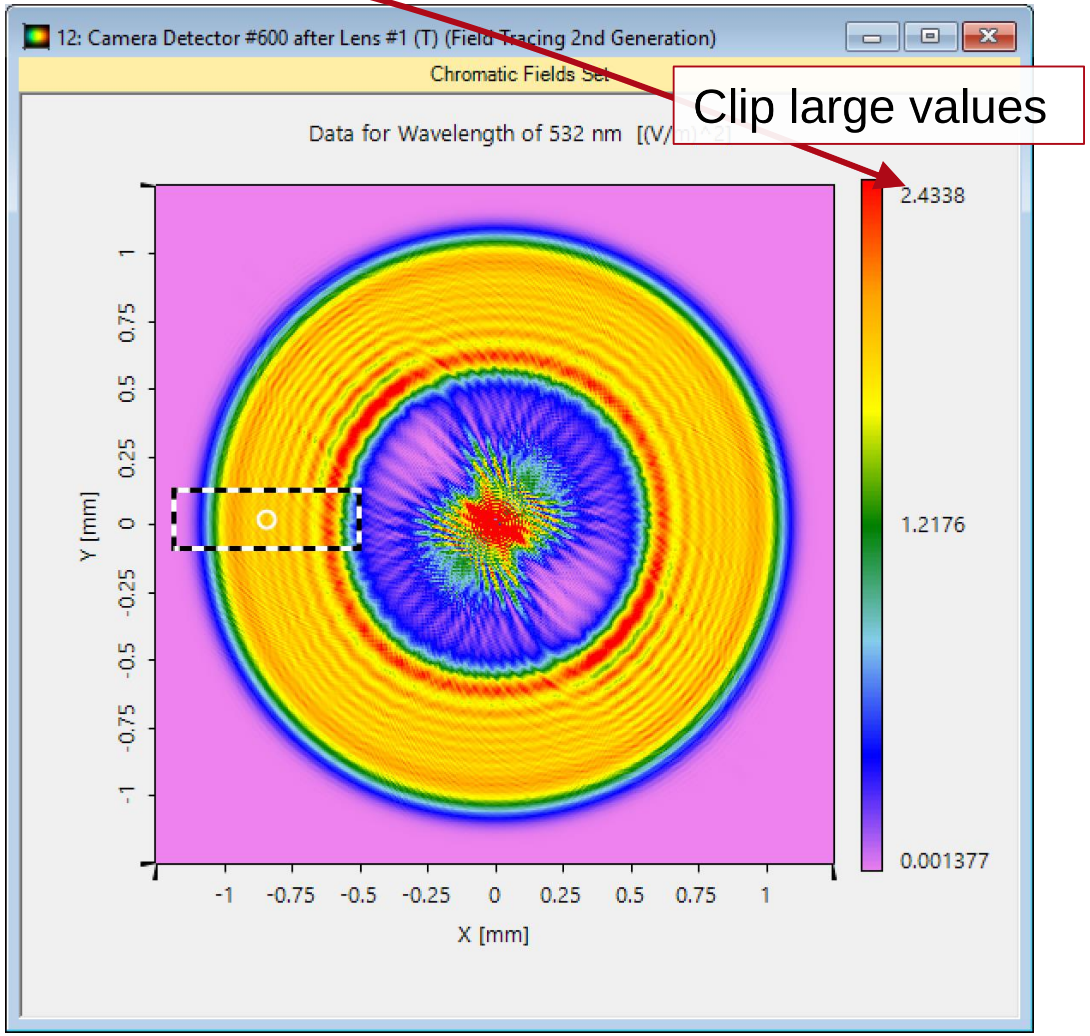
Ray Tracing Result (Focus)



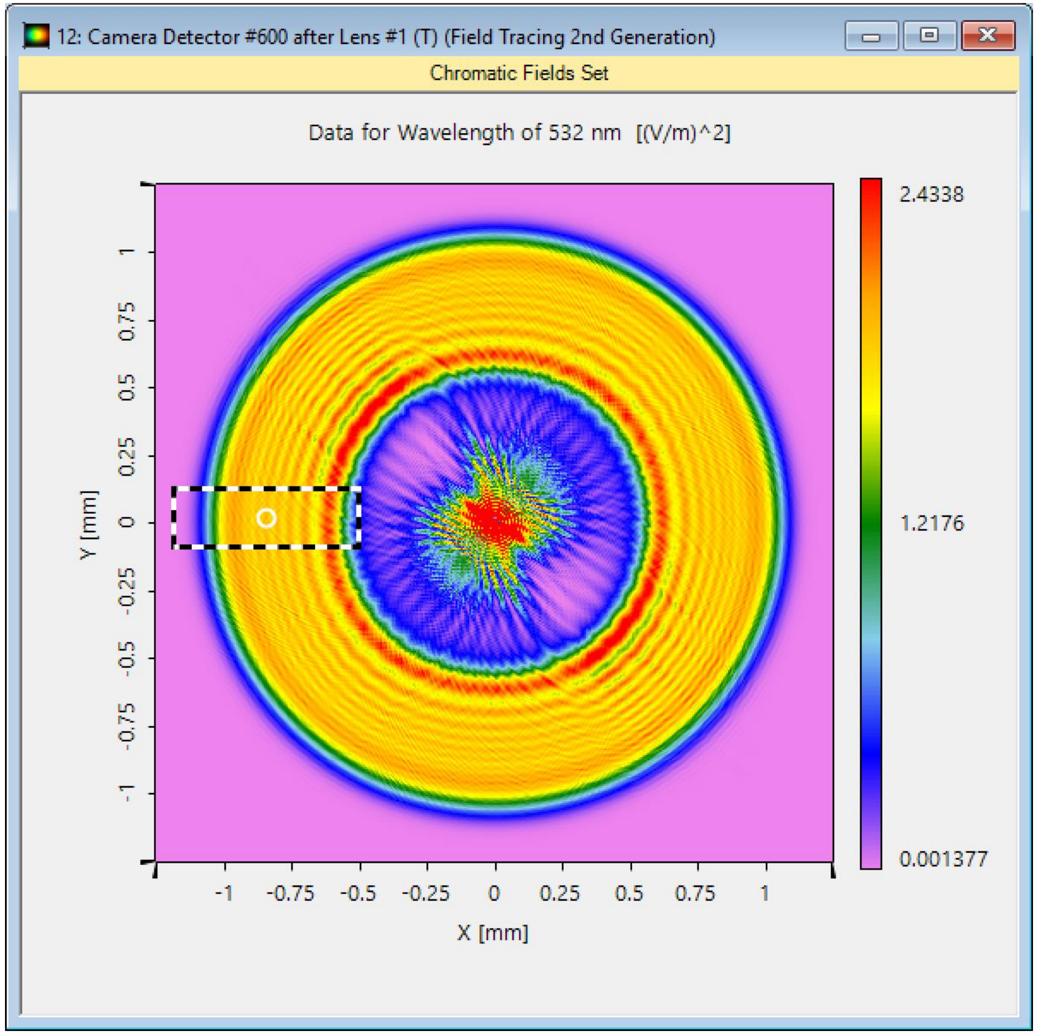


Field Tracing Result (Focus)



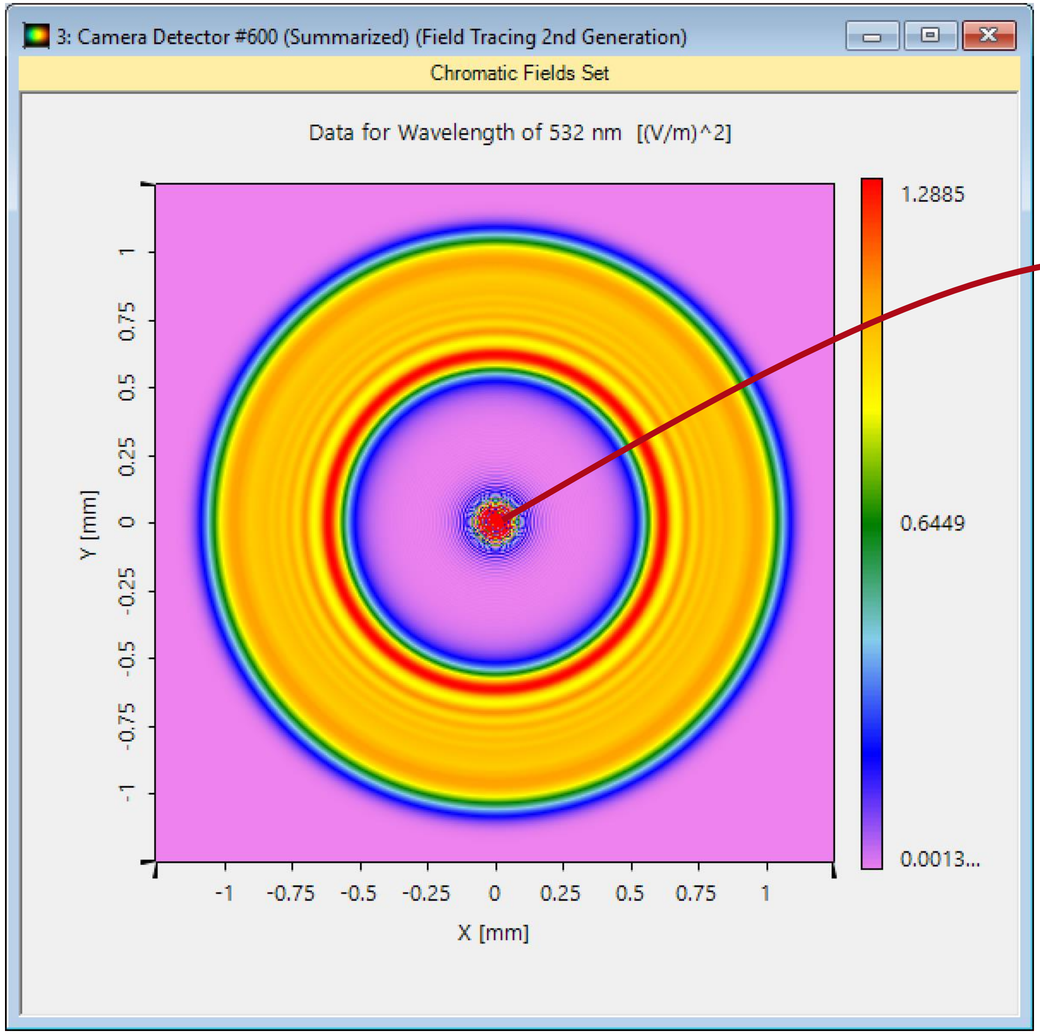


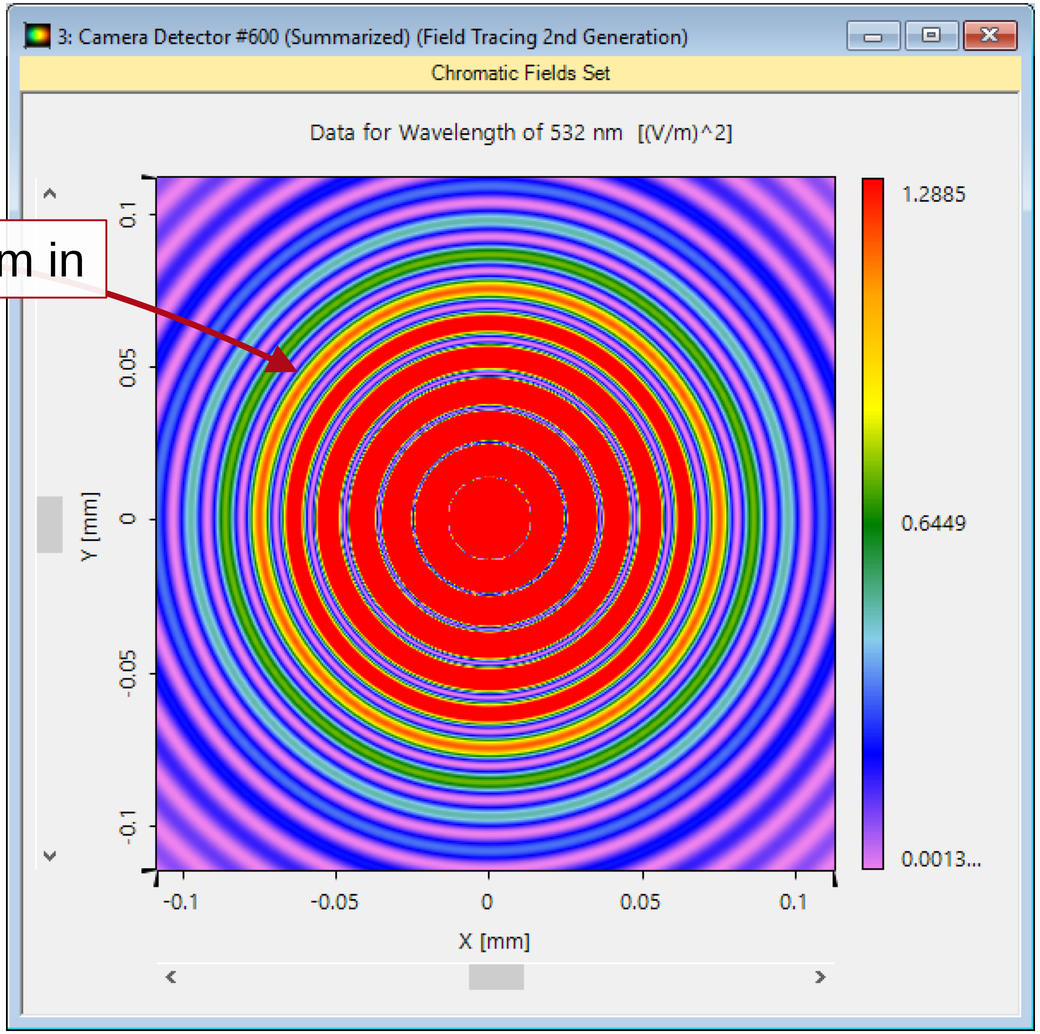
Field Tracing Result (Focus)



- This result is obtained by using one channel.
- Next, lens and plane surface are treated as two different channels.

Field Tracing Result (Focus) – Advanced Channel Handling



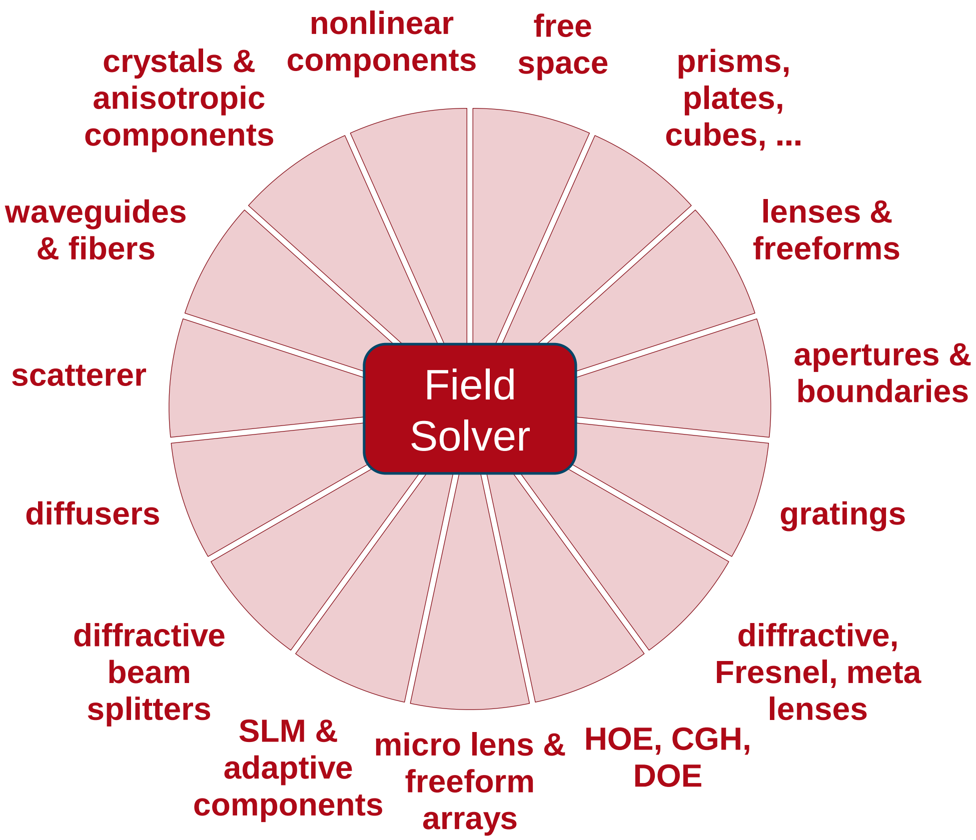


Zoom in

Tearing and Interconnection: Regional Field Solver

Problem:

Application of a single field solver, e.g. FEM or FDTD, to the entire system: **Unrealistic numerical effort**



Solution:

- Decomposition of system and application of regional field solver.
- Interconnection of solver: Channel concept and lightpath decomposition

Physical Optics Often Not Practical because …

- Source modeling by coherence functions with subsequent propagation by four dimensional integral operations: **Unrealistic numerical effort**
- Application of a single field solver, e.g. FEM or FDTD, to the entire system: **Unrealistic numerical effort**
- Field operations of order $O(N^2)$ and higher: **Typically high numerical effort**
- Nyquist sampling of complex field amplitudes: **Often results in high sampling number N**
- Physical optics modeling in one coordinate system: **Often results in high sampling number N**

- Physical optics is typically understood as to be too complex, slowly and in general not feasible in practical tasks.
- However, the need for it is growing!
- **Way out of this dilemma?**

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- However, the need for it is growing!
- **Way out of this dilemma?**

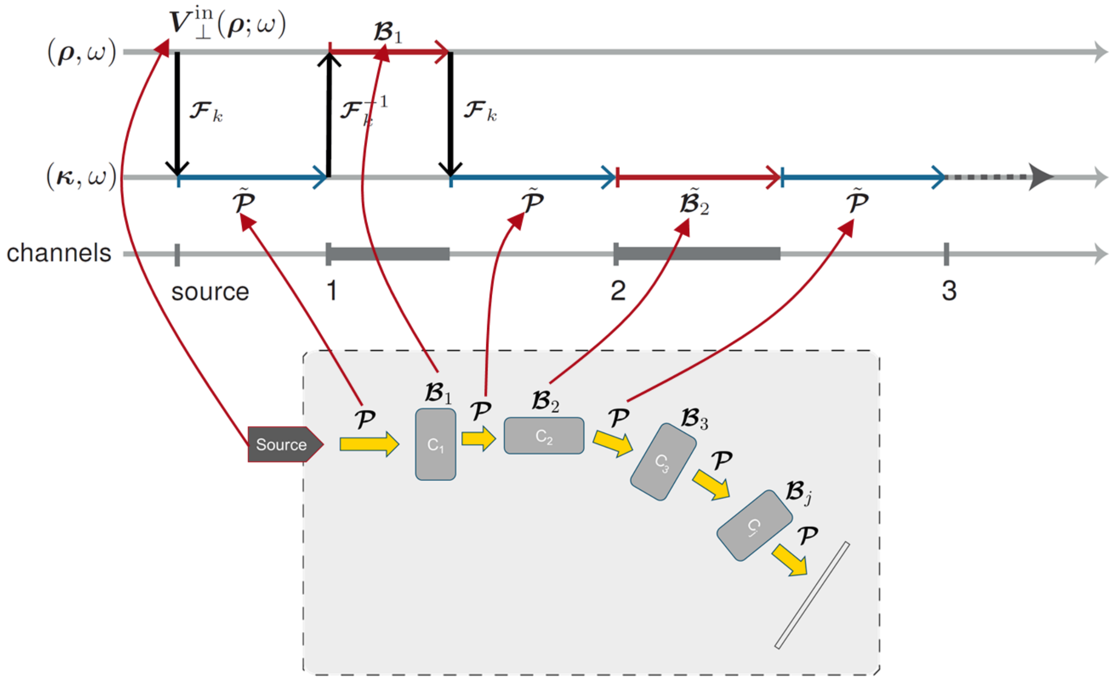
Operator Sequences and Switching Operator Domains

Problem:

Field operations of order O(N²) and higher: **Typically high numerical effort**

Solution:

- Modeling per lightpath by sequence of operators: *P* and *B*
- Switching the domains per operator to benefit from convolution theorem.



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- Nyquist sampling of complex field amplitudes: **Often results in high sampling number N**
- Physical optics modeling in one coordinate system: **Often results in high sampling number N**

- Physical optics is typically understood as to be too complex, slowly and in general not feasible in practical tasks.
- However, the need for it is growing!
- **Way out of this dilemma?**

Physical Optics Often Not Practical because …

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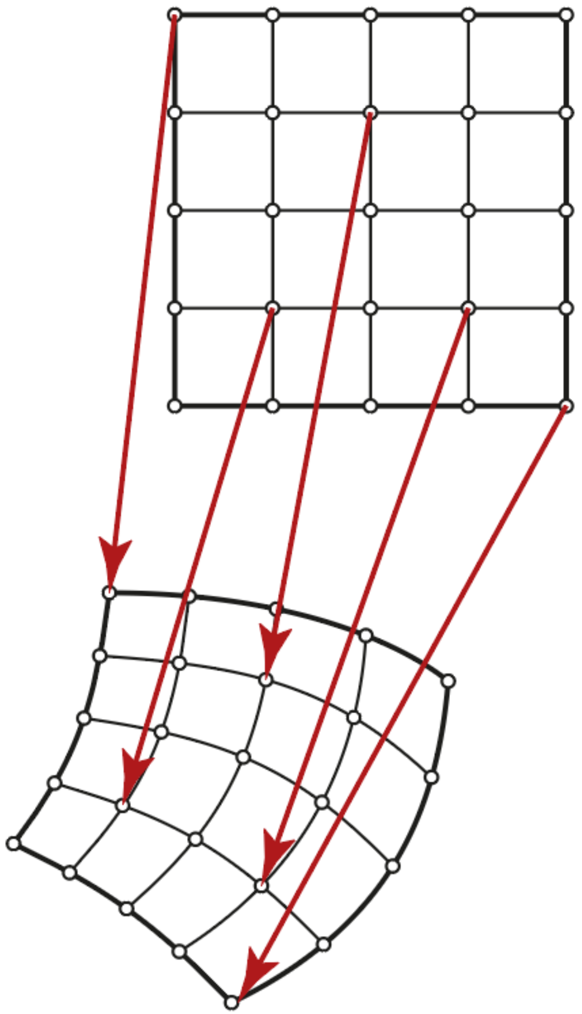
Homeomorphic Operators

Problem:

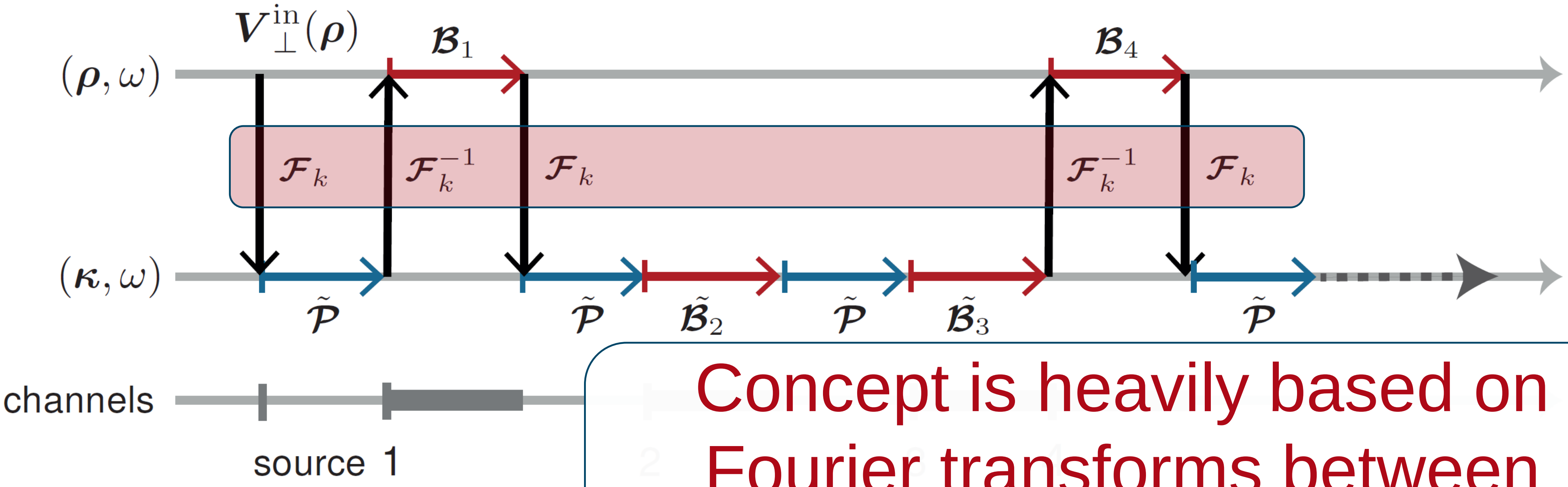
Nyquist sampling of complex field amplitudes: **Often results in high sampling number N**



Solution:

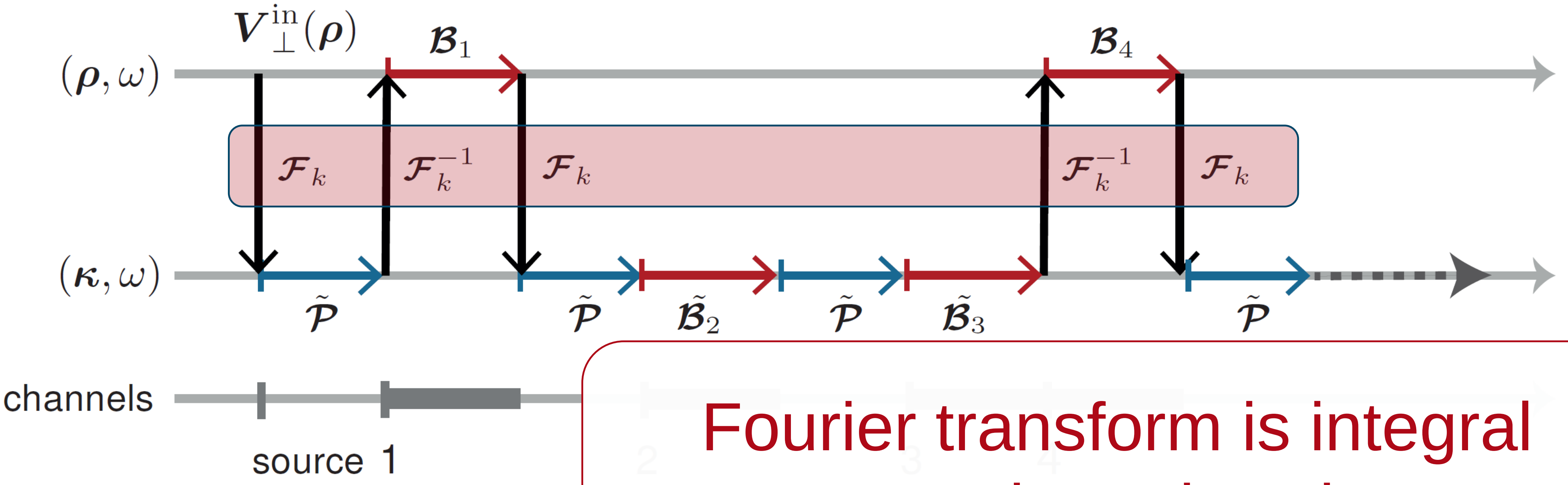
- General preference for homeomorphic operators.
- Homeorphic and semianalytical Fourier transform

Fourier Transform Integral Operator



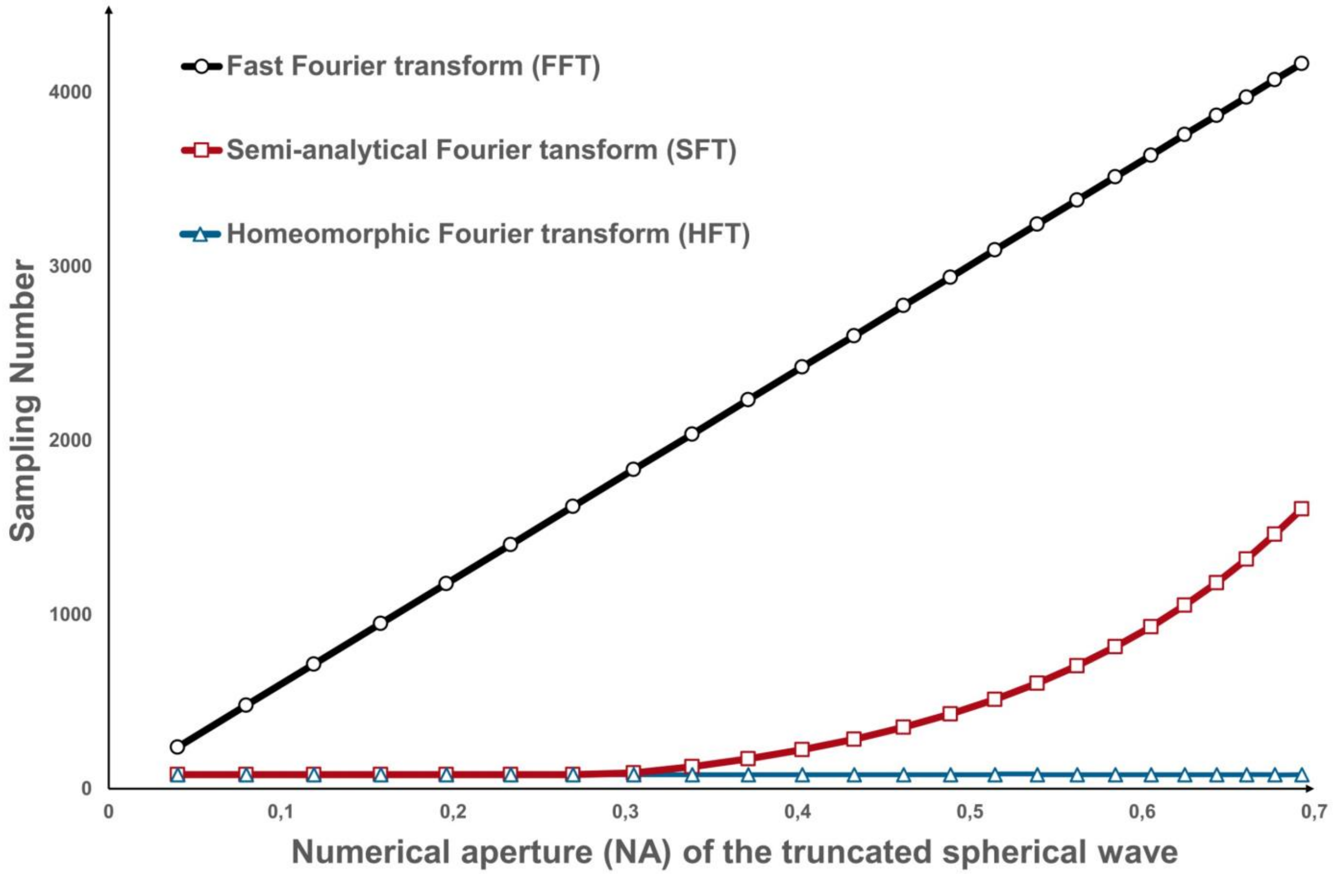
Concept is heavily based on Fourier transforms between domains.

Fourier Transform Integral Operator



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

Triad of Fourier Transform Techniques



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- However, the need for it is growing!
- **Way out of this dilemma?**

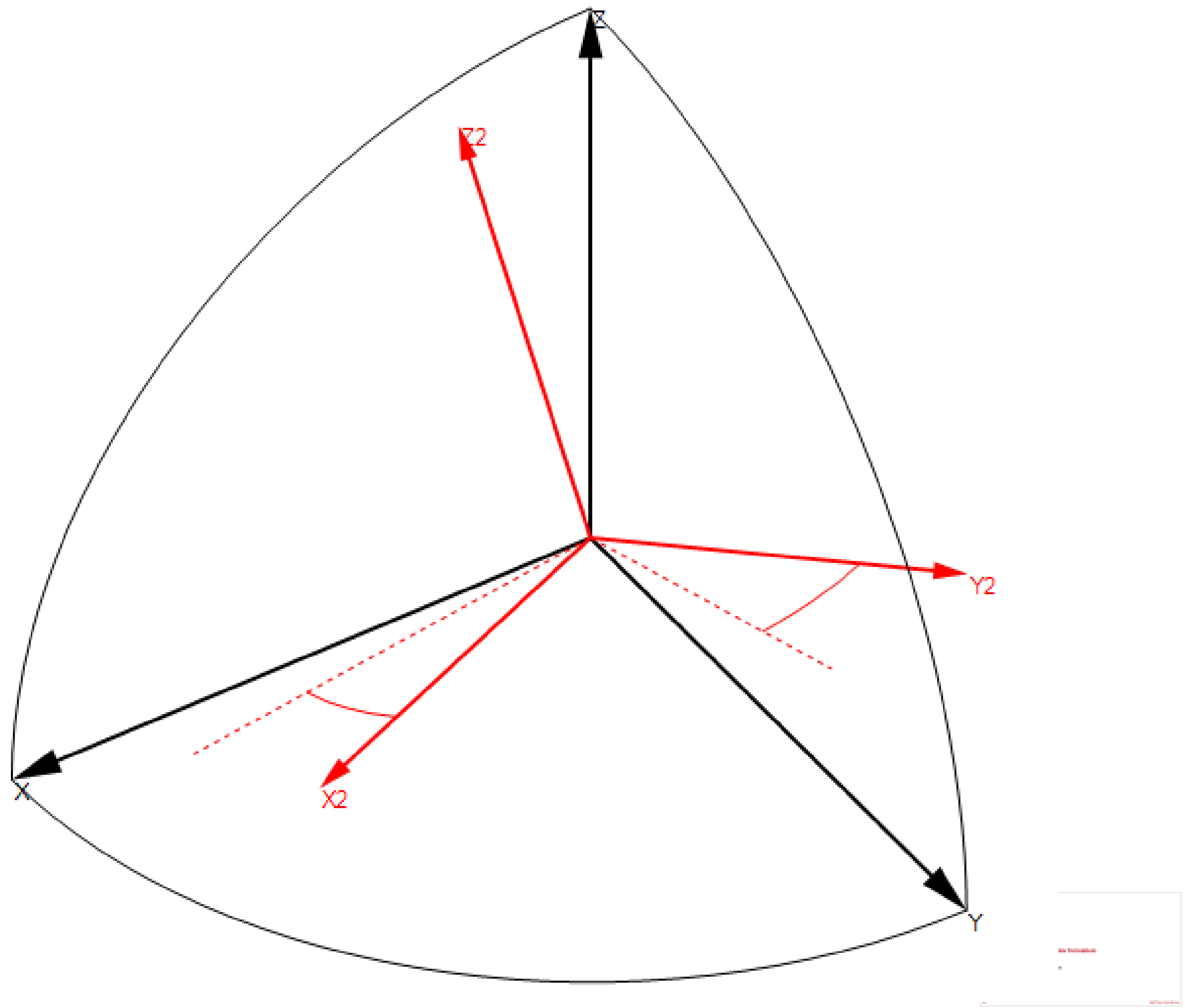
Application of Operators in Associated Coordinate Systems

Problem:

Physical optics modeling in one coordinate system: **Often results in high sampling number N**

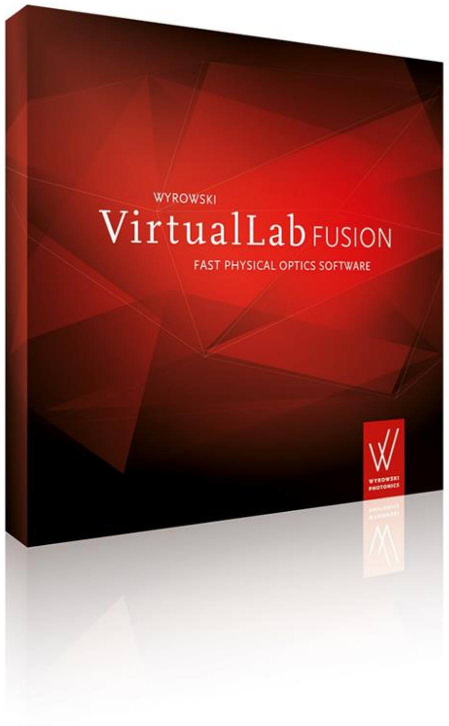
Solution:

- Operators are applied in associated coordinate systems.
- Fields are expressed in centric coordinate systems: Consequent use of shift theorem



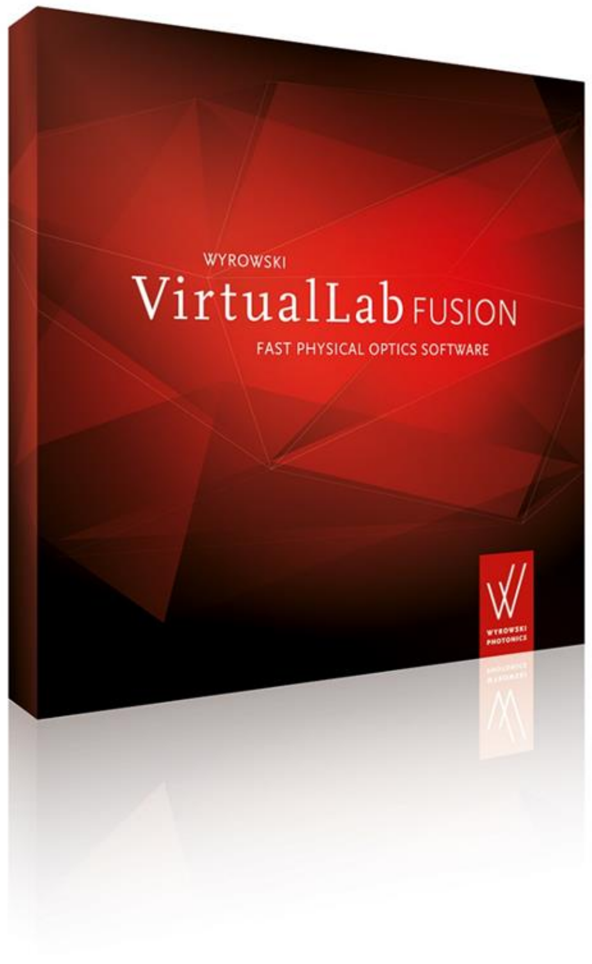
Field Tracing Concepts for Fast Physical Optics

1. Source mode decomposition and mode propagation.
2. Regional field solver and non-sequential interconnection by channel concept.
3. Switching between domains to obtain operators linear in sampling number N wherever possible.
4. Minimization of sampling number N by using homeomorphic operators wherever possible, including Fourier transform.
5. Consequent switching of coordinate systems to minimize sampling effort.
6. Enabling and optimizing #1-#5 by field decomposition strategies!



Fast Physical Optics with VirtualLab Fusion

- Fast Physical Optics does not replace ray tracing, but enriches our way to do optical modeling and design.
- Ray tracing is embedded and accessible.
- Physical optics simplifies development of systematic design workflows.



VirtualLab Fusion Technology and Applications

Microscopy

Stefan Steiner
LightTrans International UG

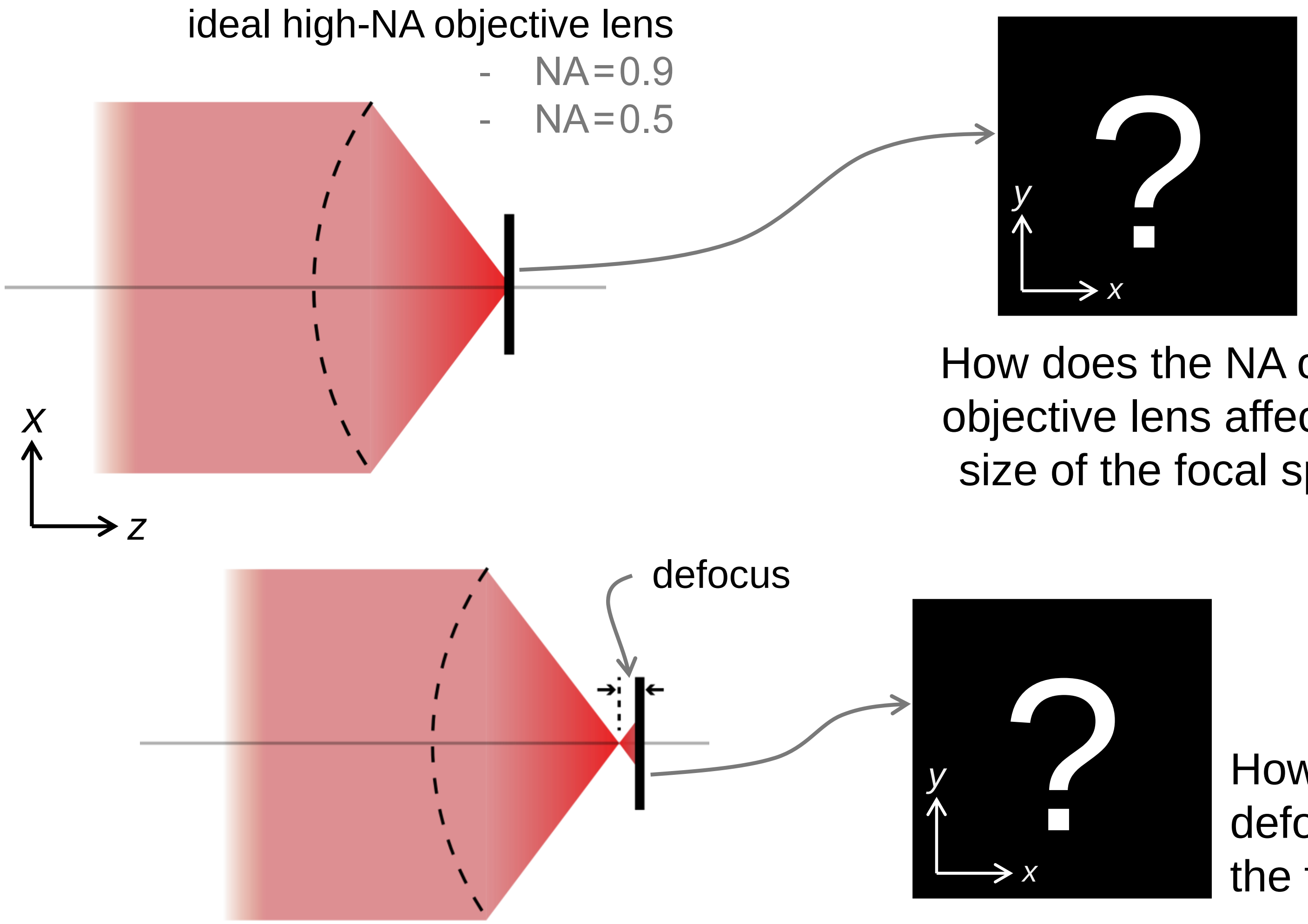
Investigation of Ideal Focusing Situation by Using Debye-Wolf Integral

Modeling Task

input plane wave

- wavelength: 532 nm, 632.8 nm
- polarization: linearly polarized in *y* direction and in *x*-*y* diagonal direction

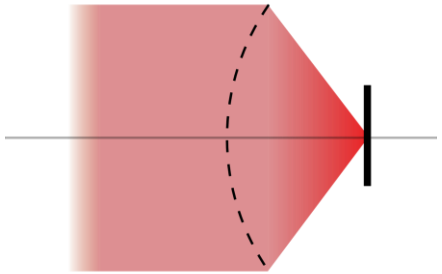
How does the wavelength and the polarization of the input field affect the focal spot?



How does the NA of the objective lens affect the size of the focal spot?

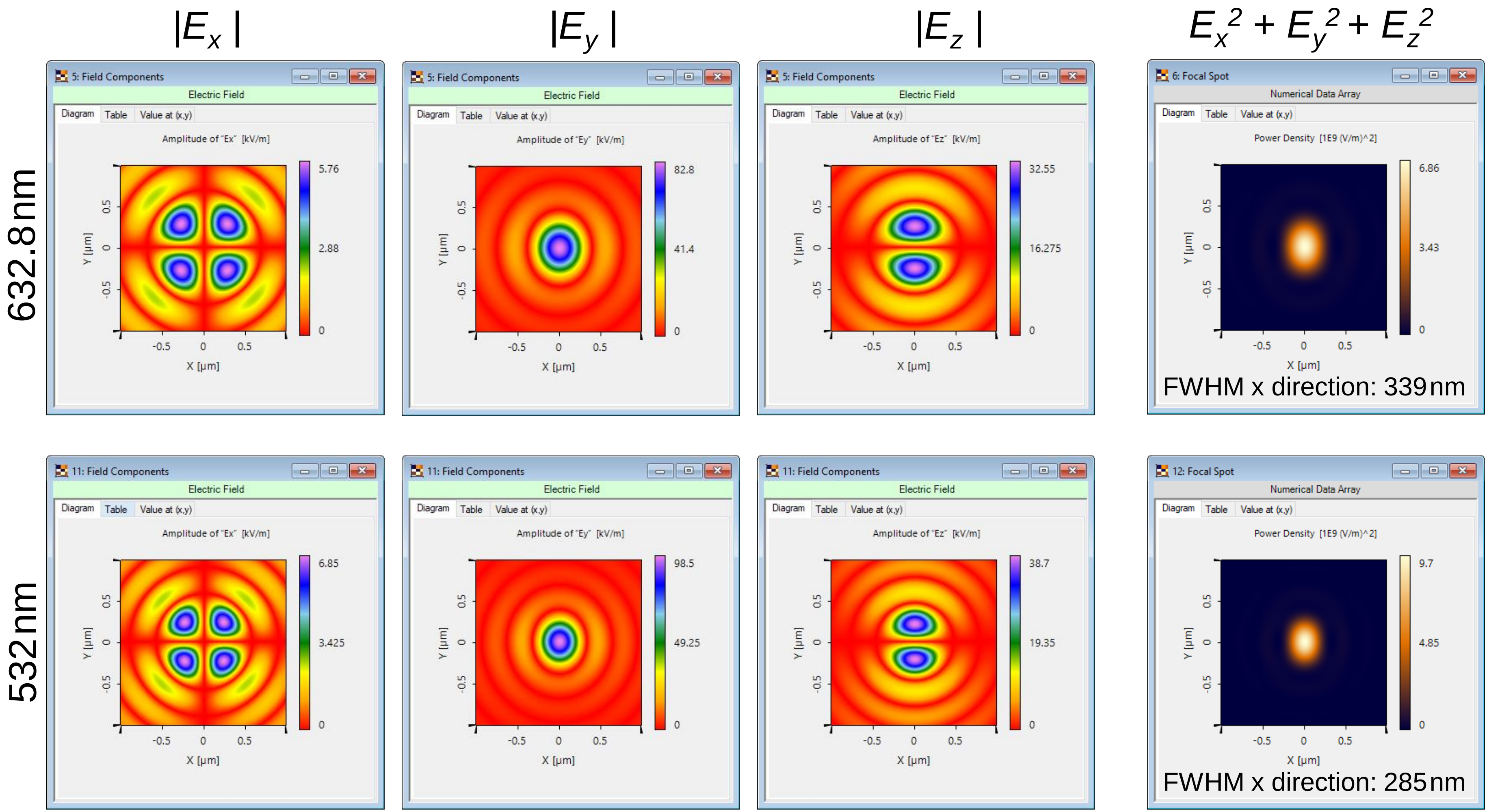
How does defocus affect the focal spot?

Influence on Focal Spot from Wavelength

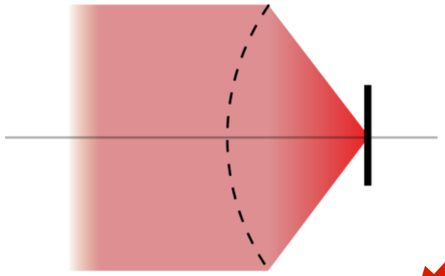


input plane wave

- wavelength: 532 nm, or 632.8 nm
- fixed linear polarization in *y*



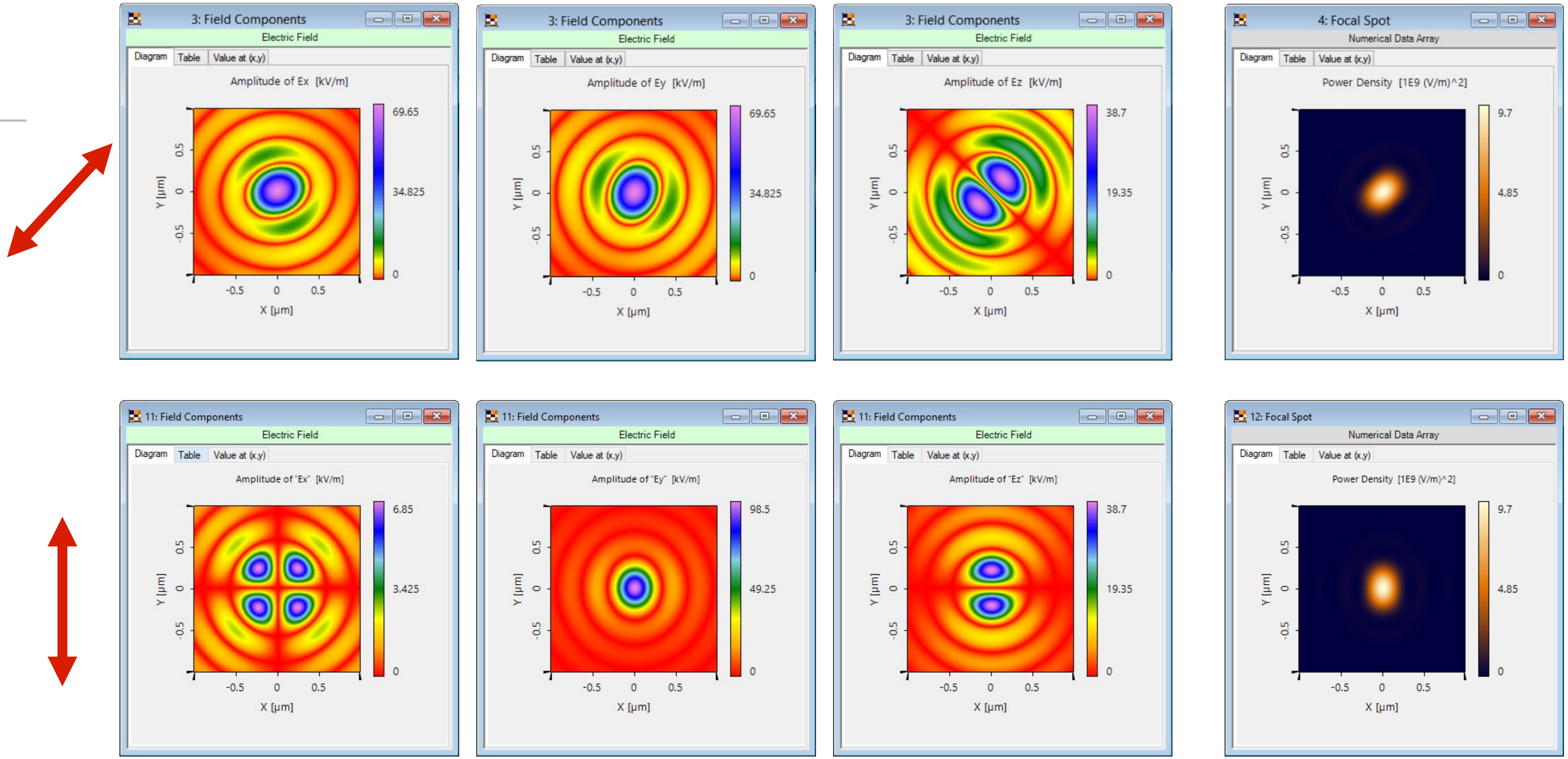
Influence on Focal Spot from Polarization



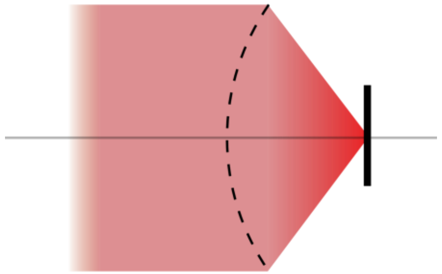
input plane wave

- fixed wavelength: 532 nm,
- linear polarization in *y* or in *x*-*y* diagonal

$|E_x|$ $|E_y|$ $|E_z|$ $E_x^2 + E_y^2 + E_z^2$



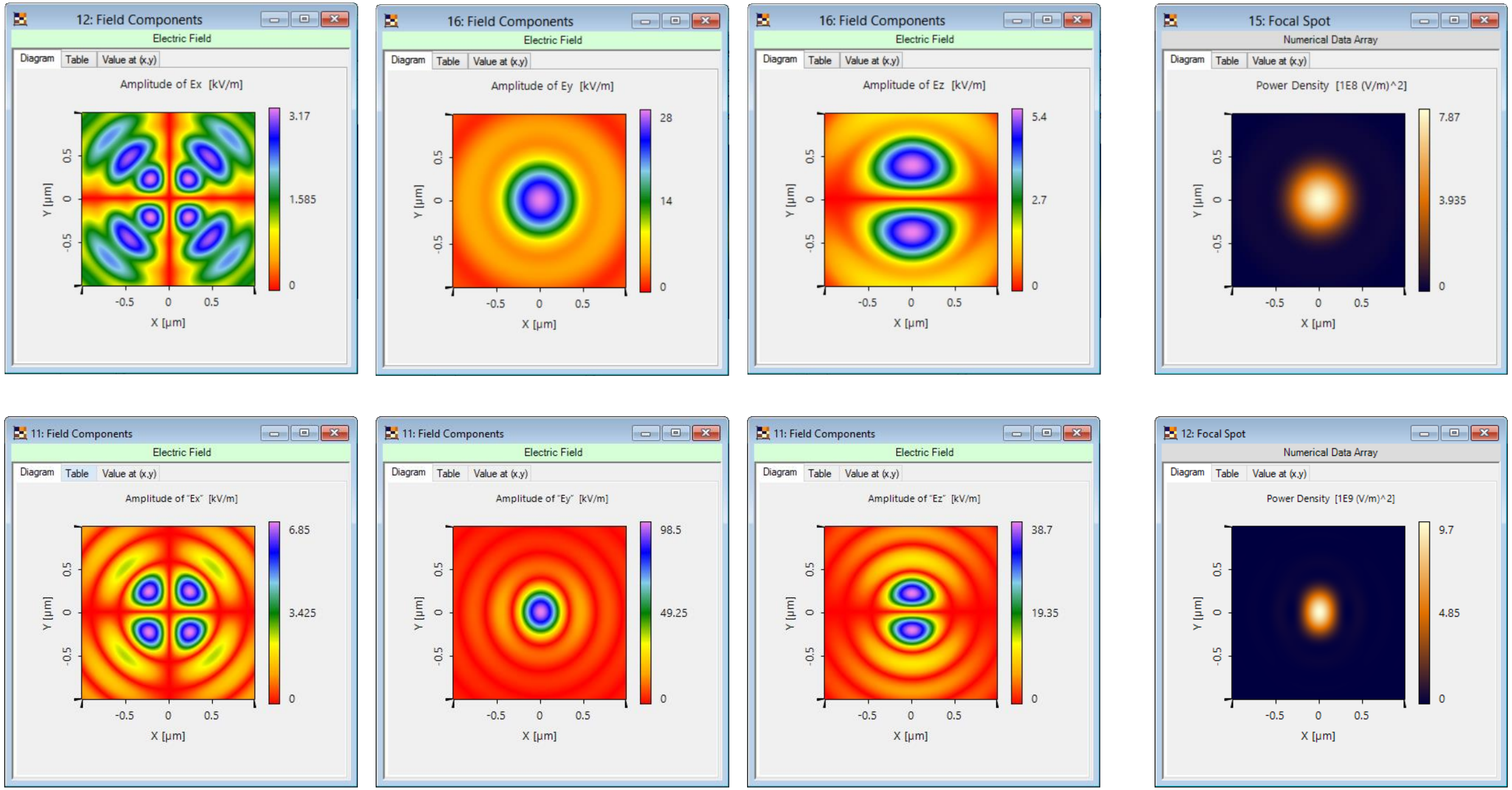
Influence on Focal Spot from NA of Objective



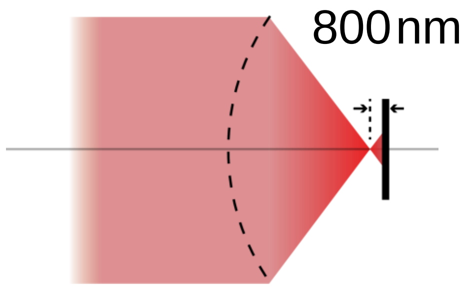
ideal high-NA objective lens

- NA=0.9
- NA=0.5

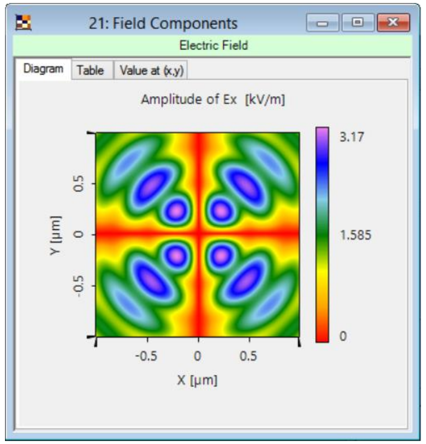
	$\lvert E_x \rvert$	$\lvert E_y \rvert$	$\lvert E_z \rvert$	$E_x^2 + E_y^2 + E_z^2$
NA=0.5				
NA=0.9				



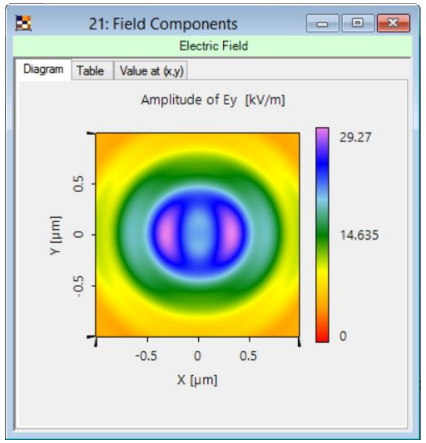
Influence on Focal Spot from Defocus



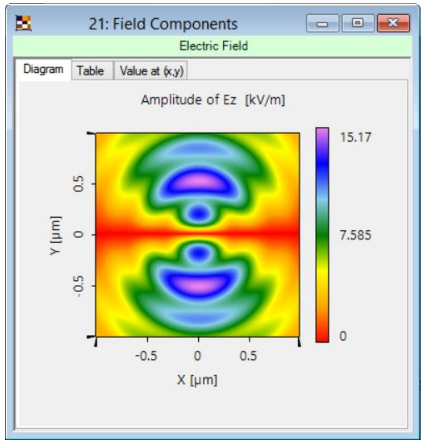
$|E_x|$



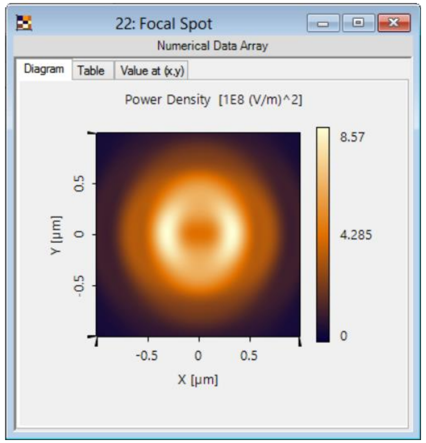
$|E_y|$

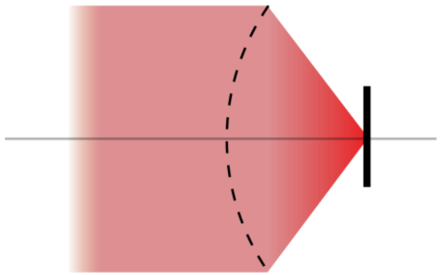


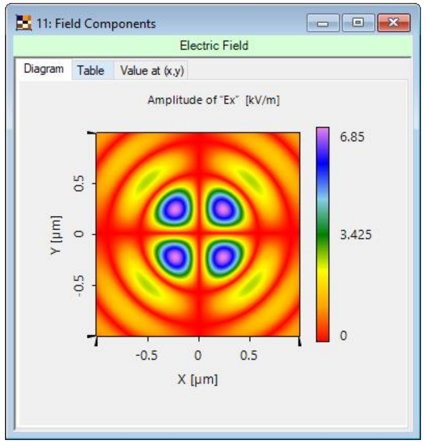
$|E_z|$

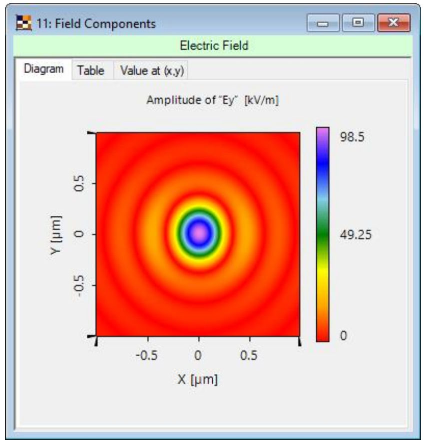


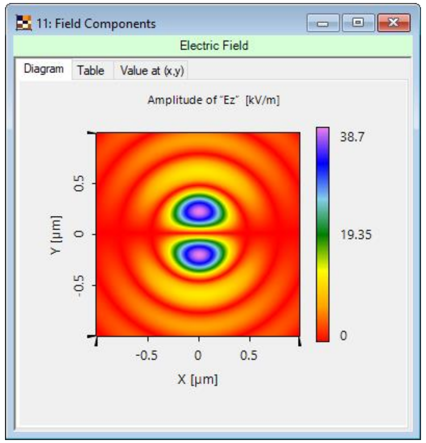
$E_x^2 + E_y^2 + E_z^2$

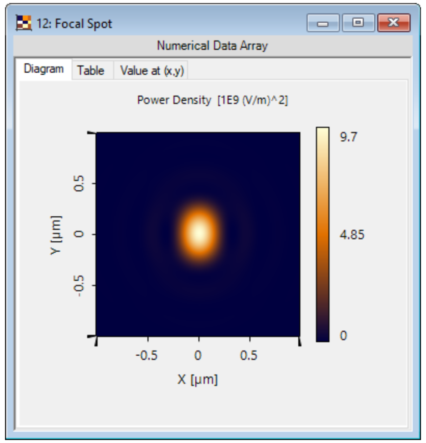




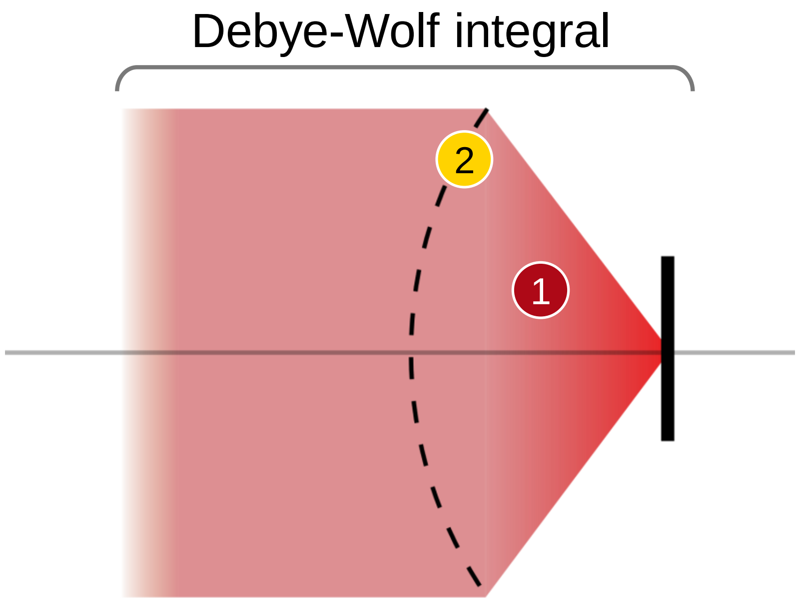


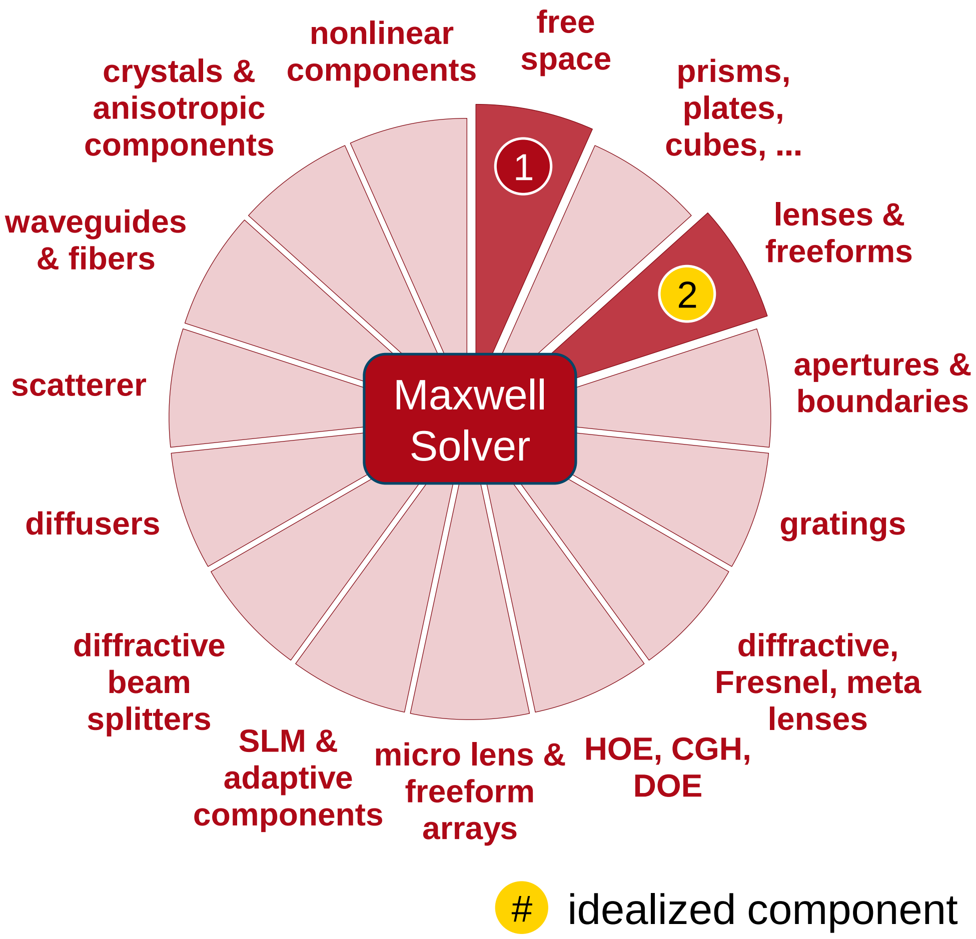






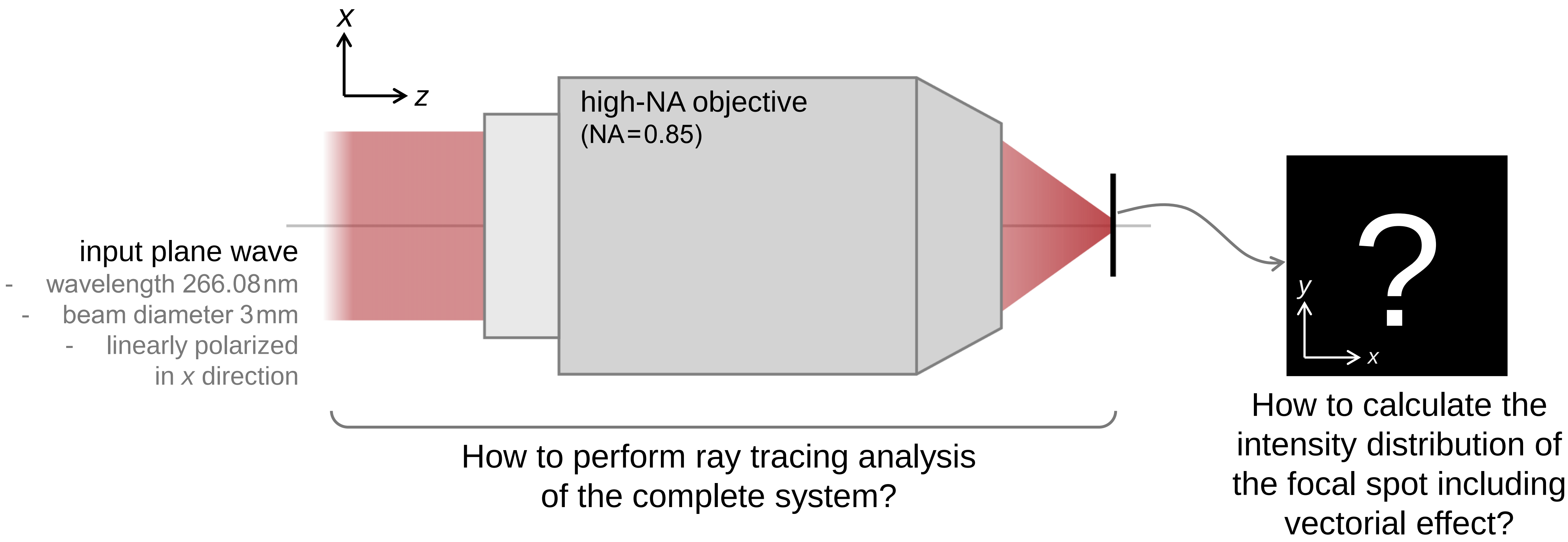
VirtualLab Technologies





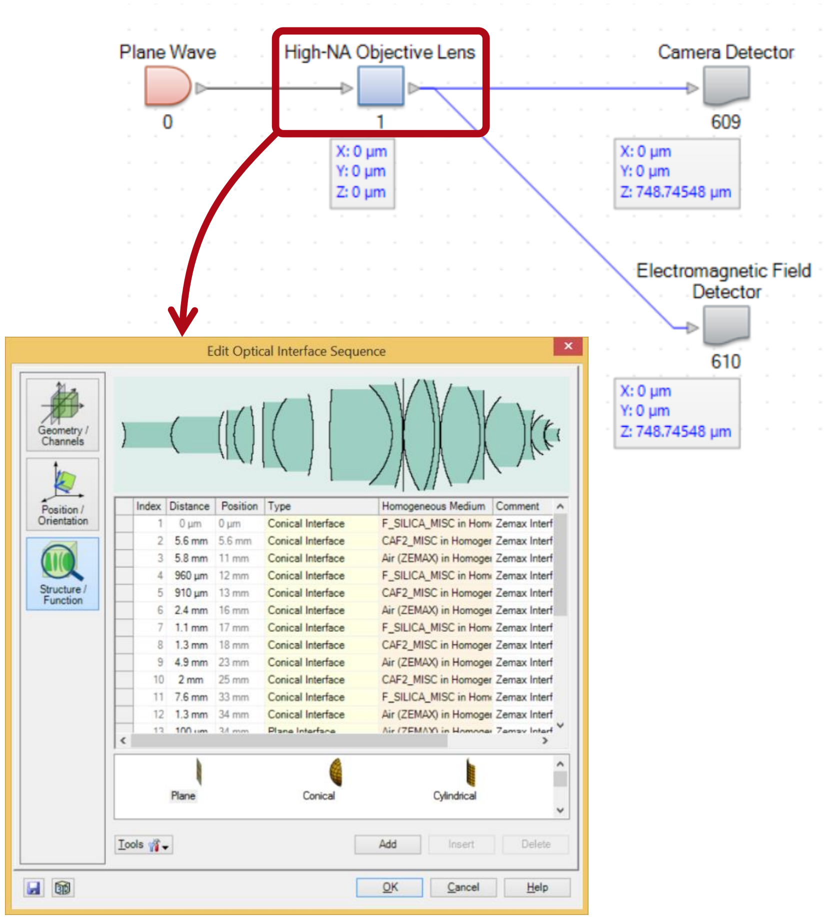
Analyzing High-NA Objective Lens Focusing

Modeling Task



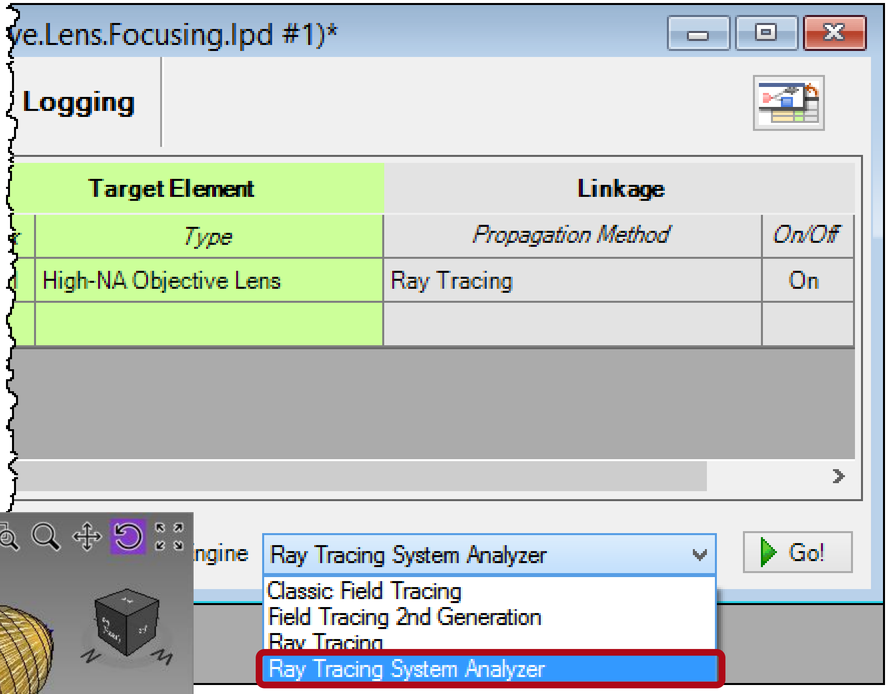
Overview

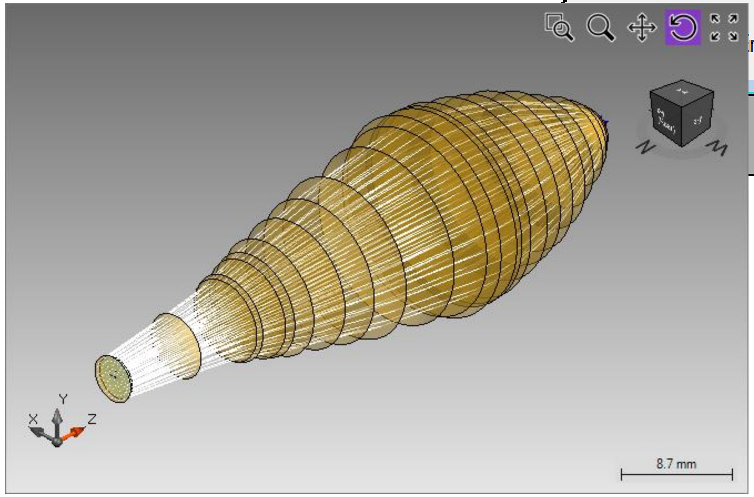
- The sample system is preset with the high-NA objective lens included.
- Next, we demonstrate how to perform simulation on the sample system following the recommended workflow in VirtualLab.



Ray Tracing Simulation

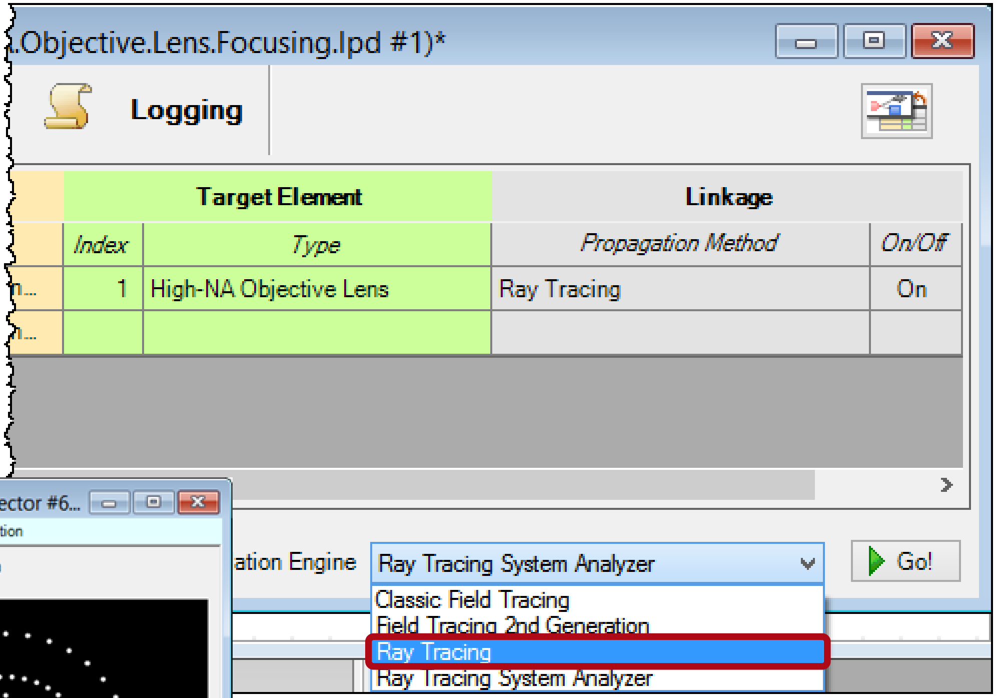
- Choose Ray Tracing System Analyzer as the simulation engine at first.
- Click on Go!
- The 3D ray tracing result is obtained.

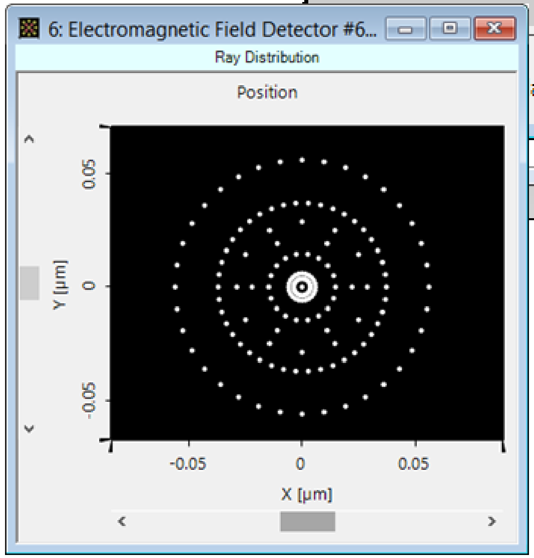




Ray Tracing Simulation

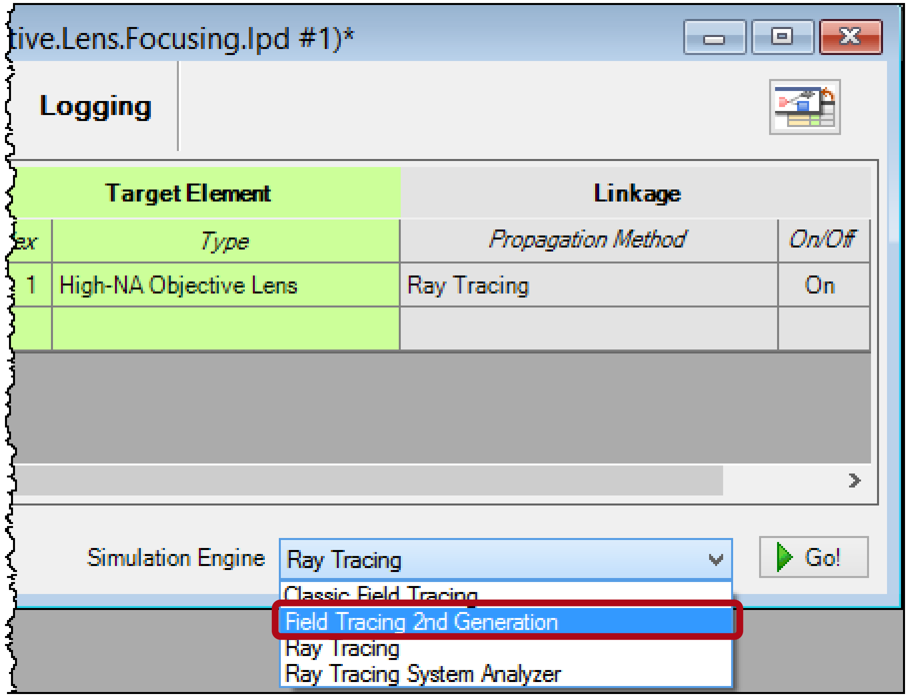
- Then, select Ray Tracing as the simulation engine.
- Click Go!
- Then the dot diagram (2D ray tracing result) is obtained.





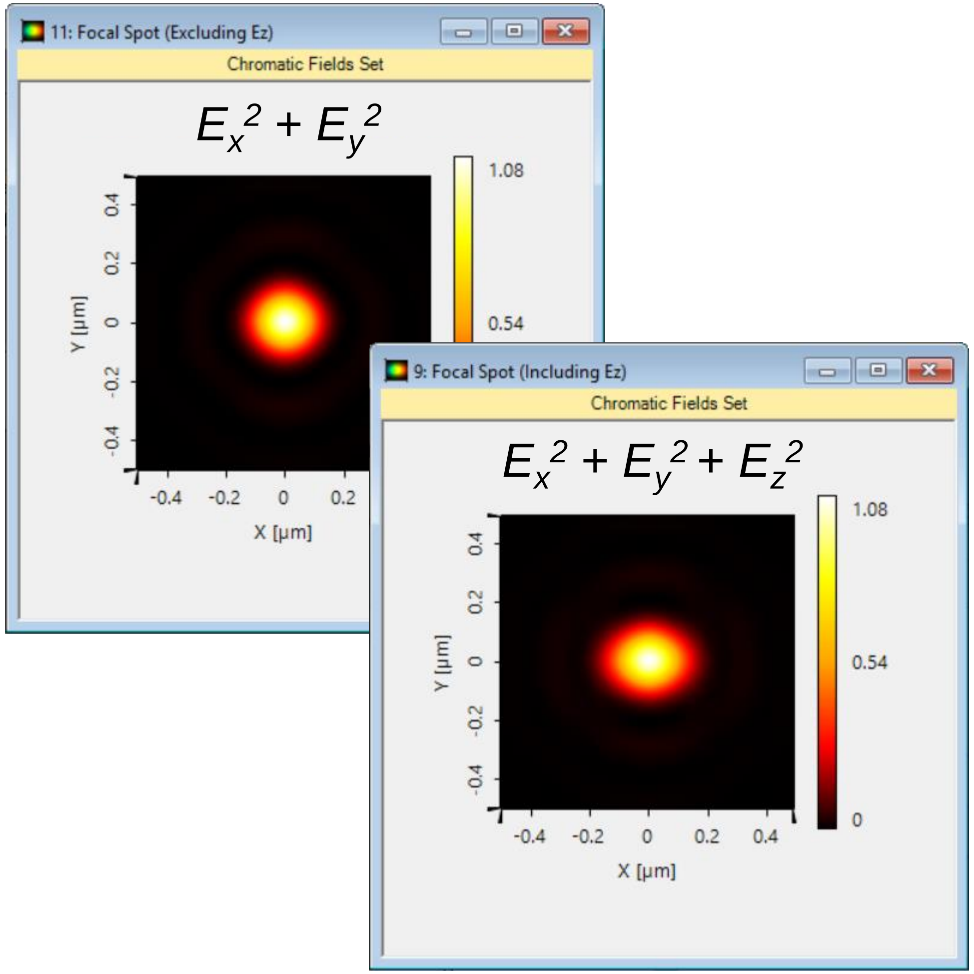
Field Tracing Simulation

- Switch to field tracing and select Field Tracing 2nd Generation as the simulation engine.
- Click Go!



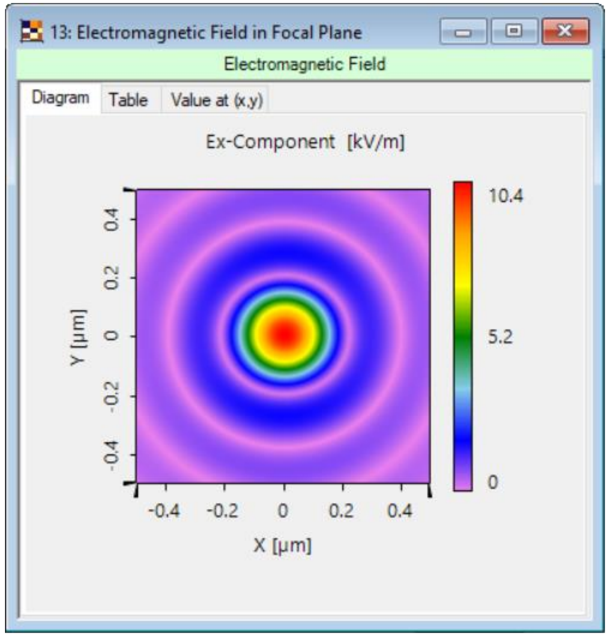
Field Tracing Results (Camera Detector)

- The top figure shows the field intensity by integrating E_x and E_y components only.
- The bottom figure shows the field 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.

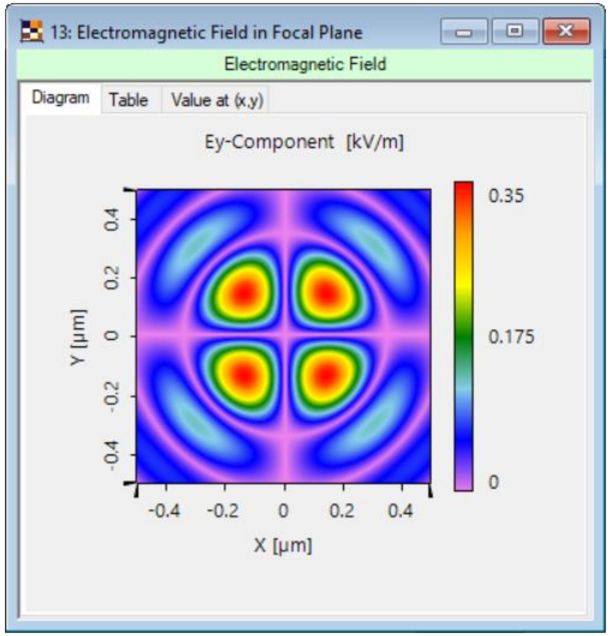


Field Tracing Results (EM Field Detector)

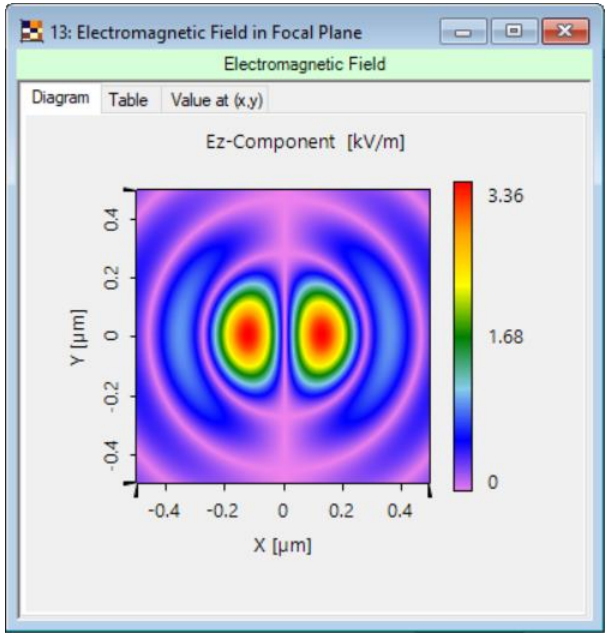
- All electromagnetic field components are obtained by using the Electromagnetic Field Detector.



amplitude of E_x



amplitude of E_y



amplitude of E_z

Field Tracing Results (EM Field Detector)

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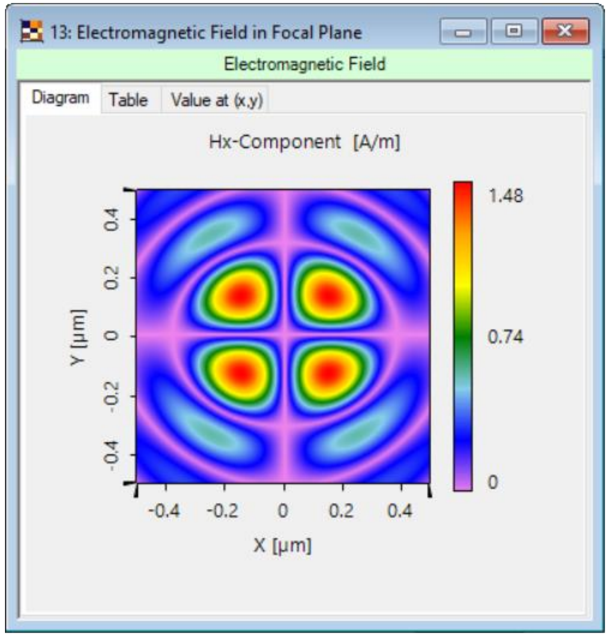
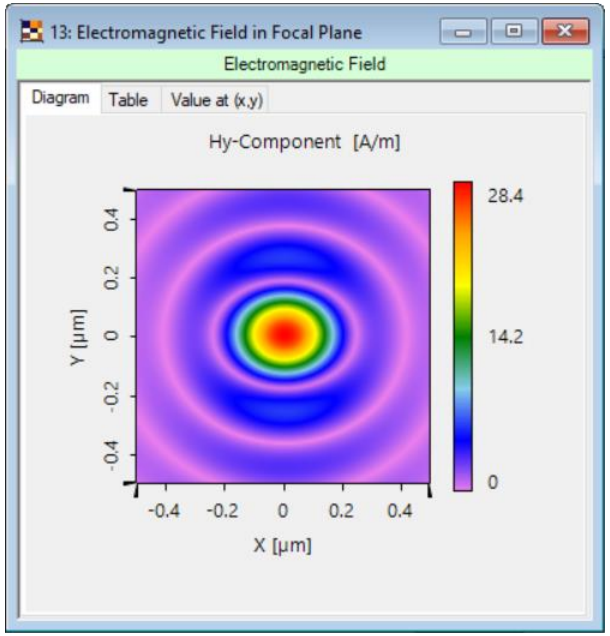
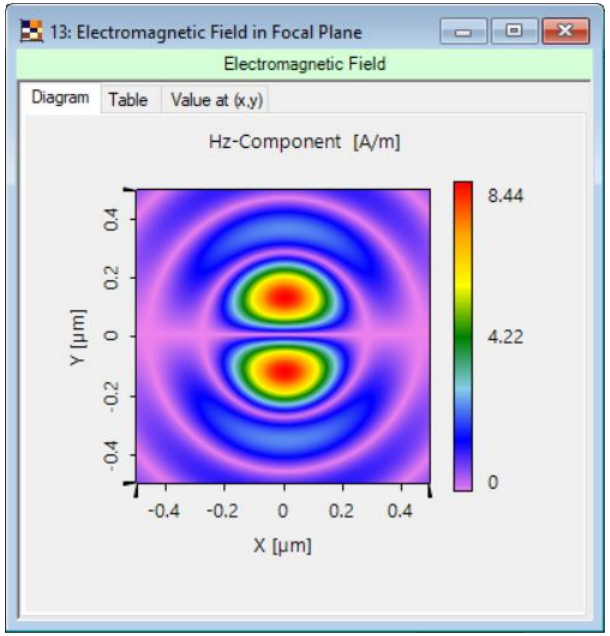


amplitude of H_x



amplitude of H_y

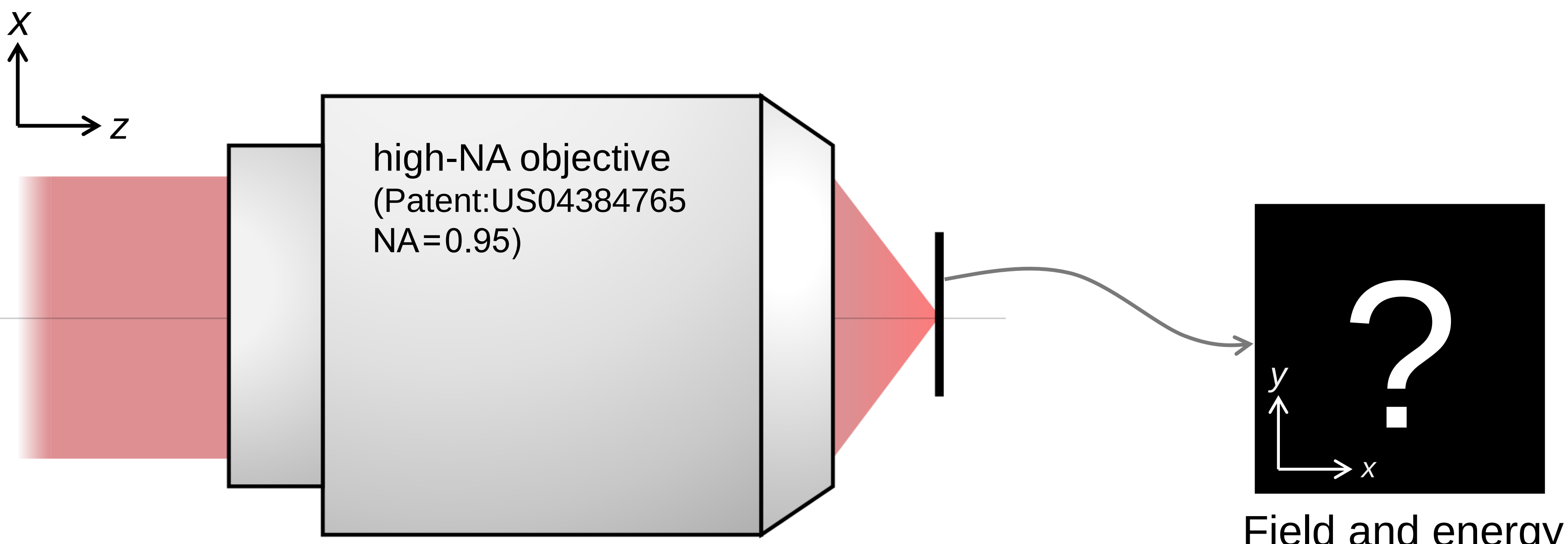


amplitude of H_z

Chromatic Aberration Analysis of High-NA Objective Lens

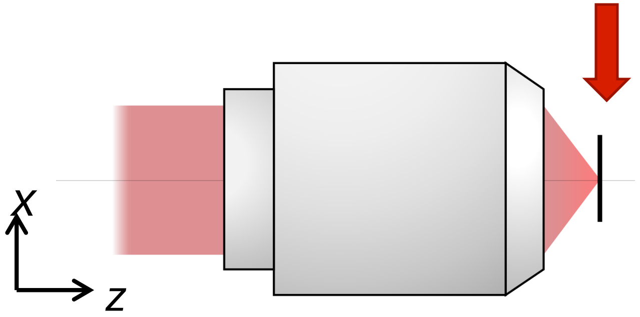
Modeling Task

input plane wave
- wavelength 473 nm, 568 nm, 780 nm
- beam diameter 3.48 mm
- linearly polarized in *x* direction



Field and energy density at the focal plane?

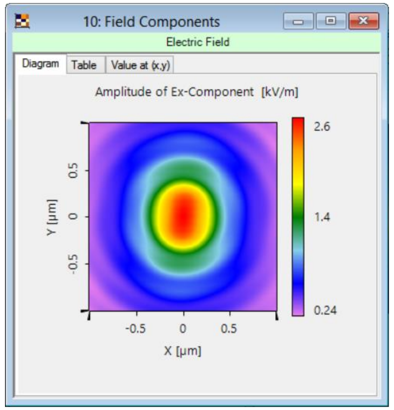
Field and Energy Density at Focal Plane: Wavelength: 473 nm

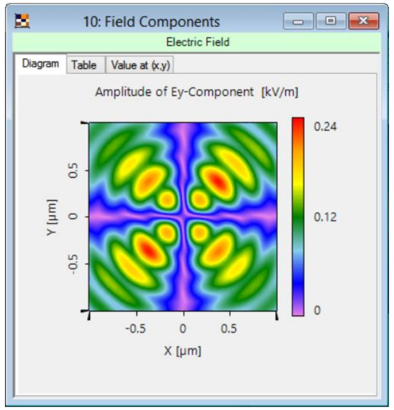


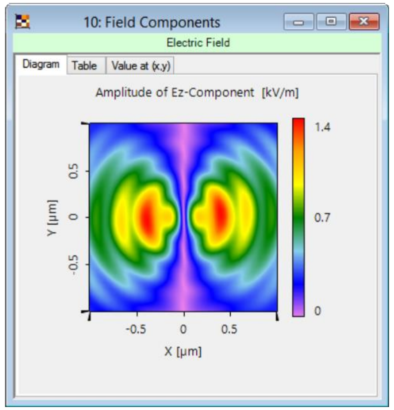
Debye-Wolf Integral

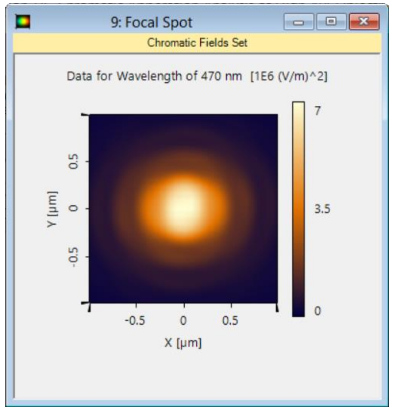
Ideal

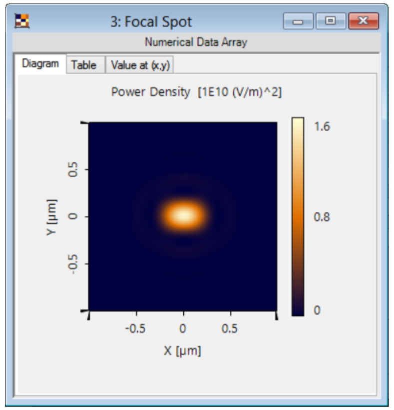
$\lvert E_x \rvert$	$\lvert E_y \rvert$	$\lvert E_z \rvert$	$E_x^2 + E_y^2 + E_z^2$	$E_x^2 + E_y^2 + E_z^2$

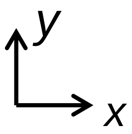








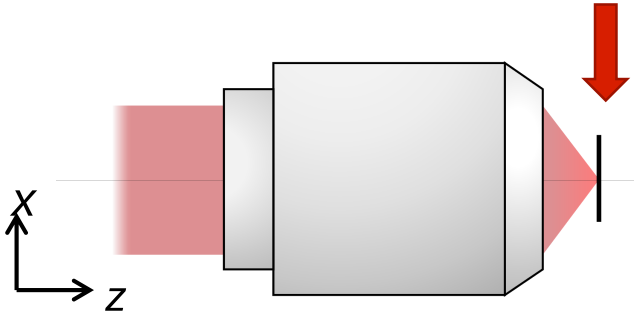




FWHM y direction: ~650 nm

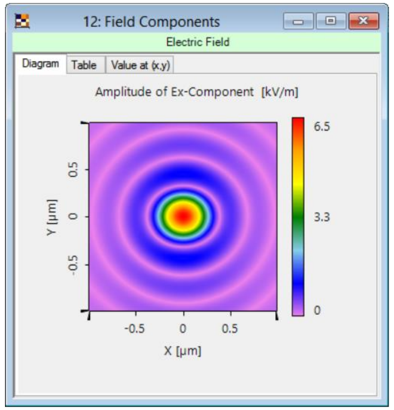
FWHM y direction: ~230 nm

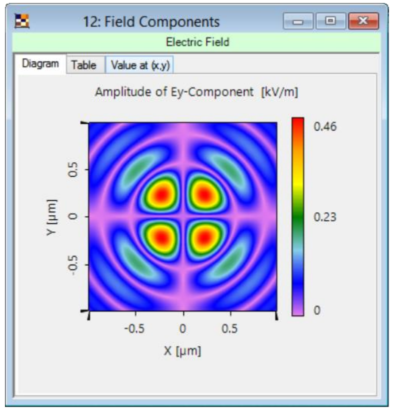
Field and Energy Density at Focal Plane: Wavelength: 568 nm

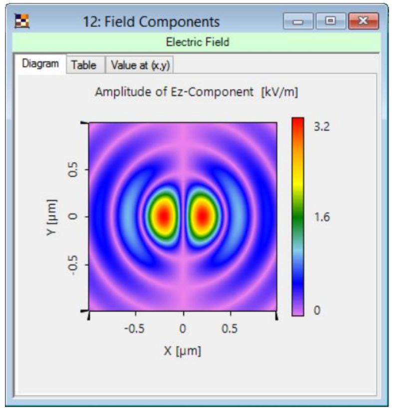


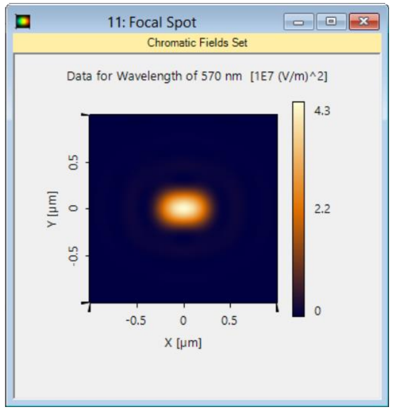
Ideal

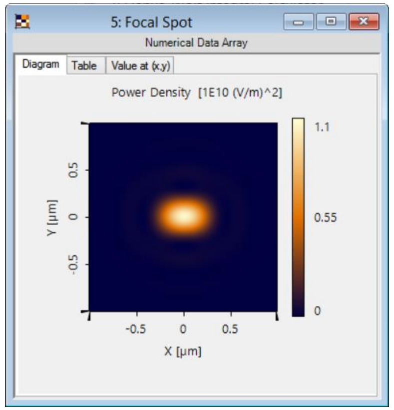
$\|E_x\|$	$\|E_y\|$	$\|E_z\|$	$E_x^2 + E_y^2 + E_z^2$	$E_x^2 + E_y^2 + E_z^2$

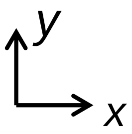








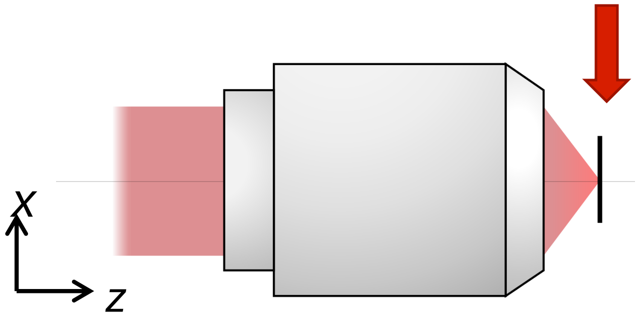




FWHM y direction: ~280 nm

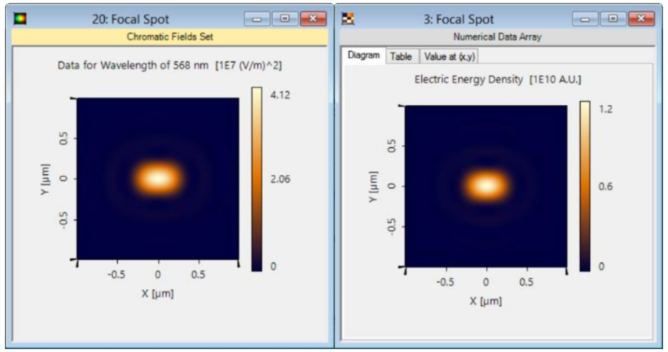
FWHM y direction: ~280 nm

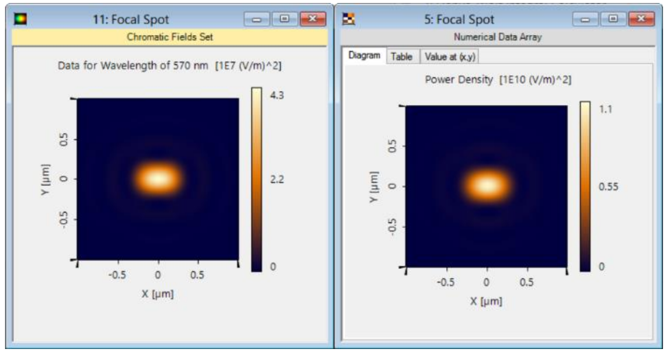
Focal Spot of Different Wavelengths

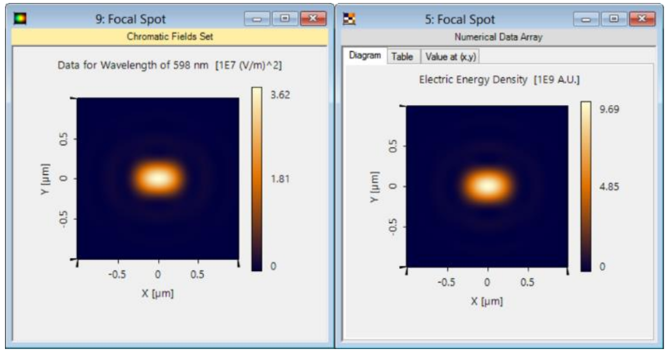


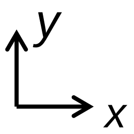
$E_x^2 + E_y^2 + E_z^2$

538 nm		568 nm		598 nm	
Real	Ideal	Real	Ideal	Real	Ideal







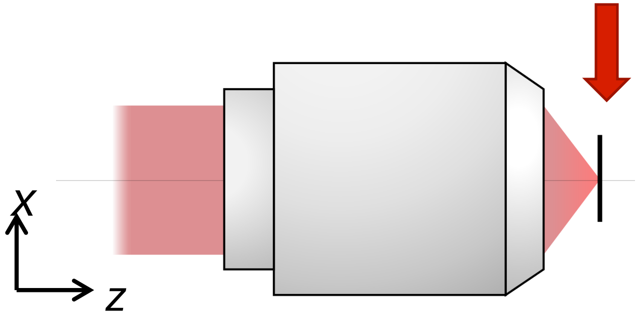


FWHM y direction: ~270 nm

FWHM y direction: ~280 nm

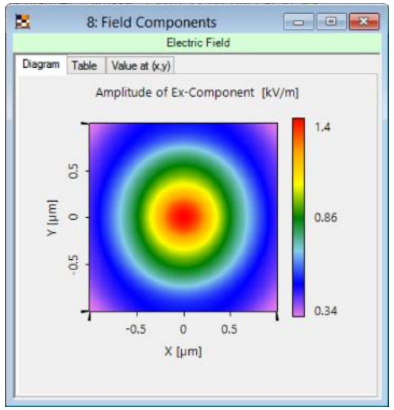
FWHM y direction: ~300 nm

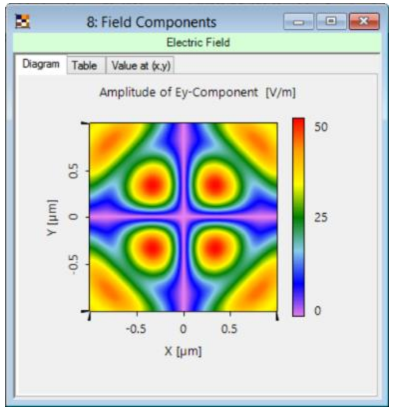
Field and Energy Density at Focal Plane: Wavelength: 780 nm

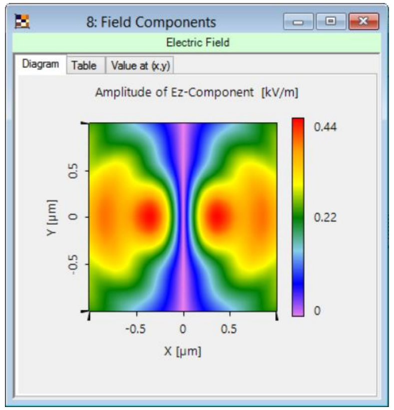


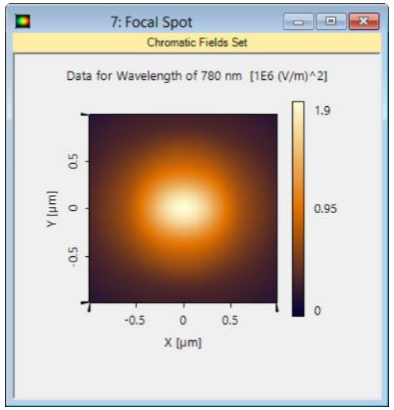
Ideal

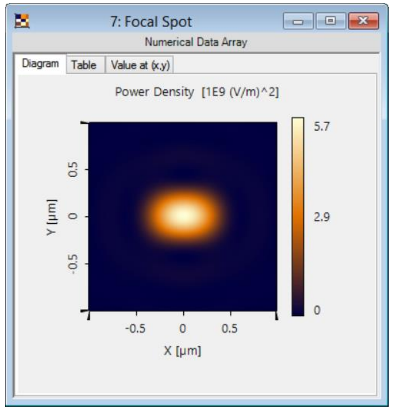
$|E_x|$ $|E_y|$ $|E_z|$ $E_x^2 + E_y^2 + E_z^2$ $E_x^2 + E_y^2 + E_z^2$

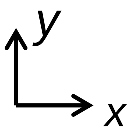










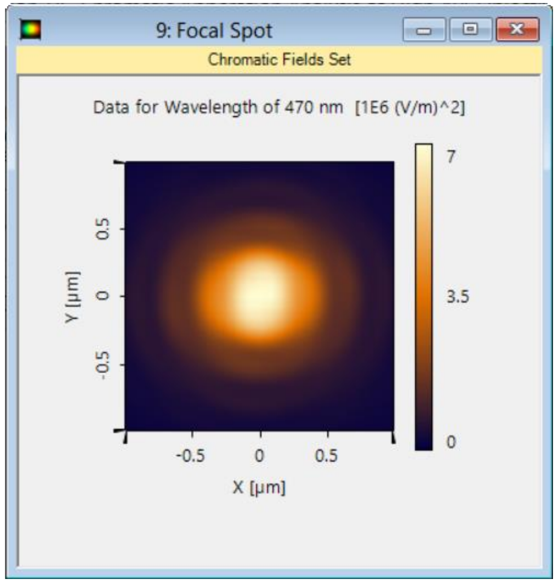


FWHM y direction: 818 nm

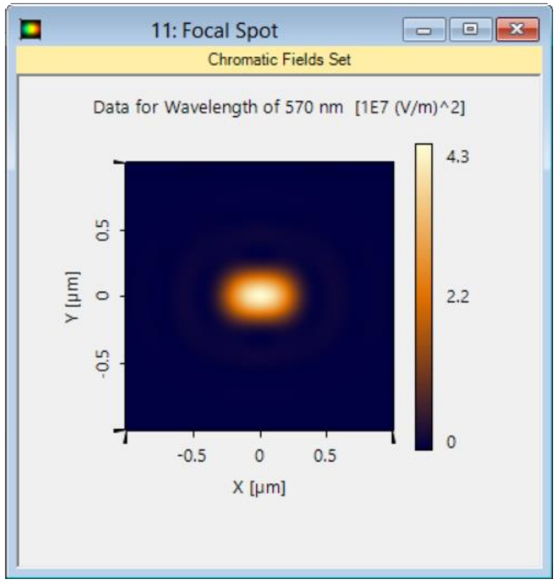
FWHM y direction: 389 nm

Energy Density at Focal Plane Comparison

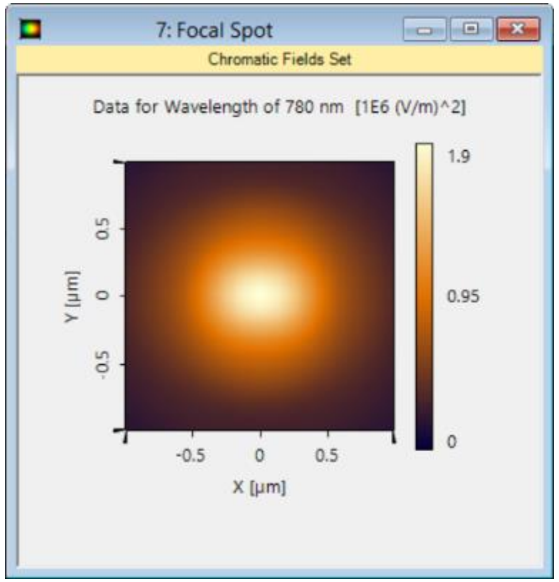
473 nm



568 nm

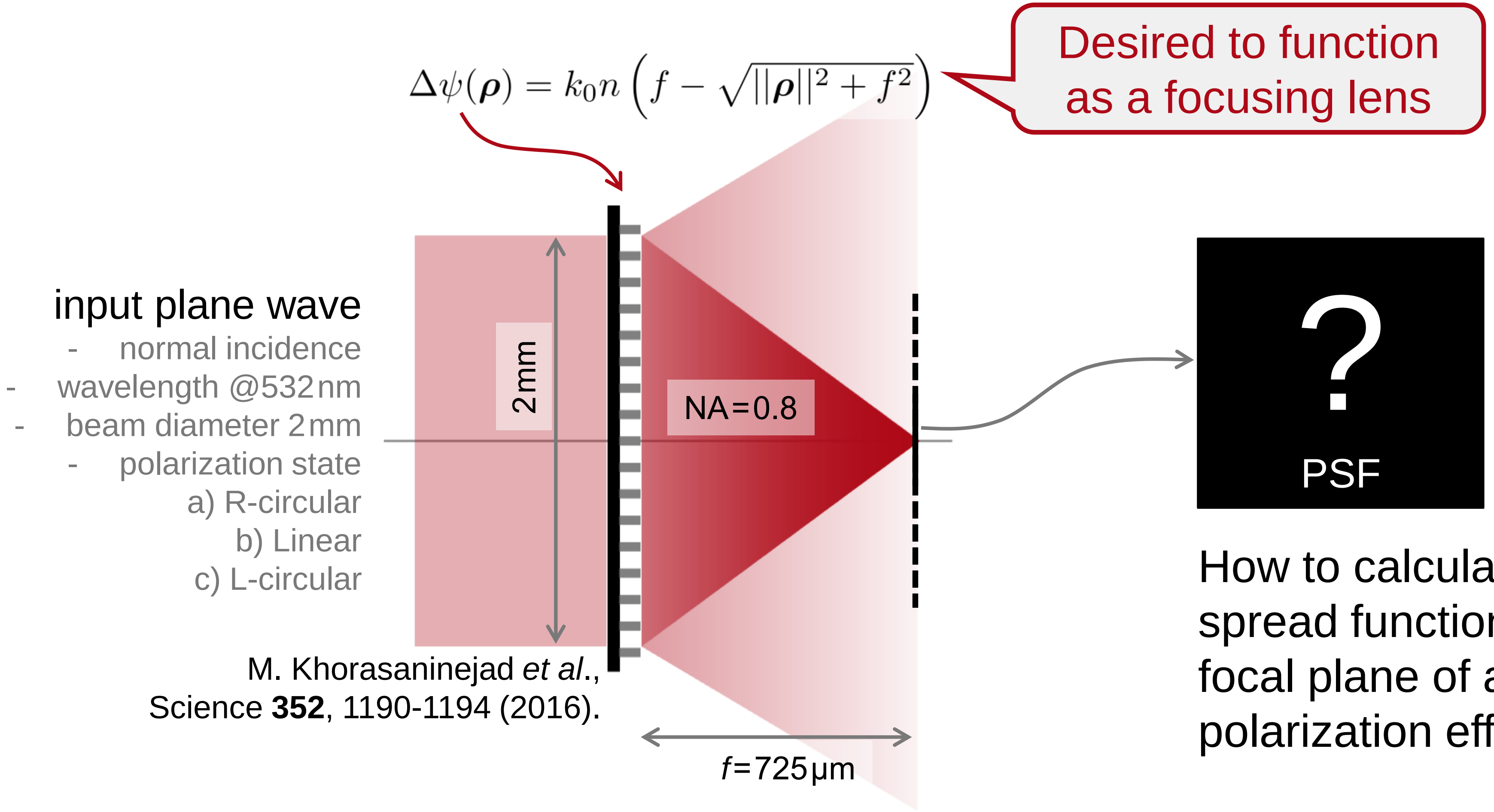


780 nm



Modeling of Meta-Lenses at Visible Wavelengths

High-NA Metalens Simulation

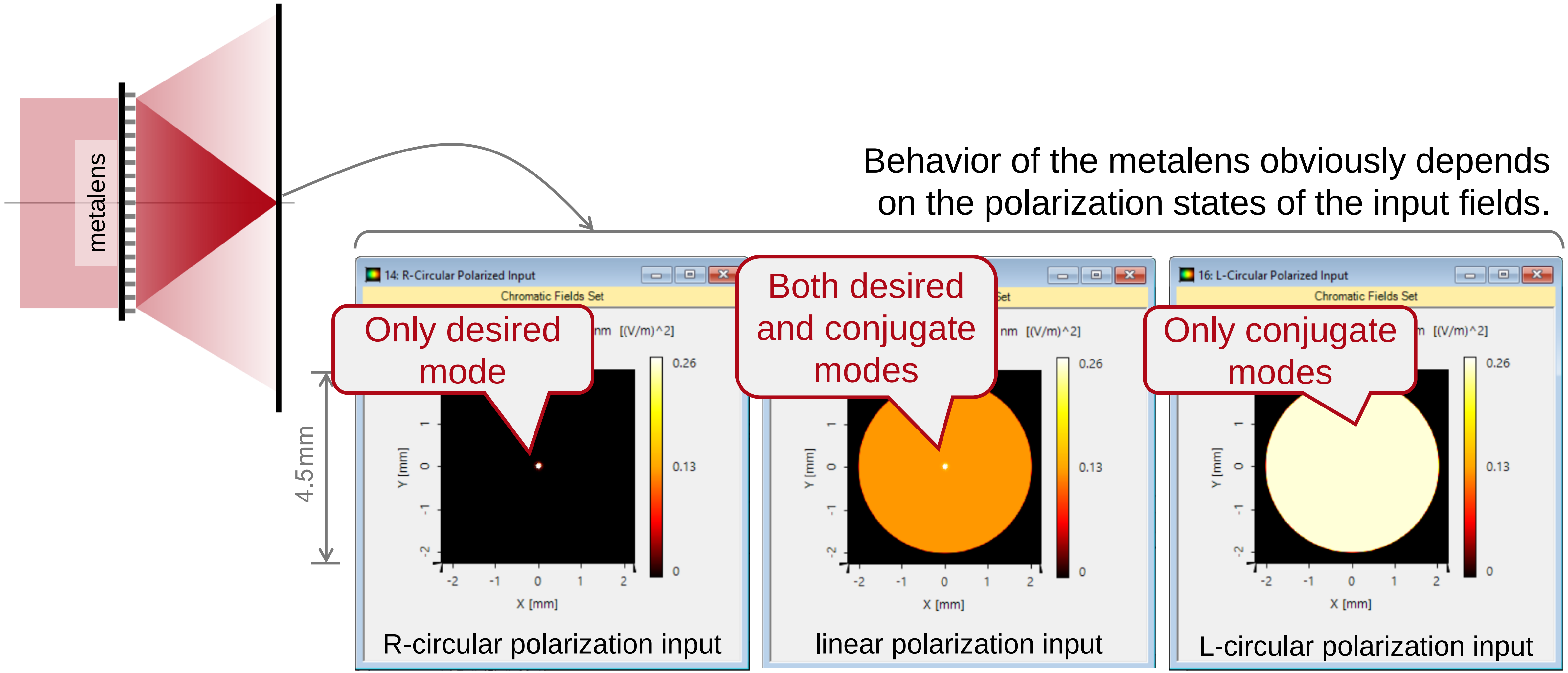


M. Khorasaninejad *et al.*, Science **352**, 1190-1194 (2016).

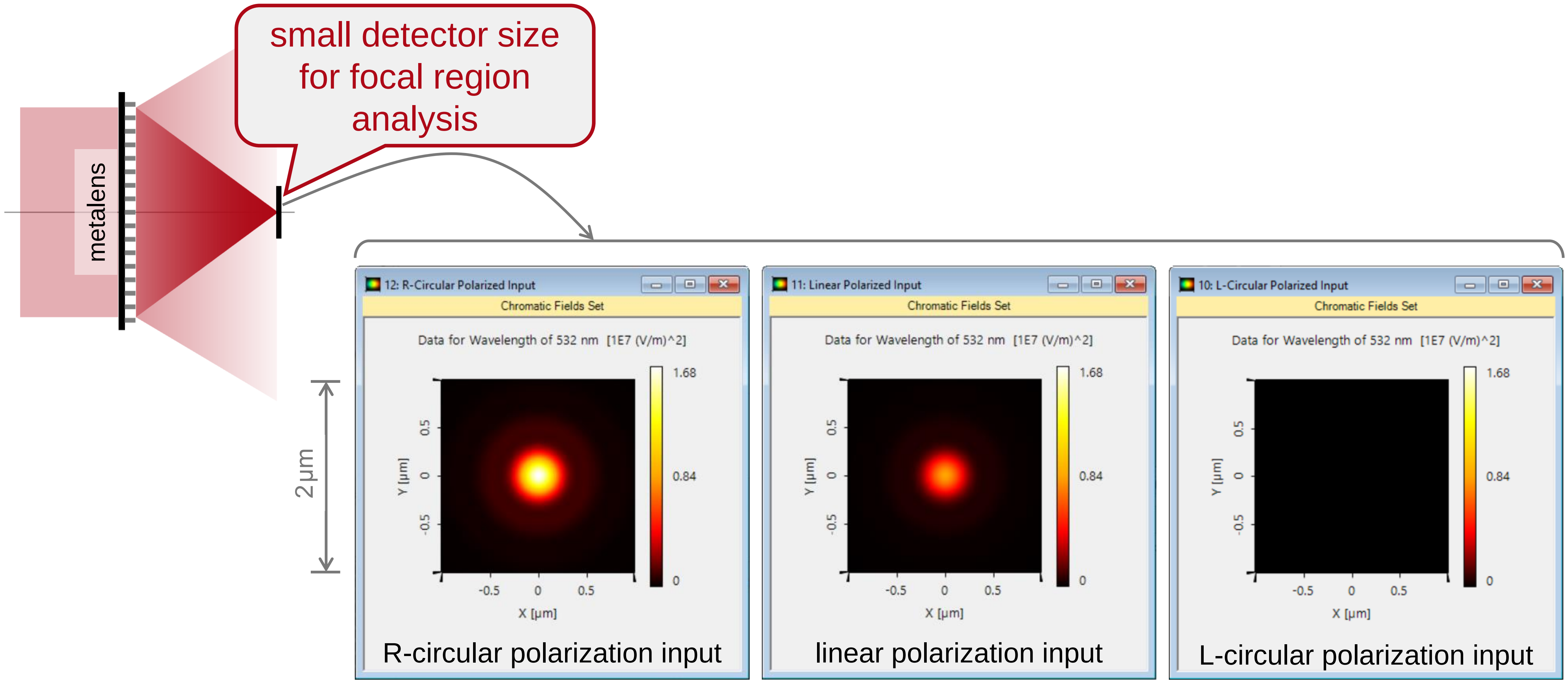
How to calculate the point spread function (PSF) at the focal plane of a metalens, with polarization effects considered?

High-NA Metalens Simulation

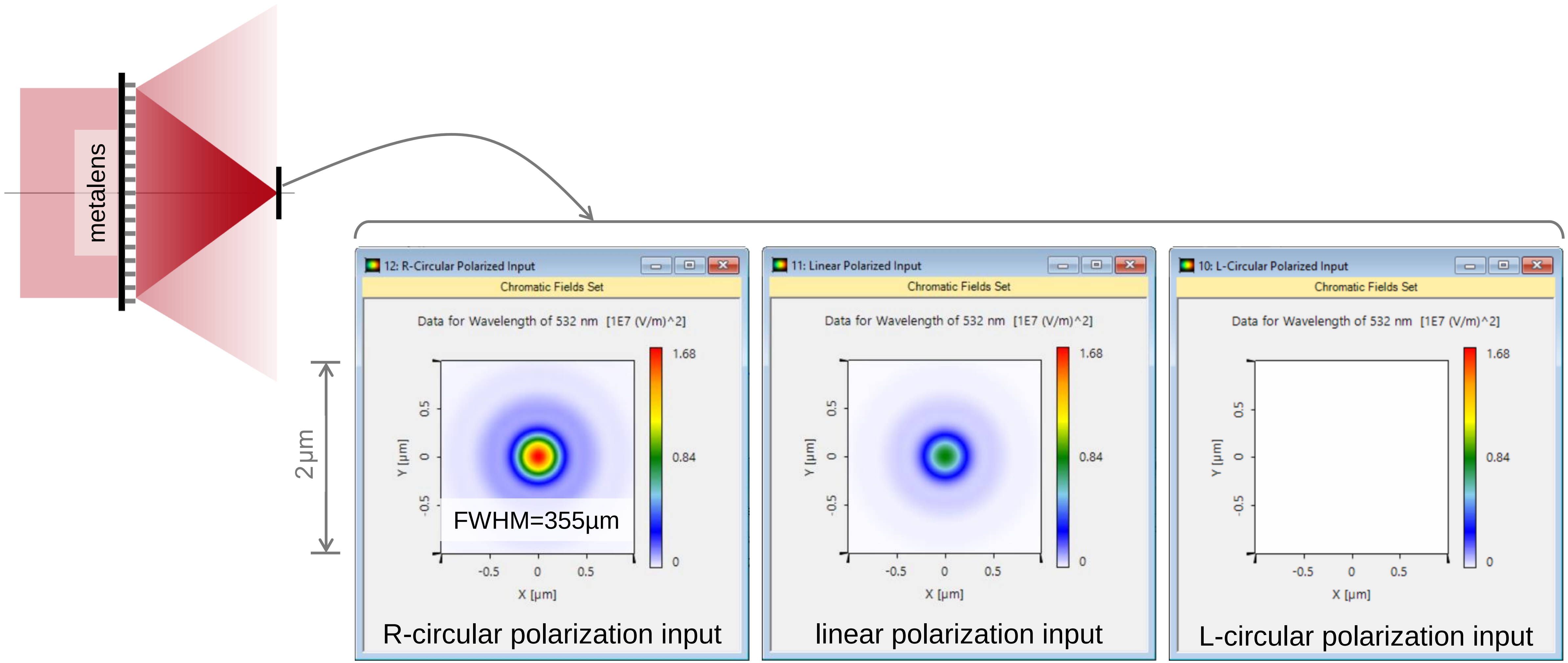
Behavior of the metalens obviously depends on the polarization states of the input fields.



High-NA Metalens Simulation



High-NA Metalens Simulation



Off-Axis Imaging Quality Analysis by High-NA Microscope

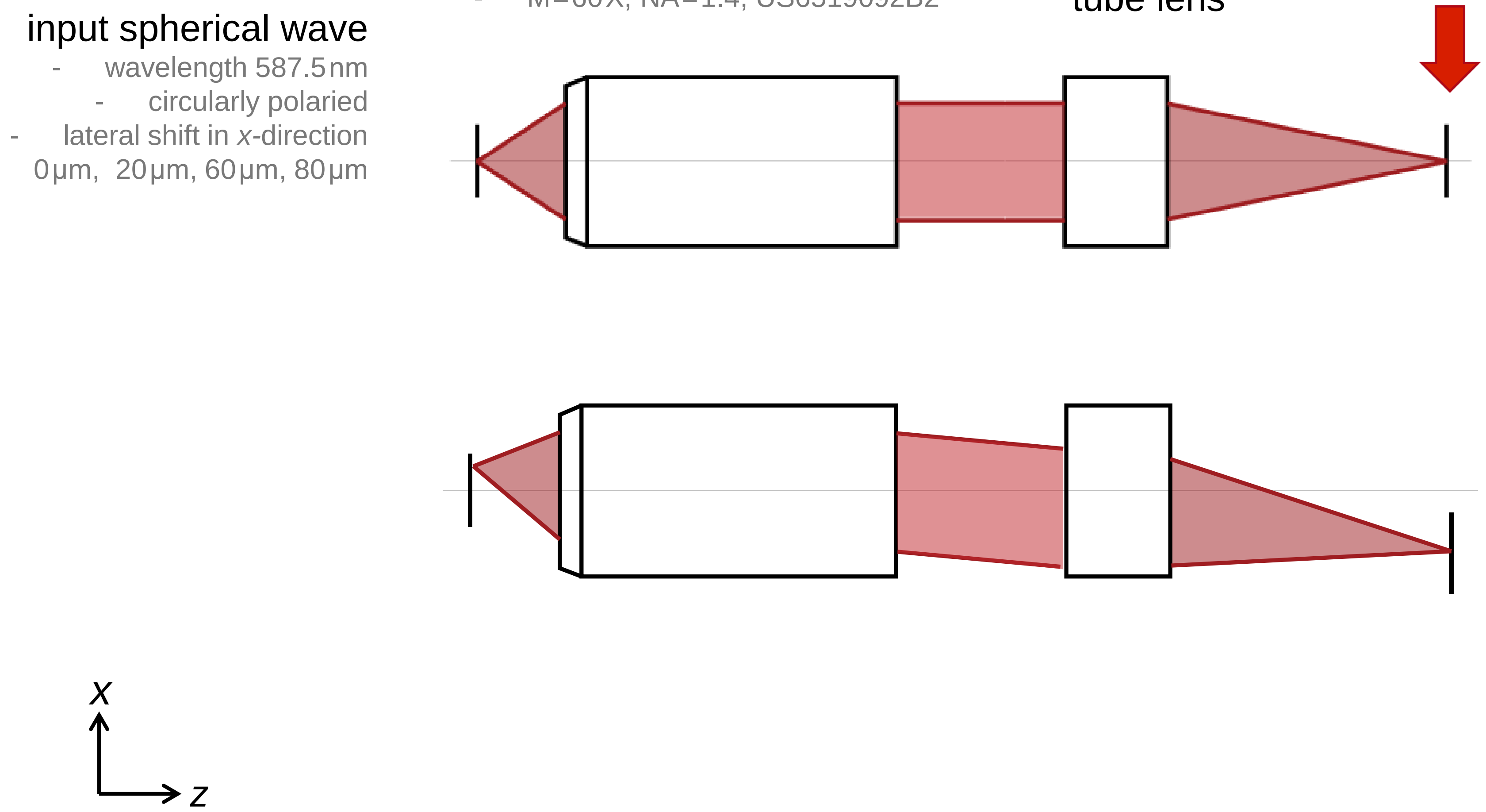
Modeling Task

input spherical wave
- wavelength 587.5 nm
- circularly polaried
- lateral shift in x-direction 0 µm, 20 µm, 60 µm, 80 µm

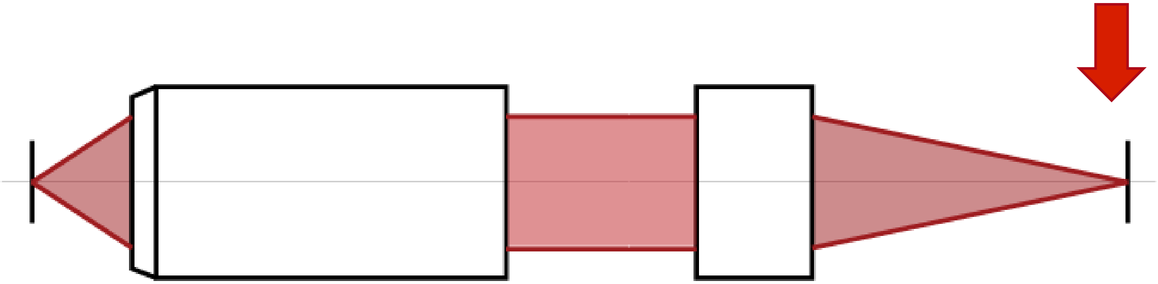
objective lens: Nikon
- M=60X, NA=1.4, US6519092B2

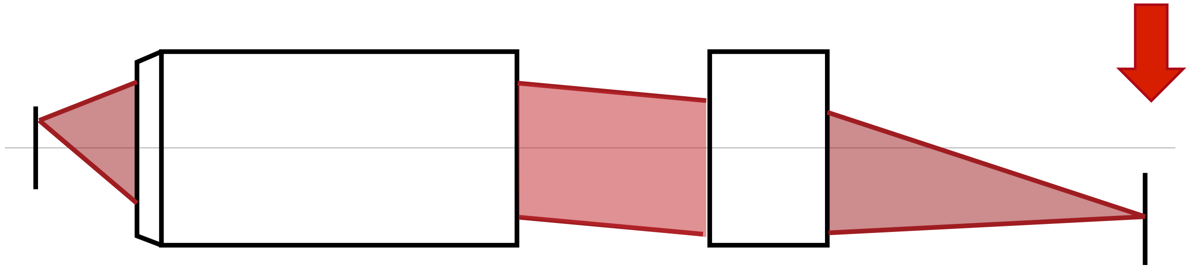
tube lens

PSF=?

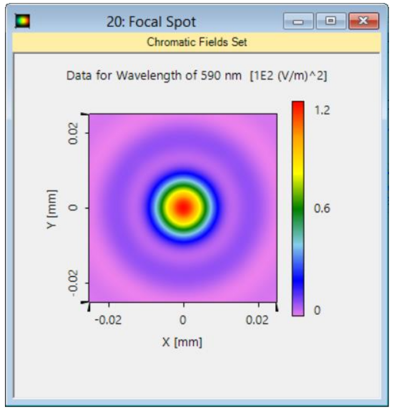


Focal Spot at Focal Plane with Lateral Shifts

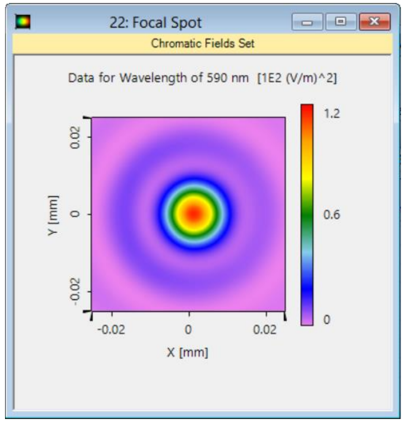




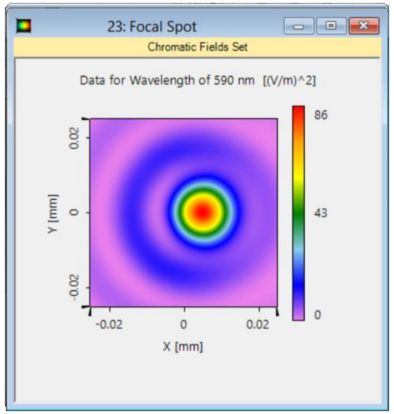
X=0



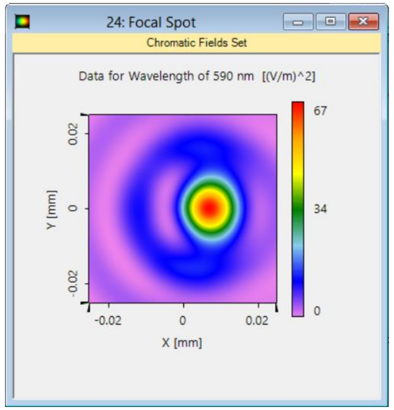
X=20 µm



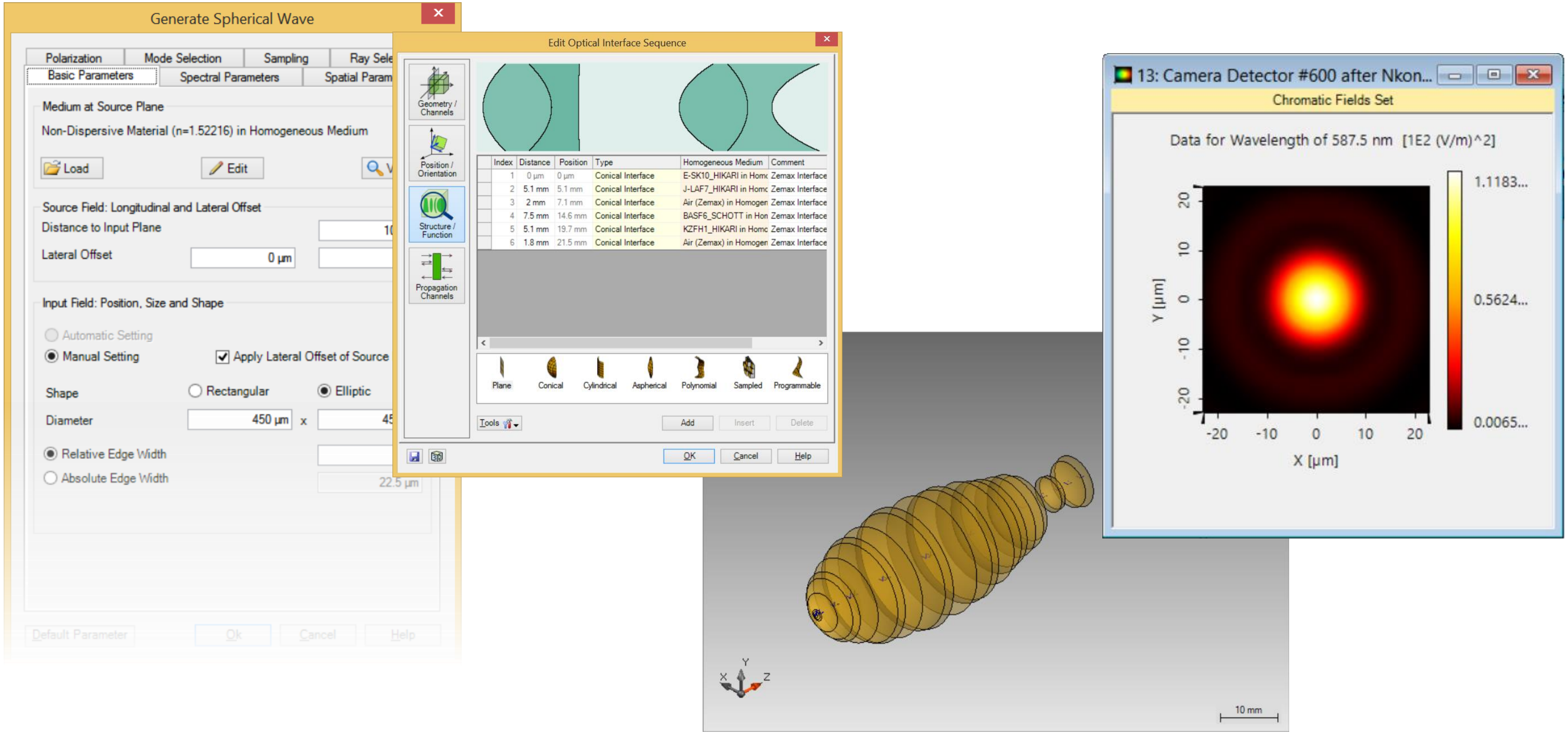
X=60 µm



X=80 µm



Peek into VirtualLab



structure demonstration

Resolution Investigation by Abbe Criterion

Modeling Task

input plane wave
- wavelength 587.5 nm
  - linearly polaried along *y* direction

grating period
- 1000 nm
- 500 nm
- 300 nm

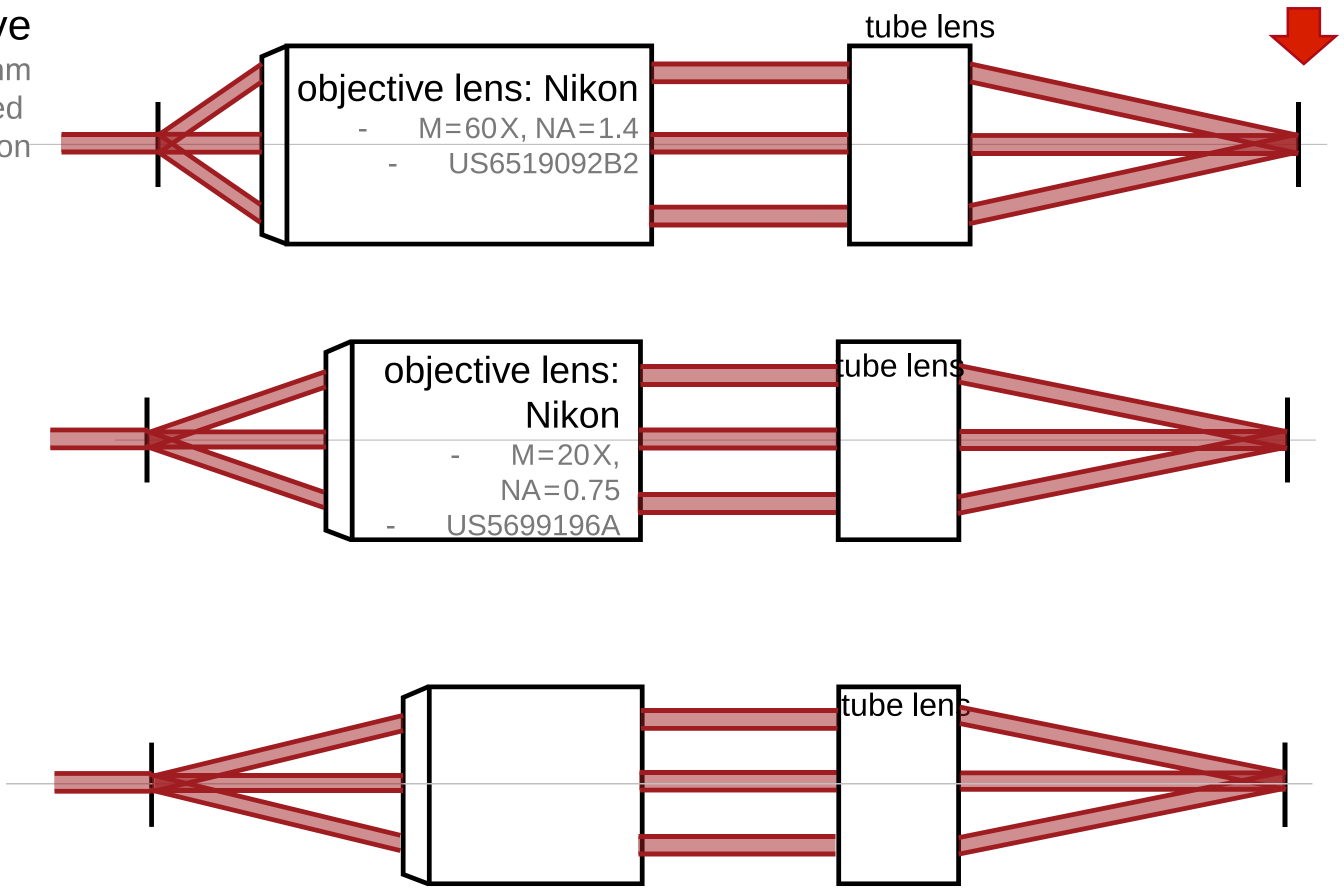
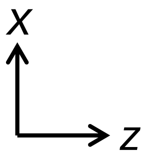
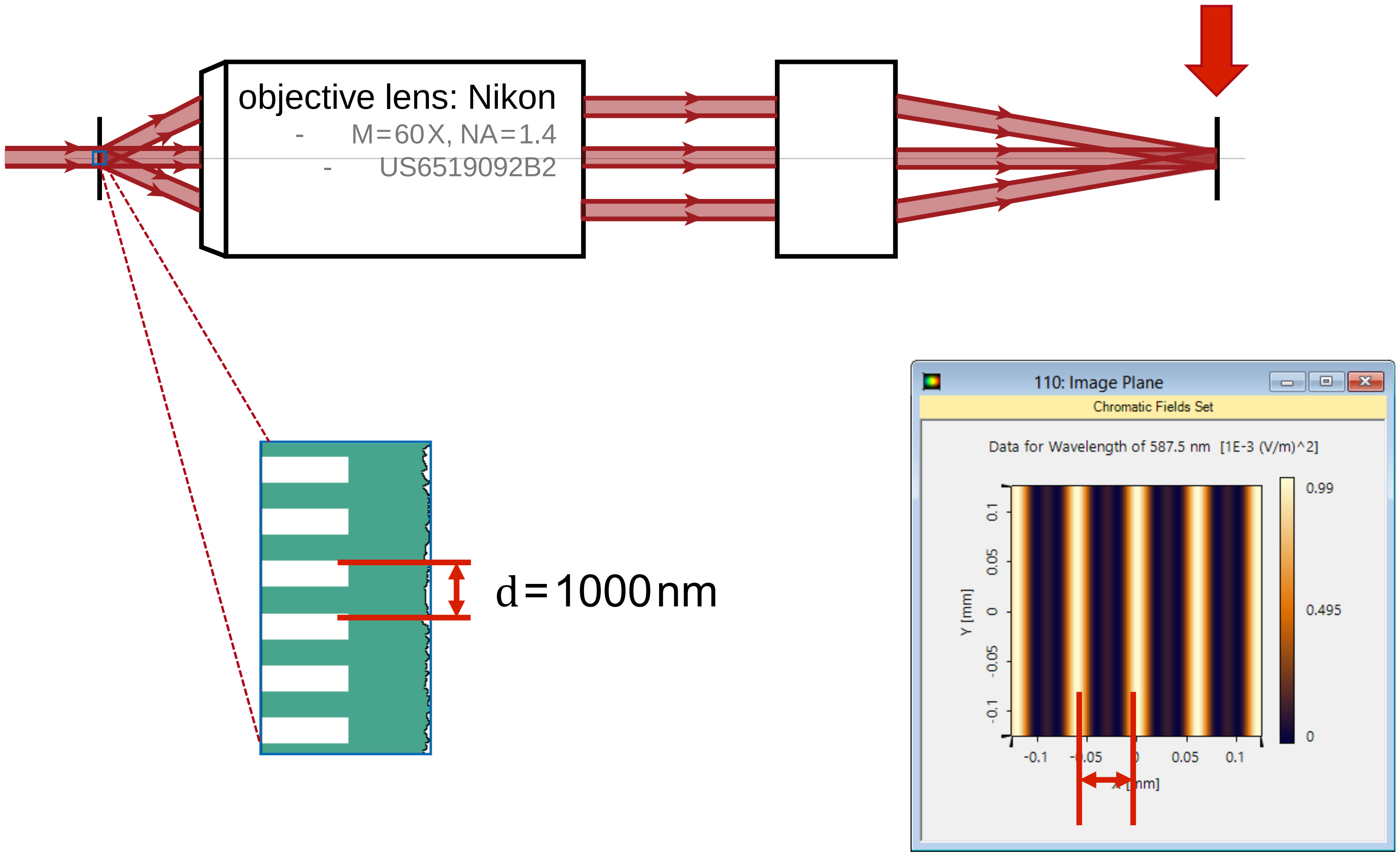


image of grating=?

objective lens: Nikon
- M=20X, NA=0.5
- US5920432A



Results: Image of Grating

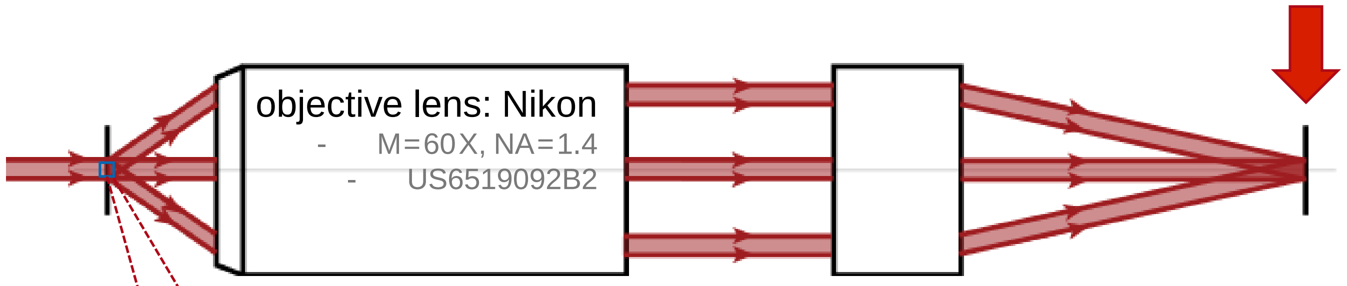


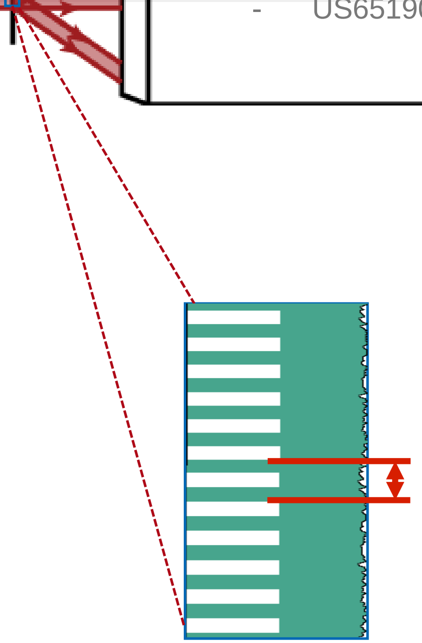
$d' = 60\ \mu m$

Abbe:

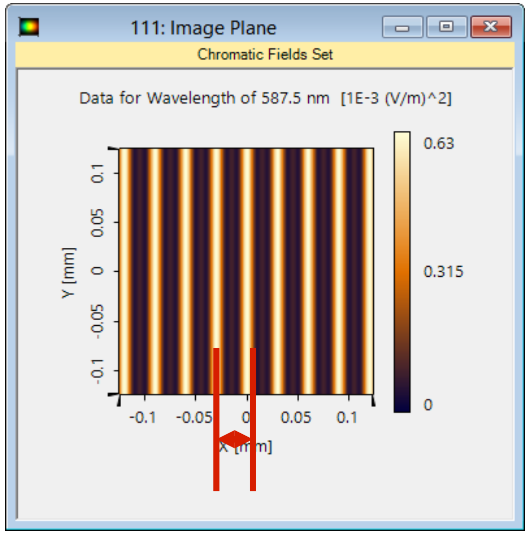
$$d = \frac{\lambda}{NA} = 419\ nm$$

Results: Image of Grating





d = 500 nm

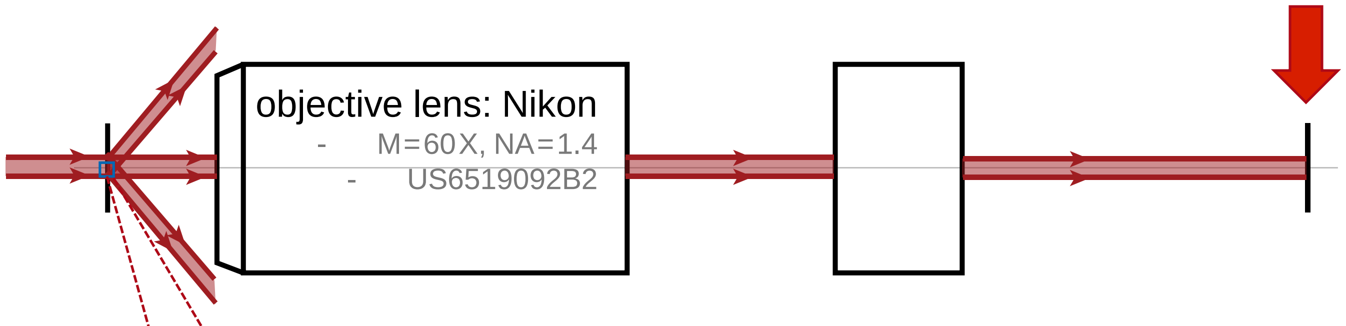


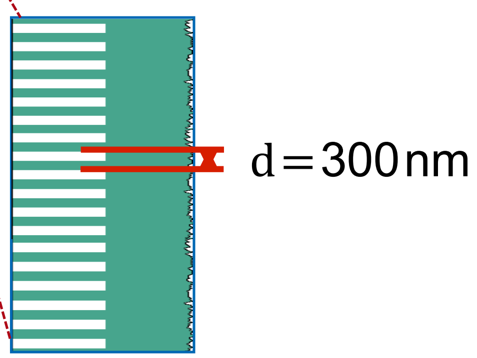
d′= 30 μm

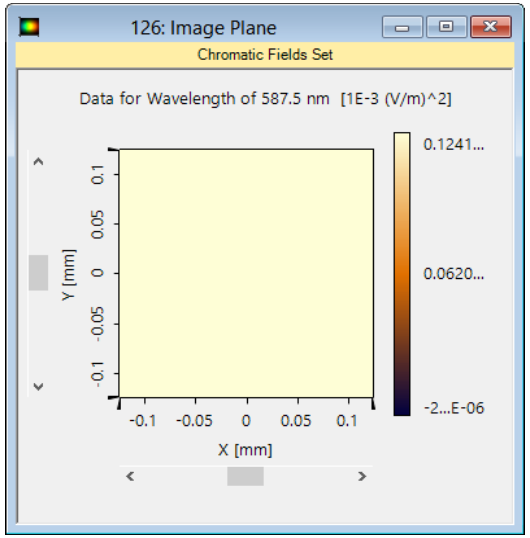
Abbe:

$$d = \frac{\lambda}{NA} = 419 \text{ nm}$$

Results: Image of Grating





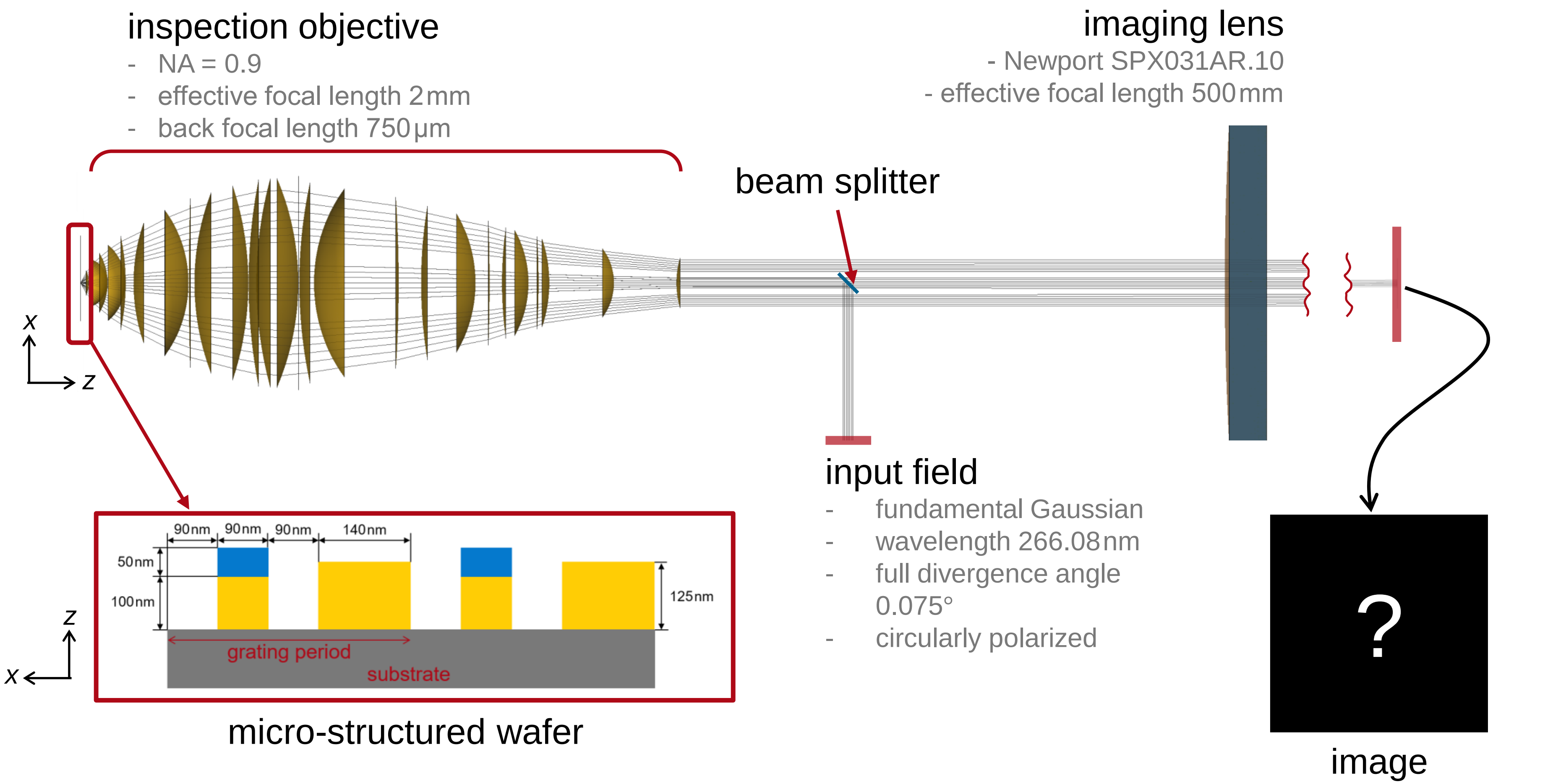


Abbe:

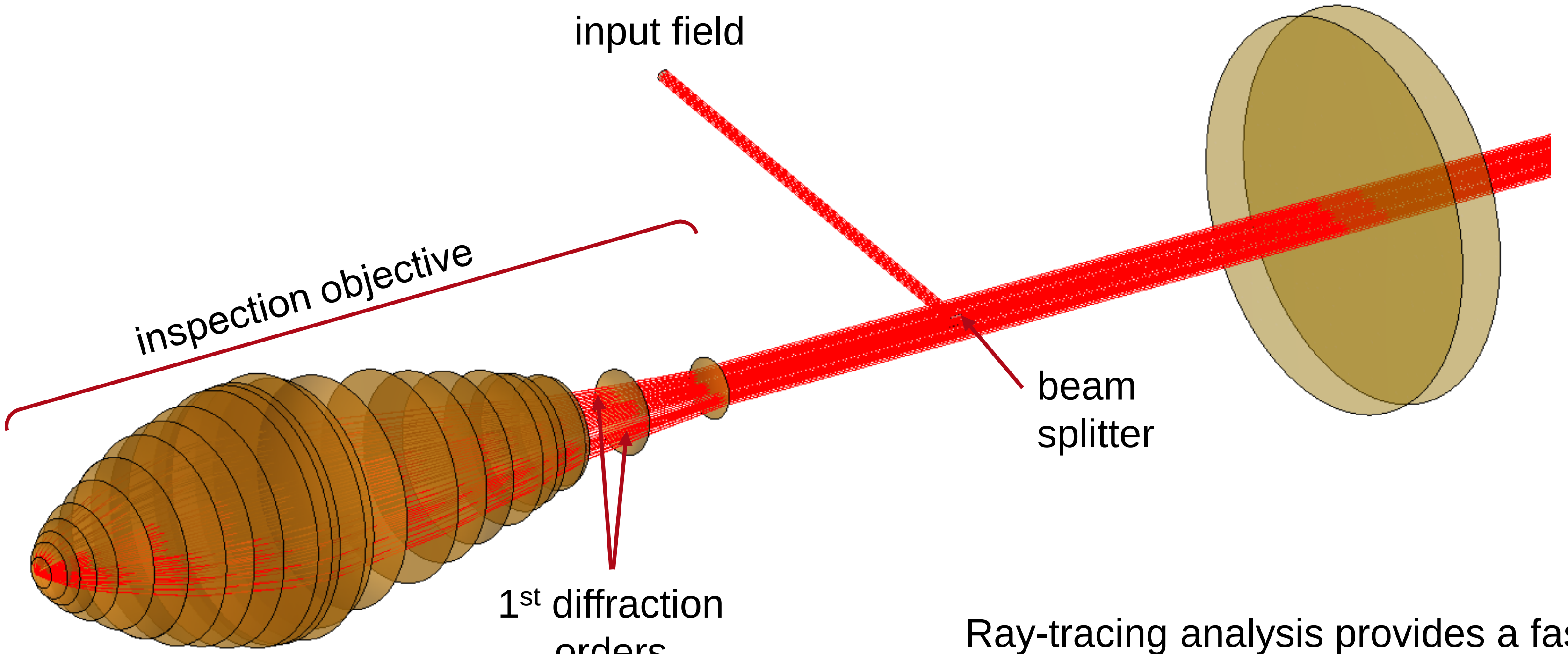
$$d = \frac{\lambda}{NA} = 419 \text{ nm}$$

Optical System for Inspection of Micro-Structured Wafer

Modeling Task

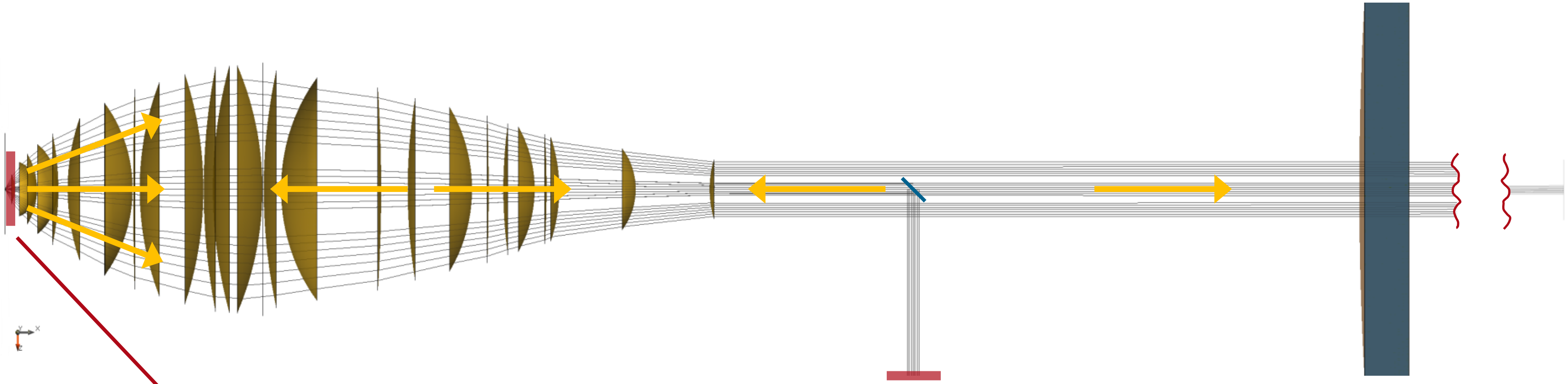


Results

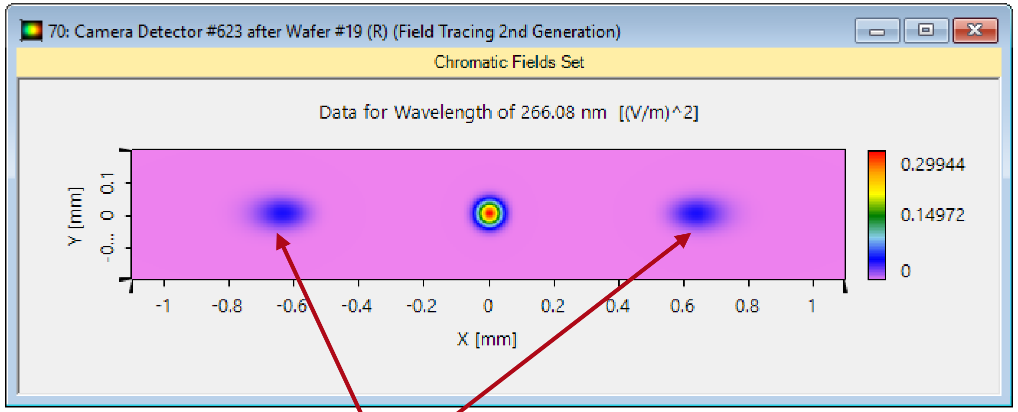


Ray-tracing analysis provides a fast overview of the complete system, including high-NA lens and grating.

Results



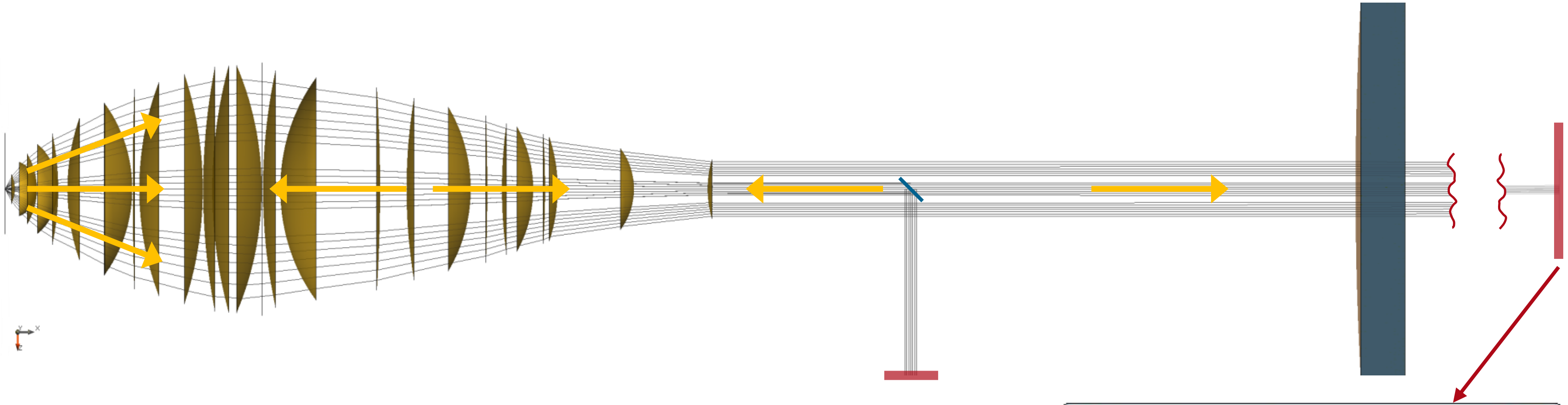
behind micro-structured wafer



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

1st diffraction orders

Results



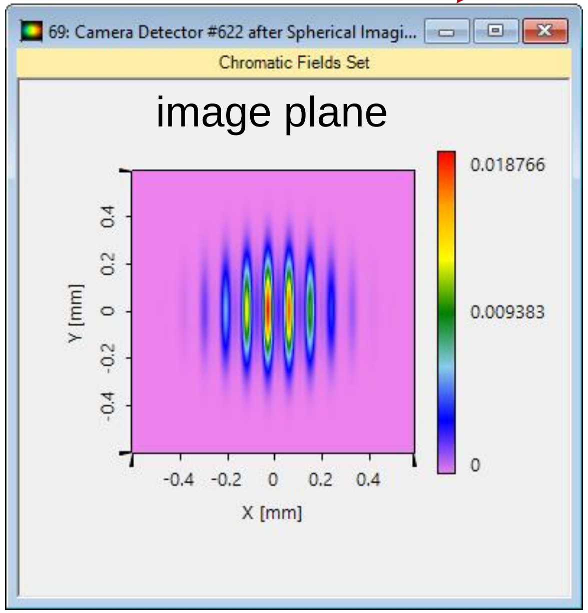
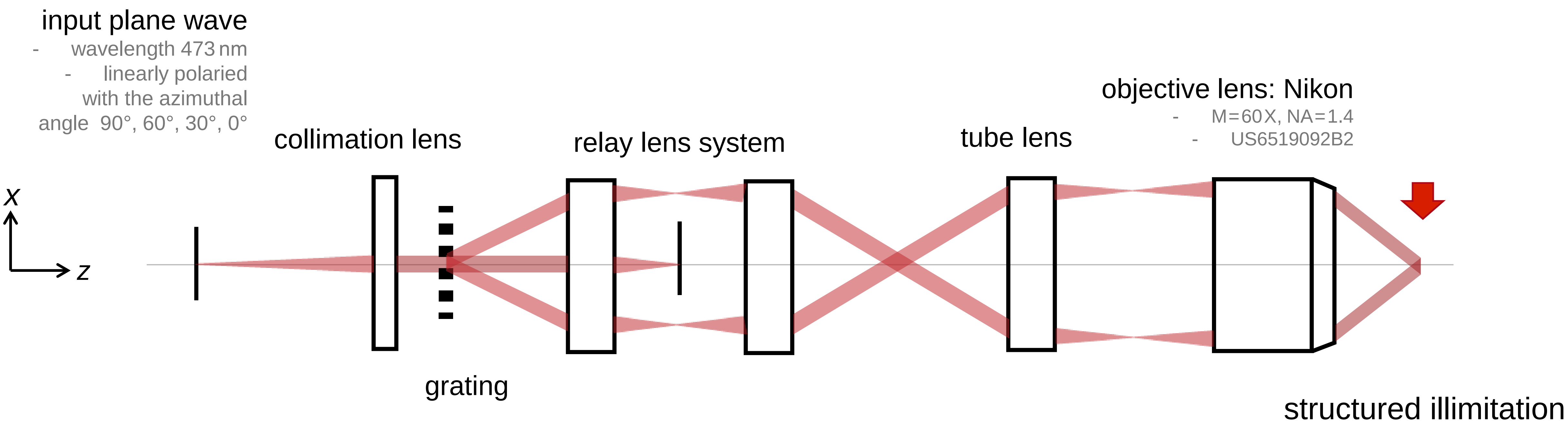


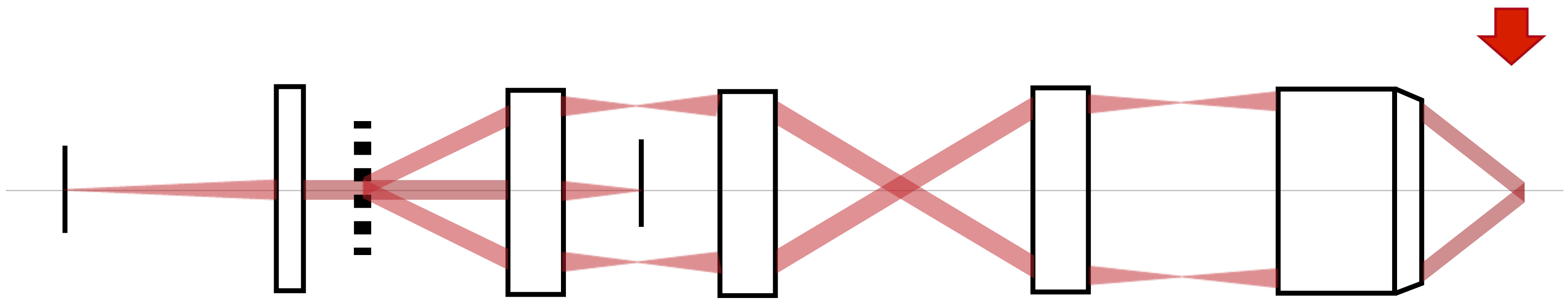
Image is formed by interference of different diffraction orders. Simulation of complete system from input field to image plane takes less than 5 seconds!

Microscopy System with Structured Illumination

Modeling Task

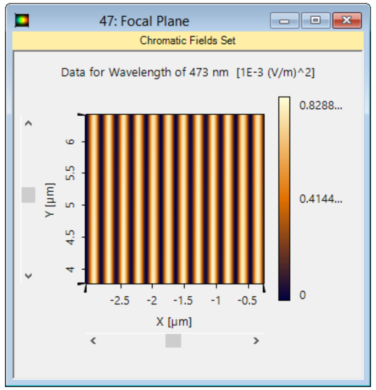


Results: Interference Pattern at Focal Plane

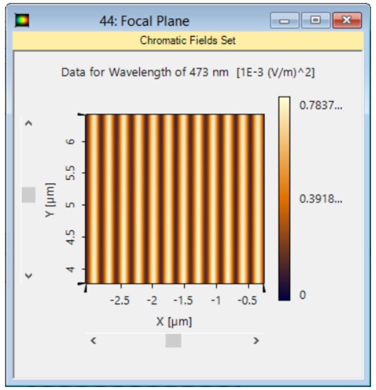


Contrast is decreasing as the azimuthal angle decreases.

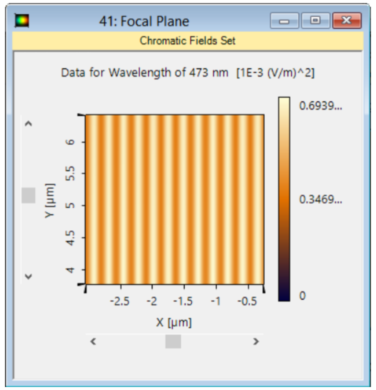
$\phi = 90°$



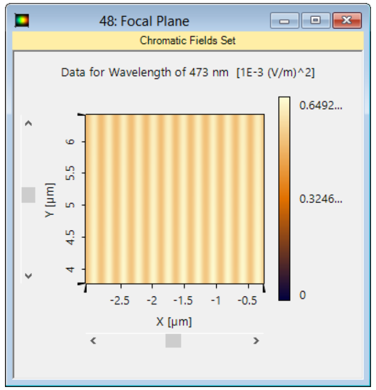
$\phi = 60°$



$\phi = 30°$

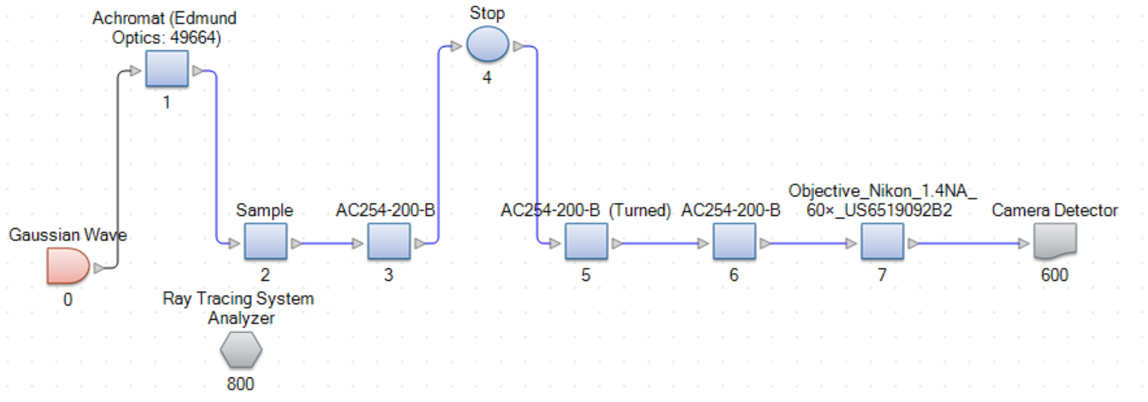


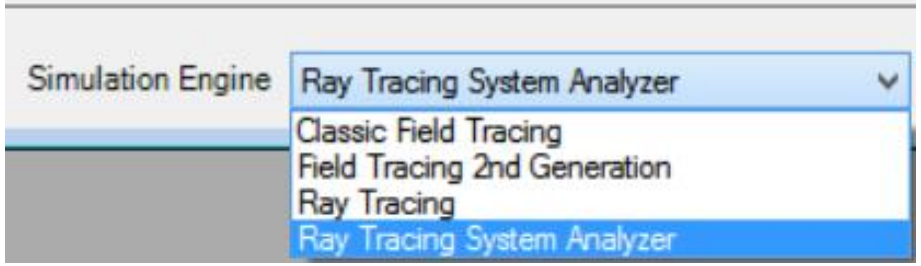
$\phi = 0°$

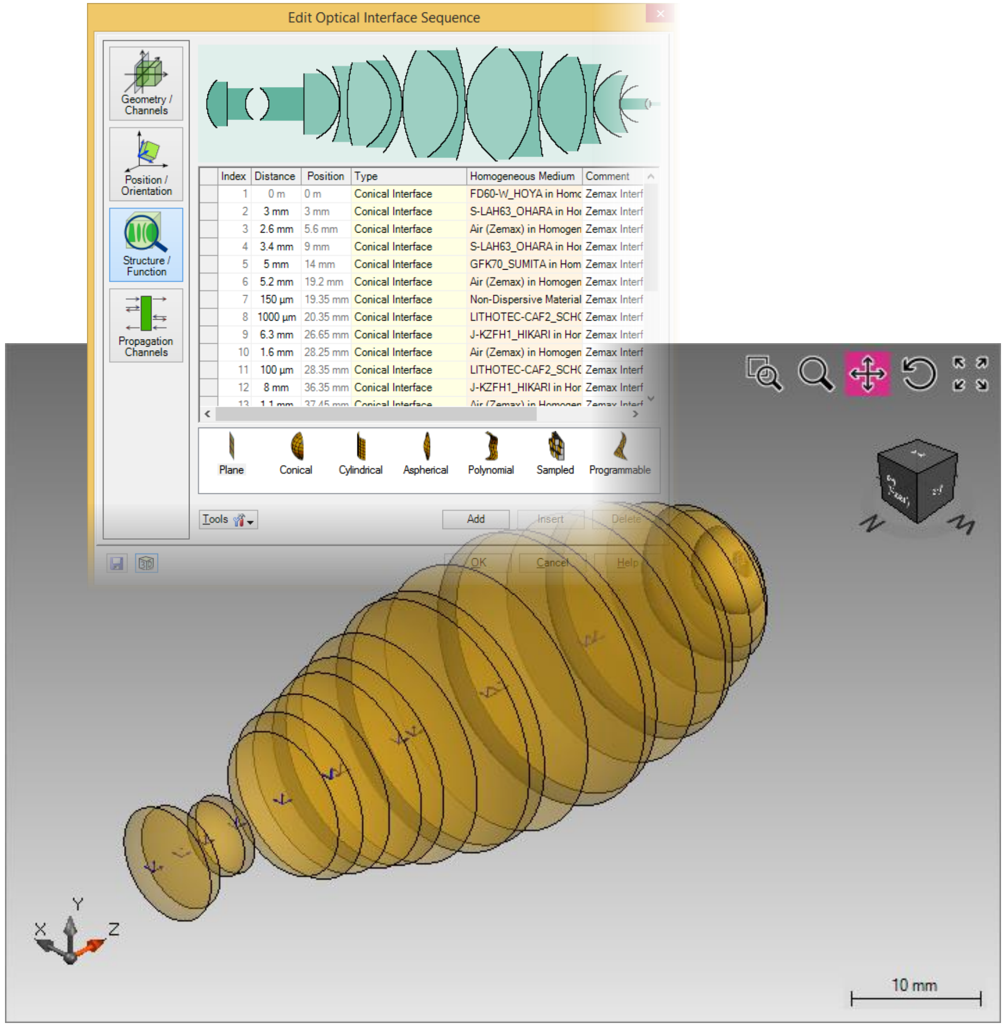


Peek into VirtualLab

Configuration of optical setup







Ray tracing demonstration

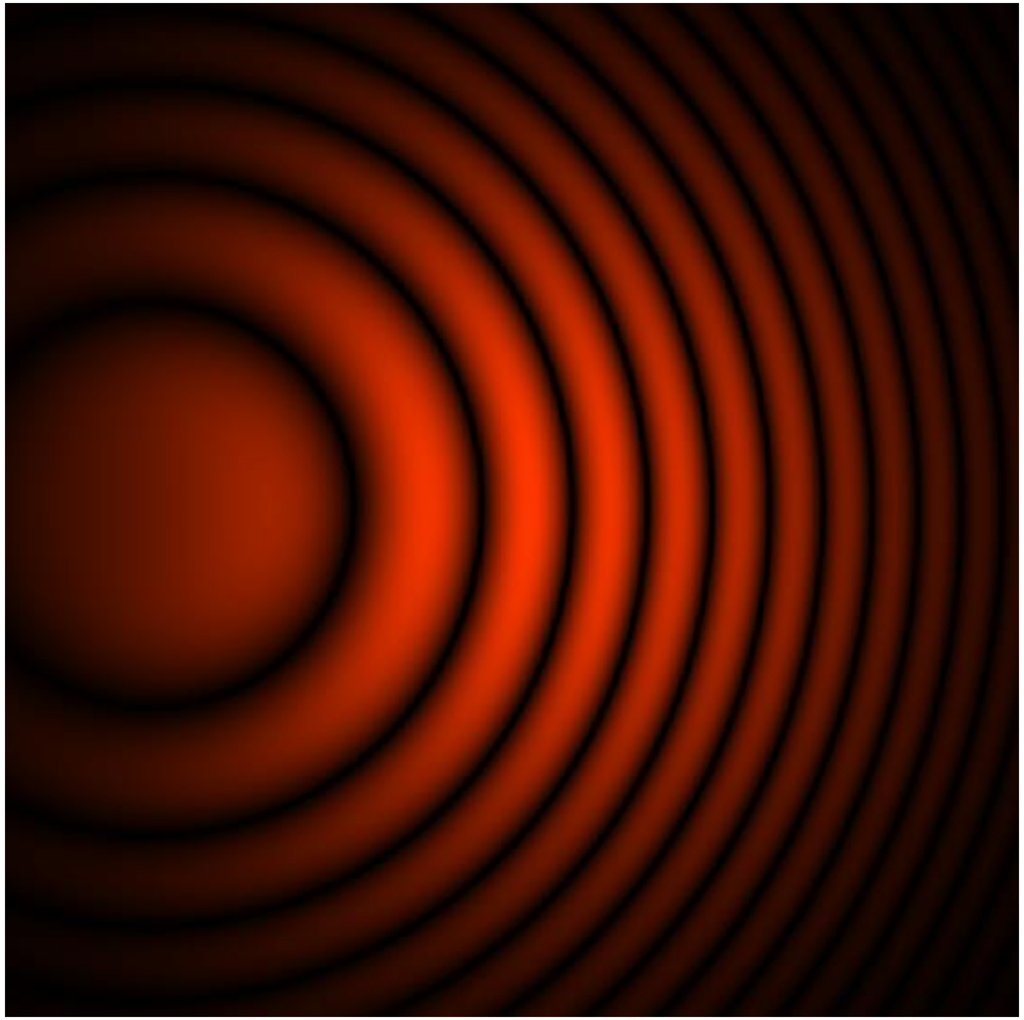
VirtualLab Fusion Technology and Applications

Interferometry

Stefan Steiner
LightTrans International UG

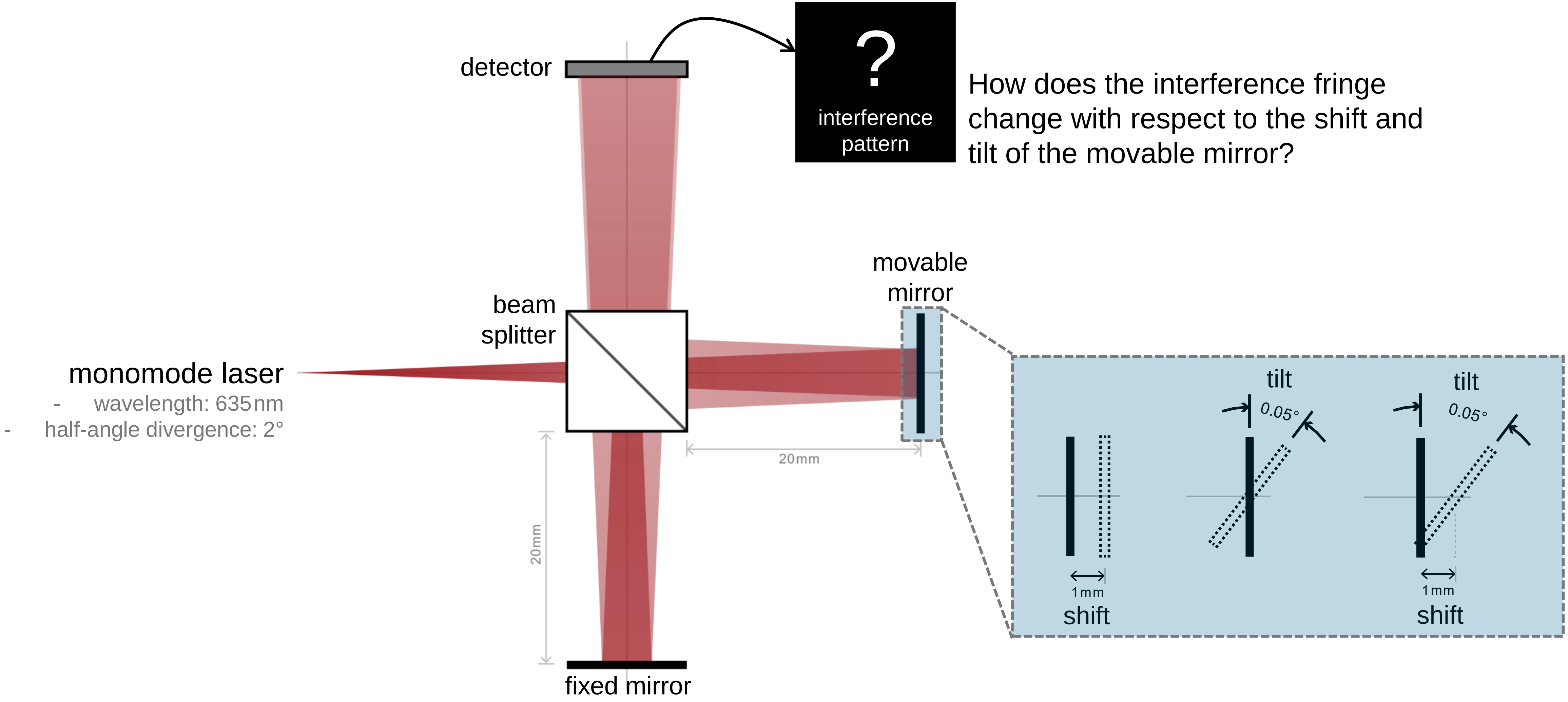
Laser-Based Michelson Interferometer and Interference Fringe Exploration

Abstract



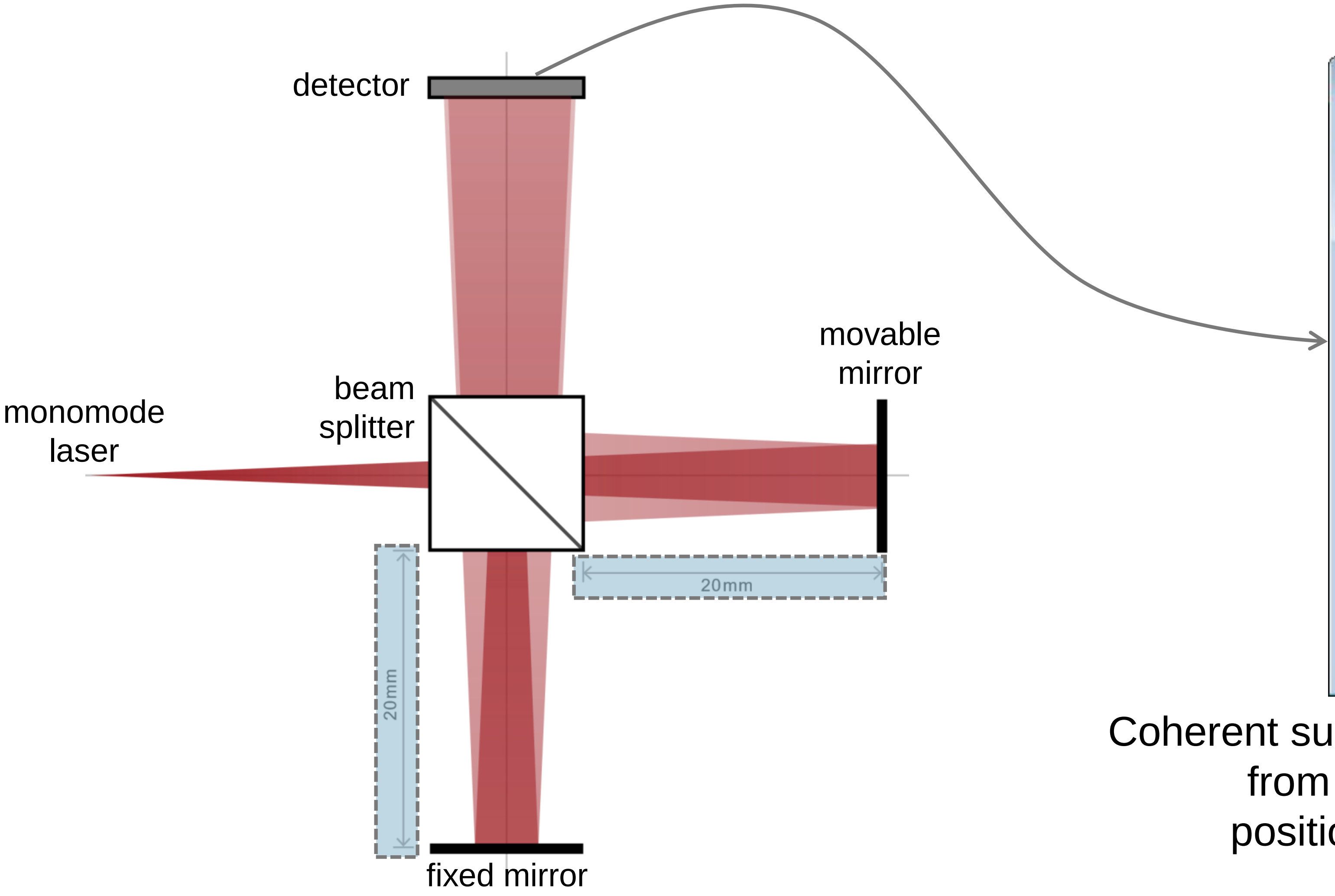
Michelson interferometer is a typical configuration for optical interferometry. Different configurations in the setup may lead to different interference fringes, and therefore it is worth of investigating the relation between them. With the help of non-sequential tracing technology in VirtualLab Fusion, it is easy to set up and to configure a Michelson interferometer, and to visualize the interference fringe in different situations. In this example, several typical situations and the corresponding fringes are demonstrated.

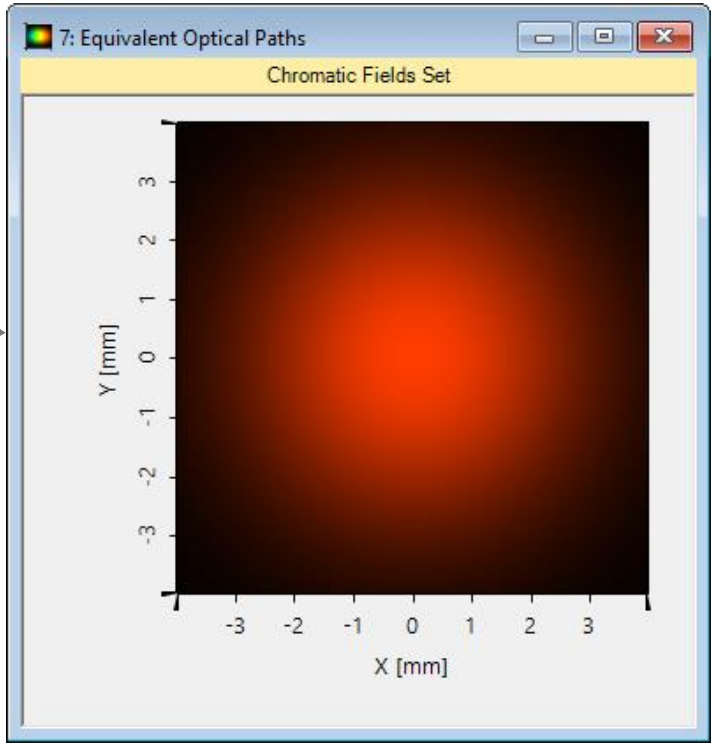
Modeling Task



How does the interference fringe change with respect to the shift and tilt of the movable mirror?

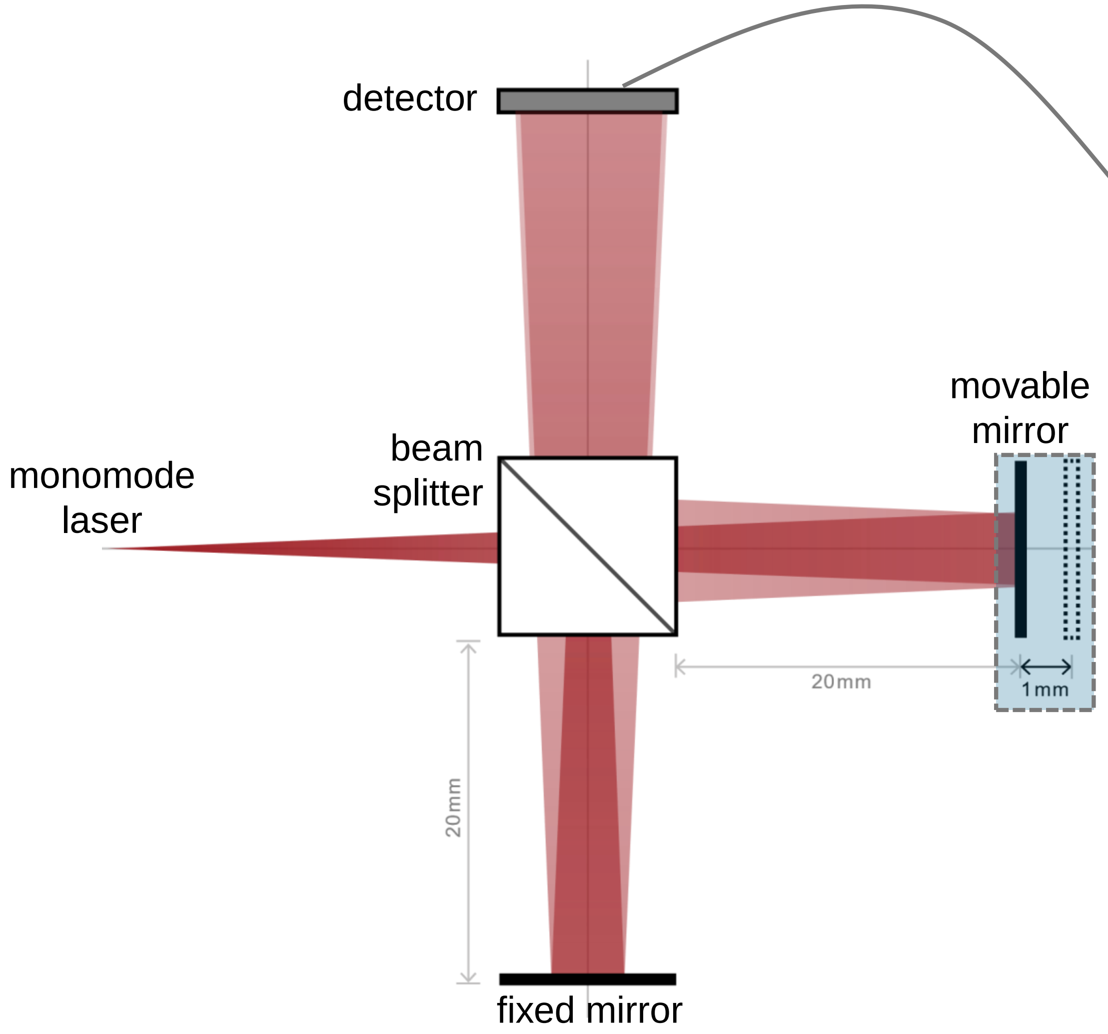
Result with Equivalent Optical Path

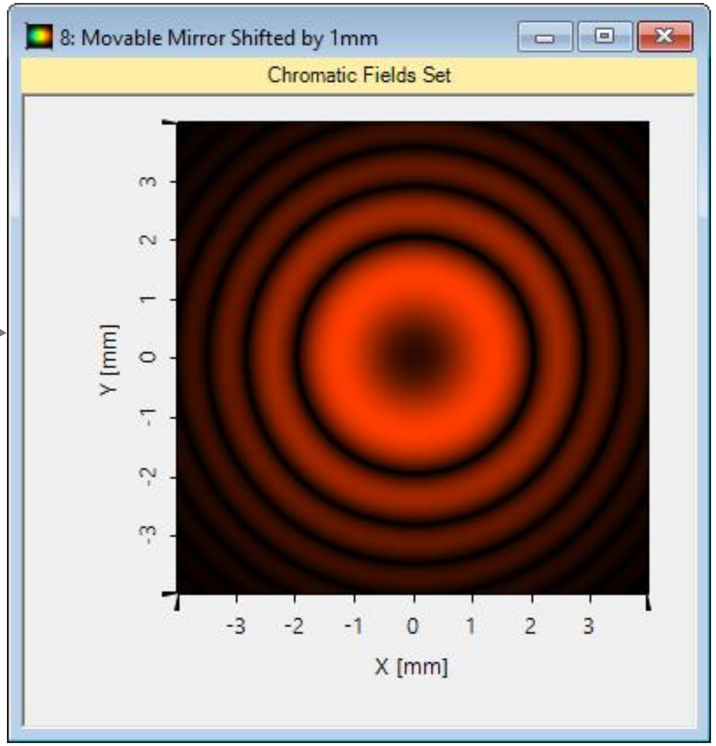




Coherent superposition of two fields reflected from planar mirrors at equivalent-path positions gives no interference fringes.

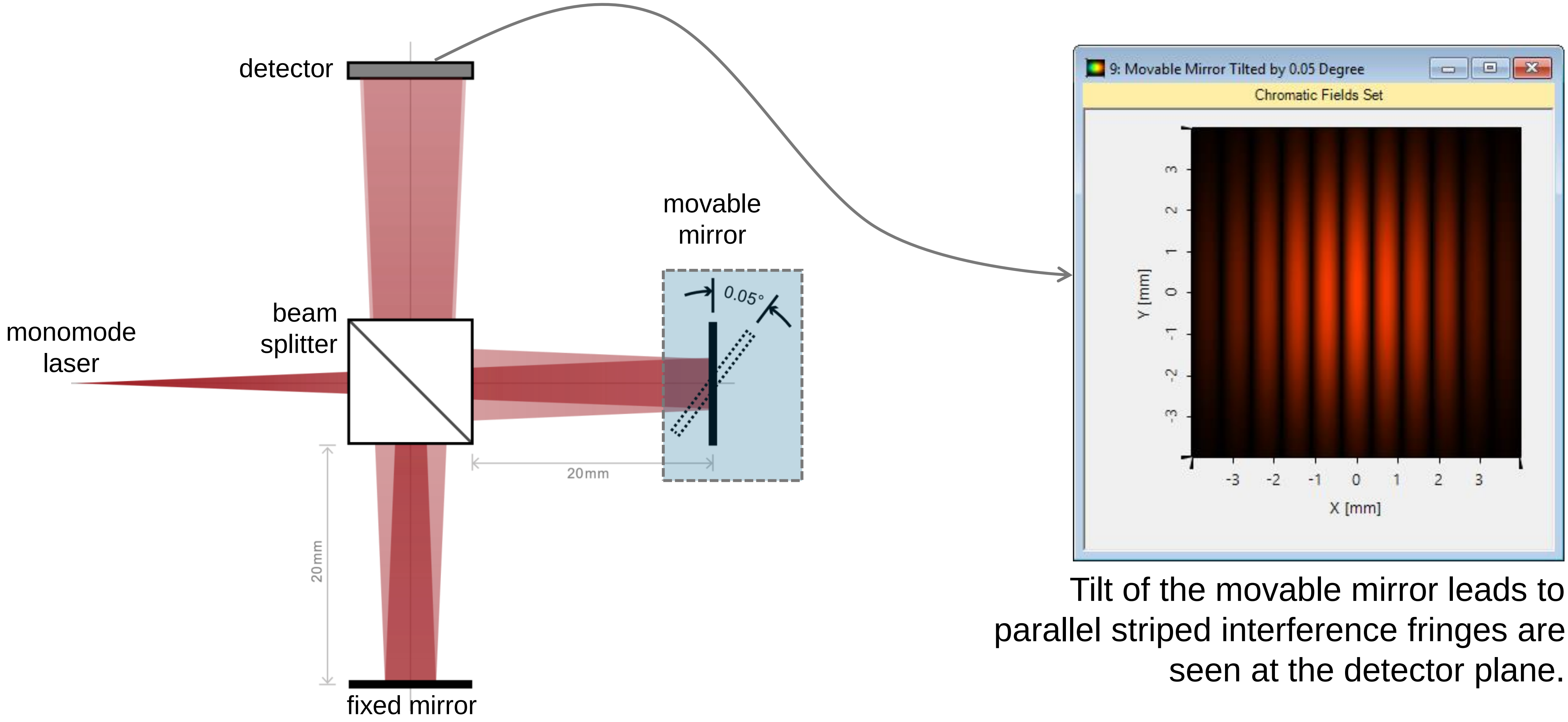
Result with Shifted Movable Mirror





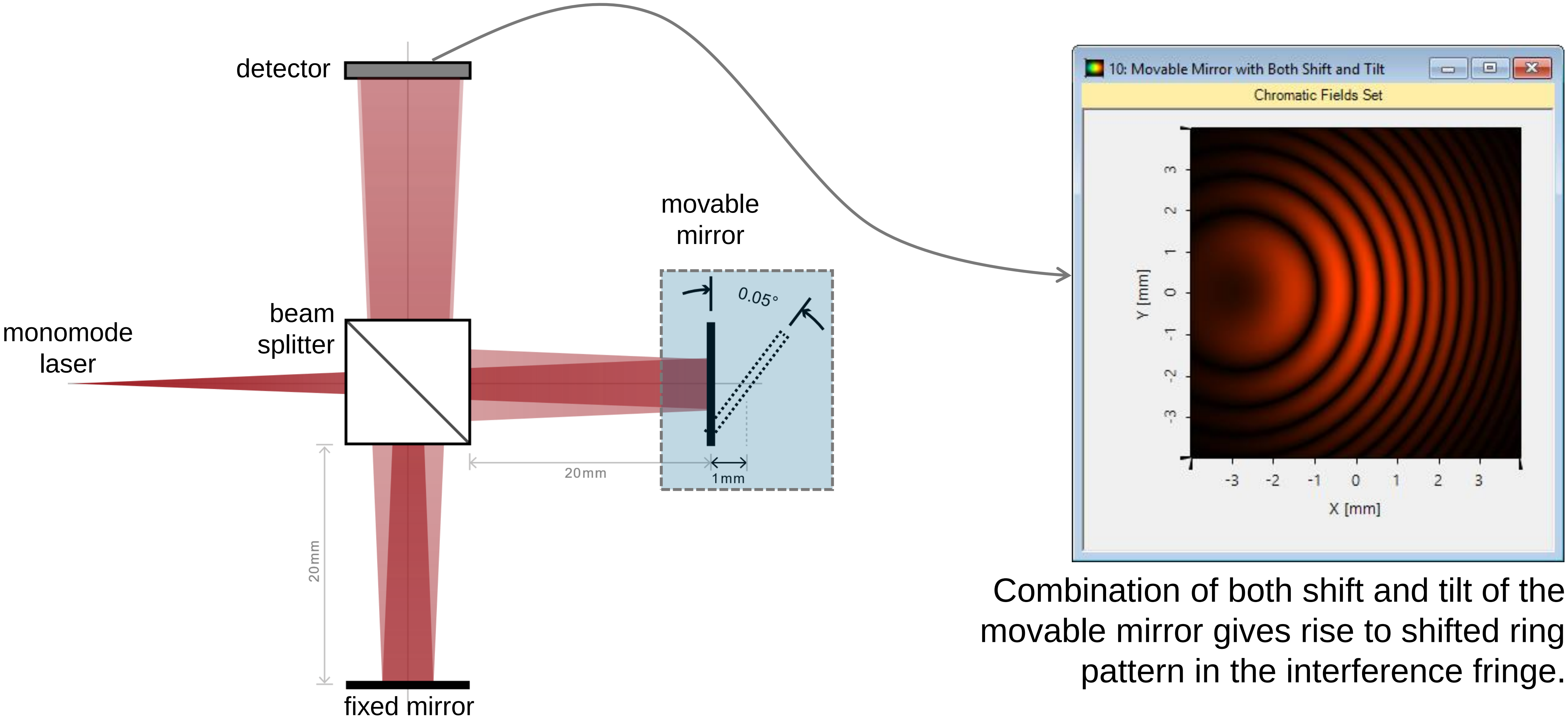
Shift of the movable mirror introduces defocus, and therefore ring fringes are observed at the detector plane.

Result with Tilted Movable Mirror



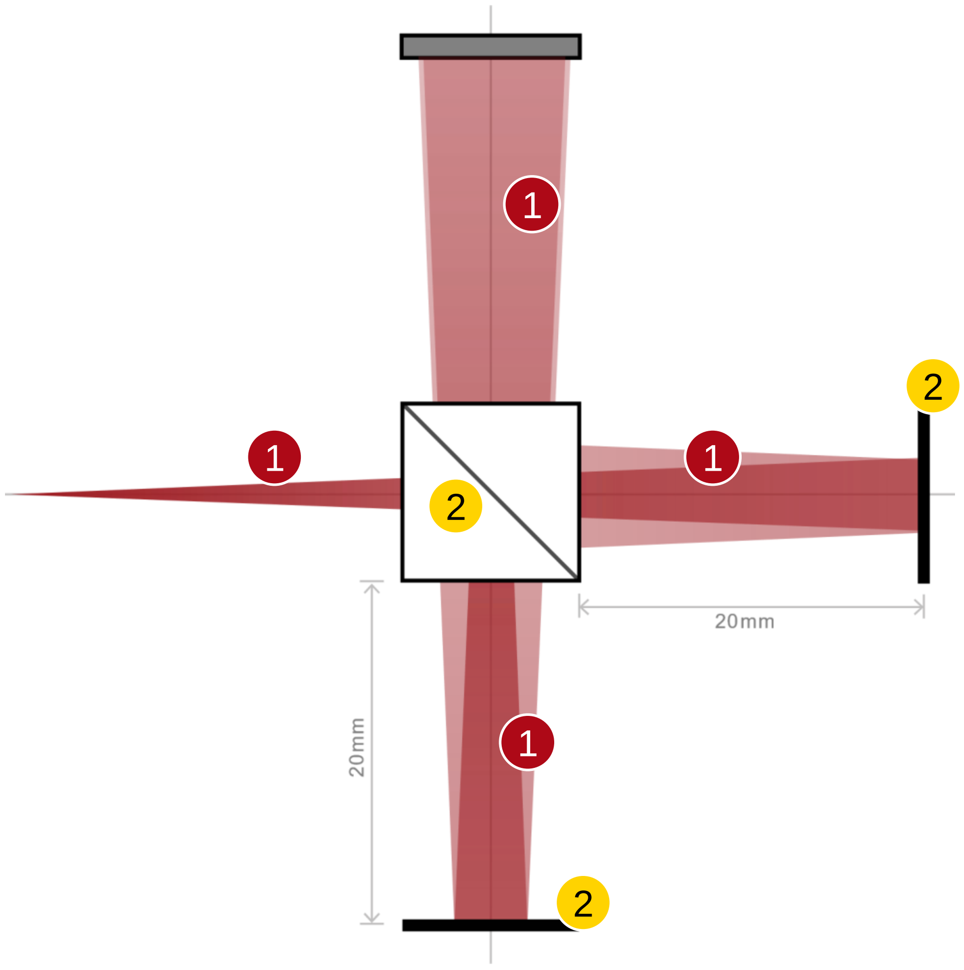
Tilt of the movable mirror leads to parallel striped interference fringes are seen at the detector plane.

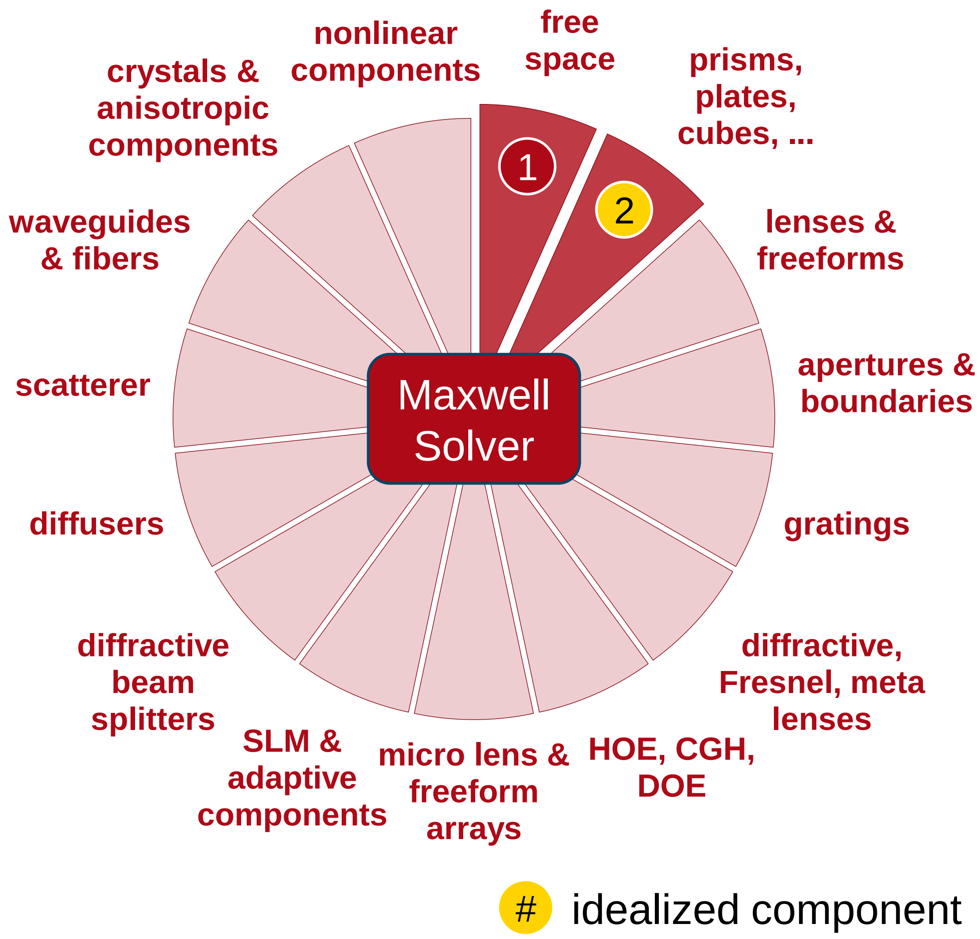
Result with Shifted and Tilted Movable Mirror



Combination of both shift and tilt of the movable mirror gives rise to shifted ring pattern in the interference fringe.

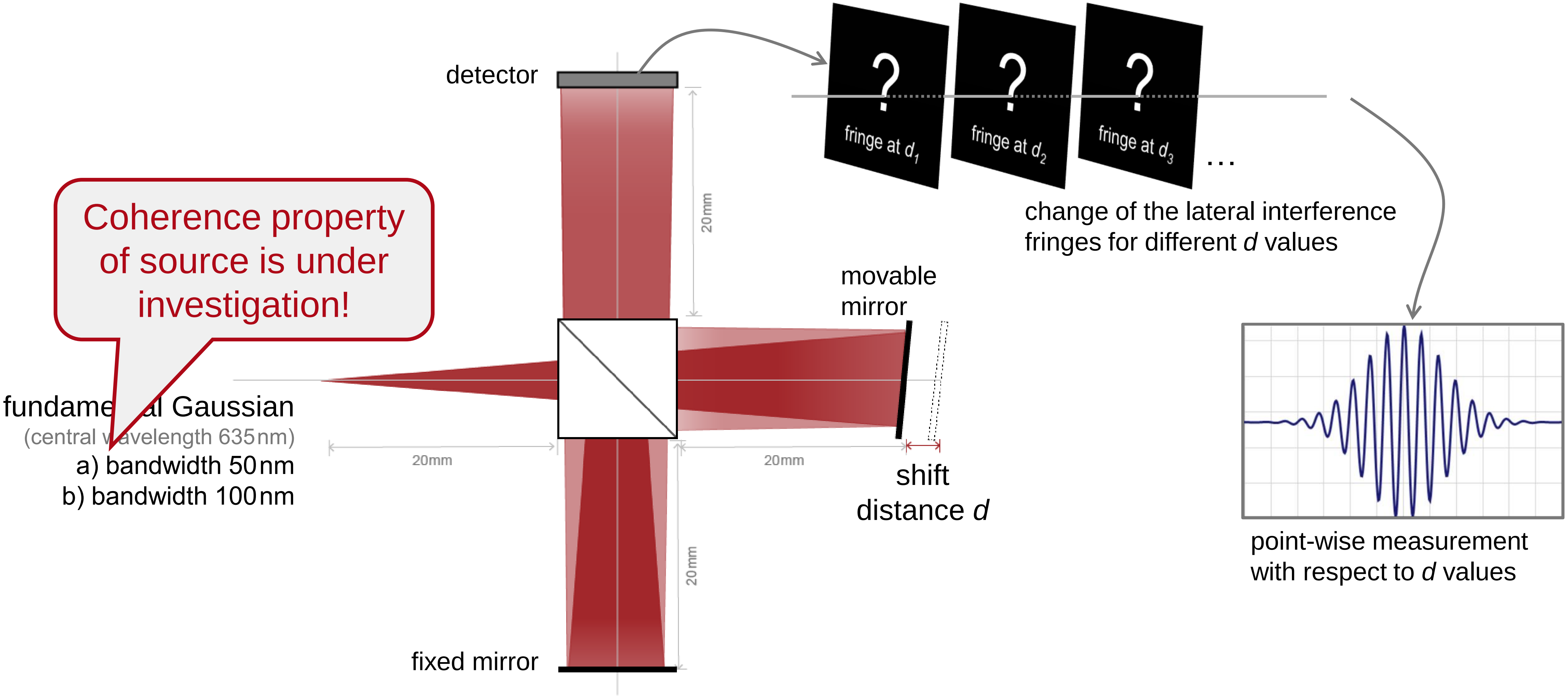
VirtualLab Technologies



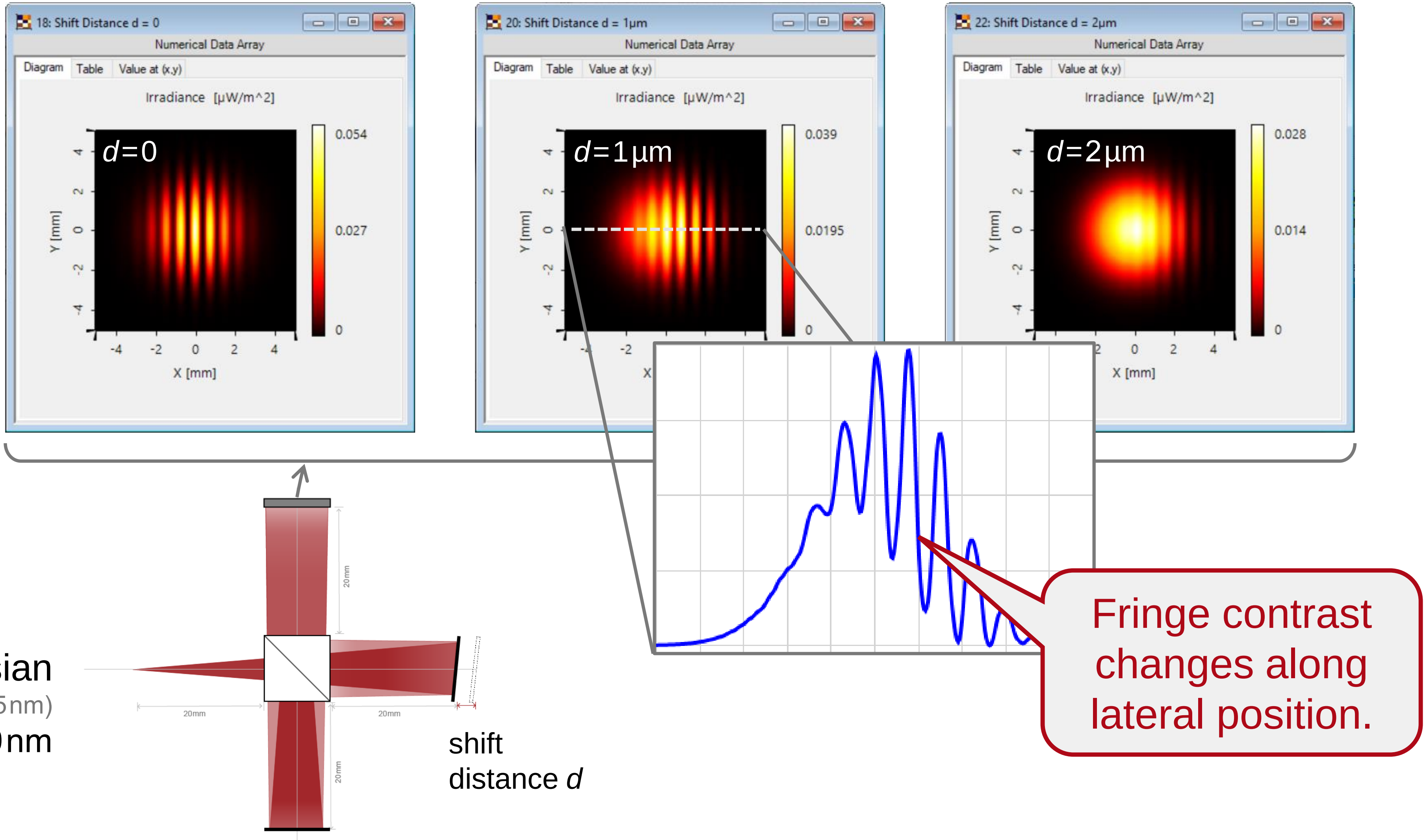


Coherence Measurement Using Michelson Interferometer and Fourier Transform Spectroscopy

Modeling Task

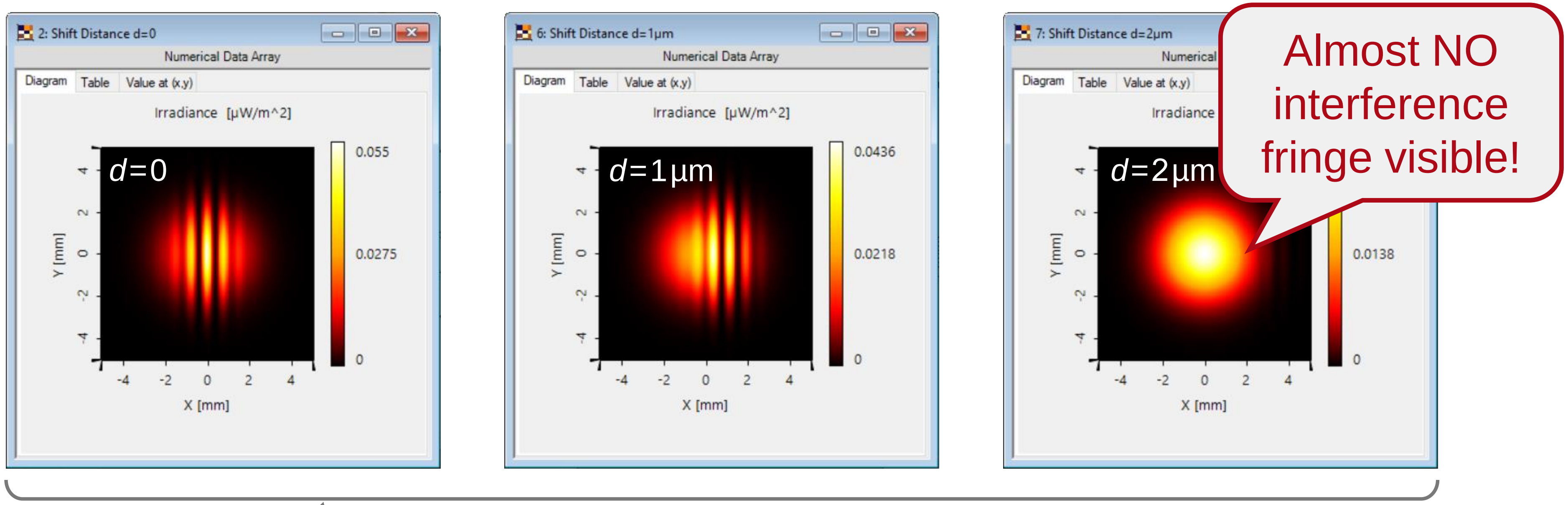


Lateral Interference Fringes – 50 nm Bandwidth

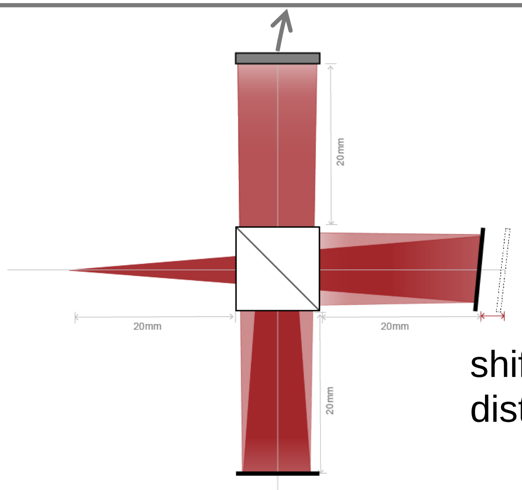


fundamental Gaussian
(central wavelength 635 nm)
a) bandwidth 50 nm

Lateral Interference Fringes – 100 nm Bandwidth



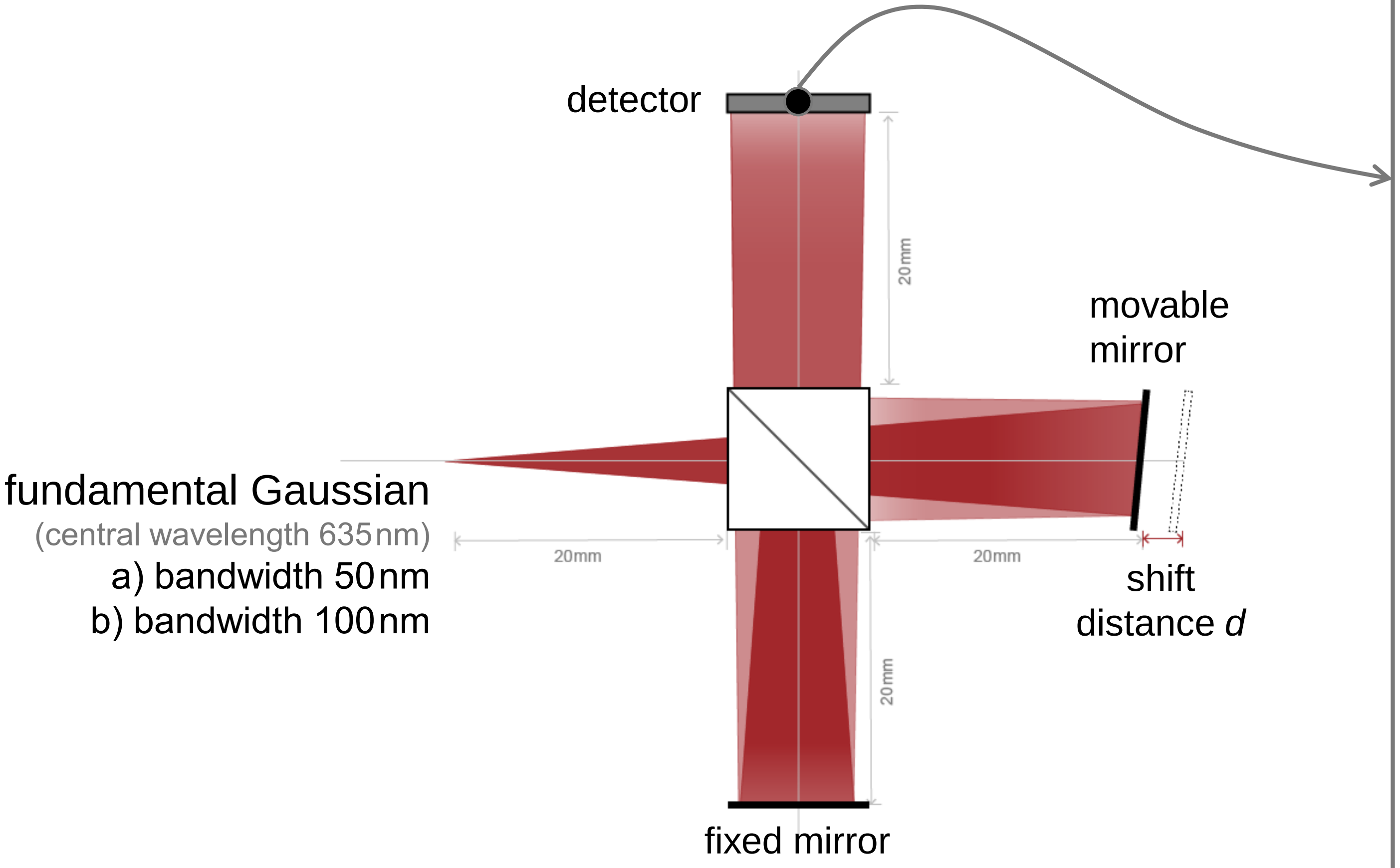
fundamental Gaussian
(central wavelength 635 nm)
b) bandwidth: 100 nm

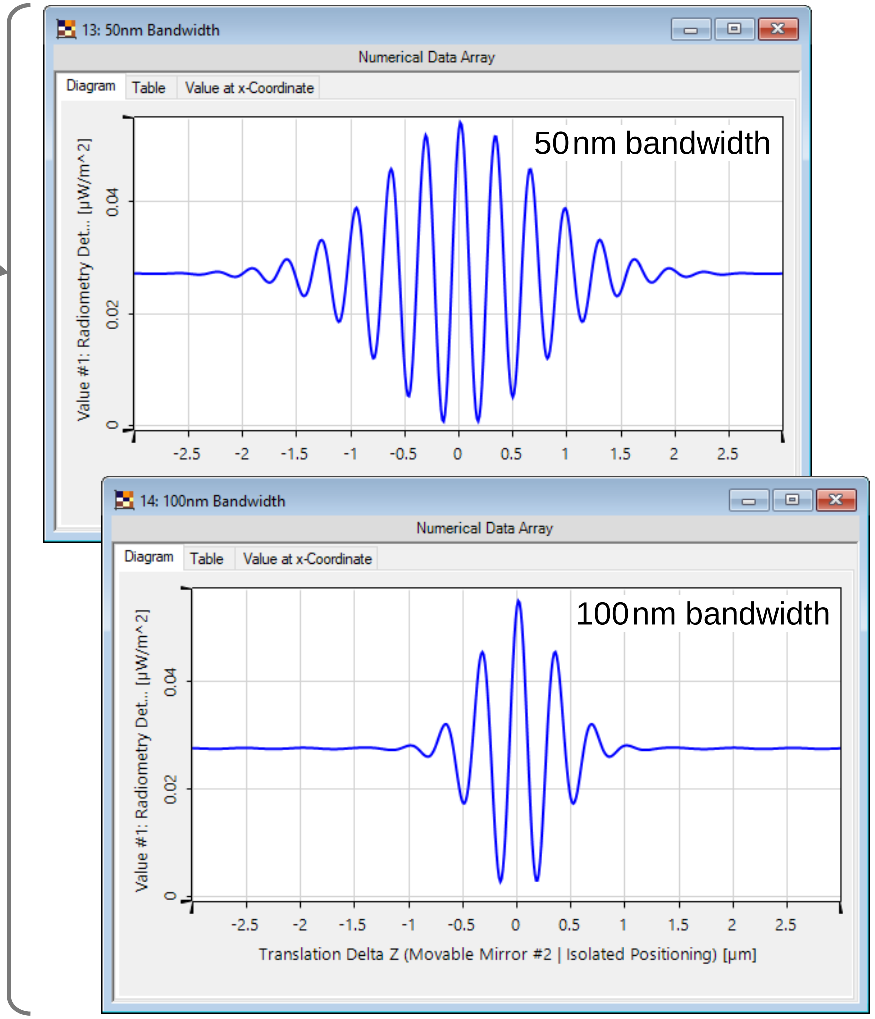


shift
distance *d*

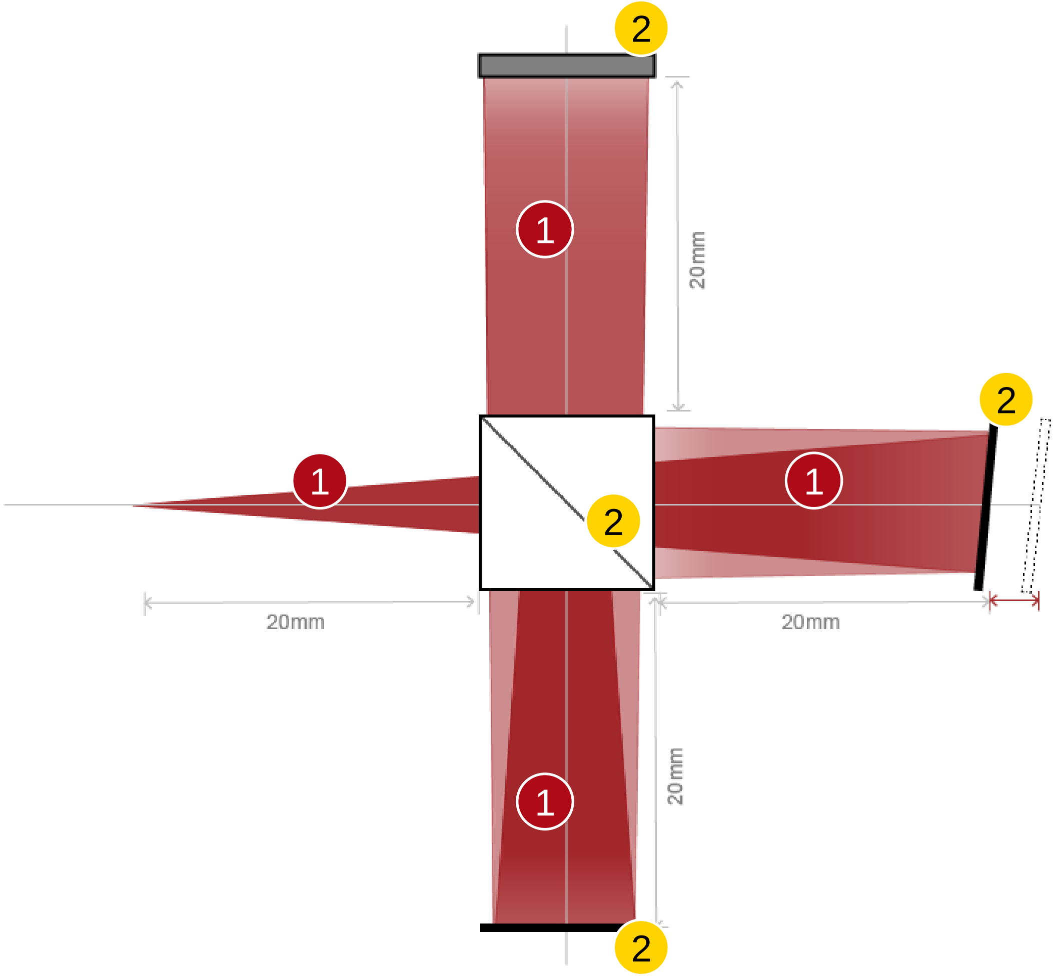
Broader spectral bandwidth leads to shorter coherent length; and therefore the interference fringe starts to vanish sooner in comparison to the case with narrower bandwidth.

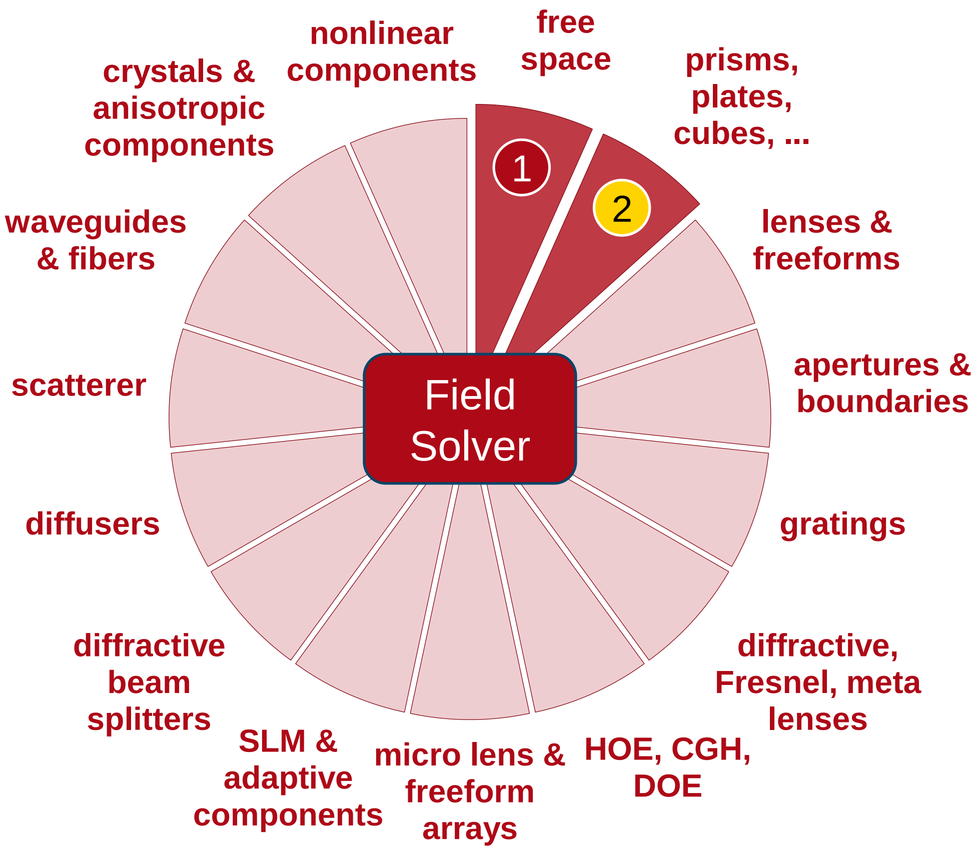
Pointwise Measurement





VirtualLab Fusion Technologies

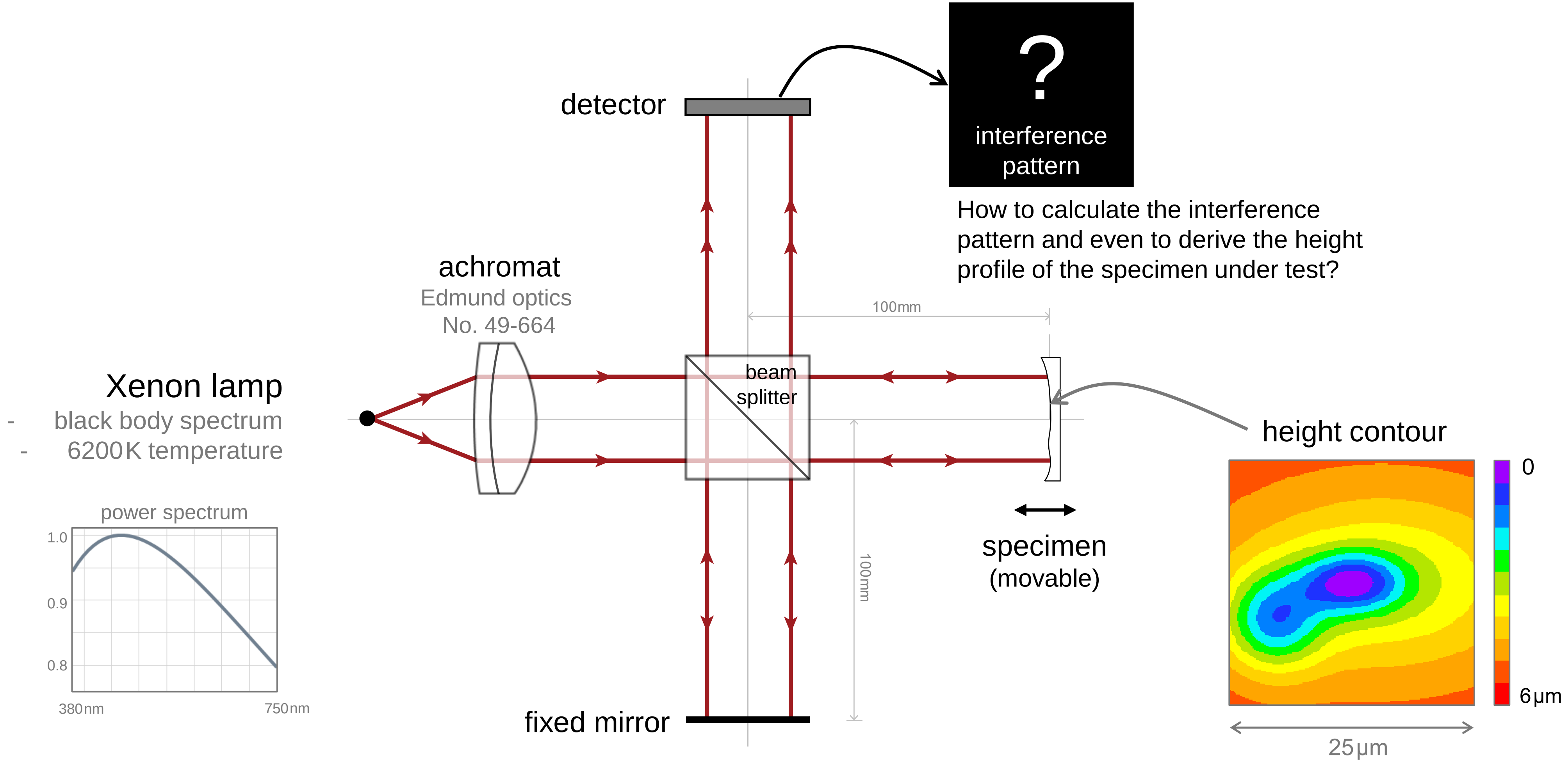




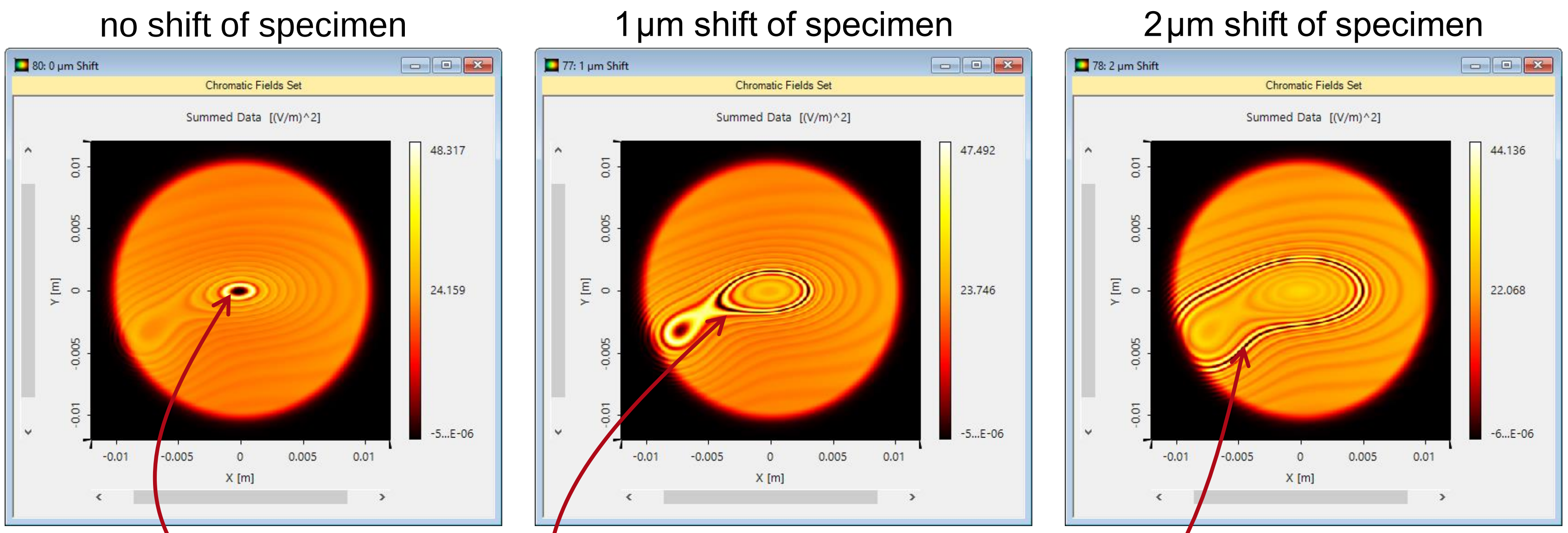
idealized component

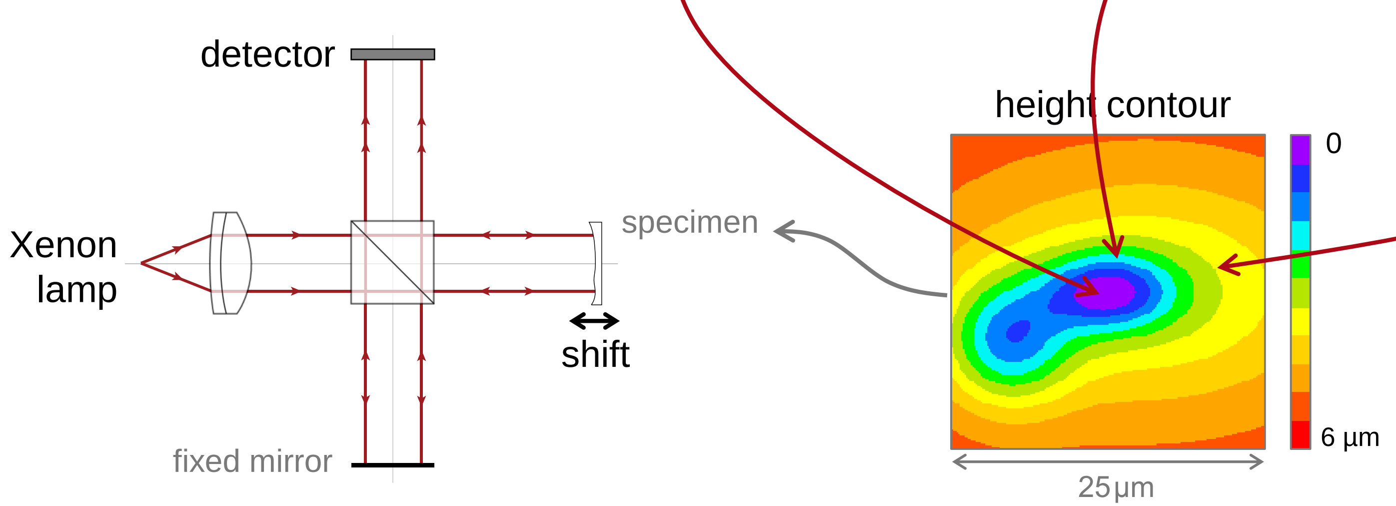
Optical Coherence Scanning Interferometry

Modeling Task



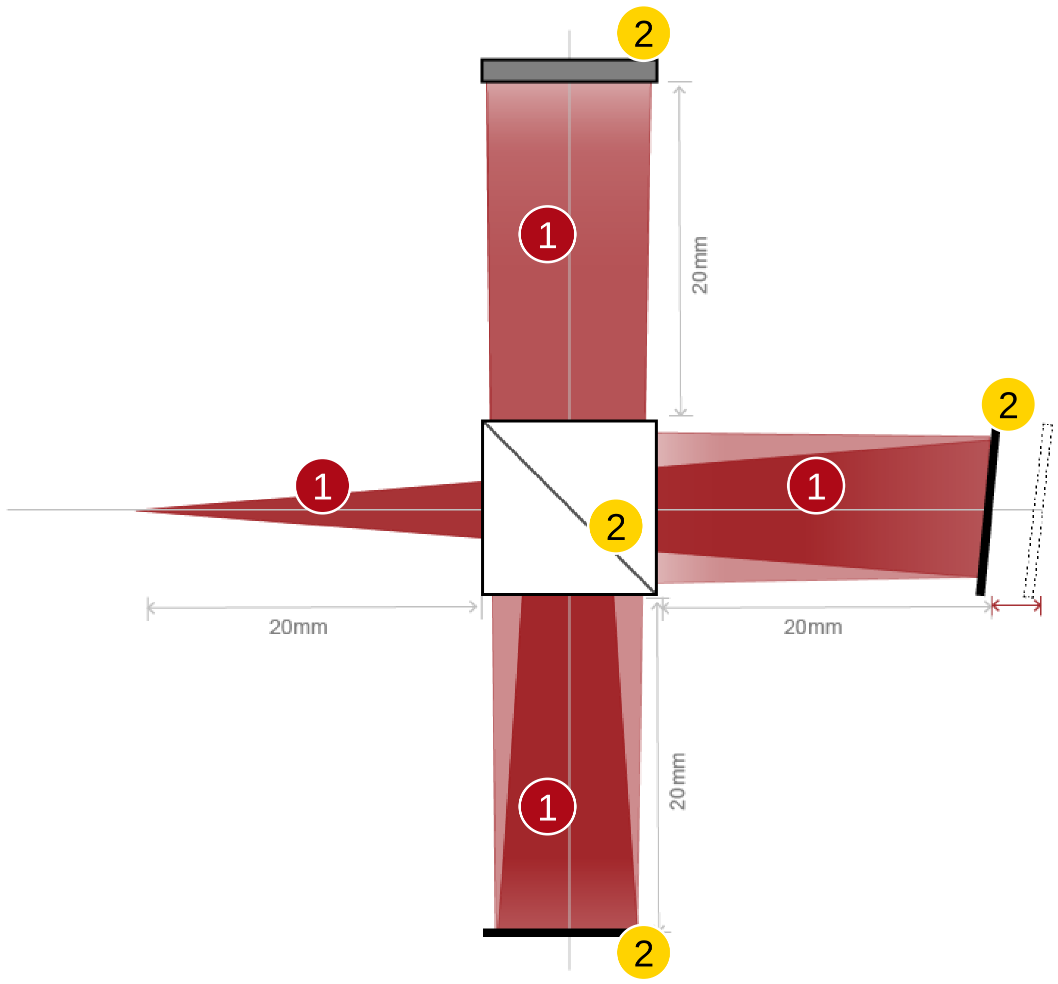
Simulated Interference Fringes

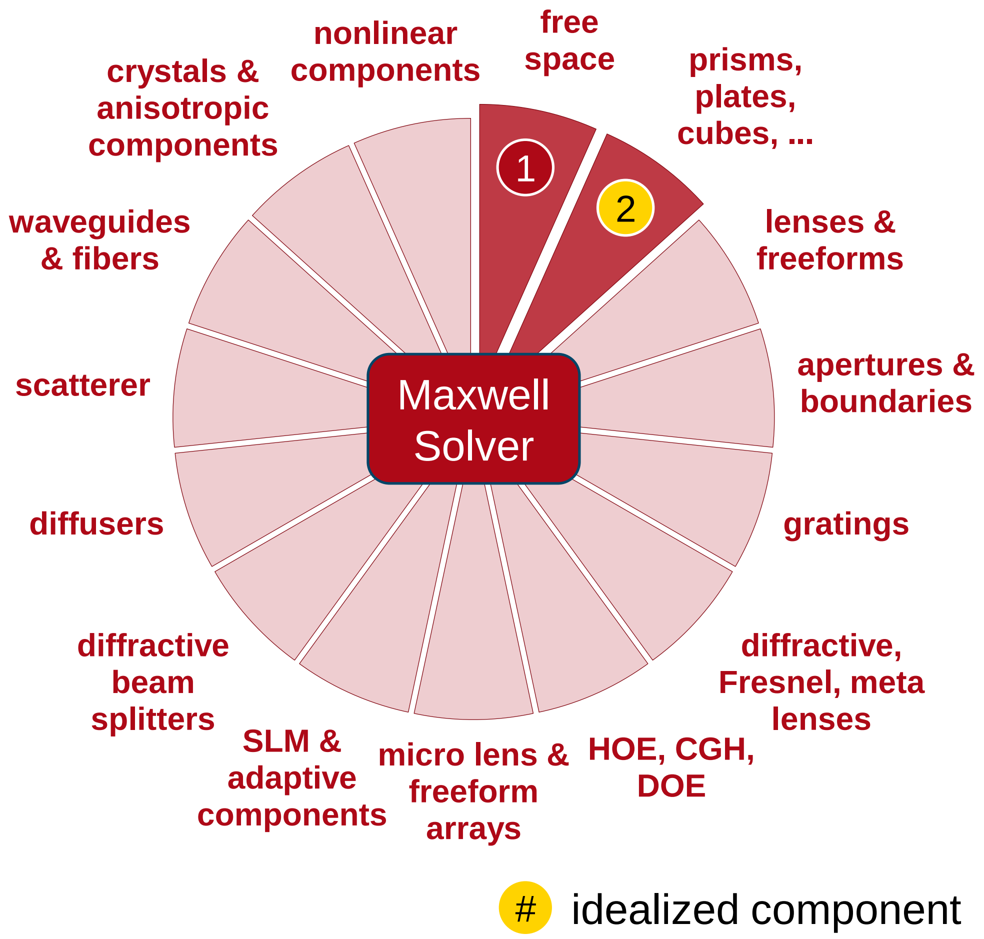




Contour lines of interference fringes corresponds to the height contour of the specimen under measurement.

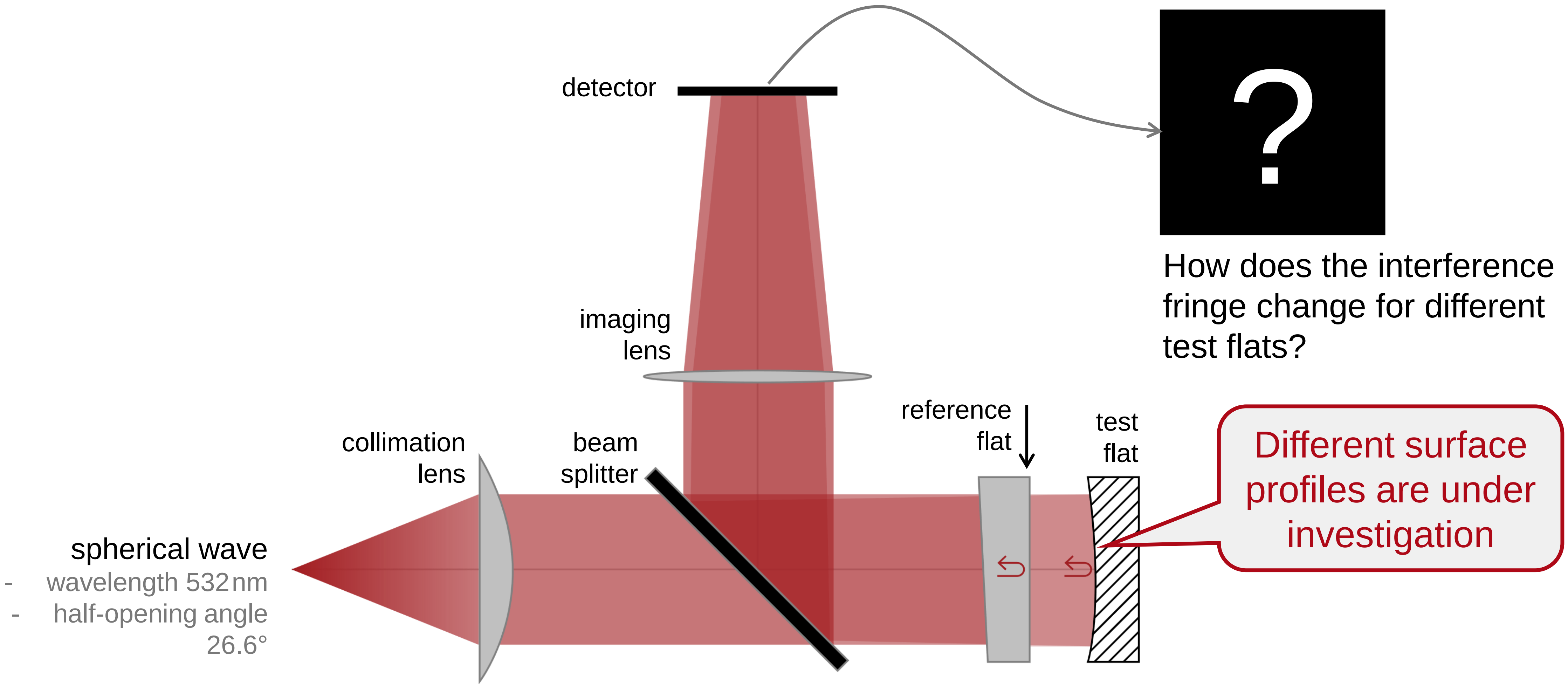
VirtualLab Technologies





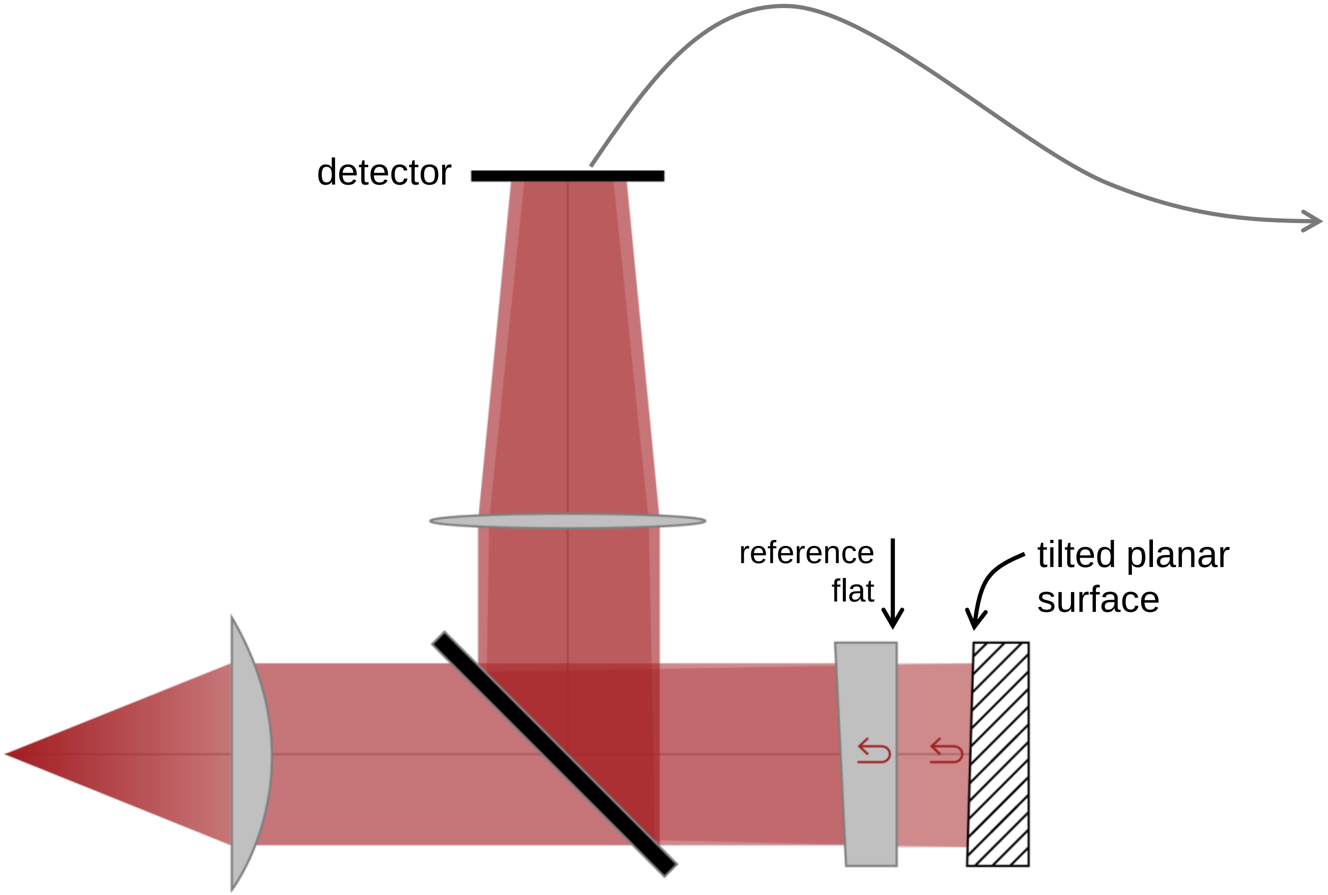
Fizeau Interferometer for Optical Testing

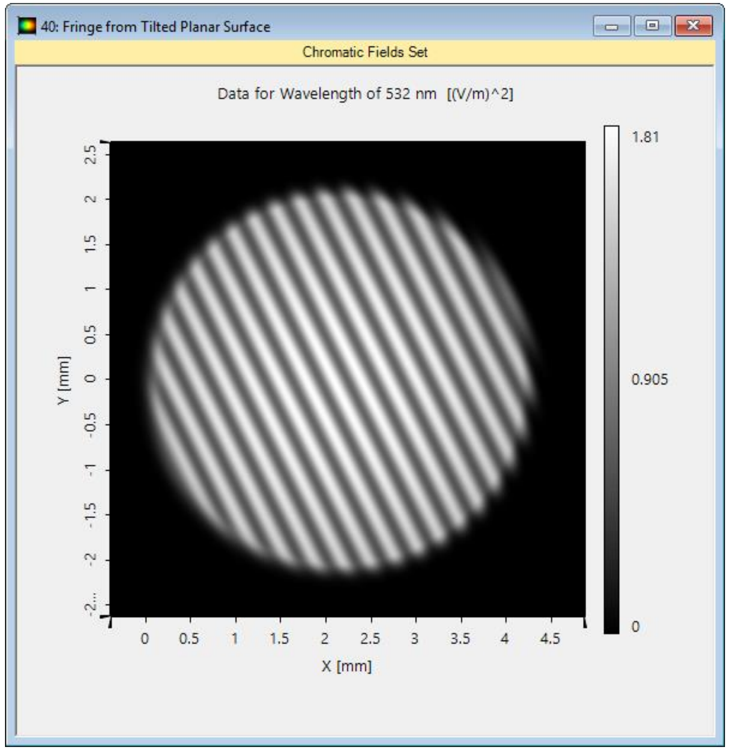
Modeling Task



How does the interference fringe change for different test flats?

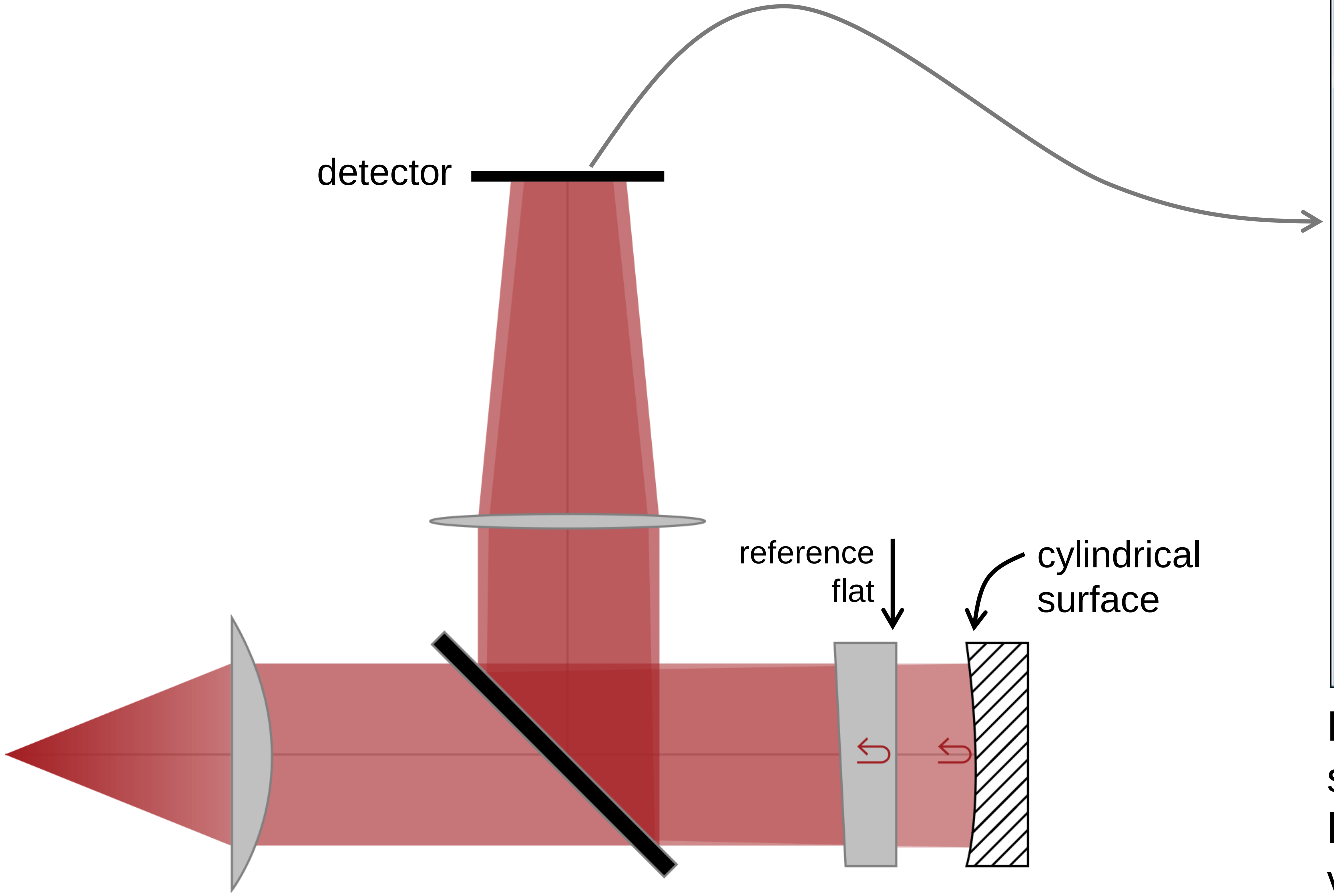
Tilted Planar Surface under Observation

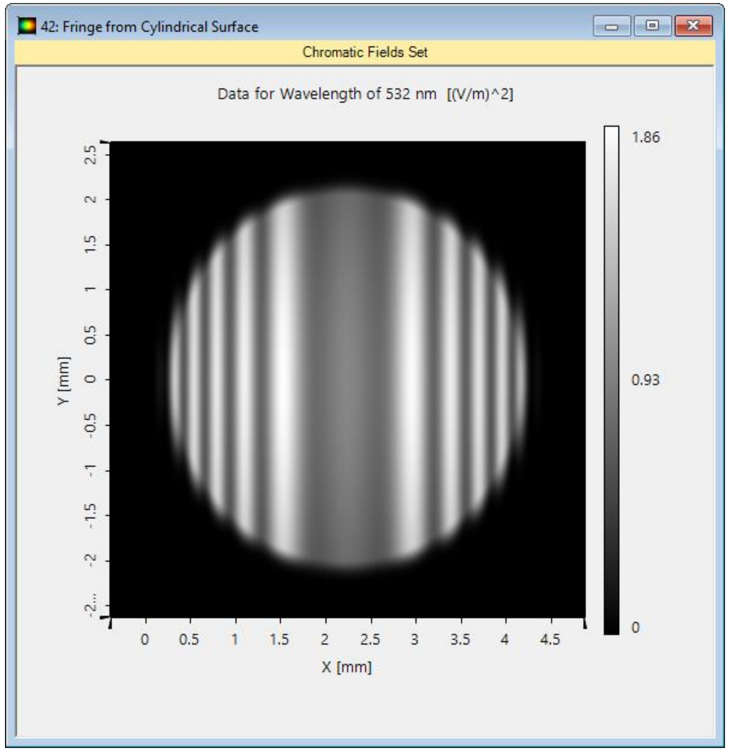




Reflection from the test planar surface remain as plane waves, but only with slightly different direction, and therefore leading to parallel striped fringes.

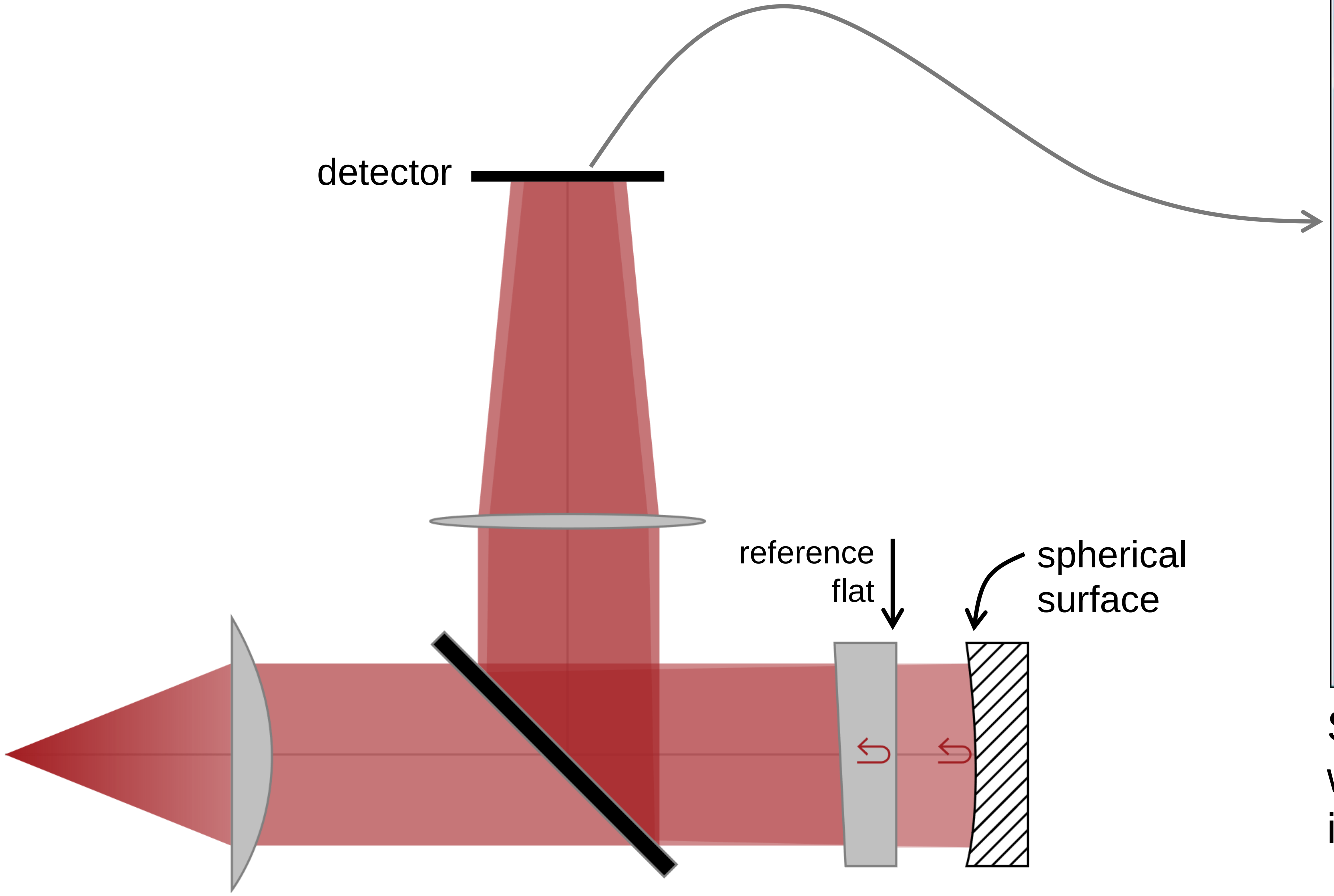
Cylindrical Surface under Observation

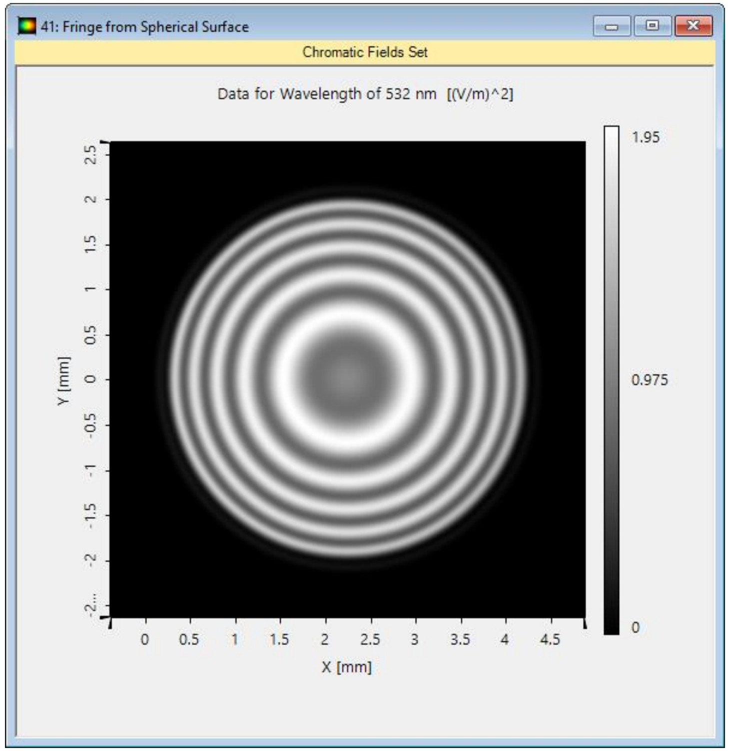




Reflected wavefront from the test cylindrical surface gets curved in one direction, therefore leading to parallel striped fringes but with varying pitch.

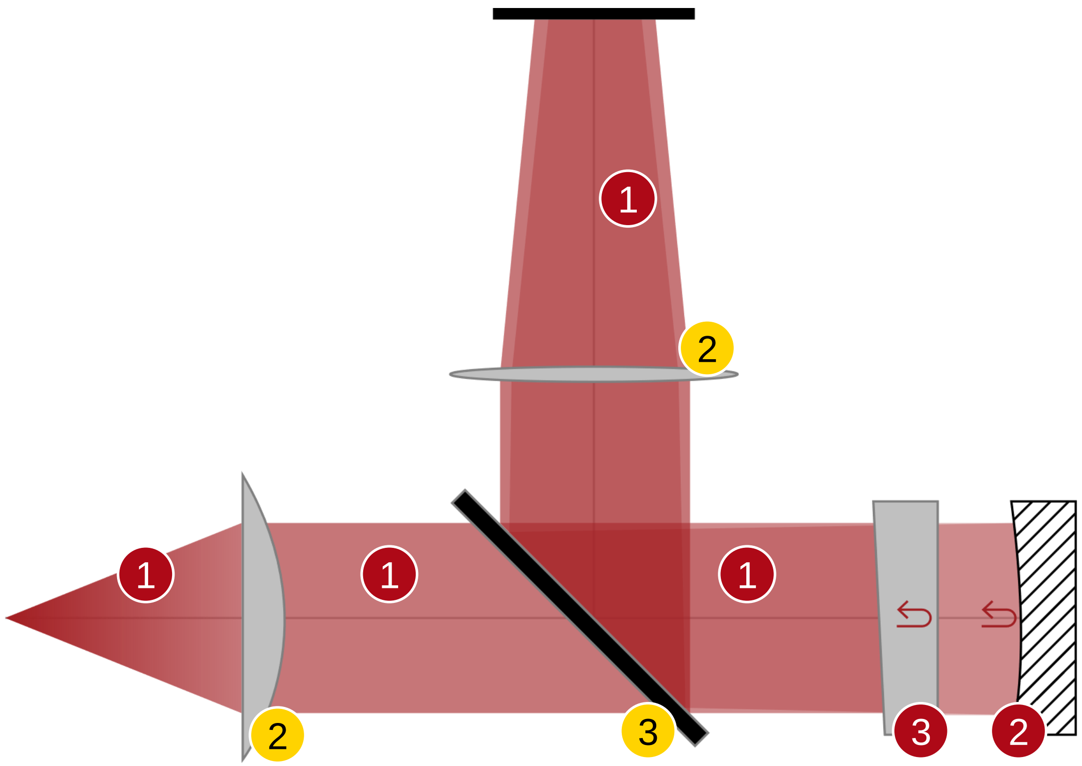
Spherical Surface under Observation

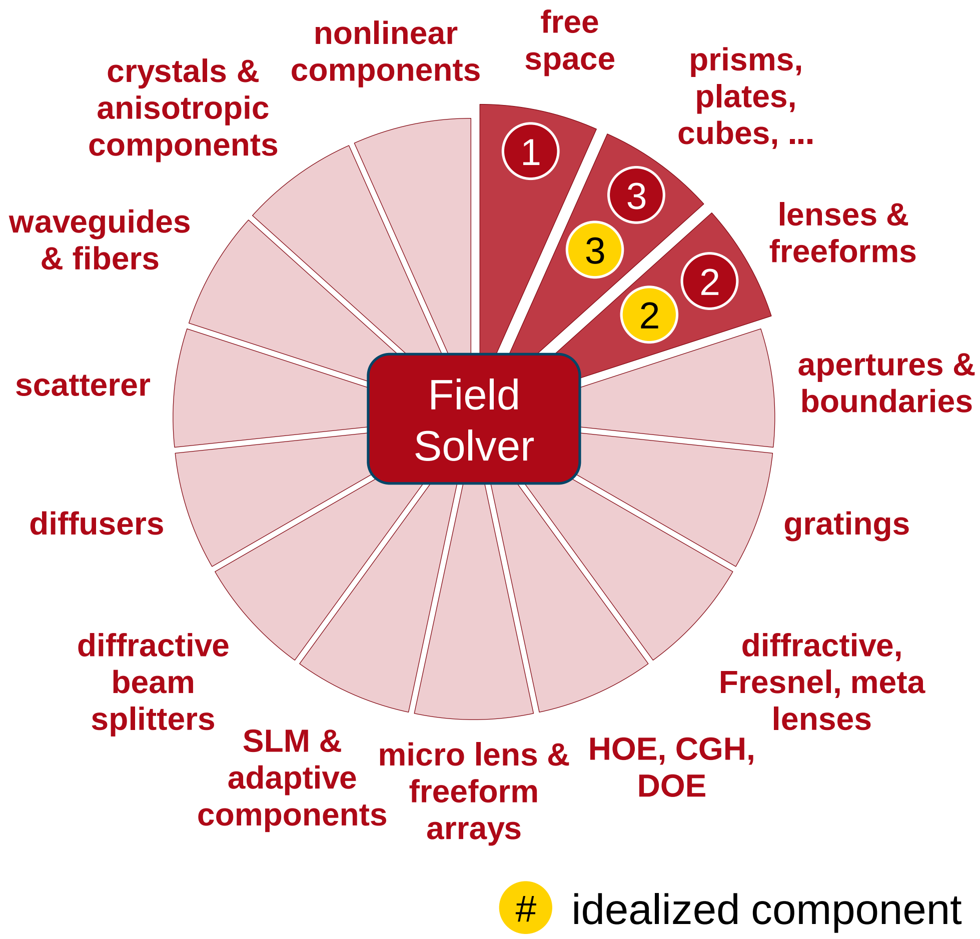




Spherical surface changes the reflected wavefront in radial direction, thus the interference fringes appears as concentric rings.

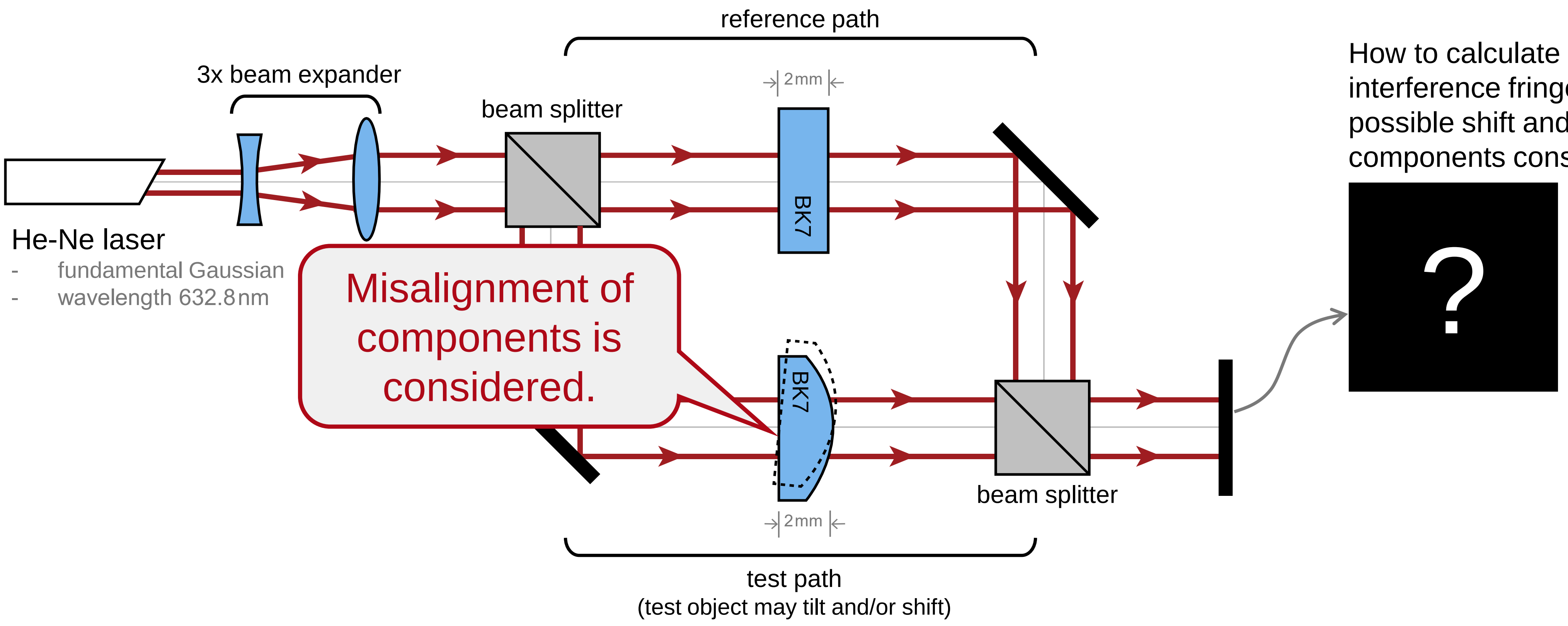
VirtualLab Fusion Technologies





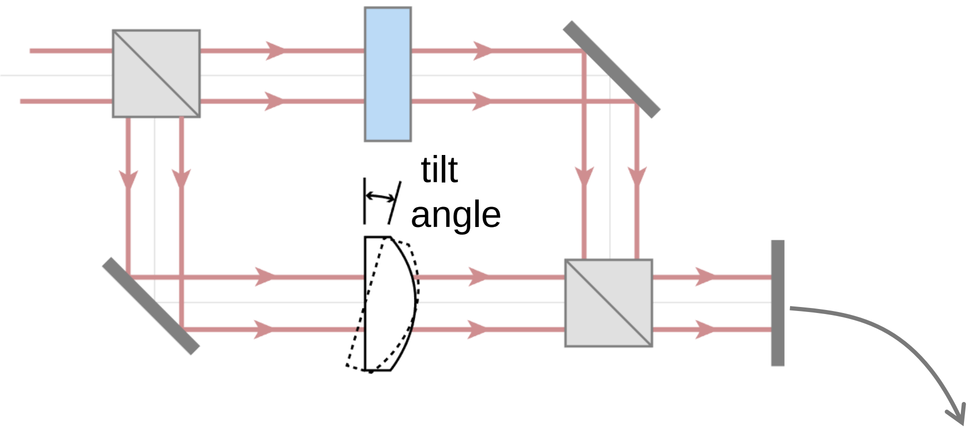
Mach-Zehnder Interferometer

Modeling Task

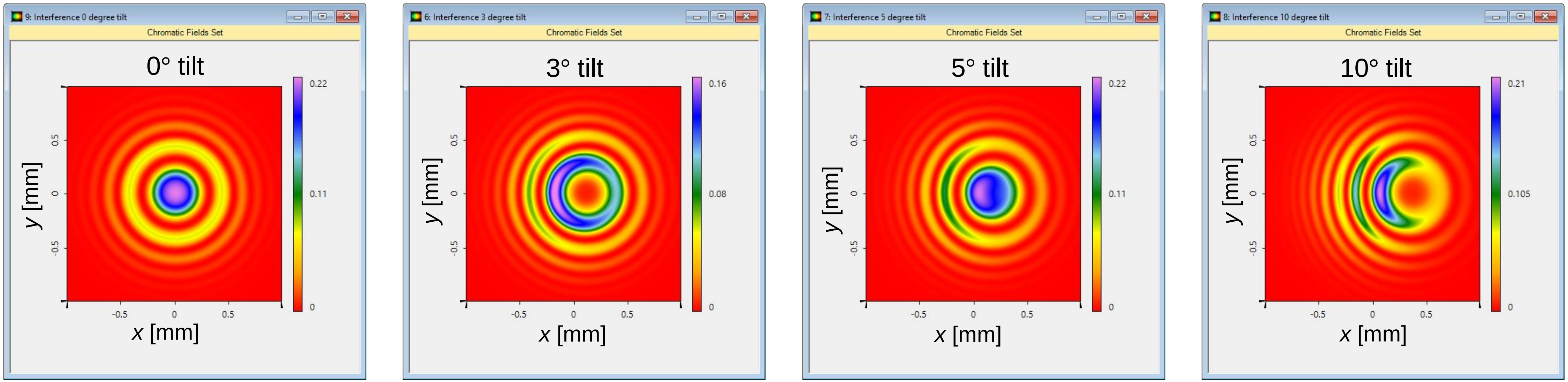


How to calculate interference fringe with the possible shift and tilt of components considered?

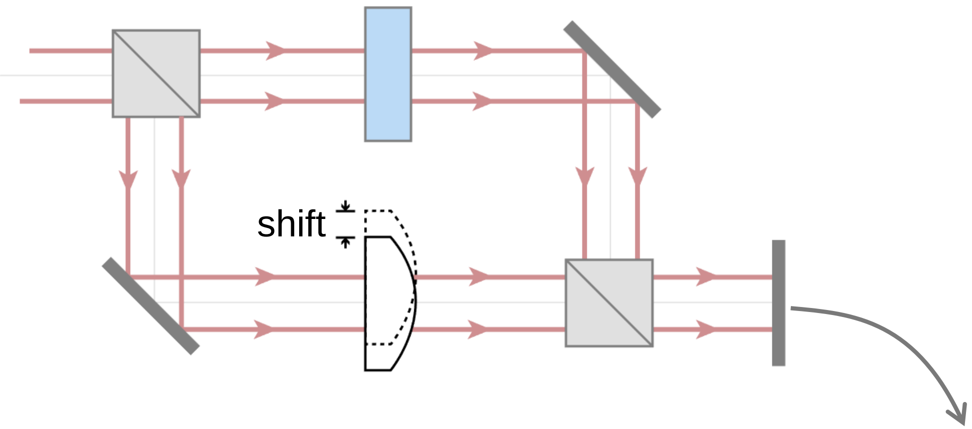
Interference Fringe Due to Component Tilt



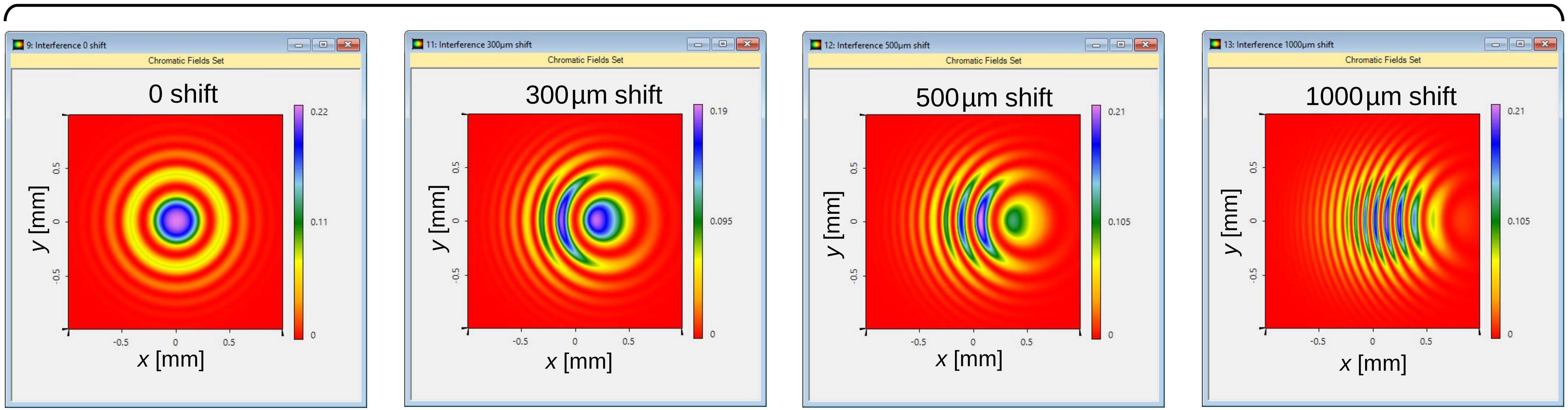
Calculation of interference pattern including element tilt takes less than 2 seconds!



Interference Fringe Due to Component Shift

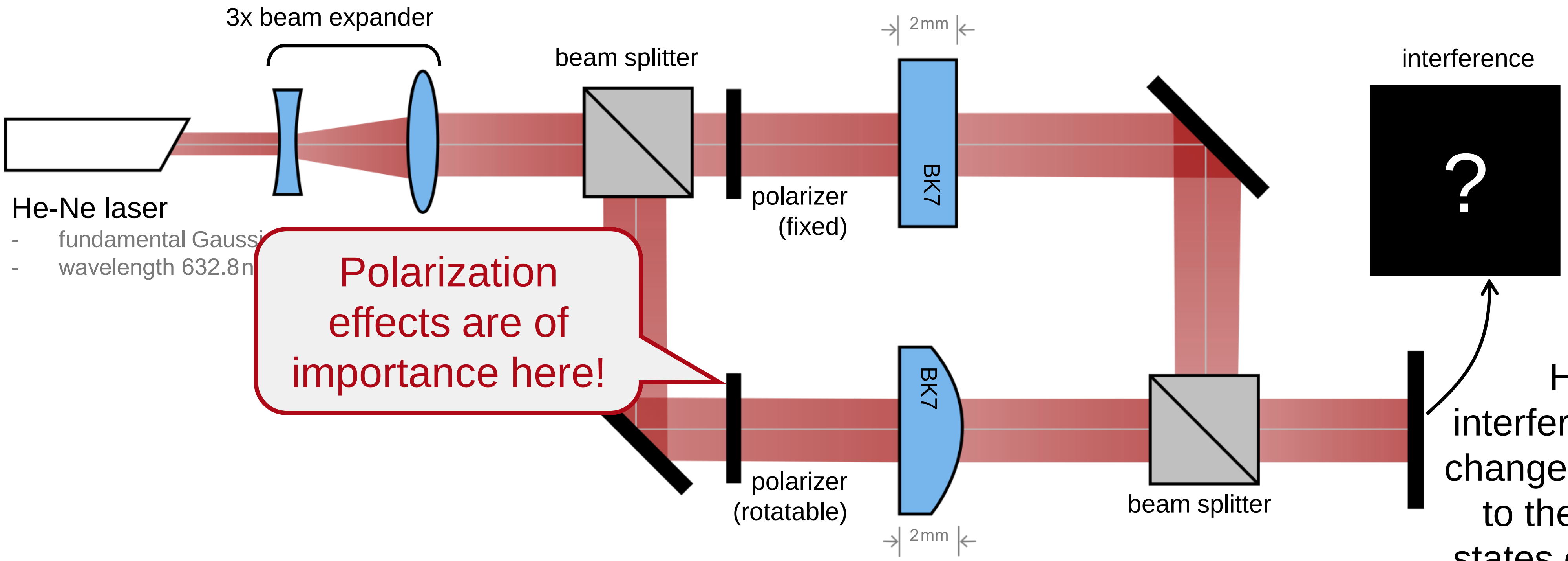


Calculation of interference pattern including element shift takes less than 2 seconds!



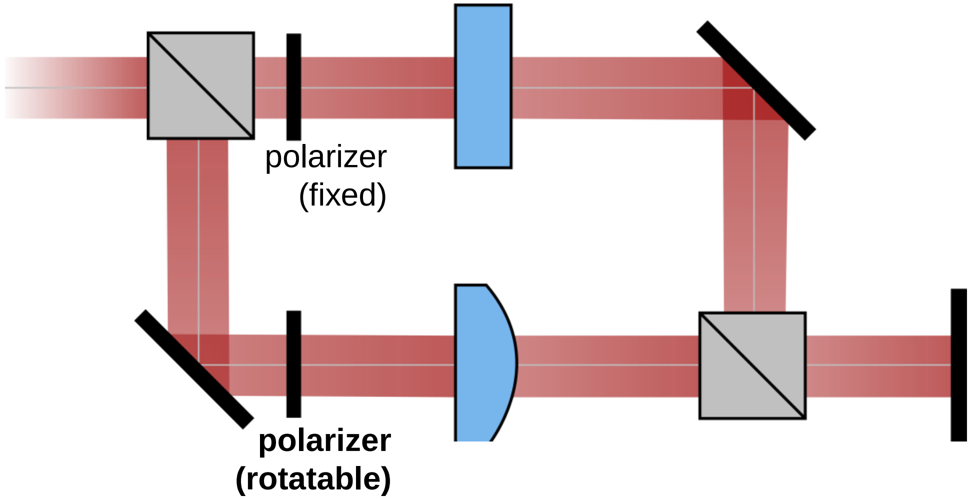
Polarization Interference

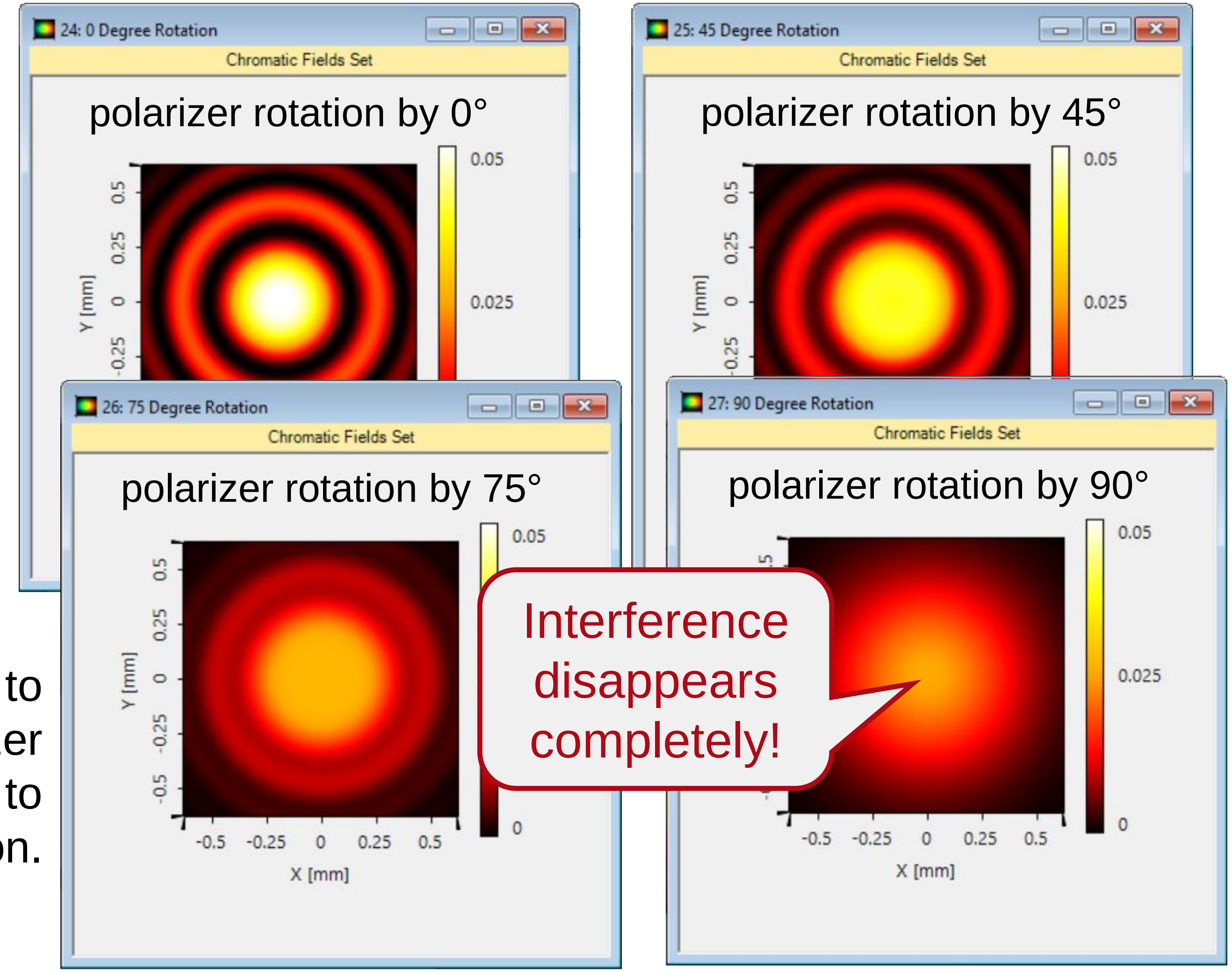
Modeling Task



How does the interference pattern change with respect to the polarization states of two arms?

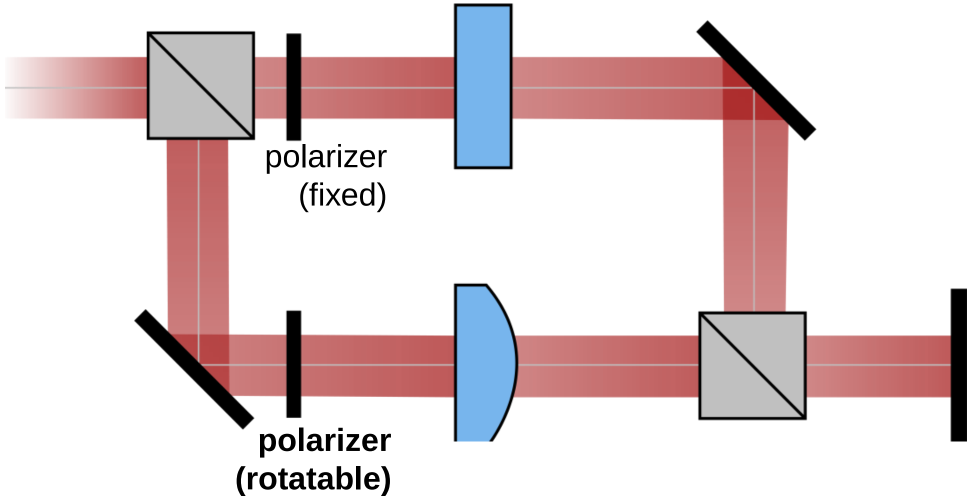
Interference Pattern Changes with Polarizer Rotation

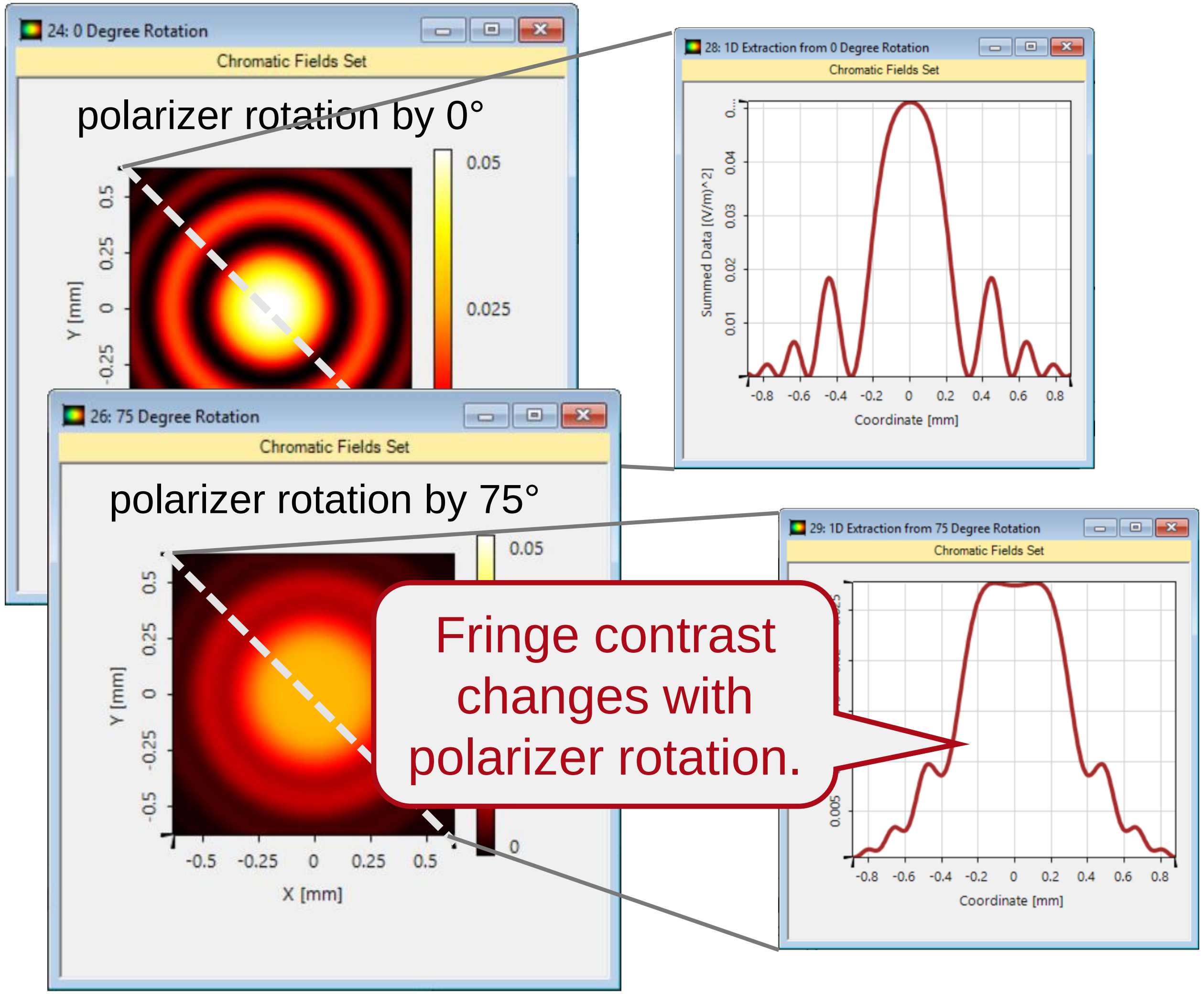




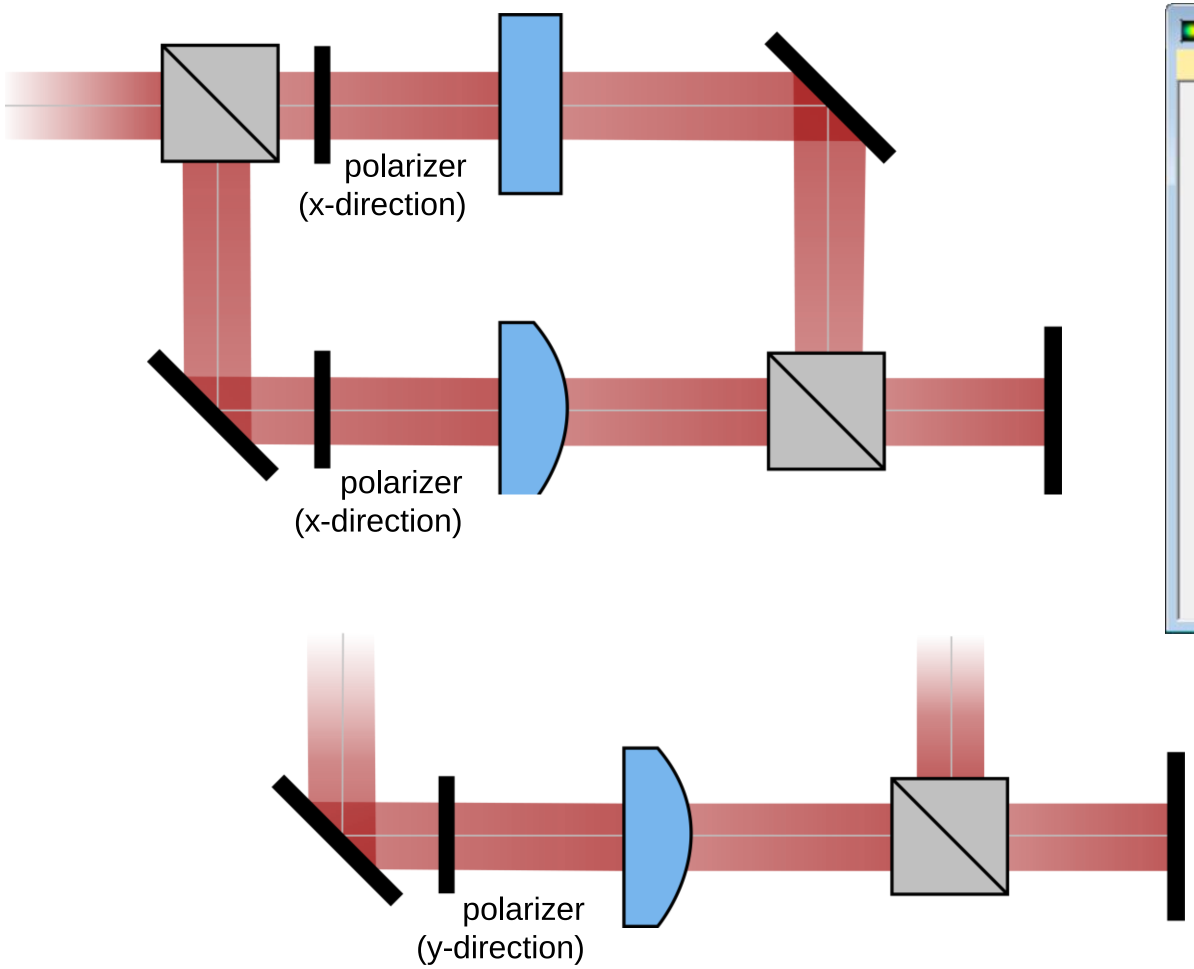
Interference fringes start to disappear, when polarizer rotates from parallel to orthogonal orientation.

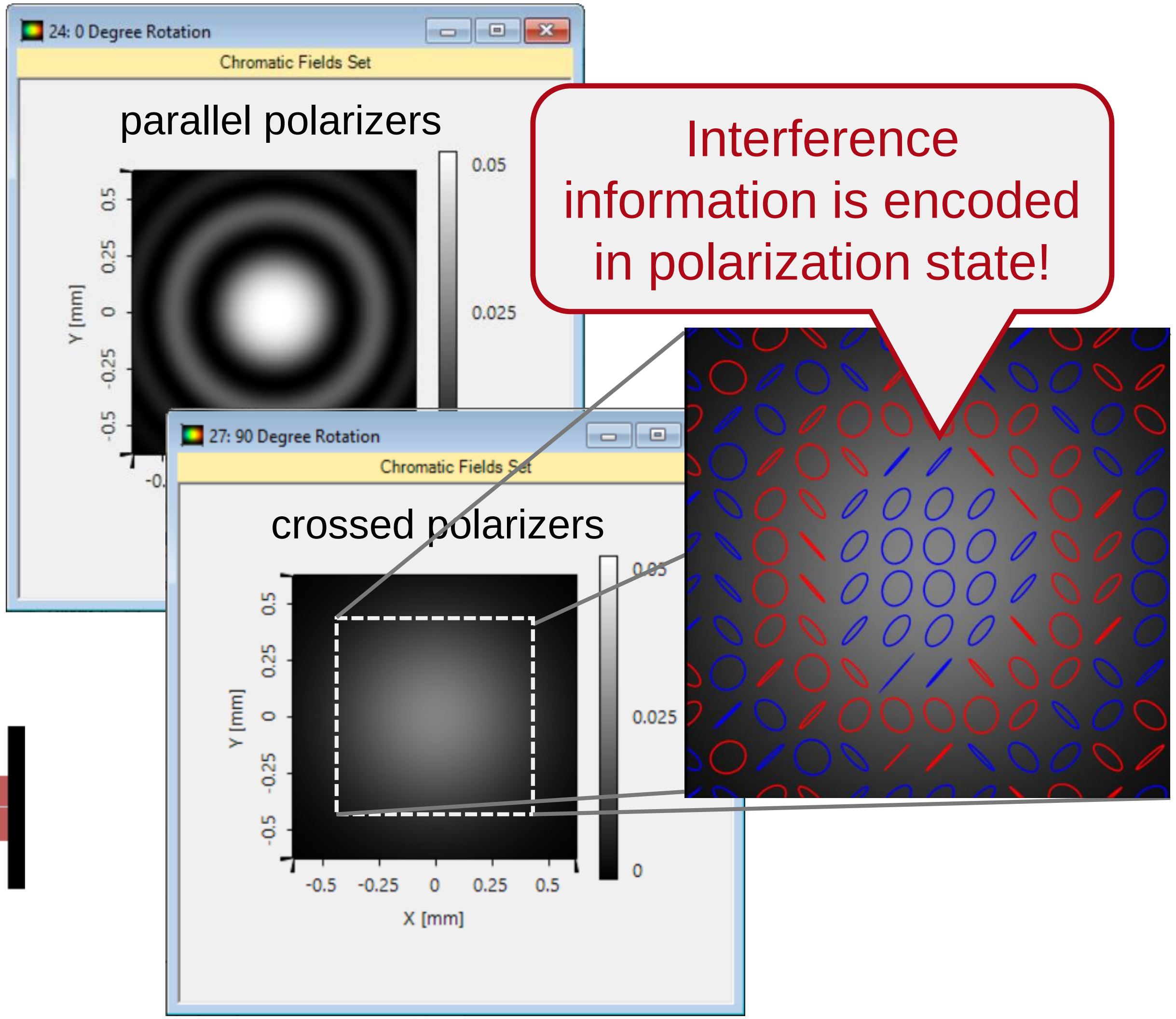
Interference Pattern Changes with Polarizer Rotation





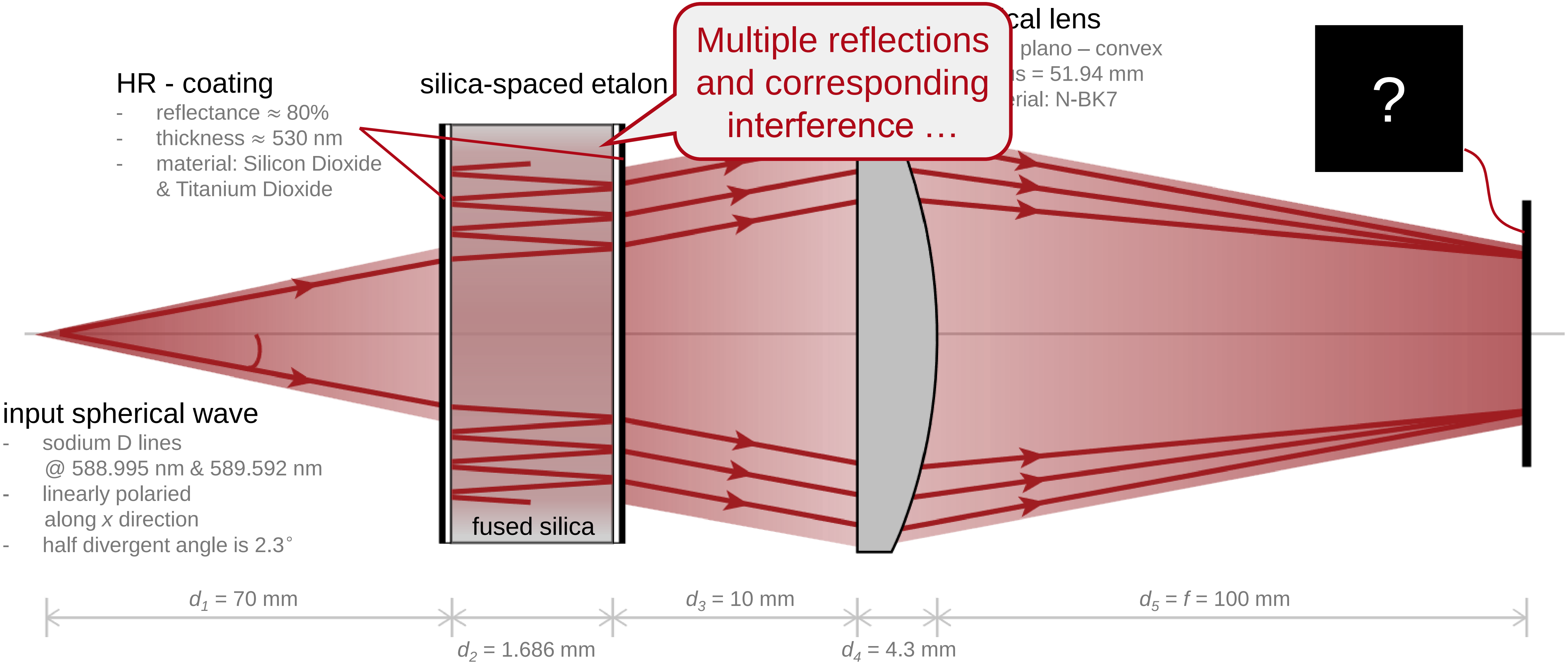
Interference Pattern



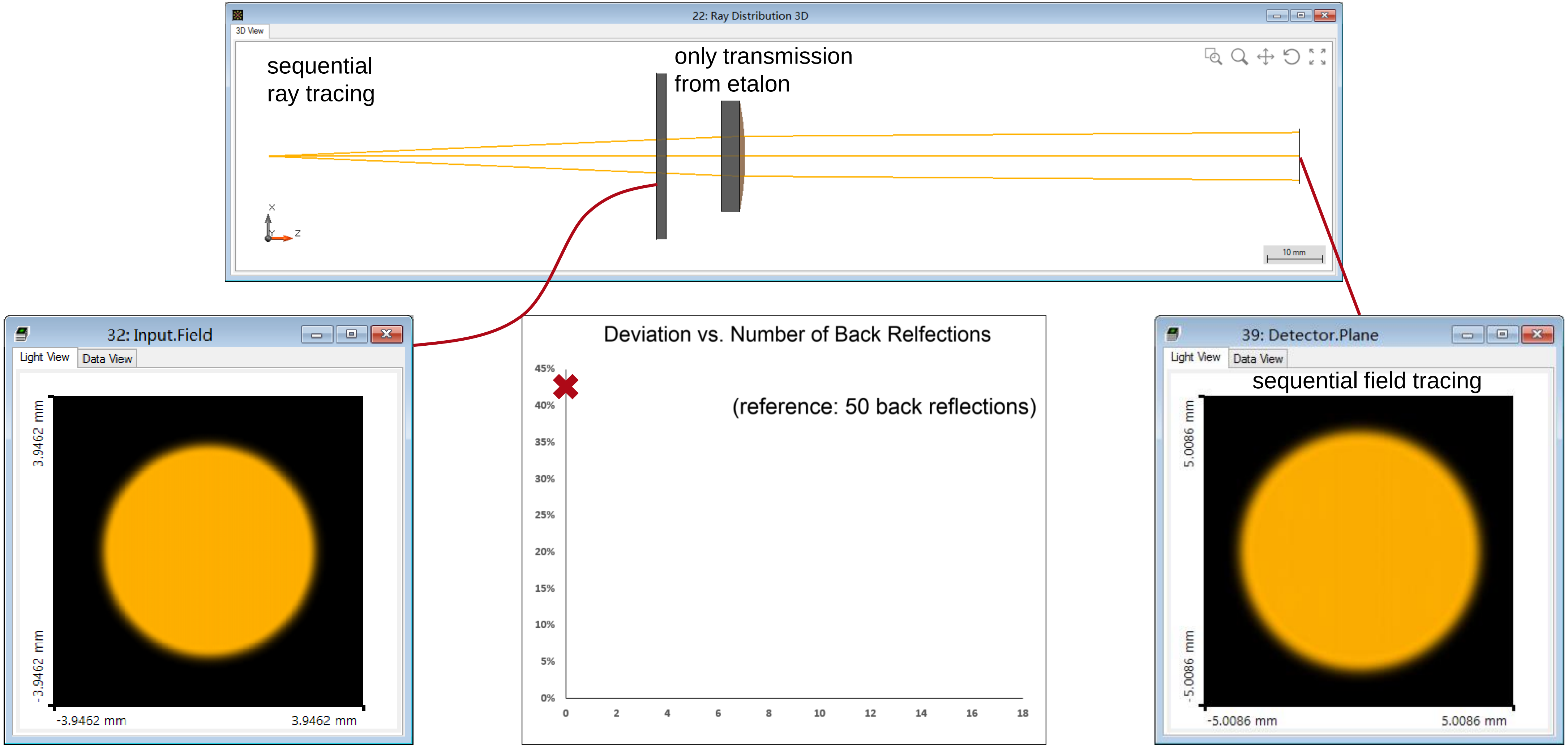


Examination of Sodium D Lines with Etalon

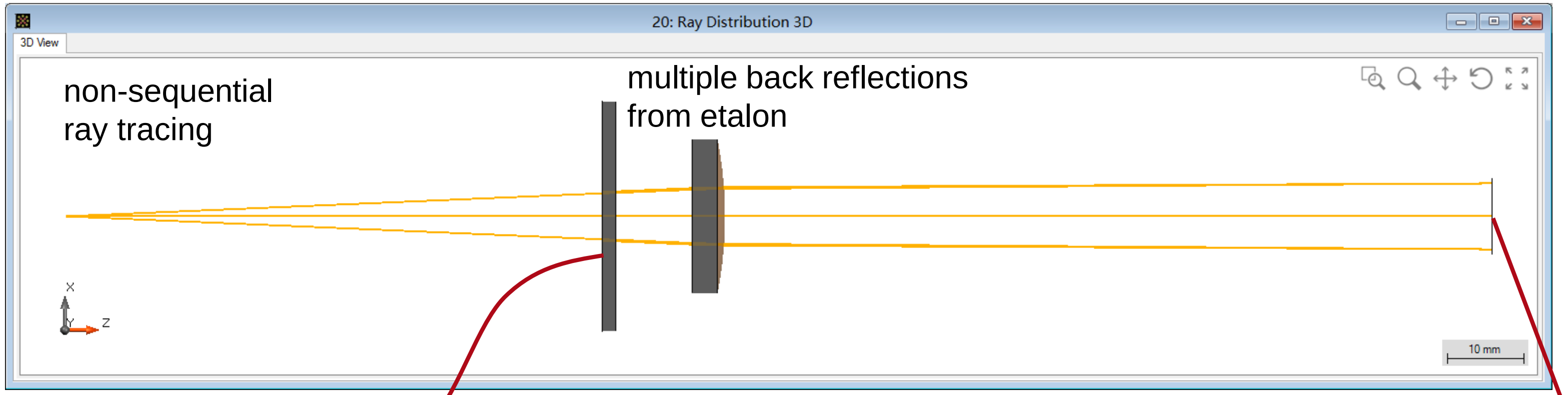
Modeling Task

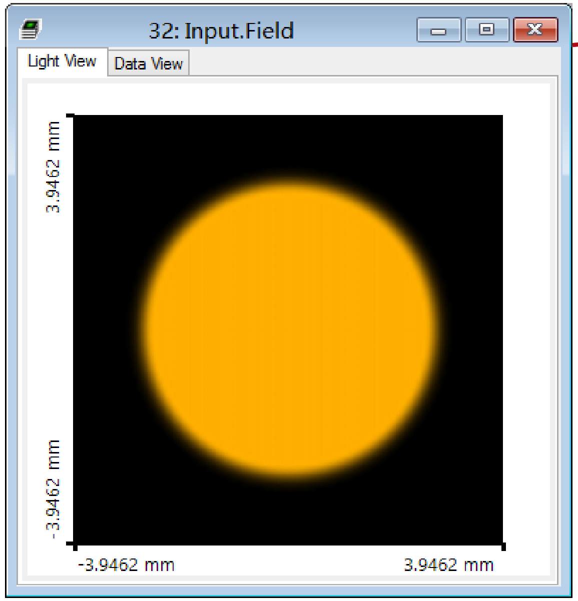


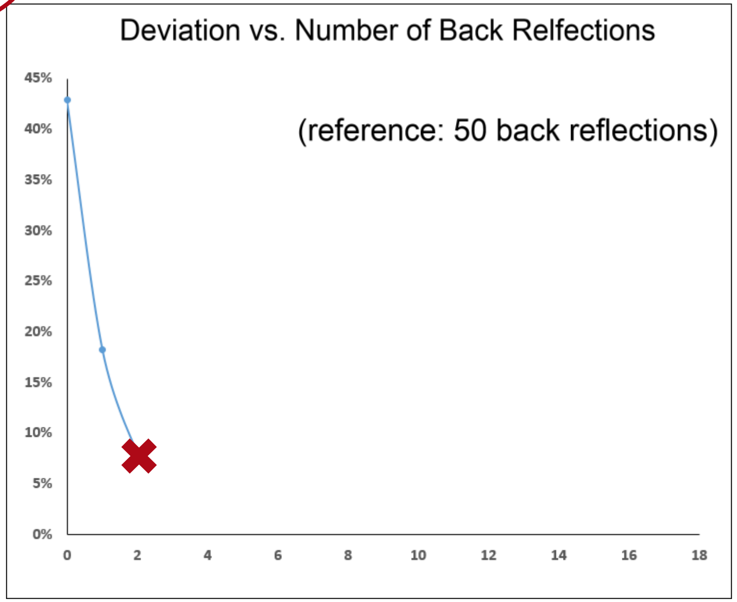
Result: only Transmitted Field

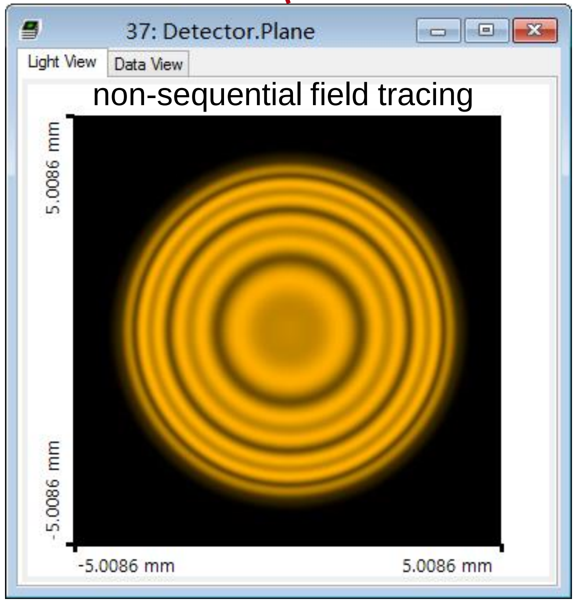


Result: Transmitted Field + 2 Back Reflections

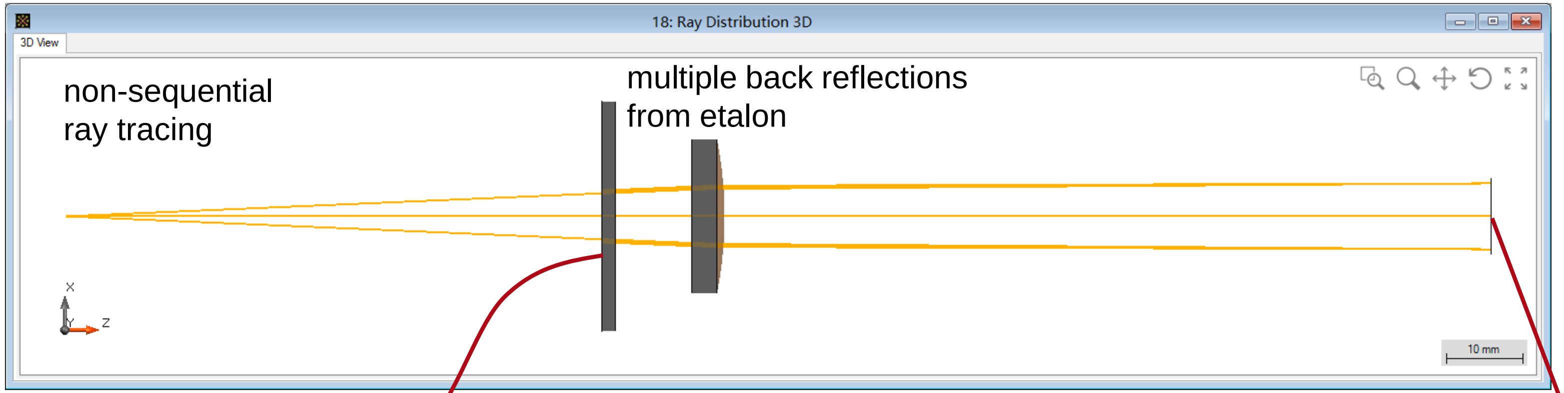


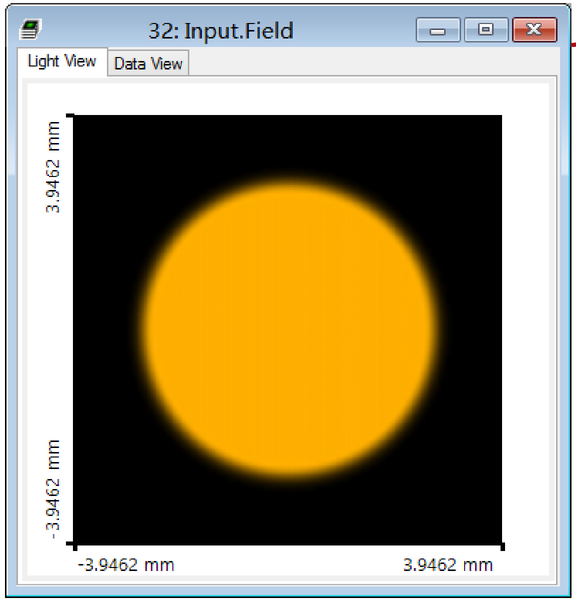


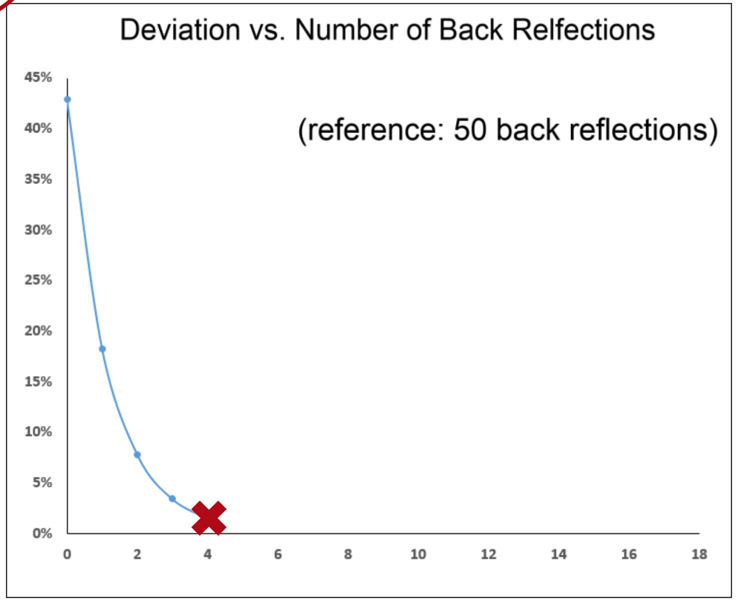


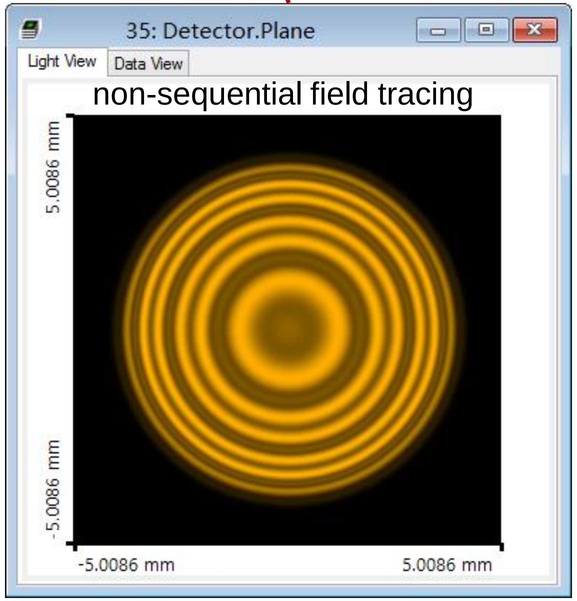


Result: Transmitted Field + 4 Back Reflections

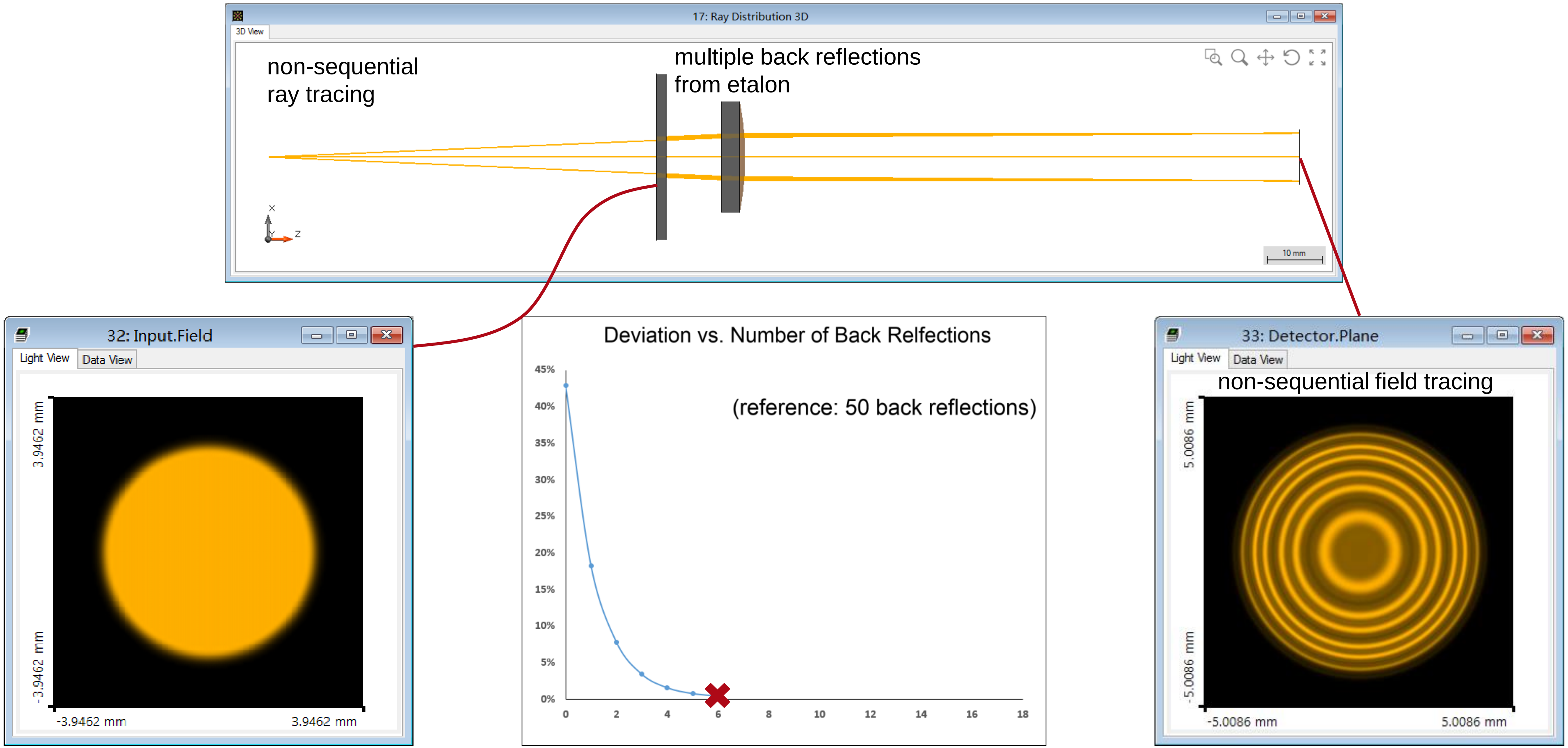




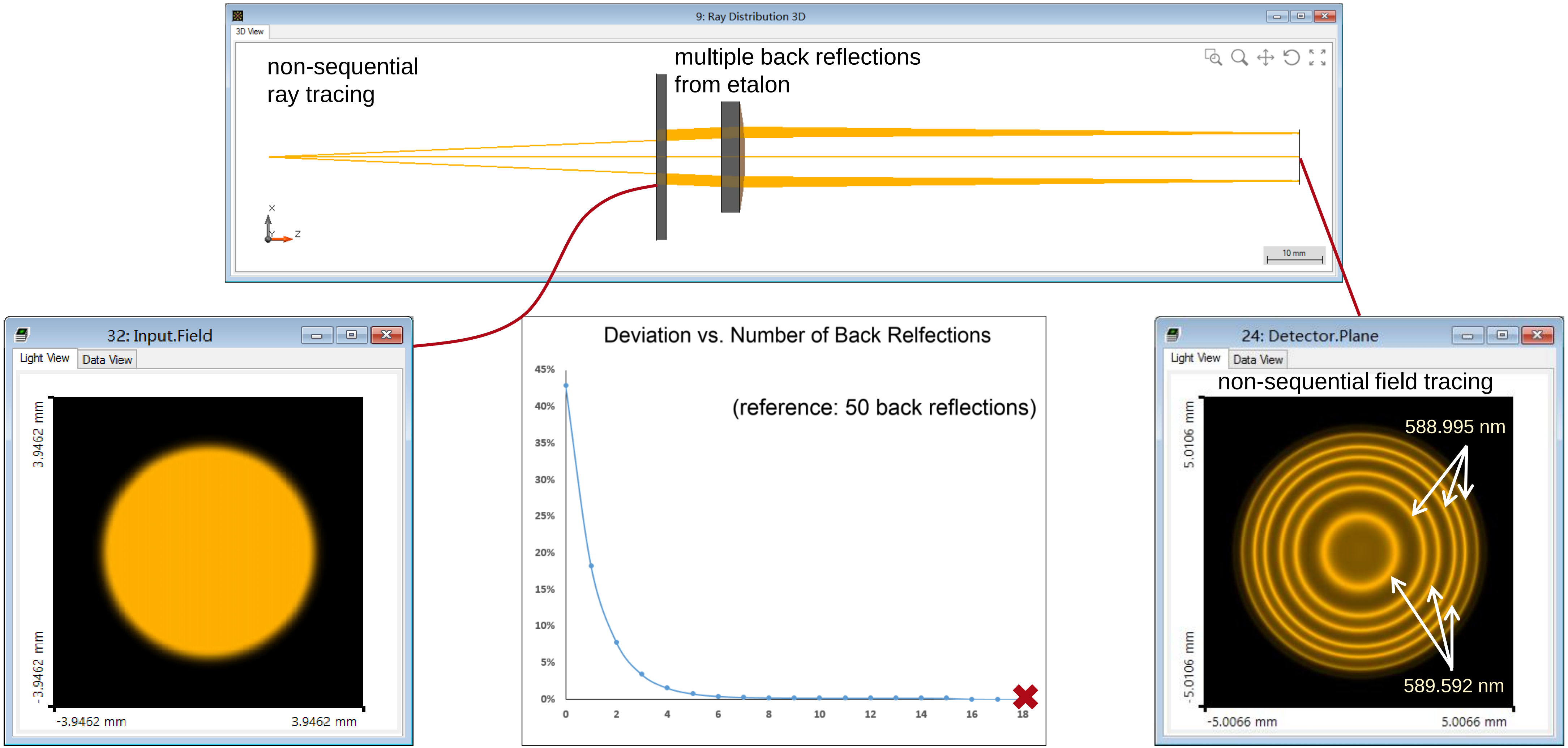




Result: Transmitted Field + 6 Back Reflections

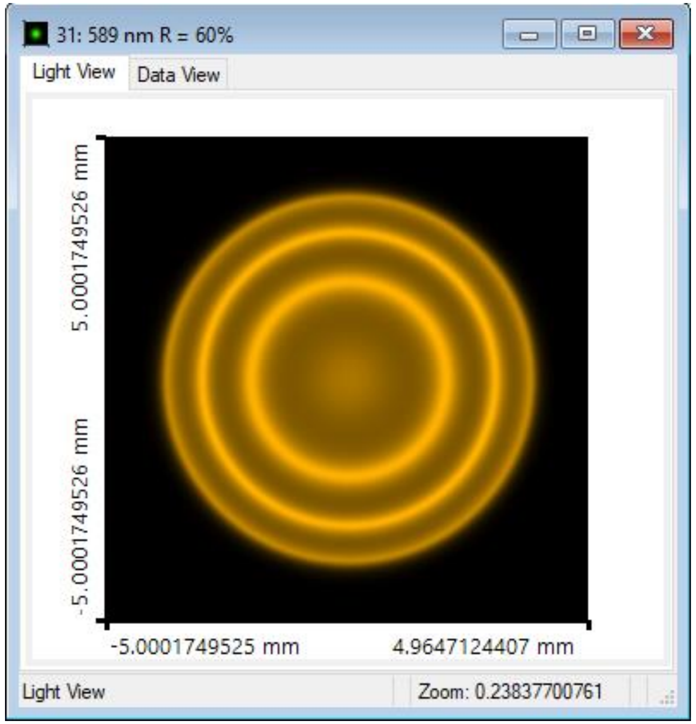


Result: Transmitted Field + 18 Back Reflections

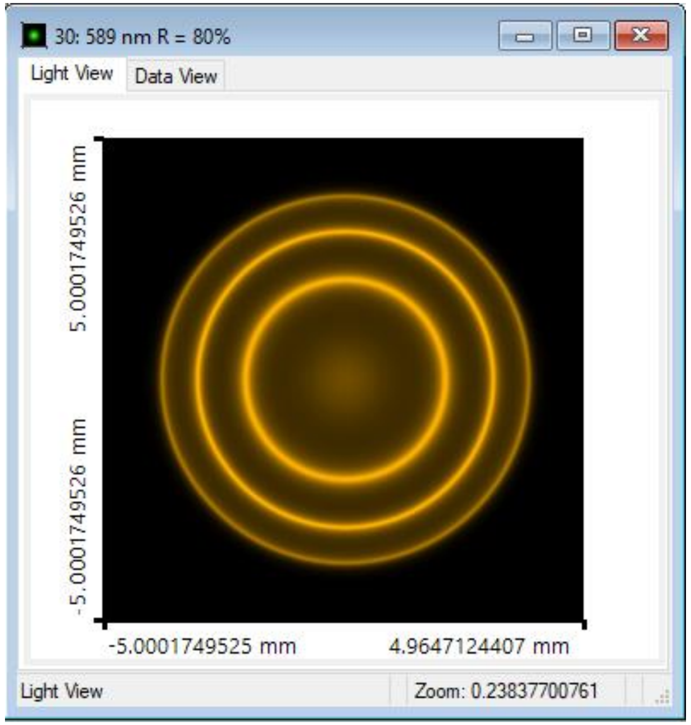


Result: HR-Coating Reflectance vs. Finesse

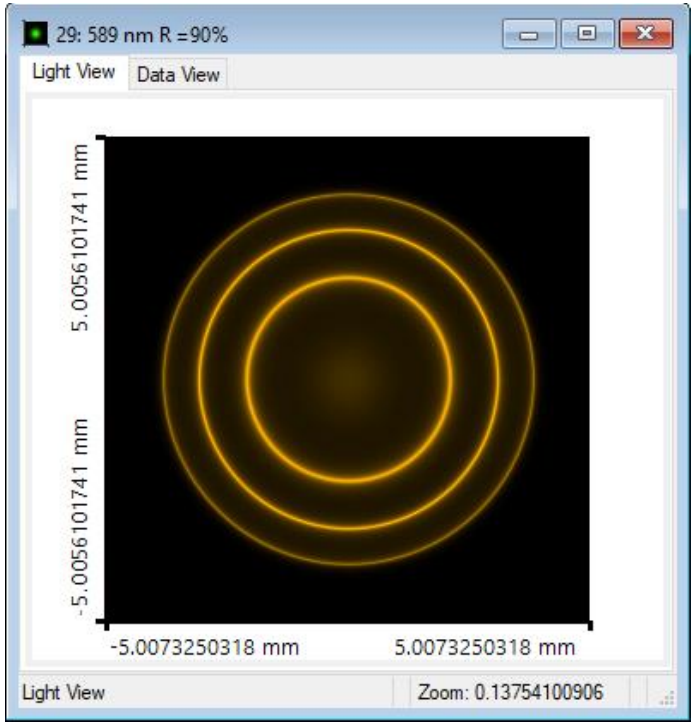
Coating **R = 60%** @ 589nm



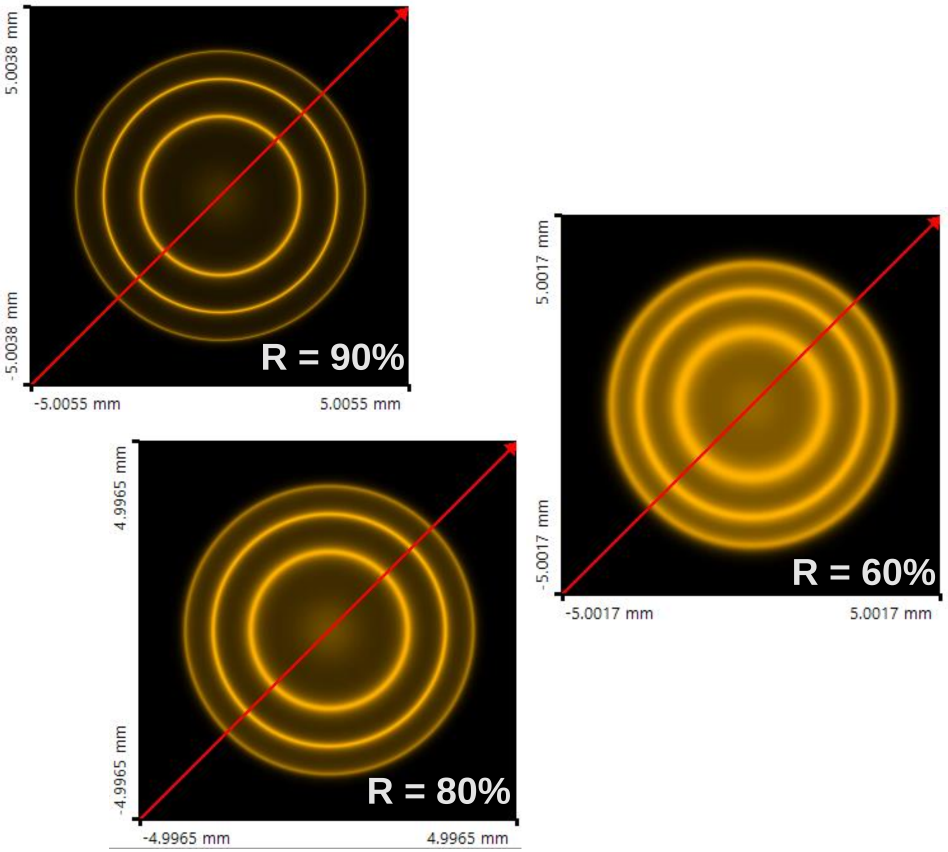
Coating **R = 80%** @ 589nm



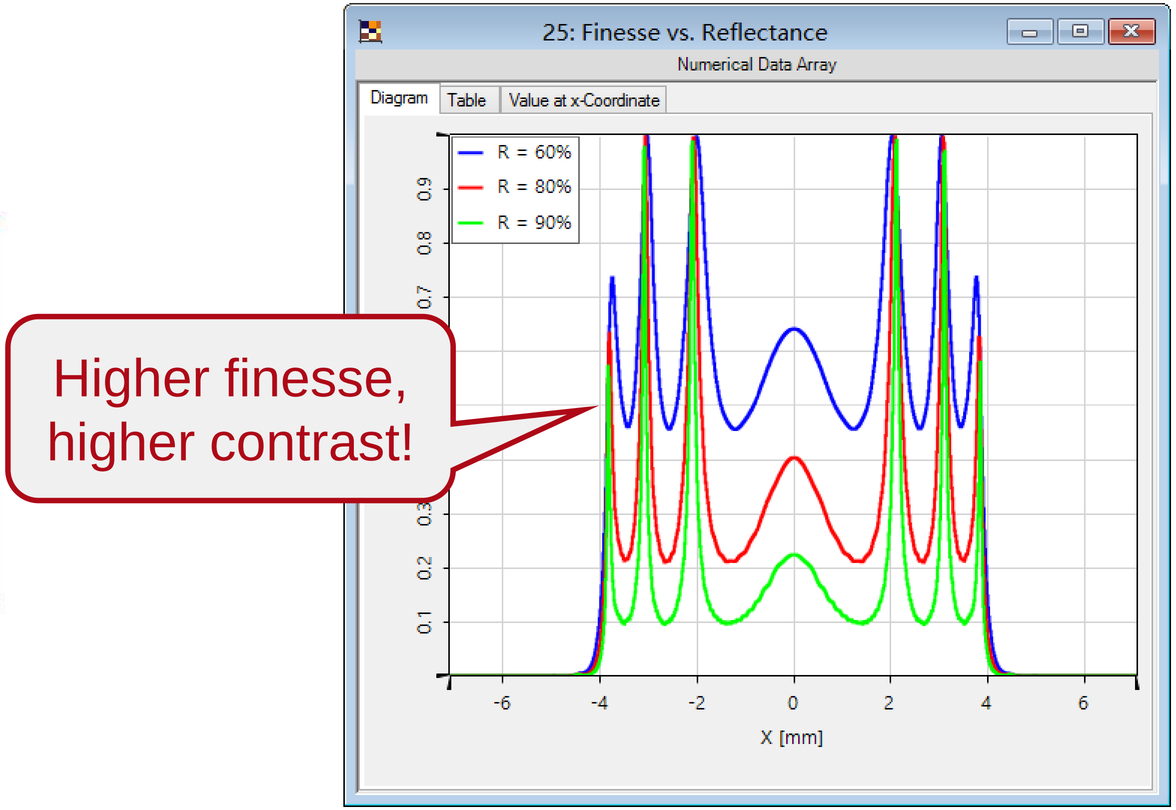
Coating **R = 90%** @ 589nm



Result: HR-Coating Reflectance vs. Finesse

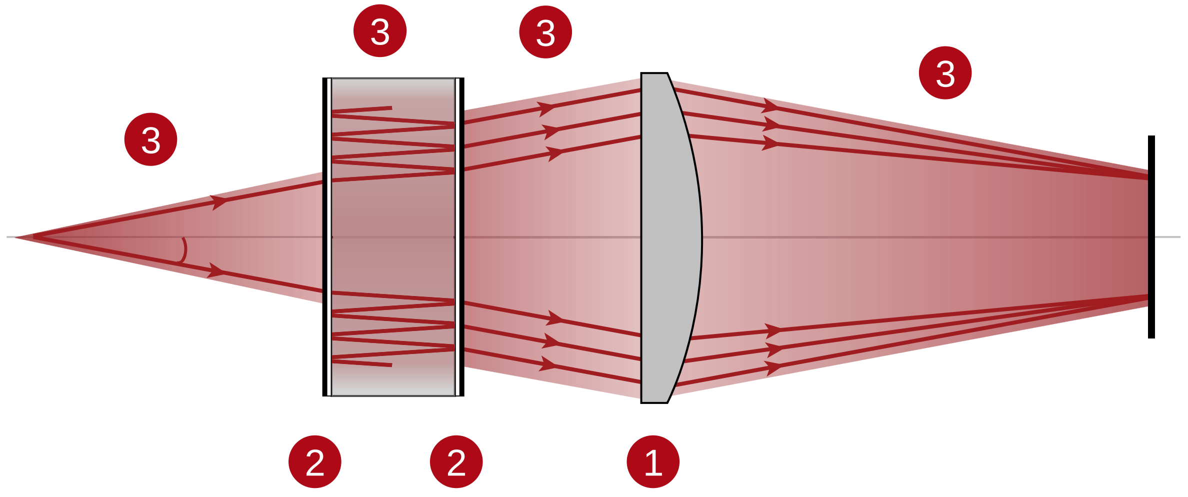


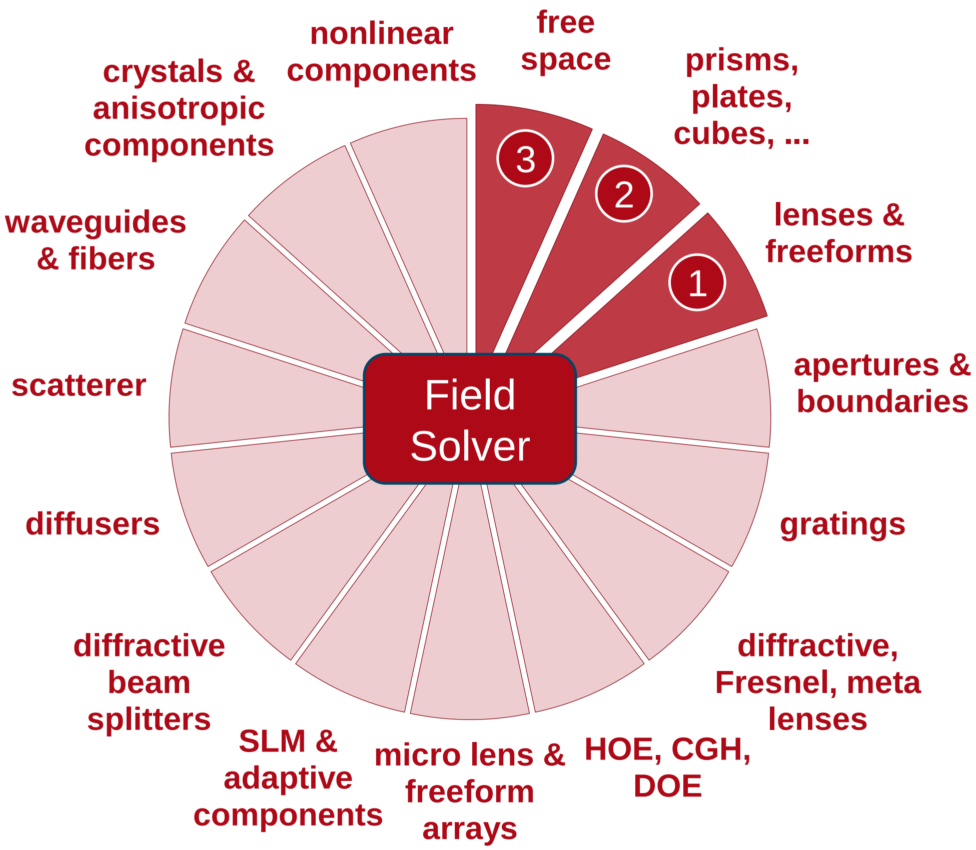
Extract 1D data along the diagonal line



The higher reflectance, the sharper interference stripe

VirtualLab Technologies





VirtualLab Fusion Technology and Applications

Fiber Coupling

Stefan Steiner
LightTrans International UG

Introduction

Optical fibers play an important role in various applications, such as telecommunication, sensing, and lasers.

How to couple light into optical fibers with high efficiency is therefore of great concerns.

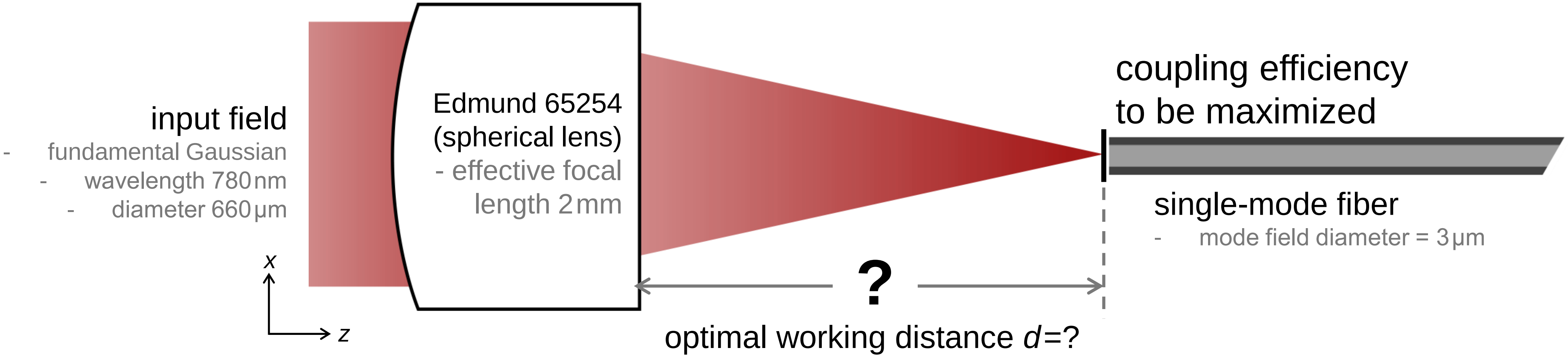
With the following topics, you may explore the possibilities of VirtualLab Fusion on solving fiber coupling tasks, and learn about the typical workflows we recommend.

- Finding the optimal working distance for the coupling lens [Use Case]
- Evaluate the coupling efficiency with different coupling lenses [Use Case]
- Design of coupling lenses by parametric optimization [Use Case]
- Tolerance and sensitivity analysis for fiber coupling setup [Use Case]

Following the guide above, you will see the application of VirtualLab Fusion features, like Parameter Run [Use Case] and Parametric Optimization [Use Case], in practical examples.

Optimal Working Distance for Coupling Light into Single-Mode Fibers

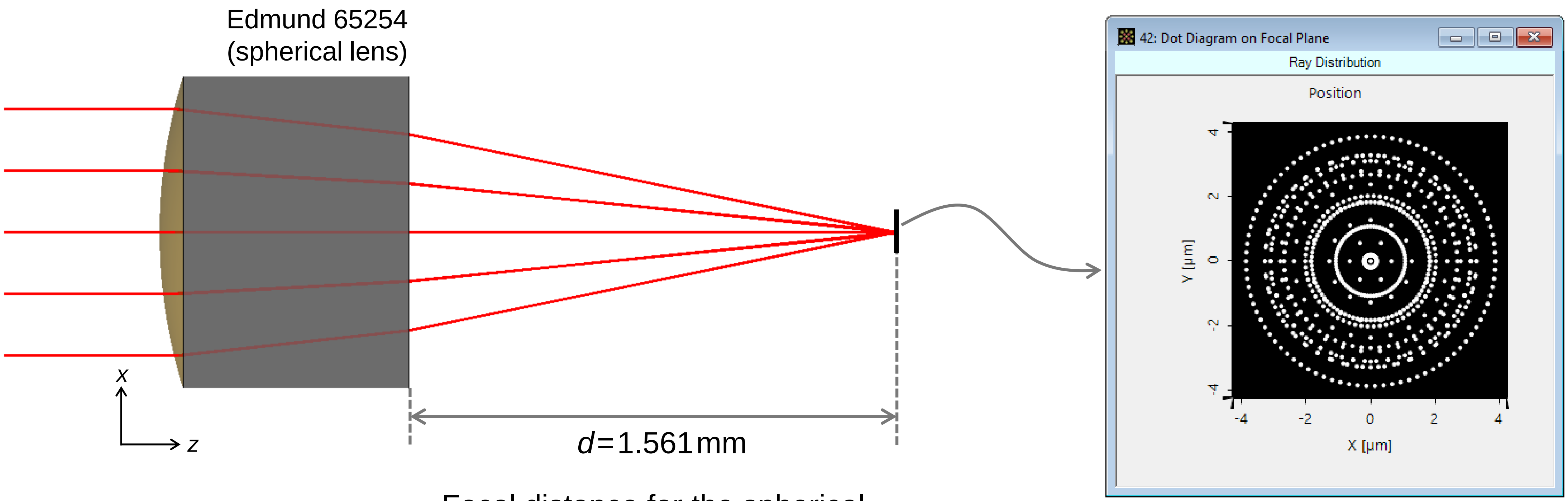
Modeling Task



optimal working distance d=?

- Is it the best solution to place the fiber end at the ray-optics focal plane behind the lens?
- How to find the optimal working distance to achieve maximum coupling efficiency?

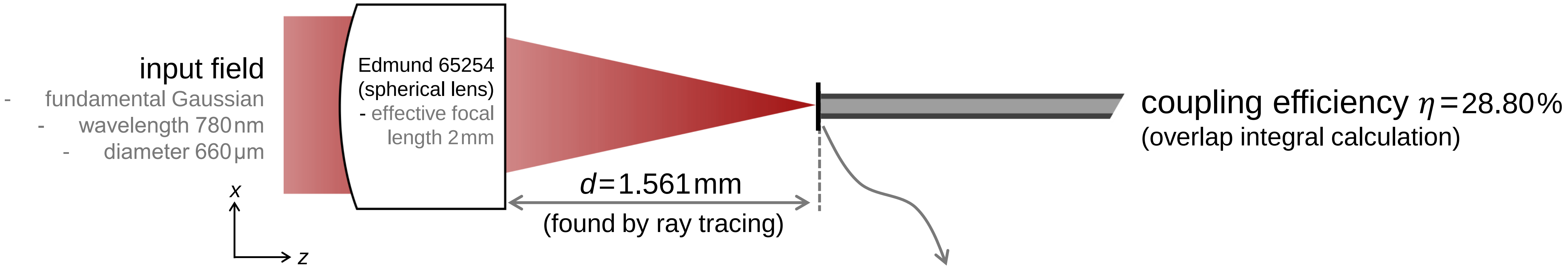
Focal Distance Found by Using Ray Tracing



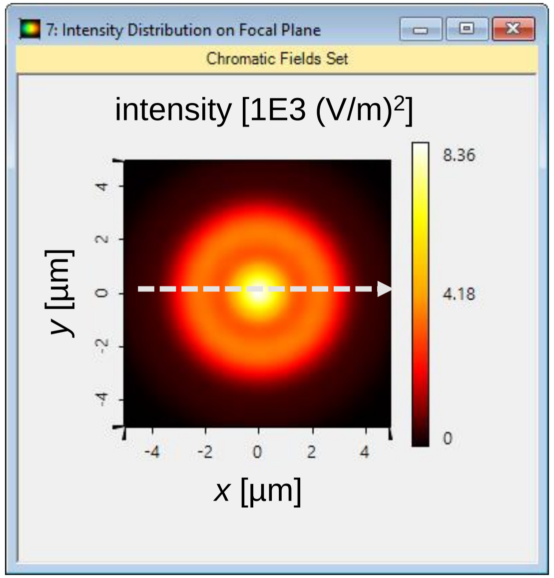
Focal distance for the spherical lens is found first by using ray tracing in VirtualLab.

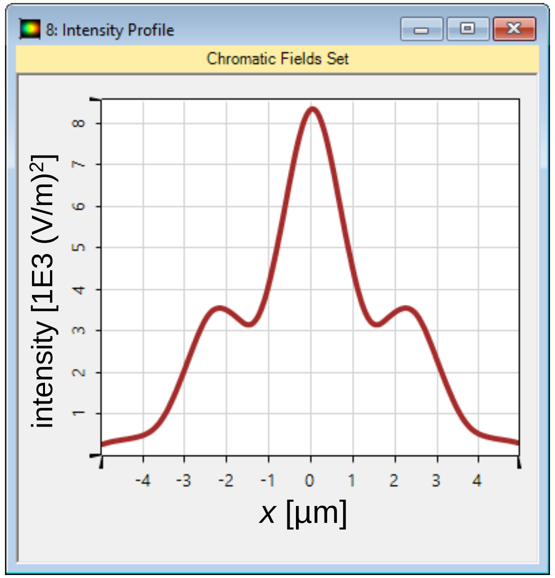
The beam diameter (RMS) evaluated with ray tracing is 5.95µm.

Field Tracing Evaluation at Ray-Optics Focal Distance

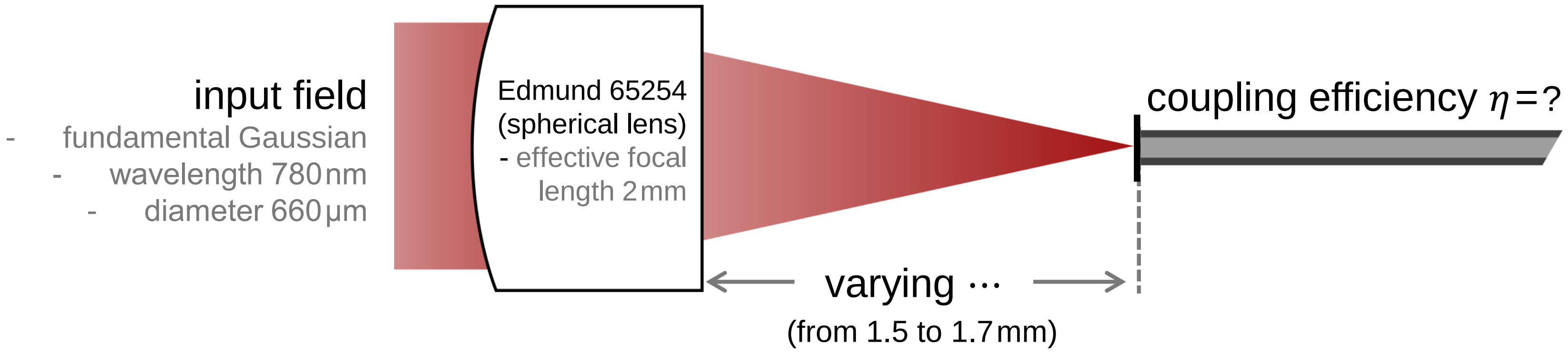


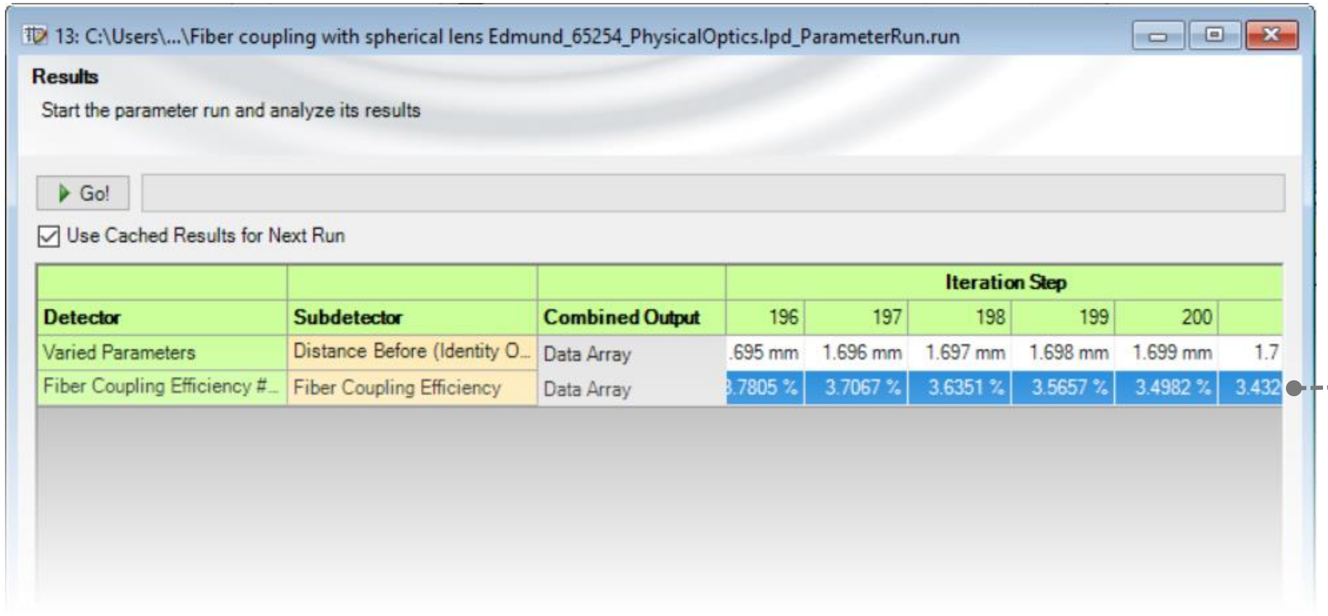
Field tracing in VirtualLab provide access to the full field information at any desired plane in the system.

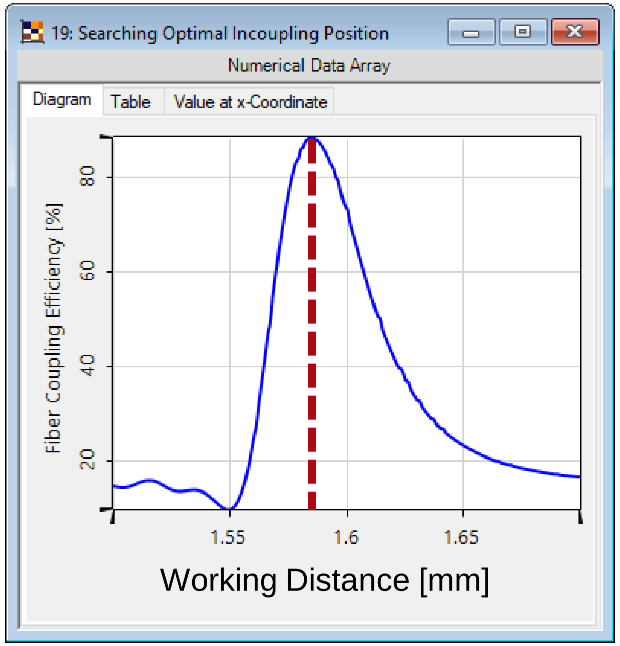




Find Optimal Working Distance by Using Field Tracing

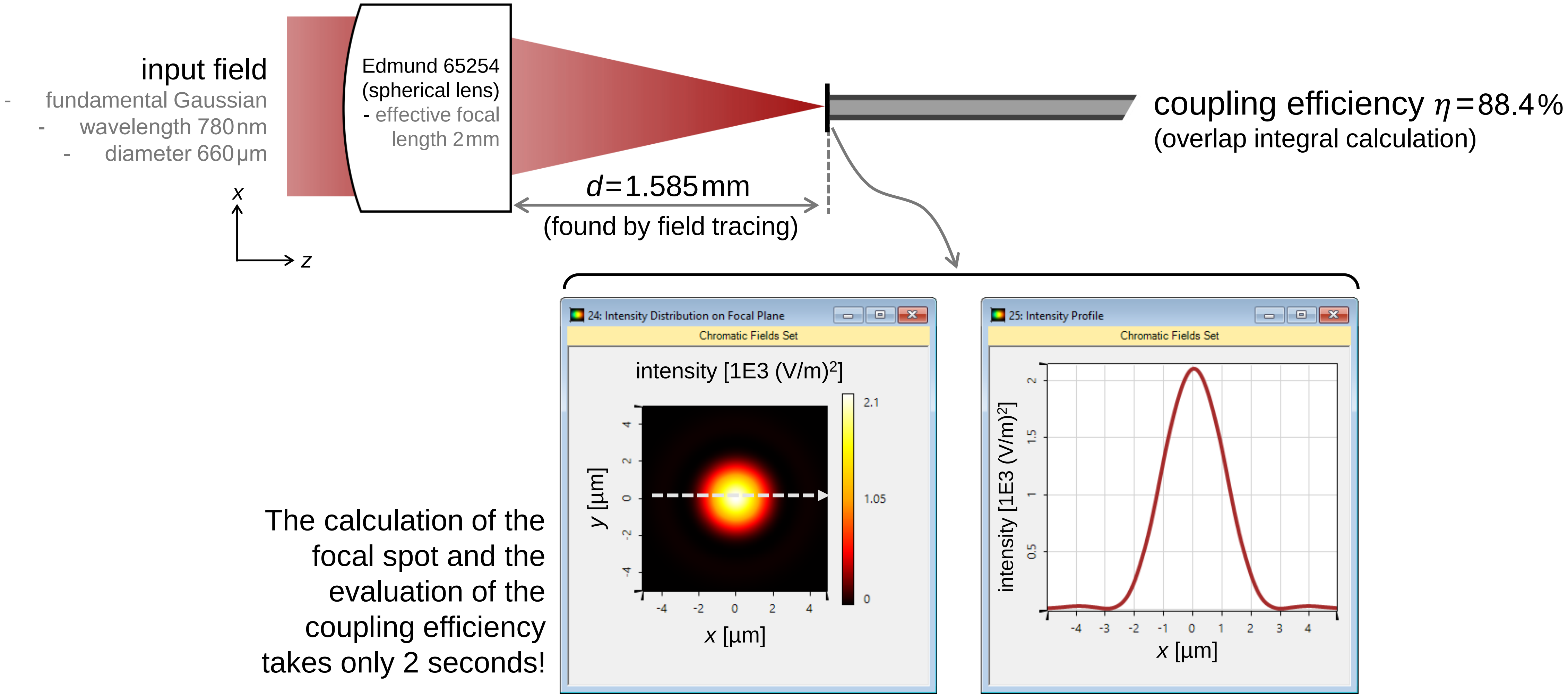






The optimal working distance found by field tracing is 1.585 mm.

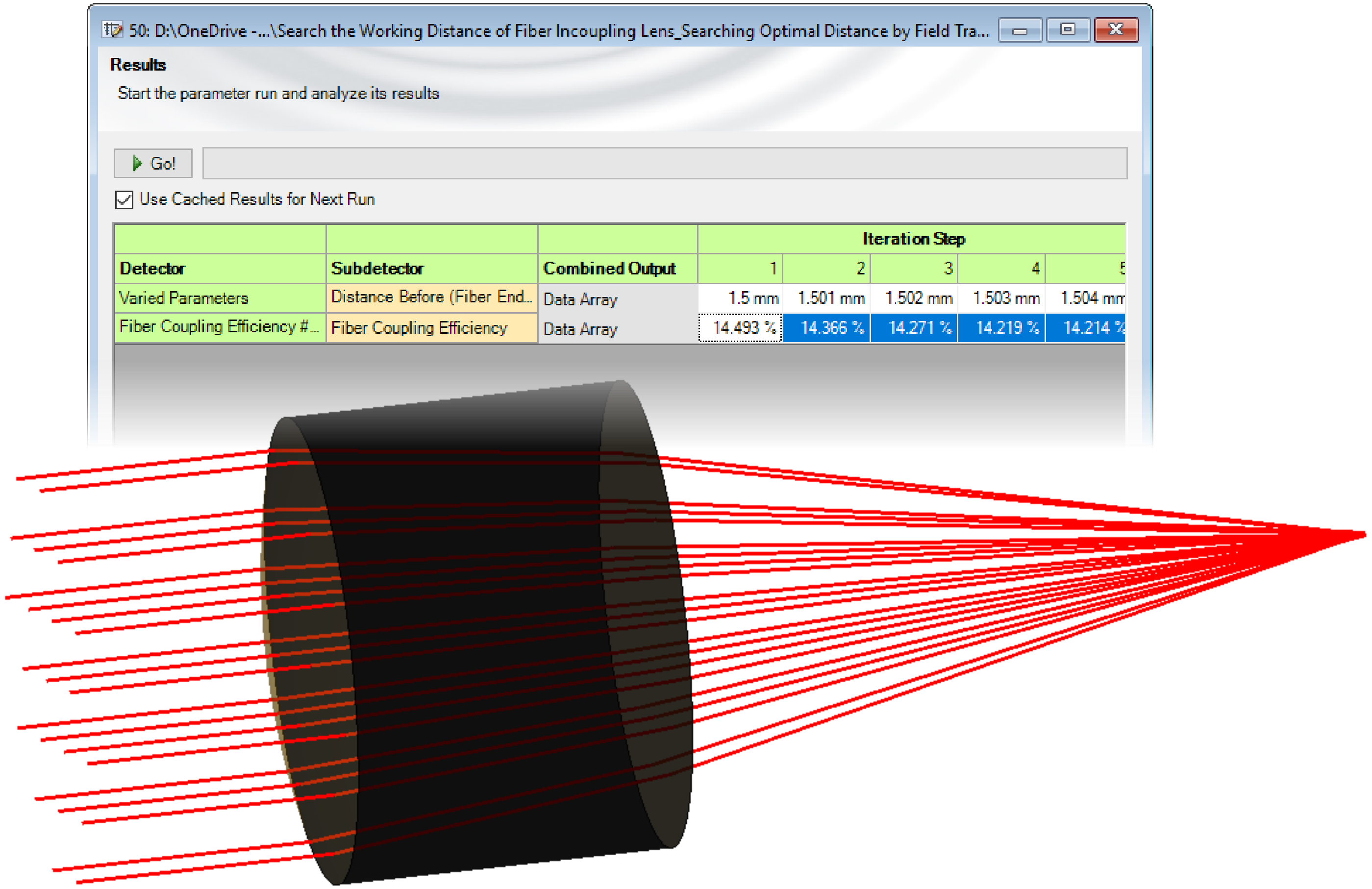
Evaluation at Optimal Working Distance



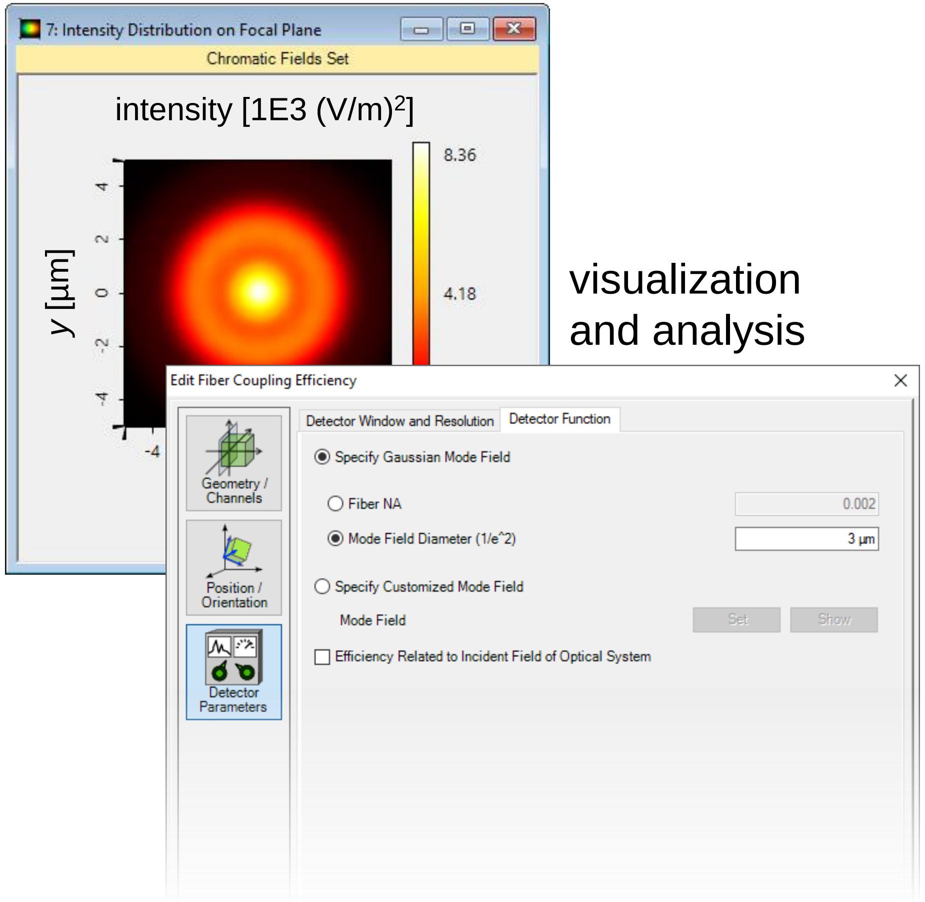
The calculation of the focal spot and the evaluation of the coupling efficiency takes only 2 seconds!

Peek into VirtualLab Fusion

Parameter Run for selected variables in system



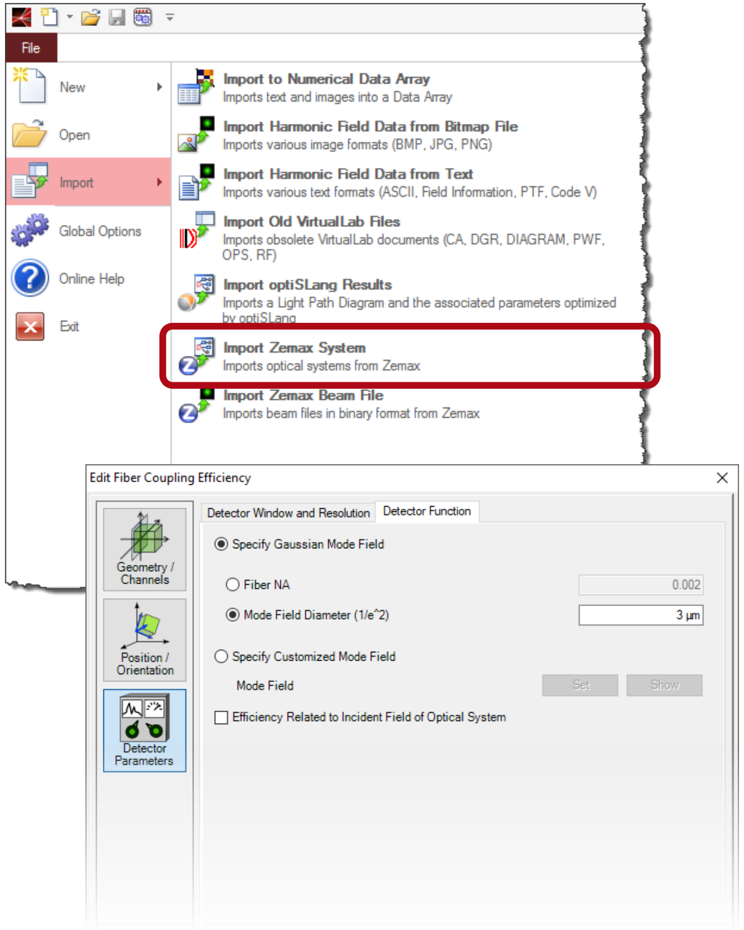
ray tracing system analysis



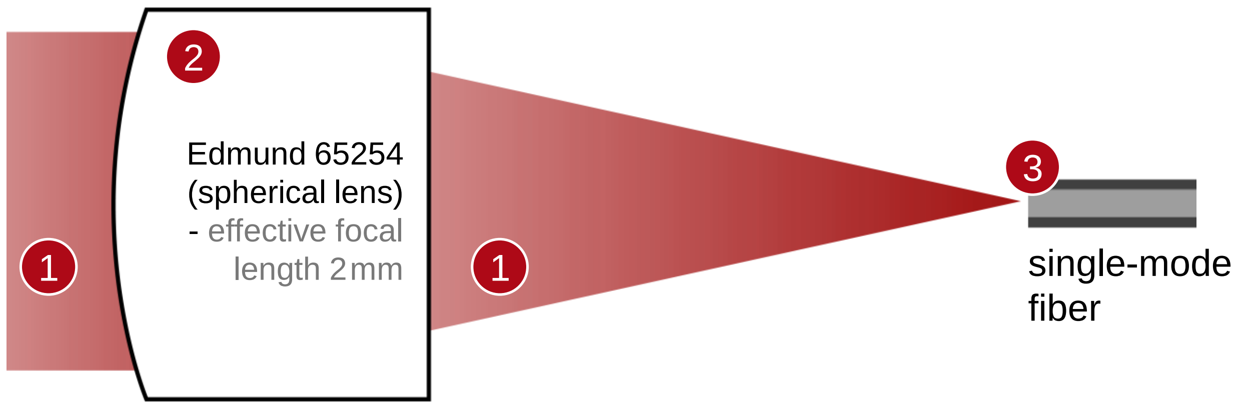
visualization and analysis

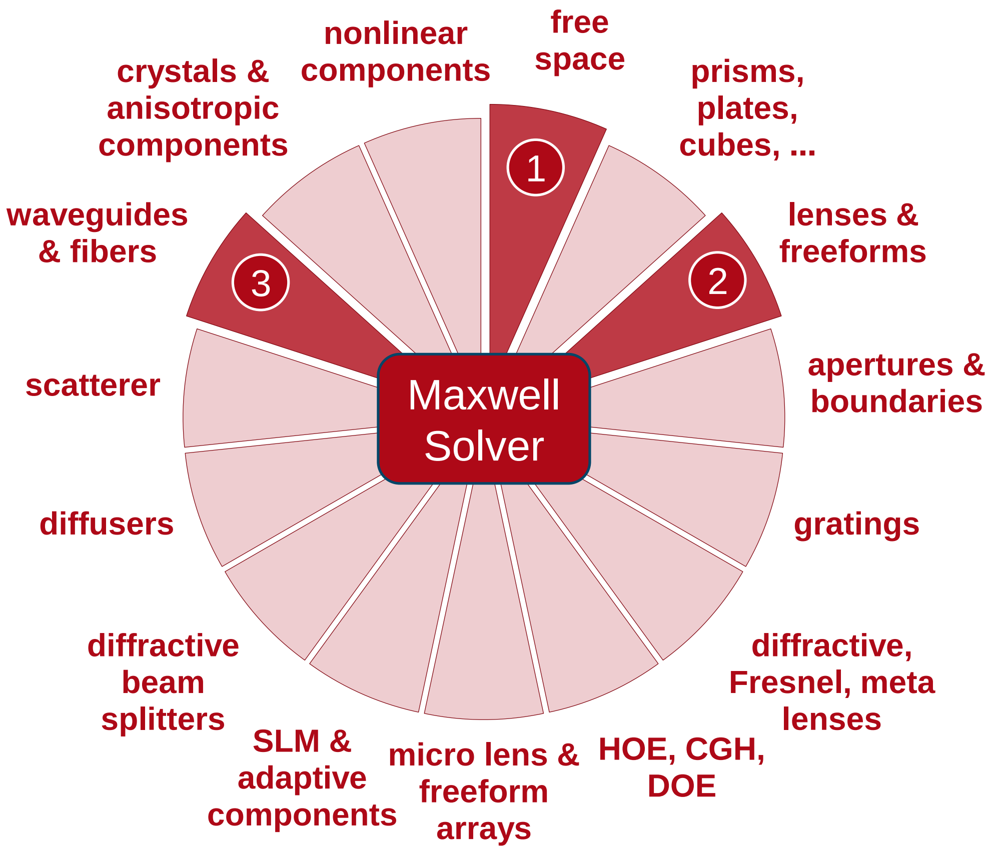
Workflow in VirtualLab Fusion

- Set up input Gaussian field
  - Basic Source Models [Tutorial Video]
- Import coupling lens from Zemax file
  - Import Optical Systems from Zemax [Use Case]
- Find focal distance using ray optics
- Evaluate fiber coupling efficiency for initial working distance with field tracing
- Use Parameter Run to find optimal working distance



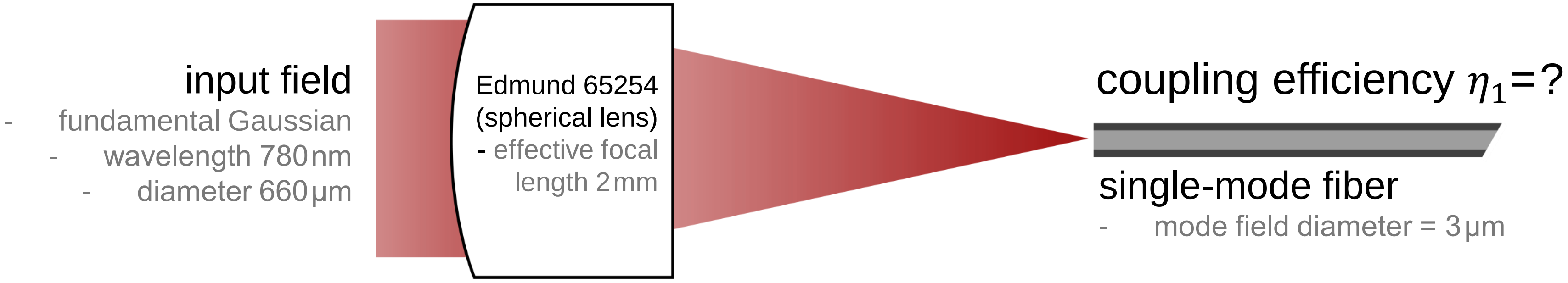
VirtualLab Fusion Technologies



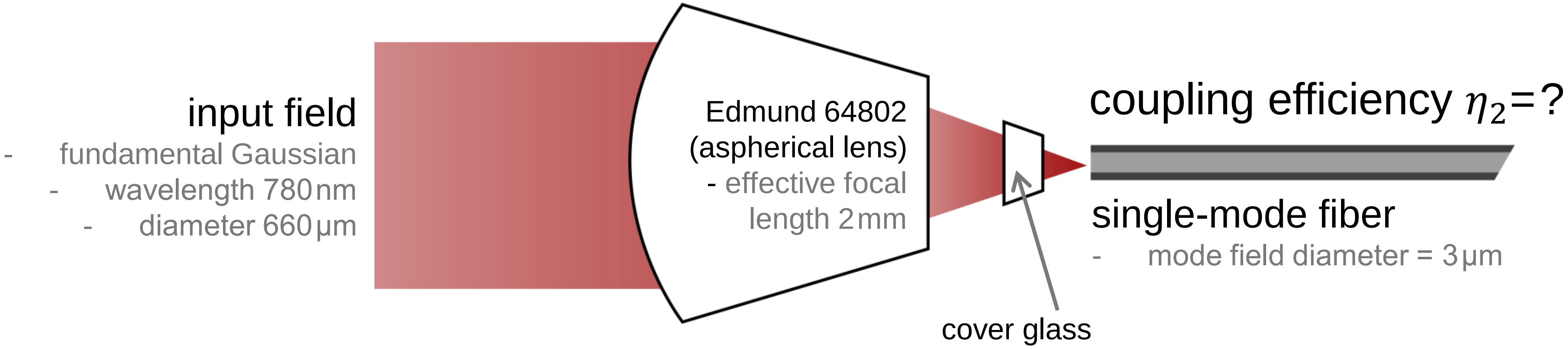


Comparison of Different Lenses for Fiber Coupling

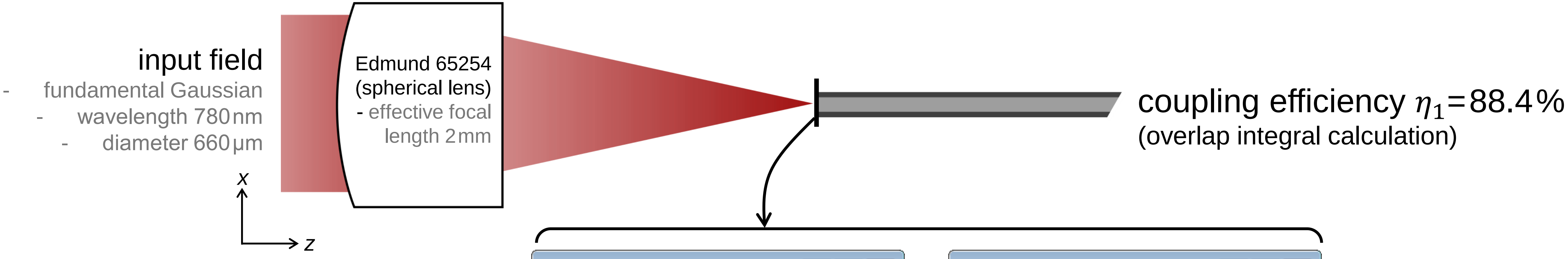
Modeling Task

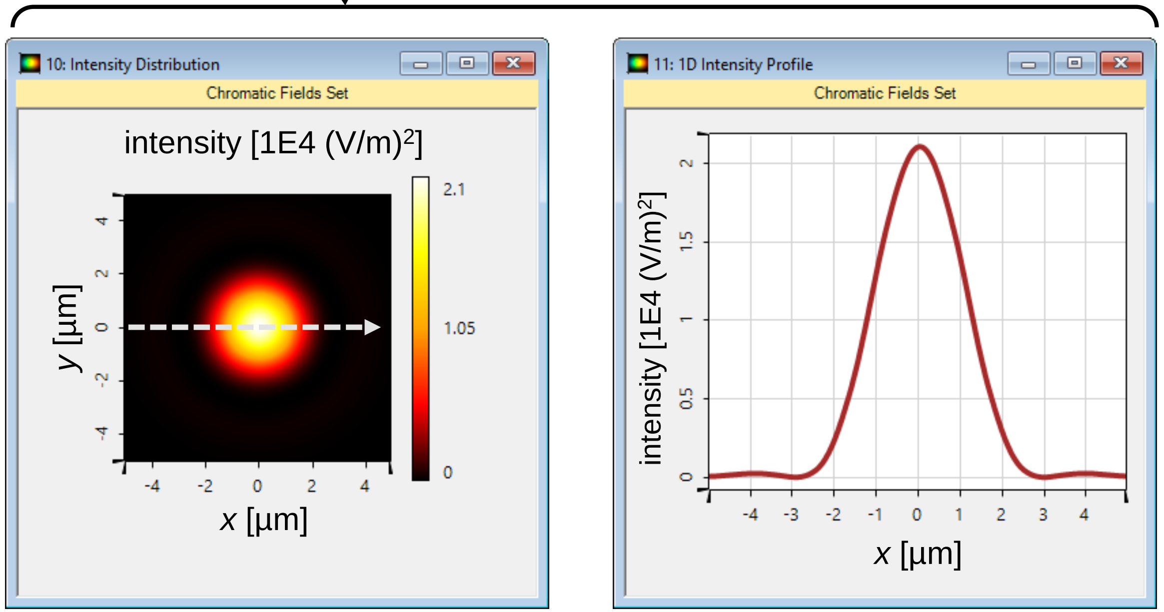


When two lenses with the same effective focal length are available for fiber coupling task, how to evaluate their performance in terms of coupling efficiency?



Simulation Results

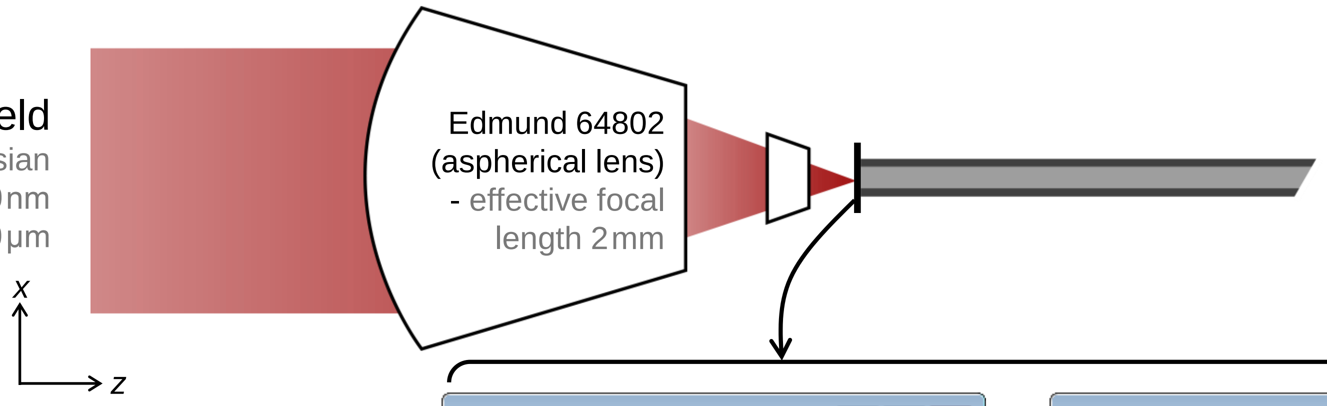




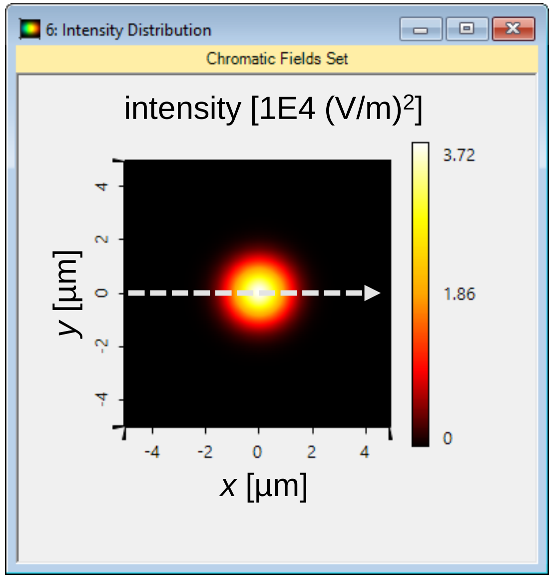
Due to aberrations from the spherical lens, the focal spot at the end of the fiber deviates from a Gaussian mode, and therefore it leads to poor coupling efficiency.

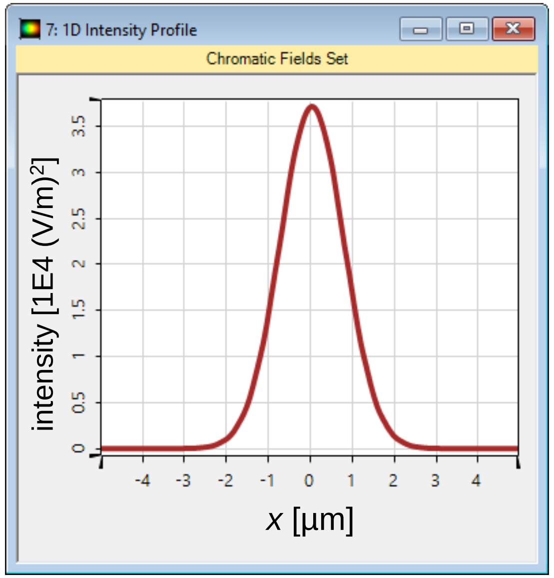
Simulation Results

input field
- fundamental Gaussian
- wavelength 780 nm
- diameter 660 µm



coupling efficiency $\eta_1 = 99.9\%$
(overlap integral calculation)

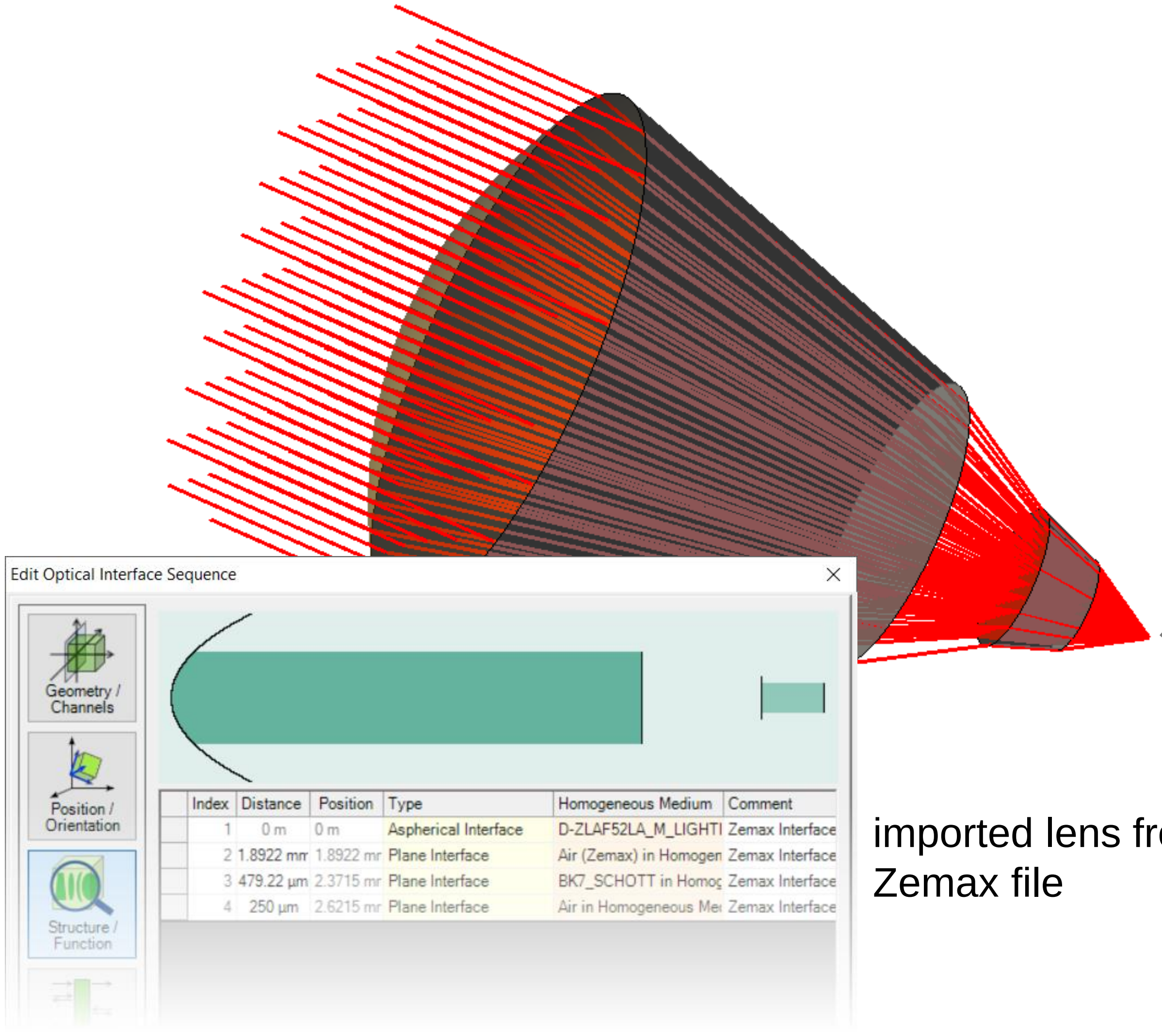




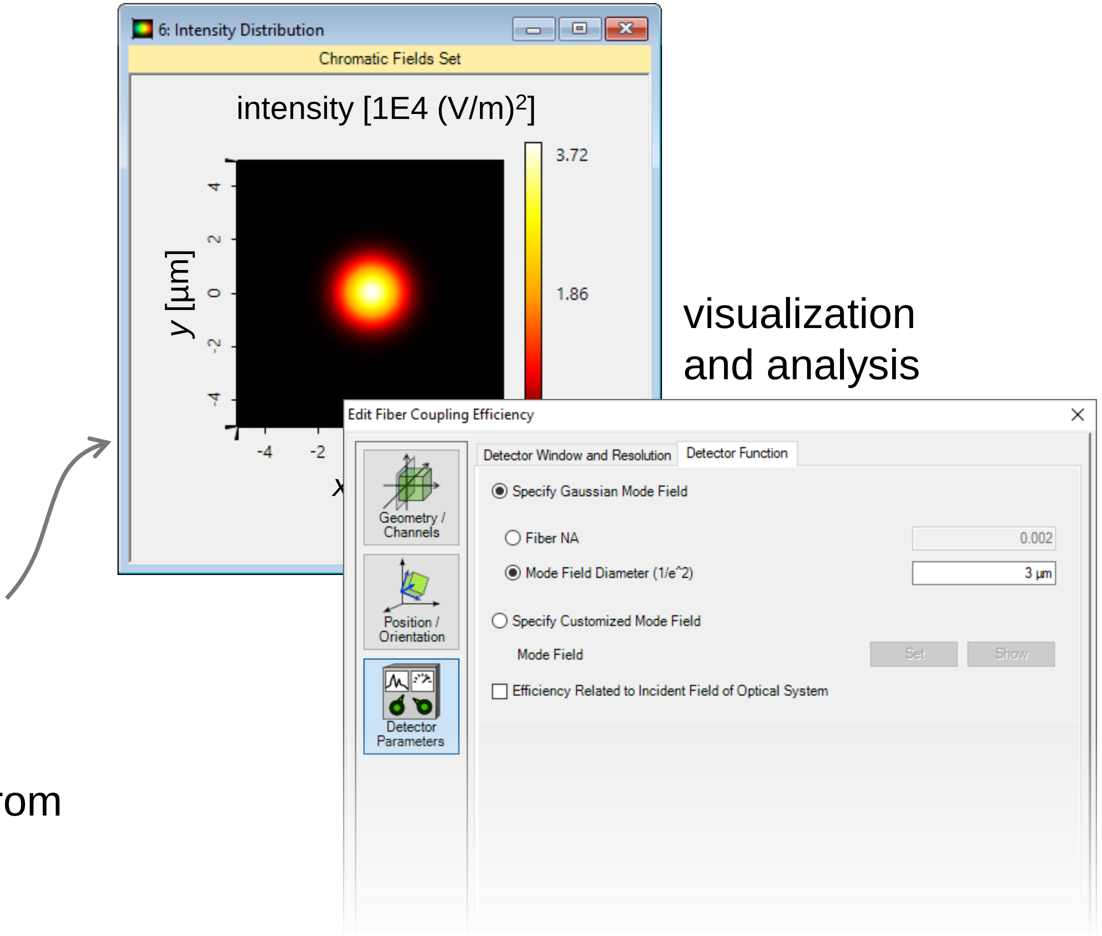
Field tracing simulation of the fiber coupling system takes only 2 seconds.

Aspherical lens controls the aberrations well and that guarantees a focal spot in smaller size, and with Gaussian profile that fits to the fiber.

Peak into VirtualLab Fusion



imported lens from Zemax file

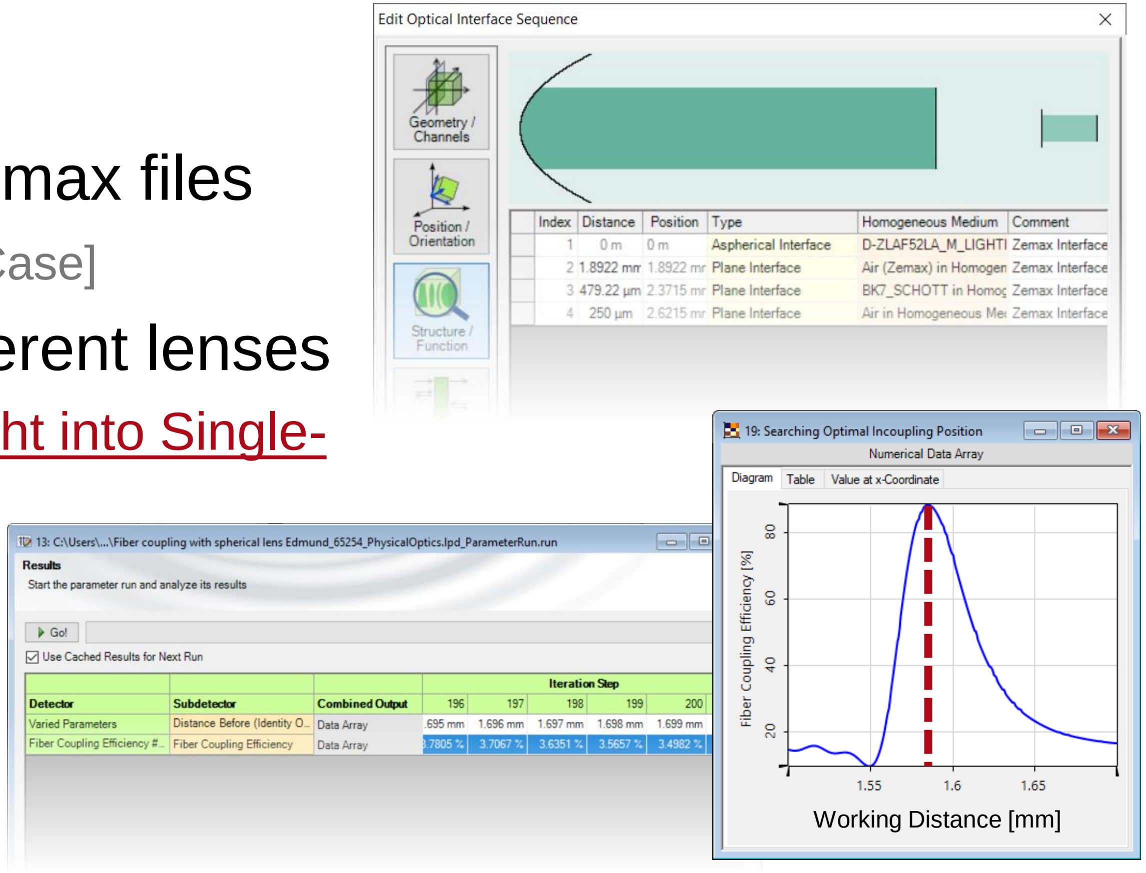


visualization and analysis

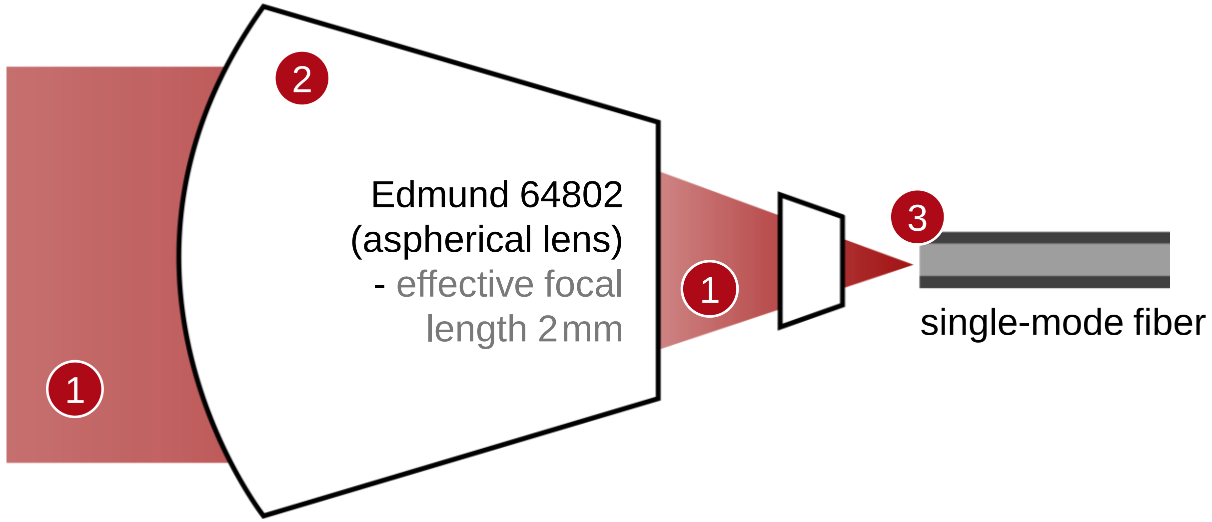
Workflow in VirtualLab Fusion

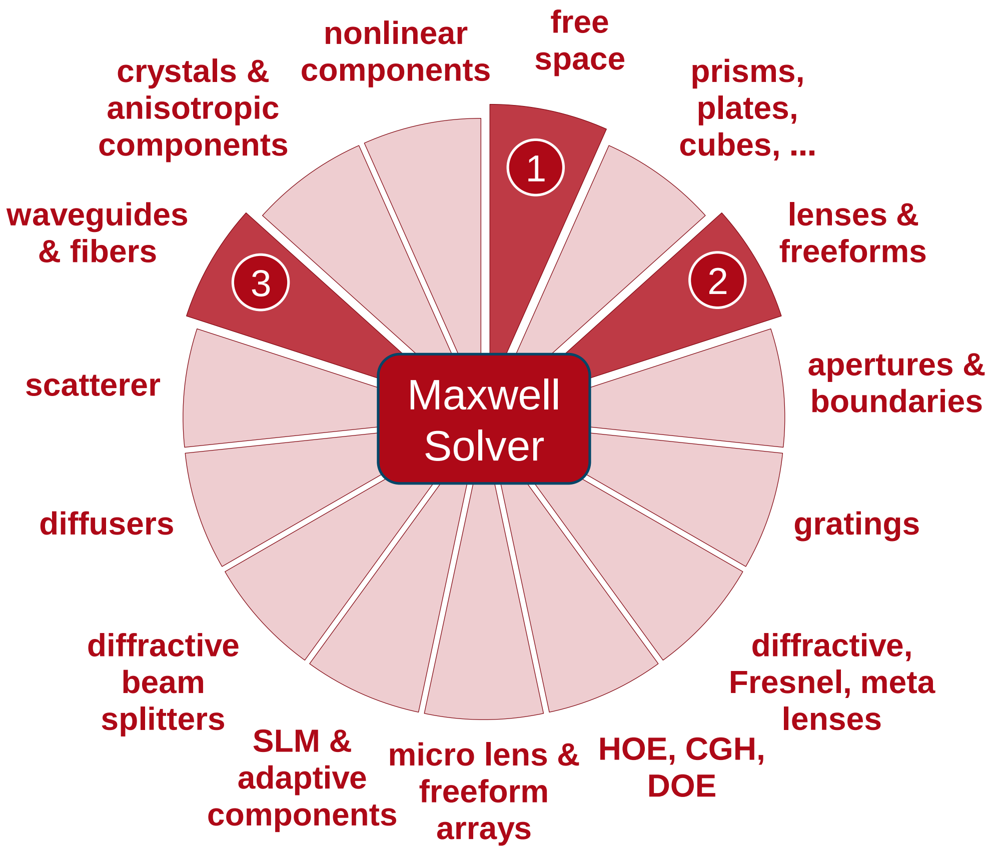
- Set up input Gaussian field
  - Basic Source Models [Tutorial Video]
- Load different coupling lenses from Zemax files
  - Import Optical Systems from Zemax [Use Case]
- Find optimal working distances for different lenses
  - Optimal Working Distance for Coupling Light into Single-Mode Fibers [Use Case]

and then compare their performance



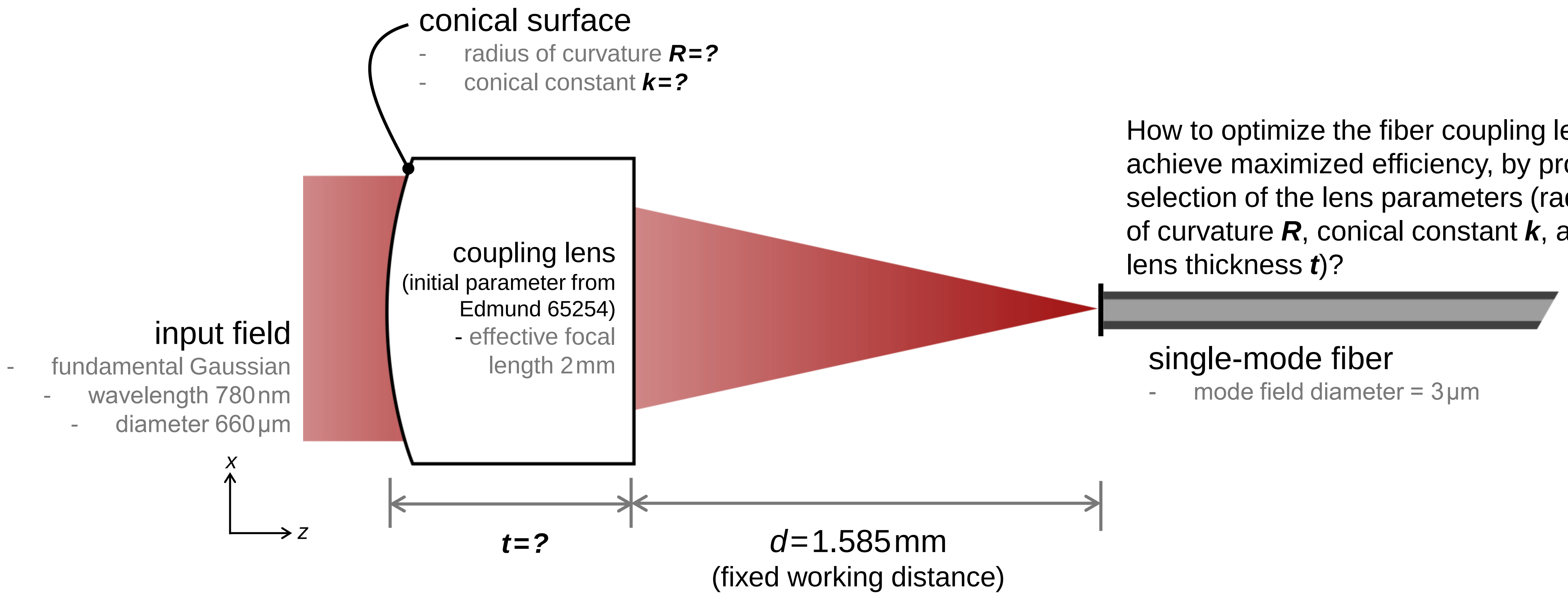
VirtualLab Fusion Technologies





Parametric Optimization of Fiber Coupling Lenses

Design Task

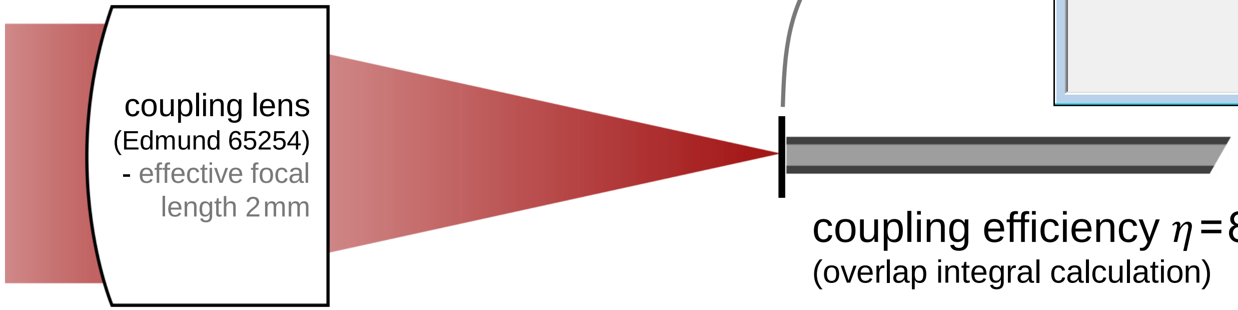


How to optimize the fiber coupling lens to achieve maximized efficiency, by proper selection of the lens parameters (radius of curvature ***R***, conical constant ***k***, and lens thickness ***t***)?

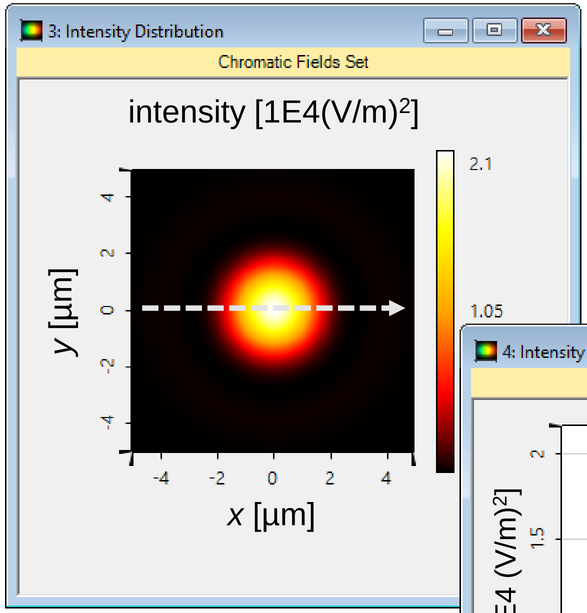
Evaluation of Initial Lens

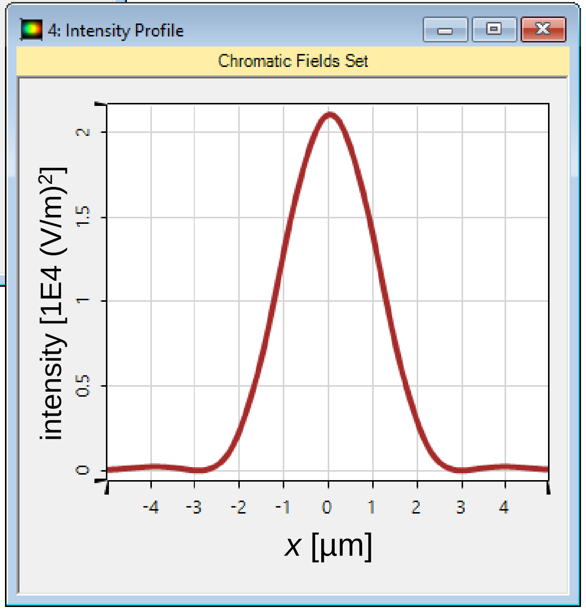
initial lens parameters

- radius of curvature $\boldsymbol{R}=1.7\,\text{mm}$
- conical constant $\boldsymbol{k}=0$
- lens thickness $\boldsymbol{t}=0.8\,\text{mm}$

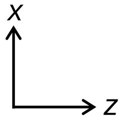


coupling efficiency $\eta=88.4\%$
(overlap integral calculation)





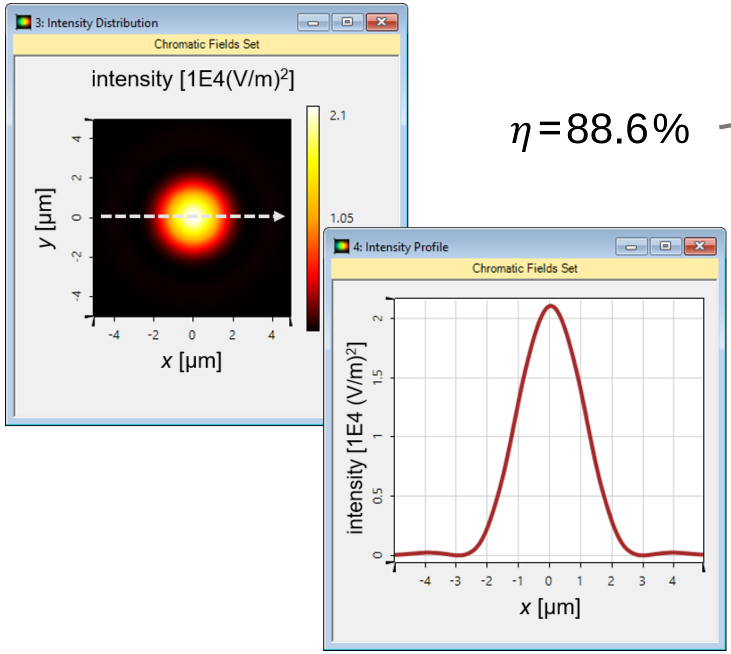
The coupling efficiency obtained from the initial spherical lens is not optimal, due to mismatch to the mode inside the single-mode fiber.



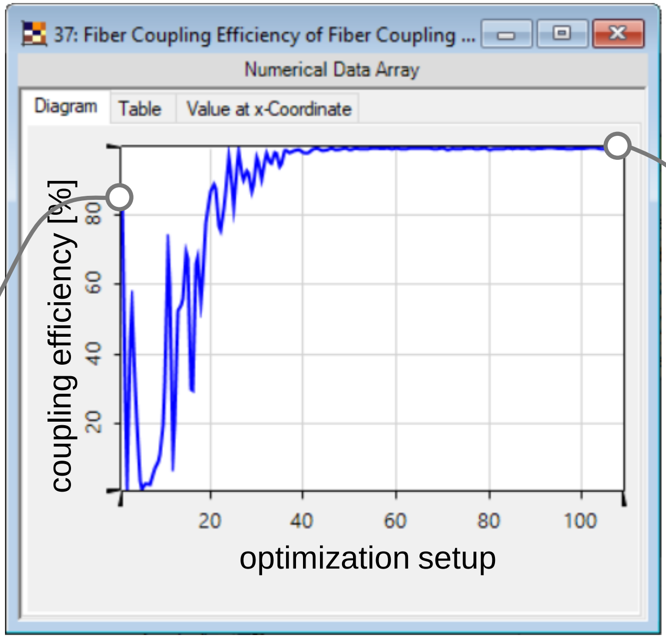
Parametric Optimization

initial lens parameters

- radius of curvature ***R***=1.7mm
- conical constant ***k***=0
- lens thickness ***t***=0.8mm

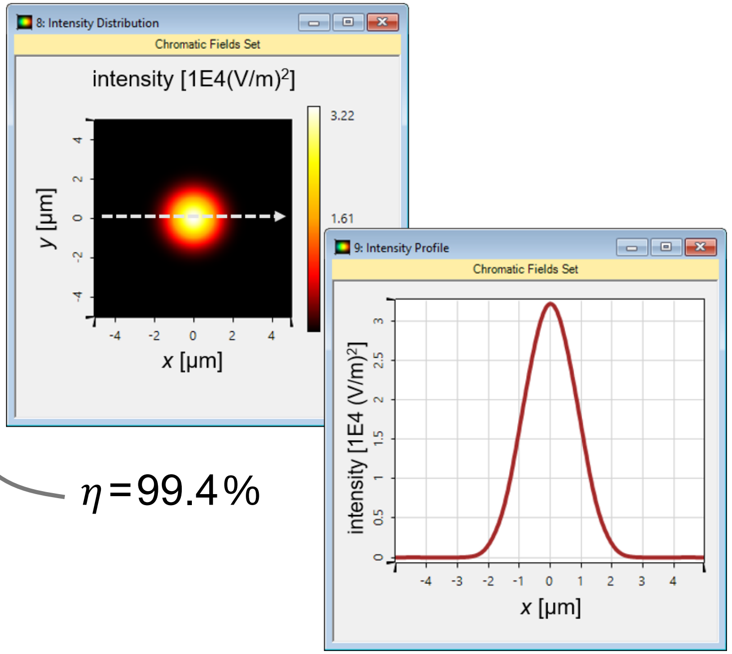


η=88.6%



parametric optimization of coupling efficiency with downhill simplex algorithm

η=99.4%



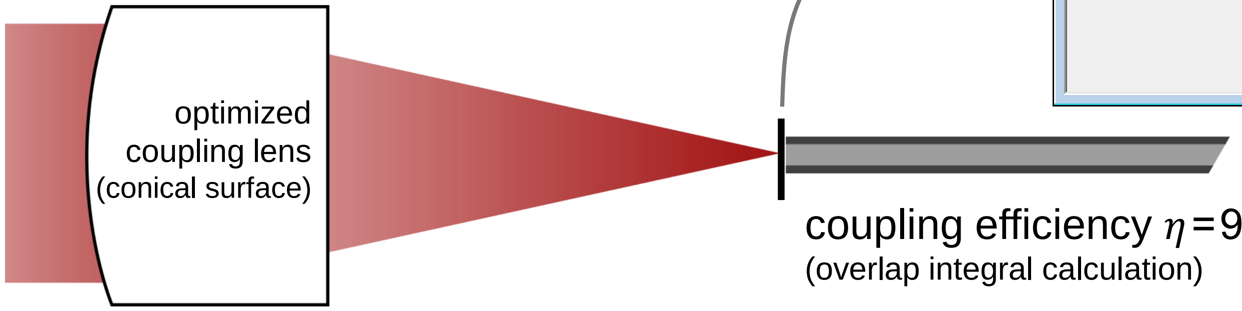
optimized lens parameters

- radius of curvature ***R***=1.704mm
- conical constant ***k***=-0.67278
- lens thickness ***t***=0.841mm

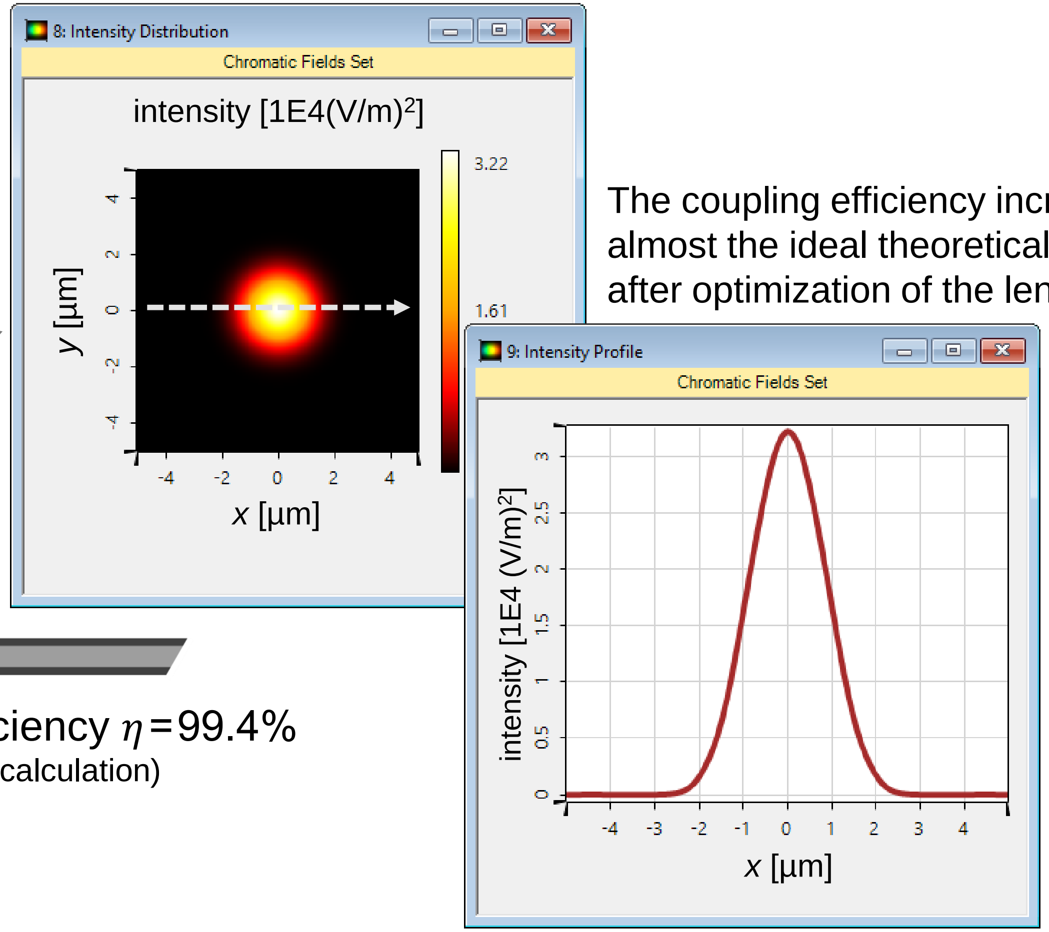
Evaluation of Optimized Lens

optimized lens parameters

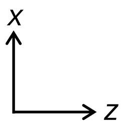
- radius of curvature $\boldsymbol{R}=1.704\,\mathrm{mm}$
- conical constant $\boldsymbol{k}=-0.67278$
- lens thickness $\boldsymbol{t}=0.841\,\mathrm{mm}$



coupling efficiency $\eta=99.4\%$
(overlap integral calculation)

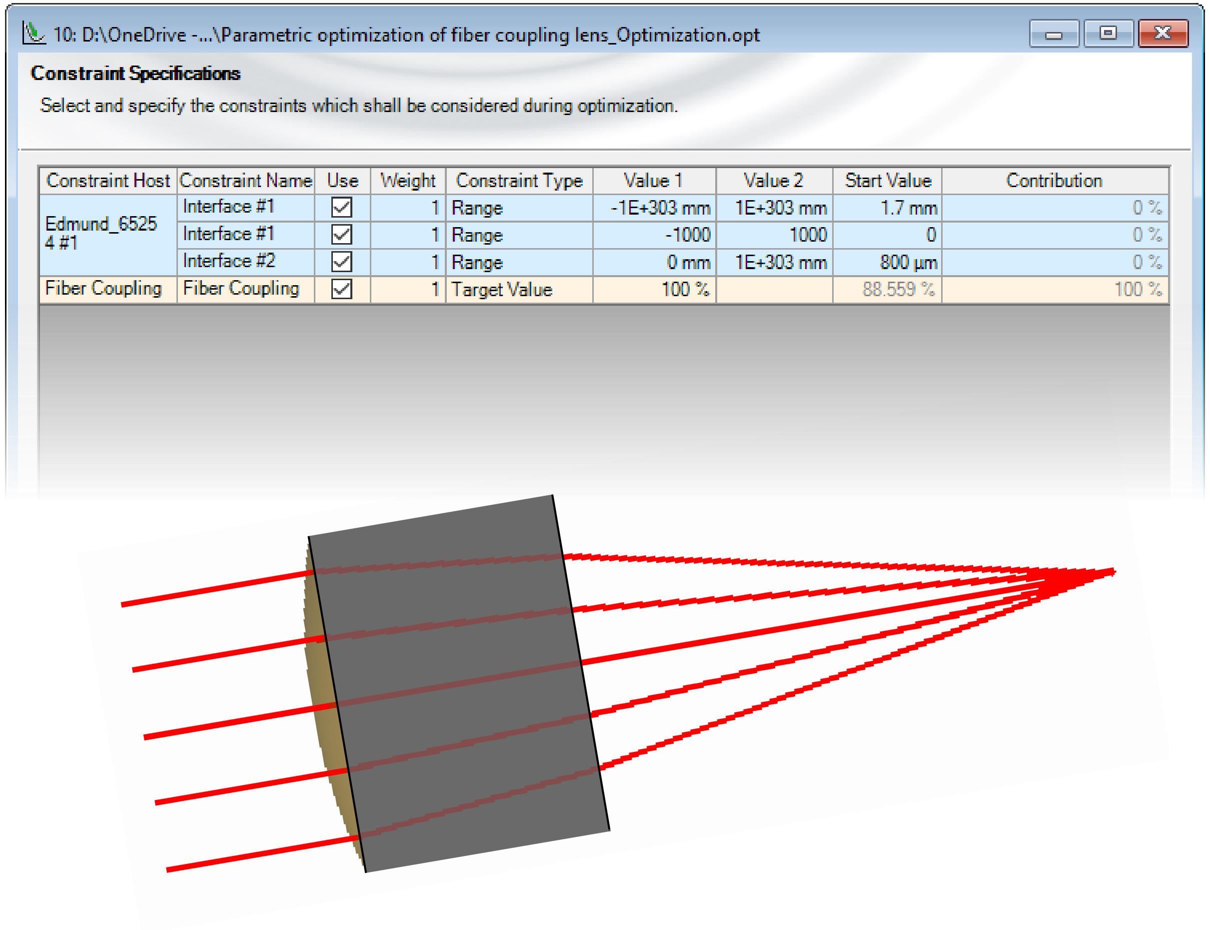


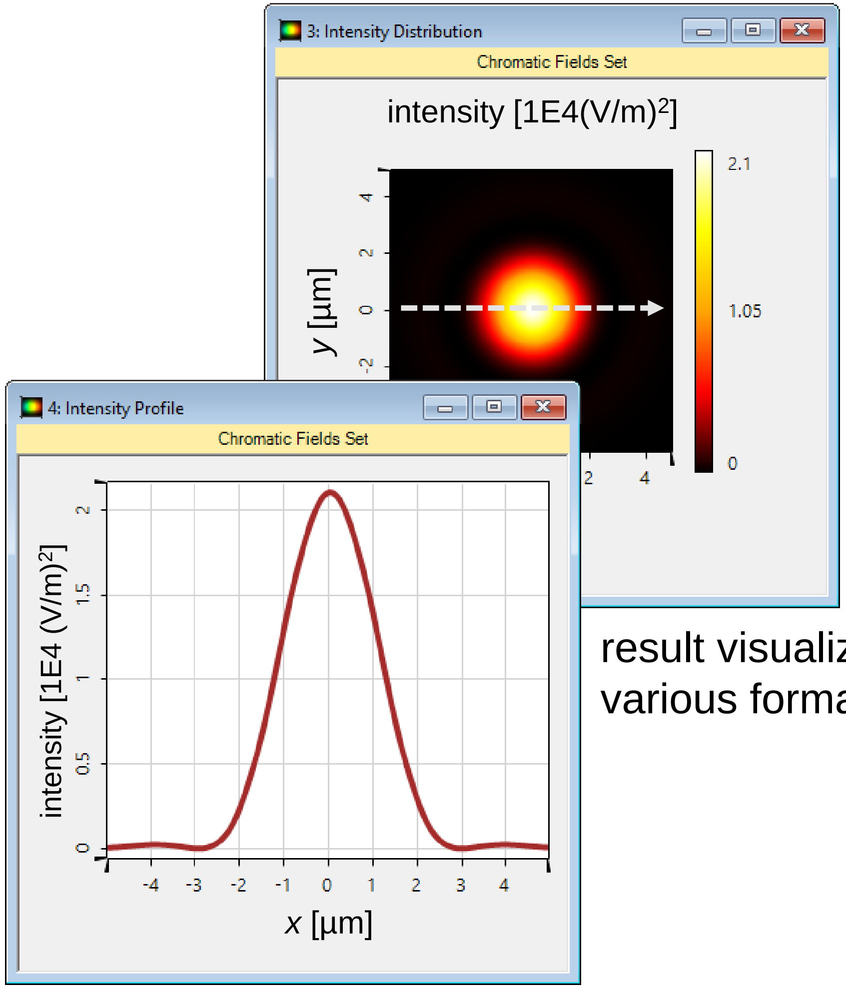
The coupling efficiency increases to almost the ideal theoretical value after optimization of the lens.



Peak into VirtualLab Fusion

parametric optimization with flexible variables and merit functions definition

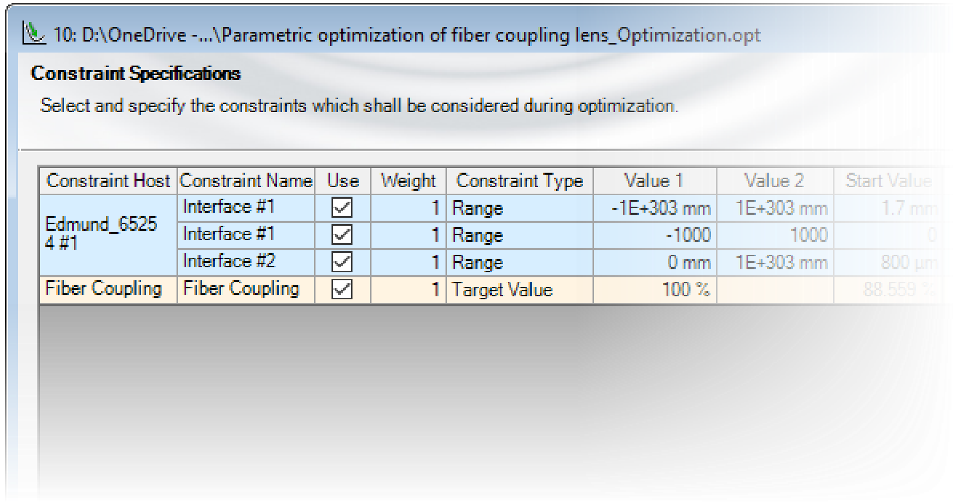


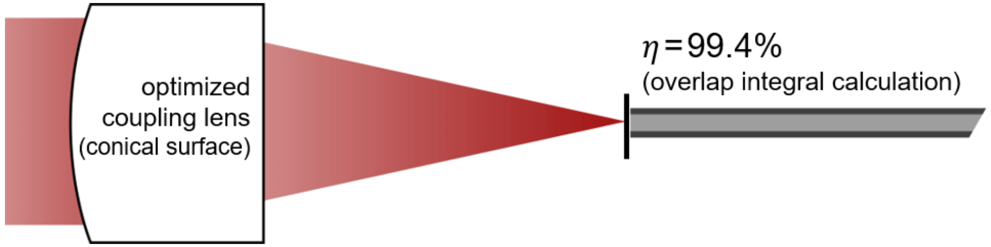


result visualization in various formats

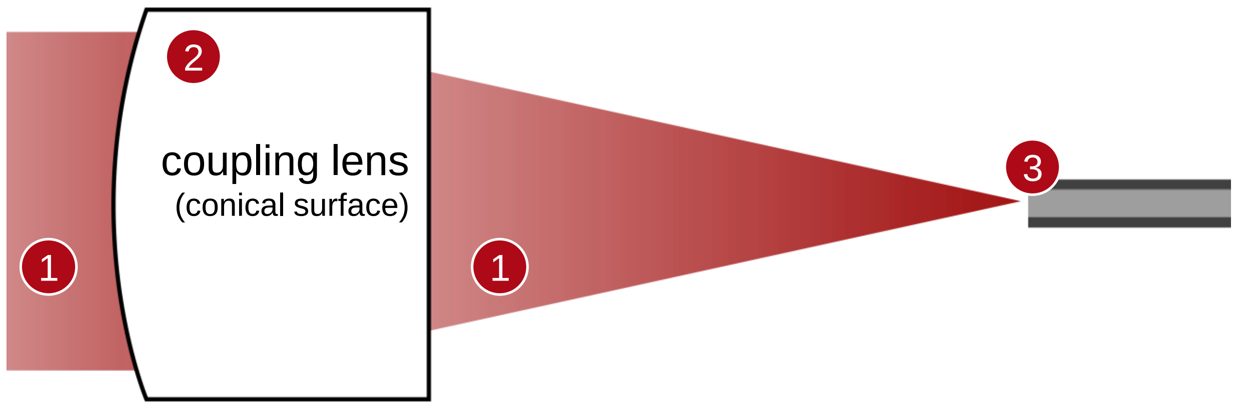
Workflow in VirtualLab Fusion

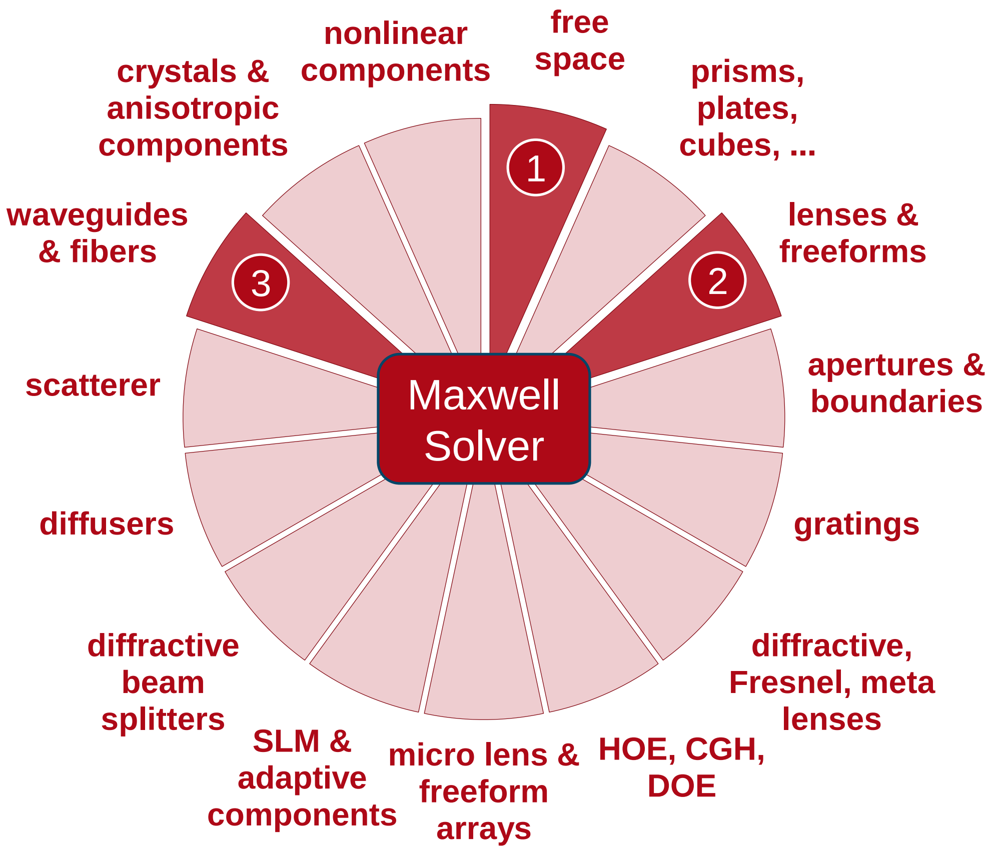
- Set up input Gaussian field
  - Basic Source Models [Tutorial Video]
- Import initial coupling lens from Zemax file
  - Import Optical Systems from Zemax [Use Case]
- Evaluate fiber coupling efficiency with initial lens
  - Optimal Working Distance for Coupling Light into Single-Mode Fibers [Use Case]
- Use Parametric Optimization to find proper values for selected lens parameters





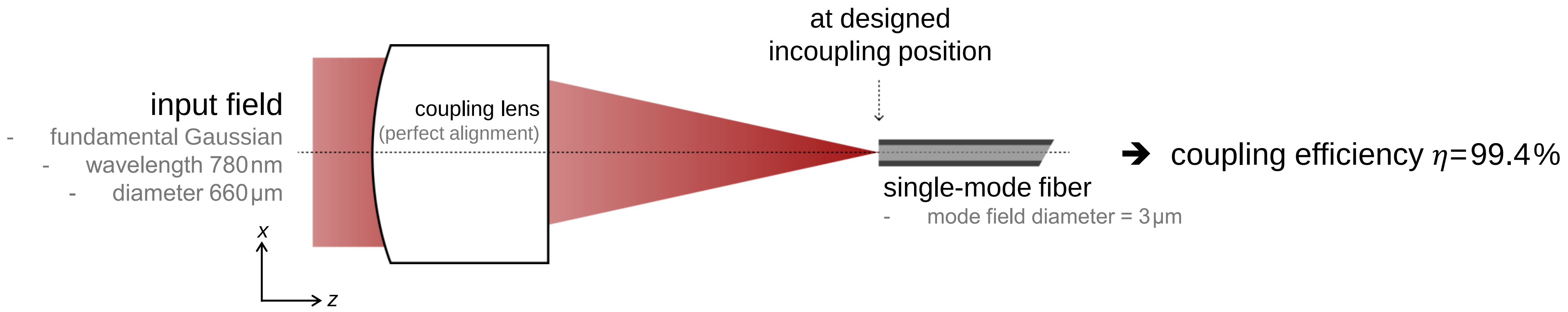
VirtualLab Fusion Technologies



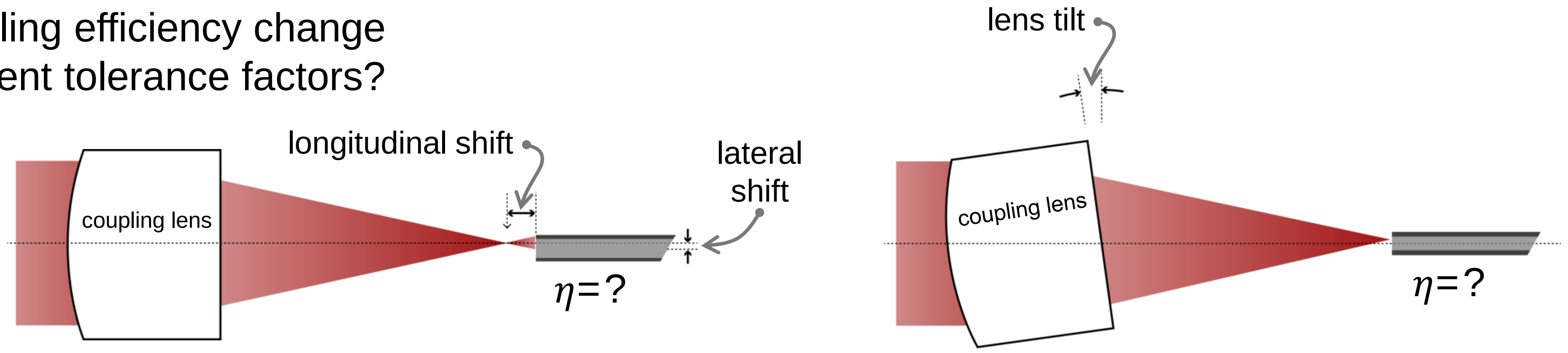


Tolerance Analysis of a Fiber Coupling Setup

Modeling Task



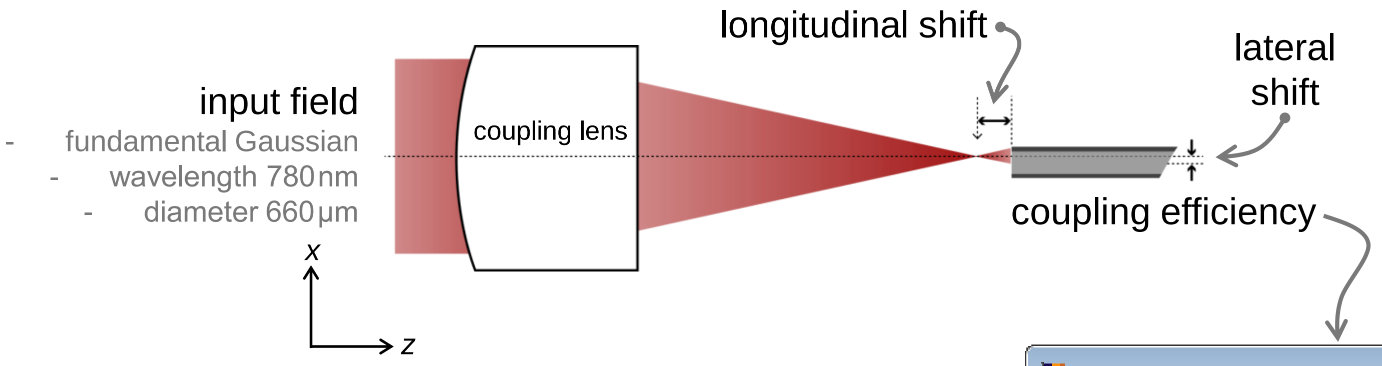
How does the coupling efficiency change with respect to alignment tolerance factors?



(a) shift of fiber end position

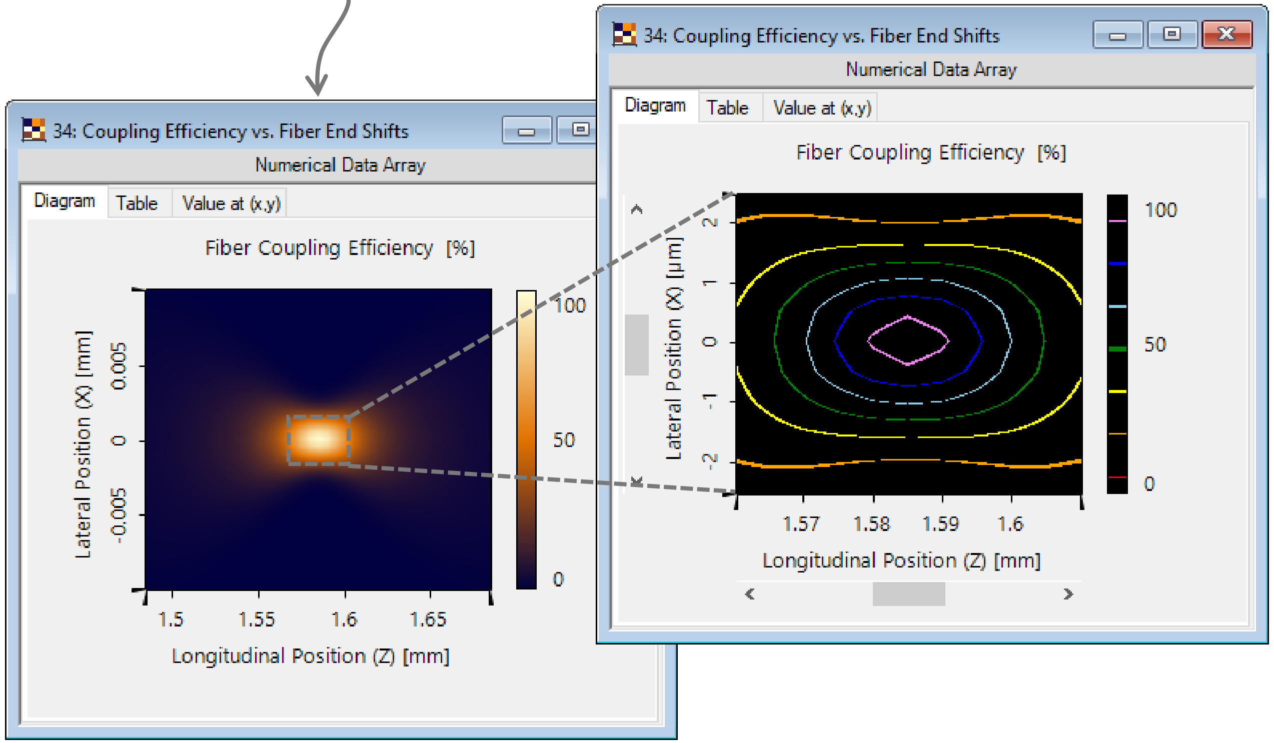
(b) tilt of coupling lens

Coupling Efficiency vs. Fiber End Position Shift

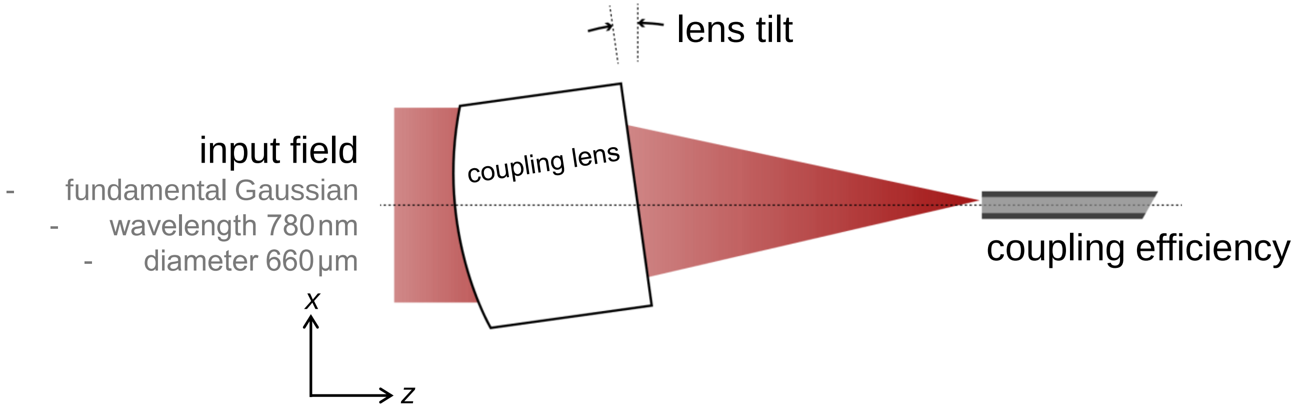


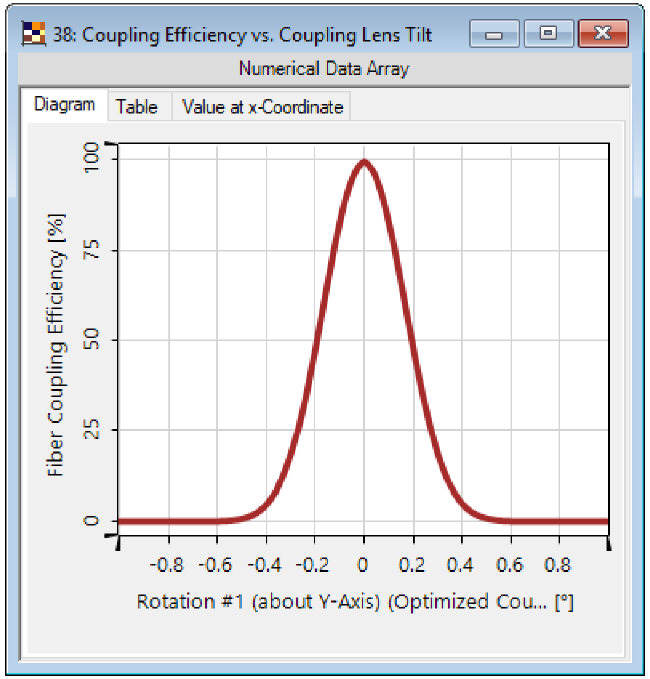
Contour plot helps with the identification of the parameter range for desired coupling efficiency threshold.

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



Coupling Efficiency vs. Coupling Lens Tilt

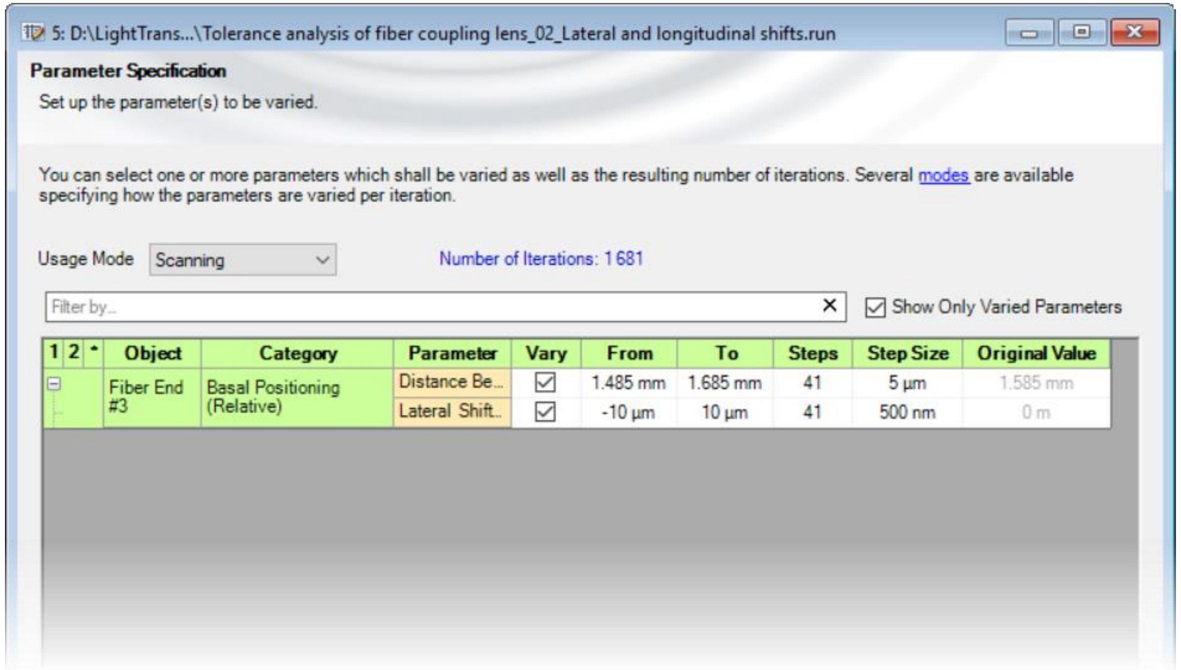


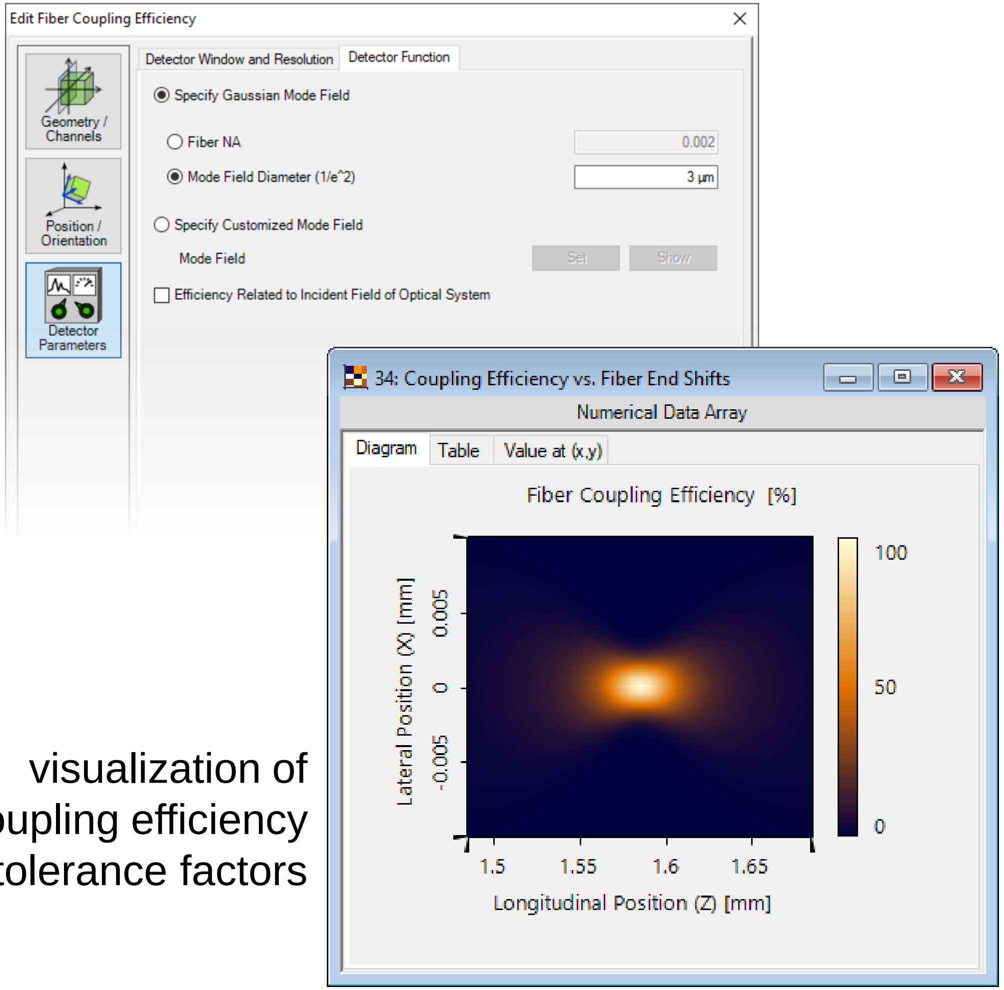


Physical-optics analysis of the coupling efficiency with respect to lens tilt, over 200 angles, takes only 50 seconds.

Peek into VirtualLab Fusion

multi-dimensional scanning of system parameters





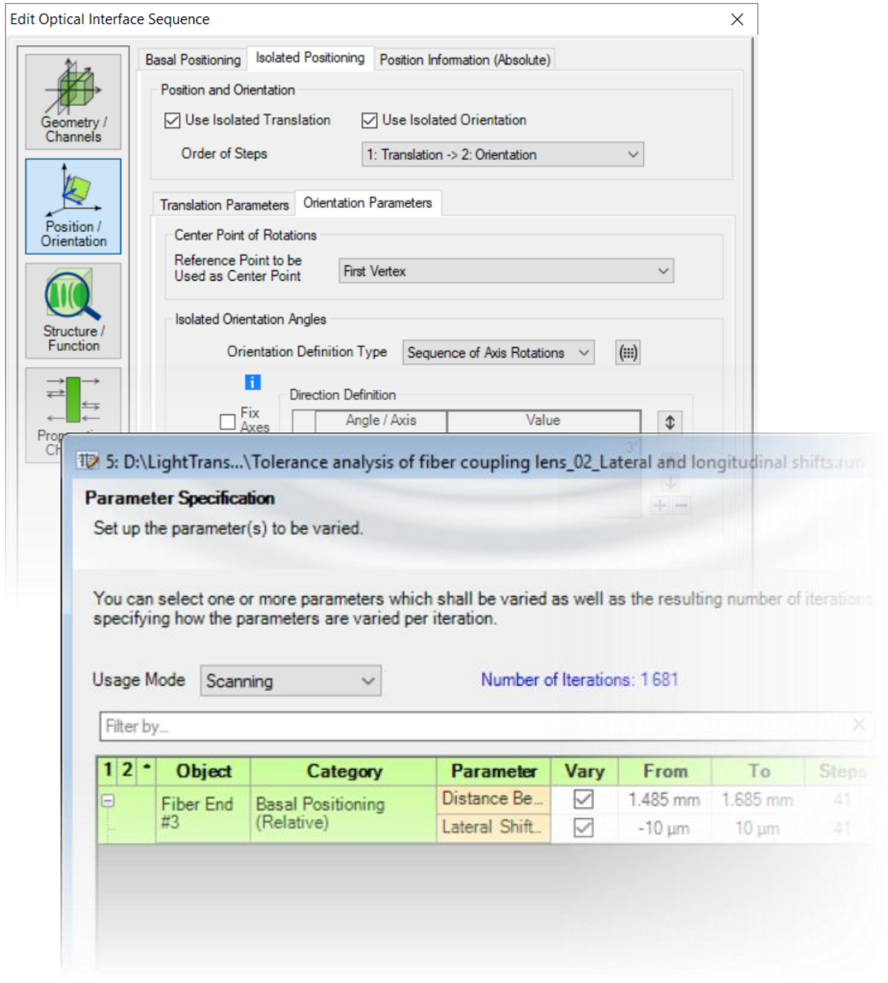
visualization of coupling efficiency vs. tolerance factors

Workflow in VirtualLab Fusion

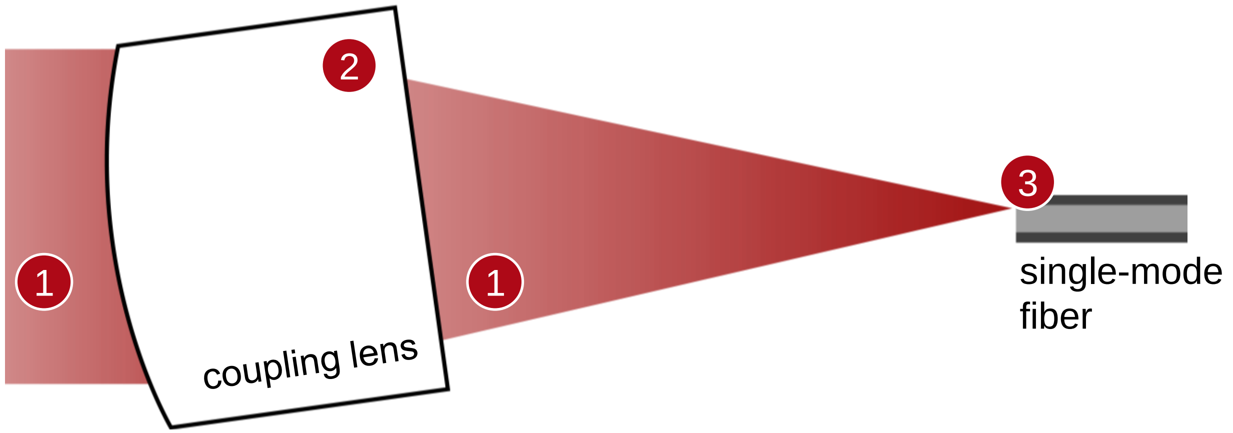
- Set up input Gaussian field
  - Basic Source Models [Tutorial Video]
- Load fiber coupling lens e.g. from Zemax file
  - Import Optical Systems from Zemax [Use Case]

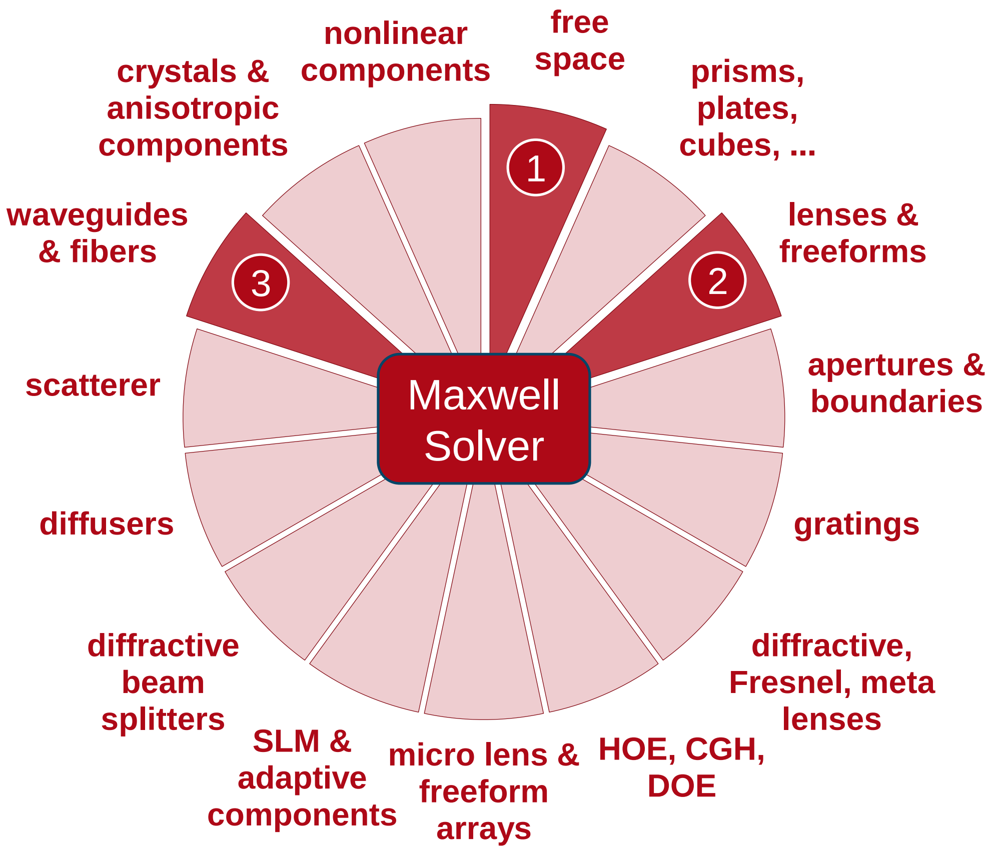
  find the optimal working distance
  - Optimal Working Distance for Coupling Light into Single-Mode Fibers [Use Case]

  or, optimize your own lens in VirtualLab
  - Parametric Optimization of Fiber Coupling Lenses [Use Case]
- Use Parameter Run to scan over tolerance factors of concern



VirtualLab Fusion Technologies



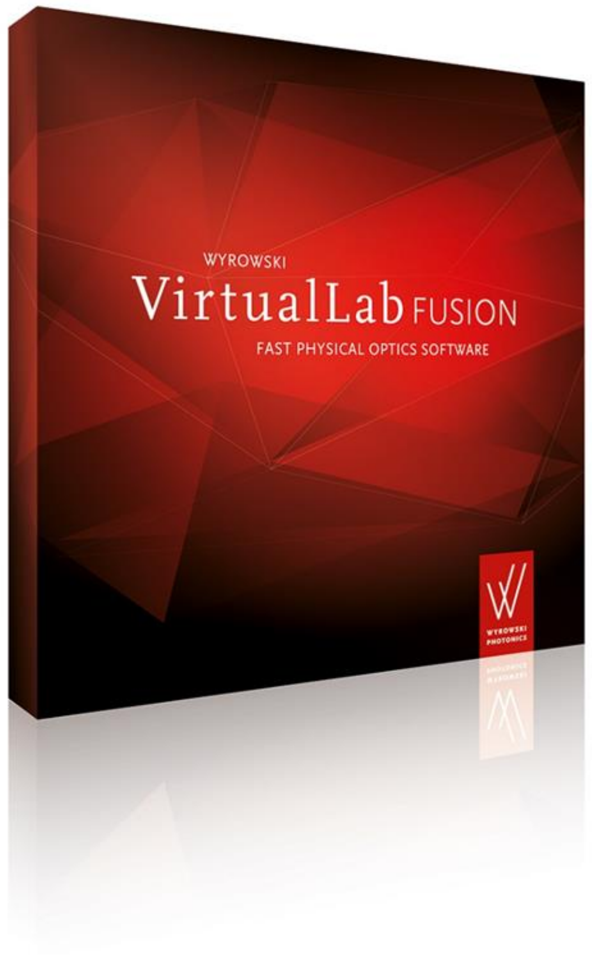


Document Information

title	Tolerance Analysis of a Fiber Coupling Setup
document code	FCP.0004
version	1.0
toolbox(es)	Starter Toolbox
VL version used for simulations	7.4.0.49
category	Application Use Case
further reading	- Comparison of Different Lenses for Fiber Coupling - Parametric Optimization of Fiber Coupling Lens

Fast Physical Optics with VirtualLab Fusion

- Fast Physical Optics does not replace ray tracing, but enriches our way to do optical modeling and design.
- Ray tracing is embedded and accessible.
- Physical optics simplifies development of systematic design workflows.

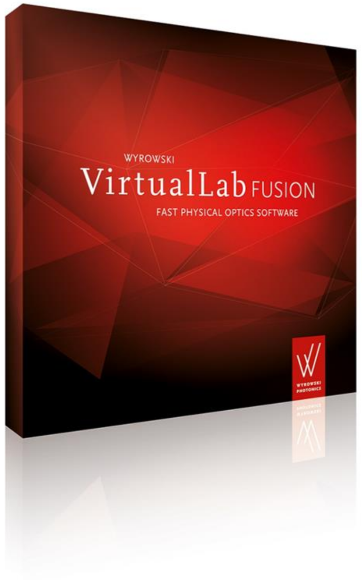


Our Key Messages on Modeling

#1: **Make physical optics the platform in optical modeling.**

#2: **Field Tracing** enables **Fast Physical Optics**.

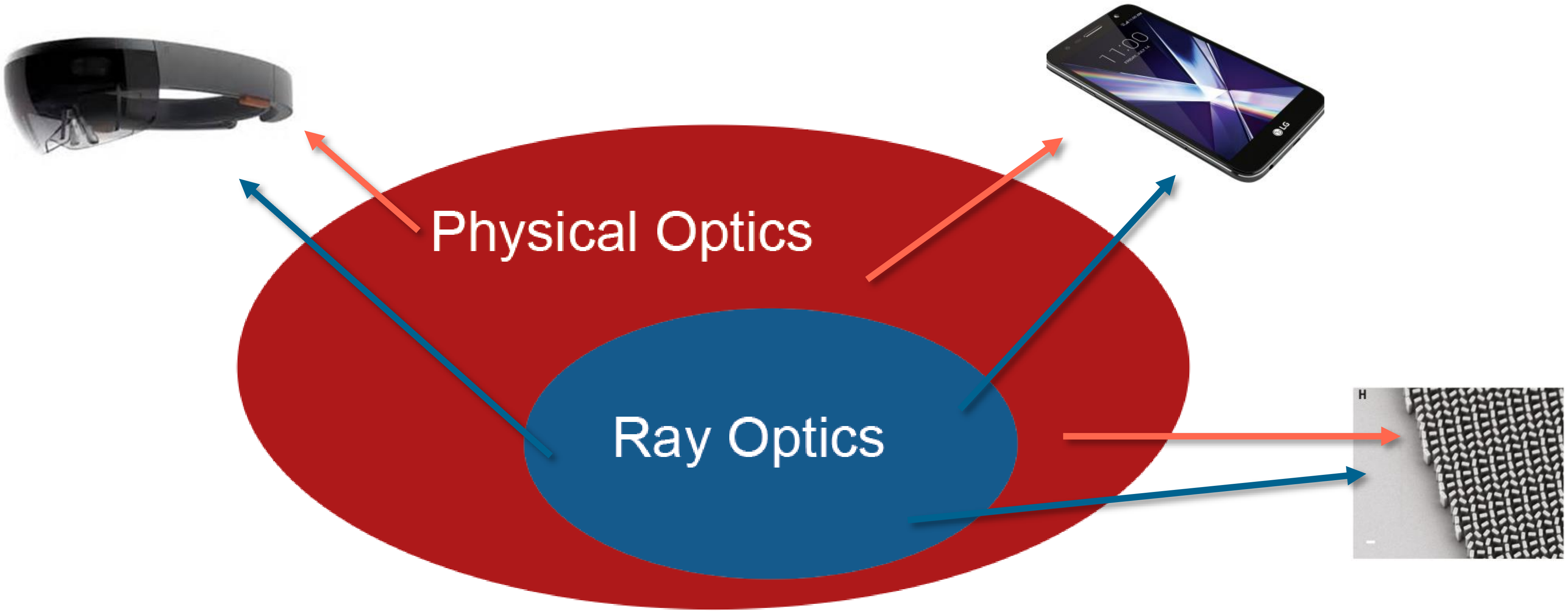
#3: Ray tracing is fully embedded in fast physical optics.



Why Physical Optics?

Fast physical optics modeling with VirtualLab Fusion

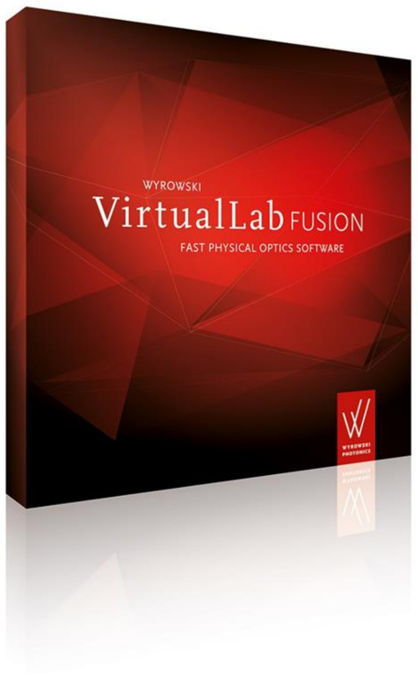
Physical Optics Modeling and Design



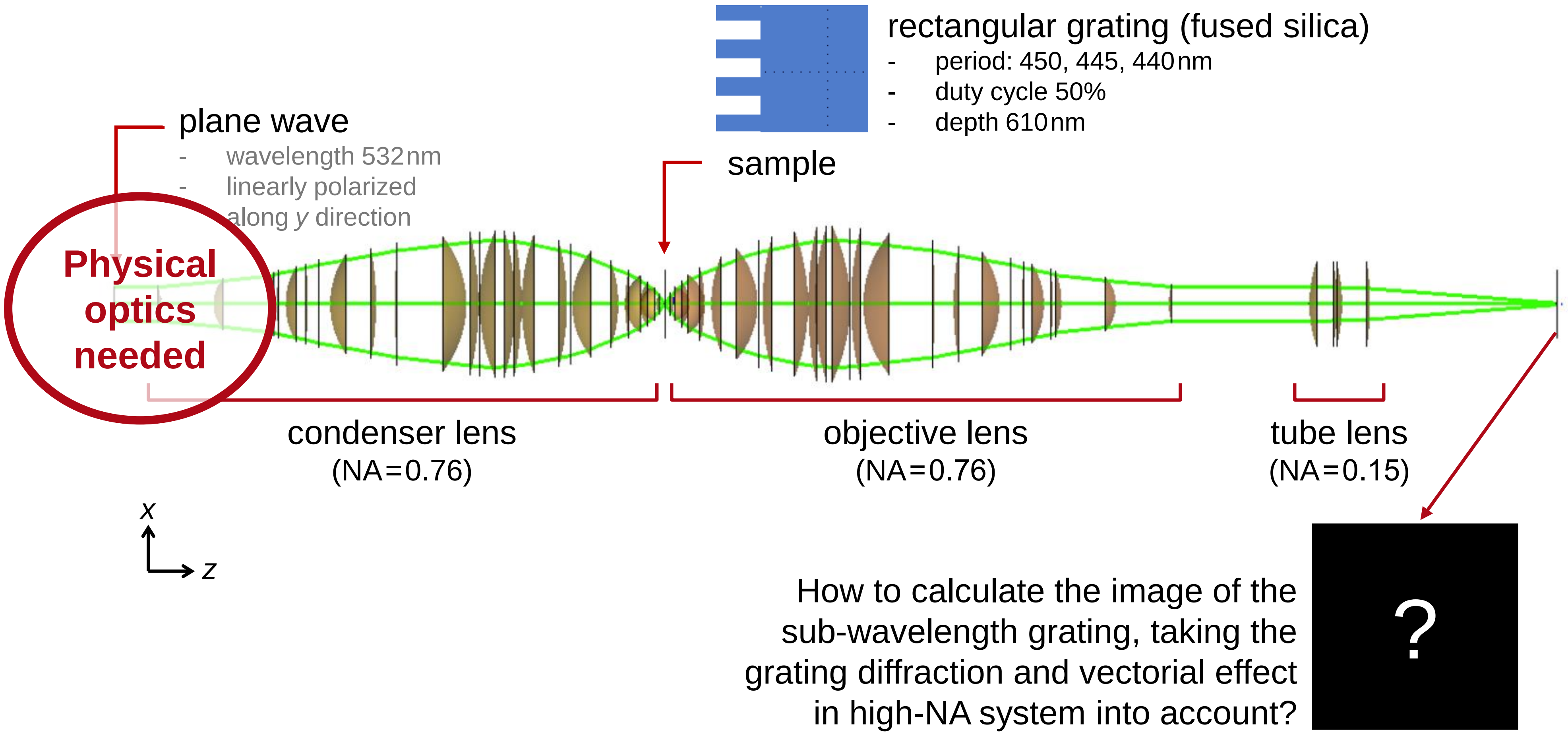
Physical optics provides the fundament of innovative concepts for harnessing light!

Physical Optics Enables Theoretically Solid Inclusion of ….

- Investigation of fields in focal regions
- Diffraction at apertures and of light beams
- Vectorial effects and polarization; no paraxial assumption
- Coherence phenomena and source models
- Ultrashort pulse modeling
- Interference and speckles
- Diffraction at gratings and diffractive optical elements
- Scattering effects
- Crystal and metamaterial modeling
- Nano- and microoptics
- Special effects like Gouy phase shift and Goos Hänchen shift
- Nonlinear optics

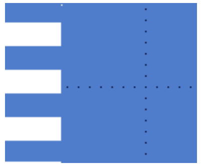


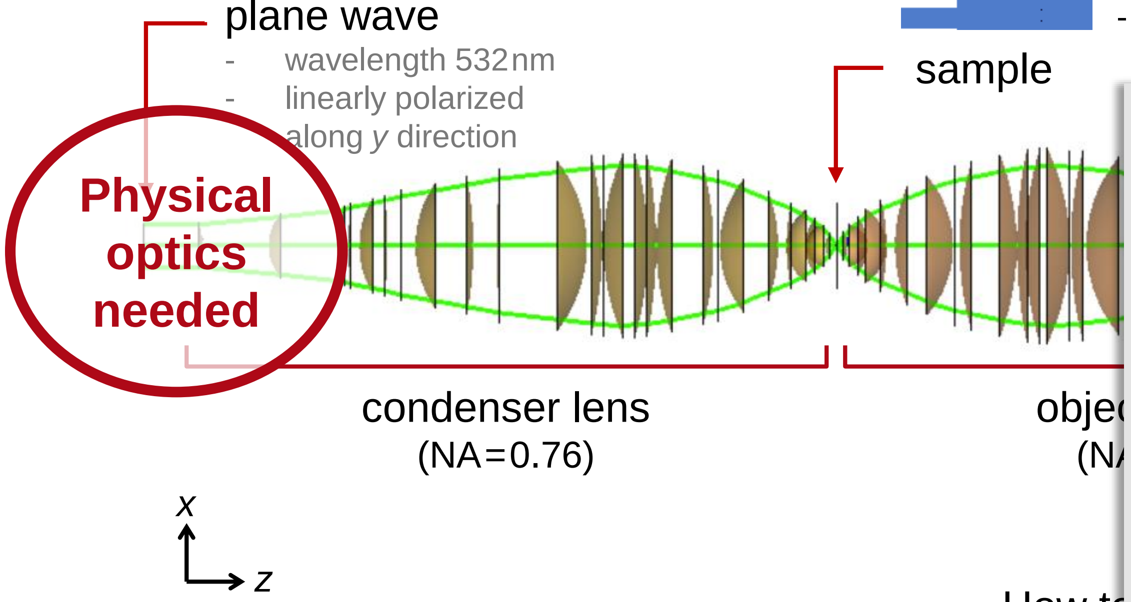
Modeling Task



How to calculate the image of the sub-wavelength grating, taking the grating diffraction and vectorial effect in high-NA system into account?

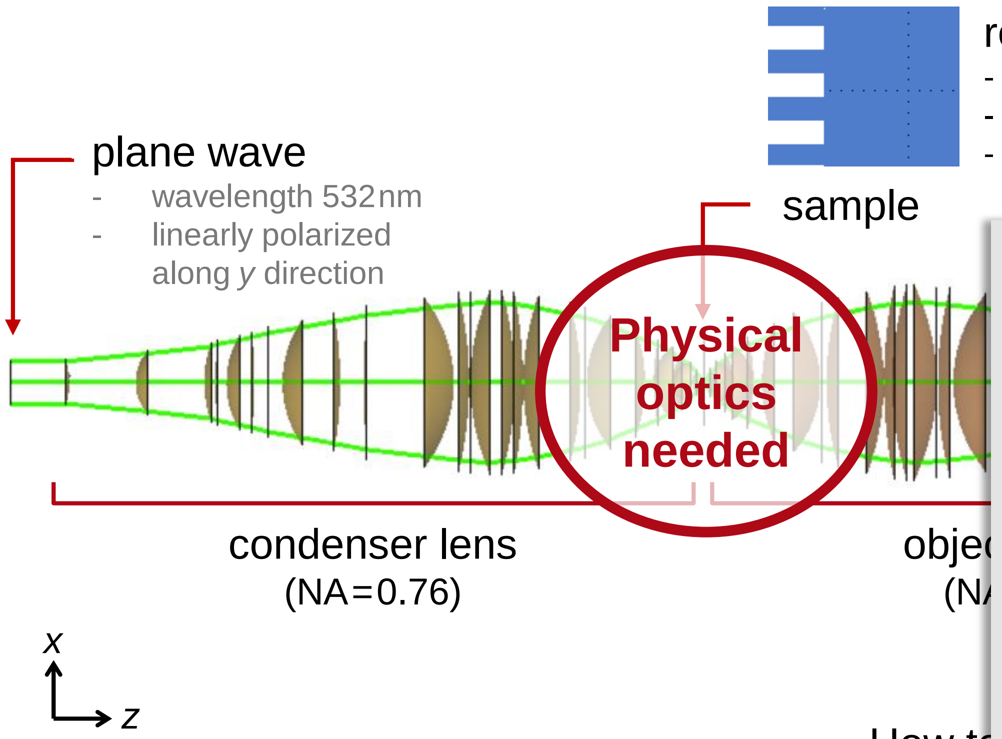
Modeling Task





- Investigation of fields in focal regions
- Diffraction at apertures and of light beams
- Vectorial effects and polarization; no paraxial assumption ✓
- Coherence phenomena and source models ✓
- Ultrashort pulse modeling
- Interference and speckles
- Diffraction at gratings and diffractive optical elements
- Scattering effects
- Crystal and metamaterial modeling
- Nano- and microoptics
- Special effects like Gouy phase shift and Goos Hänchen shift
- Nonlinear optics

Modeling Task



- Investigation of fields in focal regions ✓
- Diffraction at apertures and of light beams
- Vectorial effects and polarization; no paraxial assumption ✓
- Coherence phenomena and source models
- Ultrashort pulse modeling
- Interference and speckles
- Diffraction at gratings and diffractive optical elements ✓
- Scattering effects
- Crystal and metamaterial modeling
- Nano- and microoptics
- Special effects like Gouy phase shift and Goos Hänchen shift
- Nonlinear optics

Modeling Task

rectangular grating (fused silica)
- period: 450, 445, 440 nm
- duty cycle 50%
- depth 610 nm

- Investigation of fields in focal regions ✓
- Diffraction at apertures and of light beams ✓
- Vectorial effects and polarization; no paraxial assumption ✓
- Coherence phenomena and source models
- Ultrashort pulse modeling
- Interference and speckles
- Diffraction at gratings and diffractive optical elements
- Scattering effects
- Crystal and metamaterial modeling
- Nano- and microoptics
- Special effects like Gouy phase shift and Goos Hänchen shift
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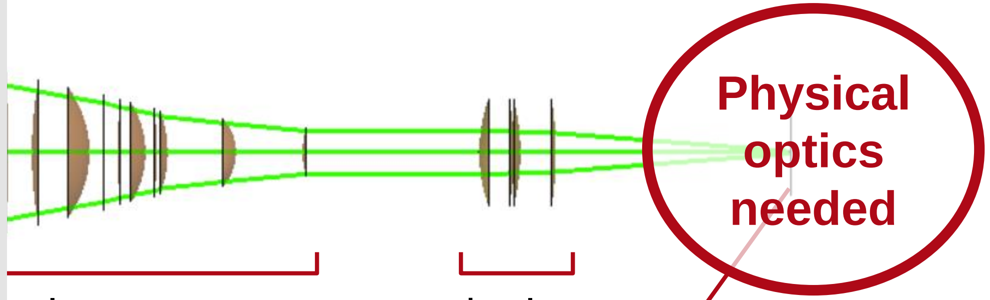
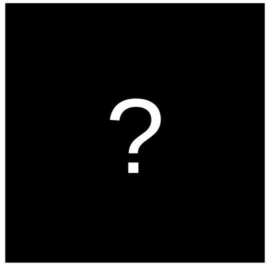


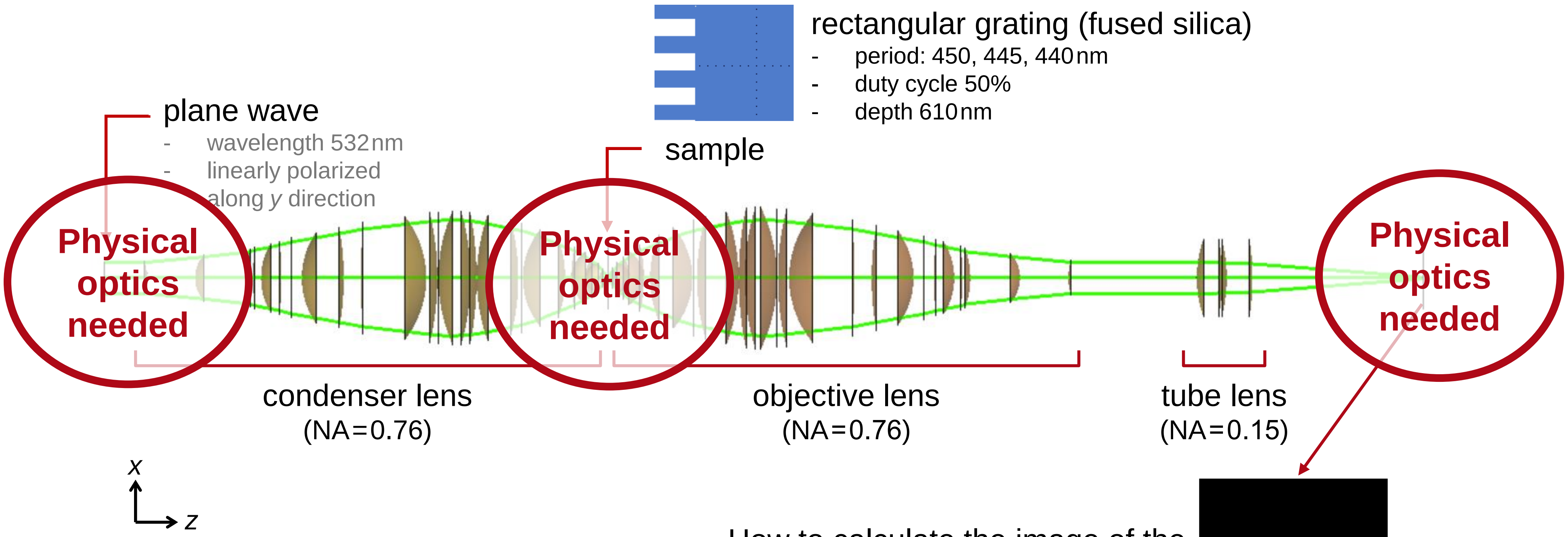
…e lens
…).76)

tube lens
(NA = 0.15)

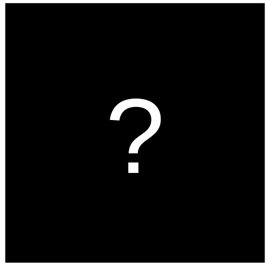
…alculate the image of the …ength grating, taking the …ction and vectorial effect in high-NA system into account?



Modeling Task



How to calculate the image of the sub-wavelength grating, taking the grating diffraction and vectorial effect in high-NA system into account?



Modeling Task

- Investigation of fields in focal regions ✓
- Diffraction at apertures and of light beams ✓
- Vectorial effects and polarization; no paraxial assumption ✓
- Coherence phenomena and source models ✓
- Ultrashort pulse modeling
- Interference and speckles
- Diffraction at gratings and diffractive optical elements ✓
- Scattering effects
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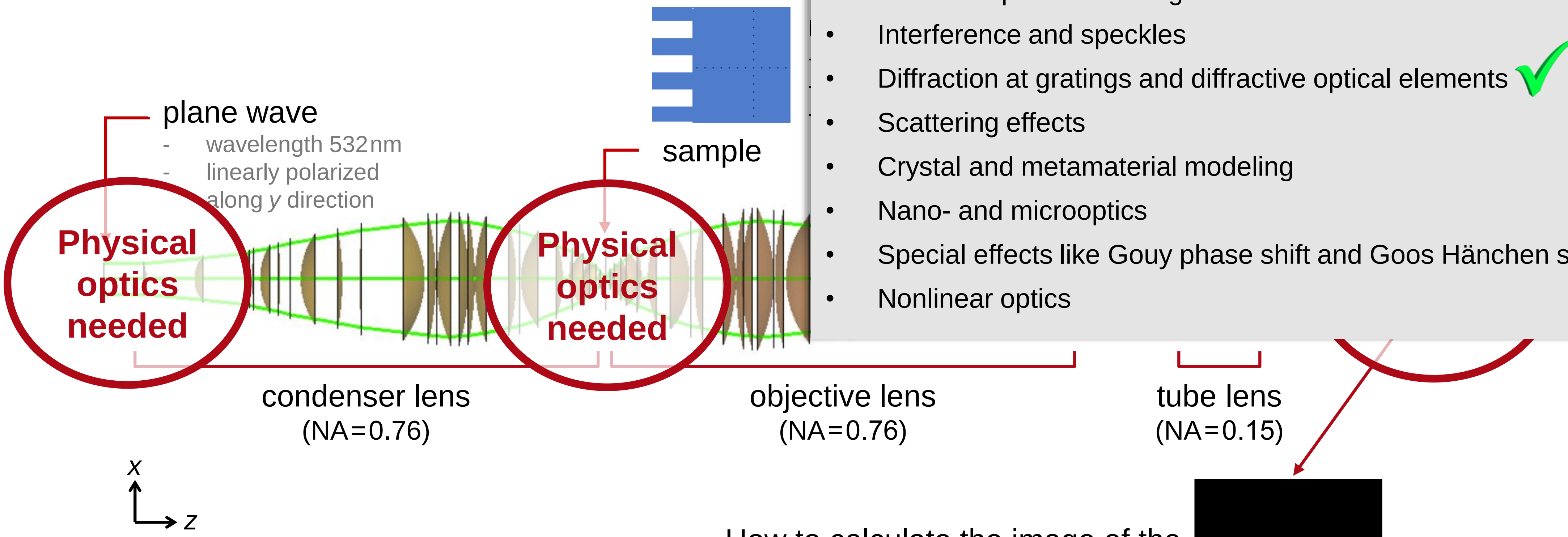
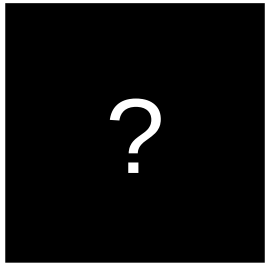
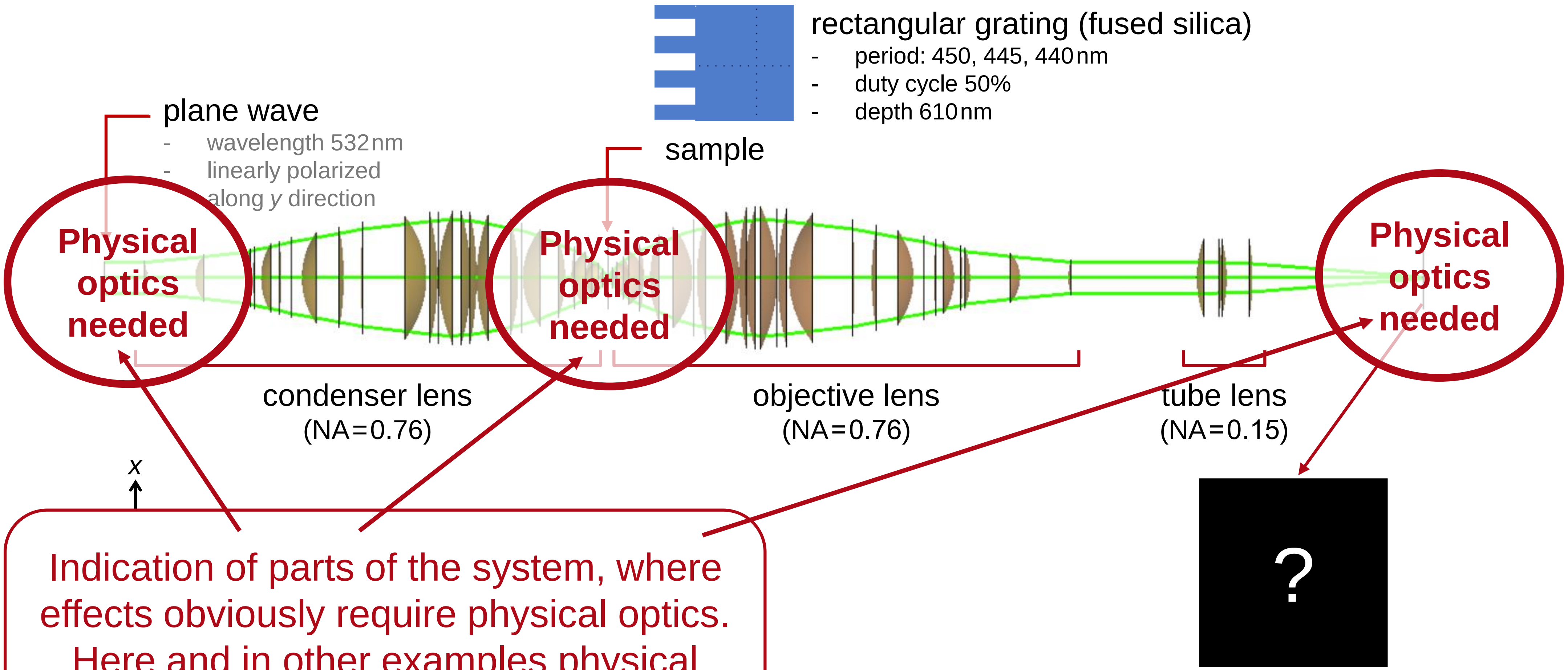


How to calculate the image of the sub-wavelength grating, taking the grating diffraction and vectorial effect in high-NA system into account?

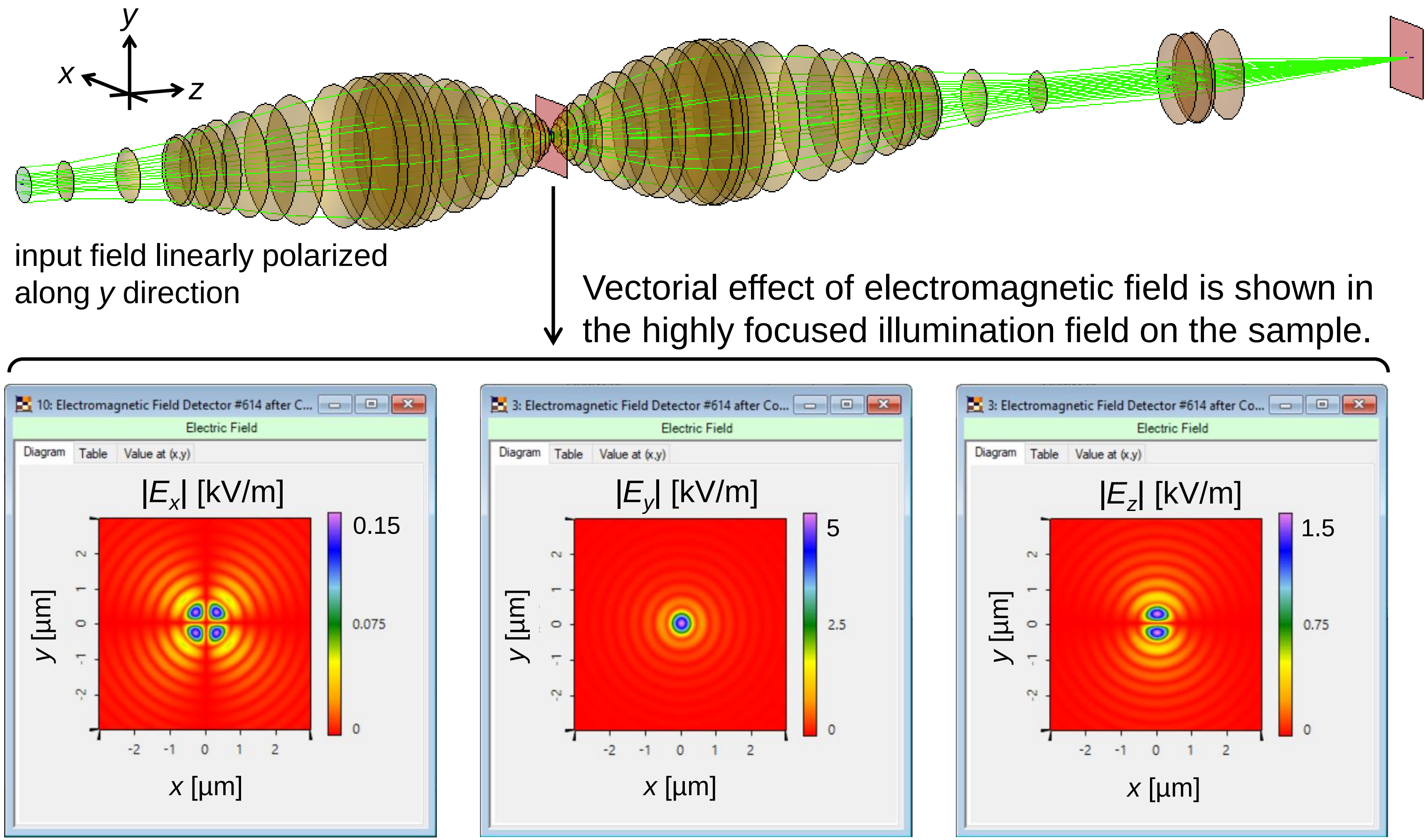


Modeling Task



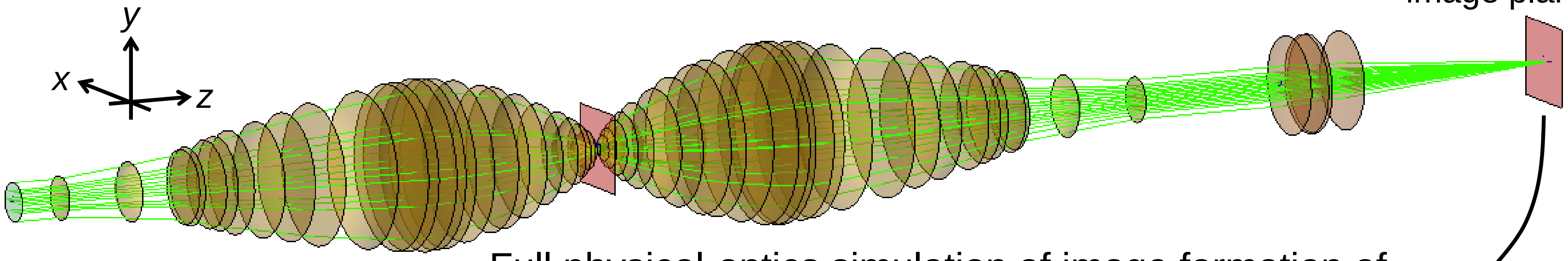
Indication of parts of the system, where effects obviously require physical optics. Here and in other examples physical optics modeling is used in entire system.

Results



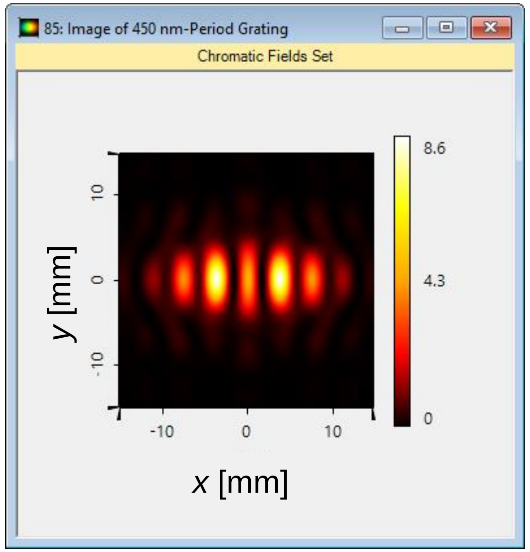
y
x
z
input field linearly polarized along y direction
Vectorial effect of electromagnetic field is shown in the highly focused illumination field on the sample.
10: Electromagnetic Field Detector #614 after C...
Electric Field
Diagram
Table
Value at (x,y)
|Ex| [kV/m]
0.15
0.075
0
y [µm]
x [µm]
3: Electromagnetic Field Detector #614 after Co...
Electric Field
Diagram
Table
Value at (x,y)
|Ey| [kV/m]
5
2.5
0
y [µm]
x [µm]
3: Electromagnetic Field Detector #614 after Co...
Electric Field
Diagram
Table
Value at (x,y)
|Ez| [kV/m]
1.5
0.75
0
y [µm]
x [µm]

Results

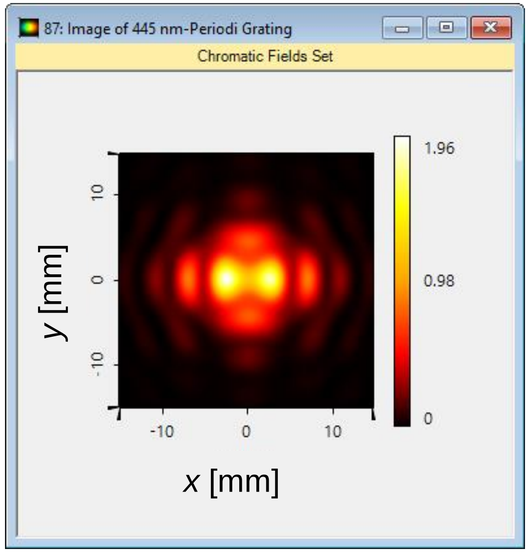


input field linearly polarized along *y* direction

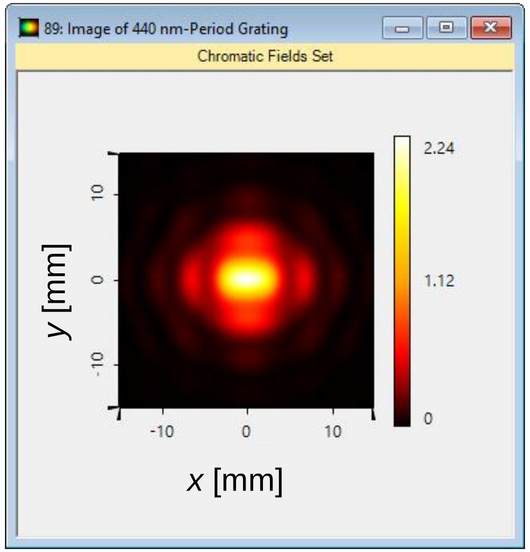
Full physical-optics simulation of image formation of sub-wavelength grating (modeled with FMM) in high-NA imaging system takes less than 10 seconds.



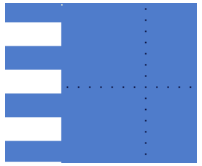
450nm-period grating



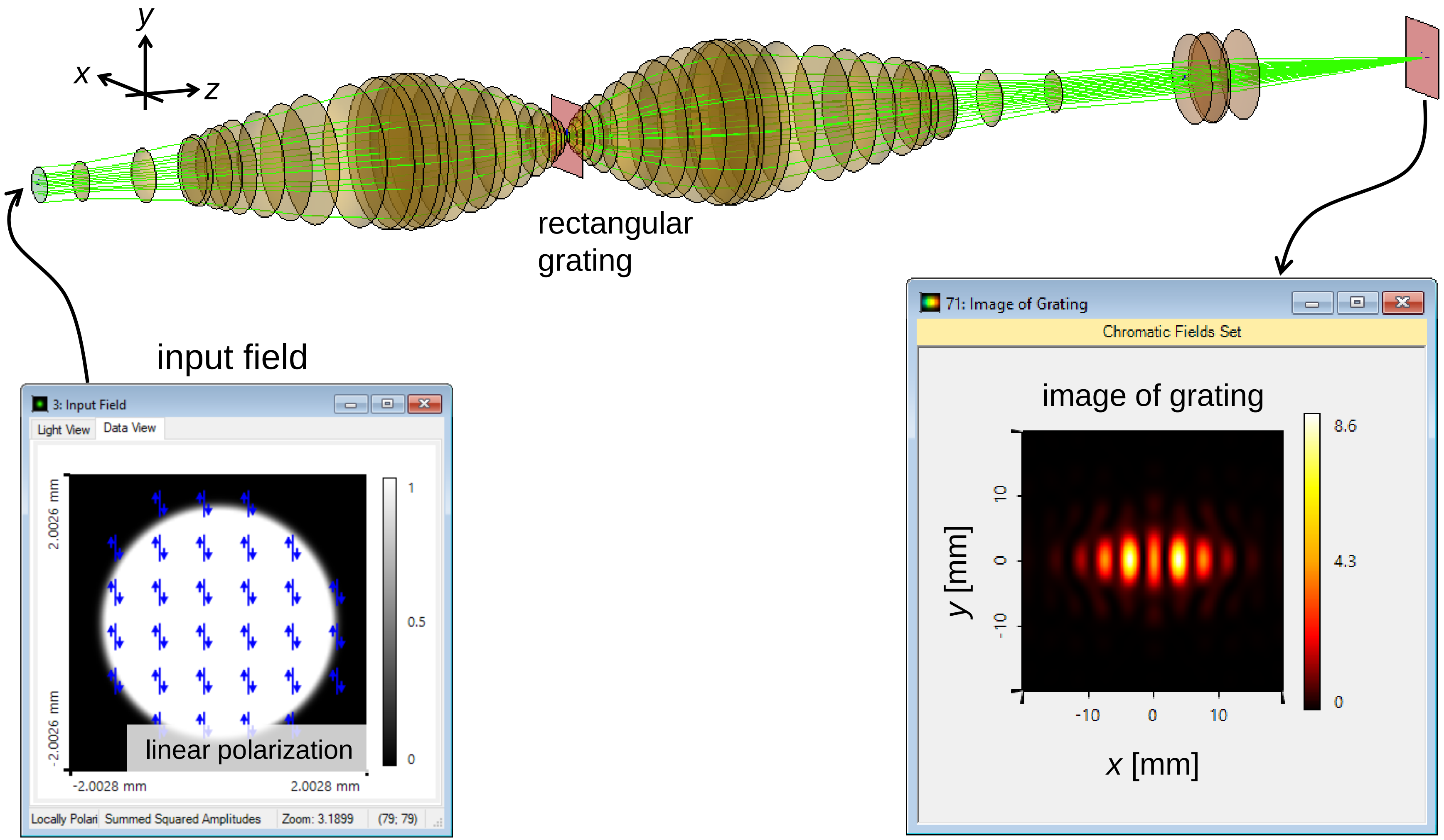
445nm-period grating



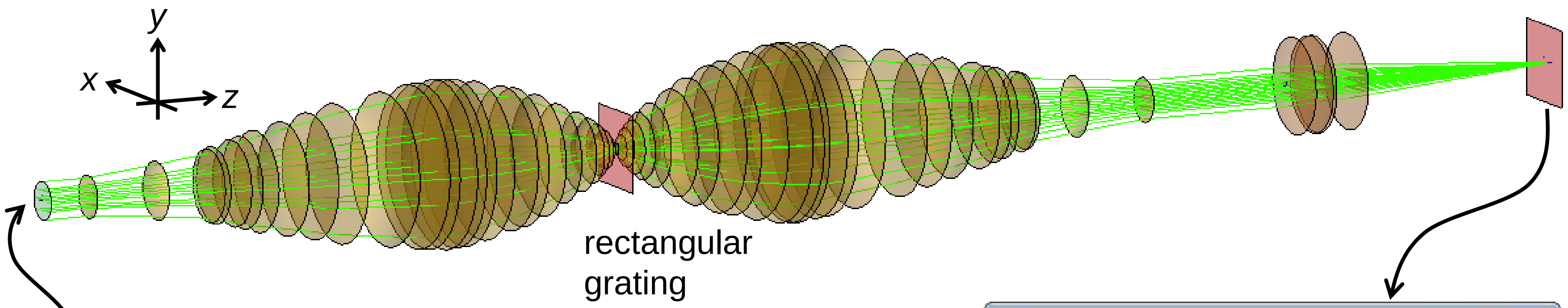
440nm-period grating

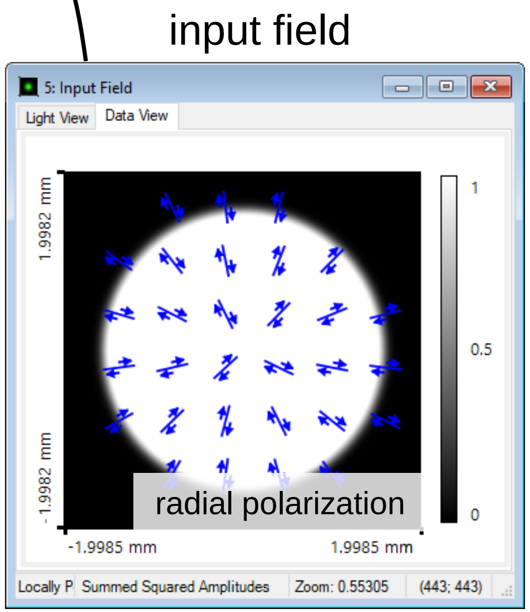


Imaging with Linearly Polarized Light

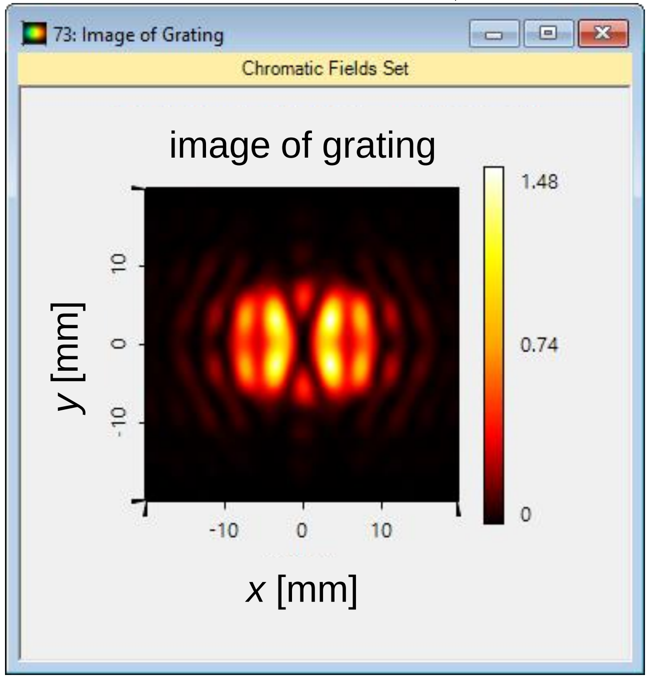


Imaging with Radially Polarized Light

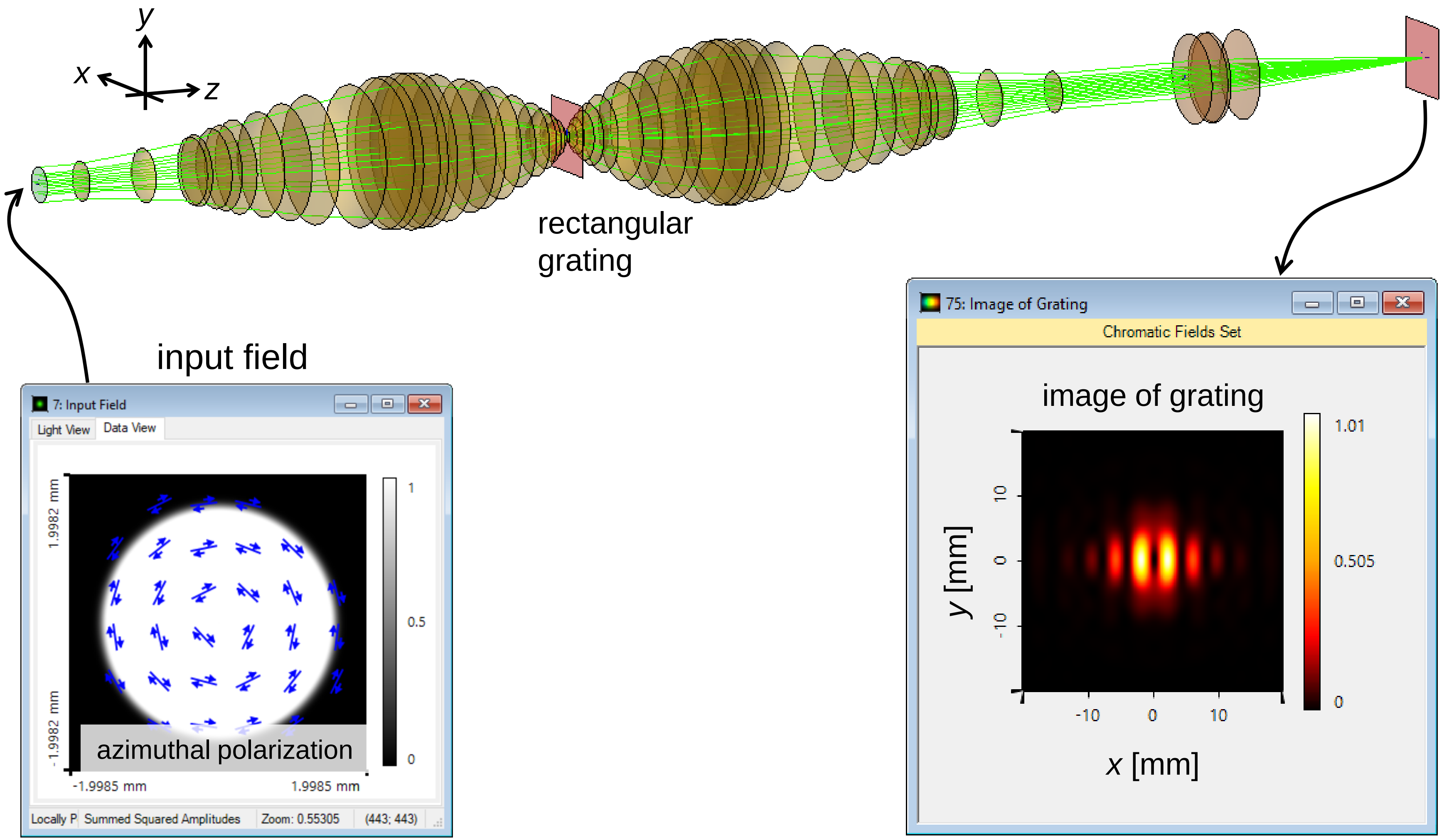




Vector nature of light is taken into account, and interaction with grating is modeled by using Fourier modal method.

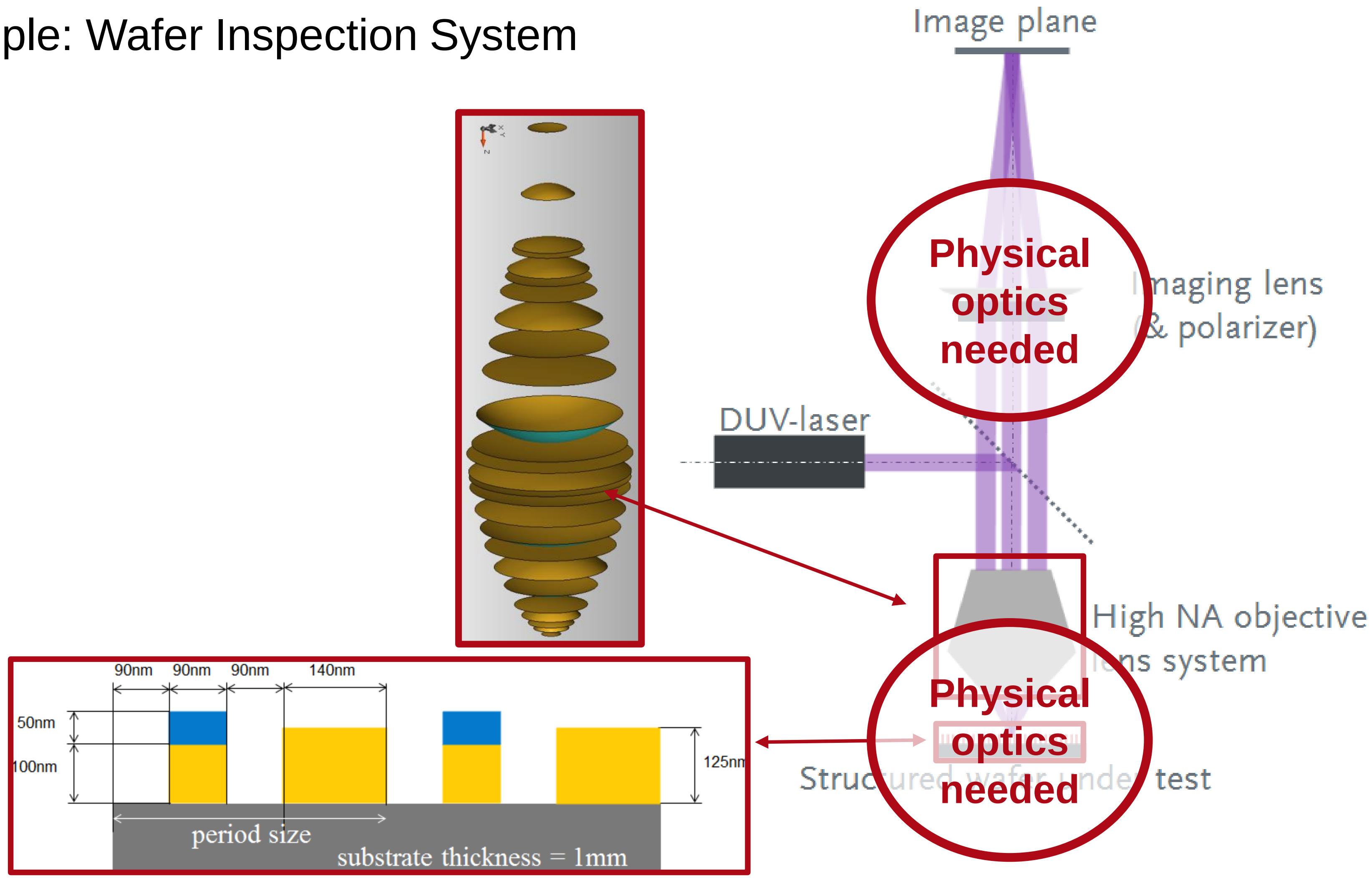


Imaging with Azimuthally Polarized Light

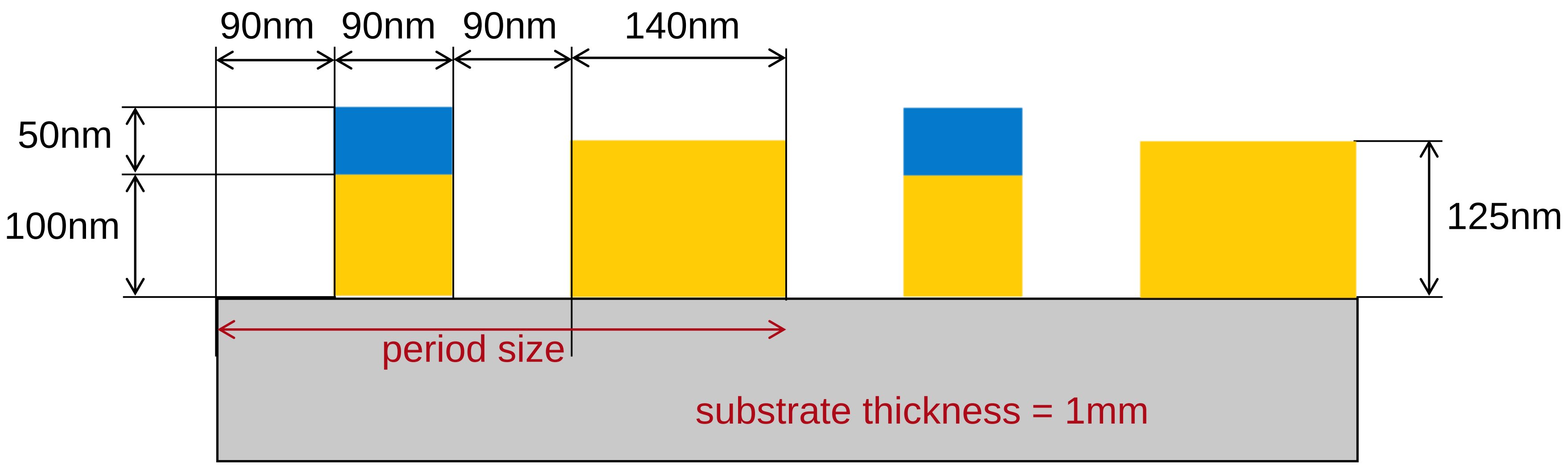


Example of Multi-Scale Optical System

Example: Wafer Inspection System

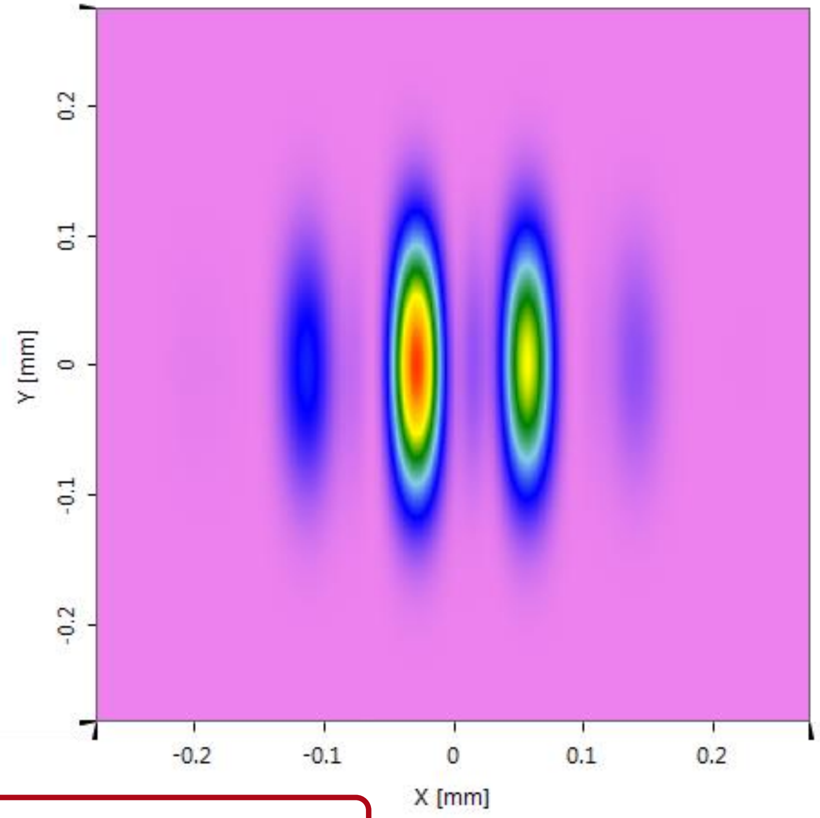


Base Grating Structure

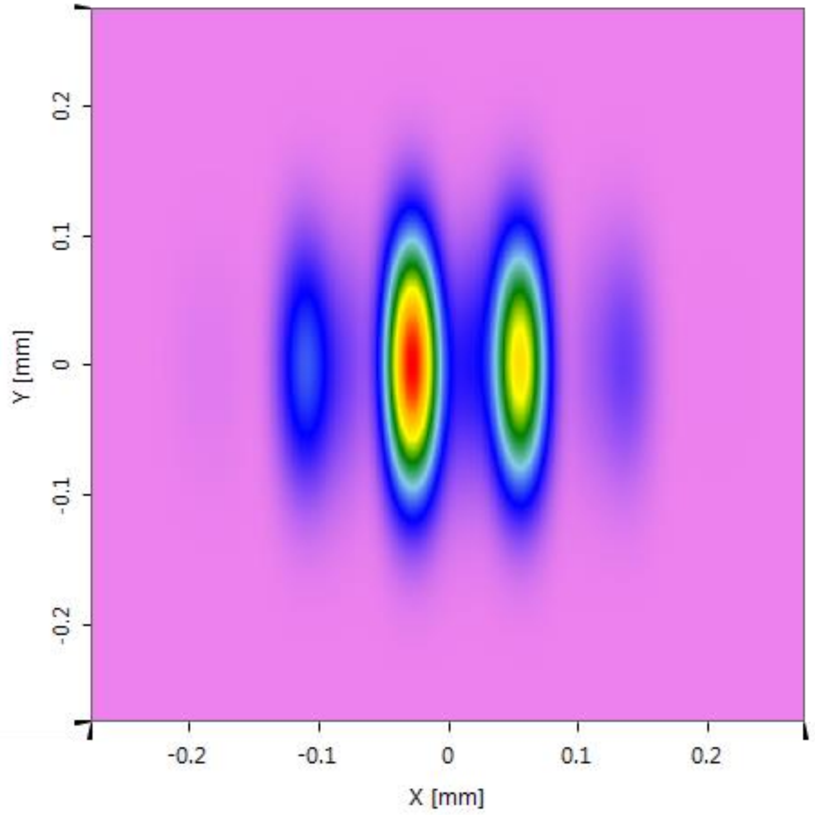


Base Structure Analysis

Intensity Image of Grating after Polarizer in X-Direction

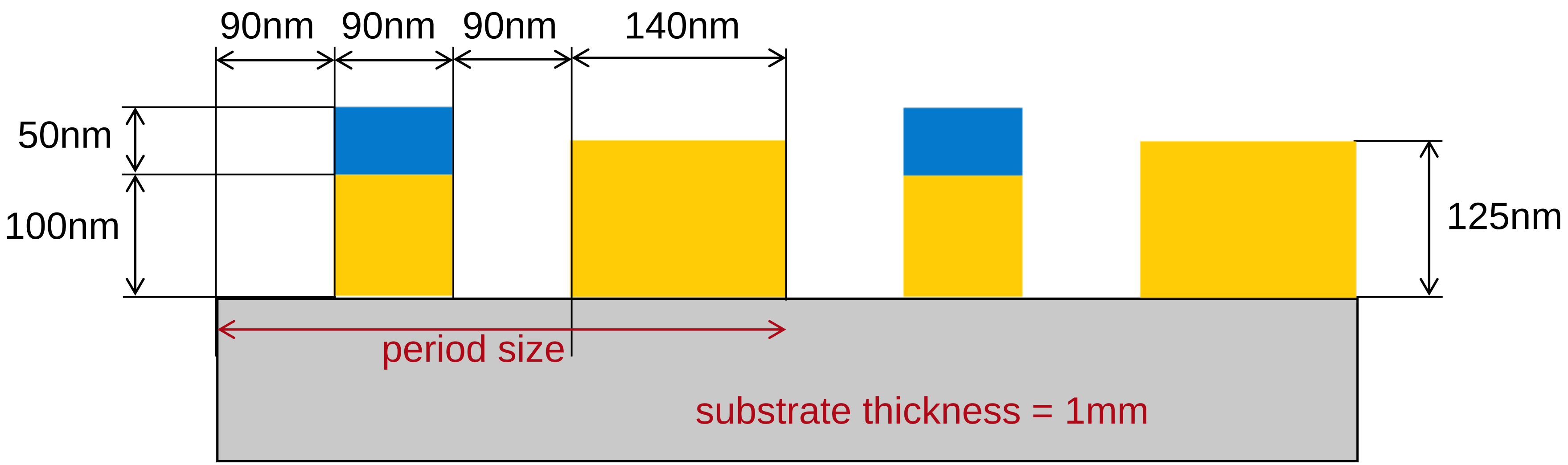


Intensity Image of Grating after Polarizer in Y-Direction

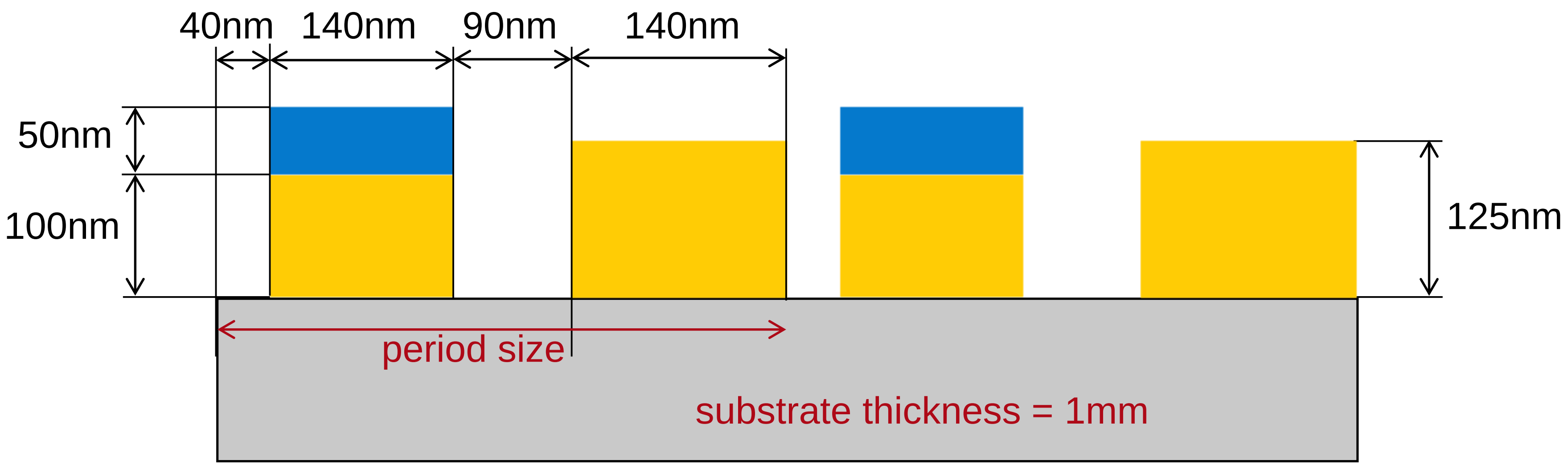


Simulation time few seconds

Base Grating Structure

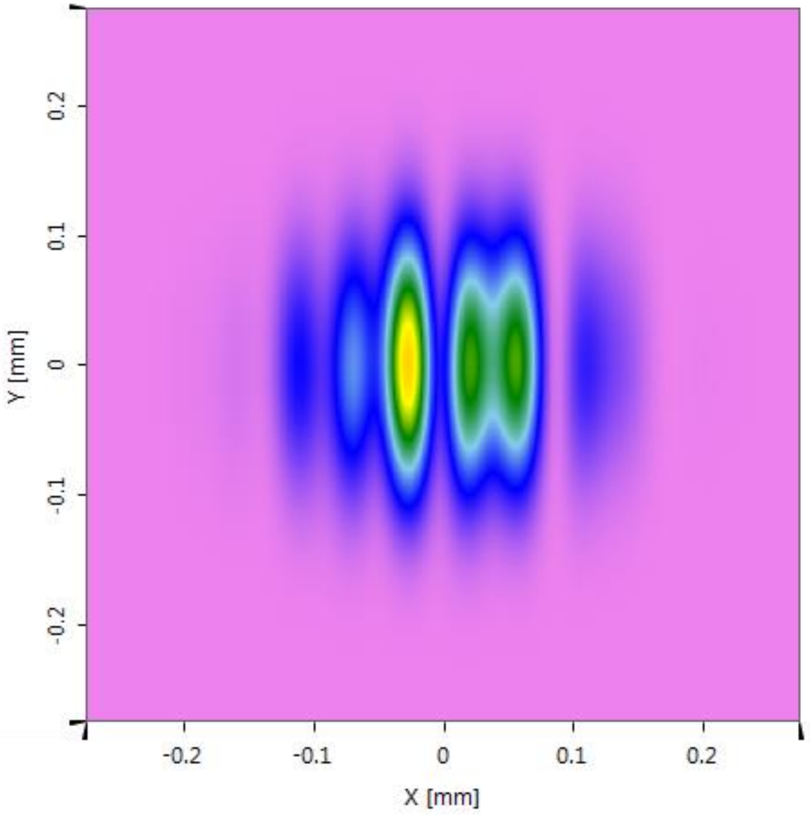


Modified Grating Structure

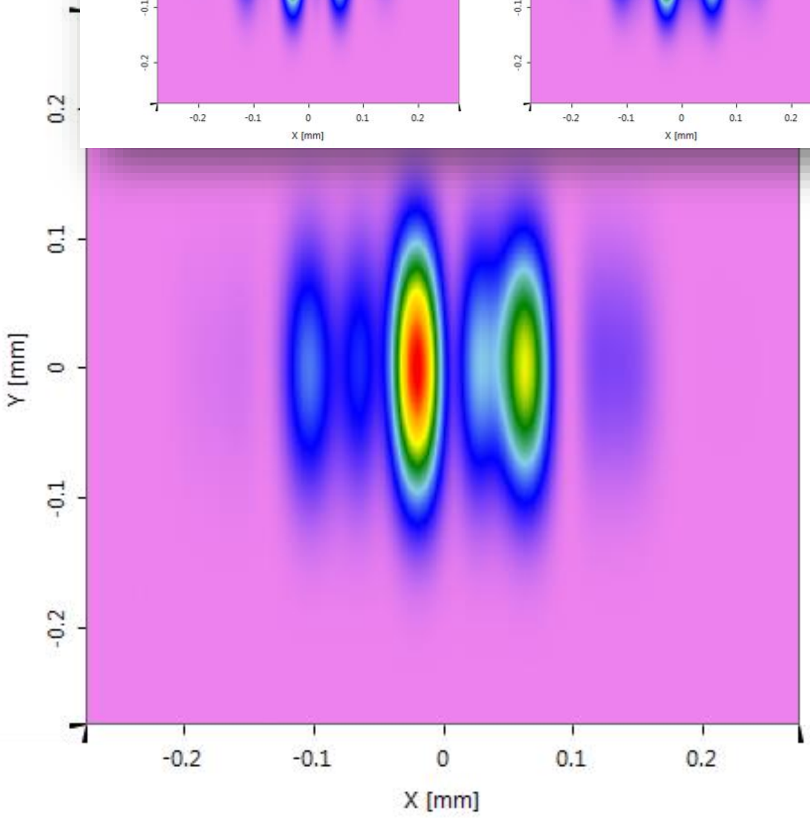


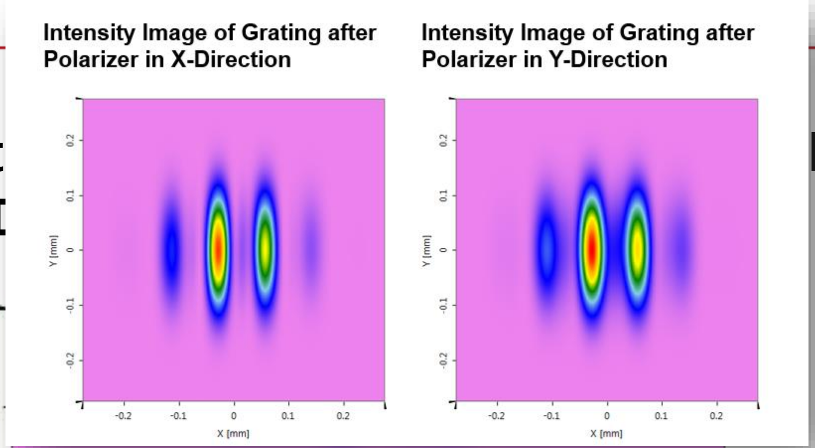
Modified Structure Analysis

Intensity Image of Grating after Polarizer in X-Direction

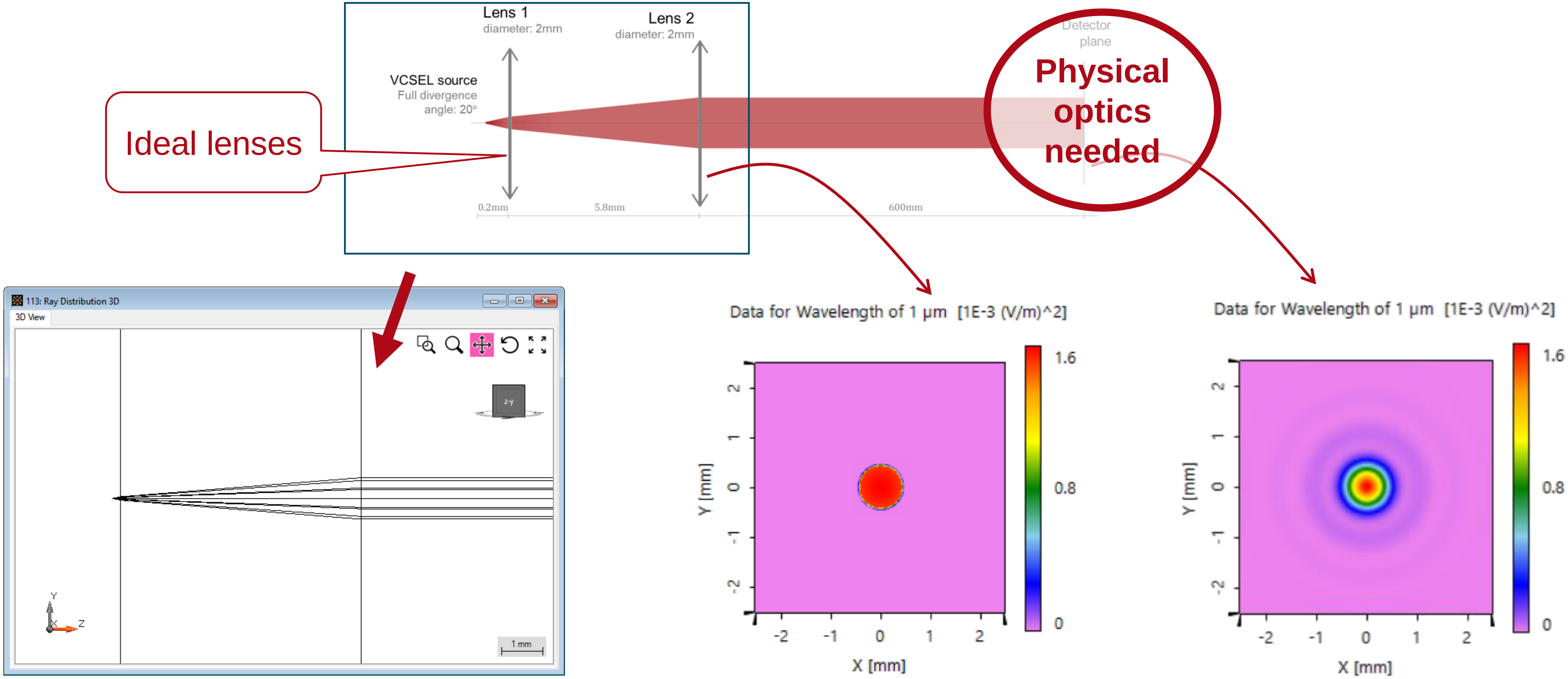


Int larizer in Y-D





Point Cloud Generation (Face ID)

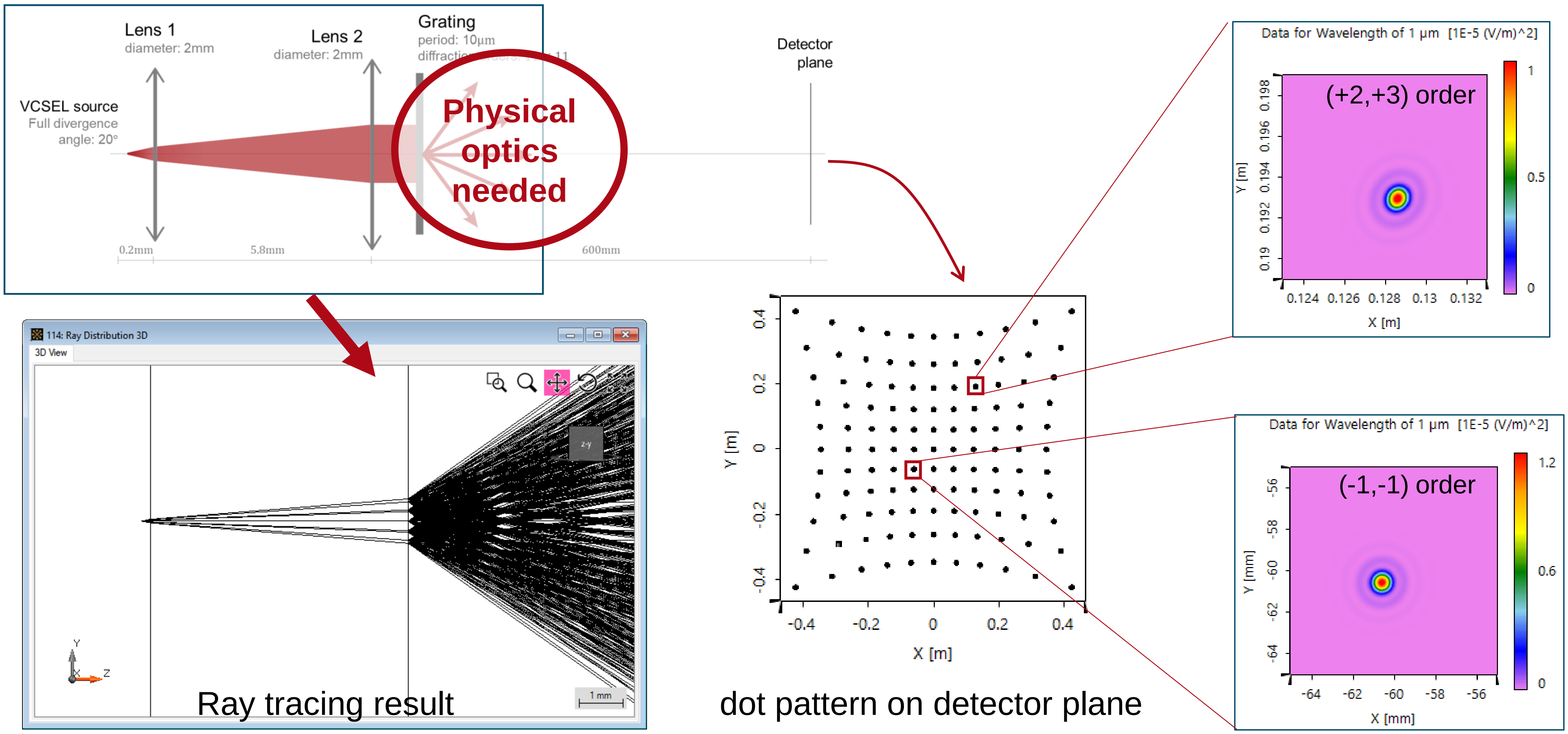


Ray tracing result

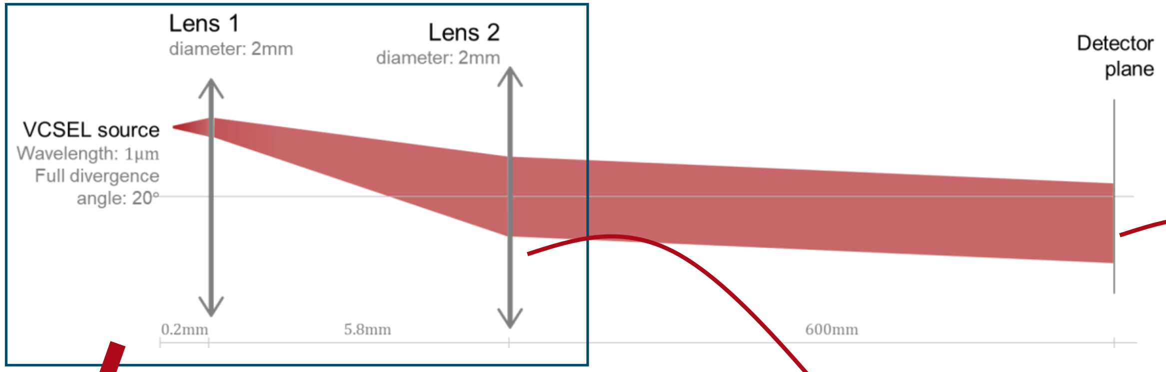
intensity distribution on Lens2

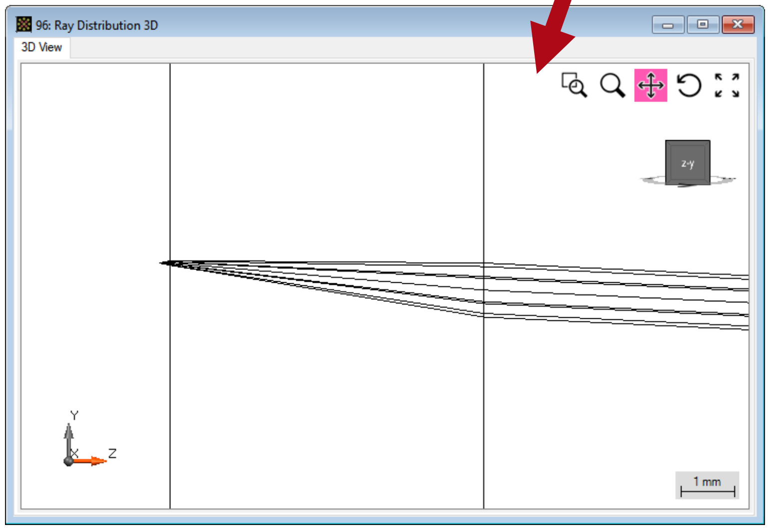
intensity distribution on detector

Simulation Result

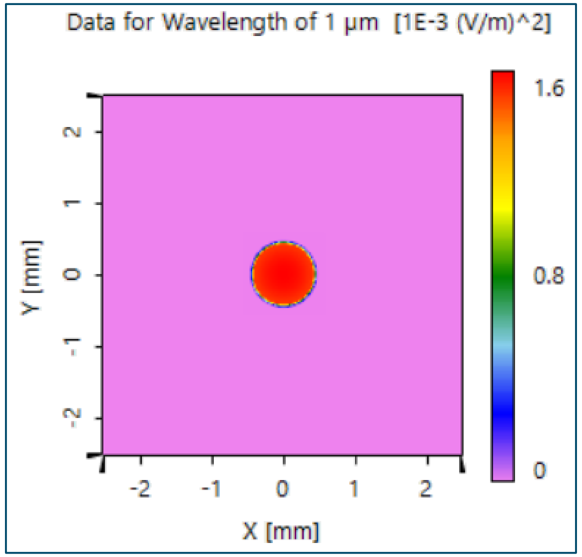


Simulation Result

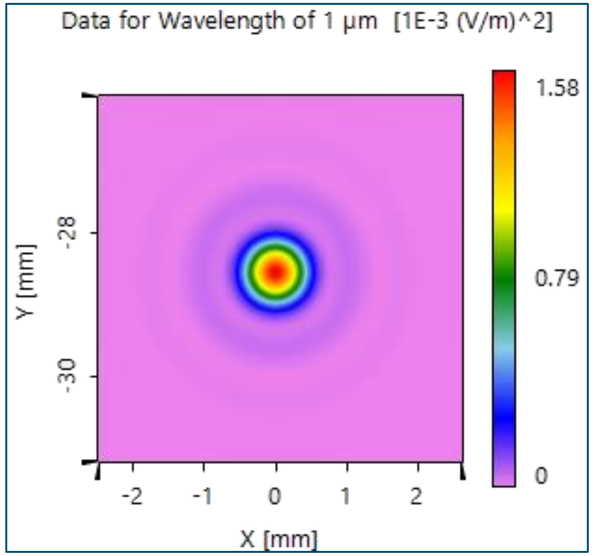




Ray tracing result

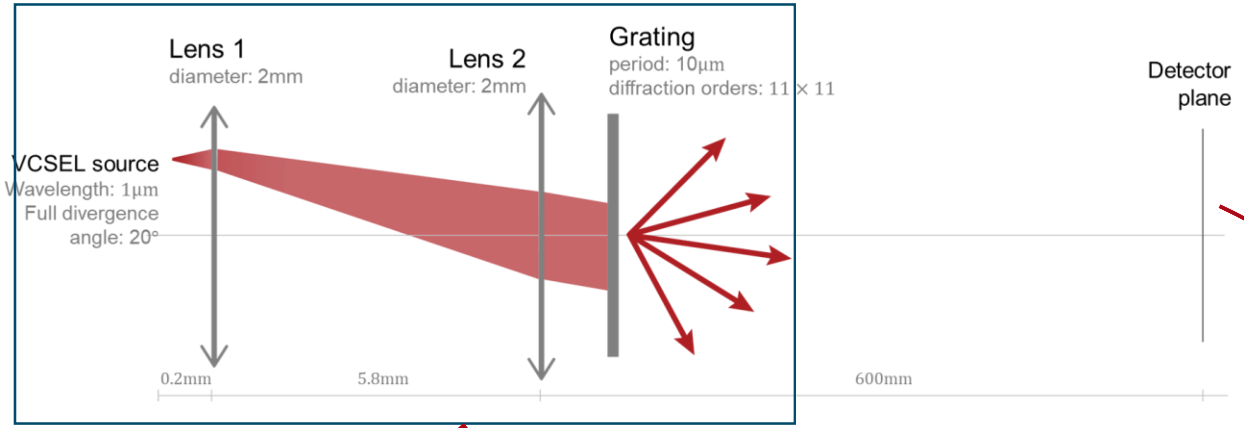


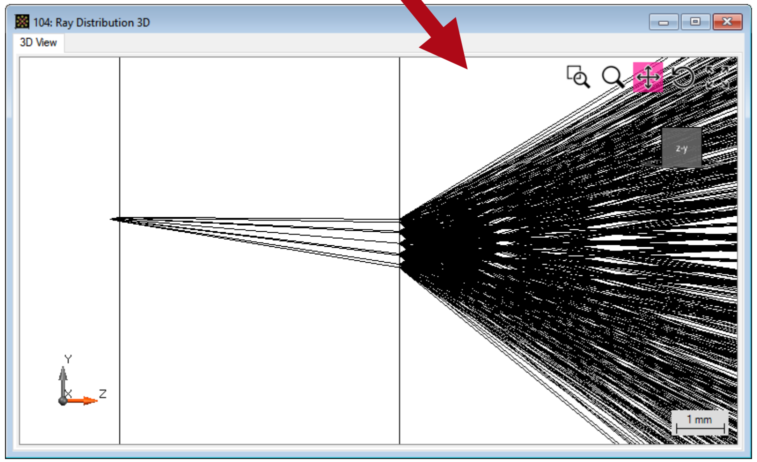
intensity distribution on Lens2



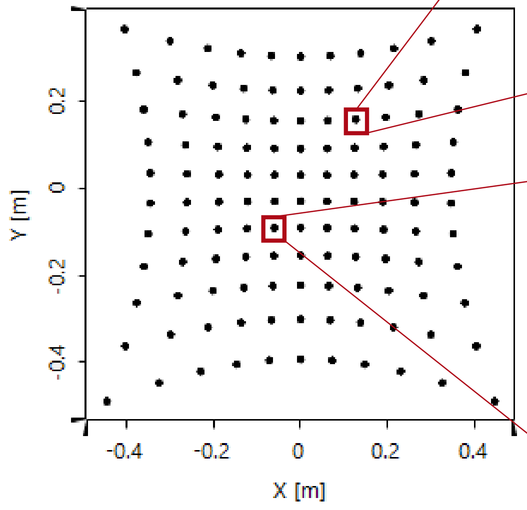
intensity distribution on detector

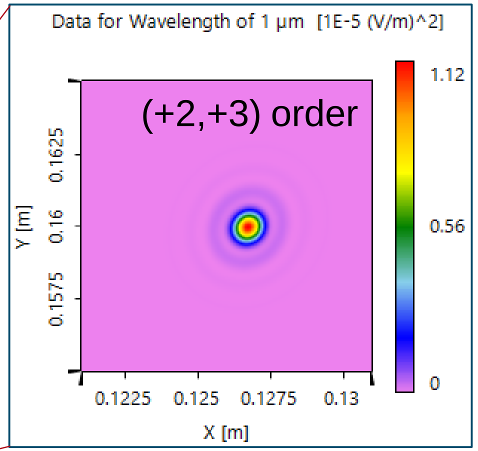
Simulation Result

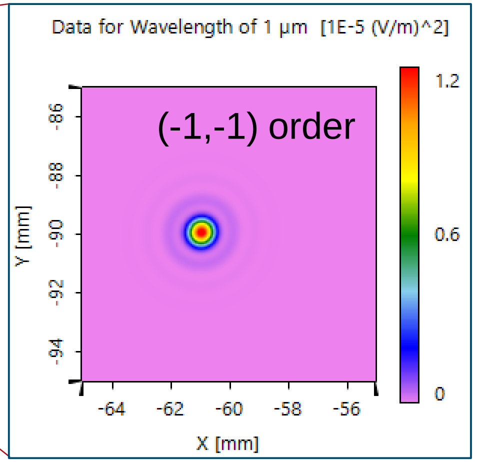




Ray tracing result

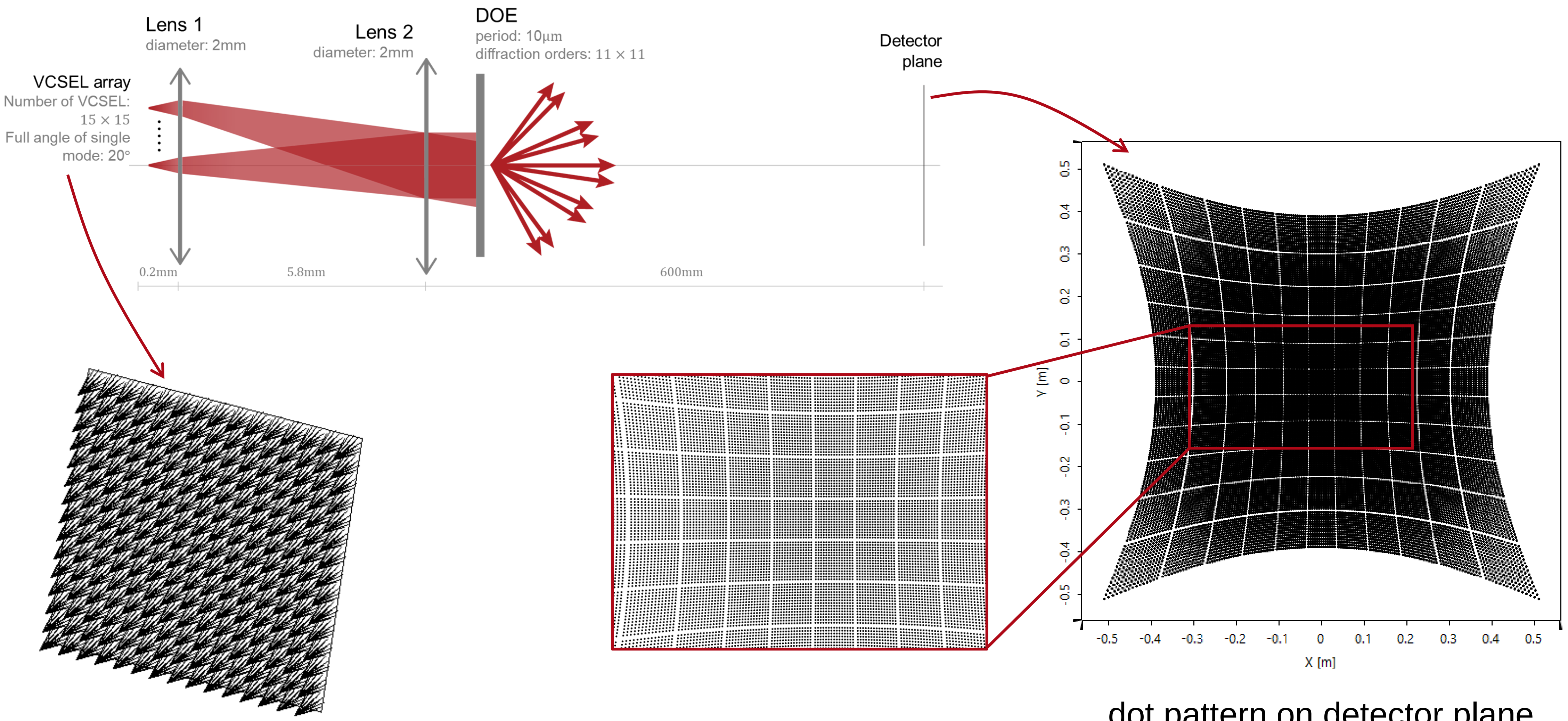






dot pattern on detector plane

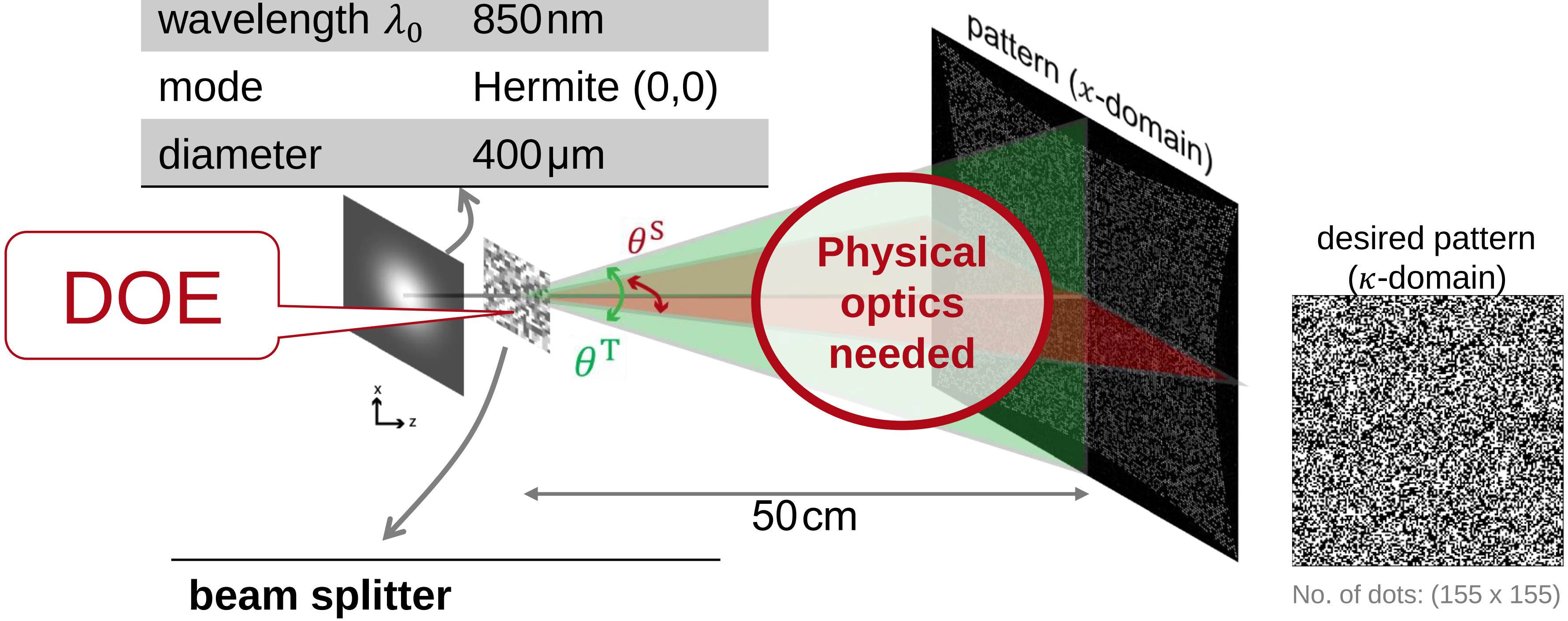
Simulation Result



dot pattern on detector plane

Design Task

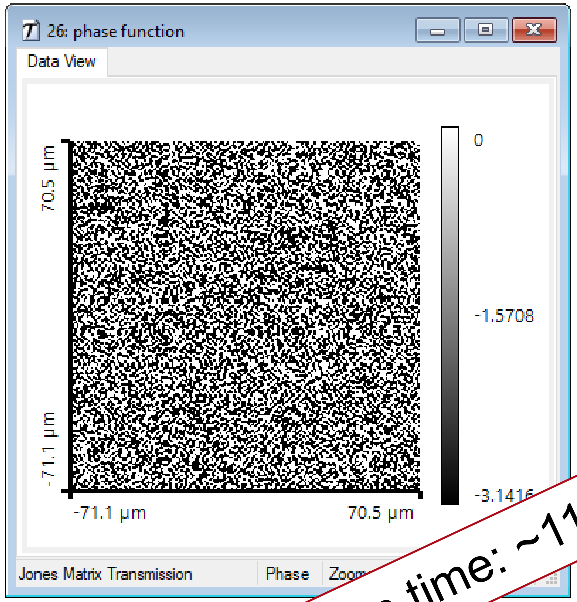
Gaussian beam	
wavelength λ_0	850 nm
mode	Hermite (0,0)
diameter	400 µm



beam splitter	
phase level	2
NA(θ^Tx θ^S)	55° x 55°
working dist.	50 cm

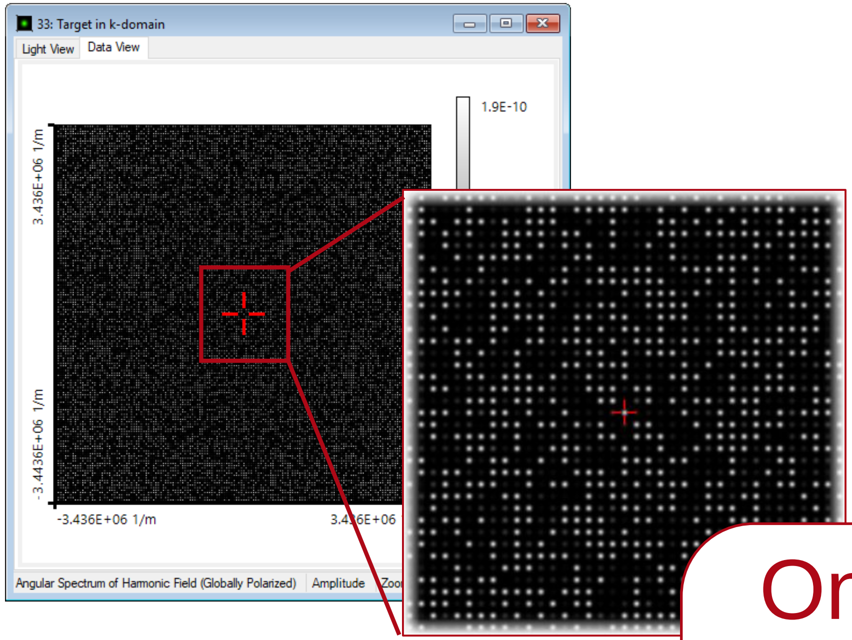
Result: Phase and Target in K-Domain

phase



design time: ~11 s

target in κ-domain



Param. in one period	
samp. dist. ($\delta x = \delta y$)	600 nm
period ($p_x = p_y$)	141 µm

Analysis	
conversion effic.	57.8%

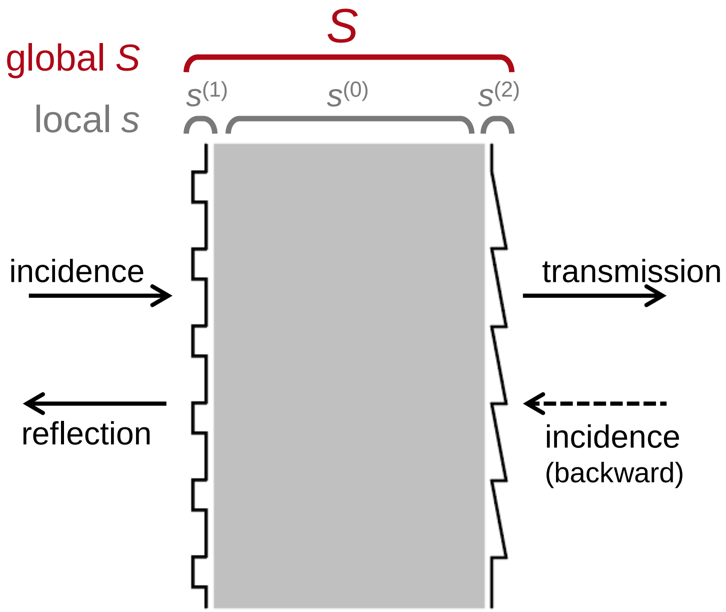
Ongoing R&D: Improved non-paraxial DOE design

Non-sequential coupling of FMM solver

Example: Reduction of numerical effort in modeling of grating structures

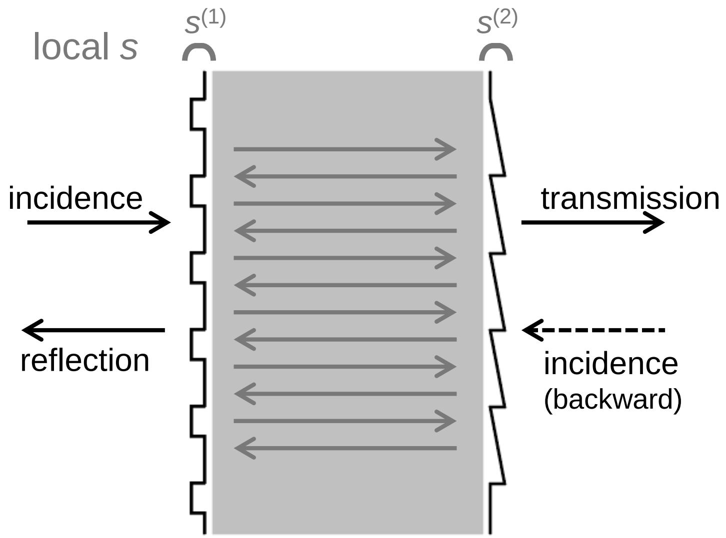
Theory Background

- Global S matrix



  - Recursion with respect to number of regions / layers

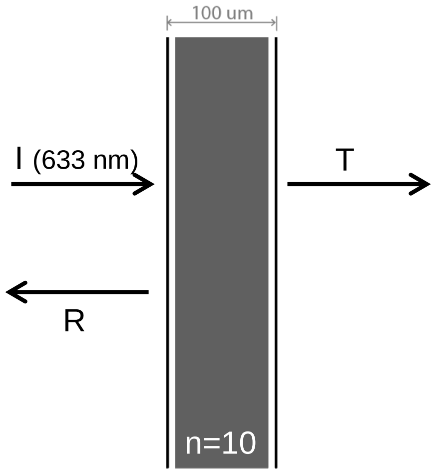
- Non-sequential field tracing

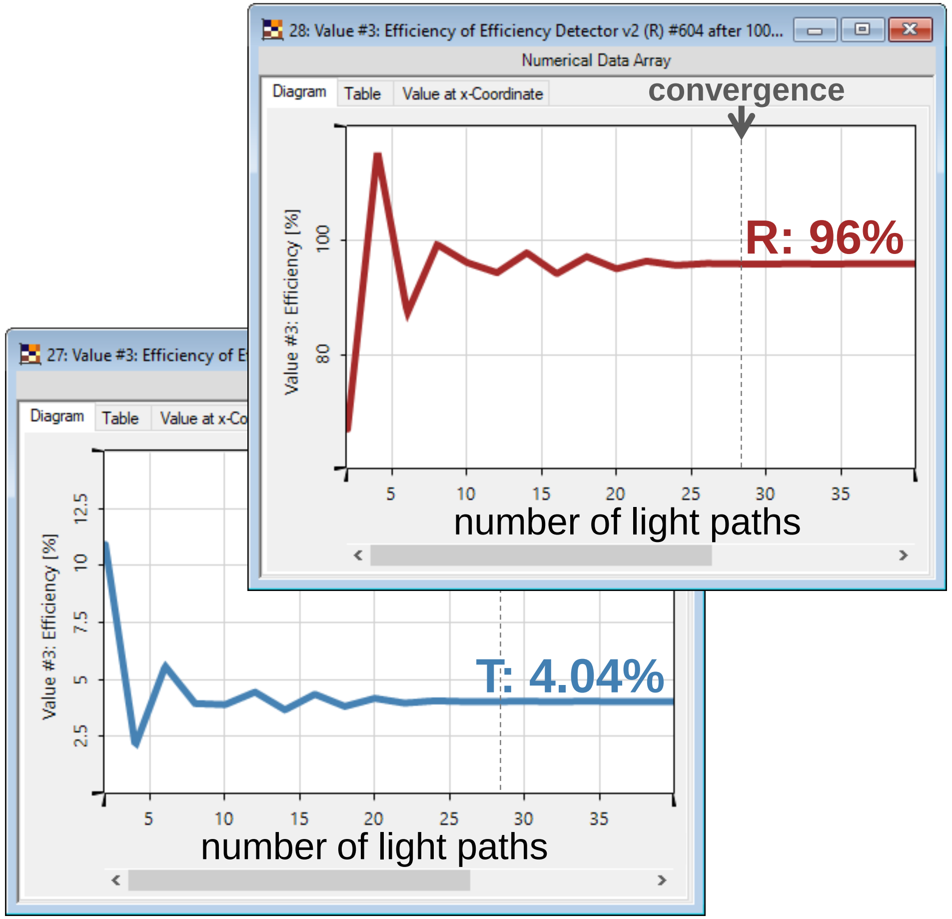


  - Recursion with respect to number of light paths

Planar Surface + Planar Surface

- Structure
- Non-sequential field tracing



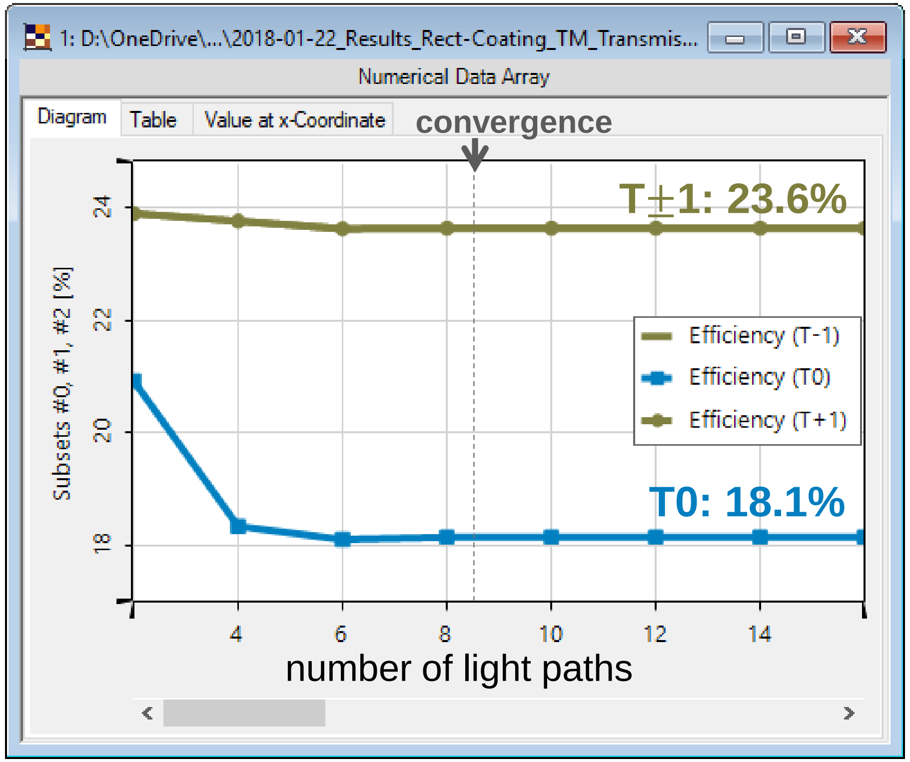


Global S matrix

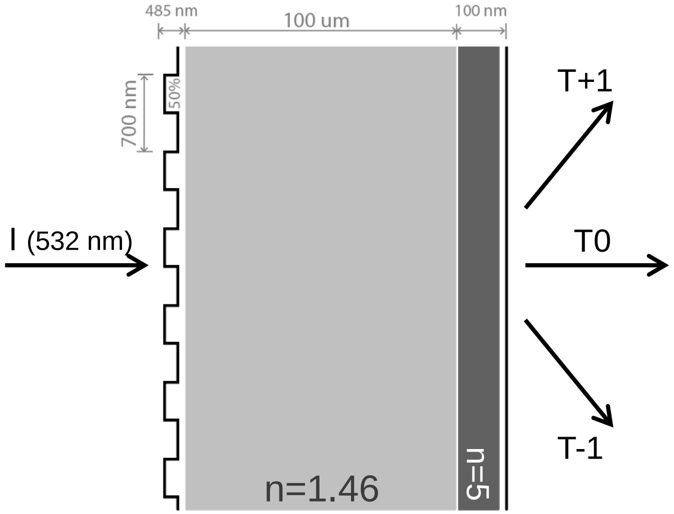
Eff. (T)	Eff. (R)
4.04%	96%

Rectangular Grating + Backside Coating

- Non-sequential field tracing



- ... with backside coating

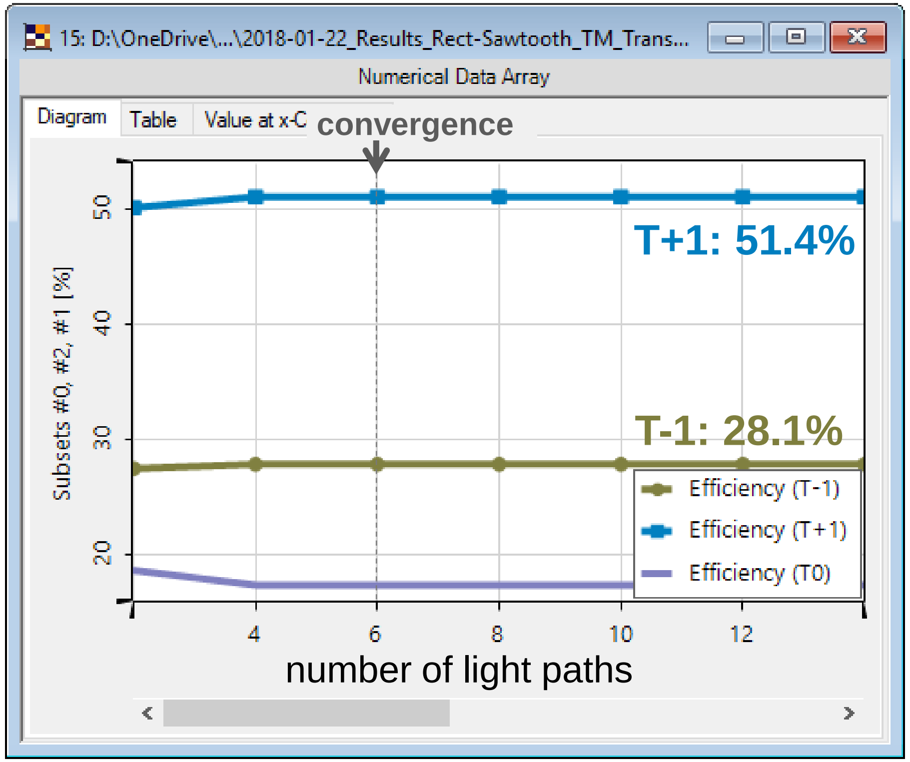


Global S matrix (TM)

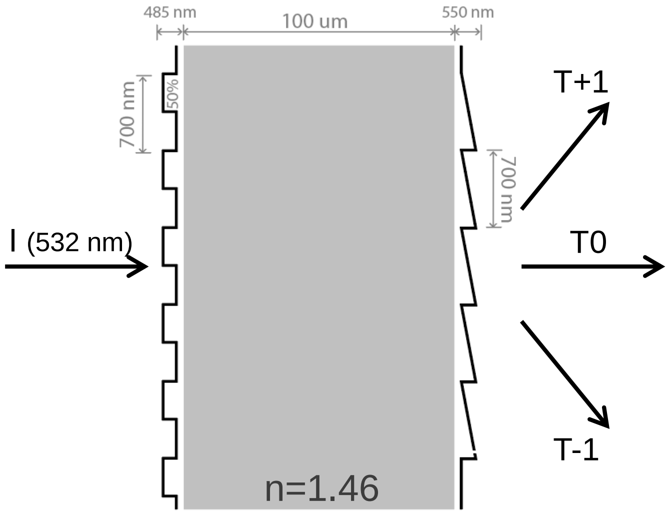
T	Eff.	R	Eff.
±1	23.6%	±1	0.762%
0	18.1%	0	33.1%

Rectangular + Sawtooth Grating (parallel)

- Non-sequential field tracing



- ... with sawtooth coating

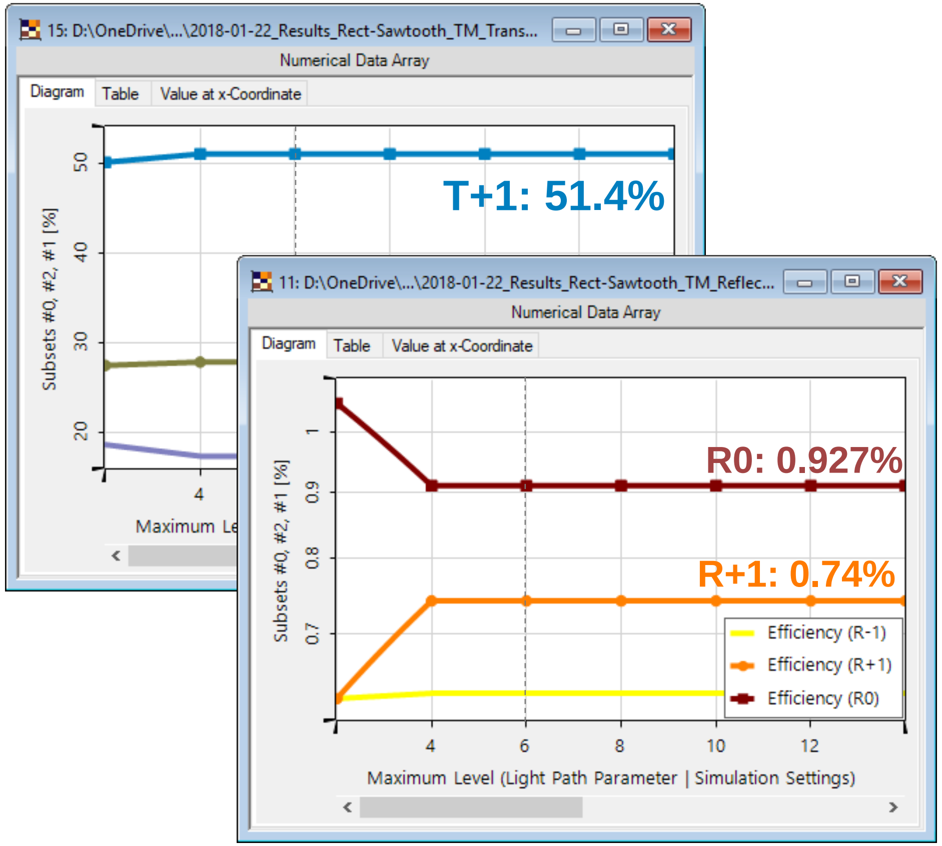


Global S matrix (TM)

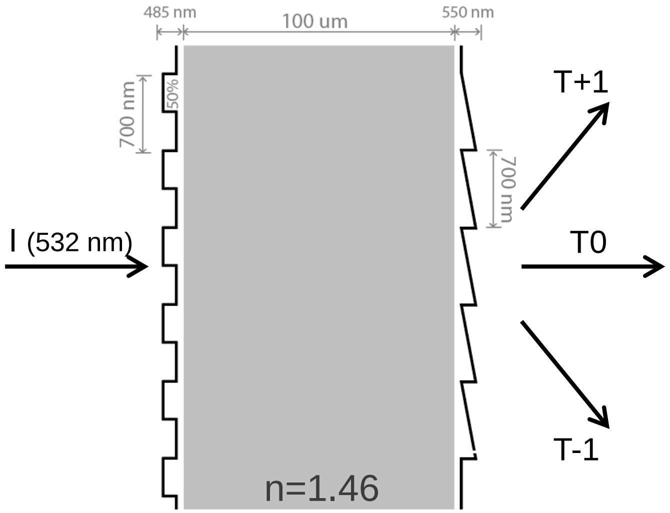
T	Eff.	R	Eff.
-1	28.1%	-1	0.65%
0	18.2%	0	0.923%
+1	51.4%	+1	0.74%

Rectangular + Sawtooth Grating (parallel)

- Non-sequential field tracing



- ... with sawtooth coating

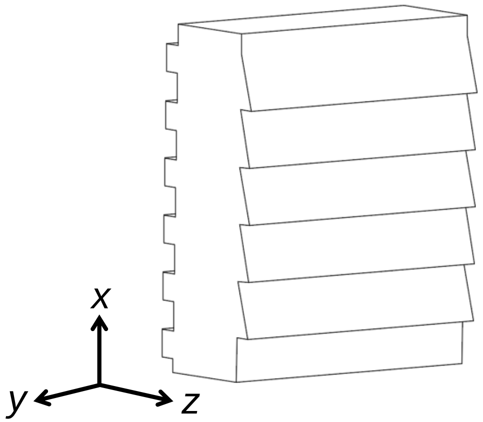


Global S matrix (TM)

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

Computational Effort

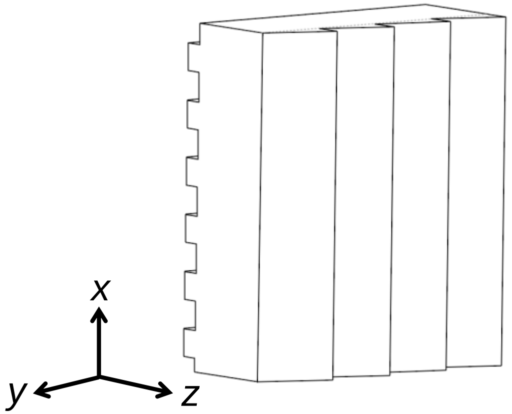
- Parallel gratings



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

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

- Crossed gratings

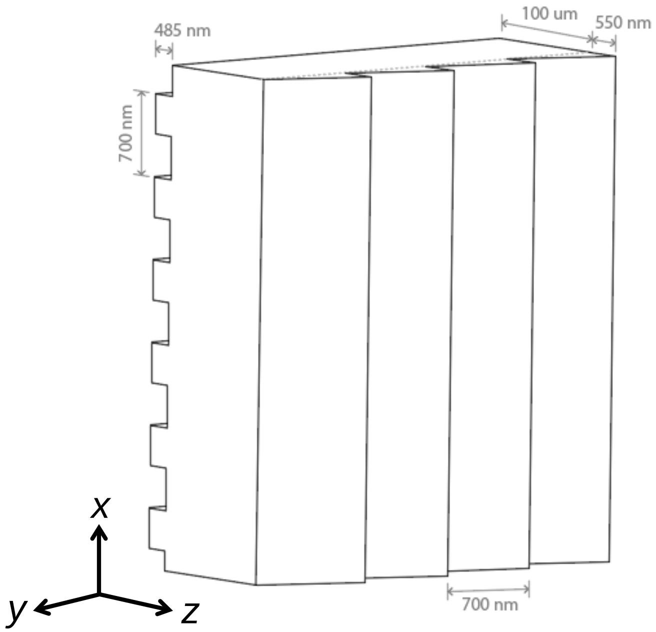


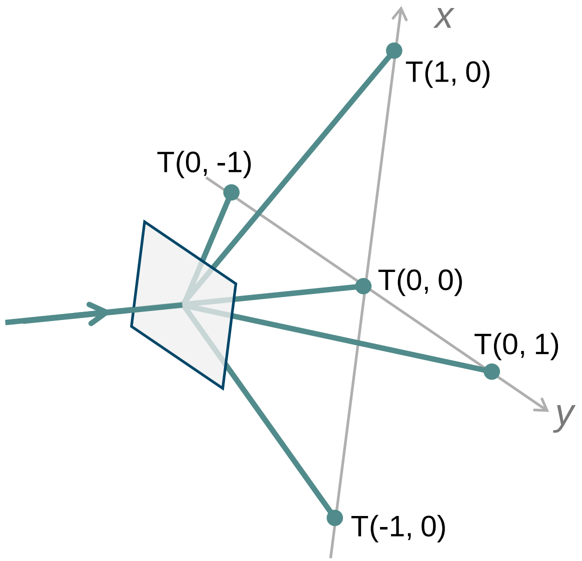
Global S matrix	Non-sequential field tracing
$\sim(M_x \times M_y)^3$ (scaling with number of layers)	$\sim(M_x^3 + M_y^3)$ (scaling with number of light paths)

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

Rectangular + Sawtooth Grating (crossed)

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



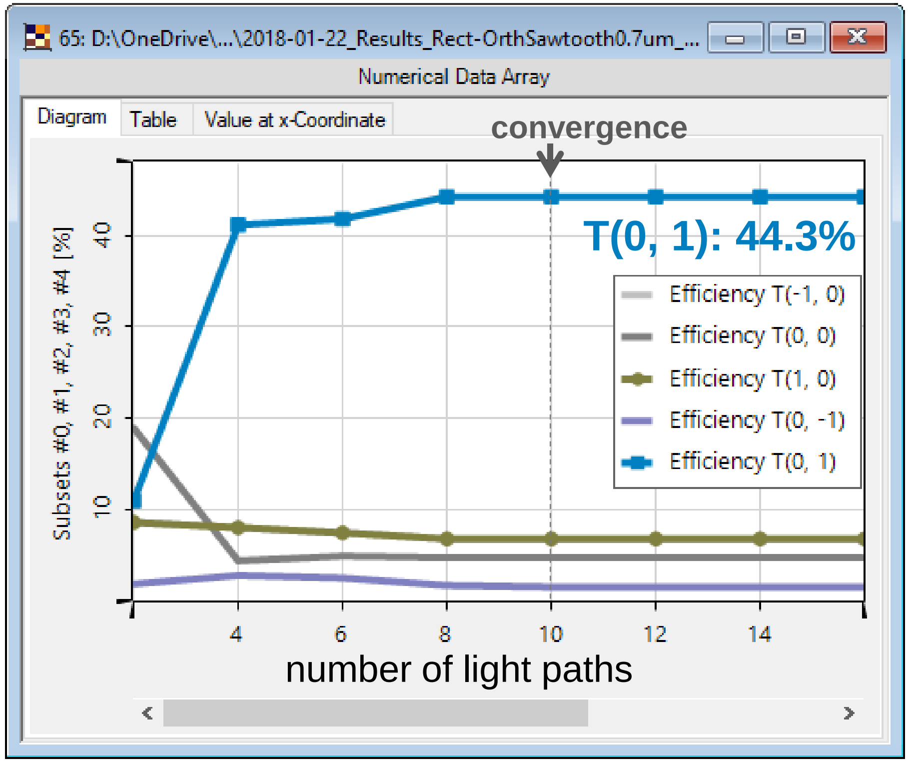


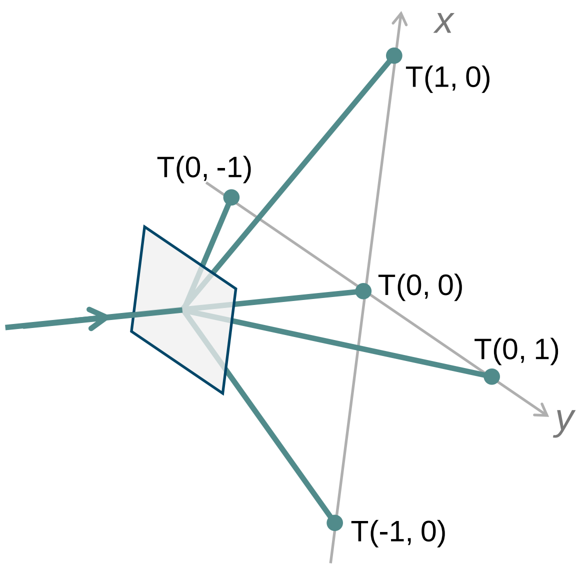
Global S matrix (TM)

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

Rectangular + Sawtooth Grating (crossed)

- Non-sequential field tracing (TM)



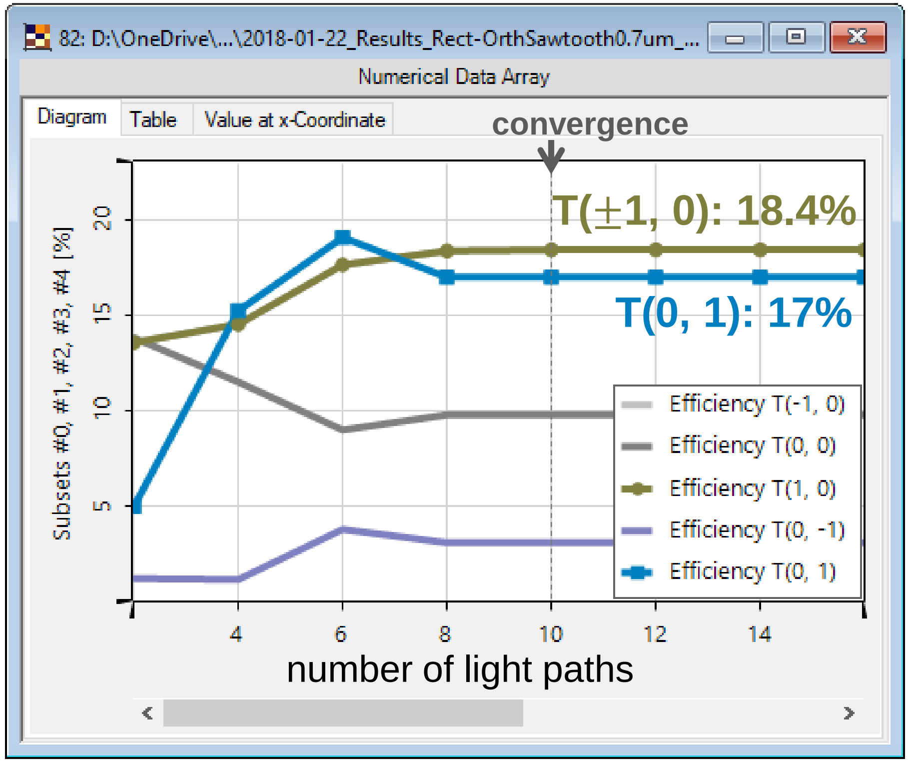


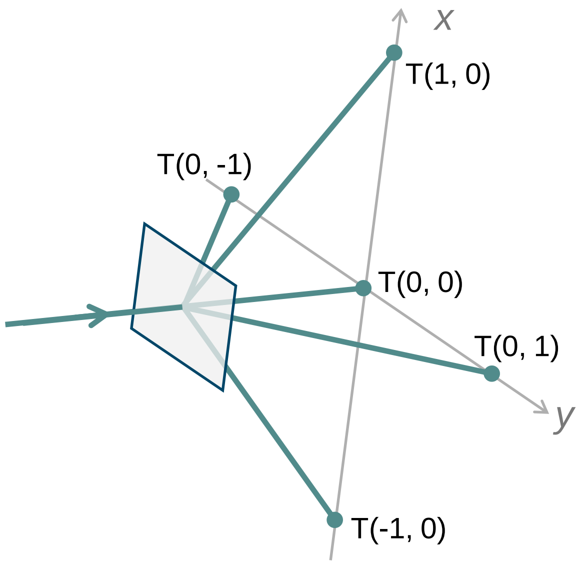
Global S matrix (TM)

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

Rectangular + Sawtooth Grating (crossed)

- Non-sequential field tracing (TE)



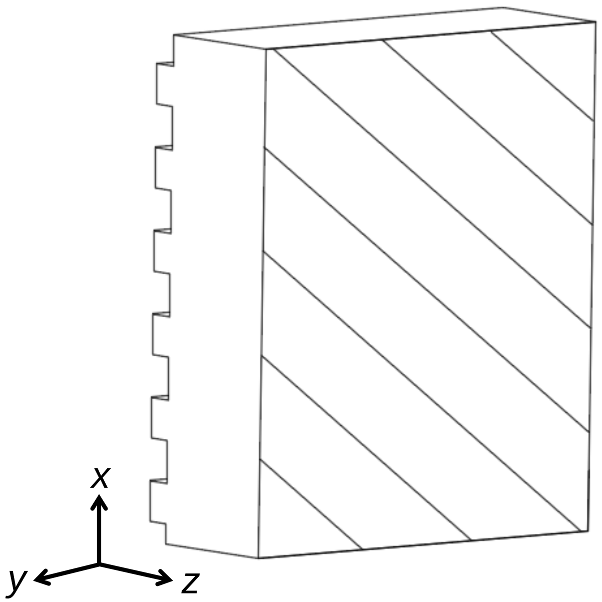


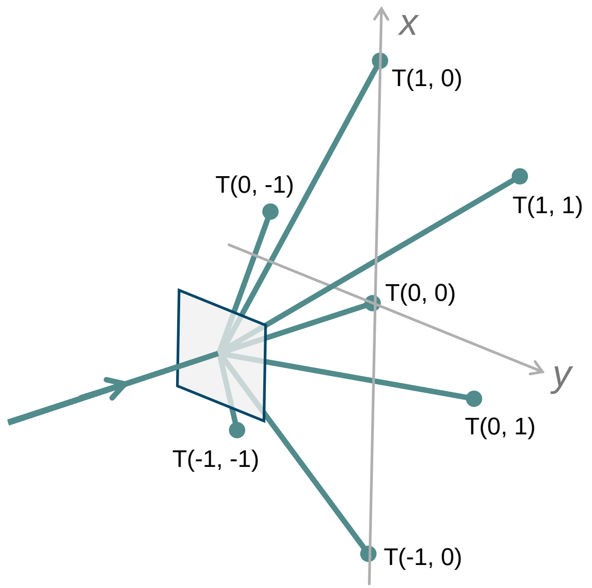
Global S matrix (TE)

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

Rectangular + Sawtooth Grating (45° rotated)

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

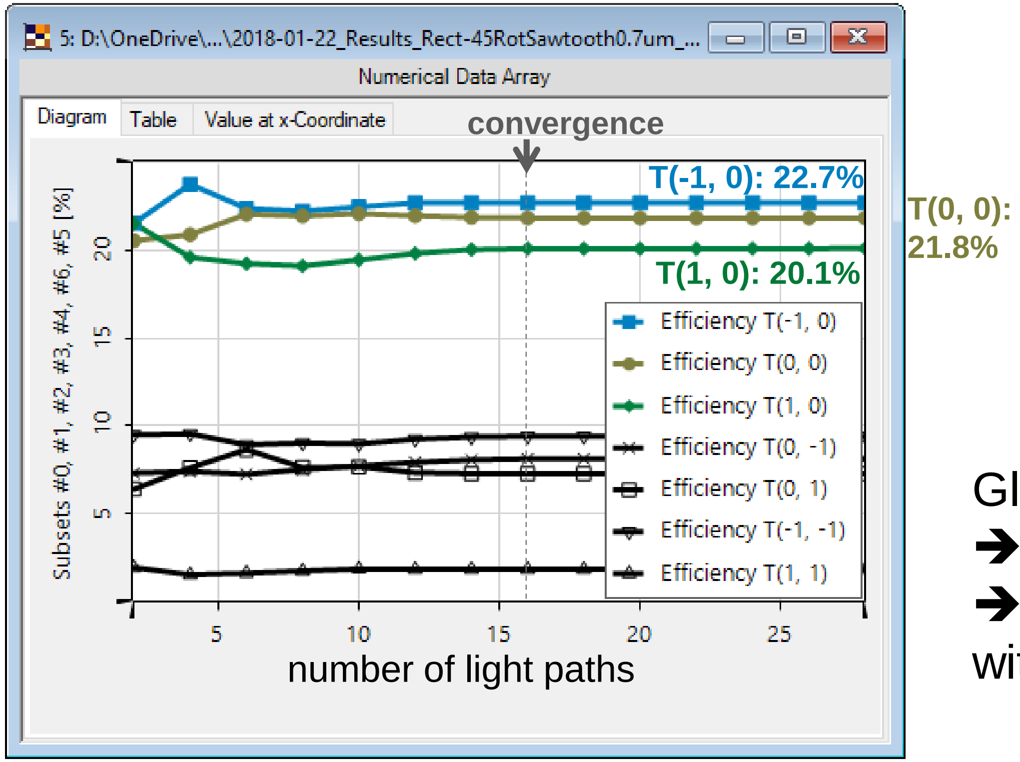


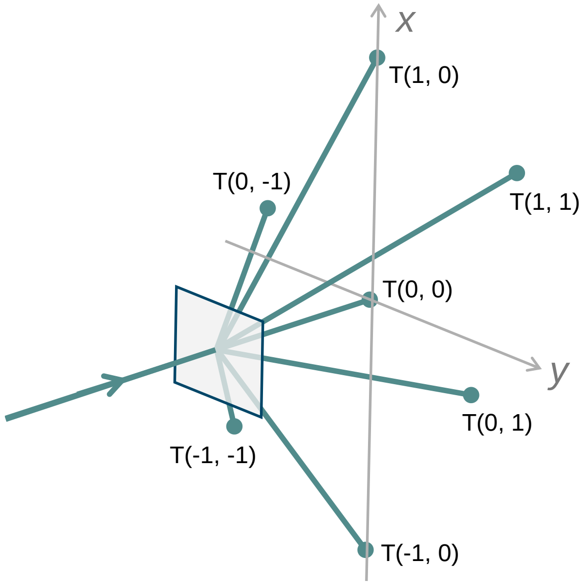


Global S matrix (TM)
➔ No common period!
➔ Huge computational effort even with approximated common period

Rectangular + Sawtooth Grating (45° rotated)

- Non-sequential field tracing (TM)

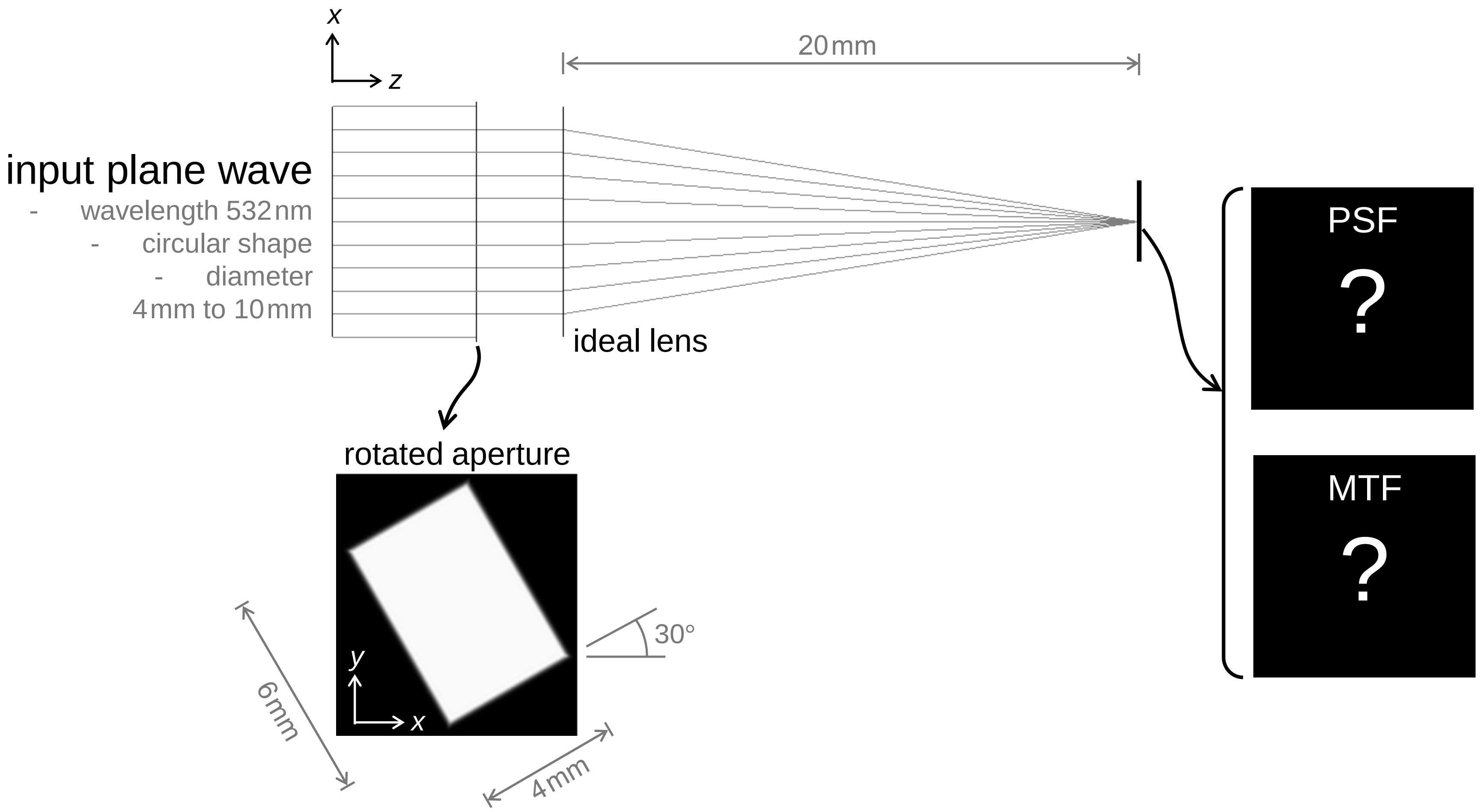




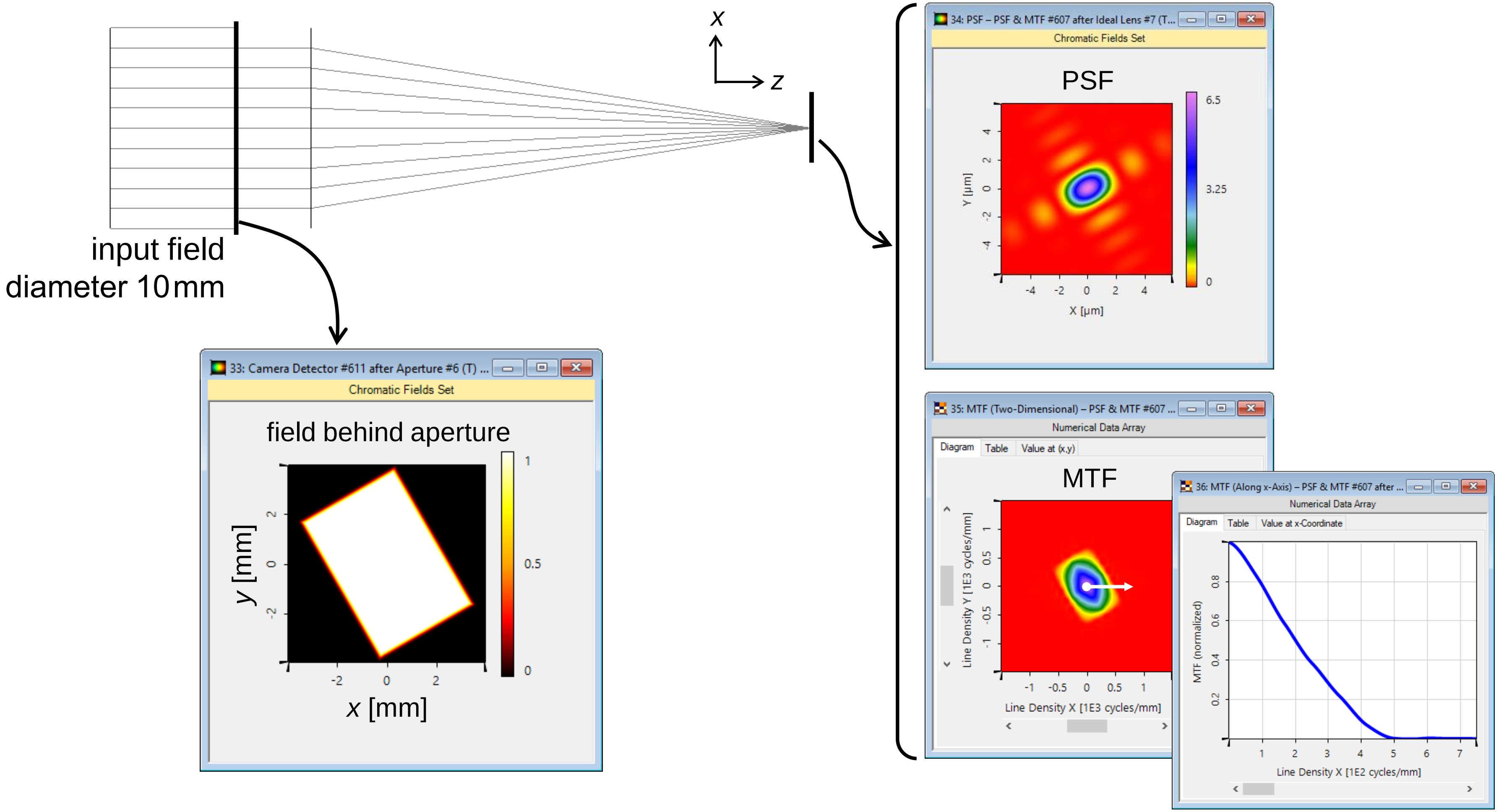
Global S matrix ***NOT*** possible!
➔ No common period
➔ Huge computational effort even with approximated common period

Advanced PSF & MTF Calculation for System with Rectangular Aperture

Modeling Task

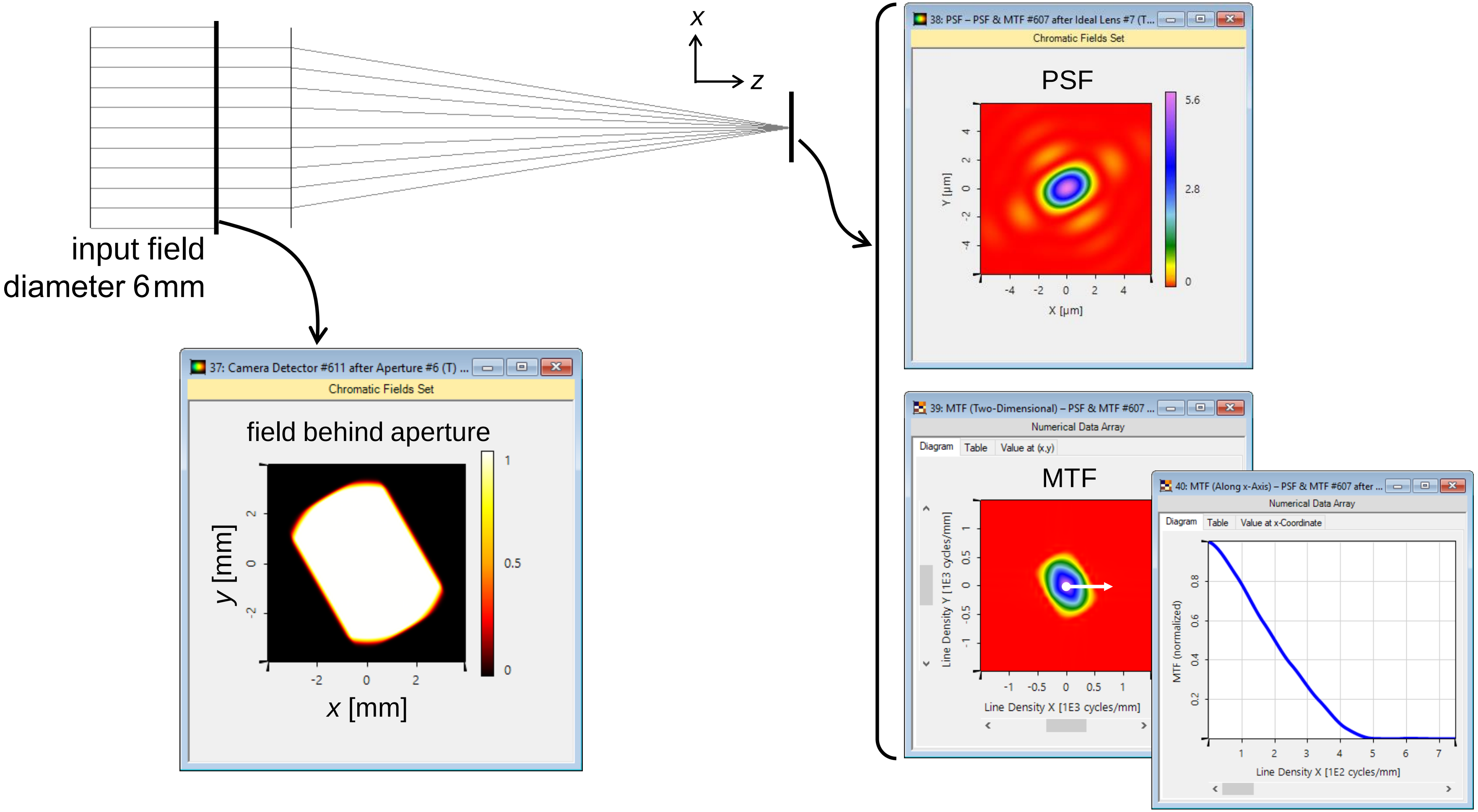


Results

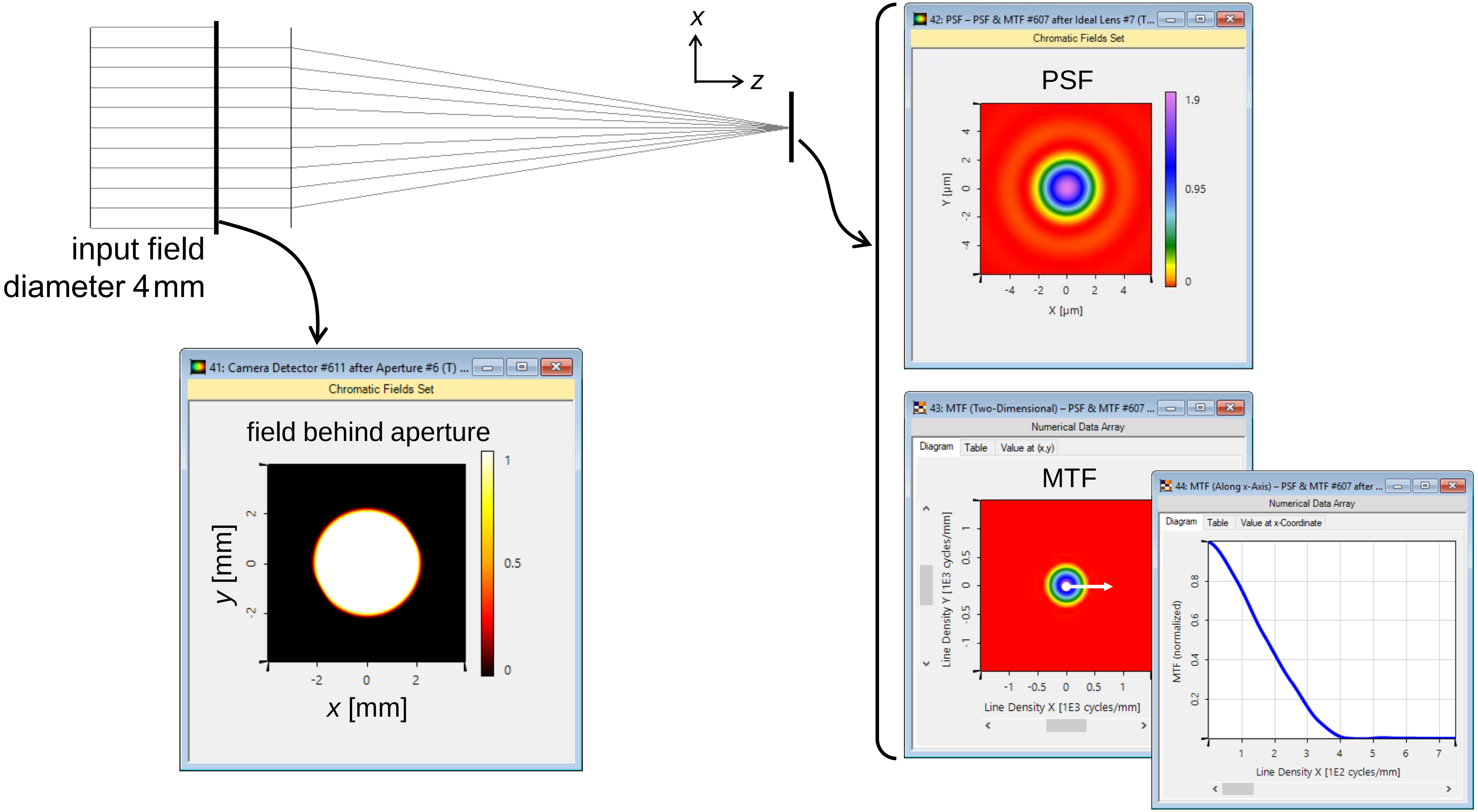


x
z
input field
diameter 10 mm
33: Camera Detector #611 after Aperture #6 (T) ...
Chromatic Fields Set
field behind aperture
y [mm]
x [mm]
34: PSF – PSF & MTF #607 after Ideal Lens #7 (T...
Chromatic Fields Set
PSF
Y [µm]
X [µm]
35: MTF (Two-Dimensional) – PSF & MTF #607 ...
Numerical Data Array
Diagram
Table
Value at (x,y)
MTF
Line Density Y [1E3 cycles/mm]
Line Density X [1E3 cycles/mm]
36: MTF (Along x-Axis) – PSF & MTF #607 after ...
Numerical Data Array
Diagram
Table
Value at x-Coordinate
MTF (normalized)
Line Density X [1E2 cycles/mm]

Results


x
z
input field
diameter 6 mm
37: Camera Detector #611 after Aperture #6 (T) ...
Chromatic Fields Set
field behind aperture
y [mm]
x [mm]
38: PSF – PSF & MTF #607 after Ideal Lens #7 (T...
Chromatic Fields Set
PSF
Y [µm]
X [µm]
39: MTF (Two-Dimensional) – PSF & MTF #607 ...
Numerical Data Array
Diagram
Table
Value at (x,y)
MTF
Line Density Y [1E3 cycles/mm]
Line Density X [1E3 cycles/mm]
40: MTF (Along x-Axis) – PSF & MTF #607 after ...
Numerical Data Array
Diagram
Table
Value at x-Coordinate
MTF (normalized)
Line Density X [1E2 cycles/mm]

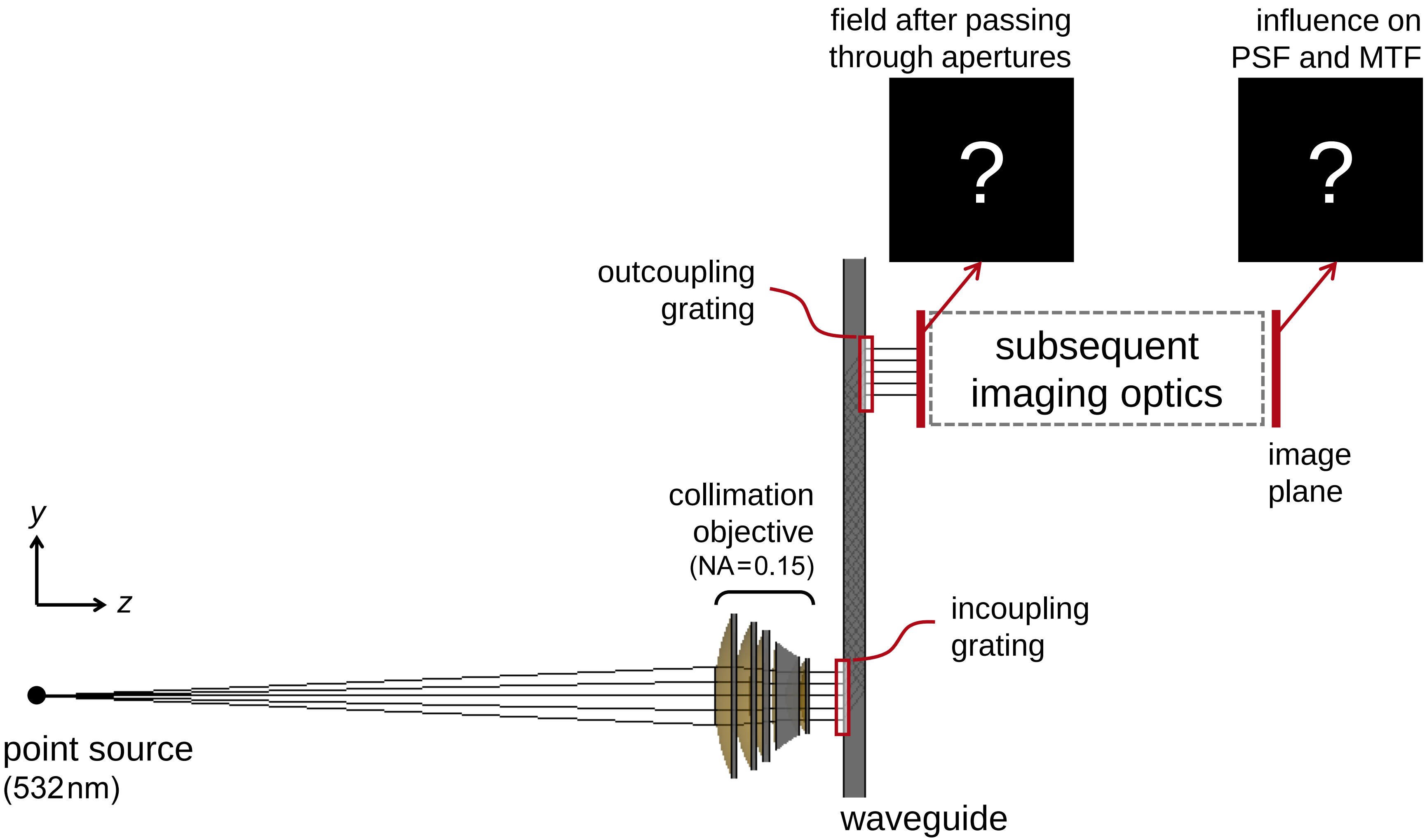
Results



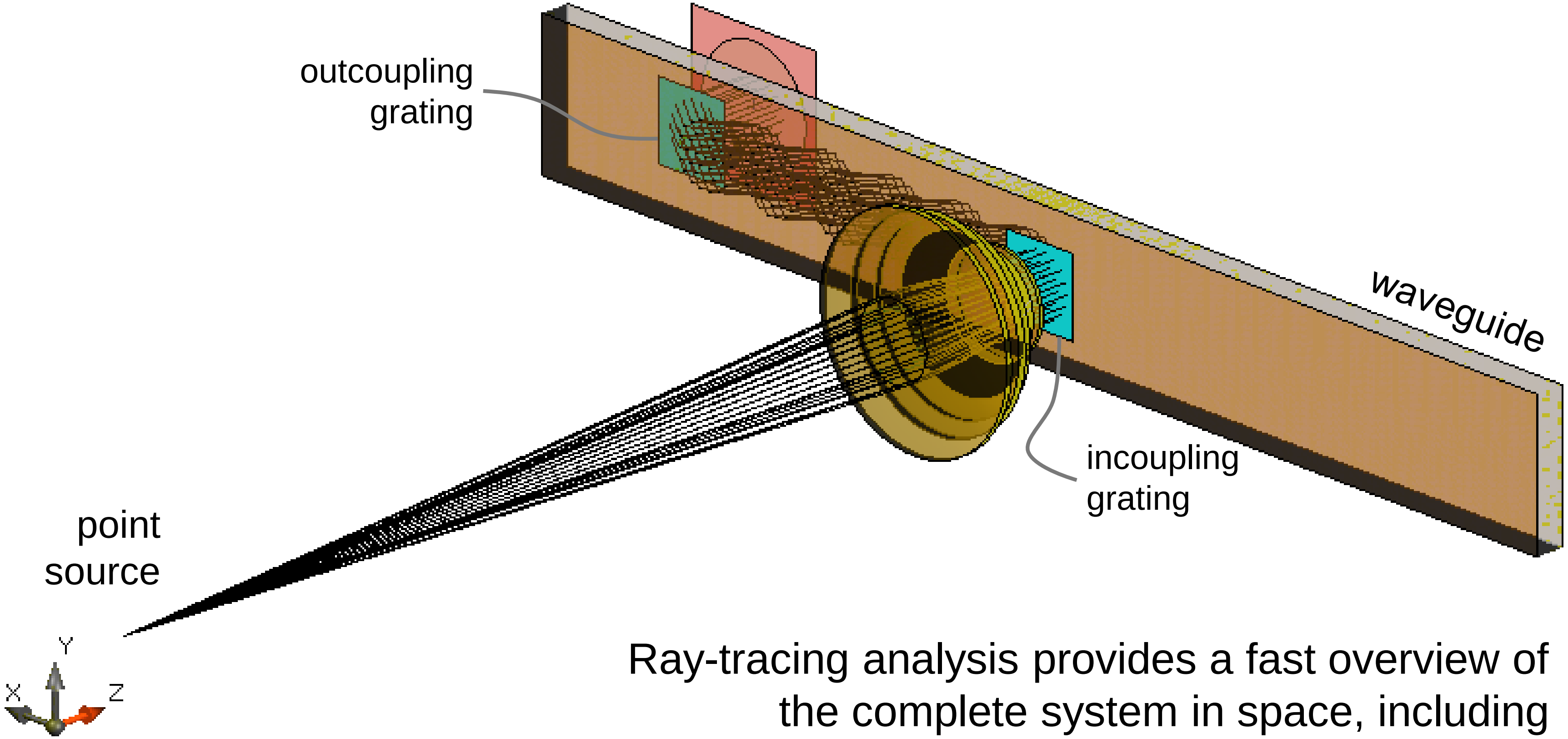
PSF Calculation with Rectangular Aperture.LPD

Analysis of Folded Imaging System with Multiple Apertures

Modeling Task

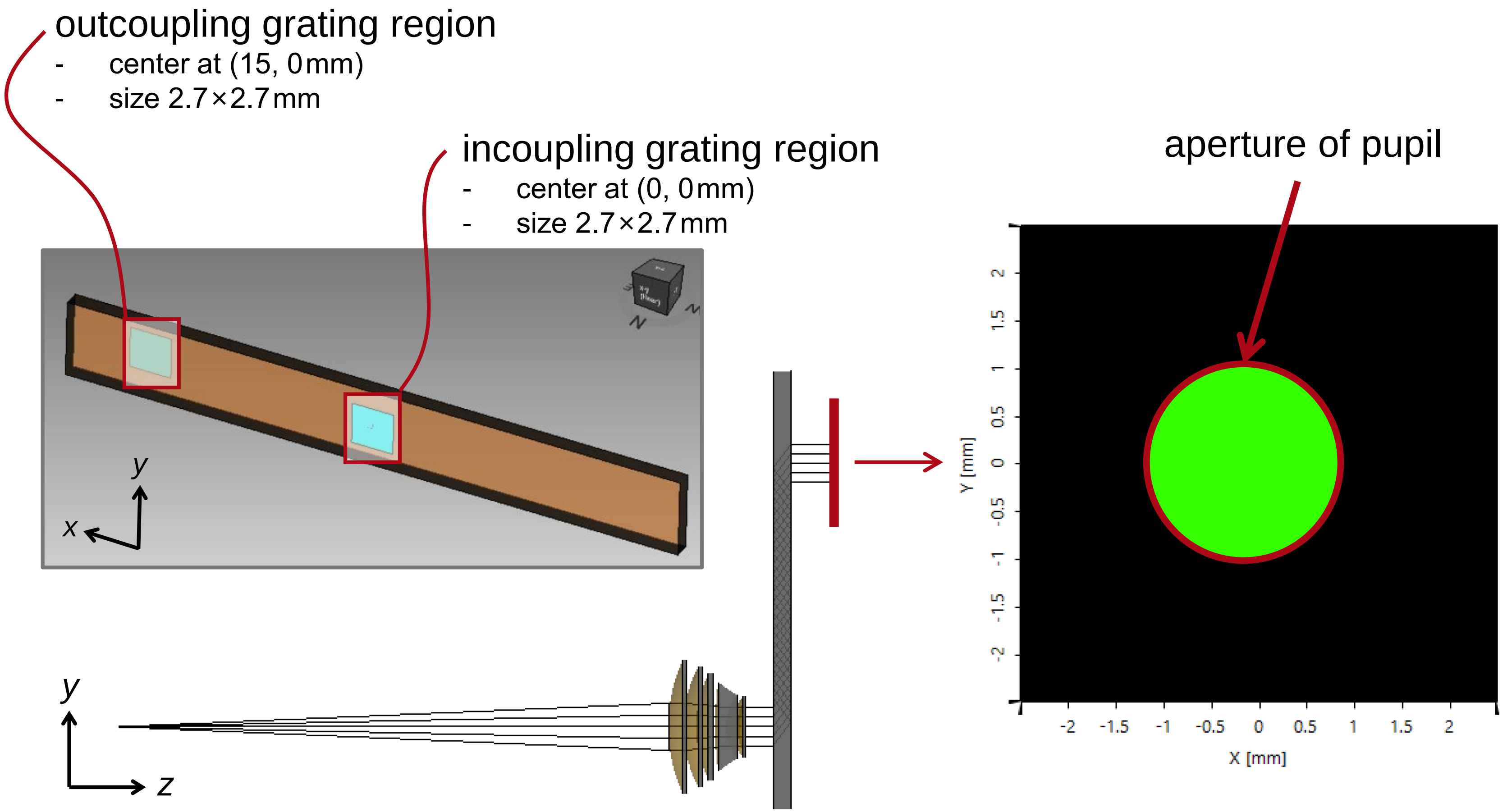


Results

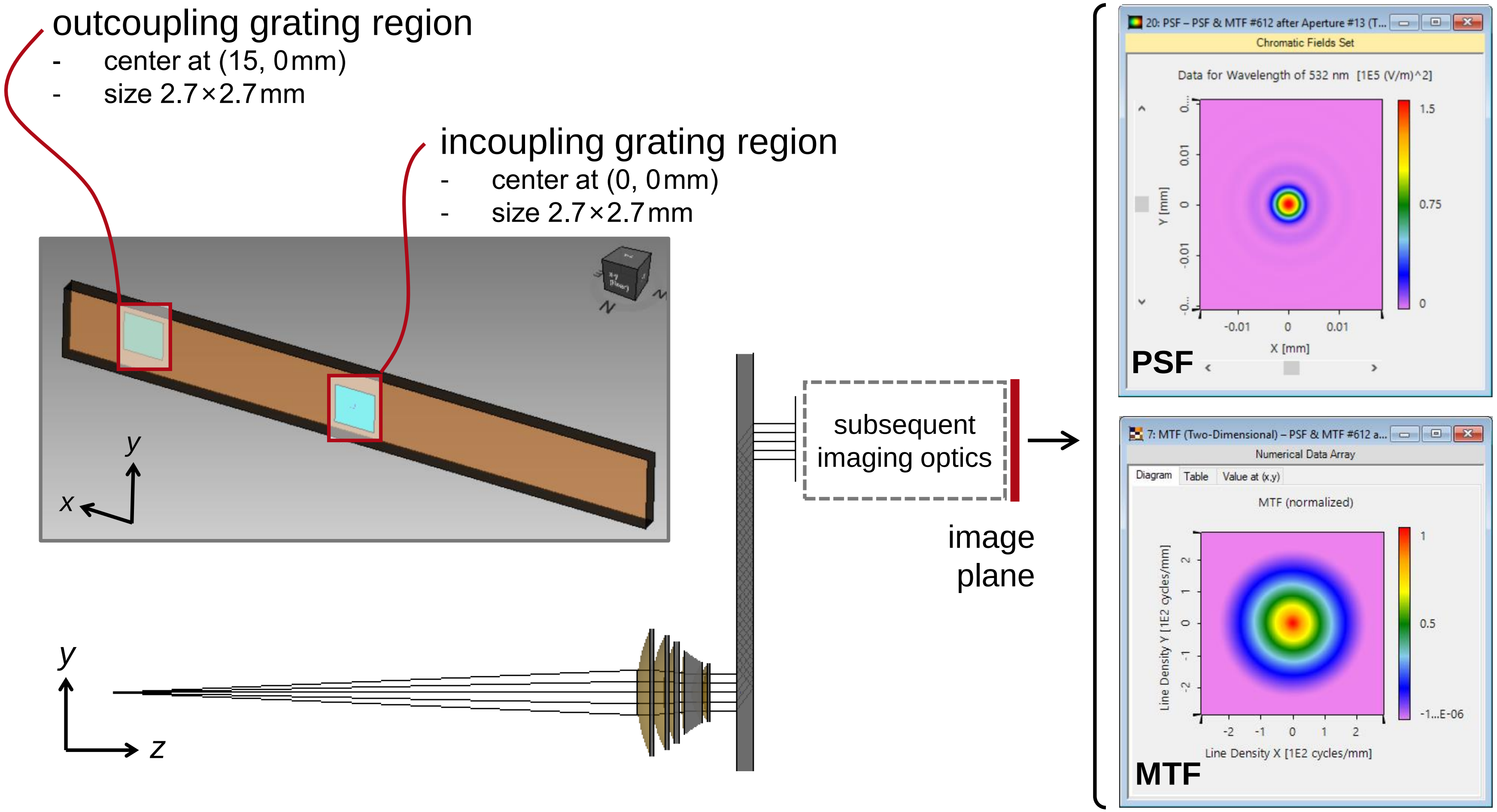


Ray-tracing analysis provides a fast overview of the complete system in space, including waveguide and coupling gratings.

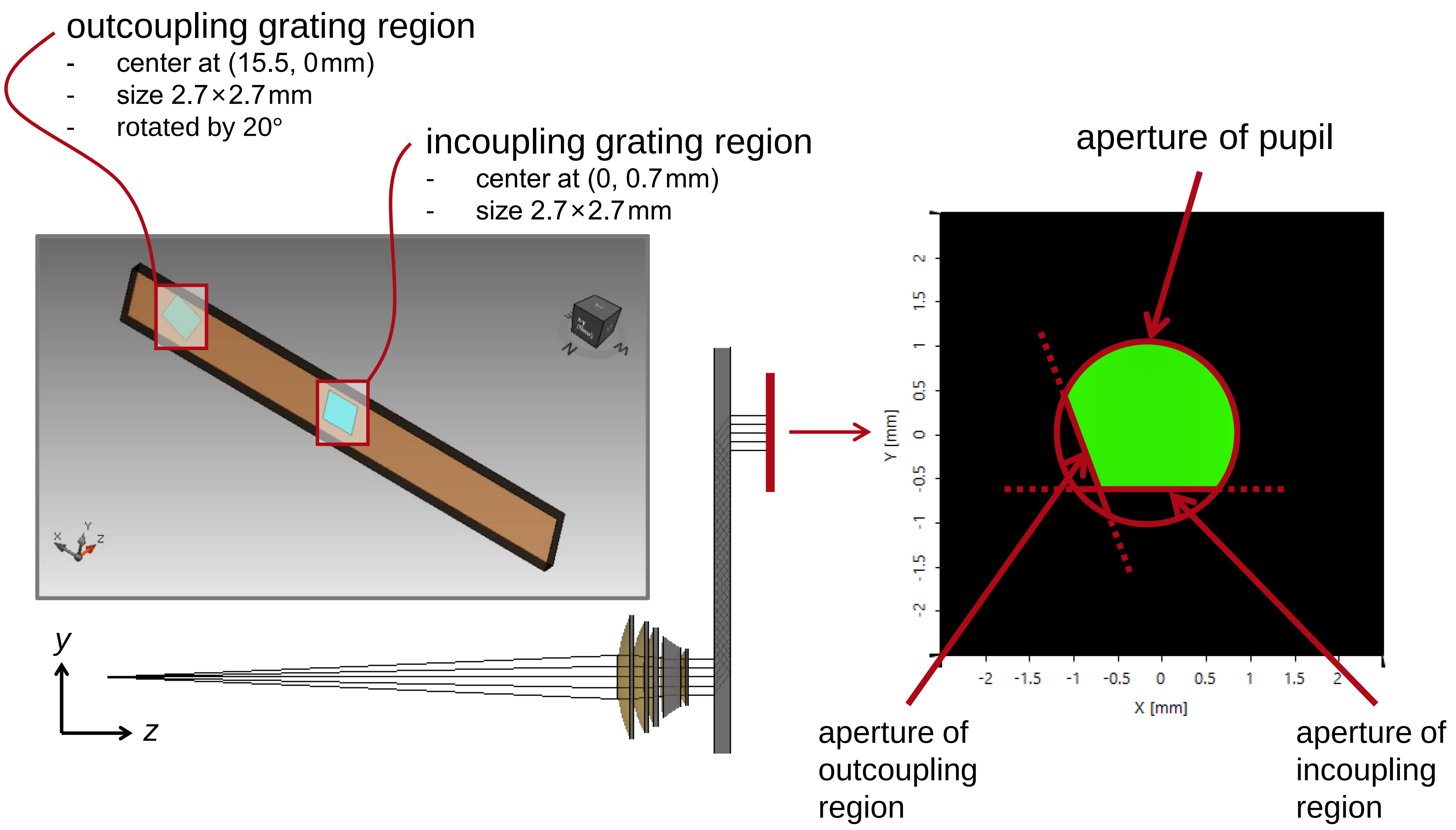
Results


outcoupling grating region
- center at (15, 0 mm)
- size 2.7×2.7 mm
incoupling grating region
- center at (0, 0 mm)
- size 2.7×2.7 mm
aperture of pupil
y
x
y
z
Y [mm]
X [mm]
-2 -1.5 -1 -0.5 0 0.5 1 1.5 2

Results

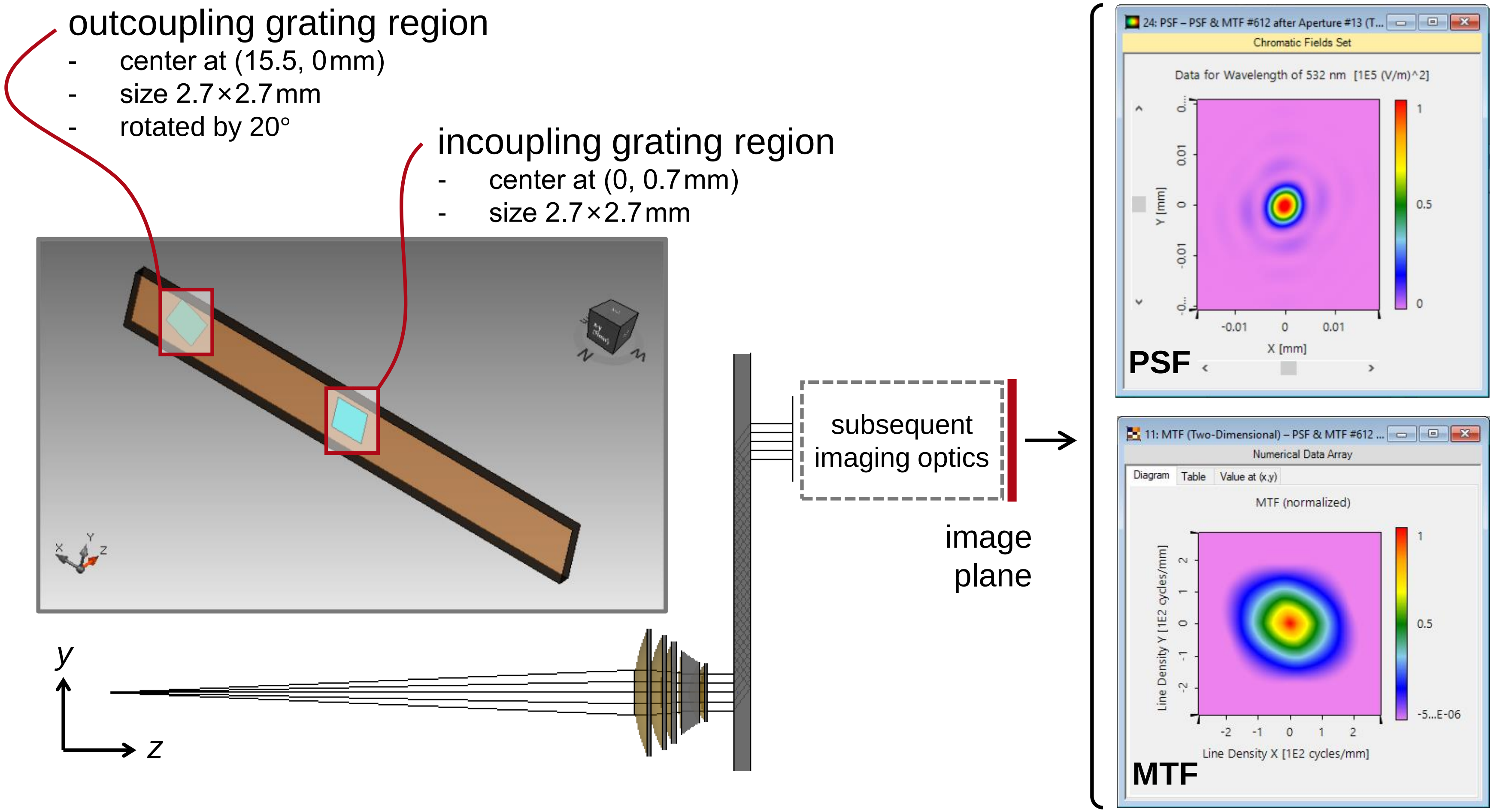

outcoupling grating region
- center at (15, 0 mm)
- size 2.7×2.7 mm
incoupling grating region
- center at (0, 0 mm)
- size 2.7×2.7 mm
y
x
y
z
subsequent imaging optics
image plane
20: PSF – PSF & MTF #612 after Aperture #13 (T...
Chromatic Fields Set
Data for Wavelength of 532 nm [1E5 (V/m)^2]
Y [mm]
X [mm]
1.5
0.75
0
-0.01
0
0.01
PSF
7: MTF (Two-Dimensional) – PSF & MTF #612 a...
Numerical Data Array
Diagram
Table
Value at (x,y)
MTF (normalized)
Line Density Y [1E2 cycles/mm]
Line Density X [1E2 cycles/mm]
1
0.5
-1...E-06
-2
-1
0
1
2
MTF

Results



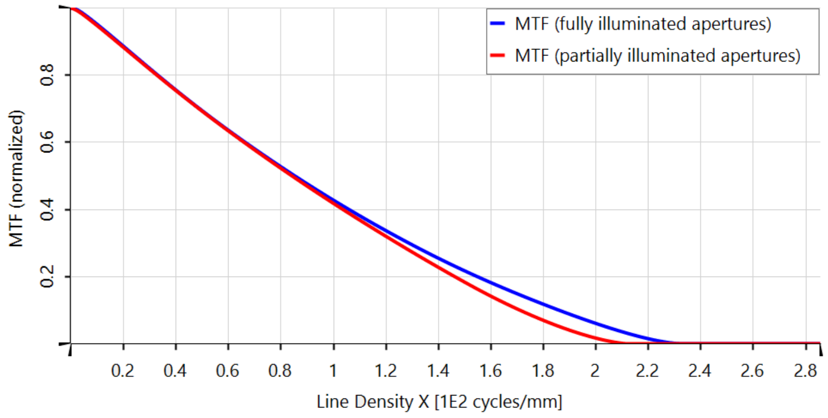
outcoupling grating region
- center at (15.5, 0 mm)
- size 2.7×2.7 mm
- rotated by 20°
incoupling grating region
- center at (0, 0.7 mm)
- size 2.7×2.7 mm
aperture of pupil
y
z
Y [mm]
X [mm]
aperture of outcoupling region
aperture of incoupling region

Results

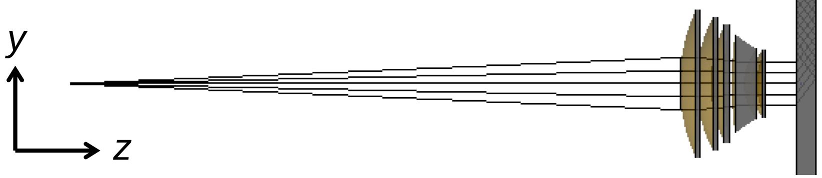


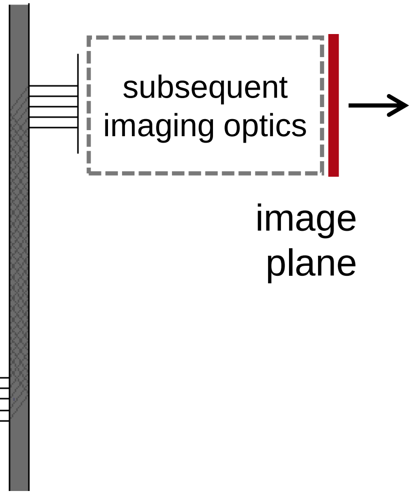
outcoupling grating region
- center at (15.5, 0 mm)
- size 2.7×2.7 mm
- rotated by 20°
incoupling grating region
- center at (0, 0.7 mm)
- size 2.7×2.7 mm
y
z
subsequent imaging optics
image plane
24: PSF – PSF & MTF #612 after Aperture #13 (T...
Chromatic Fields Set
Data for Wavelength of 532 nm [1E5 (V/m)^2]
Y [mm]
X [mm]
PSF
11: MTF (Two-Dimensional) – PSF & MTF #612 ...
Numerical Data Array
Diagram
Table
Value at (x,y)
MTF (normalized)
Line Density Y [1E2 cycles/mm]
Line Density X [1E2 cycles/mm]
MTF

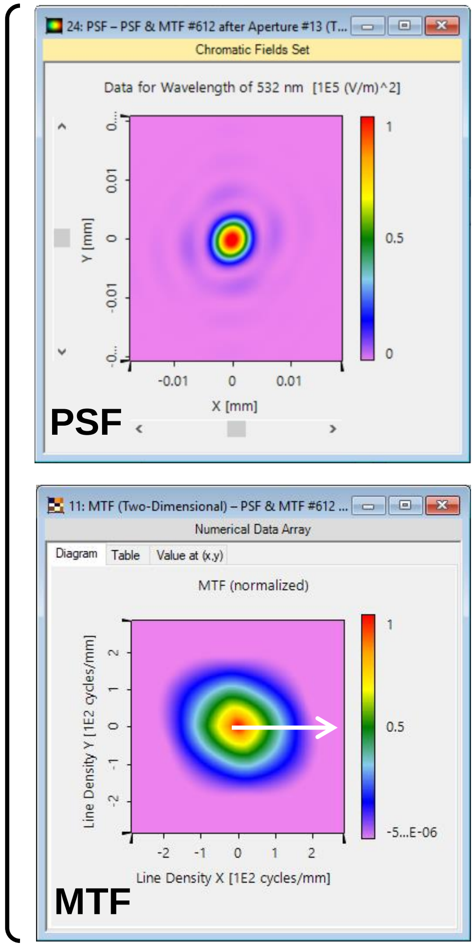
Results



comparison between MTFs with full and partial illumination of the aperture

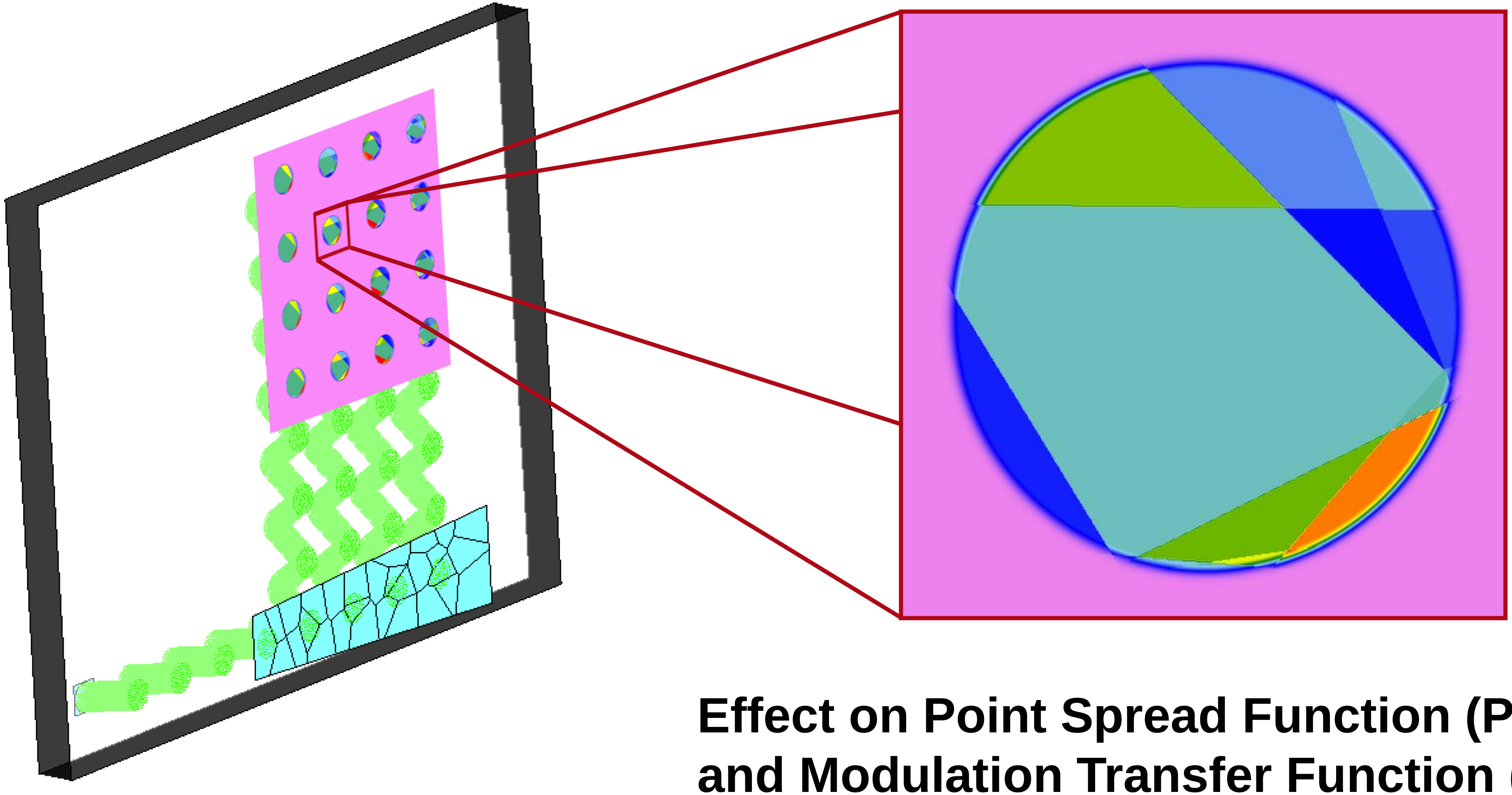






Analysis of Folded Imaging System with Multiple Apertures.LPD

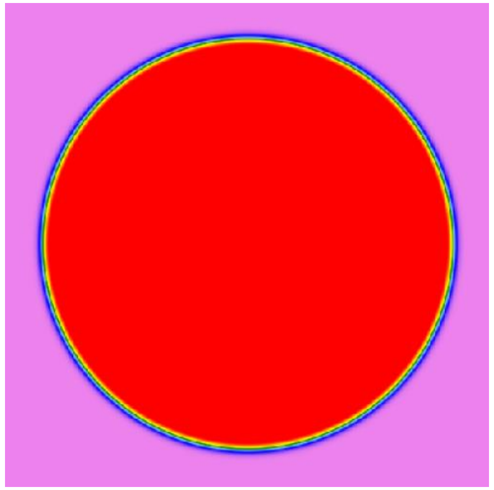
Simulation Task



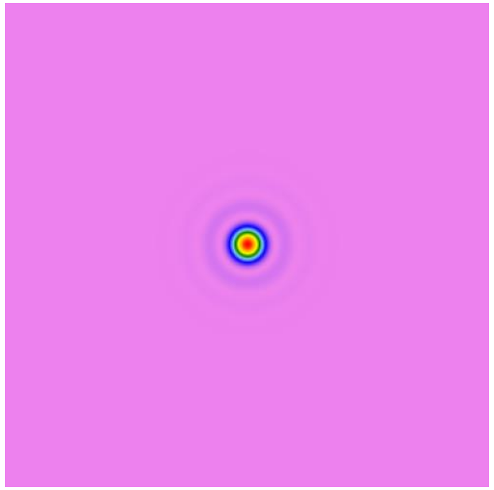
Effect on Point Spread Function (PSF) and Modulation Transfer Function (MTF)?

Pupil Segmentation – PSF Evaluation

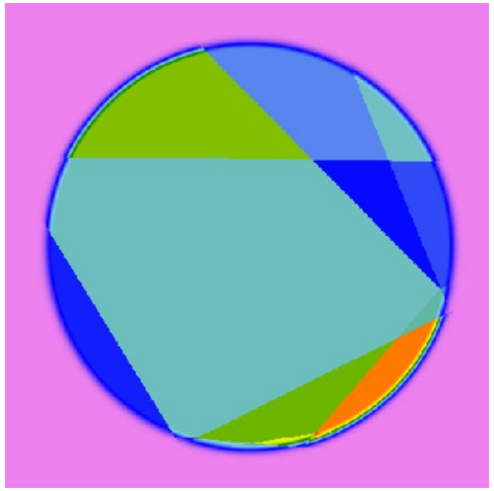
Diffraction limited beam



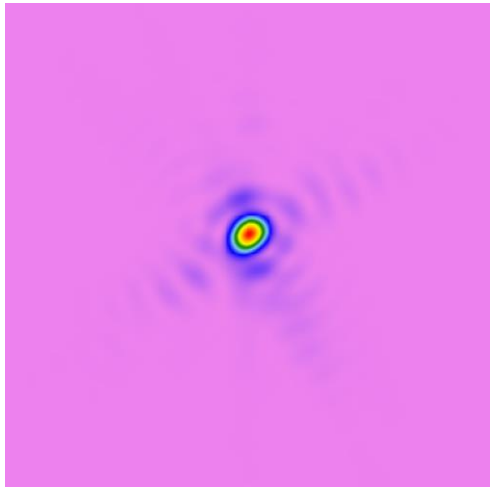
PSF



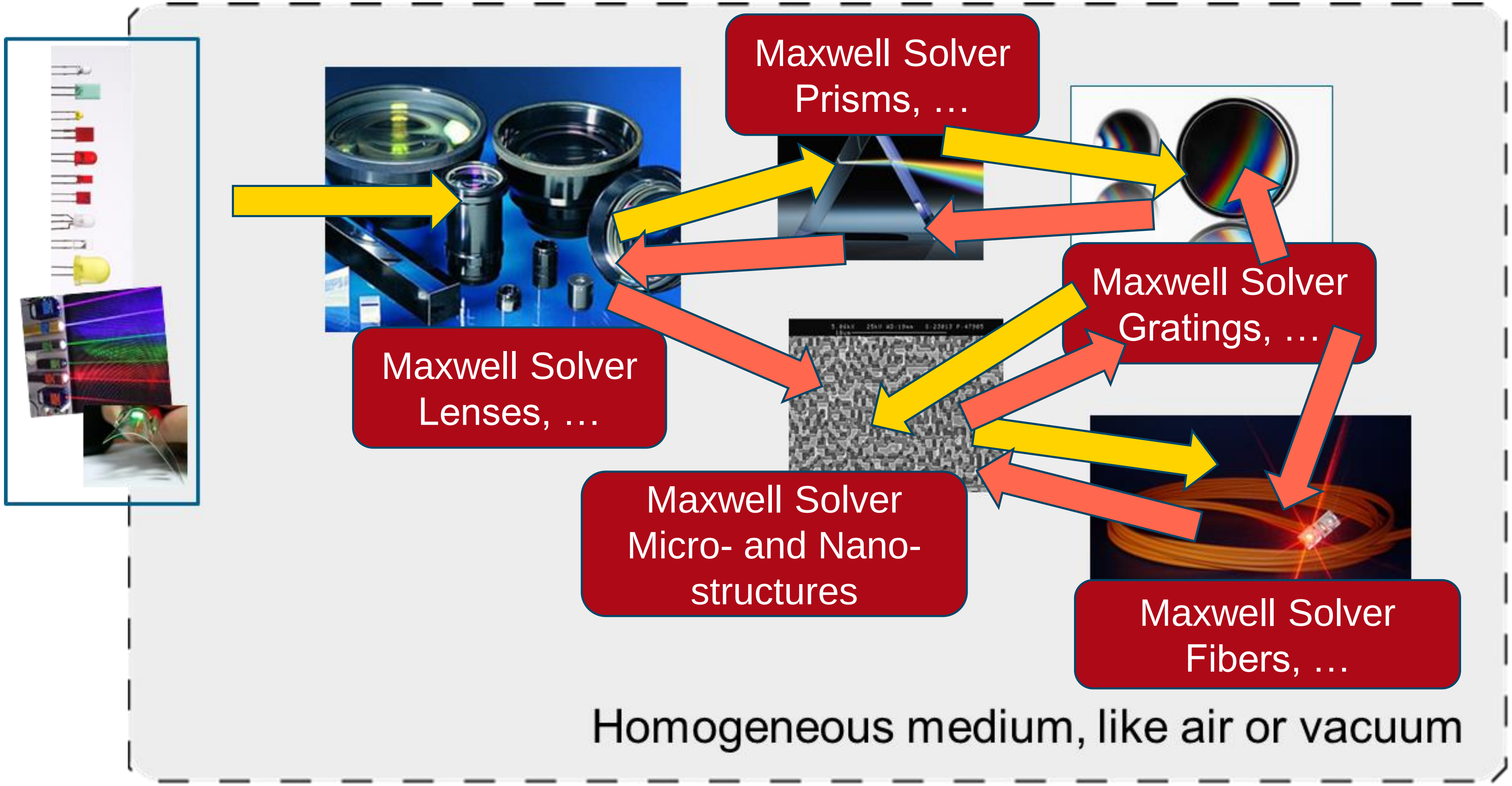
Segmented beam



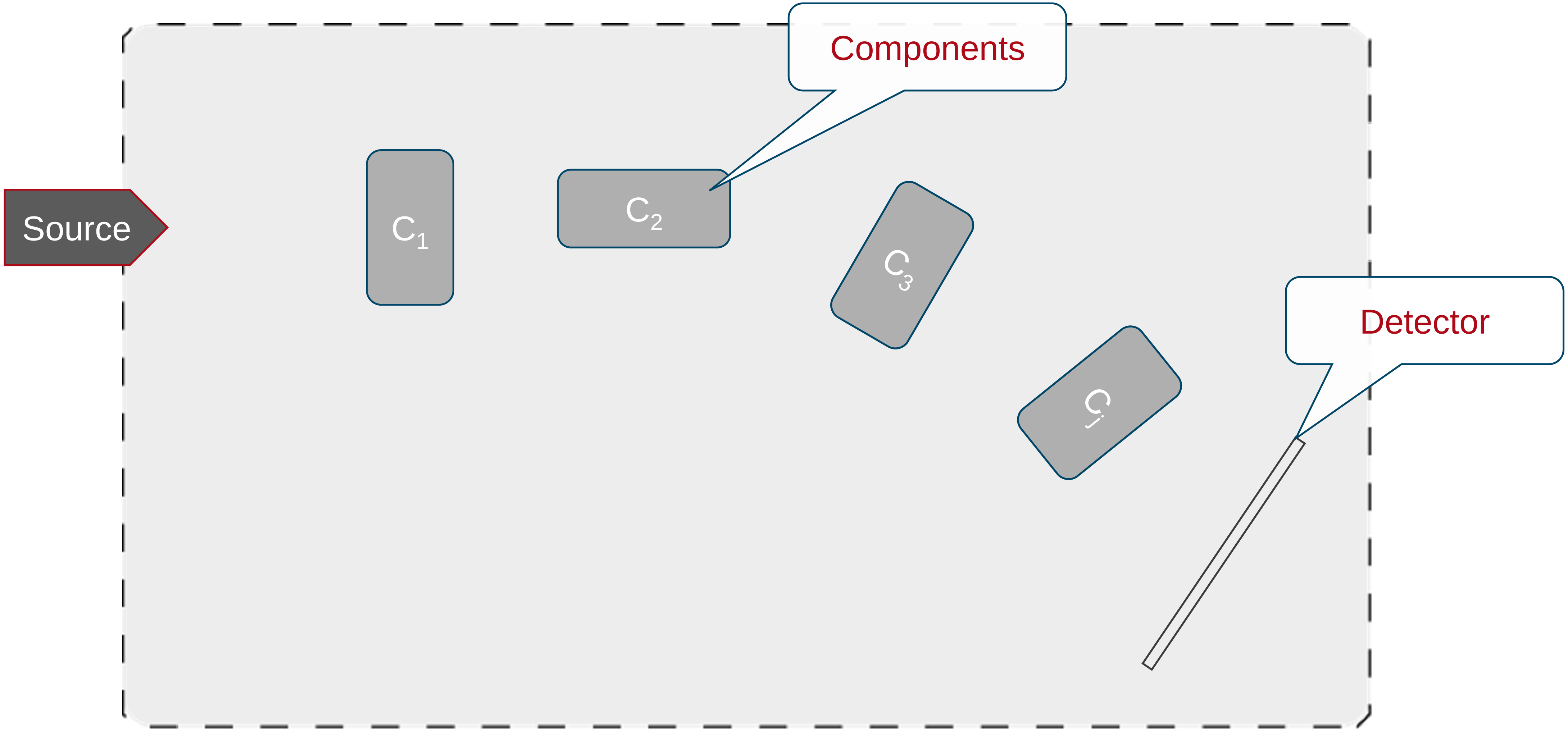
PSF



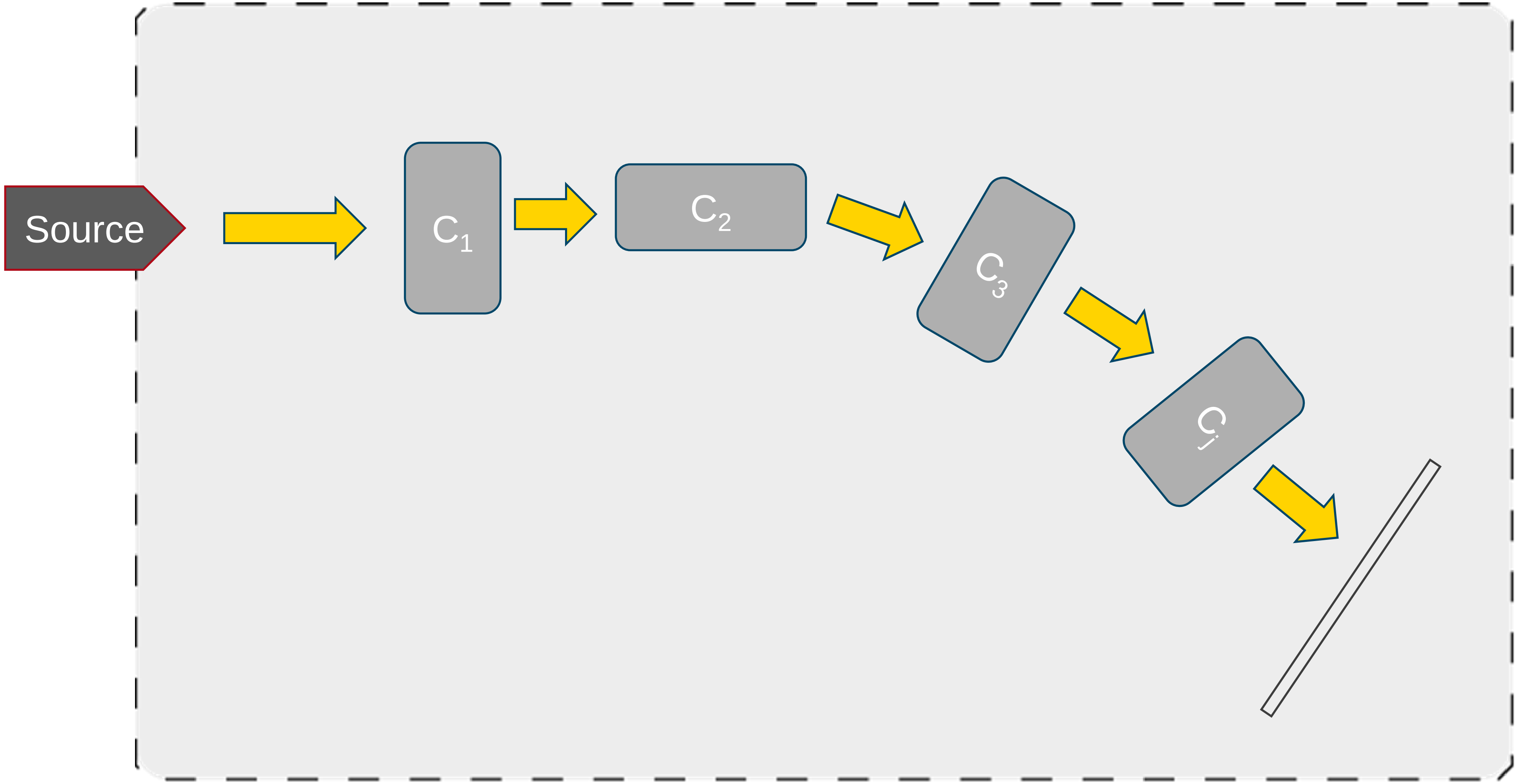
Non-Sequential Connection of Regional Maxwell Solver



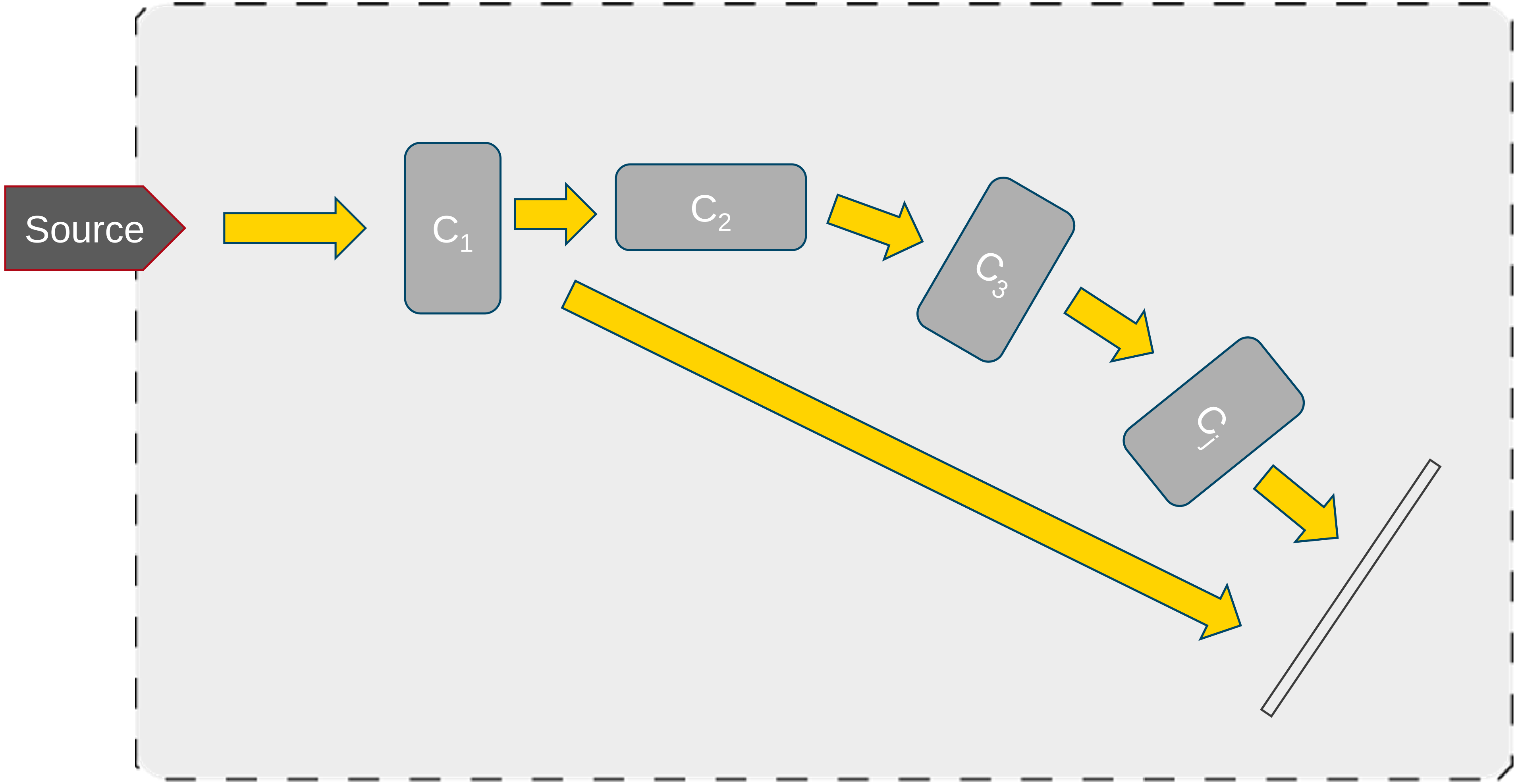
Lightpaths for Field Tracing Through System



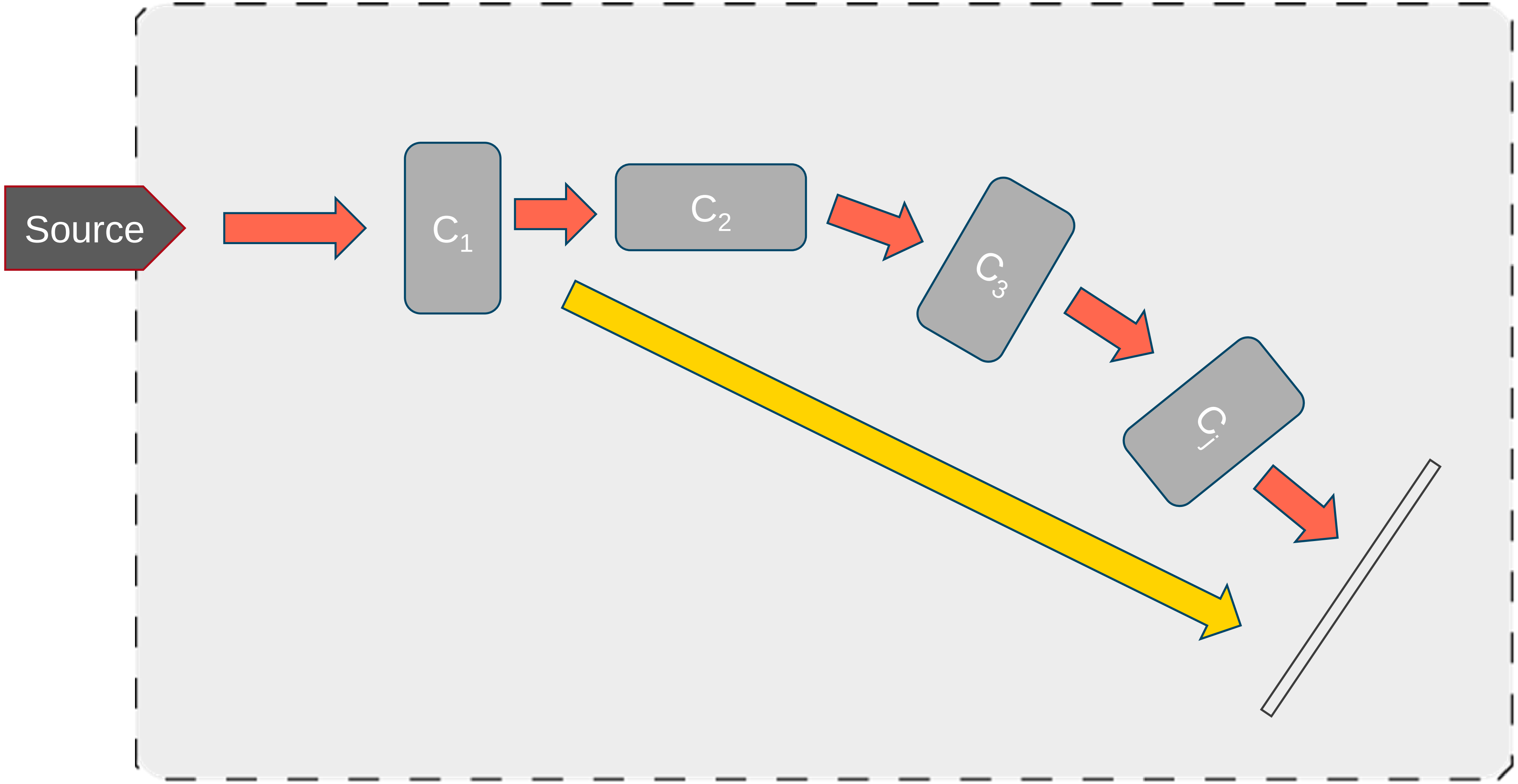
Lightpaths for Field Tracing Through System



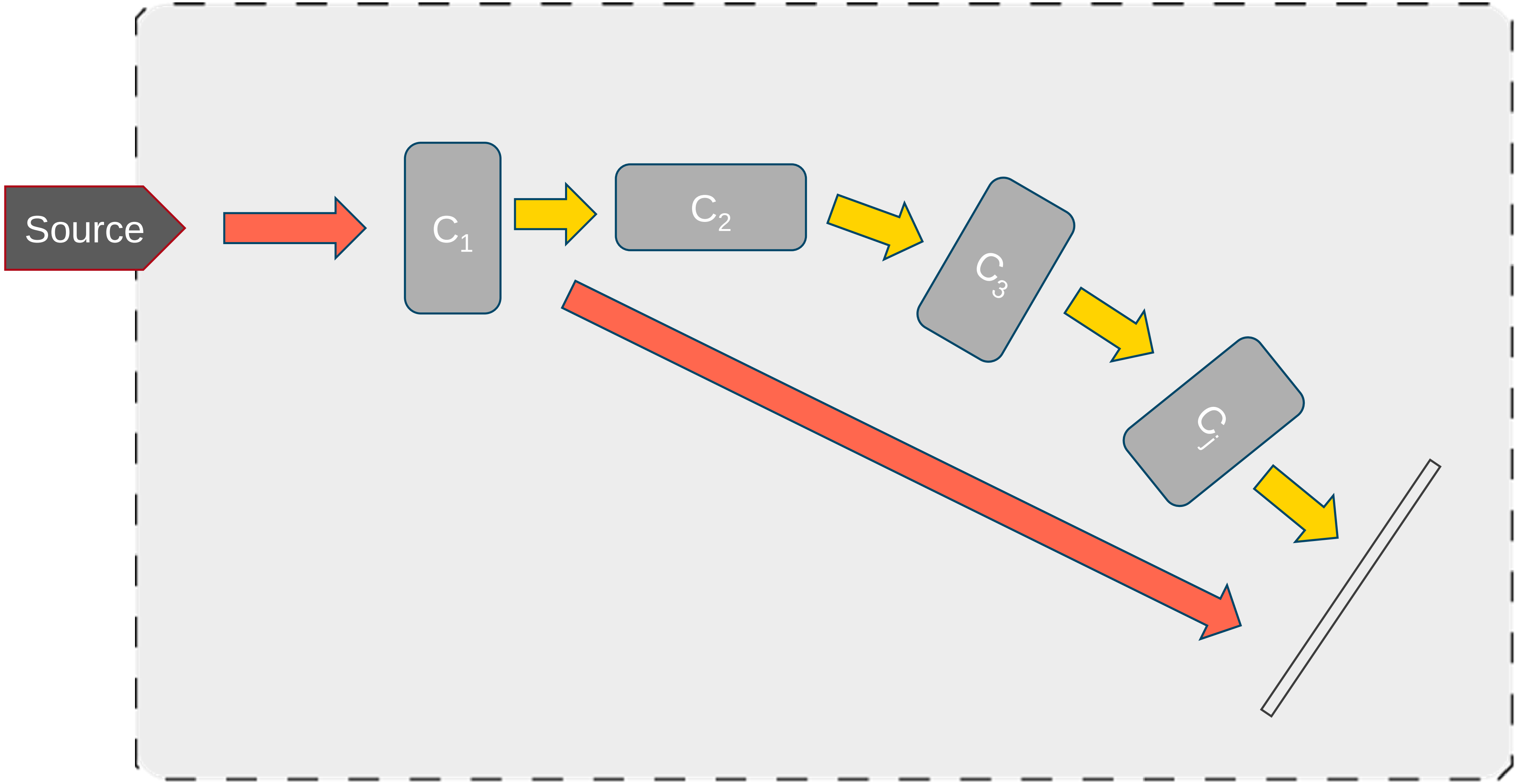
Lightpaths in Non-Sequential Modeling



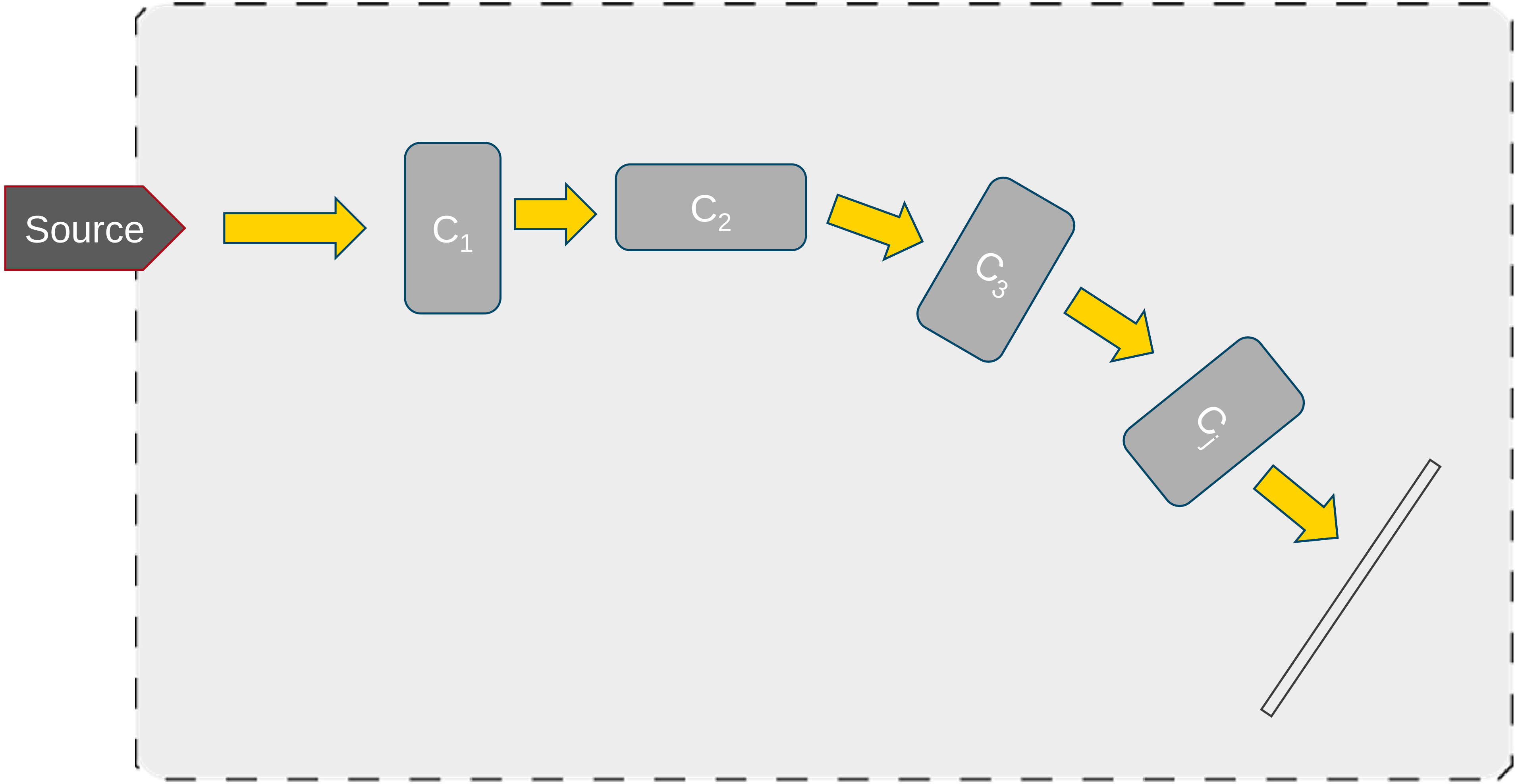
Lightpaths in Non-Sequential Modeling



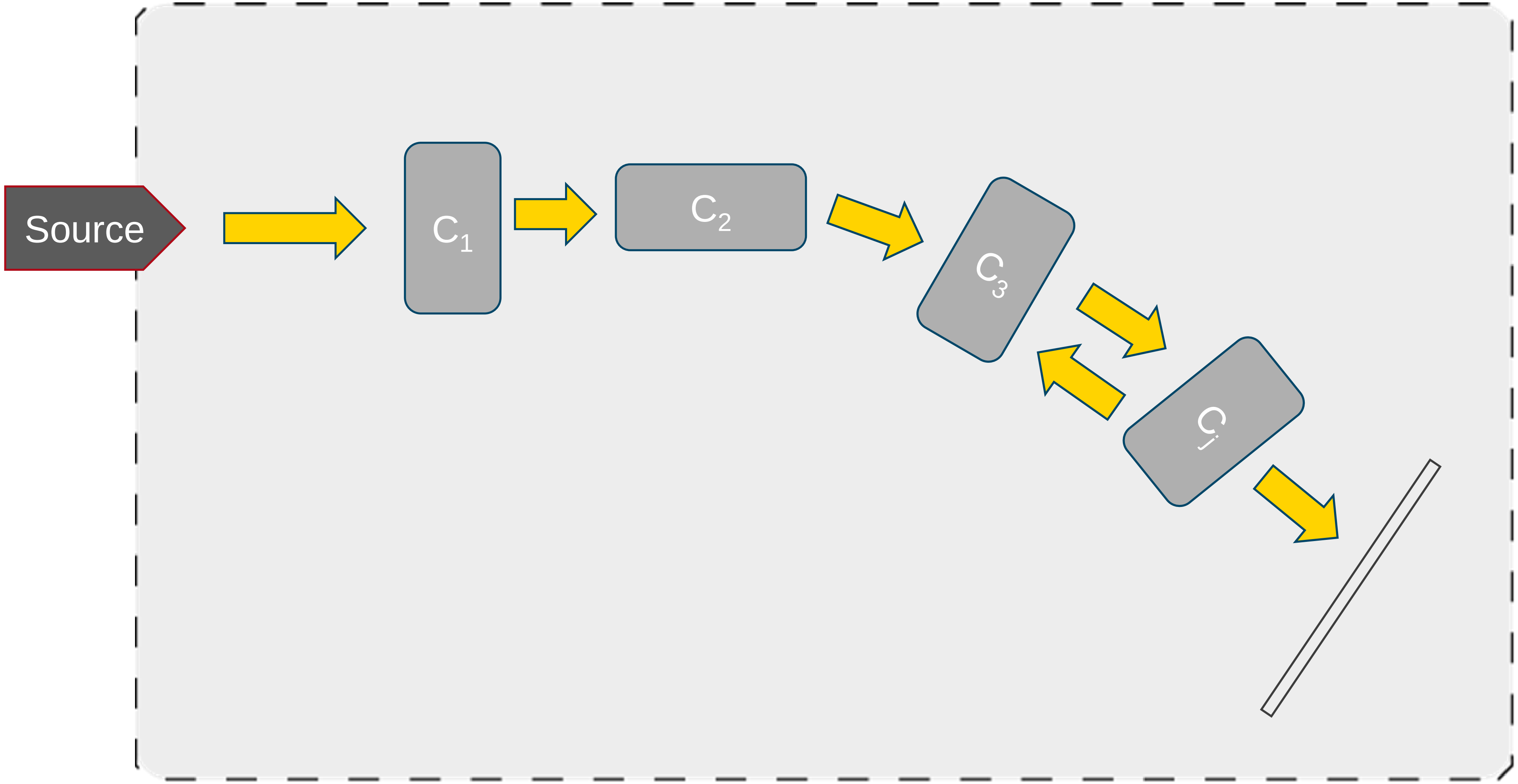
Lightpaths in Non-Sequential Modeling



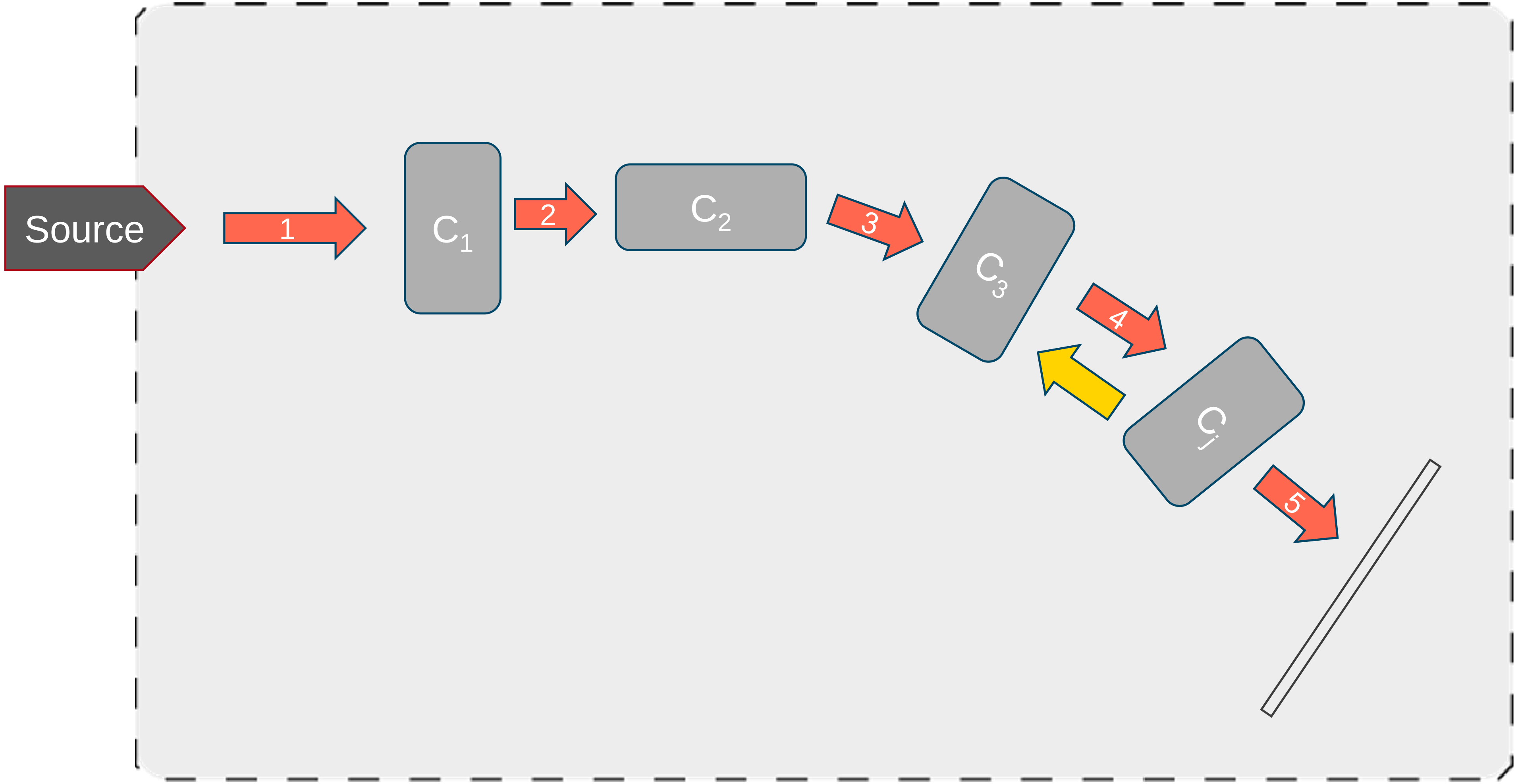
Lightpaths in Non-Sequential Modeling



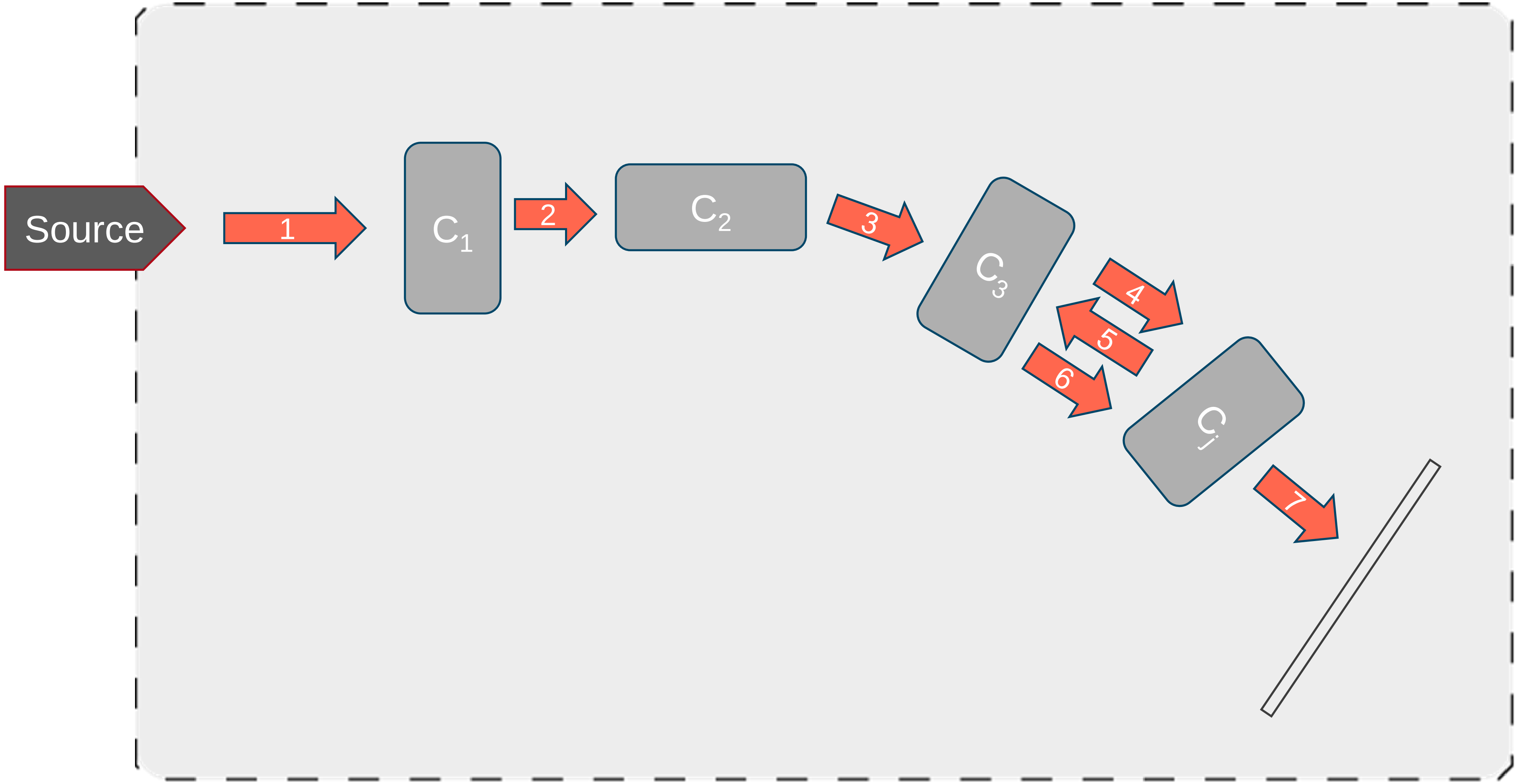
Lightpaths in Non-Sequential Modeling

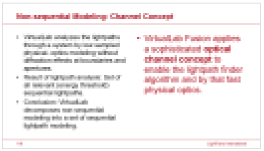


Lightpaths in Non-Sequential Modeling



Lightpaths in Non-Sequential Modeling

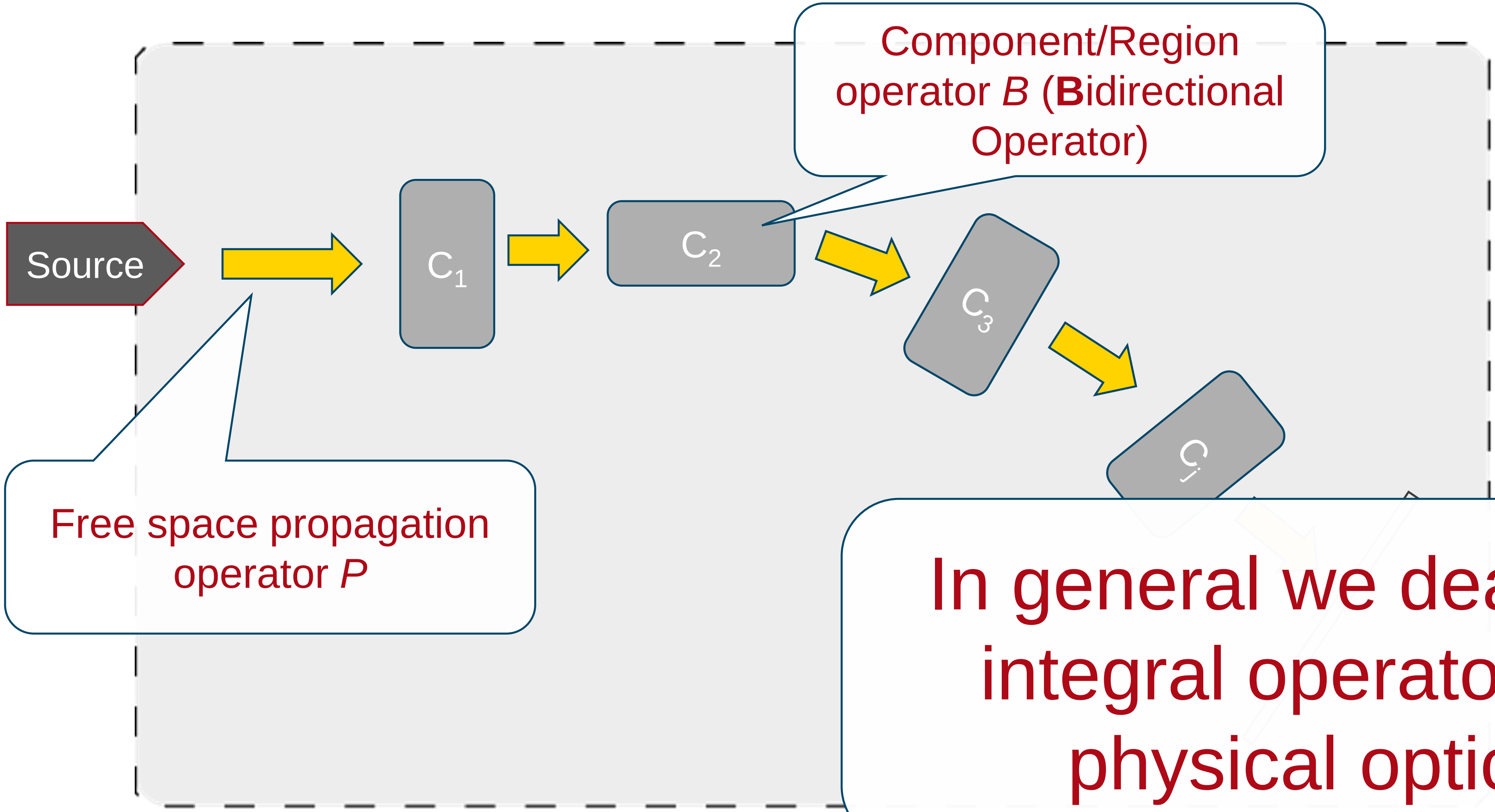




Field tracing: Operator formalism

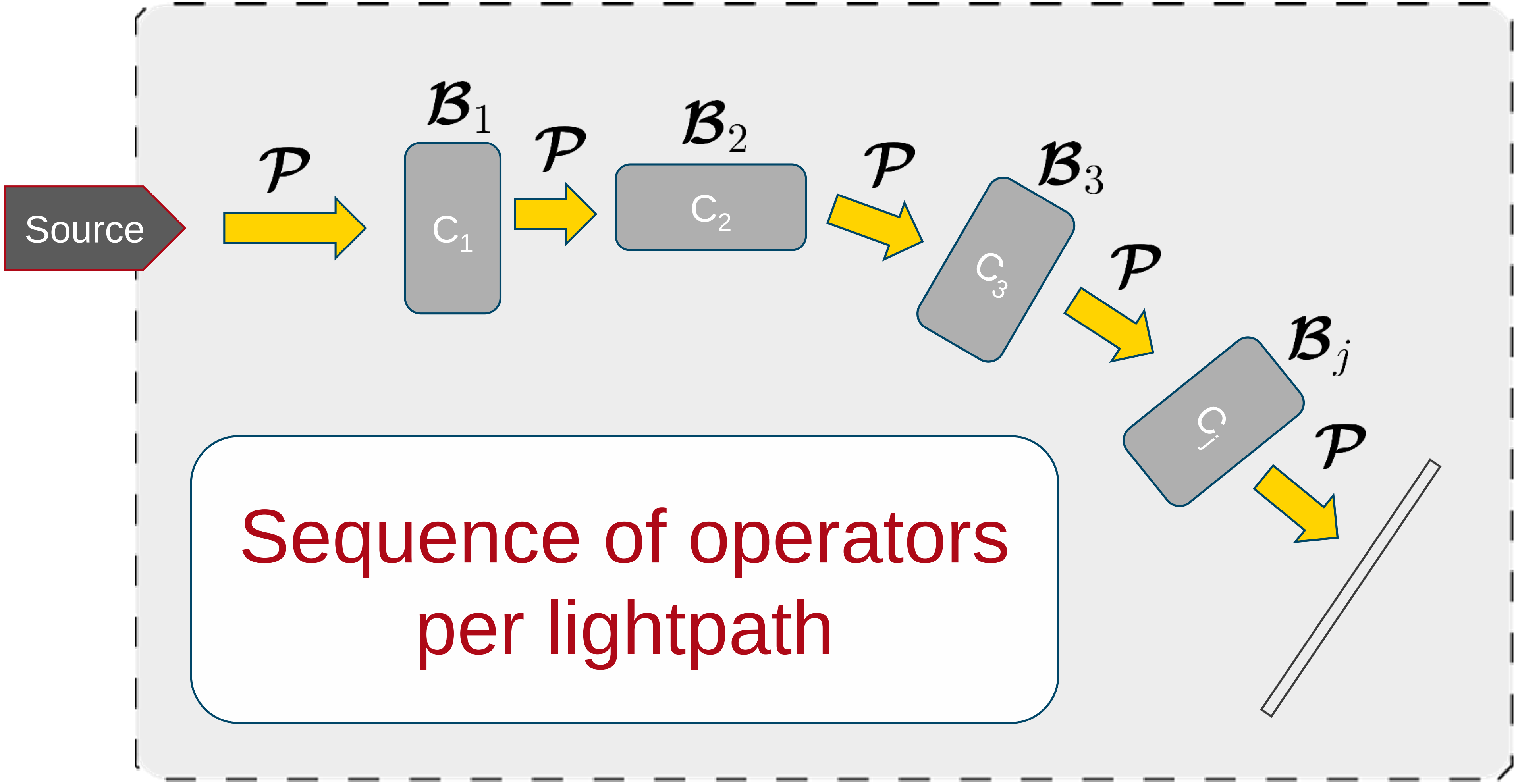
Field tracing diagrams

Field Tracing Sequence per Lightpath

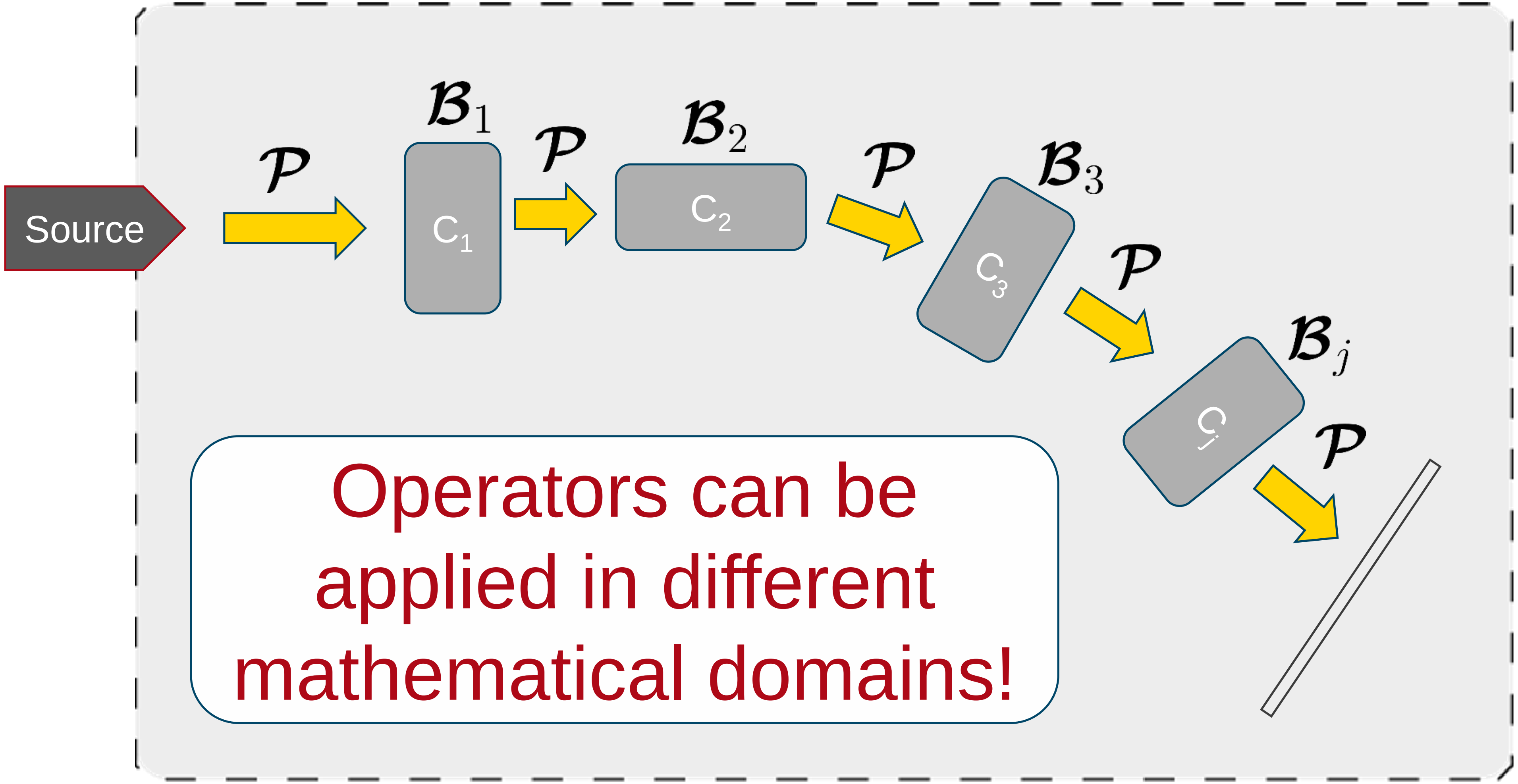


In general we deal with integral operators in physical optics

Field Tracing Sequence per Lightpath



Field Tracing Sequence per Lightpath



Operators can be applied in different mathematical domains!

Electromagnetic Field Representation

- Fields are fully specified by two of six field components, that is with $\boldsymbol{\rho} = (x, y)$

$$\boldsymbol{V}_{\perp}(\boldsymbol{\rho};\omega) = \big(V_1(\boldsymbol{\rho};\omega), V_2(\boldsymbol{\rho};\omega)\big)\ .$$

- In the k-domain we have with $\boldsymbol{\kappa} = (k_x, k_y)$

$$\tilde{\boldsymbol{V}}_{\perp}(\boldsymbol{\kappa};\omega) = \big(\tilde{V}_1(\boldsymbol{\kappa};\omega), \tilde{V}_2(\boldsymbol{\kappa};\omega)\big)\ .$$

- Operators connect two fields via:

$$\boldsymbol{V}_{\perp}^{\mathrm{out}}(\boldsymbol{\rho};\omega) = \boldsymbol{\mathcal{B}}\boldsymbol{V}_{\perp}^{\mathrm{in}}(\boldsymbol{\rho};\omega)$$
$$\tilde{\boldsymbol{V}}_{\perp}^{\mathrm{out}}(\boldsymbol{\kappa};\omega) = \tilde{\boldsymbol{\mathcal{B}}}\tilde{\boldsymbol{V}}_{\perp}^{\mathrm{in}}(\boldsymbol{\kappa};\omega)$$

- The six field components are defined by:

$$\boldsymbol{V}(\boldsymbol{r};\omega) = \begin{pmatrix} E_x(\boldsymbol{r};\omega) \\ E_y(\boldsymbol{r};\omega) \\ E_z(\boldsymbol{r};\omega) \\ H_x(\boldsymbol{r};\omega) \\ H_y(\boldsymbol{r};\omega) \\ H_z(\boldsymbol{r};\omega) \end{pmatrix}$$

- From E_x and E_y the other components can be calculated on demand.

Field Tracing Operators

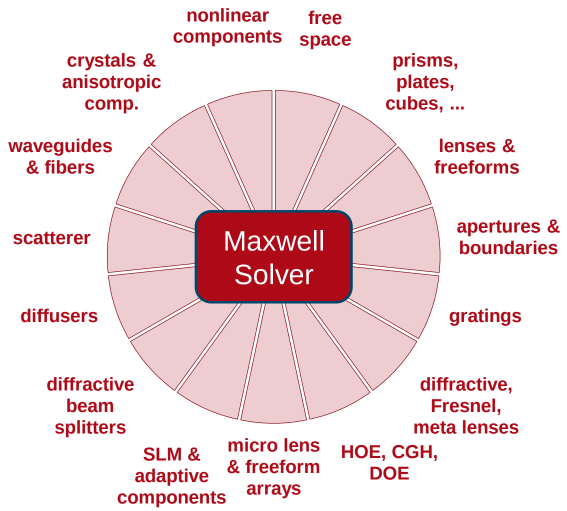
- The operator matrices are given by:

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

- The operators $\mathcal{B}_{ij}$ and $\tilde{\mathcal{B}}_{ij}$ are in general integral operators:

$$V^{\text{out}}(\boldsymbol{\rho};\omega) = \int\int B(x,y,x',y';\omega)V^{\text{in}}(x',y';\omega)\,\mathrm{d}x'\,\mathrm{d}y'$$

$$\tilde{V}^{\text{out}}(\boldsymbol{\kappa};\omega) = \int\int \tilde{B}(k_x,k_y,k_x',k_y';\omega)\tilde{V}^{\text{in}}(k_y',k_y';\omega)\,\mathrm{d}k_x'\,\mathrm{d}k_y'$$

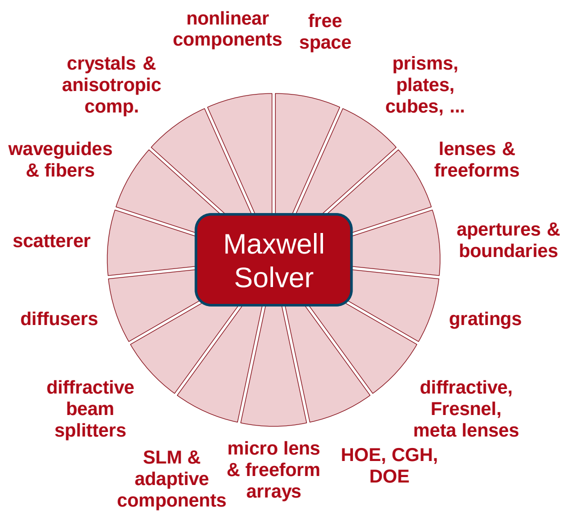


Bidirectional Operators

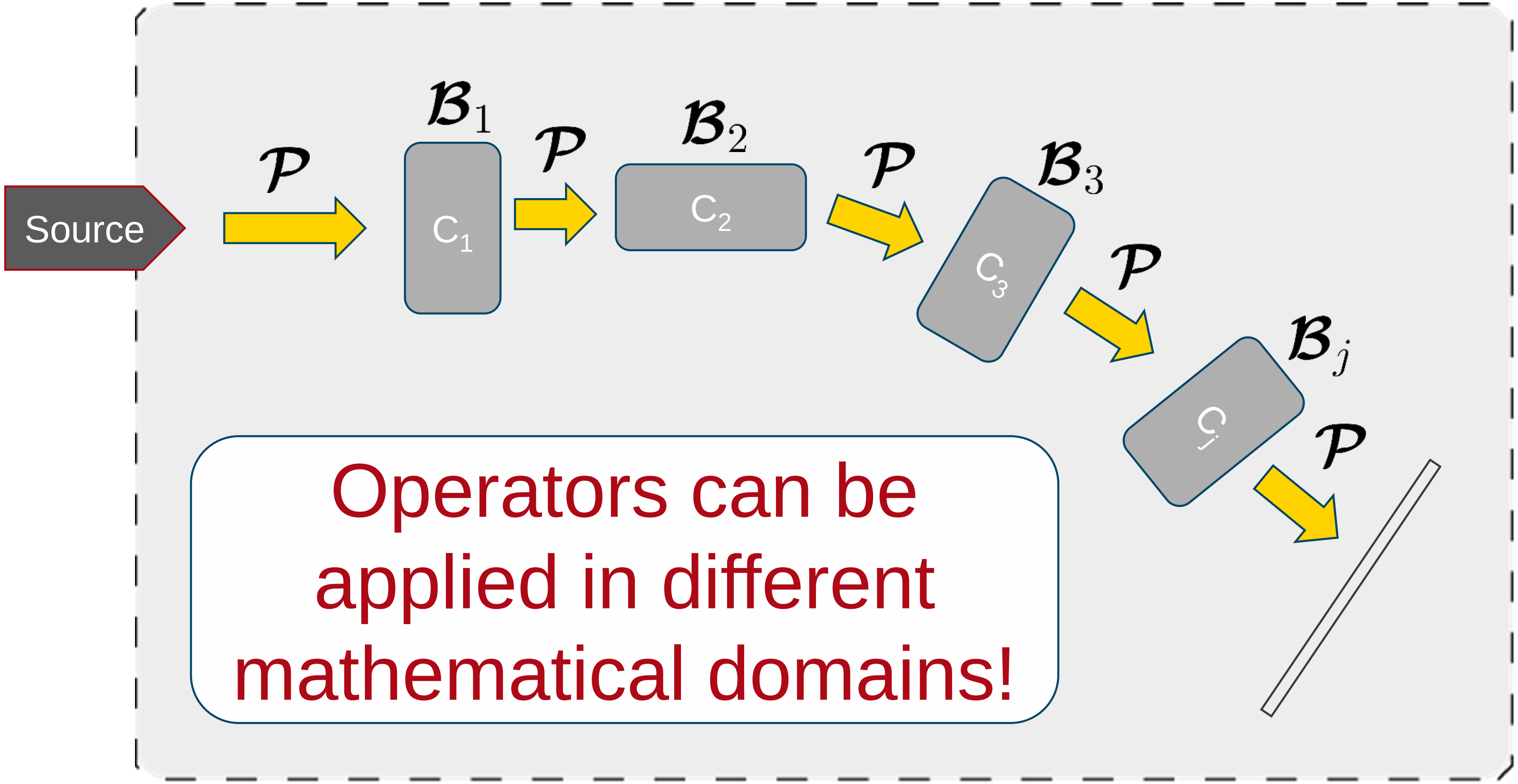
- We refer to $\tilde{\mathcal{B}}$ as the bidirectional operator, because it connects the $\boldsymbol{\kappa}$-variables of the input and the output fields:

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

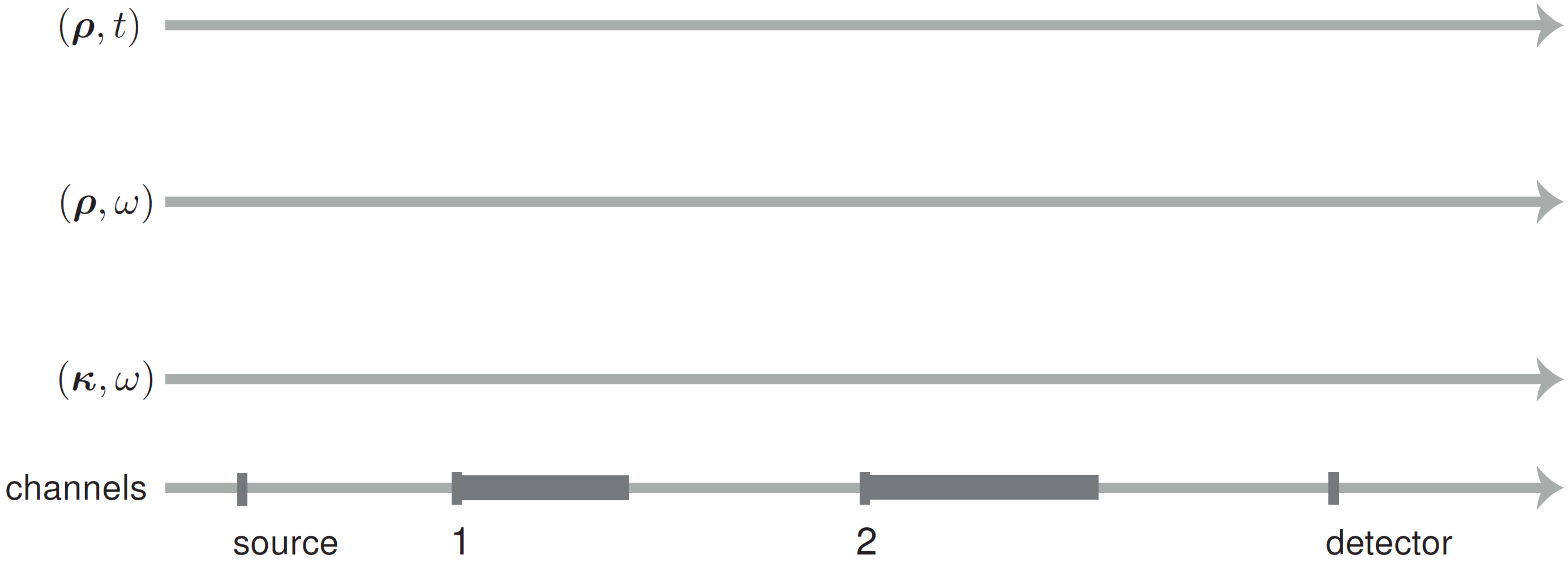
- It can be understood as the physical-optics generalization of the Bidirectional Scattering Distribution Function (BSDF) in ray tracing.
- Independent of the domain we refer to B-operators in field tracing for the algorithms of regional Maxwell solvers.
- The propagation operator through free space, e.g. $\mathcal{P}$ is a special case of a B-operator which gets a special symbol because of its importance.



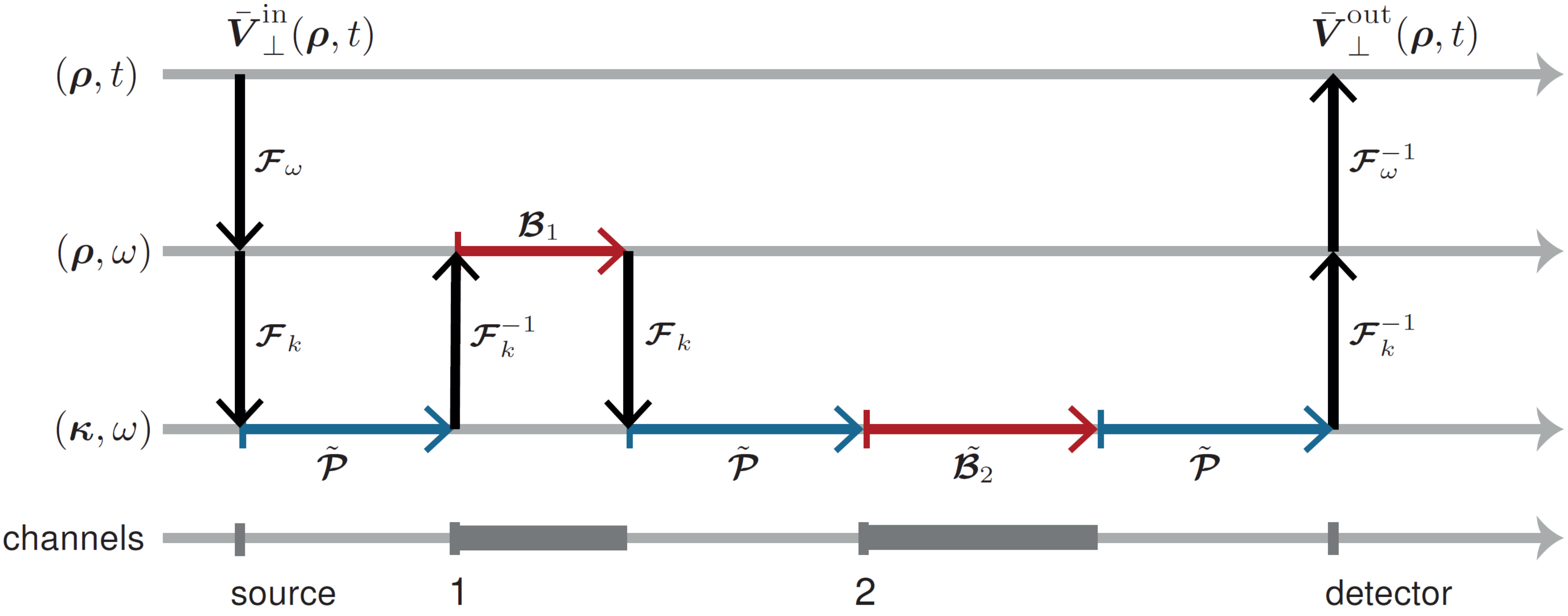
Field Tracing Sequence per Lightpath



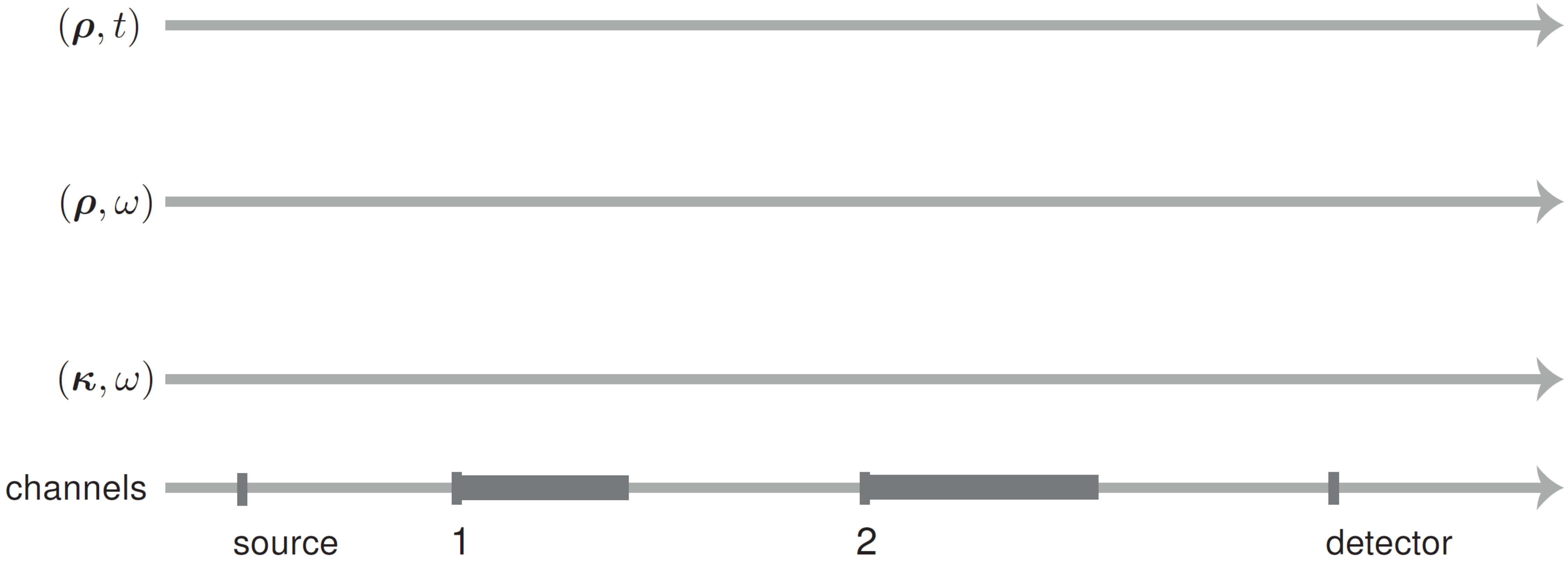
Field Tracing Diagrams



Field Tracing Diagrams: Ultrashort-Pulse Modeling

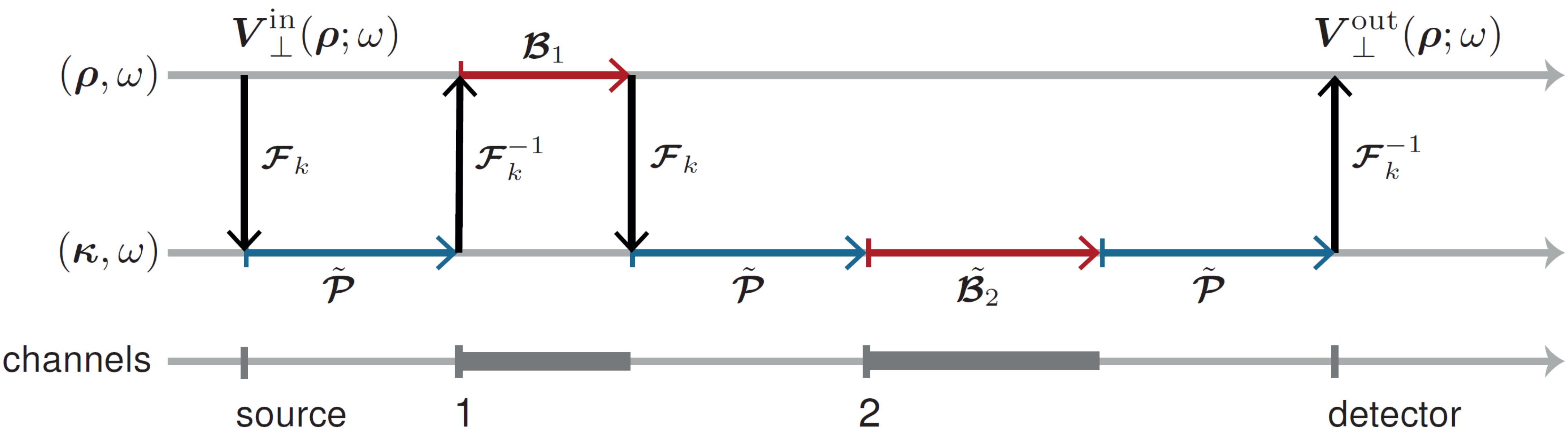


Field Tracing Diagrams

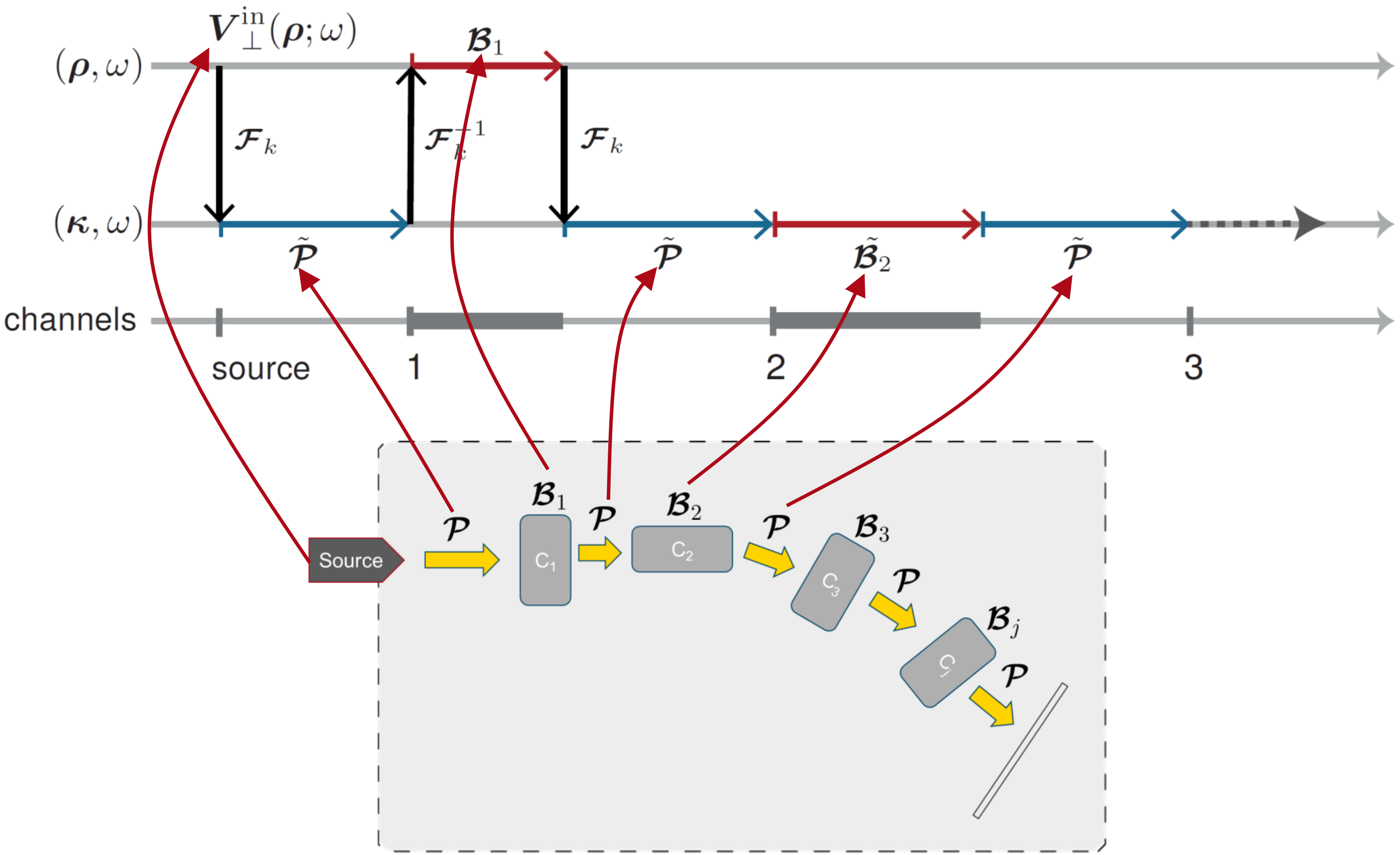


Field Tracing Diagrams

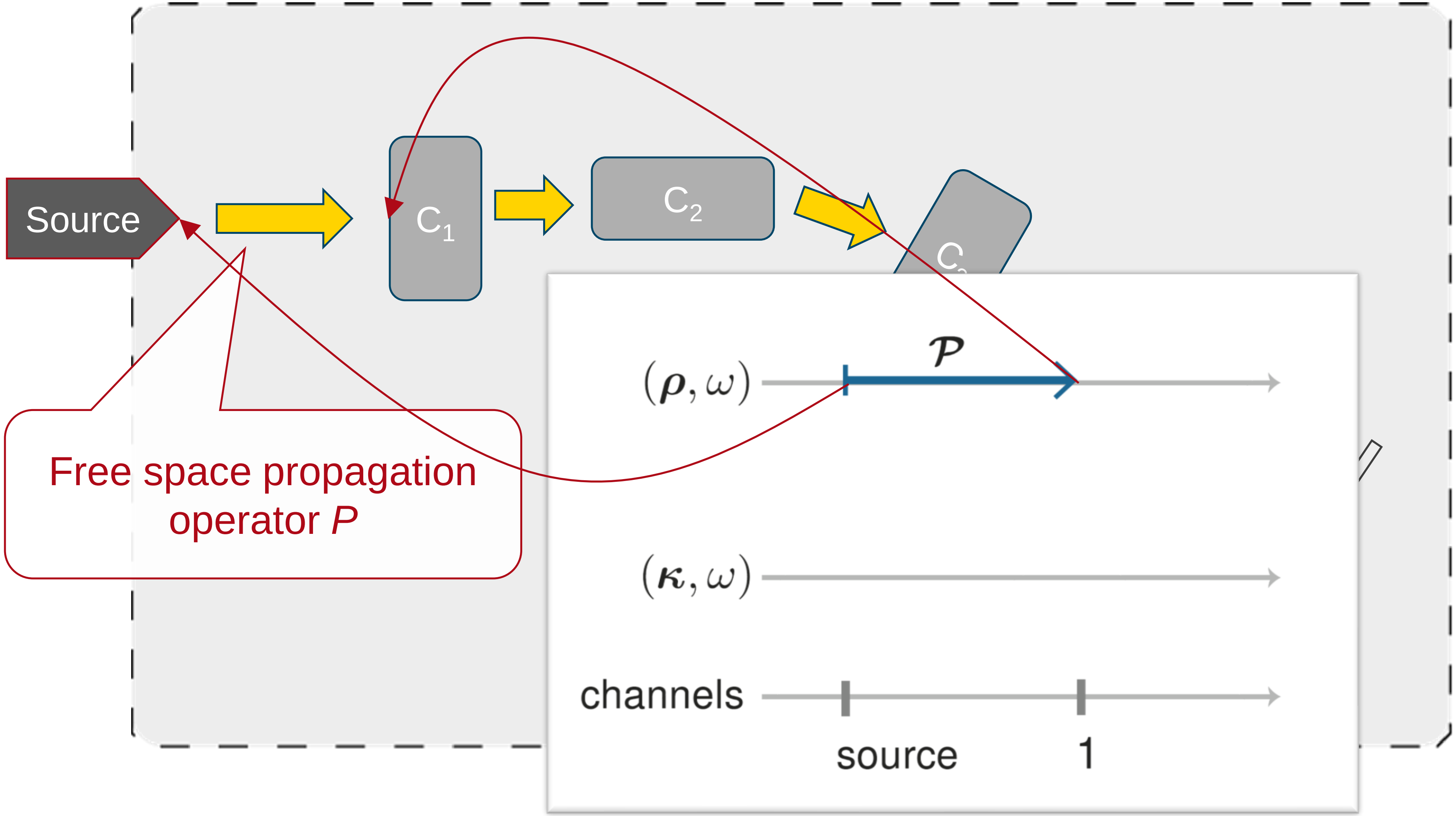
Field Tracing Diagrams



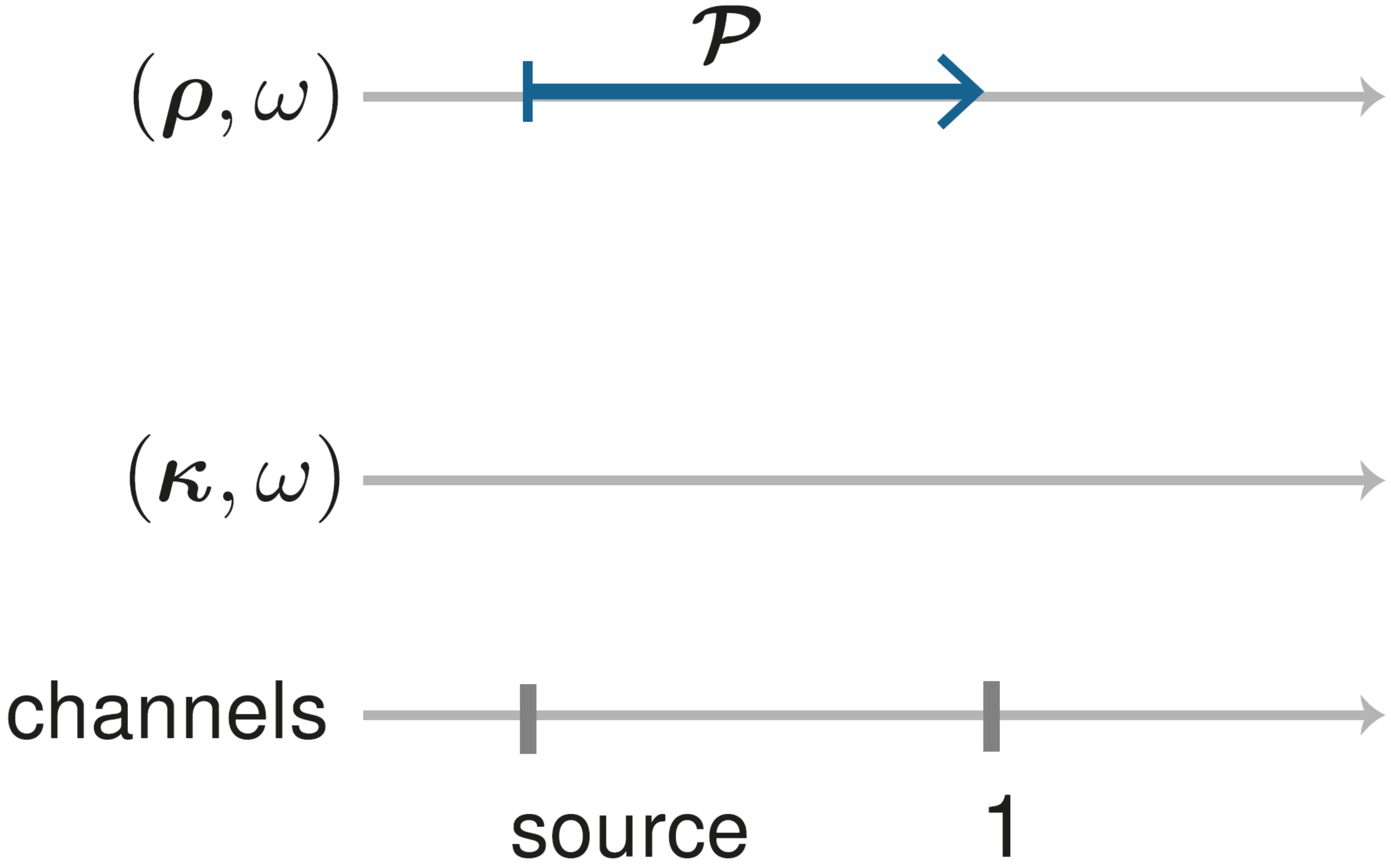
Field Tracing Diagrams



Field Tracing Diagrams



Free-Space Propagation Operator: x-Domain



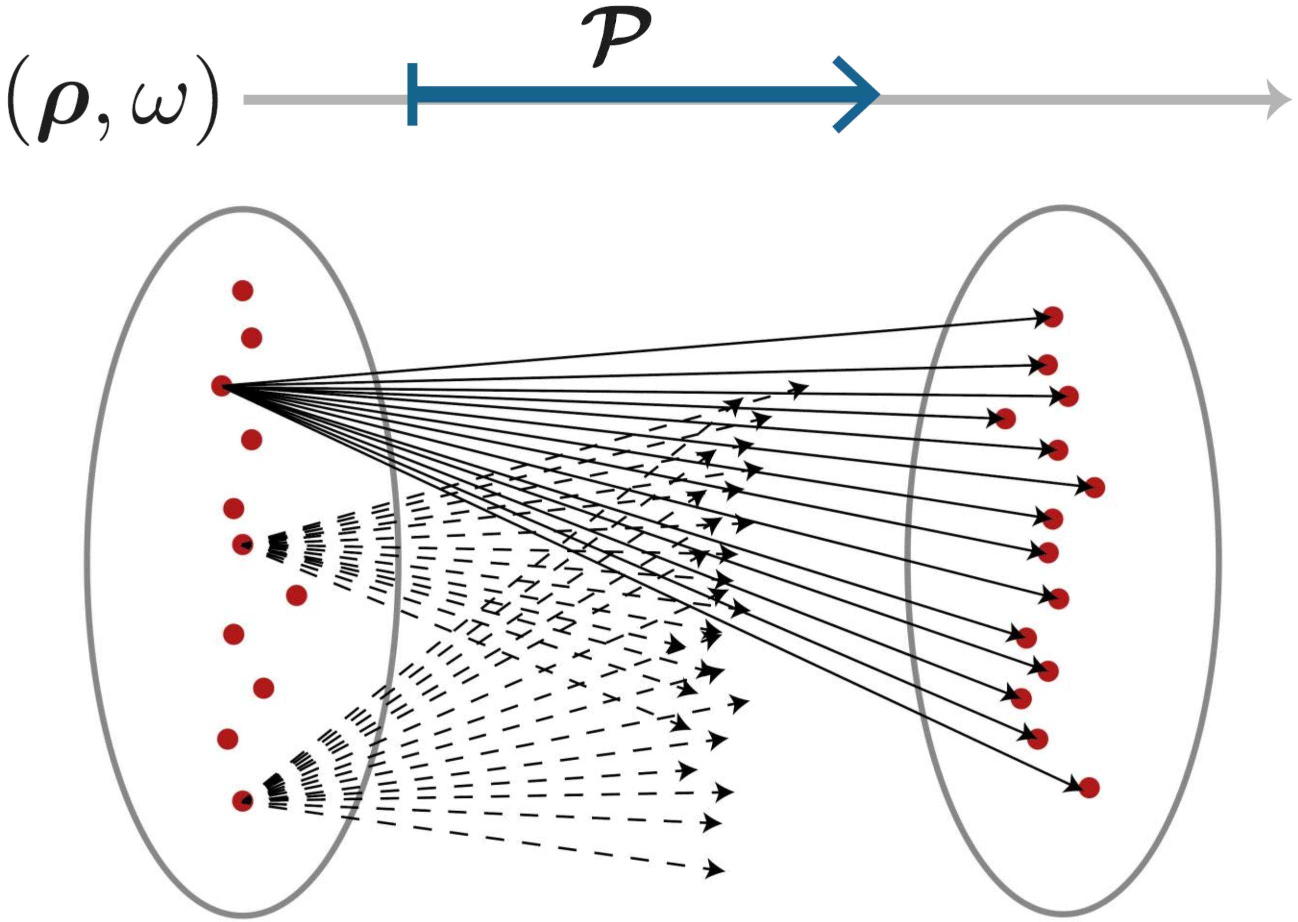
Free-Space Propagation Operator: x-Domain

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

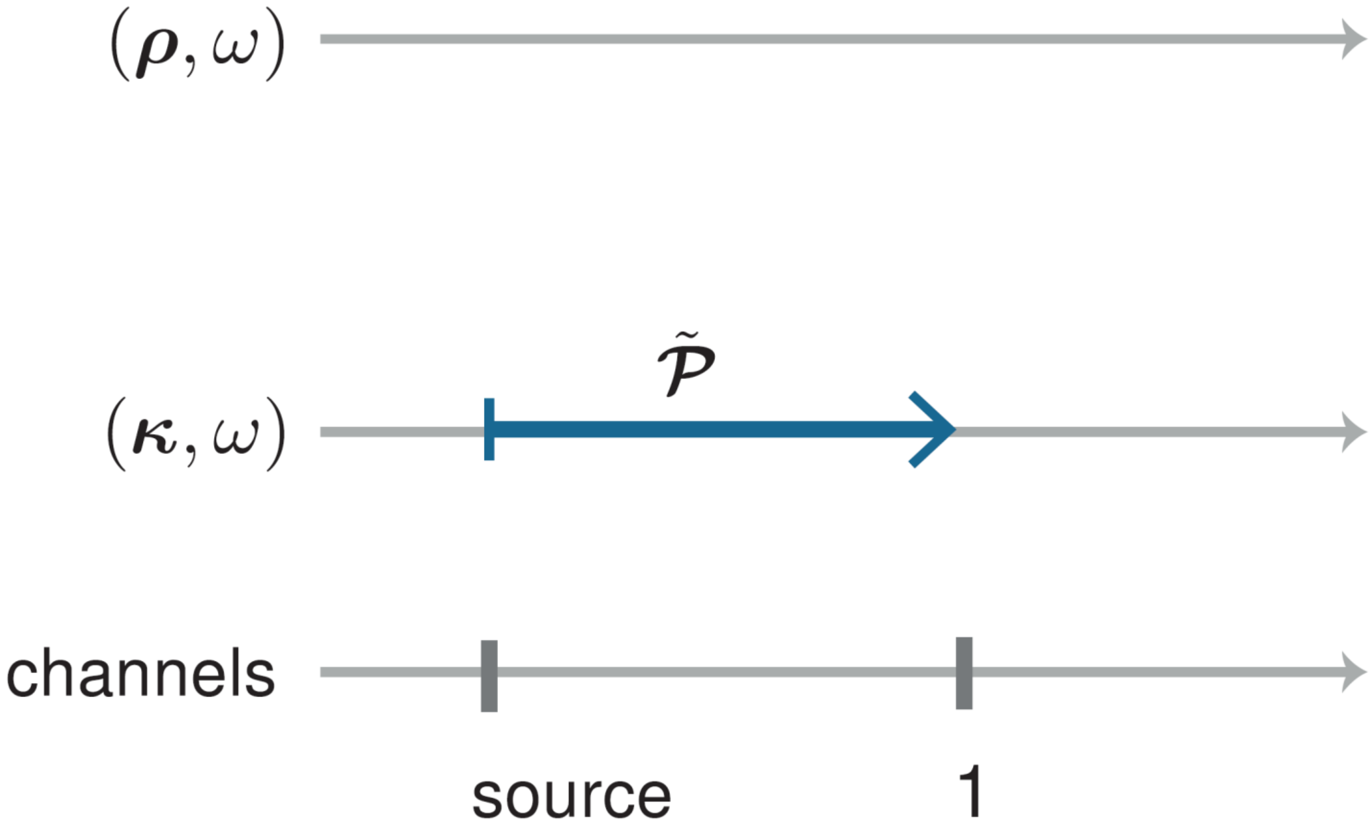
$$V^{\mathrm{out}}(\boldsymbol{\rho}, z) \propto \int\int_{-\infty}^{\infty} V^{\mathrm{in}}(\boldsymbol{\rho}', z_0)\, \frac{\exp(\mathrm{i}k_0\check{n}R)}{R} \left(\mathrm{i}k_0\check{n} - \frac{1}{R}\right) \frac{\Delta z}{R}\, \mathrm{d}^2\rho'$$

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

Free-Space Propagation Operator: x-Domain



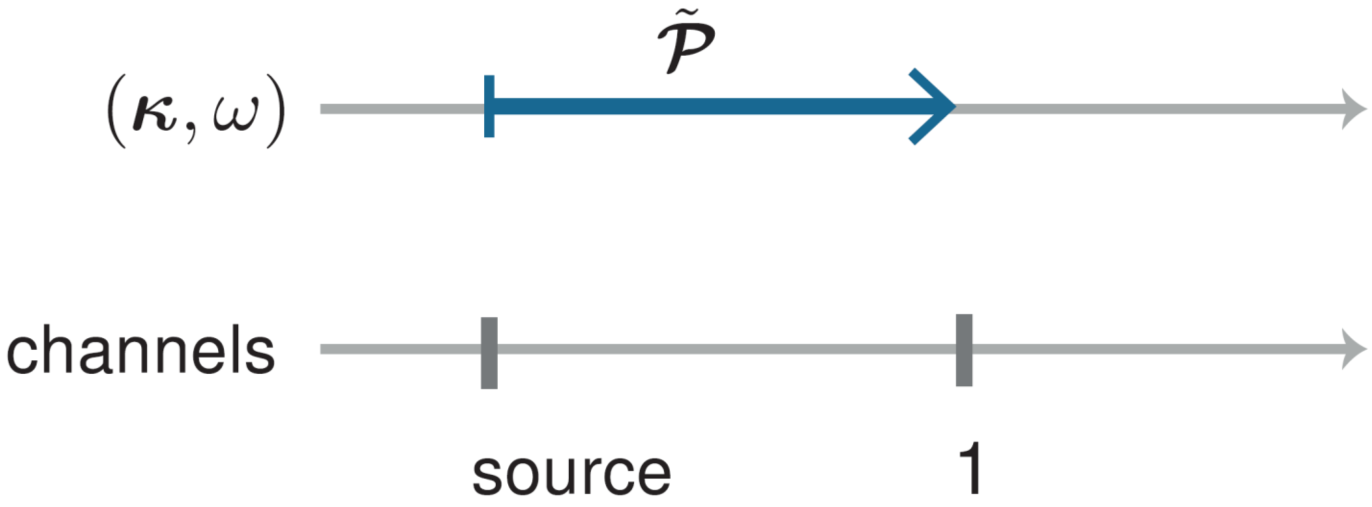
Free-Space Propagation Operator: k-Domain



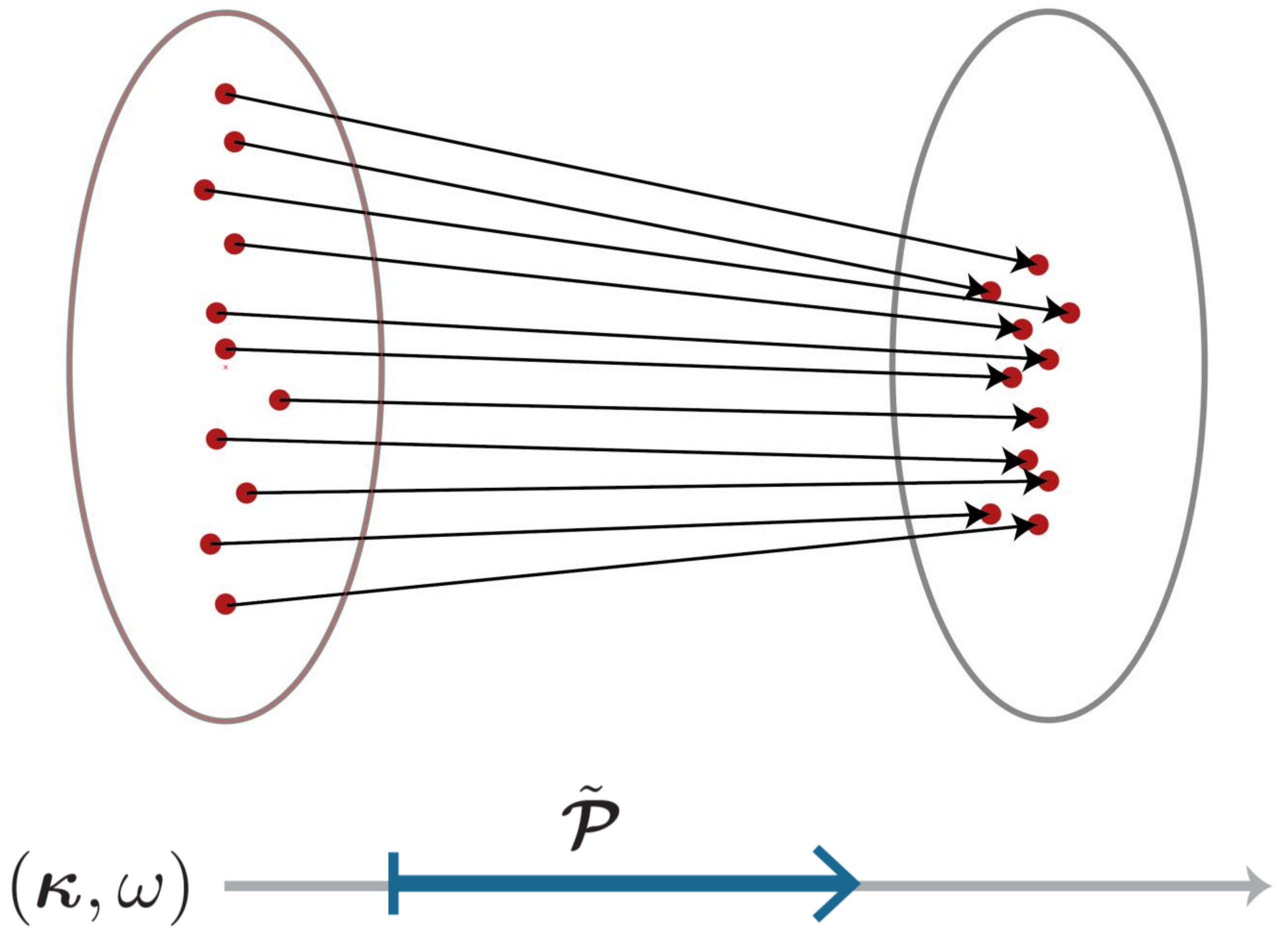
Free-Space Propagation Operator: k-Domain

Rigorous propagation in k-domain:

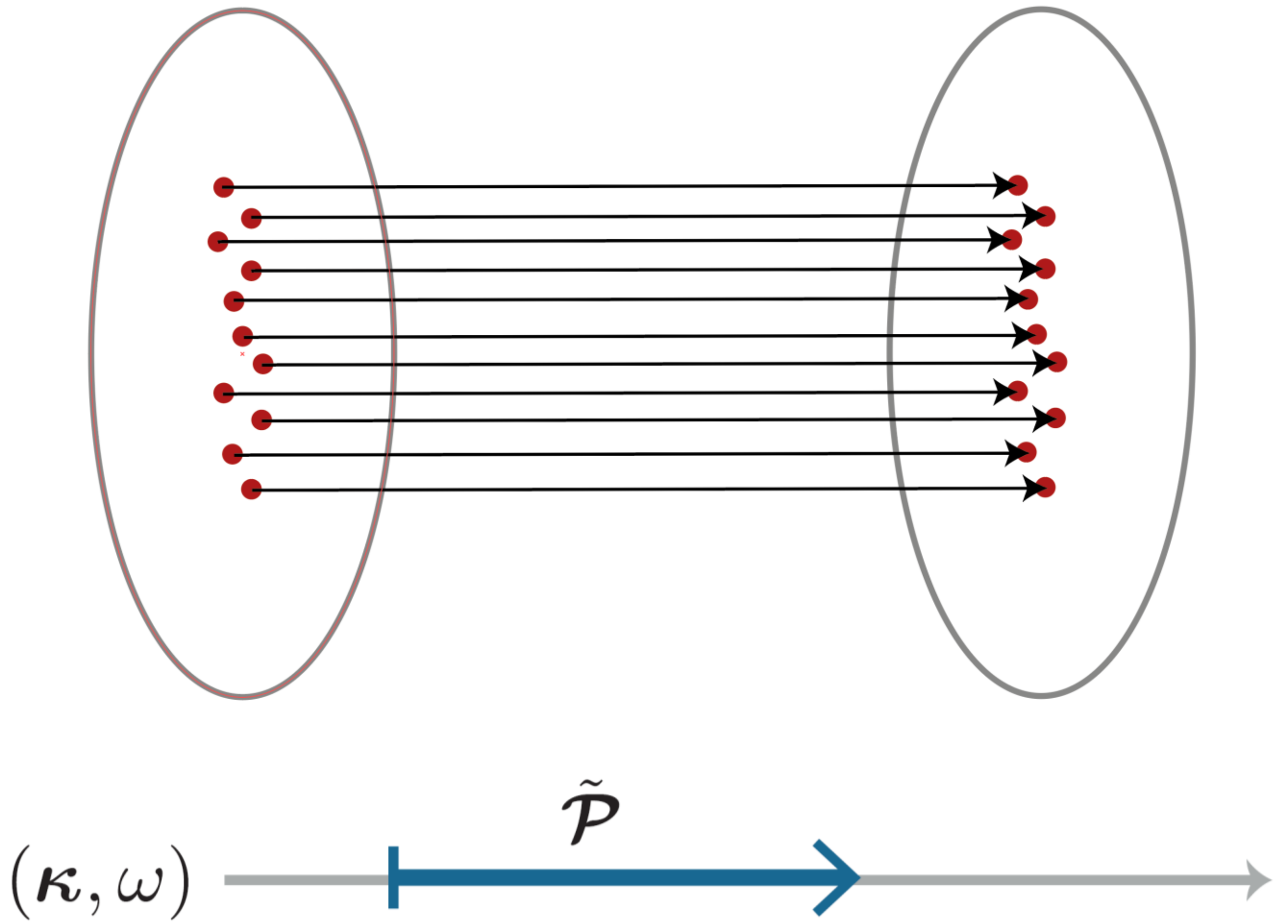
$$\tilde{V}^{\text{out}}(\boldsymbol{\kappa}, z) = \tilde{V}^{\text{in}}(\boldsymbol{\kappa}, z_0) \times \exp\left(\mathrm{i}\check{k}_z(\kappa)\Delta z\right)$$



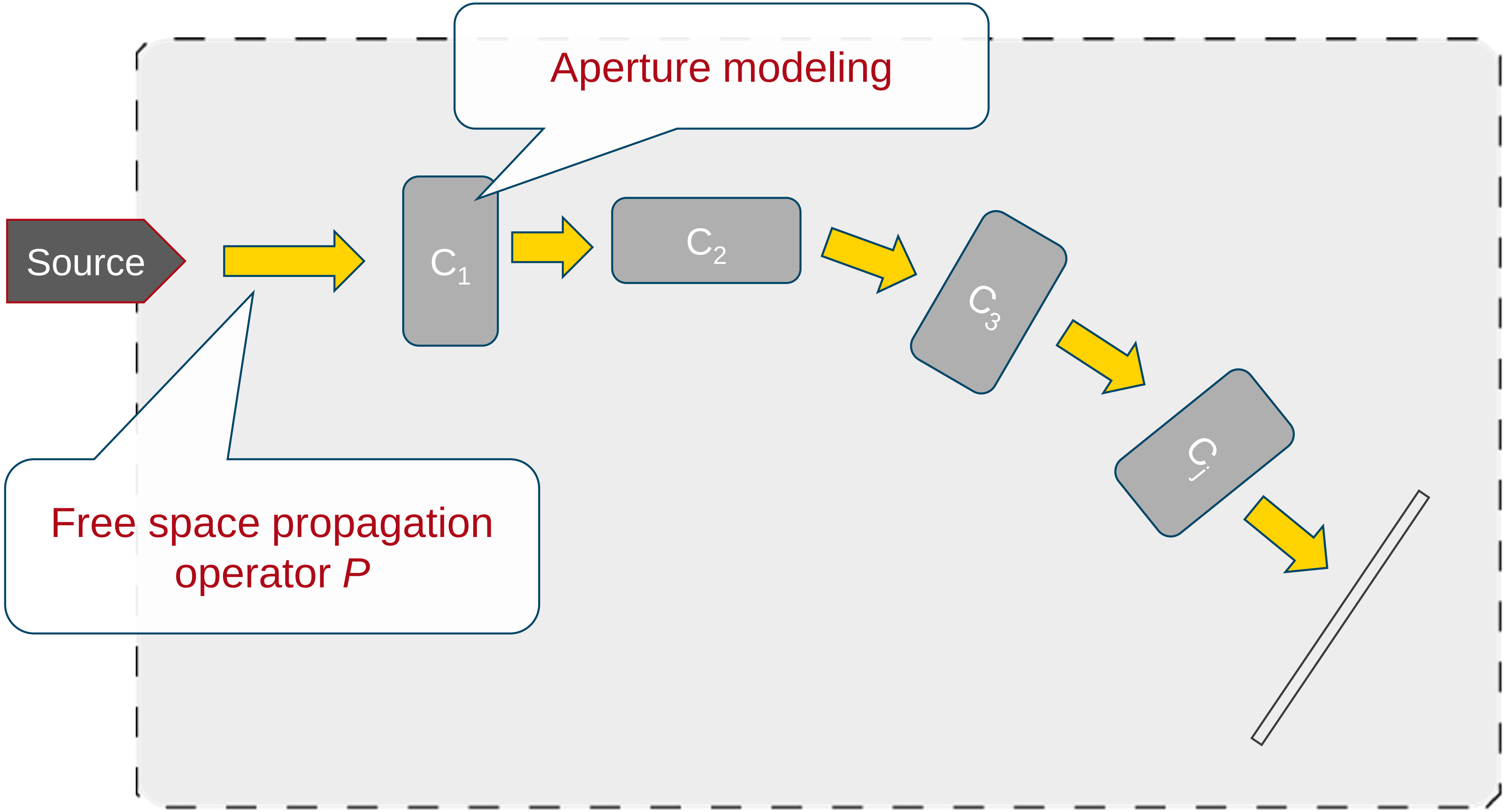
Free-Space Propagation Operator: k-Domain



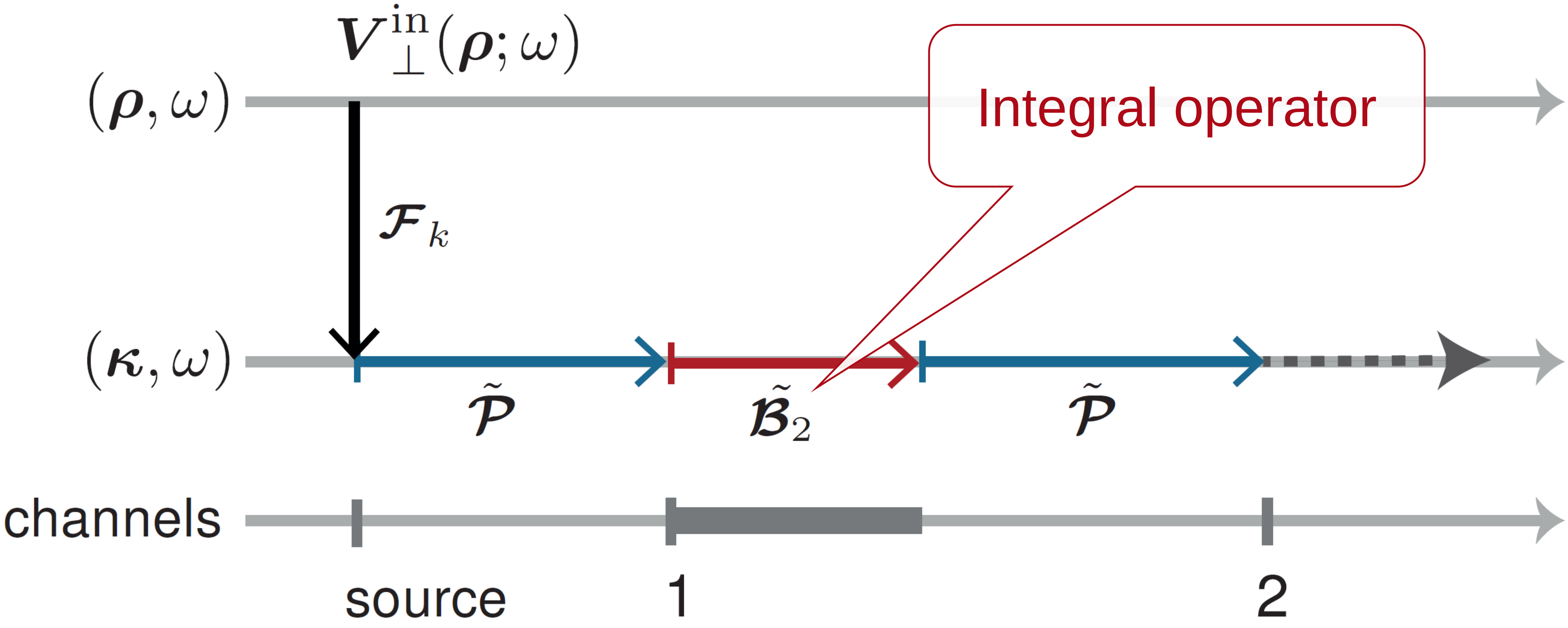
Free-Space Propagation Operator: k-Domain



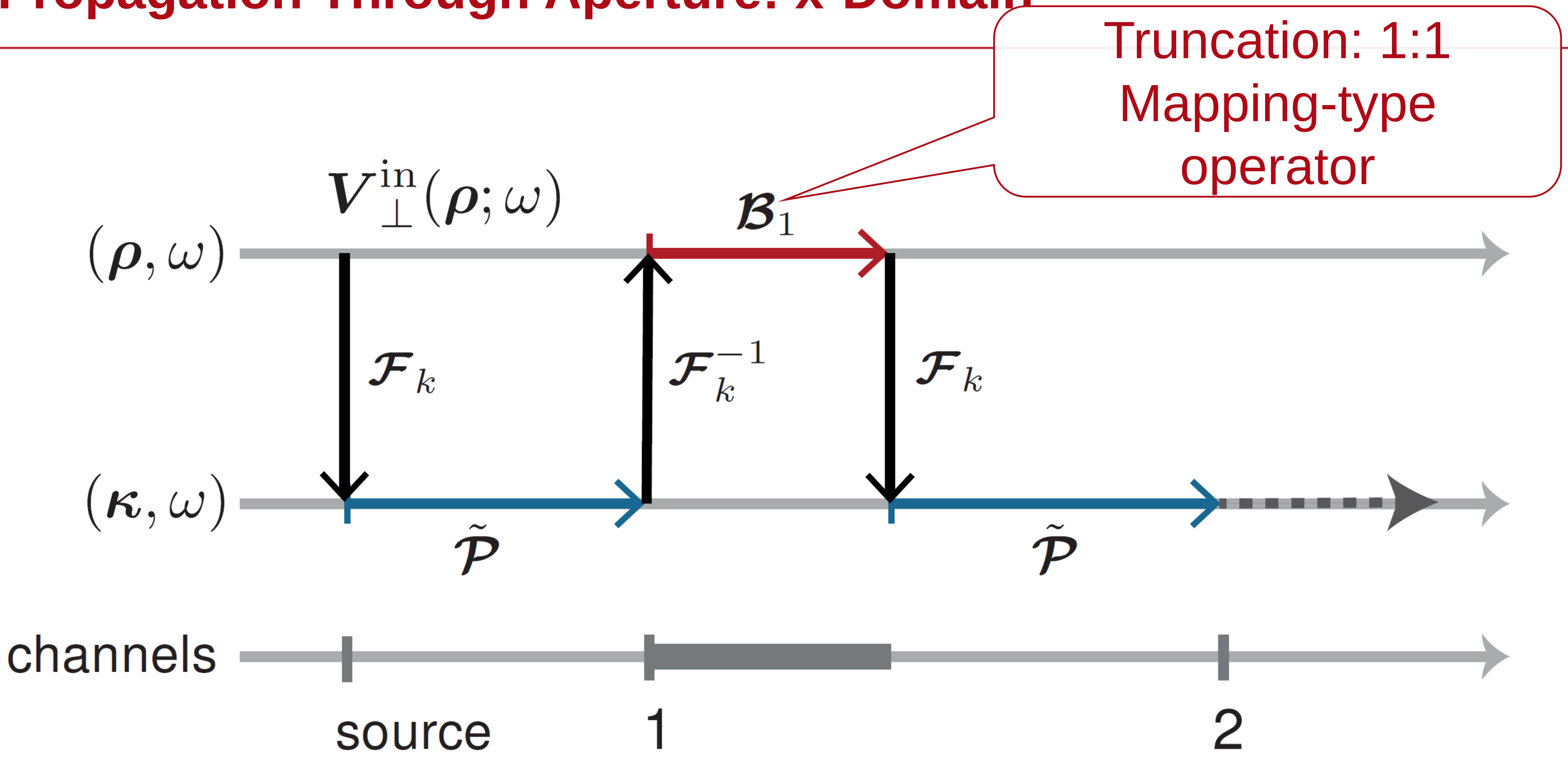
Field Tracing Sequence per Lightpath



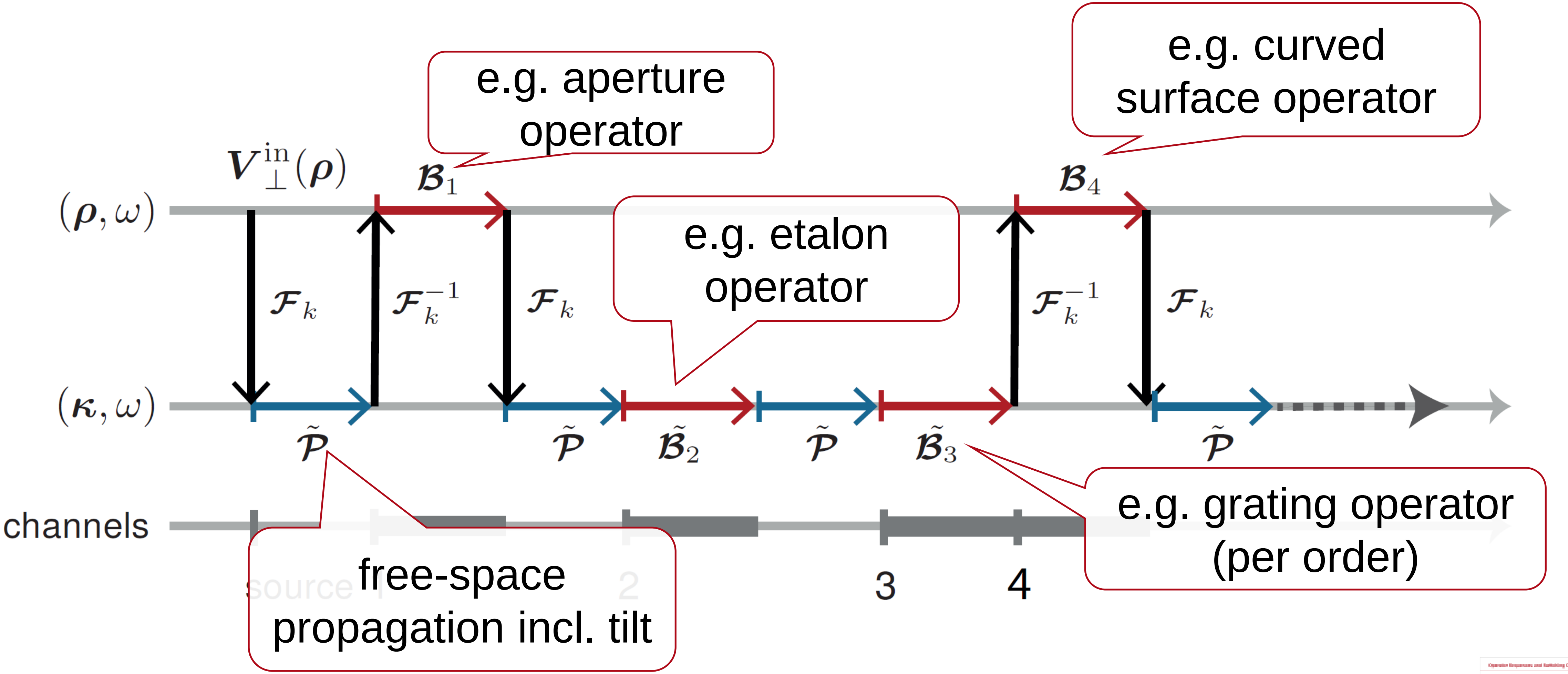
Propagation Through Aperture: k-Domain



Propagation Through Aperture: x-Domain



Switching Domains: Preferable Operators Linear in N



Homeomorphic and semianalytical Fourier transform

Reducing sampling effort of Fourier transform integrals and sampling in modeling in general

Wavefront Phase of Electromagnetic Fields

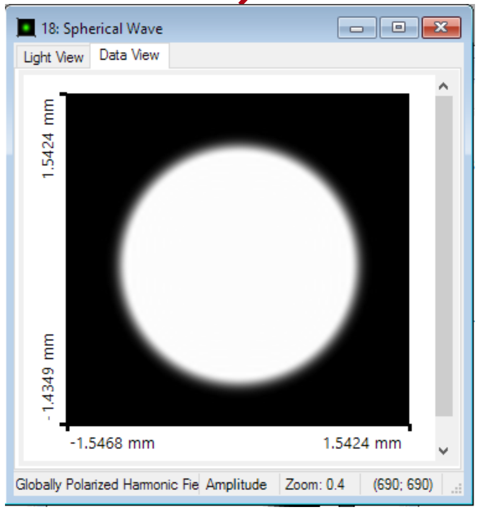
We identify in both domains the common smooth part of the phase and separate them from the field components and obtain:

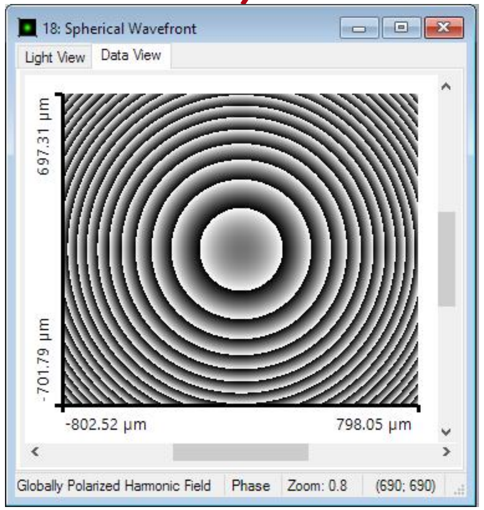
$$\begin{aligned} V_\ell(\boldsymbol{\rho},z,\omega) &= U_\ell(\boldsymbol{\rho},z,\omega)\exp\big(\mathrm{i}\psi(\boldsymbol{\rho},z,\omega)\big) \\ &= |V_\ell(\boldsymbol{\rho},z,\omega)|\exp\big(\mathrm{i}\varphi_\ell(\boldsymbol{\rho},z,\omega)\big)\,\exp\big(\mathrm{i}\psi(\boldsymbol{\rho},z,\omega)\big)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

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

Example Spherical Field

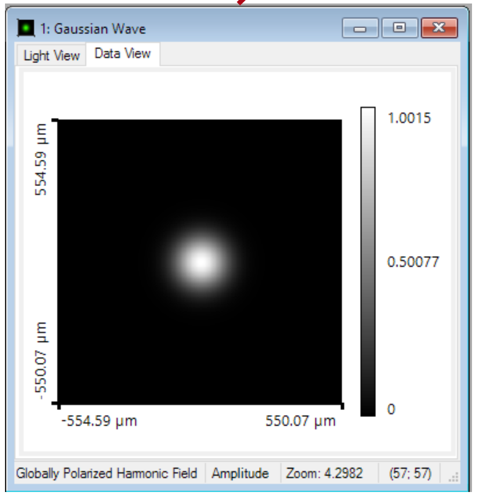
$$V_\ell(\boldsymbol{\rho},z,\omega) = |V_\ell(\boldsymbol{\rho},z,\omega)| \exp\left(\mathrm{i}\varphi_\ell(\boldsymbol{\rho},z,\omega)\right) \exp\left(\mathrm{i}\psi(\boldsymbol{\rho},z,\omega)\right)$$

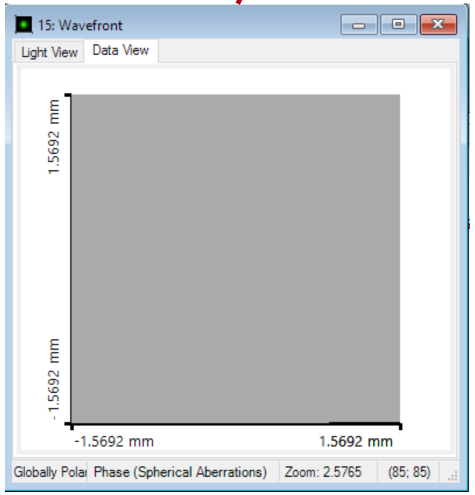




Example Gaussian Beam in Its Waist

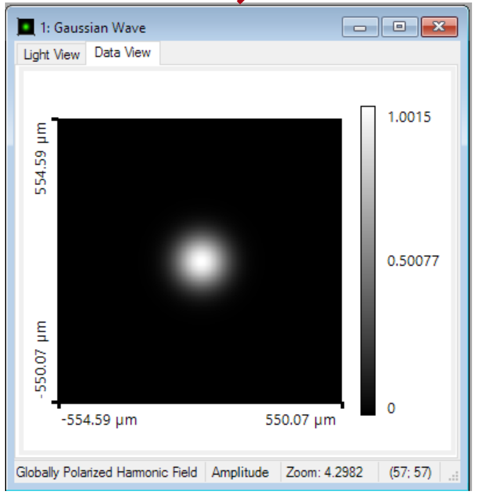
$$V_\ell(\boldsymbol{\rho},z,\omega) = |V_\ell(\boldsymbol{\rho},z,\omega)| \exp(\mathrm{i}\varphi_\ell(\boldsymbol{\rho},z,\omega)) \exp(\mathrm{i}\psi(\boldsymbol{\rho},z,\omega))$$

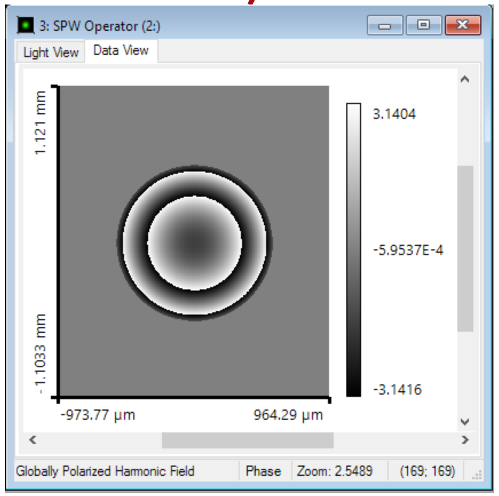




Example Propagated Gaussian Beam

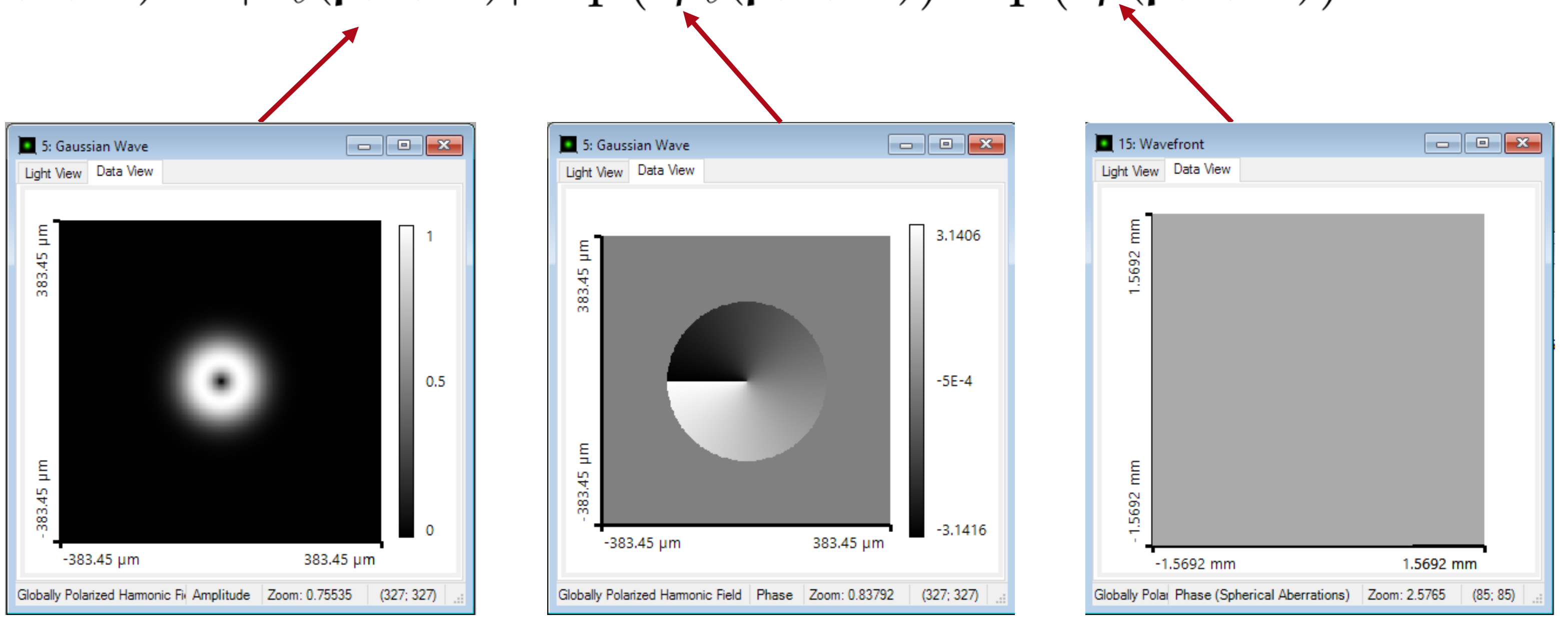
$$V_\ell(\boldsymbol{\rho},z,\omega) = |V_\ell(\boldsymbol{\rho},z,\omega)| \exp\left(\mathrm{i}\varphi_\ell(\boldsymbol{\rho},z,\omega)\right) \exp\left(\mathrm{i}\psi(\boldsymbol{\rho},z,\omega)\right)$$





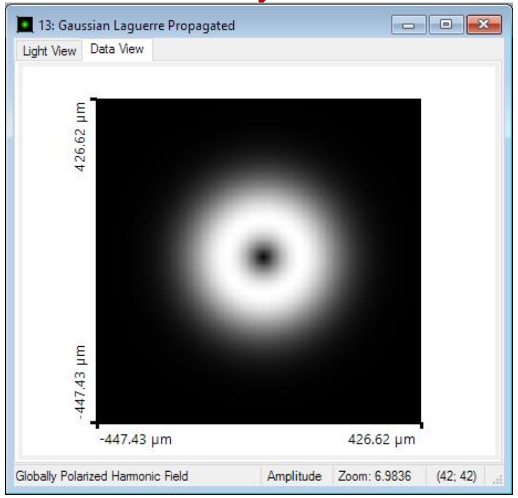
Example Gaussian Laguerre Beam in Waist

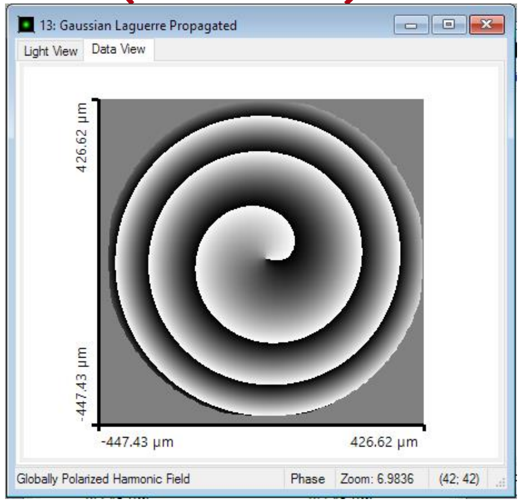
$$V_\ell(\boldsymbol{\rho},z,\omega) = |V_\ell(\boldsymbol{\rho},z,\omega)| \exp\left(i\varphi_\ell(\boldsymbol{\rho},z,\omega)\right) \exp\left(i\psi(\boldsymbol{\rho},z,\omega)\right)$$



Example Propagated Gaussian Laguerre Beam

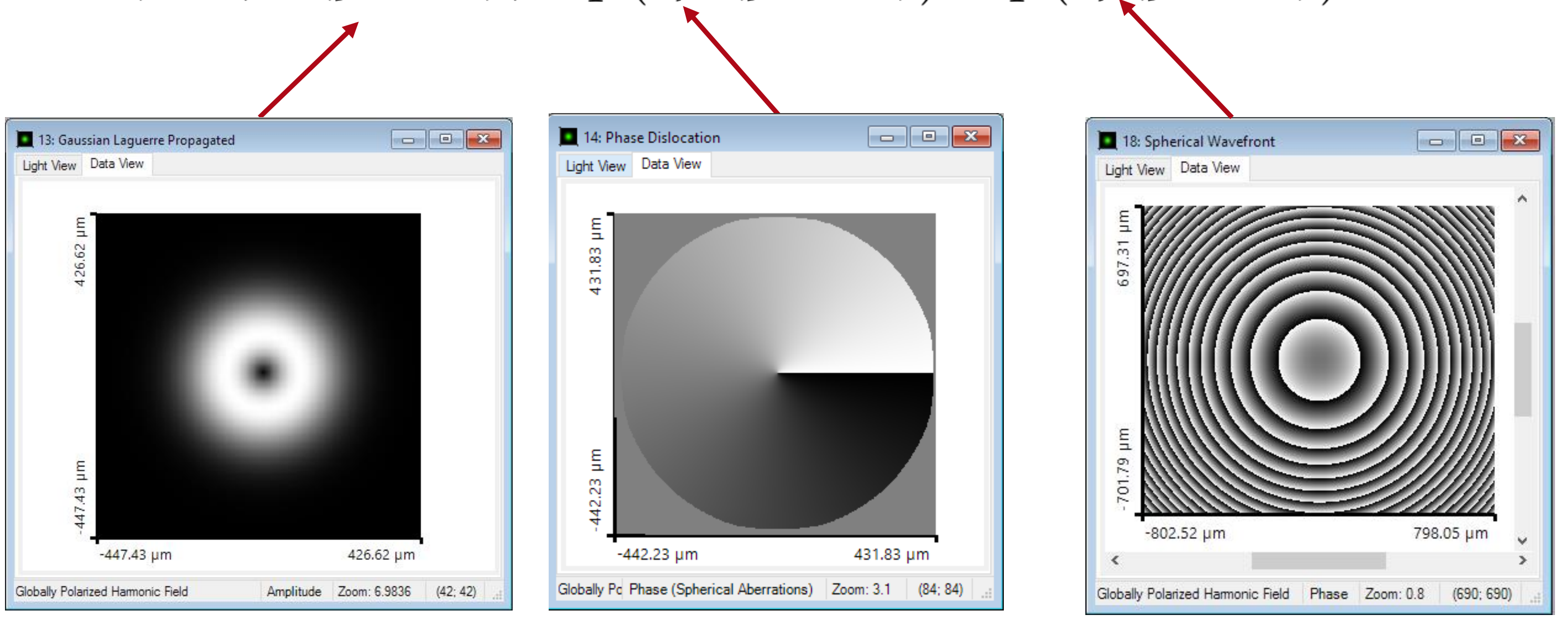
$$V_\ell(\boldsymbol{\rho},z,\omega) = |V_\ell(\boldsymbol{\rho},z,\omega)| \exp\left(\mathrm{i}\varphi_\ell(\boldsymbol{\rho},z,\omega)\right) \exp\left(\mathrm{i}\psi(\boldsymbol{\rho},z,\omega)\right)$$





Example Propagated Gaussian Laguerre Beam

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



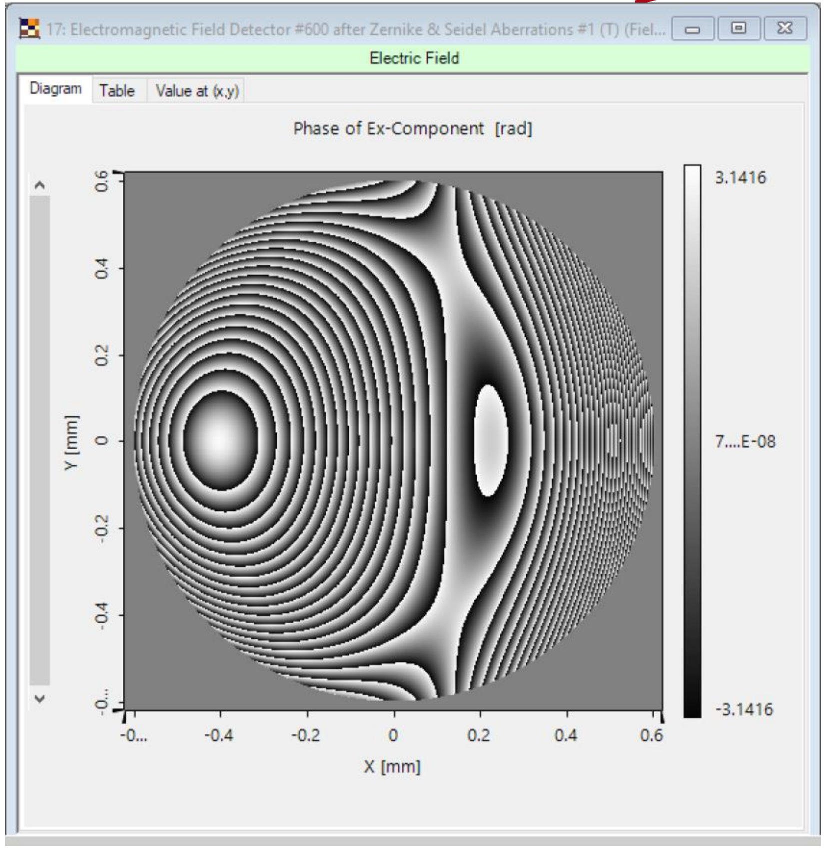
General Example with Aberrations

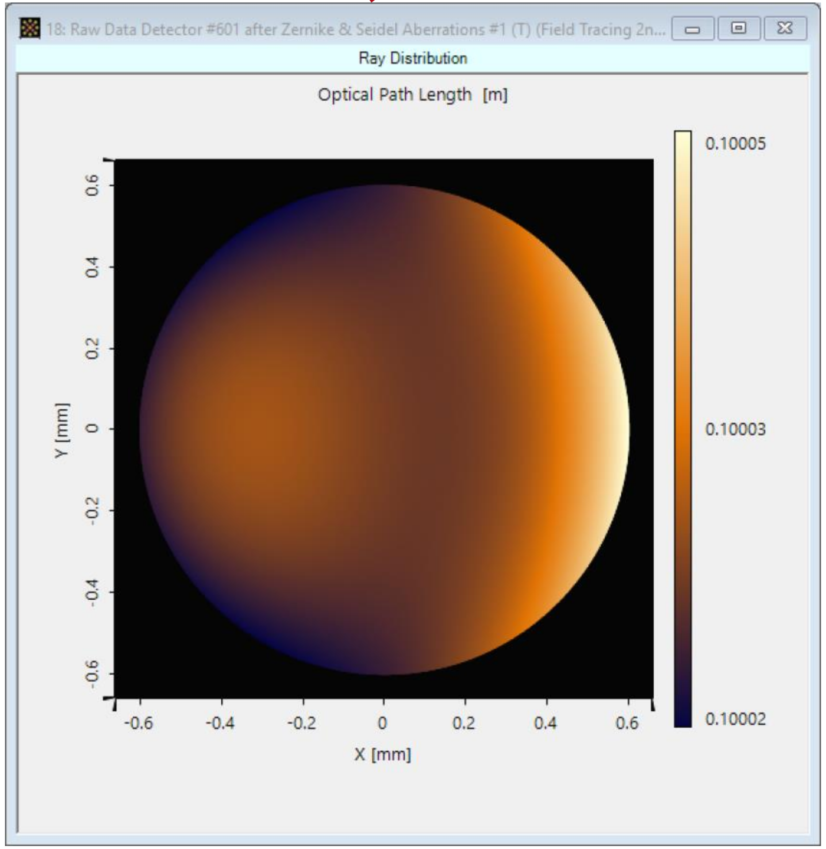
$$V_\ell(\boldsymbol{\rho},z,\omega) = |V_\ell(\boldsymbol{\rho},z,\omega)| \exp\left(\mathrm{i}\varphi_\ell(\boldsymbol{\rho},z,\omega)\right) \exp\left(\mathrm{i}\psi(\boldsymbol{\rho},z,\omega)\right)$$

Arbitrary amplitude and phase of diffractive factor.

General Example with Aberrations

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





Wavefront Phase of Electromagnetic Fields

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

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

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

FFT requires sampling of complex amplitude V

Wavefront Phase of Electromagnetic Fields

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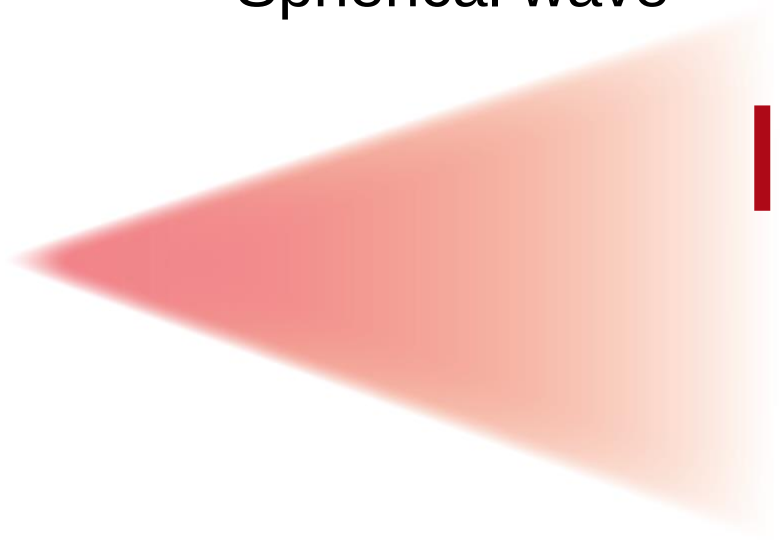
To enable fast physical optics modeling we must avoid sampling of strong wavefront phase factors for Fourier transform.

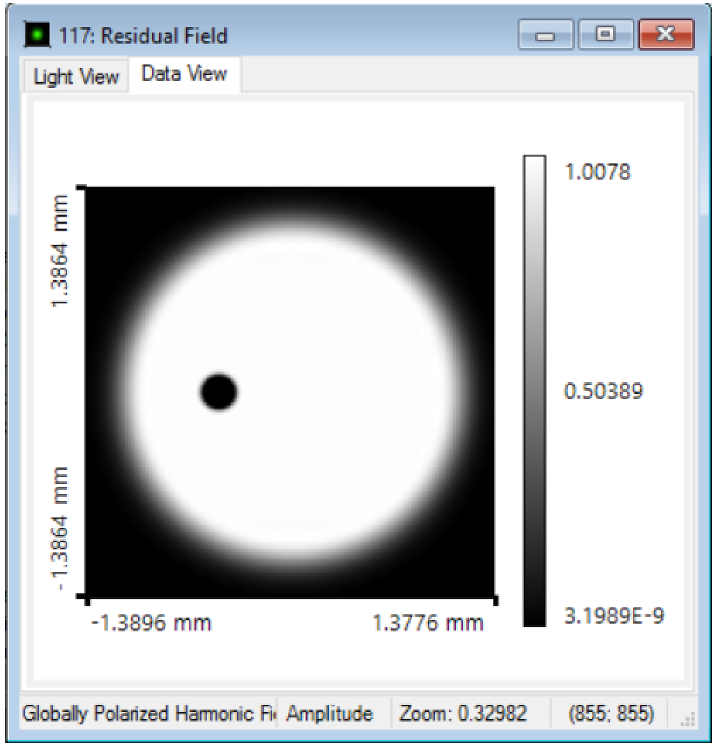
Modeling the Propagation Through a Stop

Spherical wave

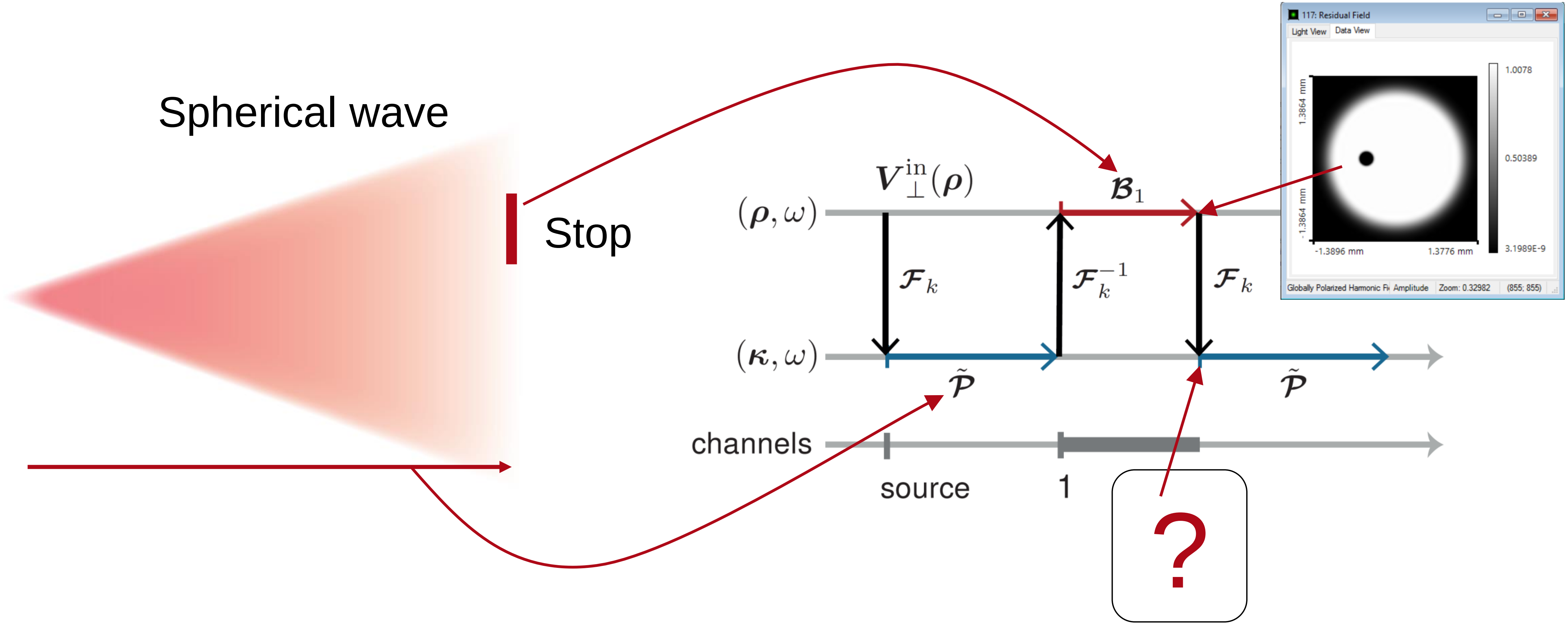


Stop

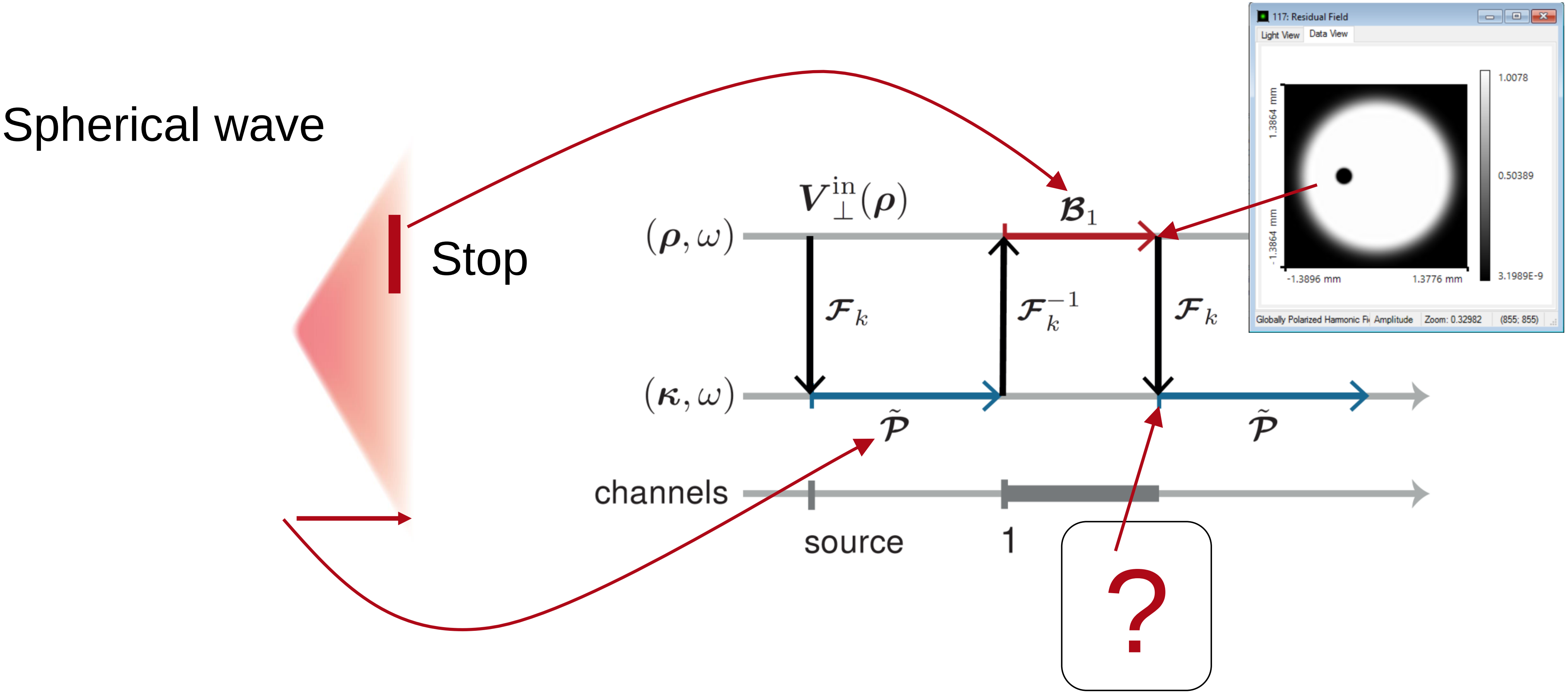
Field after stop (Amplitude)



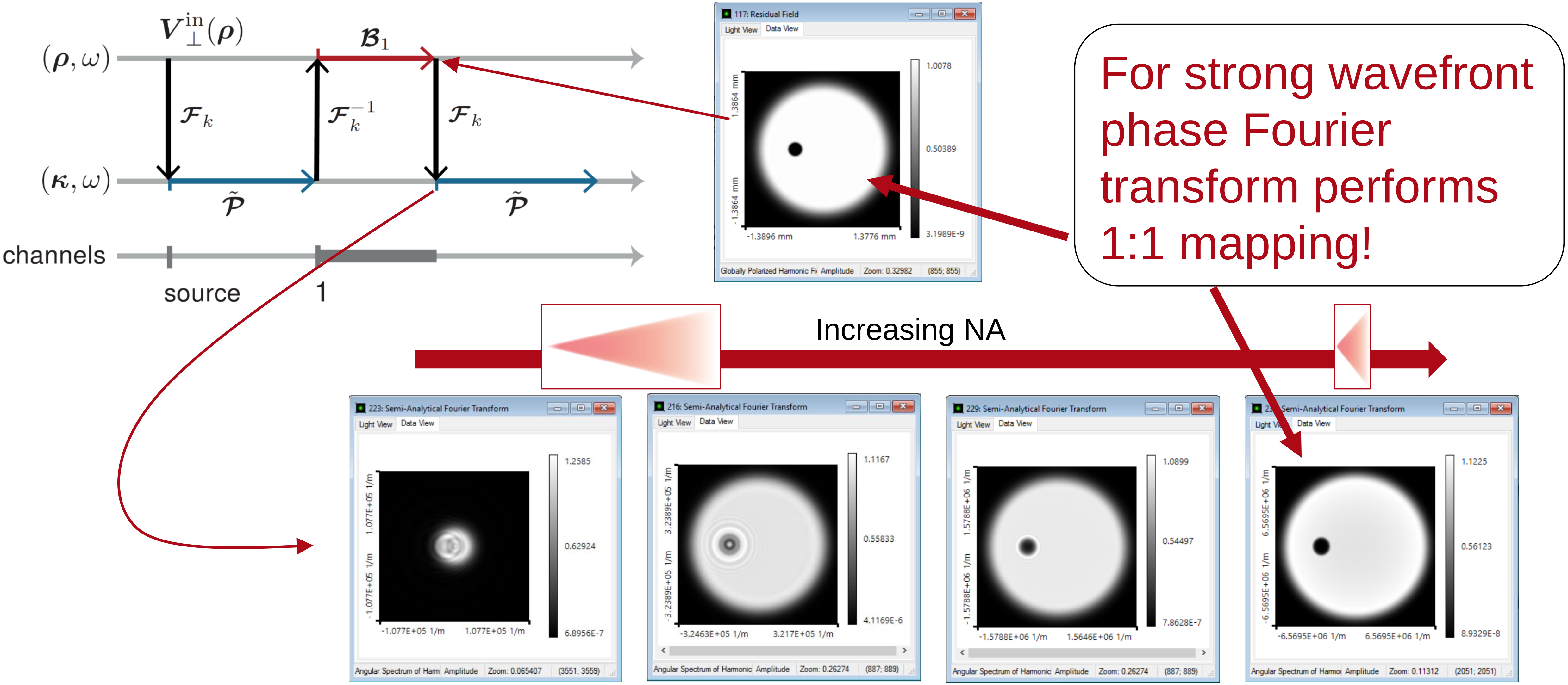
Modeling the Propagation Through a Stop



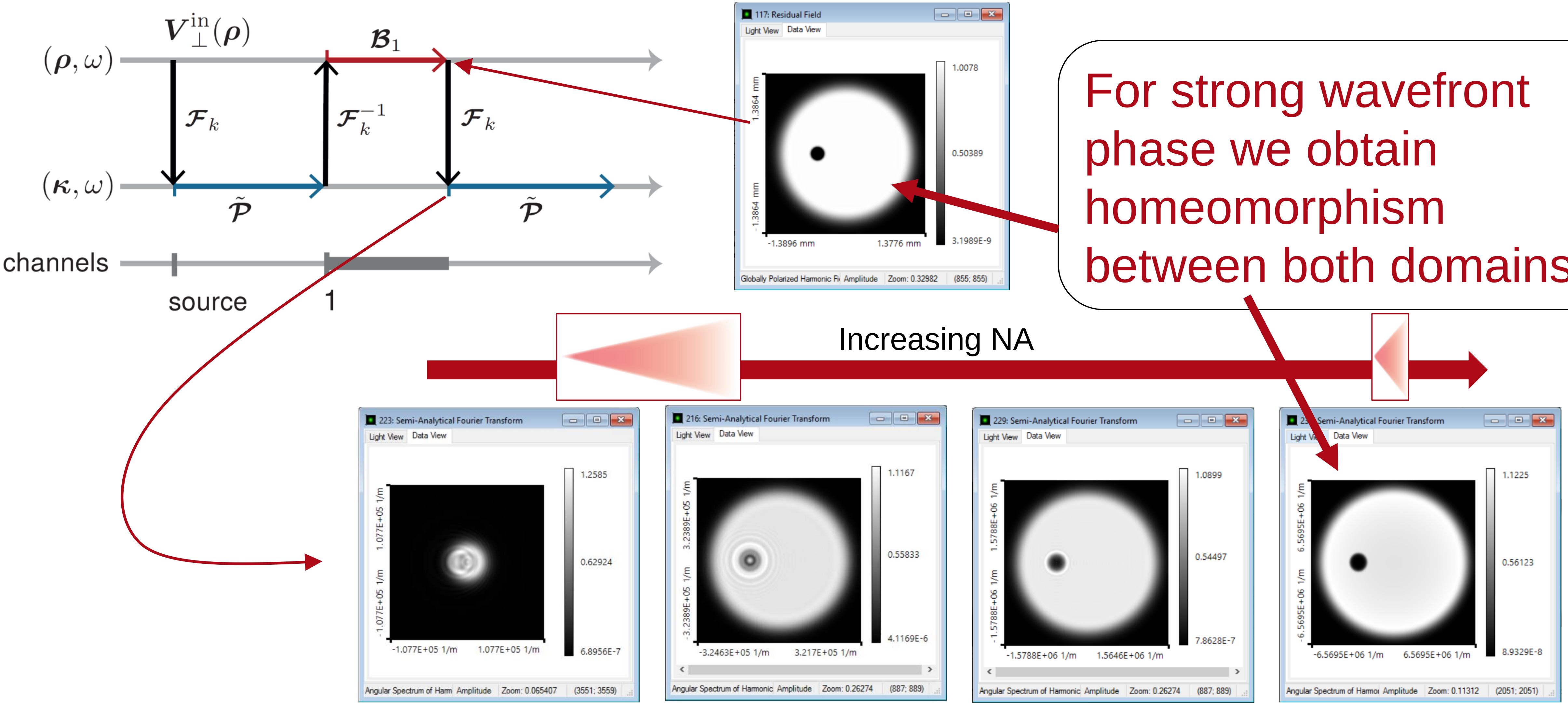
Modeling the Propagation Through a Stop



Results of Fourier Transform



Results of Fourier Transform



For strong wavefront phase we obtain homeomorphism between both domains.

Homeomorphic Fourier Transform

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

Homeomorphic Fourier Transform

- The mapping characteristic can be mathematically derived by application of the s…

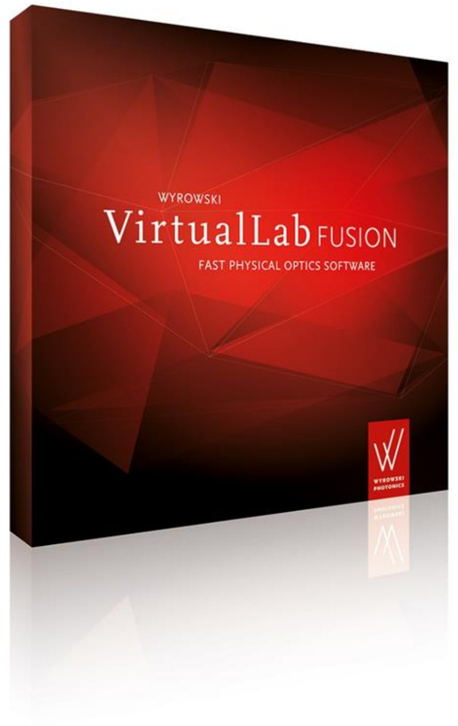
Mathematics of homeomorphic Fourier transform quite straightforward.

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

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

Types of Fourier Transform Algorithms in VirtualLab Fusion

- Fast Fourier Transform FFT
  - Fast for weak wavefront phase
- Semianalytical Fourier transform
  - Fast for wavefront phase with medium local gradient



Linear and Quadratic Wavefront Phases

- We assume to have field components of the form

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

  with the polynomial phase of 2nd degree

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

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

Linear and Quadratic Wavefront Phases

- We assume to have field components of the form

$$V_\ell(\boldsymbol{\rho}) = U_\ell(\boldsymbol{\rho}) \exp\left(\mathrm{i}\psi(\boldsymbol{\rho})\right)$$

$$= U_\ell(\boldsymbol{\rho}) \exp\left(\mathrm{i}\psi^{\mathrm{res}}(\boldsymbol{\rho})\right) \exp\left(\mathrm{i}\psi_{\mathrm{q}}(\boldsymbol{\rho})\right)$$

$$\int_{-\infty}^{\infty} \exp(c'_1 x - c_2 x^2)\,\mathrm{d}x = \sqrt{\frac{\pi}{c_2}} \exp\left(\frac{c'^2_1}{4c_2}\right)$$

with the polynomial phase of 2nd degree

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

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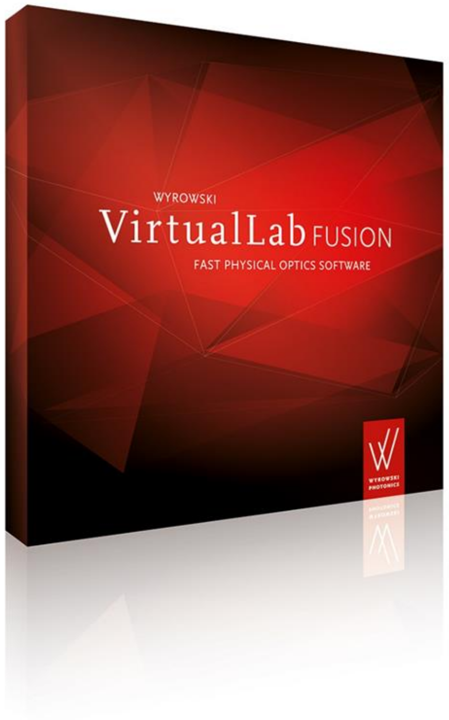
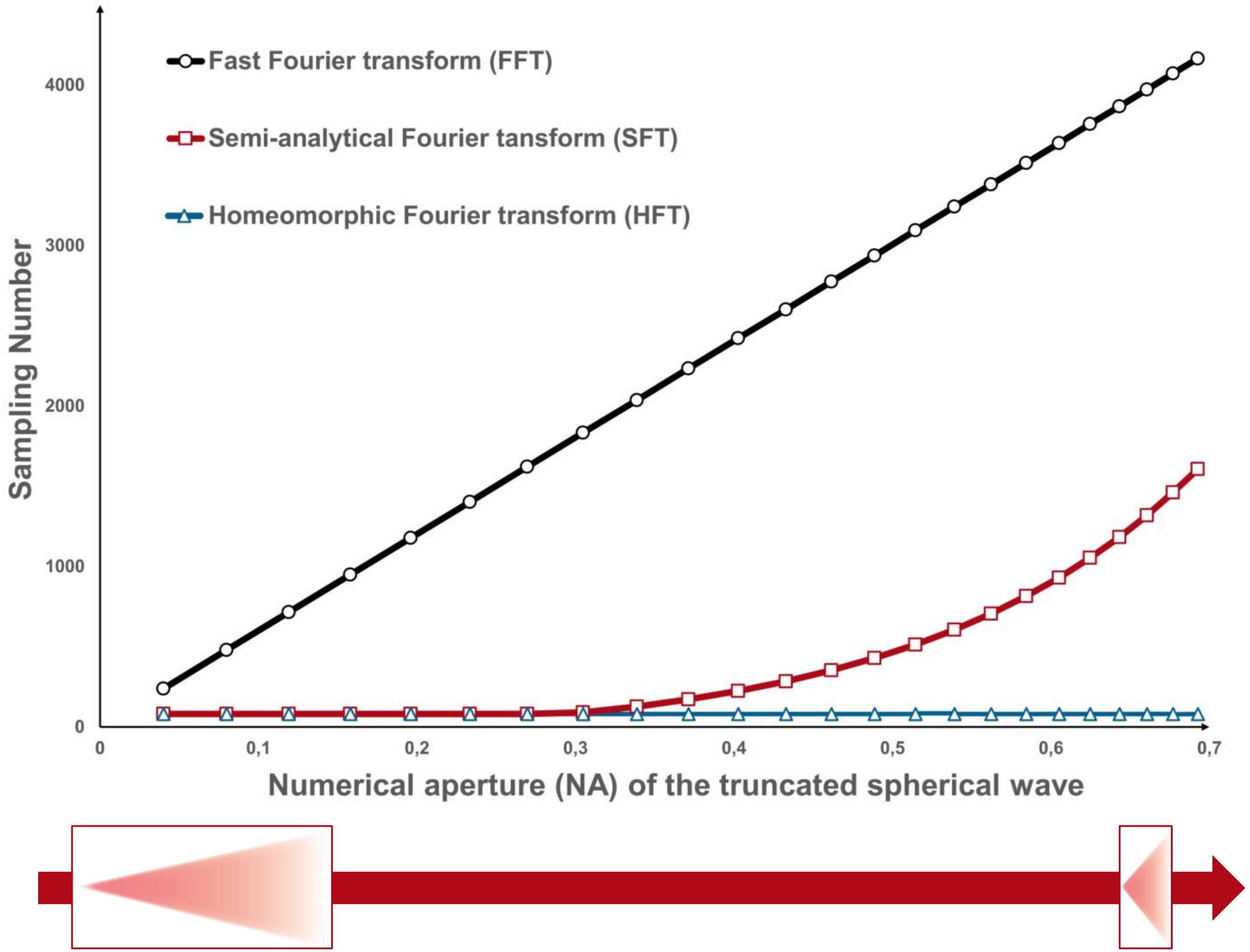
Types of Fourier Transform Algorithms in VirtualLab Fusion

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

→ Combination of Fourier transform algorithms essential for fast physical optics!



Triad of Fourier Transform Techniques



Triad of Fourier Transform Techniques